# M82 starburst galaxy: possible origin of the northern hot spot

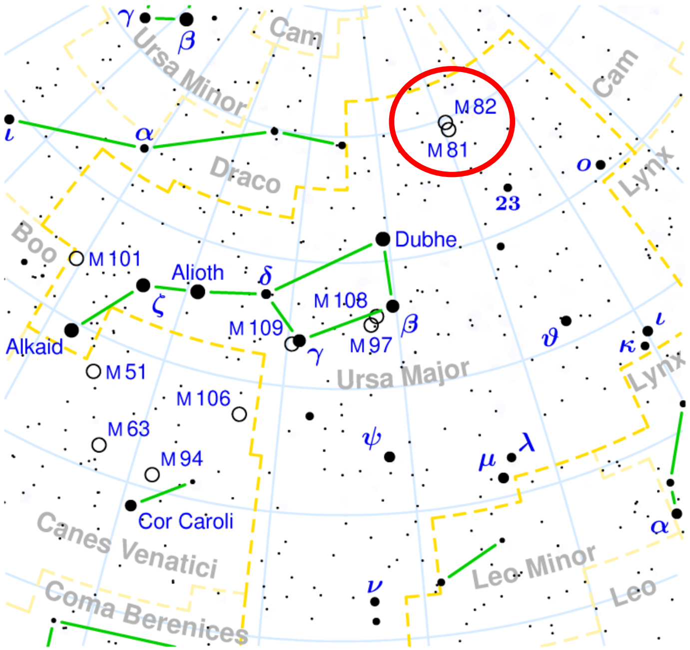
Toshikazu Ebisuzaki and Akira Mizuta (RIKEN)

Toshiki Tajima (UC Irvine)

# contents

1. Star burst galaxy M82 and North hot spot
2. Bow wake acceleration
3. Bending by cosmological filaments
4. Conclusion

# M82 galaxy

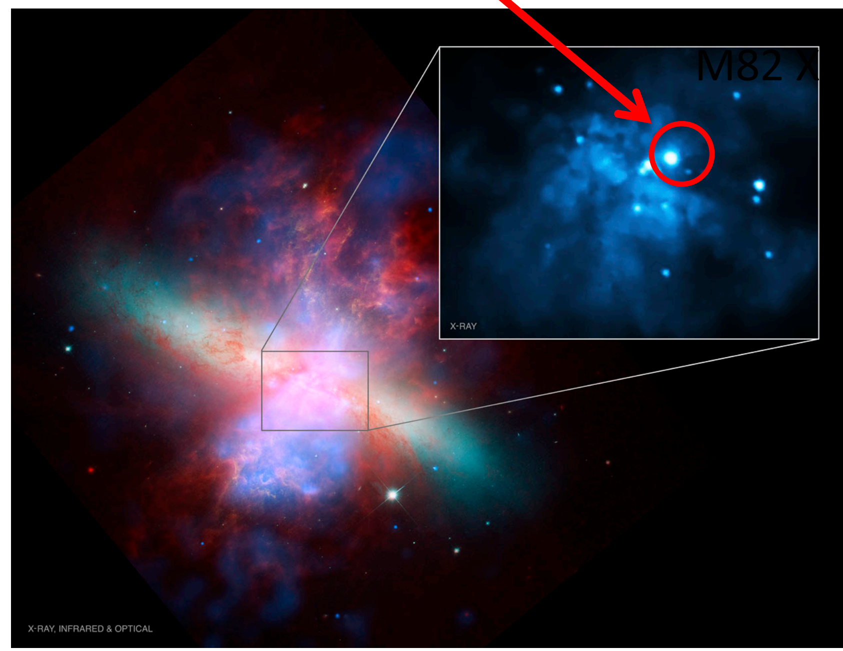


M 82
M 81
Dubhe
Alioth
Alkaid
M 101
M 108
M 109
M 97
M 51
M 106
M 63
M 94
Cor Caroli
Ursa Minor
Draco
Cam
Lynx
Boo
Ursa Major
Canes Venatici
Coma Berenices
Leo Minor
Leo
23


# M82: Nearest Star Burst Galaxy

M82 X-1: 100-10000 Ms BH

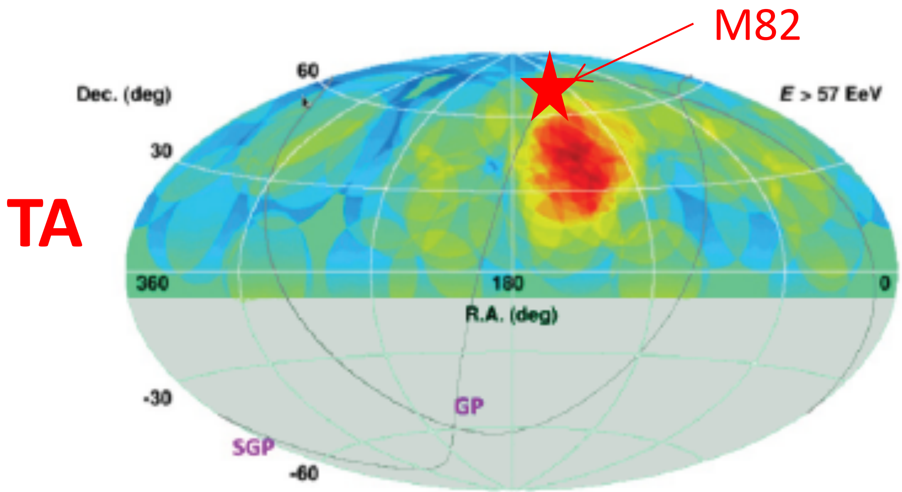
Just after the collision with M81

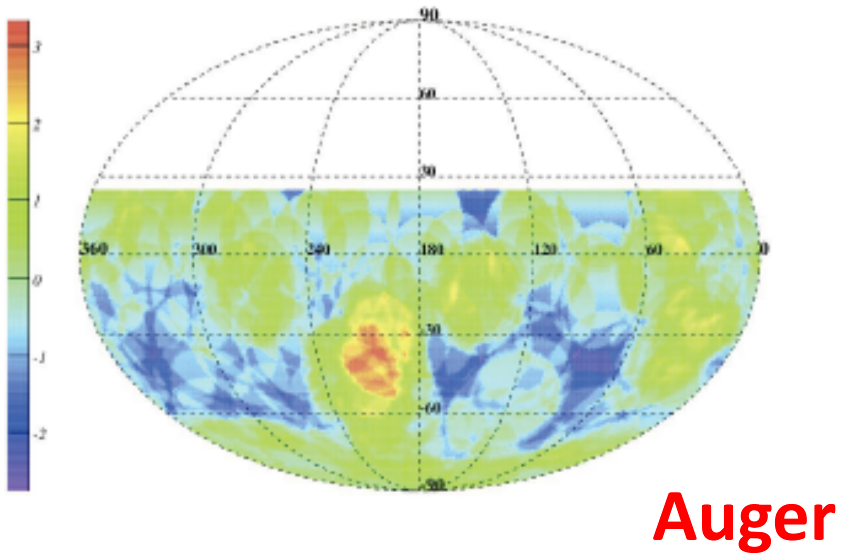



Composite of X-ray, IR, and optical emissions

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.

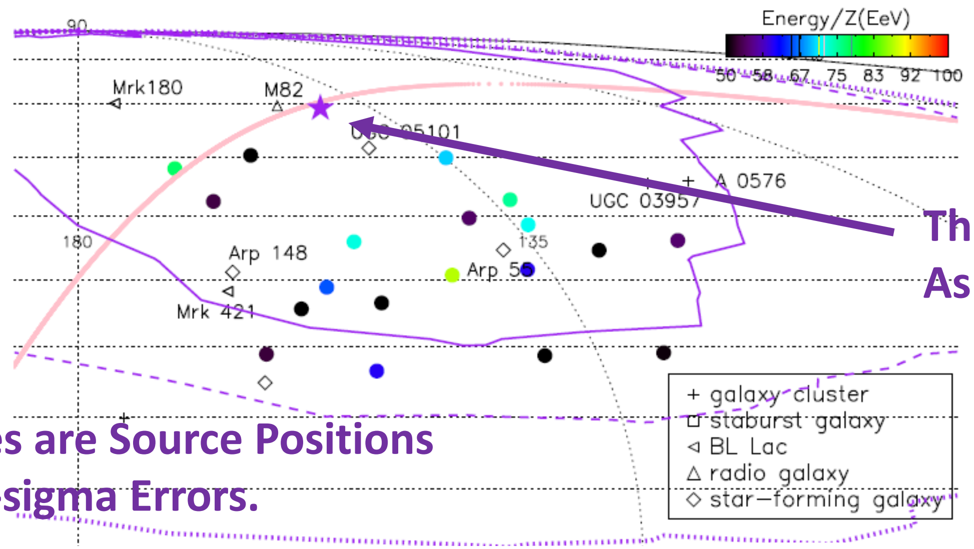
# Arrival Direction Map (Auger/TA)



# 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 |

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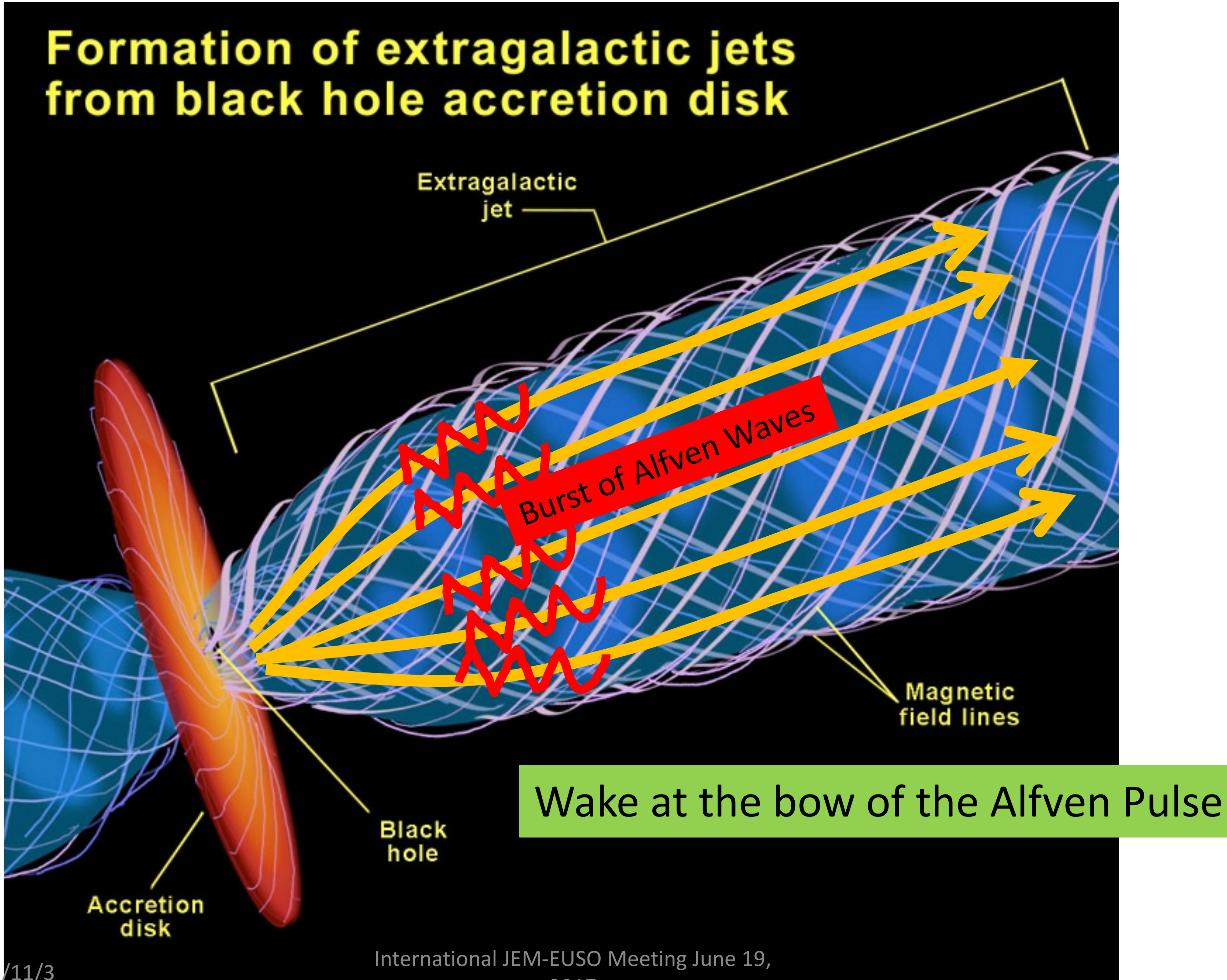
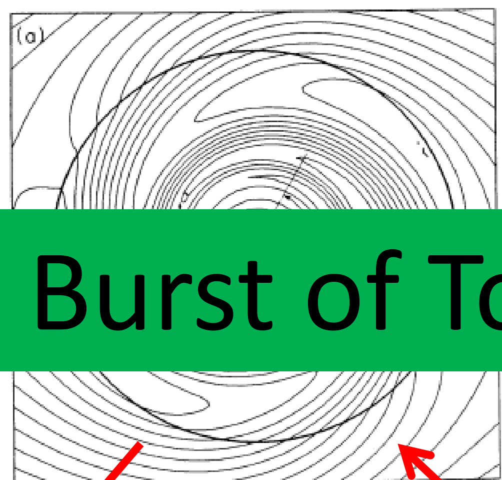
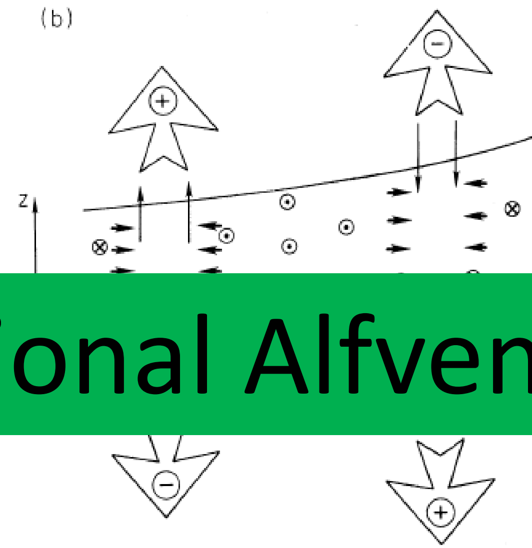
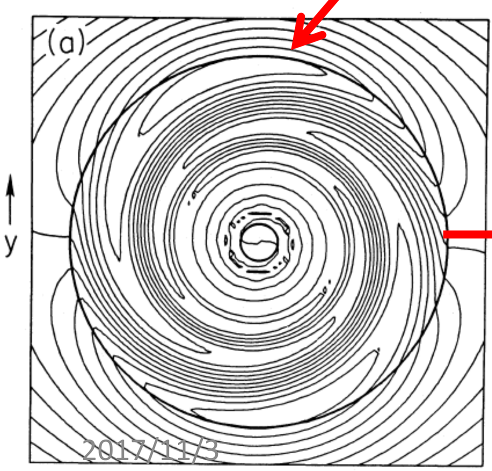

Formation of extragalactic jets from black hole accretion disk
Extragalactic jet
Burst of Alfven Waves
Magnetic field lines
Wake at the bow of the Alfven Pulse
Black hole
Accretion disk

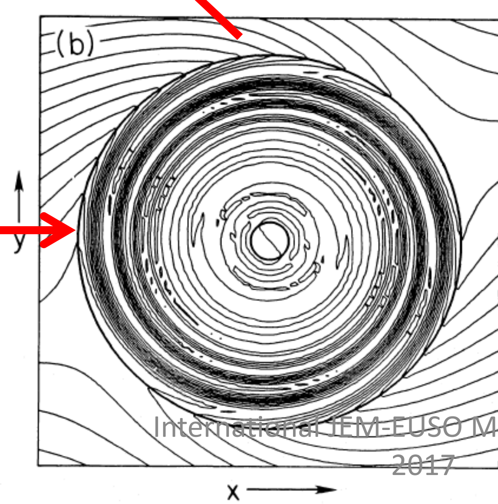
# Eruption of magnetic field in an accretion disk



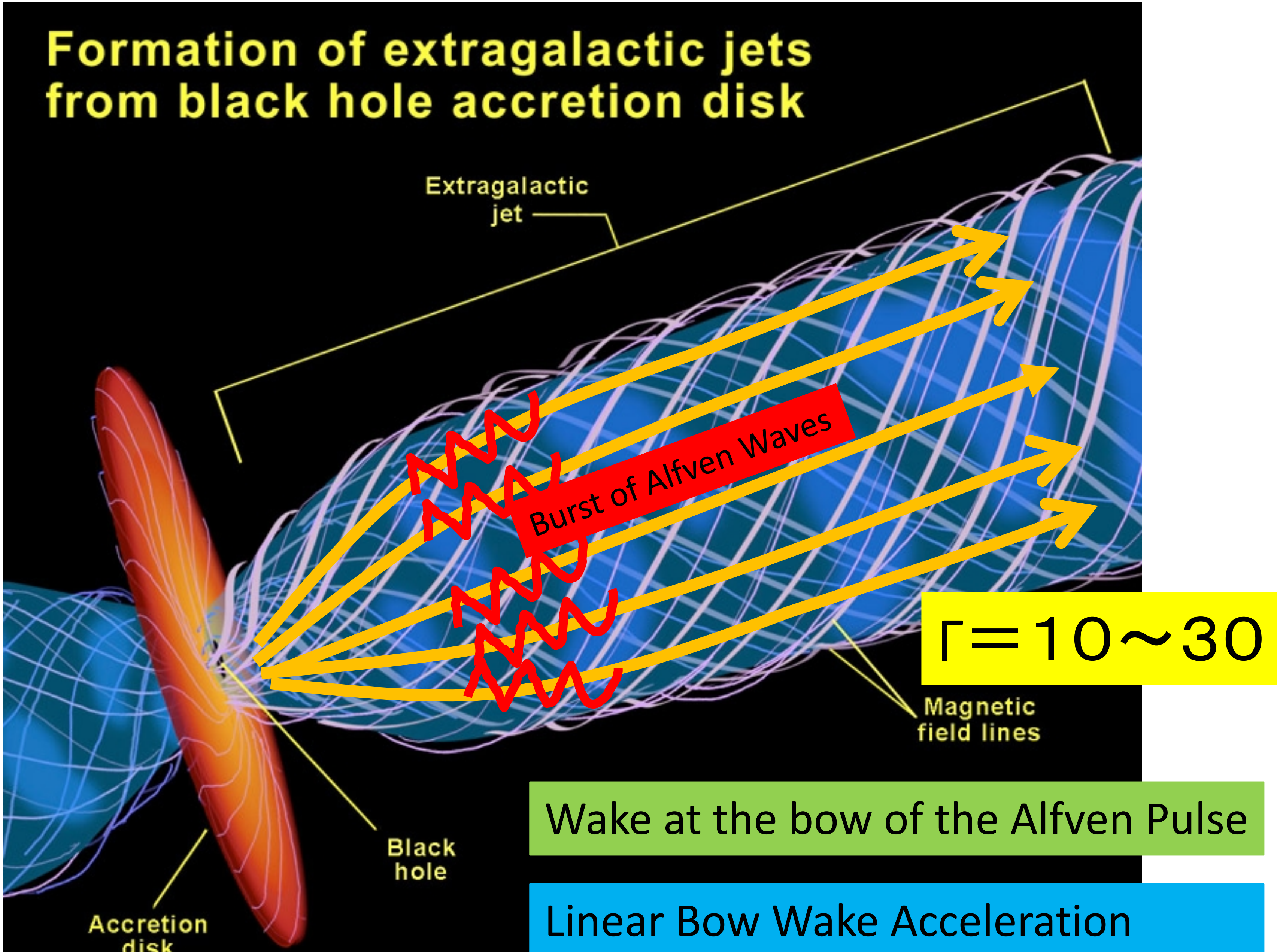




## A Burst of Torsional Alfven Waves




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


Formation of extragalactic jets
from black hole accretion disk
Extragalactic
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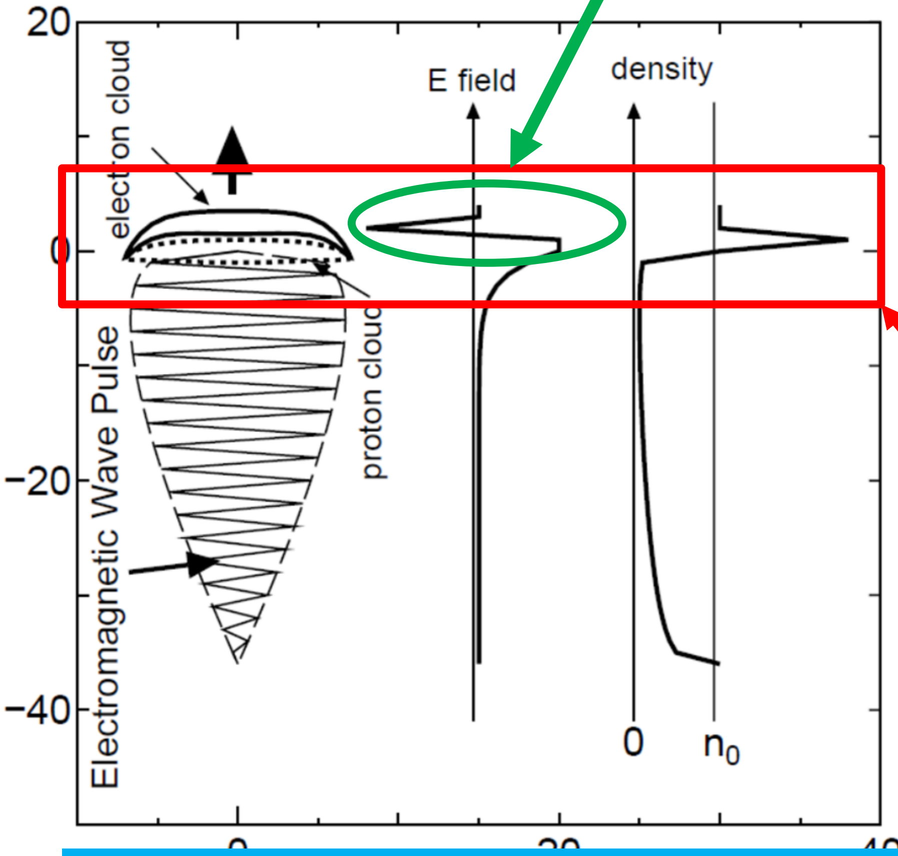
Burst of Alfven Waves
Γ＝10～30
Magnetic
field lines
Black
hole
Accretion
disk
Wake at the bow of the Alfven Pulse
Linear Bow Wake Acceleration

# Bow wake acceleration





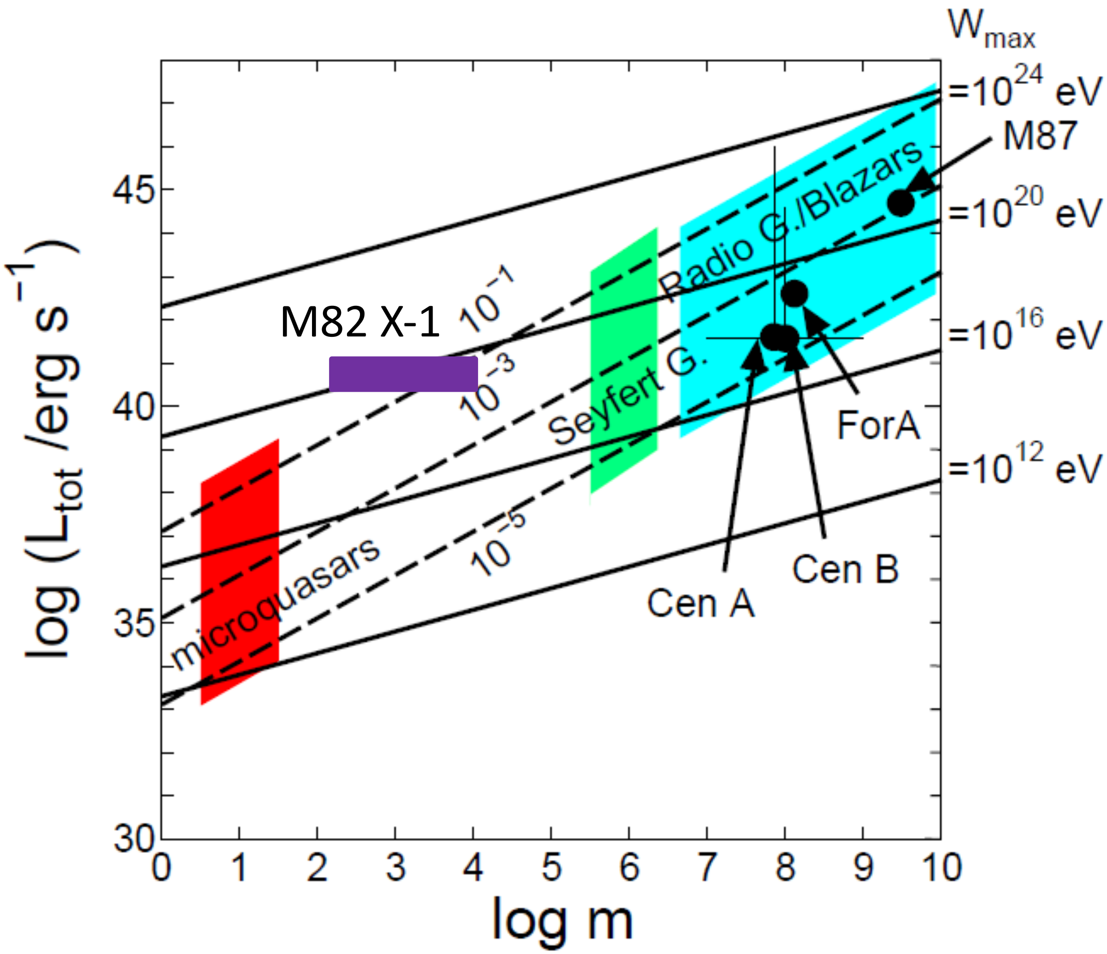
One of the wake field acceleration, which takes place when $a_0$>>1

# Acceleration by pondermotive force at "bow wake"

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

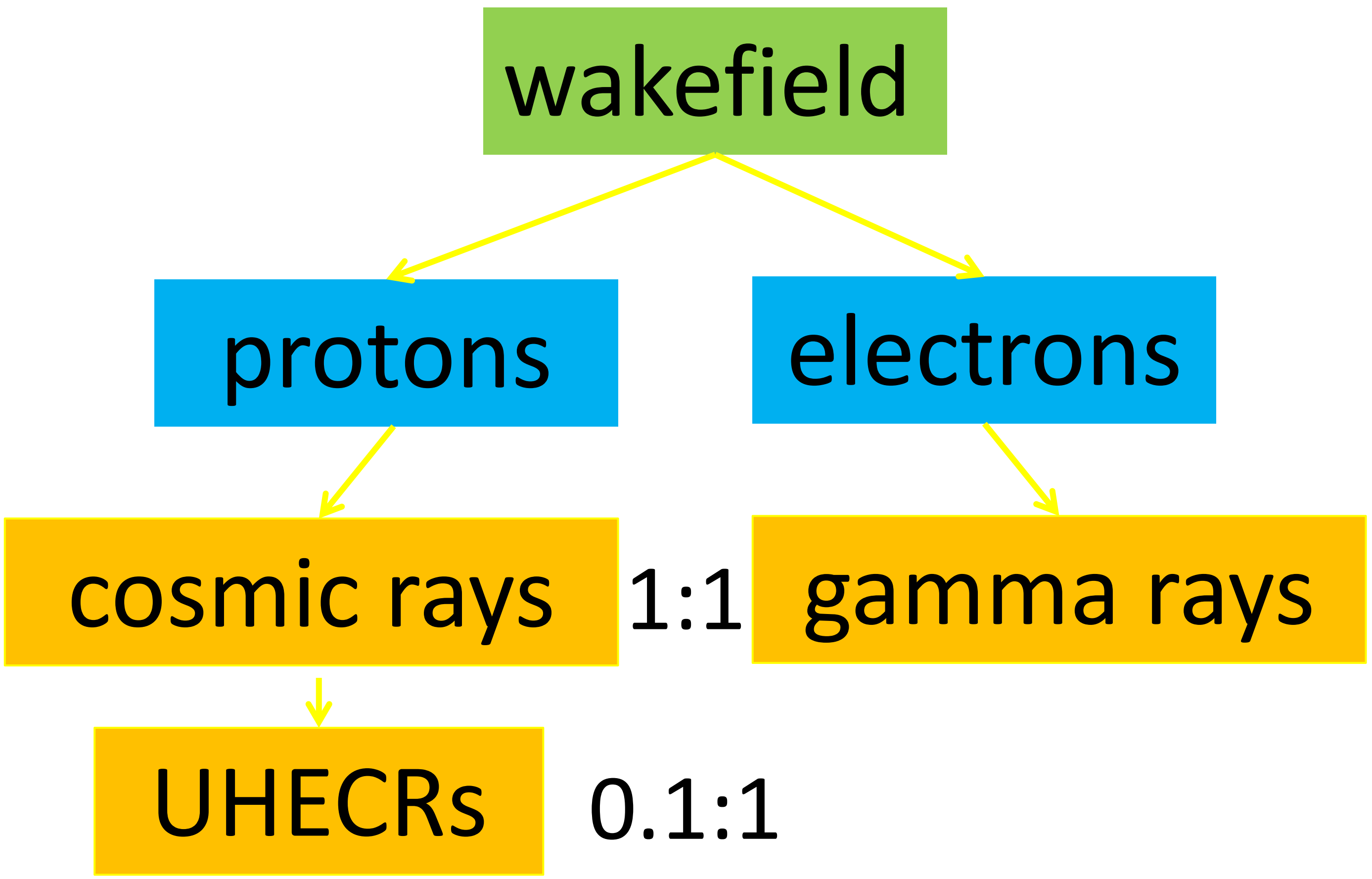
$$F_{\mathrm{pm}} = \Gamma m_{\mathrm{e}} c a_0 \omega_A$$

# comic ray acceleration and gamma-ray emission




$$L_{\text{tot}} = 1.3\times10^{38} m\dot{m}\ \text{erg s}^{-1}$$

# Energy Flow and Spectra

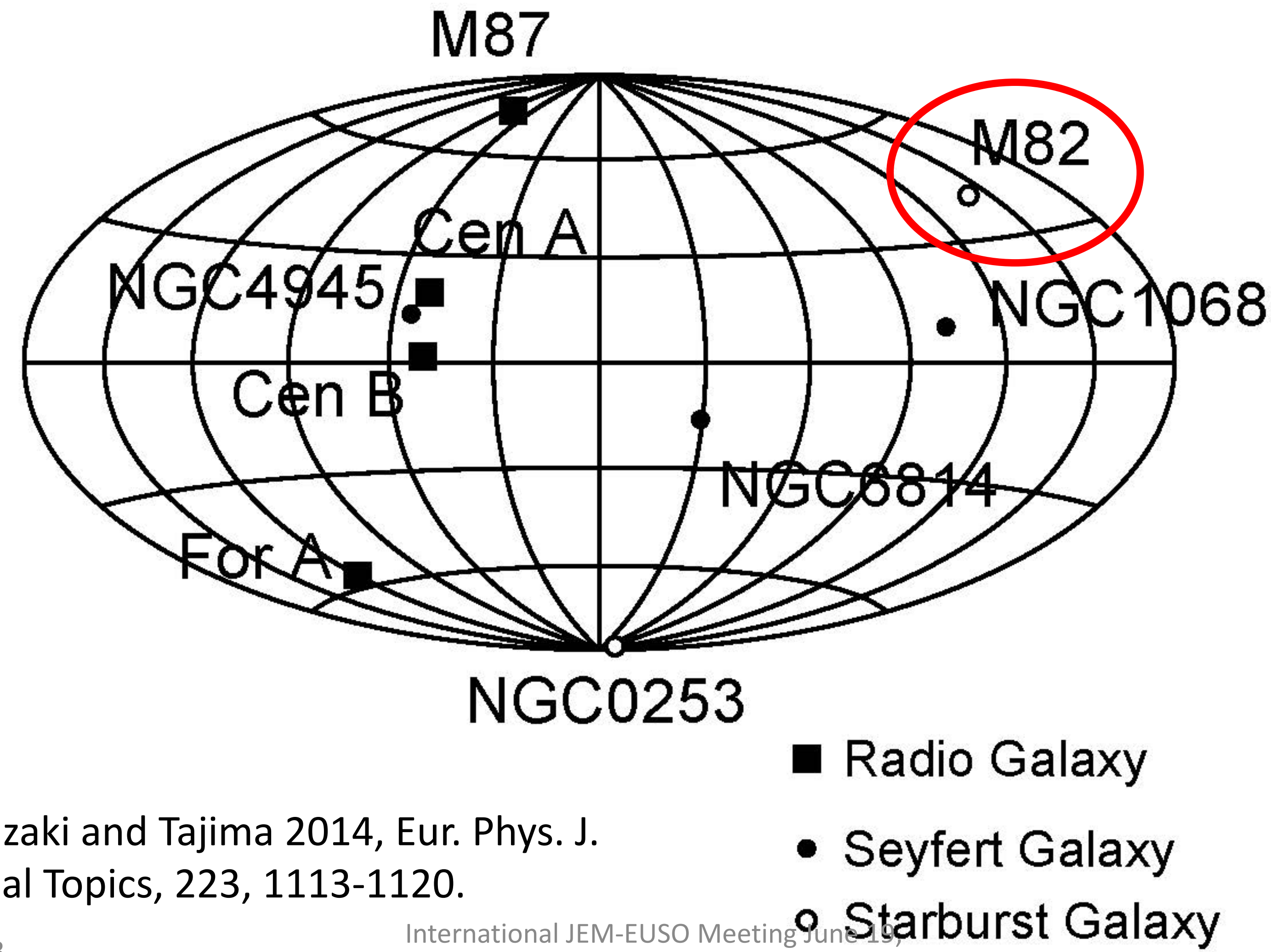



$$F(W) \propto W^{-2}$$

# 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.

# M82 X-1 is promising

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

  $L_{\gamma \mathrm{M82}} = 1.3 \times 10^{42}$ erg s$^{-1}$
- 1% of M82 total$\leftarrow$M82 X-1

  $L_{\mathrm{UHECR\ M82X-1}} = 1.3 \times 10^{39}$ erg s$^{-1}$

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

  $F_{\mathrm{UHECR\ M82X-1}} \sim 3$ UHECRs/100km$^2$/yr

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

# Astrophysical Implication

- Hot spot component came from M82
  - too near for GZK (D=3.4 Mpc)
  - mainly proton
- How about magnetic deflection?
  - We need $B \sim 10$ nG for $D = 3.2$ Mpc
    - $\theta = 0.5° \left(\frac{D}{\mathrm{Mpc}}\right)\left(\frac{B}{\mathrm{nG}}\right) \sim 17.4°$
    - $\Delta\theta = 0.36 \left(\frac{D}{\mathrm{Mpc}}\right)^{1/2}\left(\frac{D_\mathrm{c}}{\mathrm{Mpc}}\right)^{1/2}\left(\frac{B_\mathrm{r}}{\mathrm{nG}}\right) \sim 9.4°$

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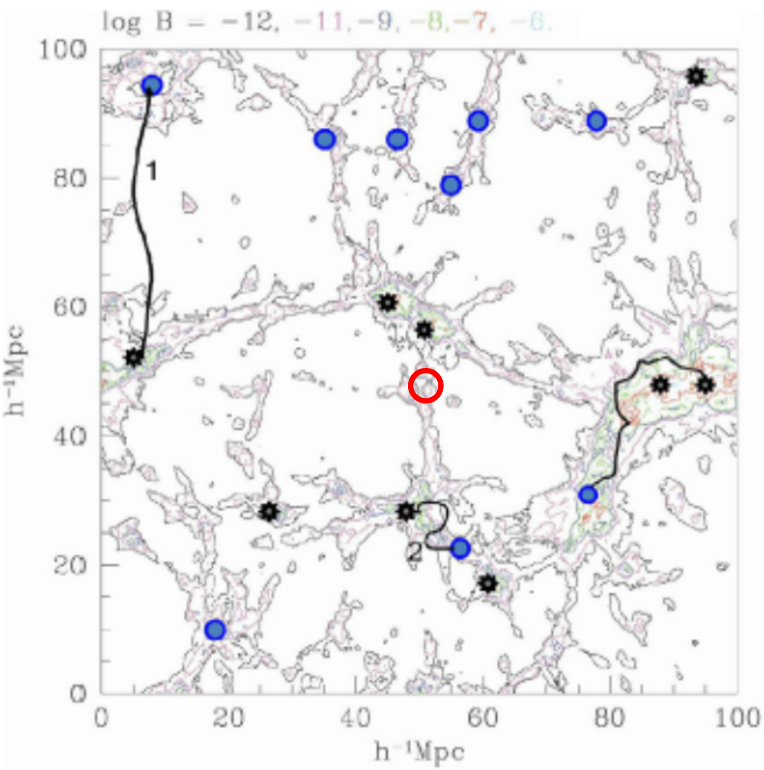
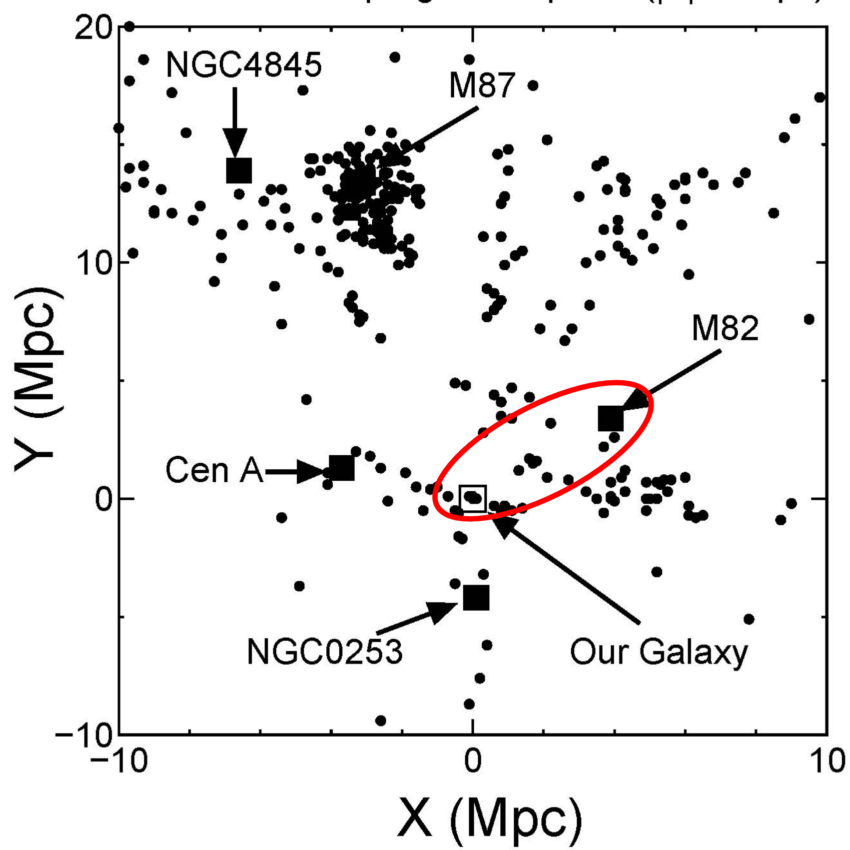
# UHECR propagation among the cosmological web (1)

Ryu et al. 2010 ApJ, 710, 1422



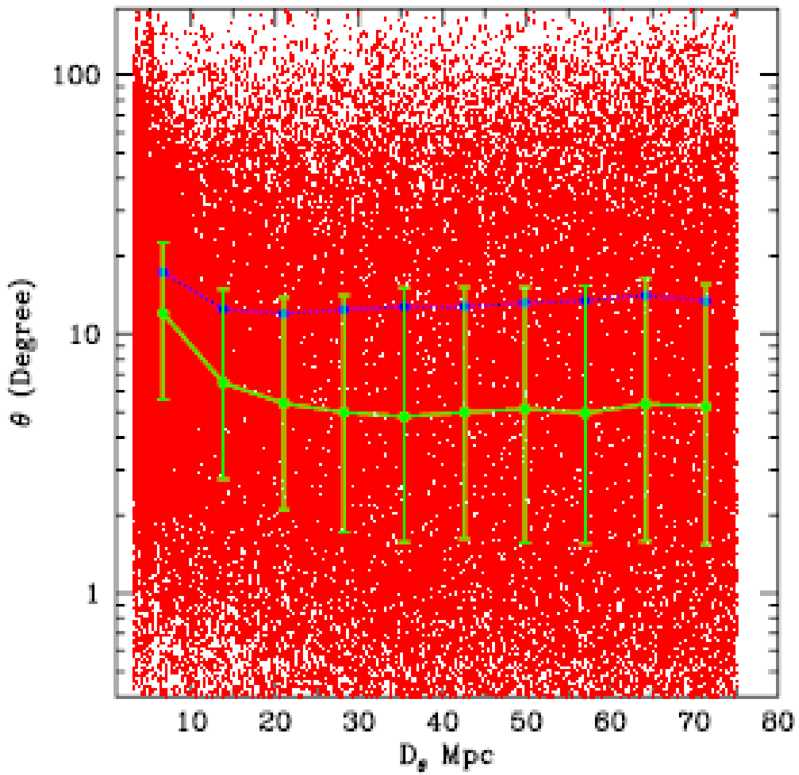

Galaxies in Supergalactic plane (|Z|<1 Mpc)




We are living on a filament of the cosmological web!

# UHECR propagation among cosmological magnetic web (2)

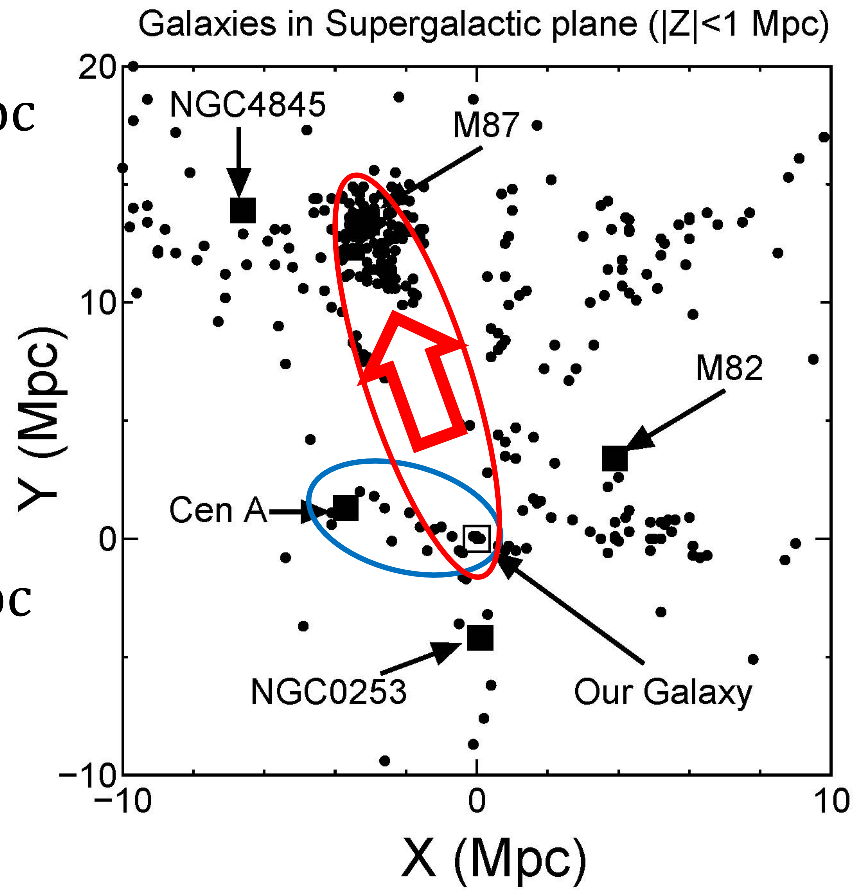
- Huge variation ～1-100°
  - Strongly depends on the source location and the path
- Average ~10°at 3 Mpc
- $\epsilon_{\mathrm{B}} = \phi\left(\frac{t}{t_{\mathrm{eddy}}}\right)\epsilon_{\mathrm{turb}}$
  - $t_{\mathrm{eddy}}$ and $\epsilon_{\mathrm{turb}}$: simulation
  - $\phi$: different simulations with fine meshes




Ryu et al. 2010 ApJ, 710, 1422

# How about Cen A and M87/Vir A ?

- **Cen A**
  - $D = 4.3\text{Mpc} \geq D_{\text{M87}} = 3.4\ \text{Mpc}$
  - **In the filaments**
  - $\theta, \Delta\theta \sim 10 - 20$ degree
  - CNO rich?
    =WR stars in the jets
- **M87/Vir A**
  - $D = 18\ \text{Mpc} \gg D_{\text{M87}} = 3.4\ \text{Mpc}$
  - **In the filaments**
    Virgo centric inflow
  - $\theta, \Delta\theta \sim 60$ degree
  - $\rightarrow$ diffuse source along SGP



# Conclusions

- **M82: the nearest starburst galaxy**
  - M82 X-1: Intermediate Mass Blackholes ($10^2$-$10^4$ Ms)
    =**possible origin of northern hot spot**
- **Bow Wake Acceleration**
  - Accreting BH+disk+jet
    = **Astronomical Linear accelerator**
  - Bursts of Intense Alfven waves ←Laser
  - Jet ←wave guide
- Bending by magnetic field
  - **$\mathbf{B \sim 10nG}$ in the cosmic filaments of local supercluster**
  - Study of **supercluster magnetic field**

# Back up

# Background Component: Numerous number of Distant Sources

Ebisuzaki and Tajima 2014

- **Distant Blazers**
  - Local gamma-ray Luminosity of blazers:

    $l_\gamma = 10^{37}\text{-}10^{38}\ \mathrm{erg\ s^{-1}\ Mpc^{-3}}$

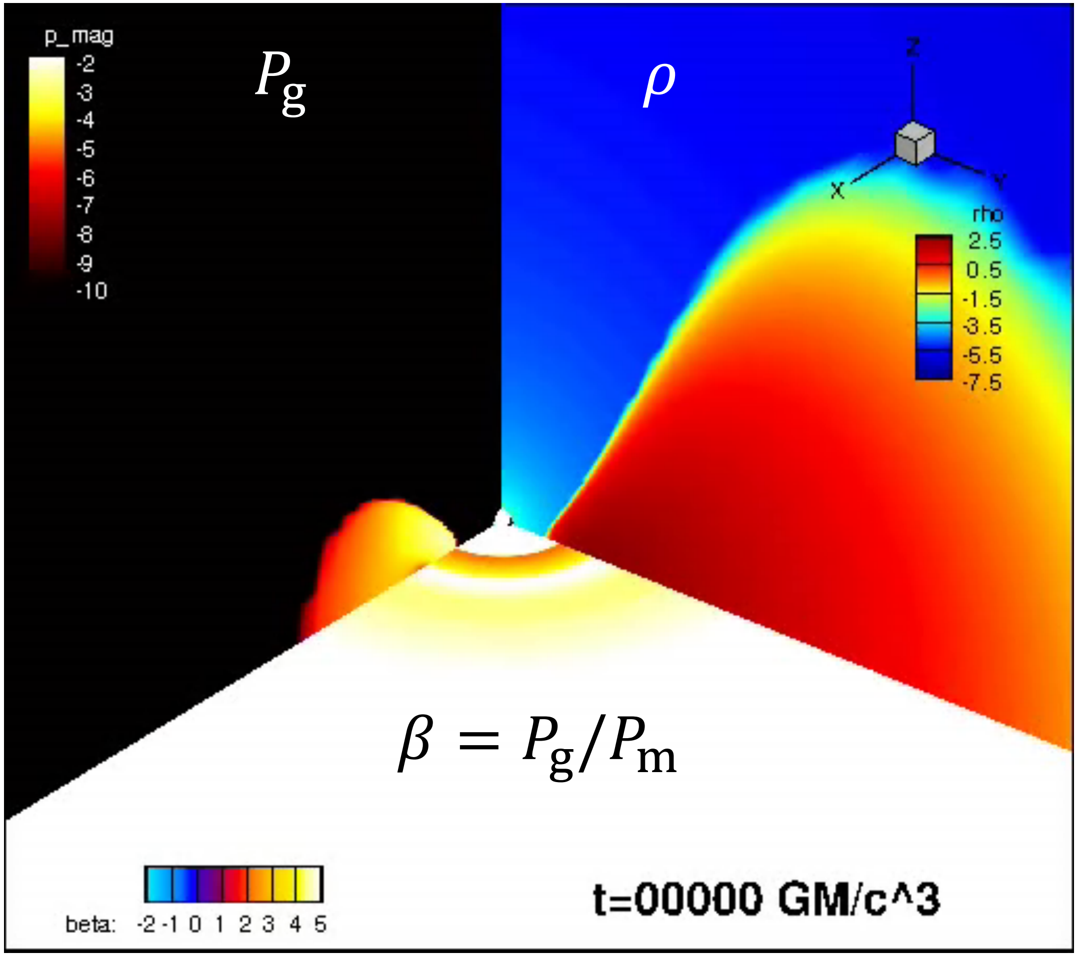
  →$\Phi_{\mathrm{UHECR}}\sim 0.1$ particles/(100 km$^2$ yr sr)

  GZK (if mainly protons)

  →$\Phi_{\mathrm{UHE}\nu}\sim 5$ particles/(100 km$^2$ yr sr)

  for $E_{\mathrm{UHE\nu}} > 10^{20}\ \mathrm{eV}$

# 3-D relativistic MHD simulation

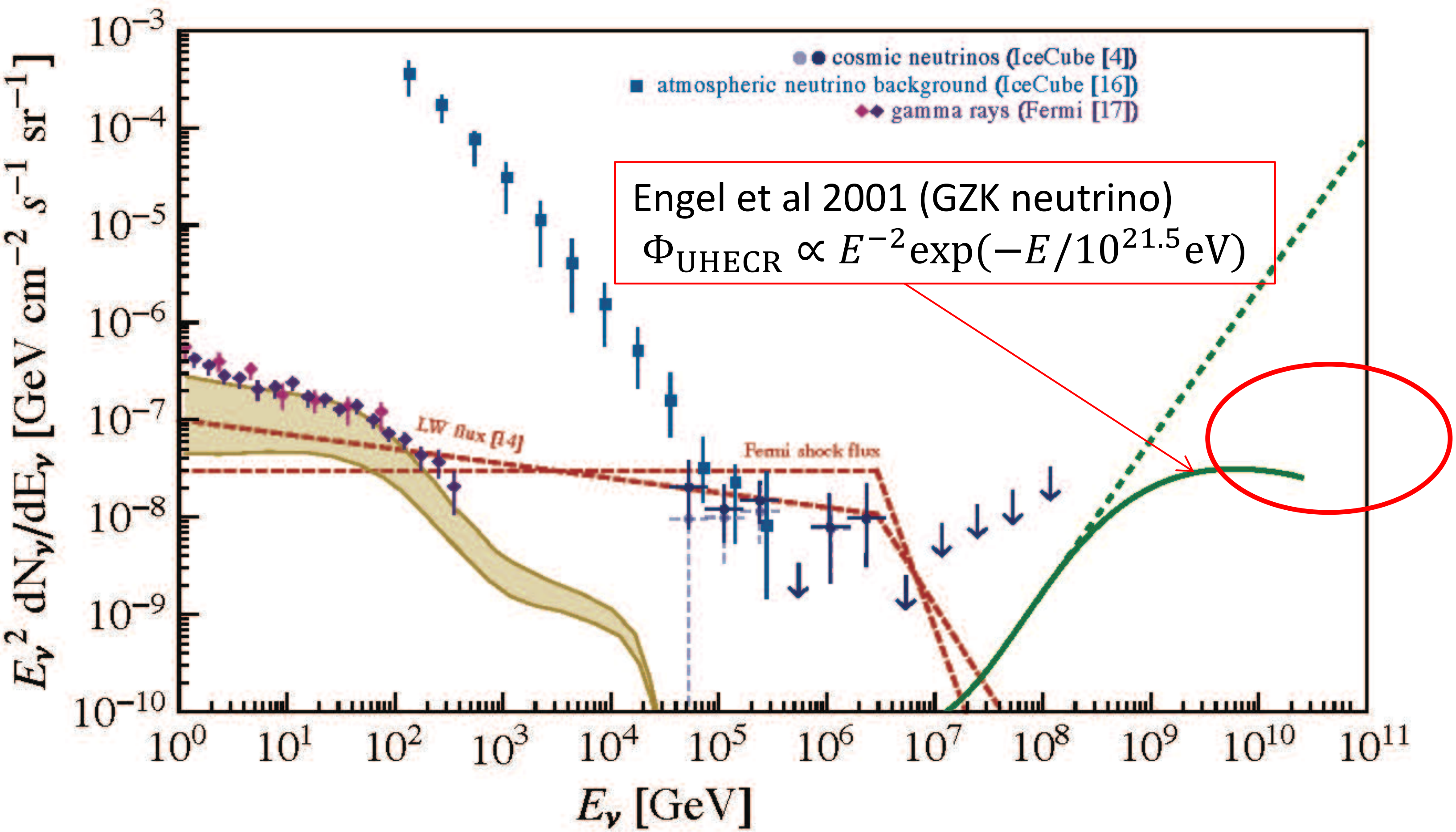







A. Mizuta et al. 2016

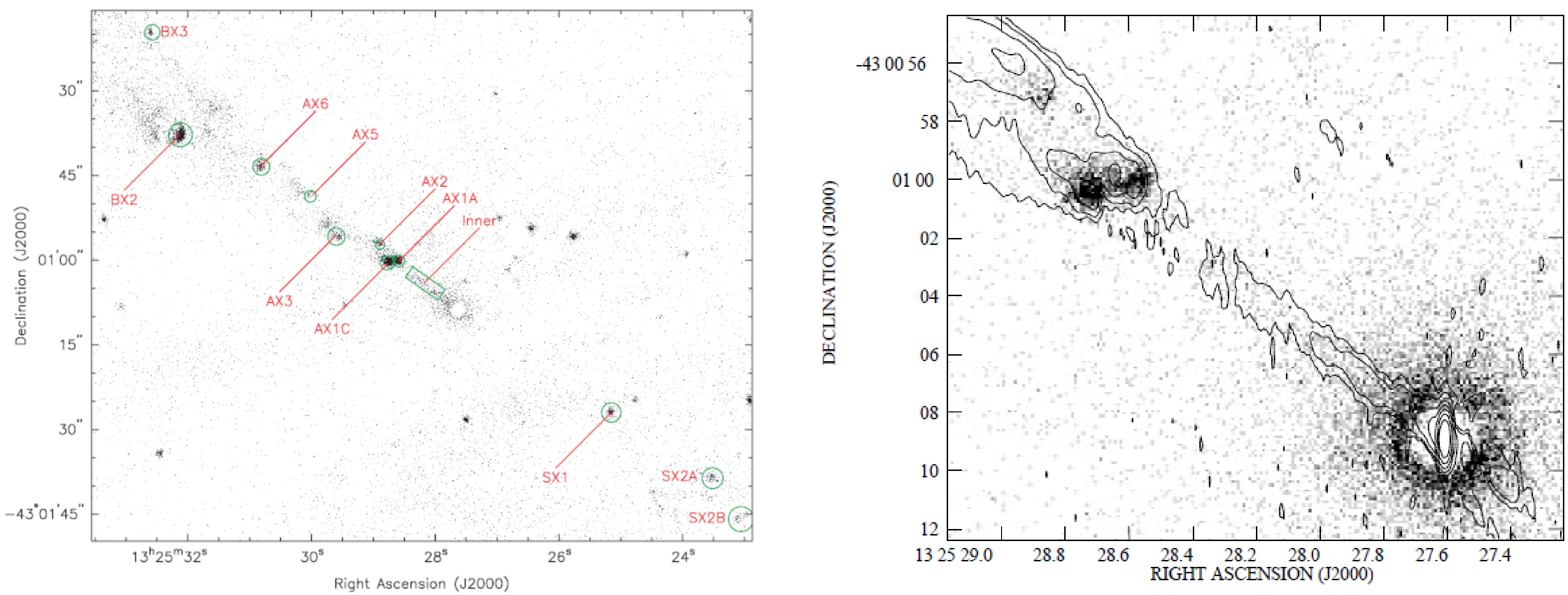
# Neutrino and gamma ray flux




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

# Radio/X-ray nots in Cen X-1 Jets

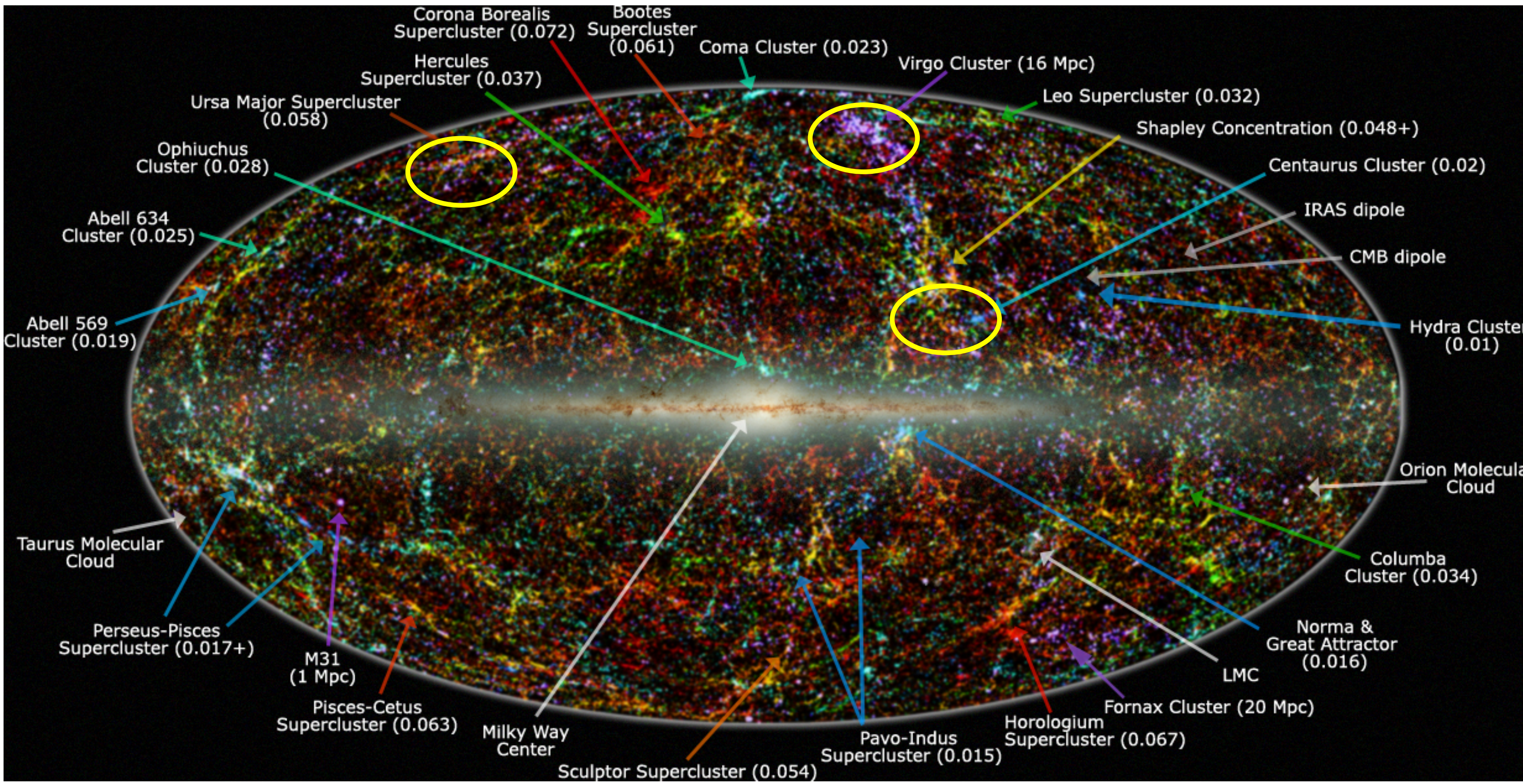
Hardcastle et al. 2003, ApJ 903 160-183




Wolf-Rayet Stars in the Jets?

effective CNO supply? ()

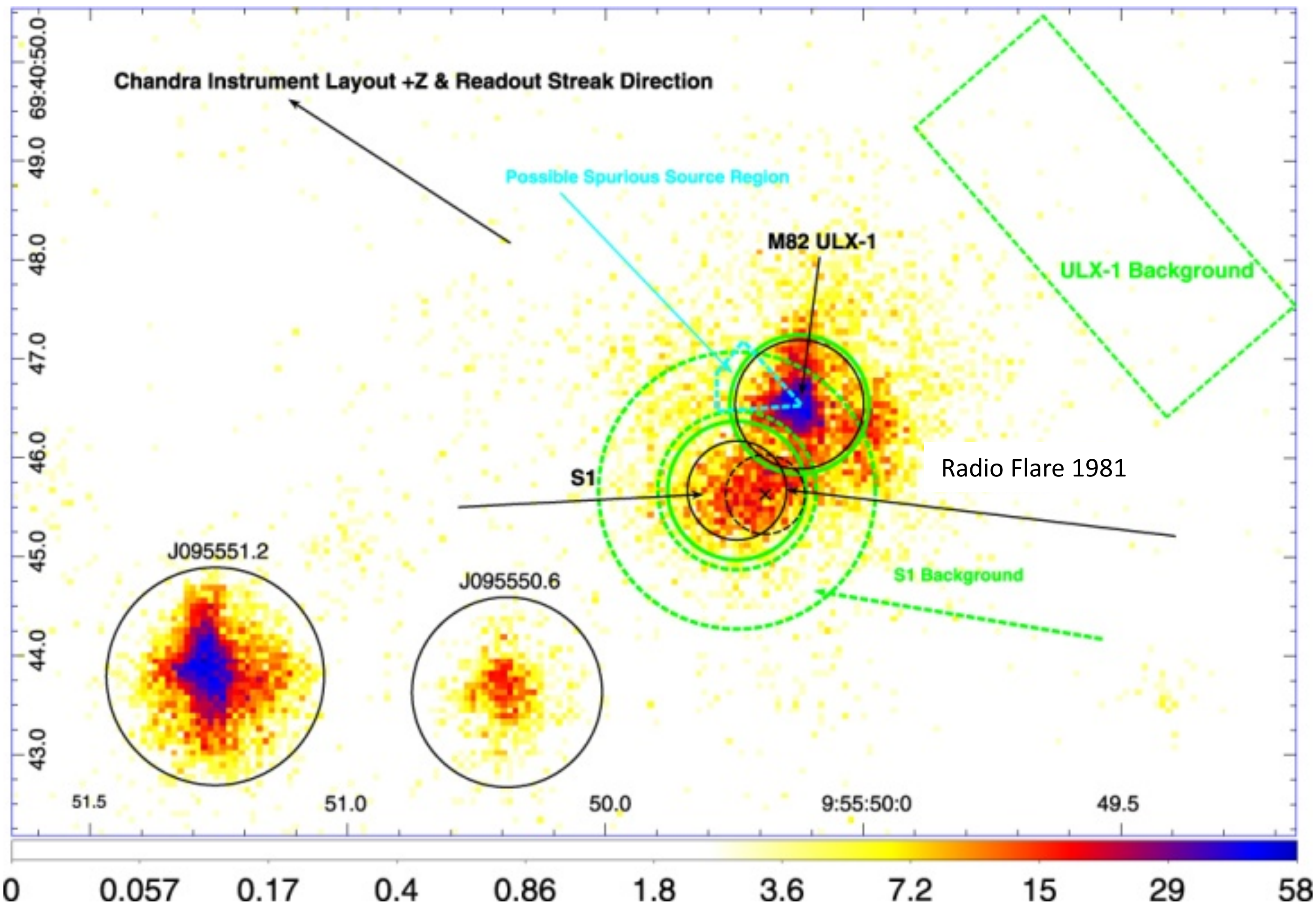
# 2MASS galaxy distribution




IPAC/Caltech, by Thomas Jarrett - "Large Scale Structure in the Local Universe: The 2MASS Galaxy Catalog", Jarrett, T.H. 2004, PASA, 21, 396

# An AGN-like Jet in M87? X-ray/Radio (flare in 1981)

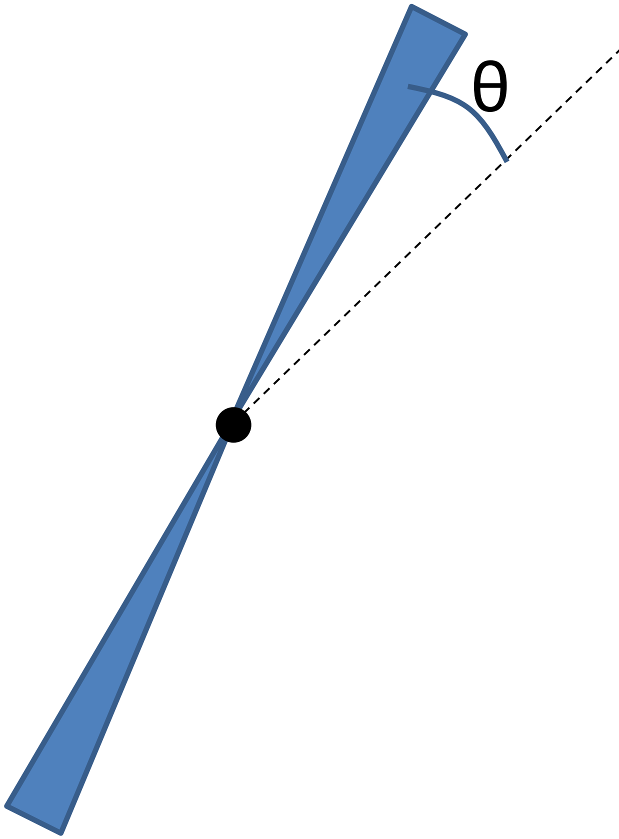
Xu et al. 2015 ApJ Letters 799, L28

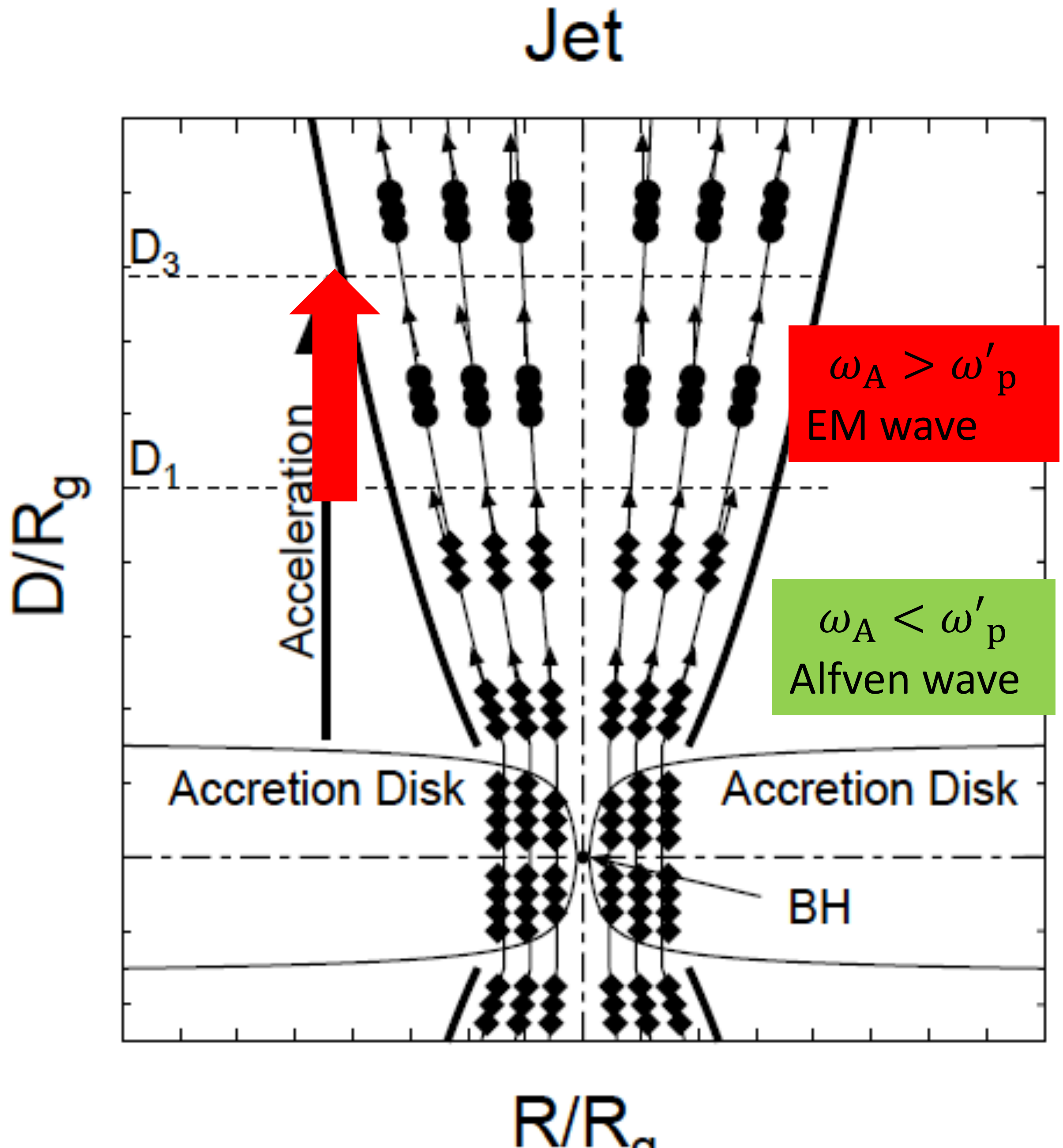


# UHECR emission: Isotropic or Beaming?

- Radio galaxies: Angle to Line of sight θ>10-20°
  - M87 43°
  - Cen A 50-80°
- Blazers: θ<10°
- No information for M82 X-1
  - Single jet?
- UHECR beam may suffer from

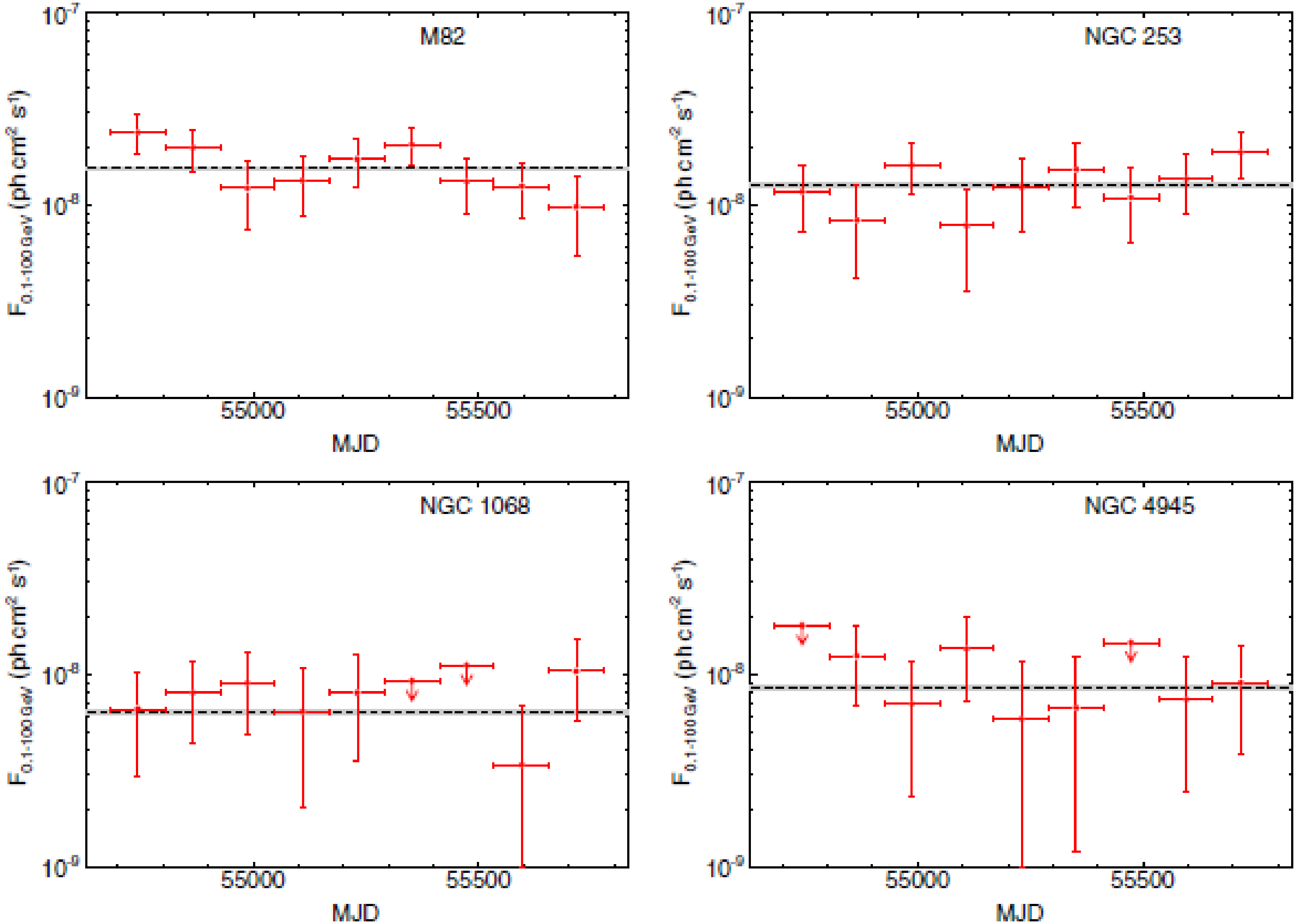
the from the local magnetic field



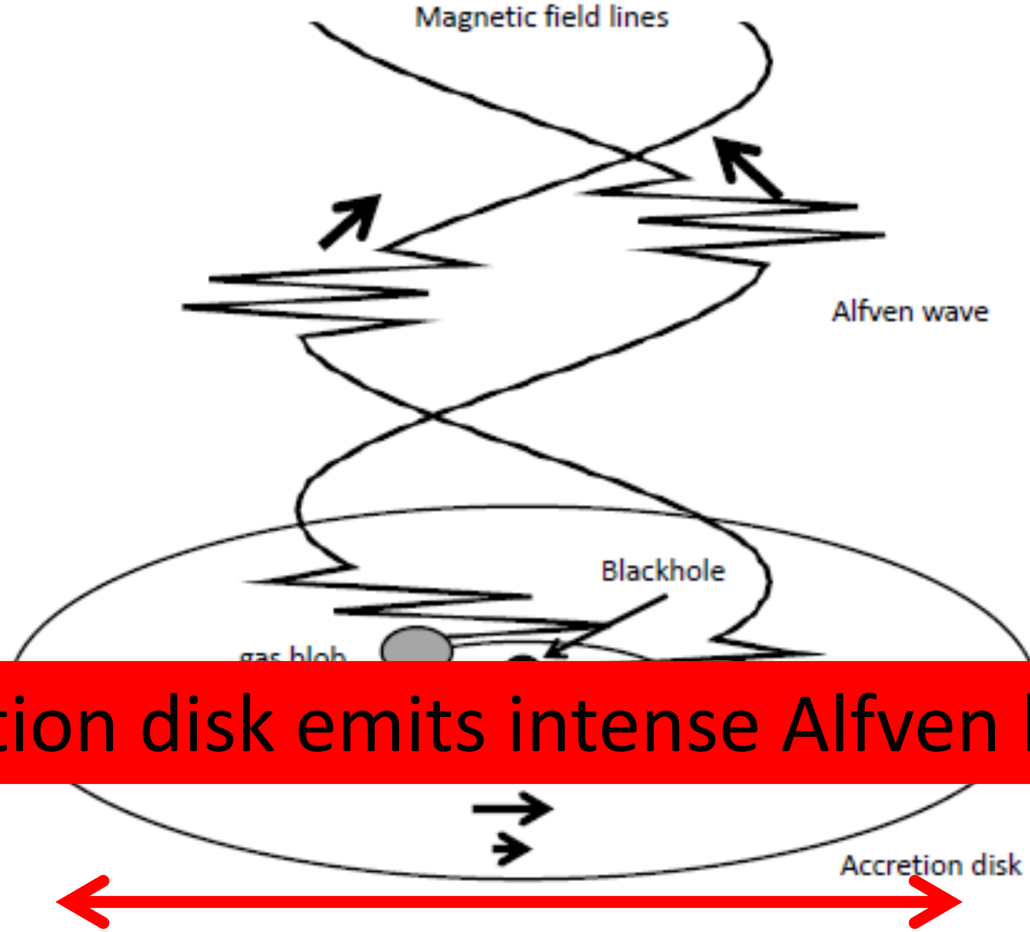


Jet
$D_3$
$D_1$
Acceleration
$D/R_g$
$\omega_A > \omega'_p$
EM wave
$\omega_A < \omega'_p$
Alfven wave
Accretion Disk
Accretion Disk
BH
$R/R_g$

# Light Curves

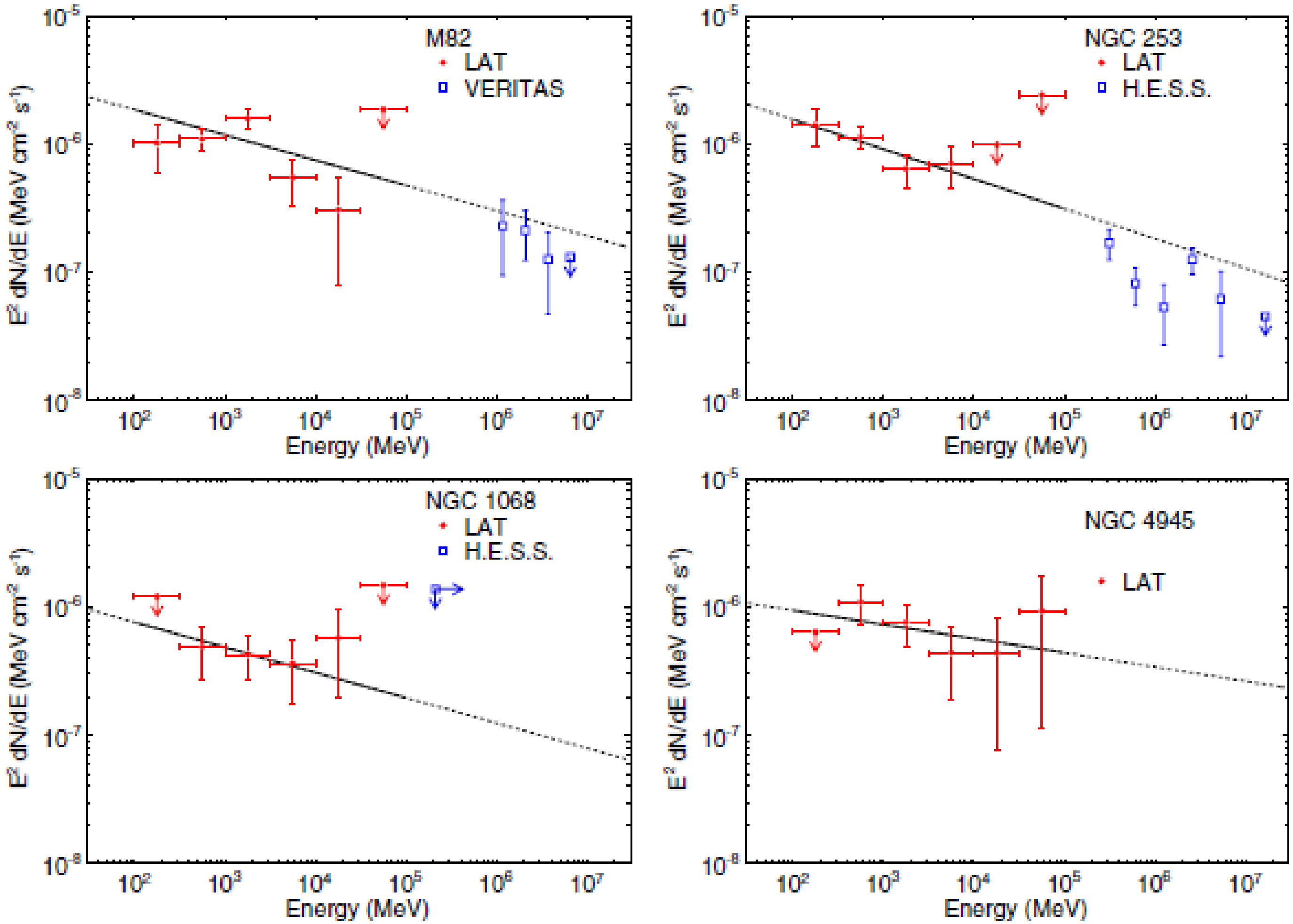


# Accretion Disk around a BH




Accretion disk emits intense Alfven bursts

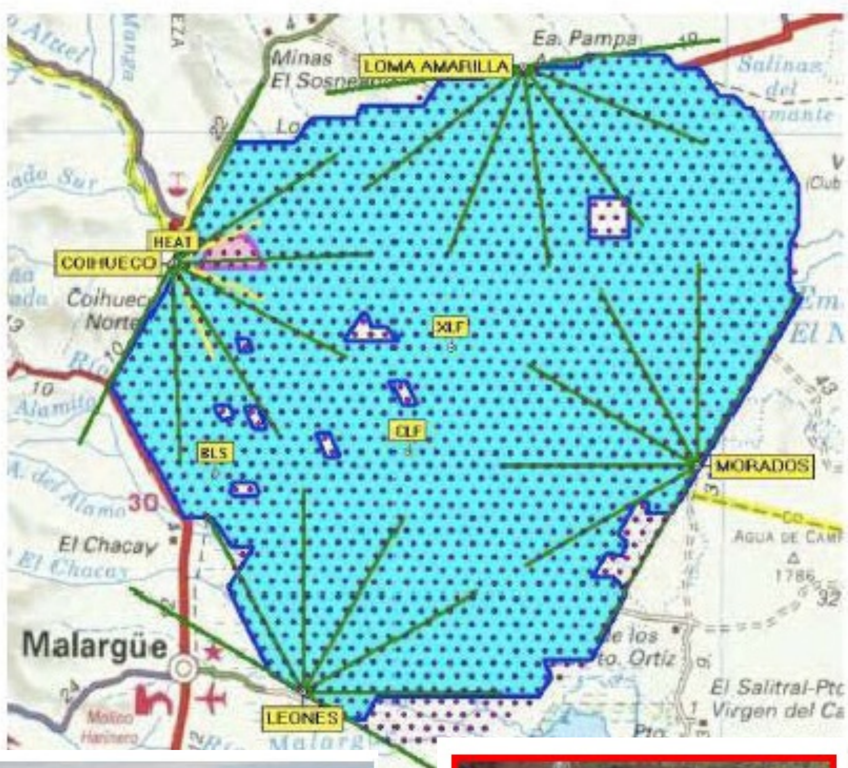
# Energy Spectra



# Ground Based Observatories

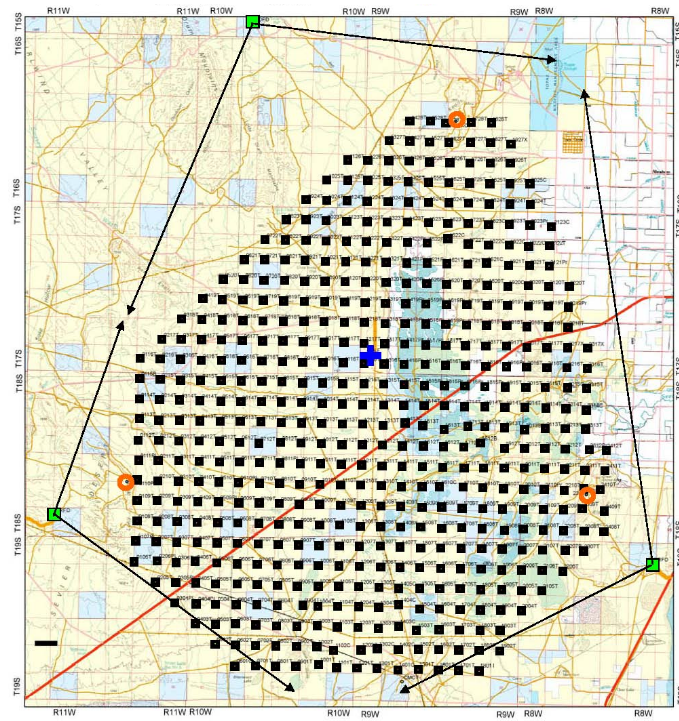
**Auger**

1600 surface detectors
3000 km$^2$




**TA**

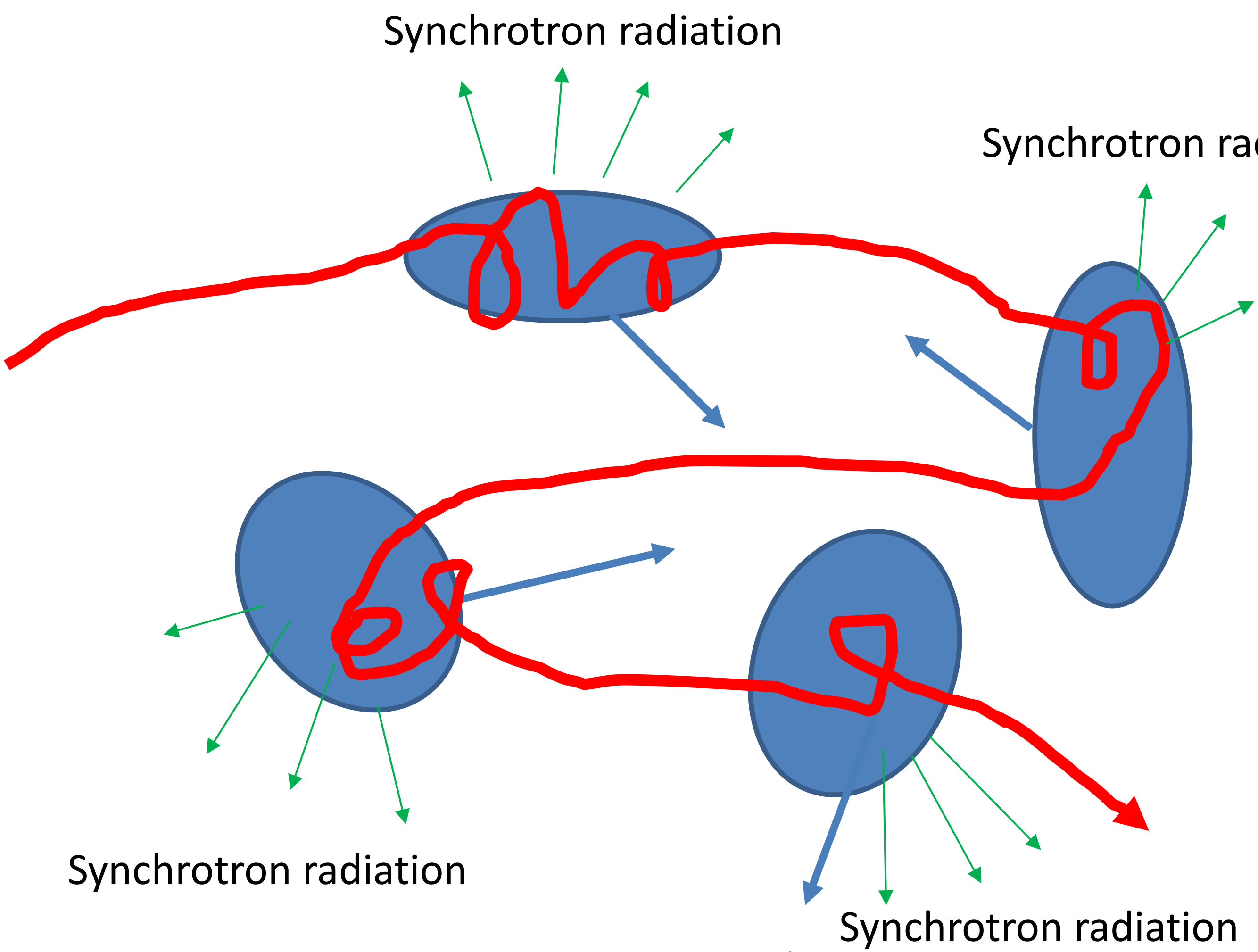
507 surface detectors
700 km$^2$

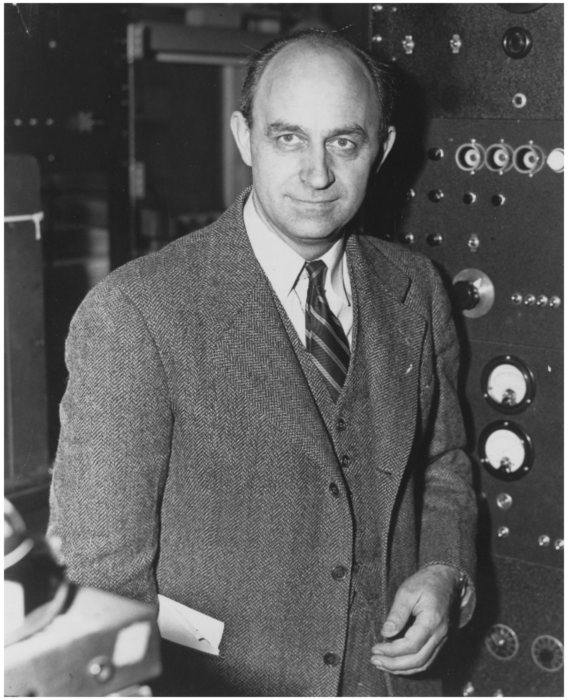





# Fermi mechanism

## requires bending→synchrotron loss



By Department of Energy. Office of Public Affairs

E. Fermi, ApJ 119 (1954) 1.

# Difficulties of Fermi acceleration in UHECR

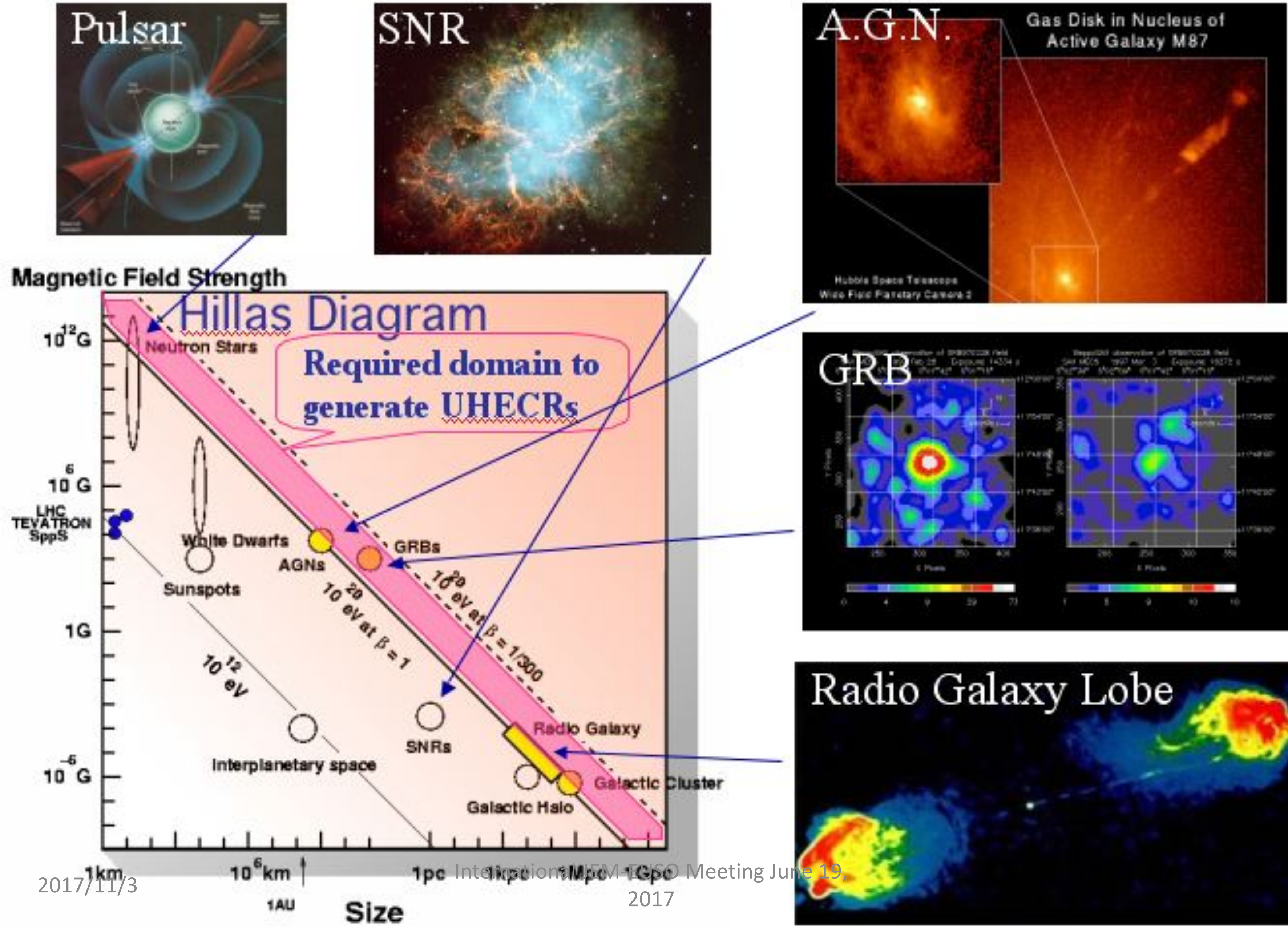
1. Bending is inevitable

   →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

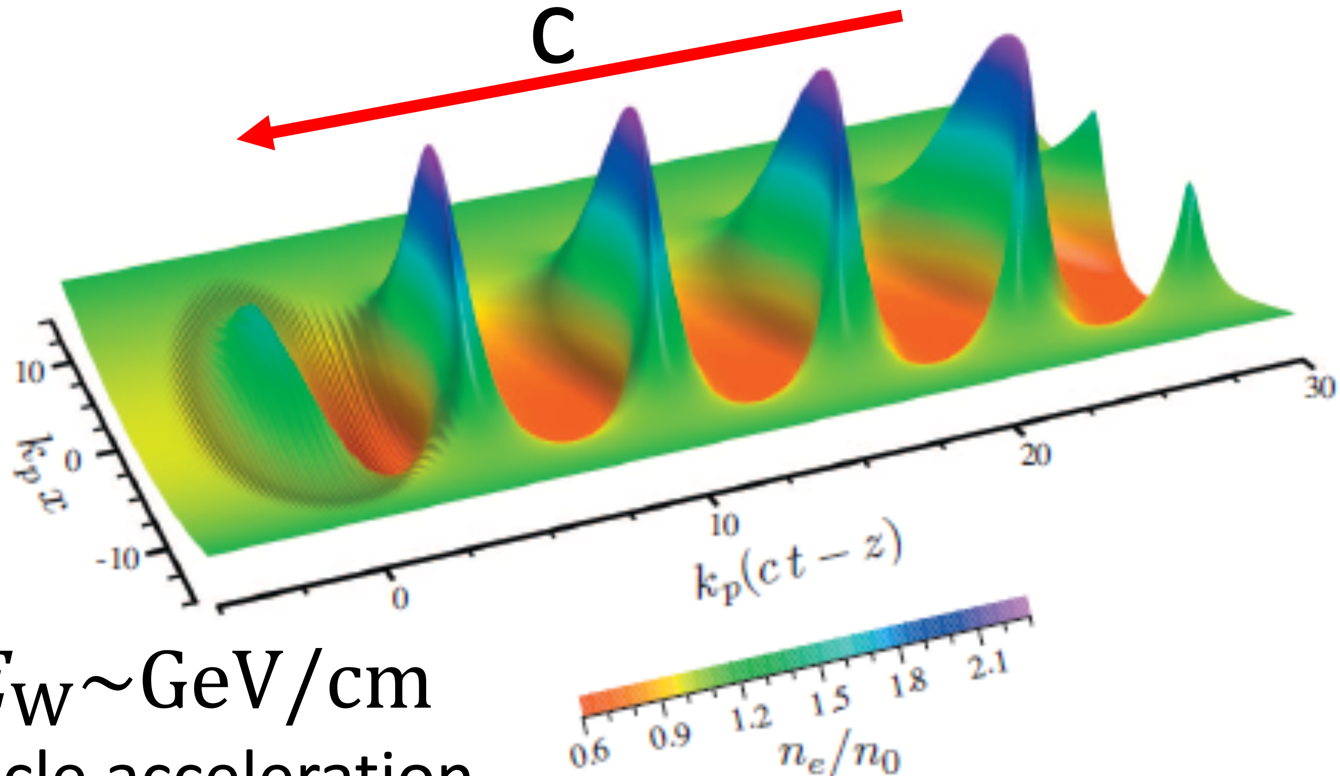
3. Escape problem

   →magnetic field does not disappear without adiabatic loss

**Wakefield acceleration**

# Wake of a ship

# Laser Wakefield



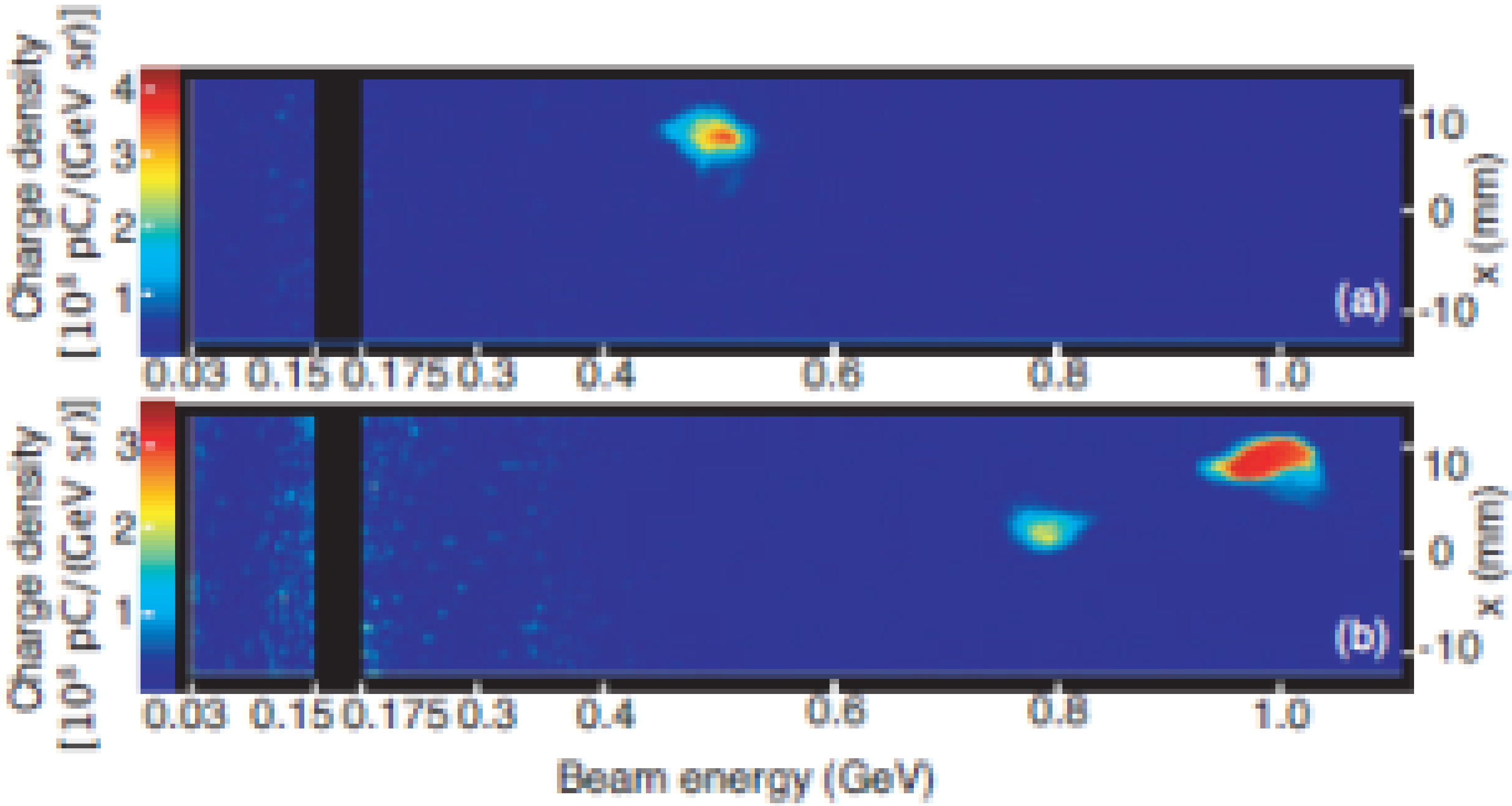

$E_W \sim \mathrm{GeV/cm}$

Particle acceleration

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

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

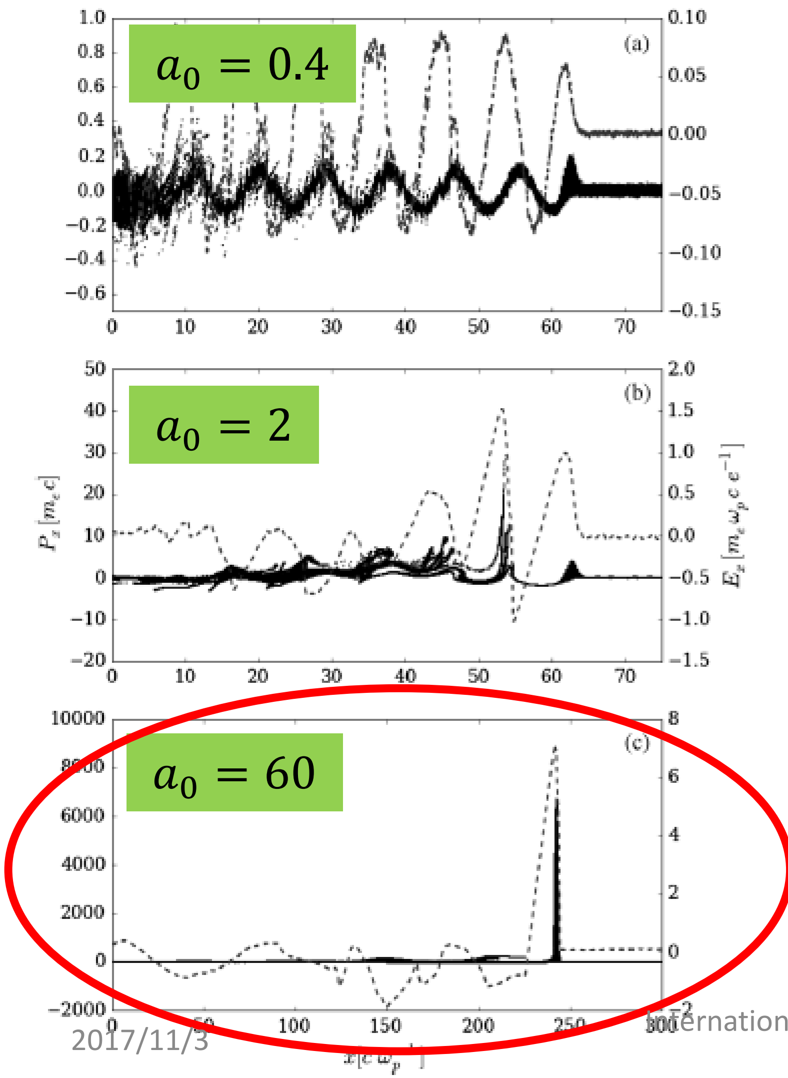
# Electron bunch by a single shot of laser beam

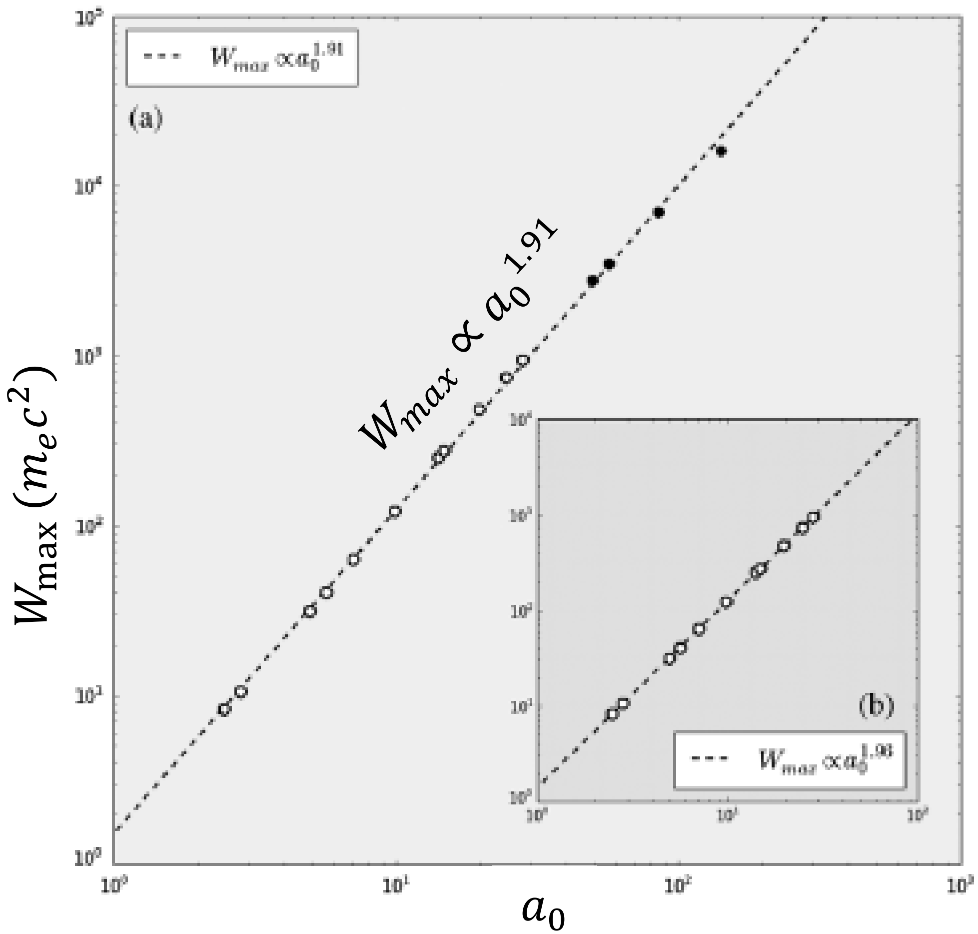



Leemans et al. (2006) Nature Physics, 2, 696.
Nakamura et al. (2007) Phys. Plasma, 14, 056078

# 1D Particle-in-Cell simulation

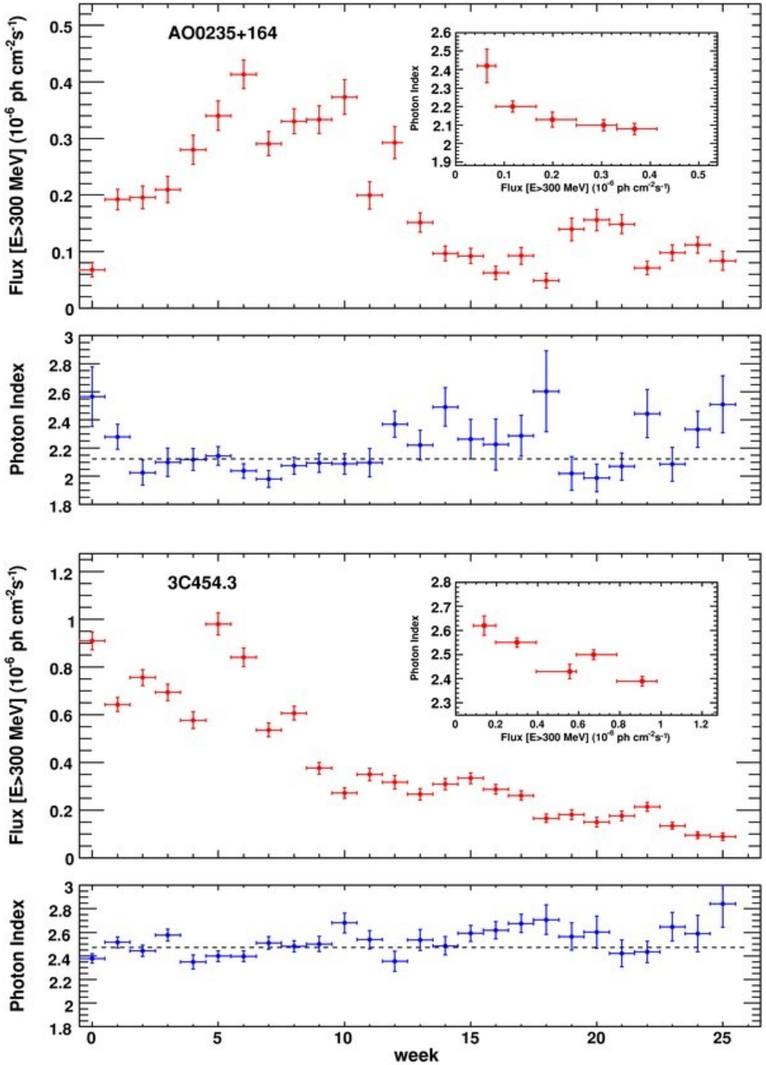
with the code by Nagata2008



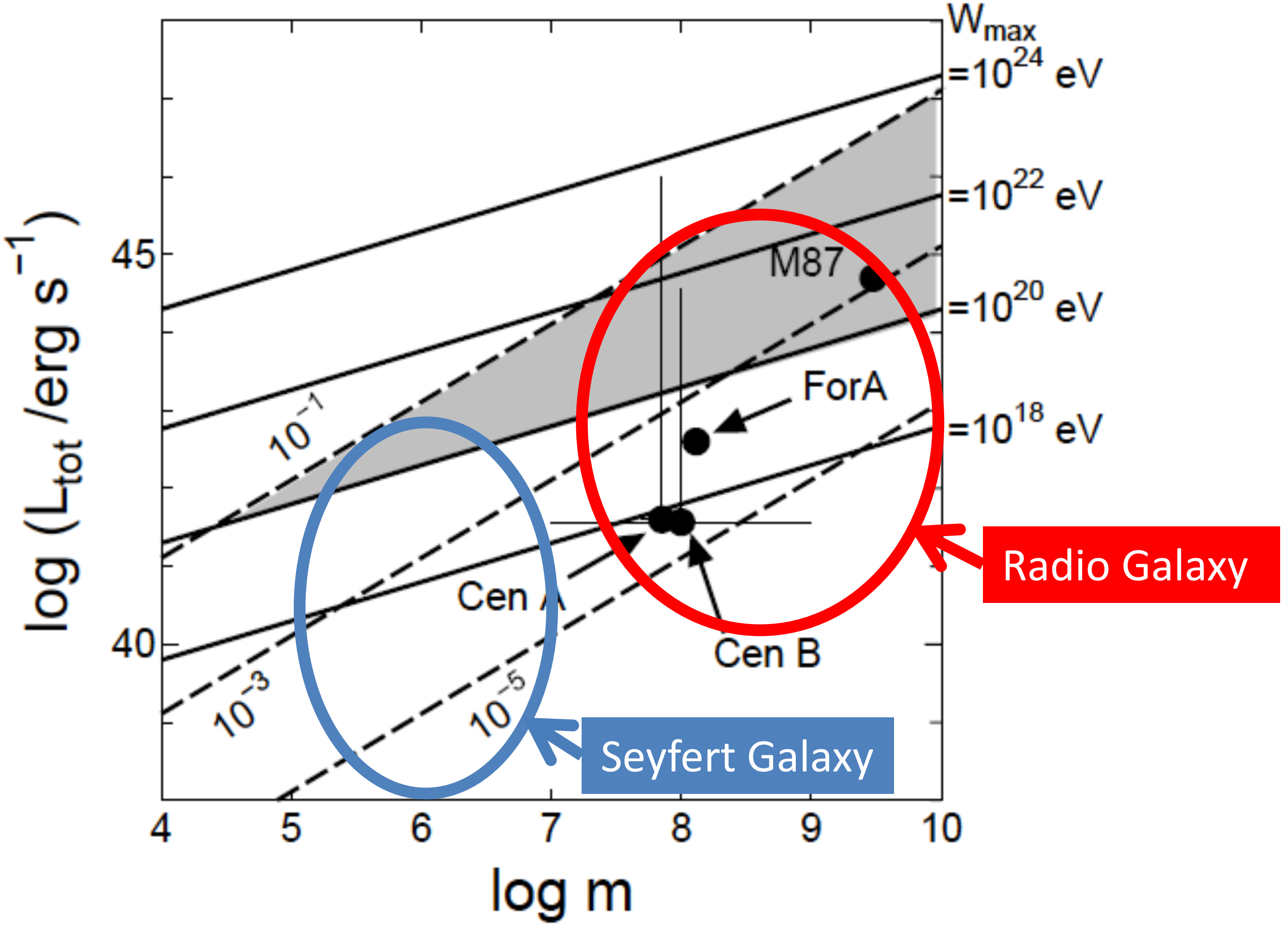




Lau et al. 2015, Phys. Rev. 18, 024401

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

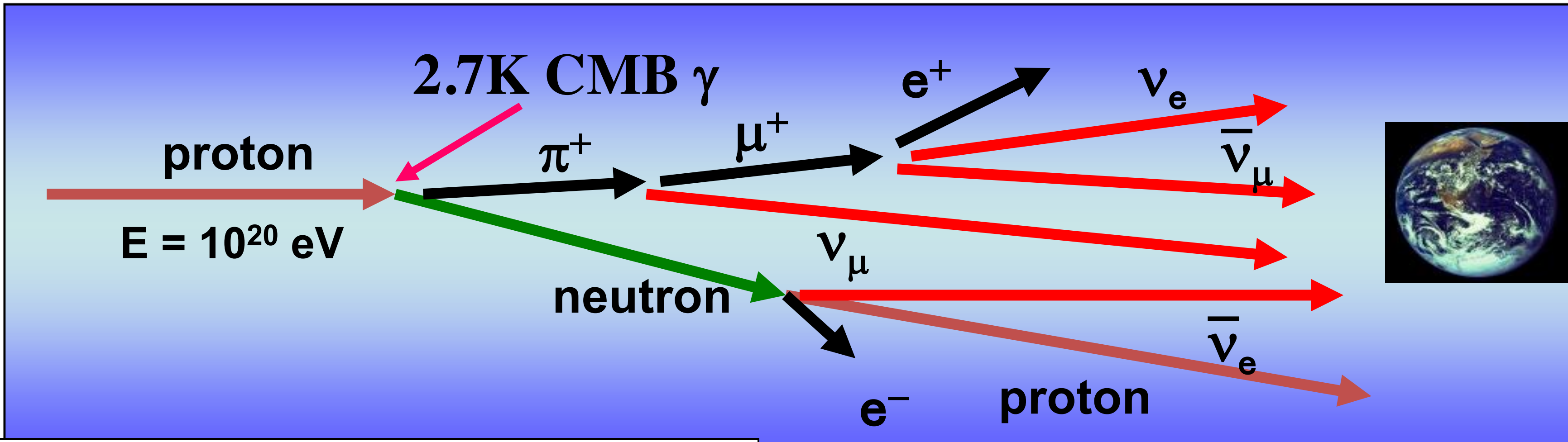



$L_{\text{tot}} = 1.3{\times}10^{38} m\dot{m}\ \ \text{erg s}^{-1}$

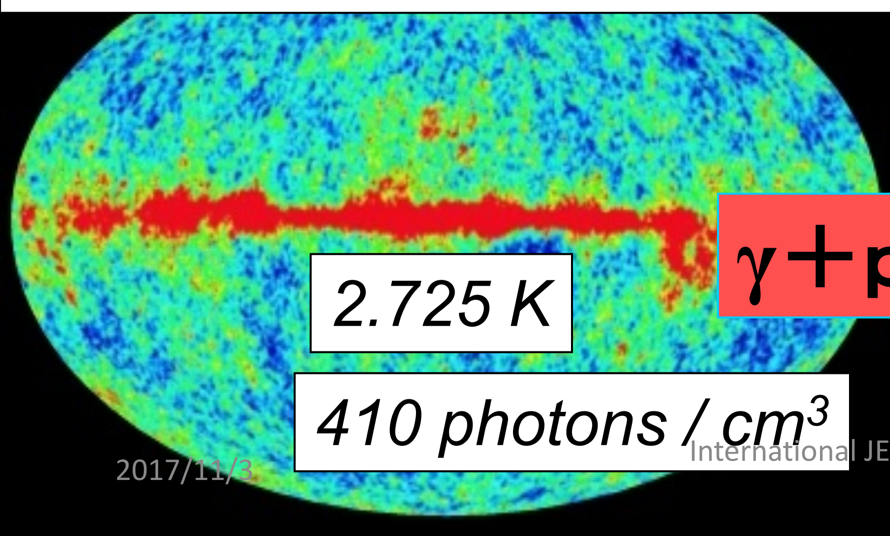
# How about neutrinos?

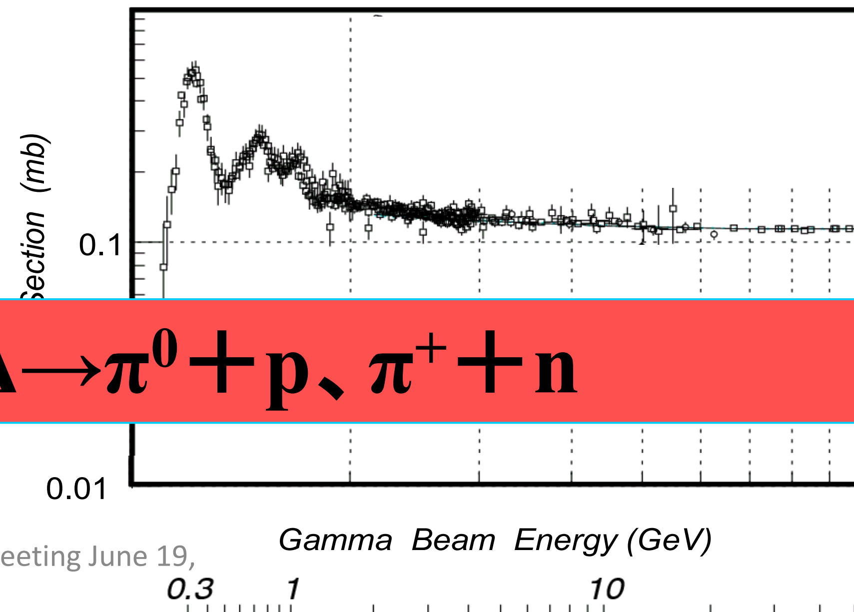
Greisen-Zatsepin-Kuz’min Process

Greisen1966; Zatsepin and Kuz’min1966




**Microwave Cosmic Background Radiation**

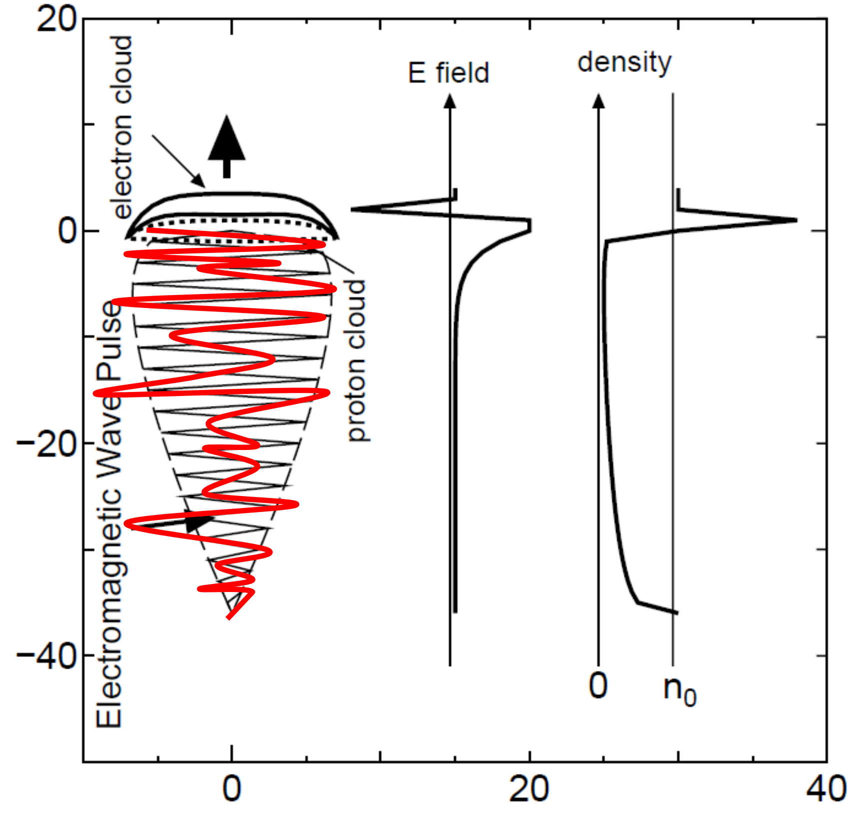


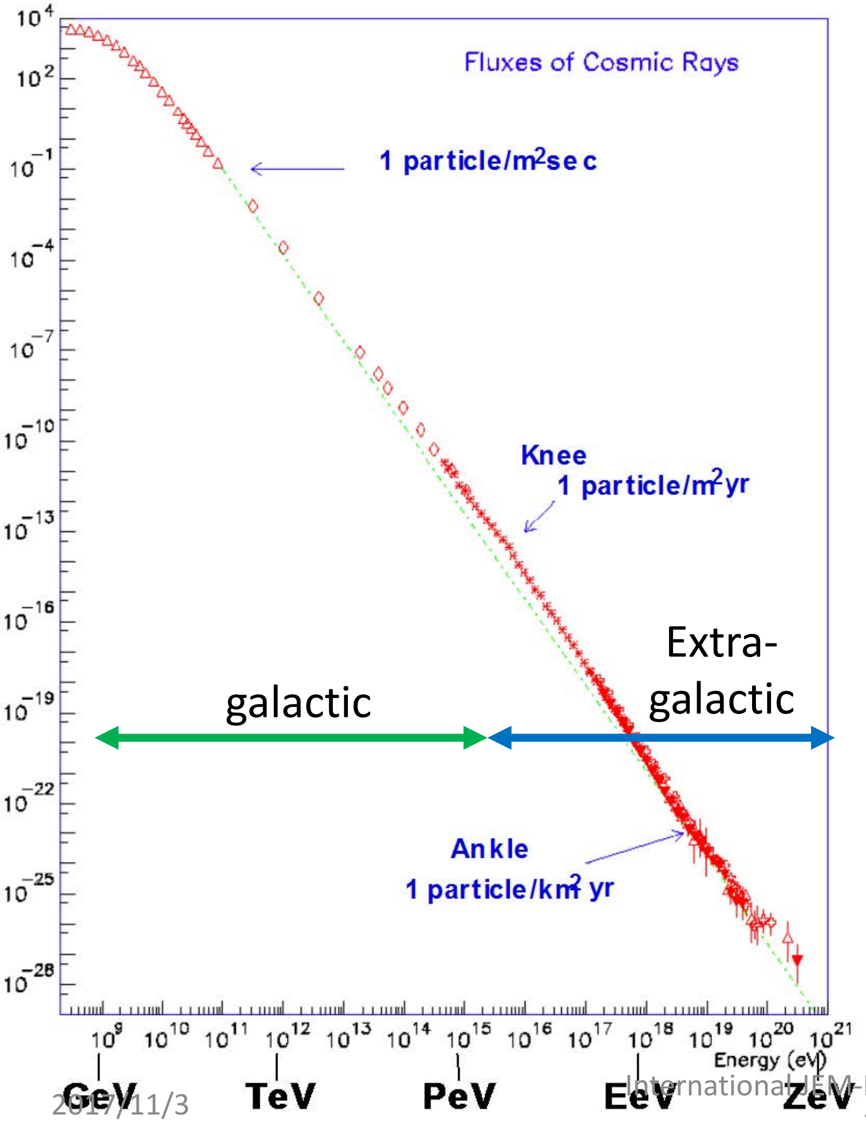

$$\gamma + p \rightarrow \Delta \rightarrow \pi^0 + p、\pi^+ + n$$

# Relativistic coherence

- Extremely relativistic
  →freezing-out

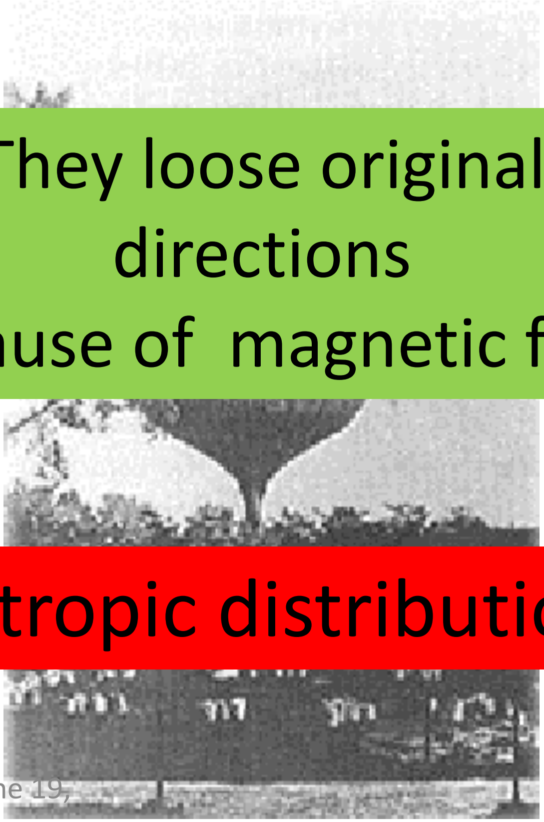


# Origin of Cosmic rays



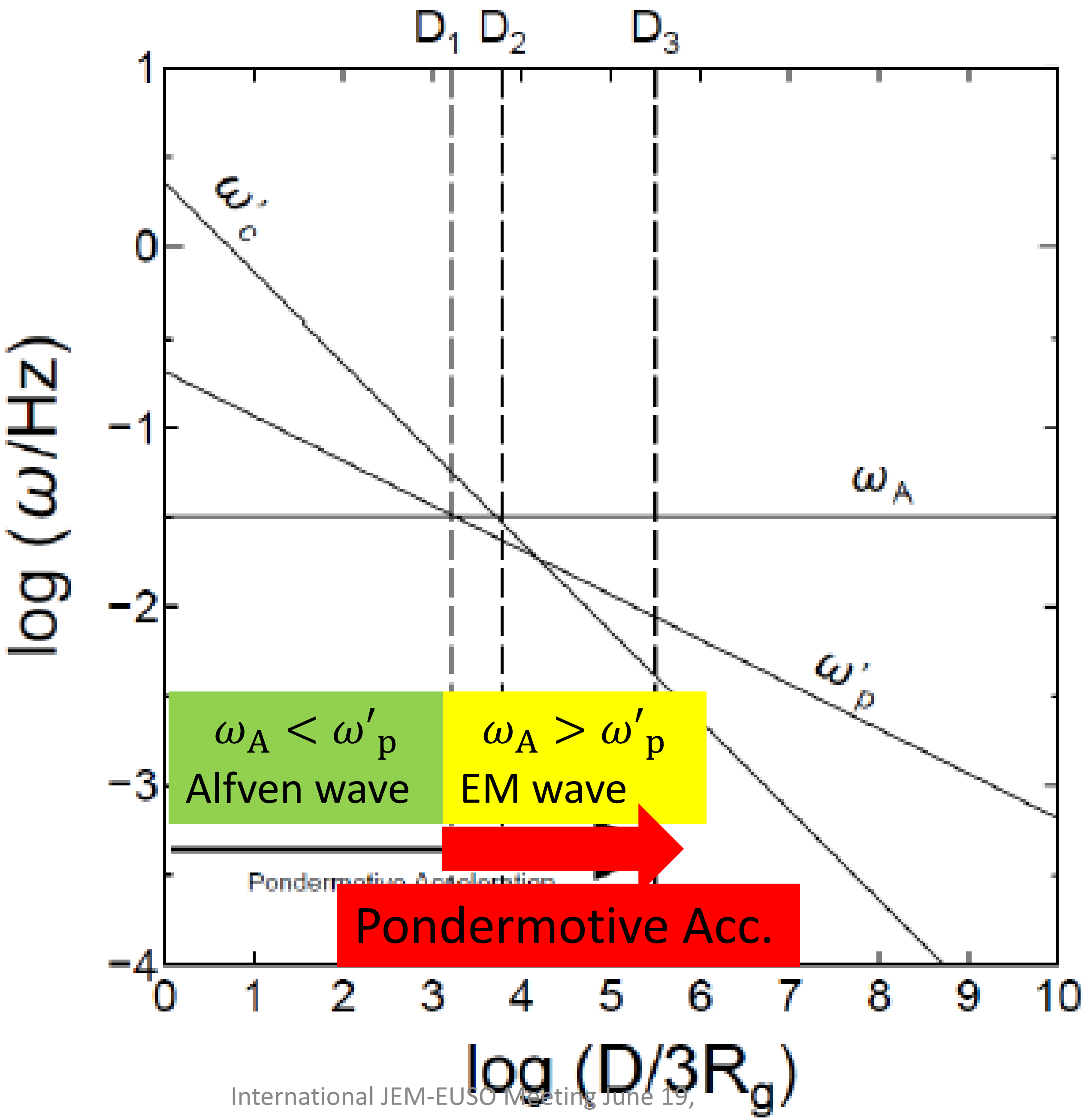

- 100 years enigma
  - Discovered in 1912

    by Victor Hess



They loose original directions because of magnetic field

Isotropic distribution



D1 D2 D3
log (ω/Hz)
log (D/3Rg)
ω'c
ωA
ω'p
$\omega_A < \omega'_p$
Alfven wave
$\omega_A > \omega'_p$
EM wave
Pondermotive Acc.