M82 starburst galaxy: possible origin of the northern hot spot

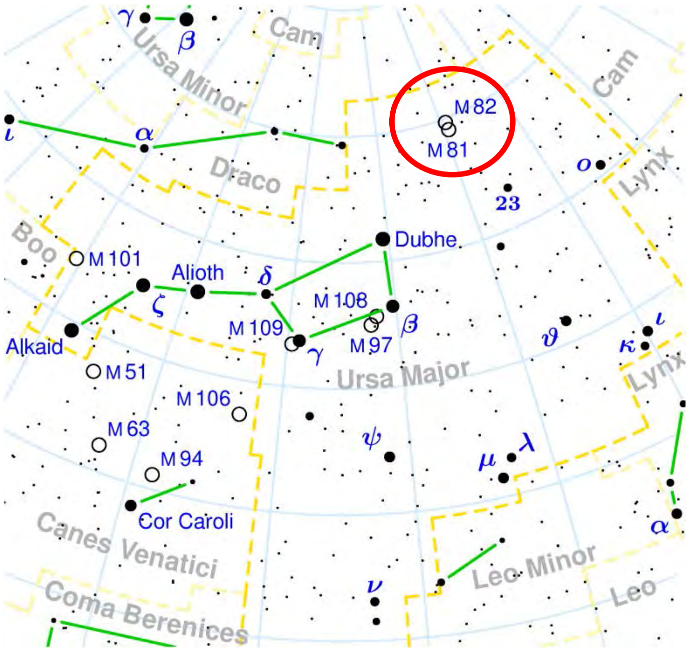
Toshikazu Ebisuzaki and Akira Mizuta (RIKEN)

Toshiki Tajima (UC Irvine)

contents

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

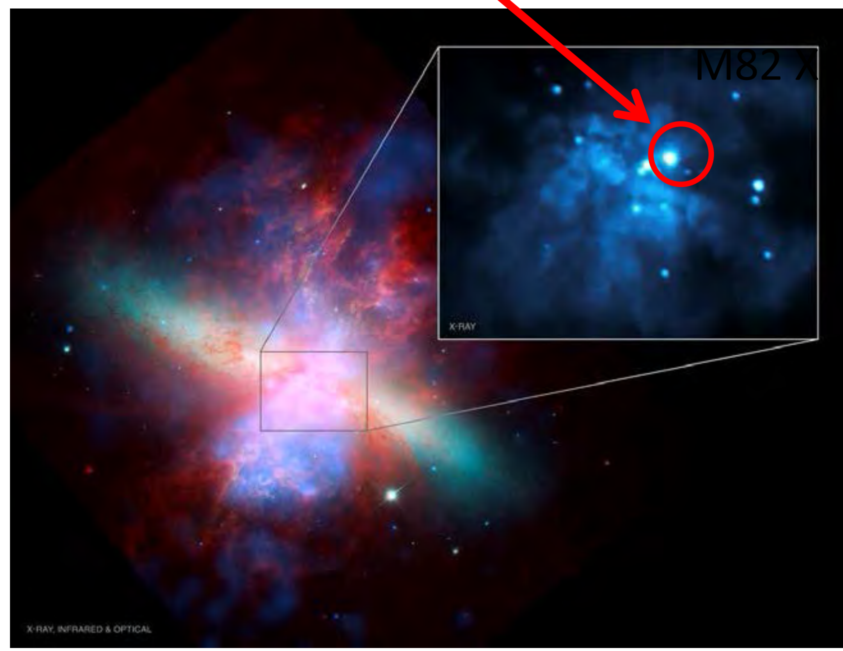
M82 galaxy


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

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.

Ground Based Observatories

Auger

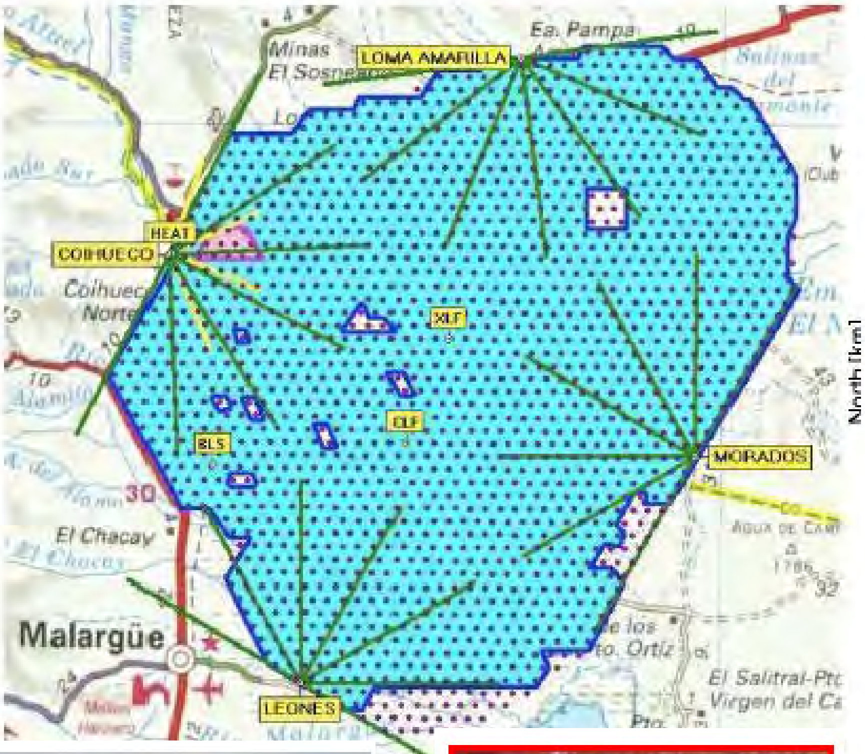
1600 surface detectors

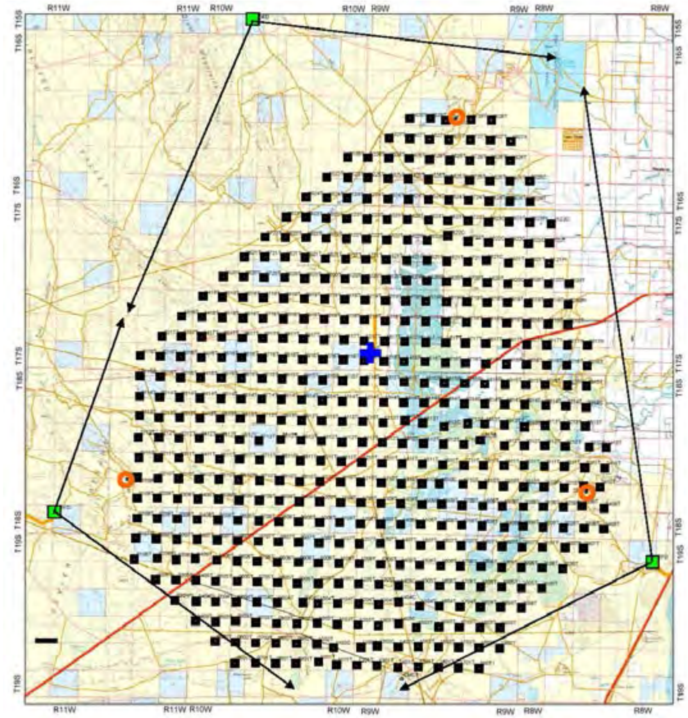
3000 km^2

TA

507 surface detectors

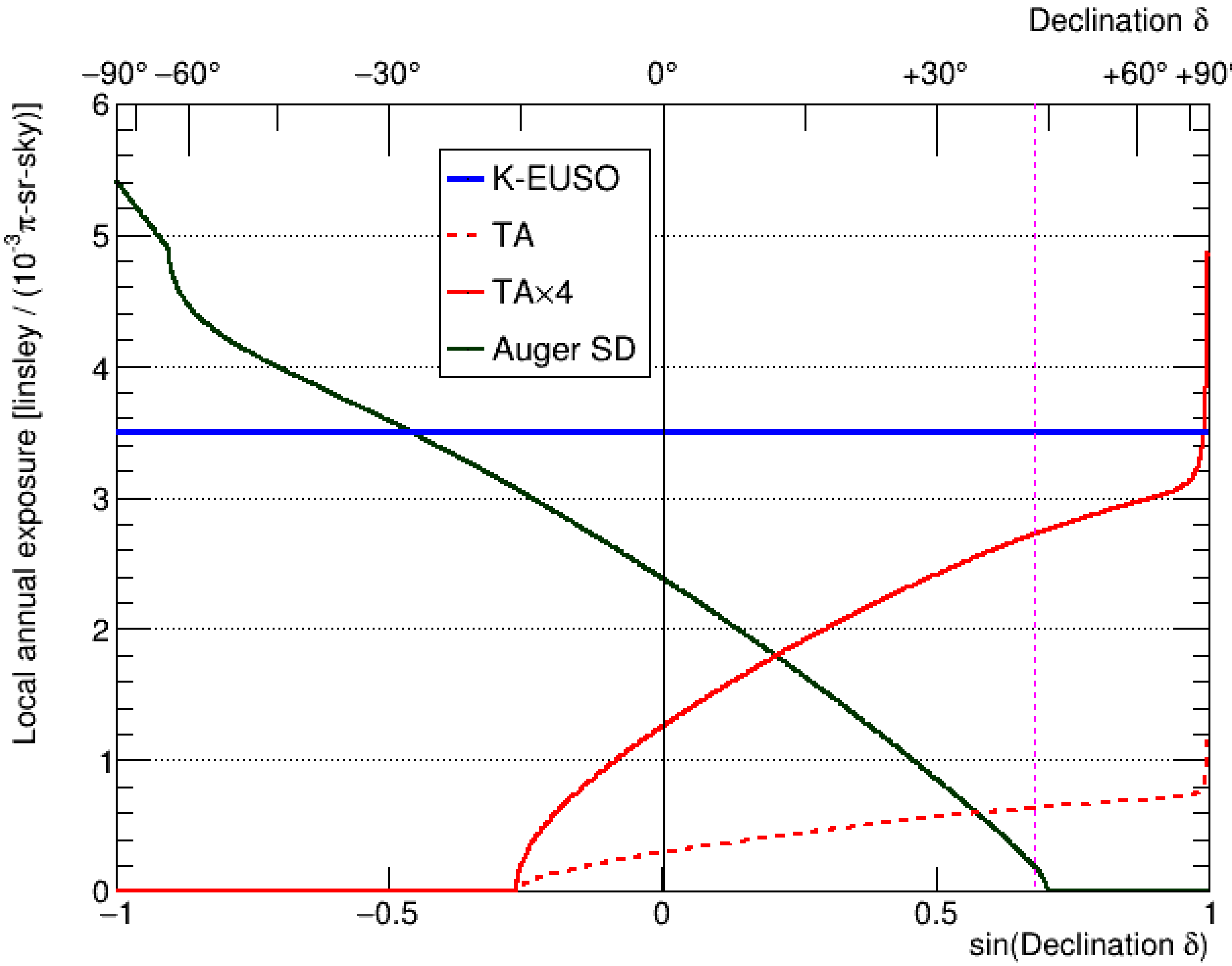
700 km^2



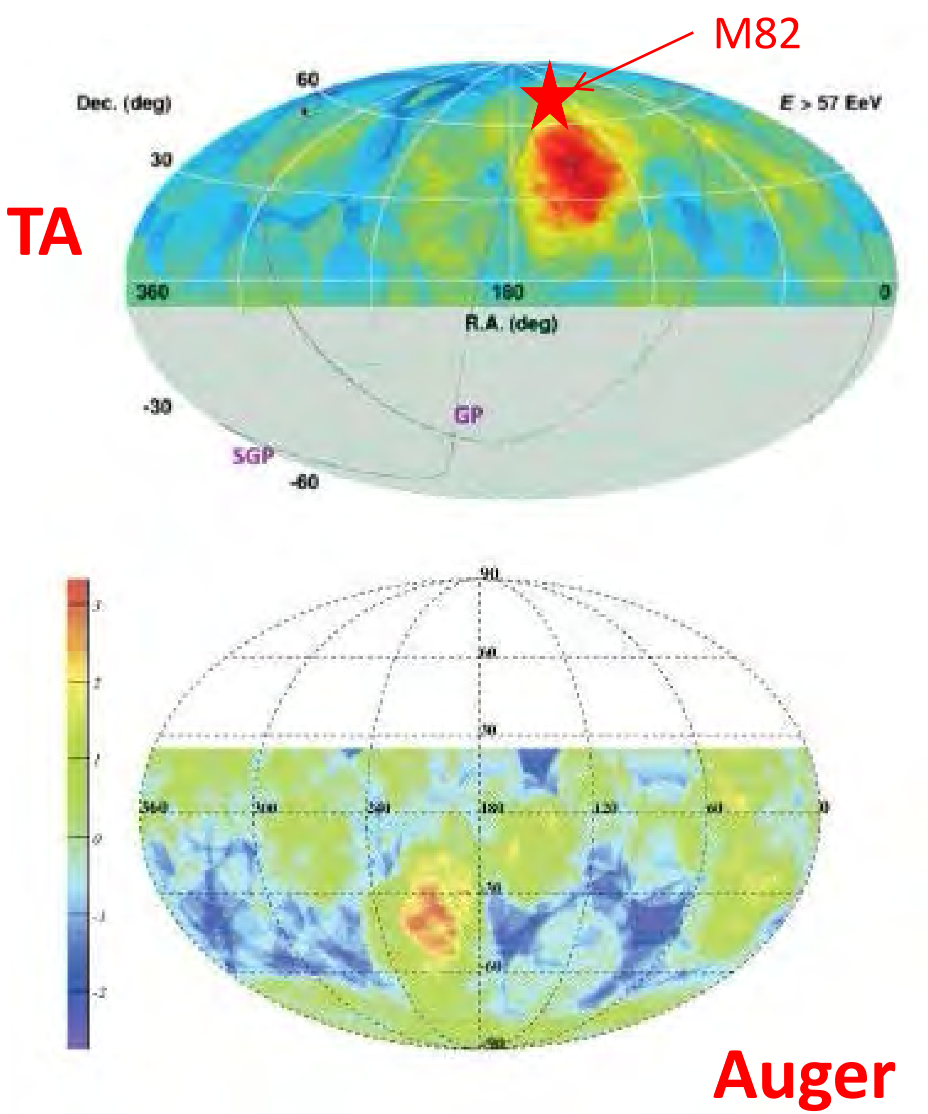


One hemisphere by one instrument

Some (5%) disuniformity due to clouds, continents and moon phase

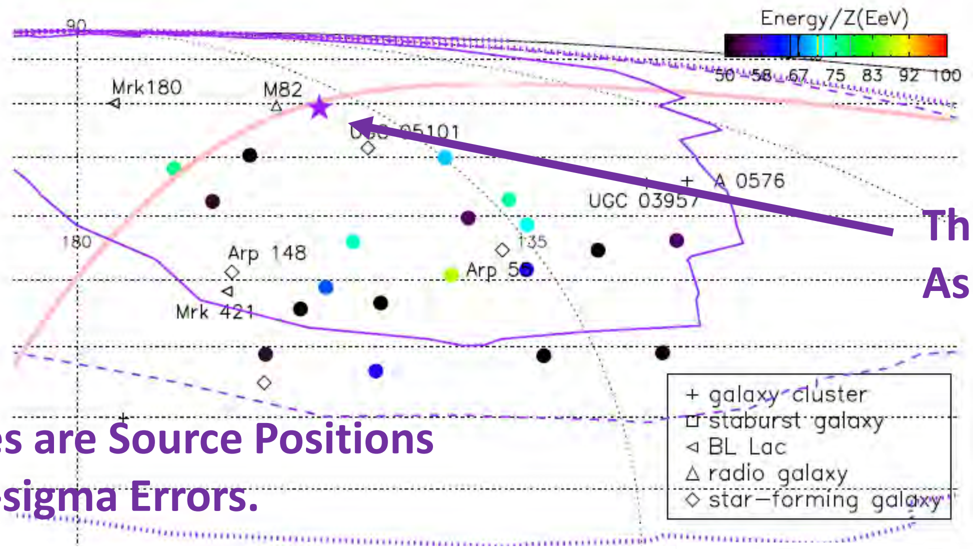


Arrival Direction Map (Auger/TA)



TA Hot Spot: UHECRs from M82?

He, Kusenko, Nagataki + PRD 2016.



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

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

M82 is very Close from the most likely Source Position!

Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\mathrm{bes-fit}}$ (%)
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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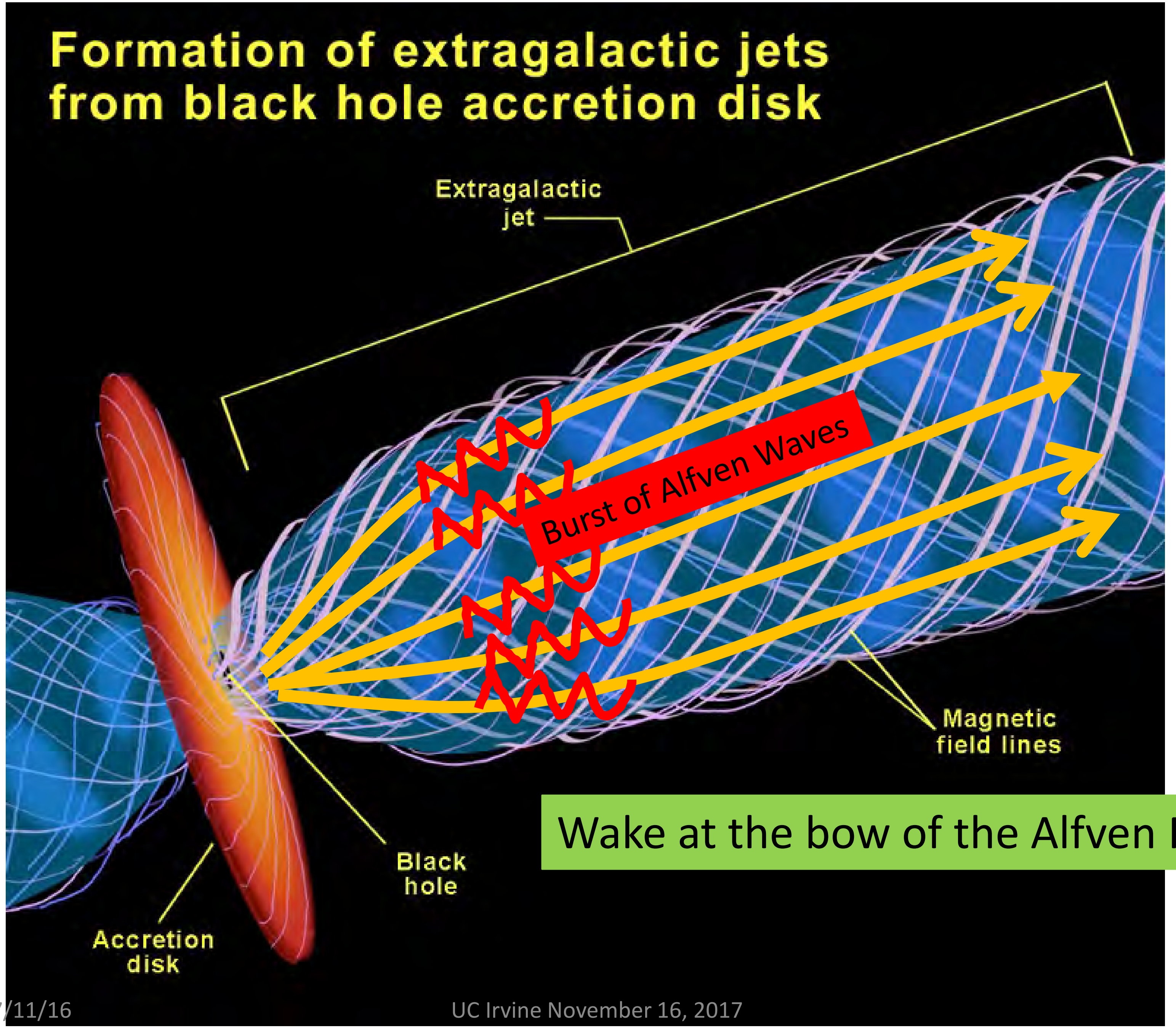
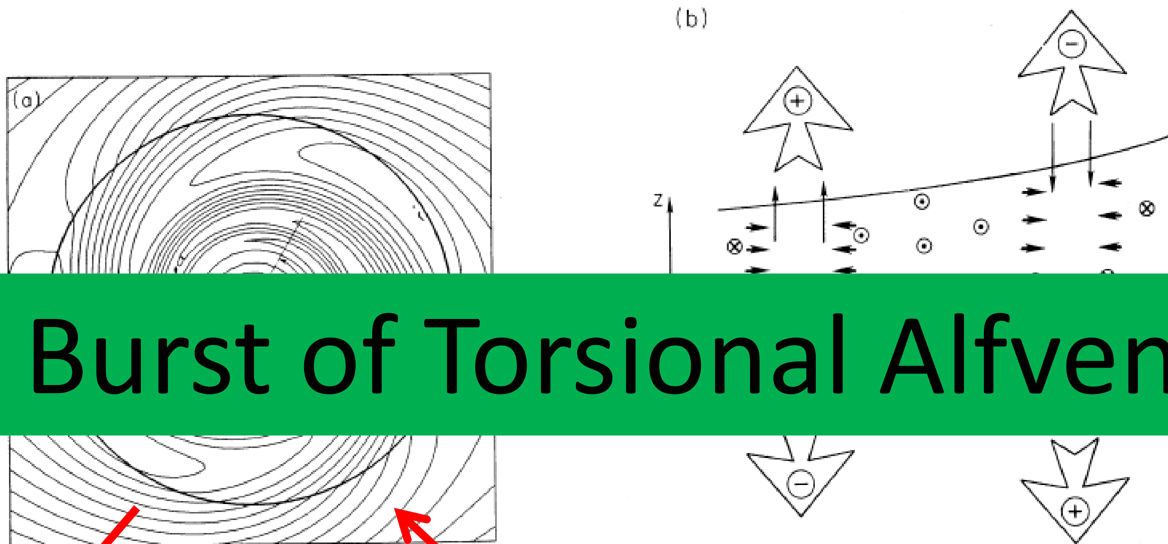
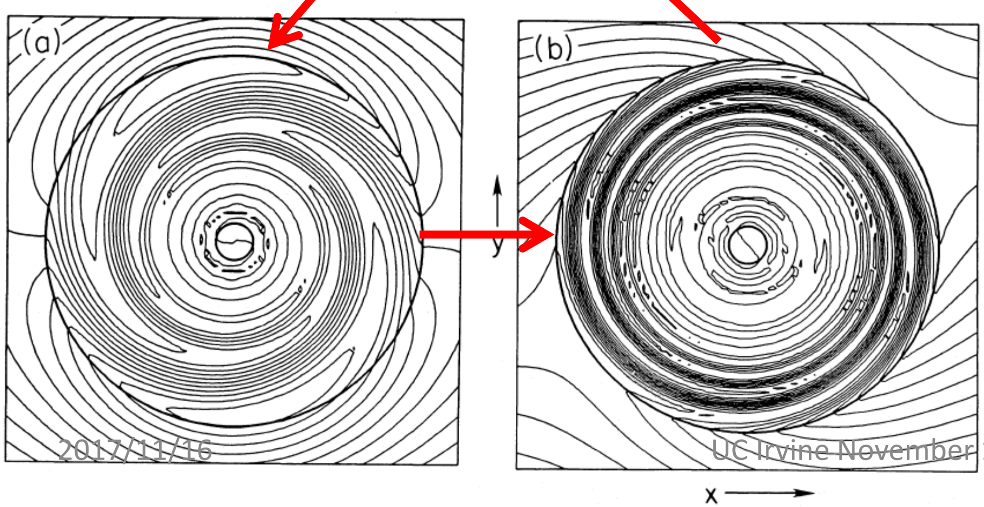


Wake at the bow of the Alfven Pulse

Eruption of magnetic field in an accretion disk

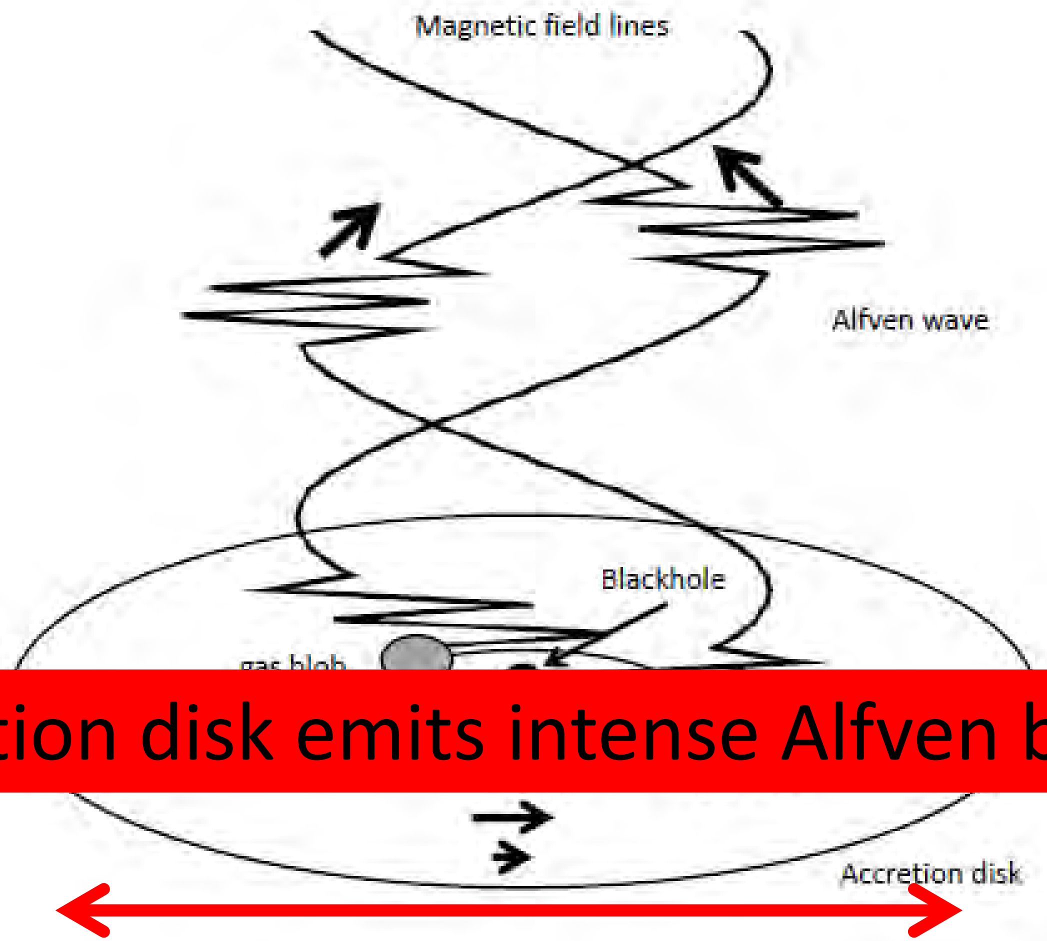


A Burst of Torsional Alfven Waves



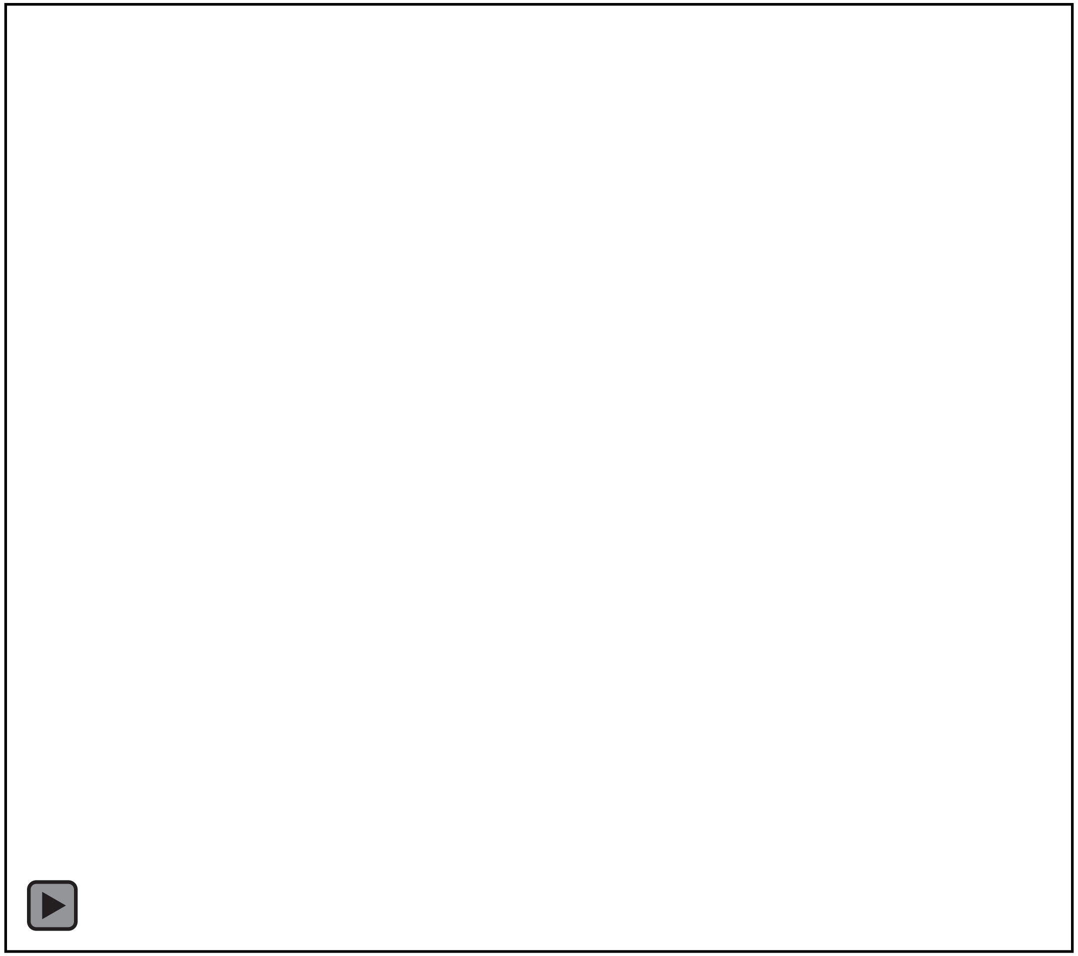
Tajima and Gilden 1987, ApJ 320, 741-745
Haswell, Tajima, and Sakai, 1992, ApJ, 401, 495-507

Accretion Disk around a BH

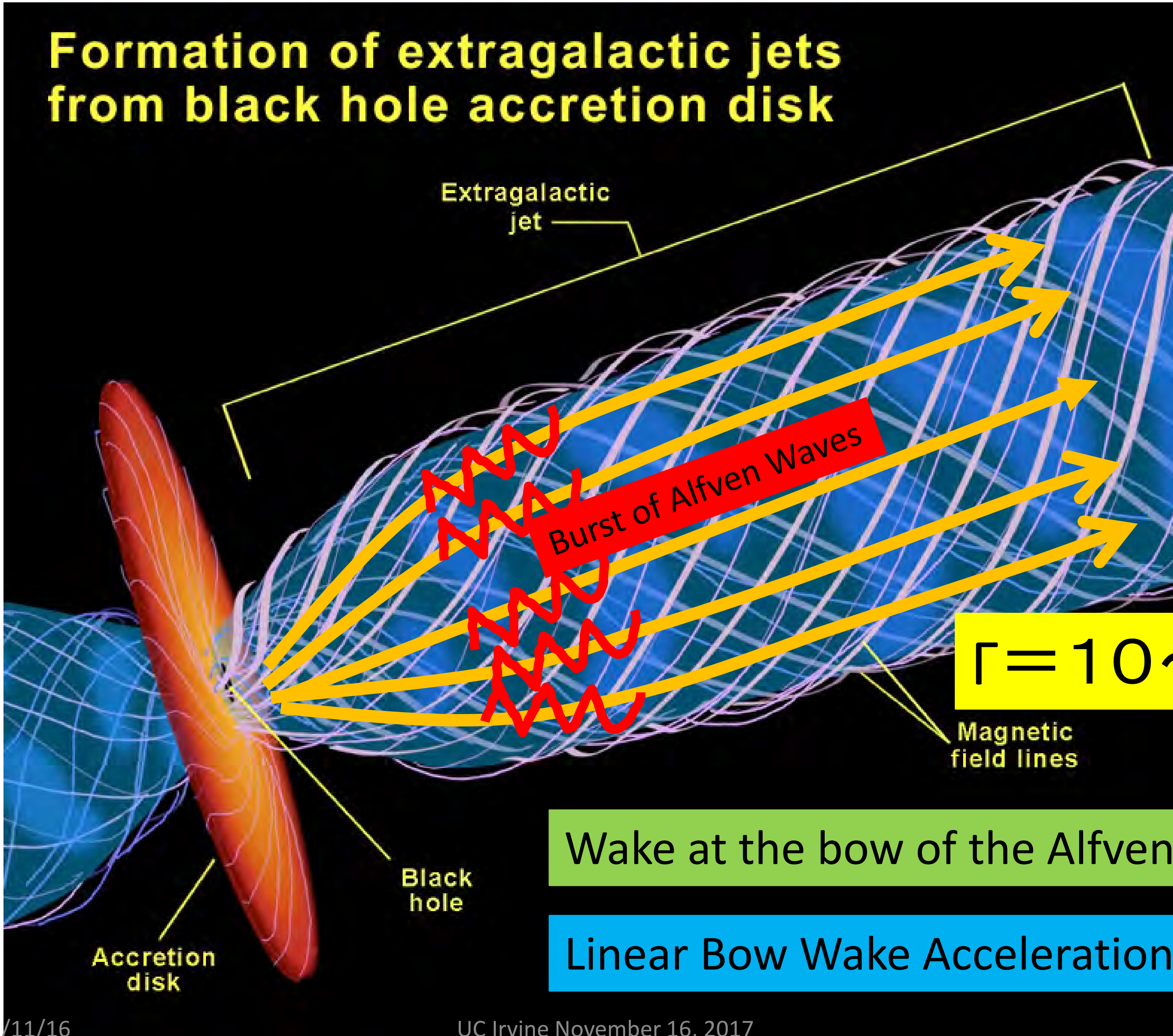


Accretion disk emits intense Alfven bursts

3-D relativistic MHD simulation



A. Mizuta et al. 2016



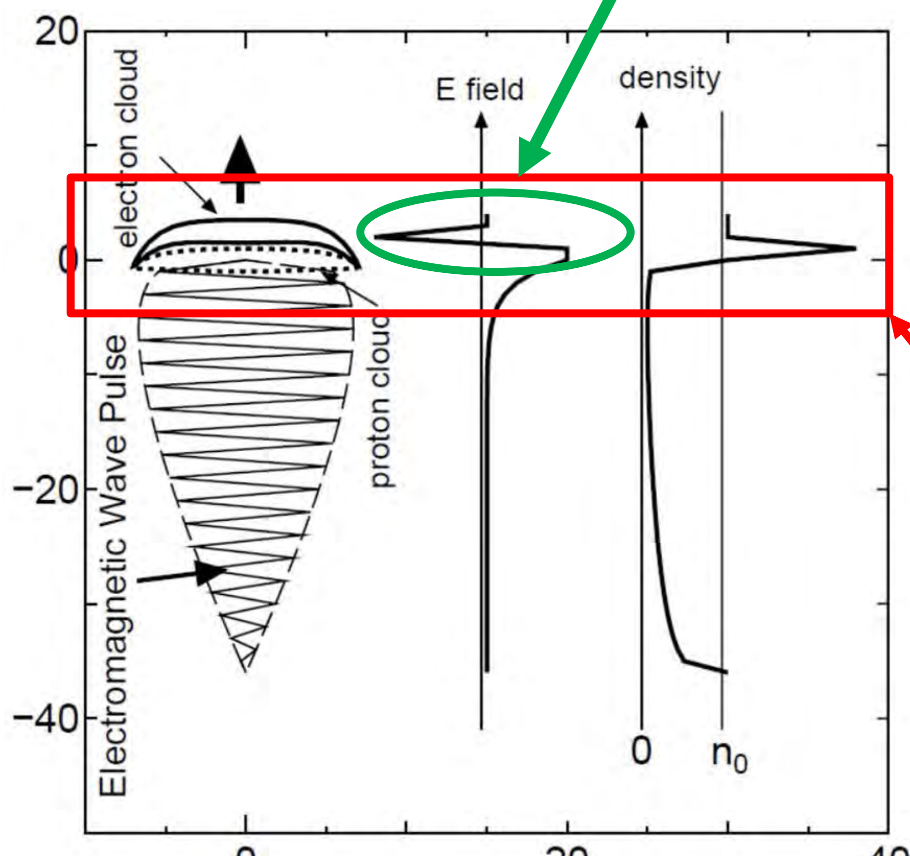
Γ＝10～30

Wake at the bow of the Alfven Pulse

Linear Bow Wake Acceleration

Bow wake acceleration

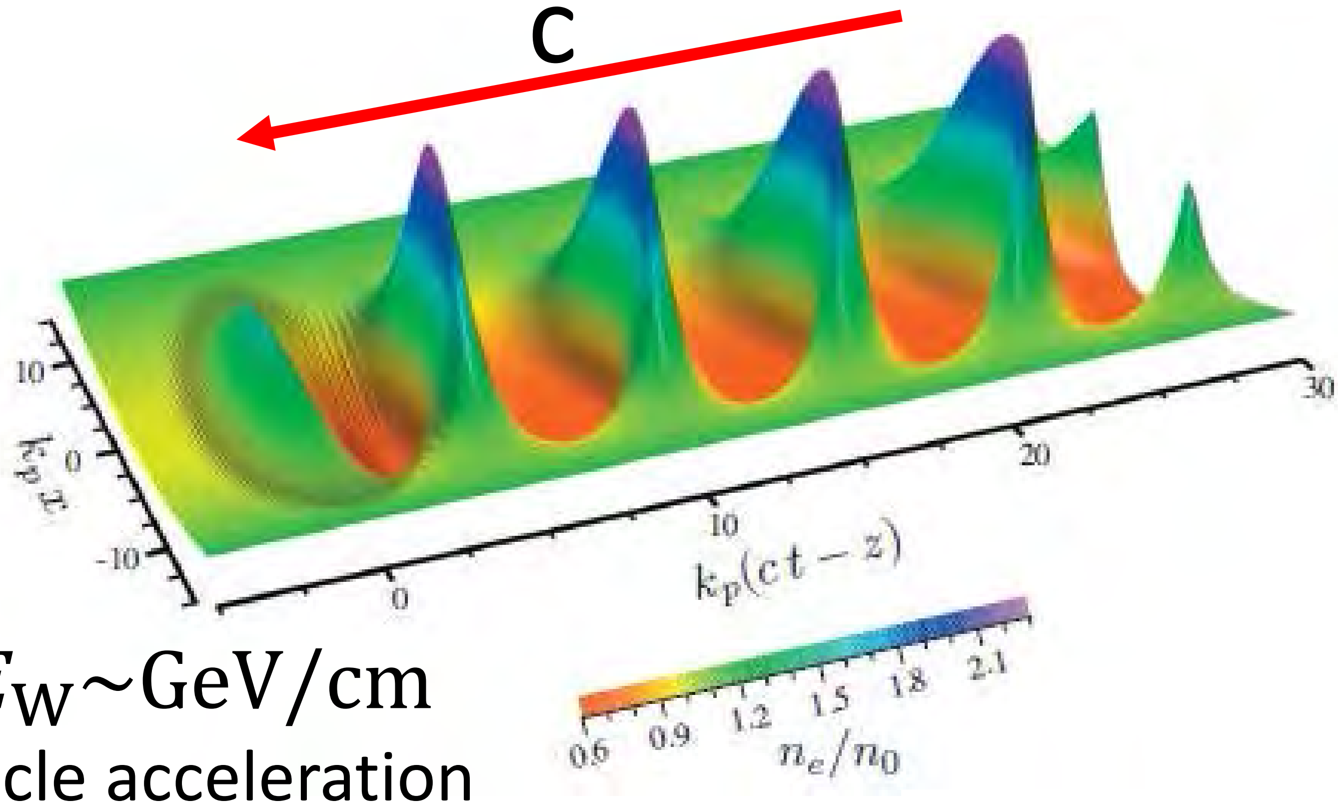
linear acceleration by electrostatic field



Bow wake

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

Laser Wakefield



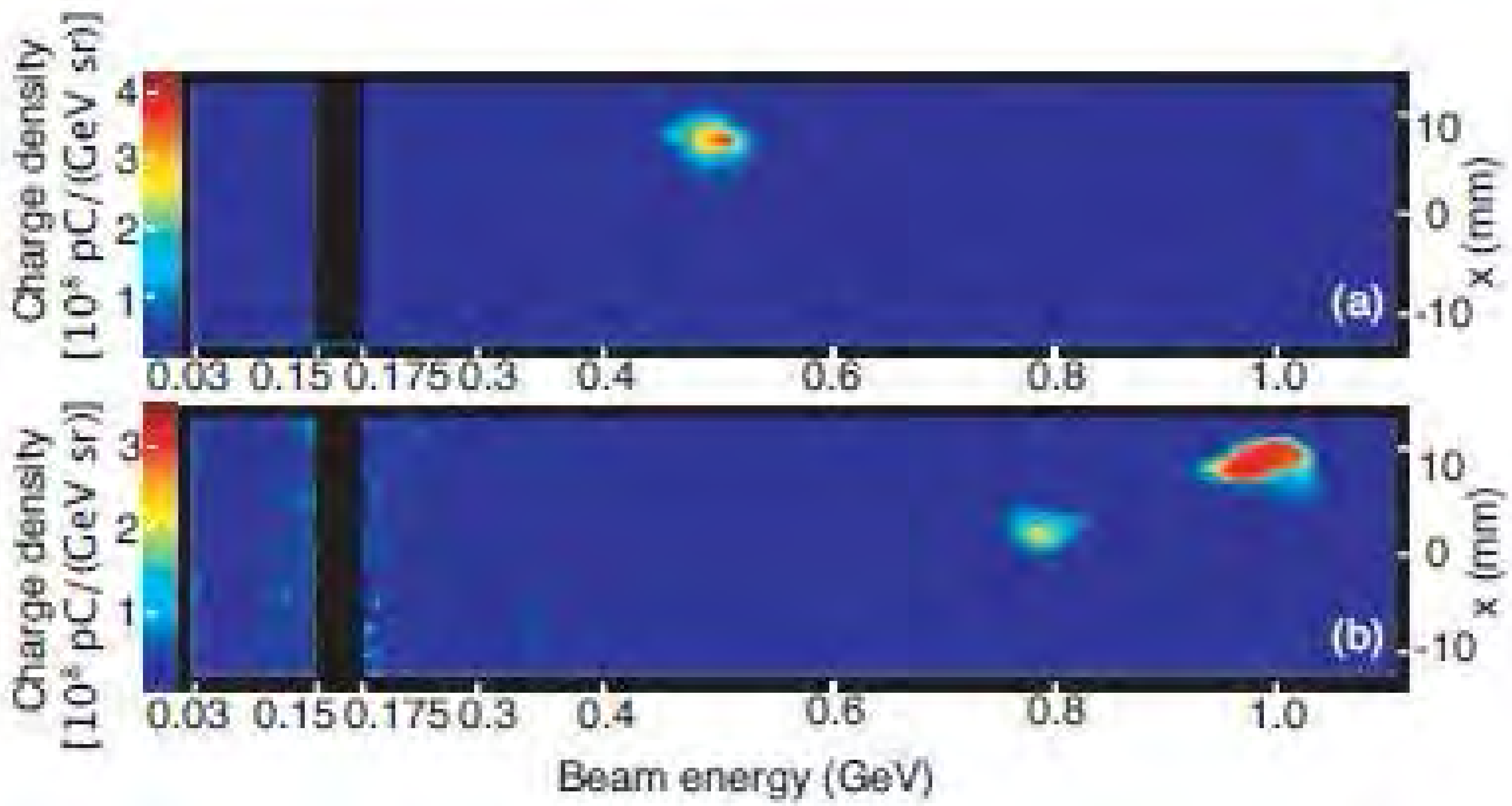
E_W~GeV/cm

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.

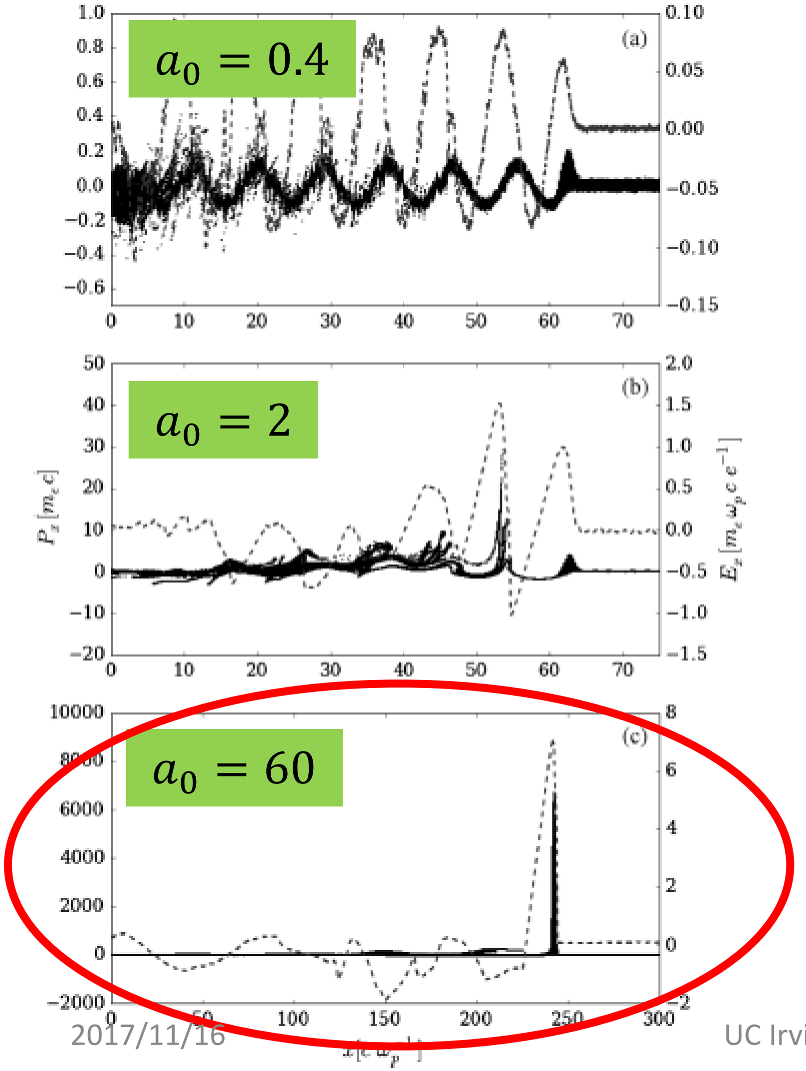
Electron bunch by a single shot of laser beam

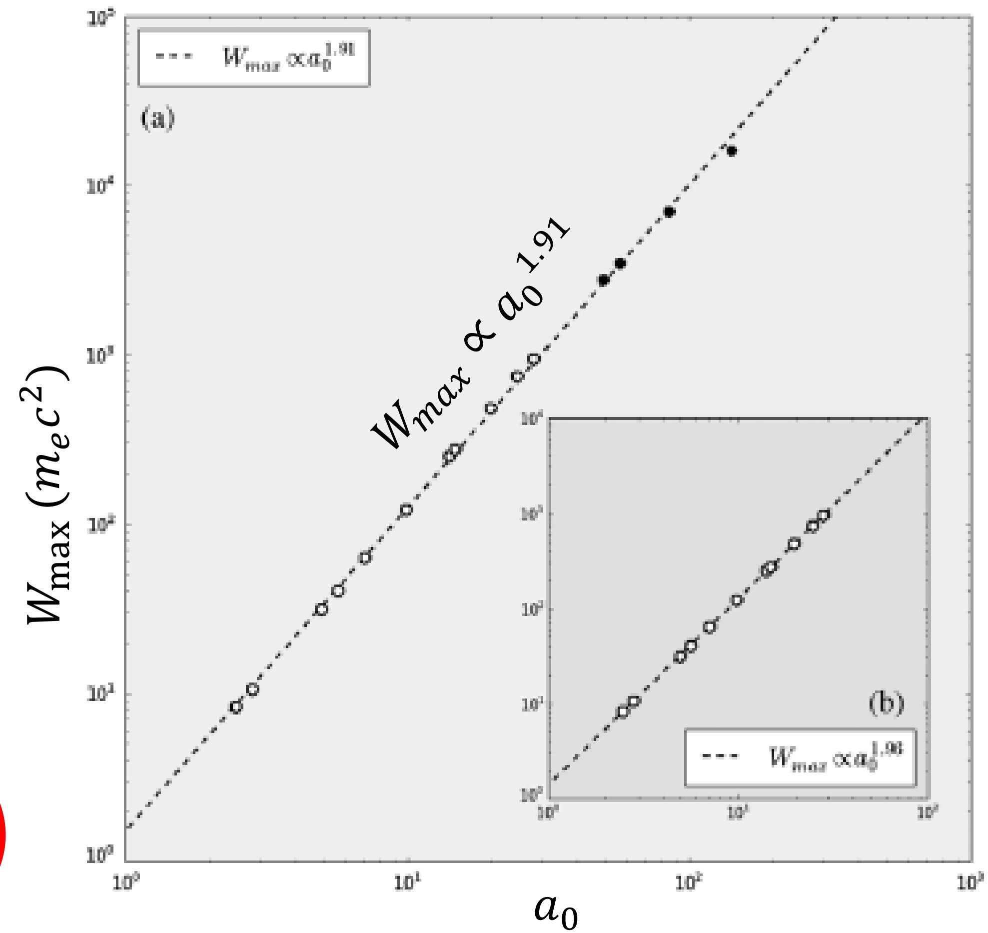


Leemans et al. (2006) Nature Physics, 2, 696.
Nakamura et al. (2007) Phys. Plasma, 14, 056078

1D Particle-in-Cell simulation

with the code by Nagata2008





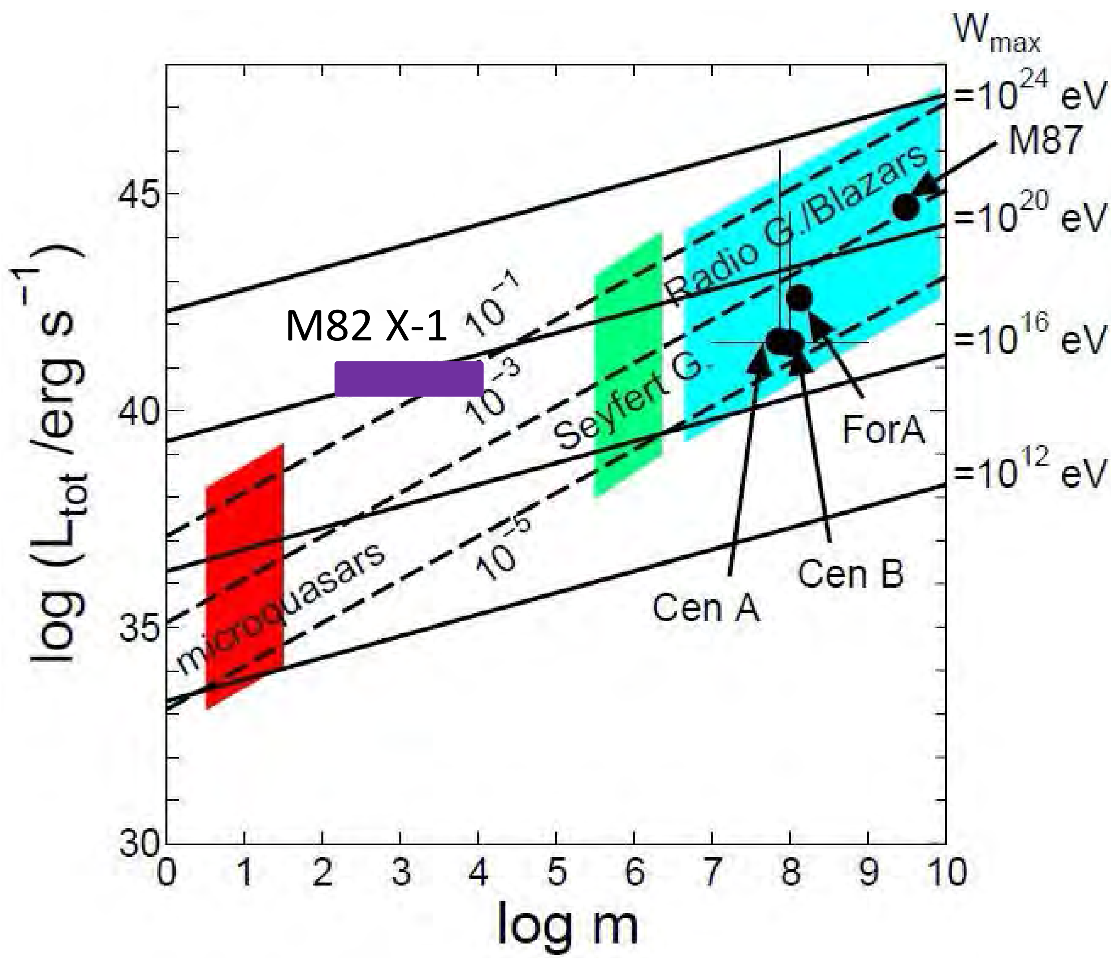
Lau et al. 2015, Phys. Rev. 18, 024401

Acceleration by pondermotive force at "bow wake"

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

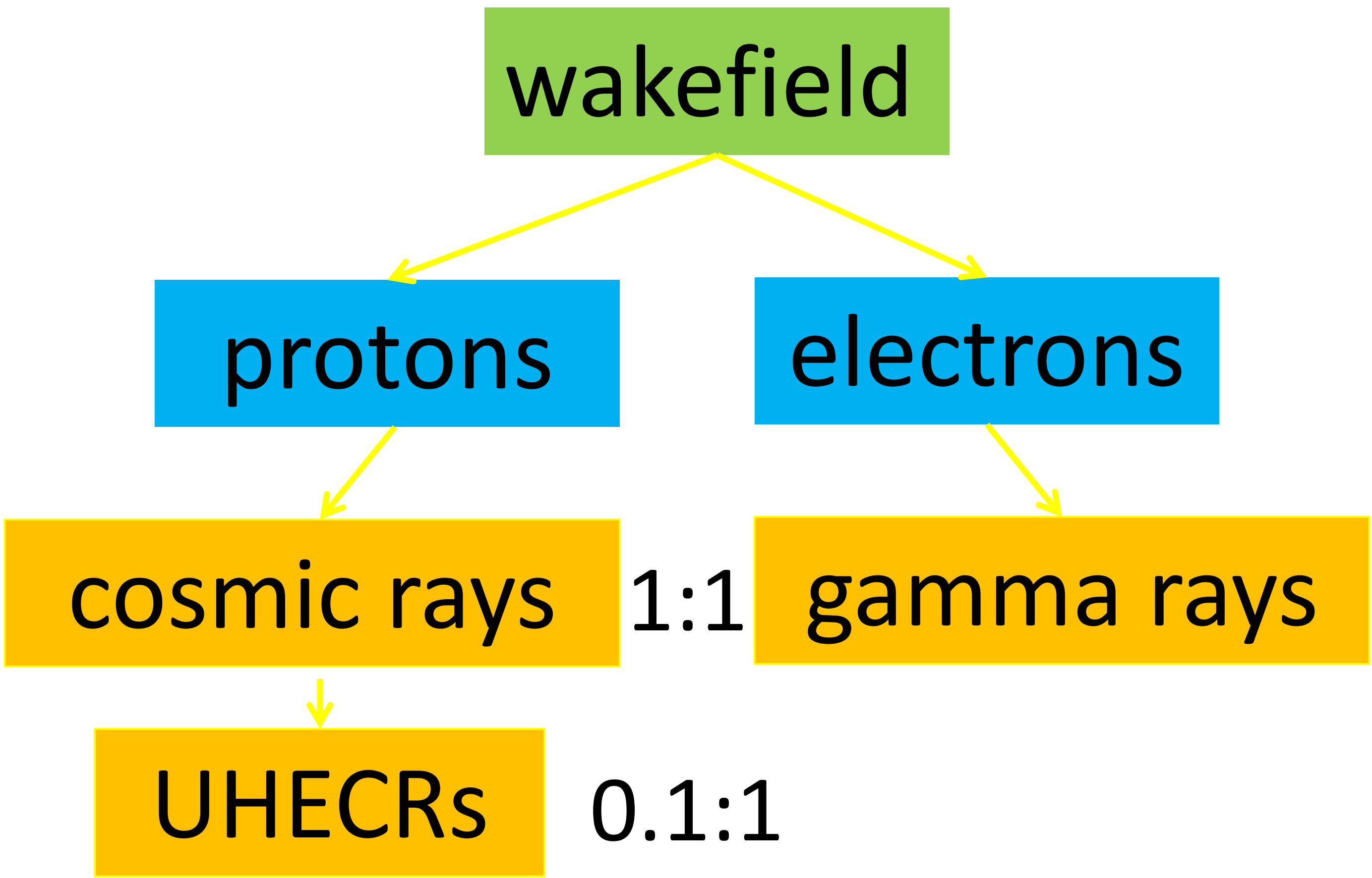
$$F_{\mathrm{pm}} = \Gamma m_{\mathrm{e}} c a_0 \omega_A$$

cosmic ray acceleration and gamma-ray emission



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

Energy Flow and Spectra

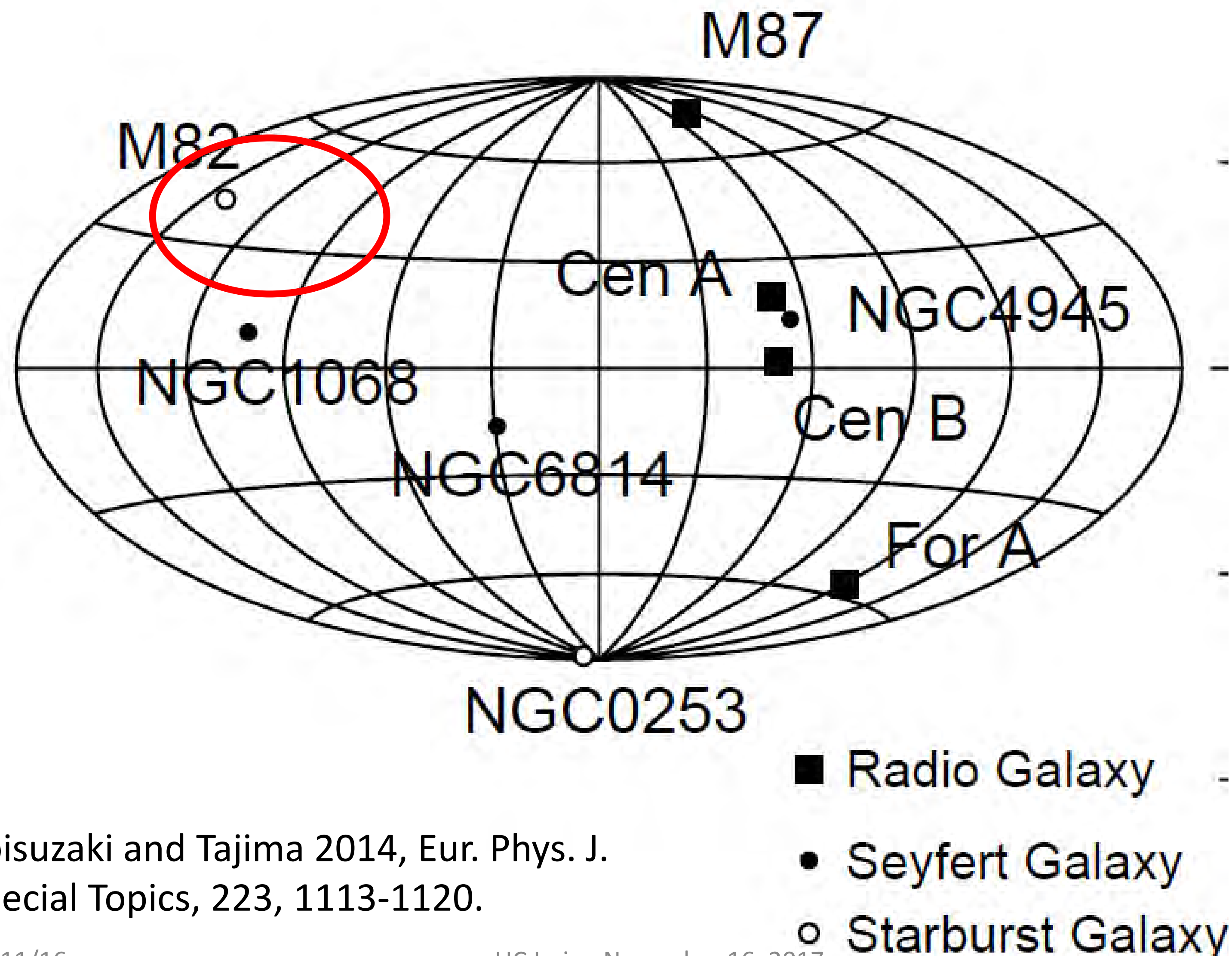


$$F(W) \propto W^{-2}$$

Nine nearby Fermi AGNs

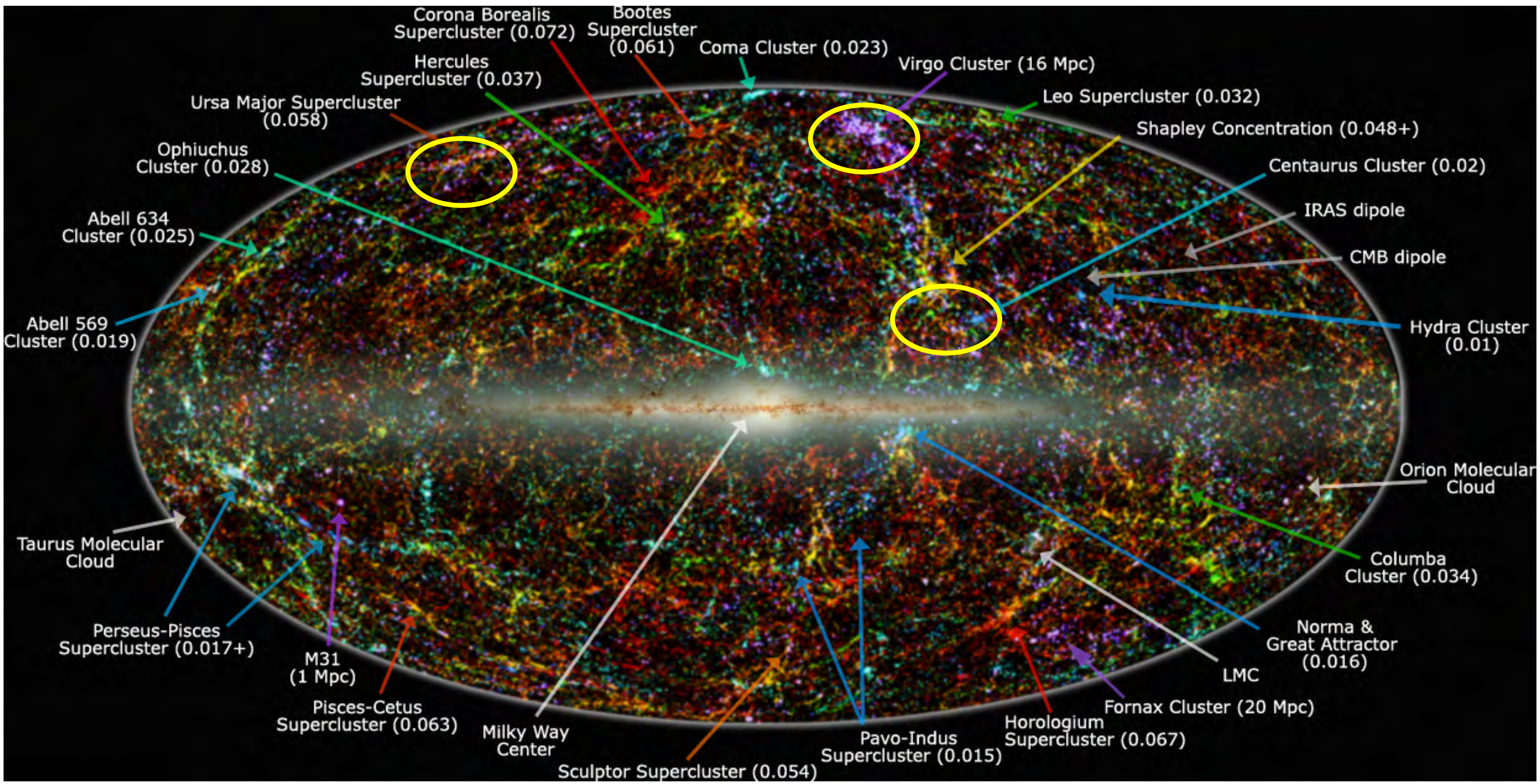
Counterpart name	LII	BII	Class	Redshift	Flux1GeV-100 GeV (erg cm^{-2} s^{-1})	Spectral index	Radio flux(mJy)	X Flux (erg cm^{-2} s^{-1})
NGC 0253	97.39	-87.97	Starburst galaxy	0.001	(6.2+/-1.2) e-10	2.313	2994	6.02E-12
NGC 1068	172.1	-51.94	Seyfert galaxy	0.00419	(5.1+/-1.1) e-10	2.146	4849	4.55E-11
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

Nine nearby Fermi AGNs (Sky Map)



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

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

M82 X-1 is promising

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

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

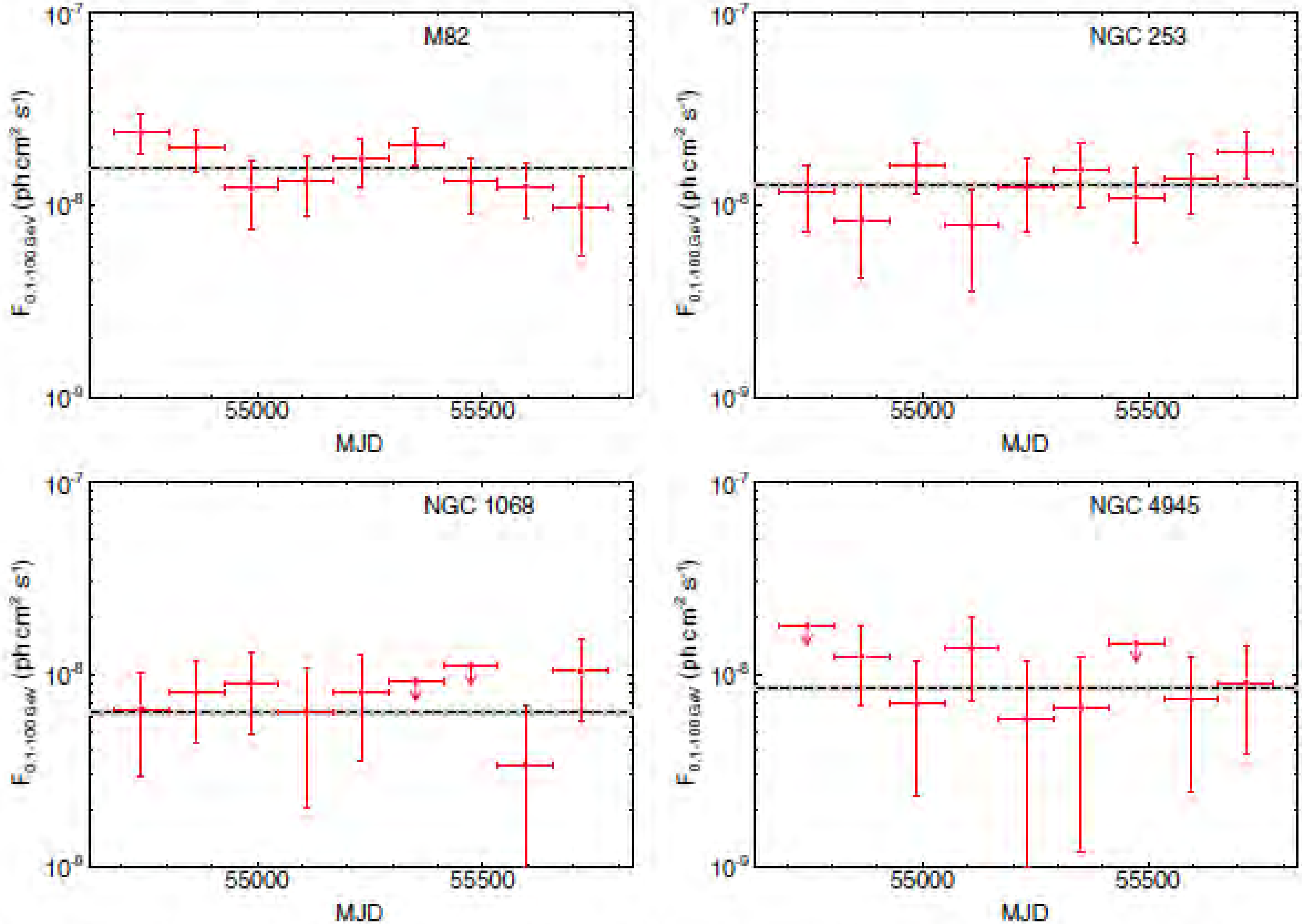
  $L_{\mathrm{UHECR\ M82X-1}} = 1.3 \times 10^{39}$ erg s^{-1}

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

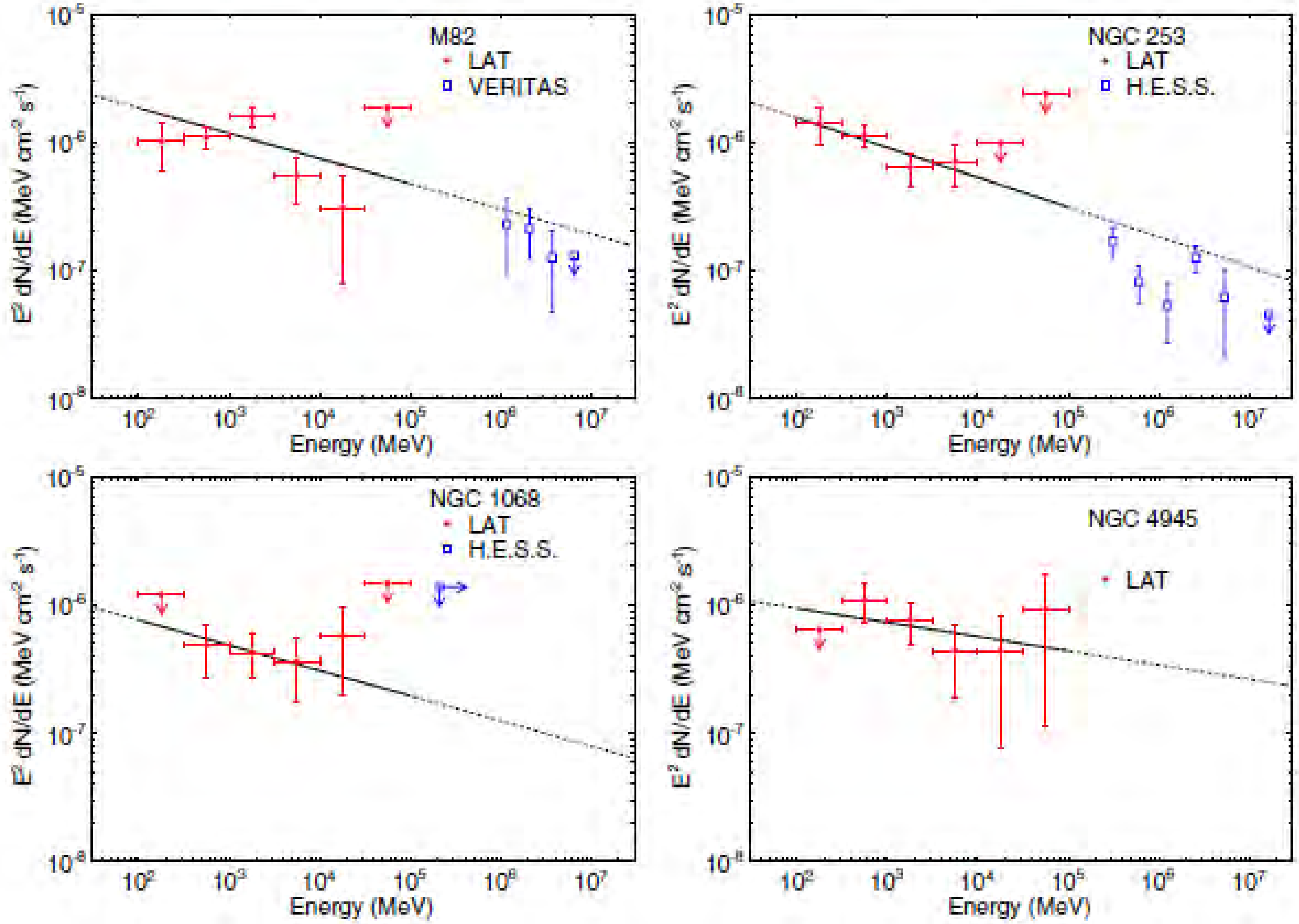
  $F_{\mathrm{UHECR\ M82X-1}} \sim$3 UHECRs/100km^2/yr

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

Light Curves

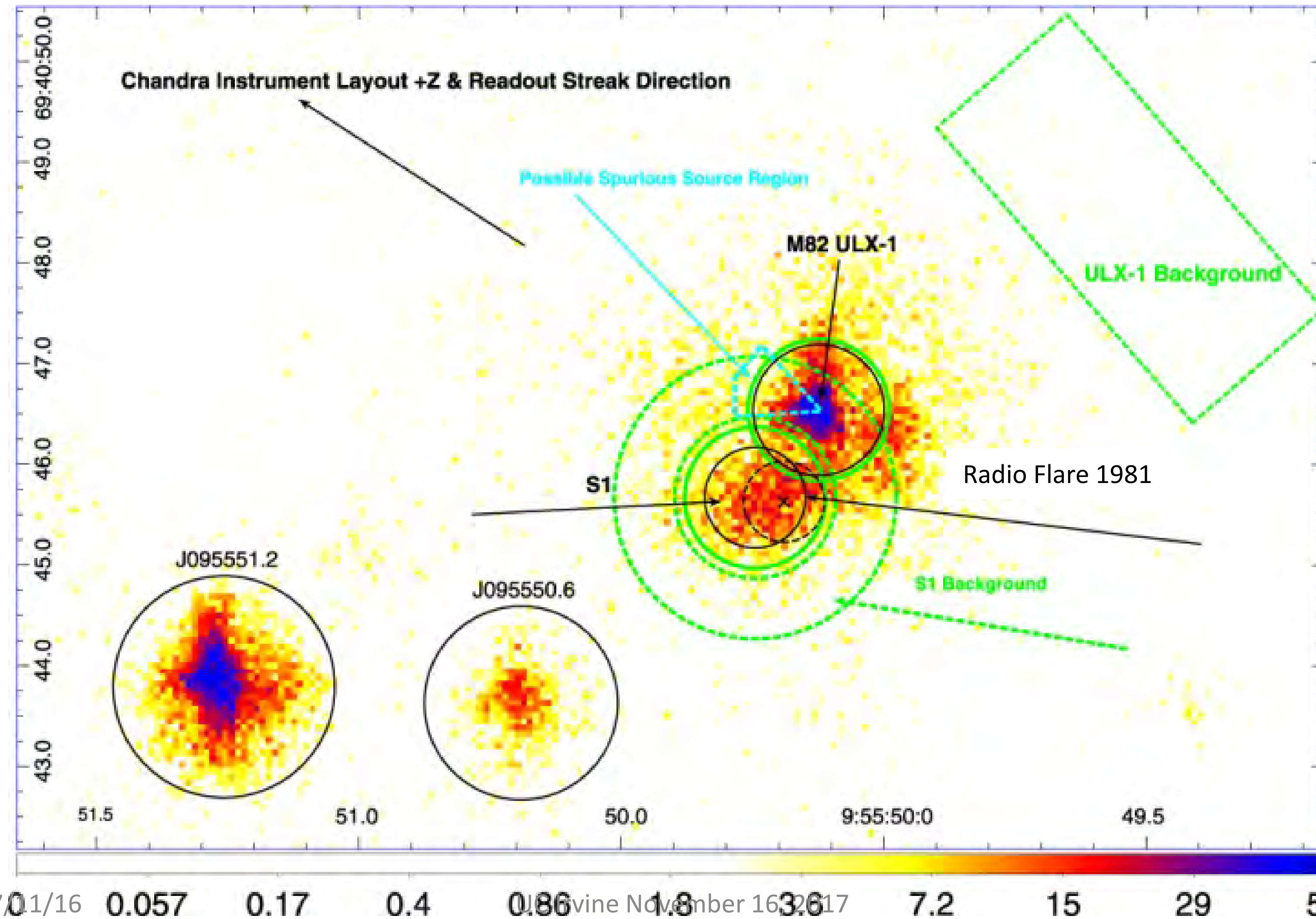


Energy Spectra



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

Xu et al. 2015 ApJ Letters 799, L28



Astrophysical Implication

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

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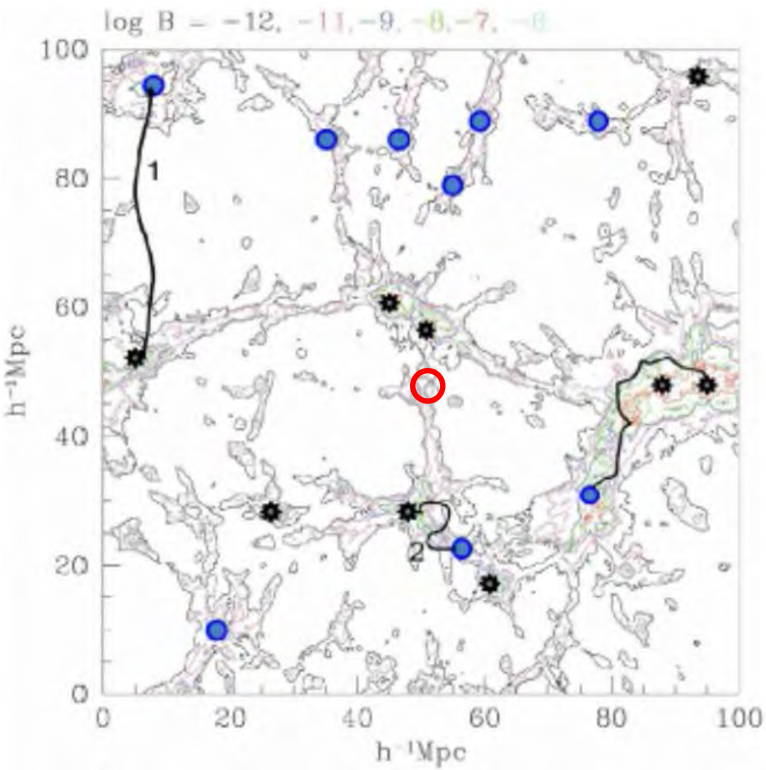
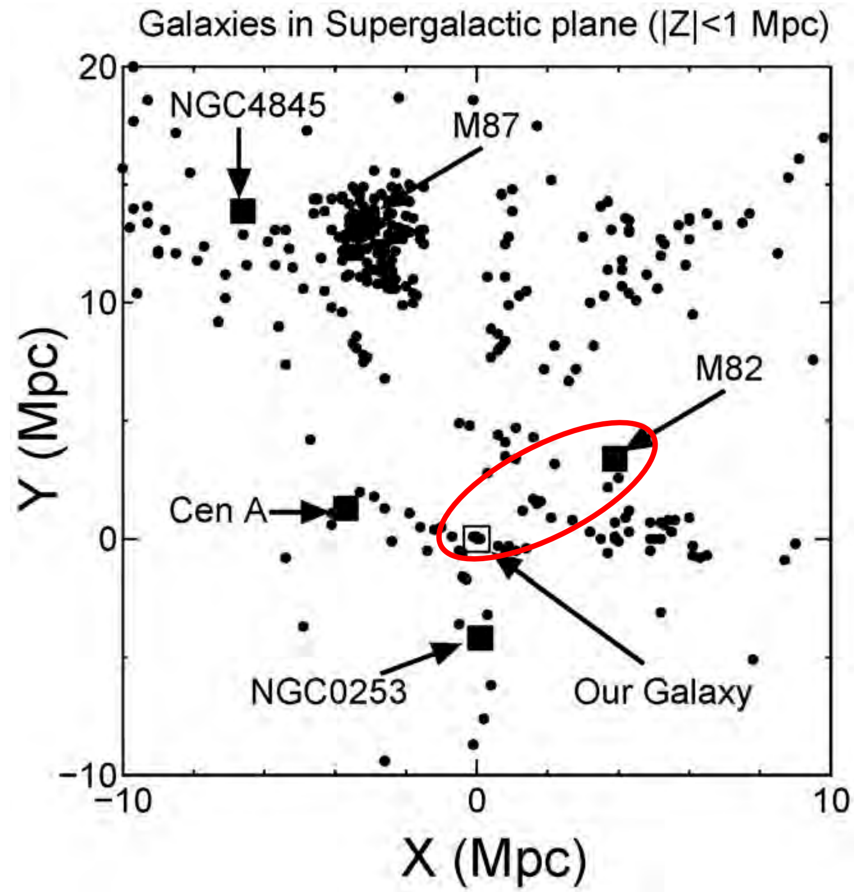
UHECR propagation among the cosmological web (1)

Ryu et al. 2010 ApJ, 710, 1422

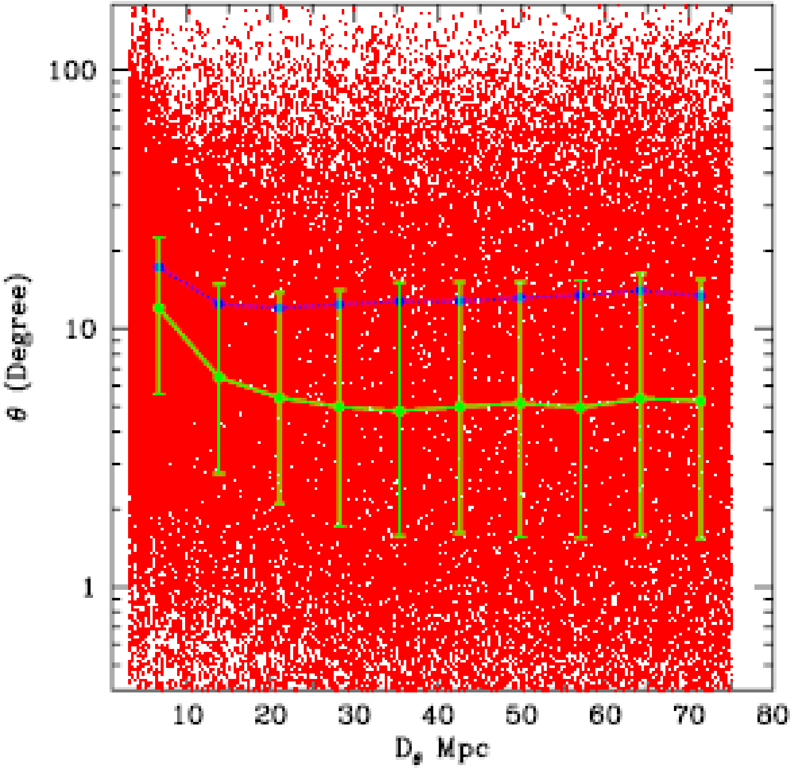




We are living on a filament of the cosmological web!

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
- $\epsilon_B = \phi\left(\frac{t}{t_{eddy}}\right)\epsilon_{turb}$
  - t_{eddy} and ϵ_{turb}: simulation
  - ϕ: different simulations with fine meshes



Ryu et al. 2010 ApJ, 710, 1422

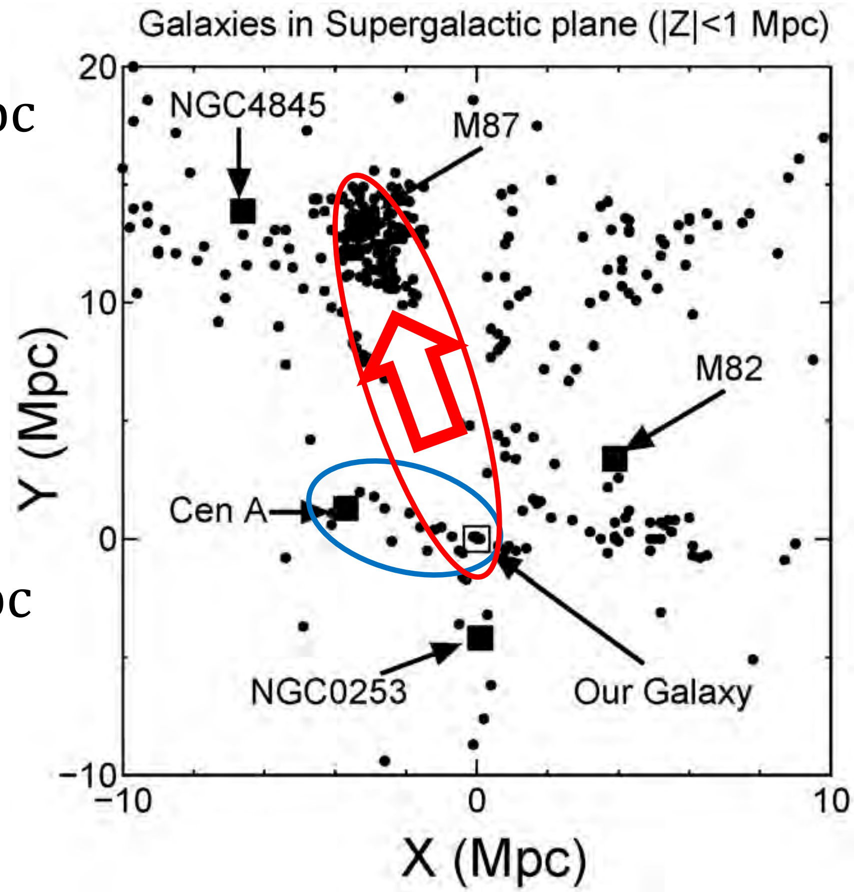
How about Cen A and M87/Vir A ?

- **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**

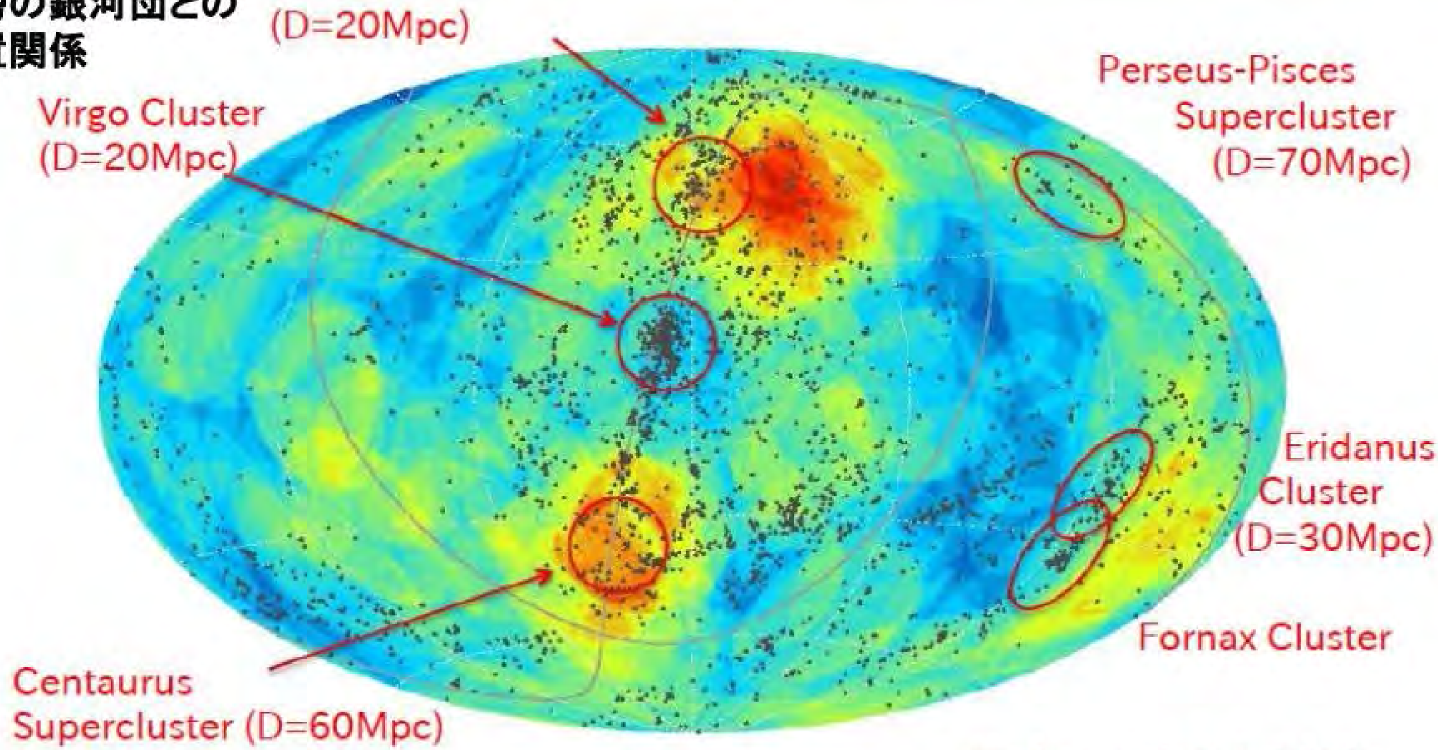
    Virgo centric inflow
  - $\theta, \Delta\theta \sim 60$ degree

  $\rightarrow$ diffuse source along SGP



全天Map (TA >57EeV, Auger > 57EeV)

近傍の銀河団との位置関係



Huchra, et al, ApJ, (2012)

◇ Dots : 2MASS catalog Heliocentric velocity <3000 km/s

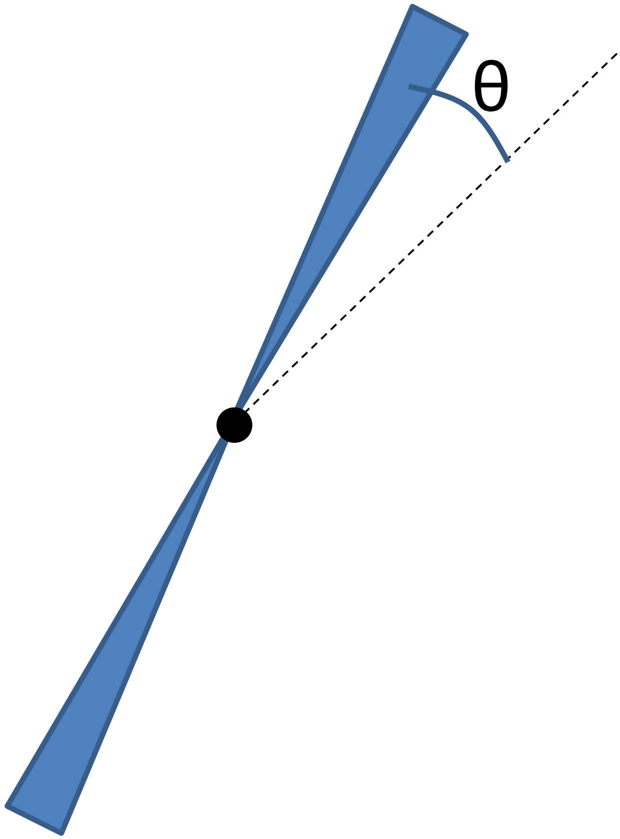
◇ TA hotspot is found near the Ursa Major Cluster

◇ TA & Auger found no excess in the direction of Virgo.

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



Background Component: Numerous number of Distant Sources

Ebisuzaki and Tajima 2014

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

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

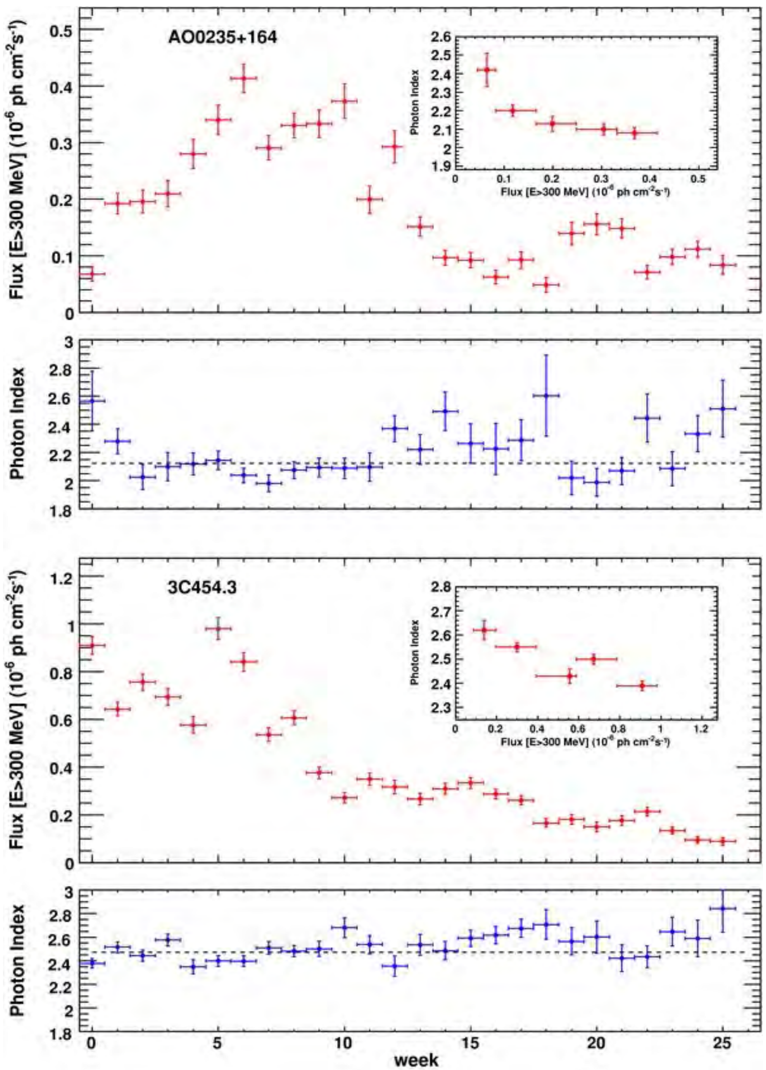
  → $\Phi_{\mathrm{UHECR}} \sim 0.1$ particles/(100 km^2 yr sr)

  GZK (if mainly protons)

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

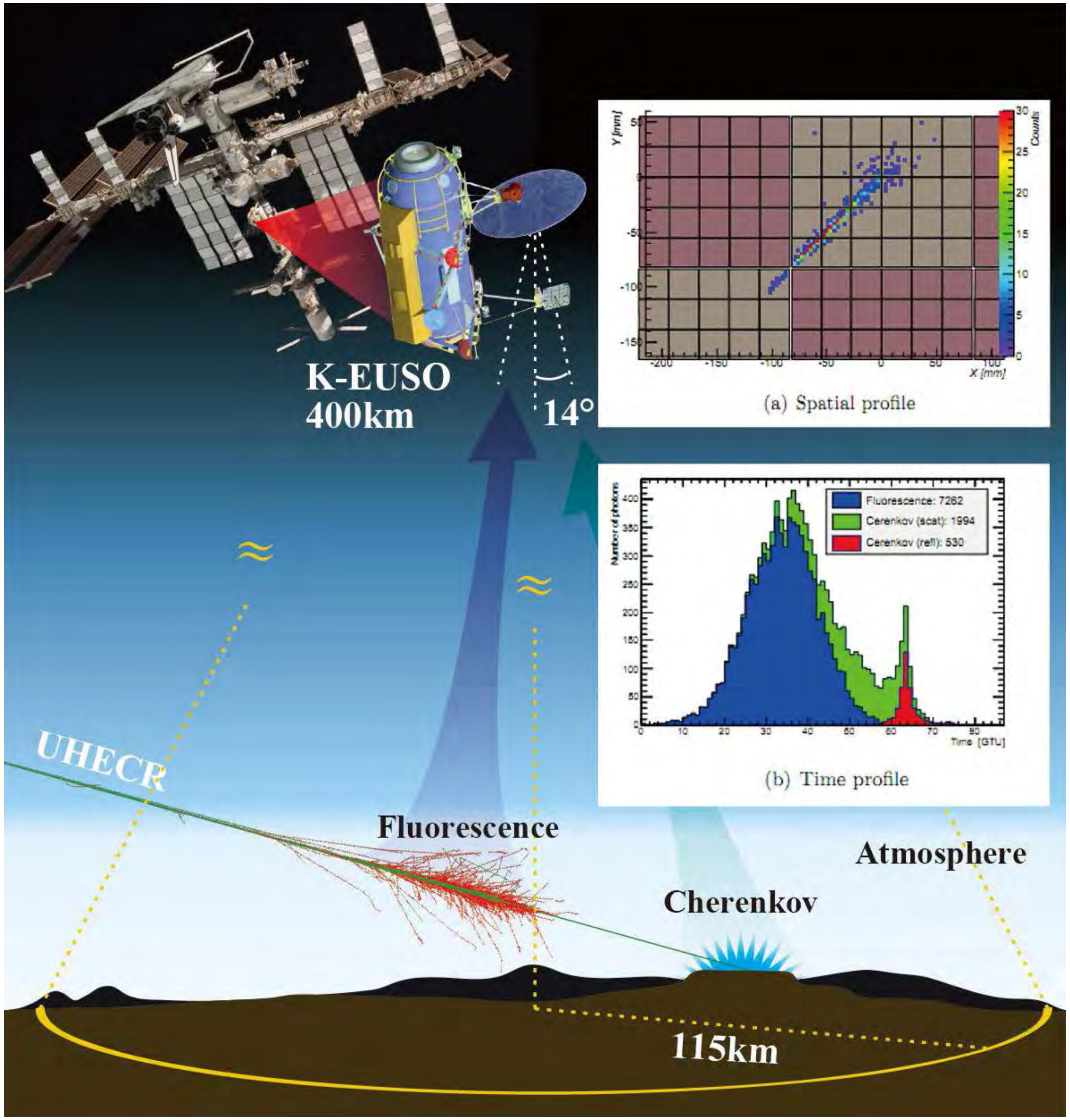
  for $E_{\mathrm{UHE\nu}} > 10^{20}$ eV

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



contents

5. K-EUSO

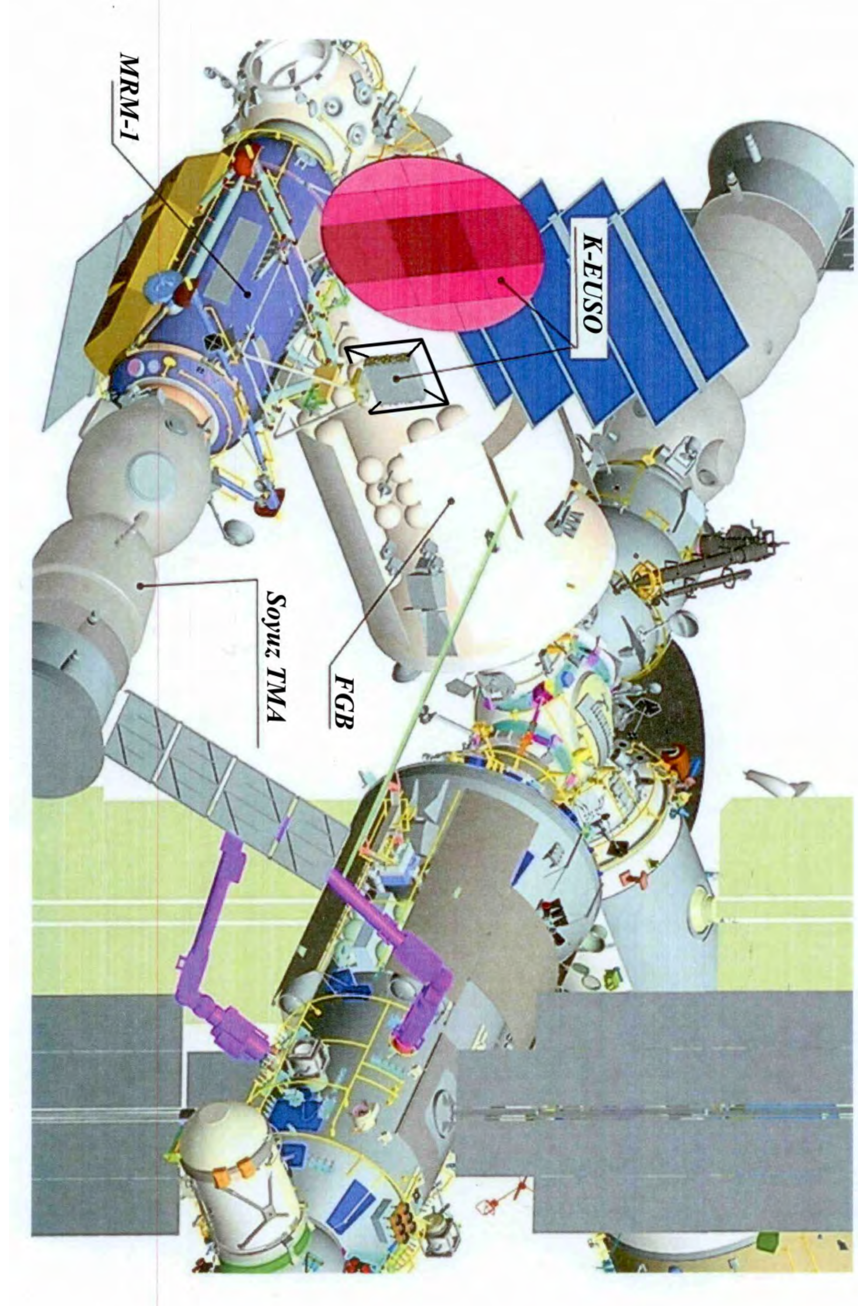


K-EUSO
400km
14°
(a) Spatial profile
(b) Time profile
Fluorescence: 7262
Cerenkov (scat): 1994
Cerenkov (refl): 530
UHECR
Fluorescence
Atmosphere
Cherenkov
115km

K-EUSO

Russian Federal Space Program

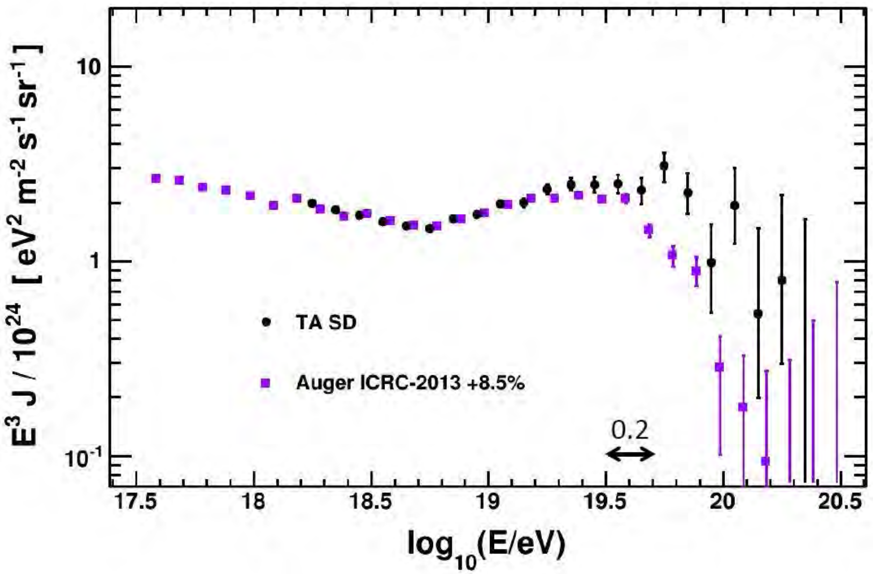
- Passed the stage of preliminary design with Roscosmoc
- Technical requirements, accomodation, operations study performed by Energia space corporation
- Evolution of KLYPVE Russian detector (reflector)
- Mission of opportunity Launch in 2022

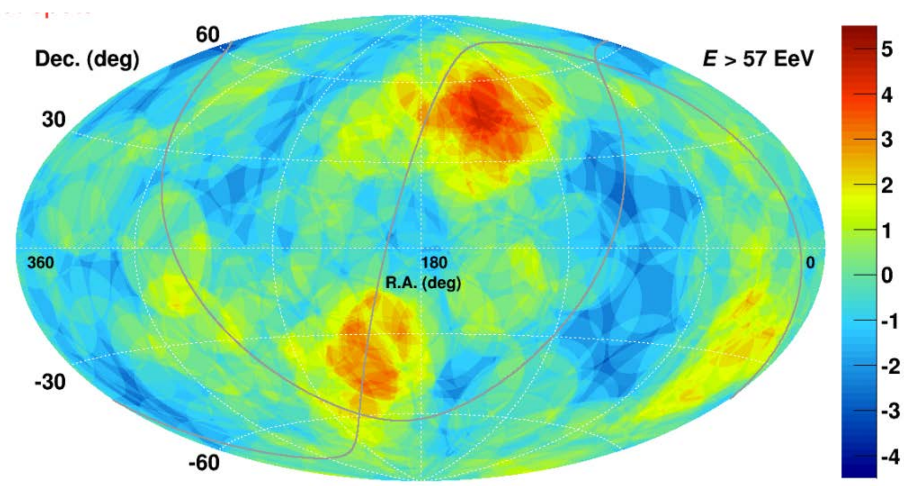


Science of K-EUSO

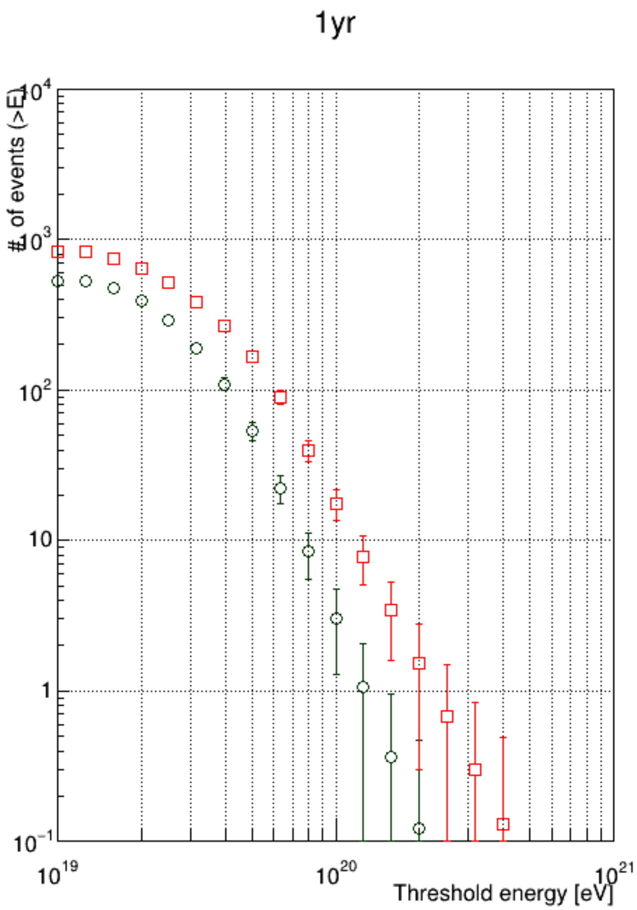
. Study of UHECR fux
  from space with uniform
  response

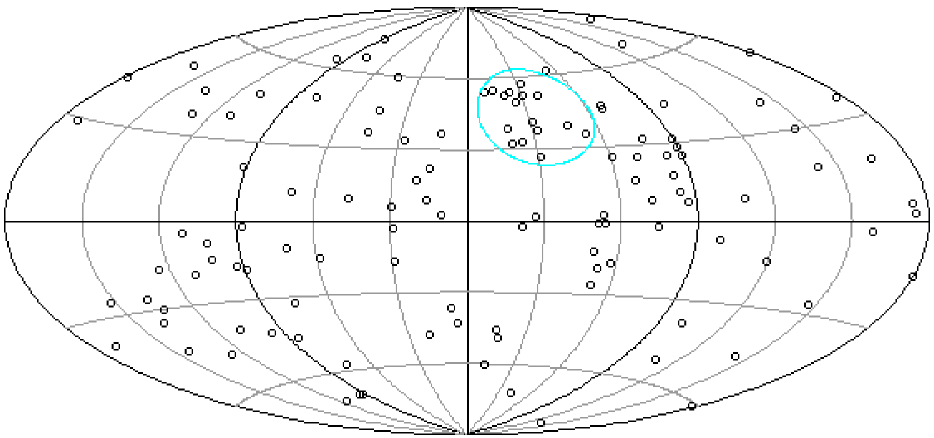
2. flux E>3 10^{19} eV
   north & south
3. Anysotropy
4. Earth observations,
   bioluminescence
5. Debris tracking and
   removal



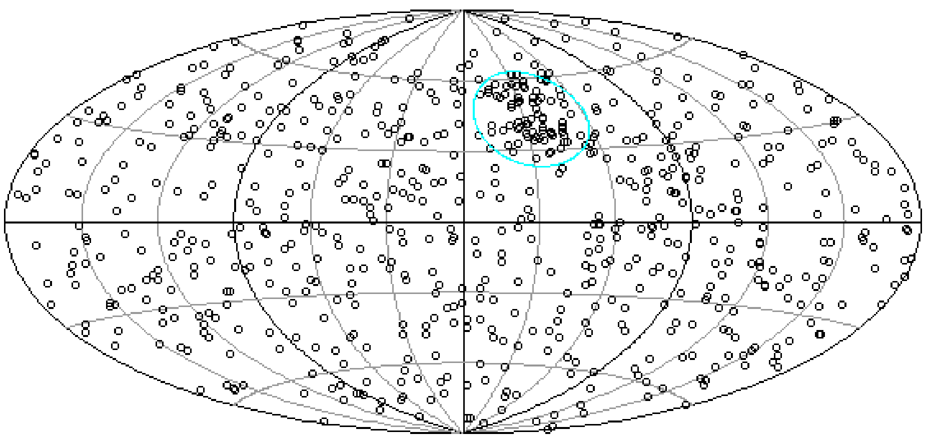


N-S spectral difference





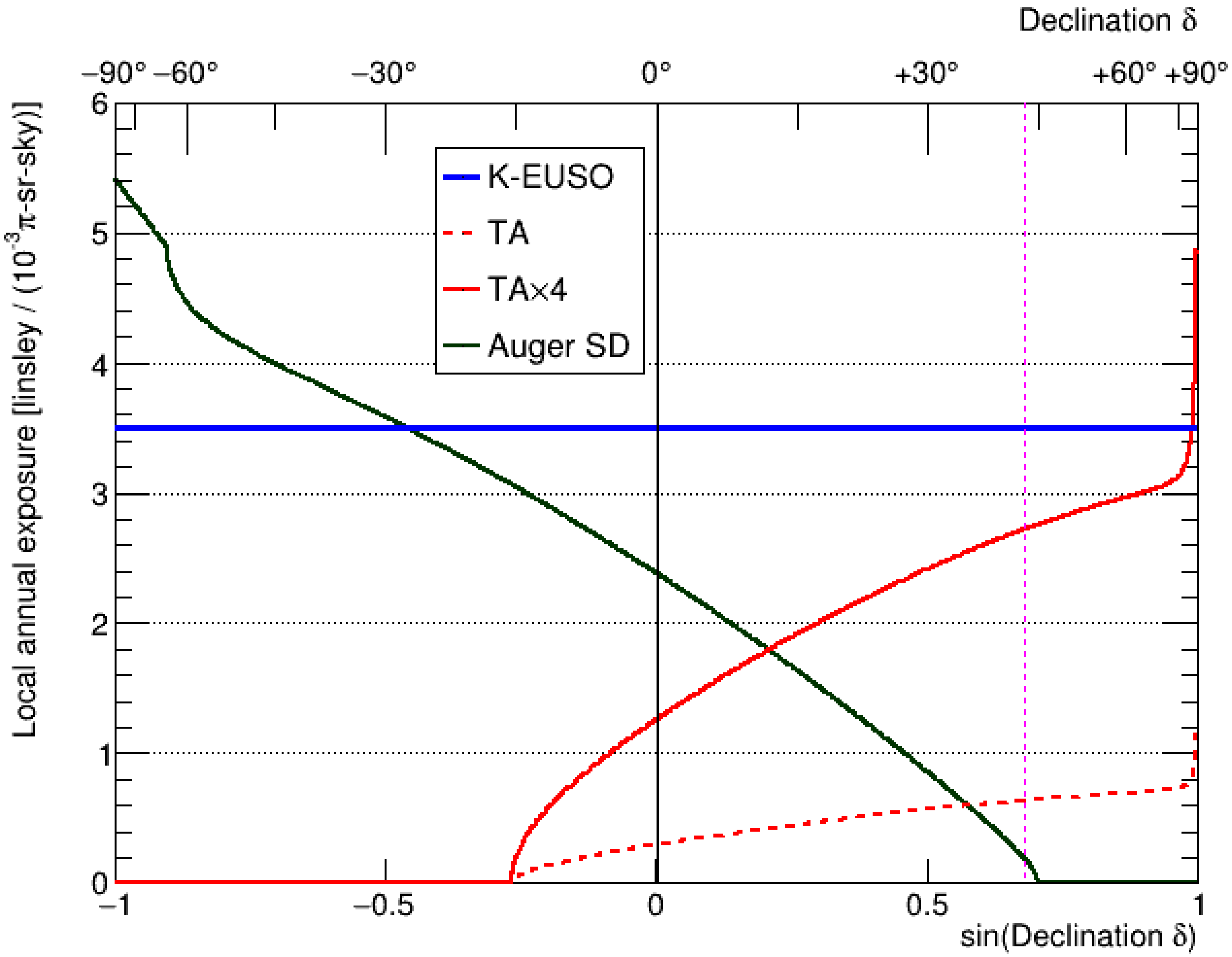
1 year



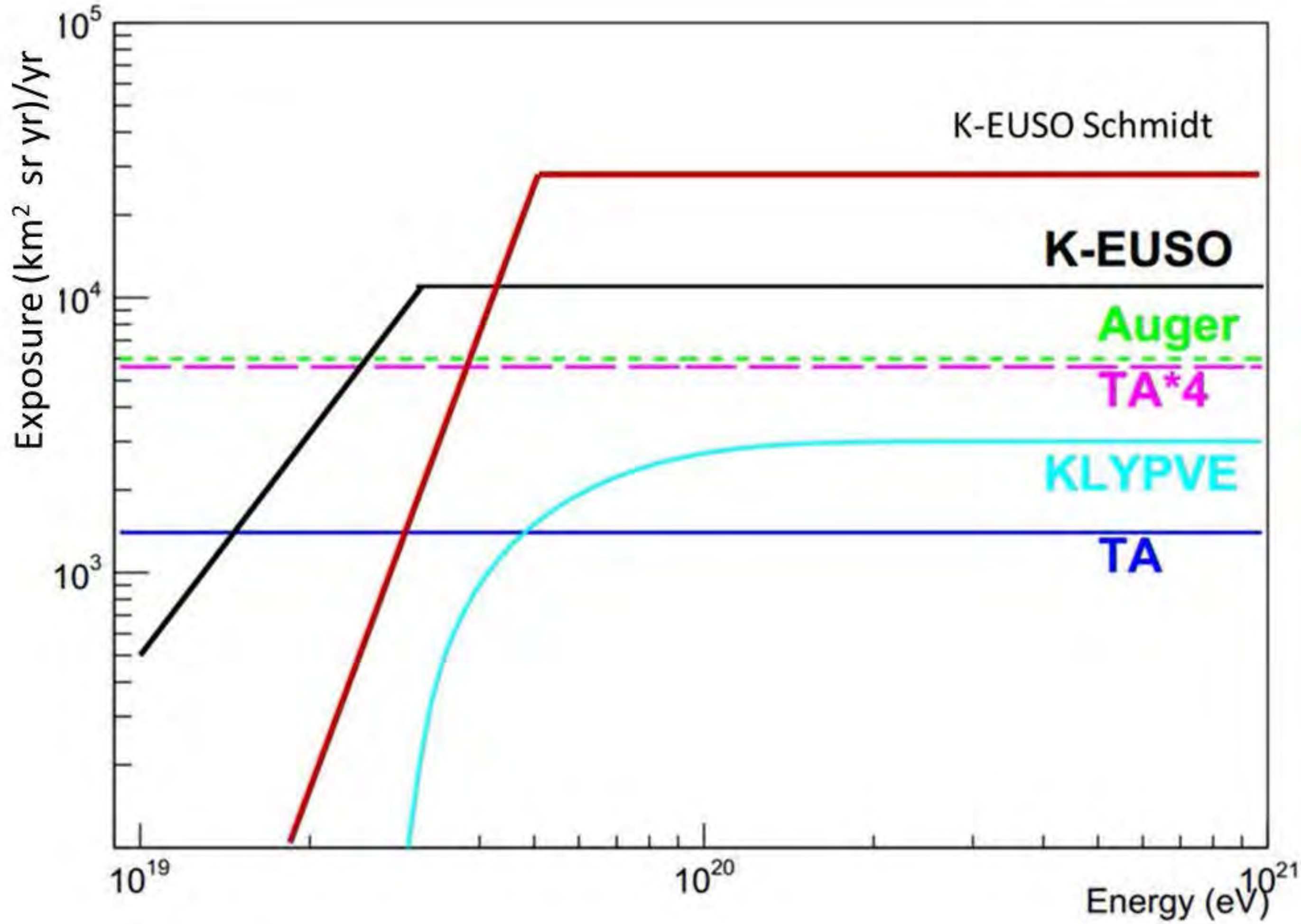
6 years

Uniform response over both hemispheres

Some (5%) disuniformity due to clouds, continents and moon phase

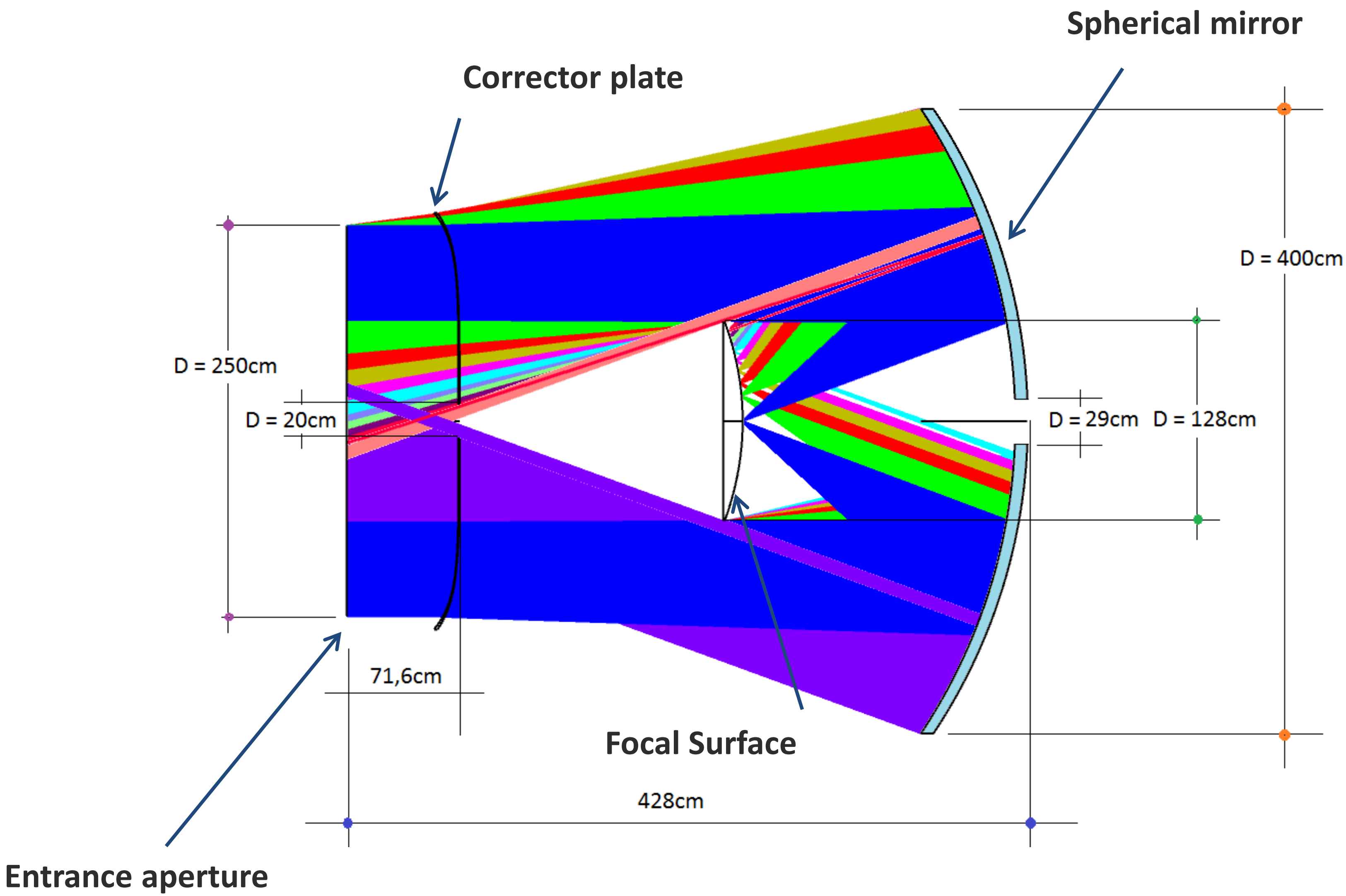


K-EUSO exposure



ADVANCED SCHMIDT OPTICAL DESIGN LAYOUT

INO-CNR
ISTITUTO NAZIONALE DI OTTICA

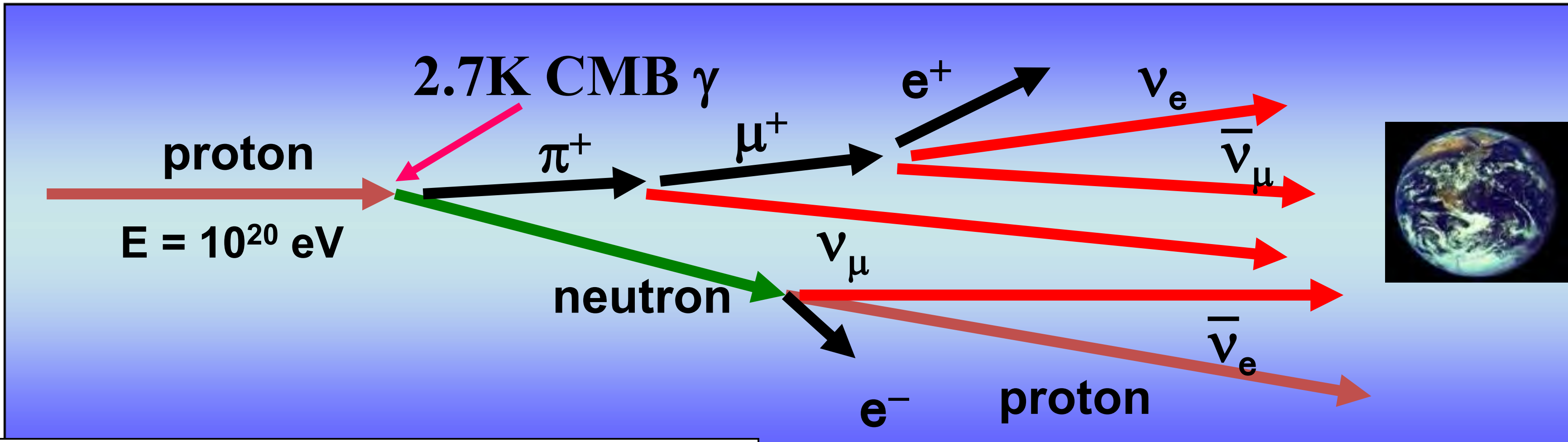


Double Donut Schmidt Camera (named by P. Mazzinghi)

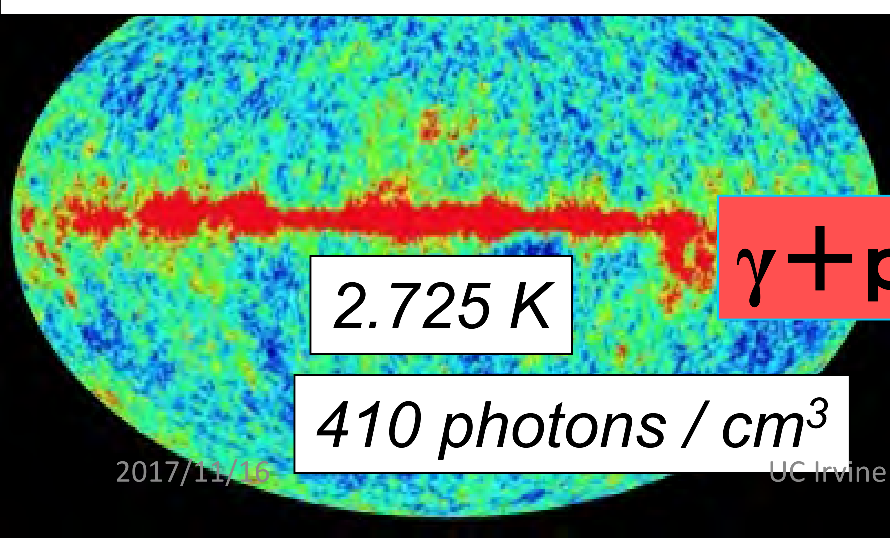
How about neutrinos?

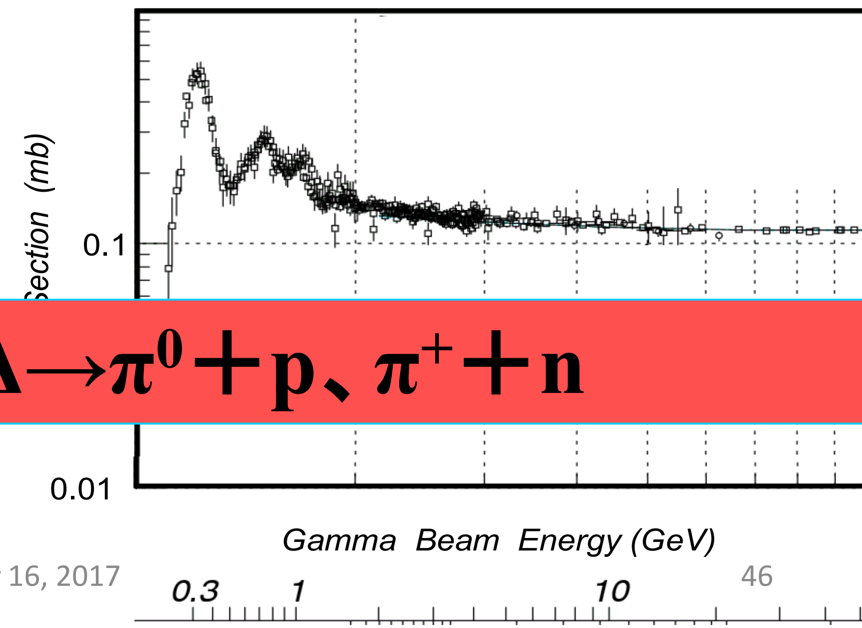
Greisen-Zatsepin-Kuz'min Process

Greisen1966; Zatsepin and Kuz'min1966



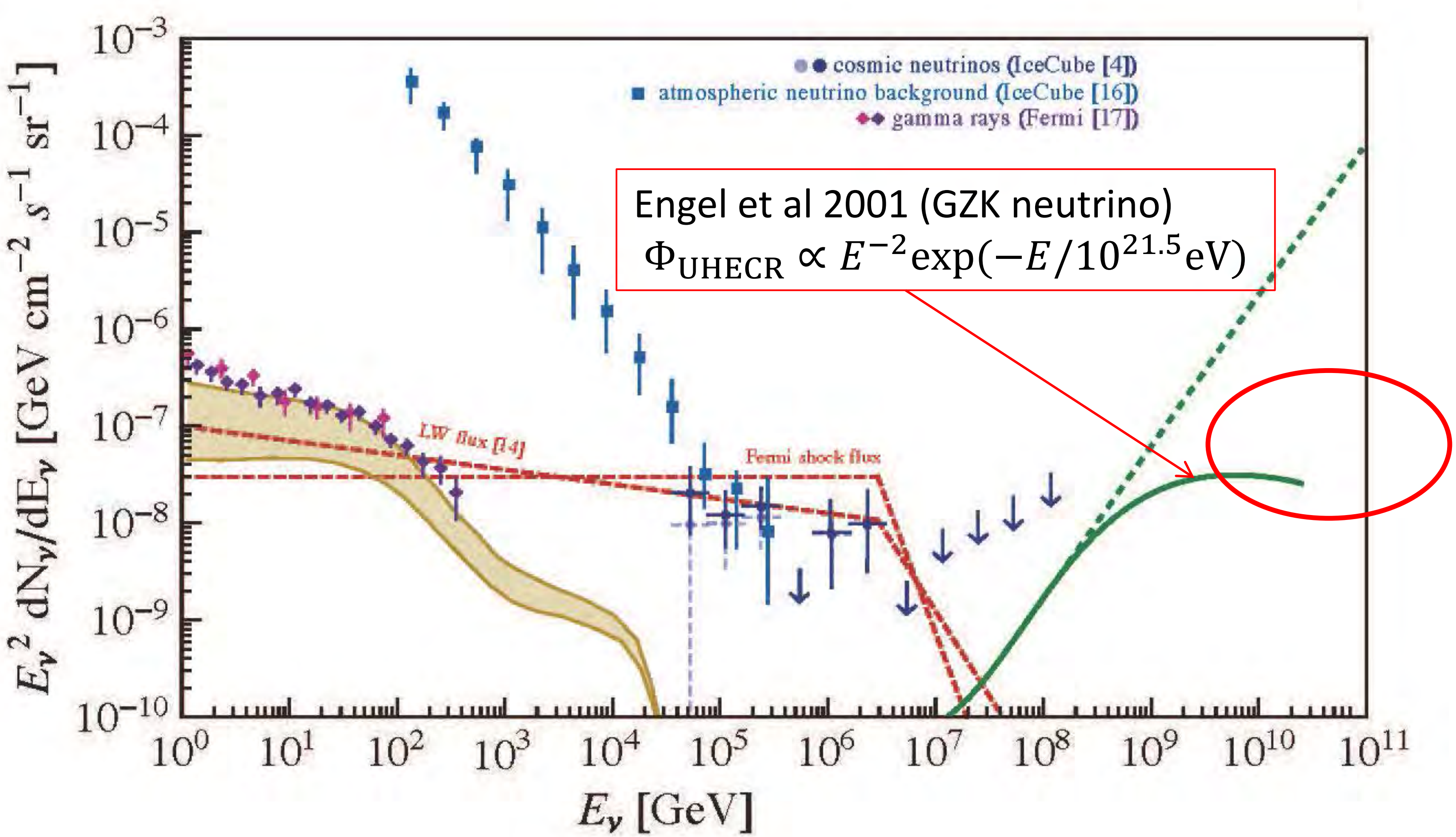
Microwave Cosmic Background Radiation





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

Neutrino and gamma ray flux



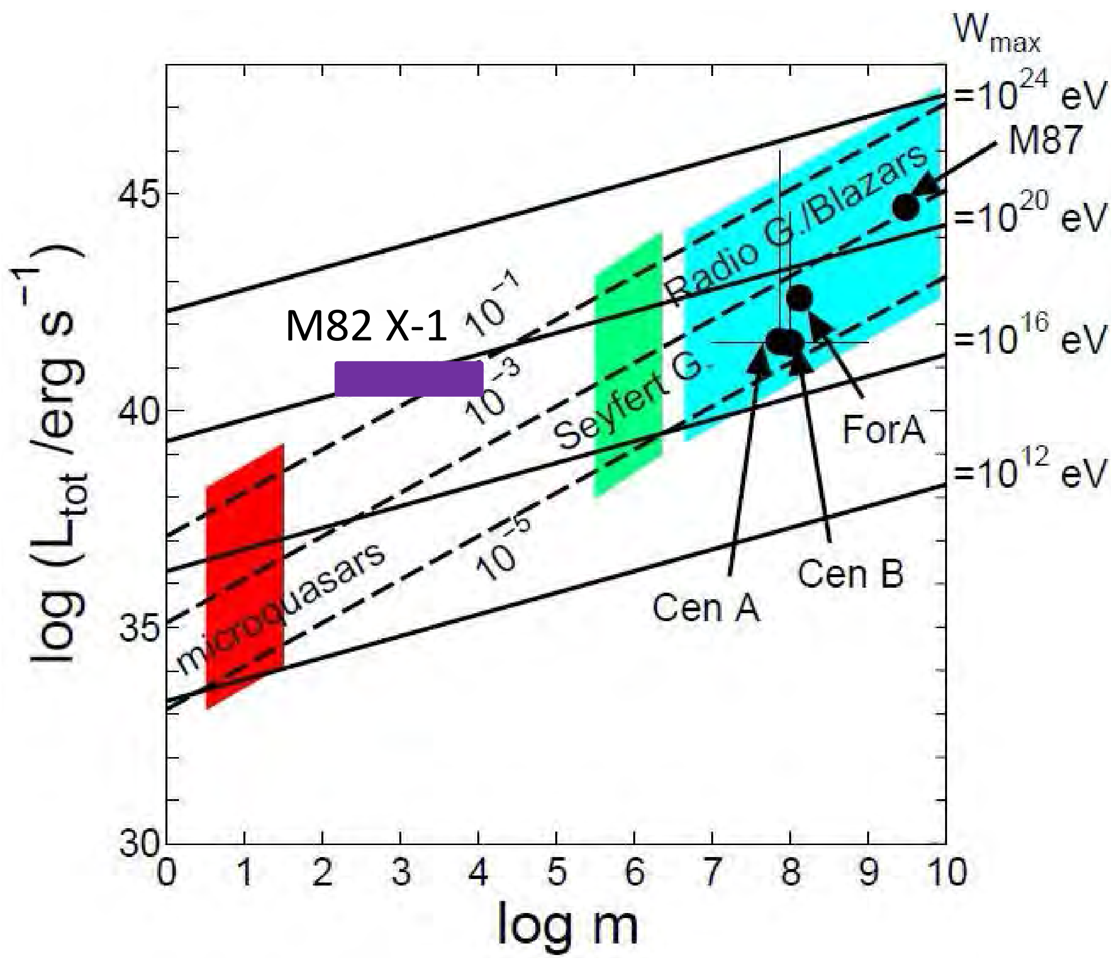
Taken from Anchordoqui et al. 2014, Phys. Rev. D., 89, 127304
and Yacobi et al. 2016, Ap. J., 823, 89, modified by TE

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
  - **B$\sim$10nG in the cosmic filaments of local supercluster**
  - Study of **supercluster magnetic field**
- **K-EUSO**
  - Confirmation of south-north anisotropy
  - Identification of M82 and other sources
- **Ultra High energy neutrinos** from distant blazers
  - Ice Cube and POEMMA

Back up

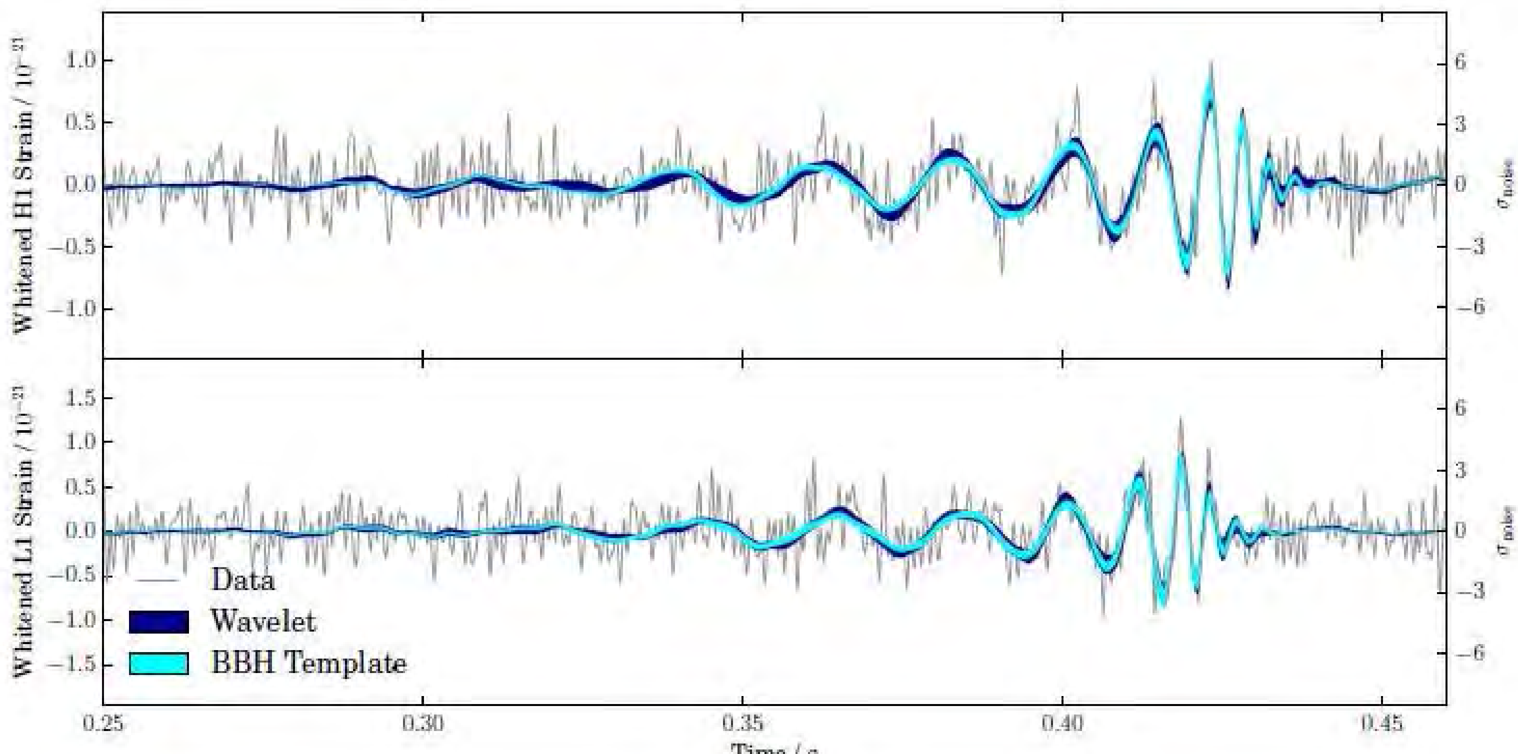
cosmic ray acceleration and gamma-ray emission

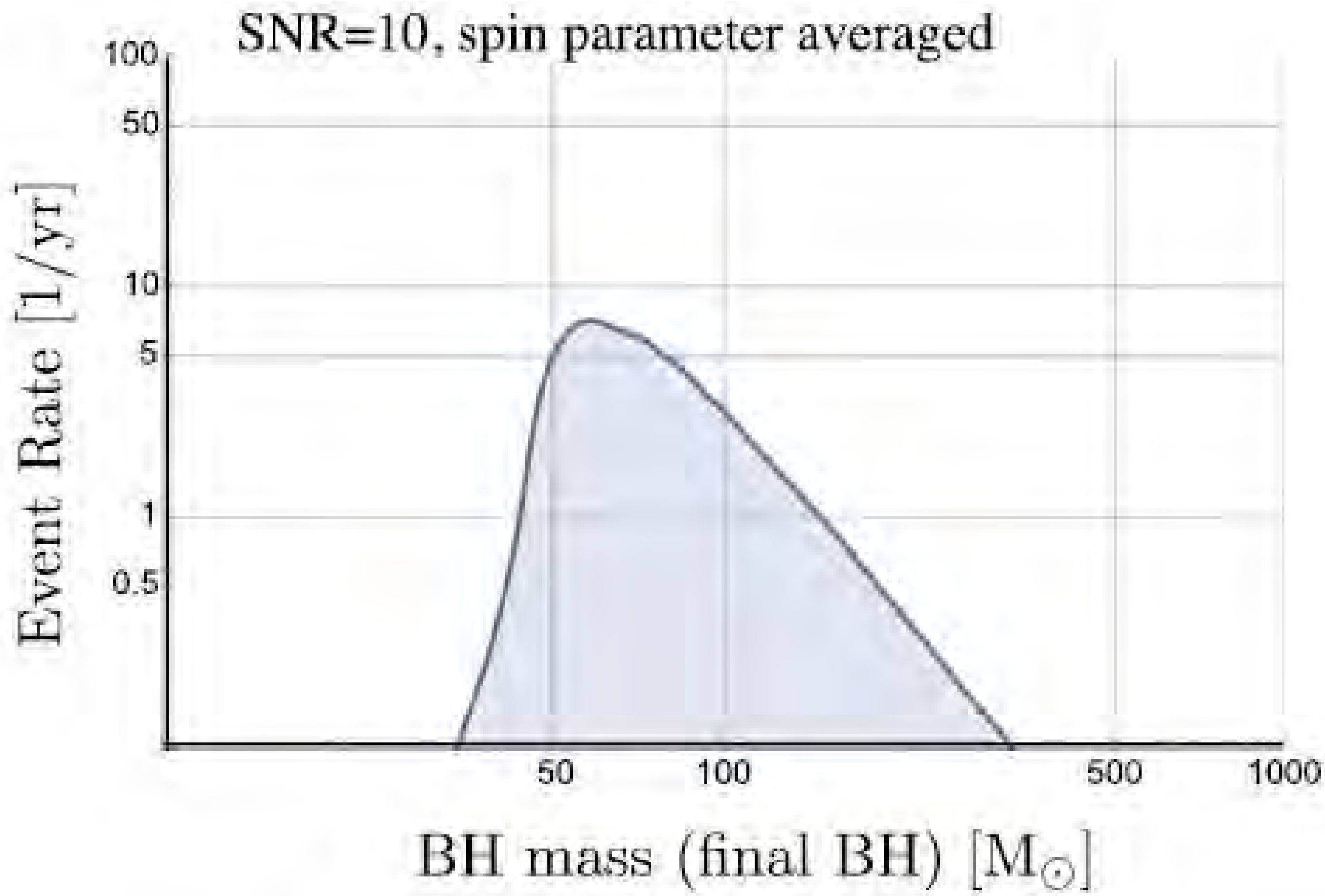


$$L_{\mathrm{tot}} = 1.3 \times 10^{38} m\dot{m}\ \ \mathrm{erg\,s^{-1}}$$

GW150914

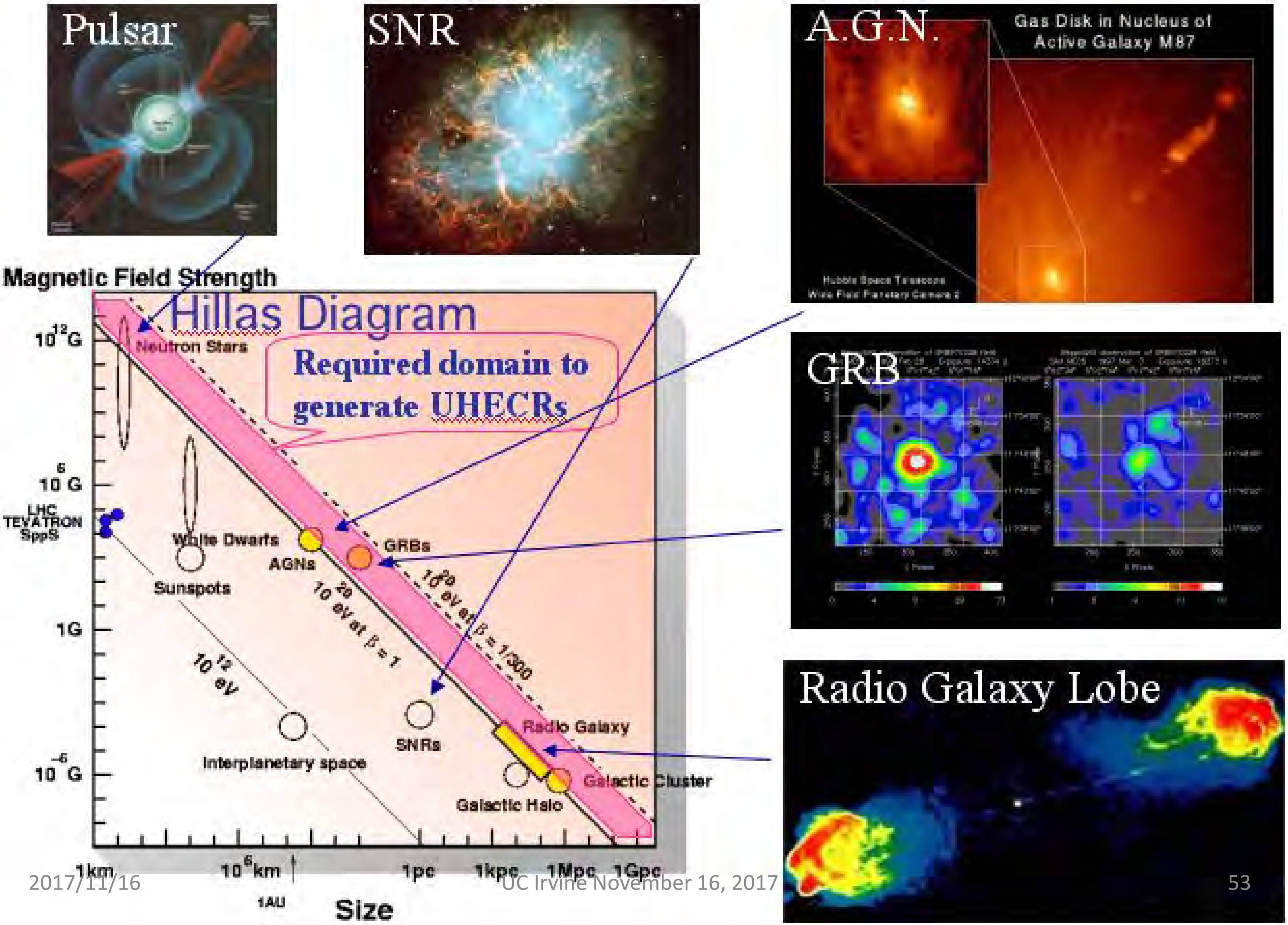
- Merging of Binary BH: 36Ms+29Ms
- Distance : 410 Mpc=0.410 Gpc (Z=0.09)



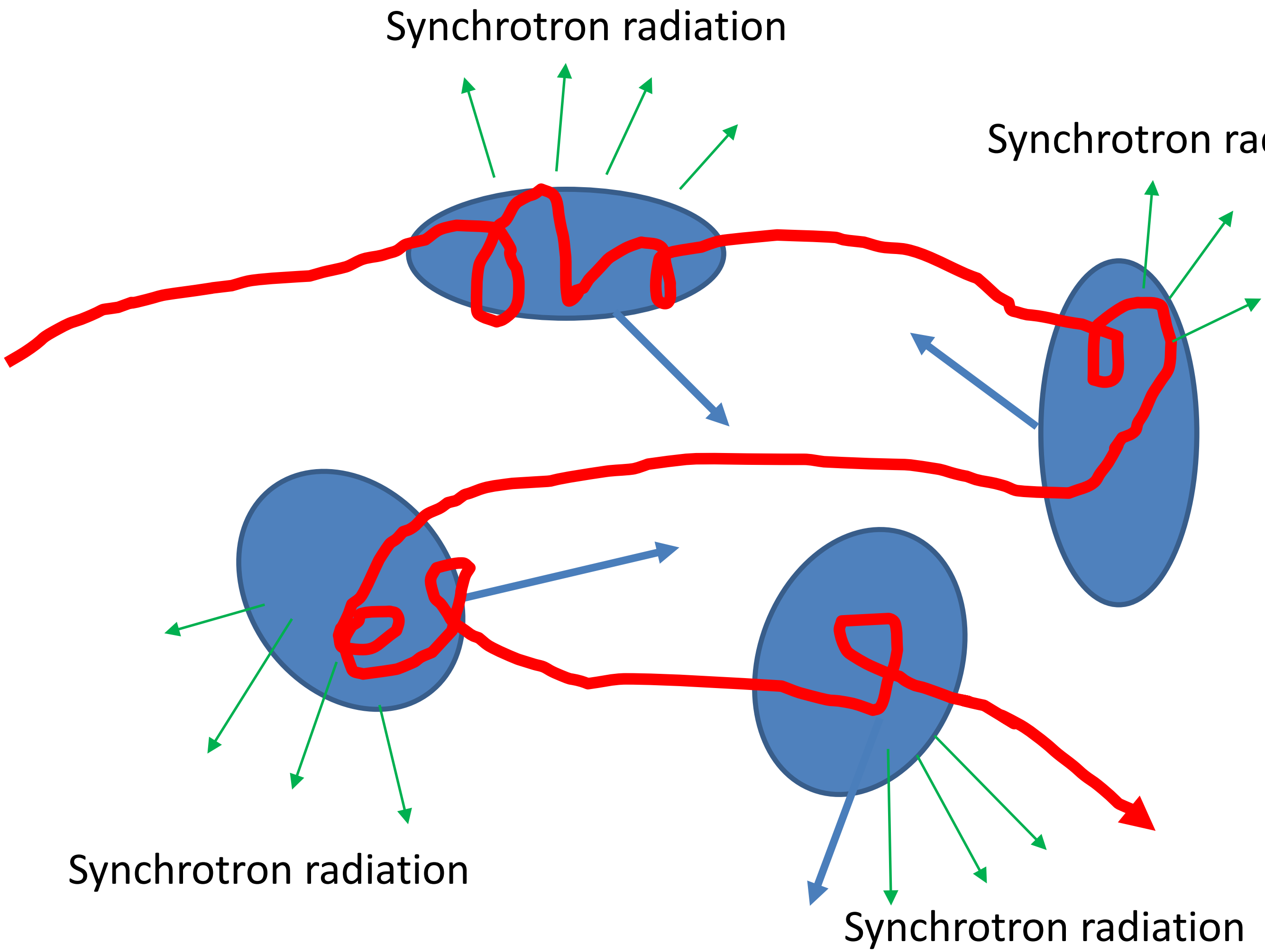


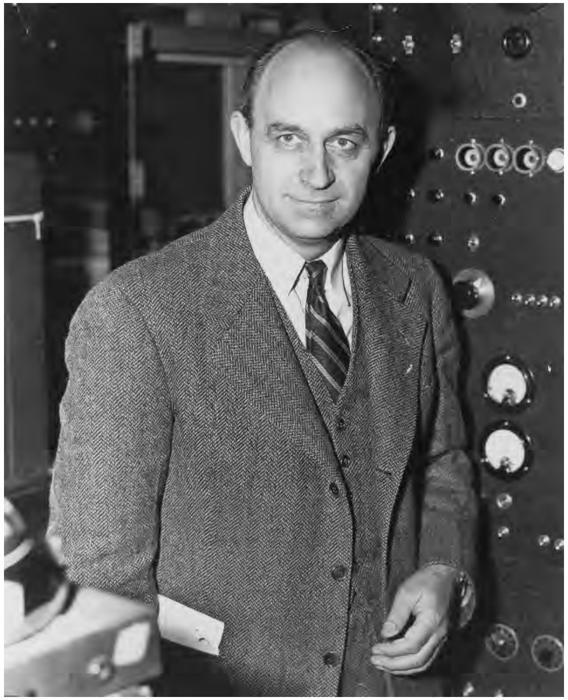
Shinkai, kanda, and Ebisuzaki, 2017, ApJ, 835, 276-283.

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



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

3. Escape problem

   →magnetic field does not disappear without adiabatic loss

Wakefield acceleration

Difficulties of Fermi acceleration in UHECR

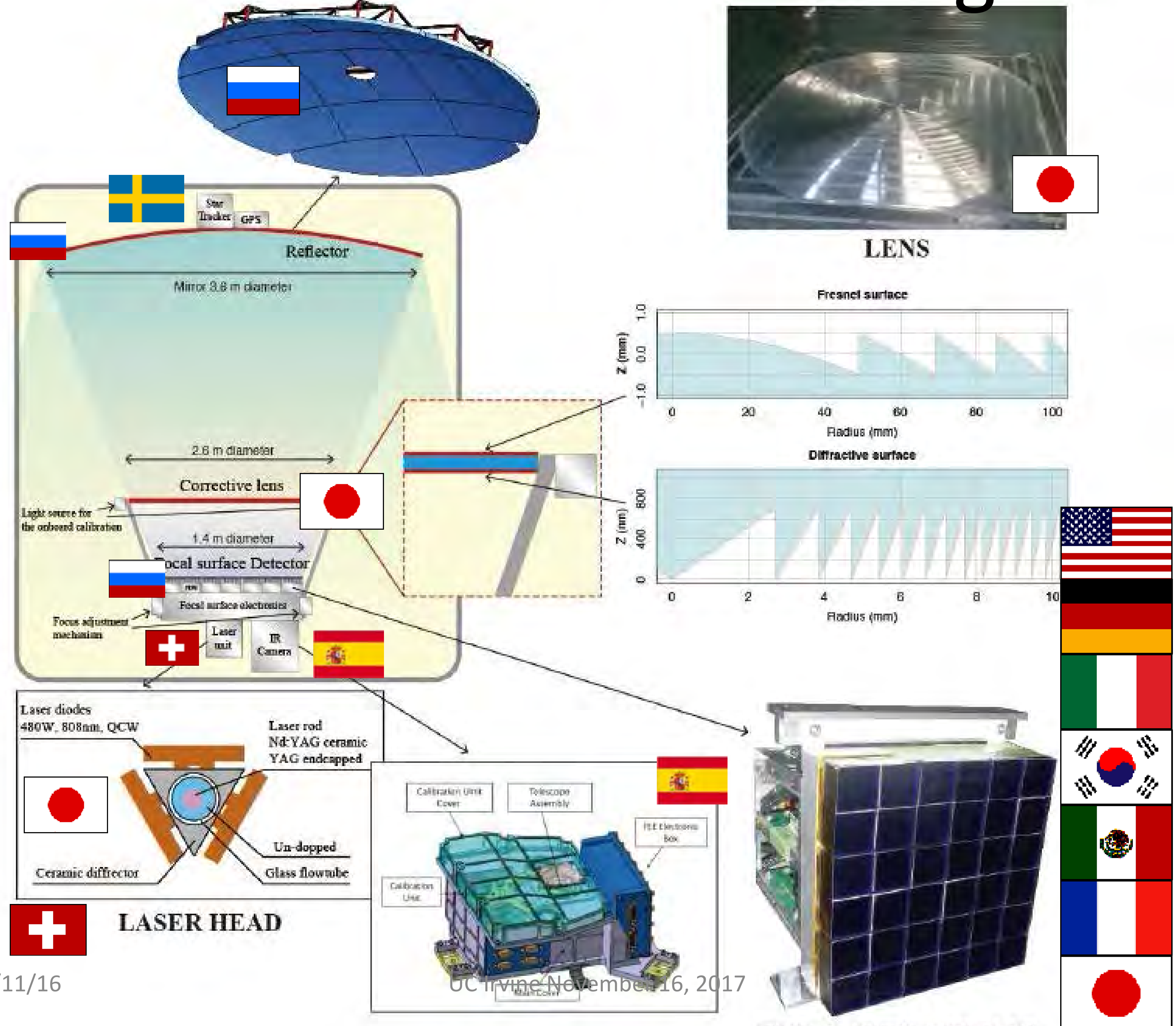
1. Bending is inevitable

    →synchrotron loss

2. Confinement is difficult

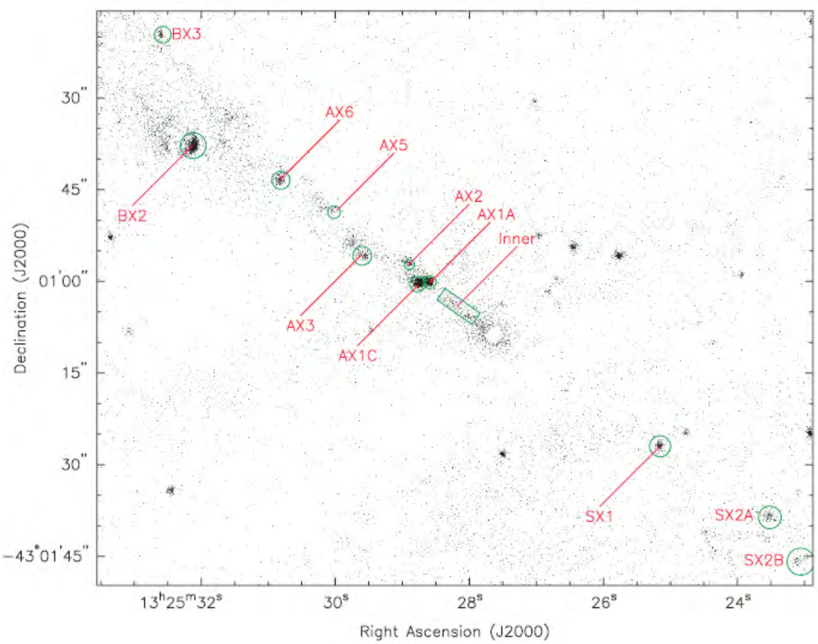
    →no acceleration

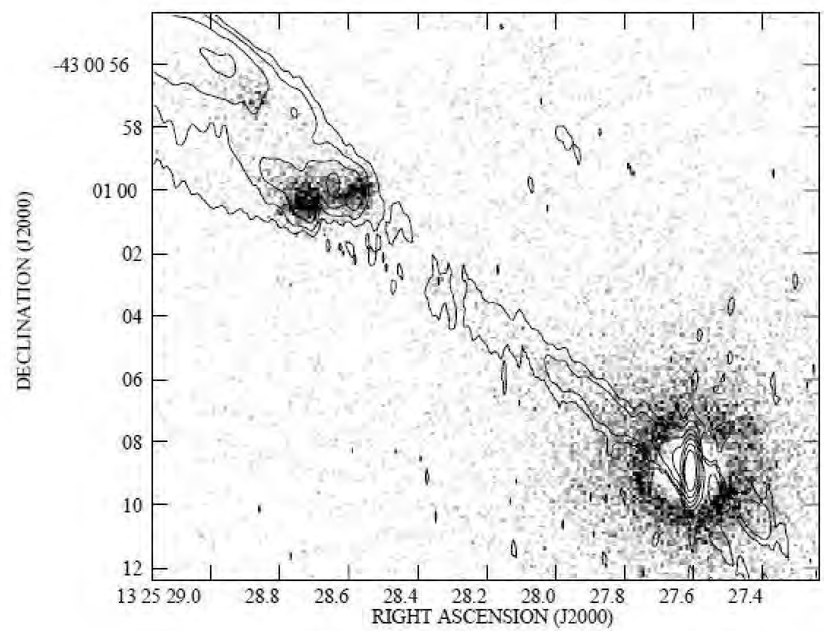
General Role Sharing



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

Hardcastle et al. 2003, ApJ 903 160-183

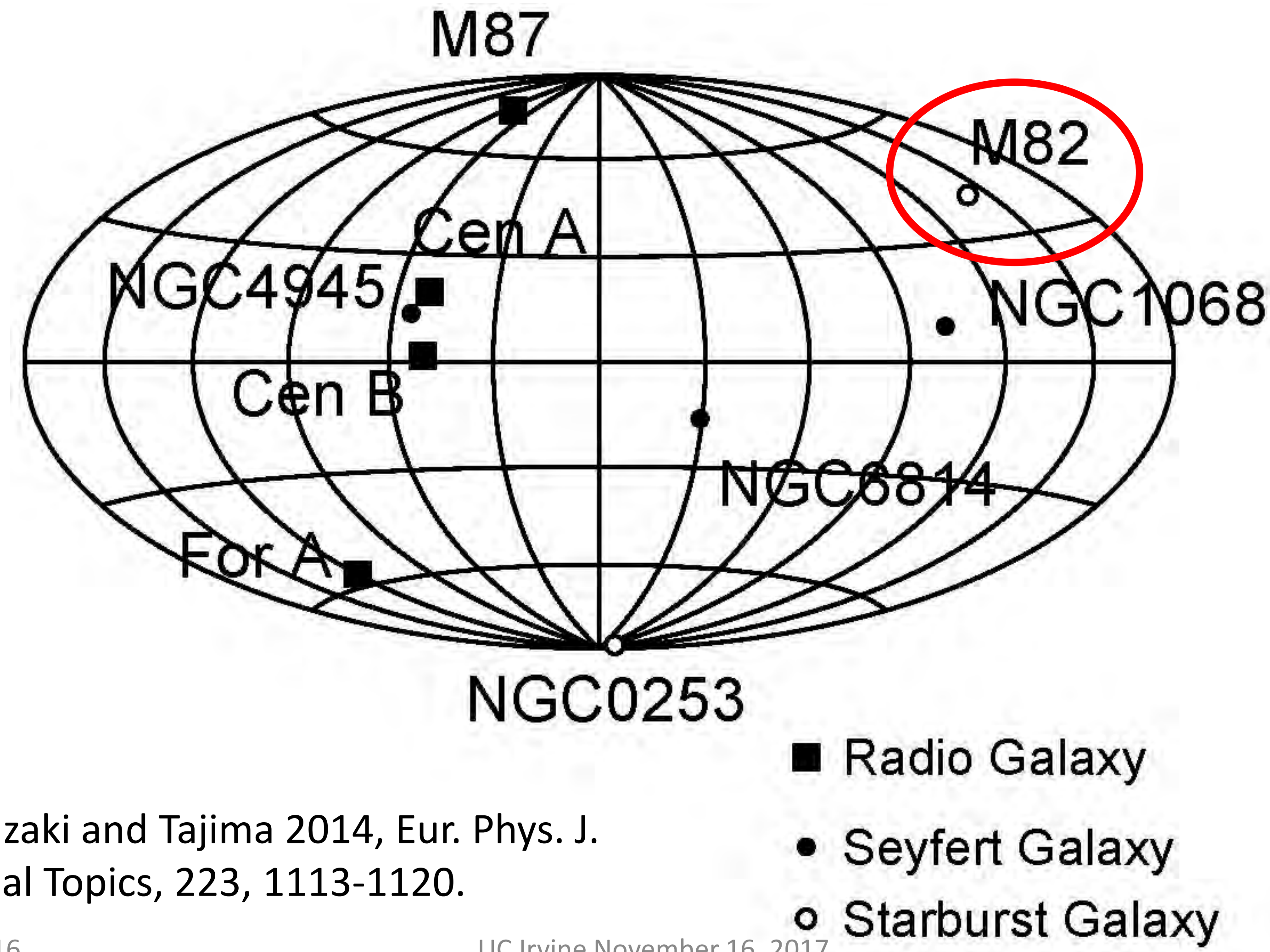




Wolf-Rayet Stars in the Jets?

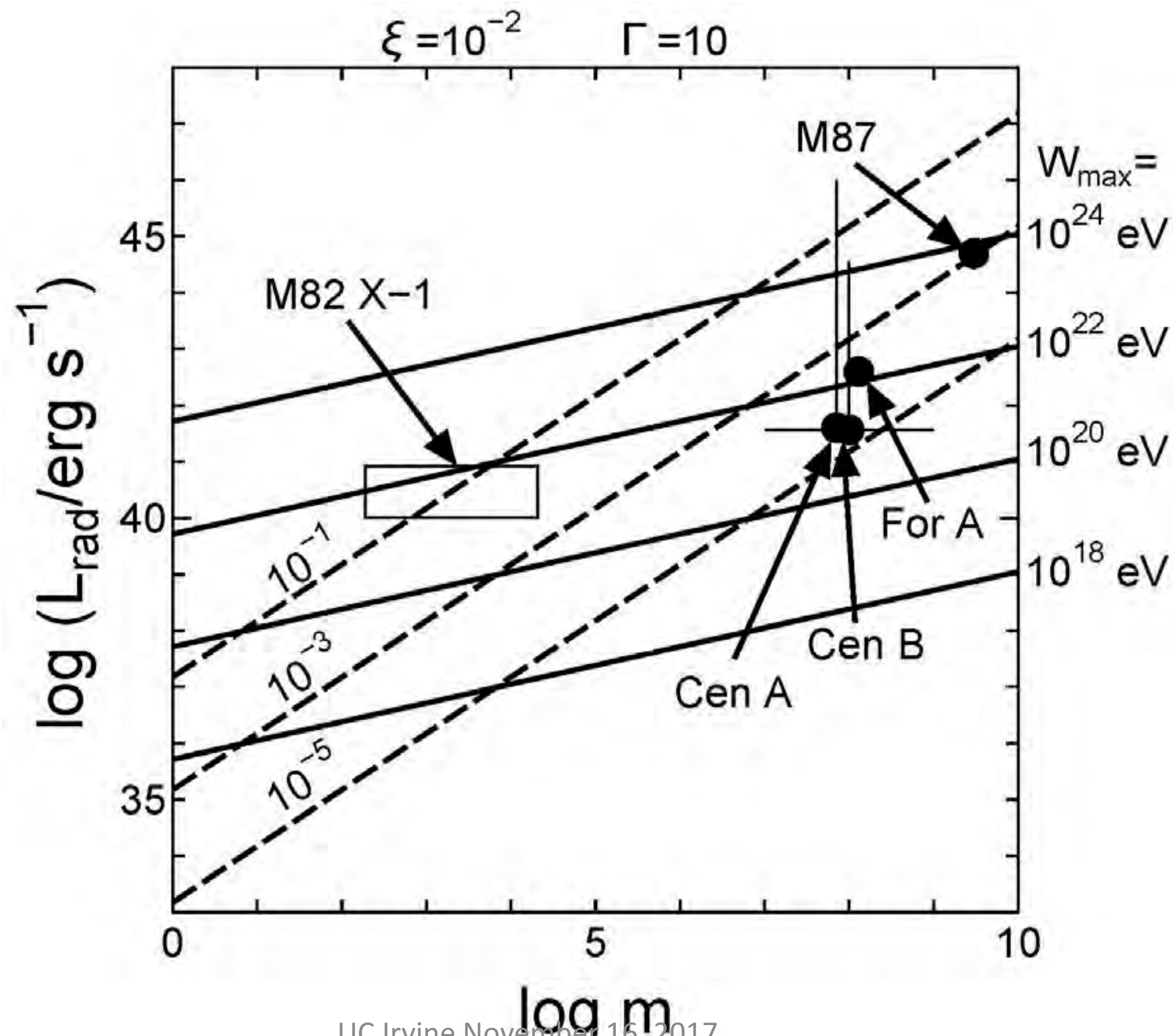
effective CNO supply? ()

Fermi gamma-ray galaxies (Nearby)



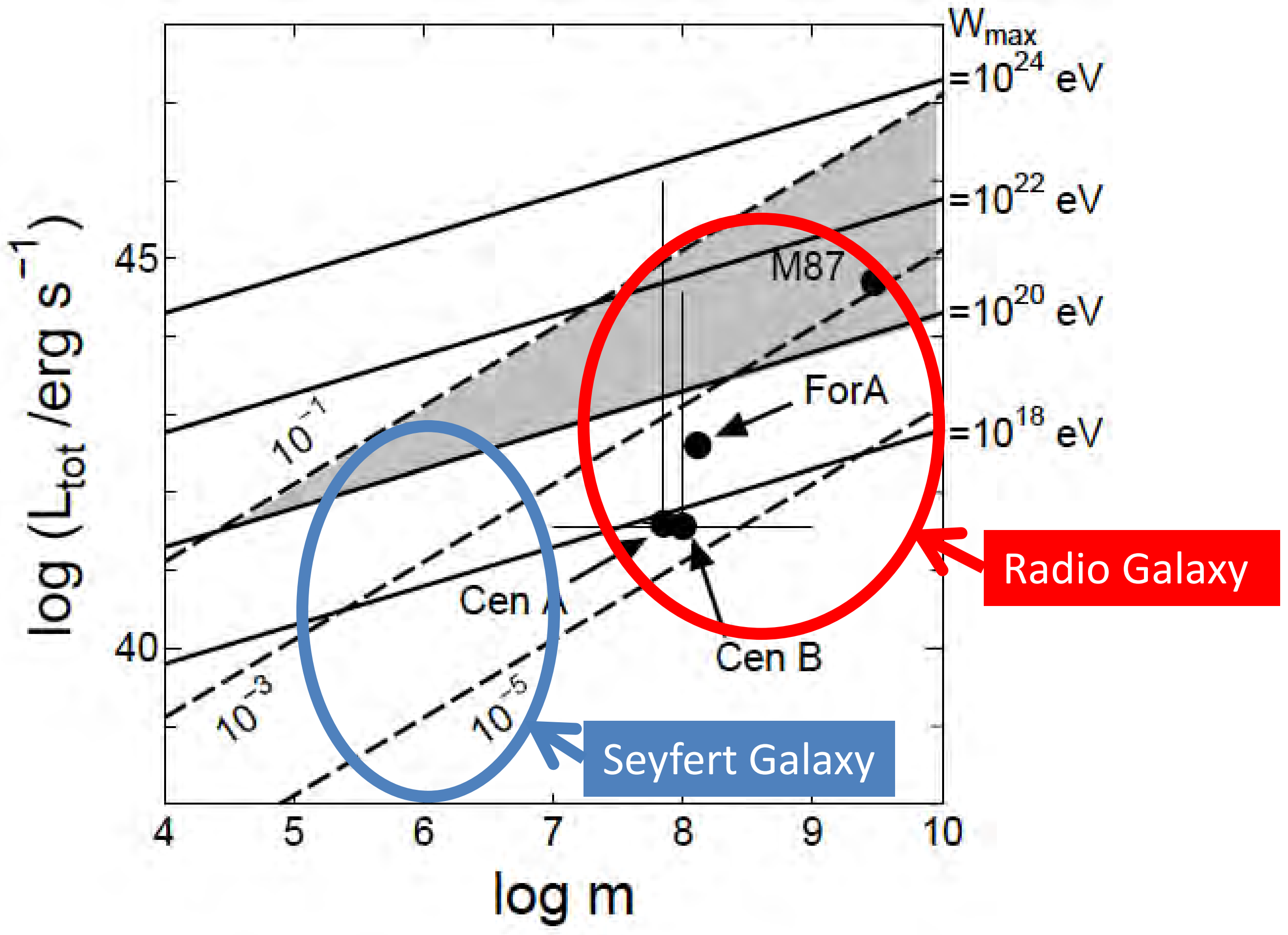
Ebisuzaki and Tajima 2014, Eur. Phys. J. Special Topics, 223, 1113-1120.

Cosmic-ray acceleration



Wake of a ship

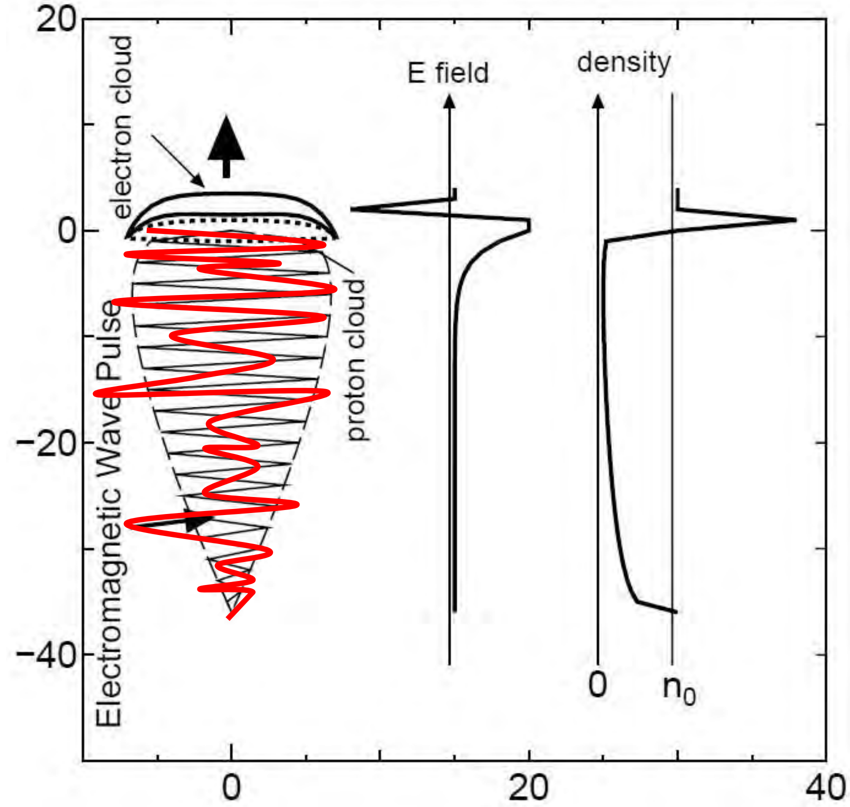
Conditions for UHECRs



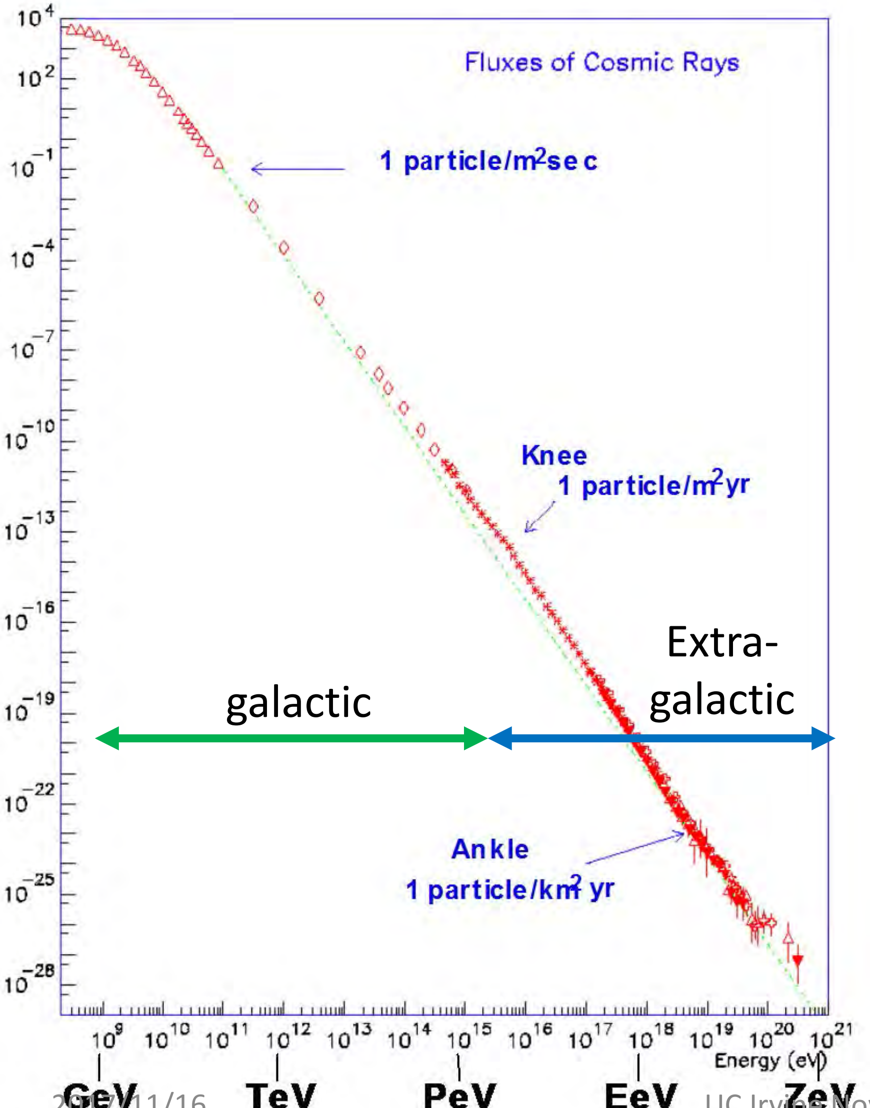
$$L_{tot} = 1.3 \times 10^{38} m \dot{m} \ \ \text{erg s}^{-1}$$

Relativistic coherence

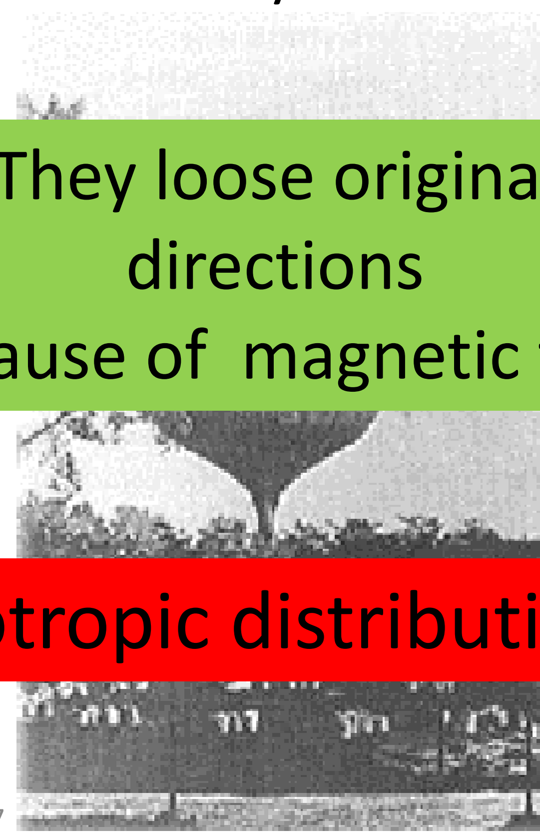
- Extremely relativistic
  →freezing-out



Origin of Cosmic rays

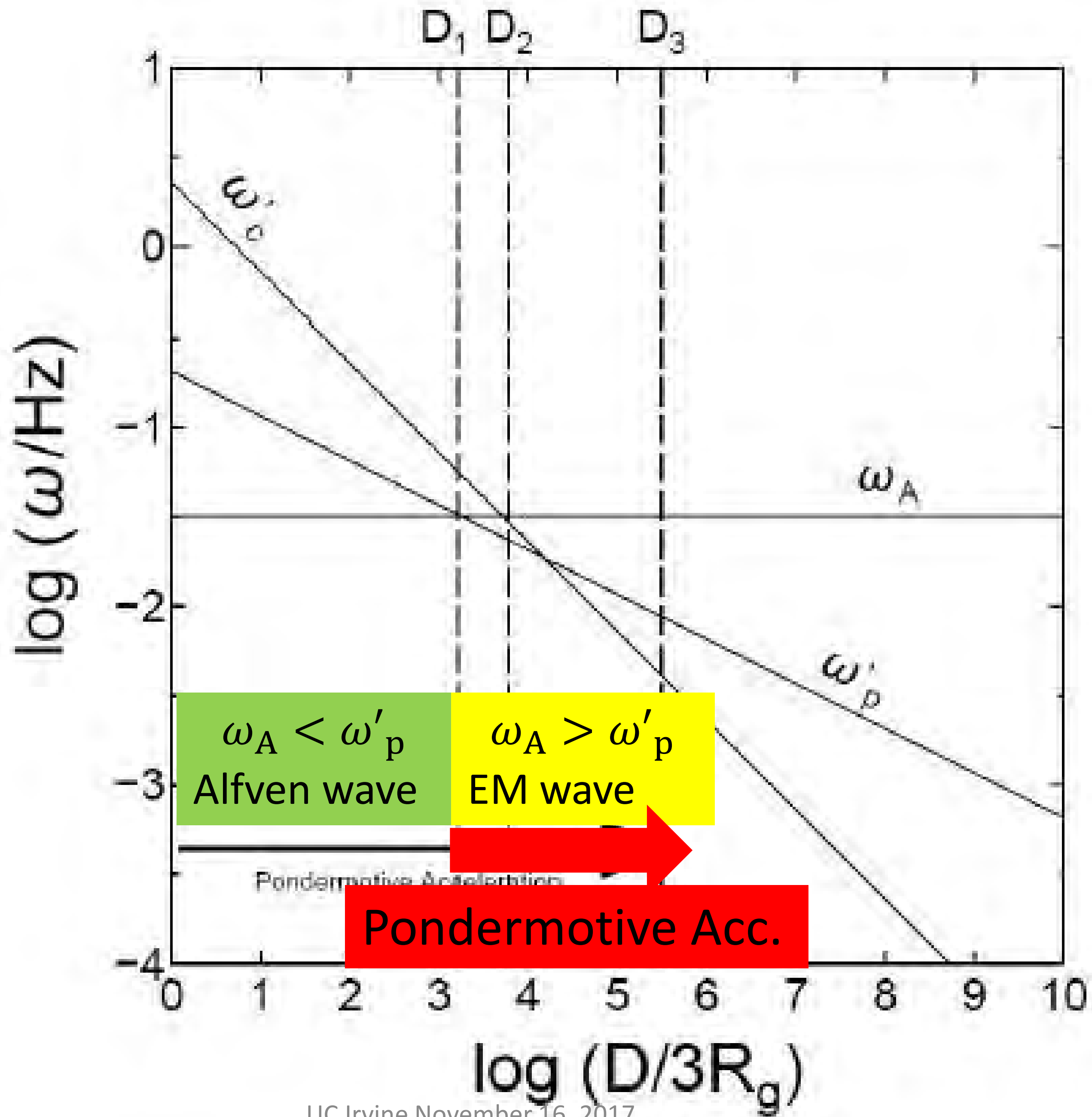


- 100 years enigma
  - Discovered in 1912 by Victor Hess

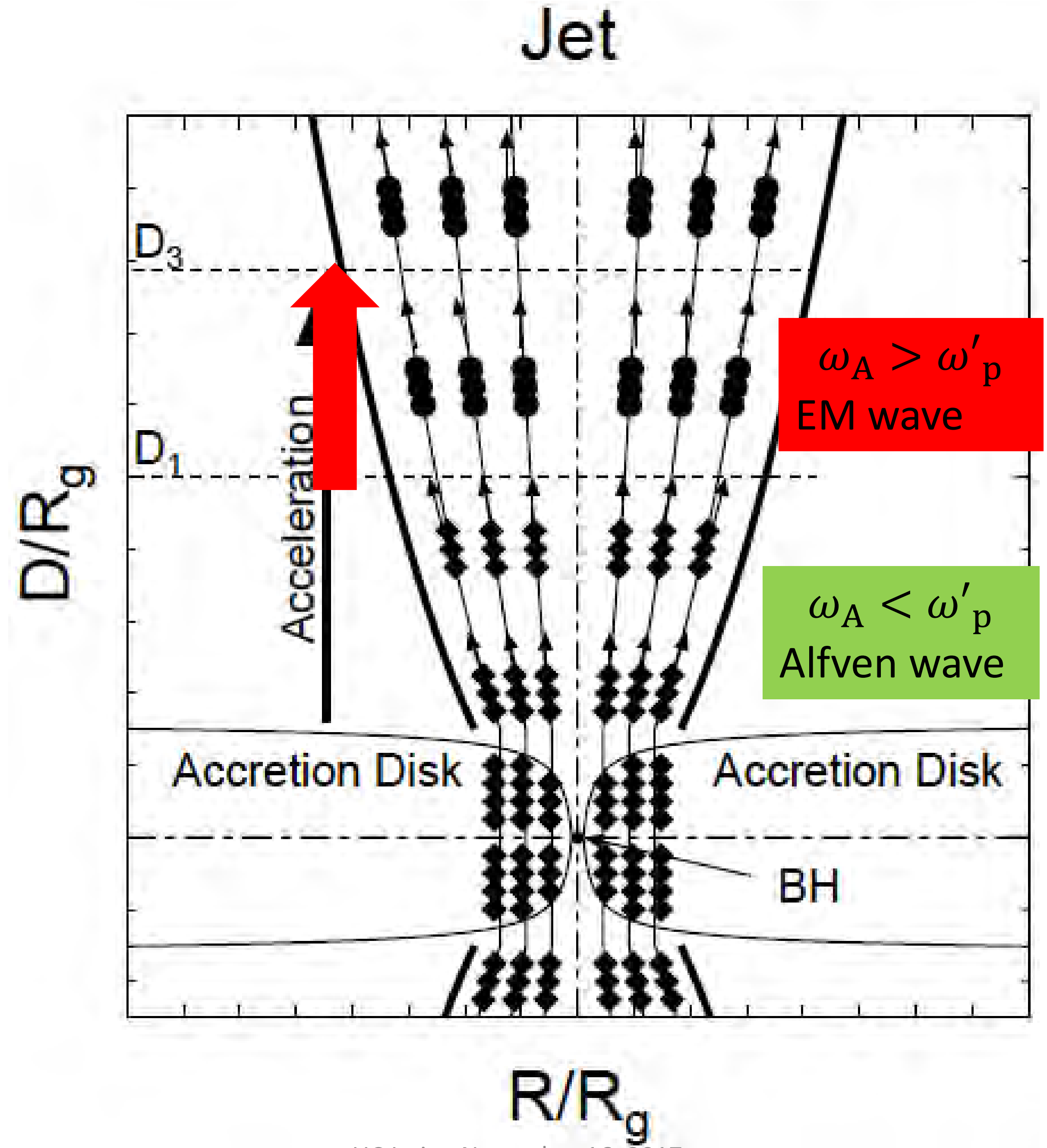


They loose original directions because of magnetic field

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.



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