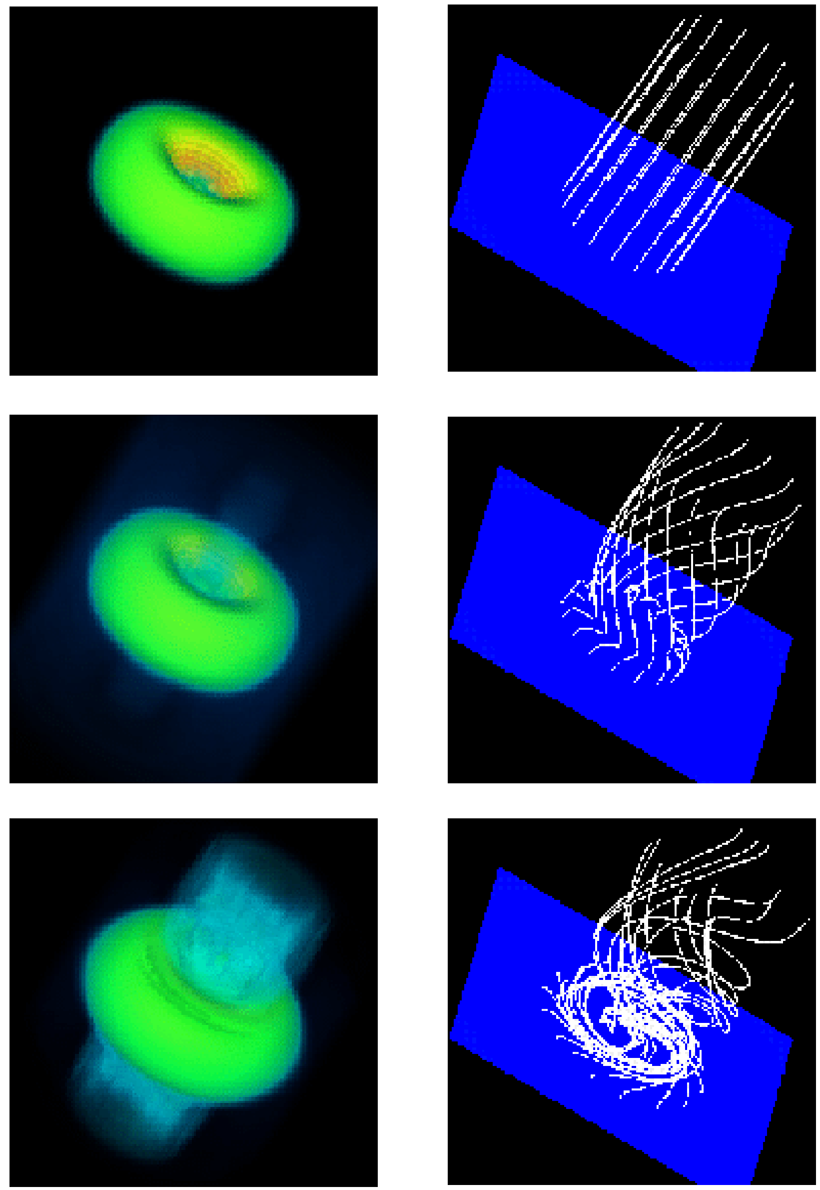
3D Structure of Disk and Jet

t=0.0

t=6.0

t=12.3



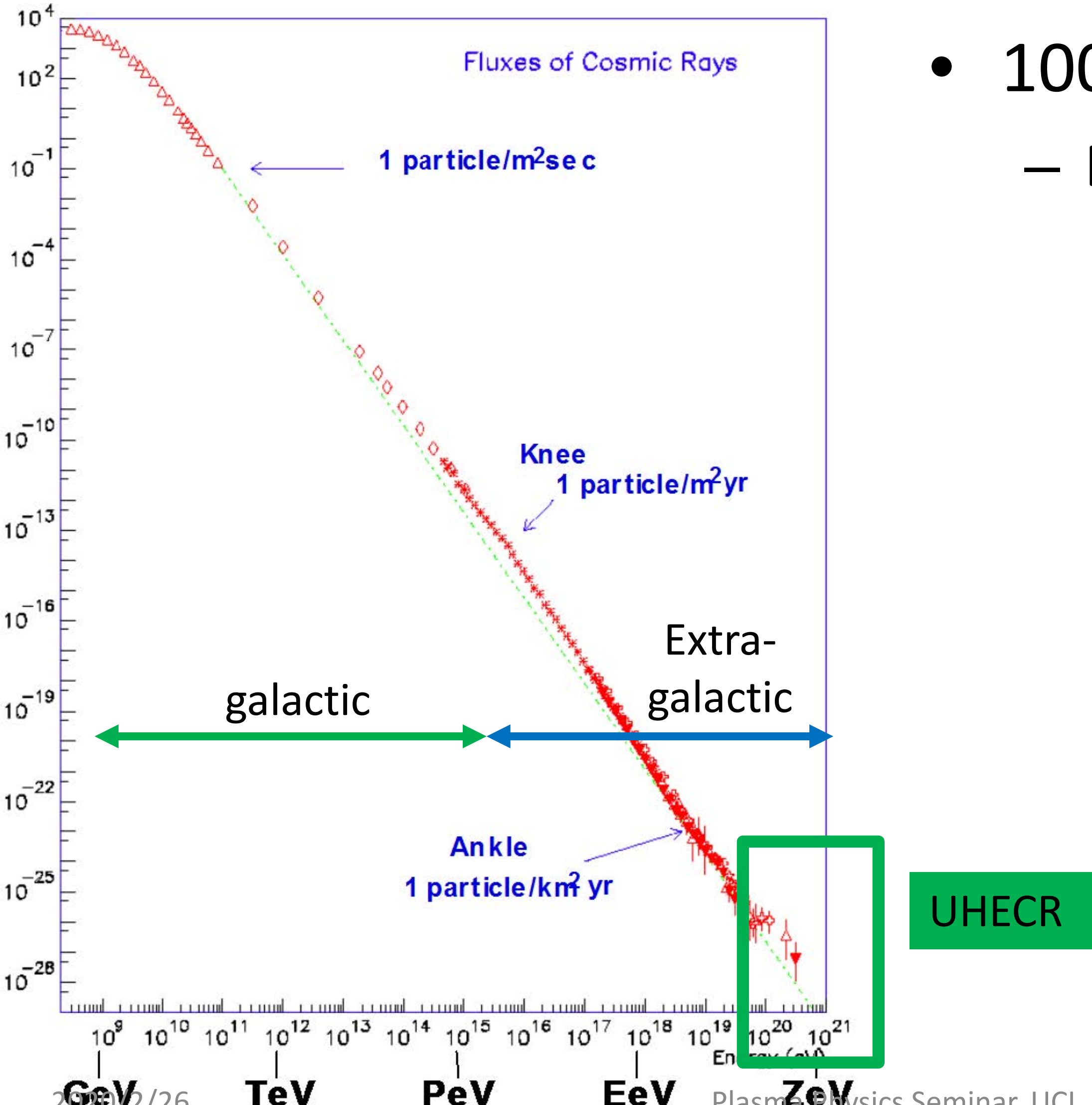
Acceleration of ultra-high energy cosmic rays and gamma-ray/neutrino sources

Toshikazu Ebisuzaki (Toshi2; RIKEN)
Toshiki Tajima (UC Irvine)

contents

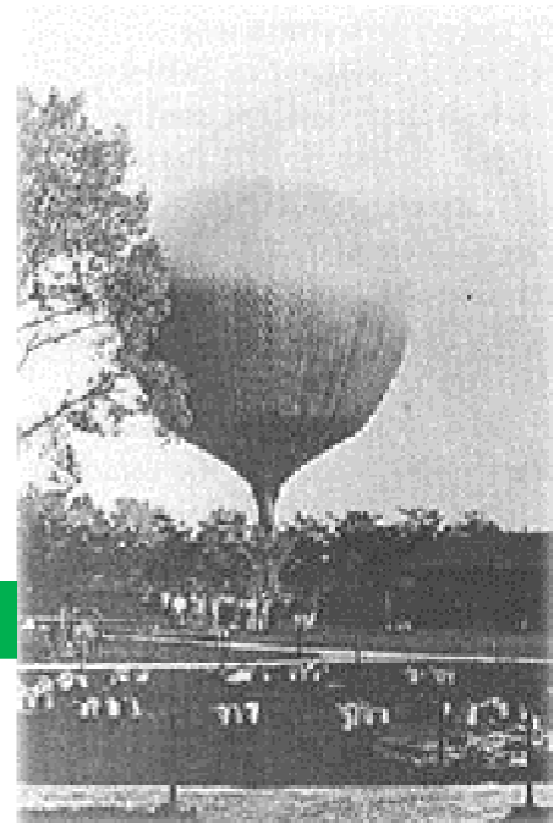
1. Ultra High Energy Cosmic rays ($\sim 10^{20}$ eV) and Star burst galaxy M82
2. Bow wake acceleration
3. Promising sources
    - Starburst/Seyfert Galaxies
    - Microquasars
    - UHECR/HE-gamma/neutrino
4. Conclusion

Origin of Cosmic rays

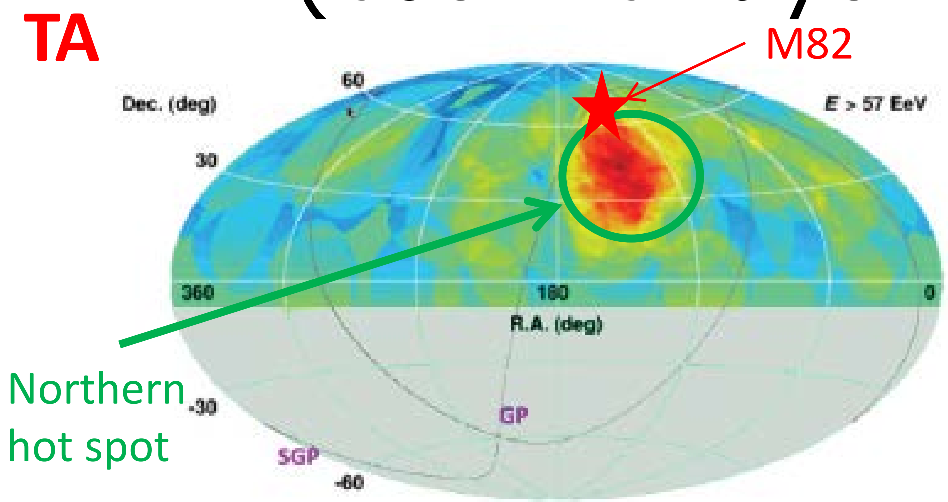


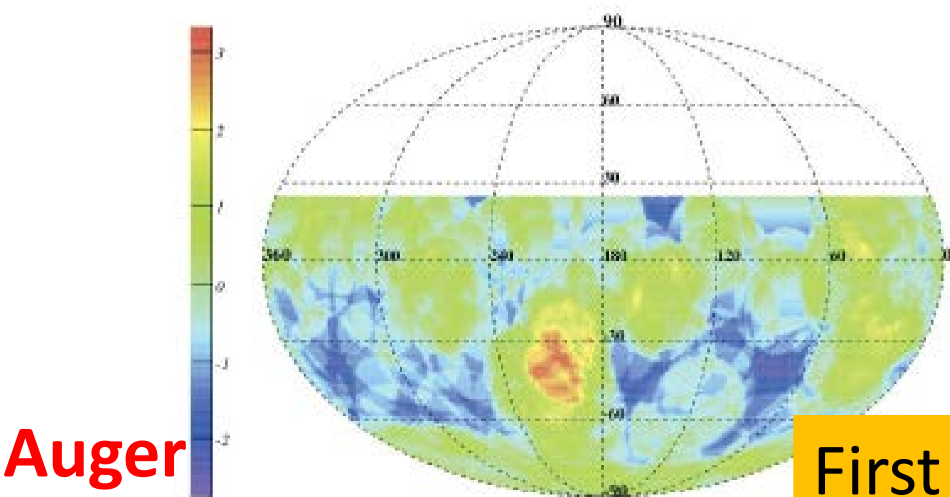
- 100 years enigma
  - Discovered in 1912

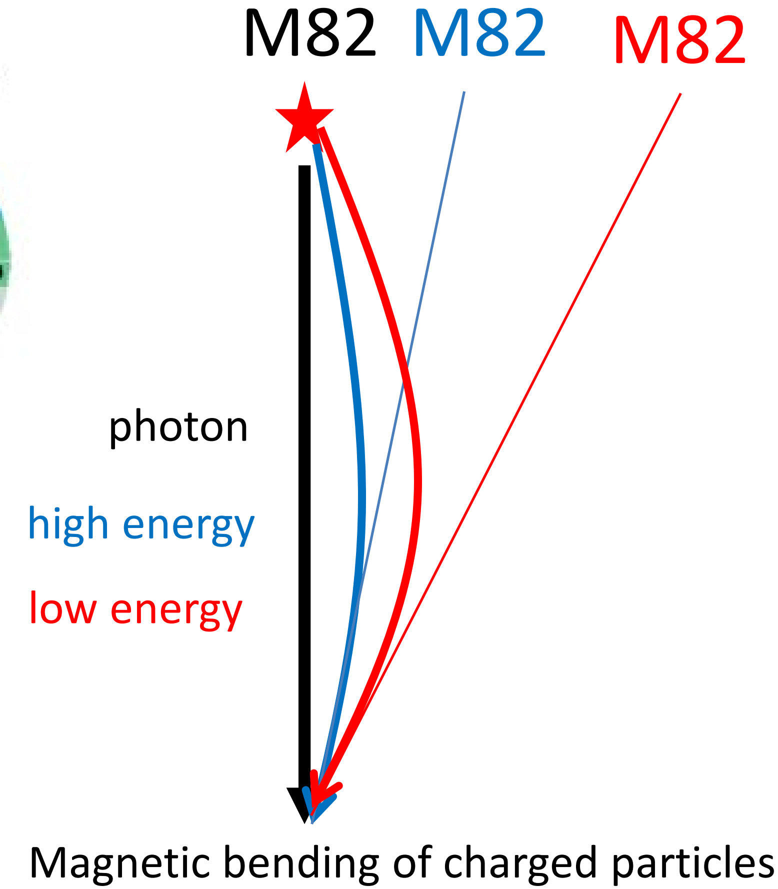
    by Victor Hess



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







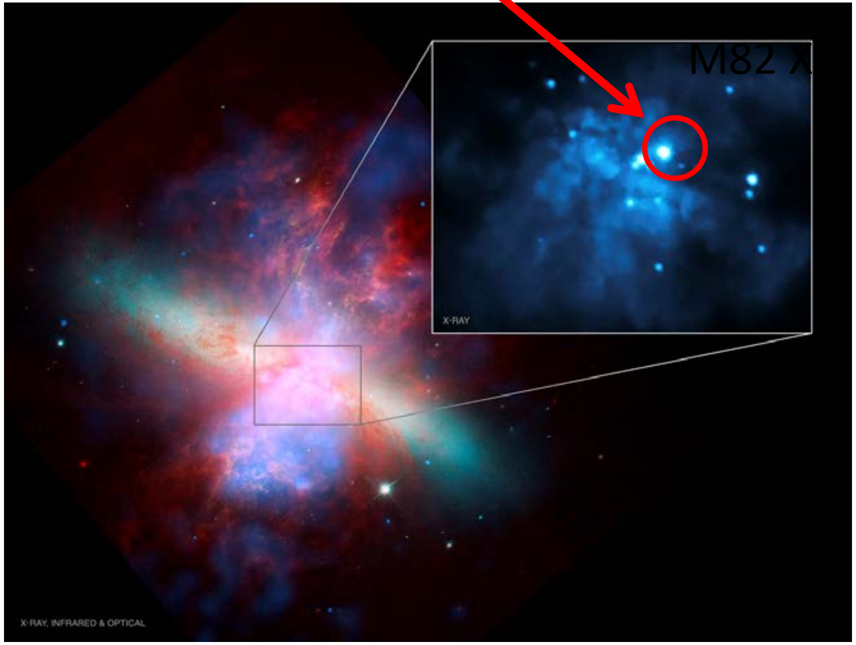
First Identification of CR sources?

First sign of anisotropy in charged particles

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.

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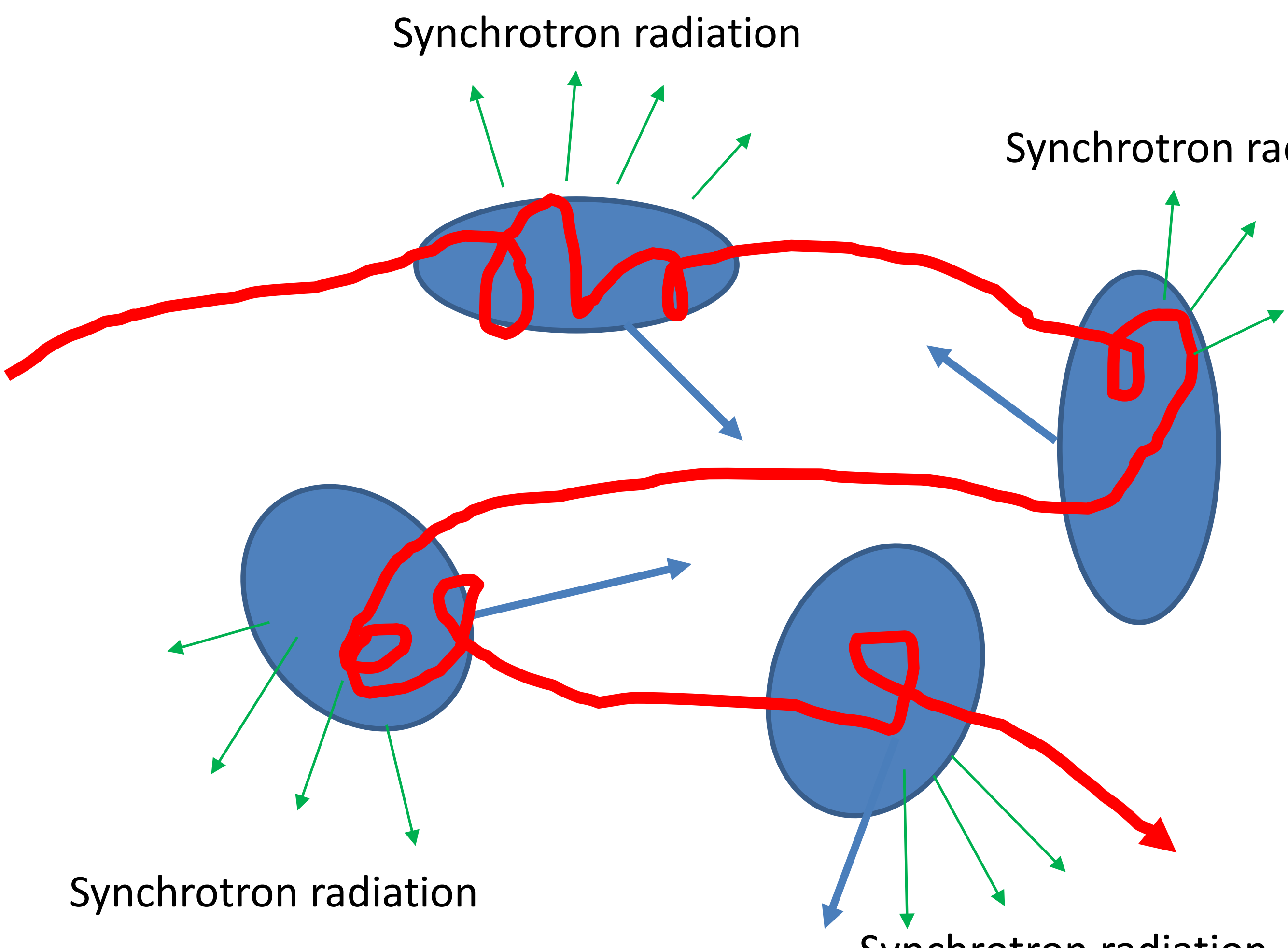
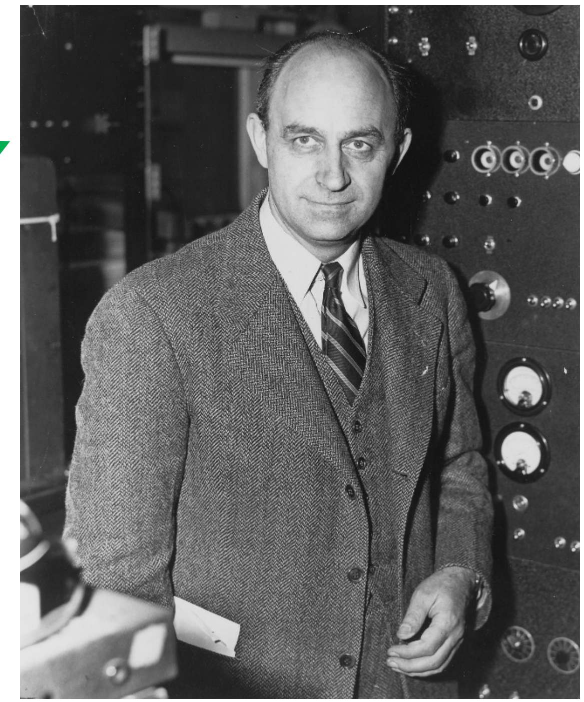
Fermi mechanism

incoherent

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

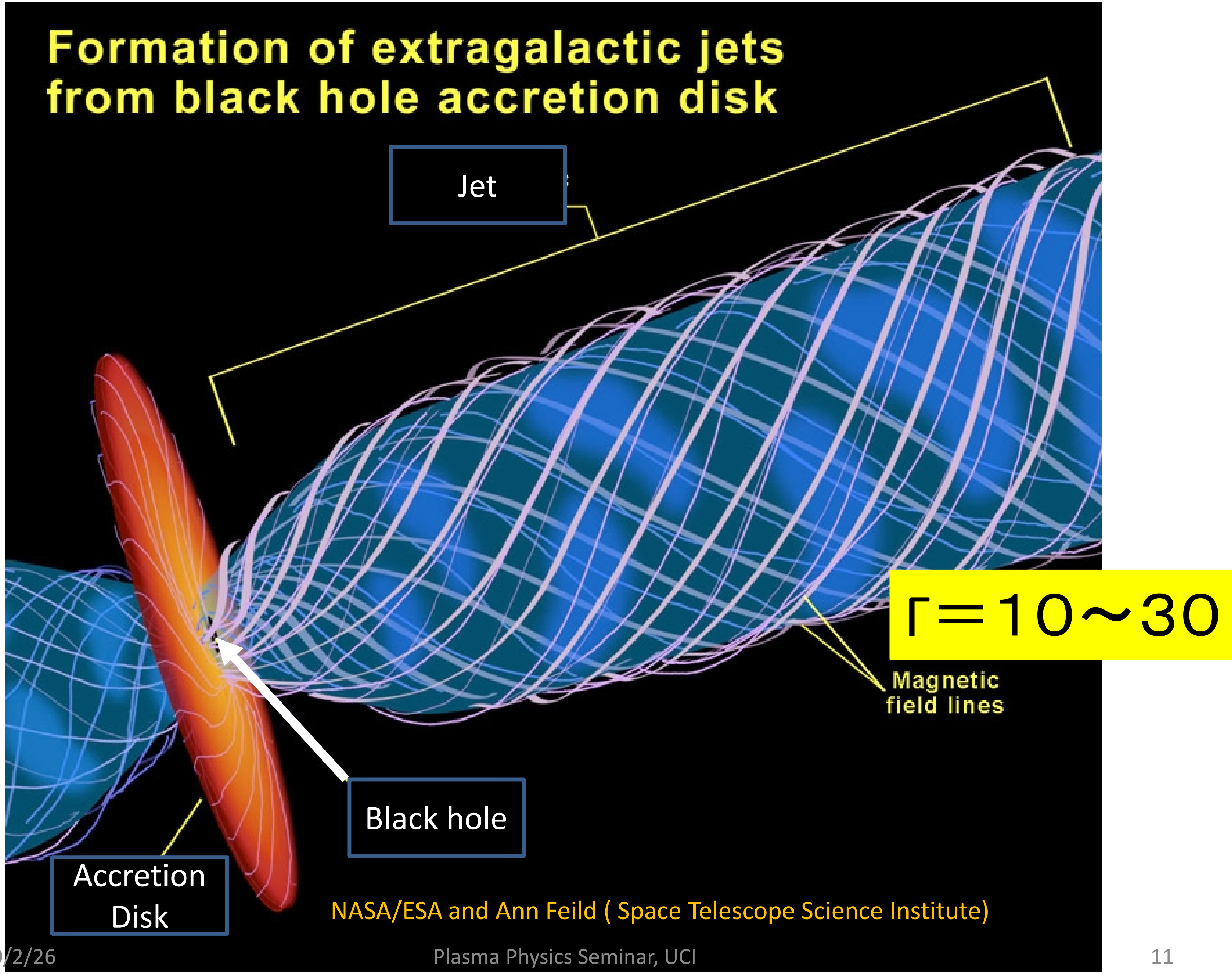
   →no acceleration

3. Escape problem

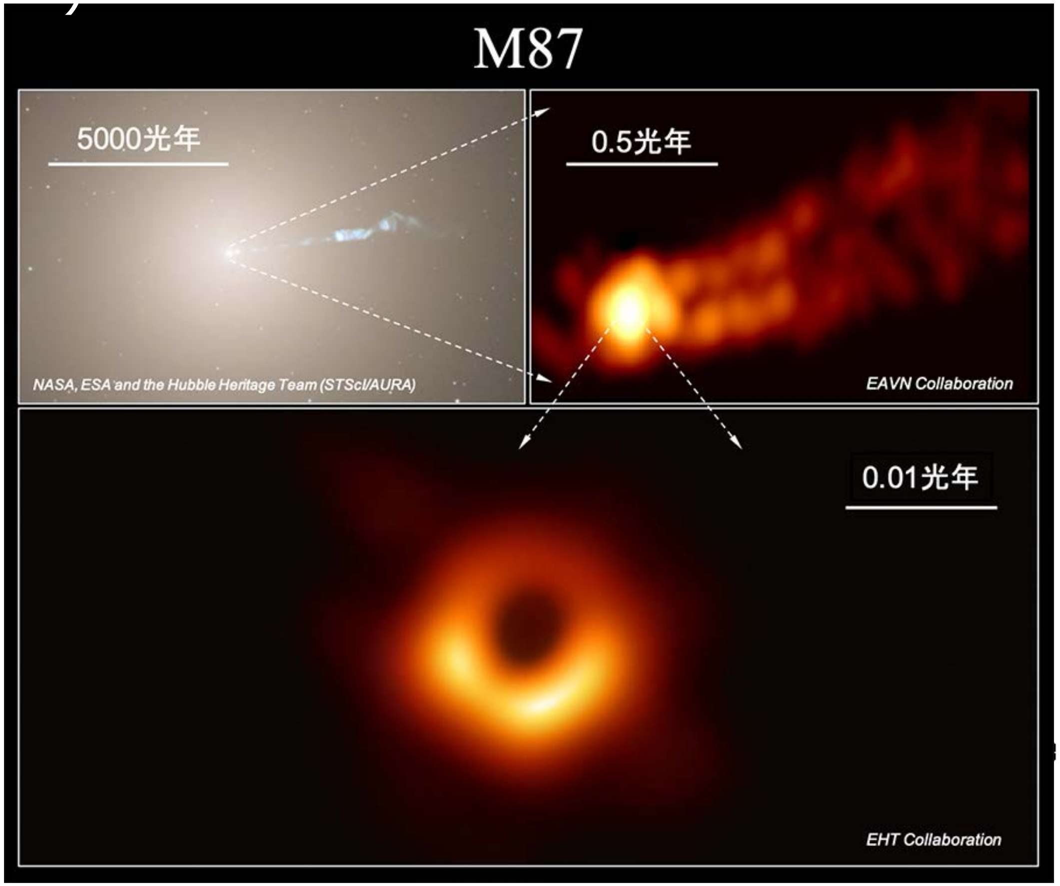
   →magnetic field does not disappear without adiabatic loss

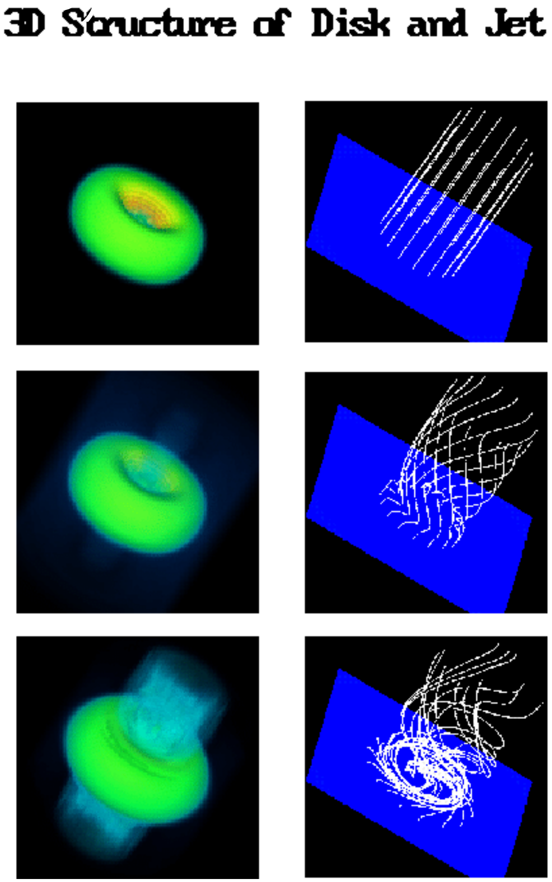
Wakefield acceleration

Coherence in Wakefield


Formation of extragalactic jets
from black hole accretion disk
Jet
Γ＝10～30
Magnetic
field lines
Black hole
Accretion
Disk
NASA/ESA and Ann Feild (Space Telescope Science Institute)

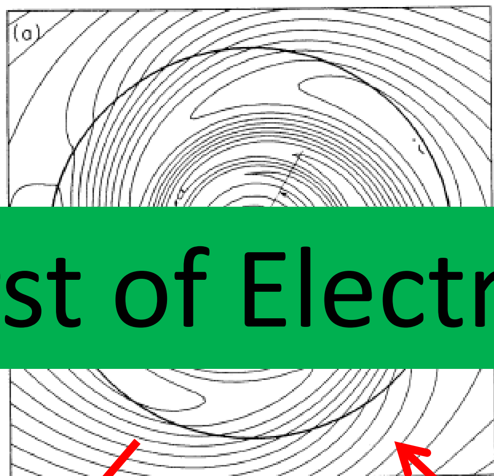
Jet of M87 Galaxy

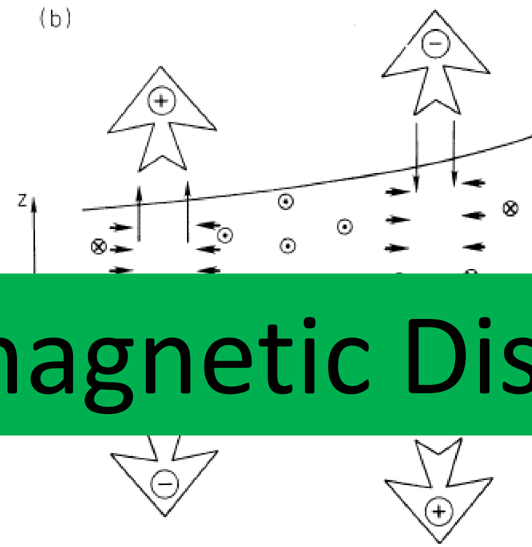




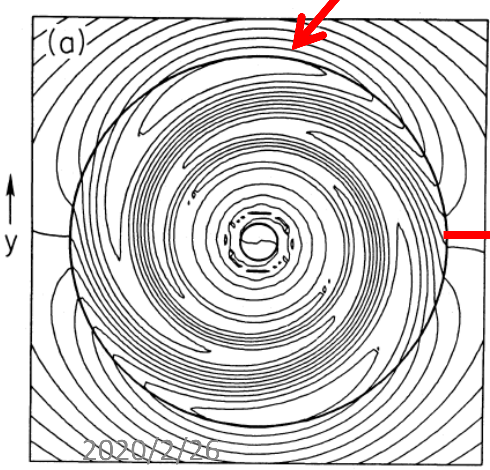
T. Tajima and K. Shibata, Plasma Astrophysics (Perseus Publishing, Cambridge Masachusetts 1997).

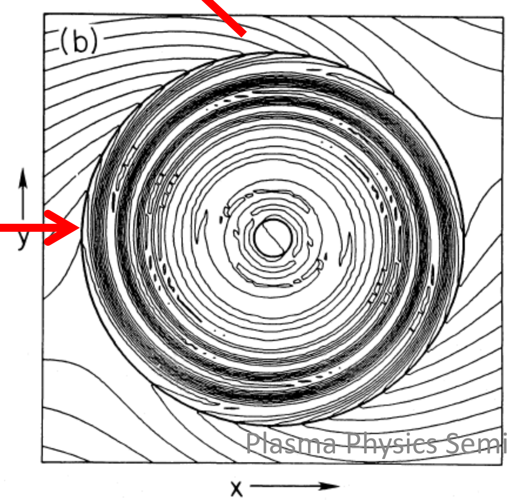
Eruption of magnetic field in an accretion disk





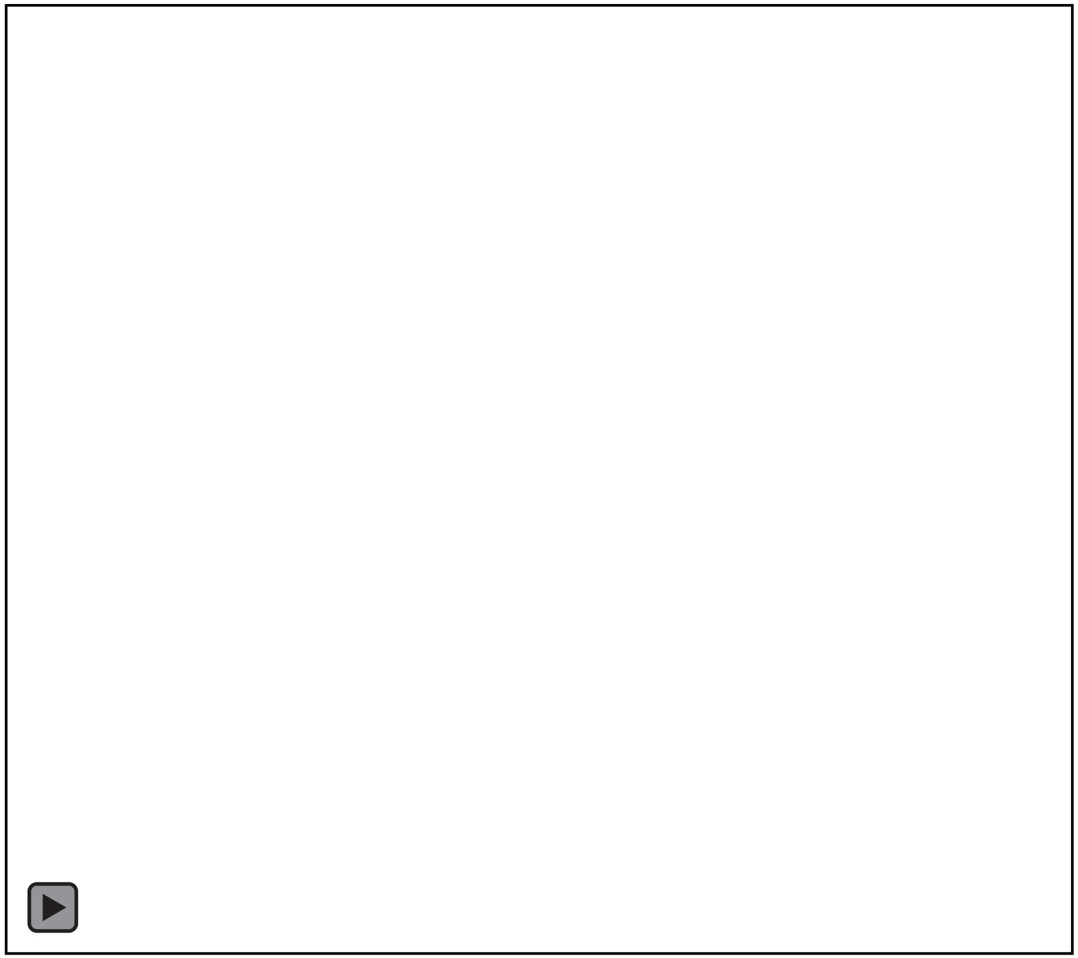
A Burst of Electromagnetic Disturbance



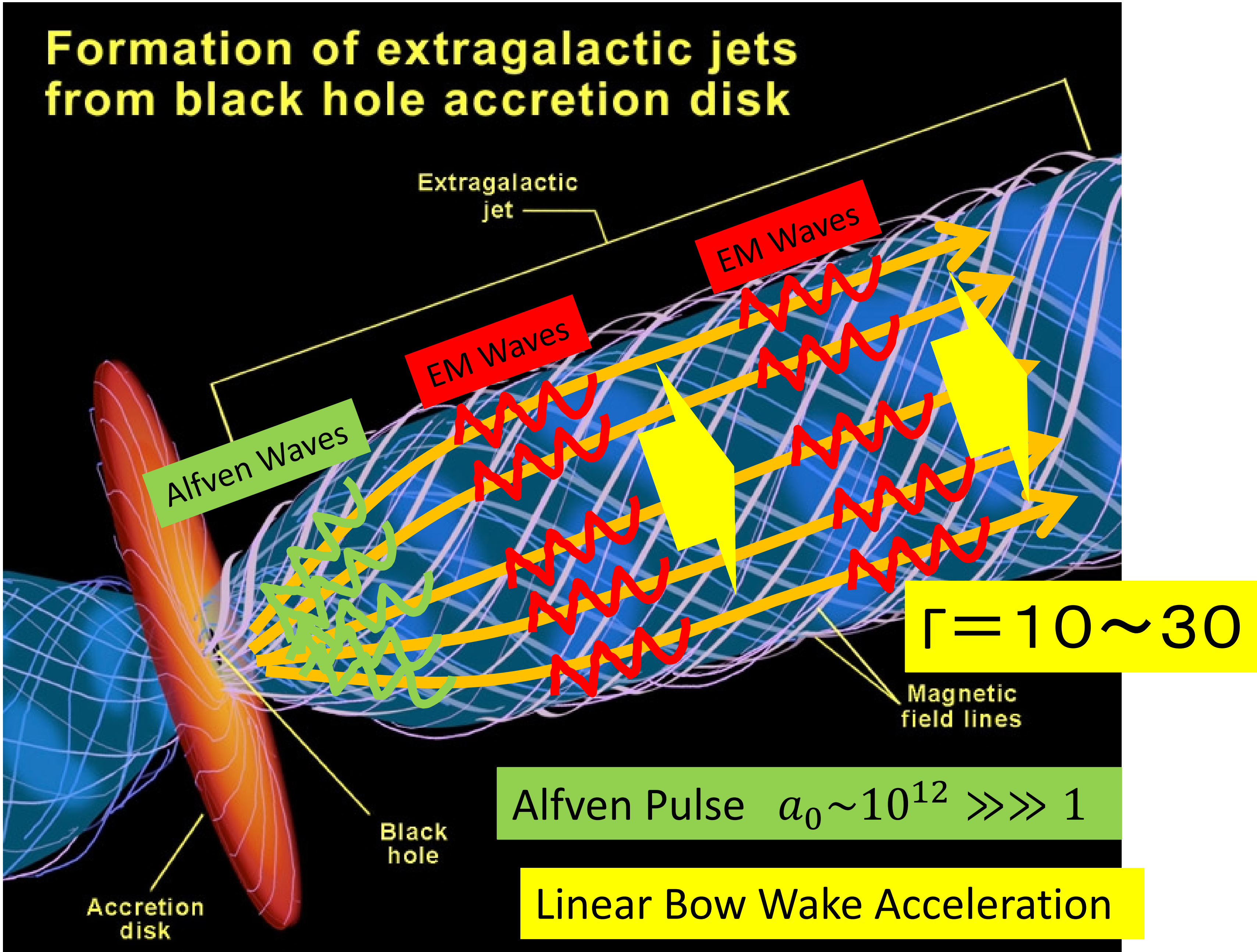


Tajima and Gilden 1987, ApJ 320, 741-745
Haswell, Tajima, and Sakai, 1992, ApJ, 401, 495-507

3-D relativistic MHD simulation

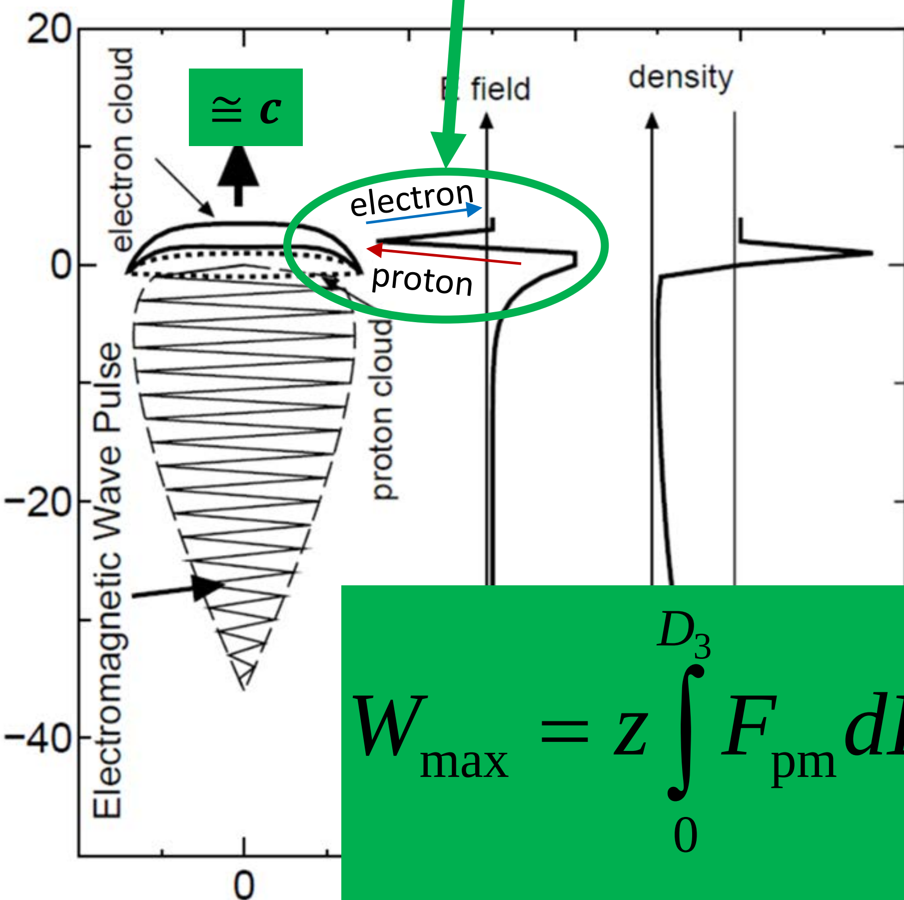


A. Mizuta et al. 2016


Formation of extragalactic jets
from black hole accretion disk
Extragalactic
jet
EM Waves
EM Waves
Alfven Waves
Γ＝10～30
Magnetic
field lines
Black
hole
Accretion
disk
Alfven Pulse $a_0 \sim 10^{12} \gg\gg 1$
Linear Bow Wake Acceleration

Wakefield Acceleration

Co-linear acceleration by electrostatic field



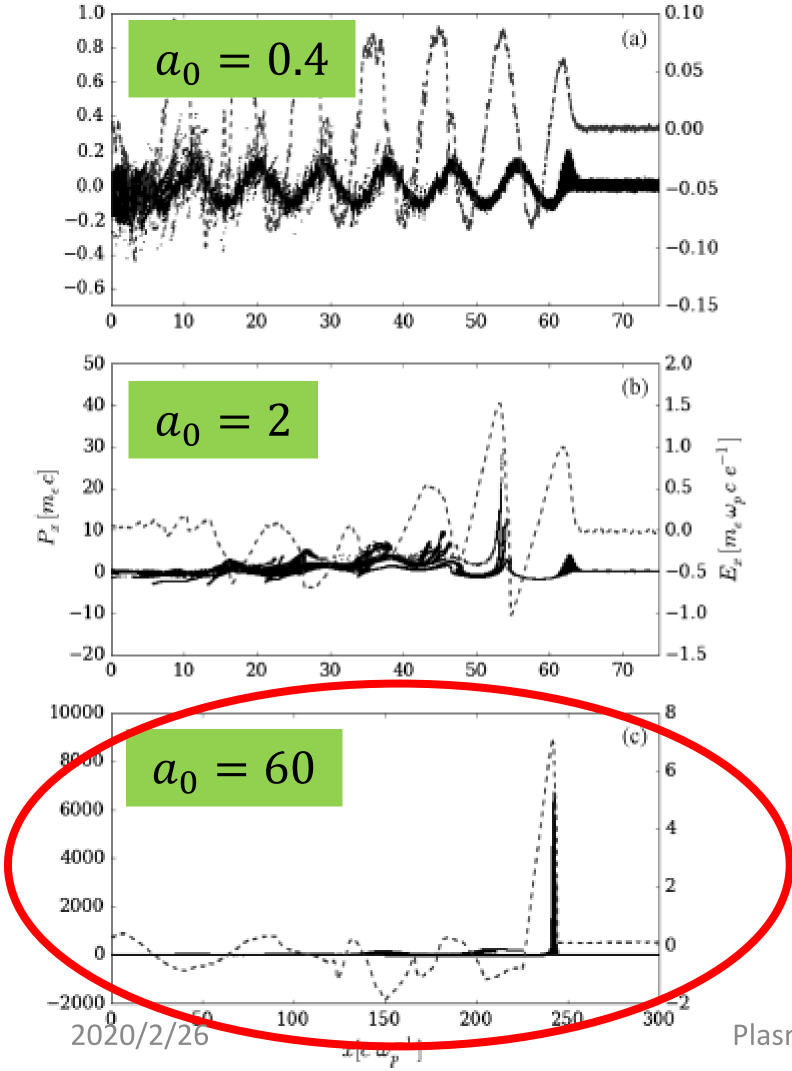
$$W_{\max} = z\int_0^{D_3} F_{\mathrm{pm}}\,dD$$

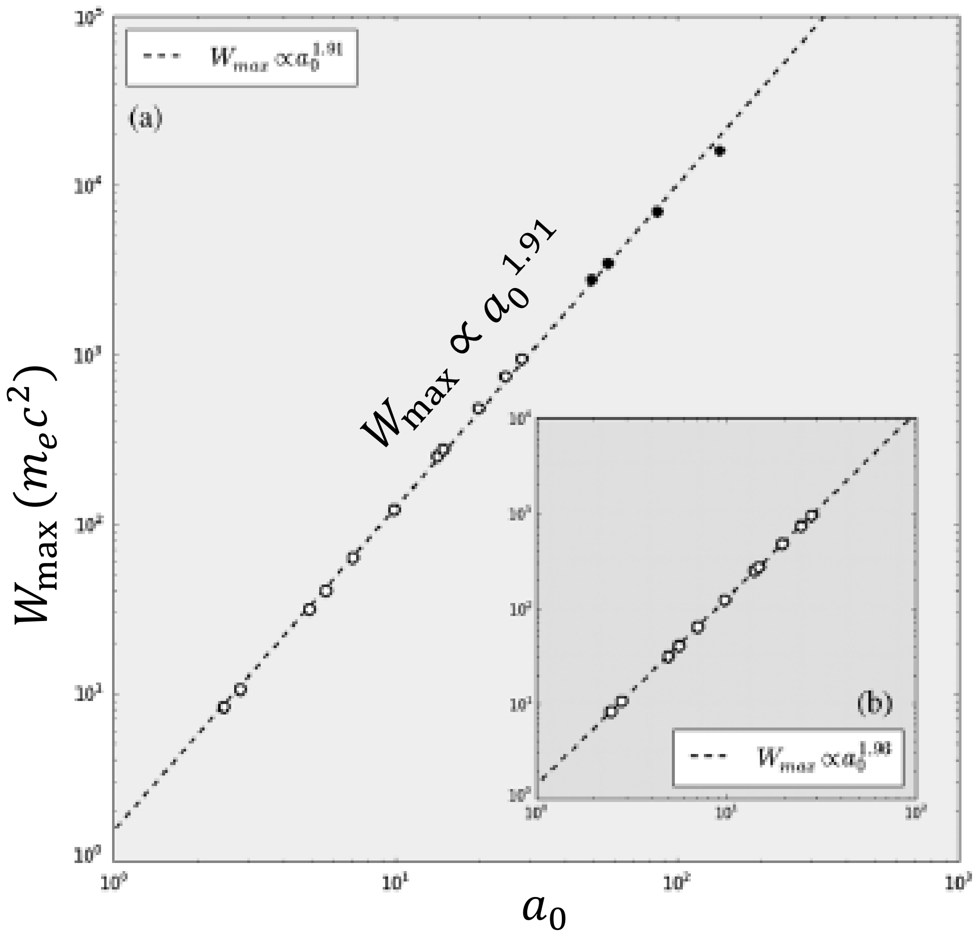
$$F_{\mathrm{pm}} = \Gamma m_{\mathrm{e}} c a_0 \omega_A$$

- **Stable acceleration structure**
  - Coherent and Strong Field
  - Moving in ≅ 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

1D Particle-in-Cell simulation

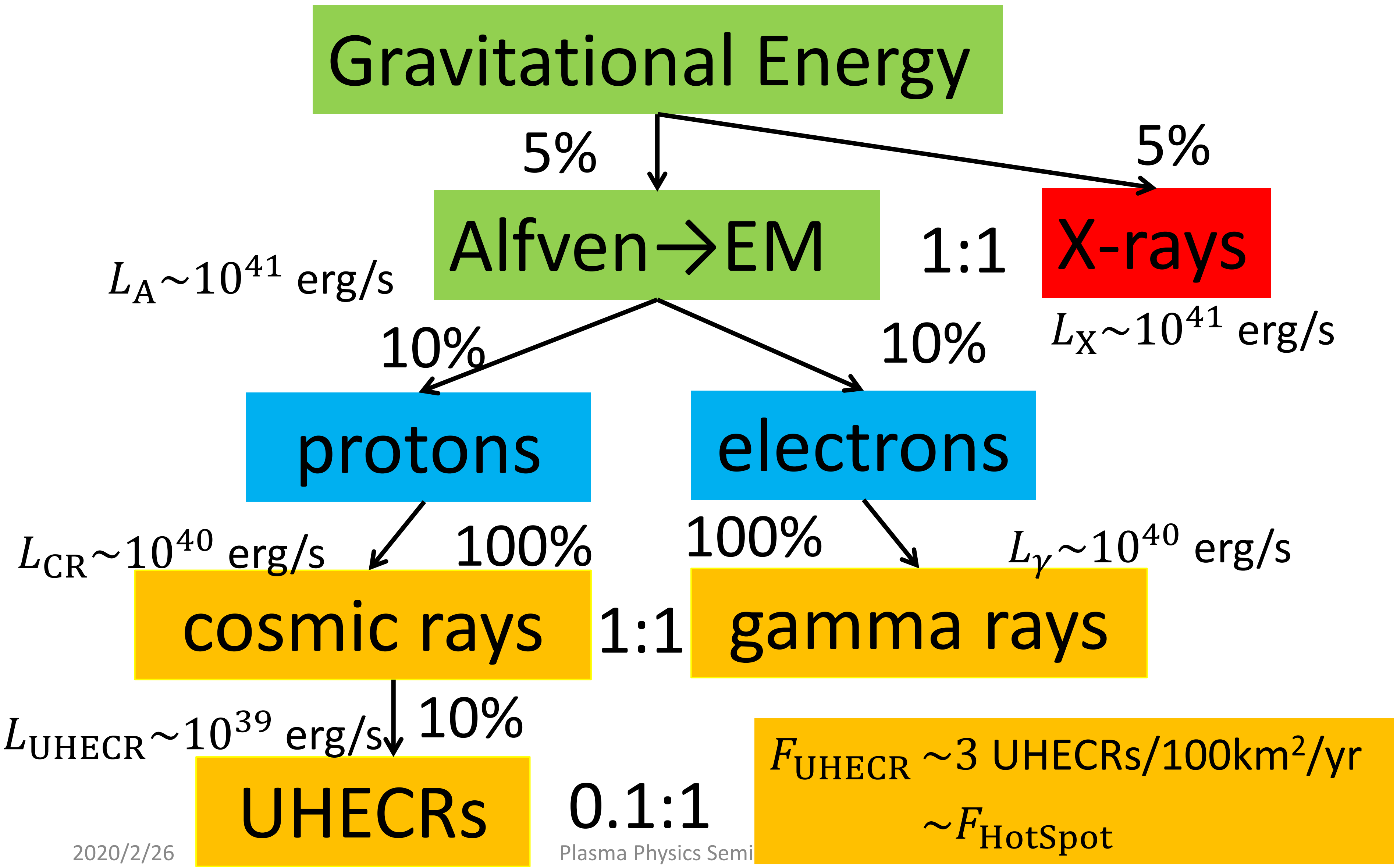
with the code by Nagata2008





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

Energy Flow (M82 X-1)



No Difficulties in wakefield acceleration even in UHECR

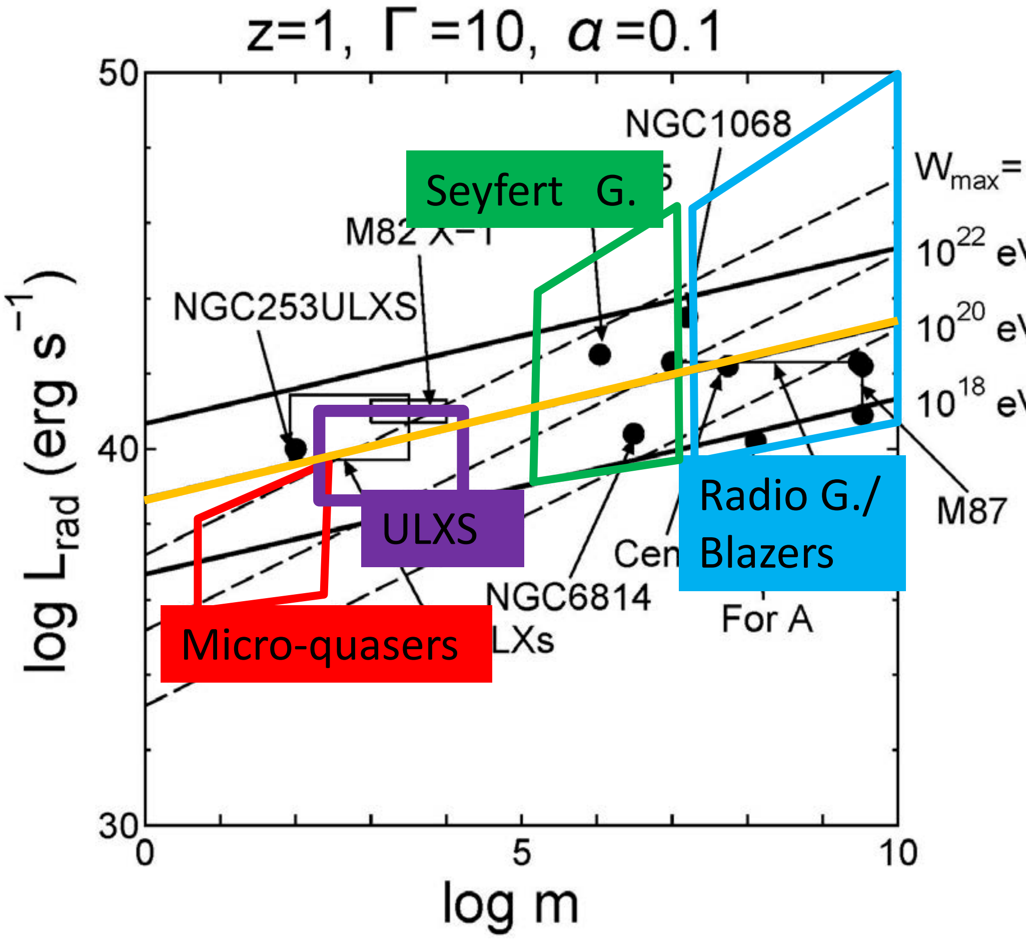
1. Bending is inevitable
   →synchrotron loss
2. Confinement is difficult
   →no acceleration
3. Escape problem
   →magnetic field does not disappear without adiabatic loss

Co-linear acceleration
No bending

Confinement in field structure with $\cong c$

Wakefield disappears naturally

cosmic ray acceleration and gamma-ray emission



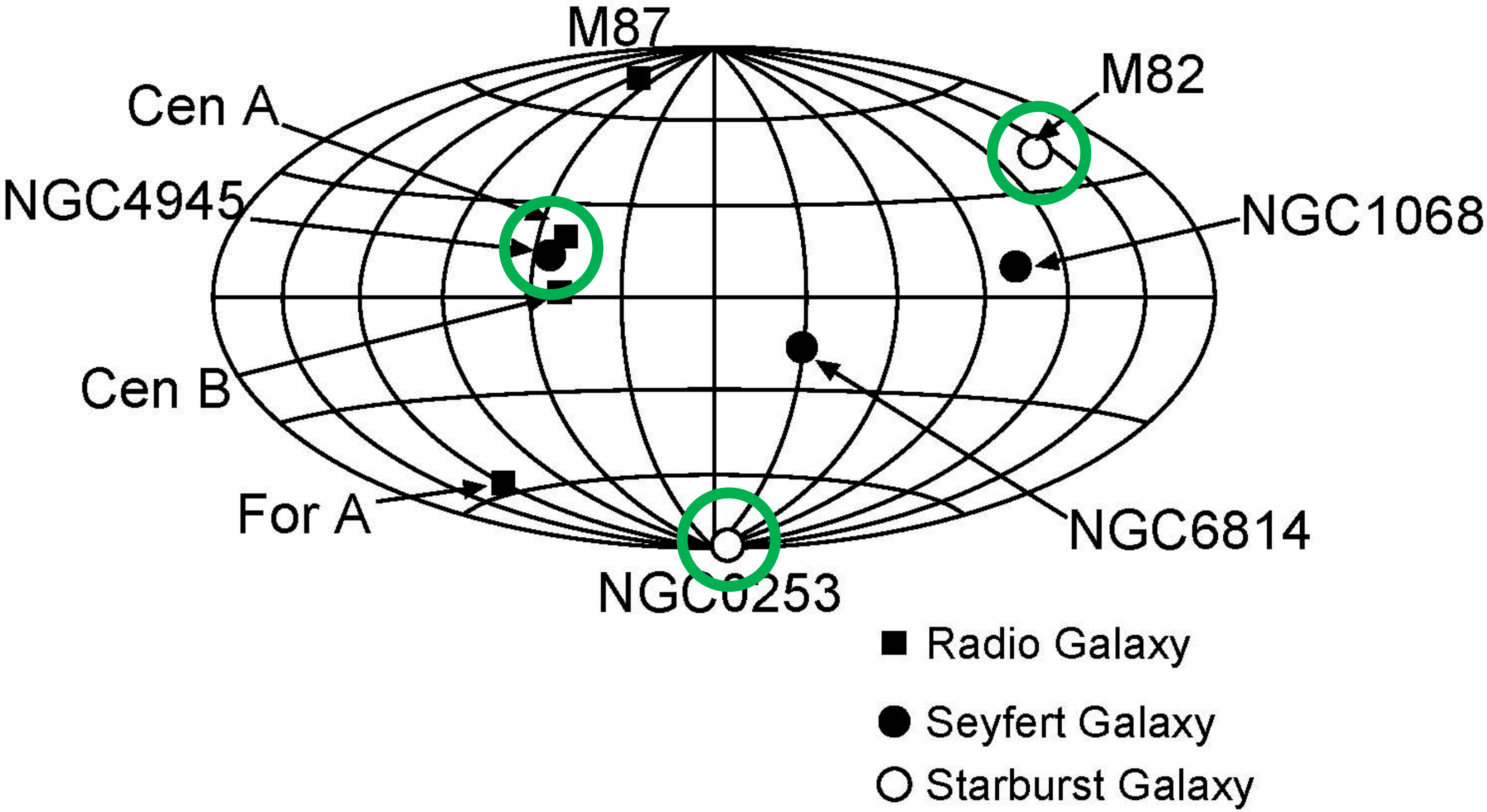
BH Astronomy with Ultra High Energy CRs

contents

1. Ultra High Energy Cosmic rays ($\sim 10^{20}$ eV) and Star burst galaxy M82
2. Bow wake acceleration
3. Promising sources
   - Starburst/Seyfert Galaxies
   - Microquasars
   - UHECR/HE-gamma/neutrino
4. Conclusion

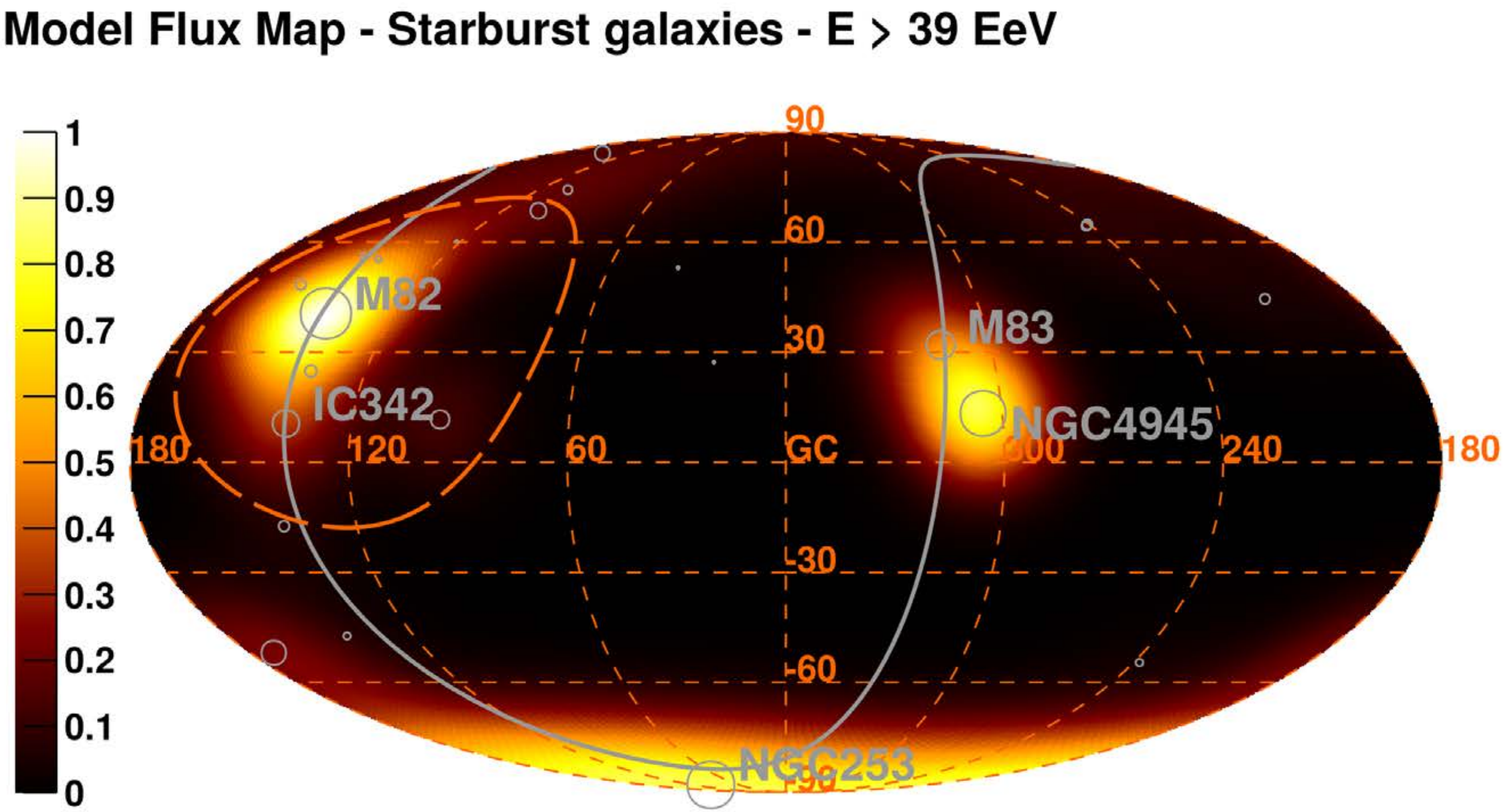
name	NGC 253	M82	NGC 4945	NGC 1068	NGC 6814	Cen A	M87	For A	Cen B
type	starburst			Seyfert			radio		
d (Mpc)	3.5	3.6	3.6	14	23	3.6	17	19	23
M_{BH} ($10^6\ M_\odot$)	0.0001	0.0001 -0.01	1.1	16	3.1	55	3400	130	10-3000
L_{rad} (10^{40} erg s^{-1})	0.91	5-20	300	3000	2.7	160	8-150	1.7	200
W_{max} (10^{20} eV)	6.1	2.7-81	28	100	0.026	0.89	0.001-0.05	0.0017	0.08-3.7
Θ (degree)	18	18	18	70	115	18	85	110	260
F_{UHECR} $\left(\frac{\text{UHECR}}{100\ \text{km}^2\ \text{yr}}\right)$	0.002	0.03-0.13	2.0	-	-	1.0	-	-	-
$F_{UHECR,obs}$ $\left(\frac{\text{UHECR}}{100\ \text{km}^2\ \text{yr}}\right)$	0.013	0.4	0.016	-	-	0.016	-	-	-
$L_{\gamma,\text{obs}}$ (10^{40} erg s^{-1})	0.61	1.2	2.0	15	20	1.7	65	27	390
$L_{\gamma,\text{jet}}$ (10^{40} erg s^{-1})	0.079	0.44-1.7	26	260	0.24	13	0.70-11	0.15	17
$W_\nu{}^2 F_\nu$ (10^{-14} GeV cm^{-2} s^{-1})	0.91	4.73-19	280	180	0.063	150	0.34-5.5	0.056	180
SNR_ν ($\times 10^{-2}$)	0.0011	0.060-0.23	3.5	2.3		1.9	0.042-0.078	-	0.011

Possible UHECR sources



Excess map: three hot spots

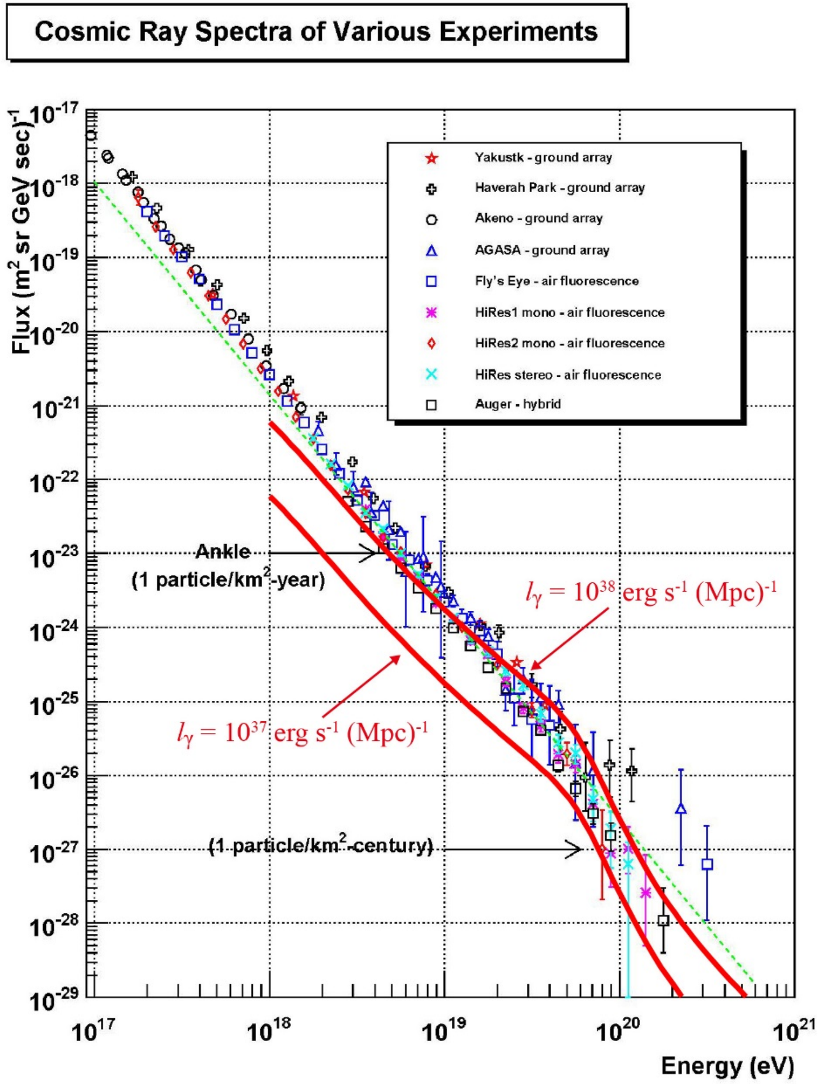
Aab et al. (2018) Astrophys. J. Letters, 853, L29



Background UHECR

- Luminosity density of AGN :

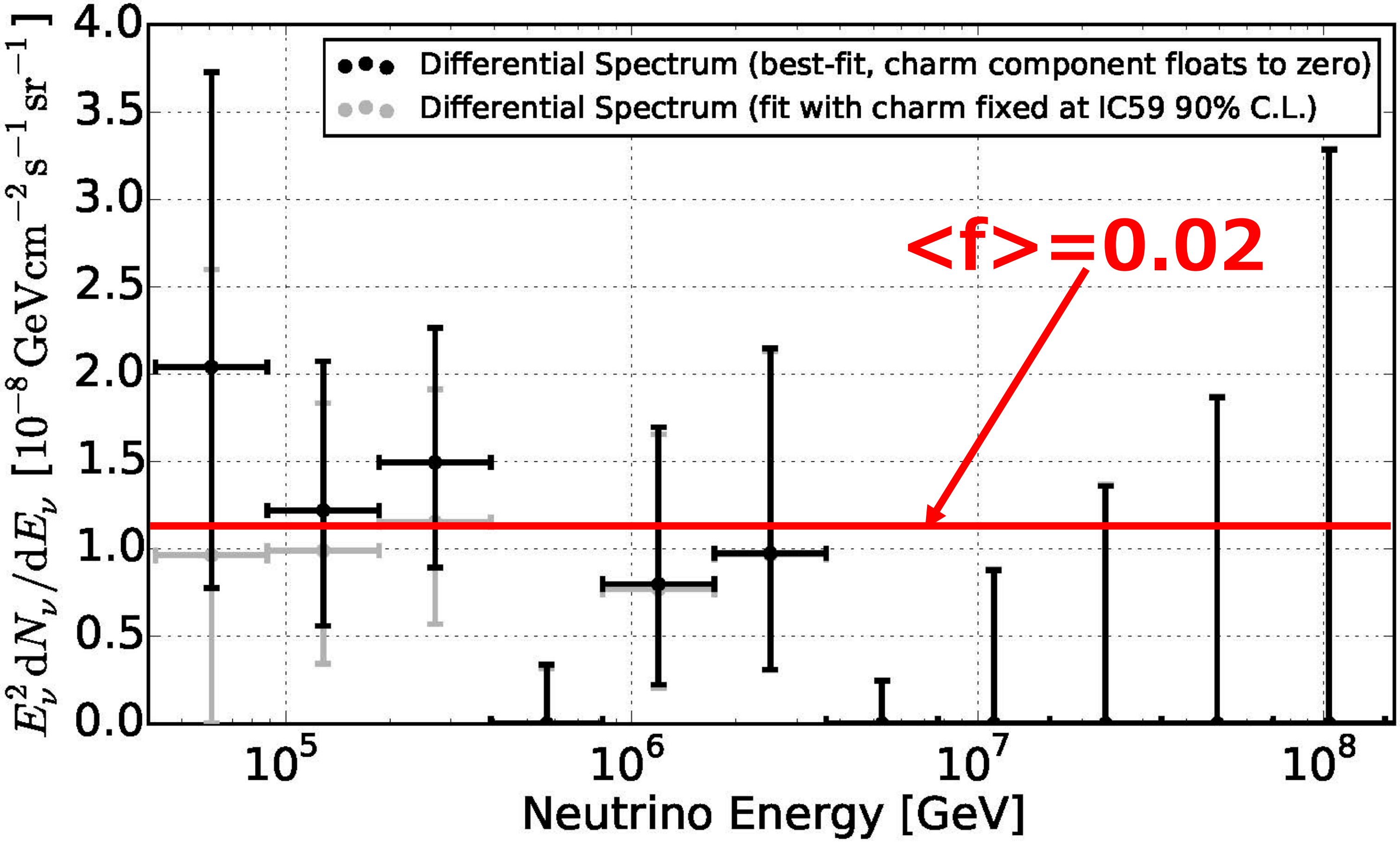
$l_\gamma: 10^{37} - 10^{38}\ \mathrm{erg\ s^{-1}\ Mpc^{-3}}$



- $J_{\mathrm{CR}} = \frac{c l_\gamma \tau_{\mathrm{CR}}}{4\pi} W^{-2} \qquad = 1.8 \times 10^{-28}\ [\mathrm{particles/(GeV\ cm^2\ s\ sr)}] \times$

$$\times \left(\frac{W}{10^{19}\ \mathrm{eV}}\right)^{-2} \left(\frac{l_\gamma}{10^{38}\ \mathrm{erg\ s^{-1}\ (Mpc)^{-3}}}\right) \left(\frac{\tau(W_{\mathrm{CR}})}{3.4\times 10^{9}\ \mathrm{yr}}\right),$$

Neutrino spectrum (Background)



$$W_\nu^2 J_\nu = 1.1 \times 10^{-8}\ [\text{neutrinos GeV} / (\text{cm}^2\ \text{s sr})] \left(\frac{< f >}{0.02}\right) \left(\frac{l_\gamma}{10^{38}\ \text{erg s}^{-1}\ (\text{Mpc})^{-3}}\right) \left(\frac{\tau_\nu}{1.5 \times 10^{10}\ \text{yr}}\right)$$

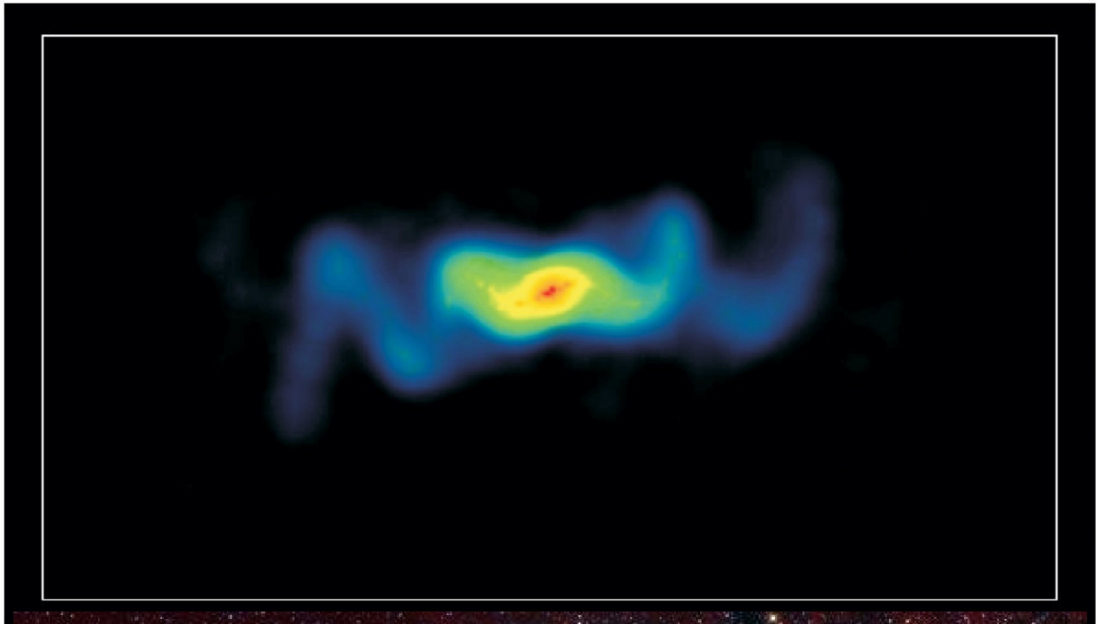
Artesen et al. ArXive:1405.5303

Galactic Microquasars

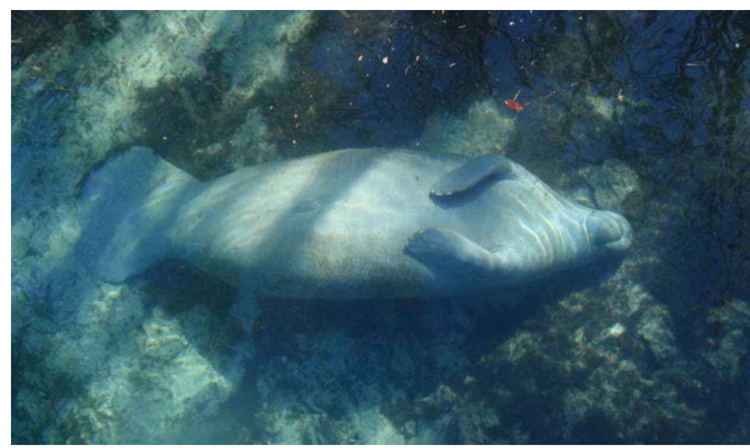
SS433, Cyg X-1, Cyg X-3, Sco X-1

- Close Binaries with BHs
  - radio jets with precessions
  - superluminal motions
  - HE gamma-ray source (Cherenkov T)
- Promising neutrino/UHECR sources

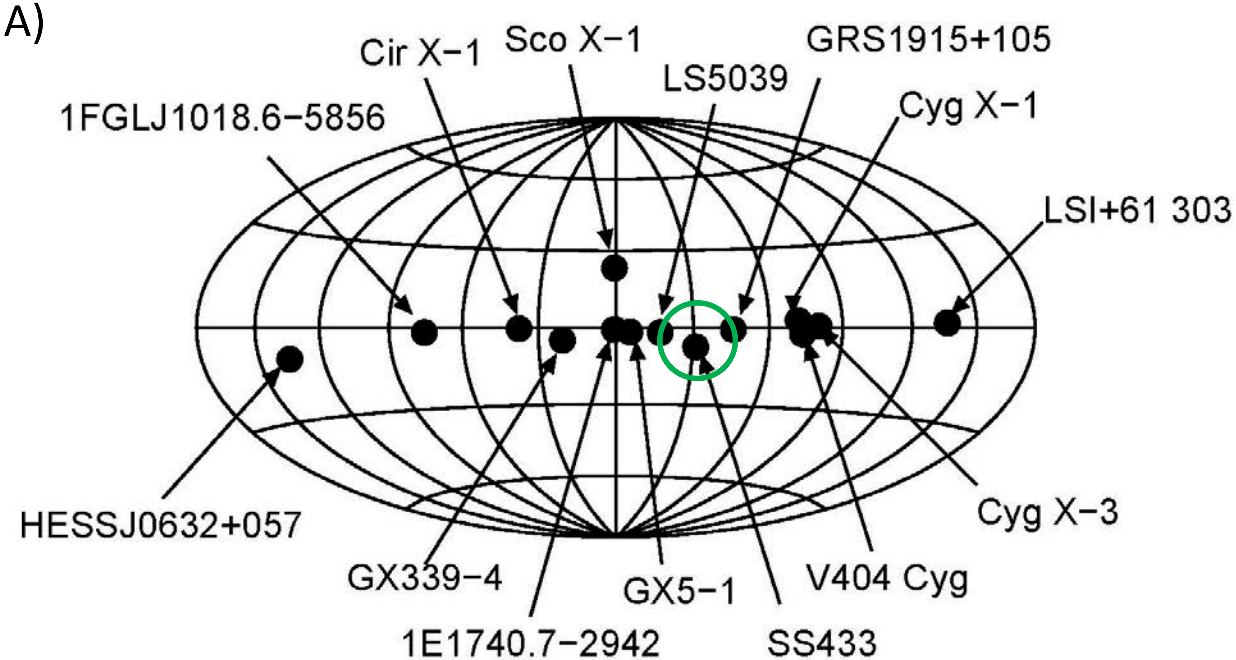
SS433 (W50) precession jets



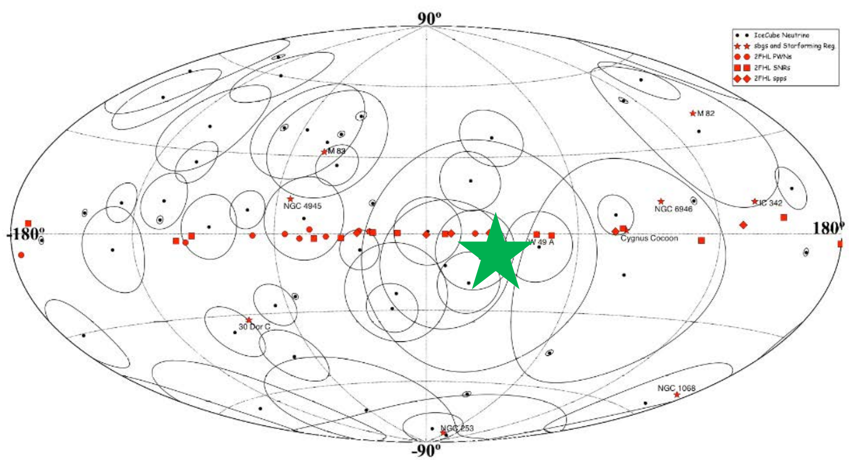
Florida manatee (Tracy Colson)



A)

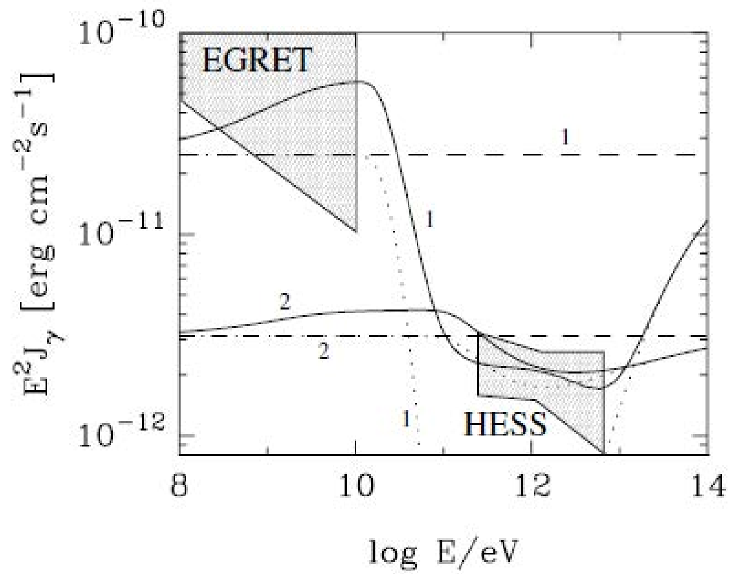

Cir X−1
Sco X−1
GRS1915+105
LS5039
1FGLJ1018.6−5856
Cyg X−1
LSI+61 303
HESSJ0632+057
Cyg X−3
GX339−4
GX5−1
V404 Cyg
1E1740.7−2942
SS433

B)

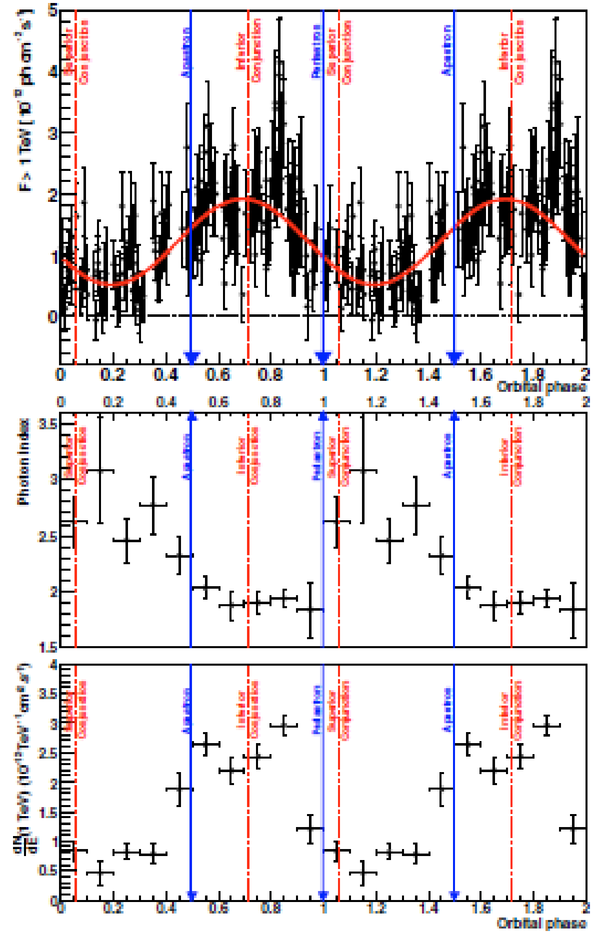

90°
IceCube Neutrino
sbgs and Starforming Reg.
2FHL PWNs
2FHL SNRs
2FHL spps
M 82
M 83
NGC 4945
NGC 6946
IC 342
-180°
180°
W 49 A
Cygnus Cocoon
30 Dor C
NGC 1068
NGC 253
-90°

Microquasar LS 5039: a TeV gamma-ray emitter and a potential TeV neutrino source

Aharonian et al 2006 J. Phys.: Conf. Ser. 39 408



Aharonian et al 2006 J. Phys.: Conf. Ser. 39 408



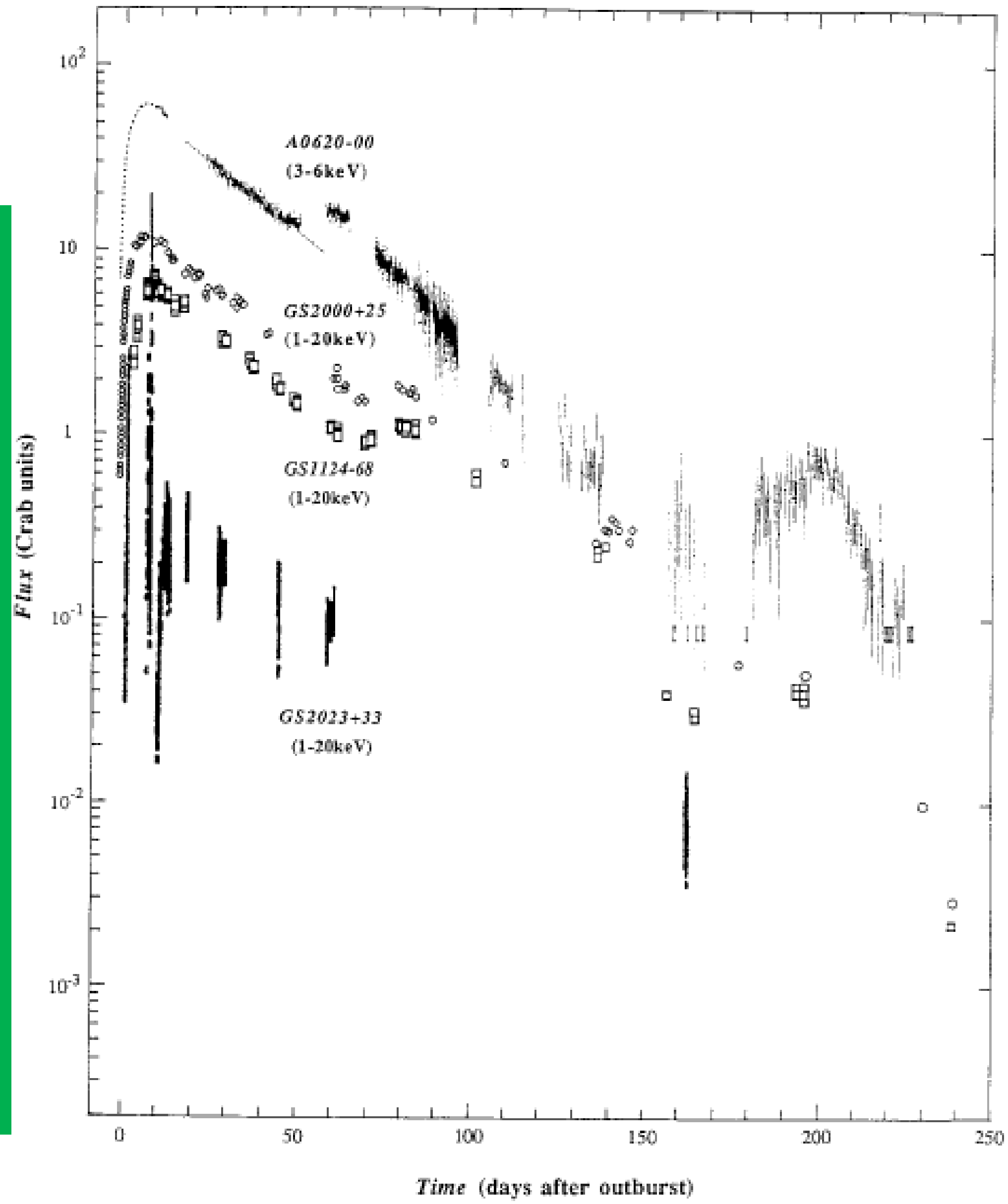
Aharonian et al 2006 A&A, 460, 743-749

X-ray Novae

- Close binaries with BH
- Transient bright microquasars
- ~One per year
- Promising candidate

BUT

Only three months



Tanaka and Shibazaki、Ann Rev. Astron. Astrophys., 1996, 34, 607-644

Conclusions

- **Wakefield Acceleration**
  - Accreting BH+disk+jet
    ←**Astronomical Linear Accelerator**
  - Bursts of Intense Alfven/EM waves ←Laser
  - Jet ←wave guide
  - **Stable, coherent, and colinear** acceleration
- **All of the messenger channels**
  - UHECRs
  - Neutrinos
  - photons (radio, optical, X-ray, and HE gamma), and GW (NS mergers)
  - Violent and simultaneous Variabilities
- **M82: the nearest starburst galaxy**
  - **M82 X-1**: Intermediate Mass Blackholes (10^3-10^4 $M_{\odot}$) 10^{41} erg/s
  - Other nearby starburst galaxies (NGC253 and NGC4945)
  - They are all **gamma-ray sources** (Fermi satellite)

  =**possible origin of the hot spots in UHECRs**

  =likely High Energy Neutrino sources: IceCube and POEMMA
- **Galactic Microquasars**
  - SS433, Cyg X-1, Cyg X-3, Sco X-1,,,
  - radio jets with precessions, superluminal motions, and HE gamma-rays
  - X-ray Novae=Highly transient: **Instantaneous exposre**
  - promising gamma-ray/neutrino/UHECR sources
- **Future mission: K-EUSO space observatory with Russian Space Agency**
  - Confirmation of south-north anisotropy
  - Identification of starburst galaxies and galactic microquasars

Mini-EUSO
launched August 22

22/8/2019 Launch,
Site 31, Baikonur Cosmodrome

The EUSO program

1. **EUSO-TA:** ***Ground detector installed in 2013 at Telescope Array site: currently operational***

2. **EUSO-BALLOONS:**
   - ***2014, Timmins, Canada***
   - ***2017 NASA Ultra long duration flight. EUSO-SPB***

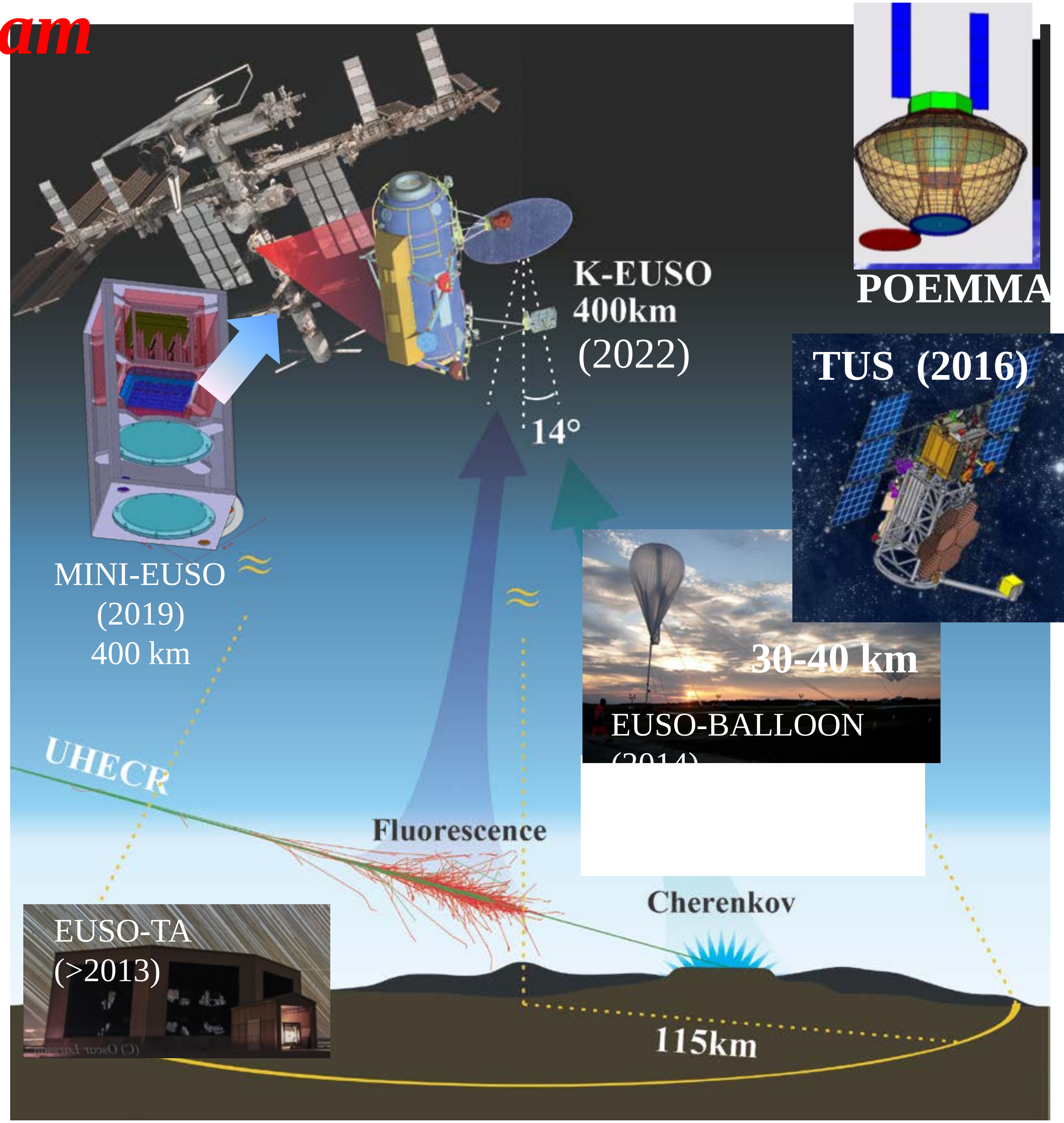
3. **TUS (2016):** free-flyer

4. **MINI-EUSO (2019):** ***Detector from International Space Station (ISS): 40 kg total.***

5. ***2022 NASA EUSO-SPB-2***

6. **K-EUSO (2023):** ***ISS Approved by Russian Space Agency***

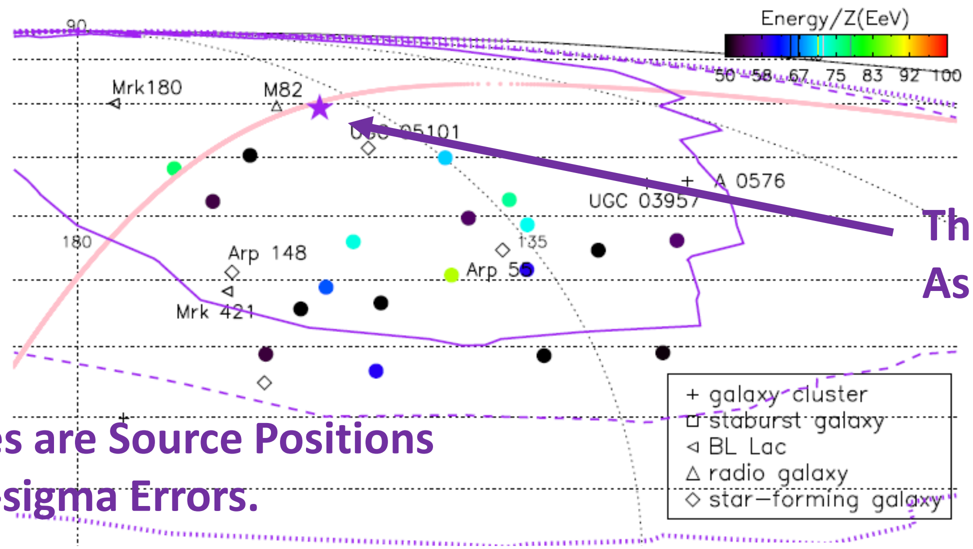
7. **POEMMA (2025+):** ***NASA***



Back up

TA Hot Spot: UHECRs from M82?

He,   Kusenko, Nagataki + PRD 2016.



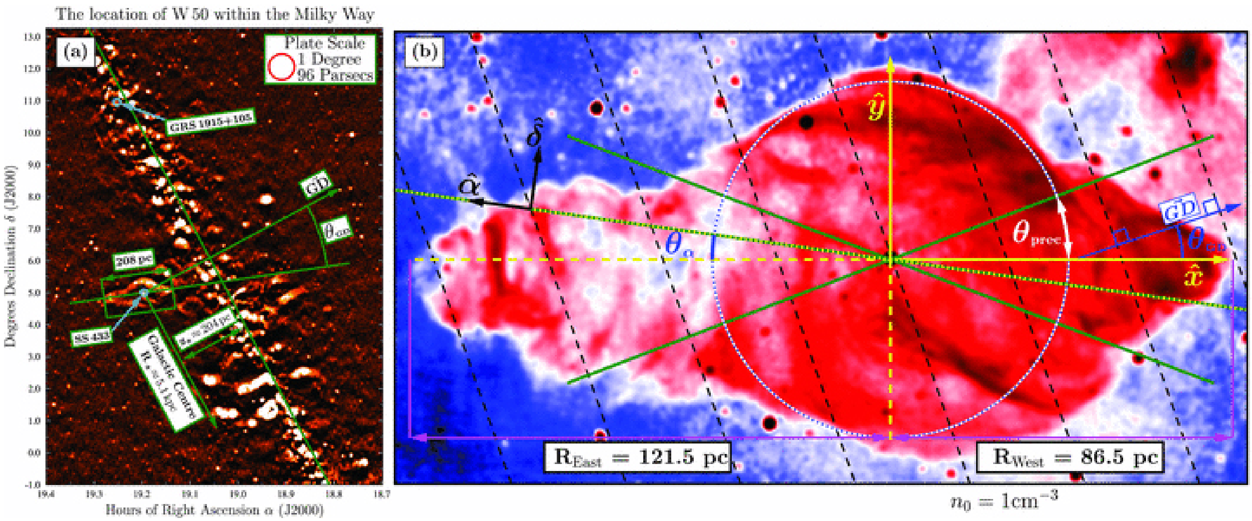
The most likely Source Position As a Result of Our Analysis.

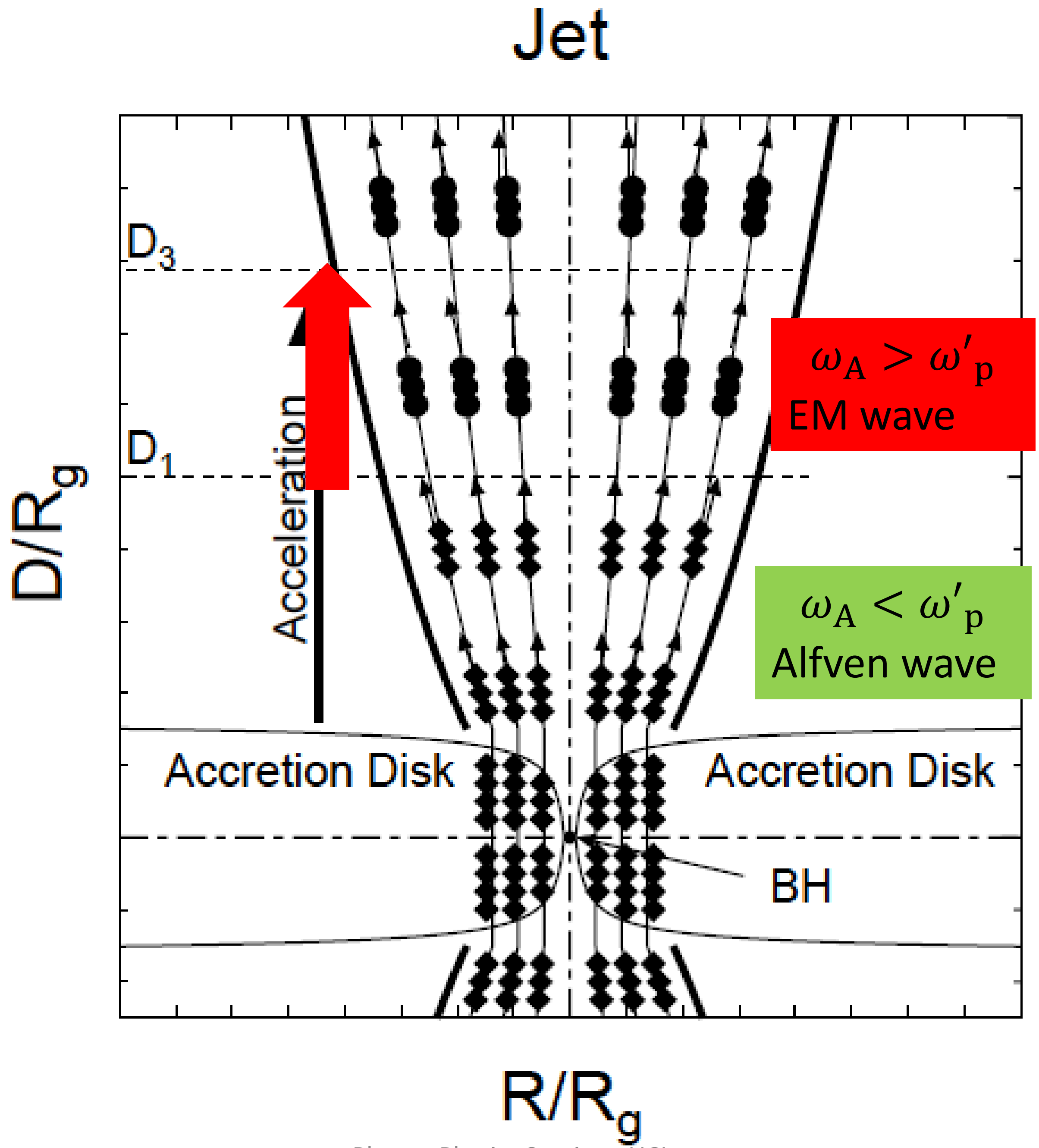
M82 is very Close from the most likely Source Position!

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

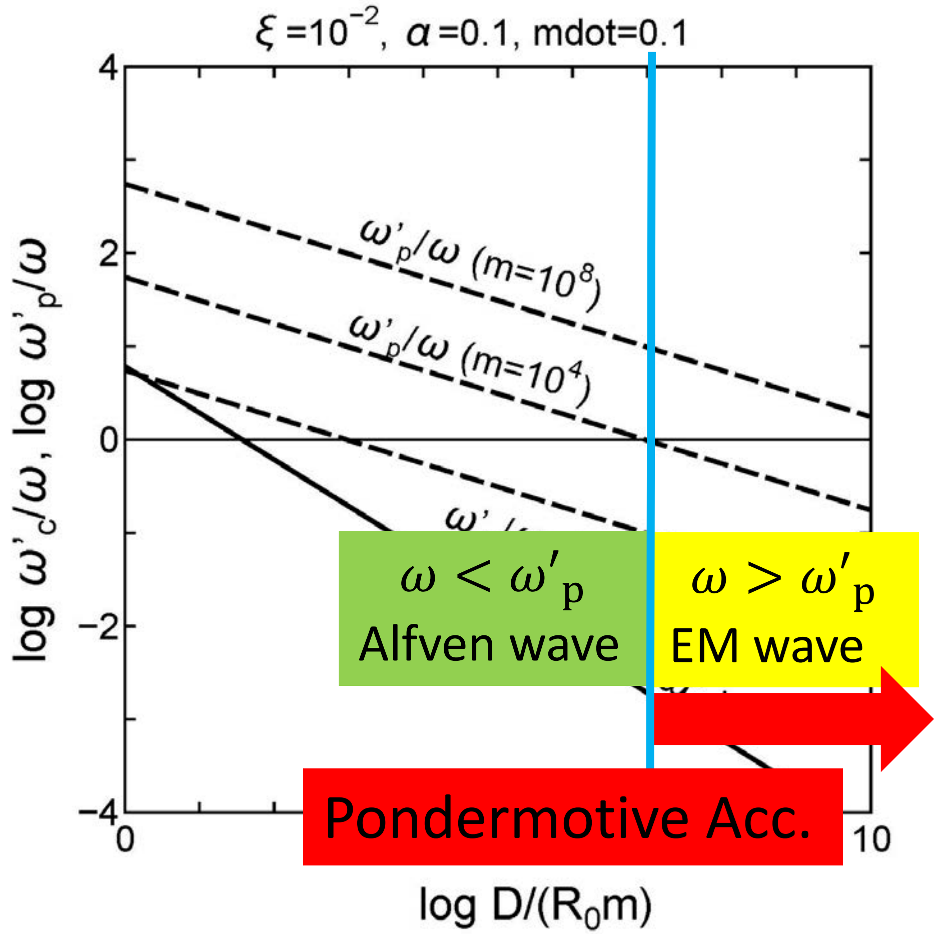
Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\rm bes-fit}$ (%)
best-fit	-	-	$17.4^{+17.0}_{-11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	11.6	9.2	96.9
Mrk 180	blazar	185	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	14.9	9.5	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

Figure 1 This figure describes the geometry of the SS 433–W 50 system. (a) This mosaic was created using archival data ...

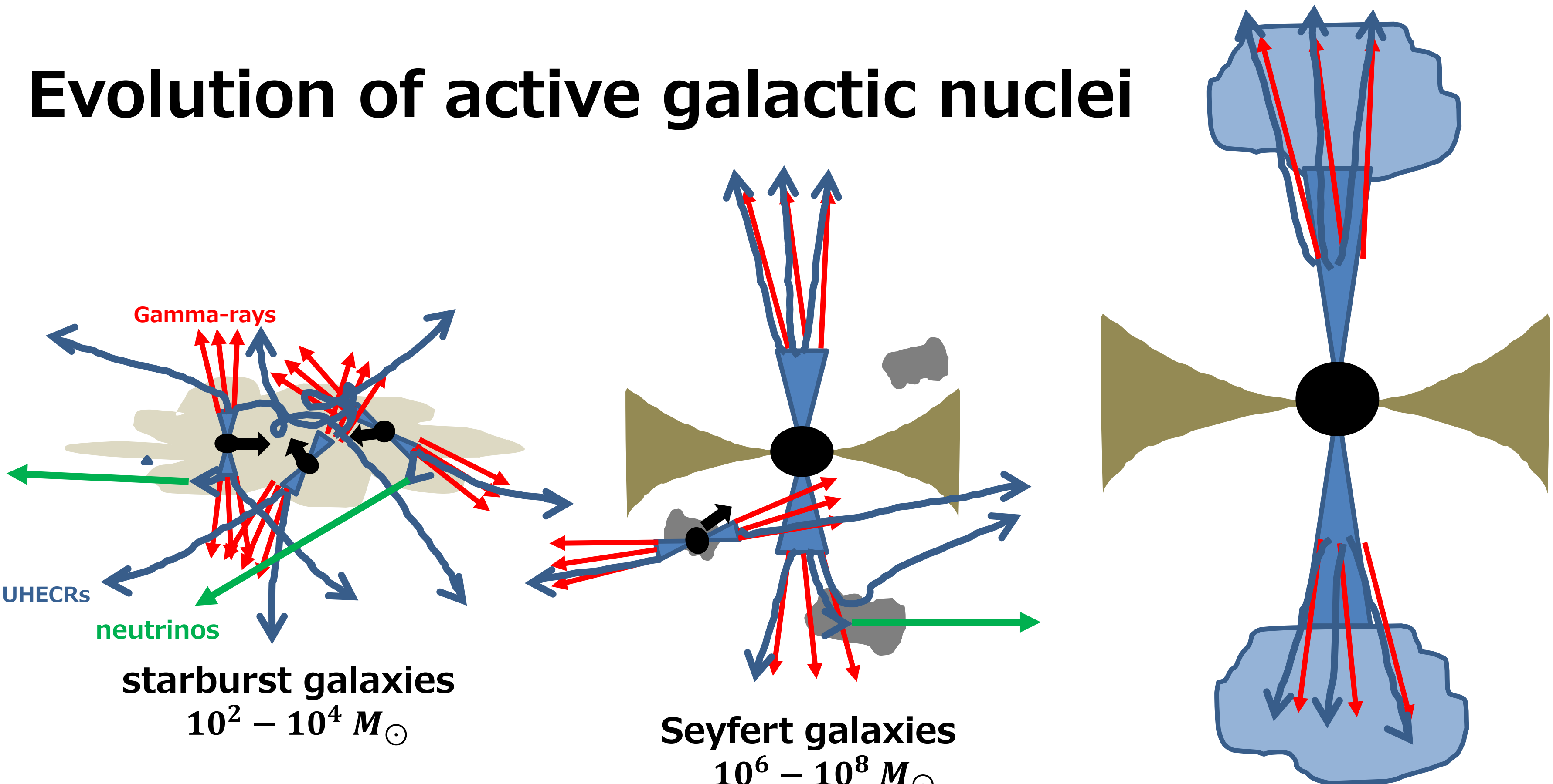



Jet
D/R_g
D_3
D_1
Acceleration
$\omega_A > \omega'_p$
EM wave
$\omega_A < \omega'_p$
Alfven wave
Accretion Disk
Accretion Disk
BH
R/R_g

Wave propagation in the jet



Evolution of active galactic nuclei



starburst galaxies
$10^2 - 10^4\ M_\odot$

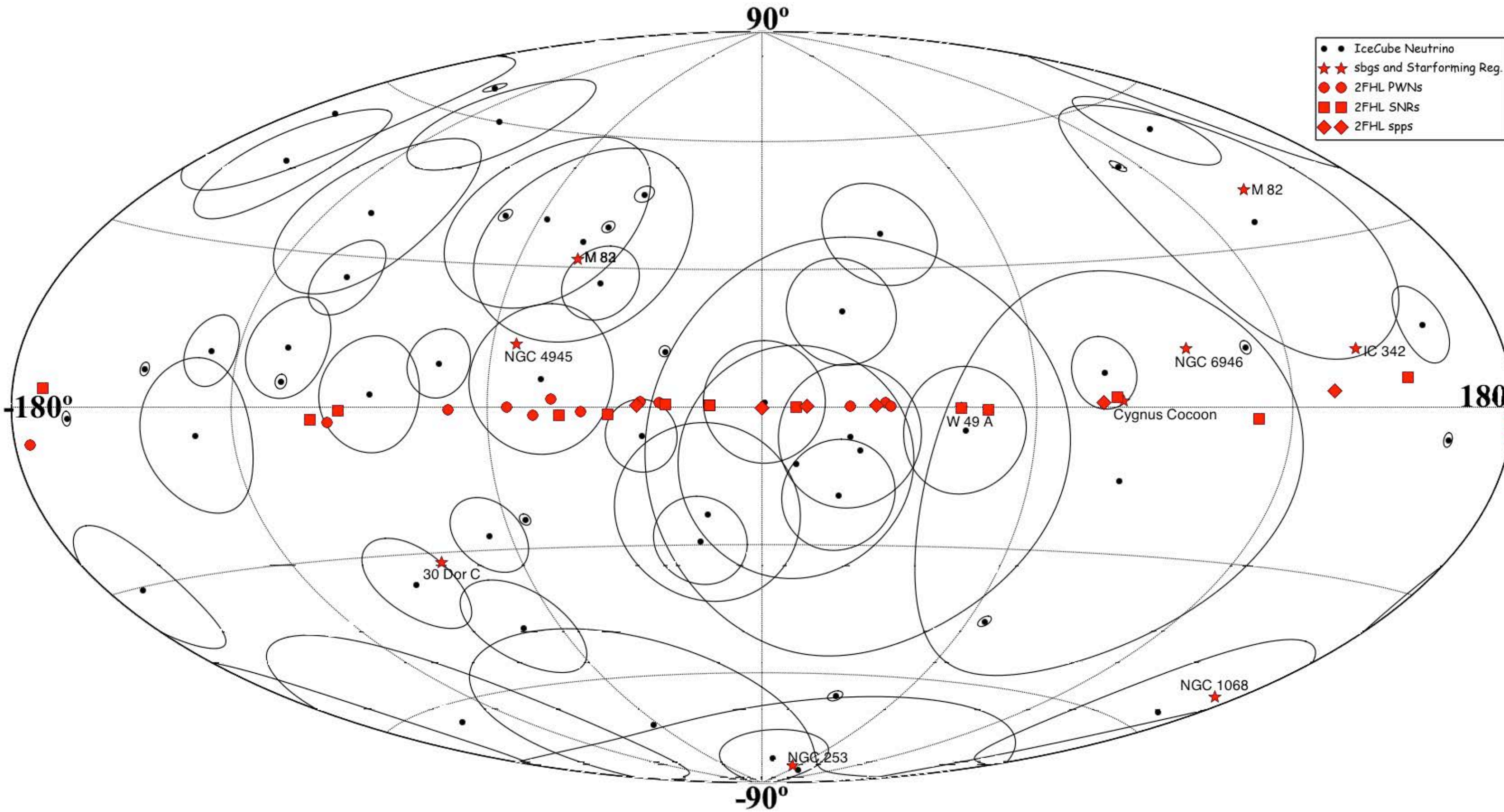
Seyfert galaxies
$10^6 - 10^8\ M_\odot$

radio galaxies
$10^8 - 10^{10}\ M_\odot$

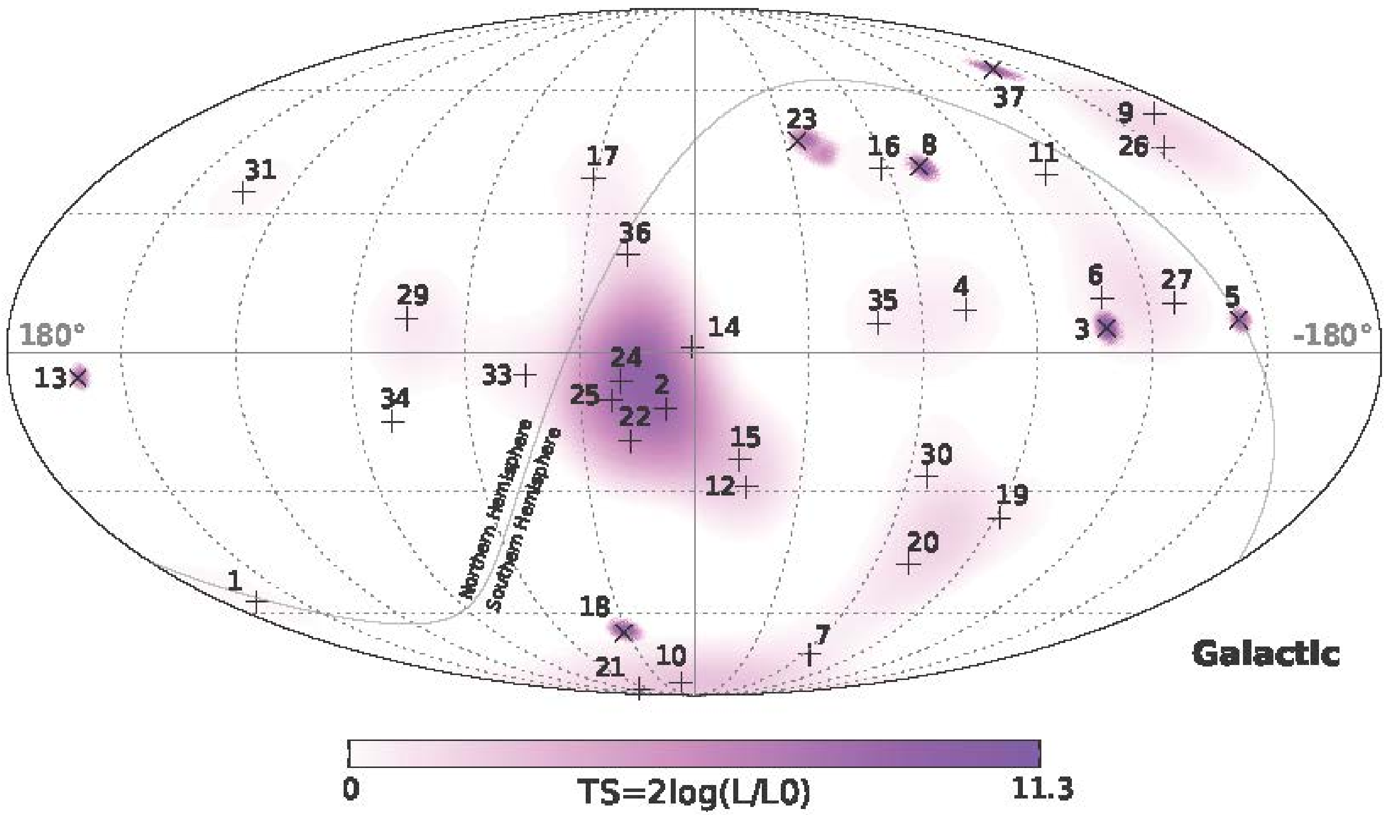
Growth of central blackhole

Skymap of neutrino events

Moharana and Razzaque, 2016, JCAP, 12, 021



Artesen et al. ArXive:1405.5303



スターバースト銀河中の伝搬

- ジェットが停まる距離

$$D_{\rm stall} = \frac{4\xi c^2}{9\kappa_{\rm T} n_0 k T_0}$$
$$= 2.8 \times 10^3\ [\rm pc] \left(\frac{T_0}{10^6\ \rm K}\right) \left(\frac{n_0}{10^2\ \rm cm^{-3}}\right)^{-1} \left(\frac{\xi}{10^{-2}}\right) \left(\frac{\dot{m}}{0.1}\right) \left(\frac{m}{10^4}\right)^{-1}$$

- pp相互作用の自由行程

$$D_{\rm pp} = \frac{1}{n_0 \sigma_{\rm pp}} = 1.2 \times 10^4\ [\rm pc]\ \left(\frac{n_0}{10^3\ \rm cm^{-3}}\right),$$

ガンマ線とニュートリノに変換される

- ラーモア半径

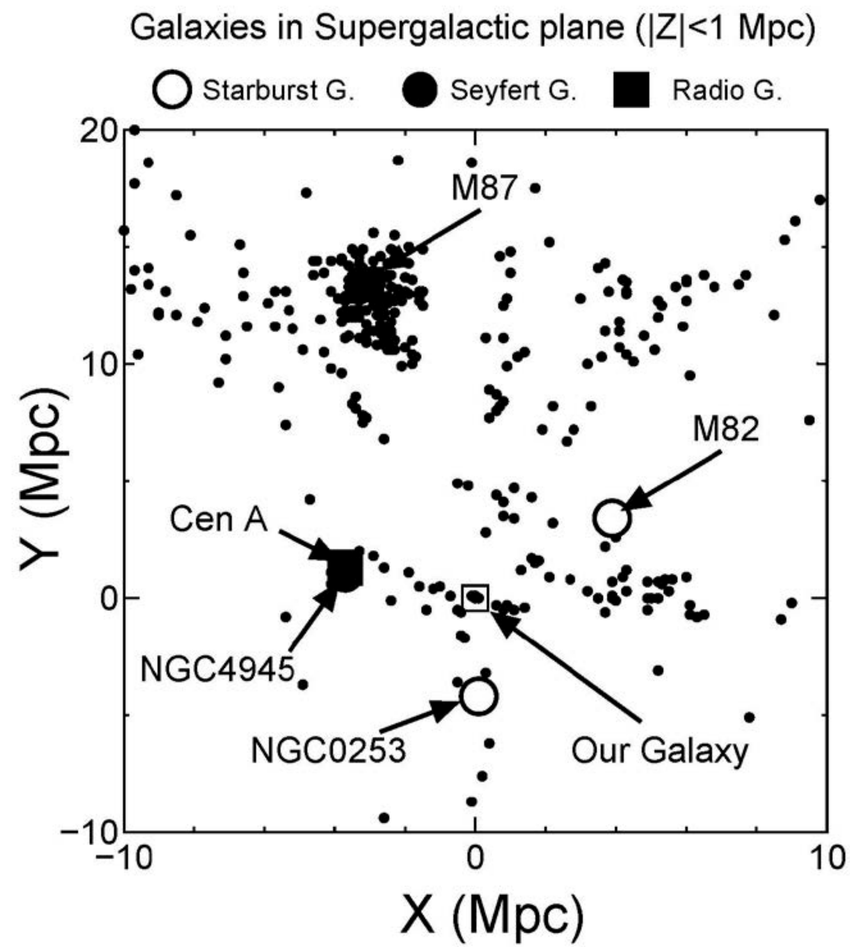
$$D_L = \frac{W_{\rm CR}}{ZecB} = 1.1 \times 10^3\ [\rm pc]\ Z \left(\frac{B}{100\ \mu \rm G}\right) \left(\frac{W_{\rm CR}}{10^{20}\ \rm eV}\right).$$

Magnetic deflection

– $B \sim 10\ \mathrm{nG}$ for $D = 3.2\ \mathrm{Mpc}$
  - $\theta = 0.5° \left(\frac{D}{\mathrm{Mpc}}\right)\left(\frac{B}{\mathrm{nG}}\right) \sim 17.4°$
  - $\Delta\theta = 0.36 \left(\frac{D}{\mathrm{Mpc}}\right)^{1/2} \left(\frac{D_\mathrm{c}}{\mathrm{Mpc}}\right)^{1/2} \left(\frac{B_\mathrm{r}}{\mathrm{nG}}\right) \sim 9.4°$

– Consistent with Local Supercluster structure

Galaxy distribution in the supergalactic plane

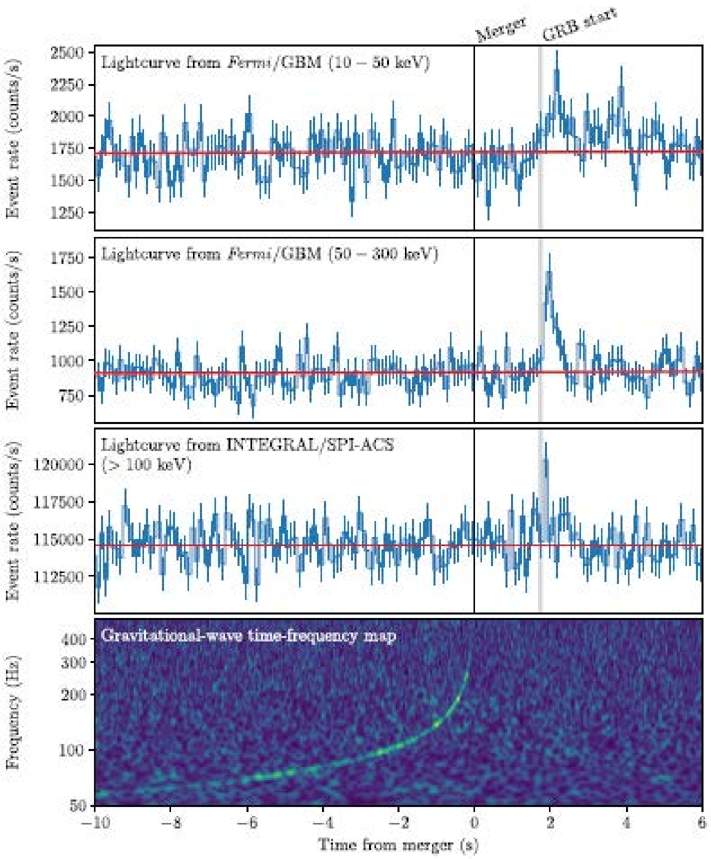


Acceleration by pondermotive force at "bow wake"

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

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

NS-NS merger/GW burst GW170817

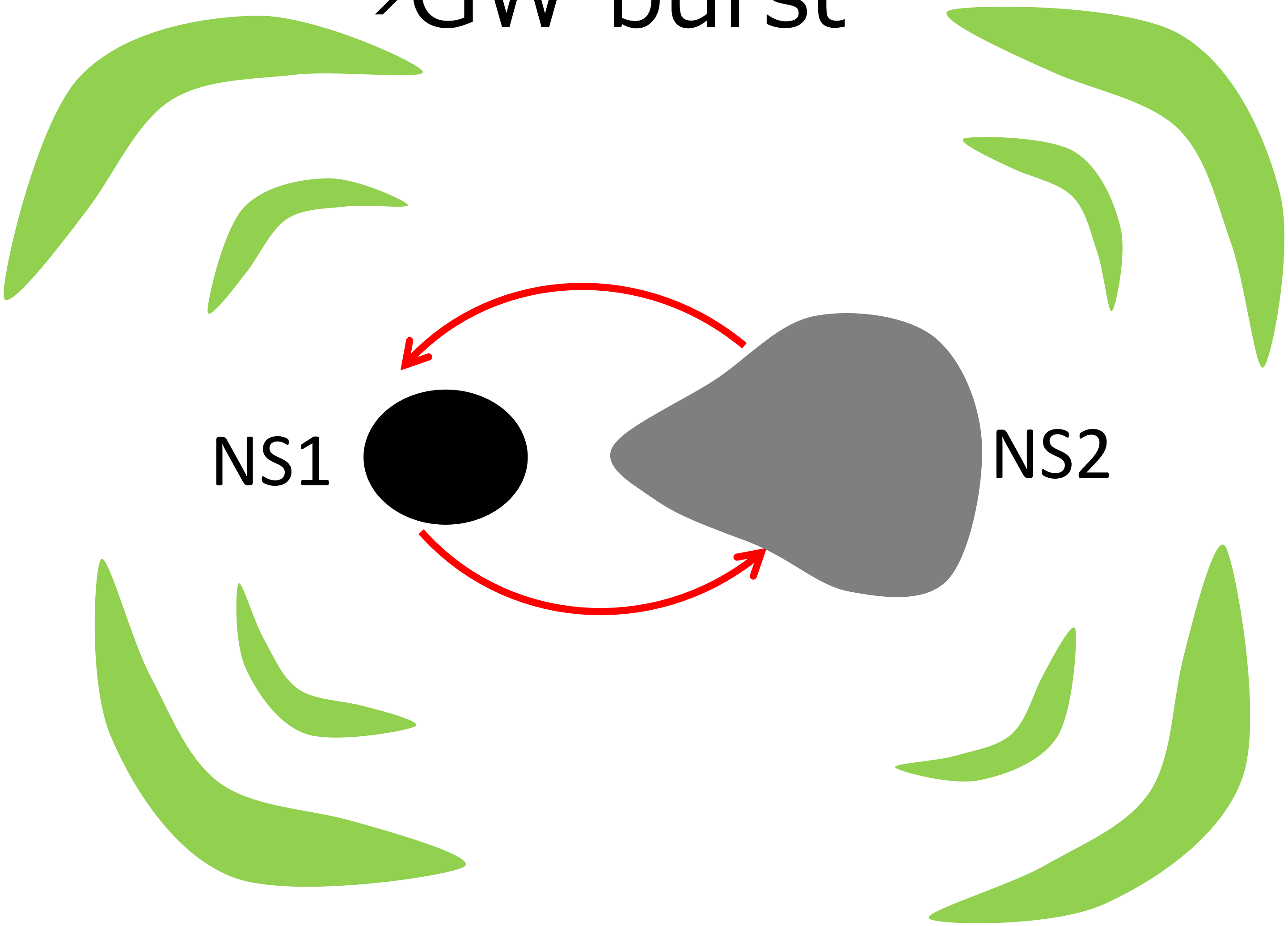


- 1.7 seconds delay in gamma-rays
- Lorentz invariance test:

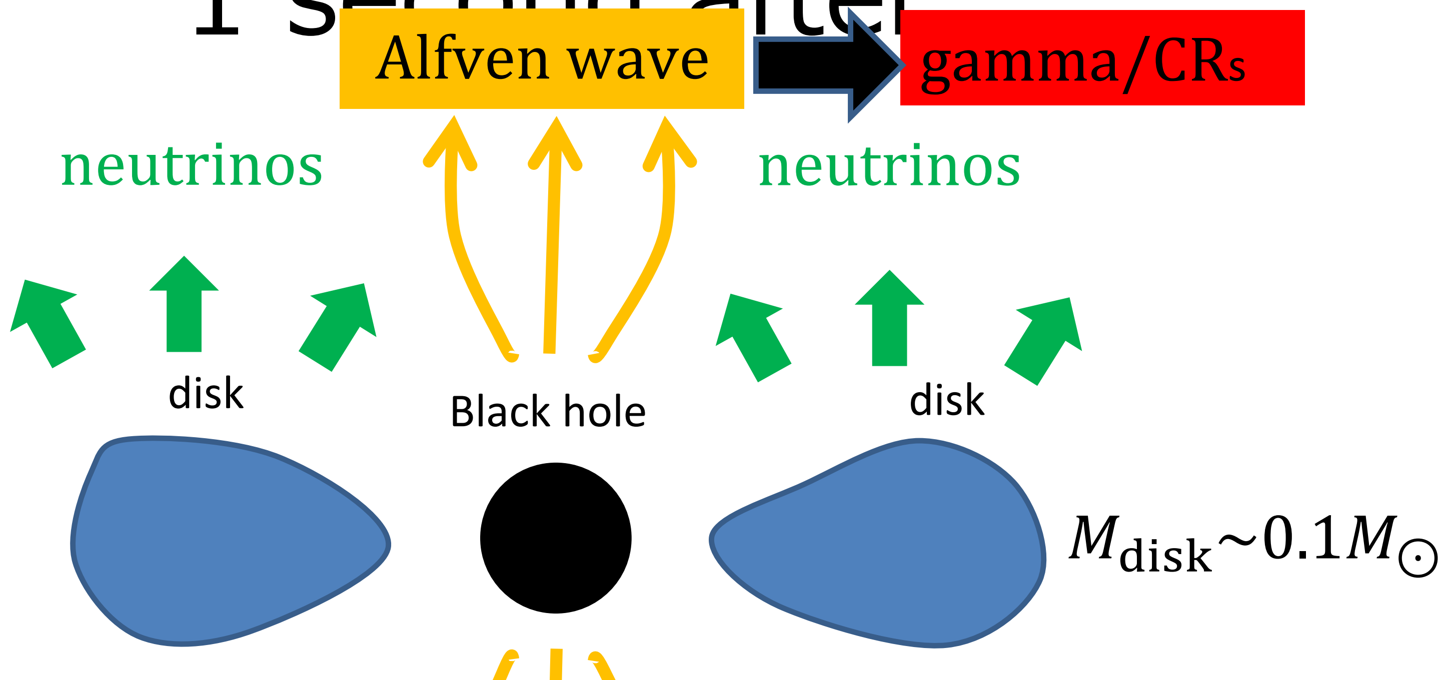
$$-3 \times 10^{-15}$$
$$+7 \times 10^{-16}$$

times of speed of light between GW and photons

NS-NS merger →GW burst



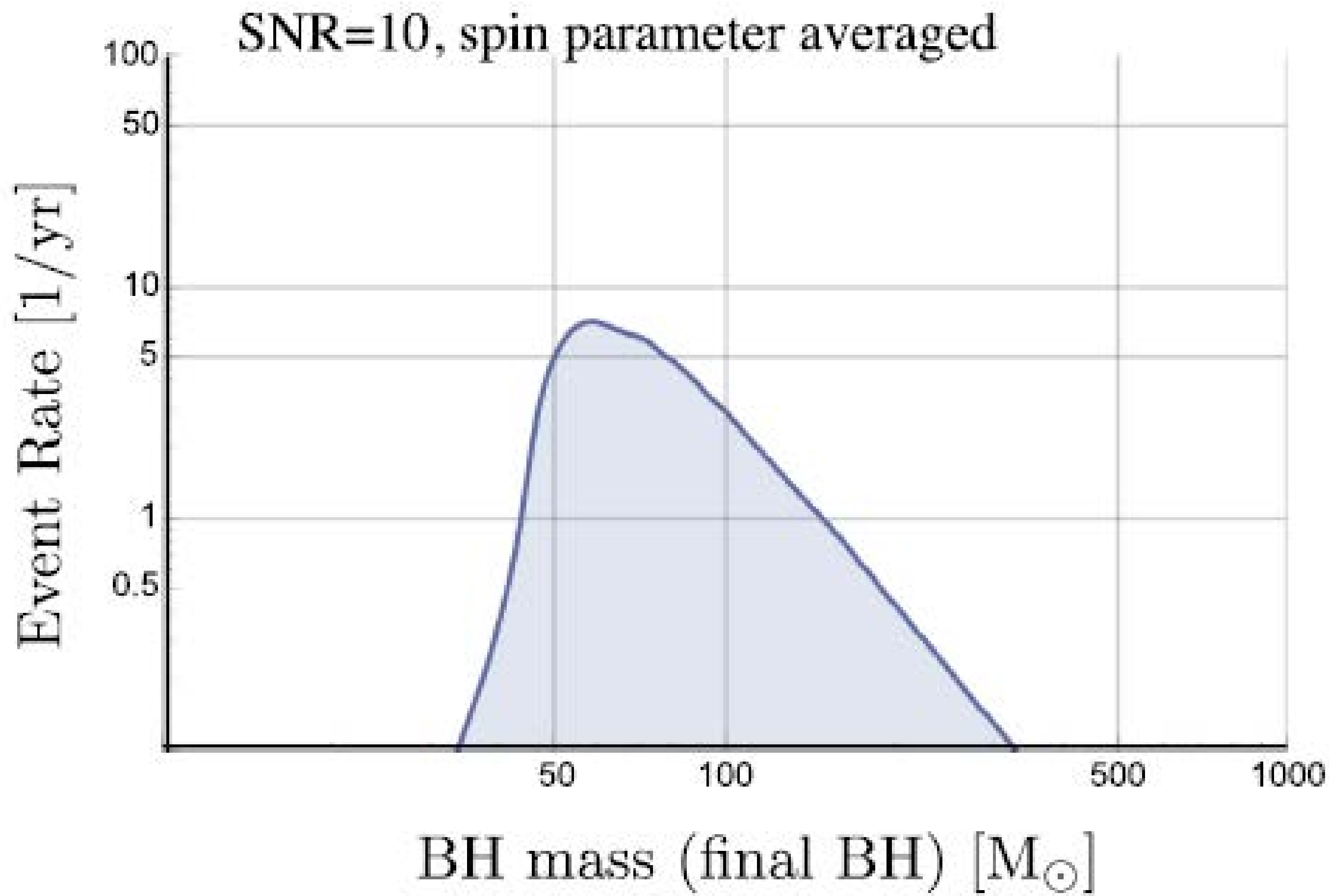
NS-NS merger→BH + Disk
1 second after



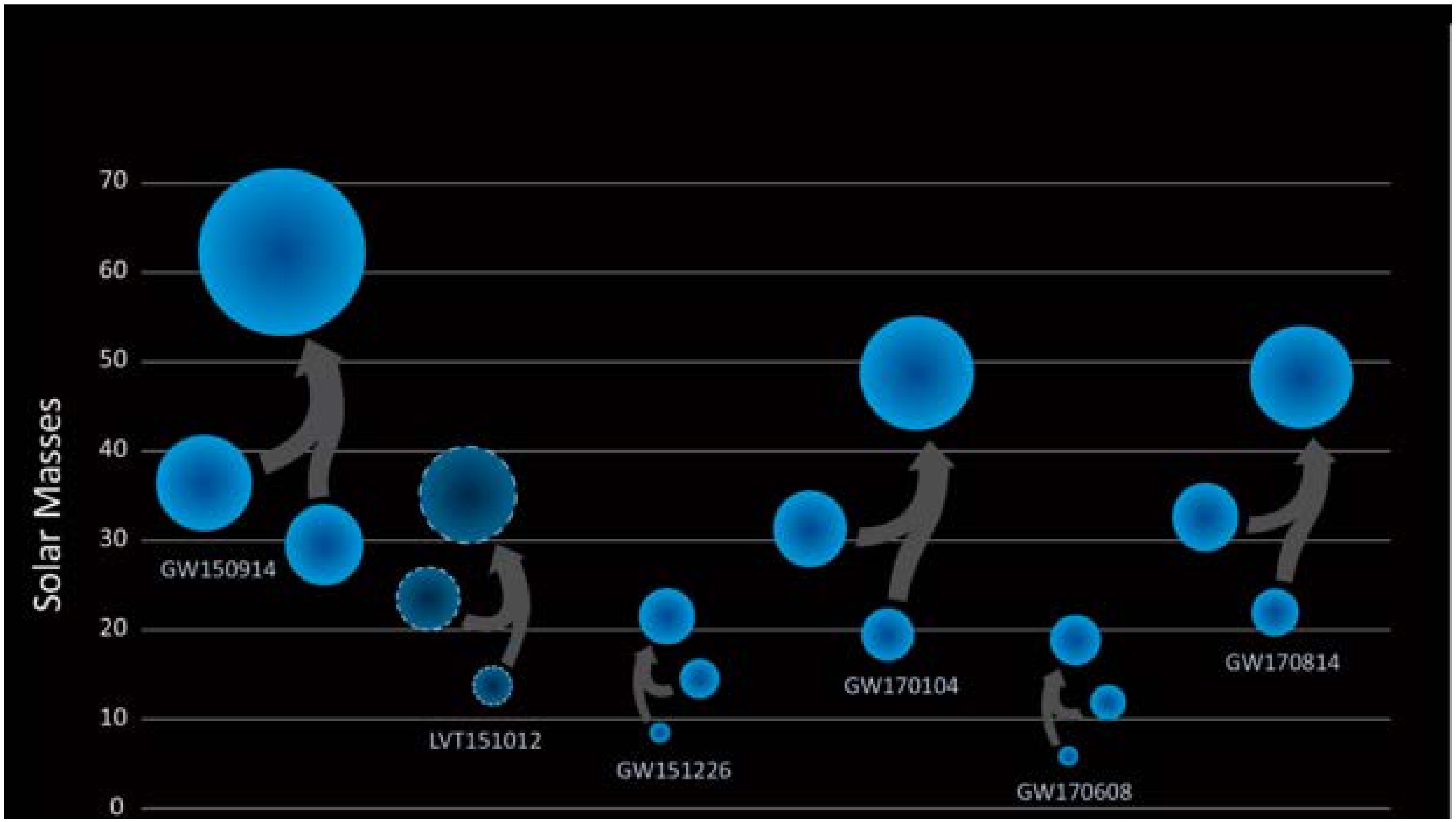
$L_\nu \sim 10^{52}$ erg/s$\sim L_A$

Central Engine of GRB/Hypernova

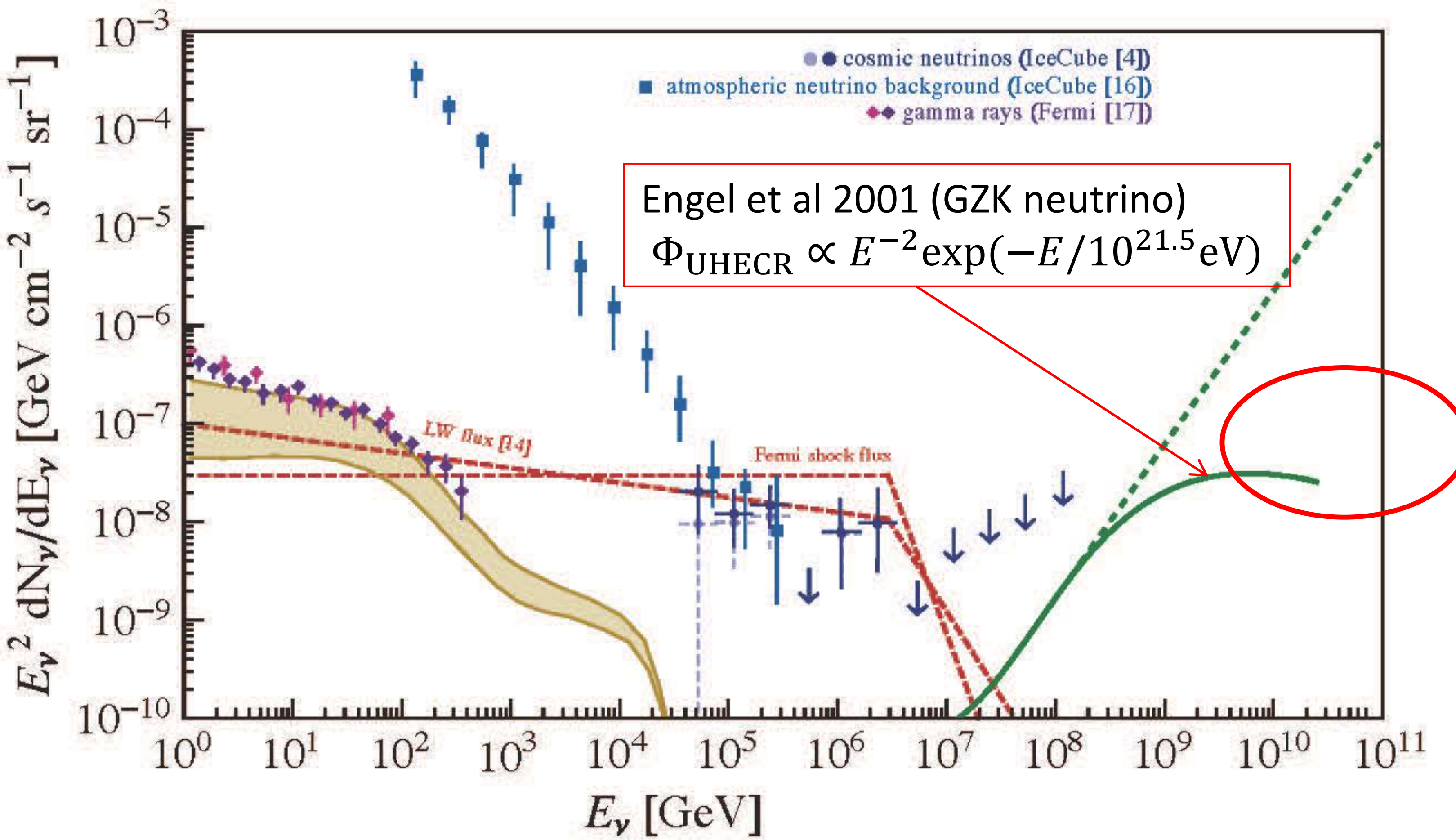
Alfven wave



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


Solar Masses
70
60
50
40
30
20
10
0
GW150914
LVT151012
GW151226
GW170104
GW170608
GW170814

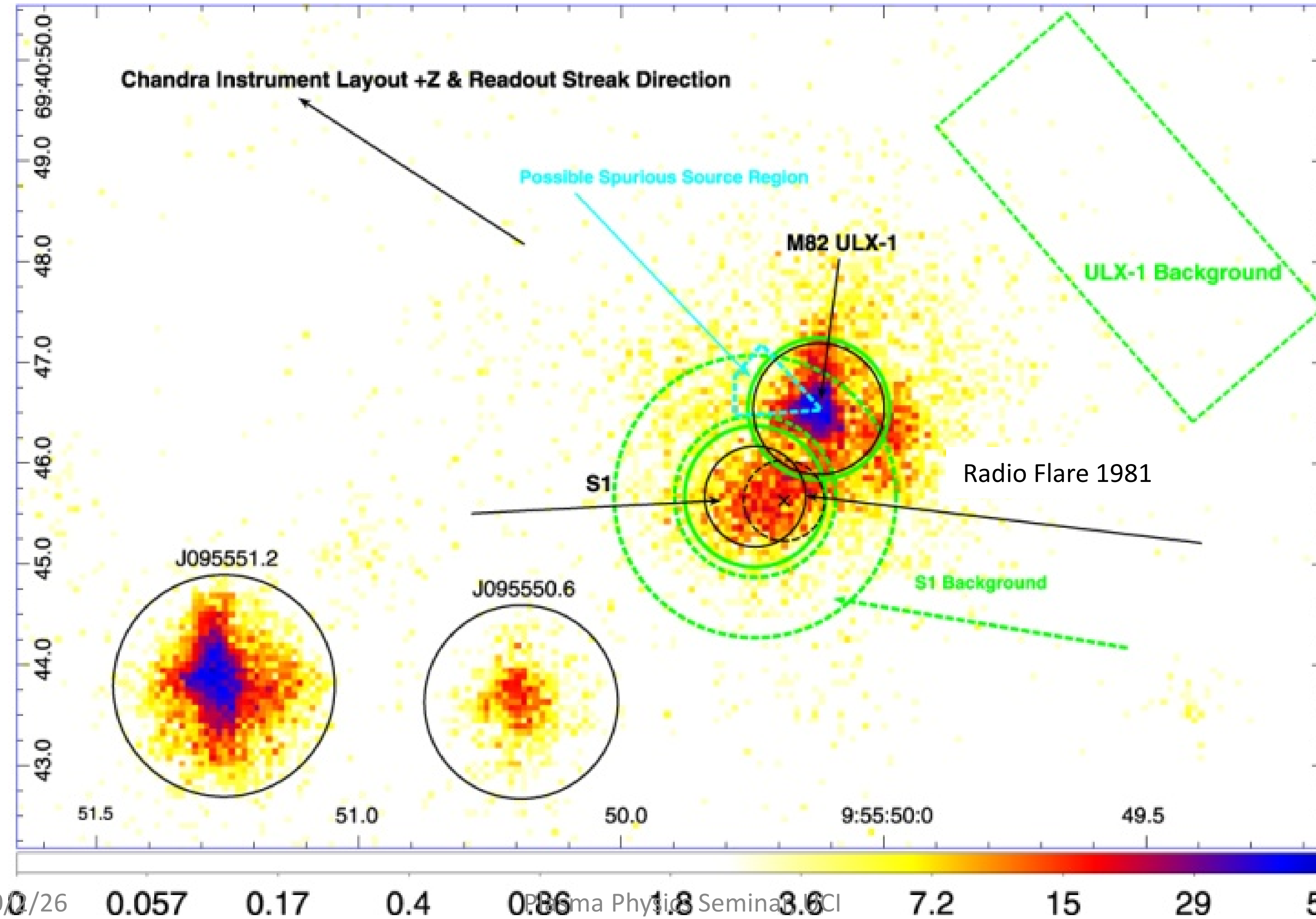
Neutrino and gamma ray flux



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

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

Xu et al. 2015 ApJ Letters 799, L28



UHECR emission: Beaming?

- Radio galaxies:

  Angle to Line of sight θ>10-20°
  - M87 43° : off-axis
  - Cen A 50-80° :off-axis
- Blazers: θ<10°
- No information for M82 X-1
  - Single jet?

  → θ<10° on-axis