# Wake Field acceleration in an accreting blackhole system: M82 starburst galaxy: possible origin of the northern hot spot

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Toshiki Tajima (UC Irvine)

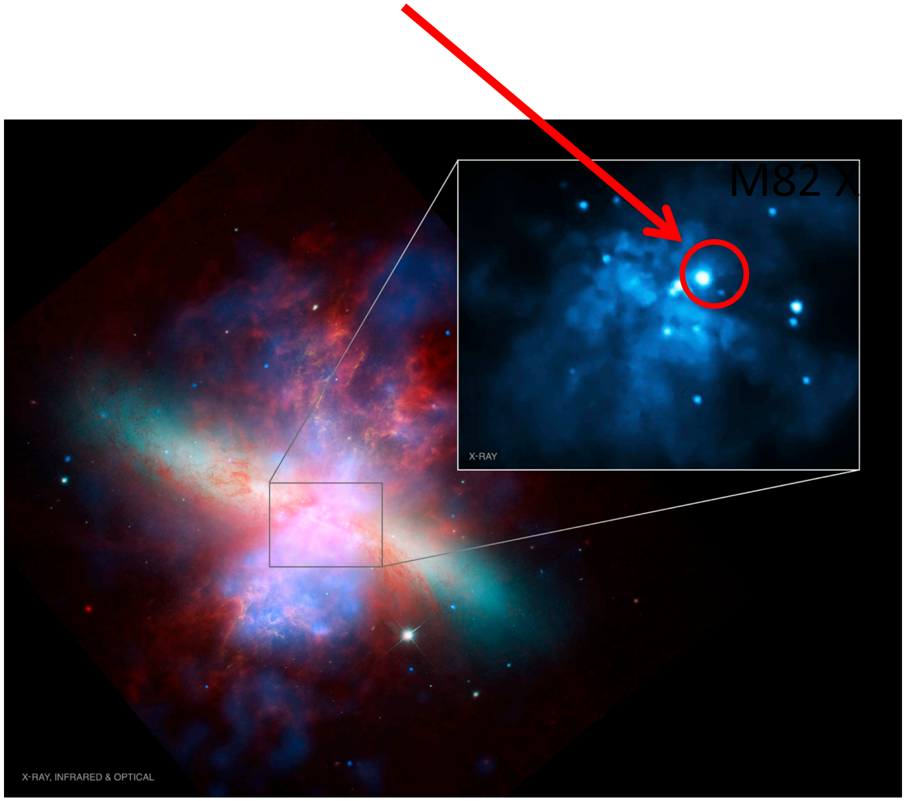
# contents

1. Star burst galaxy M82 and North hot spot
2. Bow wake acceleration
3. All sky map
4. Future Cosmic-ray Observations
5. NS-NS merger and Gravitational Wave
6. Conclusion

# M82: Nearest Star Burst Galaxy

Just after the collision with M81

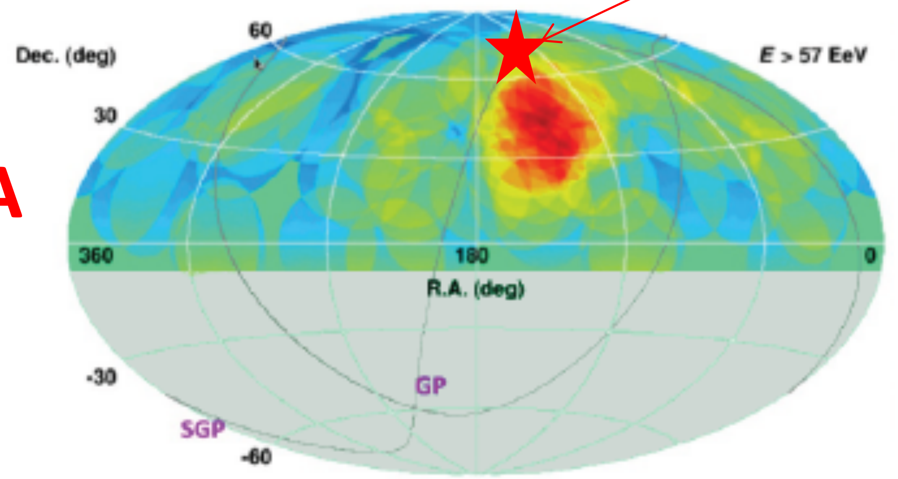
M82 X-1: 100-10000 Ms BH



Composite of X-ray, IR, and optical emissions

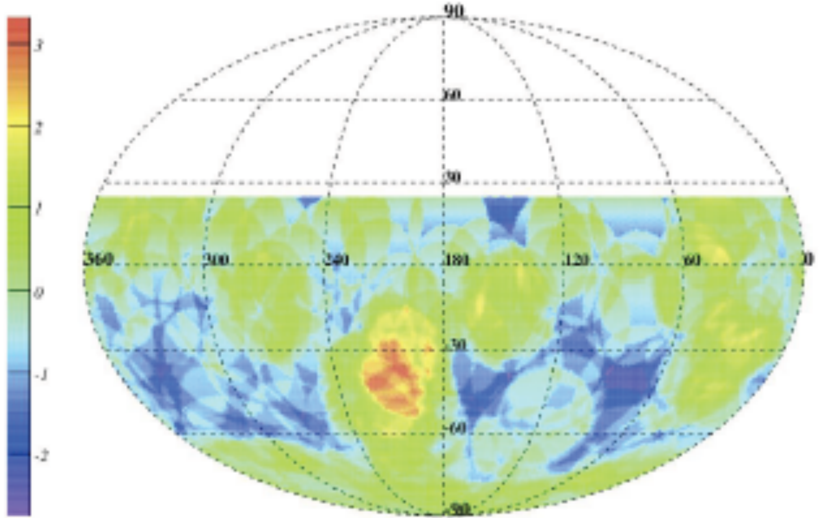
NASA / CXC / JHU / D. Strickland; optical: NASA / ESA / STScI / AURA/ Hubble Heritage Team; IR: NASA / JPL-Caltech /Univ. of AZ / C. Engelbracht; inset – NASA / CXC / Tsinghua University / H. Feng et al.

# Arrival Direction Map (Auger/TA)



M82

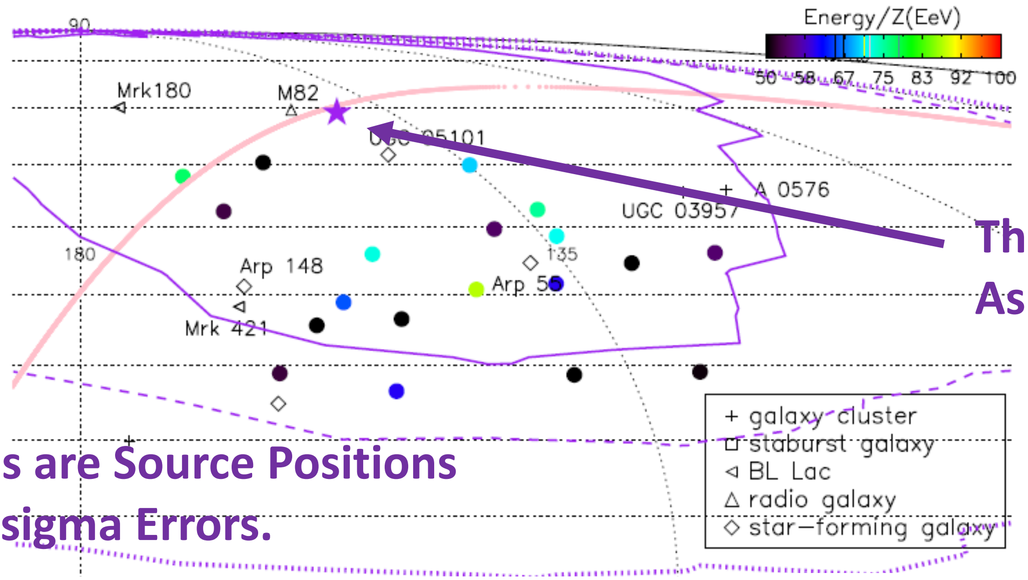
**TA**



**Auger**

# TA Hot Spot: UHECRs from M82?

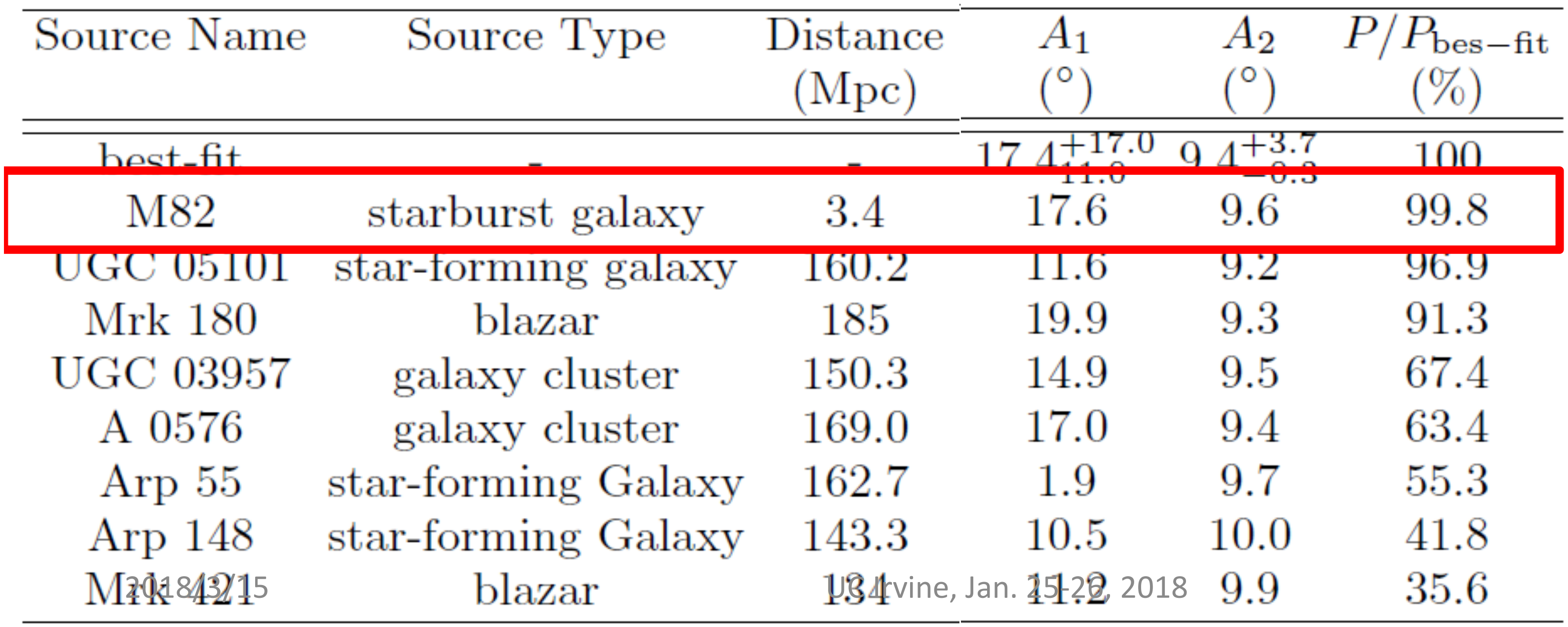
He, Kusenko, Nagataki + PRD 2016.



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

M82 is very Close from the most likely Source Position!

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



| Source Name | Source Type | Distance (Mpc) | $A_1$ (°) | $A_2$ (°) | $P/P_{\mathrm{bes-fit}}$ (%) |
|---|---|---|---|---|---|
| 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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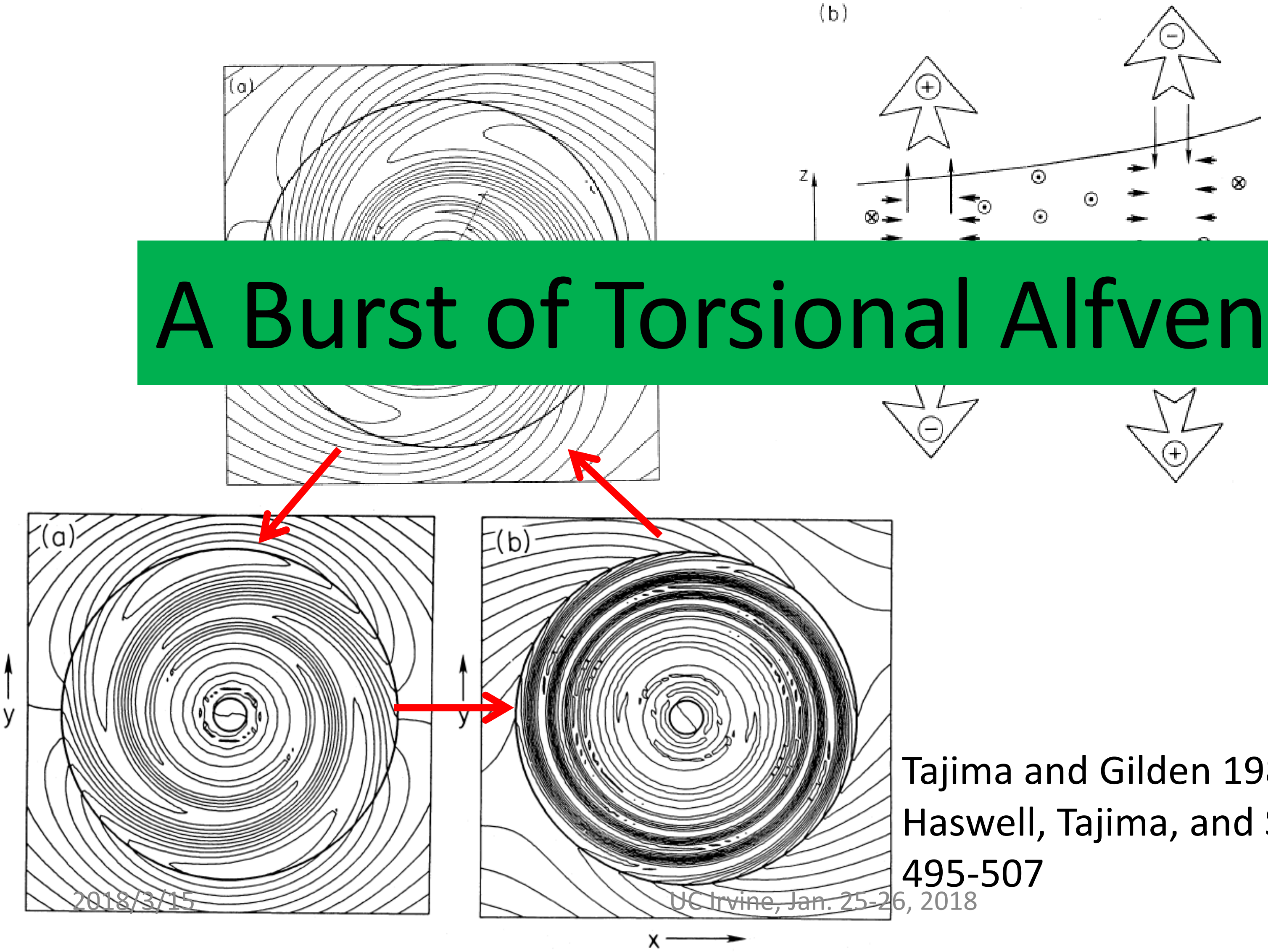
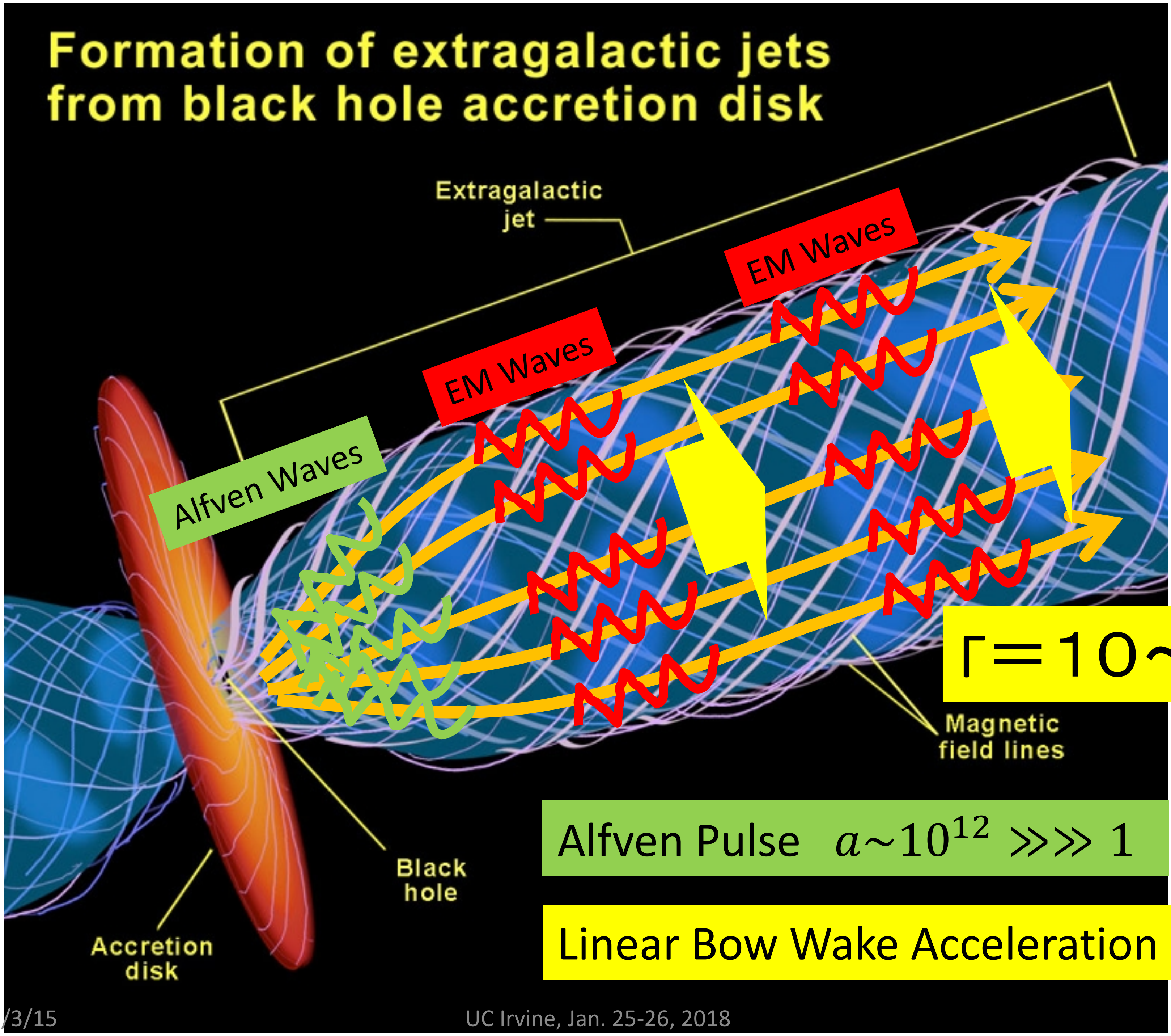
# Eruption of magnetic field in an accretion disk



**A Burst of Torsional Alfven Waves**

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



$\Gamma = 10 \sim 30$

Alfven Pulse $a \sim 10^{12} \ggg 1$

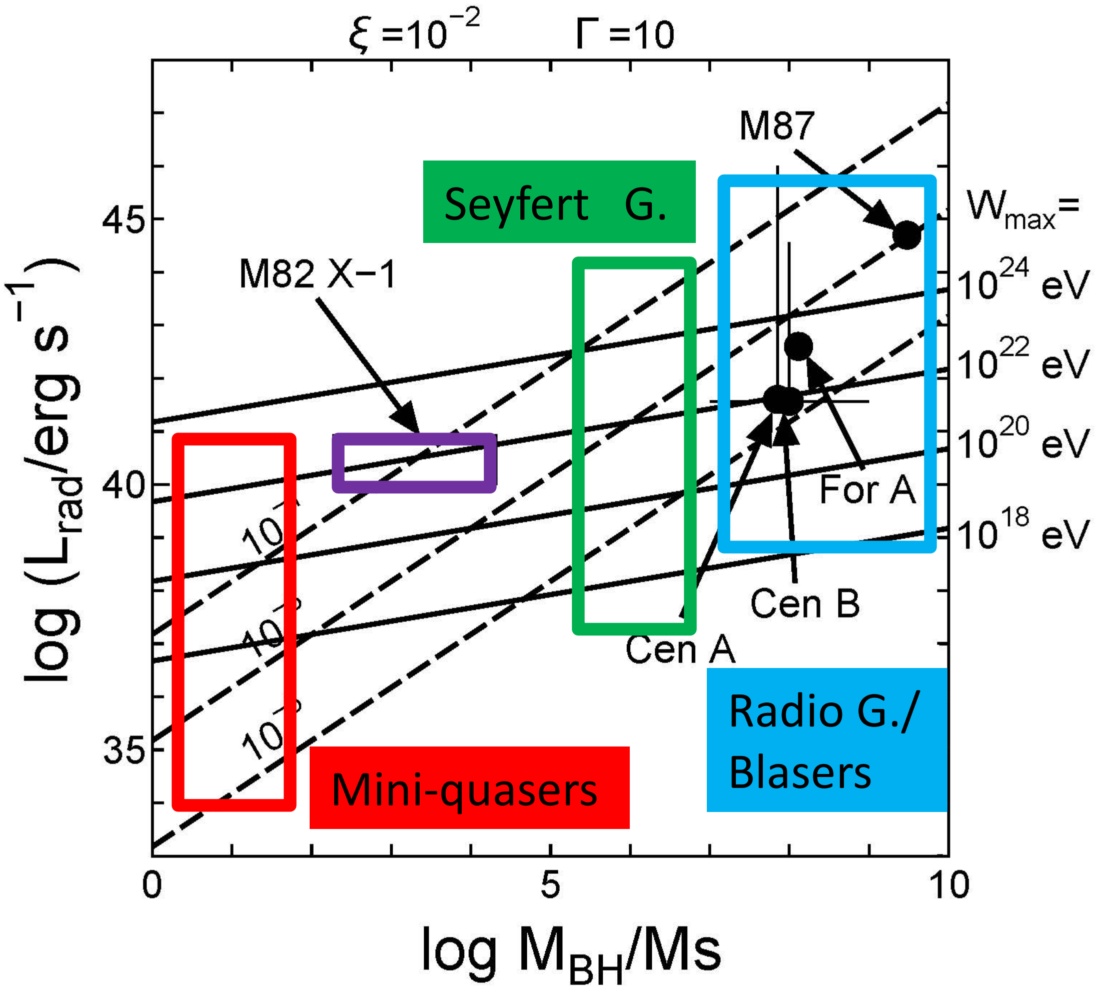
Linear Bow Wake Acceleration

# Acceleration by pondermotive force at “bow wake”

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

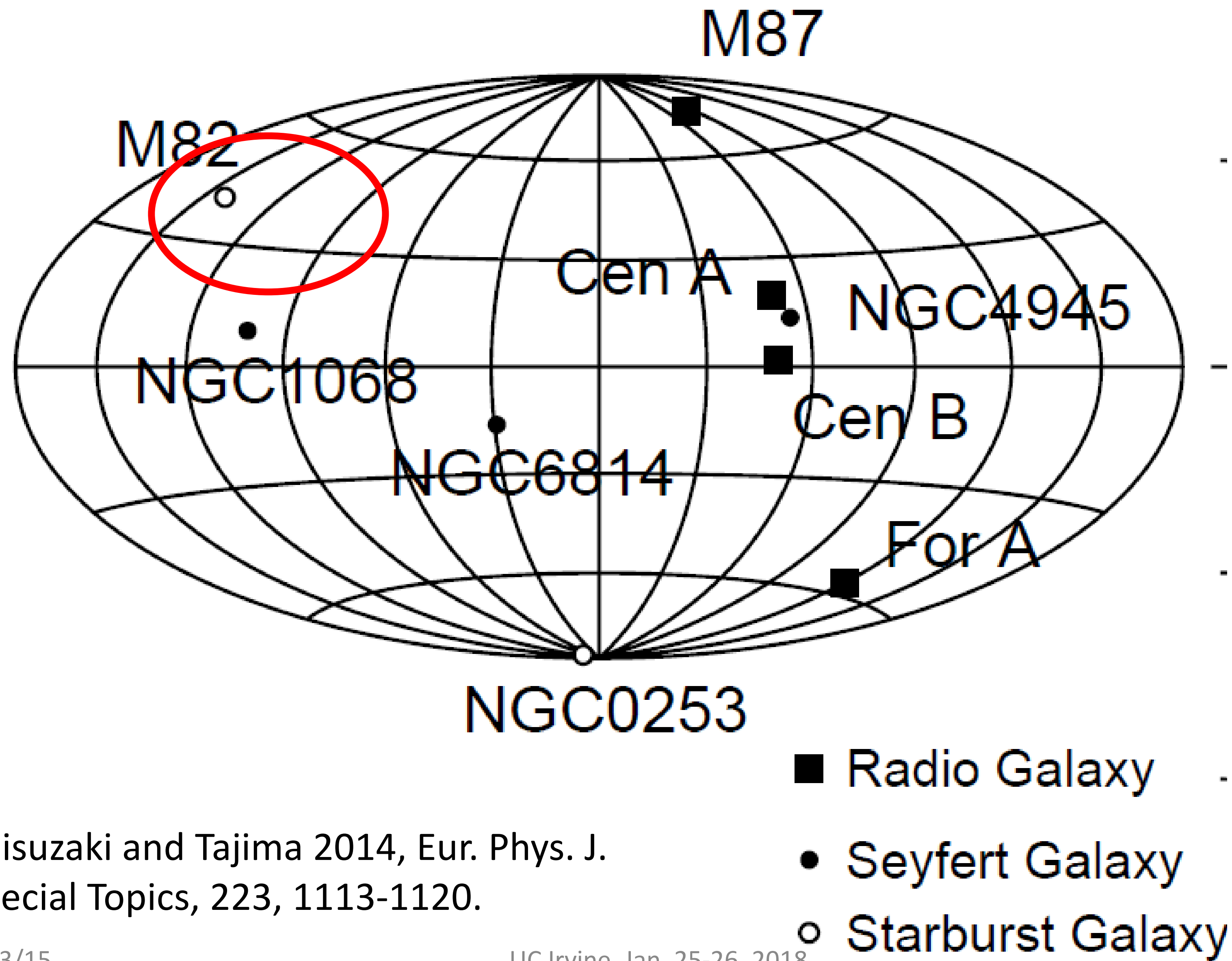
$$F_{\mathrm{pm}} = \Gamma m_{\mathrm{e}} c a_0 \omega_A$$

# cosmic ray acceleration and gamma-ray emission



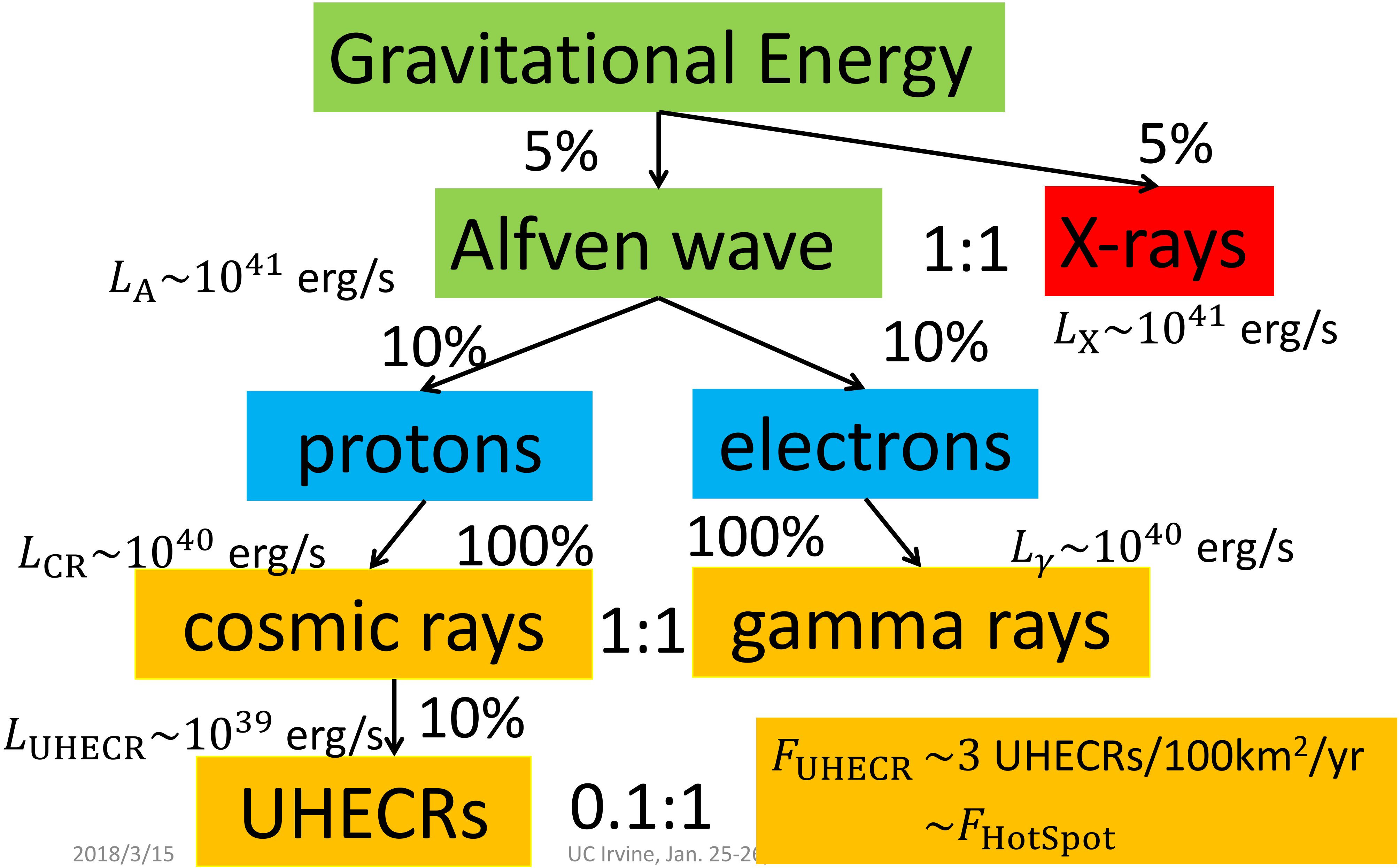
$$L_{\rm tot} = 1.3{\times}10^{38} m\dot{m}\ \ {\rm erg\,s^{-1}}$$

# Nine nearby Fermi AGNs (Sky Map)



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

# Energy Flow and Spectra (M82 X-1)



Gravitational Energy

5%

5%

Alfven wave

1:1

X-rays

$L_{\mathrm{A}} \sim 10^{41}$ erg/s

$L_{\mathrm{X}} \sim 10^{41}$ erg/s

10%

10%

protons

electrons

$L_{\mathrm{CR}} \sim 10^{40}$ erg/s

100%

100%

$L_{\gamma} \sim 10^{40}$ erg/s

cosmic rays

1:1

gamma rays

$L_{\mathrm{UHECR}} \sim 10^{39}$ erg/s

10%

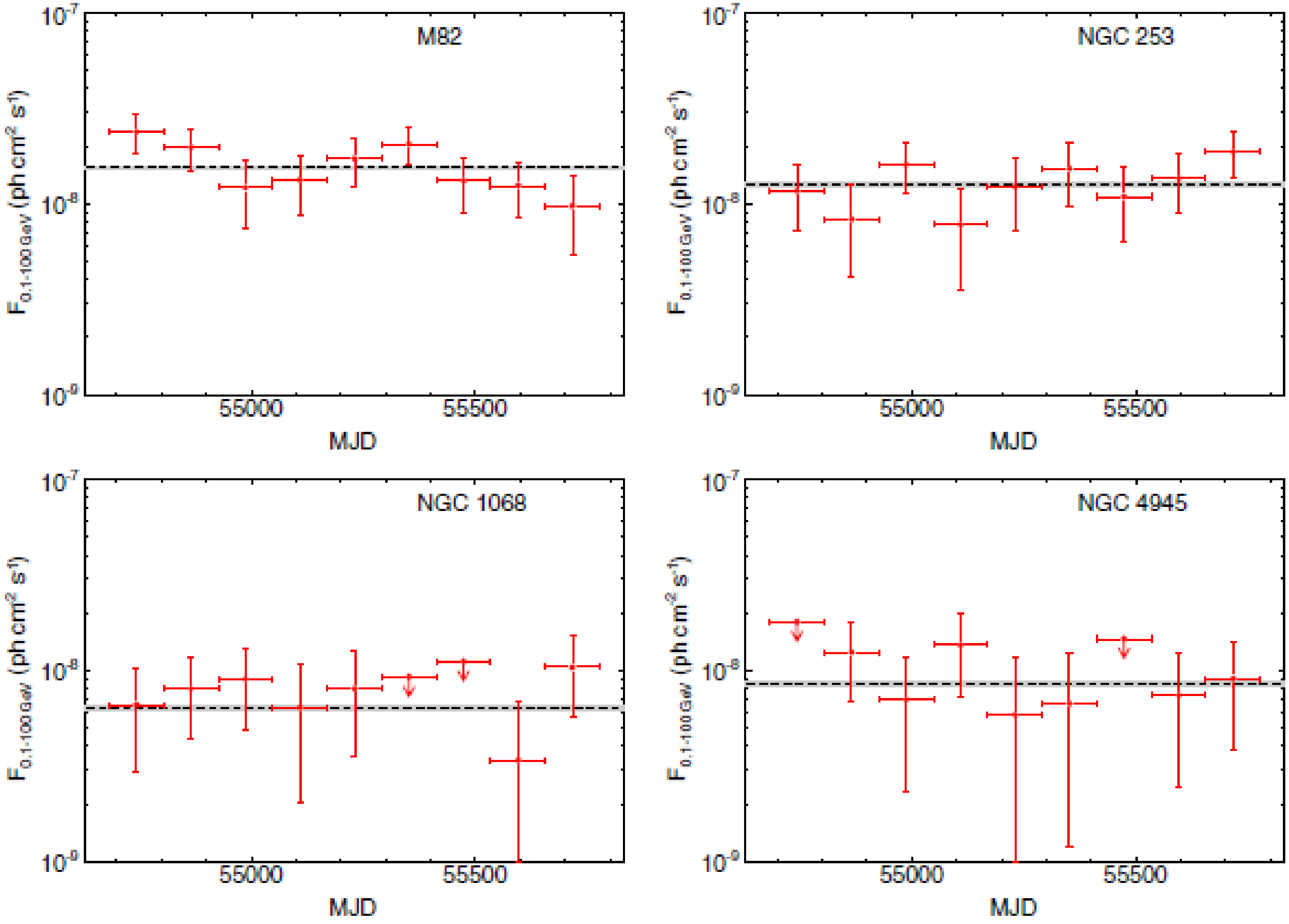
UHECRs

0.1:1

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

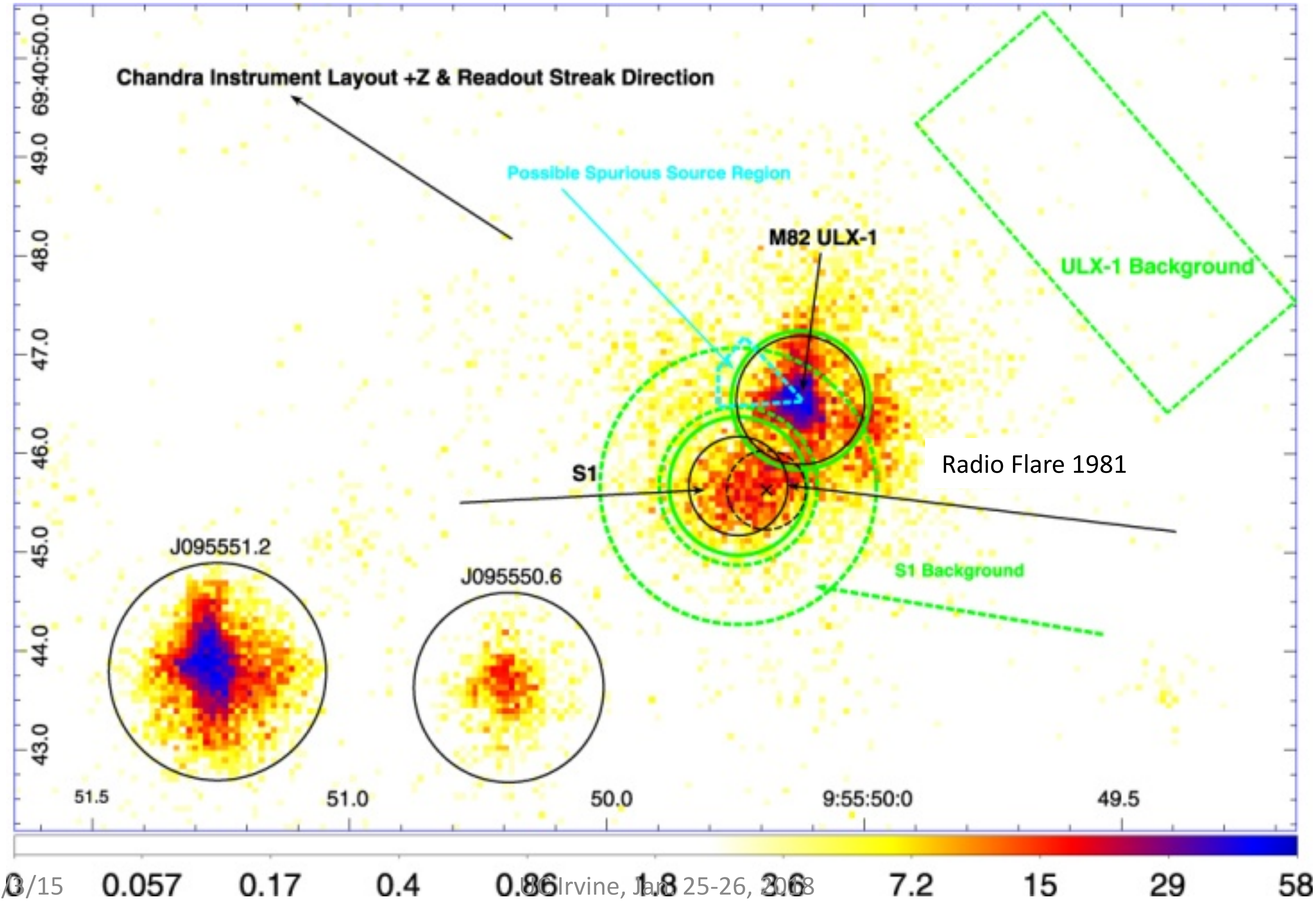
$\sim F_{\mathrm{HotSpot}}$

# Light Curves



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

Xu et al. 2015 ApJ Letters 799, L28



Radio Flare 1981

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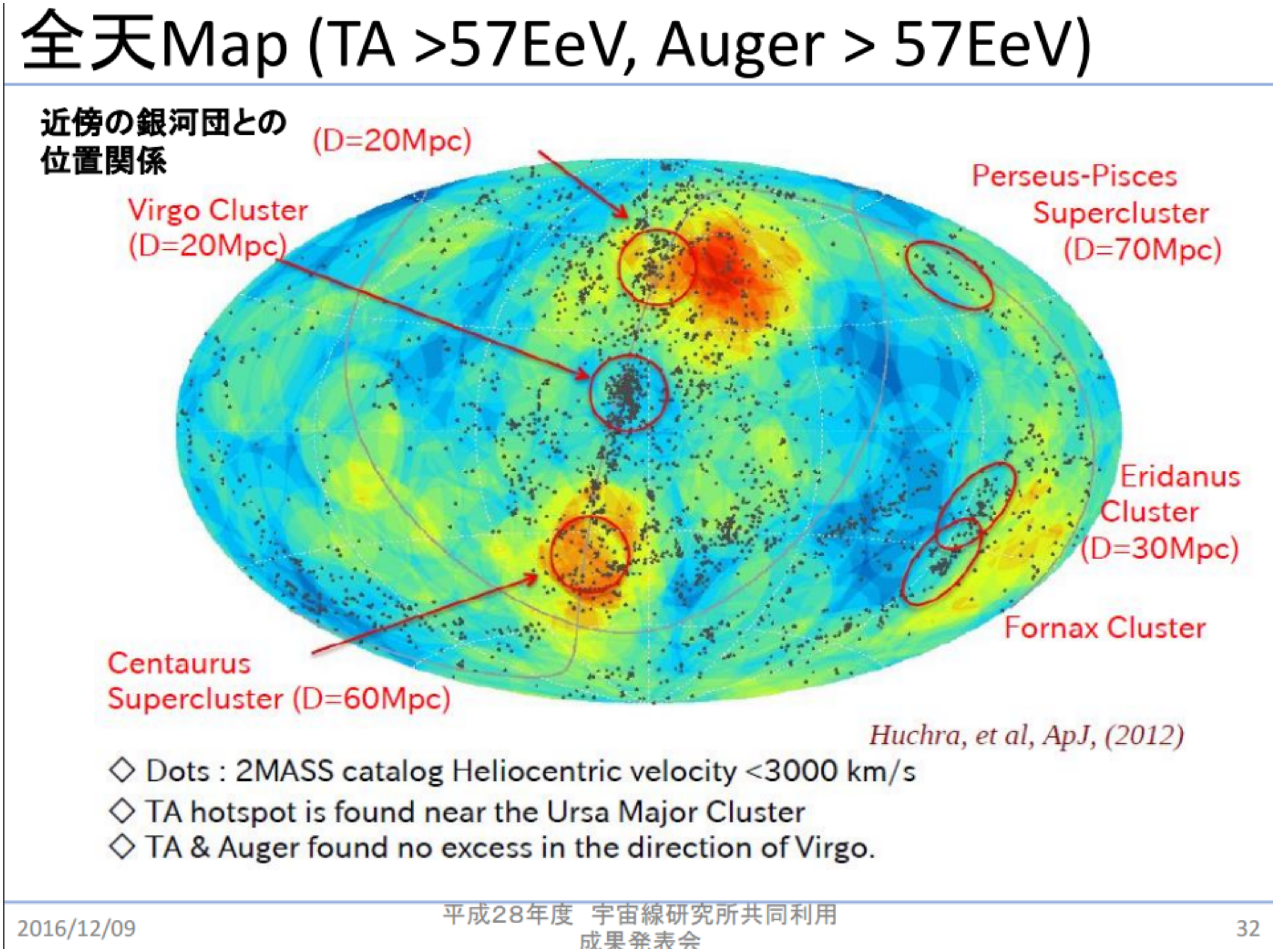

# 全天Map (TA >57EeV, Auger > 57EeV)

*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.

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# Astrophysical Implication

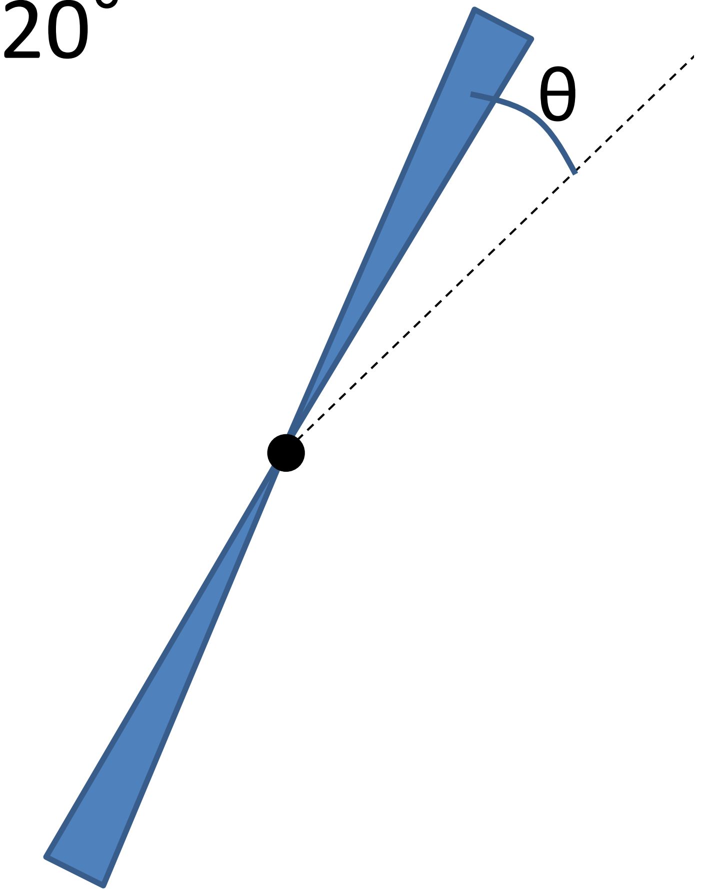
- Hot spot component came from M82
  - too near for GZK (D=3.4 Mpc)
  - mainly proton
- Magnetic deflection?
  - $B \sim 10\ \mathrm{nG}$ for $D = 3.2\ \mathrm{Mpc}$
    - $\theta = 0.5° \left(\frac{D}{\mathrm{Mpc}}\right)\left(\frac{B}{\mathrm{nG}}\right) \sim 17.4°$
    - $\Delta\theta = 0.36 \left(\frac{D}{\mathrm{Mpc}}\right)^{1/2}\left(\frac{D_\mathrm{c}}{\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

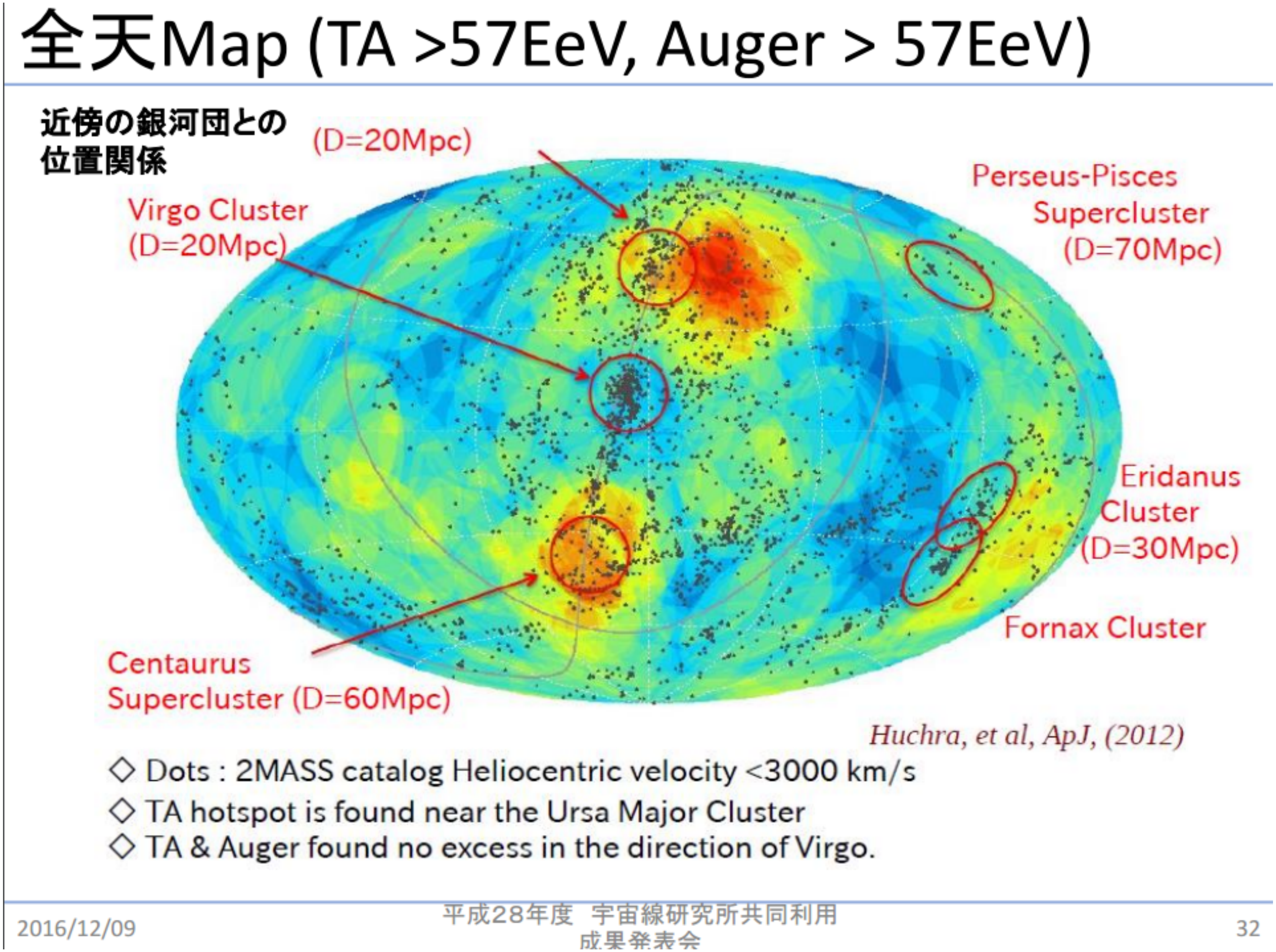
# UHECR emission: Beaming?

- 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





# 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.

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

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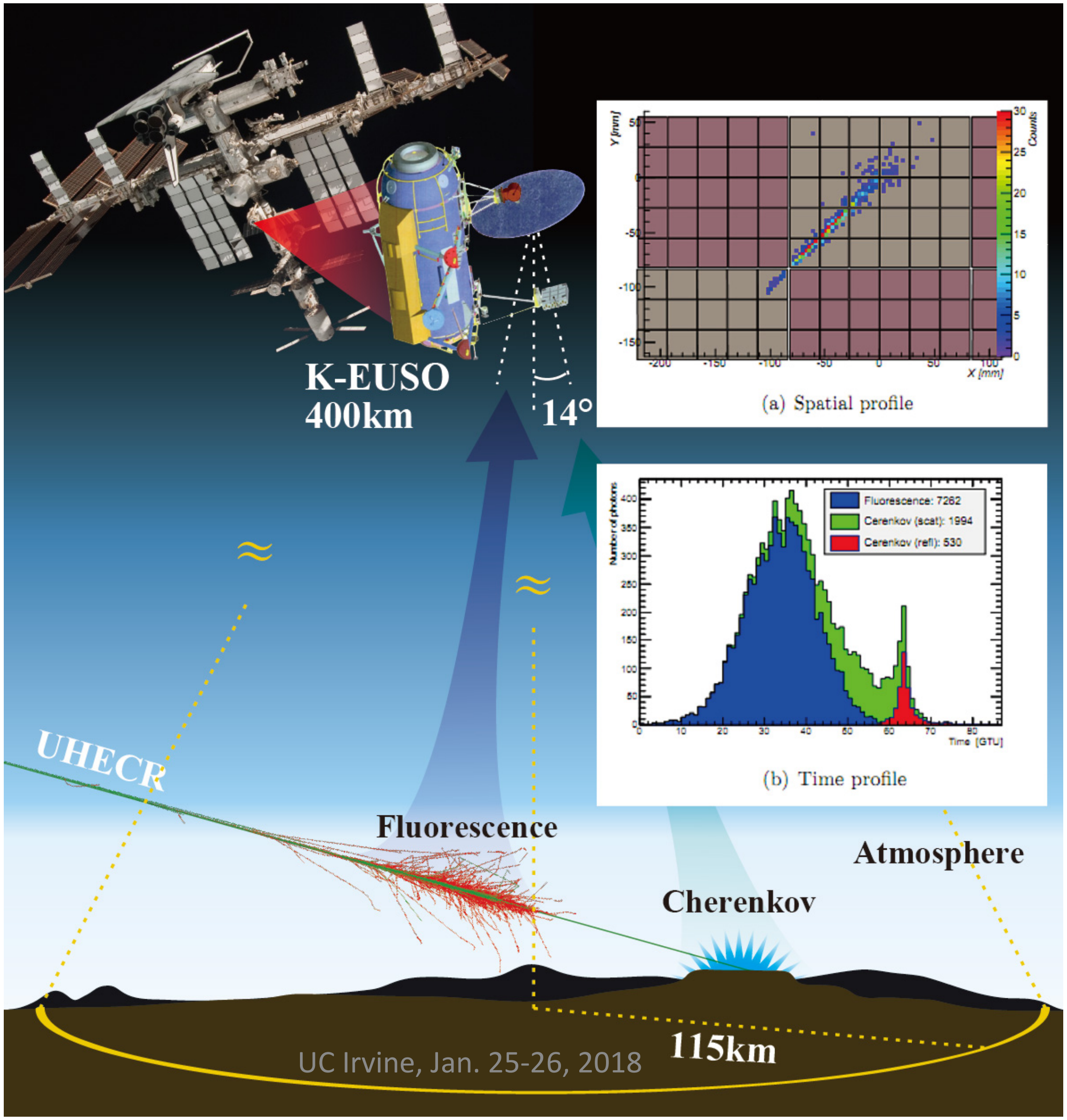
# 5. K-EUSO



(a) Spatial profile

(b) Time profile

# Science of K-EUSO

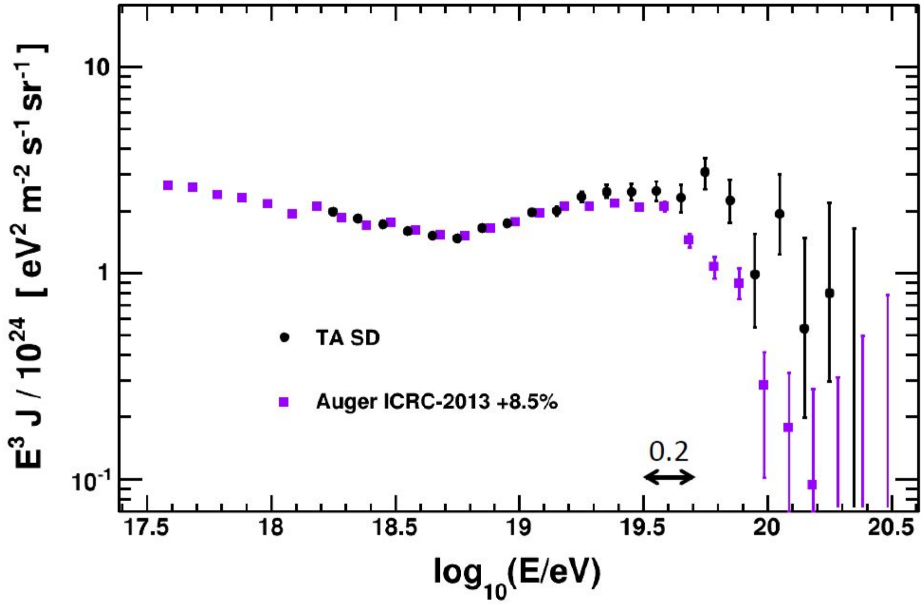
. Study of UHECR flux from space with uniform response

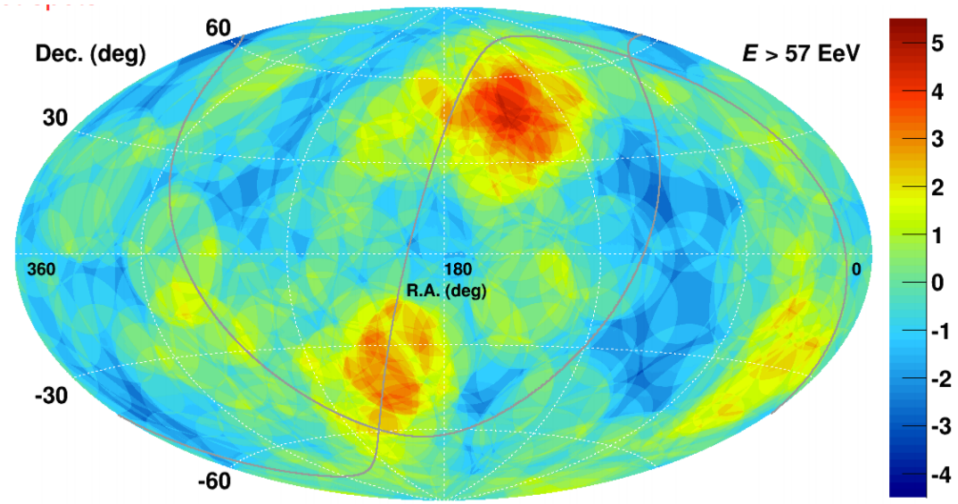
2. flux E>3 $10^{19}$ eV north & south

3. Anysotropy

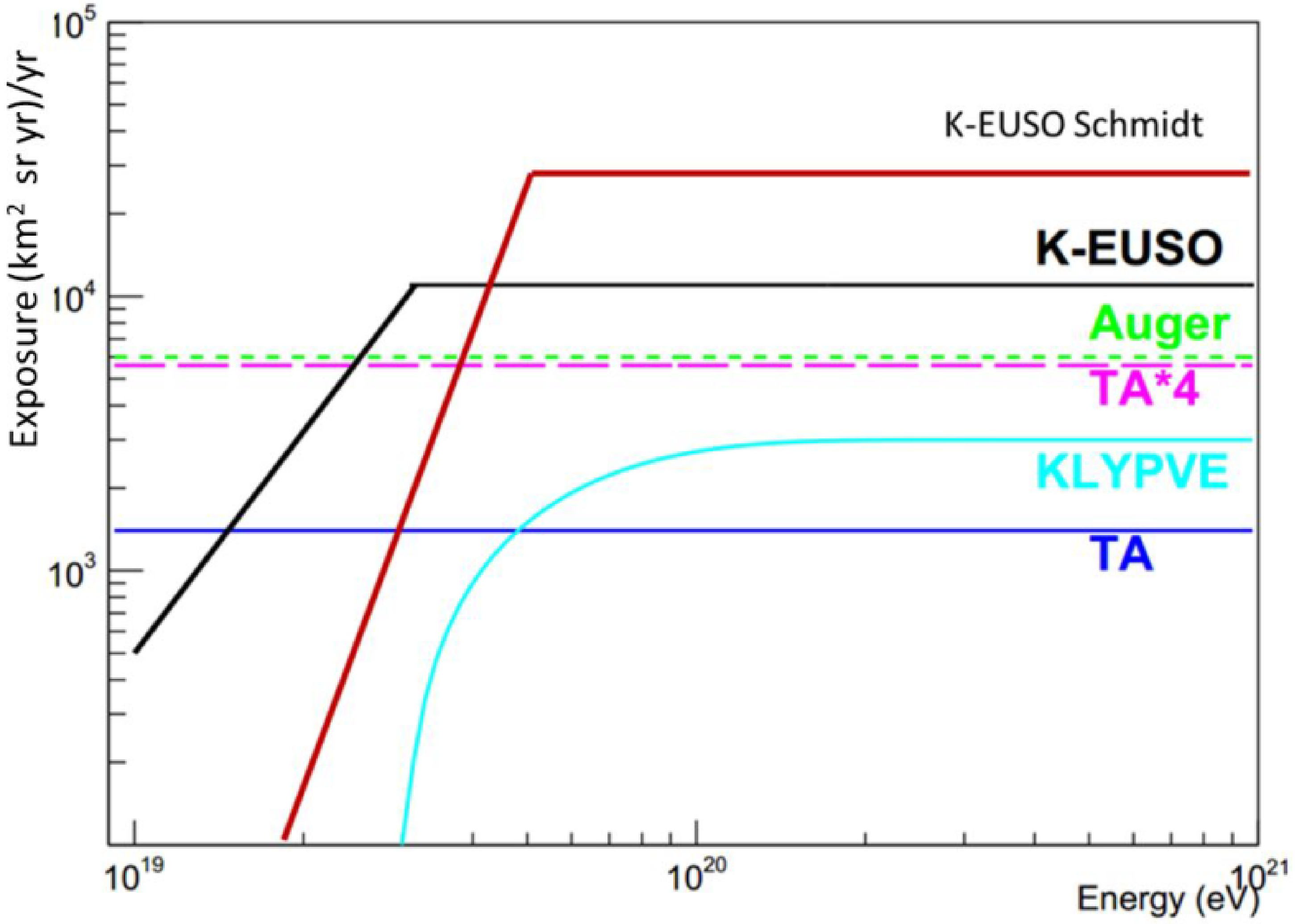
4. Earth observations, bioluminescence

5. Debris tracking and removal



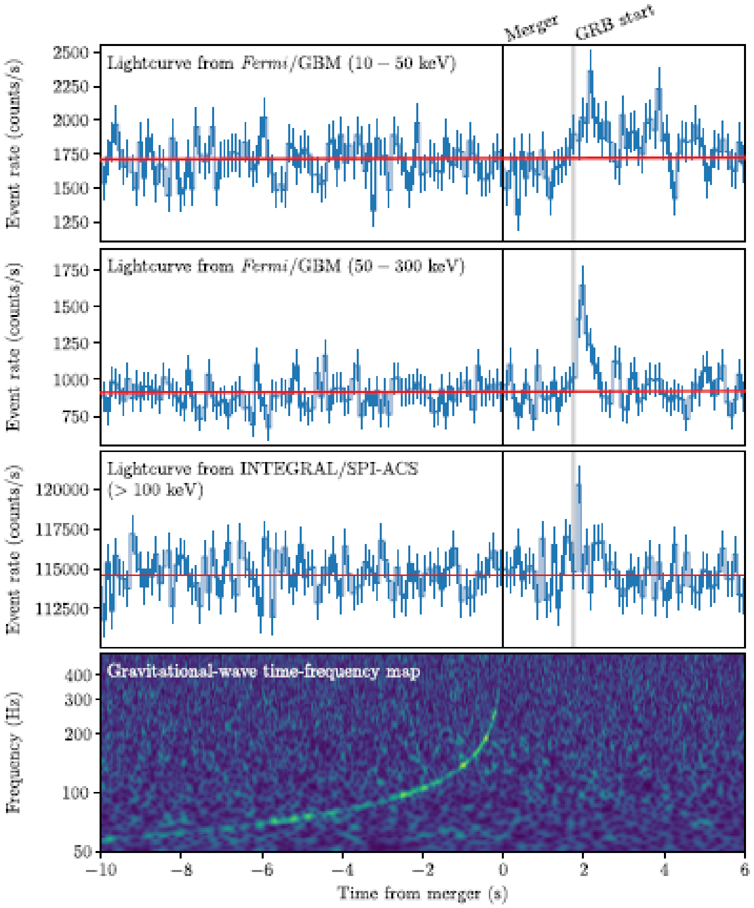


# K-EUSO exposure



# contents

# NS-NS merger/GW burst
# GW170817

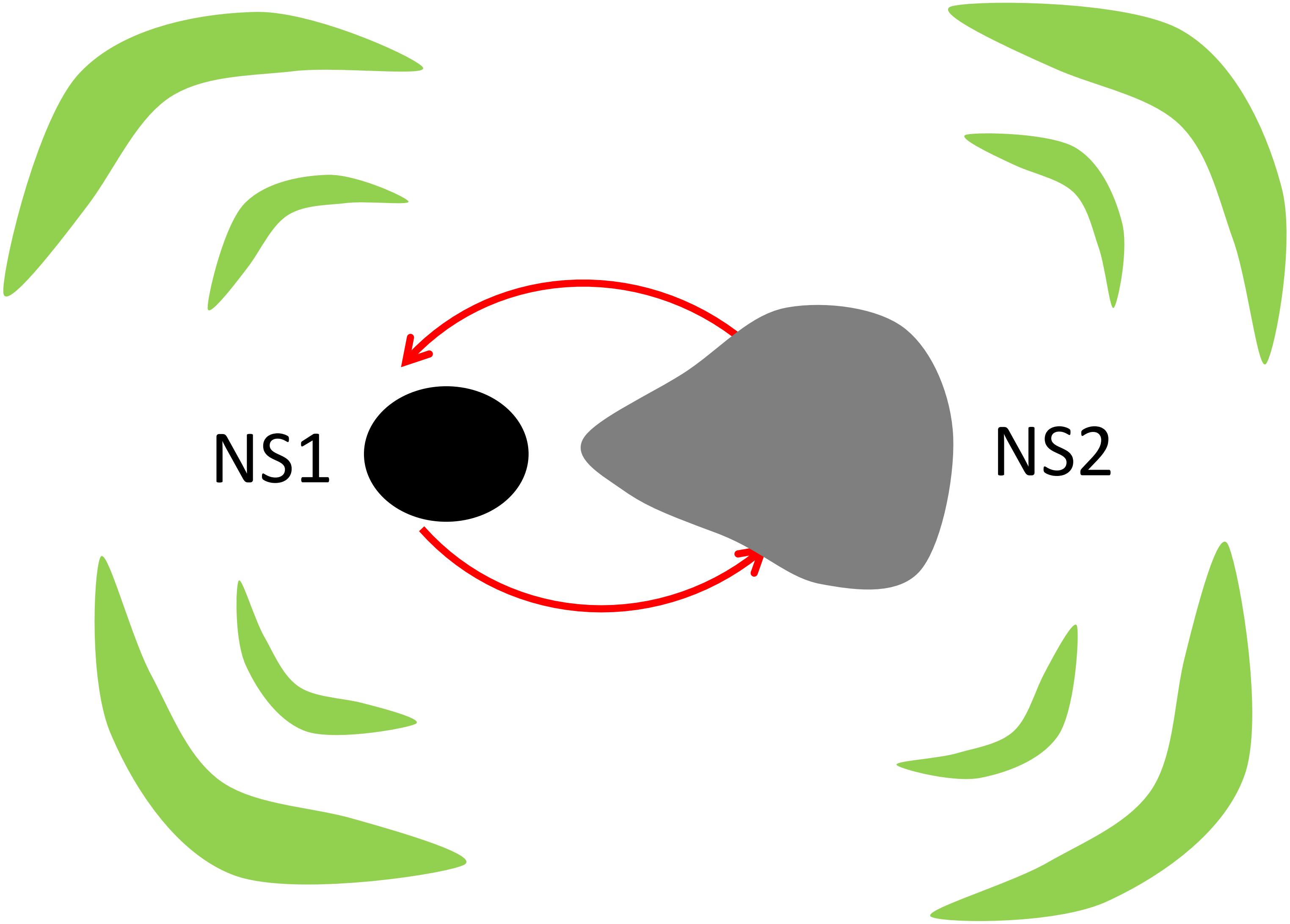


- 1.7 seconds delay in gamma-rays
- Lorentz invariance test:

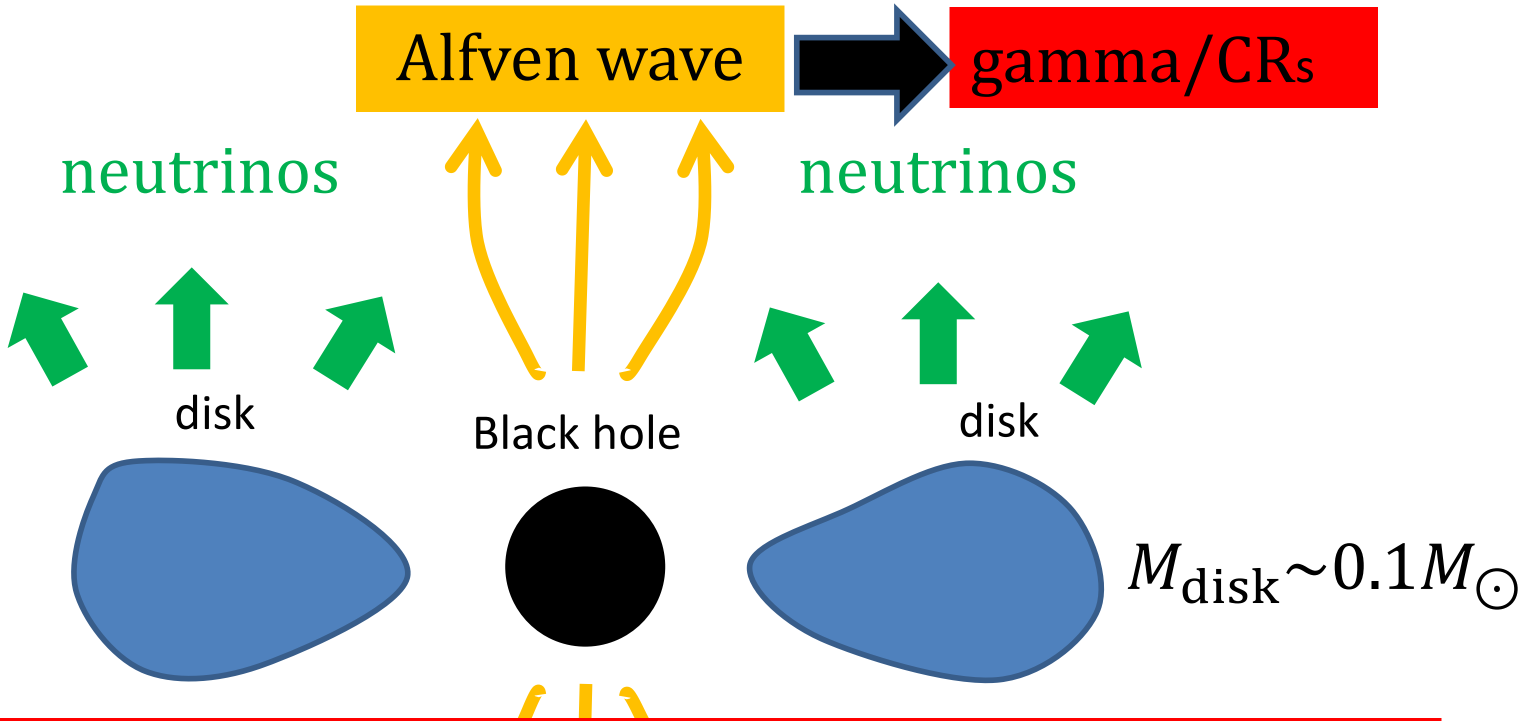
$$-3\times10^{-15}$$
$$+7\times10^{-16}$$

times of speed of light between GW and photons

# NS-NS merger→ GW burst



# NS-NS merger→BH + Disk



Alfven wave → gamma/CRs

neutrinos

neutrinos

disk

Black hole

disk

$M_{\text{disk}} \sim 0.1 M_{\odot}$

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

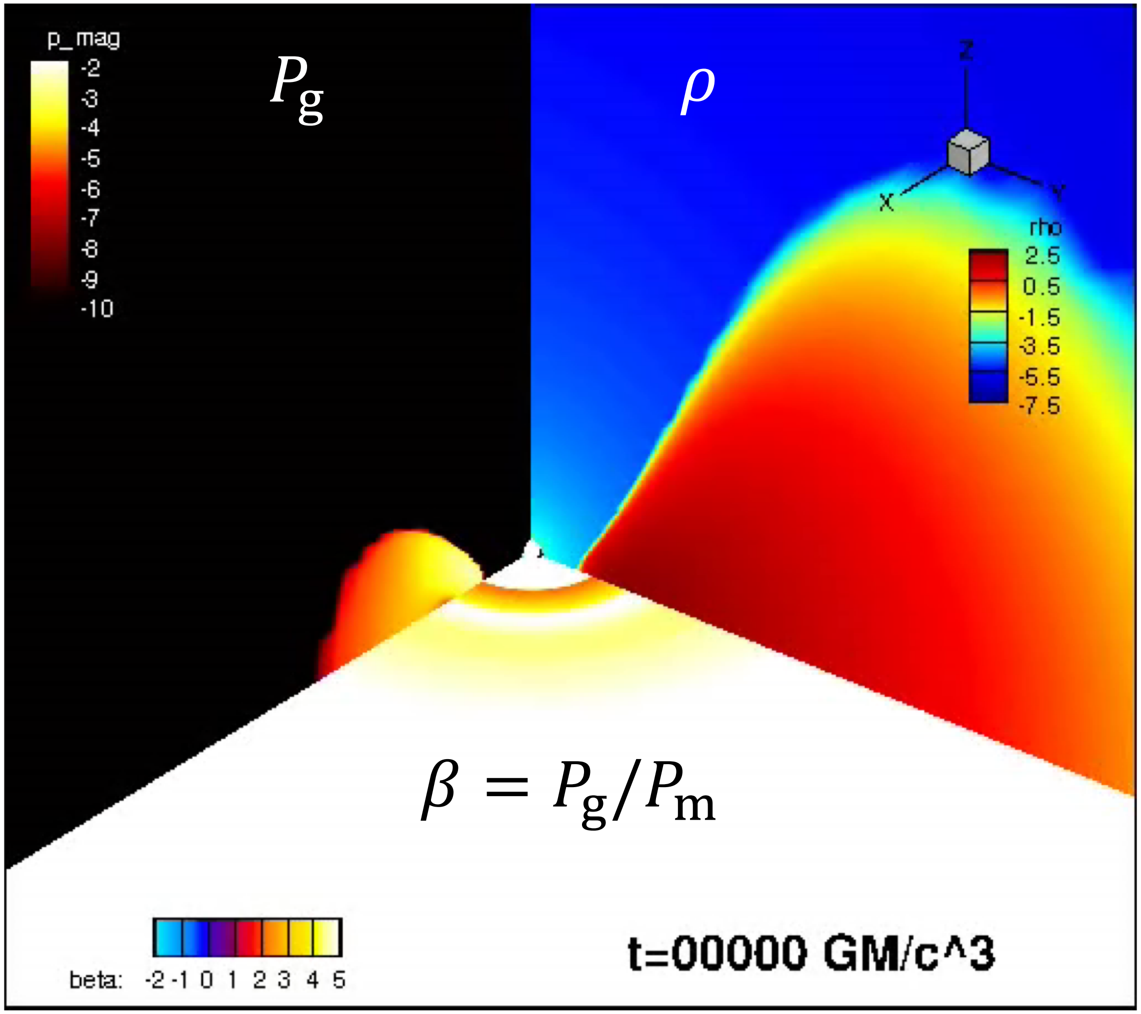
Central Engine of GRB/Hypernova

Alfven wave

# Conclusions

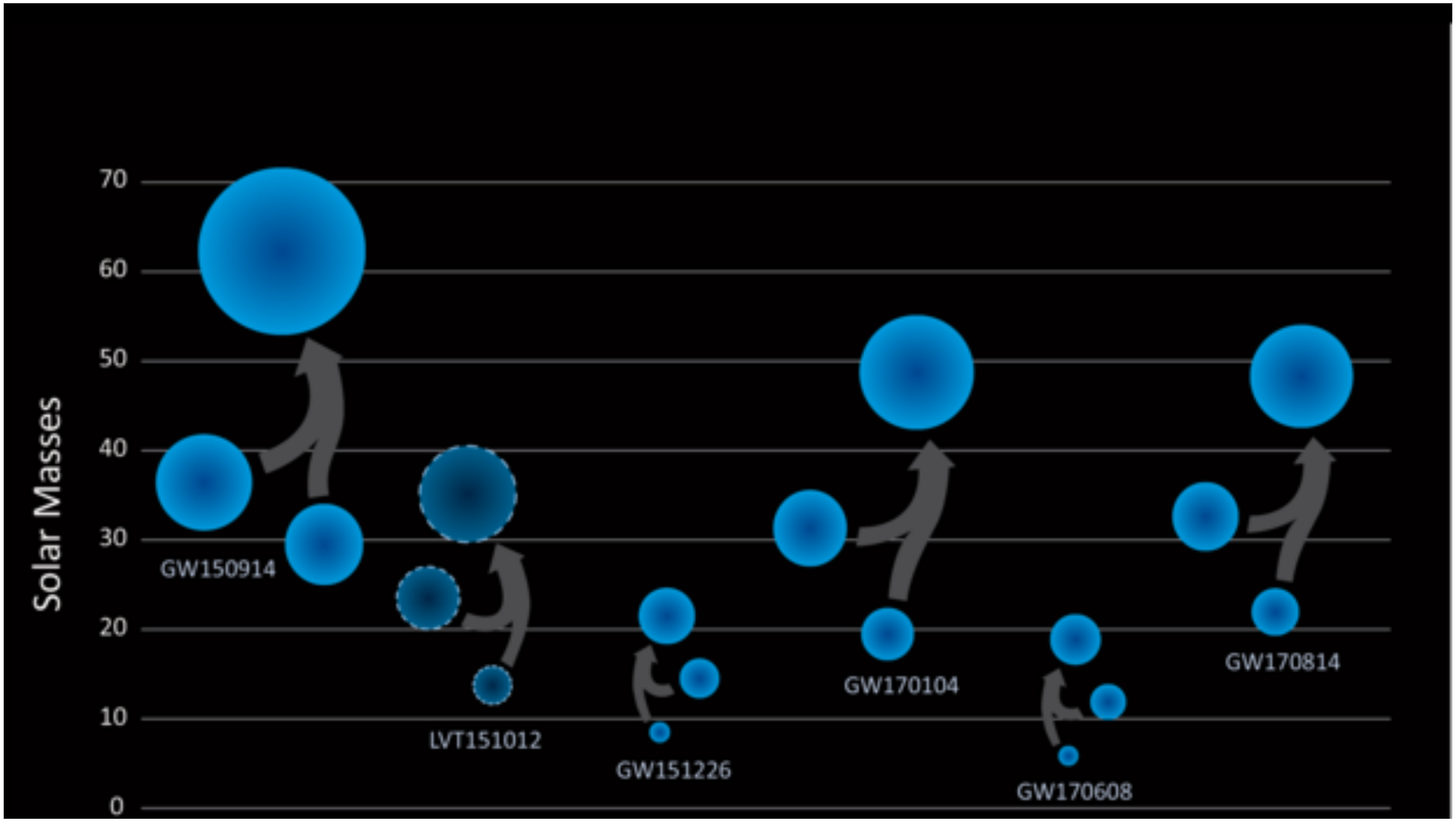
- **M82: the nearest starburst galaxy**
  - M82 X-1: Intermediate Mass Blackholes ($10^2$-$10^4$ Ms)
    =**possible origin of the northern hot spot**
- **Bow Wake Acceleration**
  - Accreting BH+disk+jet
    = **Astronomical Linear Accelerator**
  - Bursts of Intense Alfven waves ←Laser
  - Jet ←wave guide
- Bending by magnetic field
  - **$\mathbf{B \sim 10nG}$ in the cosmic filaments of local supercluster**
  - Study of **supercluster magnetic field**
- **K-EUSO**
  - Confirmation of south-north anisotropy
  - Identification of M82 and other sources
- GW burst from NS-NS merger: GW170817
  - BH+accretion disk→Alfven burst of $10^{52}$ erg/s
  - →Central engine of the entire GRB/Hypernova

# 3-D relativistic MHD simulation see our poster



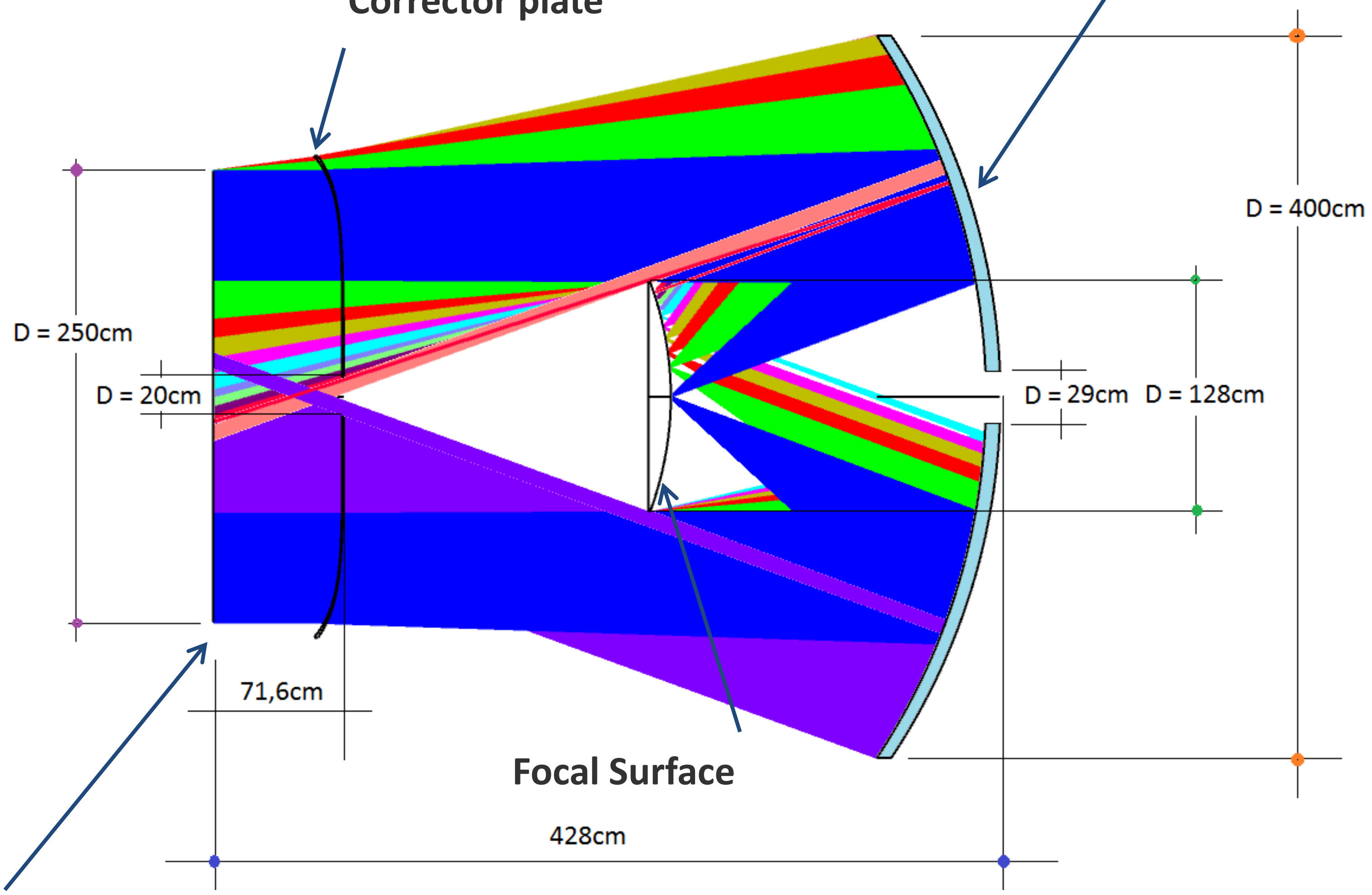
A. Mizuta et al. 2016

# Back up


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

# ADVANCED SCHMIDT OPTICAL DESIGN LAYOUT

INO-CNR
Istituto
Nazionale di
Ottica



**Spherical mirror**

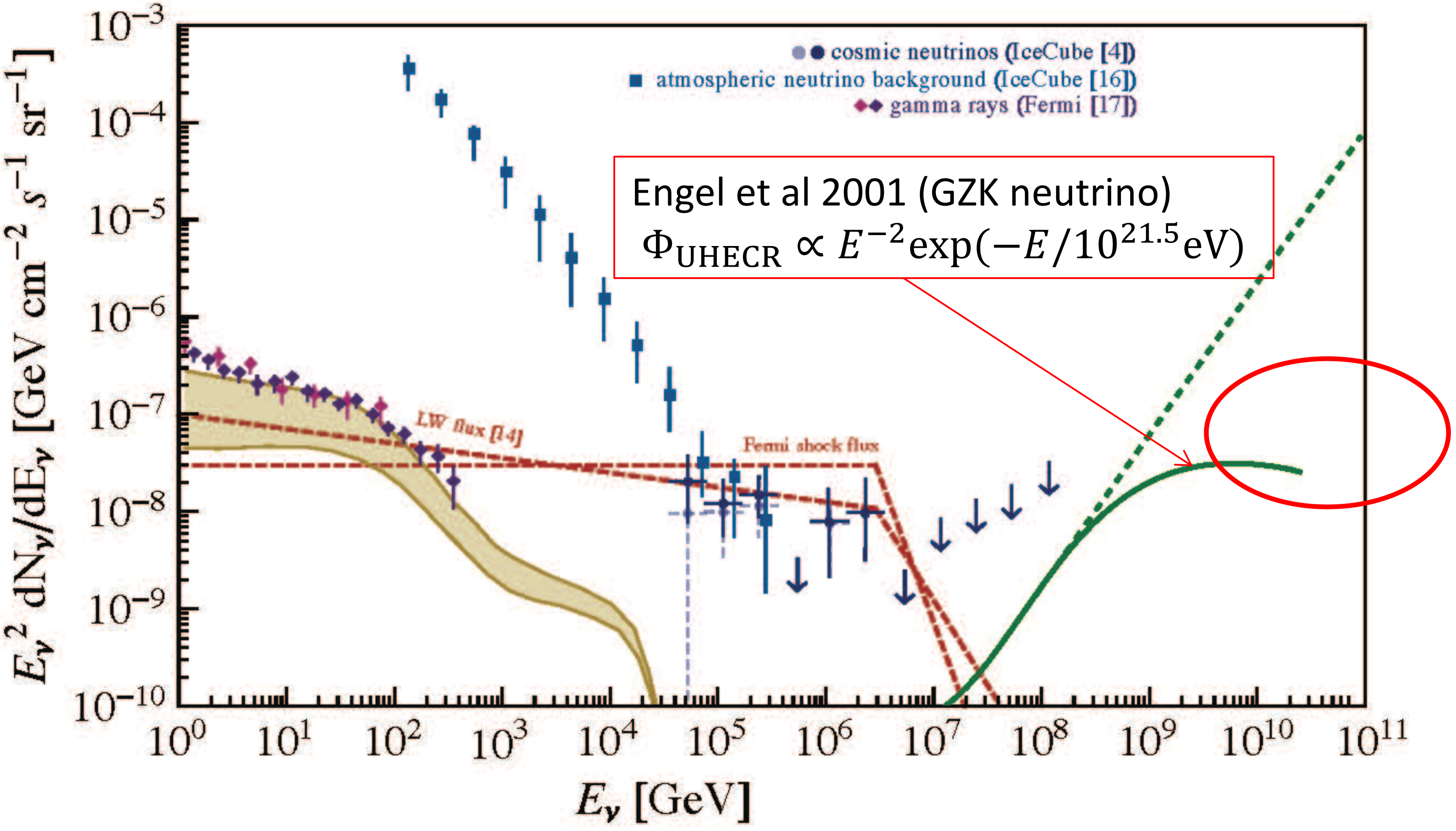
**Corrector plate**

**Focal Surface**

**Entrance aperture**

***Double Donut Schmidt Camera*** (named by P. Mazzinghi)

# Neutrino and gamma ray flux



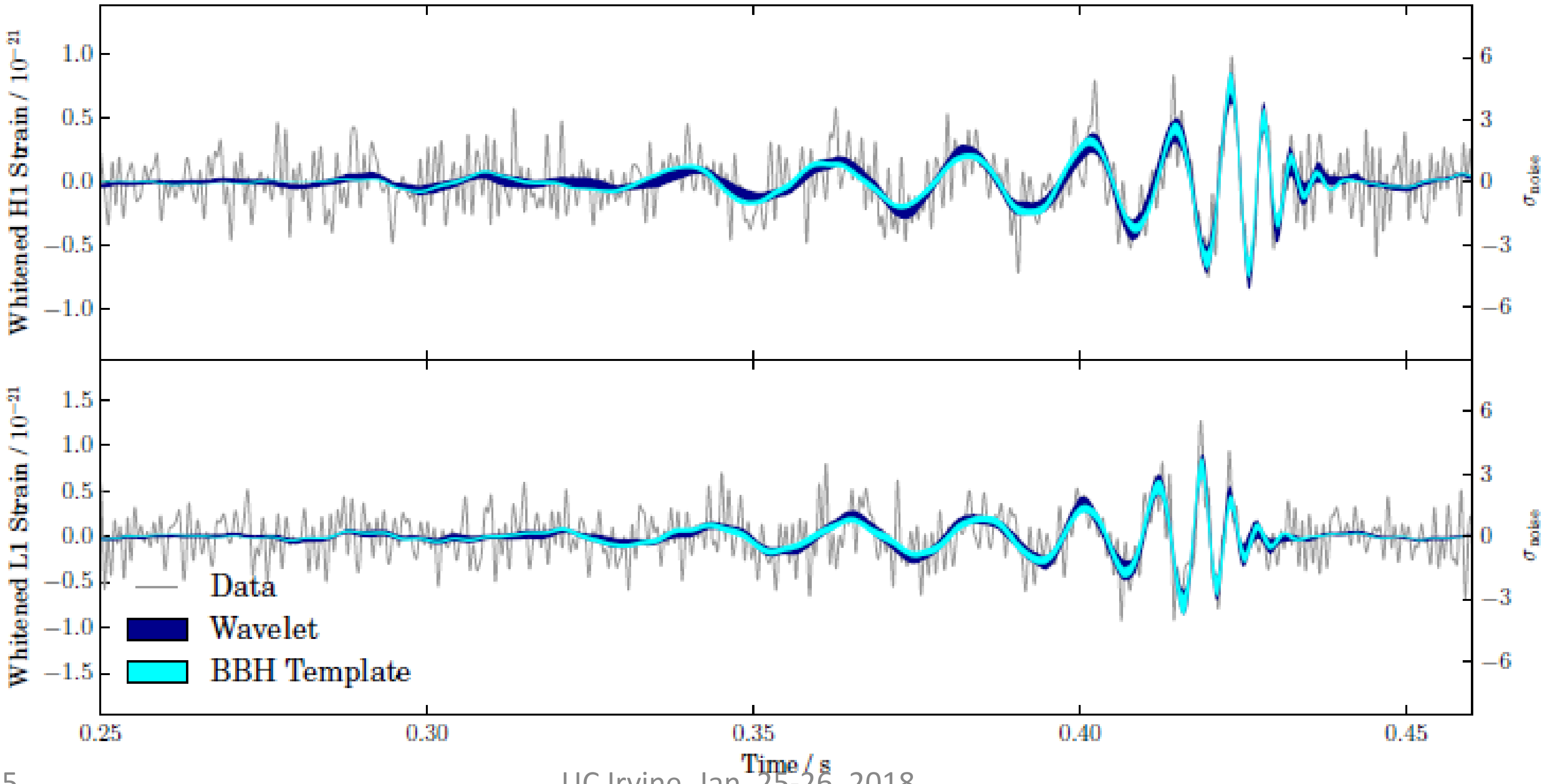
Engel et al 2001 (GZK neutrino)

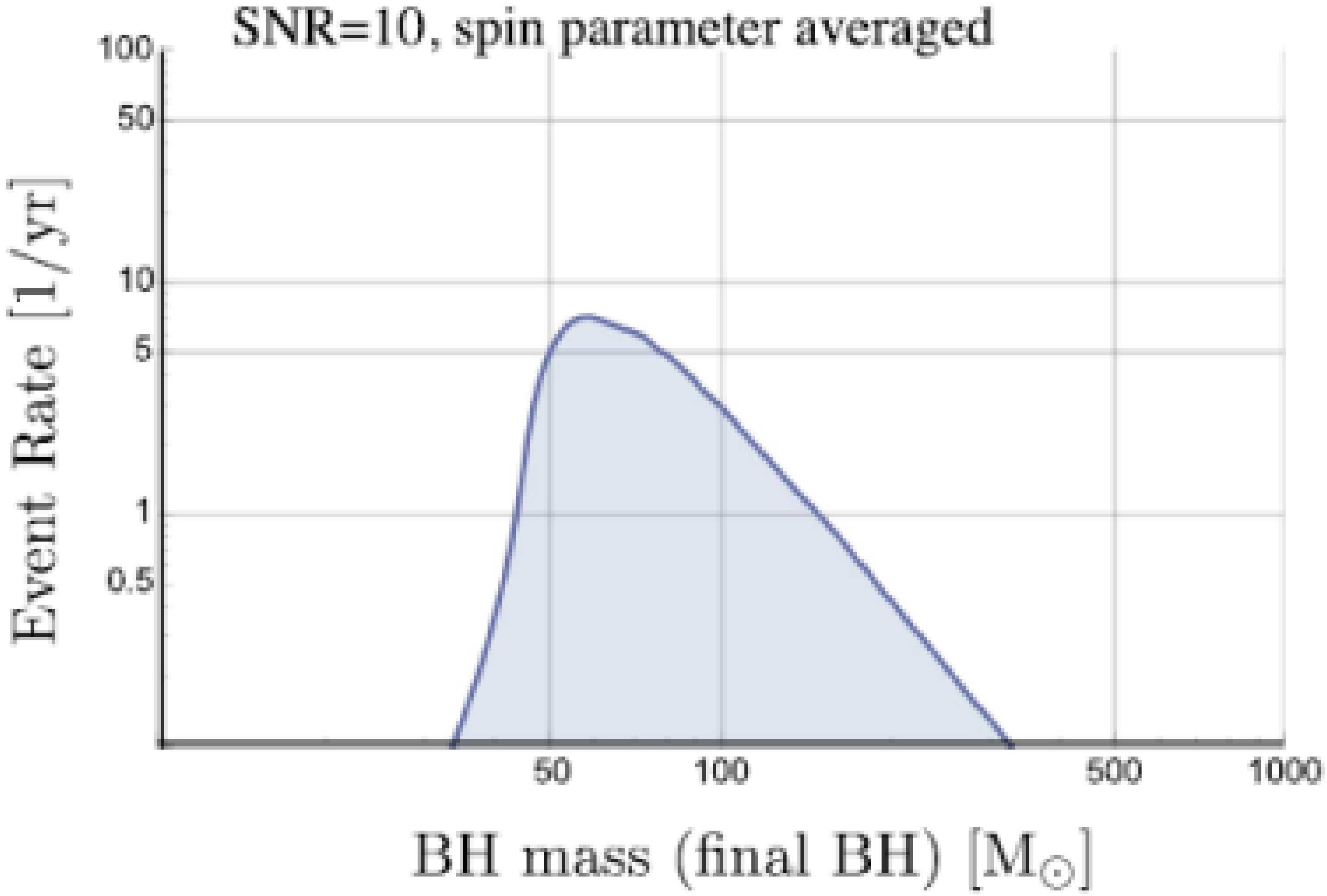
$\Phi_{\mathrm{UHECR}} \propto E^{-2}\exp(-E/10^{21.5}\mathrm{eV})$

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

# GW150914

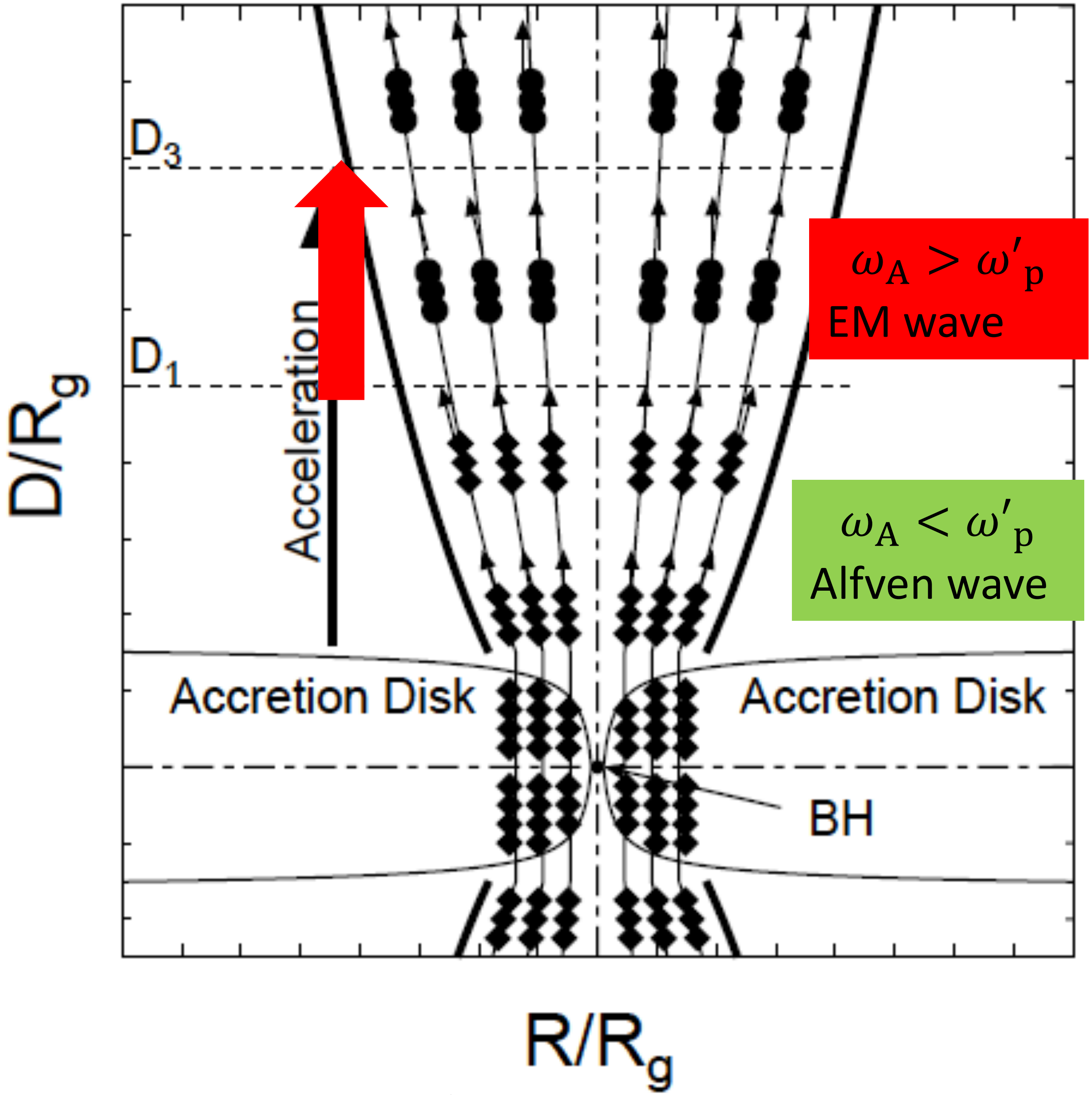
- Merging of Binary BH: 36Ms+29Ms
- Distance：410 Mpc=0.410 Gpc (Z=0.09)





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

# Jet

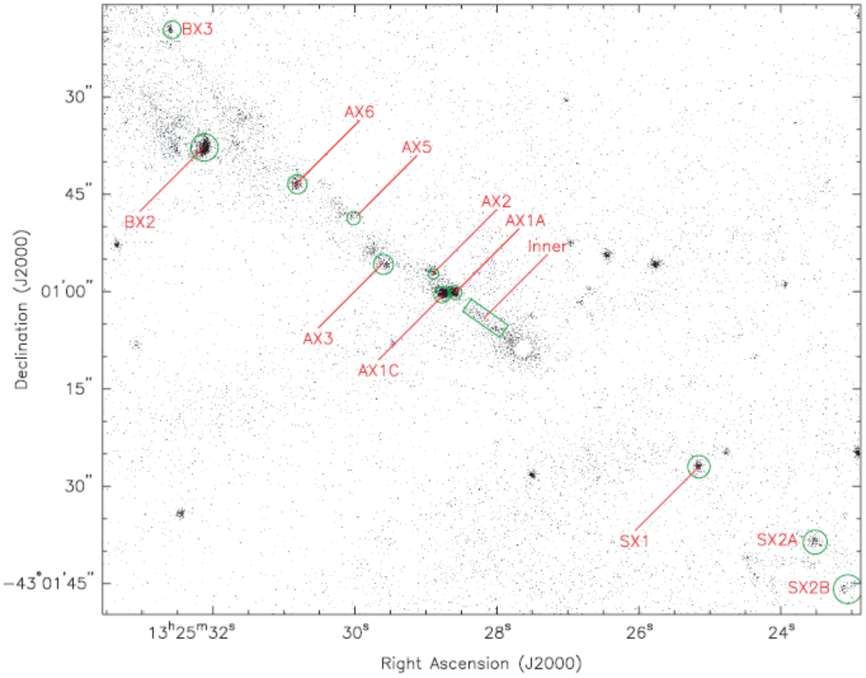


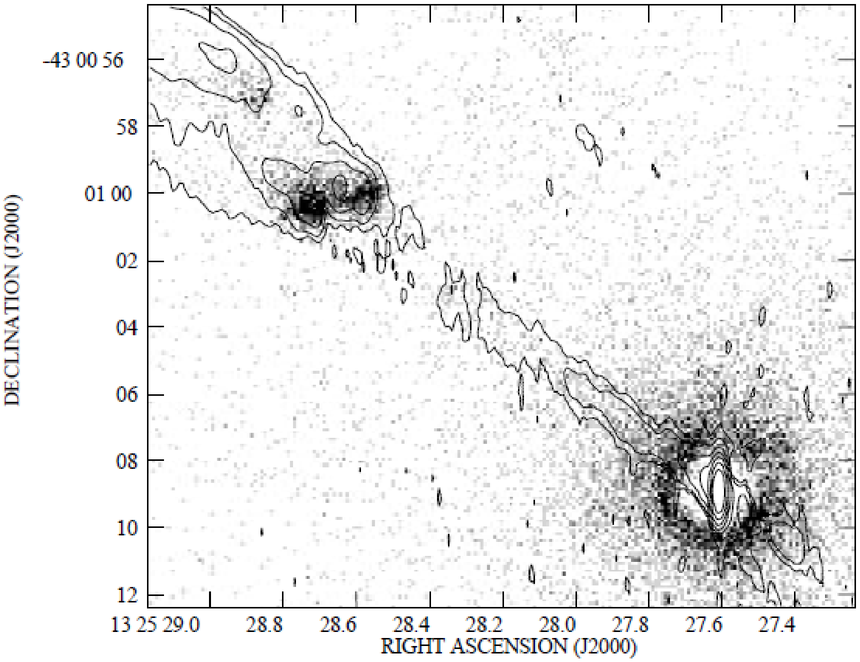
$\omega_{\mathrm{A}} > \omega'_{\mathrm{p}}$
EM wave

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

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

Hardcastle et al. 2003, ApJ 903 160-183





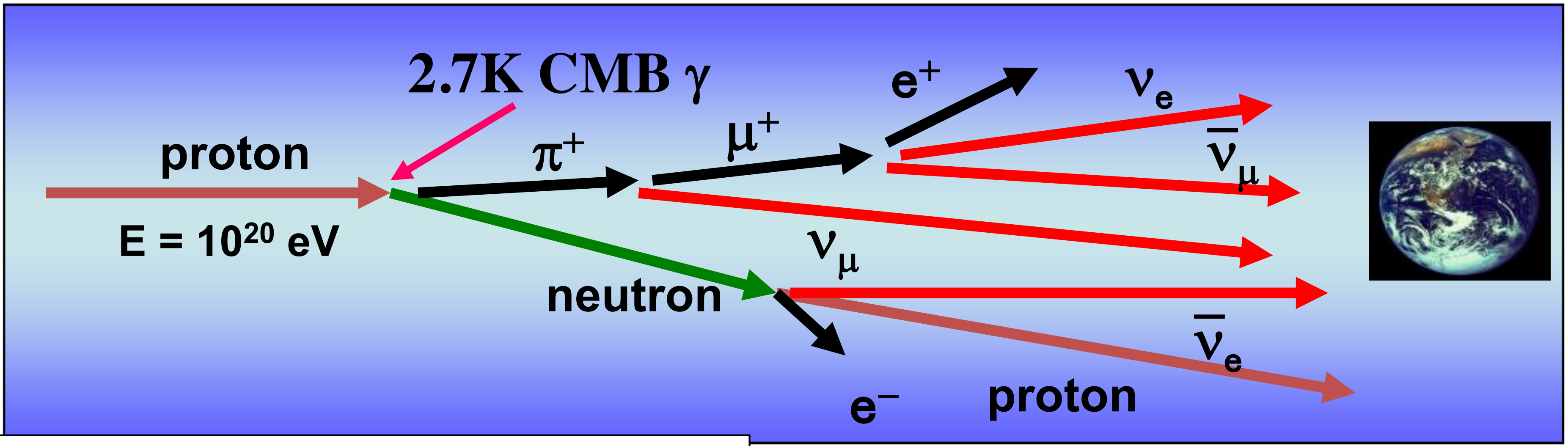
Wolf-Rayet Stars in the Jets?

effective CNO supply? ()

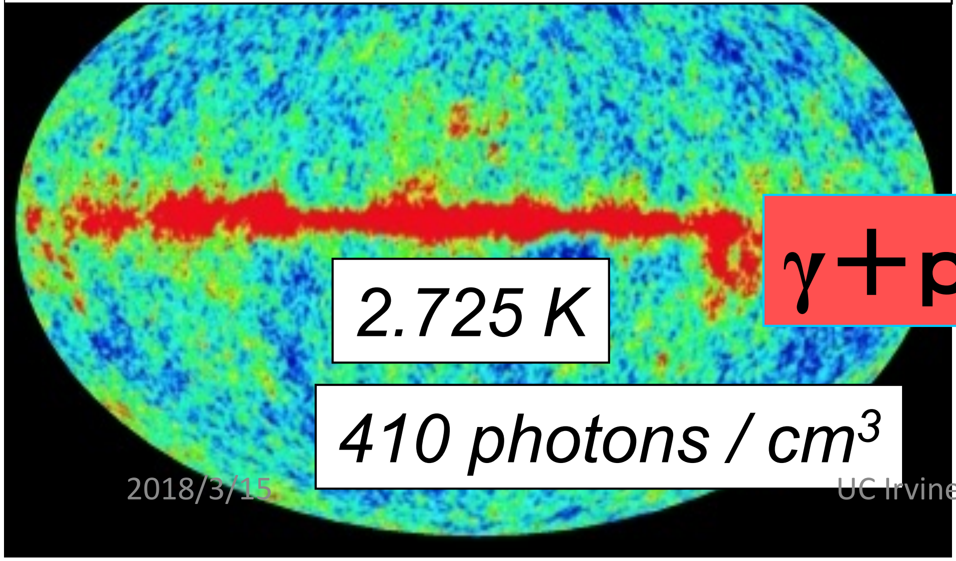
# How about neutrinos?

Greisen-Zatsepin-Kuz'min Process

Greisen1966; Zatsepin and Kuz'min1966

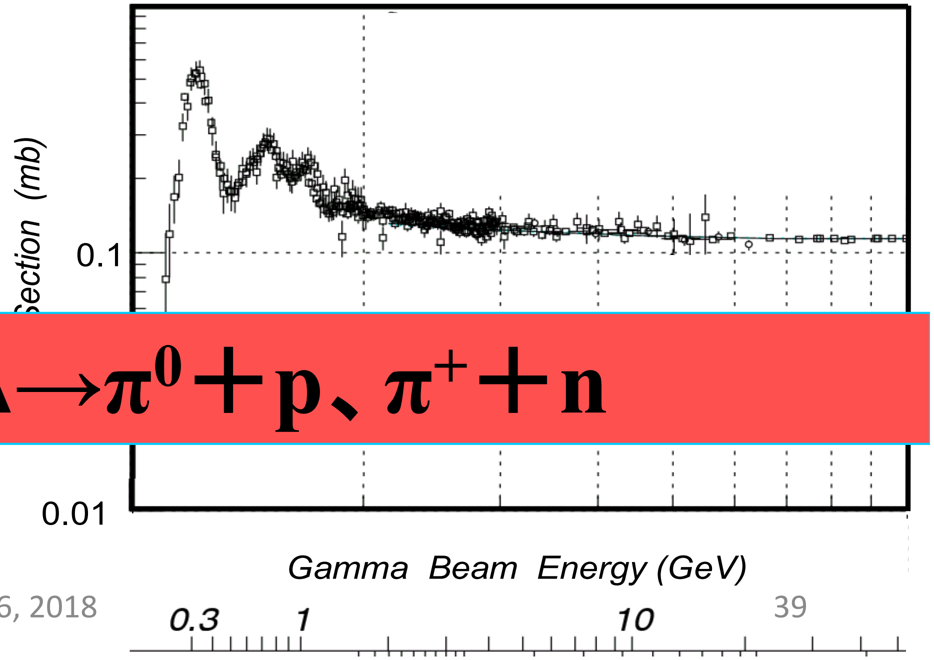


**Microwave Cosmic Background Radiation**



2.725 K

410 photons / $cm^3$

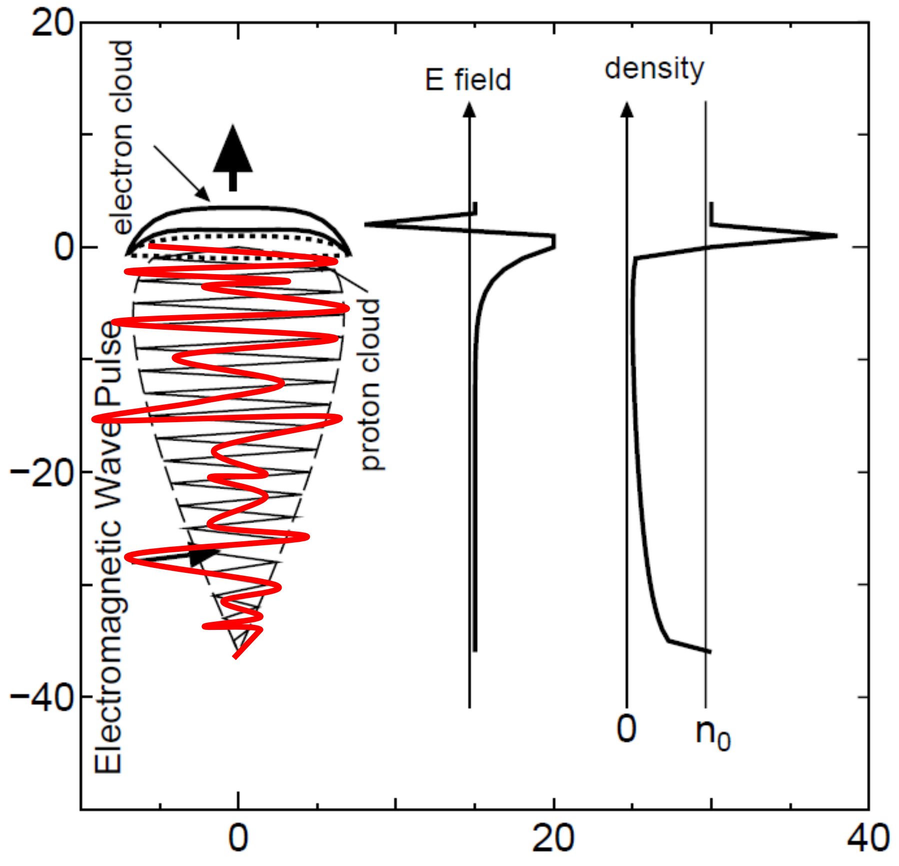


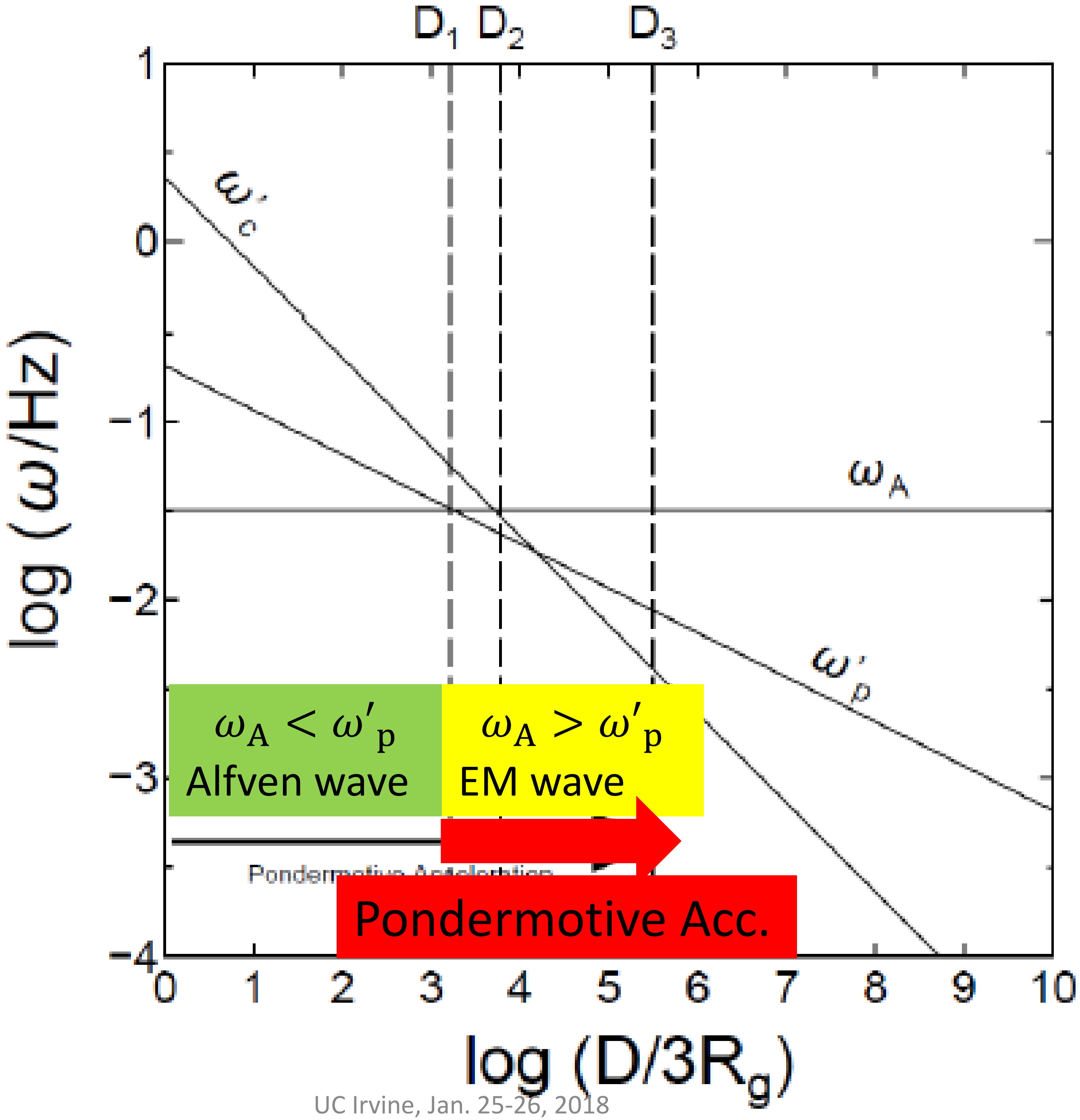
$\gamma + p \rightarrow \Delta \rightarrow \pi^0 + p$、$\pi^+ + n$

# Relativistic coherence

- Extremely relativistic

  →freezing-out





$\omega_A < \omega'_p$

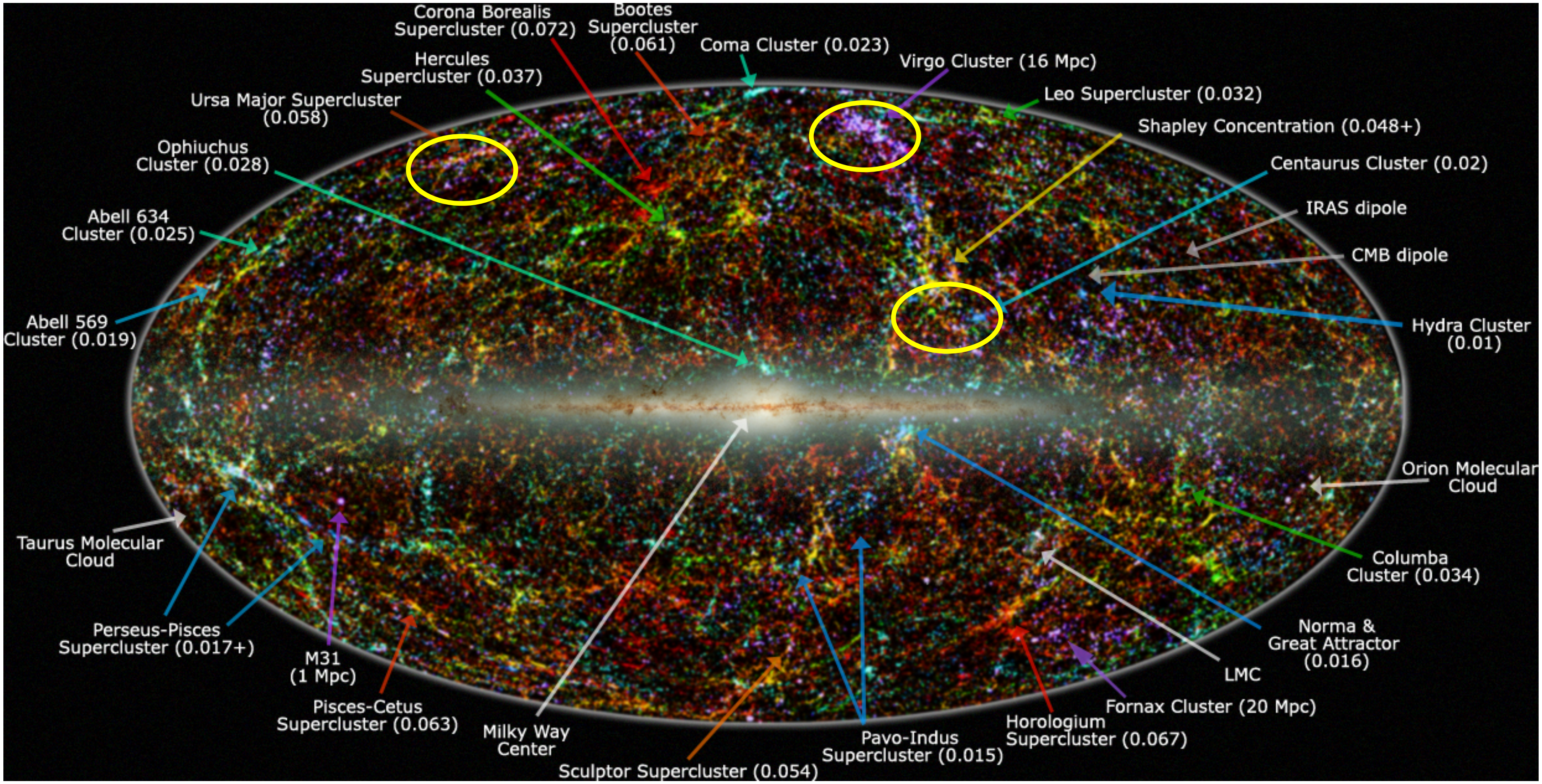
Alfven wave

$\omega_A > \omega'_p$

EM wave

Pondermotive Acc.

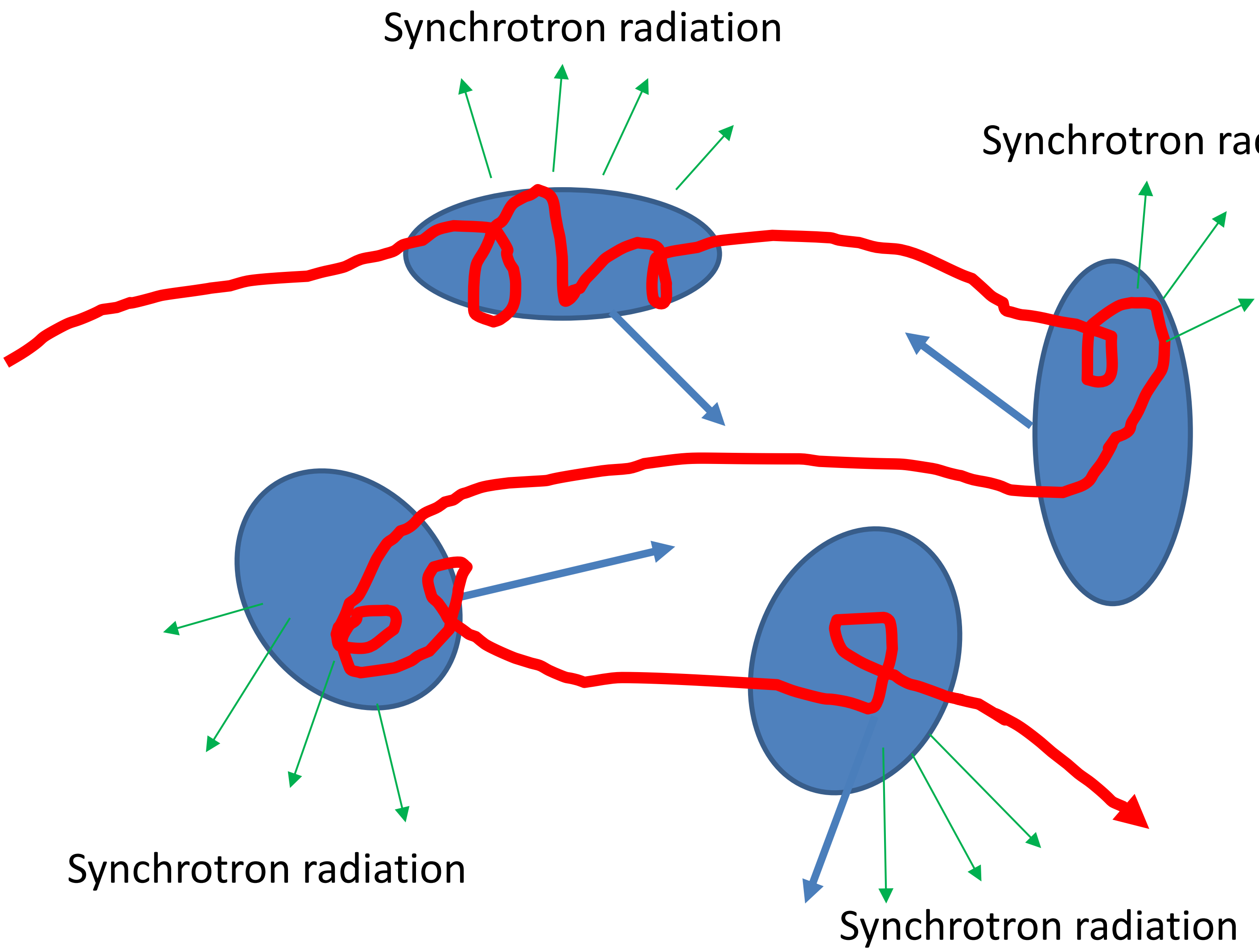
# 2MASS galaxy distribution



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

# Fermi mechanism

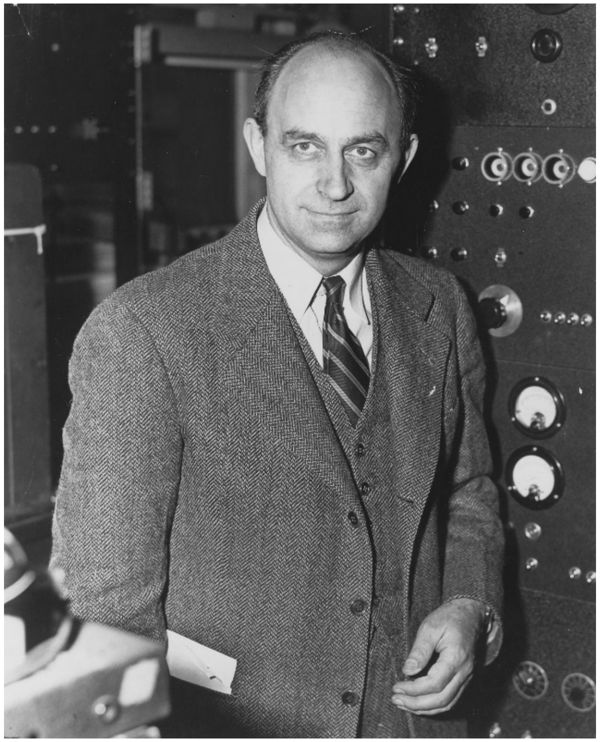
## requires bending→synchrotron loss


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

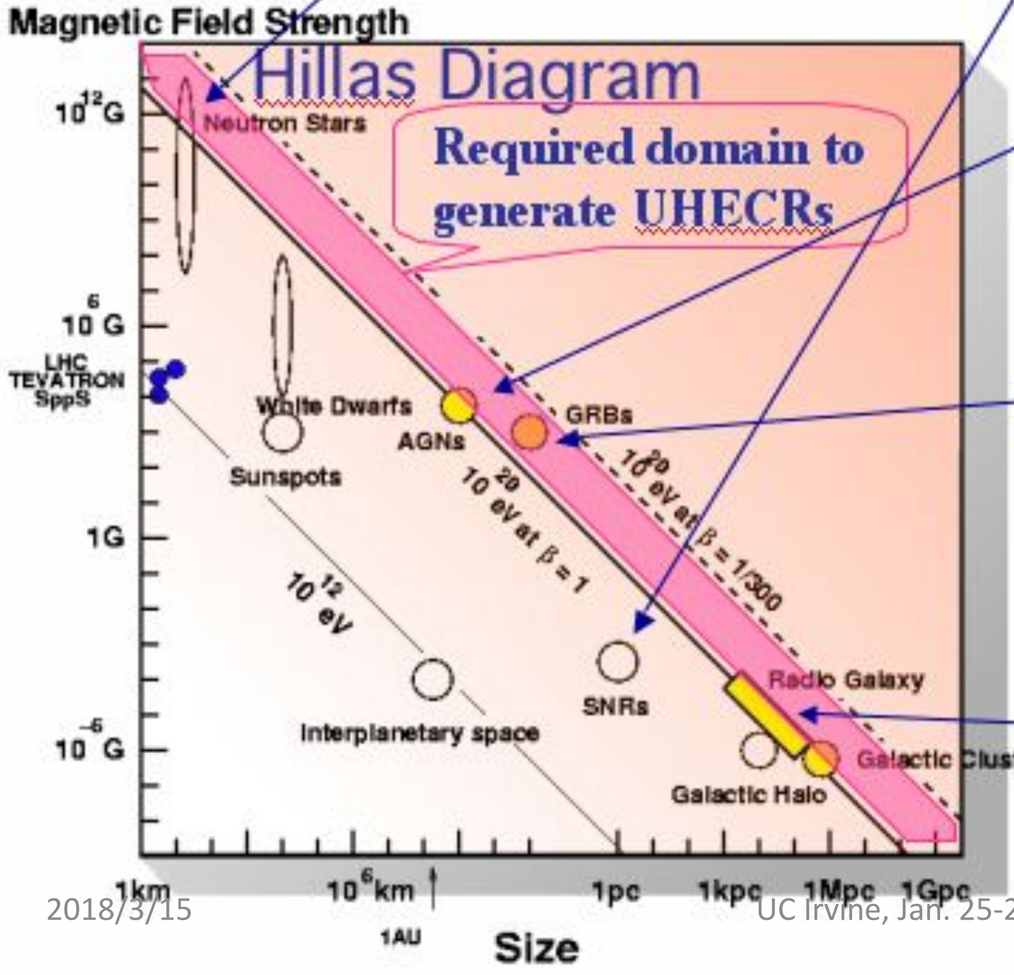
1. Bending is inevitable

    →synchrotron loss

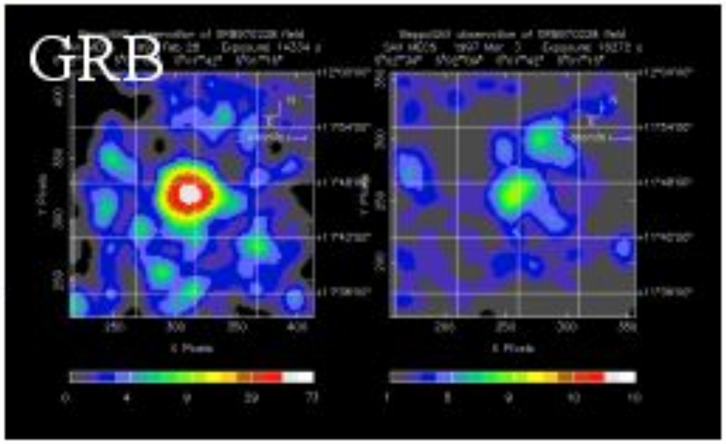
2. Confinement is difficult

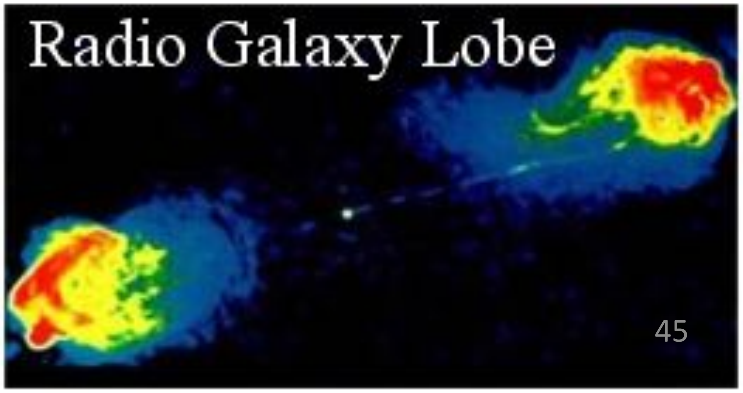
    →no acceleration

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


Hillas Diagram

Required domain to generate UHECRs





# Difficulties of Fermi acceleration in UHECR

1. Bending is inevitable

   →synchrotron loss

2. Confinement is difficult

   →no acceleration

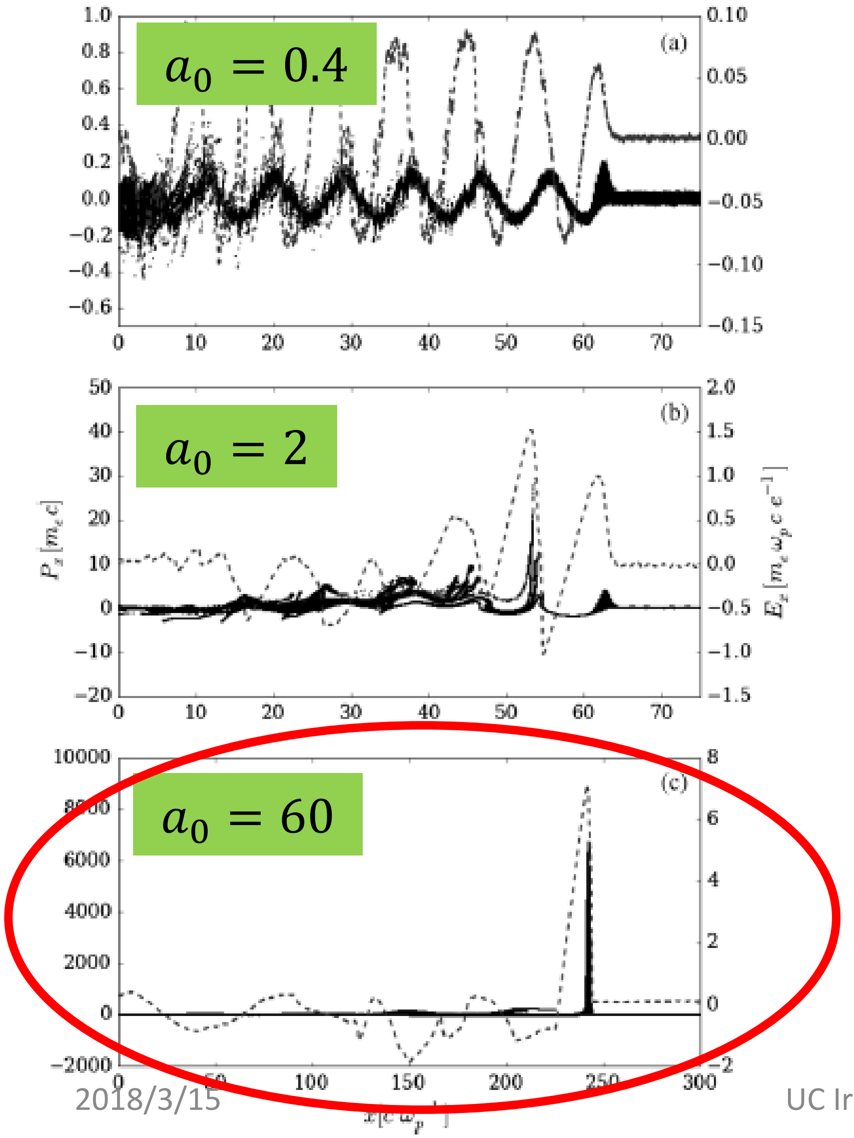
3. Escape problem

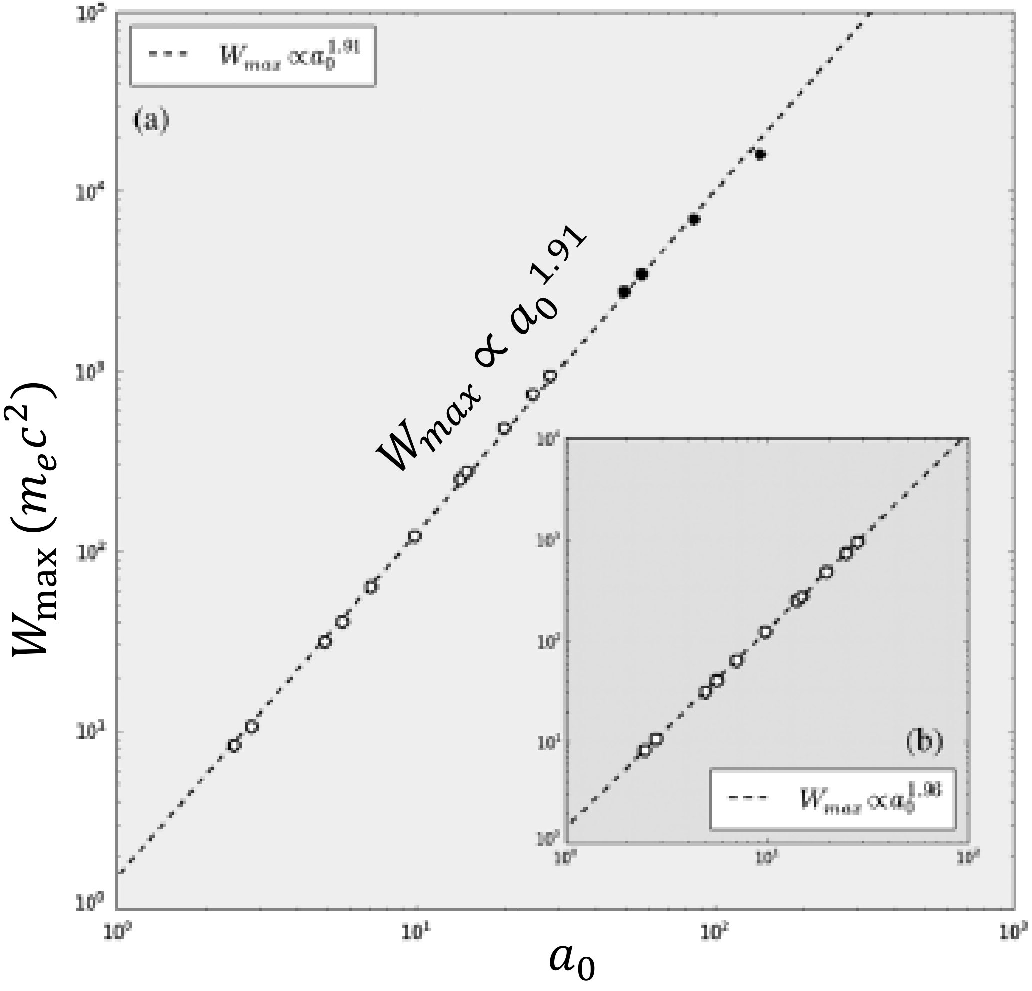
   →magnetic field does not disappear without adiabatic loss

**Wakefield acceleration**

# 1D Particle-in-Cell simulation

with the code by Nagata2008





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