Astrophysical Imprints of Wakefields: NS-NS Collision, γ-emissions from Blazars, Pinpointed High Energy Cosmic Rays

Colloquium
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Nature's wakefield accelerators in cosmos

1. <u>Collision of neutron star - neutron star</u>

2. Episodic eruption of γ-emissions from Blazars

3. Pinpointed high energy cosmic rays (and neutrinos)

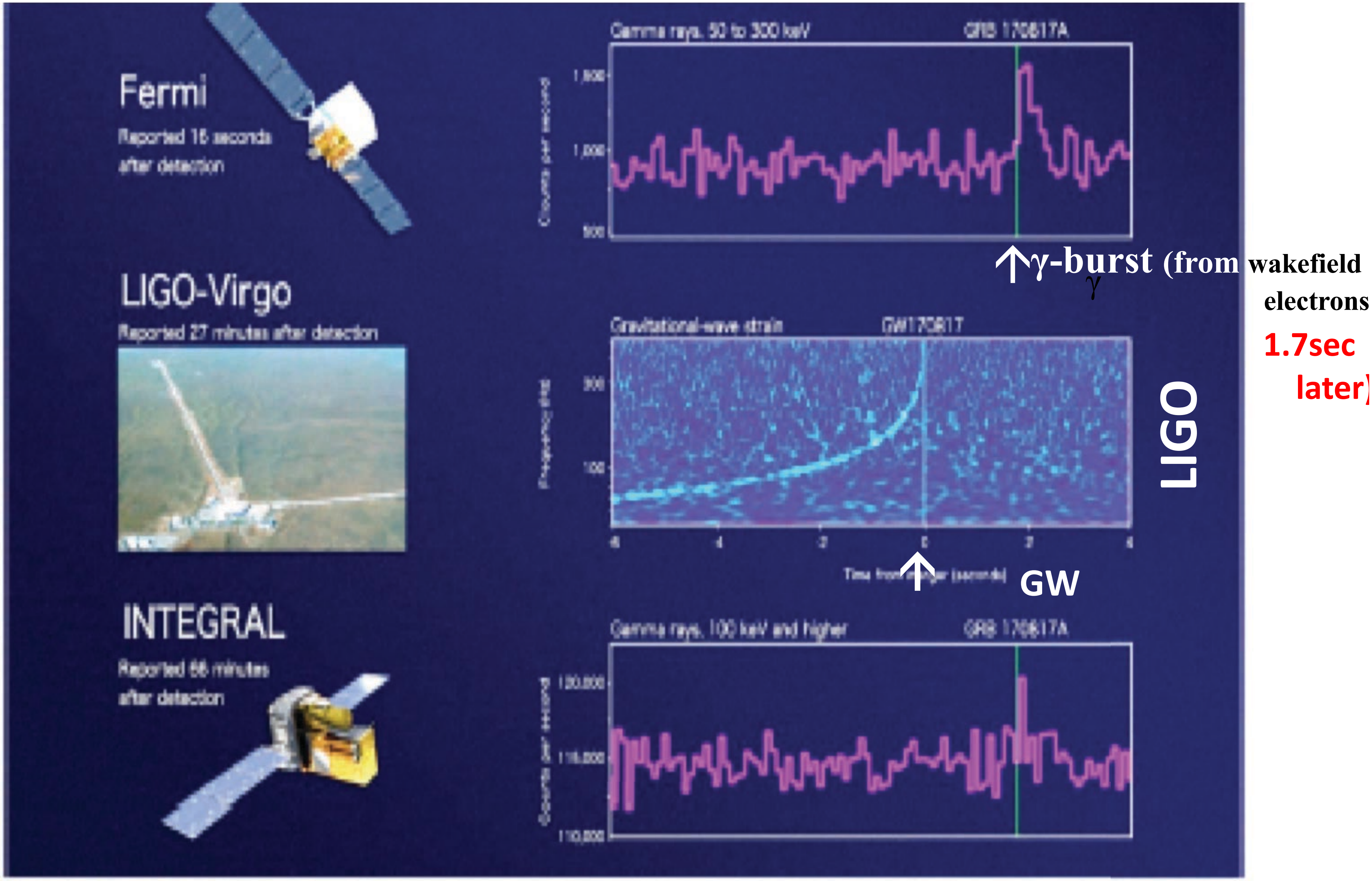
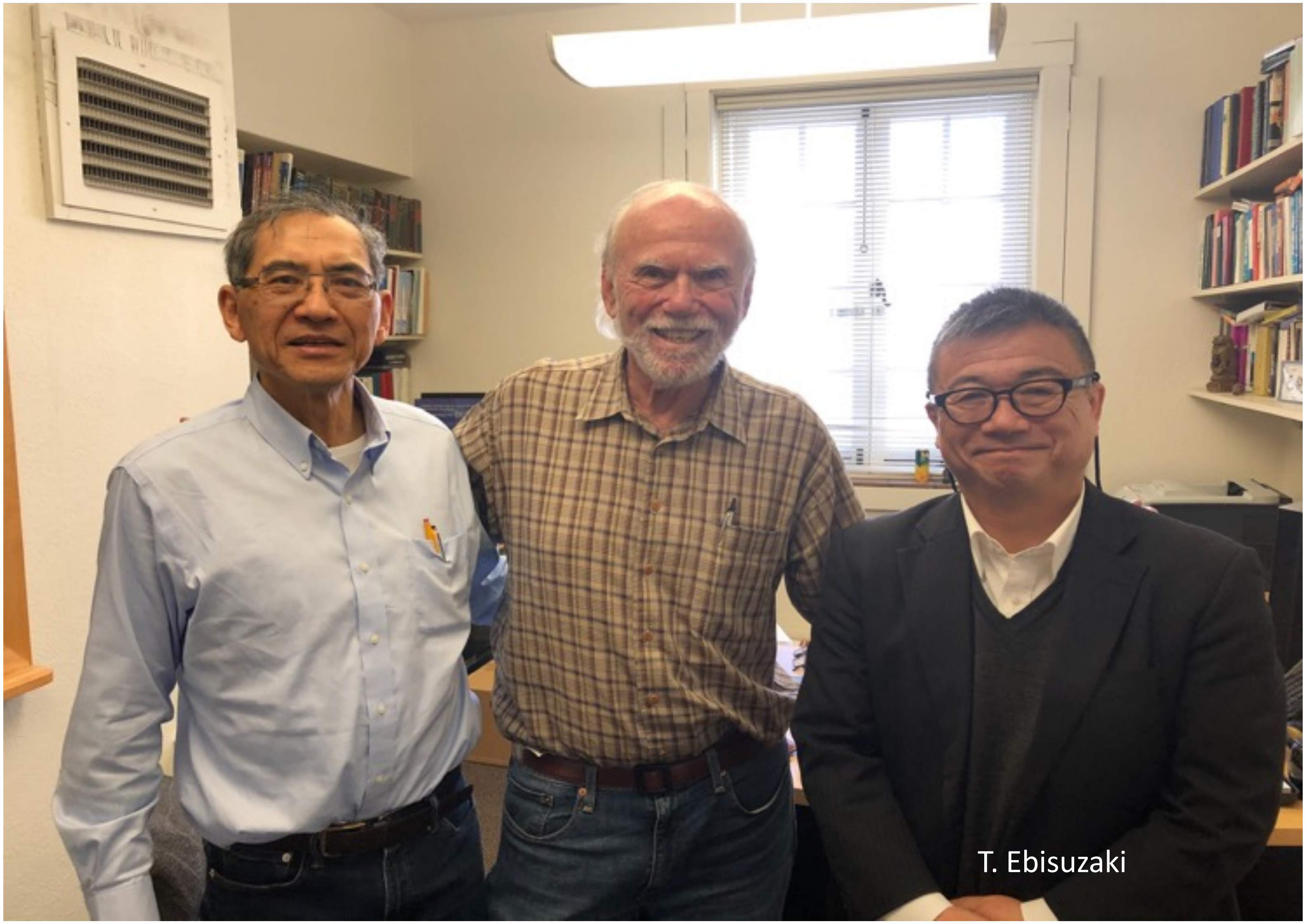


Fig. 5. Gamma-ray emission detected by Fermi and Integral satellites from the neutron star merging event (GW178017) delayed by 1.7 seconds compared with gravitational wave burst [79]. This time difference may be explained by the time to build-up the system for the acceleration of charged particles, described in the present

Barry Barish: 2017 Nobel

Observation of **Gravitational Waves**



With Professor B. Barish at **LIGO**, **Caltech**

Relativistic Lasers and High Energy Astrophysics 203

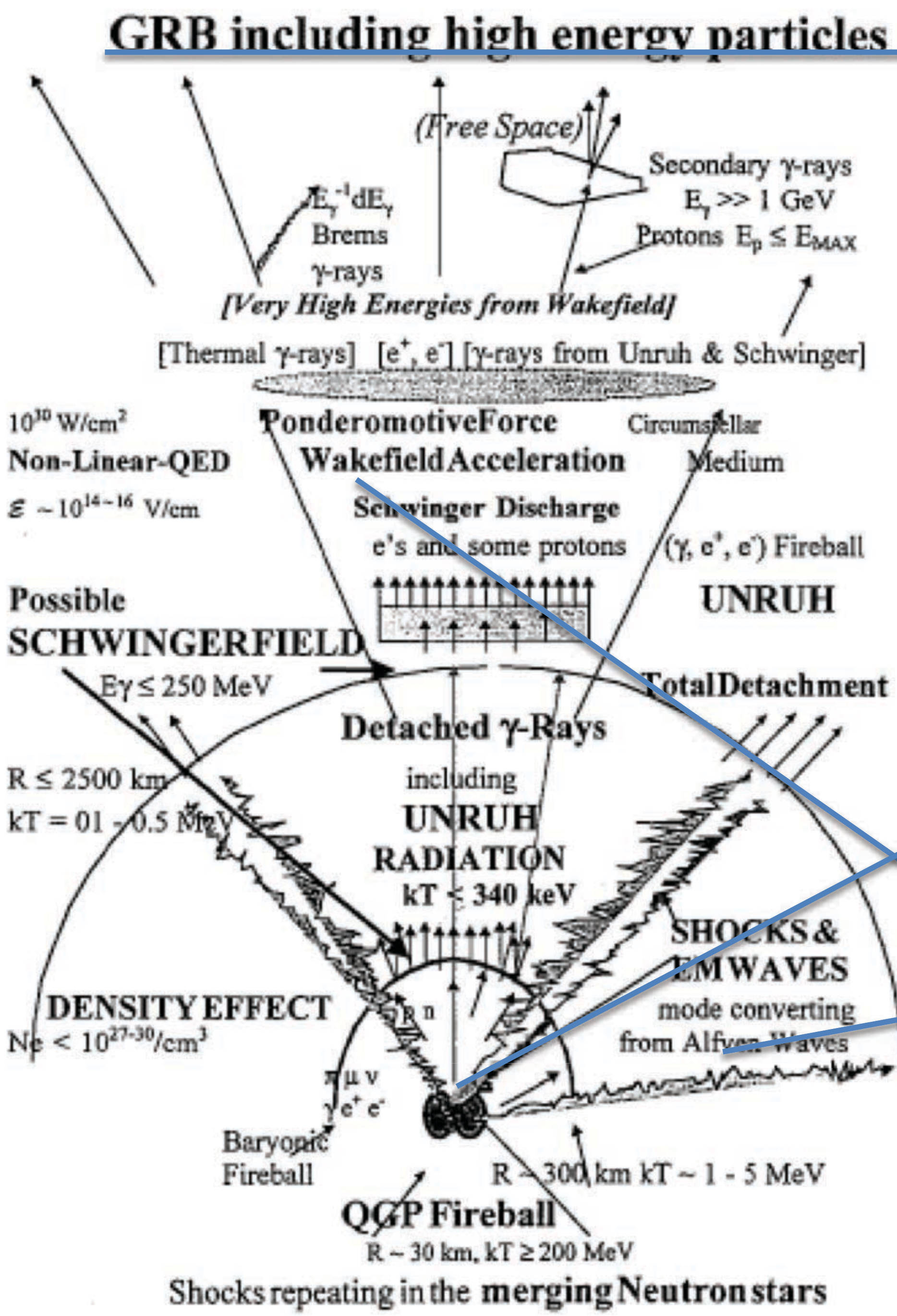


Figure 8. A schematic illustration of the proposed concept.

Prophetic picture (2000)

NS-NS collision triggers→

QGP (Quark-Gluon plasma)
Shocks /**gravitational waves**
Accretion disk
Jets
Alfven waves and EM waves
Wakefield acceleration
GRB (**gamma bursts**)
……

Takahashi, Y., Hillman, L.W., Tajima, T., in High Field Science, (Kluwer, NY, 2000)p.171.

Spacetime scales of NS-NS collision

Accretion disk

Jets/

Alfven waves and EM waves/

Wakefield acceleration / 3x 10^5km

GRB (**gamma ray bursts**) **t= 1s**

Unruh radiation 3000km **t=10ms**

Baryon fireball

300km **t=1ms**

Shocks /**gravitational waves**

QGP (Quark-Gluon plasma)

30km **t=0**

Relativistic Lasers and High Energy Astrophysics

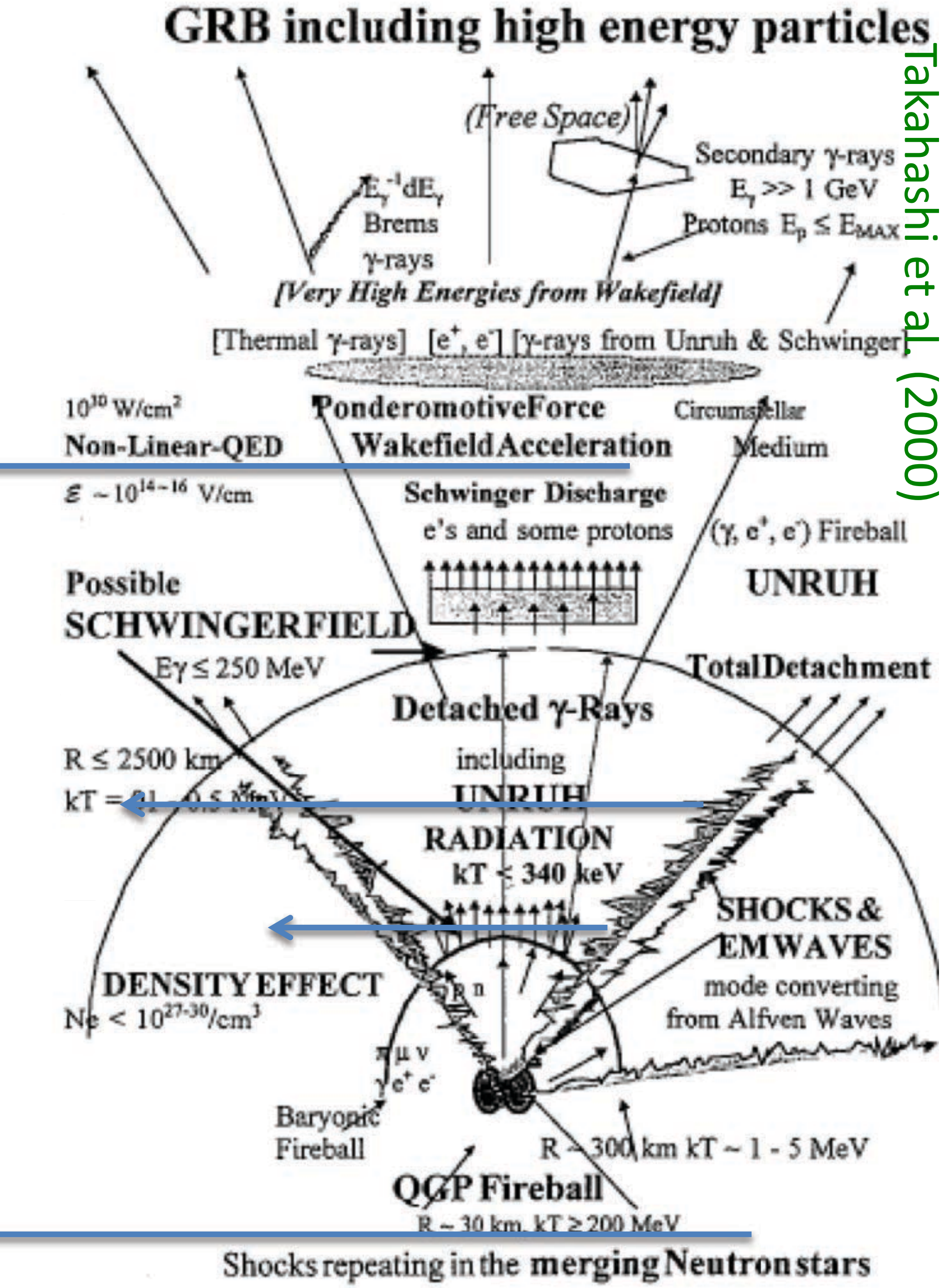
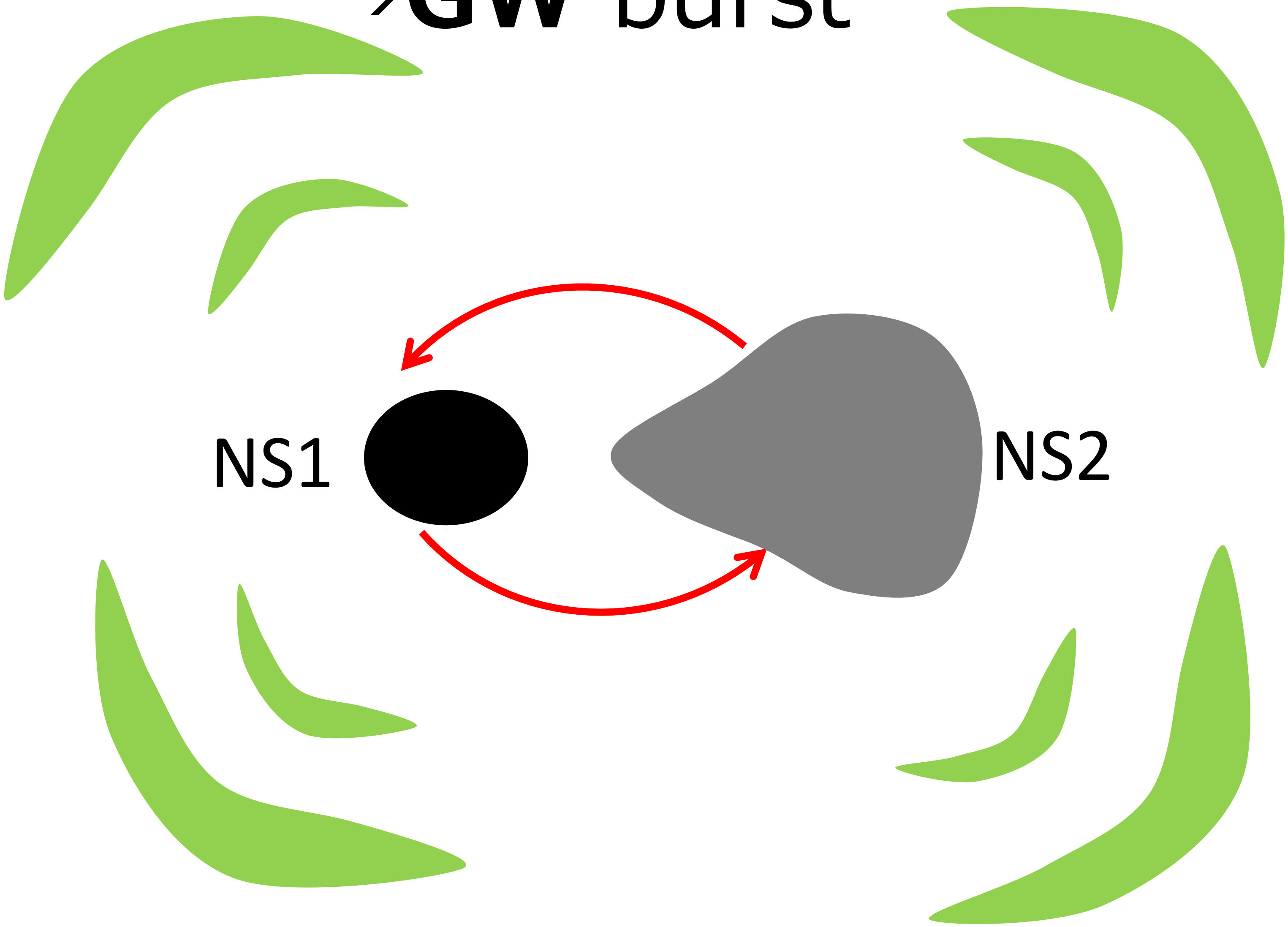


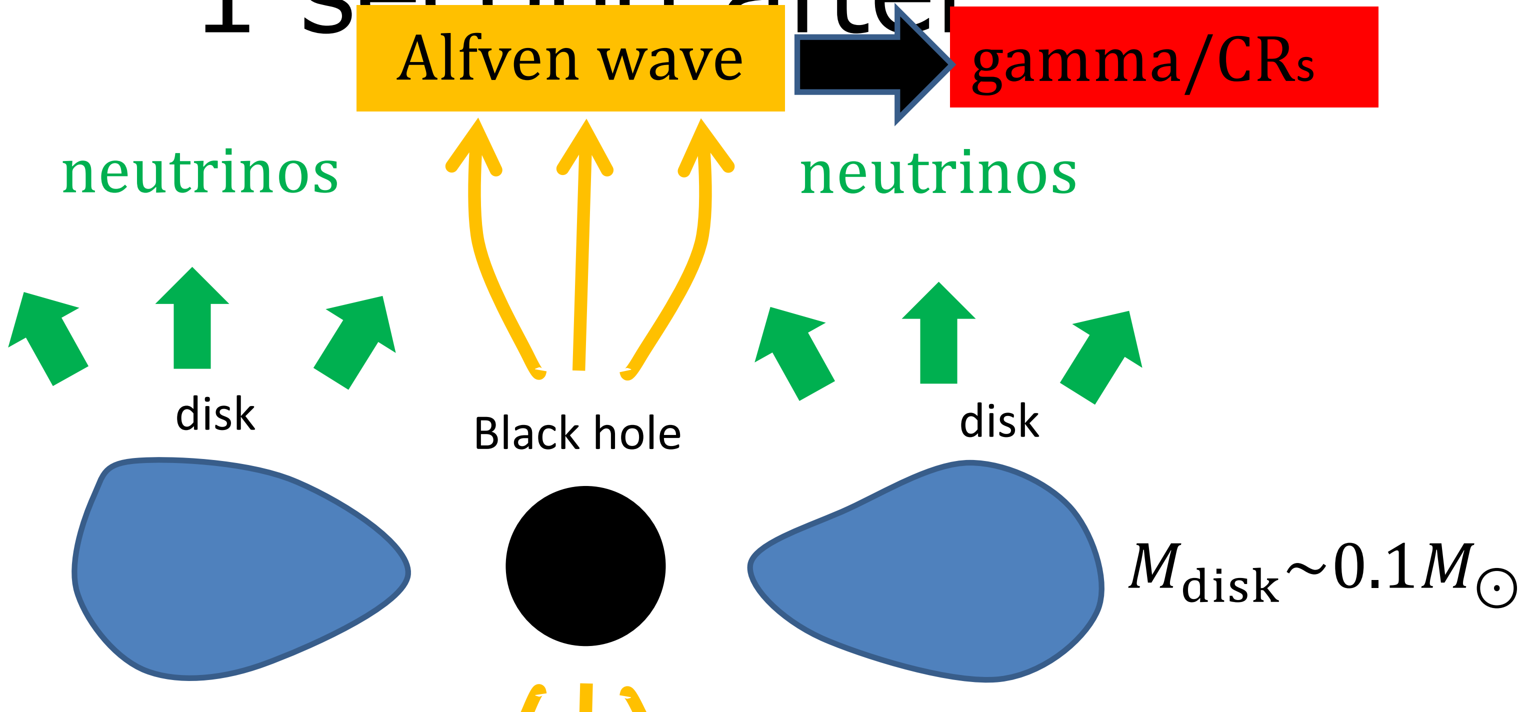
Figure 8. A schematic illustration of the proposed concept.

Takahashi et al. (2000)

NS-NS merger
→**GW** burst



NS-NS merger→BH + Disk
1 second after

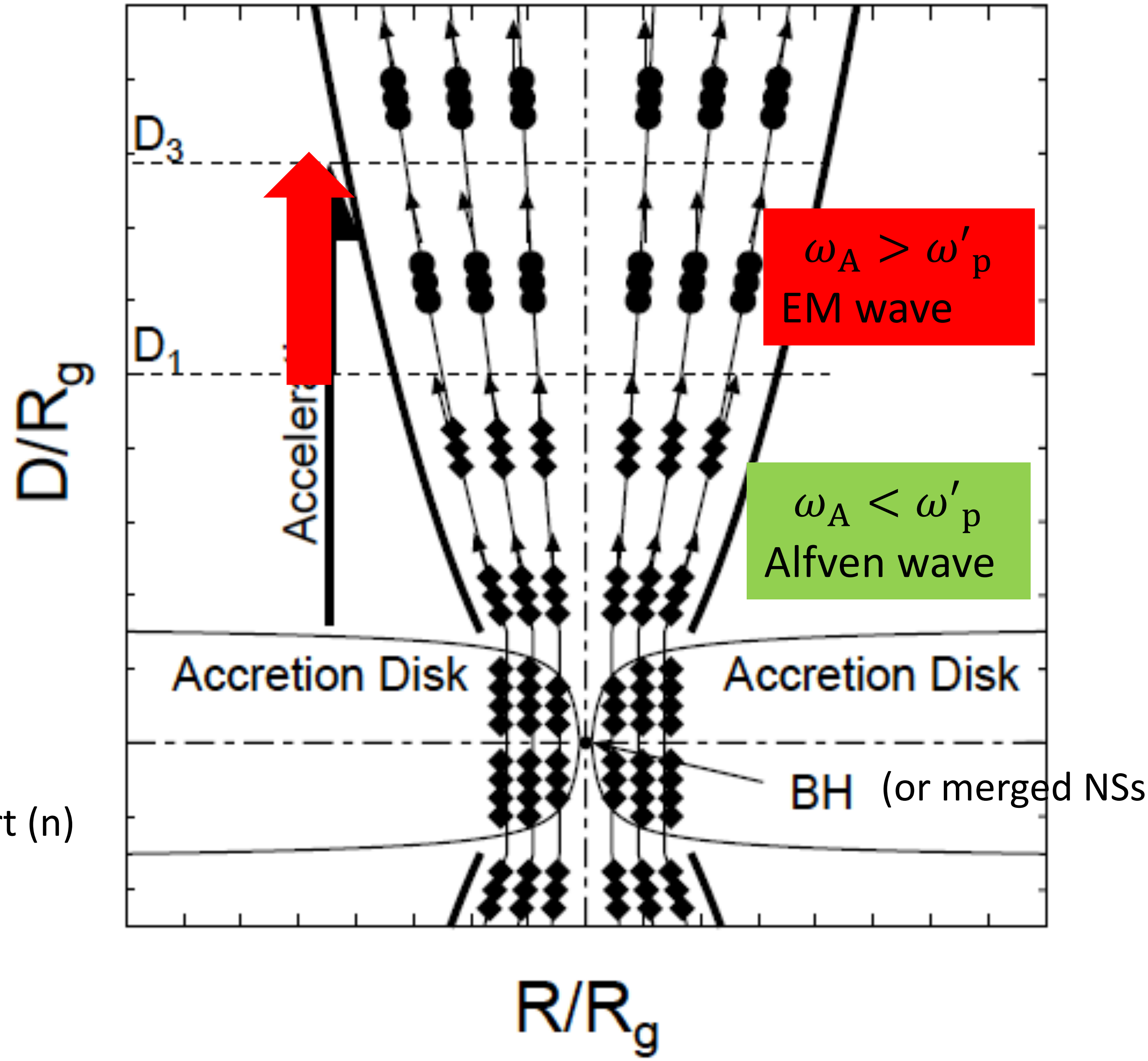


$L_{\nu} \sim 10^{52}$ erg/s $\sim L_A$
Central Engine of GRB/Hypernova

Alfven wave

Wakefield generation in Jet

↑ n_e decreases



V_A ~ B / sqrt (n)

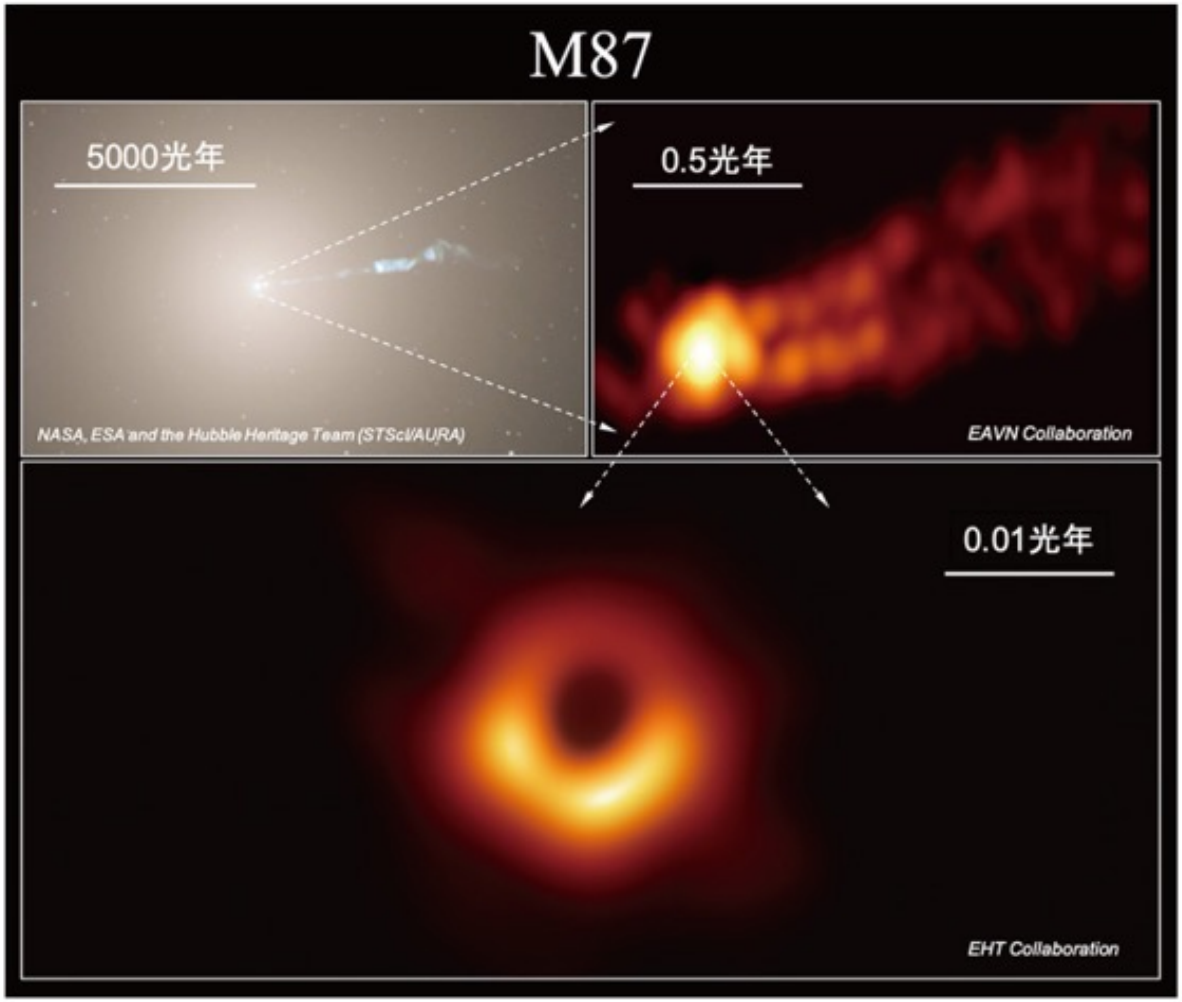
T. Ebisuzaki and T. Tajima, Astropart. Phys. (2014) [implied in Takahashi et al. (2000)]

Nature's wakefield accelerators in cosmos

2. **Episodic eruption of γ-emissions from Blazars**

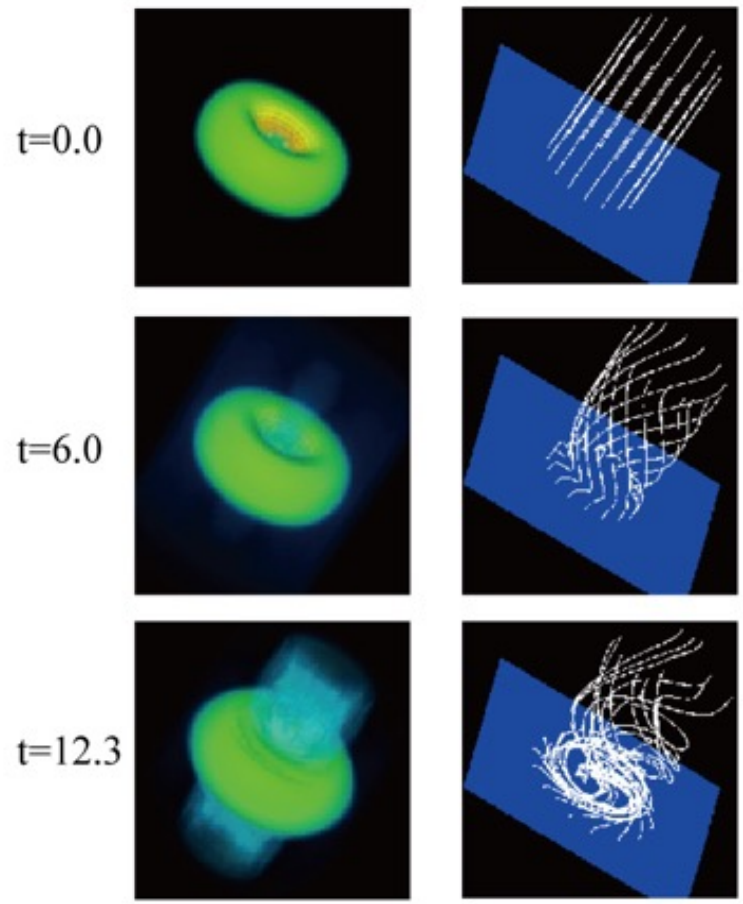
Discovery of Blackhole and Prediction

M87 blackhole: by Event Horizon Telescope (2019)



Suggestion: Tajima and Shibata
"Plasma Astrophysics"
(textbook, 1997)

3D Structure of Disk and Jet



“Physiology” of various AGNs

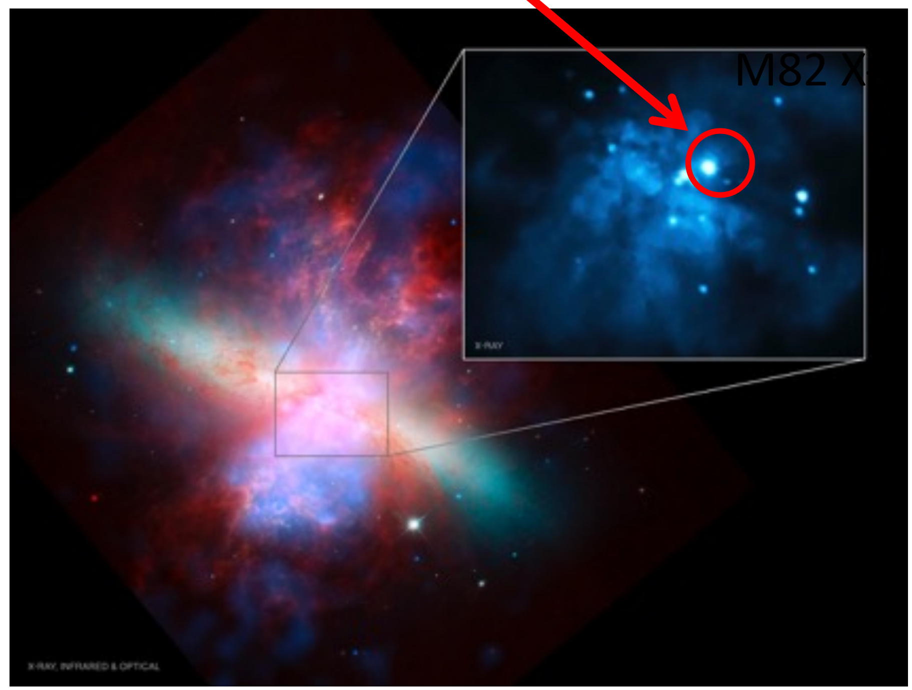
Cen A

- Distance : 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source
- Elliptical Galaxy
- Black hole at the center w/ relativistic jets

M82: Nearest Starburst Galaxy

M82 X-1: 1000-10000 Ms BH

Just after the collision with M81

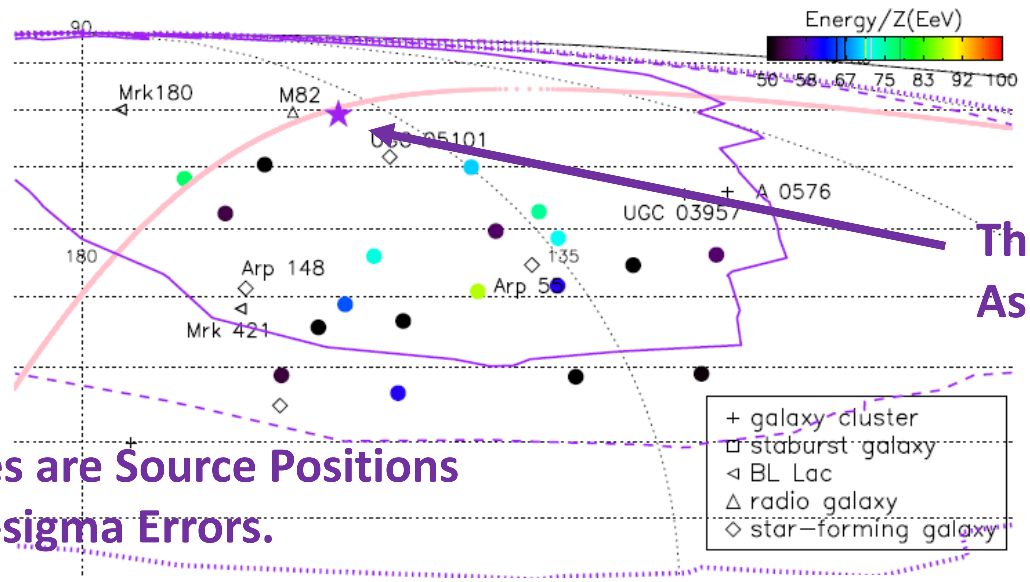


Composite of X-ray, IR, and optical emissions

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.

TA Hot Spot: UHECRs from **M82**?

He, Kusenko, Nagataki + PRD 2016.



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

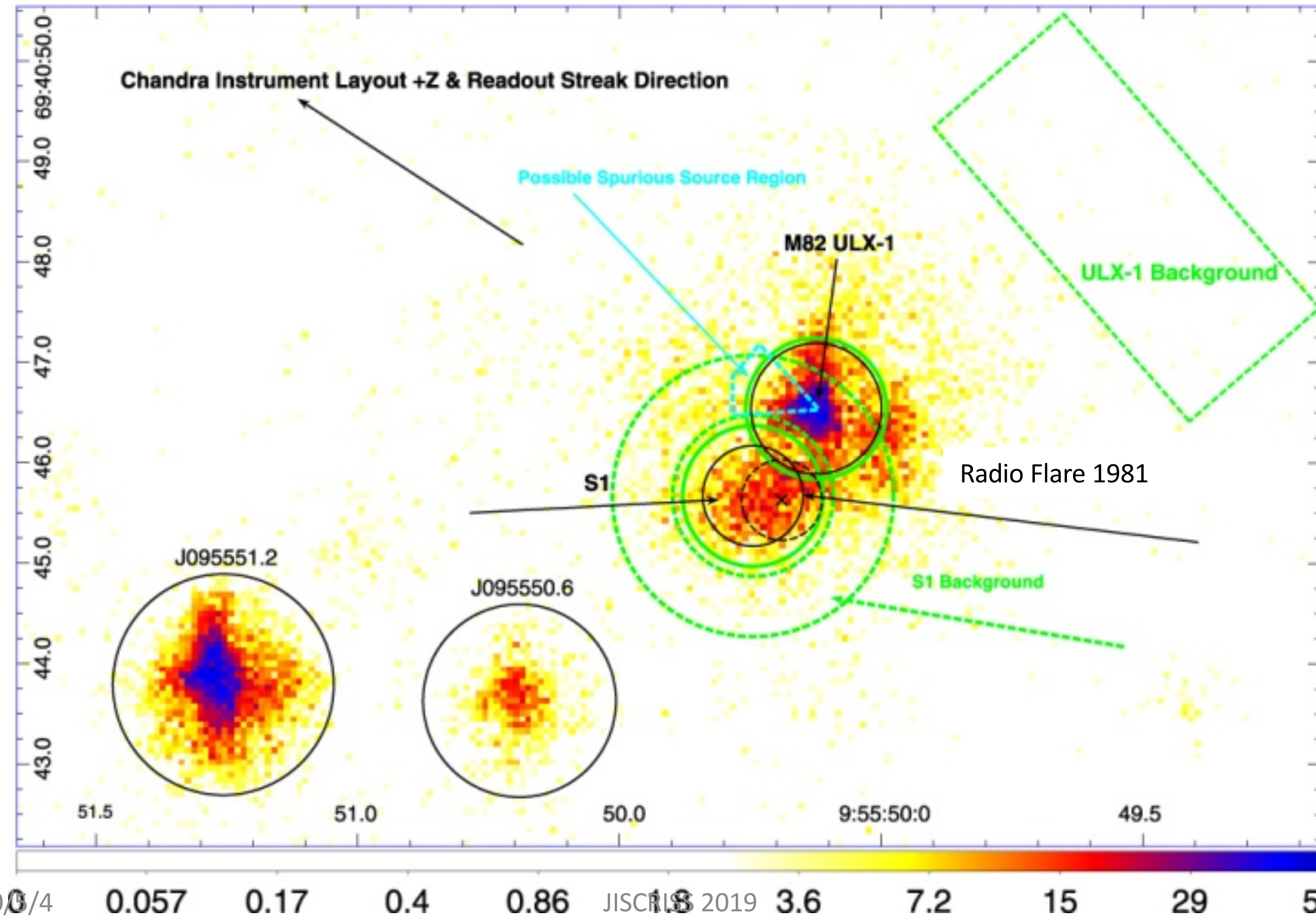
M82 is very Close from the most likely Source Position!

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

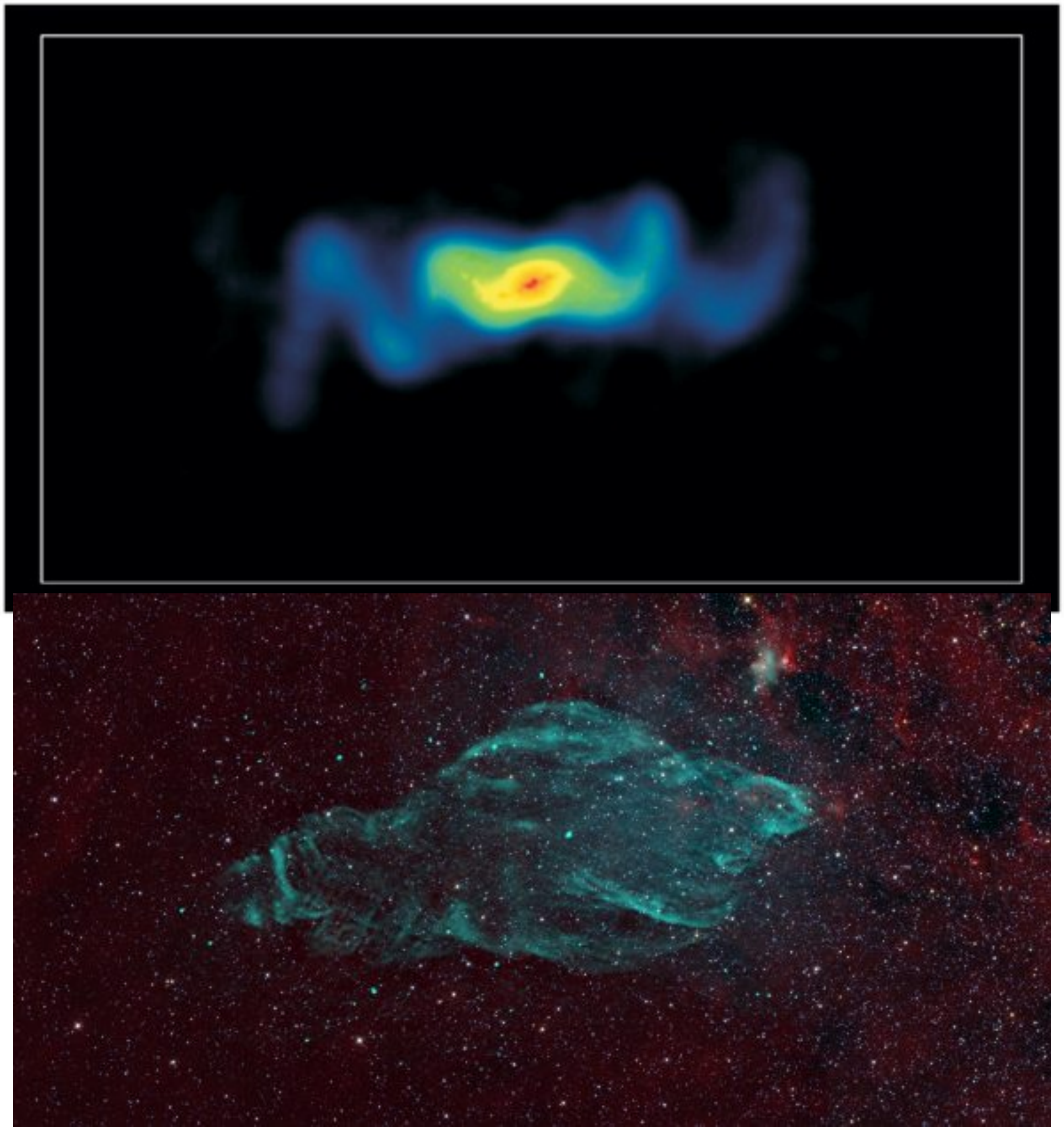
Source Name	Source Type	Distance (Mpc)	A_1 (°)	A_2 (°)	$P/P_{\rm bes-fit}$ (%)
best-fit	-	-	$17.4^{+17.0}_{-11.0}$	$9.4^{+3.7}_{-0.3}$	100
M82	starburst galaxy	3.4	17.6	9.6	99.8
UGC 05101	star-forming galaxy	160.2	11.6	9.2	96.9
Mrk 180	blazar	185	19.9	9.3	91.3
UGC 03957	galaxy cluster	150.3	14.9	9.5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

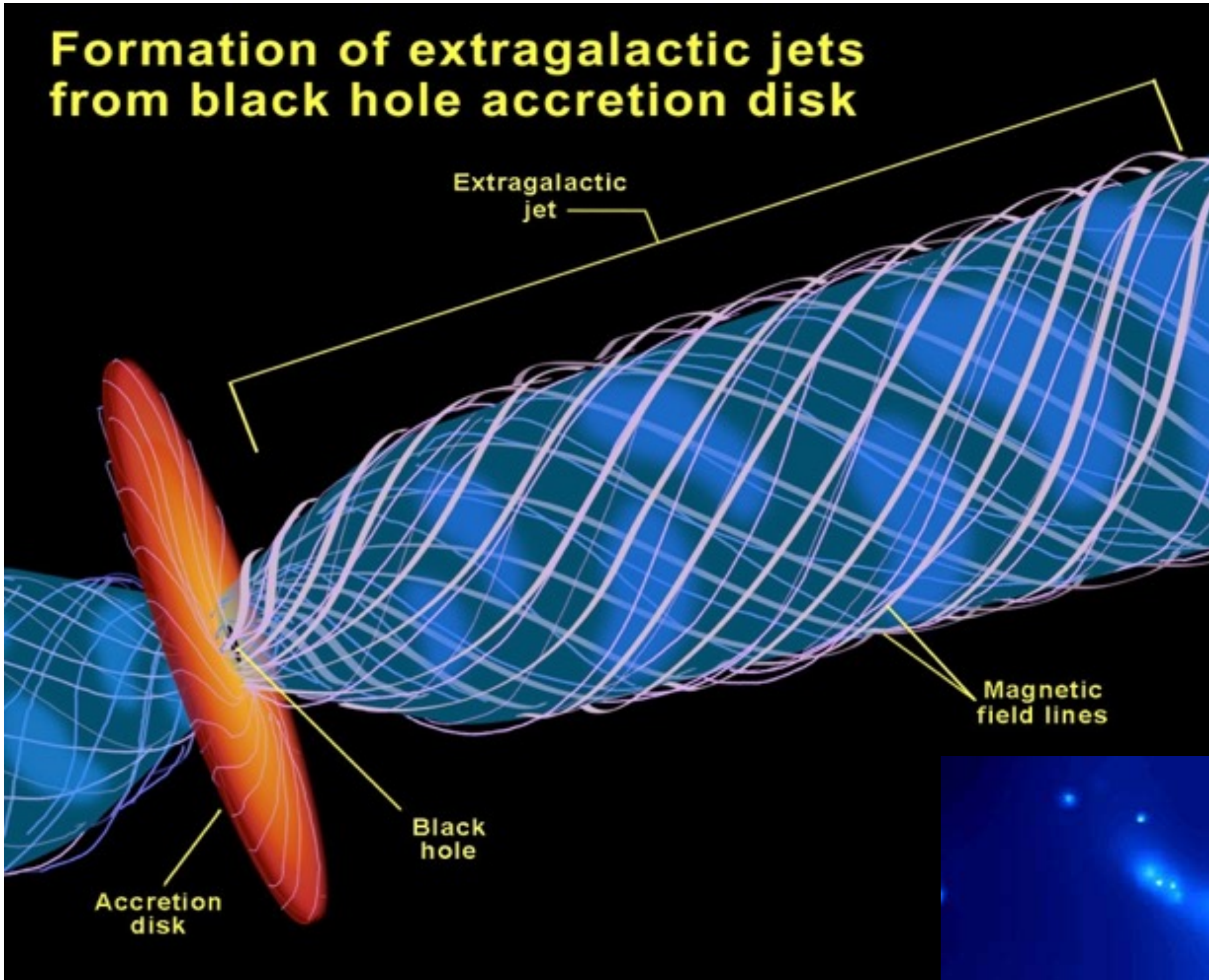
An AGN-like Jet in **M82**? X-ray/Radio (flare in 1981)

Xu et al. 2015 ApJ Letters 799, L28



SS433 precession jets



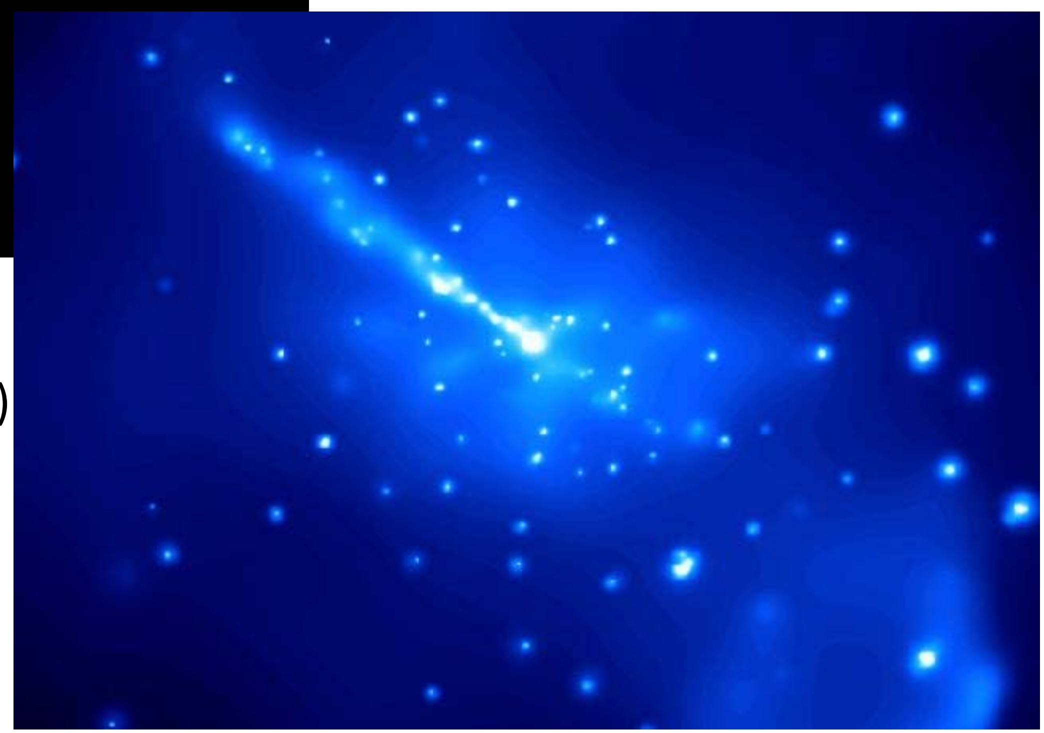


A model of Blazar

Fermi's '**Stochastic Acceleration**'
(large synchrotron radiation loss)

↓

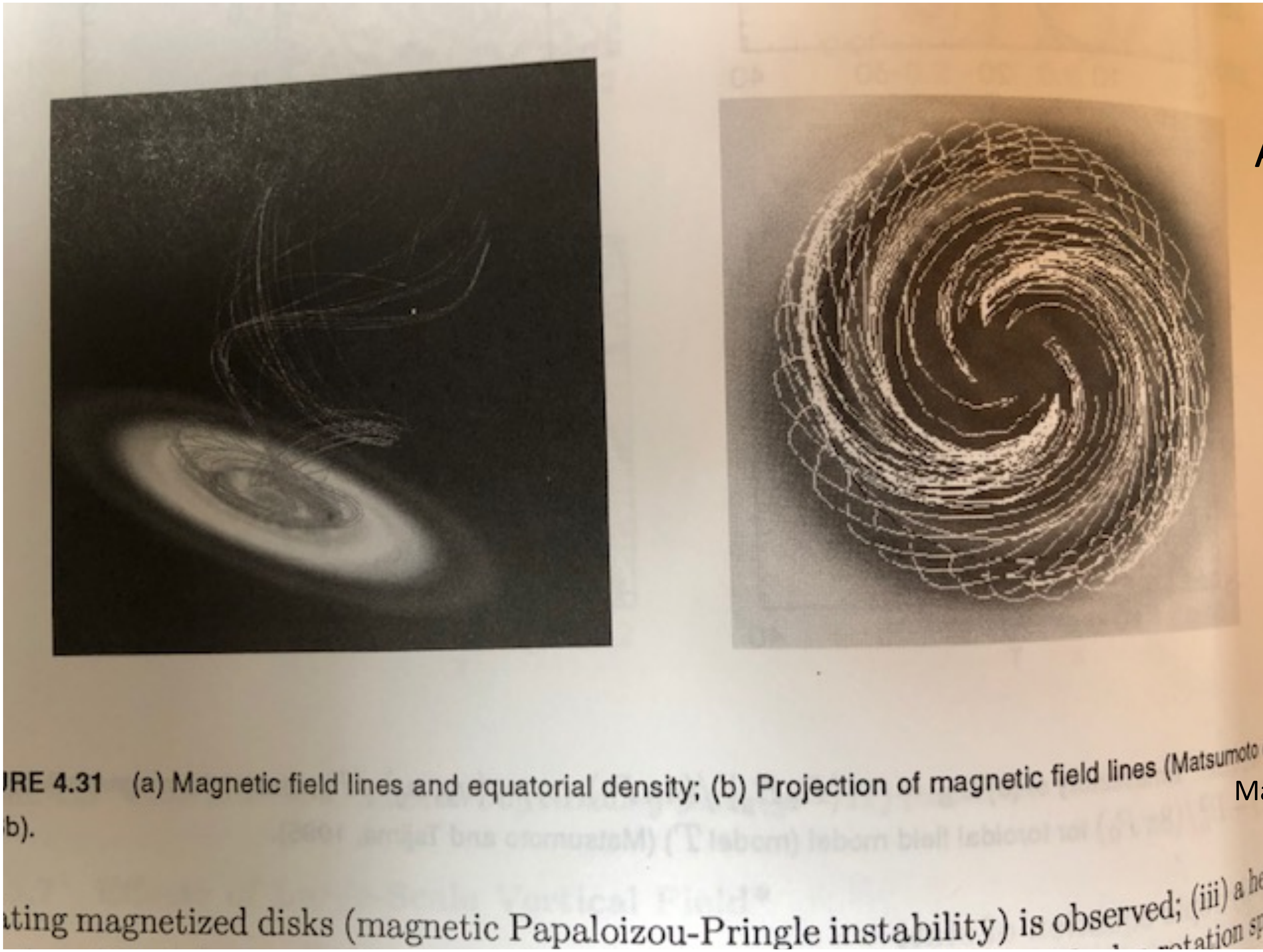
Coherent wakefield acceleration
(no limitation of the energy)



Nature's LWFA : Blazar jets
extreme high energy cosmic rays (~10^{21} eV)
episodic γ-ray bursts observed
consistent with LWFA theory

Ebisuzaki-Tajima (2014)

Magneto-Rotational Instability (MRI)



Accretion disk

rotating plasma

B-fields

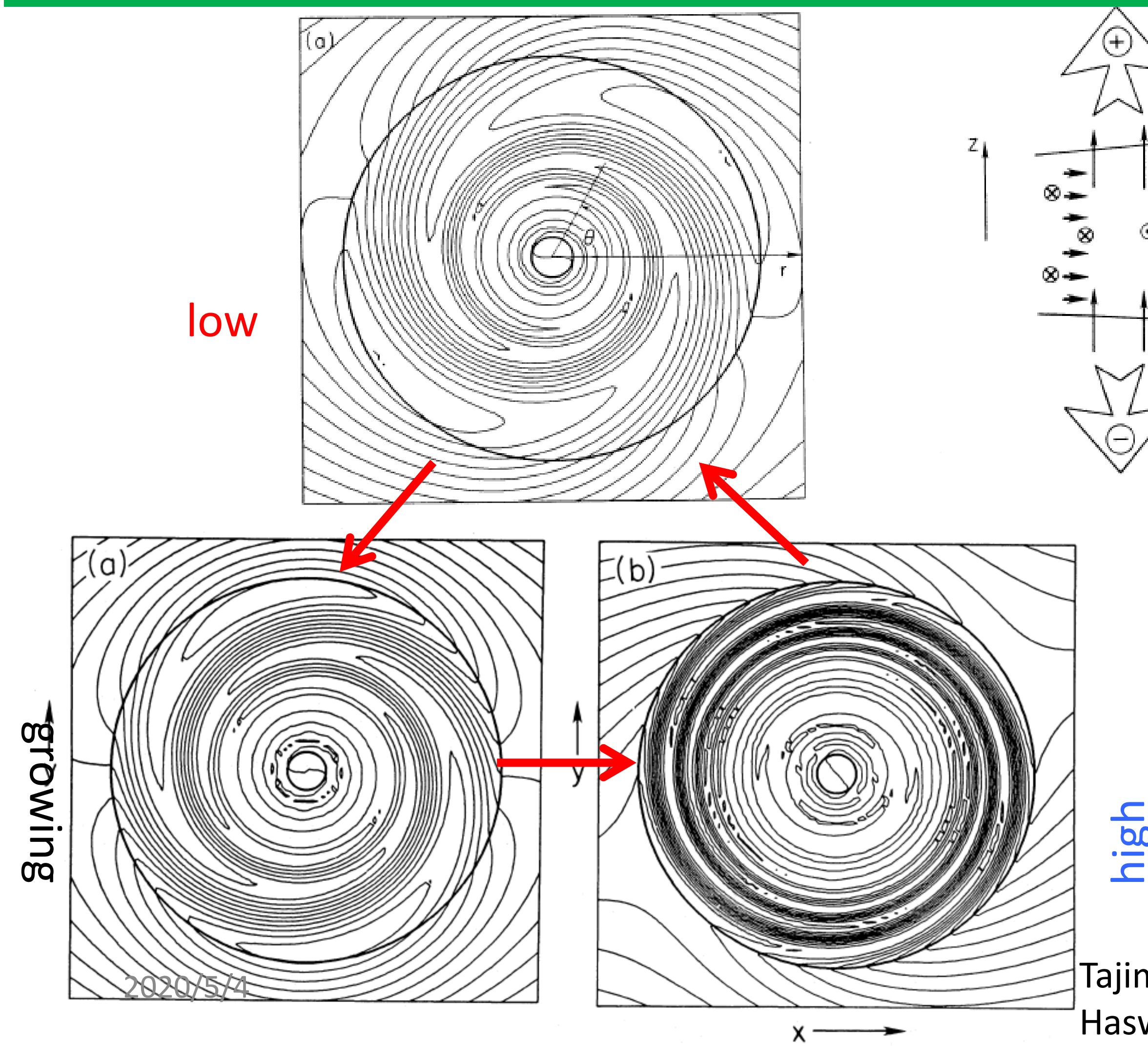
Balbus-Hawley (1991)

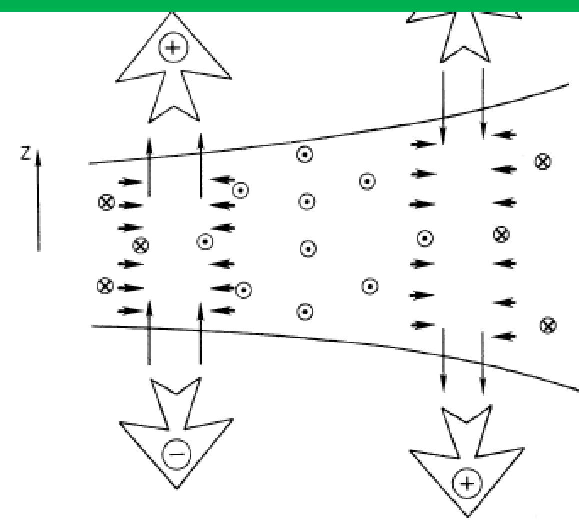
Matsumoto Tajima (1995)

Tajima, Shibata (1997)

Eruption of magnetic field in an accretion disk

A Burst of Electromagnetic Disturbance

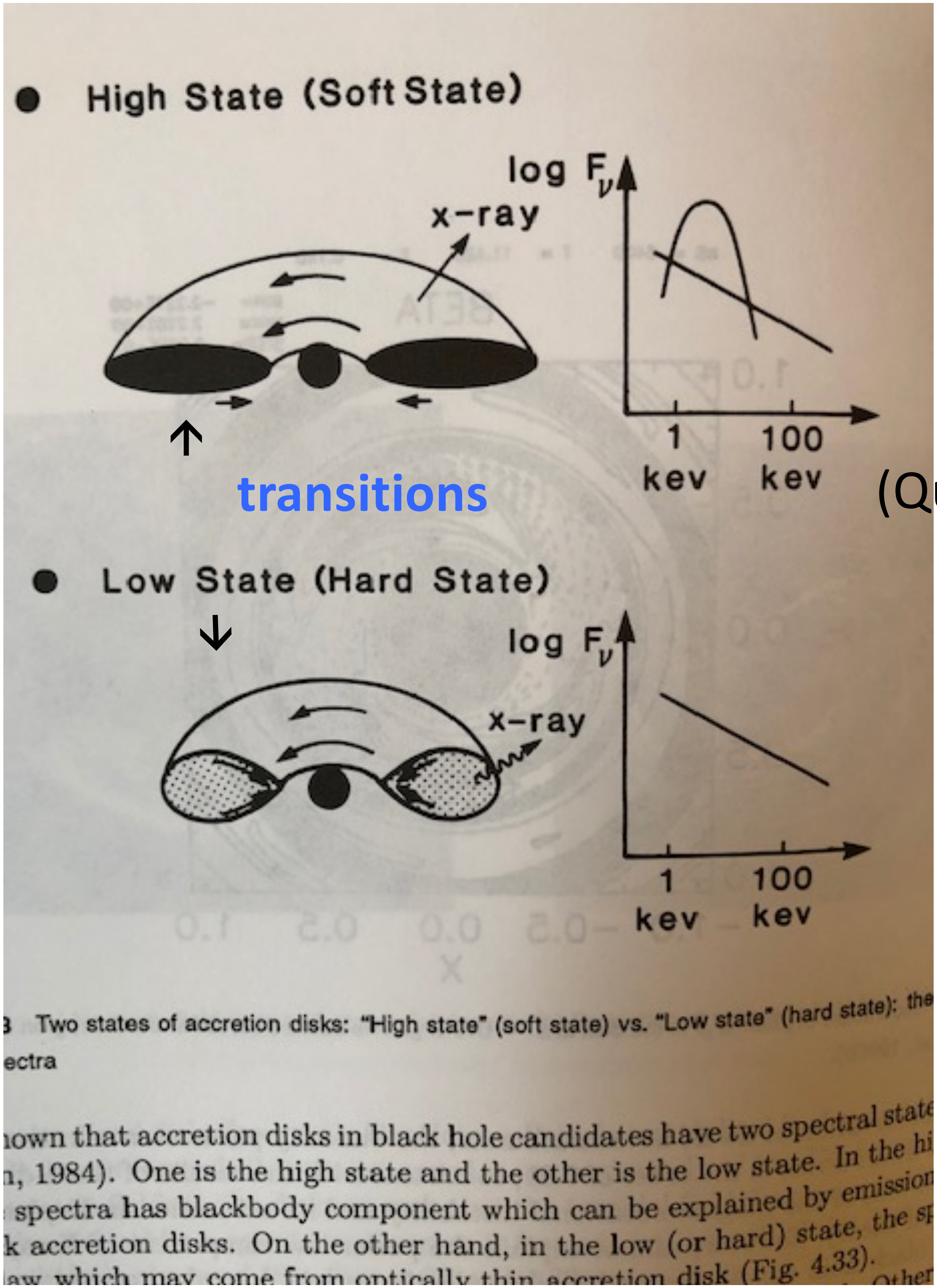




Transition between
high (eruption) and
low (recovery) states

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

Episodic transitions of accretion disks with B



3 Two states of accretion disks: "High state" (soft state) vs. "Low state" (hard state): the
ectra

...own that accretion disks in black hole candidates have two spectral state... n, 1984). One is the high state and the other is the low state. In the hi... spectra has blackbody component which can be explained by emission... k accretion disks. On the other hand, in the low (or hard) state, the sp... law which may come from optically thin accretion disk (Fig. 4.33). ... Other

(Quasi-)<u>steady state</u> accretion disks

cf.

<u>Episodic</u> accretion disks

"breathing" disks

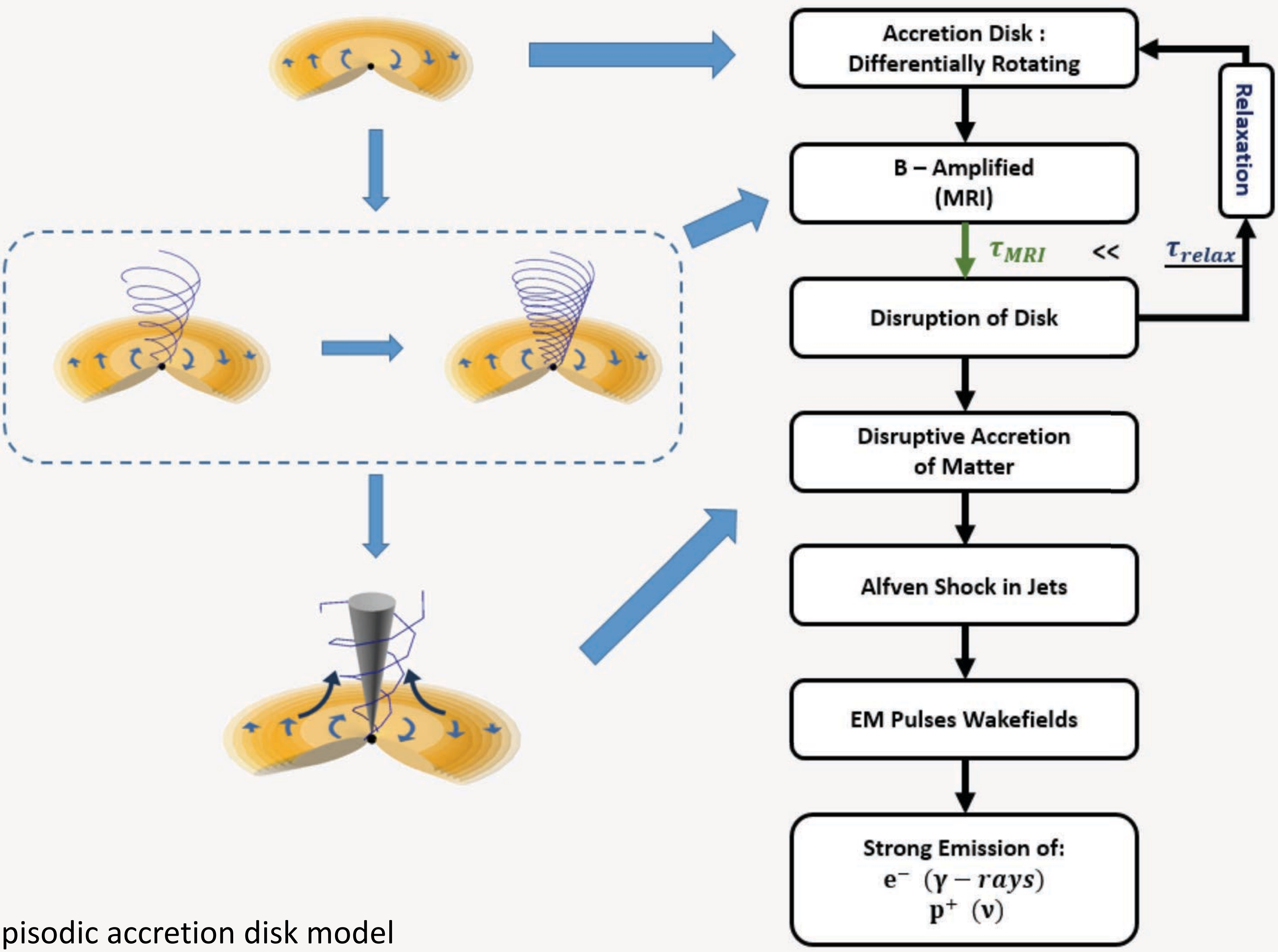
transitions between the **states**

<u>**soft** state</u> (β >>1)

↑↓

<u>**hard** state</u> (β ~ 1)

Tajima, Shibata (1997)



Episodic accretion disk model

Abazajian, Tajima, Ebisuzaki

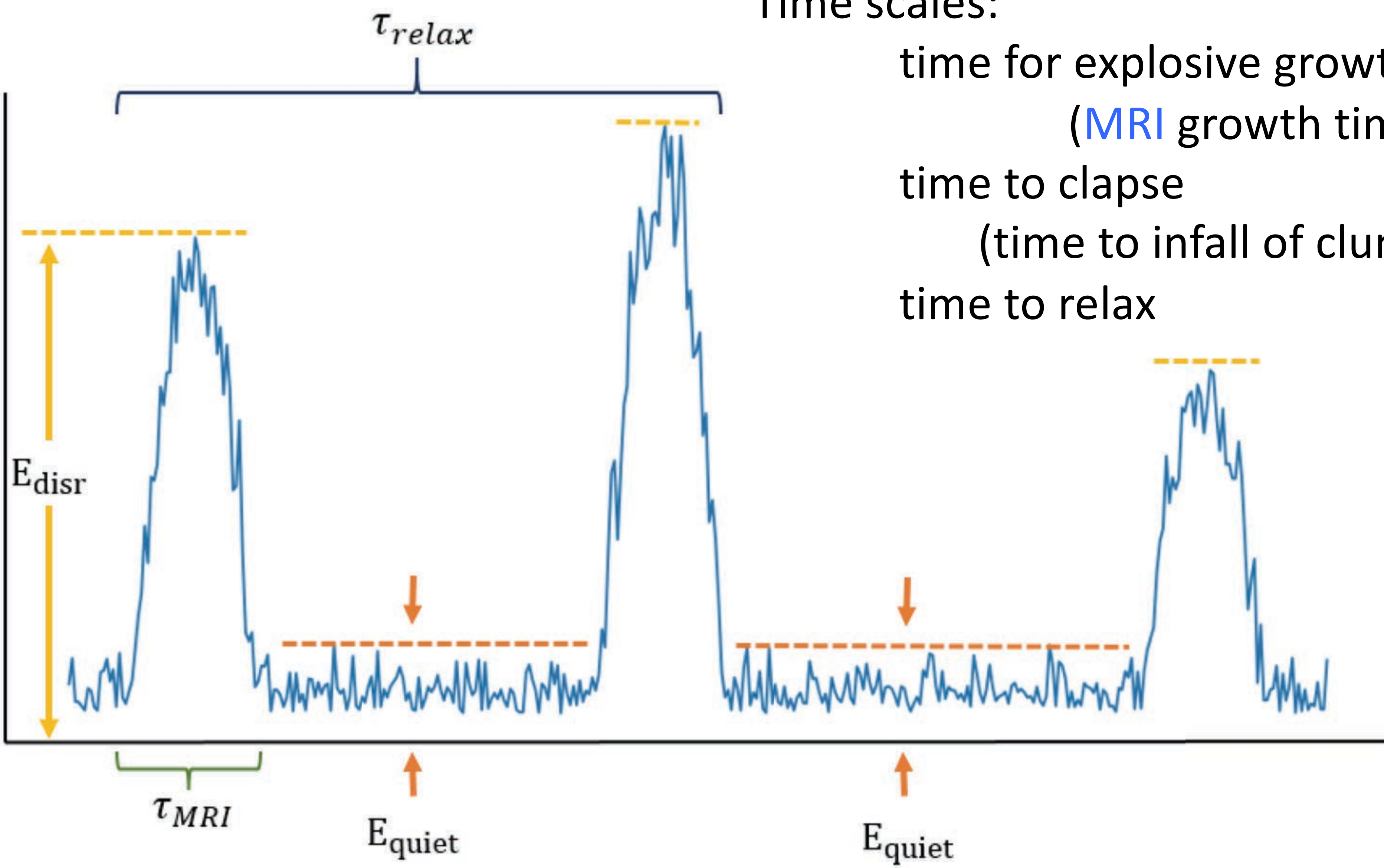
Episodic eruption of accretion disk

Time scales:

time for explosive growth
(MRI growth time)

time to clapse
(time to infall of clump)

time to relax



General Relativistic MHD simulation of accretion disk + jets: episodic feature

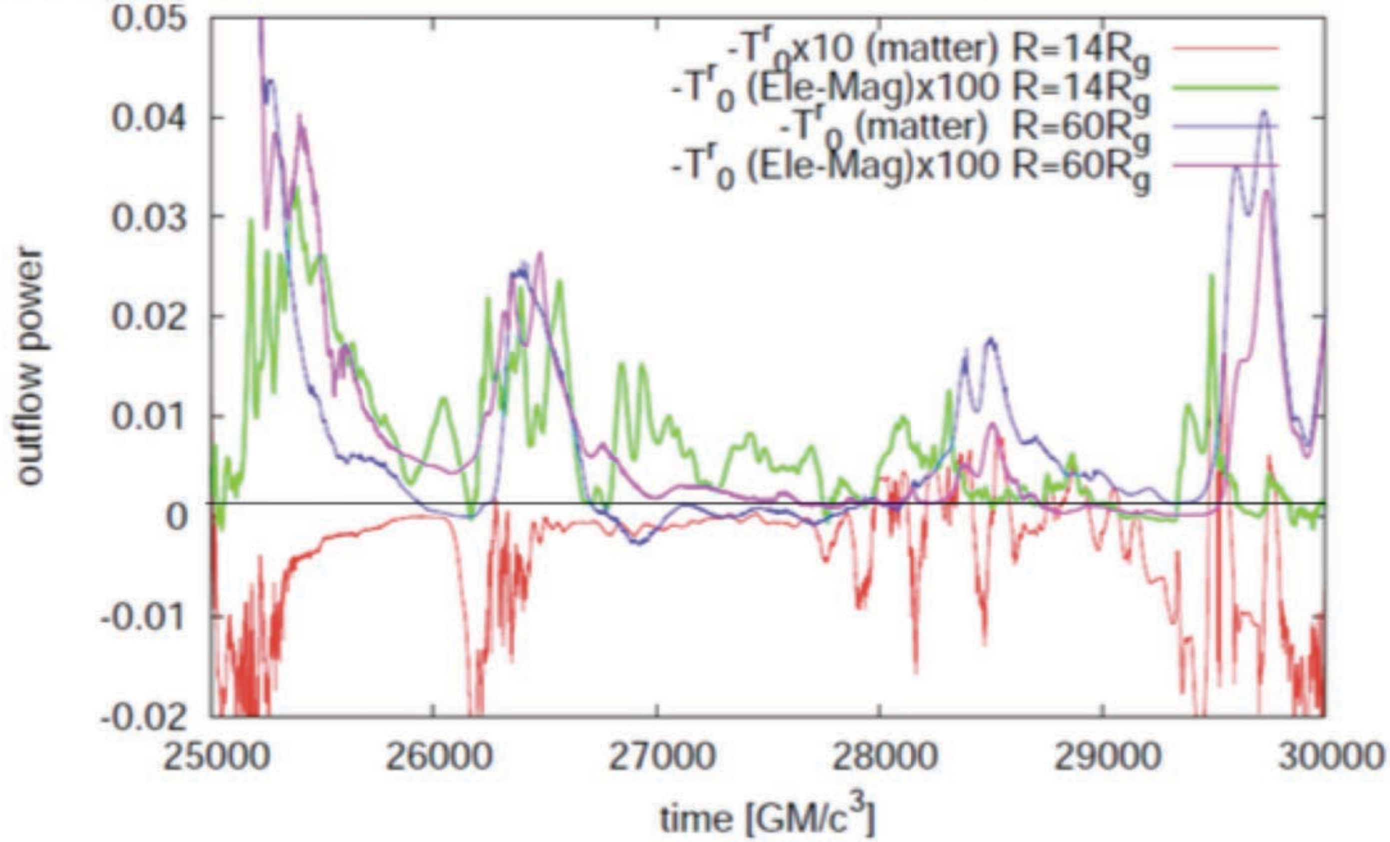
Outflow luminosity (0<θ<10°)

$$E_{\rm dot} = -\int_{\theta=\theta_0}^{\theta=\theta_1}\int_{\phi=0}^{\phi=2\pi}\sqrt{-g}T_t^r\,dA$$

outflow power $14R_g$, $60R_g$

$\theta_0=0$

$\theta_1=10$



Short time variavilitry (Δt~a few tensGM/c³) in electromagnetic components (green and pink) : Good agreement with Ebisuzaki & Tajima(2014) $t_{var} \sim M$

=> possible origine for flares in blazars,

strong Alfven wave mode => Application t wake field acc. for UHECRs

A. Mizuta, T. Ebisuzaki (2018)

Intense Alfven Shock from root of jet

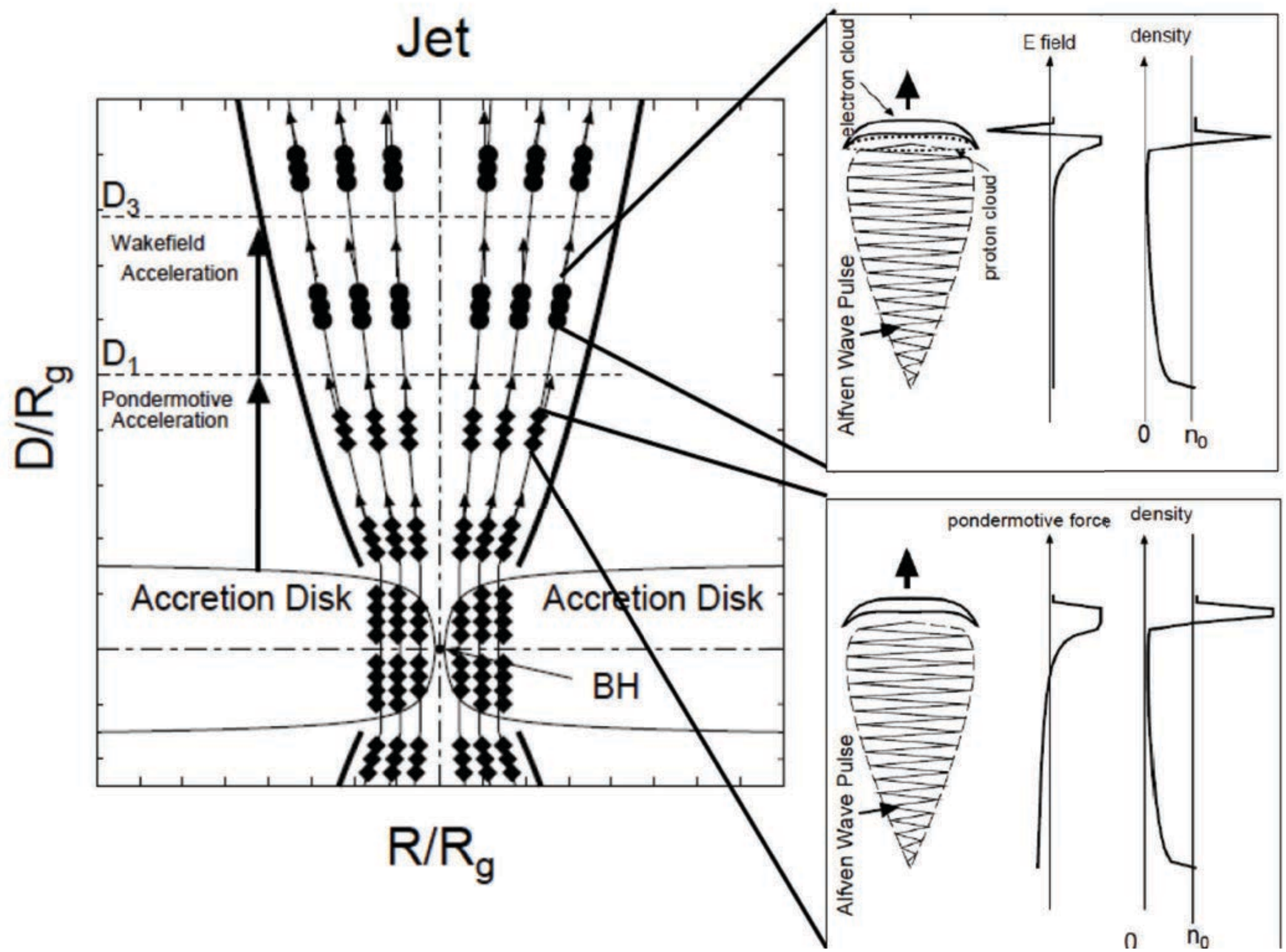
→ Intense EM pulse

→ wakefield generation → Electron acceleration

→ γ burst ion

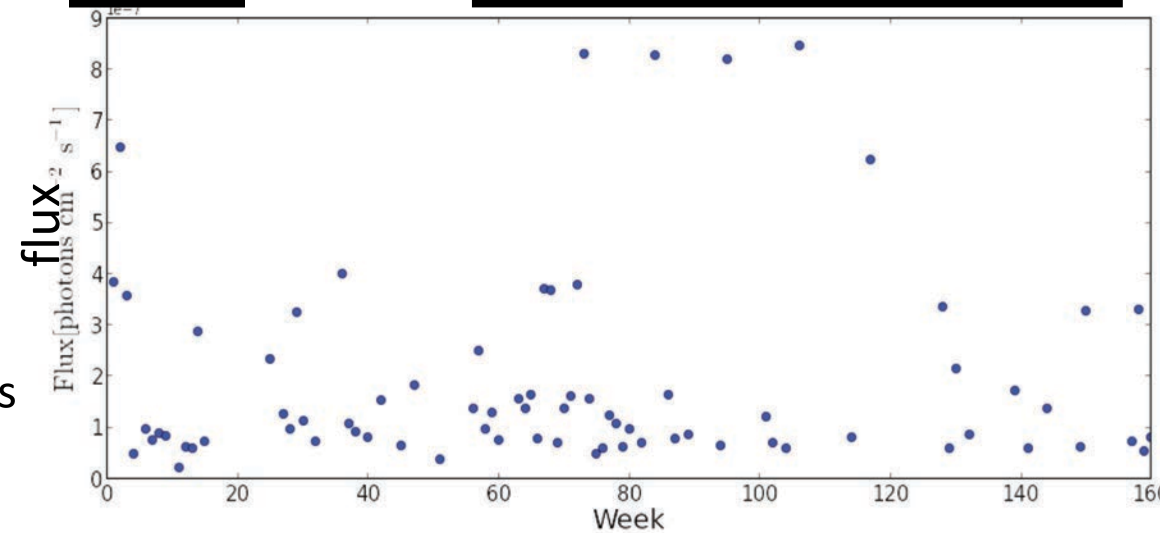
UHECR

↑ n_e decreases



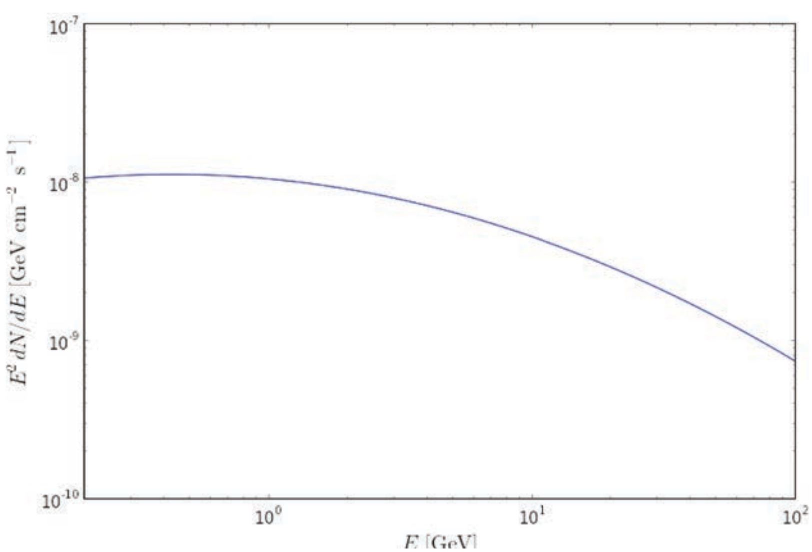
Blazar shows anti-correlation between γ burst flux and spectral index

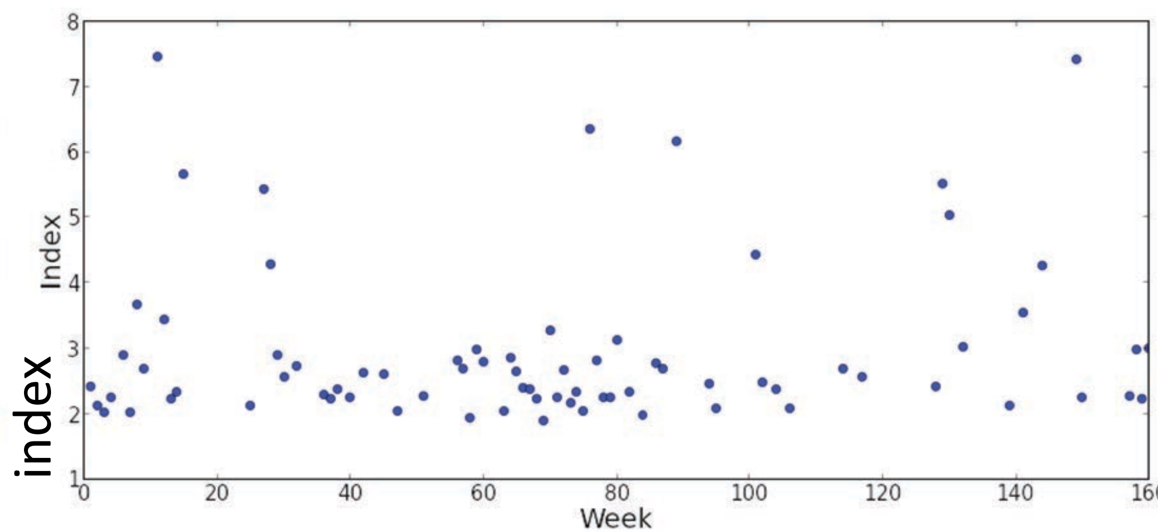
Blazar: AO0235+164
M ~ 10^8 M_{Sun}



Rise time < week (less than a unit),
Period between bursts ~> 10 weeks
Spectral index => 2
(~ Ebisuzaki/Tajima theory)

→ all quantitatively consistent with Wakefield theory



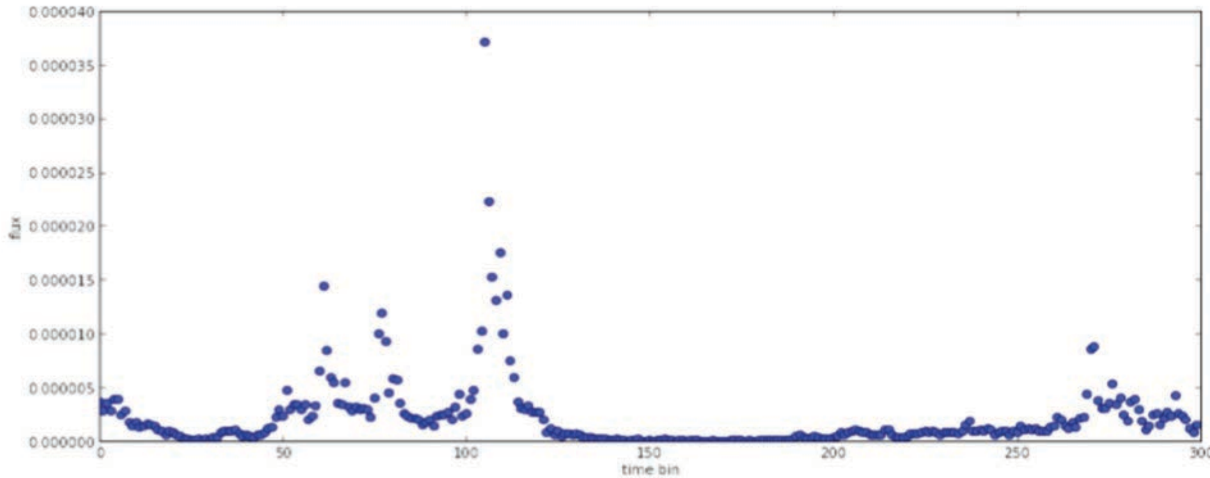


N. Canac, K. Abazajian (2020)

Again, Anti-correlation even in a bigger blazar

Blazar: 3C454.3

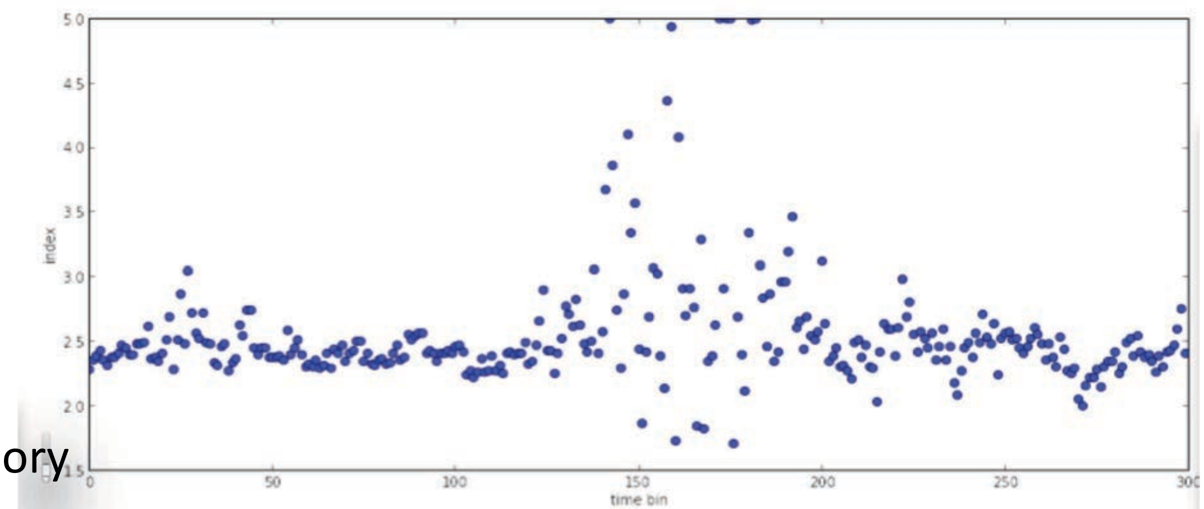
$M \sim 10^9 M_{Sun}$



Same anti-correlation as

AO0235+164

The rise time and burst periods a lot longer (by an order of magnitude)

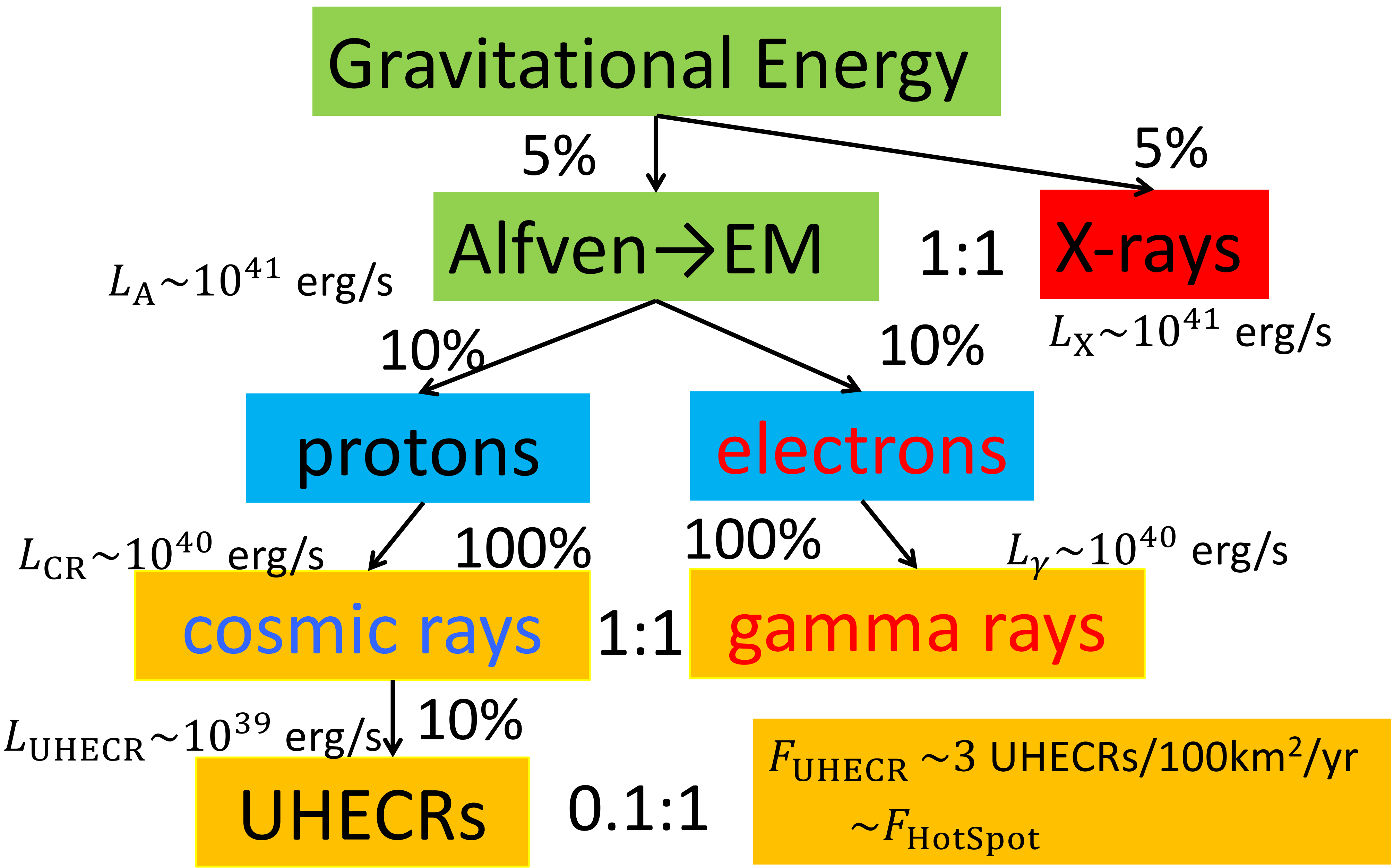


Quantitative agreement and **correct scaling** with Blazar mass with (broader sense of) Wakefield theory (Ebisuzaki/Tajima)

period ~ *M* ; luminosity ~*M*

N. Canac, K. Abazajian (2020)

Energy release by wakefield (e.g.M82 X-1)



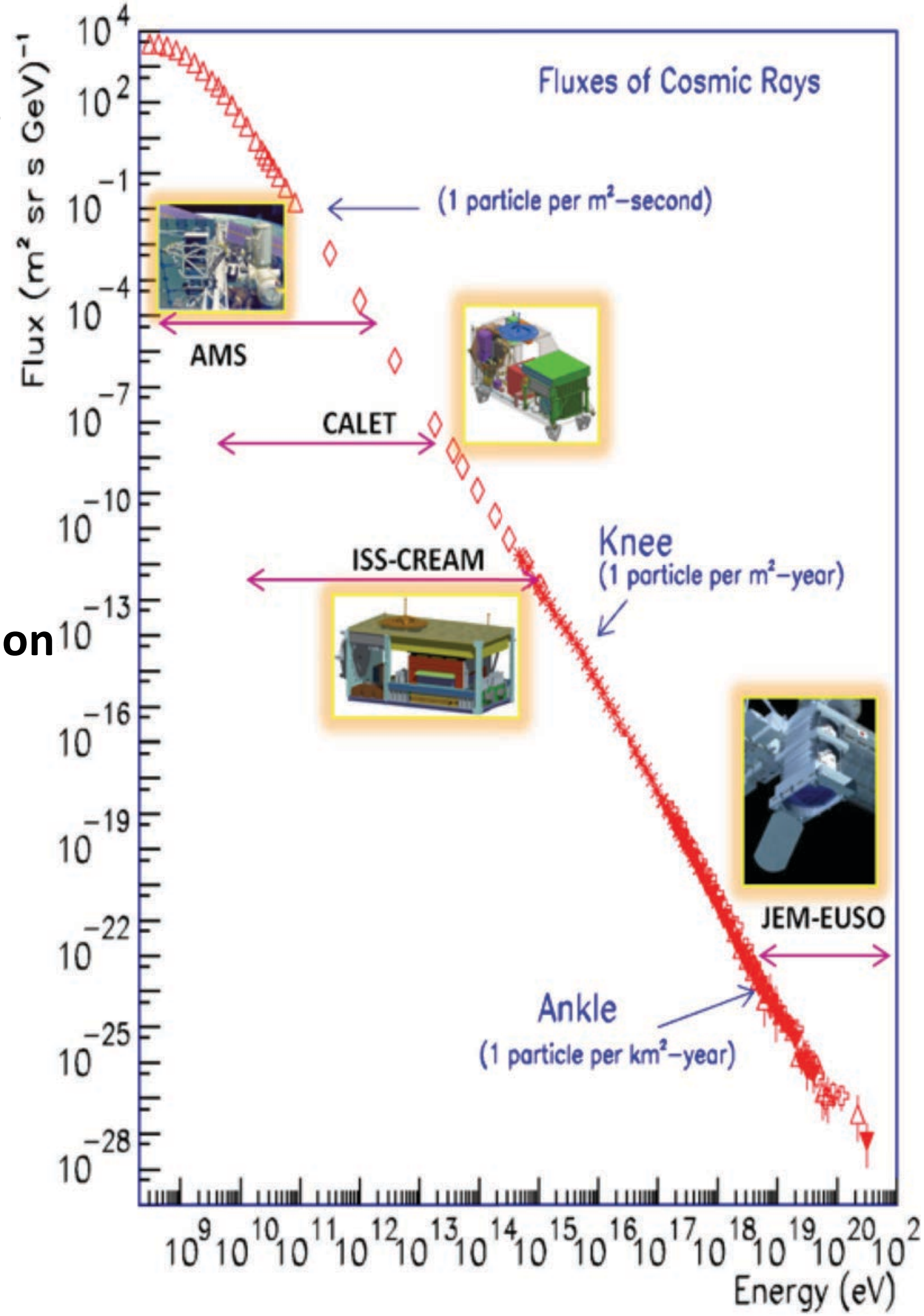
Nature’s wakefield accelerators in cosmos

3. Pinpointed high energy cosmic rays (and neutrinos)

Ultrahigh Energy Cosmic Rays (UHECR)

Fermi mechanism runs out of steam
- beyond 10^{19} eV
- due to synchrotron radiation

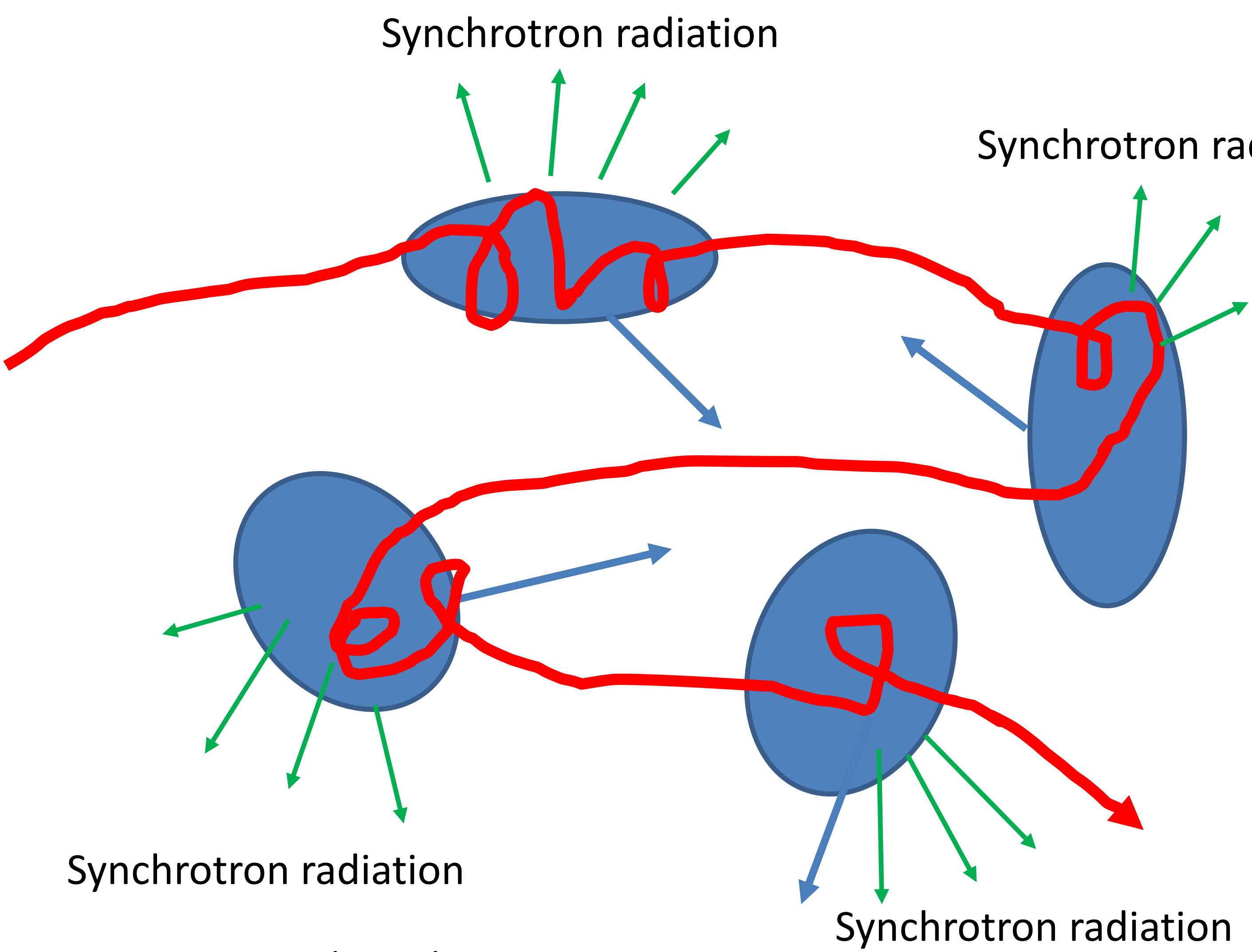
Wakefield acceleration
- comes in rescue
- prompt, intense, linear acceleration
- small synchrotron radiation
- radiation damping effects?

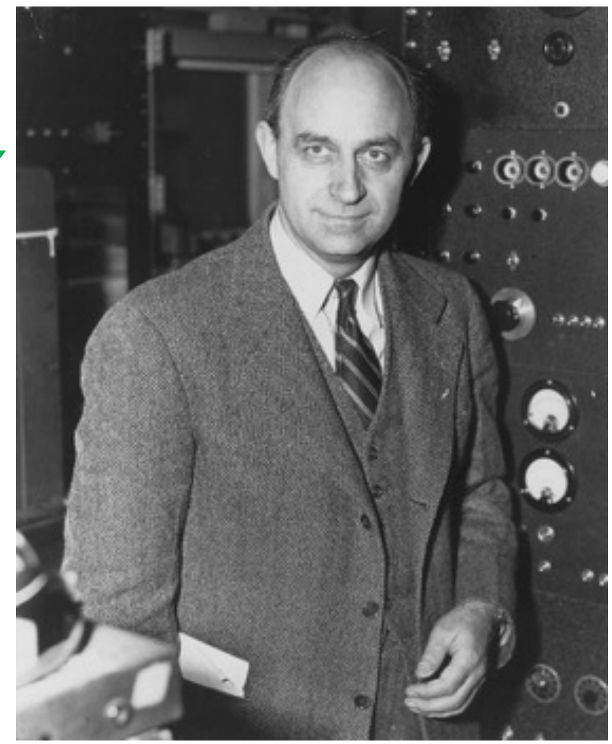


Fermi mechanism

incoherent

requires bending→synchrotron loss





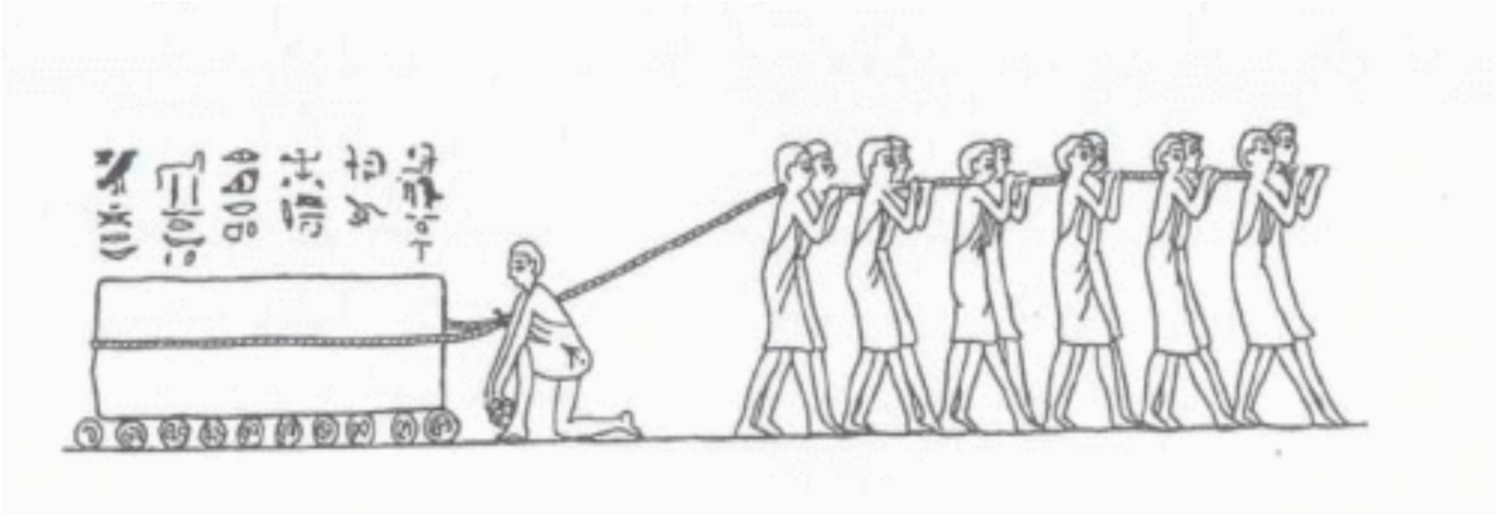
Enrico Fermi
By Department of Energy. Office of Public Affairs

E. Fermi, ApJ 119 (1954) 1.

Plasma's Collective Force / Modes

Collective force ~N^2 (nonlinear ← linear force ~N)

Coherent and smooth structure (not stochastic)



enhancement by $10^3 - 10^4$ (even by $\mathbf{10^{6-12}}$) >> interaction of one particle x one particle

Collective mode delivery (EM x plasma x B)←→ long-ranged force (gravity, EM)

what difference?

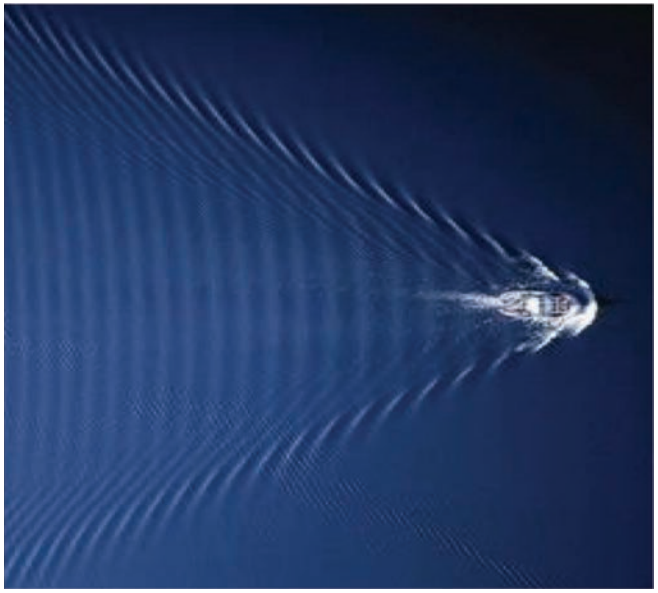
e.g. jet

e.g. galaxy-galaxy interaction

Laser Wakefield (LWFA):

Wake phase velocity >> water movement speed, maintains **coherent** and **smooth** structure

Tsunami phase velocity becomes ~0, causes **wavebreak** and **turbulence**

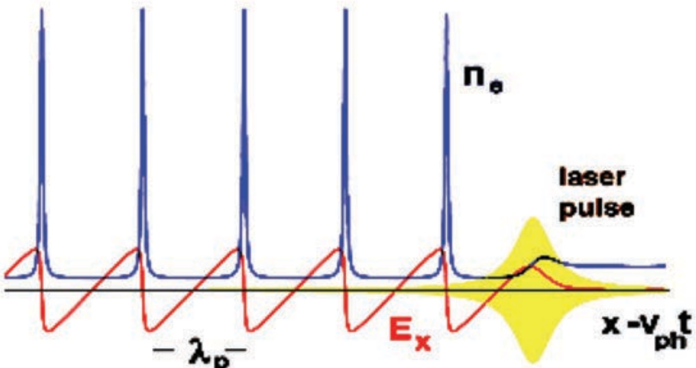


vs

Strong beam (of laser / particles) drives plasma waves to saturation amplitude: $E = m\omega v_{ph} / e$

No wave breaks and wake **peaks** at v≈c

Wave **breaks** at $v < c$



← relativity regularizes (*relativistic coherence*)

a_0 ~ 10 >> 1 (relativistic wave)

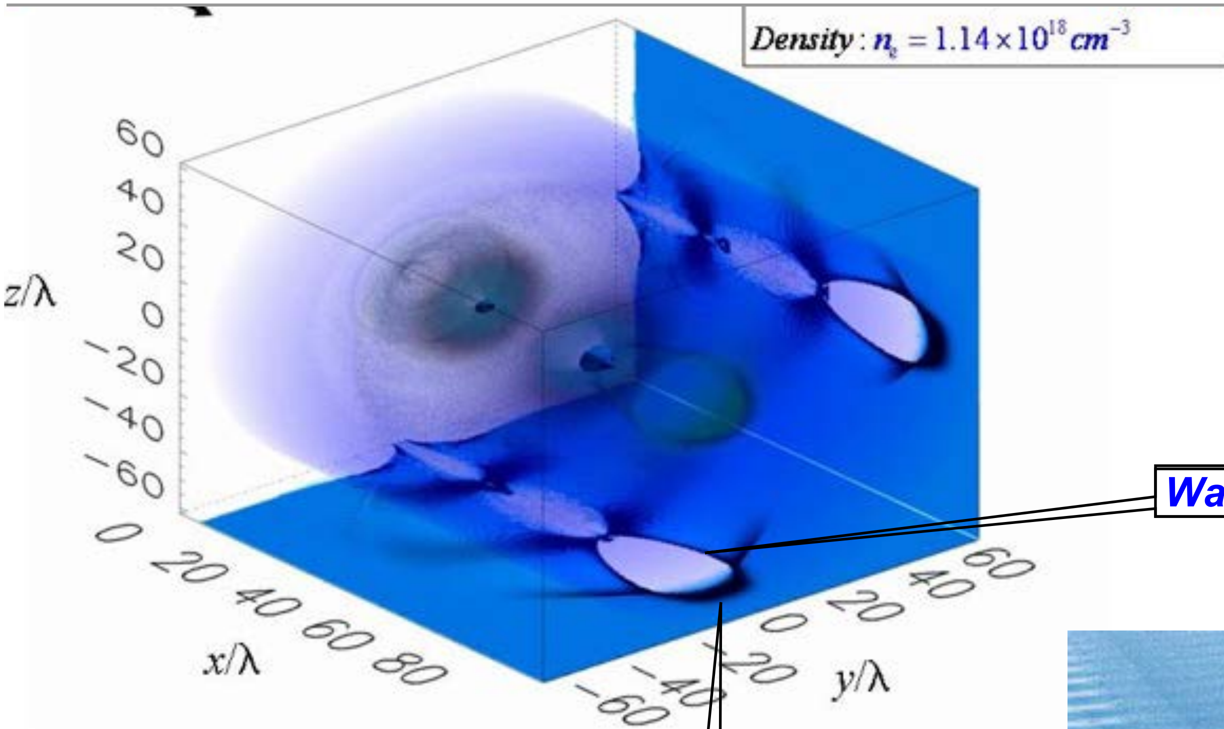
Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c / e$ (~ GeV/cm)

High phase velocity paradigm

Tajima, Yan, Ebisuzaki (2020)

unstable, chaotic	robust, coherent
Low phase velocity	**High phase velocity**
Plasma tends to be unstable	Stable state exists (Landau-Ginzburg state)
$v_{ph} \sim v_{th}$	$v_{ph} \gg v_{th}$
Mode interacts with bulk plasma (Landau resonance)	Mode insulated from bulk plasma
Mode-mode coupling ➔ More modes ➔ More turbulence	Mode maintains coherence
Strongly nonlinear regime (large Reynolds' number) → strong turbulence	Strongly nonlinear regime → strongly coherent Relativistic effects further strengthen coherence
Plasma fragile → anomalous transport, structure disintegration	Plasma cannot be destroyed, structures are formed. Violence tolerated
Trapping: $v_{tr} \lesssim v_{th} \sim v_{ph}$ $x_{tr} = \sqrt{\frac{cE}{B}\frac{L_s}{k_y v_\parallel}}$ [22]	Trapping: $v_{tr} = \sqrt{qE/mk}$ [13] If wave pumped, v_{tr} increases until $v_{tr} \sim v_{ph} \gg v_{th}$ → acceleration or injection Tajima-Dawson saturation: $E_{TD} = \frac{m\omega_p c}{e}$
Characteristic structure: Sheath	Characteristic structure: Wake
Energy gain: by coherent accumulation of electron charges of the sheath (energy amplification of sheath charge accumulation $2\alpha + 1$ (coherence parameter α) [18]	Energy gain: by energy amplification over the trapping width $v_{tr} \sim v_{ph}$ (Lorentz transform factor $2\gamma^2 = 2\ n_{cr}/\ n_e$)

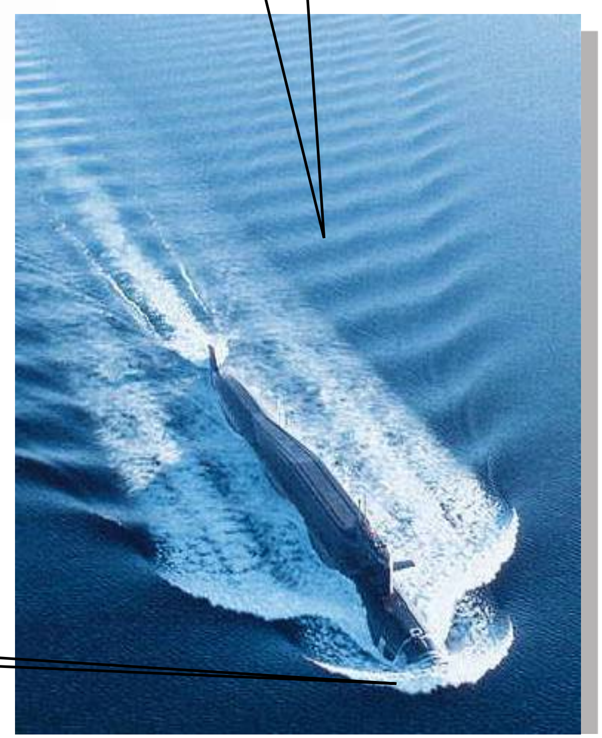
Laser-driven Bow and Wake



(Bulanov, Esirkepov)

Wakefield acceleration

Wake Wave

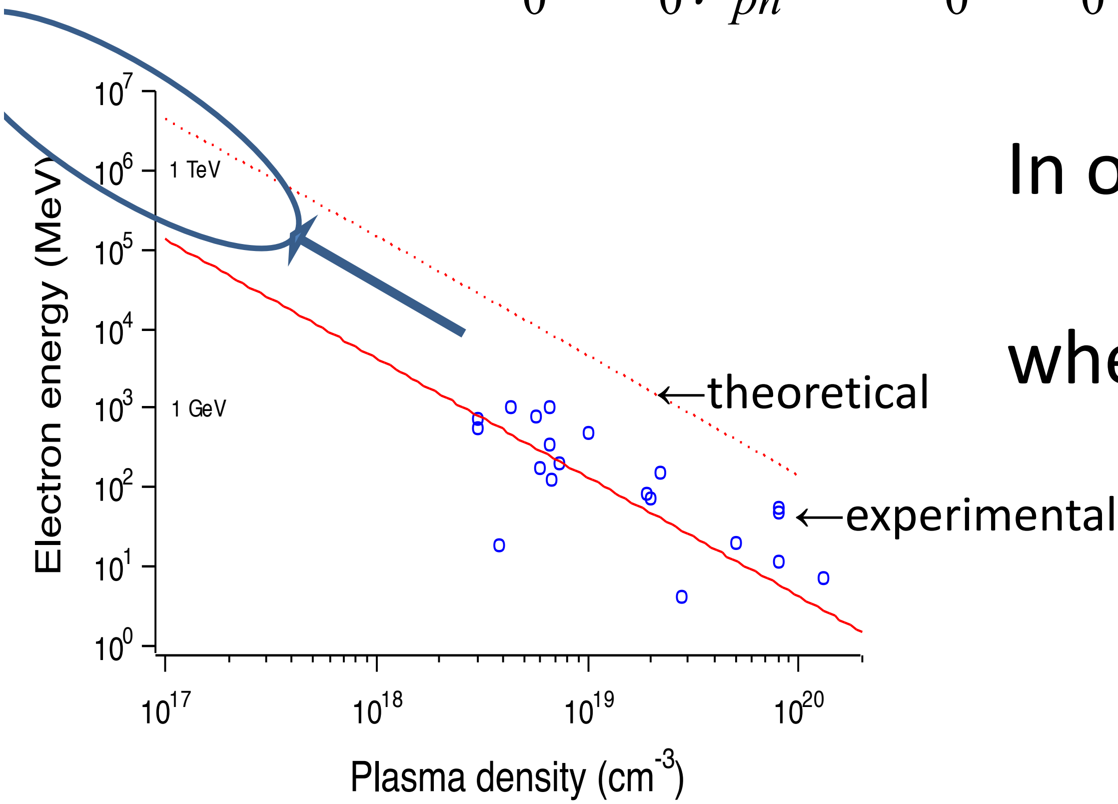


Bow Wave

Ponderomotive acceleration

Universal Theory of Wakefield toward extreme energy

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (when 1D theory applies)



In order to avoid wavebreak,

$$a_0 < \gamma_{ph}^{1/2},$$

where

$$\gamma_{ph} = (n_{cr} / n_e)^{1/2}$$

n_{cr} $=10^{21}$ (fs photon (laser))

= 10 (10^3 s wave in disk)

n_e = 10^{18} (gas)

= 10^{-2} (gas in the jet)

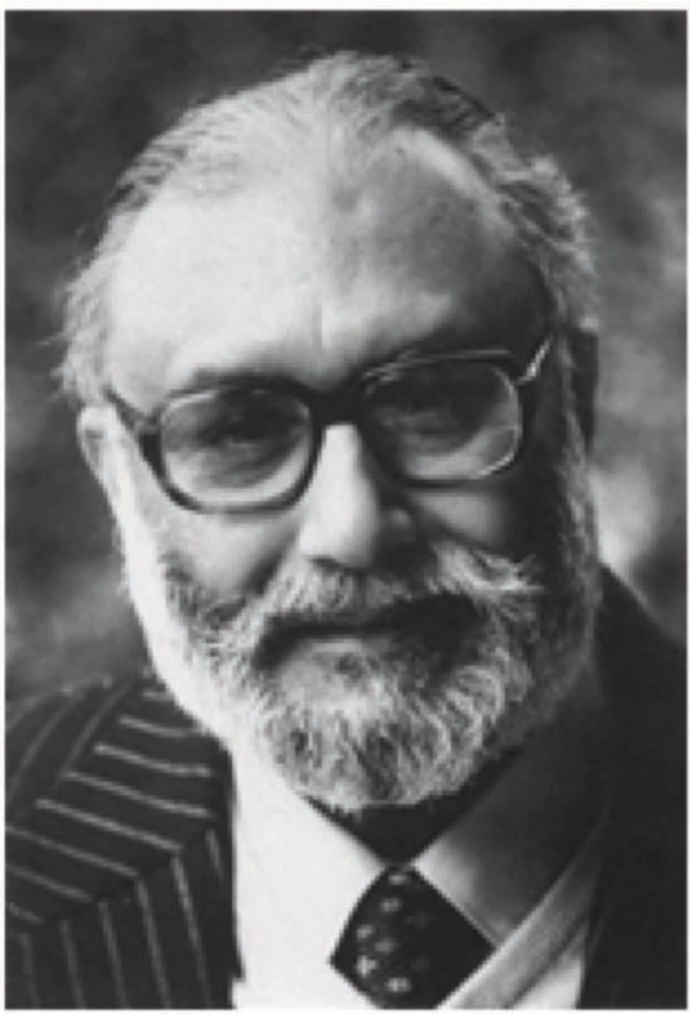
$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

dephasing length

$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

pump depletion length

The late Prof. Abdus Salam (1981)



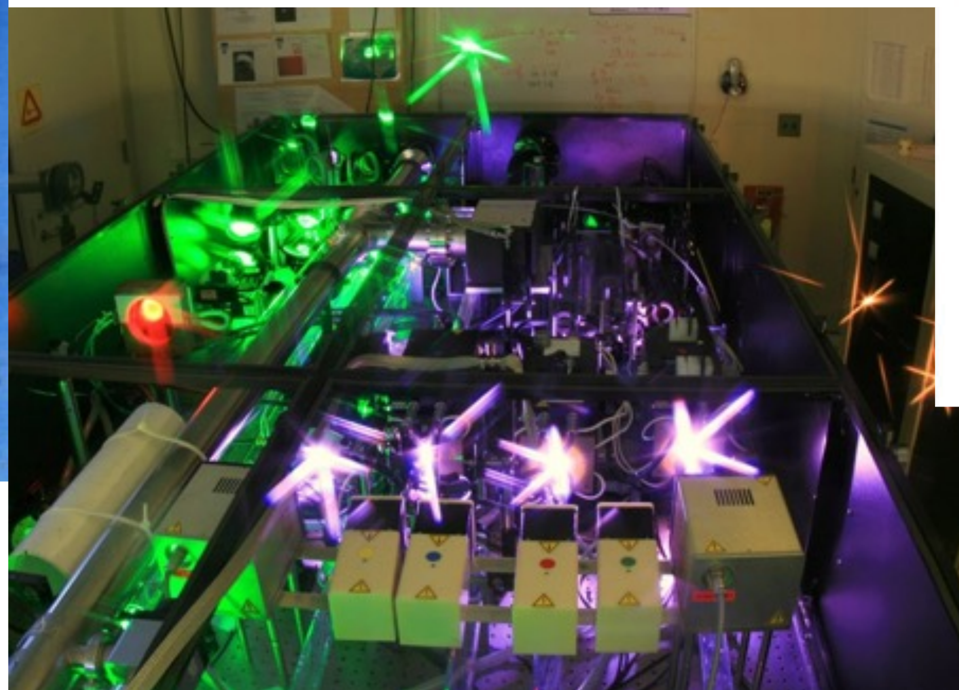
At ICTP Summer School (Trieste,1981), Prof. Abdus Salam summoned me and discussed
about laser wakefield acceleration.

Salam: *'Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged'*. **(1981)**

He organized the Oxford Workshop on laser wakefield accelerator in 1982.

Demonstration (1994), realization, and applications of laser wakefield accelerators

(2004)



(Michigan)

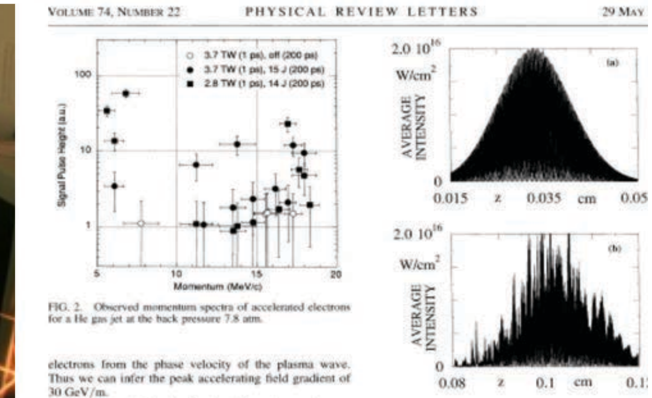
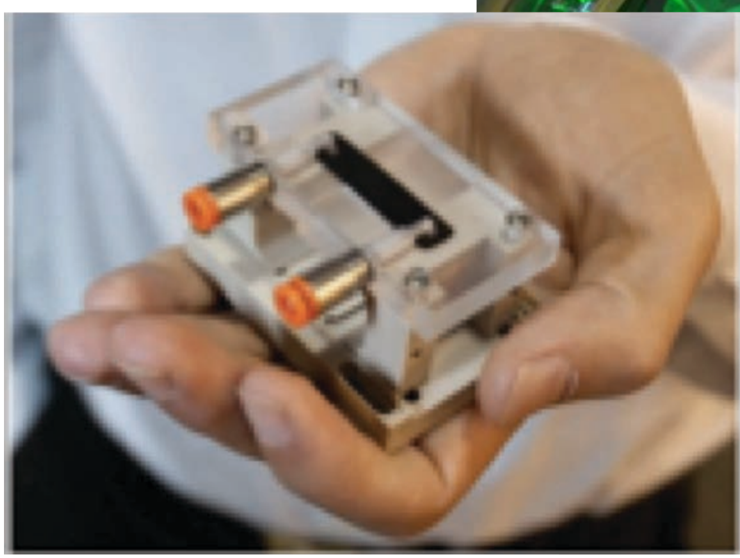

VOLUME 74, NUMBER 22 PHYSICAL REVIEW LETTERS 29 MAY

FIG. 2. Observed momentum spectra of accelerated electrons for a He gas jet at the back pressure 7.8 atm.

electrons from the phase velocity of the plasma wave. Thus we can infer the peak accelerating field gradient of 30 GeV/m.

Nakajima, et al (1994, 1995)



4 GeV laser accelerator LBL

←

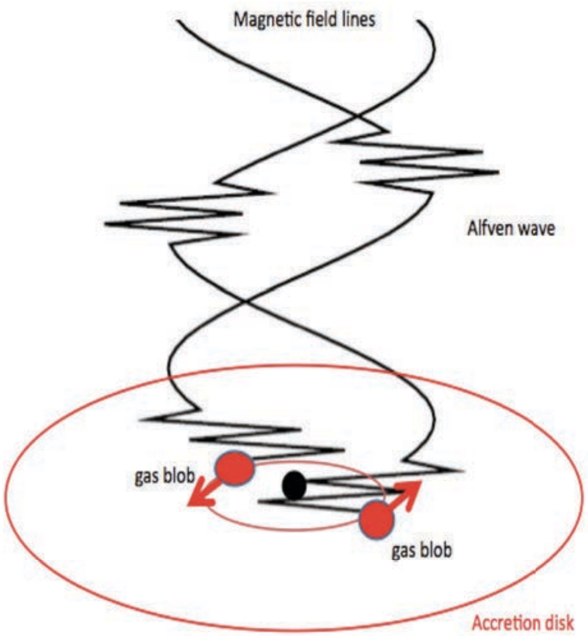
3GeV Synchrotron SOLEIL

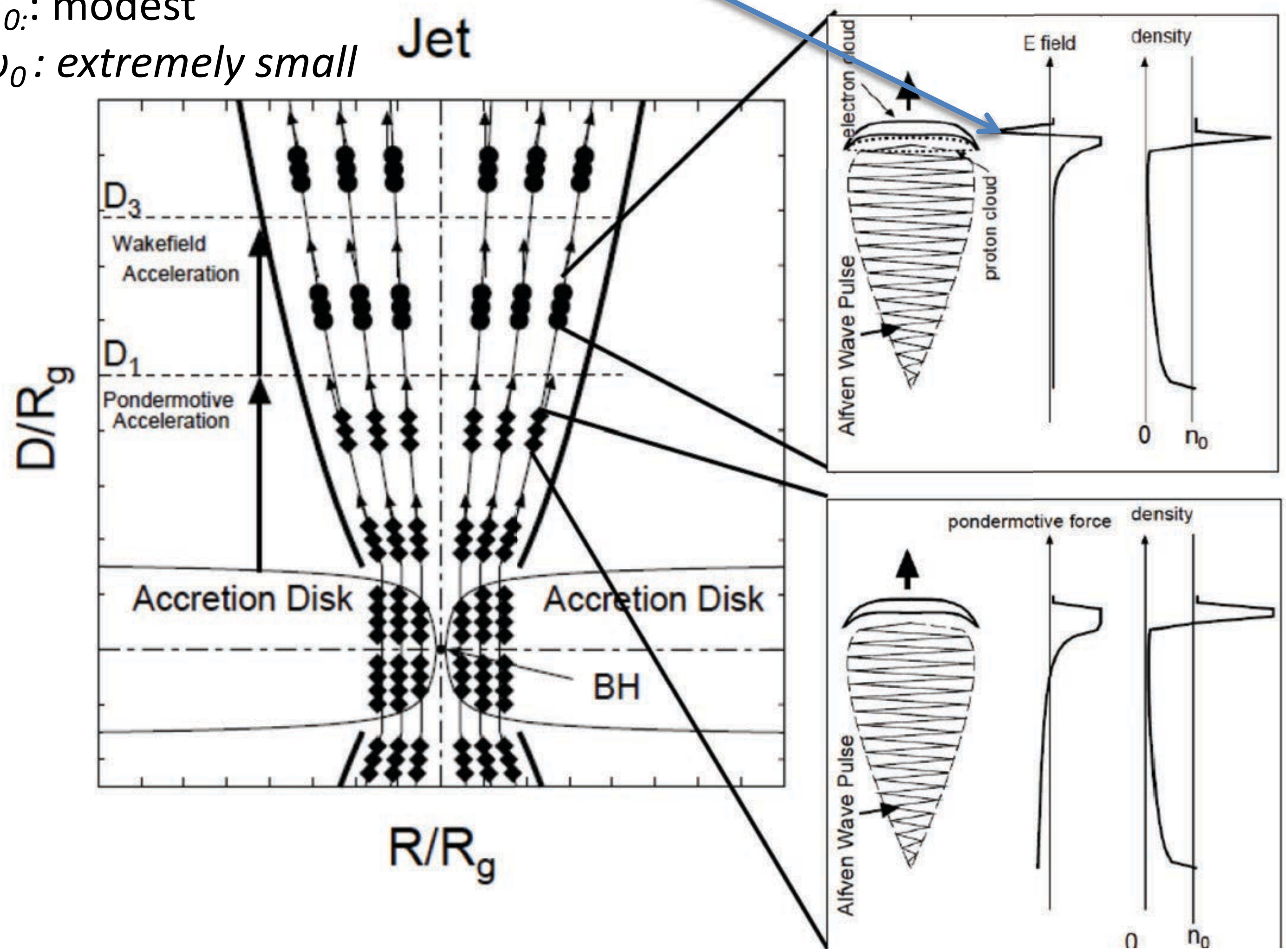
Astrophysical wakefield acceleration: Superintense Alfven Shock in the Blackhole Accretion Disk toward ZeV Cosmic Rays ($a_0 \sim 10^6 - 10^{10}$, large spatial scale)

$a_0 = eE_0 / mc\omega_0 >> 1$

E_0: modest

ω_0: extremely small

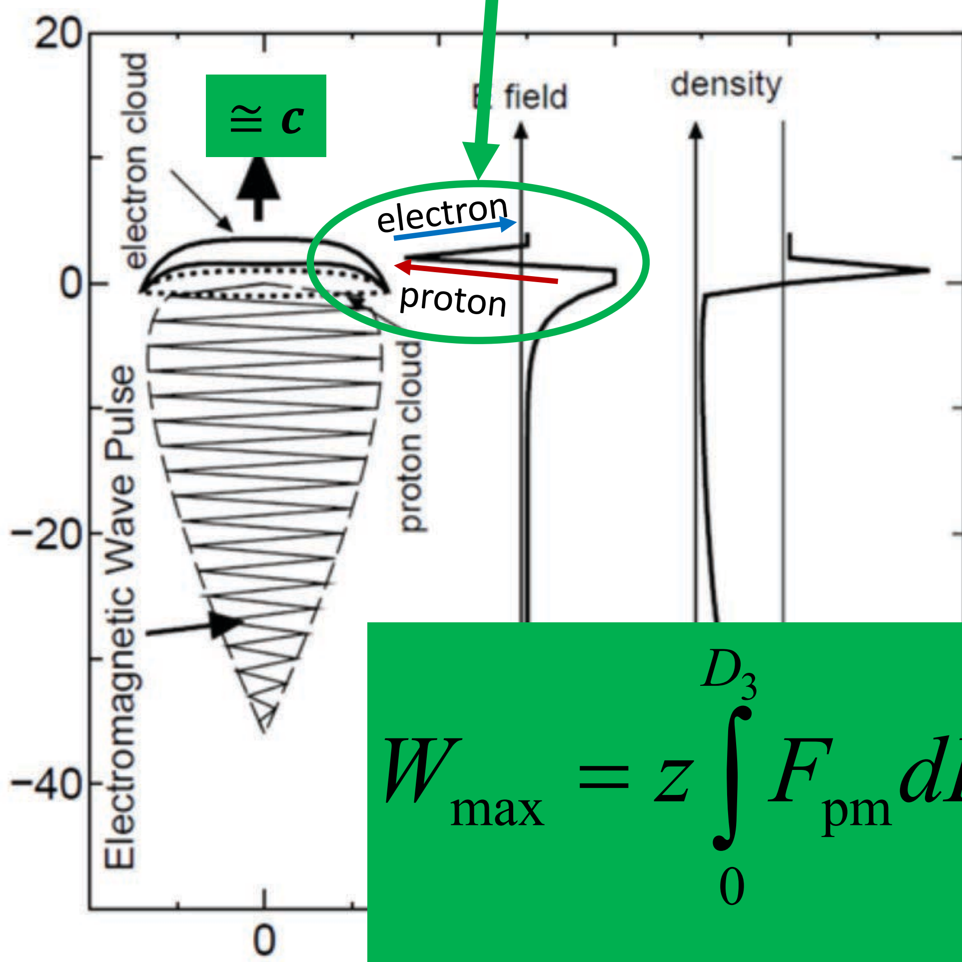




Ebisuzaki and Tajima, Astropart. Phys.(2014)

Wakefield Acceleration

Co-linear acceleration by electrostatic field

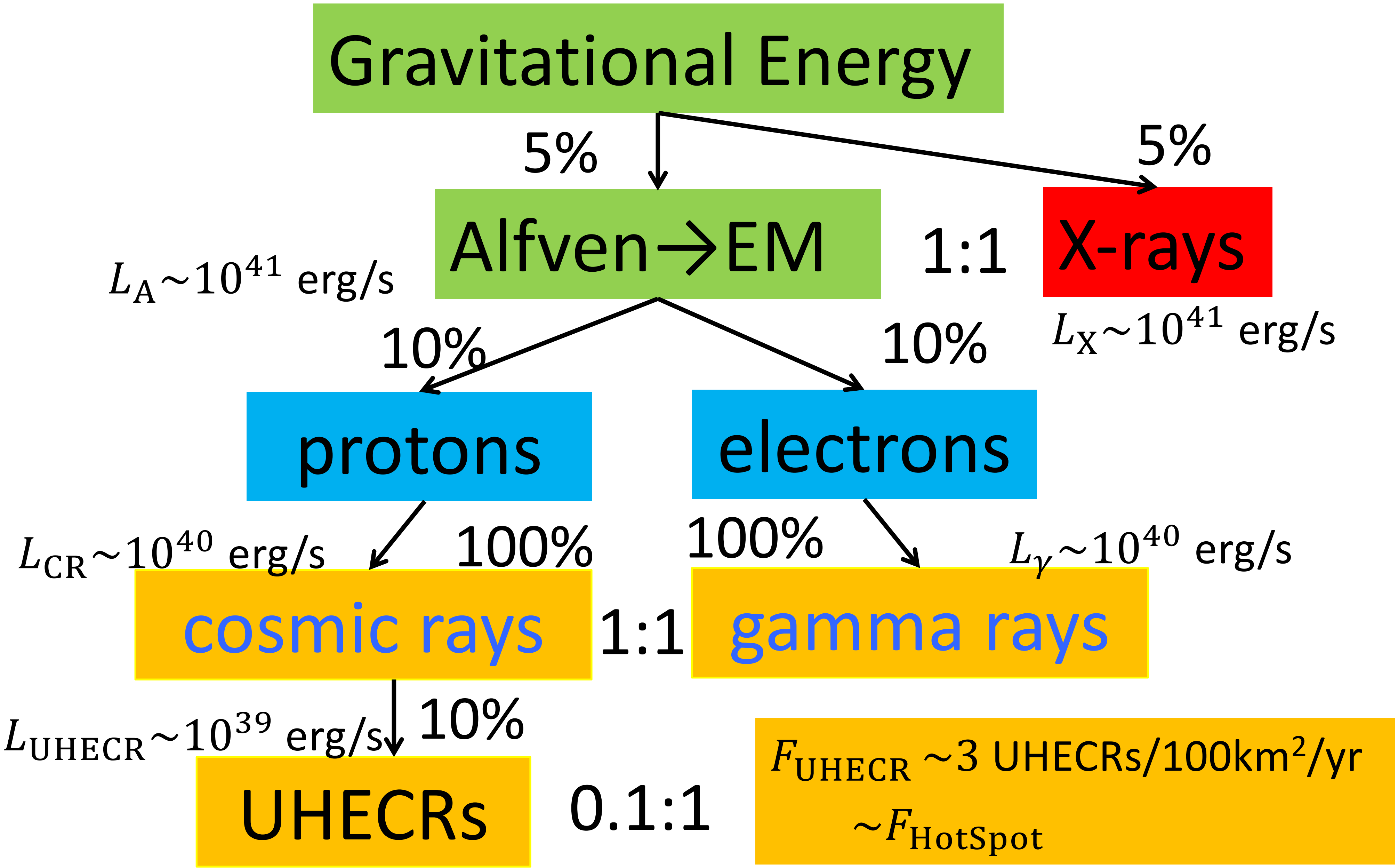


$$W_{\mathrm{max}} = z \int_0^{D_3} F_{\mathrm{pm}} \, dD$$

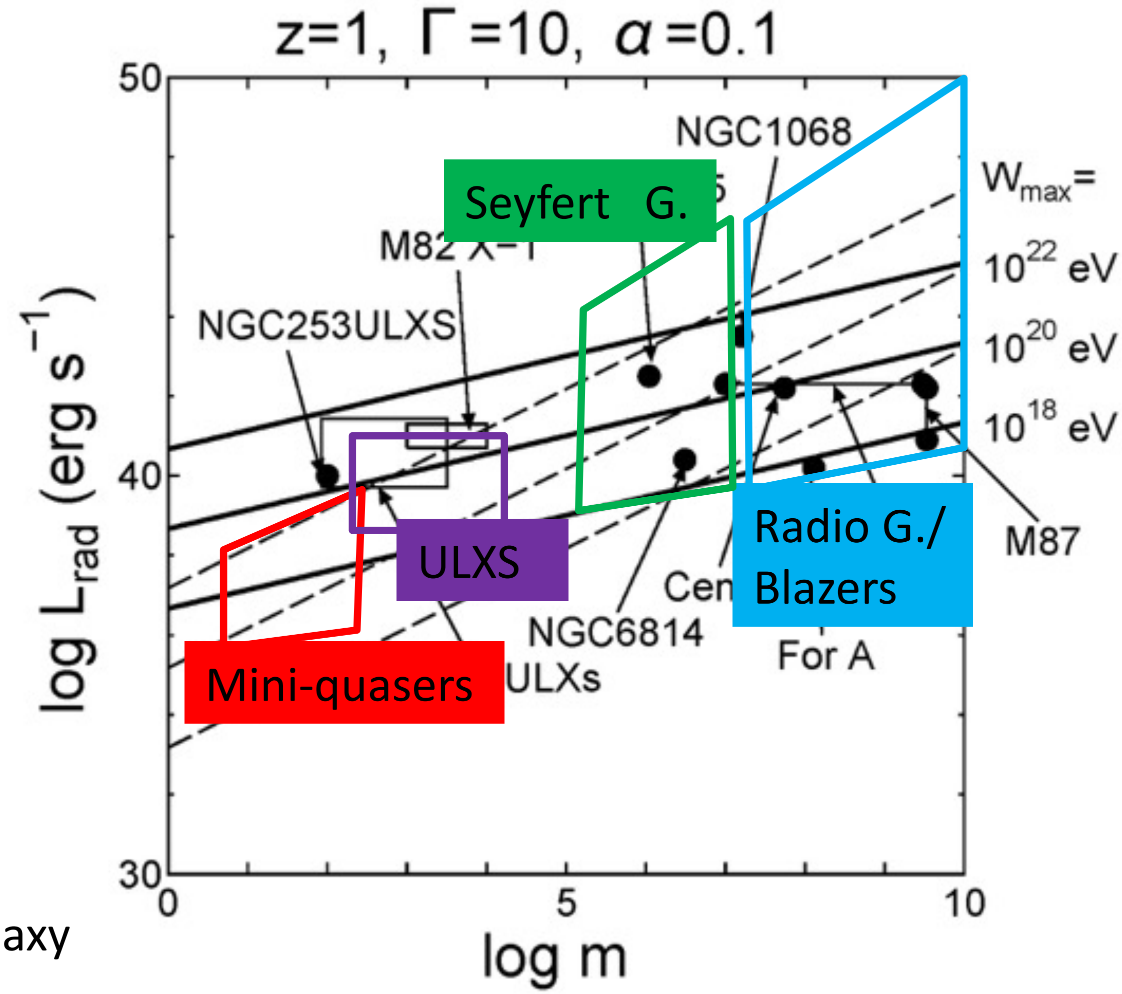
$$F_{\mathrm{pm}} = \Gamma m_e c a_0 \omega_A$$

- **Stable acceleration structure**
  - Coherent and Strong Field
  - Moving in $\cong c$
  - 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

Energy release by wakefield



cosmic ray acceleration and gamma-ray emission

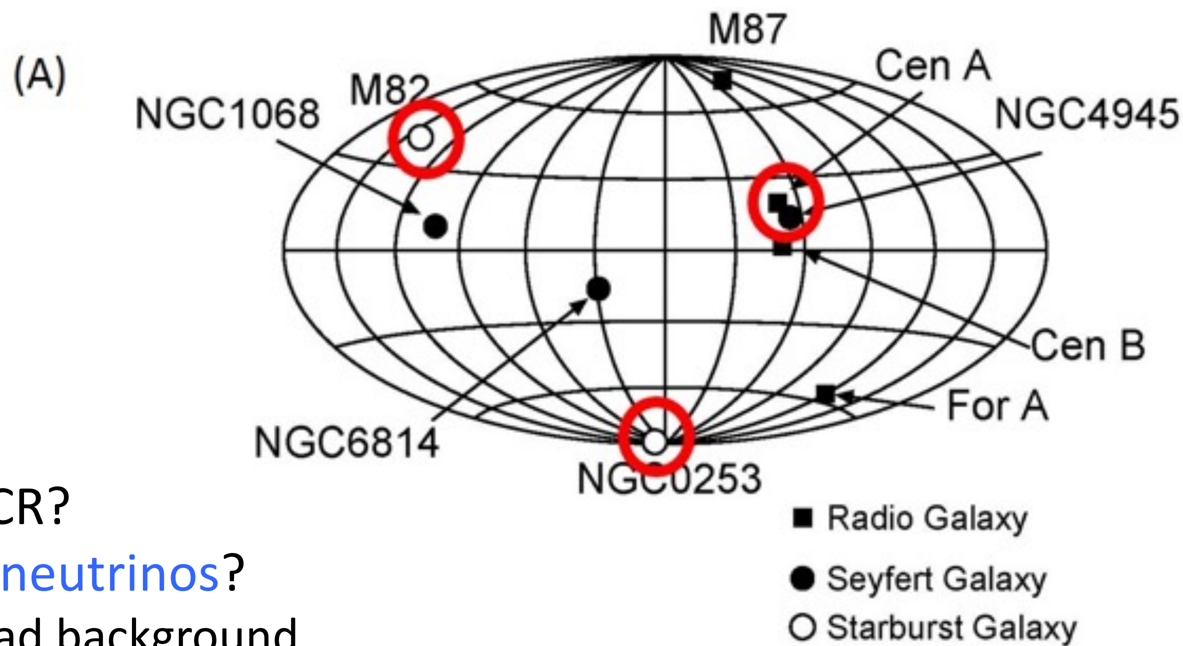


Miniquasars:
can be in our Galaxy

Ebisuzaki, Tajima
EPJ **223**, 1113(2014);
(2020)

BH Astronomy with Ultra High Energy CRs

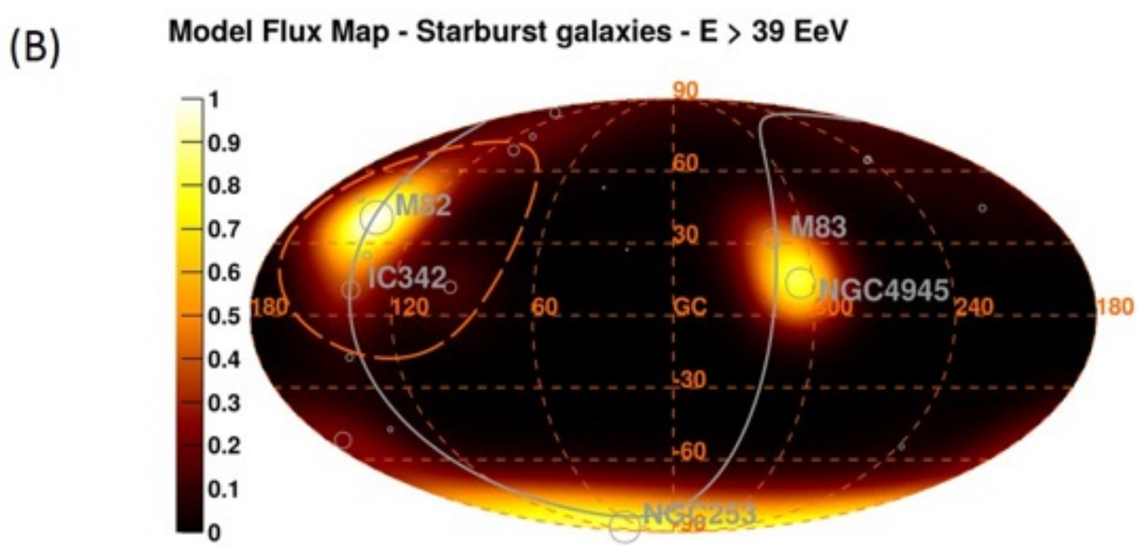
Brightest cosmic rays by **wakefields**



Localized UHECR?

thus **Localized** neutrinos?

not as a spread background



Conclusions

- **Wakefield:** demonstrated ultrafast pulses, coherent collective (robust) (GeV/cm) excitable in labs (since 1994).
- Nature: more evidence of wakefields emerging
- **NS-NS collision**: GW followed by **γ-emissions**
- **Blazars: episodic γ-emissions** ← **wakefield** accelerated electrons ← accretion disk MRI triggered
- Nature's violent phenomena = brightest spots for large and coherent actions by wakefield
- → **pinpointed UHECRs** (and high energy neutrino) arrivals
- **Gravity + plasma + B** (under certain conditions) → plasma's theater to show **huge**, robust, highest energy, and **coherent** phenomenon of s.a. wakefields

Thank you for joining!
Stay healthy!

Nature’s wakefield accelerators in cosmos