Wakefield Acceleration

EPS
Alfven Prize Lecture
July 8, 2019

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Norman Rostoker Chair Professor
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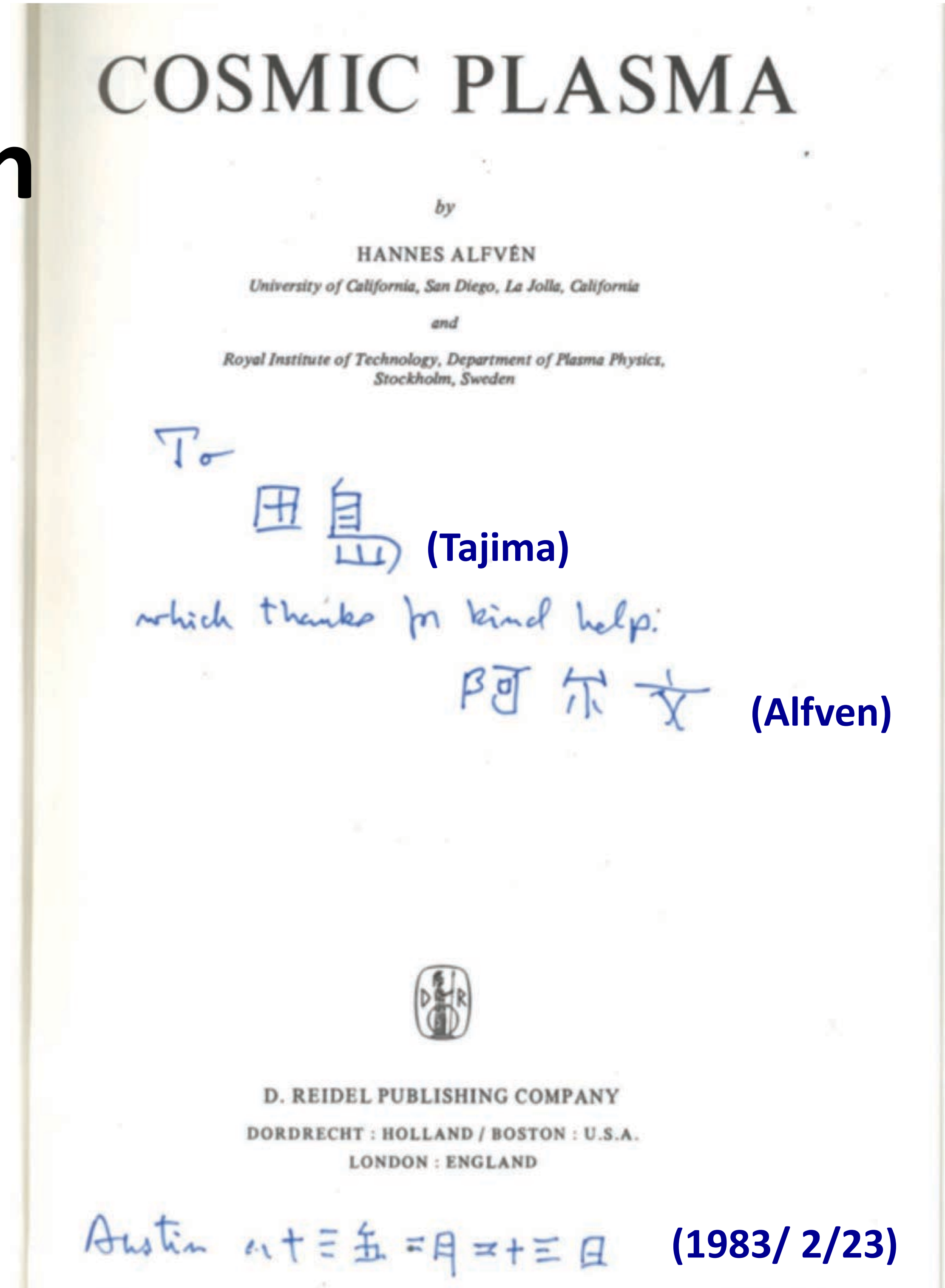
Followed by Prof. Victor Malka’s talk

collaboration: G. Mourou, K. Nakajima, S. Hakimi, S. Bulanov, T. Ebisuzaki, M. Zhou, A. Chao, K. Abazajian, X. M. Zhang, D. Farinella, P. Taborek, F. Dollar, J. Wheeler, Y.M. Shin, V. Shiltsev, N. Naumova, W. J. Sha, J. C. Chanteloup, C. Barty, V. Malka

Imprints of Alfven

- Alfven waves
- cosmic plasma
- personal imprint
  - his signature
  - on his Colloquium day
  - at U. Texas at Austin
  - onto my precious book



COSMIC PLASMA

by

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and

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To

田島 (Tajima)

which thanks for kind help.

阿尔文 (Alfven)

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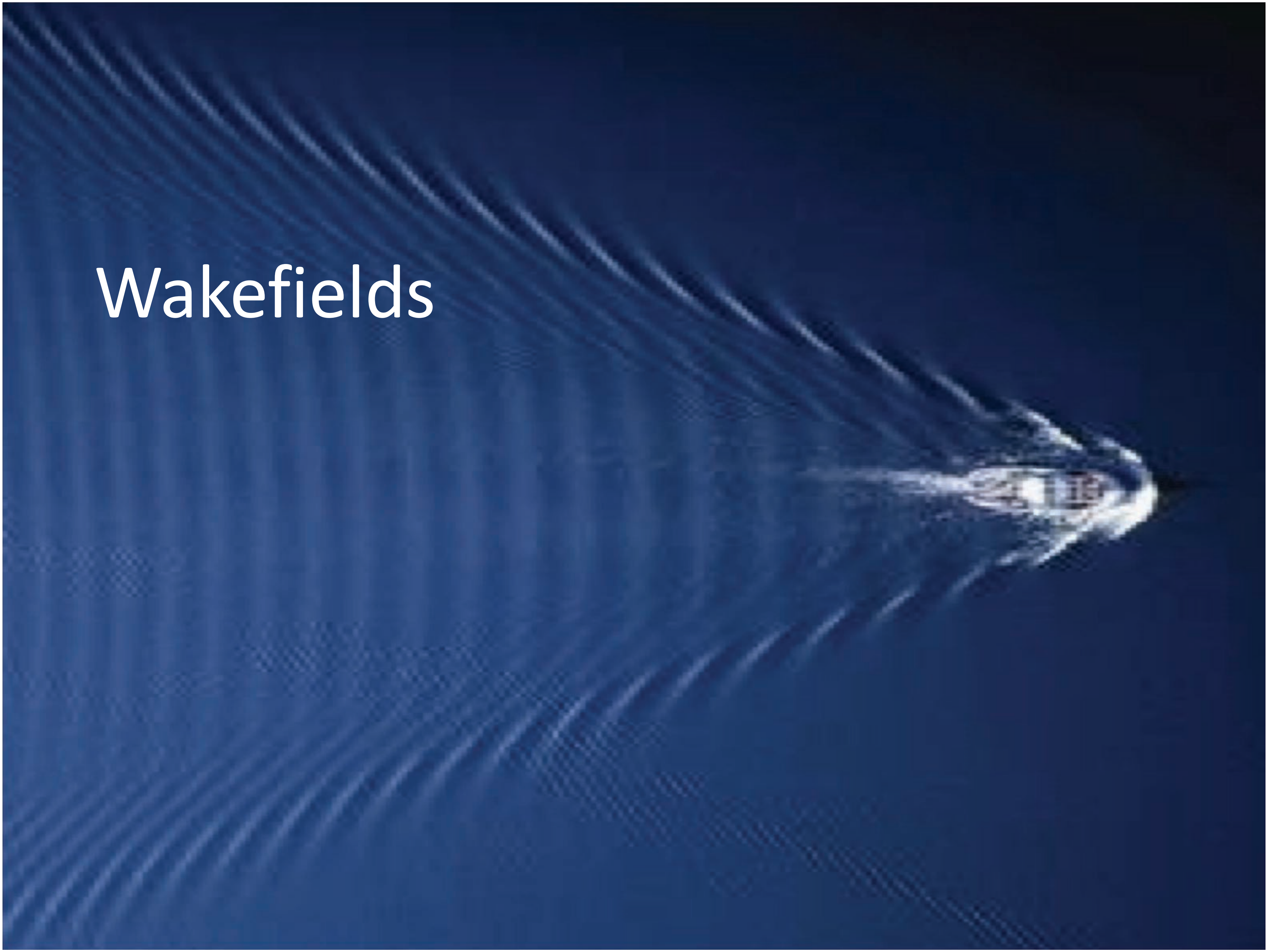
LONDON : ENGLAND

Austin 八十三年二月二十三日 (1983/ 2/23)

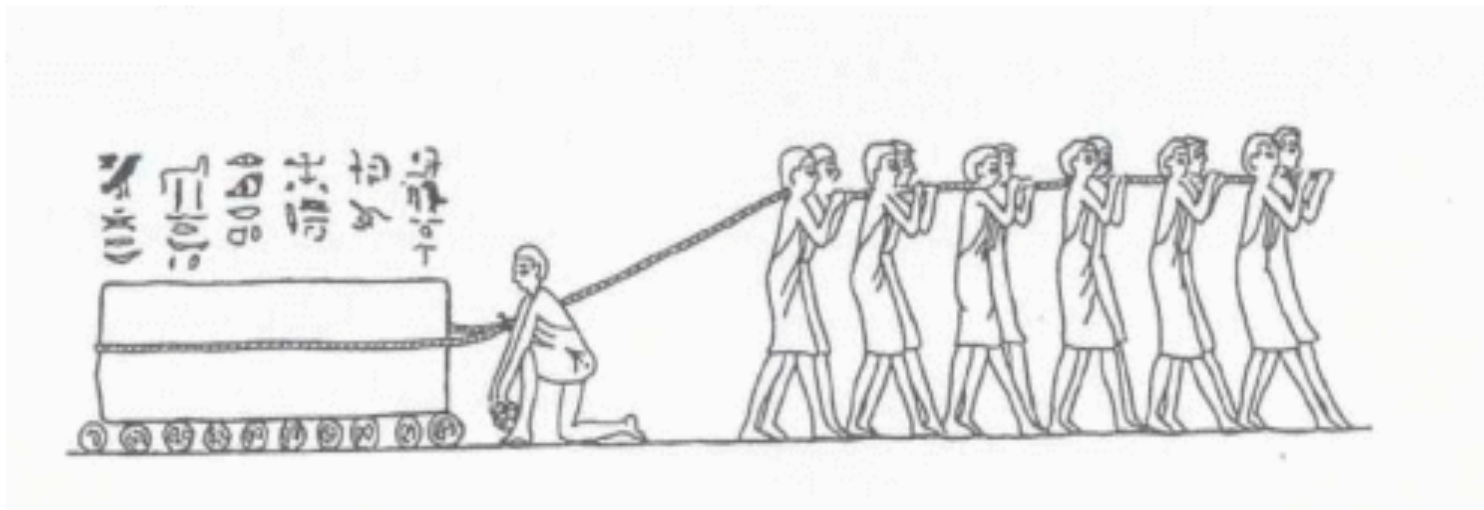
- Introduction to wakefields
- Single-cycled laser and “ TeV on a chip”
- Nature’s favorite acceleration: cosmic wakefield


Wakefields

Plasma accelerator driven by beam/pulse

Collective force ~$\boldsymbol{N^2}$ (nonlinear ← linear force ~N)

Coherent and smooth structure (not stochastic)



Plasma accelerator driven by laser (coherent photons)

compactification by 10^3 – 10^4 (even by 10^6) >> conventional accelerators

enabled by laser technology (intense ultrafast laser compression (Mourou et al.1985. 2013))

[particle beam-driven case: similar (if a bit lower)]

Acceleration by plasma wake waves: History

V. Veksler

Collective acceleration suggested:
Veksler (1956, CERN)
Driven by electron beam
(ion energy)~ (M/m)(electron energy)

Many experimental attempts of plasma acceleration (~60's -'70s, Rostoker's lab UCI included)
led to no such amplification
(ion energy)~ (2α+1)x(electron)

N. Rostoker

Sheath

Mako-Tajima (UCI) analysis (1978;1984)
sudden acceleration, ions untrapped, electrons return, while some run away
→ #1 **gradual acceleration necessary**

J. Dawson

Wake

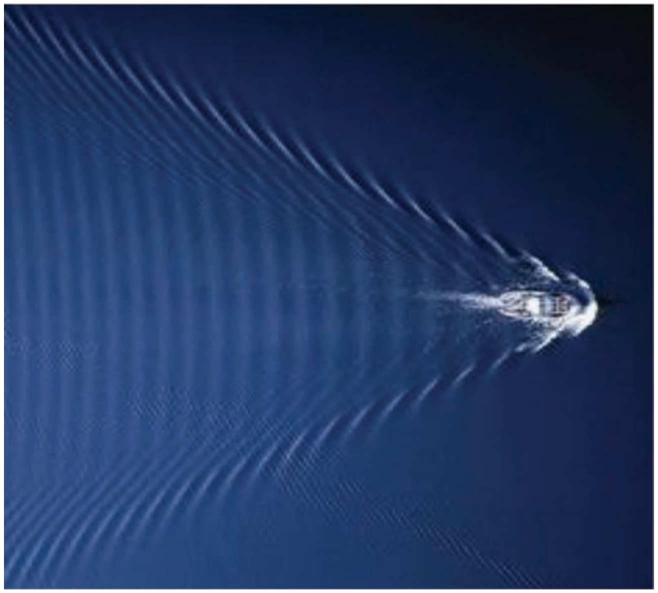
→ **Tajima-Dawson (1979, UCLA) wakefield**
#2 **electron acceleration** possible
with **trapping** **(with the Tajima-Dawson field)** with laser, more tolerant for sudden process

Target Normal Sheath Acceleration
laser-driven ion acceleration (LLNL,2000)
sudden acceleration, ions untrapped

Laser Wakefield (LWFA):

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

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

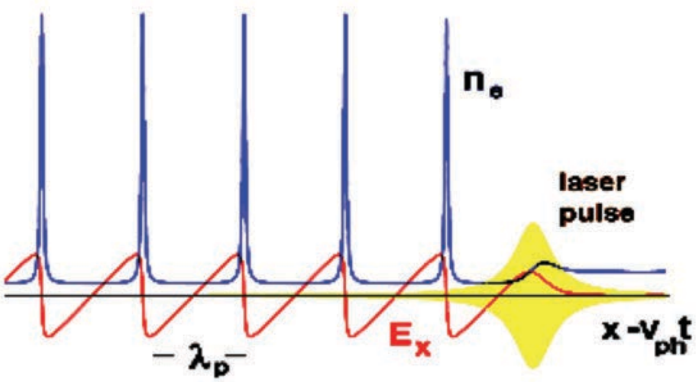


vs

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

No wave breaks and wake <u>**peaks** at v≈c</u>

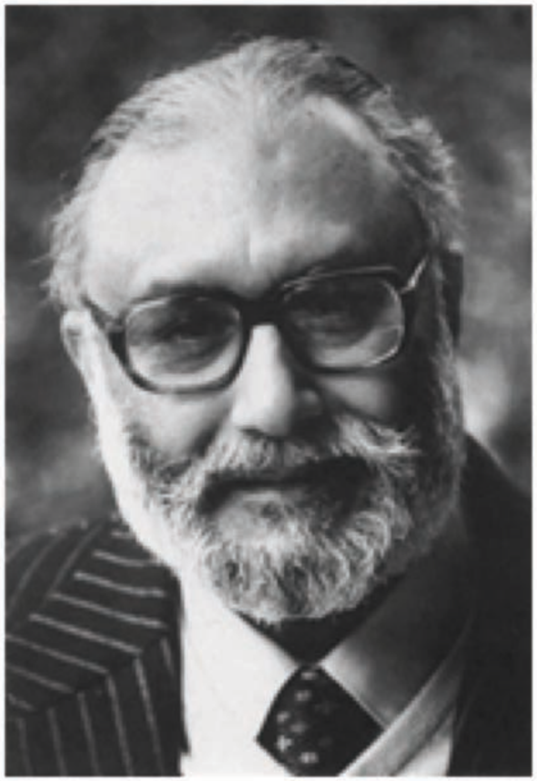
Wave **breaks** at v<c



← relativity regularizes (***relativistic coherence***)

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

The late Prof. Abdus Salam



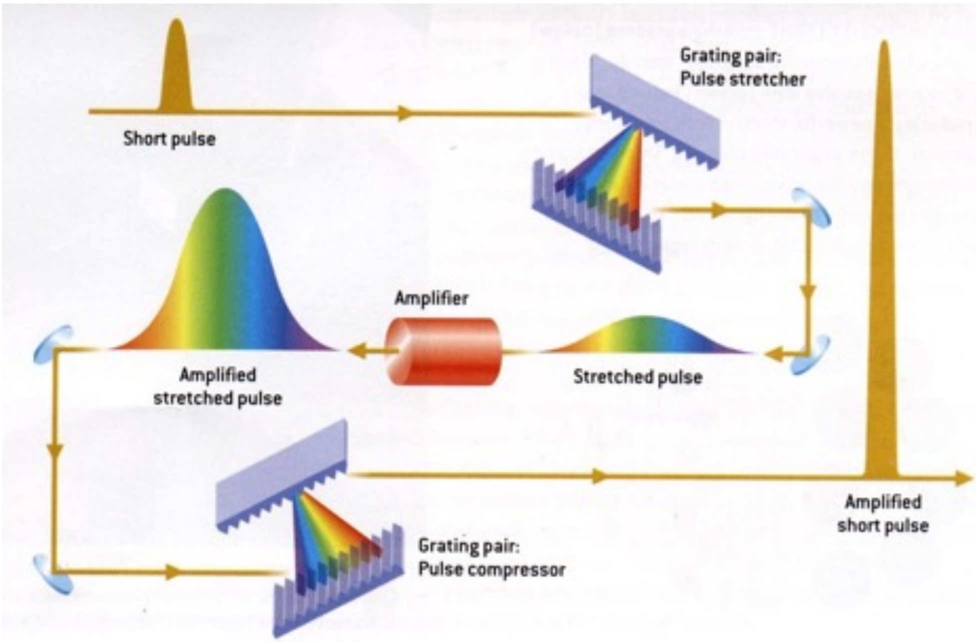
At ICTP Summer School (1981),
Prof. Salam summoned me and discussed
about laser wakefield acceleration.

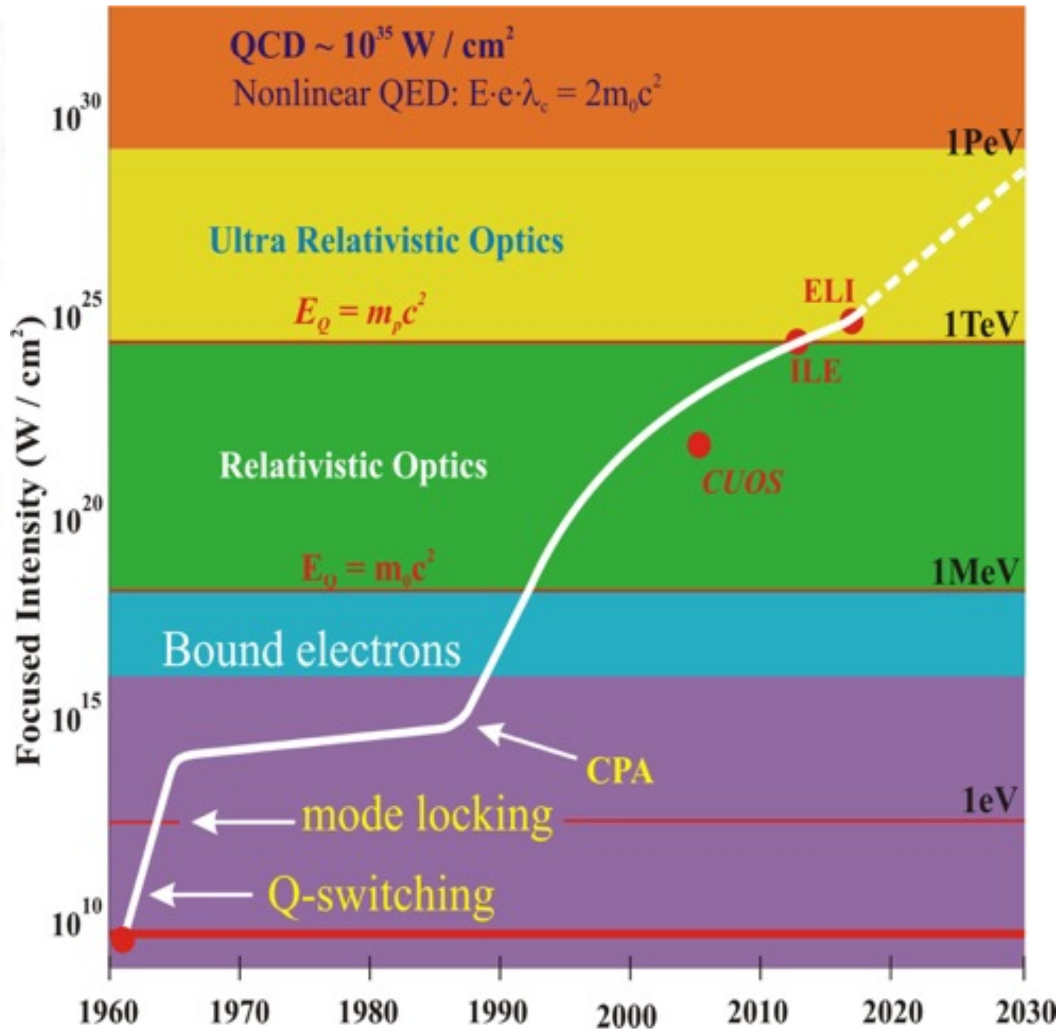
Salam*: 'Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged'*. (1981)

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

Effort: many scientists over many years to realize his vision / dream
High field science: spawned

Enabling technology: laser revolution



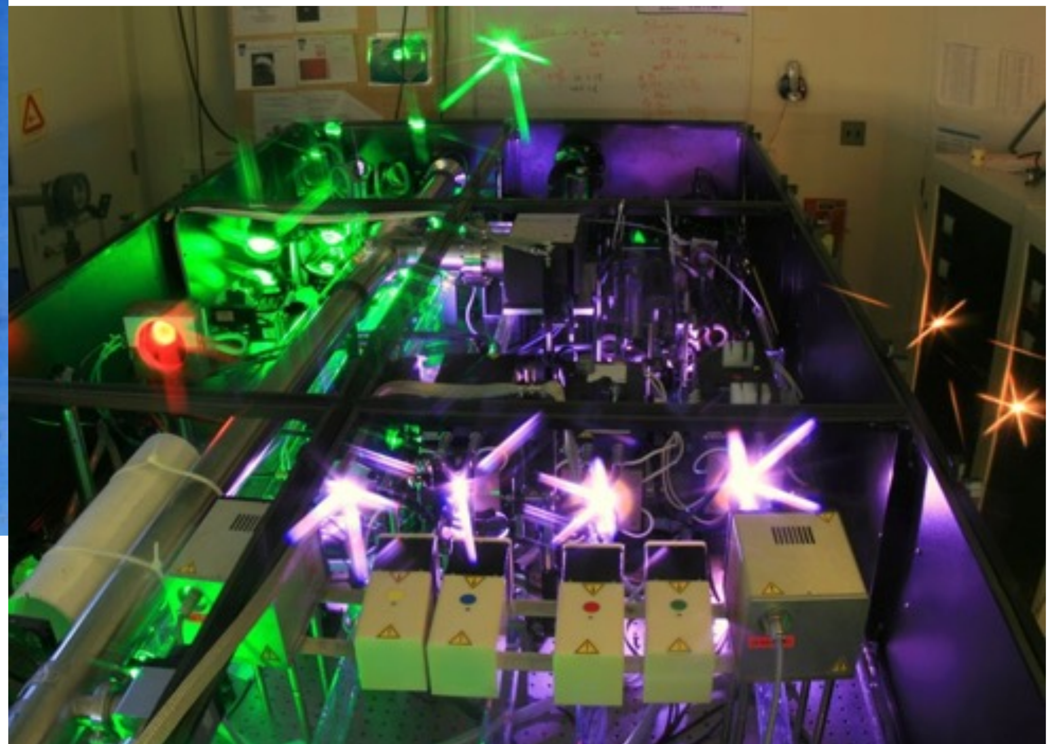


G. Mourou invented Chirped Pulse Amplification (1985)

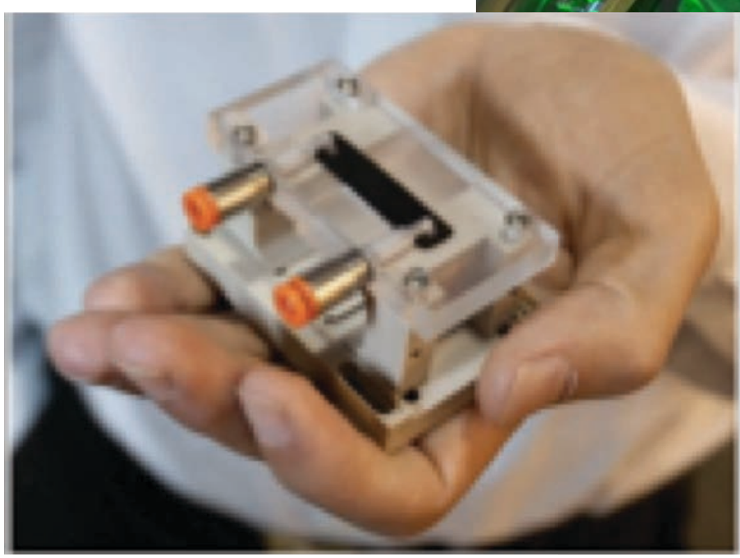
Laser intensity exponentiated since,

to match the required intensity for Tajima-Dawson's LWFA (1979)

Demonstration, realization, and applications of laser wakefield accelerators



(Michigan)



4 GeV laser accelerator LBL

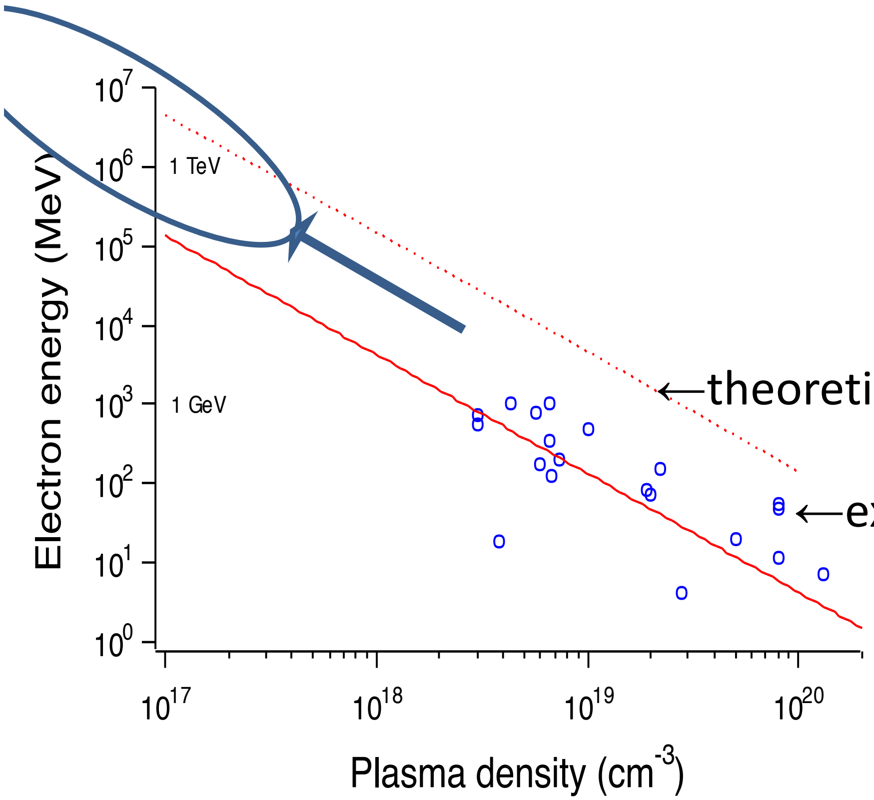
←

3GeV Synchrotron SOLEIL

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} $=10^{21}$ (1eV photon)

→ 10^{29} (10keV photon)

n_e = 10^{16} (gas) → 10^{23} (solid)

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

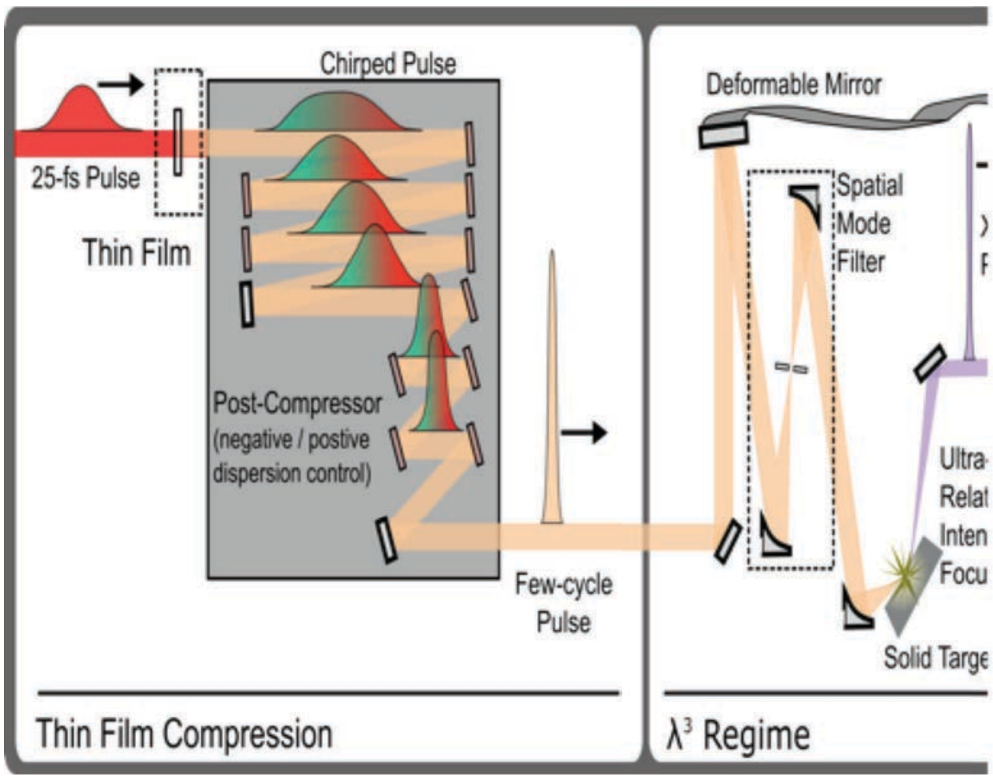
dephasing length

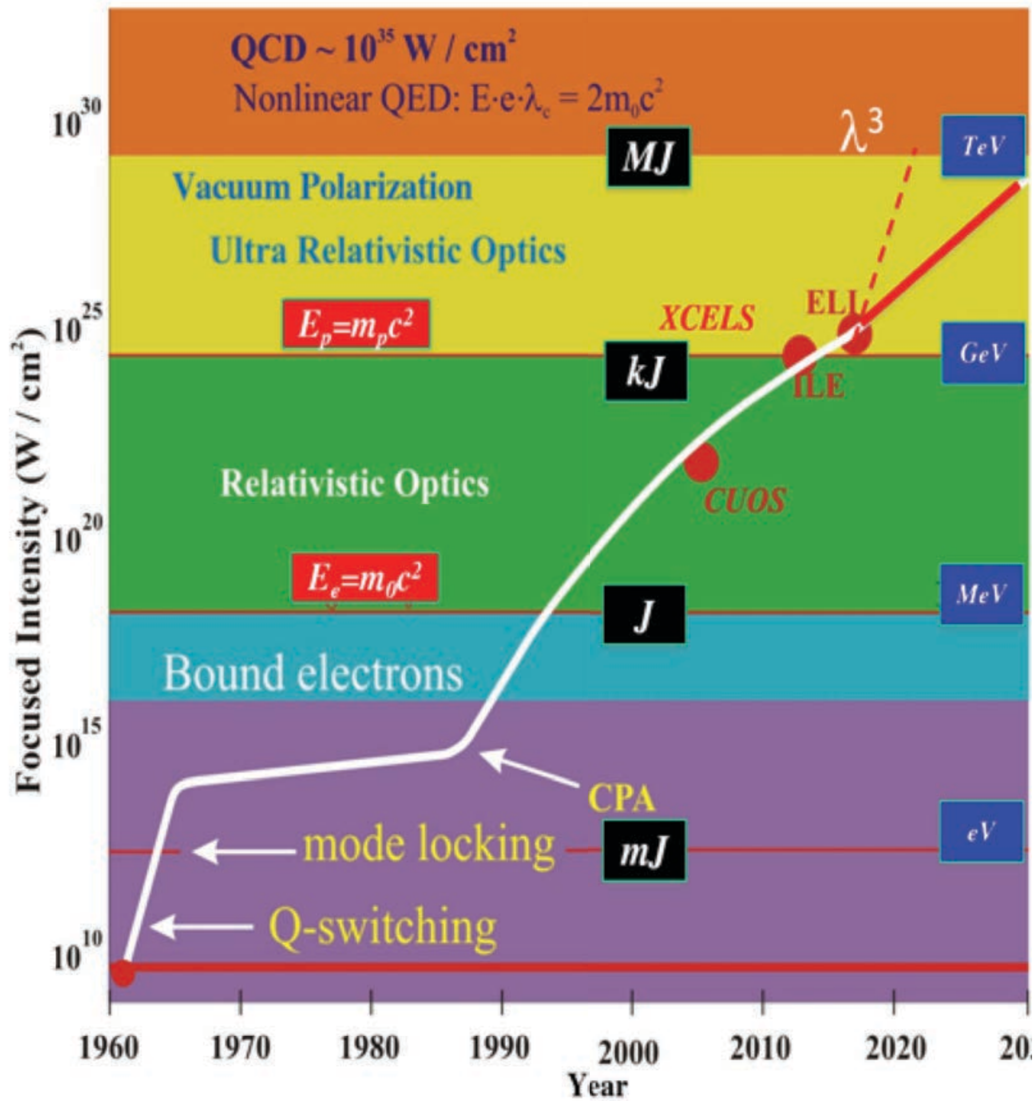
$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

pump depletion length

Single-cycled laser and “TeV on a chip”

Thin Film Compression and single-cycle optical and X-ray lasers



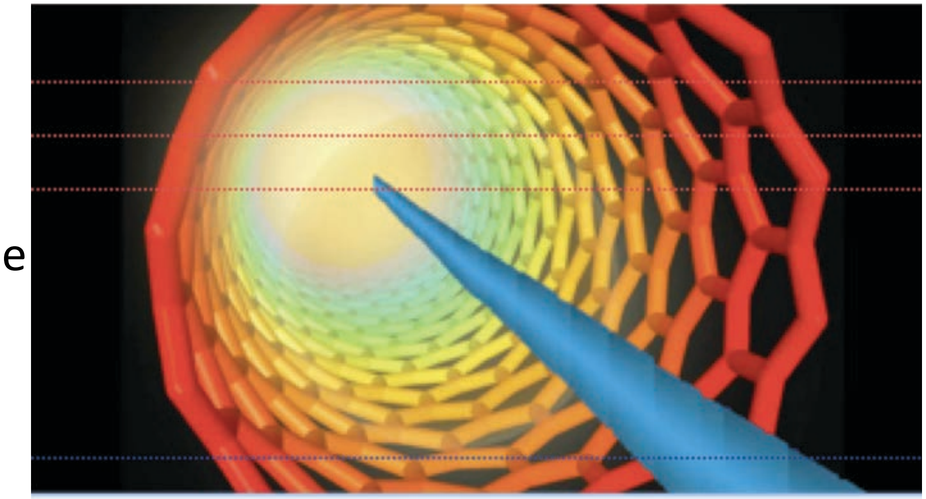


Mourou,et al. (2014)

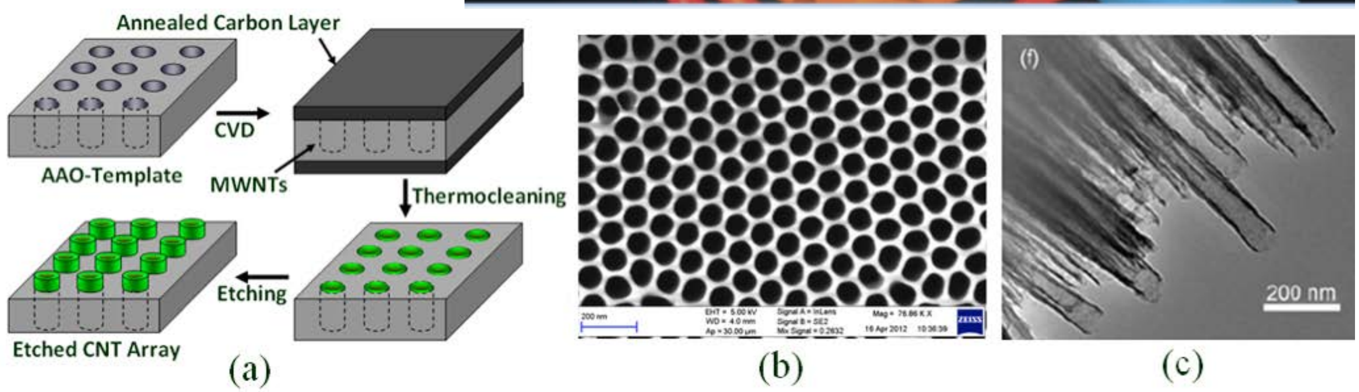
Tajima and Mourou (2002)

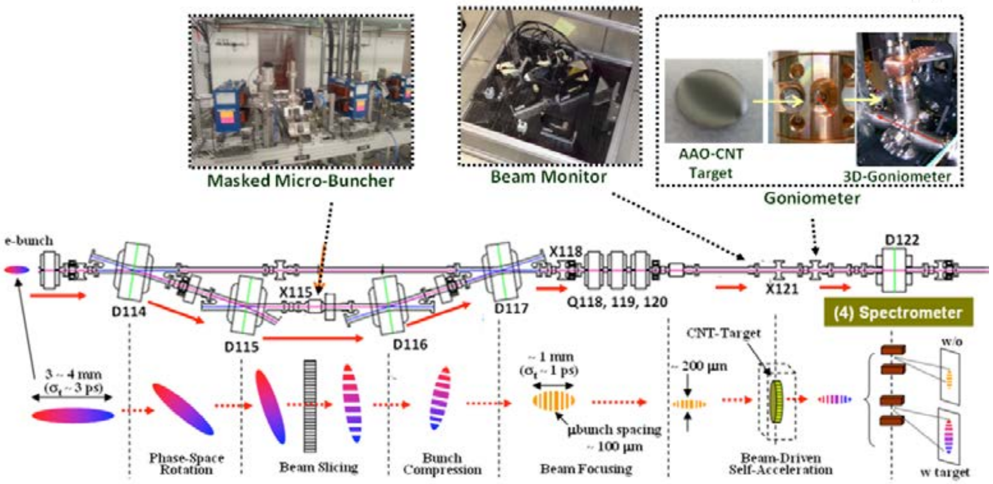
Wakefield acceleration in porous nanomaterials

Carbon nanotube with
Particle beam / X-ray laser pulse



Porous nanomaterial

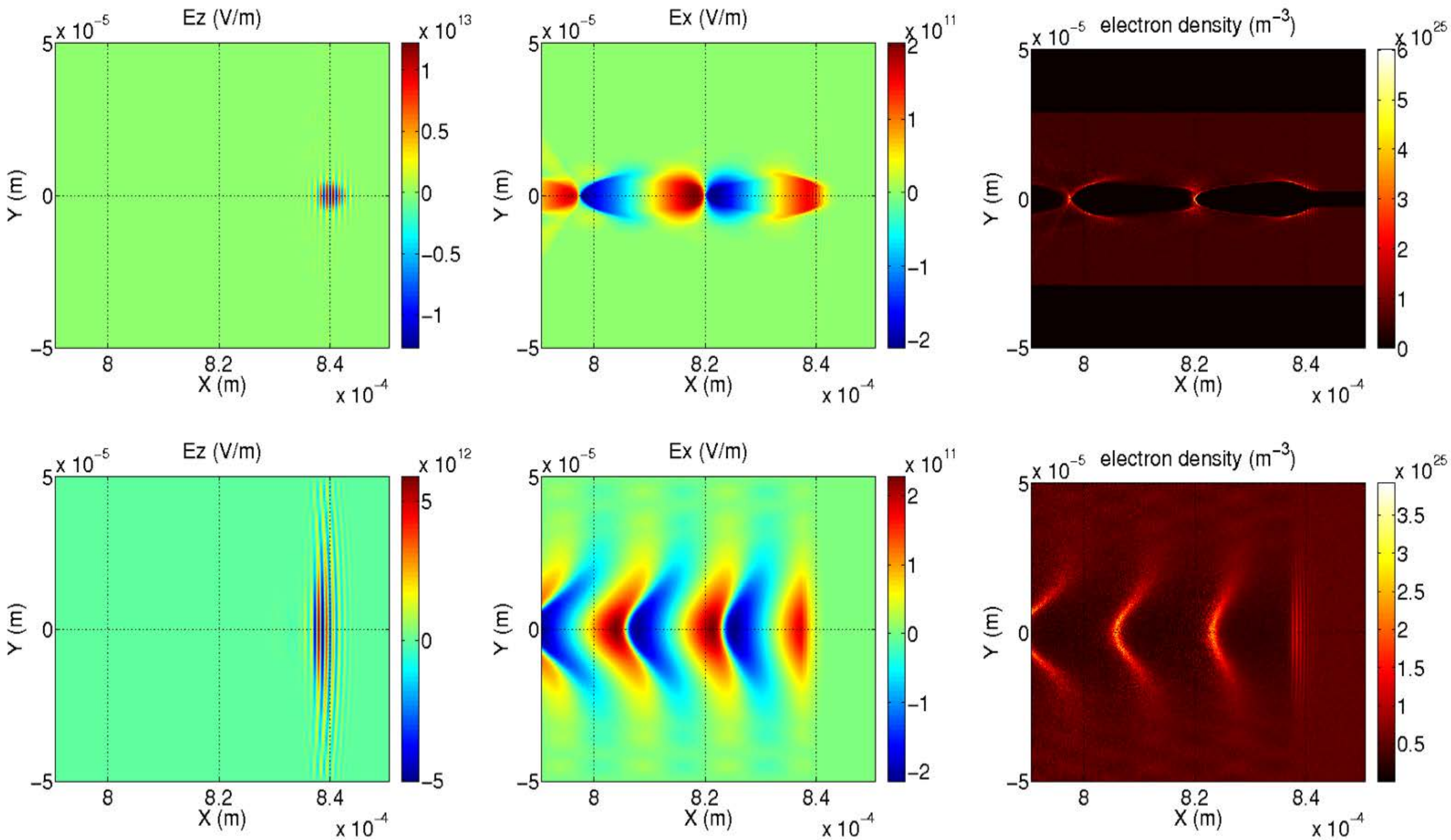




Tajima and Cavenago (1987)

Collaboration (2015) with Fermilab / NIU
Y. Shin et al.

X-ray LWFA in a tube vs. uniform solid



in nanotube

uniform solid

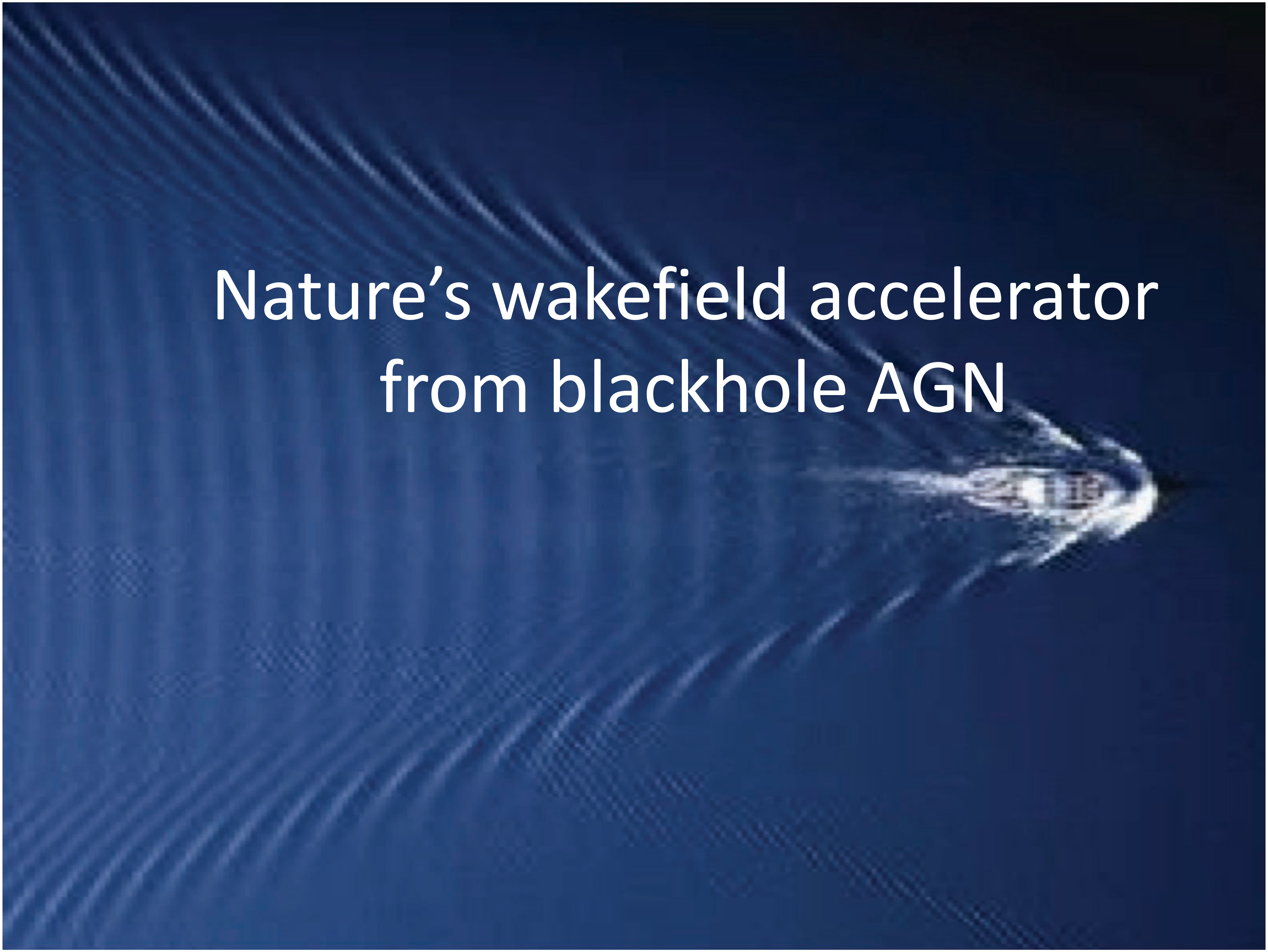
A few-cycled 1keV X-ray pulse (a_0 ~ O(1)), causing 10TeV/m wakefield in the tube

more strongly confined in the tube

cf: uniform solid

X. Zhang et al. (2016)

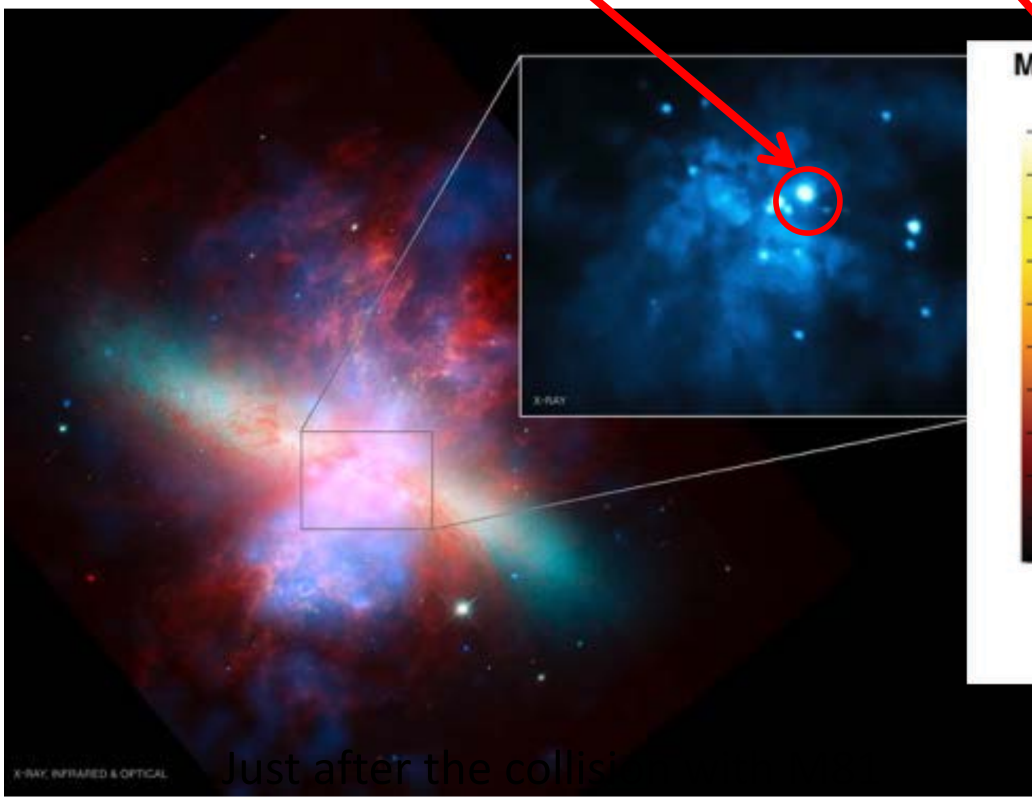
Nature’s wakefield accelerator from blackhole AGN

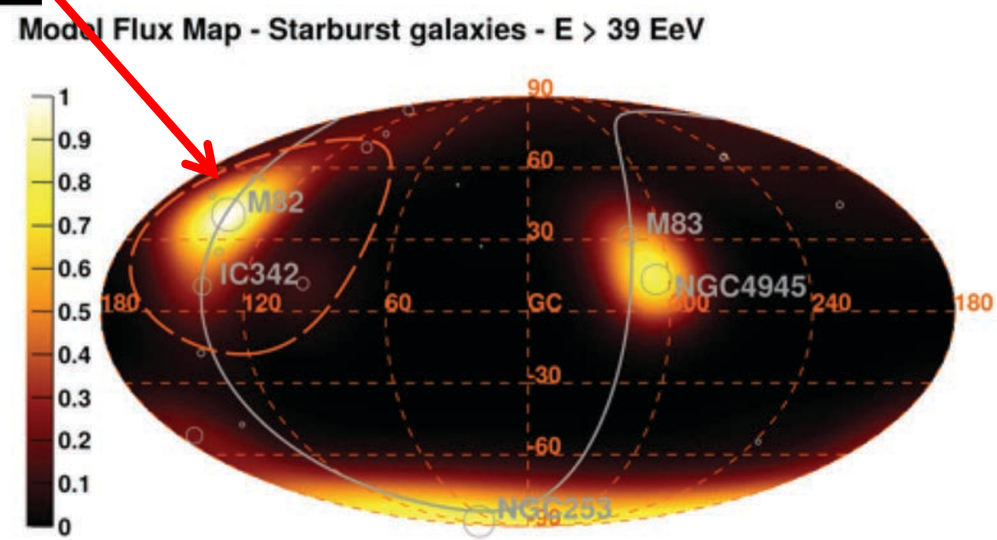


M82: Nearest Starburst Galaxy

M82 X-1: 10^3-10^4 M_s Black Hole

M82 X-1



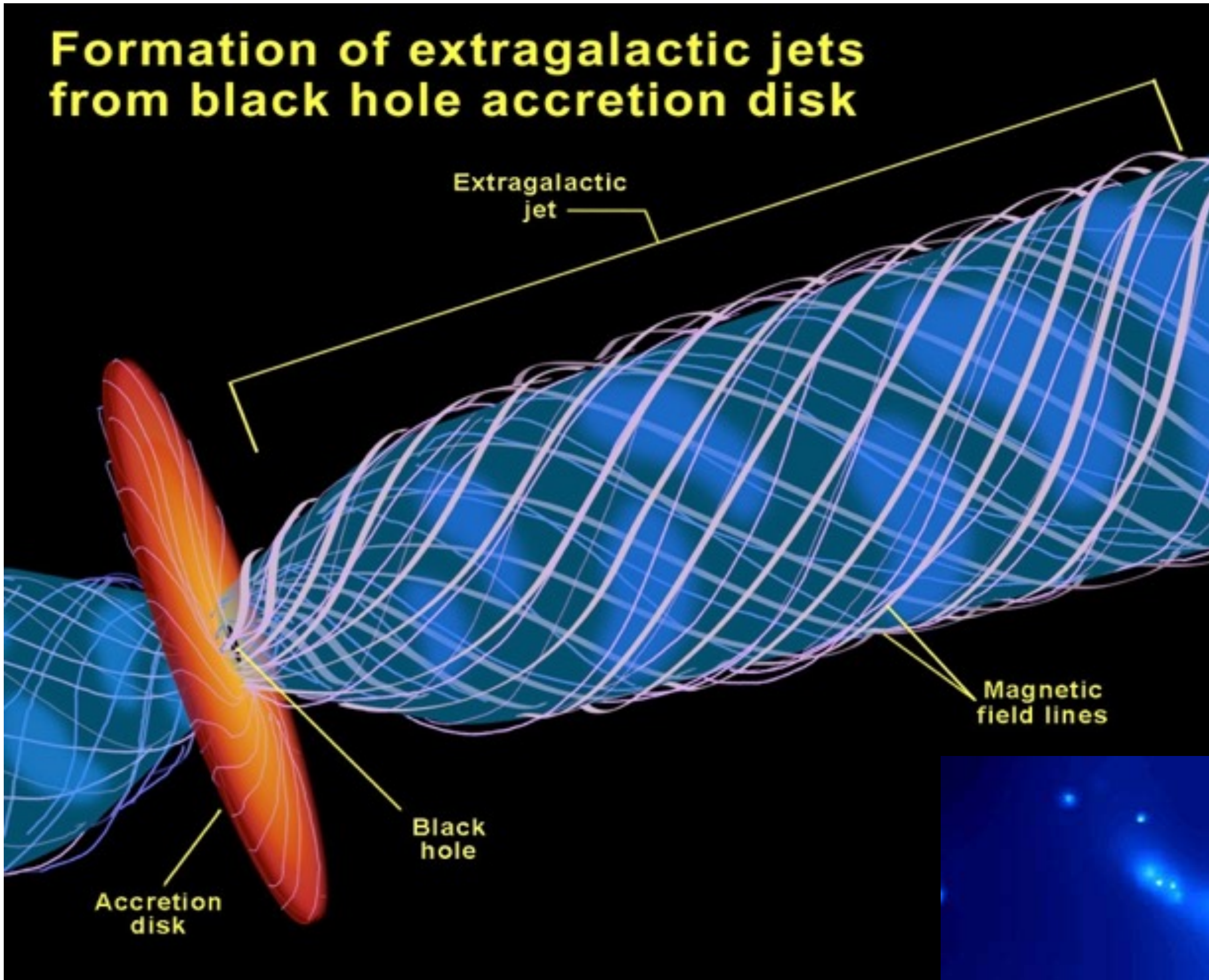


Composite of X-ray, IR, and optical emissions

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.

Excess map: three hot spots
(> 39EeV in the entire sky)

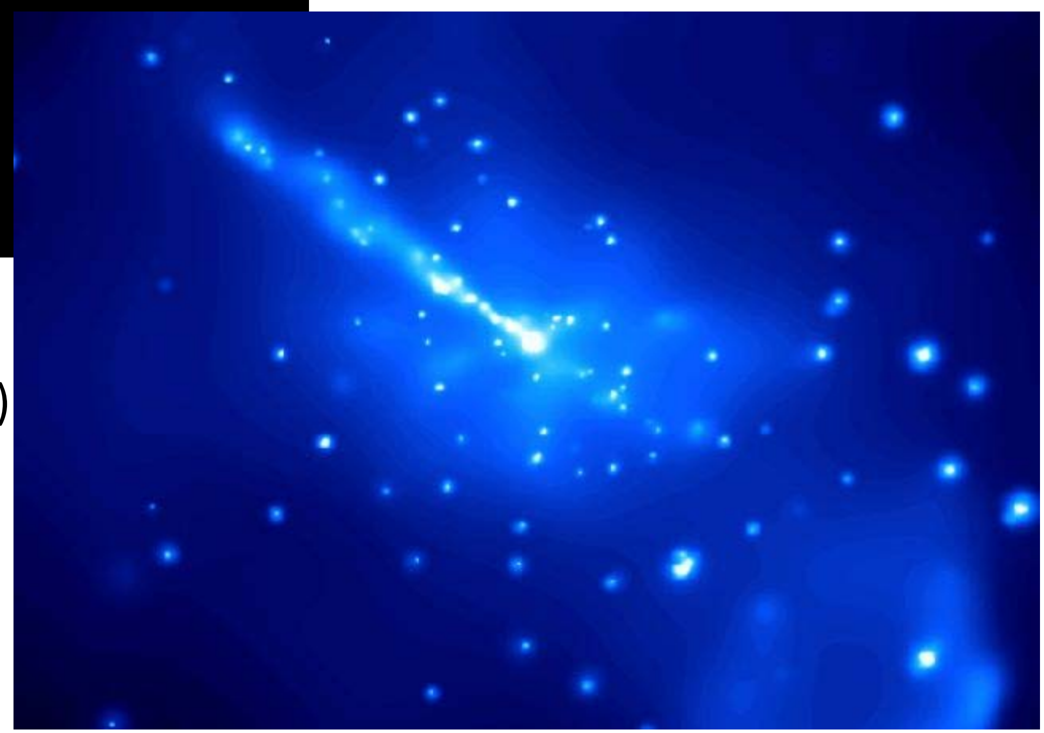
Aab et al. (2018) Astrophys. J. Letters, 853, L29



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

↓

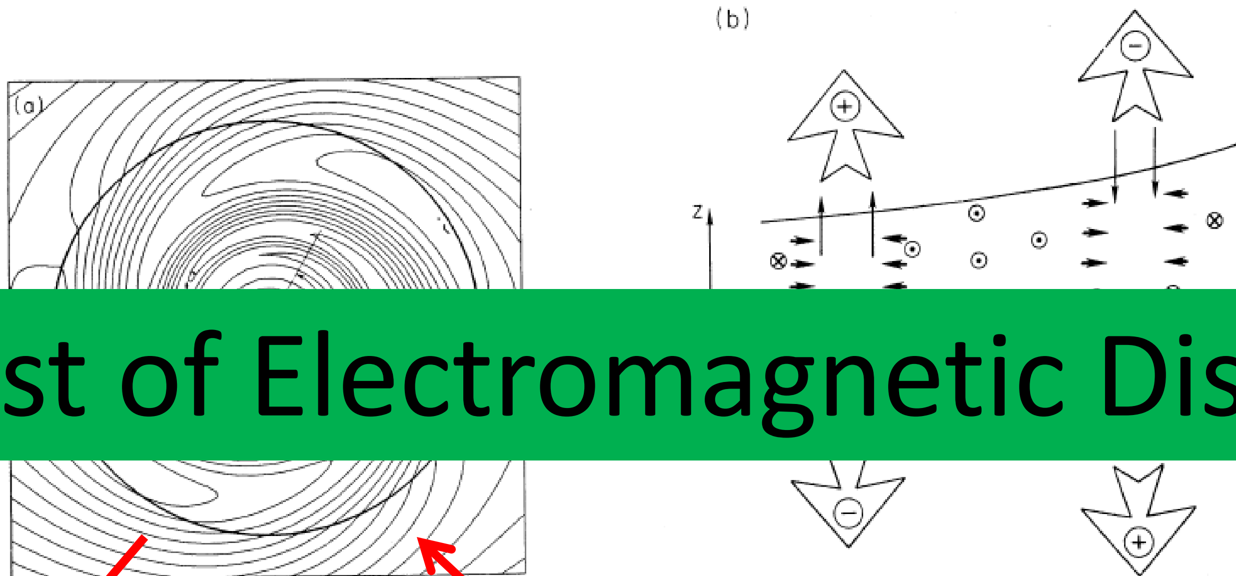
Coherent wakefield acceleration
(no limitation of the energy)



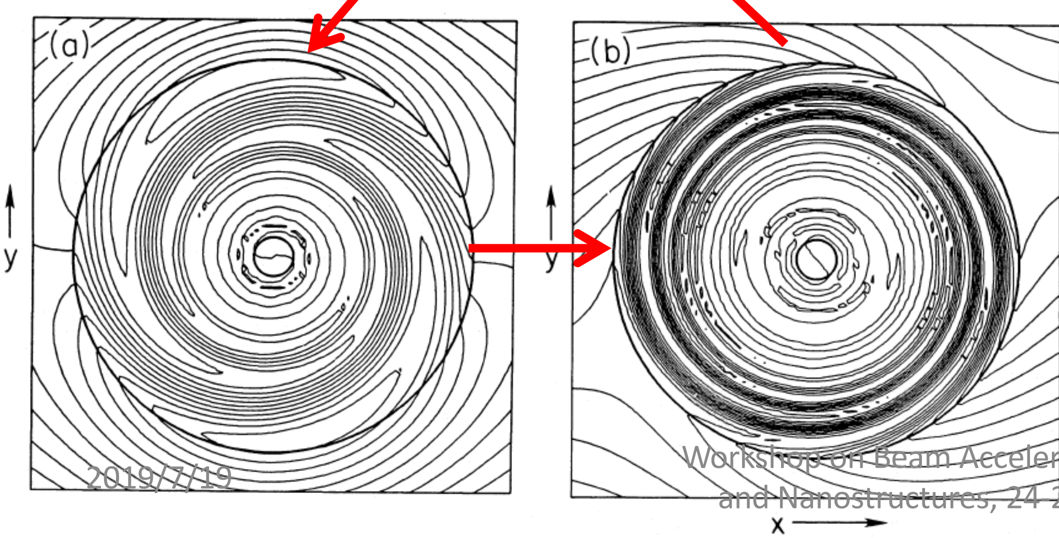
Nature's LWFA : Blazar jets
extreme high energy cosmic rays (~10^{21} eV)
episodic γ-ray bursts observed
consistent with LWFA theory

Ebisuzaki-Tajima (2014)

Eruption of magnetic field in an accretion disk

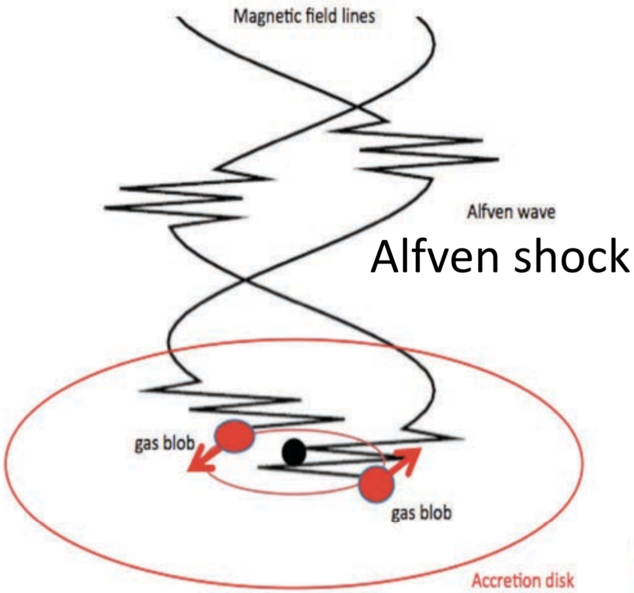


A Burst of Electromagnetic Disturbance



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

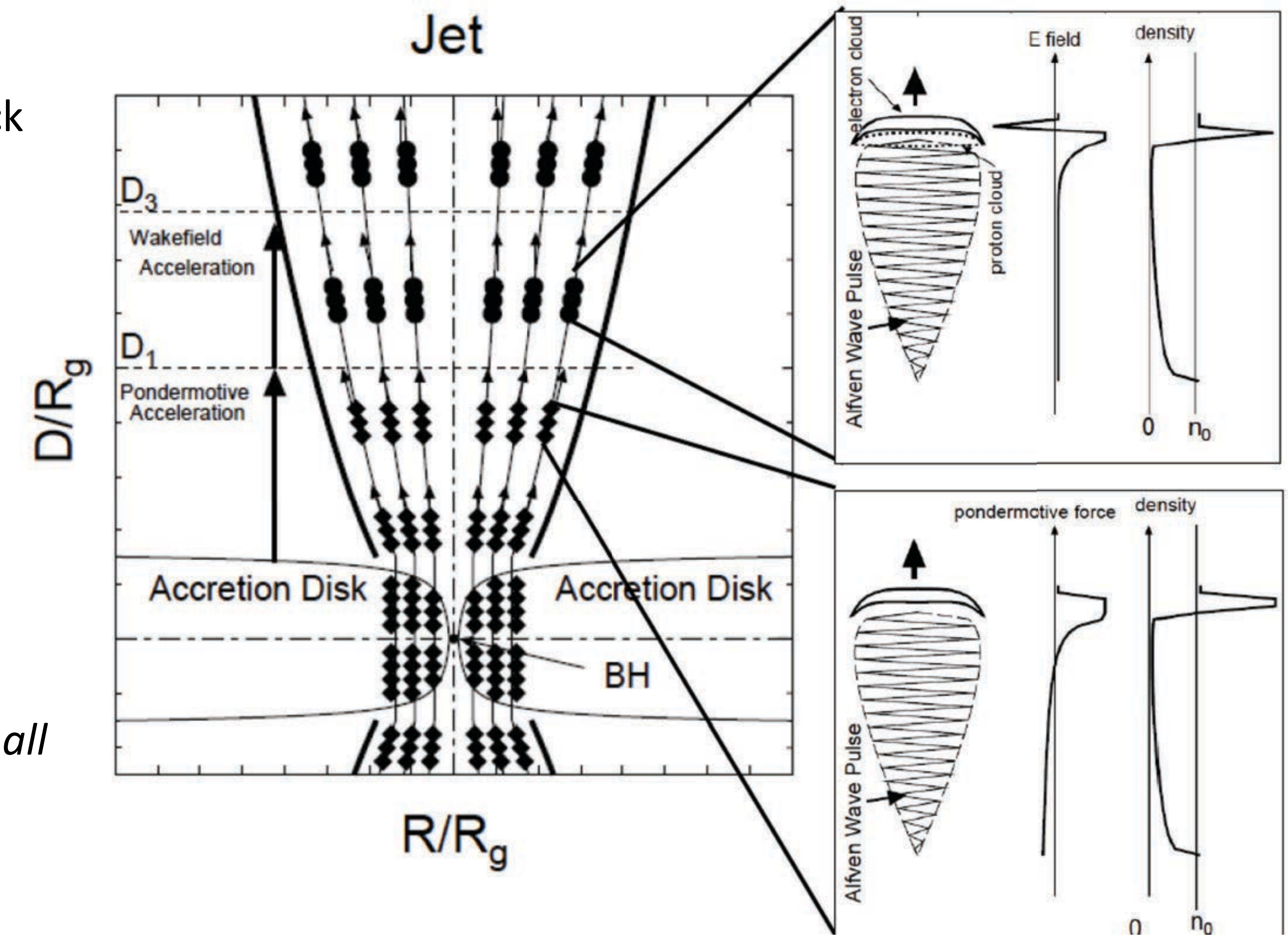
Astrophysical wakefield acceleration:
Superintense Alfven Shock in the Blackhole Accretion Disk toward ZeV Cosmic Rays ($a_0 \sim 10^6 - 10^{10}$, large spatial scale)



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

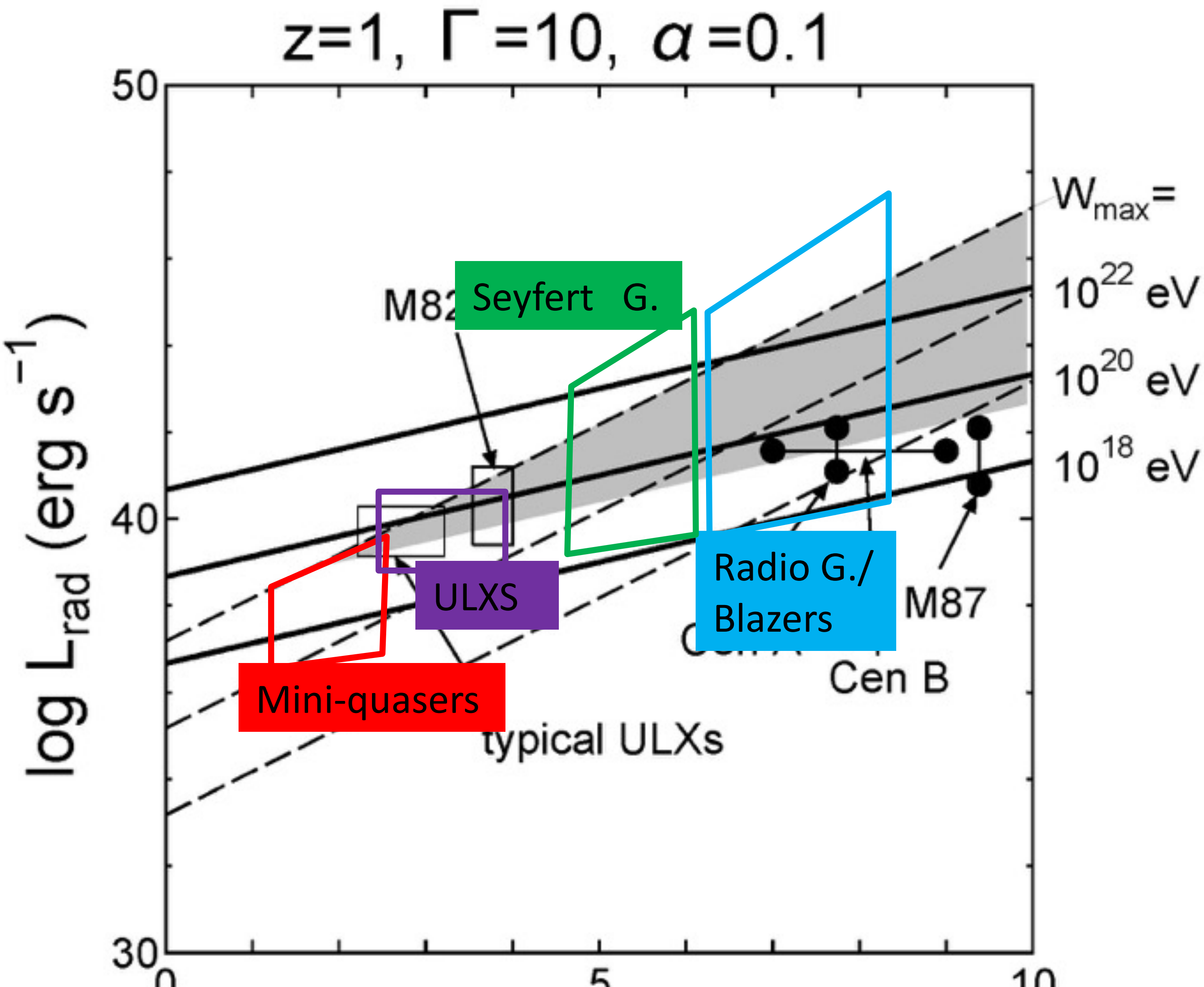
E_0: modest

ω_0: *extremely small*



Ebisuzaki and Tajima, Astropart. Phys.(2014)

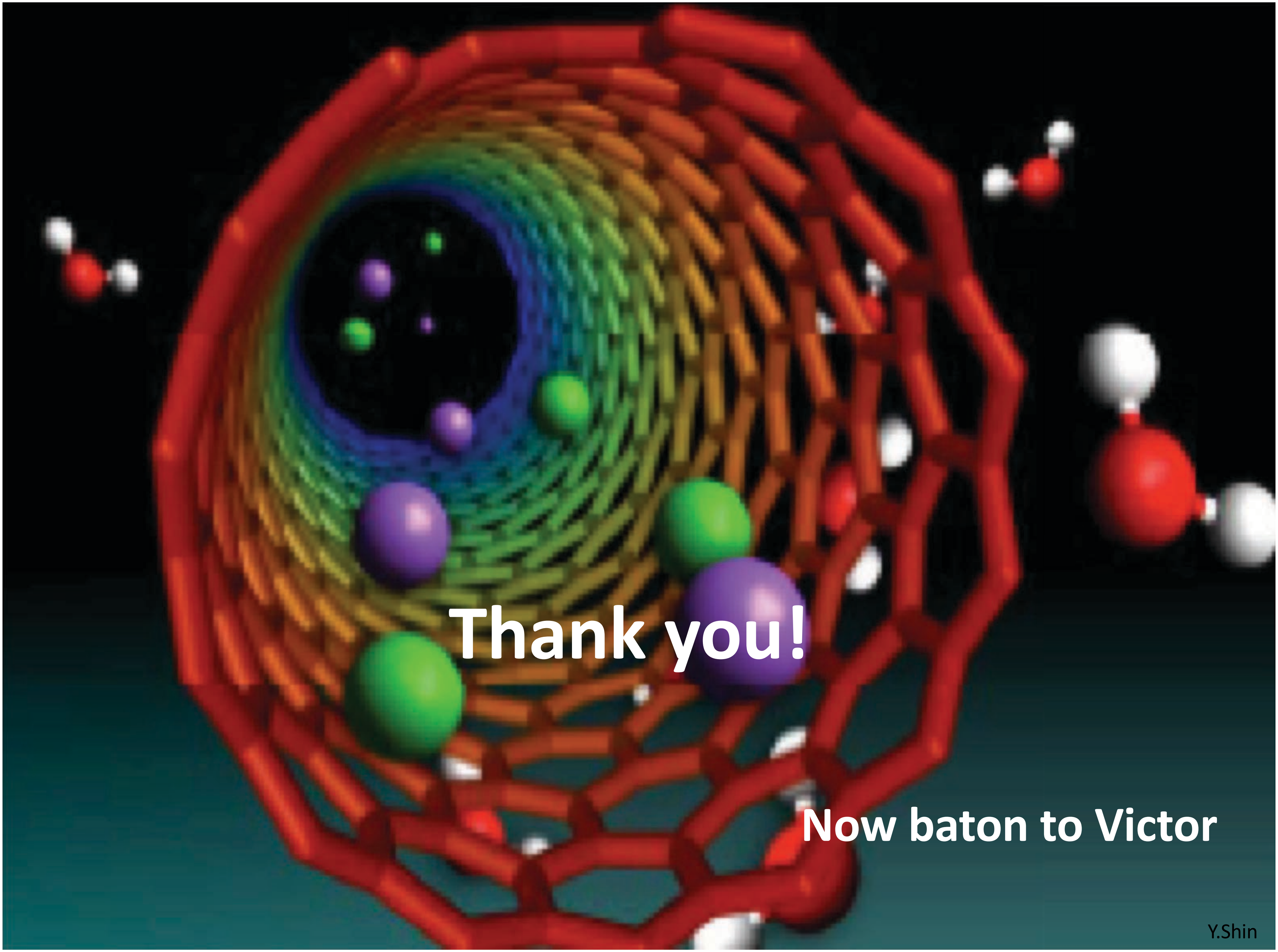
Cosmic ray acceleration and γ-ray emission



BH Astronomy with Ultra High Energy Cosmic-rays

Conclusions

- **Demonstrated**: ultrafast pulses, coherent collective (robust) **wakefield** (**GeV/cm**) excitable.
- Thin-Film Compression (TFC)
- Single-cycled laser → single-cycled X-ray laser
- Wakefield in **nanostructure** (**TeV/cm**): accessible
- Wakefield: Nature's accelerators favored for EHECR, gamma ray bursts and neutrinos from **Blazars**


Thank you!
Now baton to Victor
Y.Shin