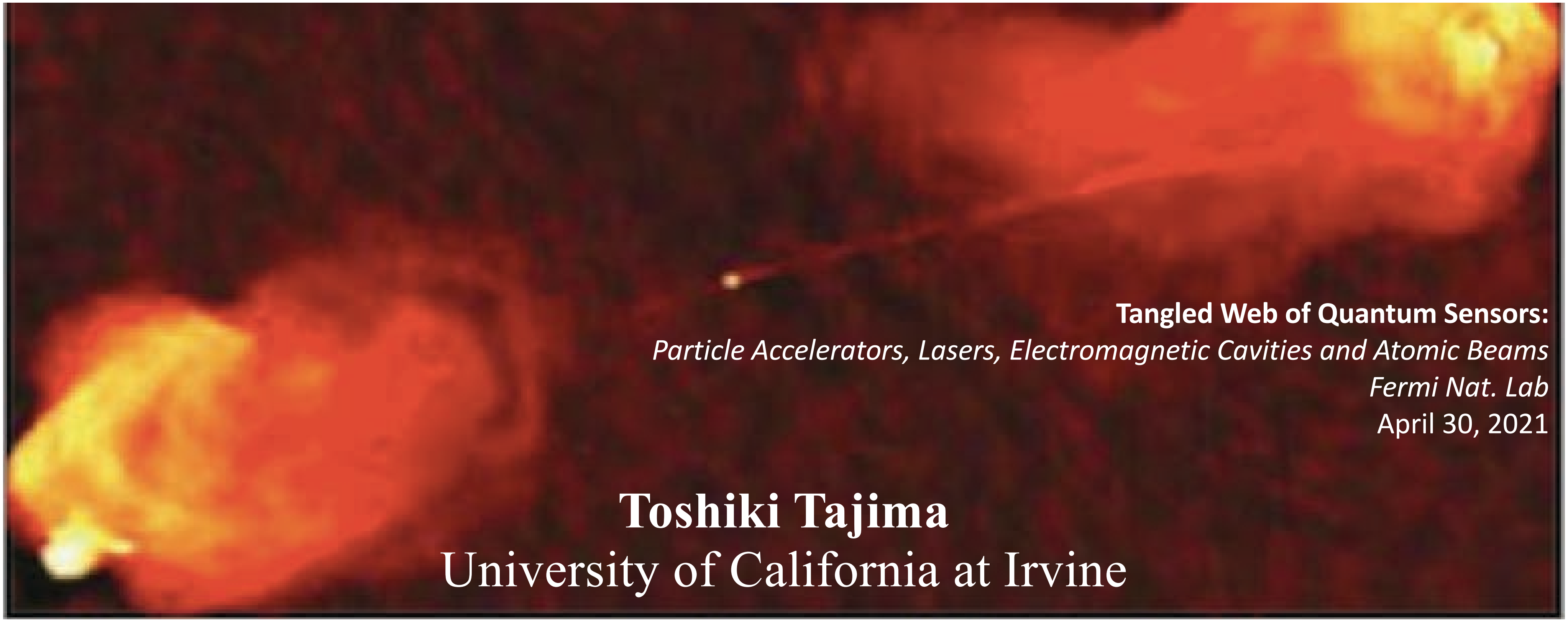
“Horizon: Sky is the limit”:
Perspective of Laser Wakefield Acceleration



Tangled Web of Quantum Sensors:
Particle Accelerators, Lasers, Electromagnetic Cavities and Atomic Beams
Fermi Nat. Lab
April 30, 2021

Toshiki Tajima
University of California at Irvine

Collaboration: S. Chattopadhyay, B. Barish, G. Mourou, V. Shiltsev, T. Ebisuzaki, K. Abazajian, S. Barwick, X. M. Zhang, D. Strickland, P. Taborek, K. Nakajima, F. Zimmermann, X. Yan, Y.M. Shin, J. Wheeler, W. J. Sha, S. Nicks, D. Roa, F. Tamanoi, G. Szabo, H. B. Yu, H. Sobel, T. Tait, J. Feng, A. Sahai, S. Corde, N. Canac, G. Huxtable, E. Barraza

UCIrvine

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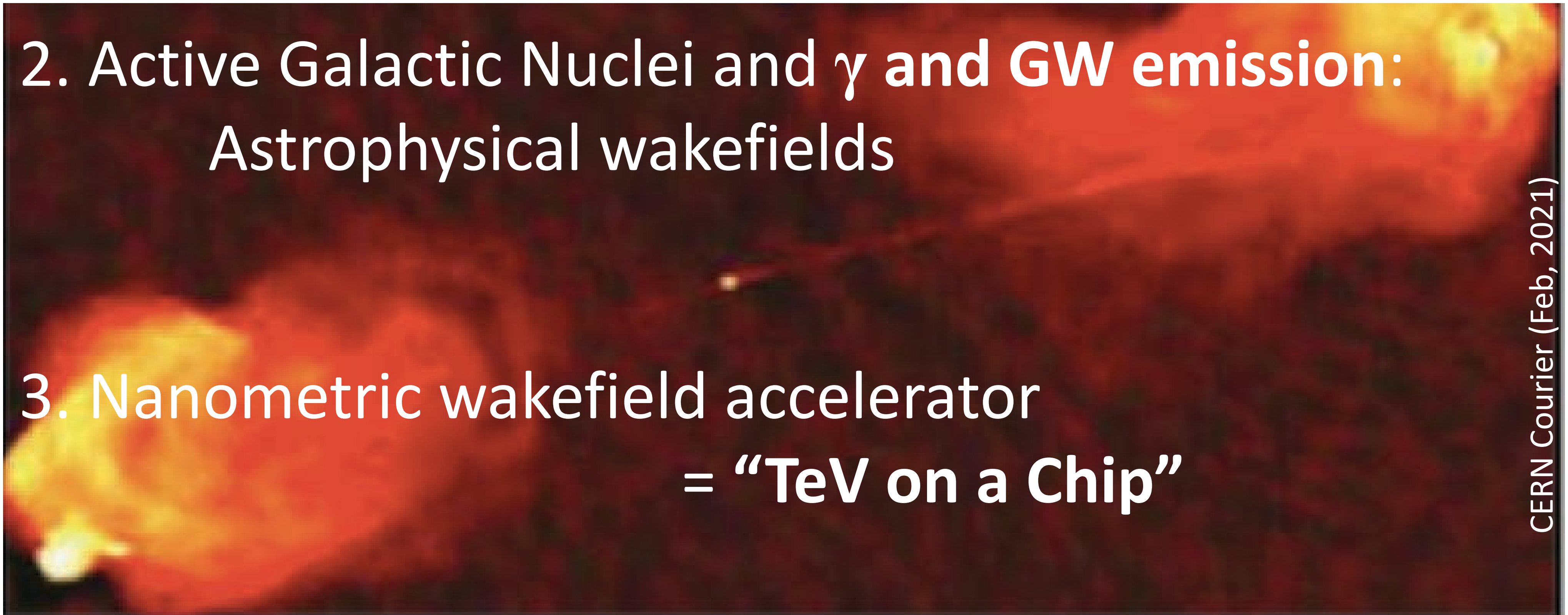
1. Fermi stochastic acceleration →
Collective (laser wakefield) acceleration



2. Active Galactic Nuclei and γ **and GW emission**:
Astrophysical wakefields

3. Nanometric wakefield accelerator
= **“TeV on a Chip”**

CERN Courier (Feb, 2021)

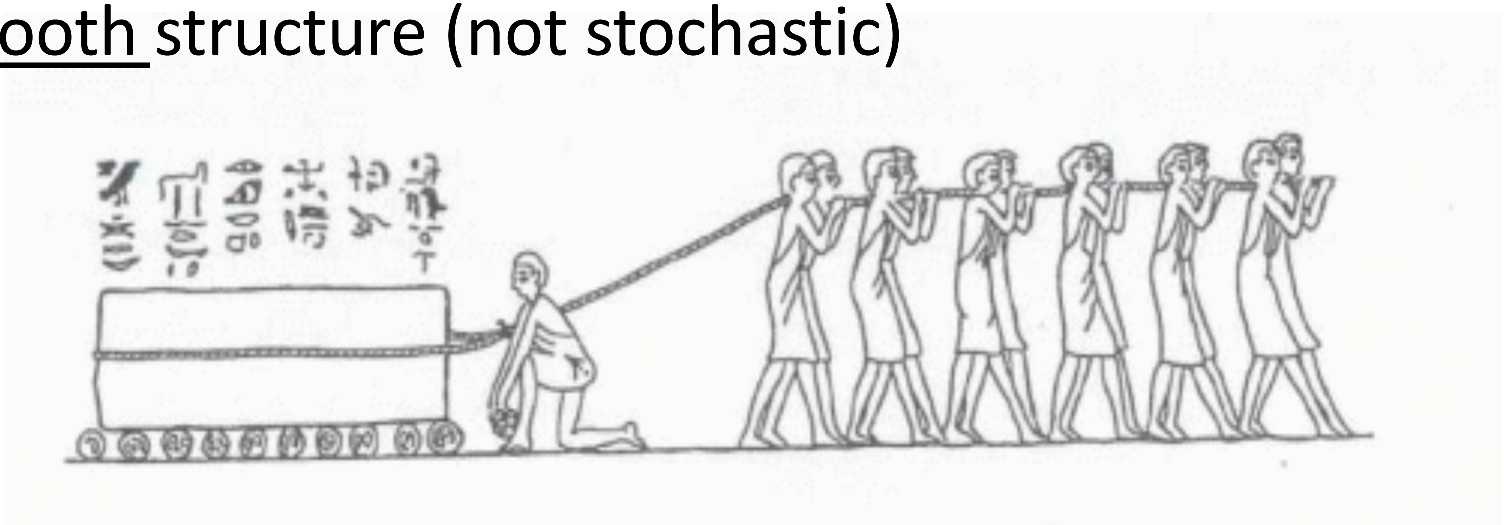
4. Nanotube wakefield endoscopic **cancer therapy**


Wakefields = Collective force

Plasma / nanomaterial accelerator driven by laser pulse

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

Coherent and smooth structure (not stochastic)



Plasma (nanomatter) accelerator driven by laser (coherent photons)

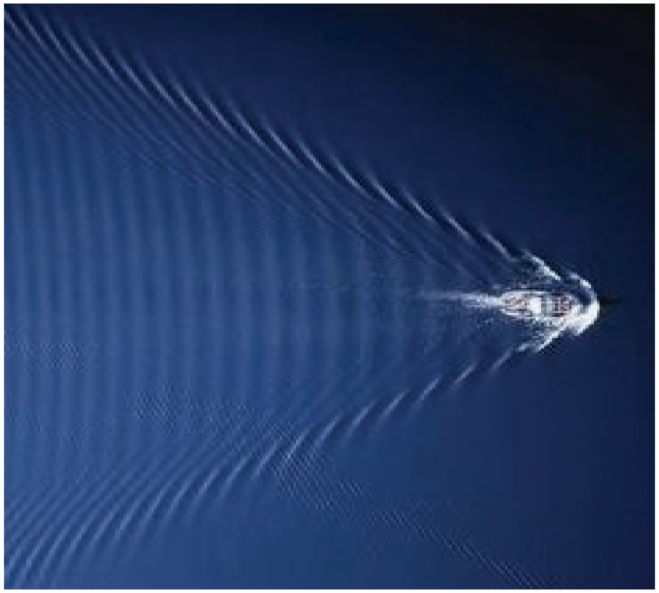
compactification by $10^3 - 10^4$ (now even by $\mathbf{10^6}$) >> conventional accelerators

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

Laser Wakefield (LWFA):

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

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

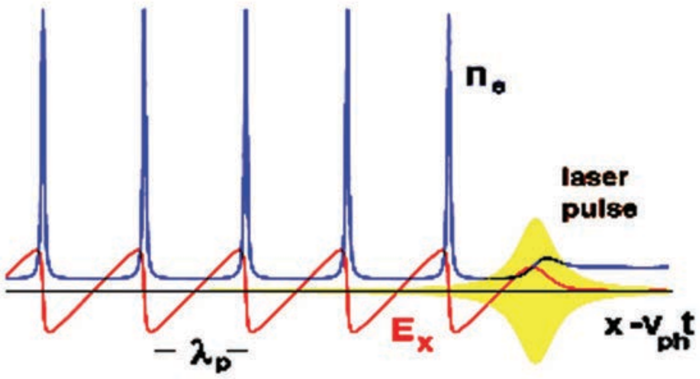


vs

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

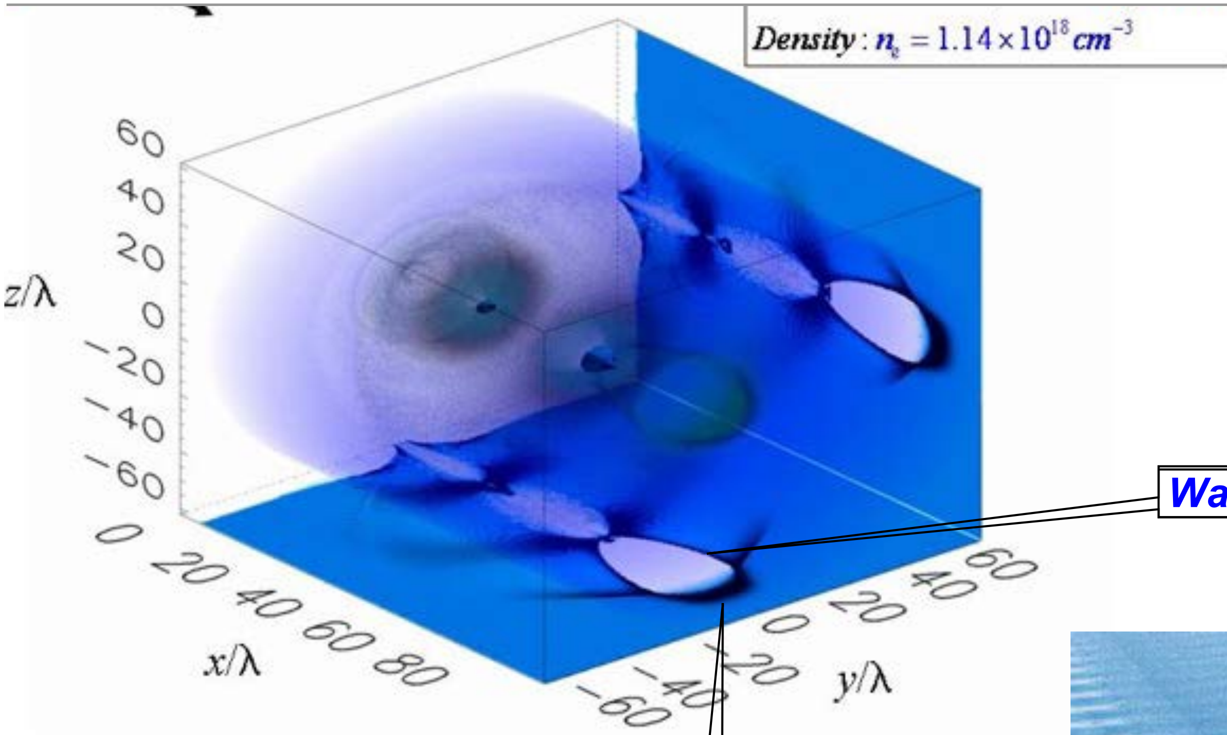
Wave **breaks** at v<c



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

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

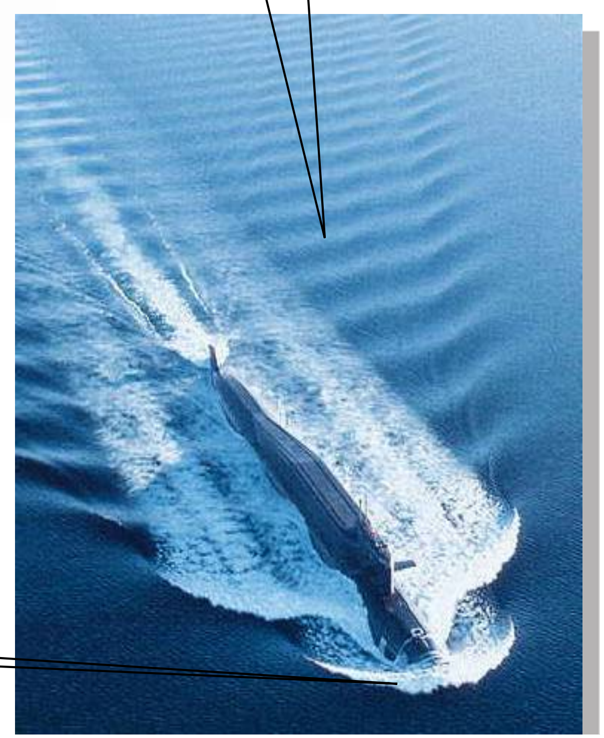
Laser-driven Bow and Wake



(Bulanov, Esirkepov)

Wakefield acceleration

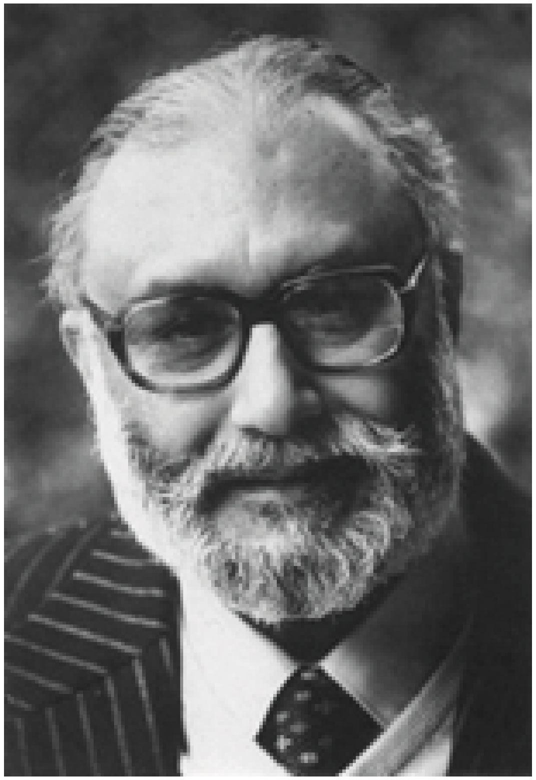
Wake Wave



Bow Wave

Ponderomotive acceleration

The late Prof. Abdus Salam



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

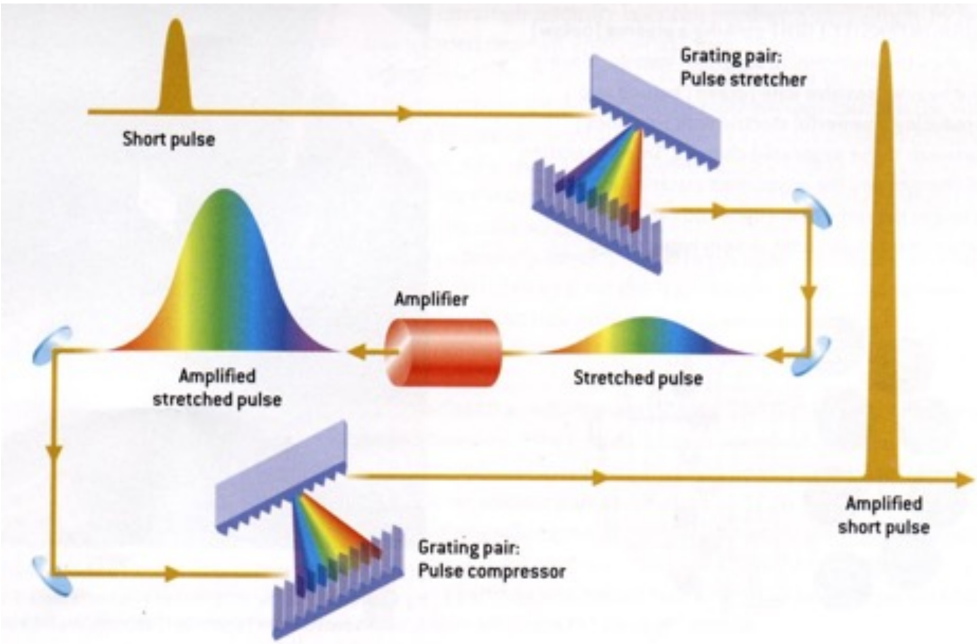
Salam*: ‘Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged’*. (1981)

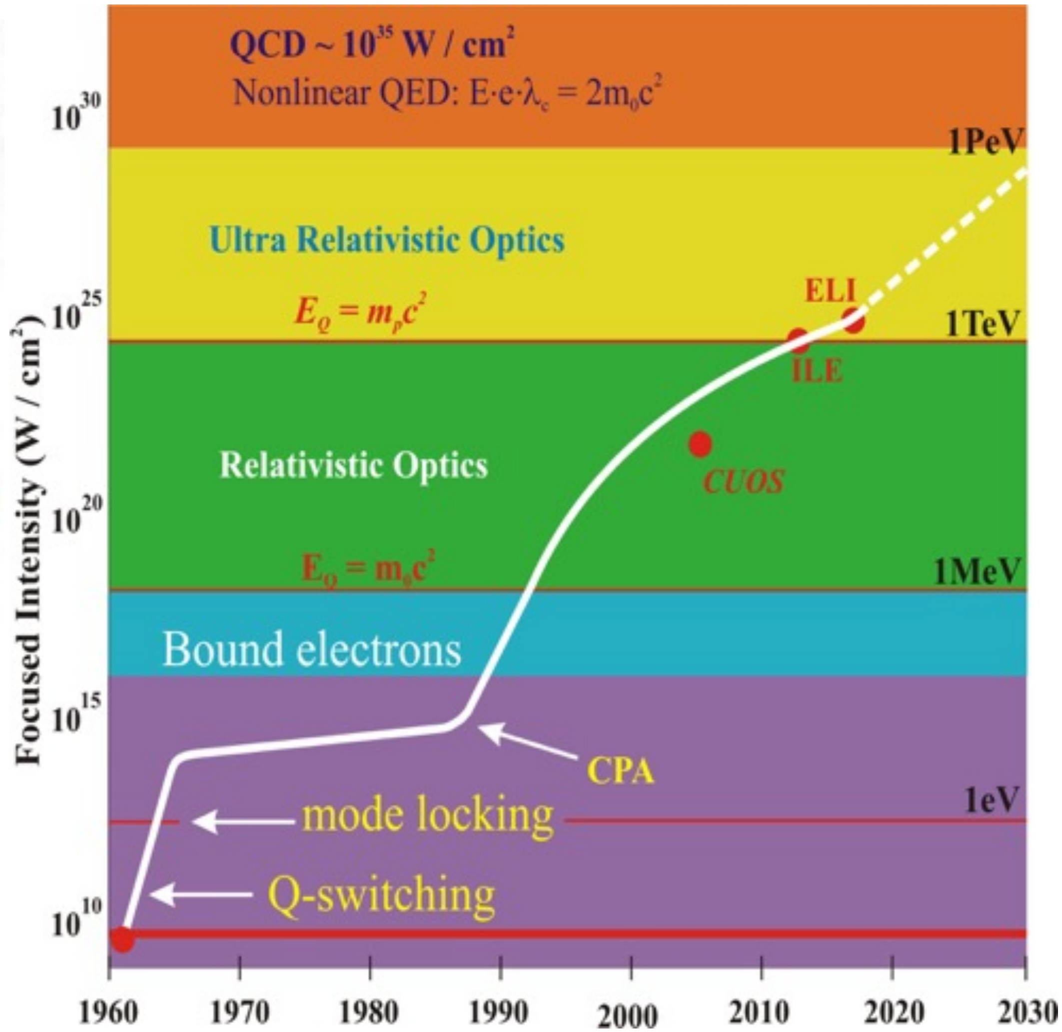
He organized the Oxford Workshop
on laser wakefield accelerator in 1982.

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

(NB: Prof. C. Rubbia et al.
discovered his bosons at CERN, 1983)

Enabling technology: laser revolution





G. Mourou invented Chirped Pulse Amplification (1985)

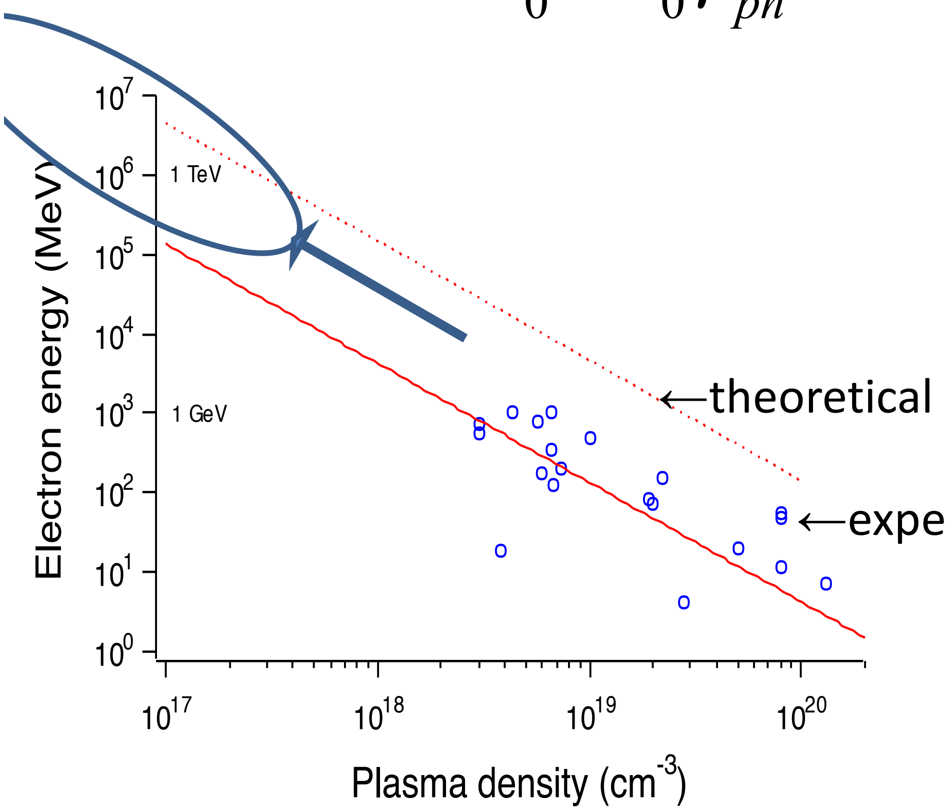
Laser intensity exponentiated since,

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

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

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

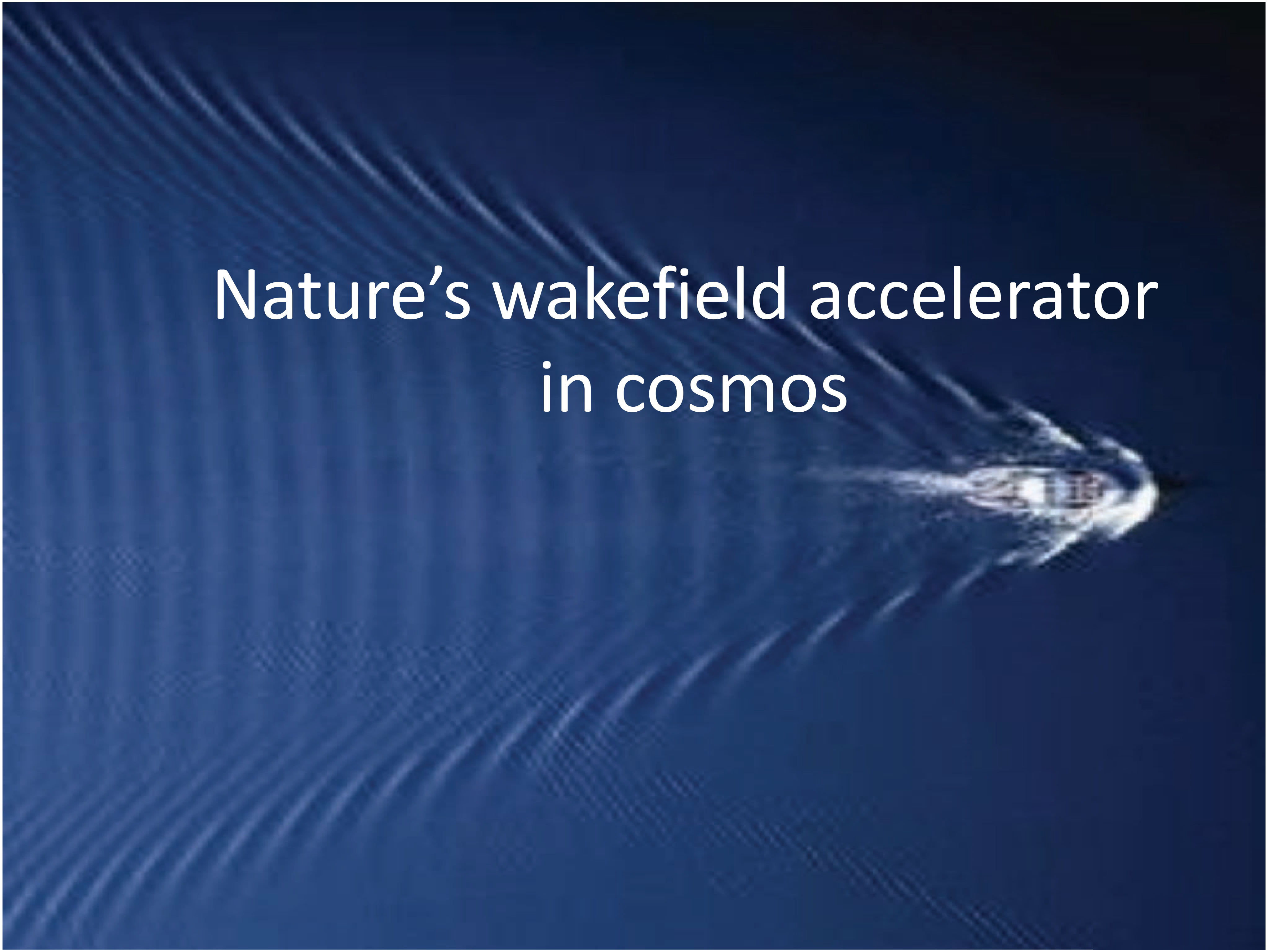
n_{cr} =10^{21}/cc (1eV photon)
→ 10^{29} (10keV photon)
n_e = 10^{16} (gas) → 10^{23} /cc(solid)

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

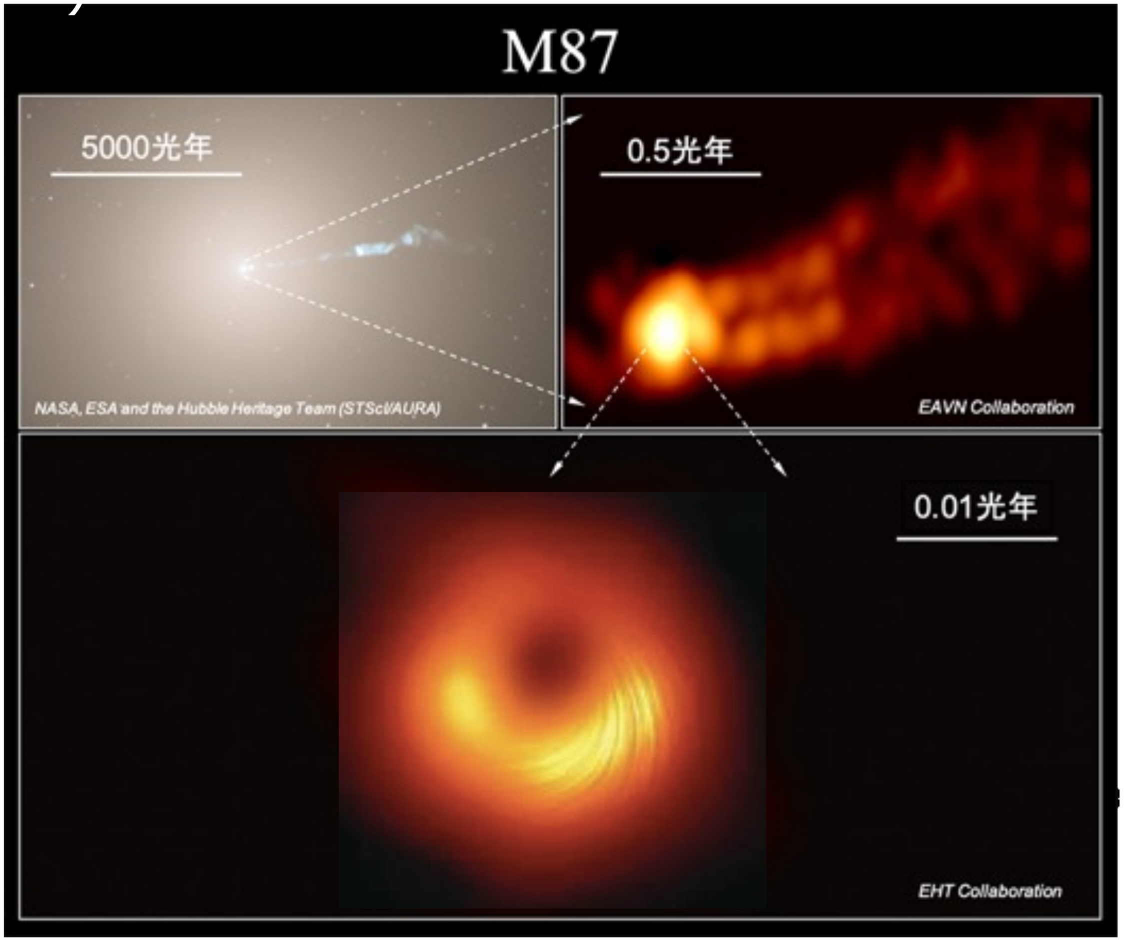
dephasing length

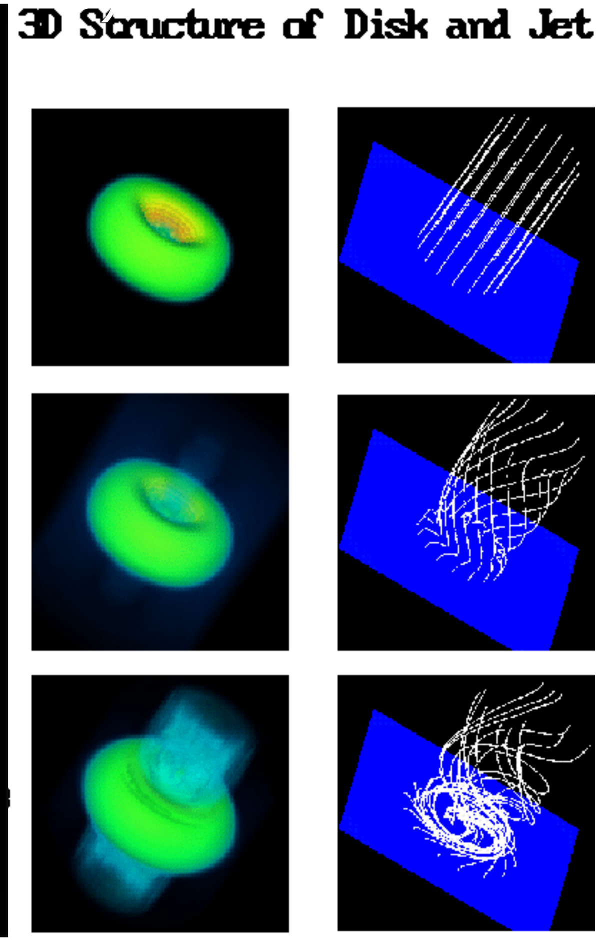
$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

pump depletion length


Nature’s wakefield accelerator
in cosmos

Jet of M87 Galaxy



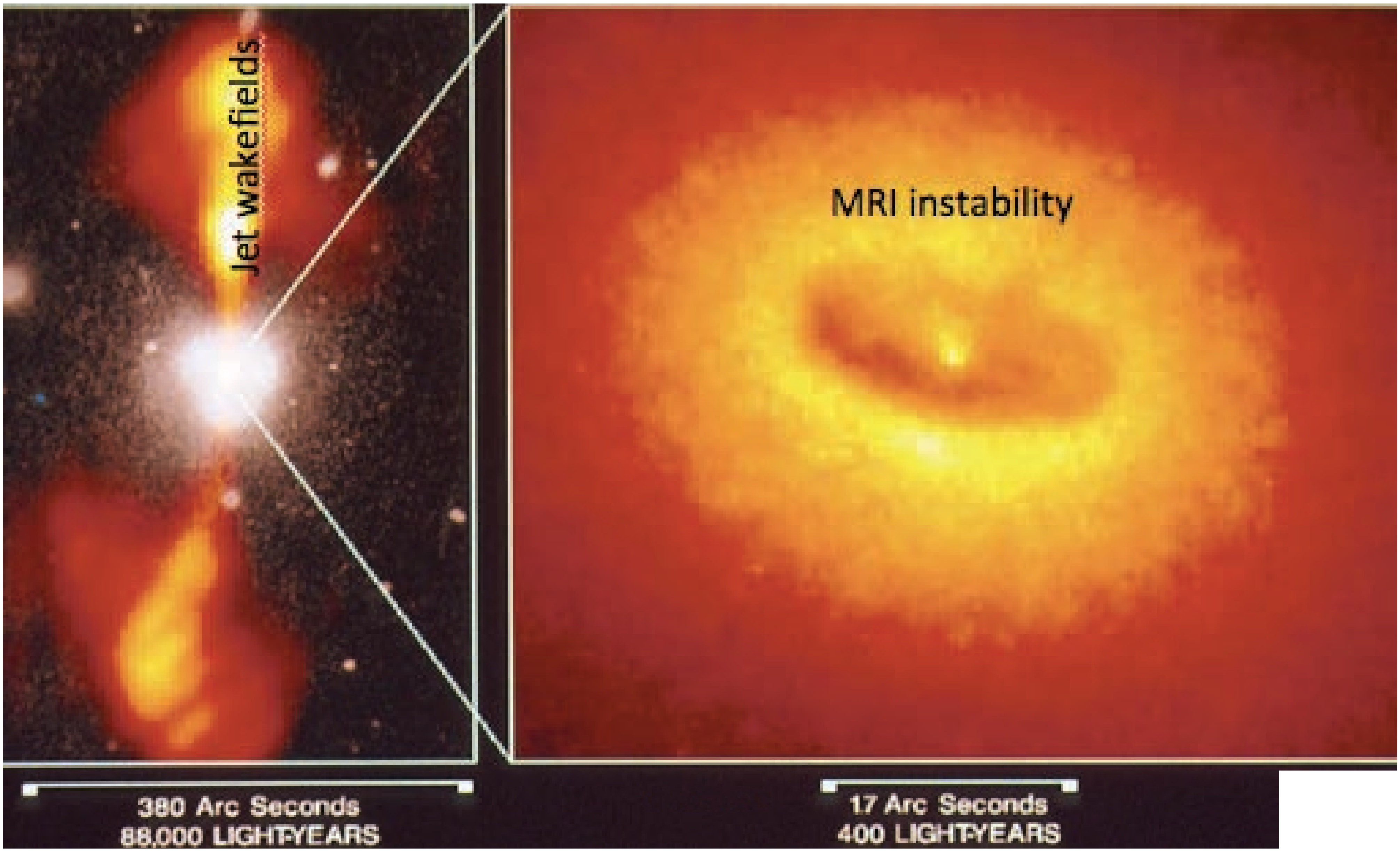


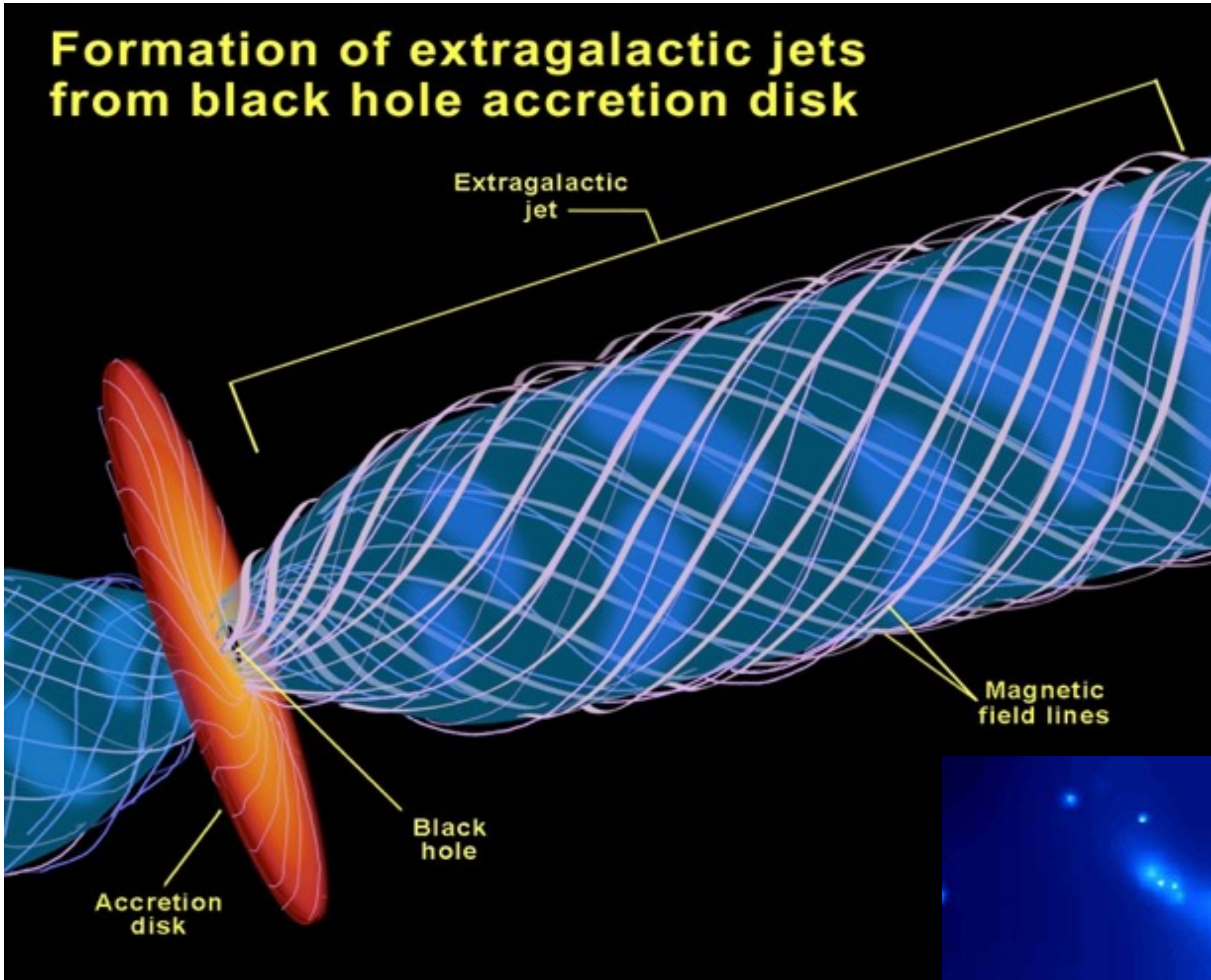
T. Tajima and K. Shibata, Plasma Astrophysics (Perseus Publishing, Cambridge Masachusetts 1997).

Hubble Space Telescope image of jets and disk

Ground-based optical/radio image

HST image of a gas and dust disk

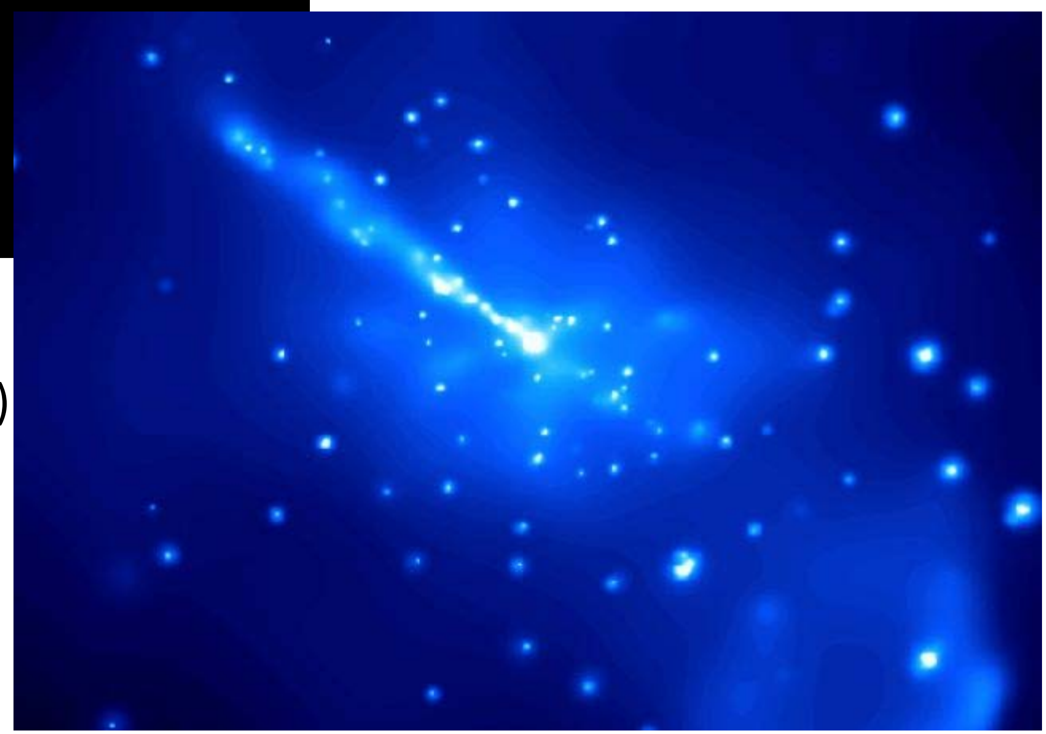




Fermi's '**Stochastic Acceleration**'
(large synchrotron radiation loss)

↓

Coherent wakefield acceleration
(no limitation of the energy)



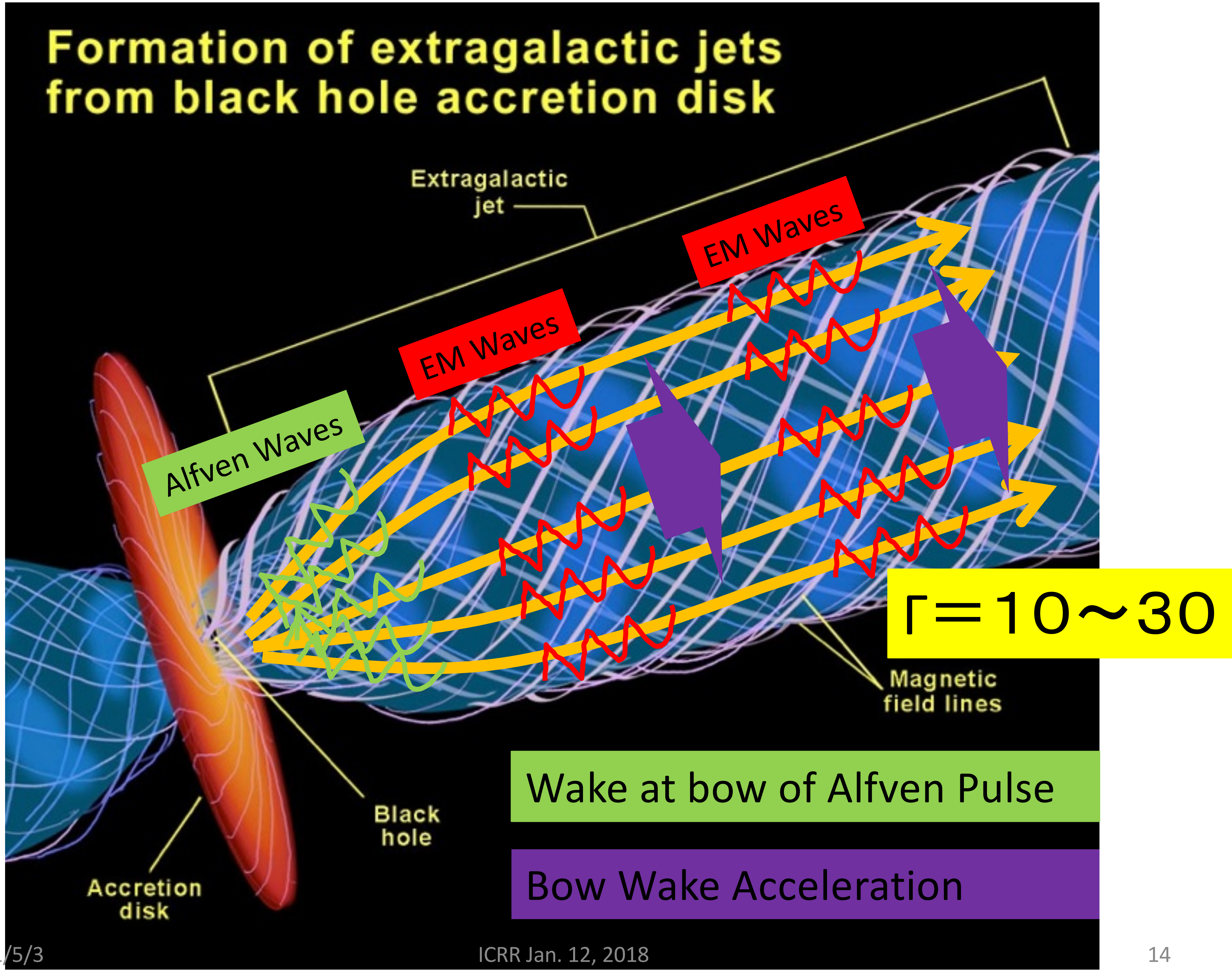
Nature's LWFA : Blazar jets

extreme high energy cosmic rays (~10^{21} eV)

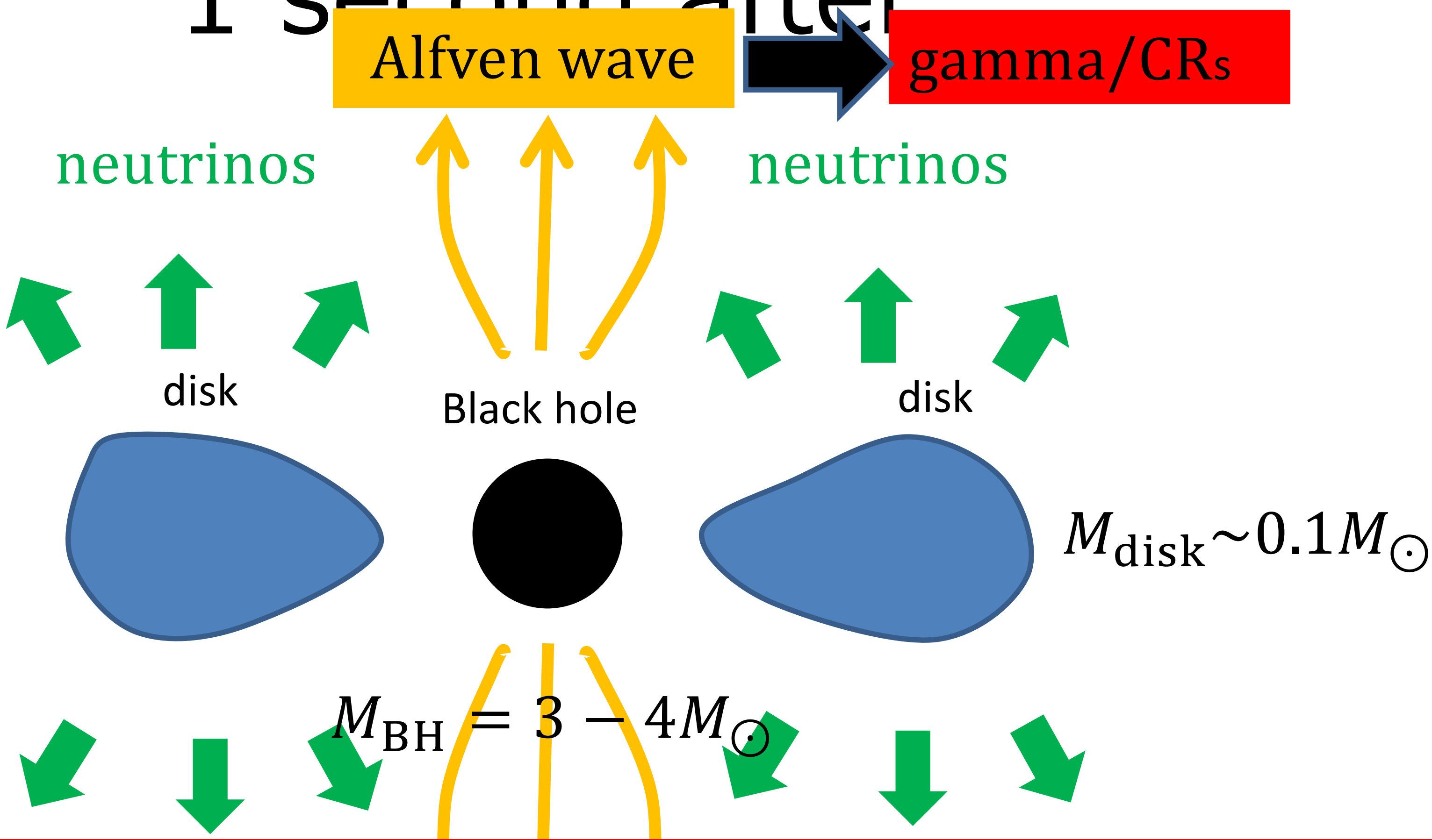
episodic γ-ray bursts observed

consistent with LWFA theory

Ebisuzaki-Tajima (2014)


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
Wake at bow of Alfven Pulse
Bow Wake Acceleration

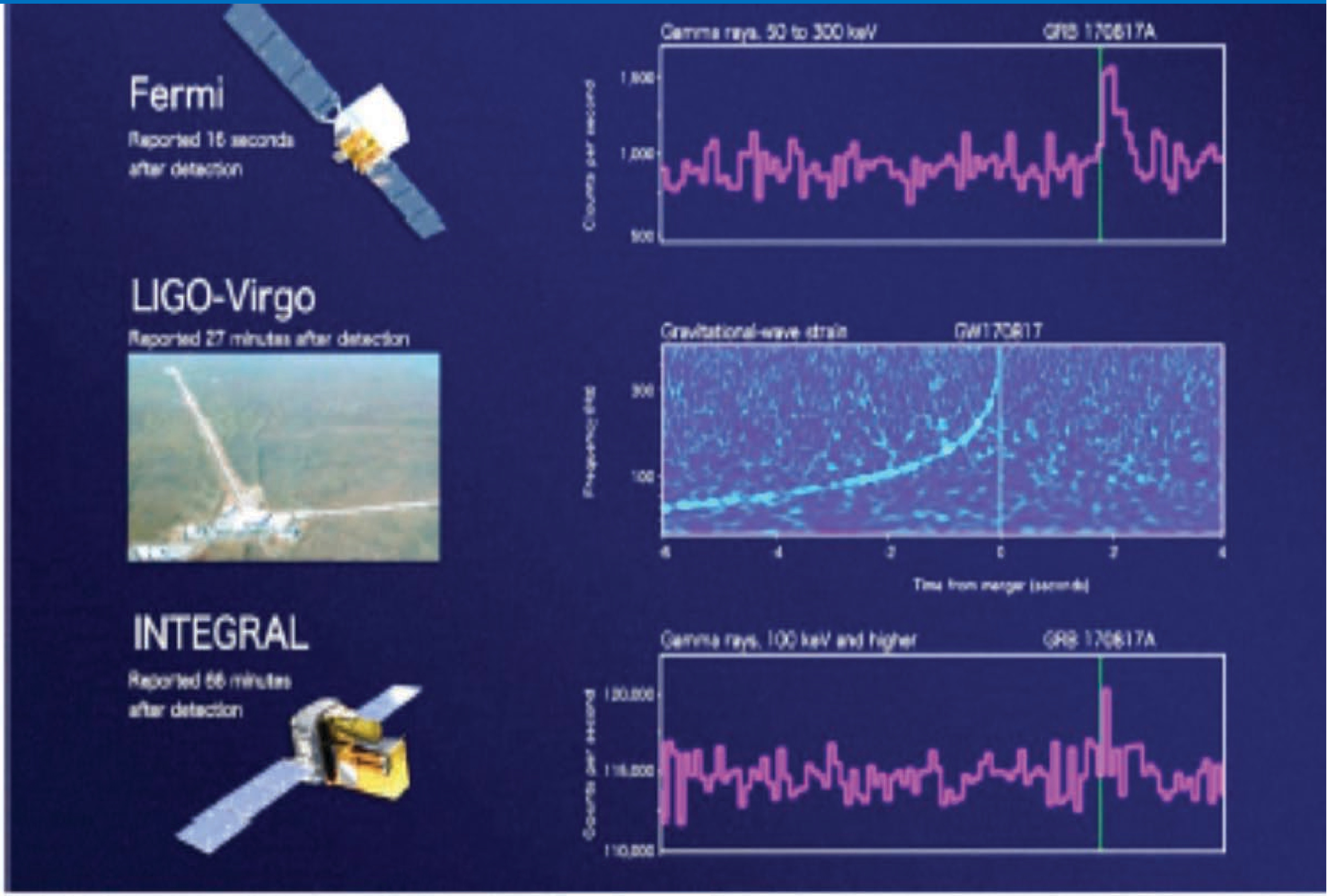
NS-NS merger→BH + Disk 1 second after

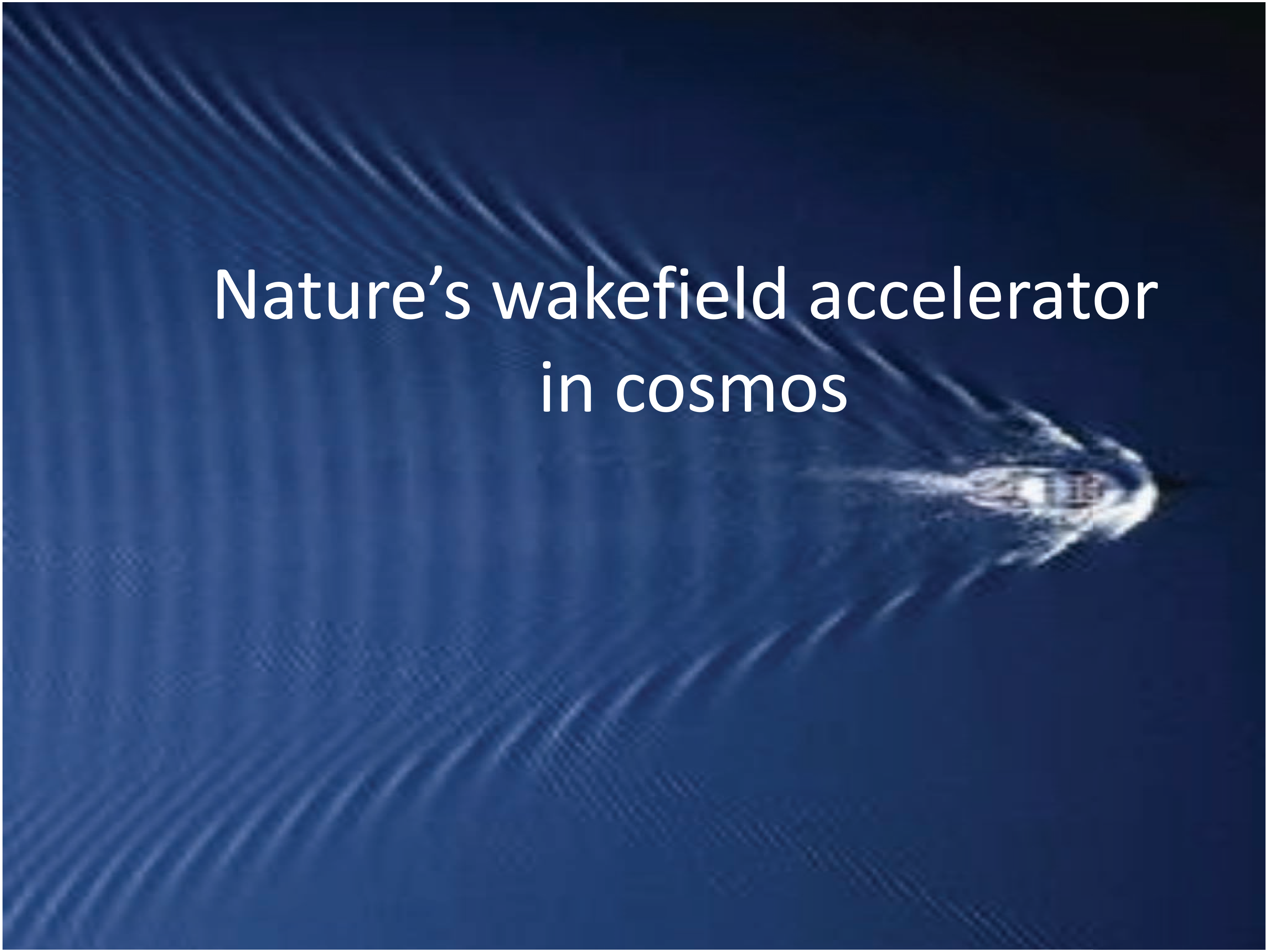


$L_{\nu} \sim 10^{52}$ erg/s$\sim L_A$

Central Engine of GRB/Hypernova

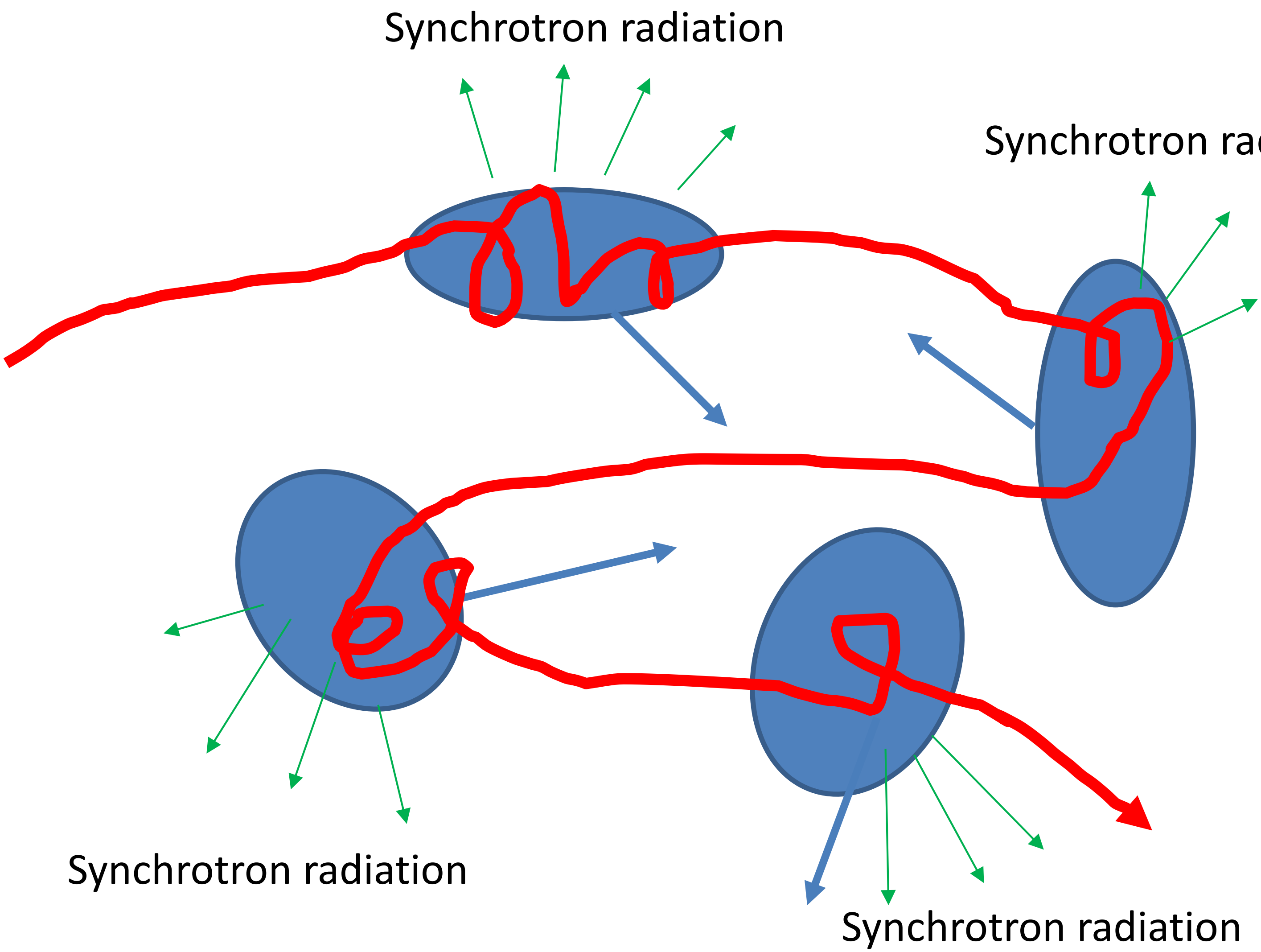
Gravitational wave and Gamma bursts

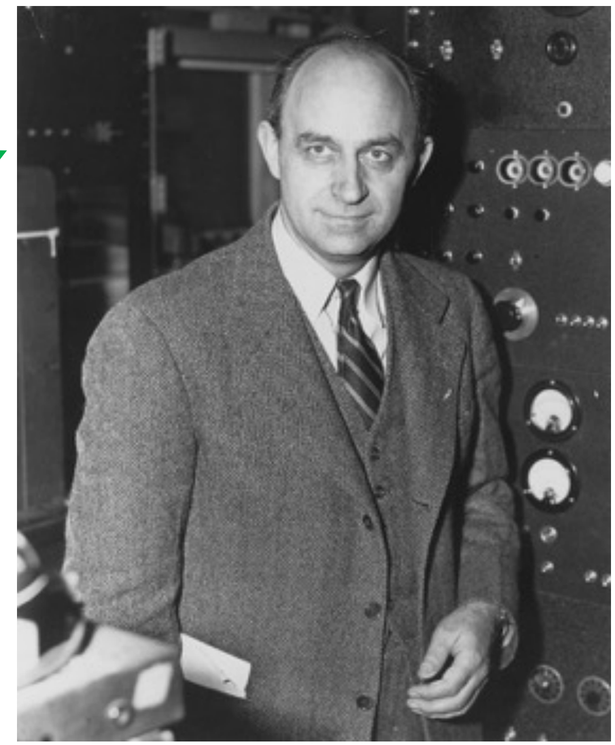



Nature’s wakefield accelerator
in cosmos

Fermi mechanism

incoherent
requires bending→synchrotron loss





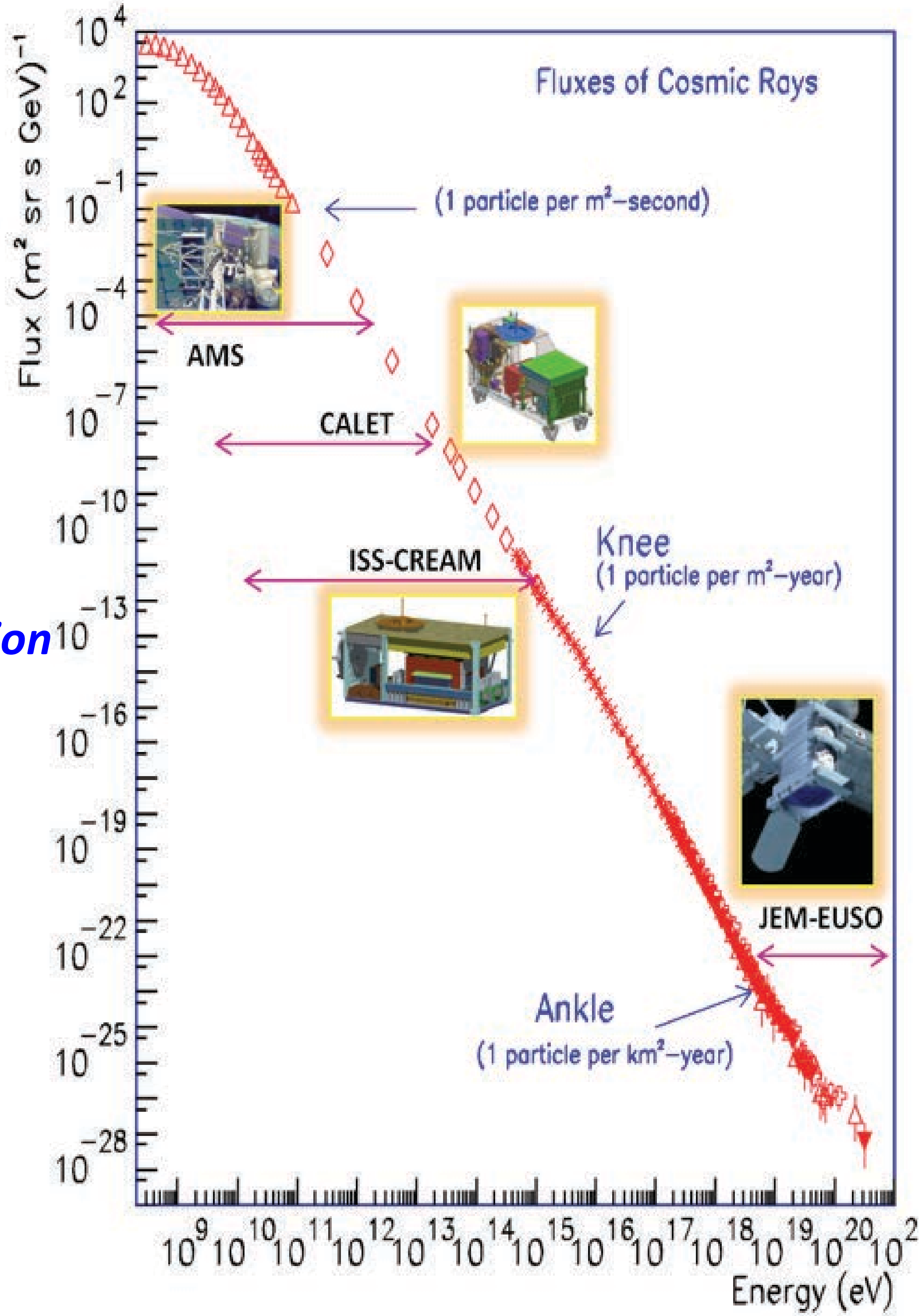
By Department of Energy. Office of Public Affairs

E. Fermi, ApJ 119 (1954) 1.

Ultrahigh Energy Cosmic Rays (UHECR)

<u>Fermi mechanism</u> runs out of steam
  beyond 10^{19} eV
  due to ***synchrotron radiation***

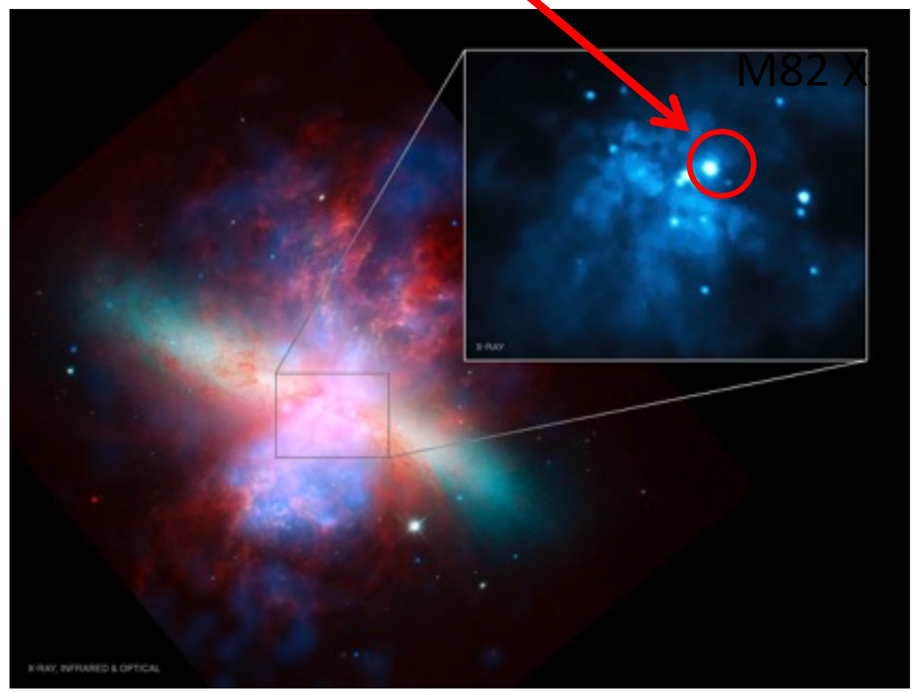
<u>**Wakefield** acceleration</u>
  comes in rescue
  prompt, intense, ***linear acceleration***
  small synchrotron radiation
  radiation damping effects?



M82: Nearest Starburst Galaxy

M82 X-1: 1000-10000 Ms BH

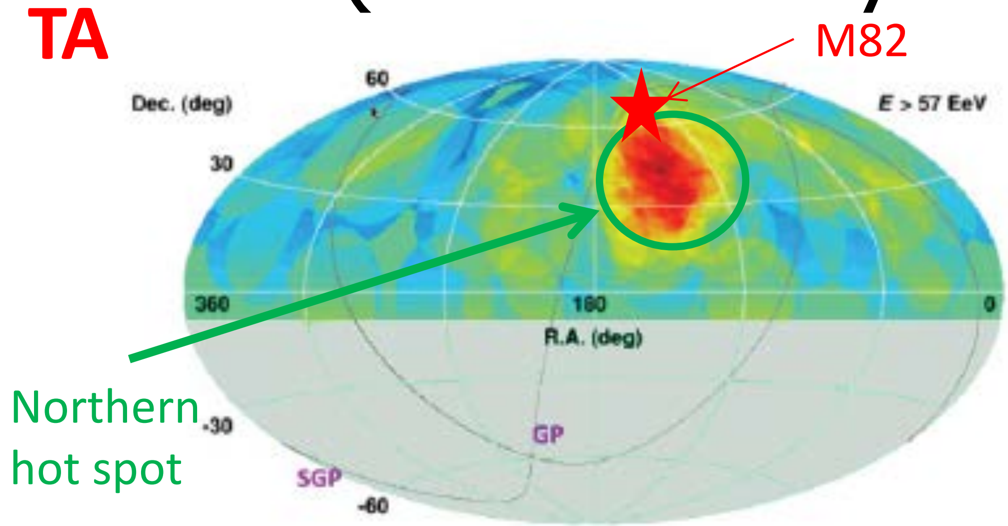
Just after the collision with M81

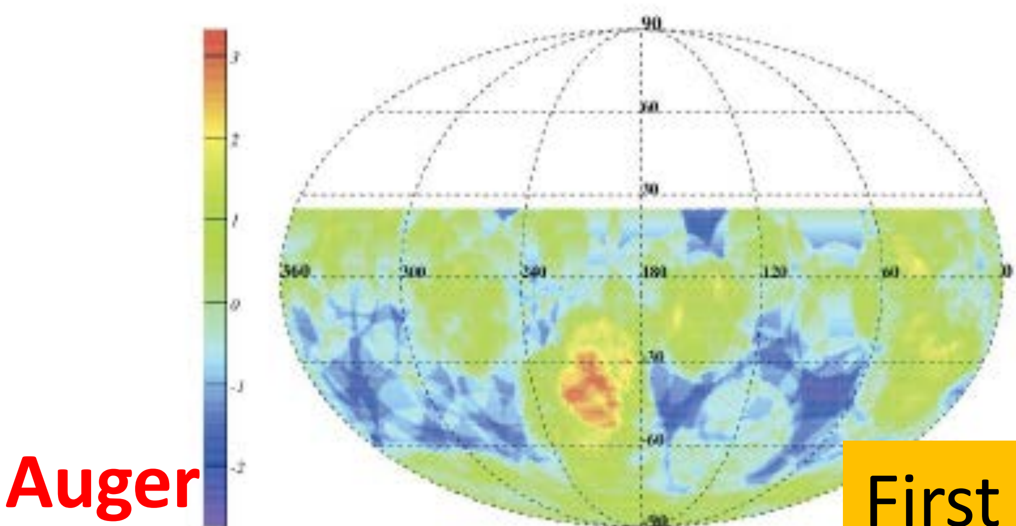


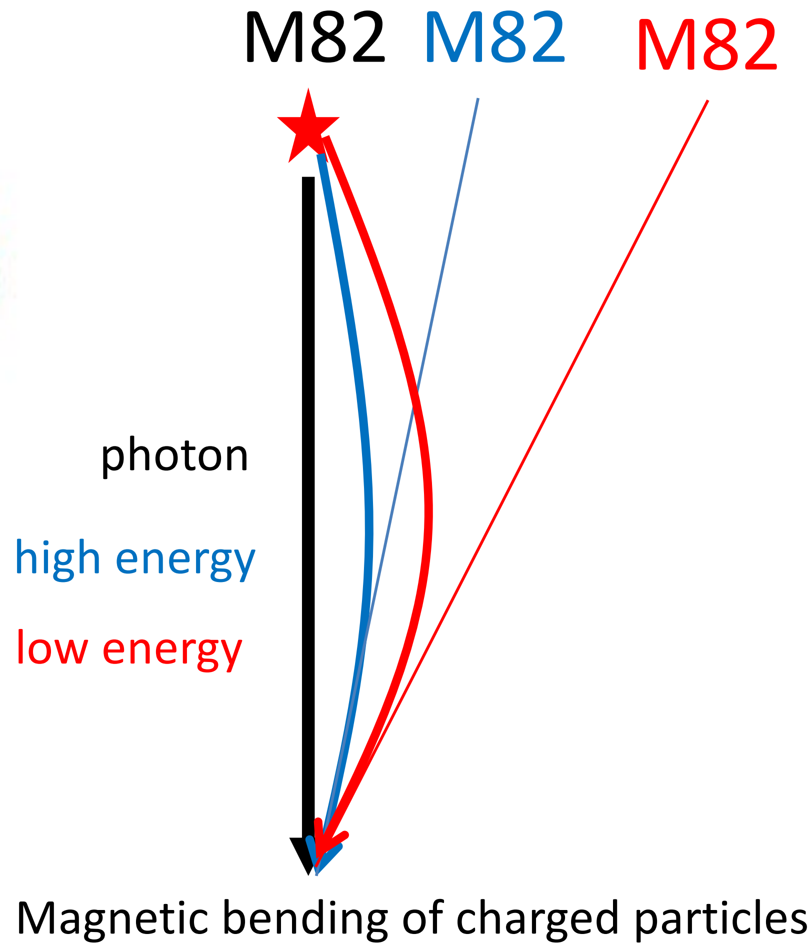
Composite of X-ray, IR, and optical emissions

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.

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







First Identification of CR sources?

First sign of anisotropy in charged particles

Cen A

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

Anti-correlation between the luminosity and the power index from Blazars

Anti-correlation of Luminosity ***L*** and Power index ***p*** in time

↑

Wakefield theory anticipated (Ebisuzaki 2014)

Blazar Variability from Wakefield Phenomena 5

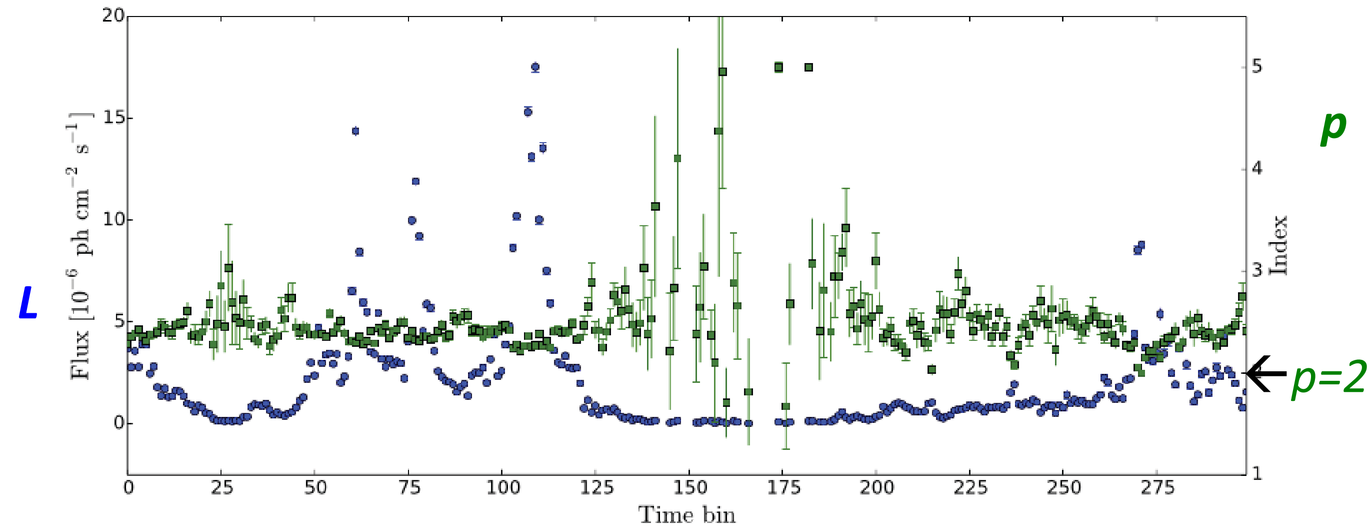
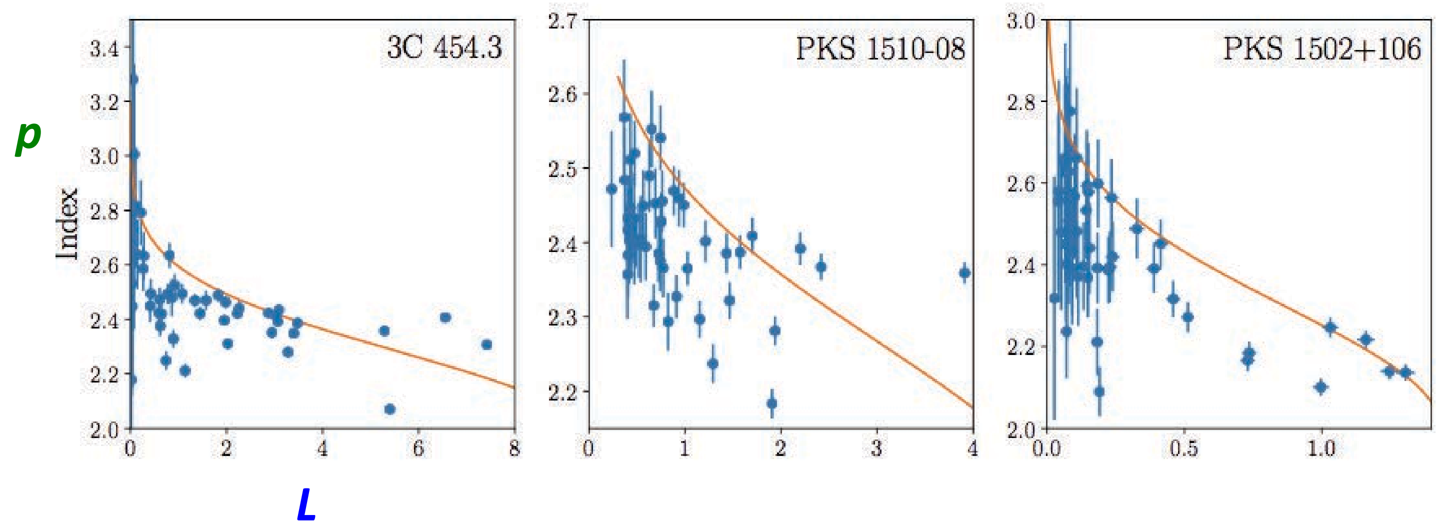


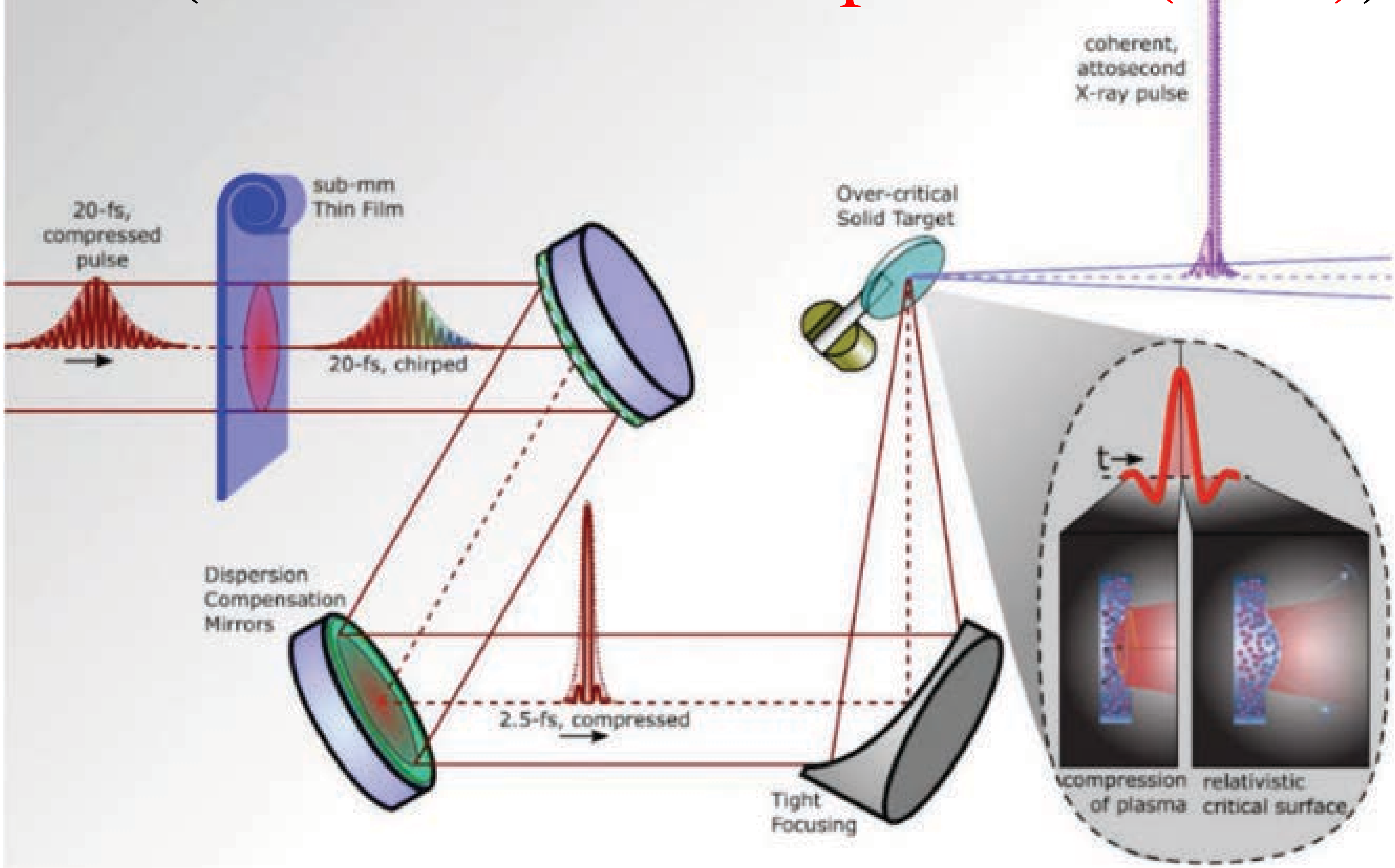
FIG. 2.— Shown are the flux (blue circles, left axis) and spectral index (green squares, right axis) for 3C 454.3 in 300 time bins of 7.9 days duration. An anti-correlation can be seen: the peaks in flux correspond to dips in the spectral index and vice versa.

Power index ***p*** vs. Luminosity ***L*** for several Blazars (more in **Abazajian** et al. arXiv **2017**)



Single-cycled laser and “TeV on a chip”

Next Generation X-ray Lasers
(on Thin Film Compression (TFC))



Wheeler J, Mourou G, Tajima T. 2016

Motivation:

1. Invention of **Thin Film Compression** (TFC, 2013) opened up
Laser Wakefield Acceleration (LWFA, 1979)
in X-ray regime,

$$E_{TD} = m\omega_{pe}\, c / e; \qquad \Delta\varepsilon = 2mc^2 a_0^2 (n_{cr} / n)$$

compactifying further by 10^3 over the gas plasma LWFA

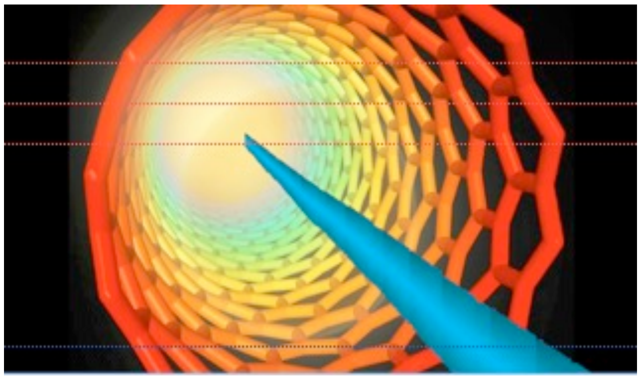
2. X-ray frequency exceeds the nanomaterial's plasma frequency ω_{pe}

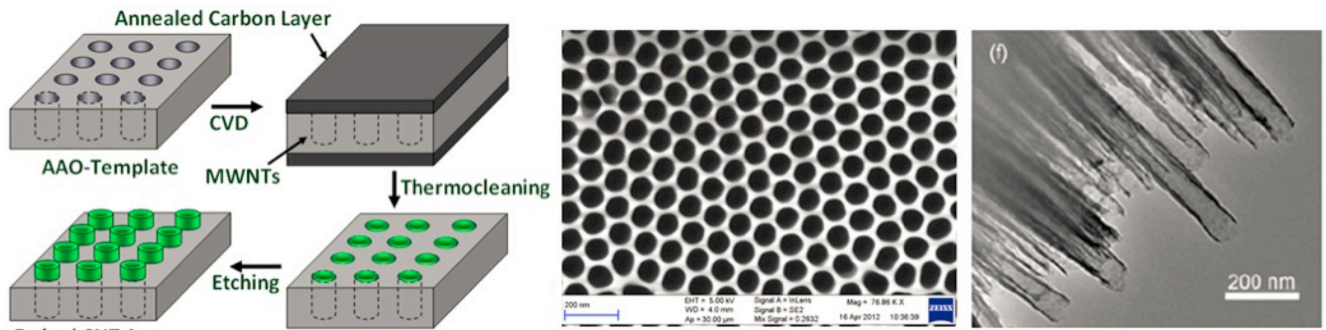
→ **carbon-nanotubes**

higher than 10TV/m wakefield (2014)

→ Explore X-ray wakefield accelerator in nanotube = "TeV on a Chip"

Why Nanotubes



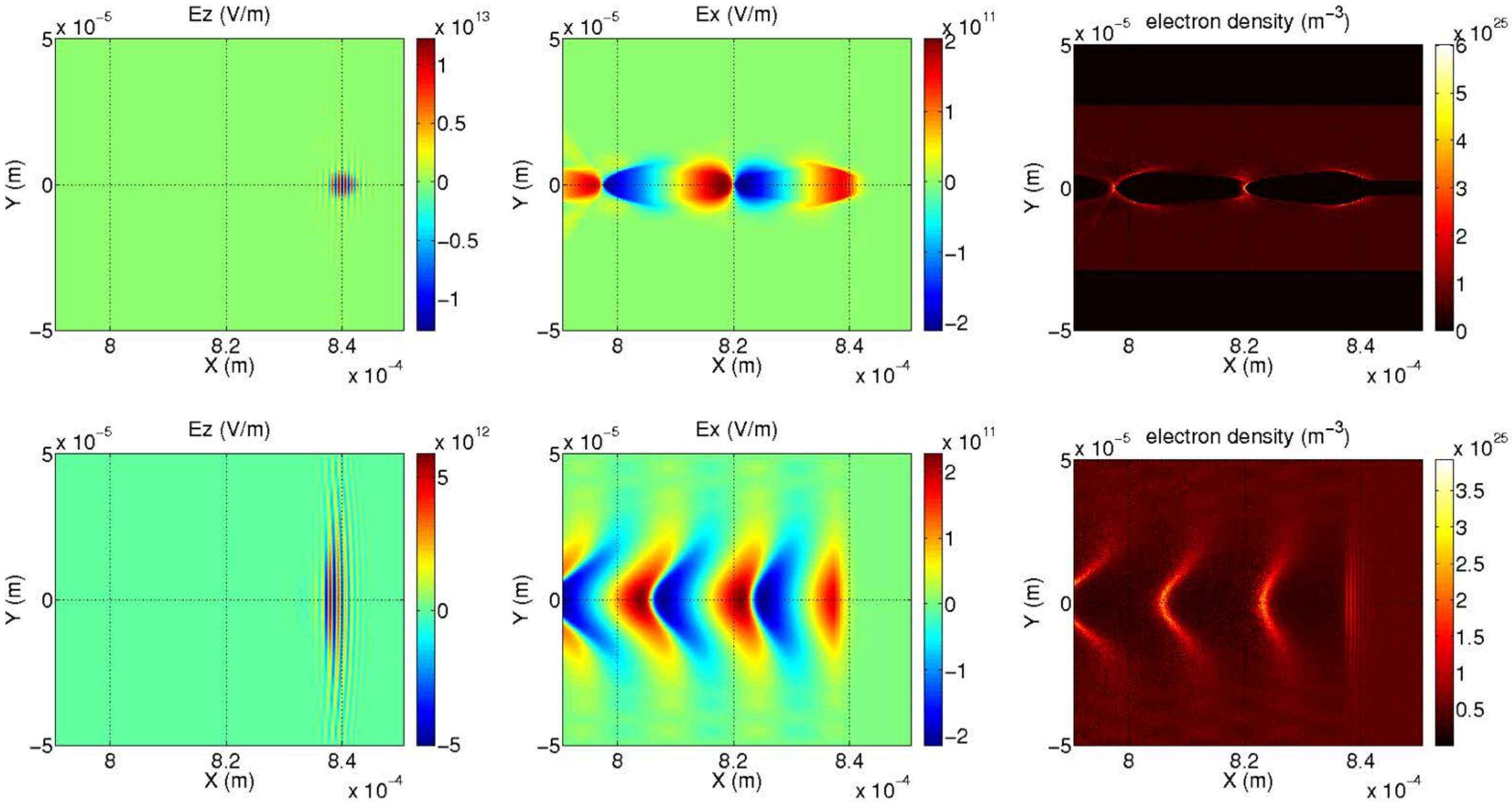


(a) (b) (c)

- High density ↔ Higher acceleration gradient (~ TeV / cm)
- Provides external structure to guide laser and electron beam
- No slowdown of electrons by collisions
- Intact for time of ionization (fs)
- More coherent electrons and betatron radiation

(b) Lazarowich RJ, Taborek P, Yoo BY, Myung NV. 2007

X-ray LWFA in a tube vs. uniform solid



in nanotube

in uniform solid

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

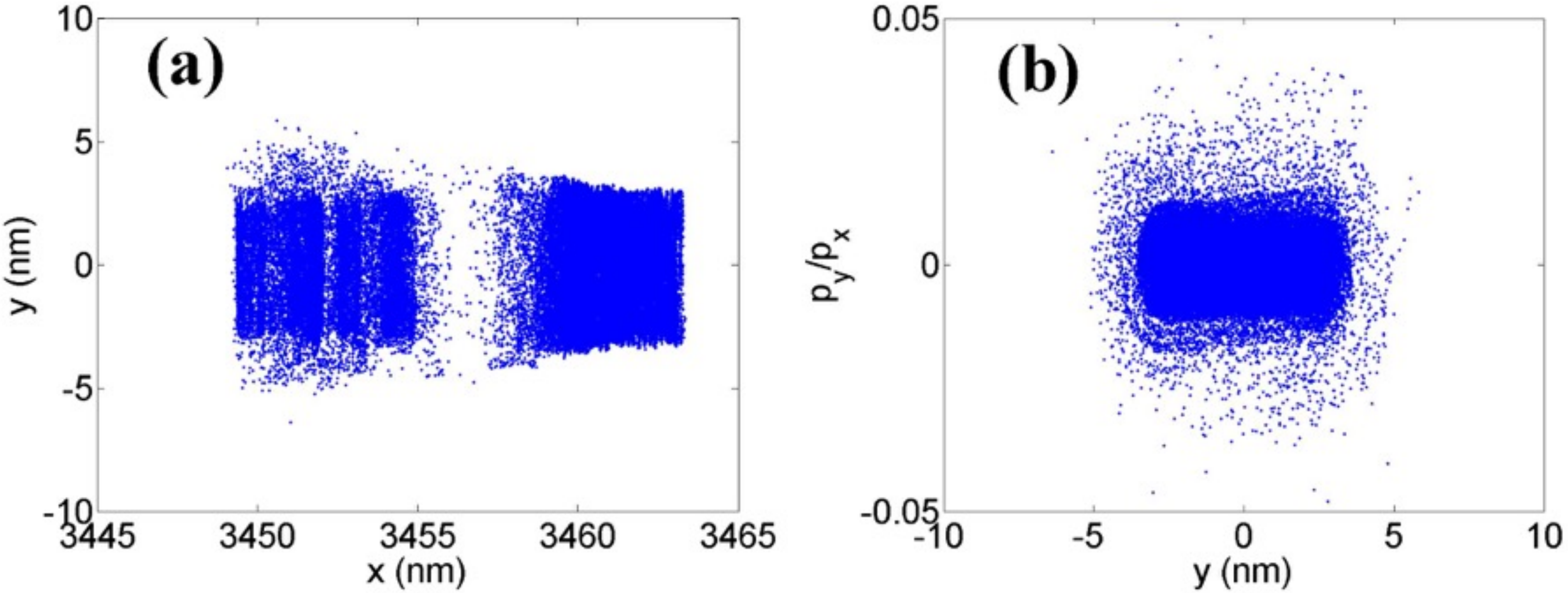
more strongly confined in the tube

cf: uniform solid

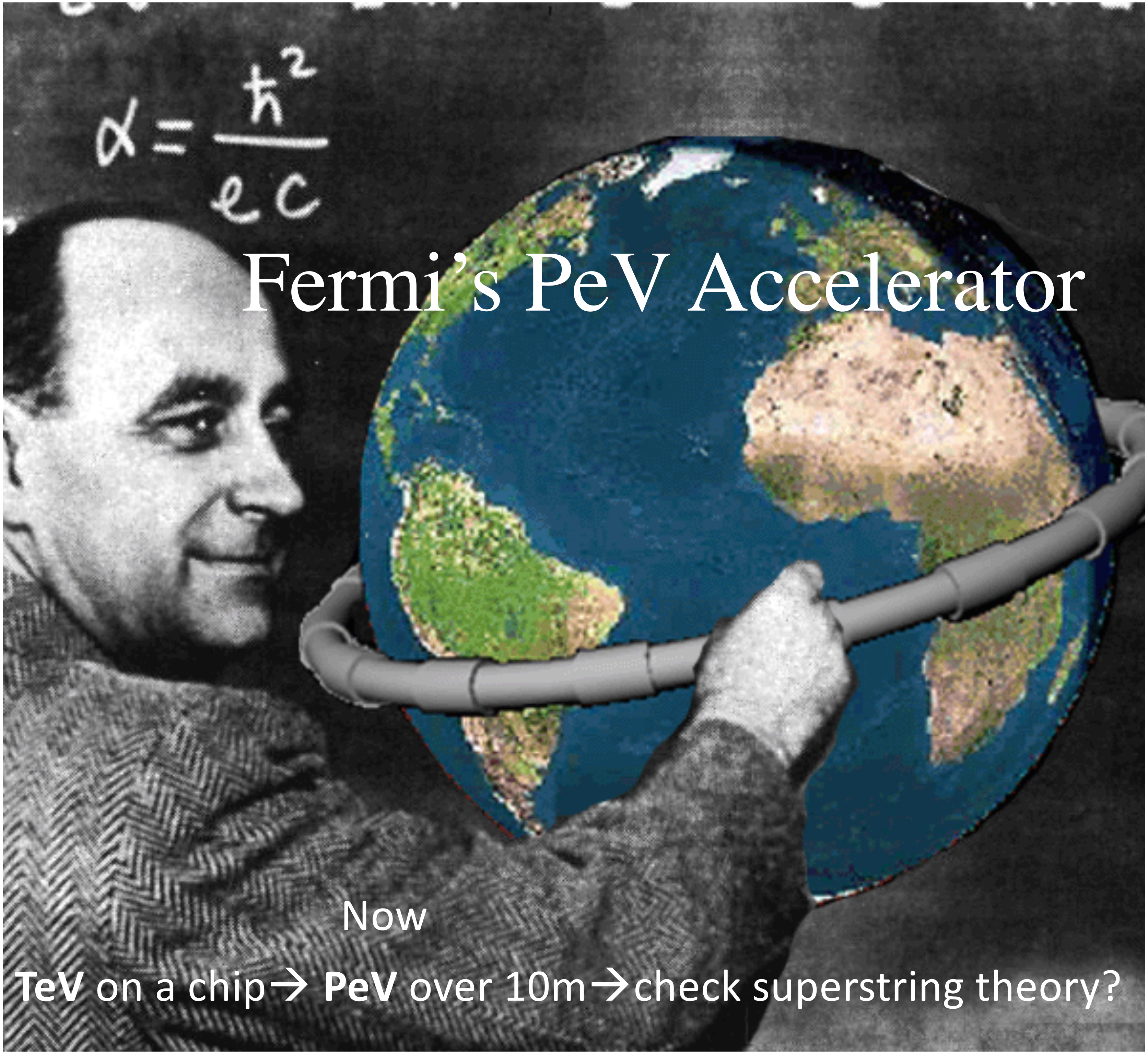
X. Zhang (2016)

Beam emittance reduction

X-ray laser driven wakefield
emittance reduction (much smaller transverse dimension)



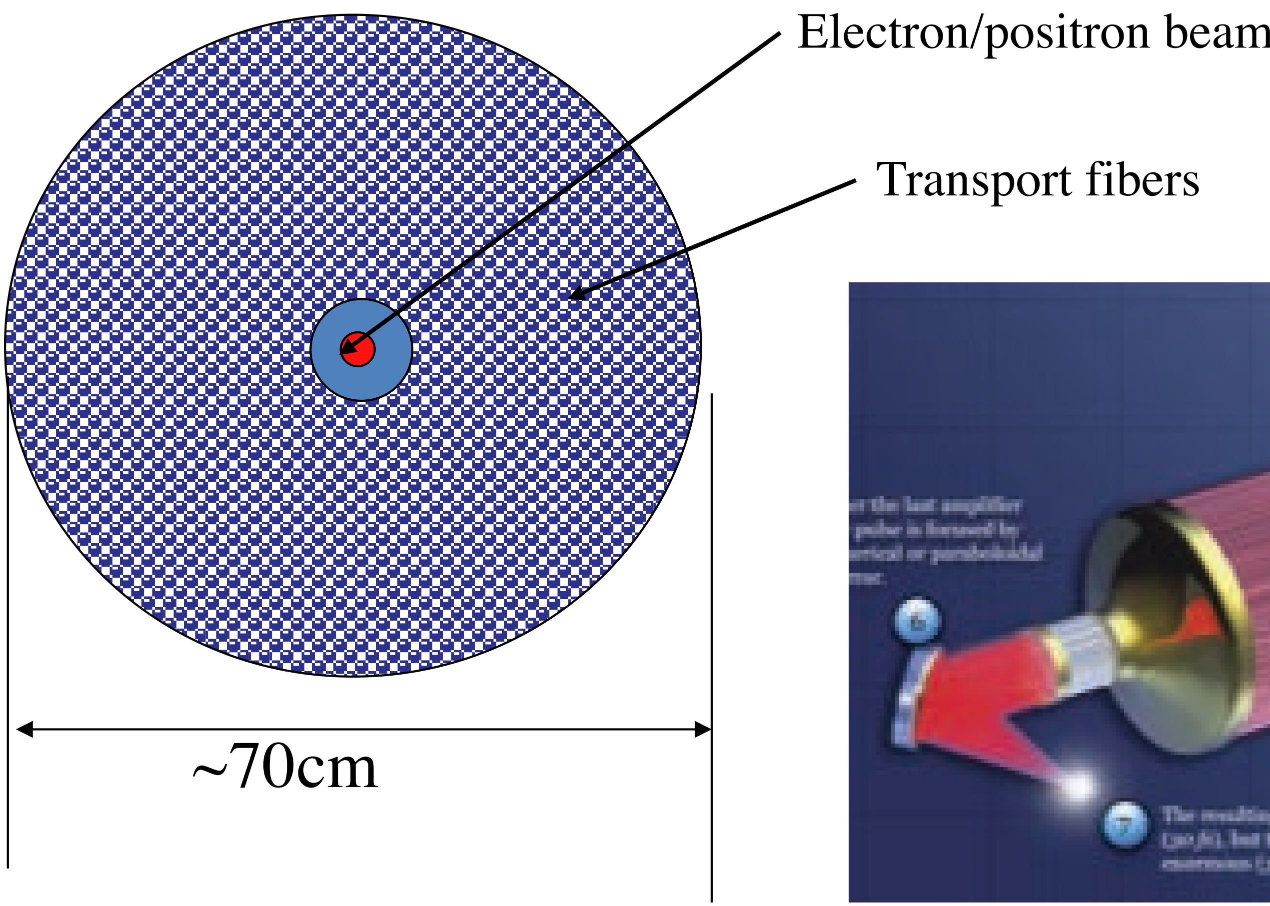
(a) The space distribution (x, y) and (b) the transverse phase space (y, p_y/p_x)


$\alpha = \frac{\hbar^2}{ec}$
Fermi's PeV Accelerator
Now
TeV on a chip→ **PeV** over 10m→check superstring theory?

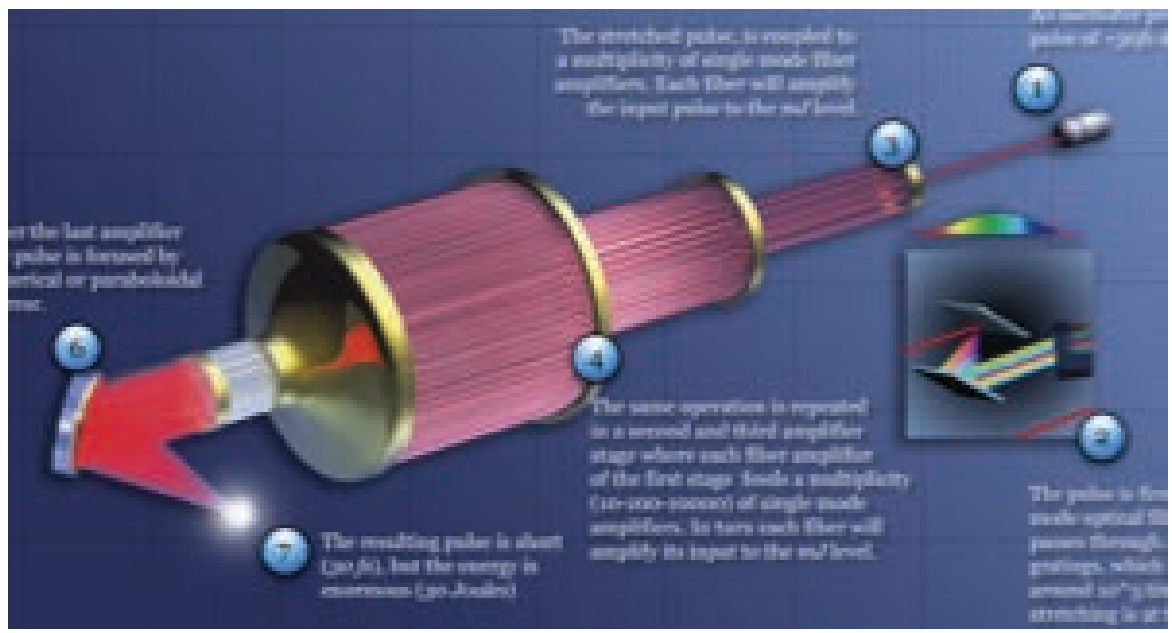

Nanotube cancer therapy

CAN Laser:

Need to Phase
32 J/1mJ/fiber~ $3x10^4$ Phased Fibers!



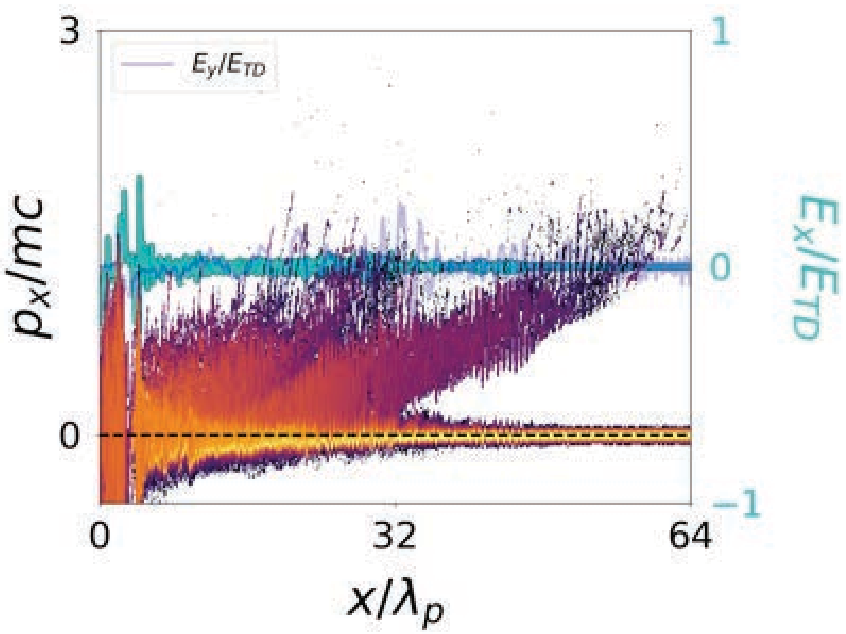
Mourou, Brockesby, Tajima, Limpert (2013)

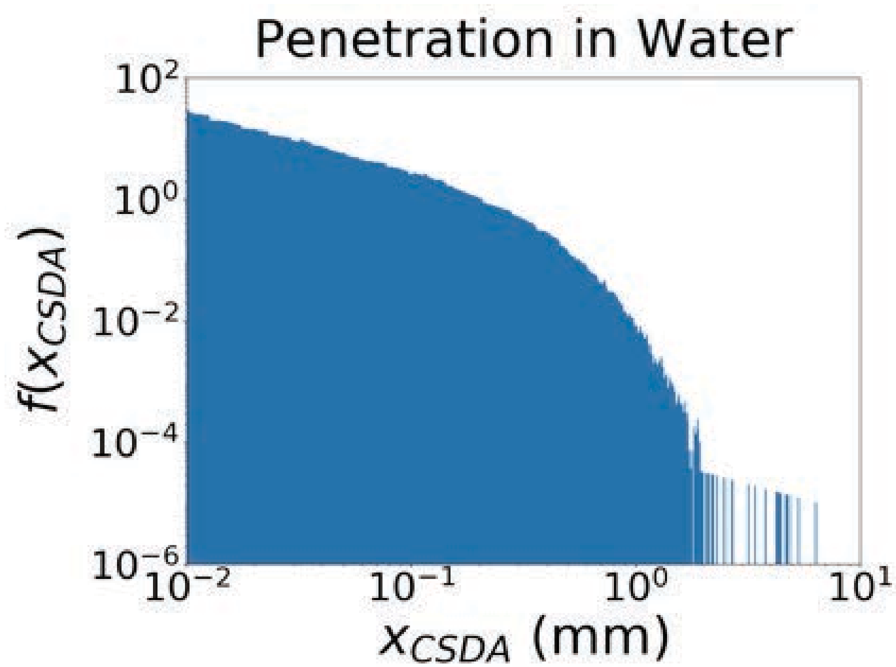


Length of a fiber ~2m Total fiber length~ $5\ 10^4$km

High density wakefields for medicine

- **Micron** accelerator (in body?) by optical laser
- **Nanomaterials** target: density ~ 10^{21} cm^{-3}





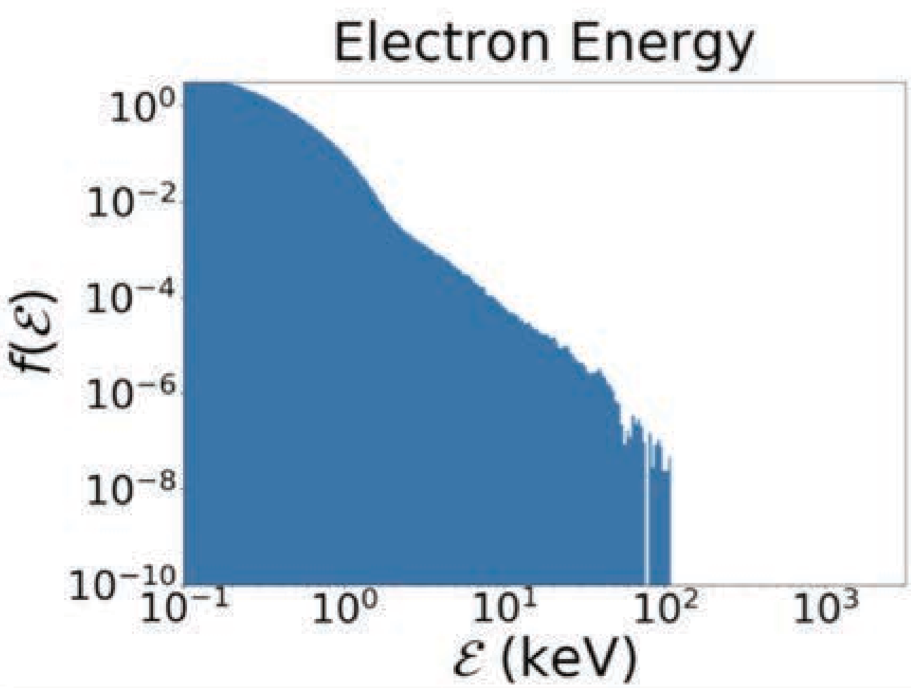
Critical density wakefield acceleration (< MeV) : e.g. skin cancer

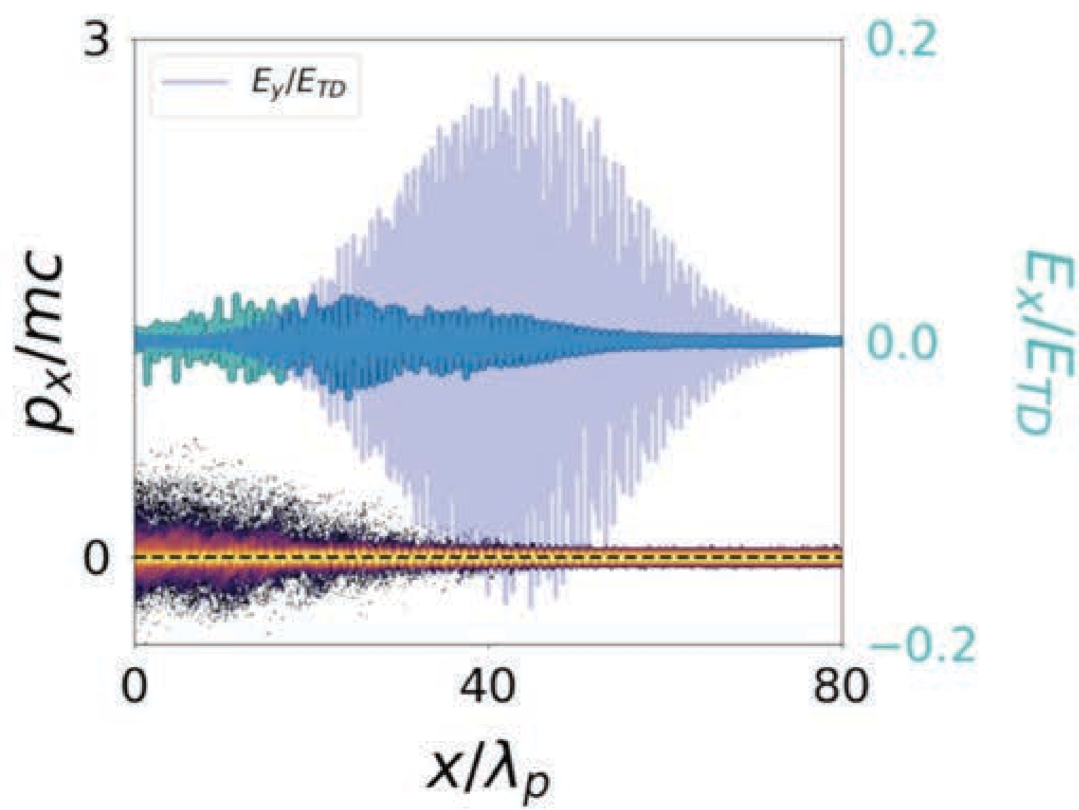
Nicks et al. (2019)

Beatwave wakefield acceleration of electron acceleration in low intensity laser

- Two laser pulses, each @ $a_0 = 0.03$
- $a_0 = 0.03 \rightarrow 1.2 \times 10^{15}\ \mathrm{W/cm^2}$
- Wavelength: $\lambda_0 = 1\ \mu\mathrm{m}$
- $\omega_1 = \omega_0 + \omega_p/2$, $\omega_2 = \omega_0 - \omega_p/2$
- Pulse length: ≈300 fs

← Tajima-Dawson (1979)





Very low intensity laser with **nanotubes** → no vacuum necessary

S. Nicks, et al. (2020)

Conclusions

- 1994-LWFA Demonstrated (Nakajima et al): ultrafast pulses, coherent collective (robust) intense (GeV/cm) accelerators.
- But B years ago, Mother Nature sent message she did
- Wakefields: Nature's favored acceleration

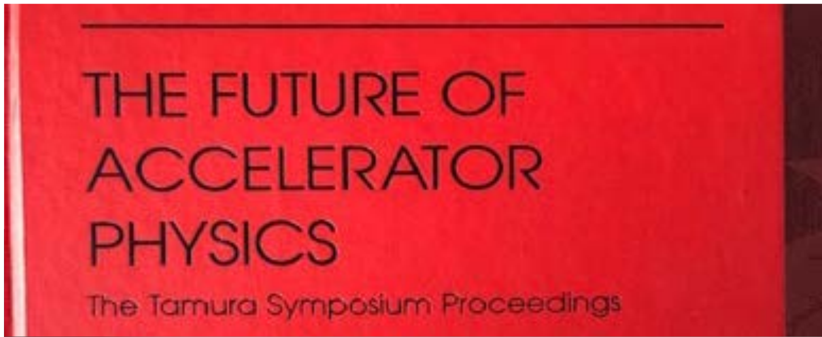
  for gamma ray bursts, UHECR from Blazars; NS collisions

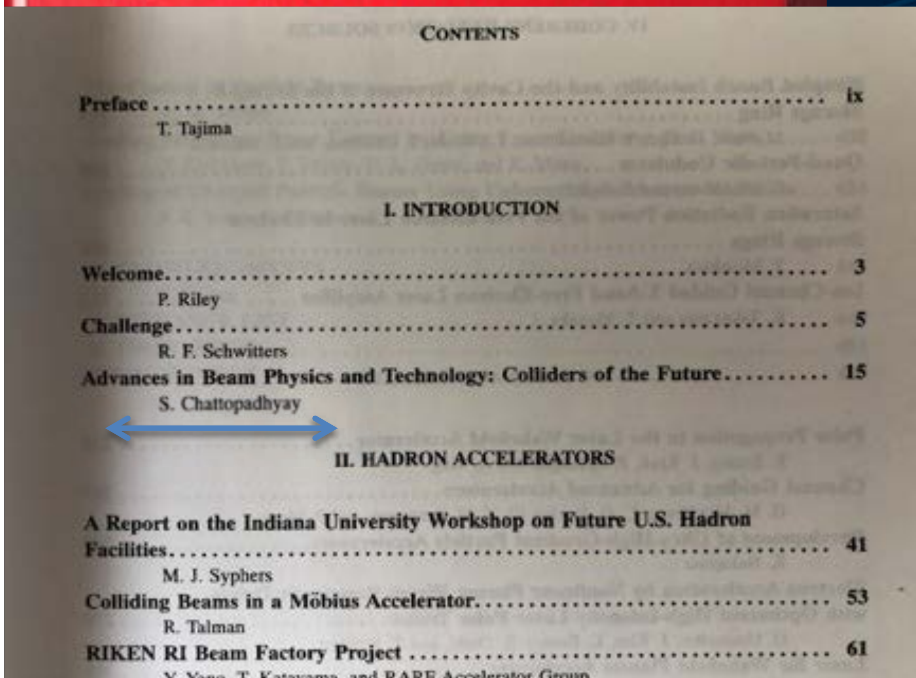
- TFC →Single-cycled laser → single-cycled X-ray
- **Wakefield in nanostructure (TeV/cm):**

  TeV on a chip accessible*

- Toward PeV (~10-100m)
- Applications: tiny (μm size) LWFA radiotherapy of cancer

* Fermilab conf book: "Beam Acceleration in Crystals and Nanostructures" (WSP, 2020)





CONTENTS

"Accelerator
Unprecedented and huge
Curious baby
Embraced by Mother Mountain
Where's her beautiful white coat?"

(Toshiki, Geneva, Feb. 13, 2020)

Thank you!

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