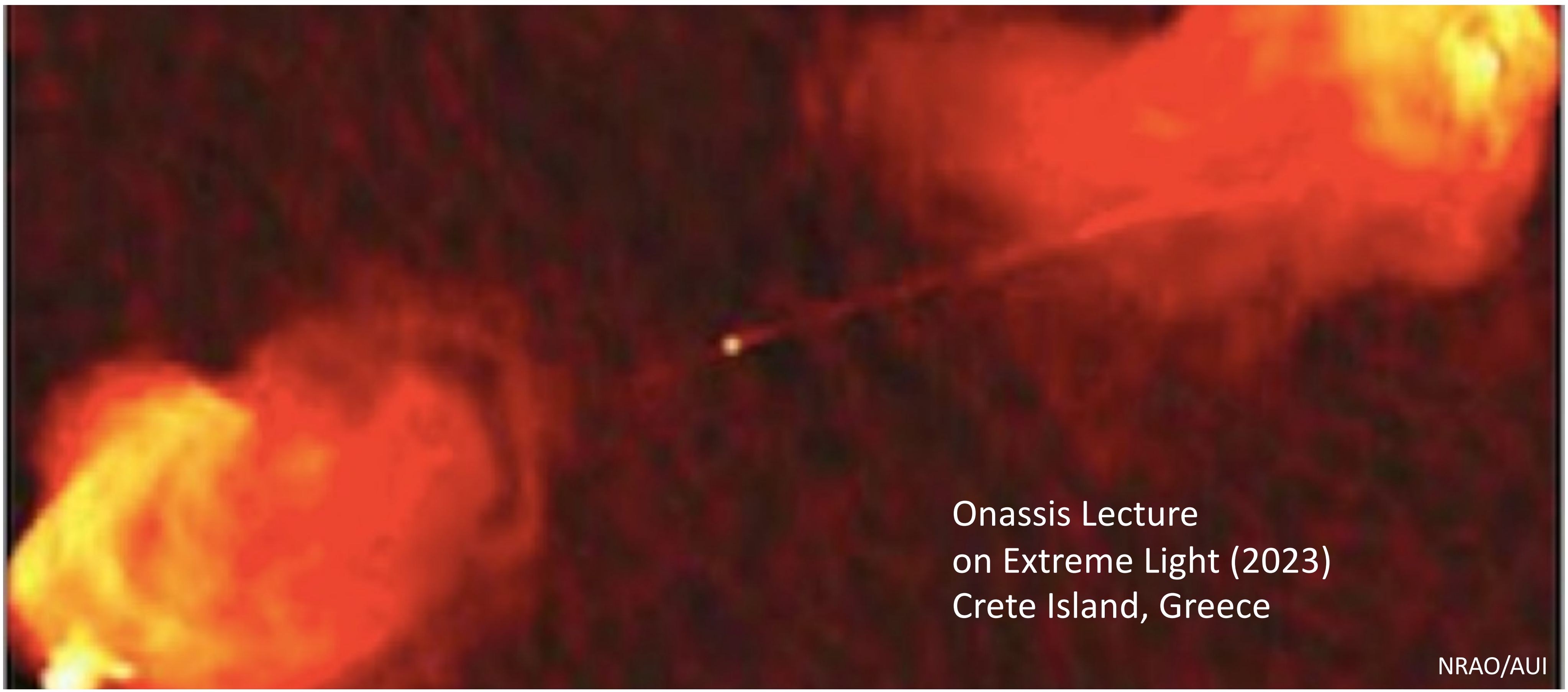
(7/4/2023)

Laser wakefield acceleration:

in Nature and lab applications

Toshiki Tajima, Norman Rostoker Chair Professor, UCI, USA

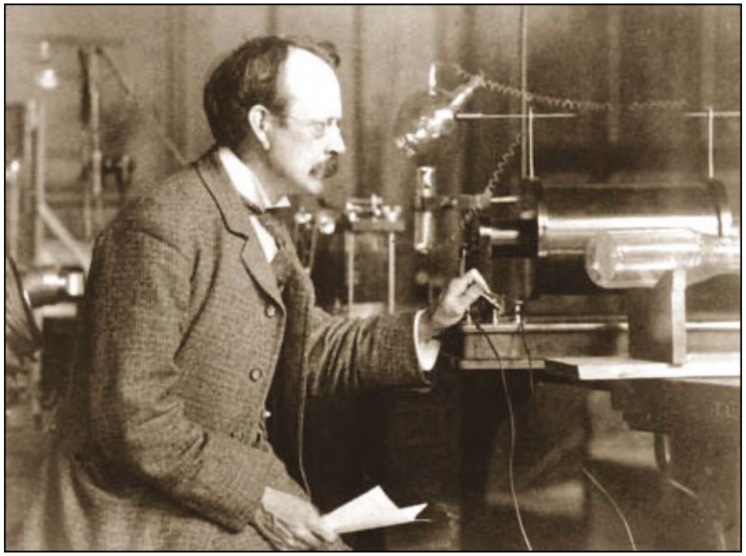
part 1:



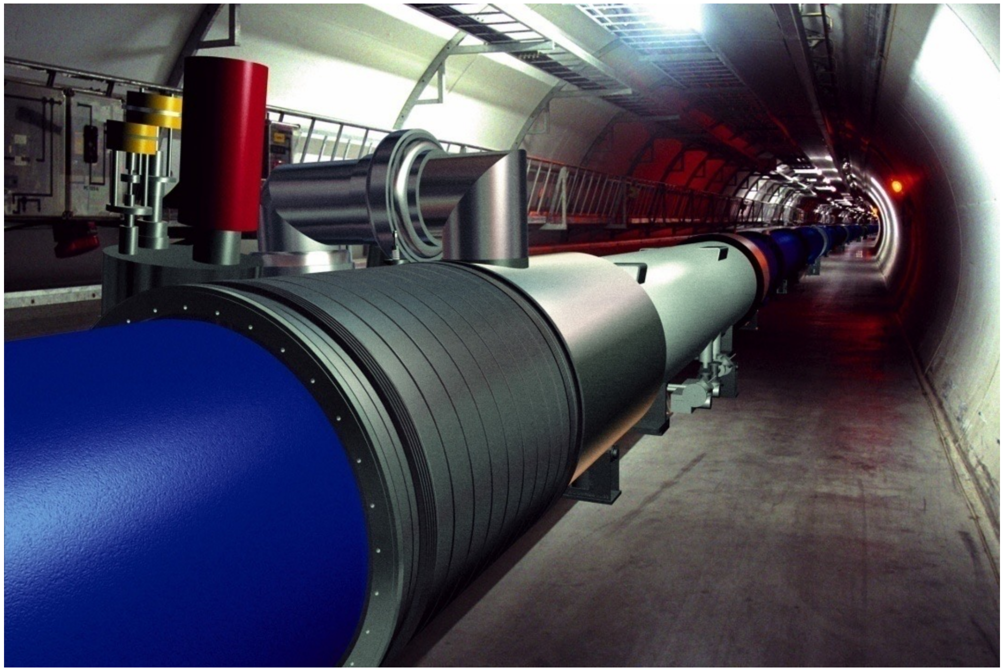
1. Conventional accelerator to LWFA
2. How to make dynamically stable wake: high phase velocity paradigm
3. Wakefields in Nature
4. Laser Driven Wakefields
5. LWFA led the High Field Science

From Conventional Accelerator to Laser Accelerator in Plasma

20th Century, the Electron Century
Basic Research Dominated by
Massive and Charged Particle Accelerators



J. J. Thomson



→ Now photons (and photon-assisted electrons)

21st Century; the Photon Century
Could basic research be driven
by the massless and chargeless particles; Photons?

C. Townes (laser invention, 1960) →
Mourou-Strickland (laser compression, 1985)
G. Mourou (Inst. Zetta- Exawatt Science and Technology)

Tajima-Dawson (laser-driven wakefields, 1979)

Conventional accelerators → Laser Plasma Accelerators

- Atoms and solids:

  nucleus vs. bound electrons

  (applied large enough fields (< MeV/cm) surface **breakdown)**

  → ionization

→ Plasma (no more breakdown problem)

However, plasma is (often) unstable? → Can we make it stable?

no binding force → need **new organizational** principle

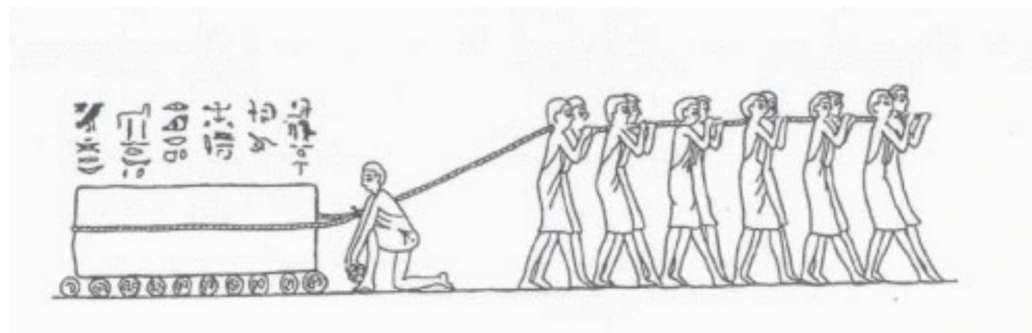
Also collective force ($\sim N^2$): large fields

→ photons drive high phase velocity wakefields (stable)

Laser-driven collective (large GeV/ cm) plasma waves

What is *collective force*?

How can a Pyramid have been built?



Individual particle dynamics → Coherent and collective movement

Some early learning from negative experiences (Veksler, 1956; Rostoker, 1960's)

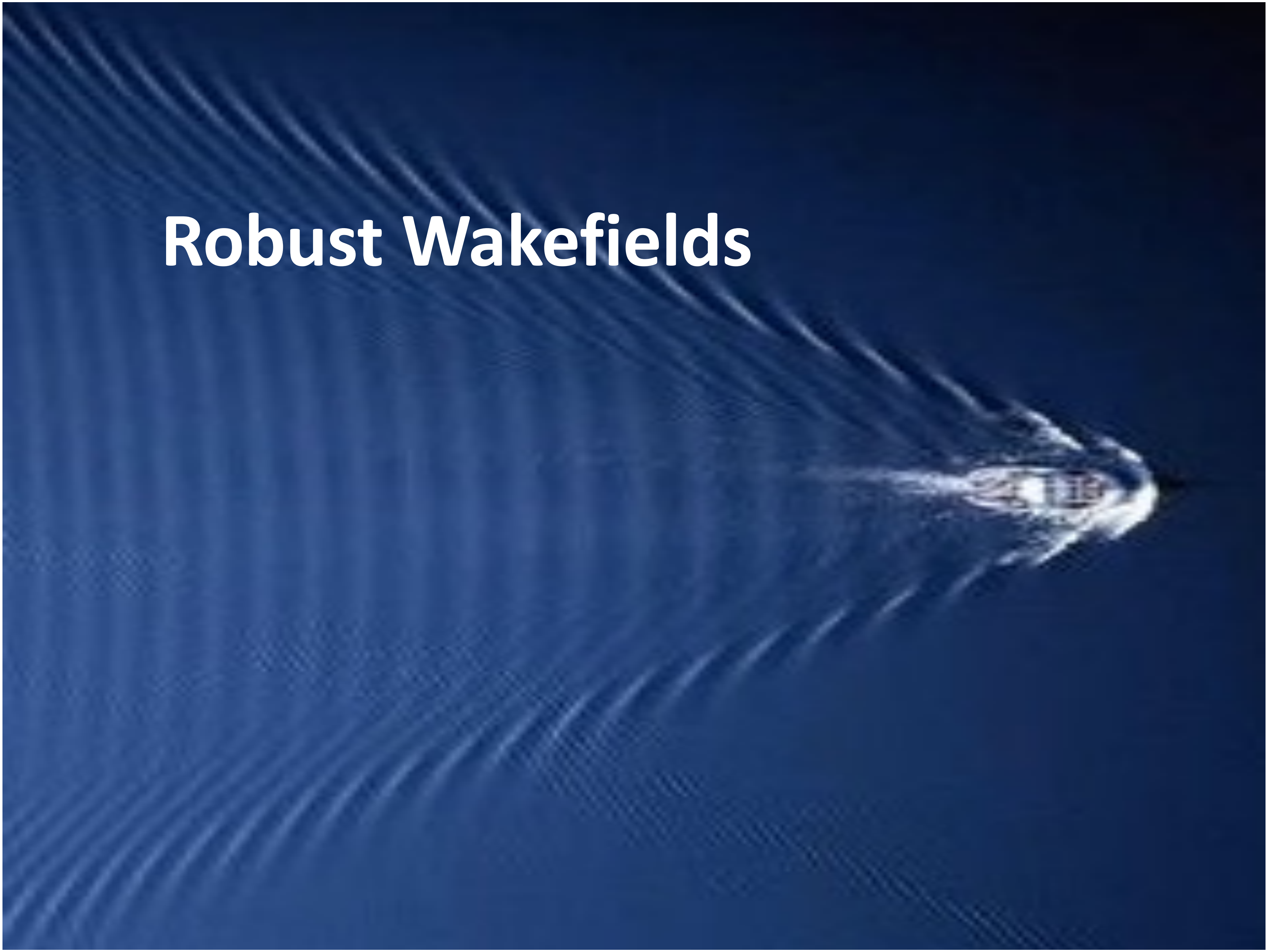
Collective acceleration (Veksler, 1956; Tajima & Dawson, 1979)

Collective radiation (N^2 radiation)

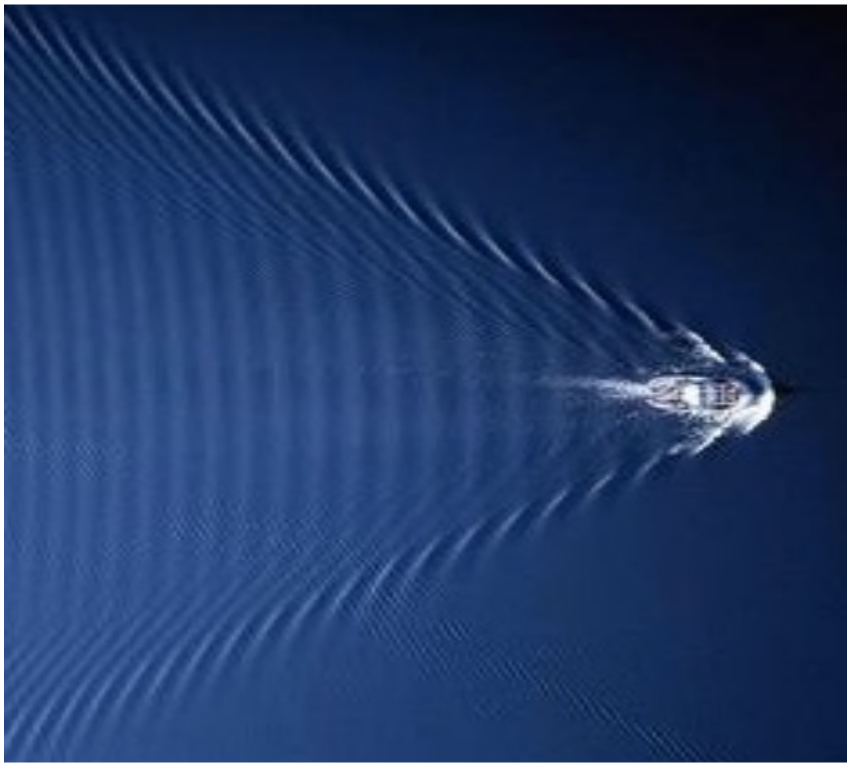
Collective ionization (N^2 ionization)

Collective deceleration (Tajima & Chao, 2008；Ogata, 2009)

Robust Wakefields



Dynamically Sustained State in Plasma : Wakefield



Water structure that is moving is dynamically stable

Cf. "Bicycle-tire principle" for stability

Some similarity and some difference with wake

too **slow**

fast enough

(Lessons I learned from early negative experiences --> next page)

Phase velocity and stability (learn from the water wave case)

Example of water wave:

Phase velocity of water wave

$v_p \sim \sqrt{d}$,

d : water depth

Shallow water

→ 1. amplitude $A \sim 1/\sqrt{d}$

→ 2. wave slows down: v_p ↓

→ 3. wave begins to trap particles

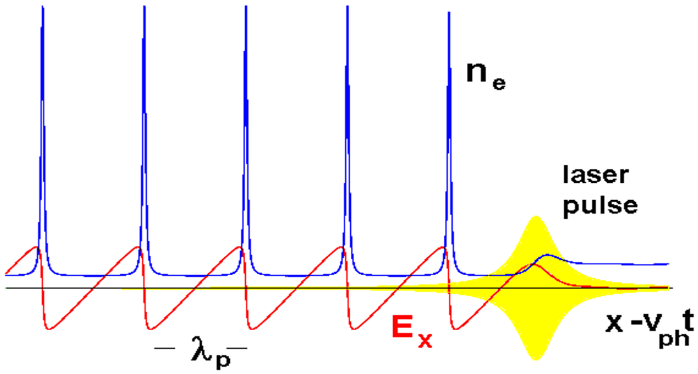
begins to break

(exceeds Tajima-Dawson field)

Laser Wakefield (LWFA) (1979):

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

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



↑ relativity regularizes (***relativistic coherence***)

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

Relativistic coherence → relativistic structure formation

<u>Relativistic</u> nonlinearity under intense laser

$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2} = v_{os}/c$$ Normalized intensity parameter

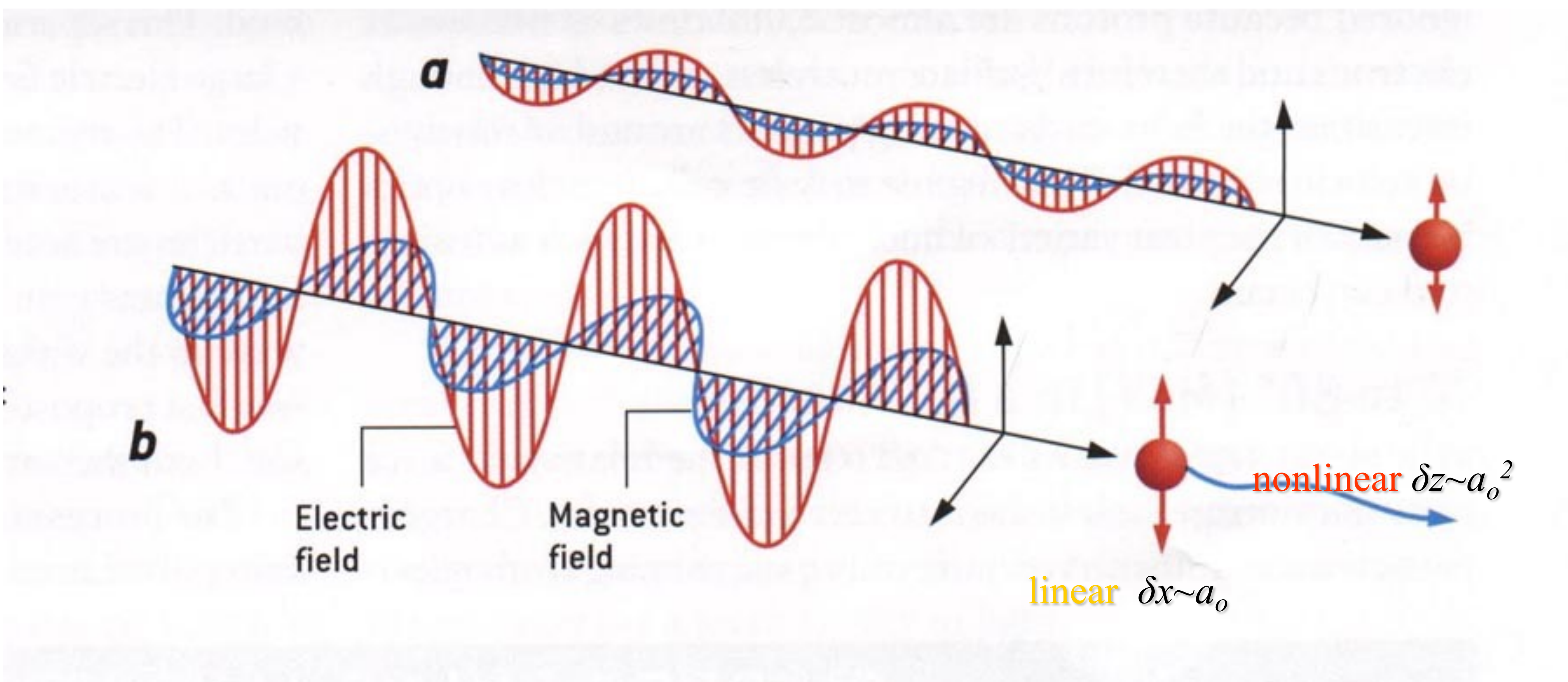
ponderomotive force ---- longitudinal →to erect **Wakefields**

a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v\sim c$

$a_0>>1$: $\delta z >> \delta x$



Basic Concepts

- **Ponderomotive force** (longitudinal)

  ← magnetic Lorentz force of laser, a_0 v_g

- **Wakefields**

  ← triggered by **ponderomotive force** (charge separation----plasma waves, ω_p v_{ph})

  (Here $v_{ph} \sim c >> v_{th}$)

  ← resonance condition: positive side of wave (π / k_p)

Plasma instability: how to avoid?

- **High phase velocity** paradigm

  Wave trapping of particles: trapping width v_{tr} (O'Neil, 1965)

  Tajima-Dawson Field $E = m\omega_p c / e$ (1979)

  ← wave breaking (saturates and trapping when $v_{ph} = v_{tr}$)

- **Wakefield: dynamically sustained stable structure in plasma**

  Structure Formation (as opposed to plasma instabilities)

Wakefield saturation

Wakefields excited: stay robust

$\leftarrow$ large phase velocity

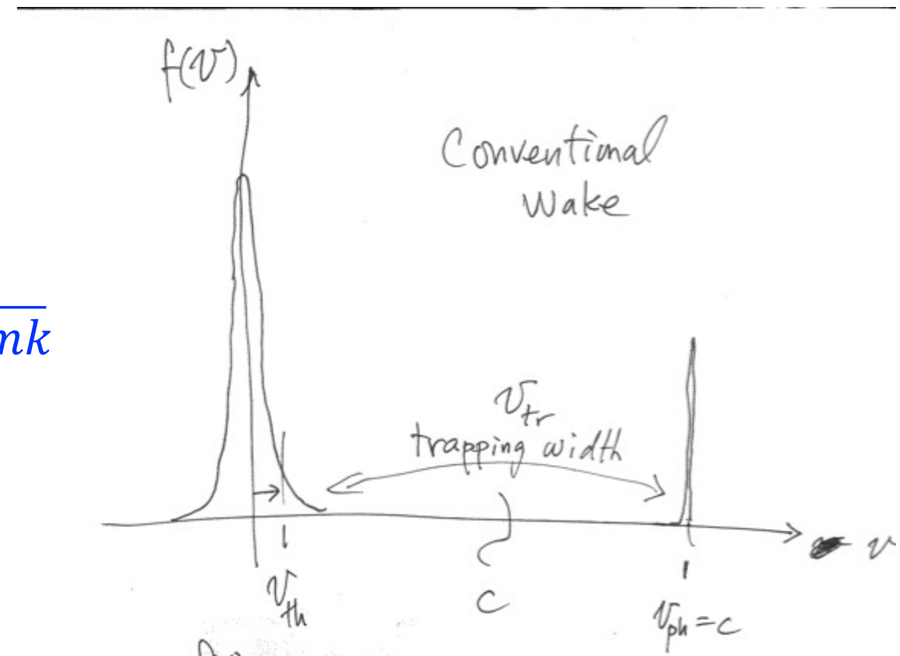
at the largest phase velocity that laser pulse group velocity can create, i.e. c

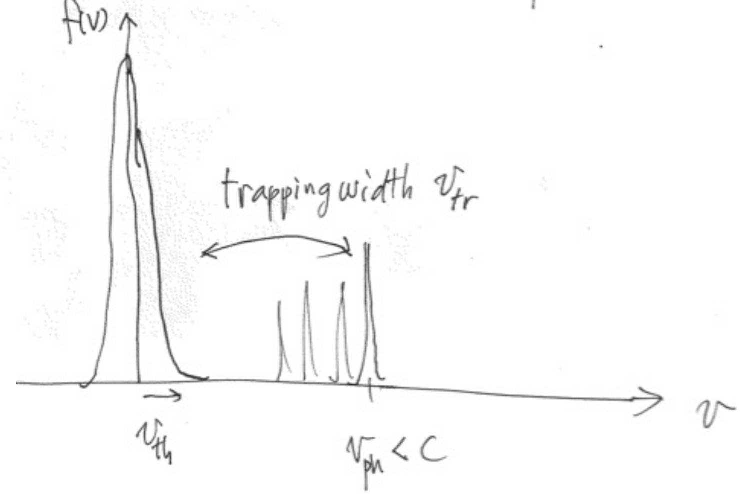
Show [Homework #2] with $v_{ph} = c$: $v_{tr} = \sqrt{eE/mk}$

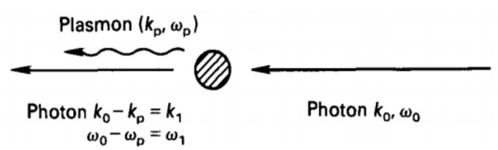
$v_{tr} = v_{ph}$ $\rightarrow$ saturation field

$$E = E_{TD} = m\omega_p c/e$$

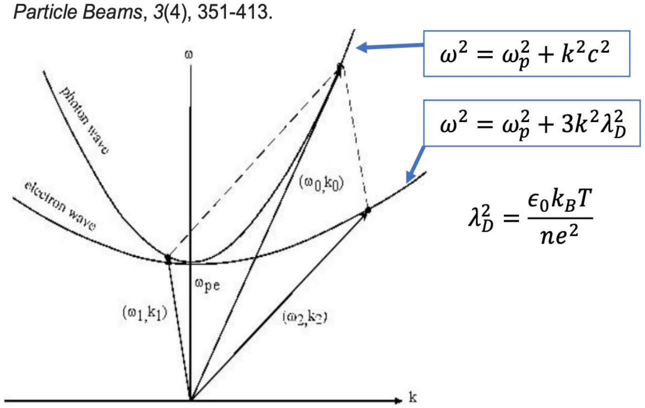
When $v_{ph} < c$, $\rightarrow v_{tr} = \sqrt{eE/mk} < c \rightarrow E < E_{TD}$

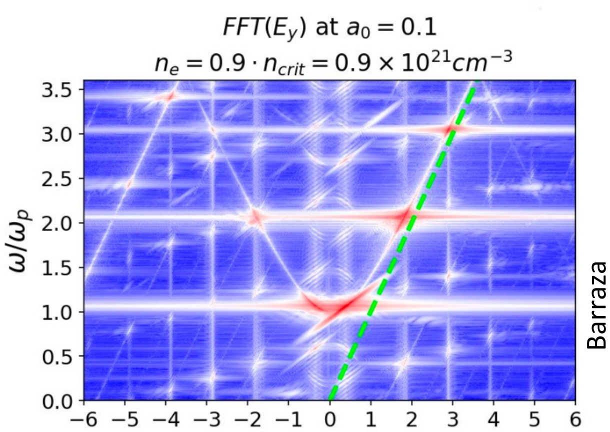


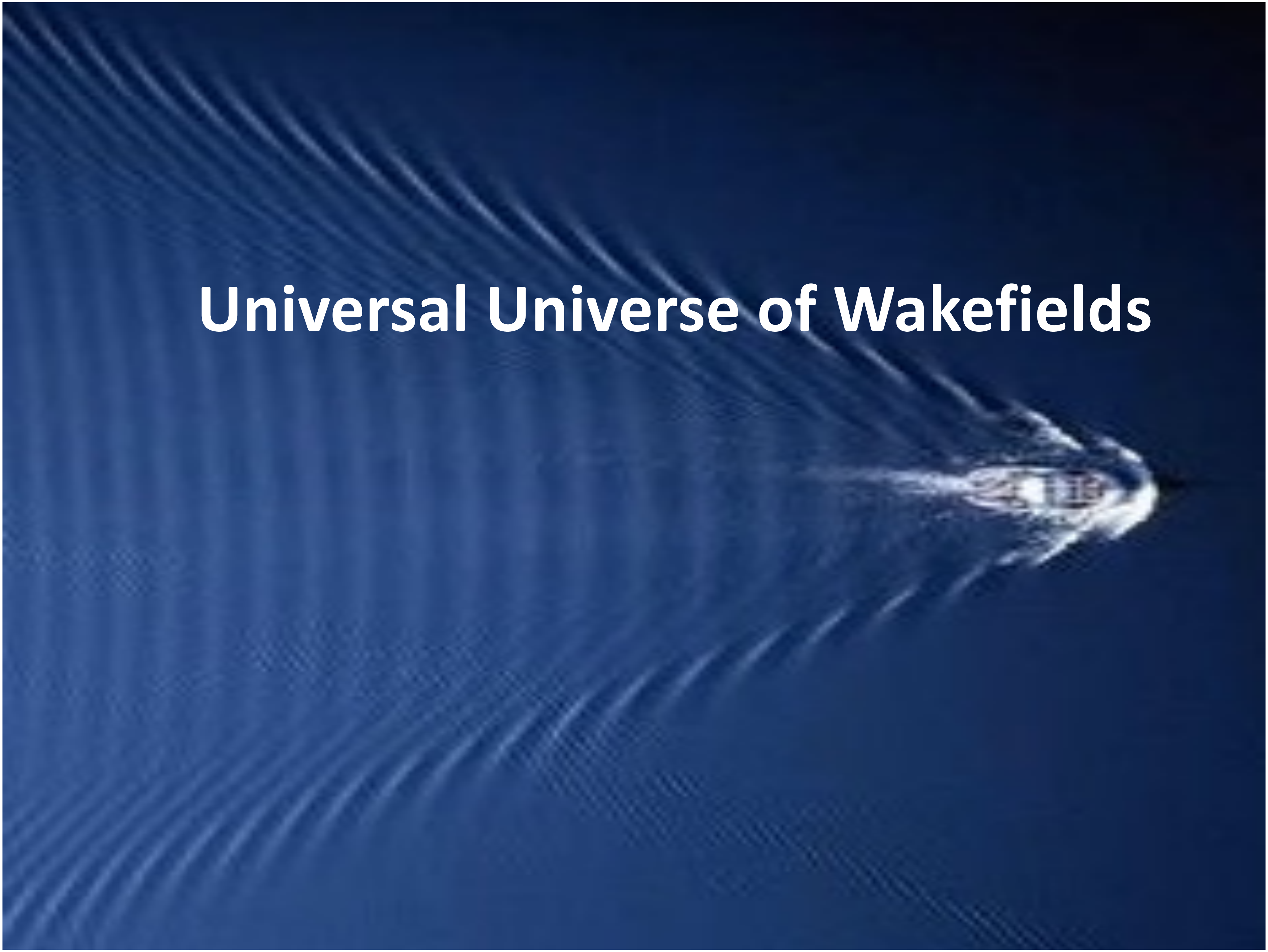




Tajima, T. (1985). High energy laser plasma accelerators. *Laser and Particle Beams*, 3(4), 351-413.

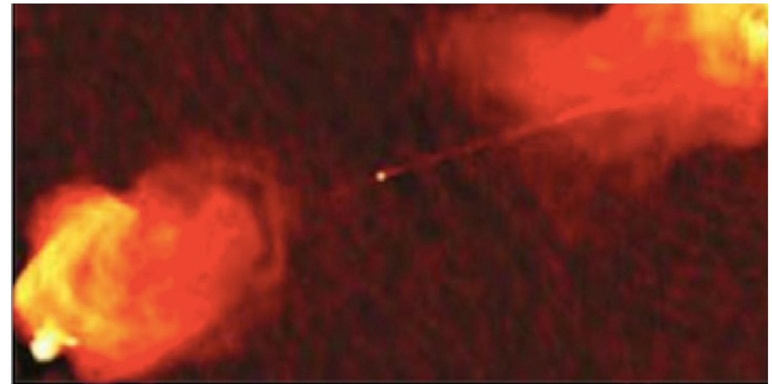




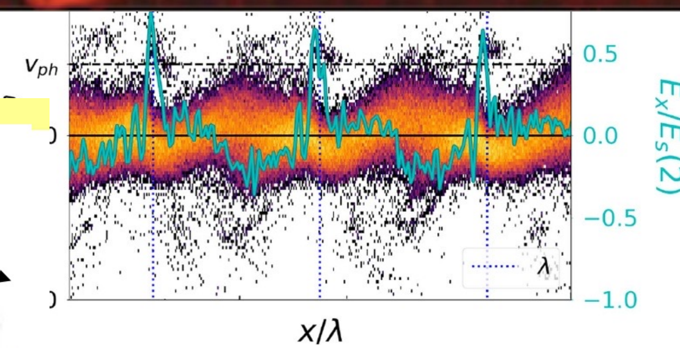

Universal Universe of Wakefields

Ranges of wakefields

λ : 10^{-13} cm ← → 10^{19} cm

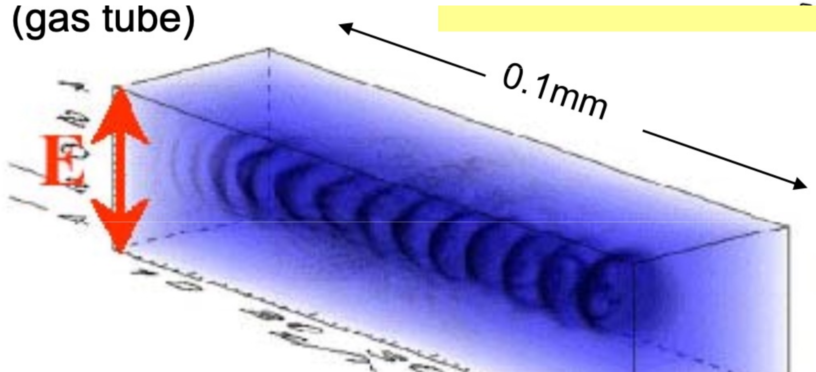


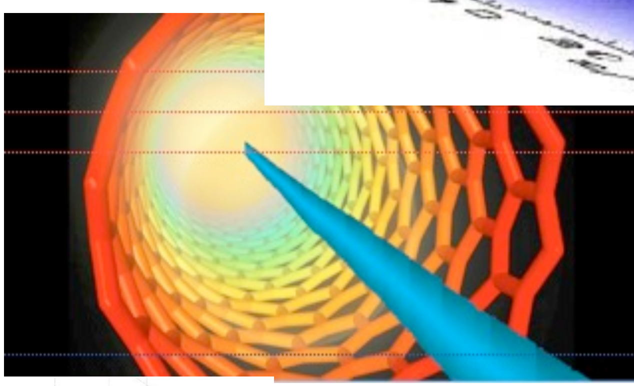
$\lambda = 10^{19}$ cm
(AGN jets)



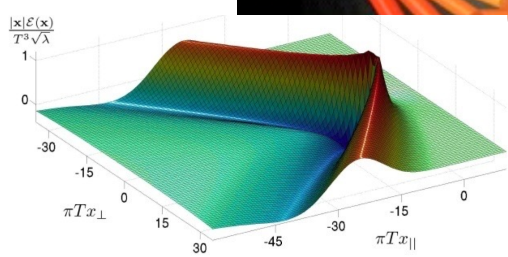
λ = 1 cm (beam-driven fusion plasma, Nicks, 2021)

$\lambda = 10^{-4}$ cm (LWFA, 2004)
(gas tube)





$\lambda = 10^{-7}$ cm
(nanotube LWFA)



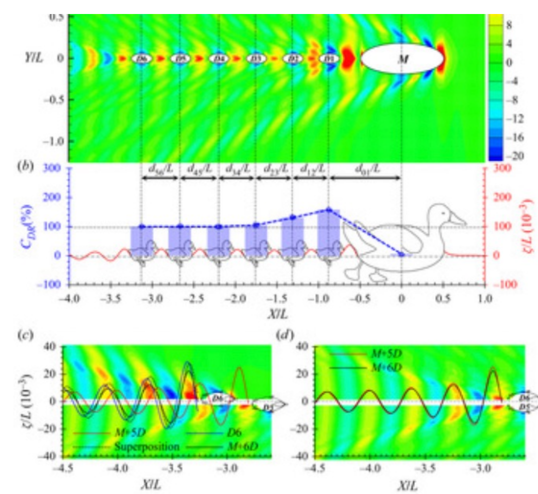
$\lambda = 10^{-13}$ cm (nuclear QCD plasma)

Wake

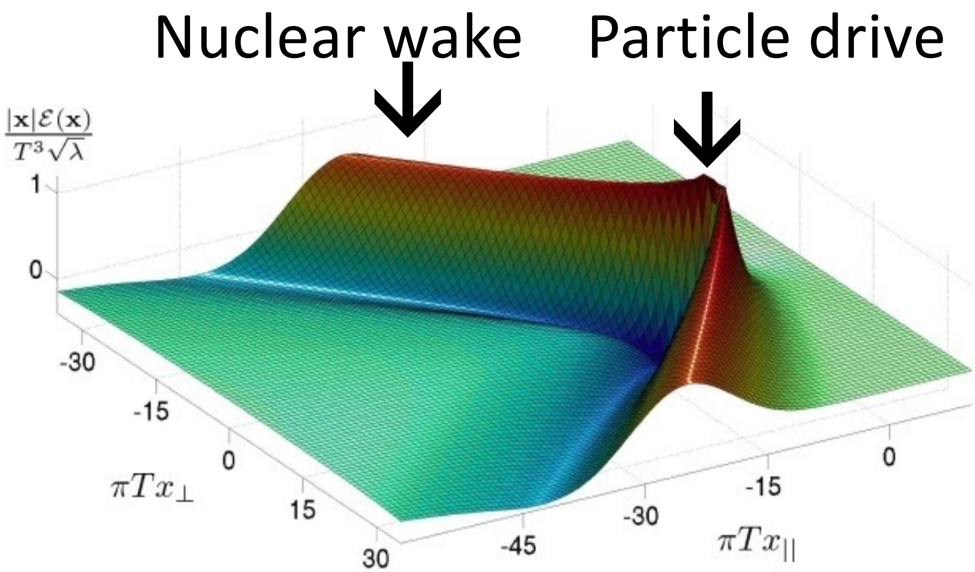
Wake by a duck

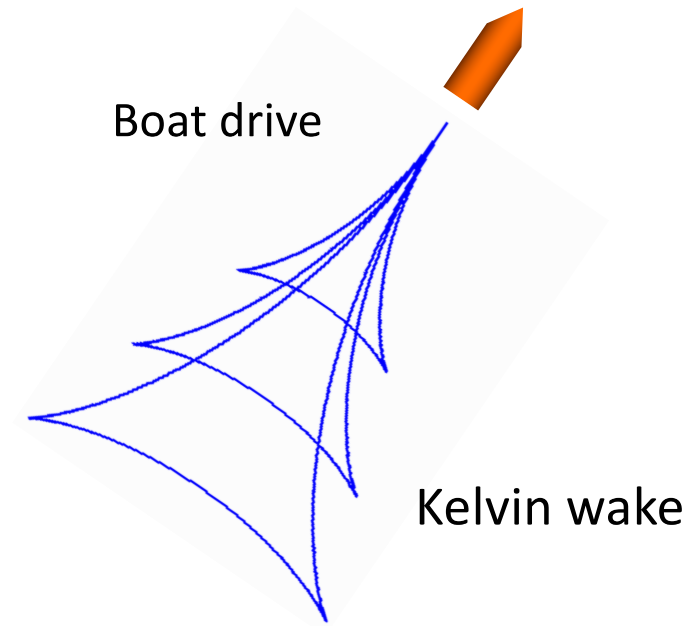
Nature (or mother duck) showed me (1968-69) when I was an undergrad student Walking by a lake toward U. Tokyo.

Yuan et al. JFM (2021)



Wakefields in nuclei (in quark-gluon plasma)





Maldacena

Maldacena (string theory) method:
QCD **wake** (Chesler/Yaffe 2008)

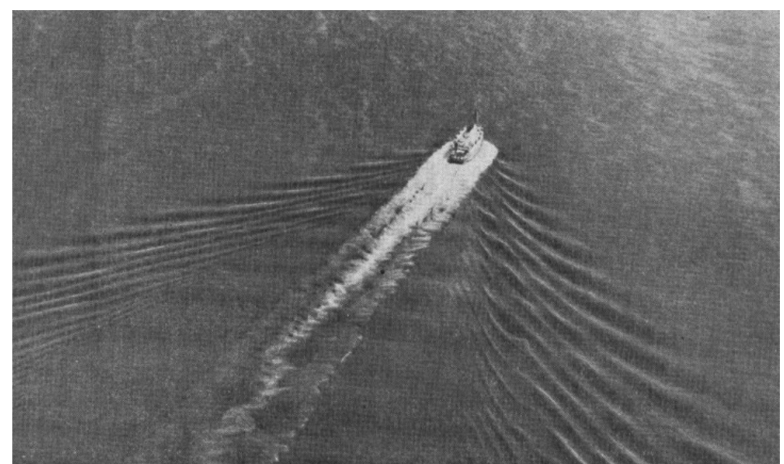
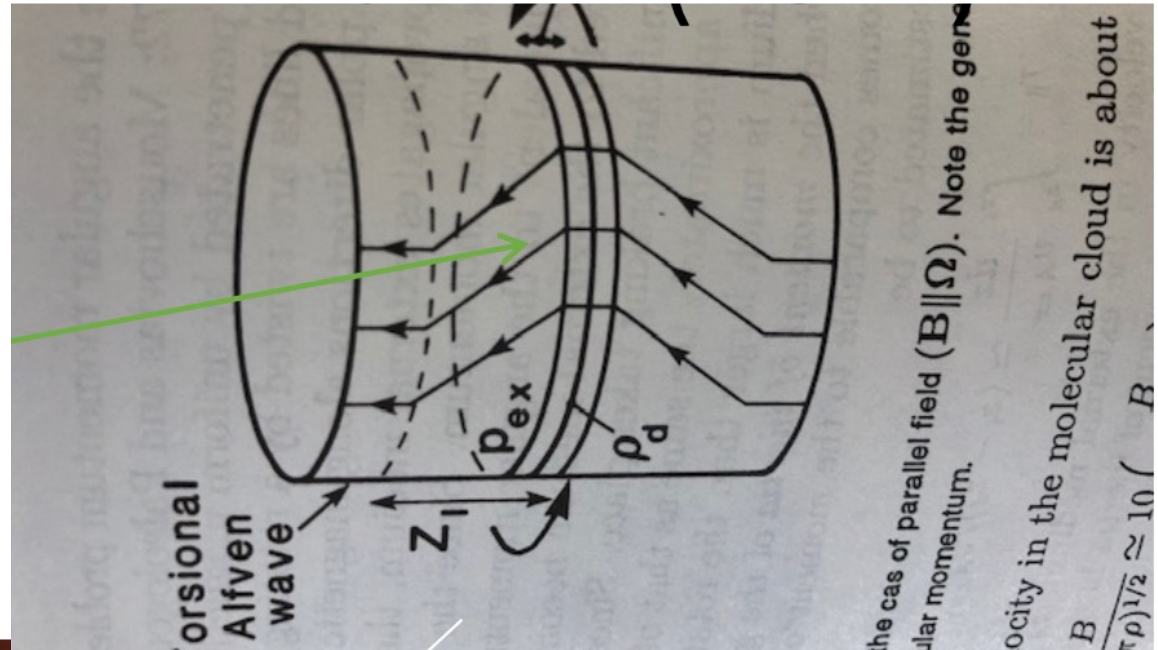


Рис. 71. Наблюдаемая картина корабельных волн. [Любезно предоставлено Aerofilms Ltd.]

Rotational twist onto magnetic field thrust→

Jets and their elongation→

Stable plasma and wave propagation



Tajima-Shibata (199

Paradigm Shift in astrophysical plasma

- Instabilities dominant in plasma science

↓

- **Structure formation** via nonlinear dynamics

    1. **jets**: structure, dynamically stable
    2. accretion disk disturbance (MRI) driven

excitation of **wake at the root of the jets**

a_0 ~ as large as O(10^{10})

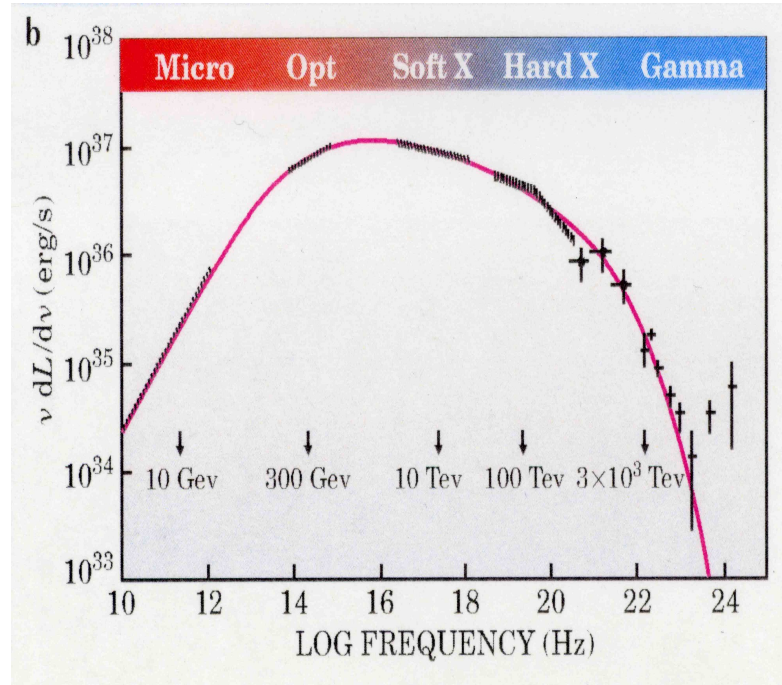
Philosophy espoused and reviewed in

Tajima et al., RMPP 4, 7 (2020), Ebisuzaki et al. (2014)

https://link.springer.com/article/10.1007/s41614-020-0043-z

[Also in the textbook; T. Tajima and K. Shibata, "Plasma Astrophysics" (Addison-Wesley, 1997)]

PeV γ from Crab Nebula



Can we see manifestation of quantum gravity, Lorentz variance in high energy γ?
How PeV electrons accelerated?

The Crab Pulsar, a city-sized, magnetized neutron star spinning 30 times a second, lies at the center of this composite image of the inner region of the well-known Crab Nebula. The spectacular picture combines optical data (red) from the Hubble Space Telescope and x-ray images (blue) from the Chandra Observatory, also used in the popular Crab Pulsar movies. Like a cosmic dynamo the pulsar powers the x-ray and optical emission from the nebula, accelerating charged particles and producing the eerie, glowing x-ray jets. Ring-

Takahashi et al. (2000)

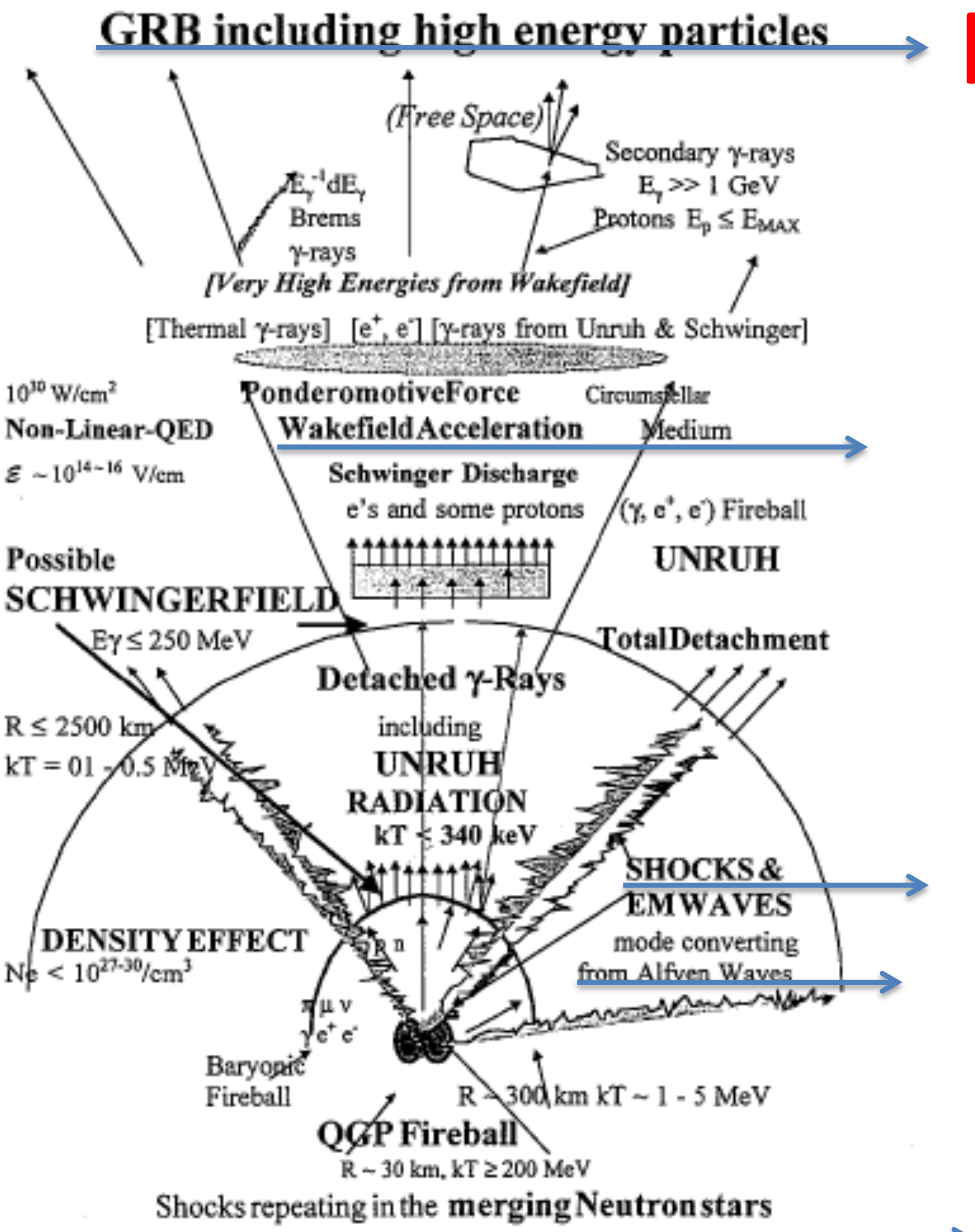


Figure 8. A schematic illustration of the proposed concept.

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**)
……

Neutron star-neutron star collision

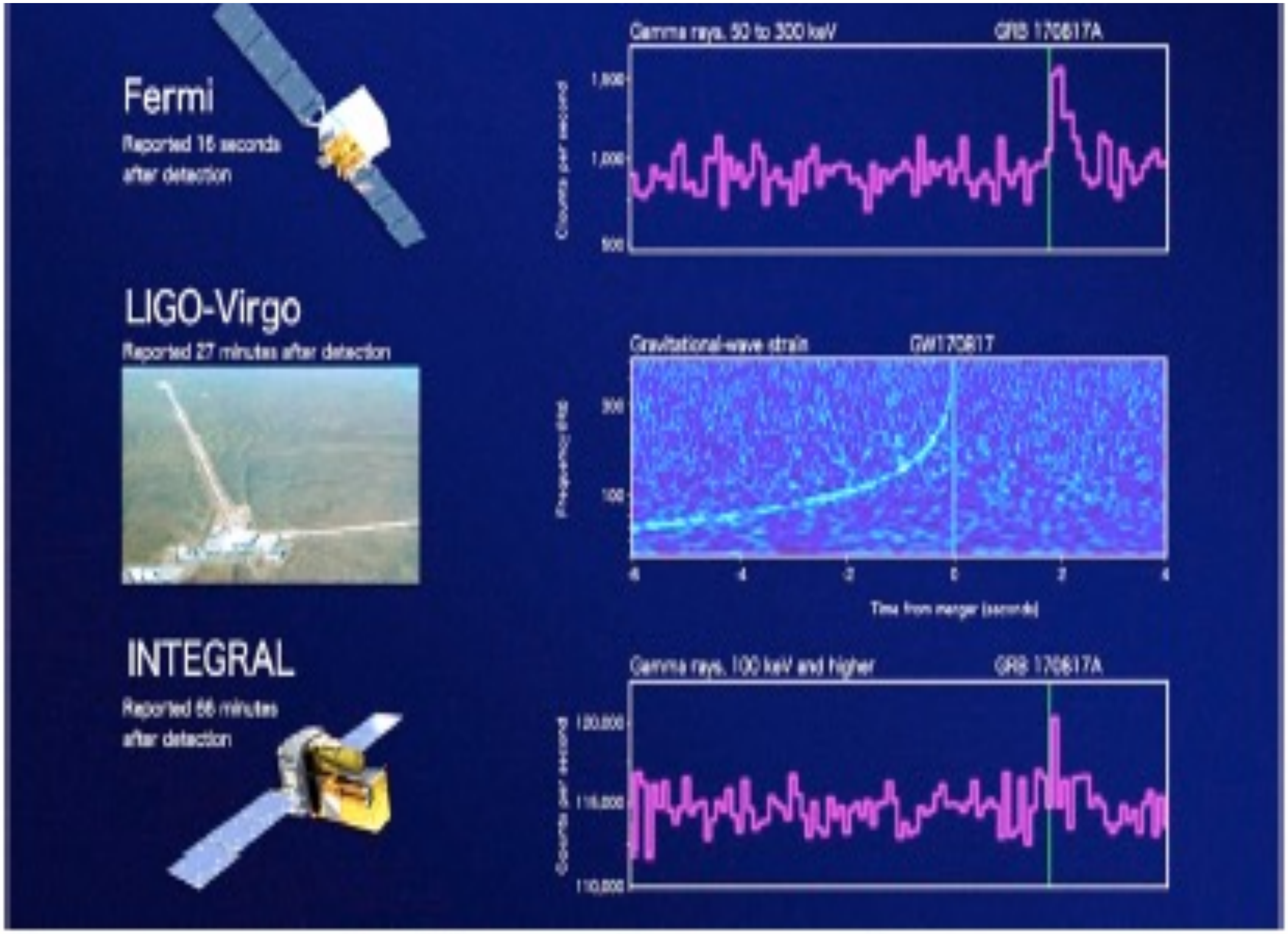


Fig. 5. Gamma-ray emission detected by Fermi and Integral satellites from the neutron star merging event (GW178017) delayed by 1.7 seconds compared with gravitational wave burst [79]. This time difference may be explained by the time to build-up the system for the acceleration of charged particles, described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

LIGO (2017)

(Laser Interferometric Gravitational wave Observatory)

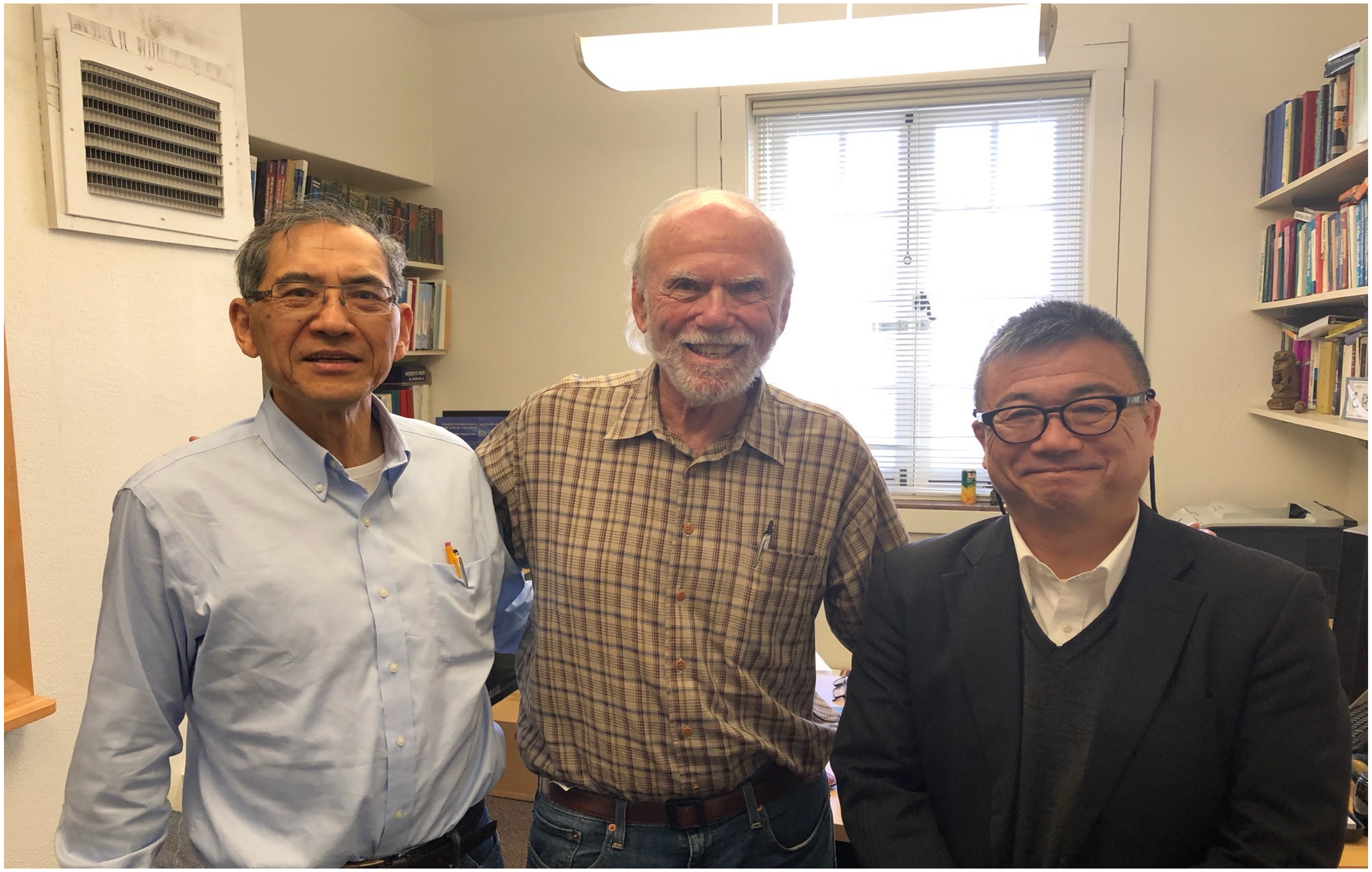
GW emission and **gamma emission**

and jets emanated from NS-NS collision →

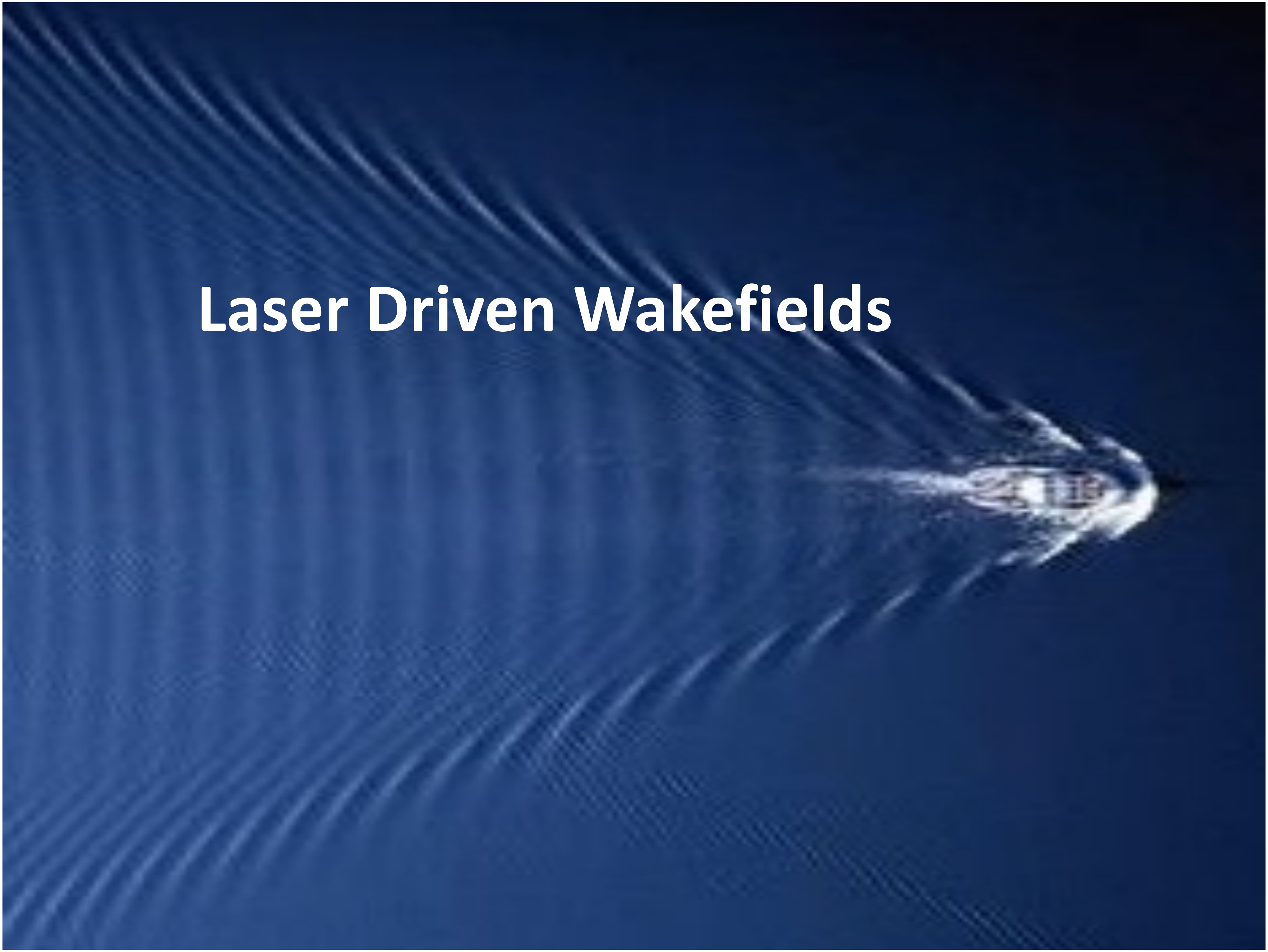
from accretion disk

Observation of LWFA **evidence** in Nature (astrophysics)

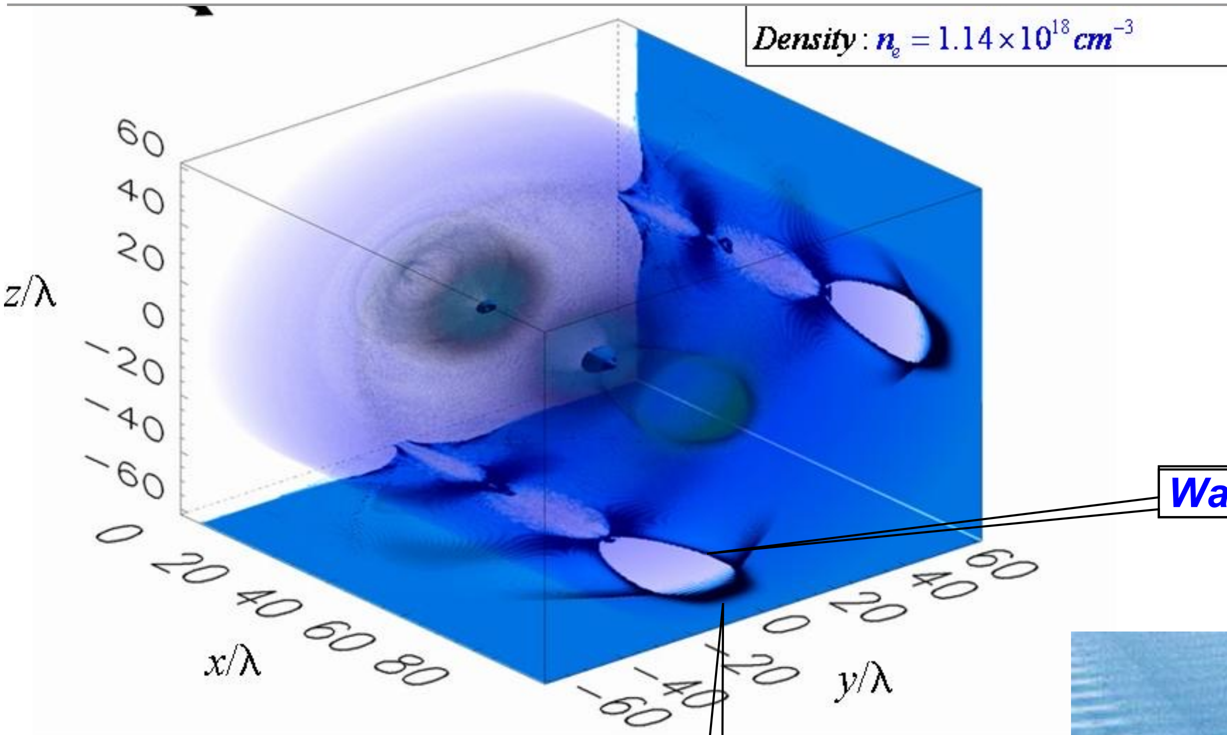
- Review article by us (**Ebisuzaki-Tajima-Barish**): IJMP D (2023)
- Prediction of gamma emission by **LWFA** by NS-NS collision (Tajima et al. book, 2000)
- Barish: discovery of simultaneous emission of gravitational wave with gamma from NS-NS collision (Nobel, 2017)



Laser Driven Wakefields



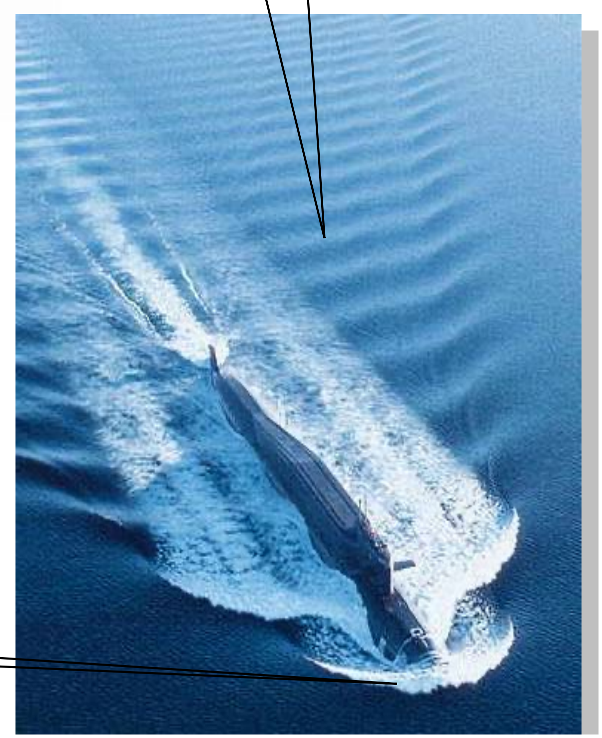
Laser-driven Bow and Wake



(Bulanov, Esirkepov)

Wakefield acceleration

Wake Wave



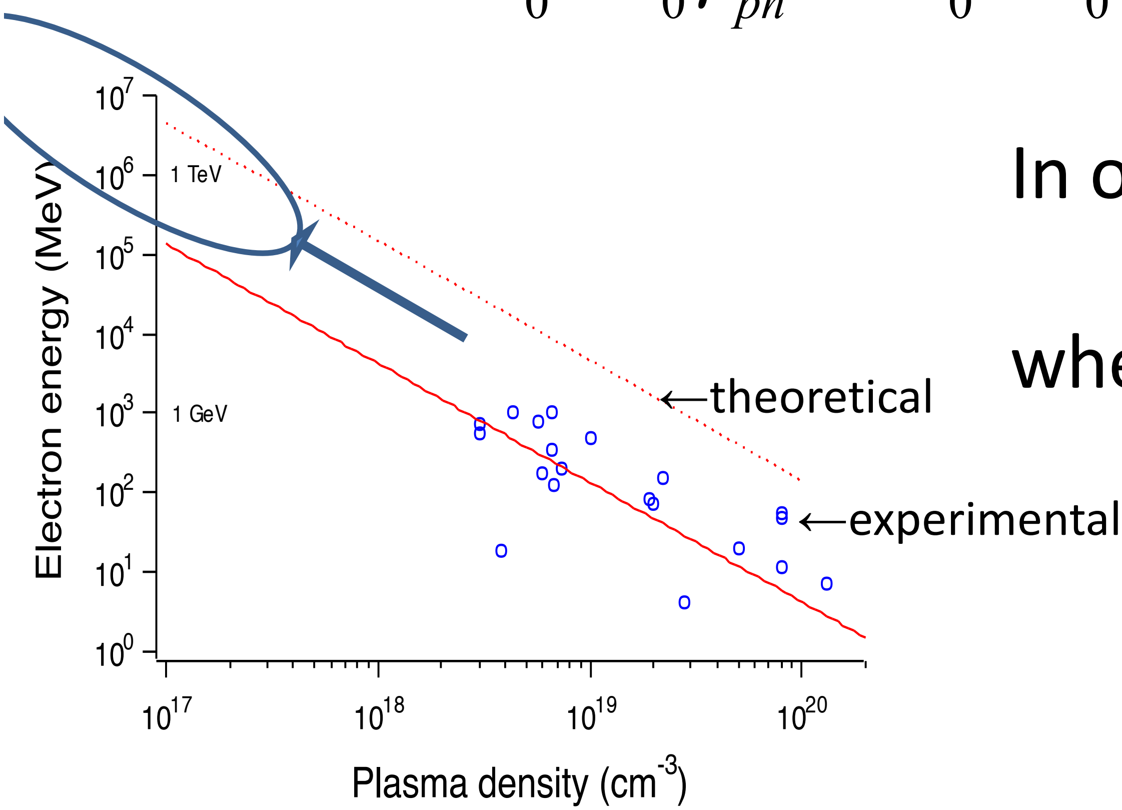
Bow Wave

Ponderomotive acceleration

Theory of wakefield toward high energies

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

(when 1D theory applies Tajima / Dawson, 1979)



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)

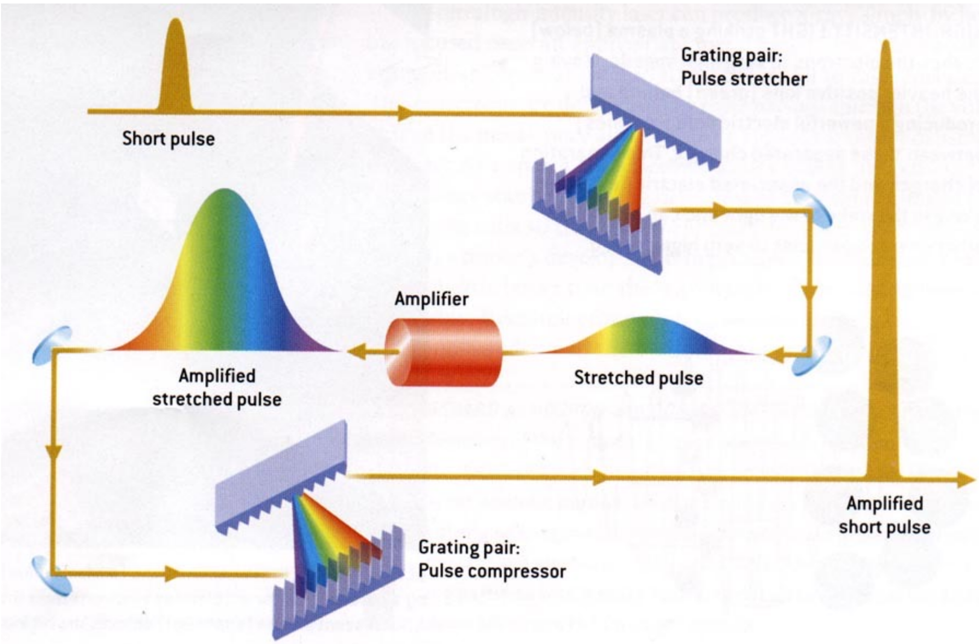
→ 10^{29} (10keV photon)

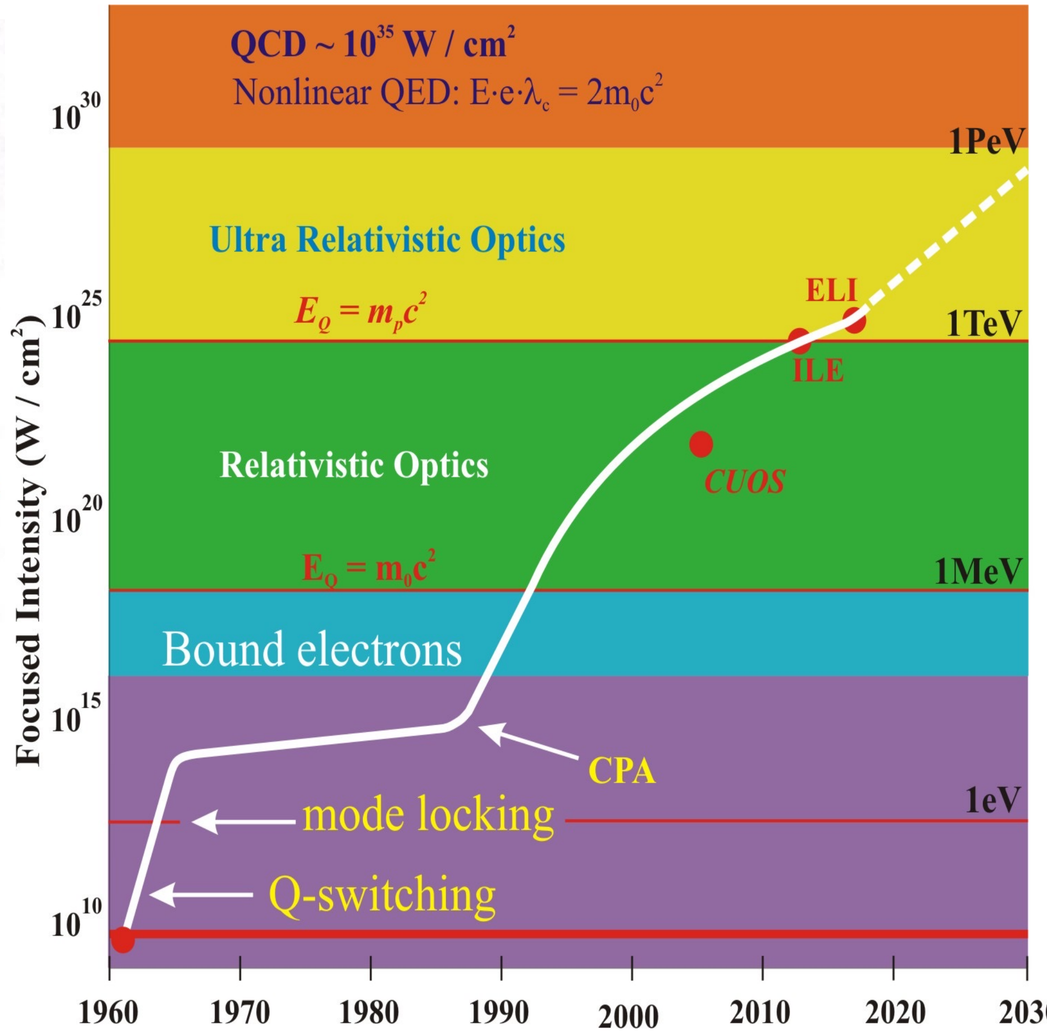
n_e = 10^{16} (gas) → 10^{23} /cc(solid)

$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right), \qquad L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

dephasing length — pump depletion length

Enabling technology: laser revolution





G. Mourou invented Chirped Pulse Amplification (1985)

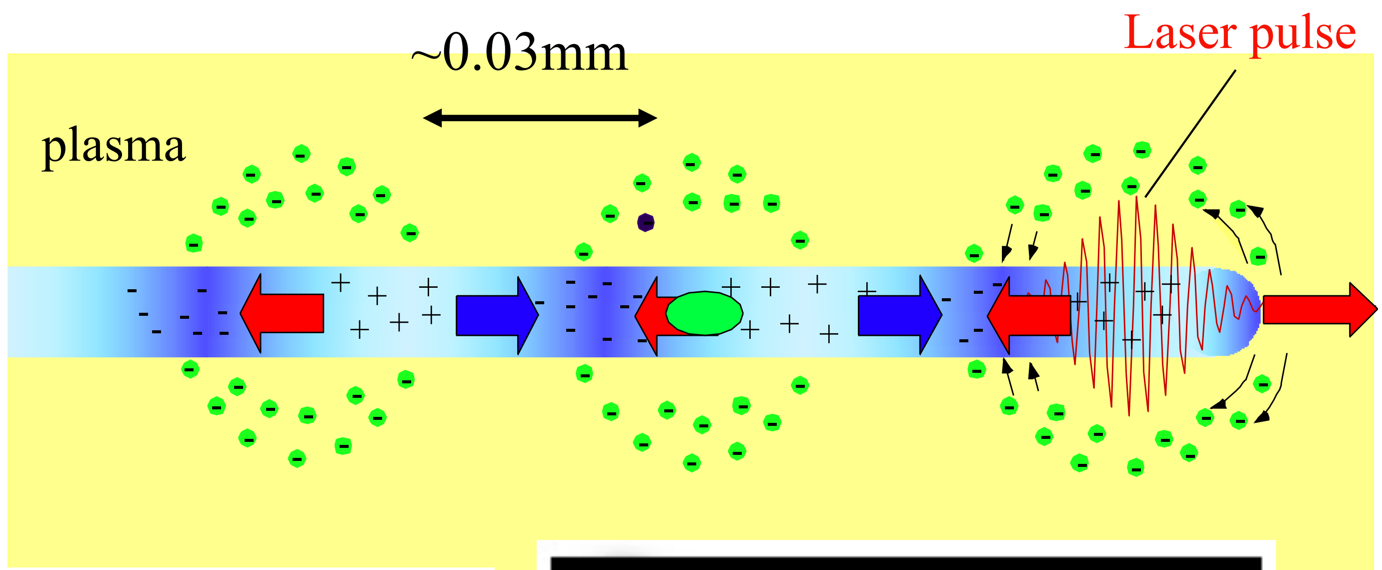
Laser intensity exponentiated since,

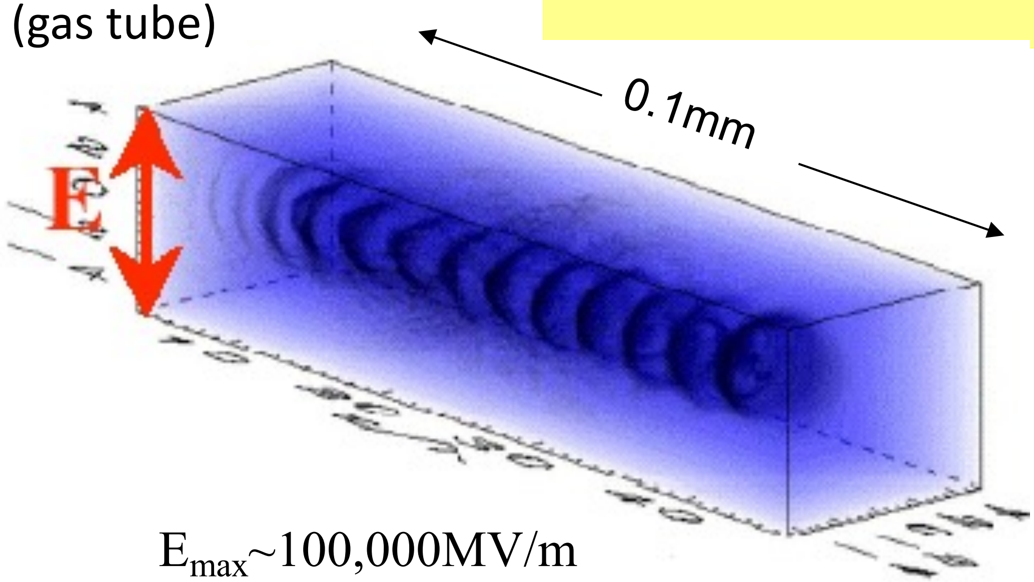
to match the required intensity for Tajima-Dawson's LWFA (1979)

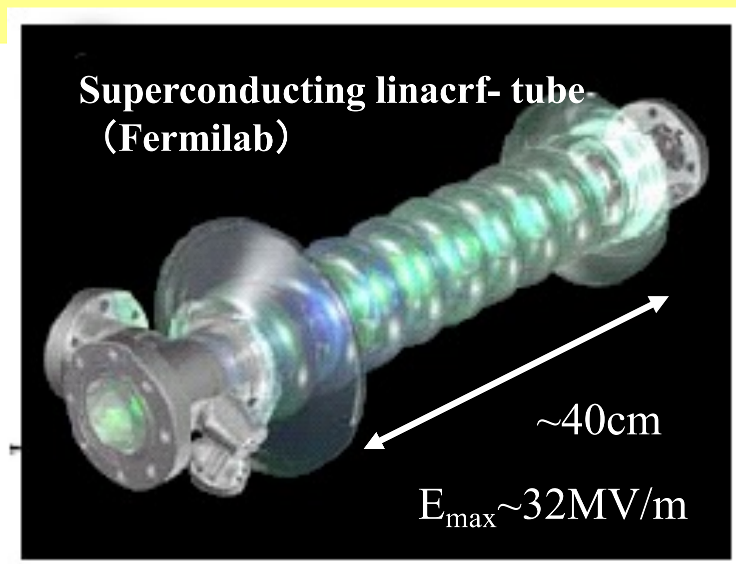
Thousand-fold Compactification

Laser wakefield: thousand folds gradient (and emittance reduction)

First experimental realization: Nakajima,….., Tajima, (1994)

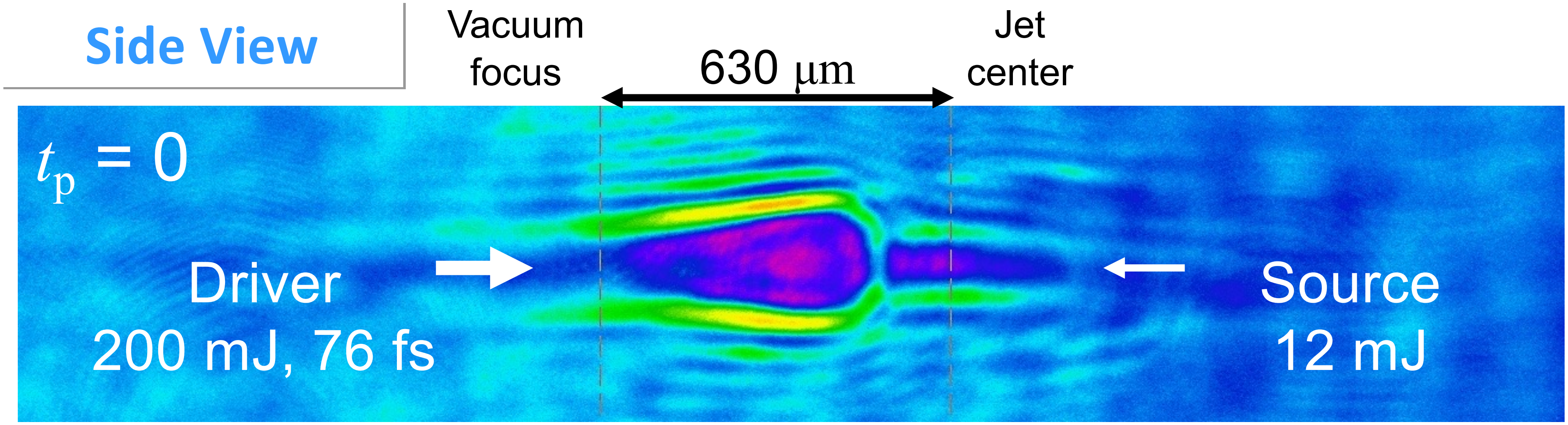




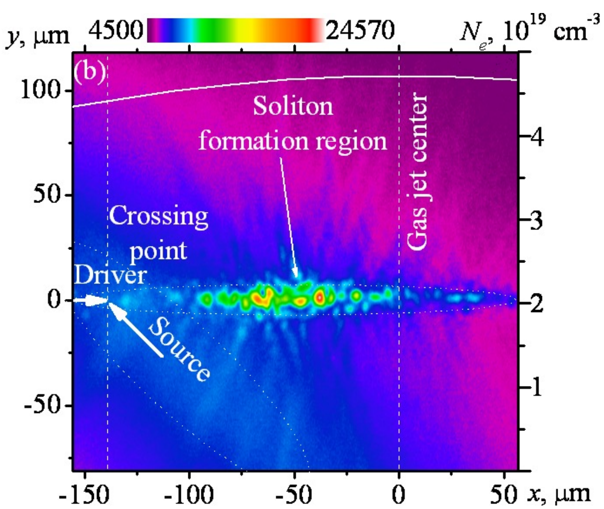


Laser pulse-driven stable wakfefields (plasma oscillations) : observed

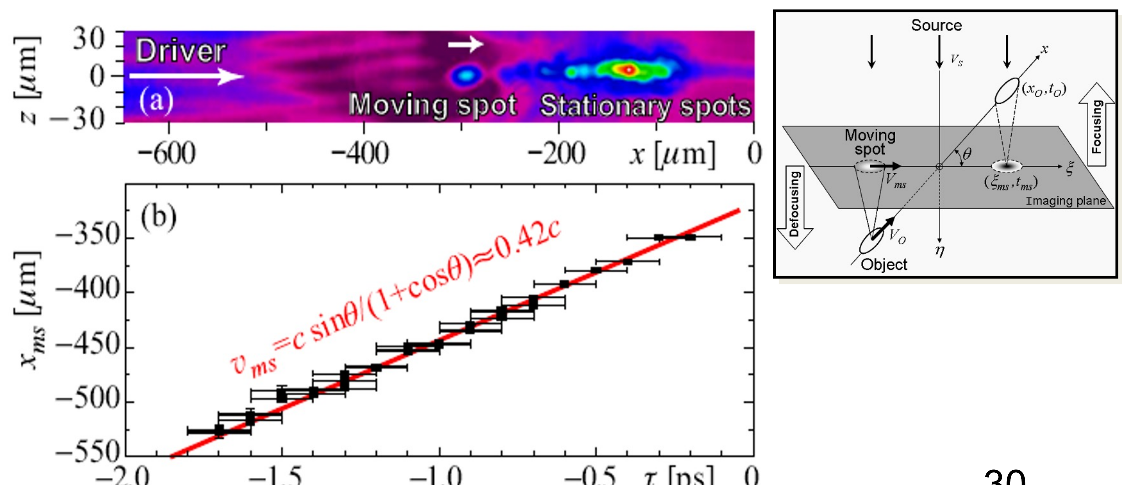
Side View



Top View



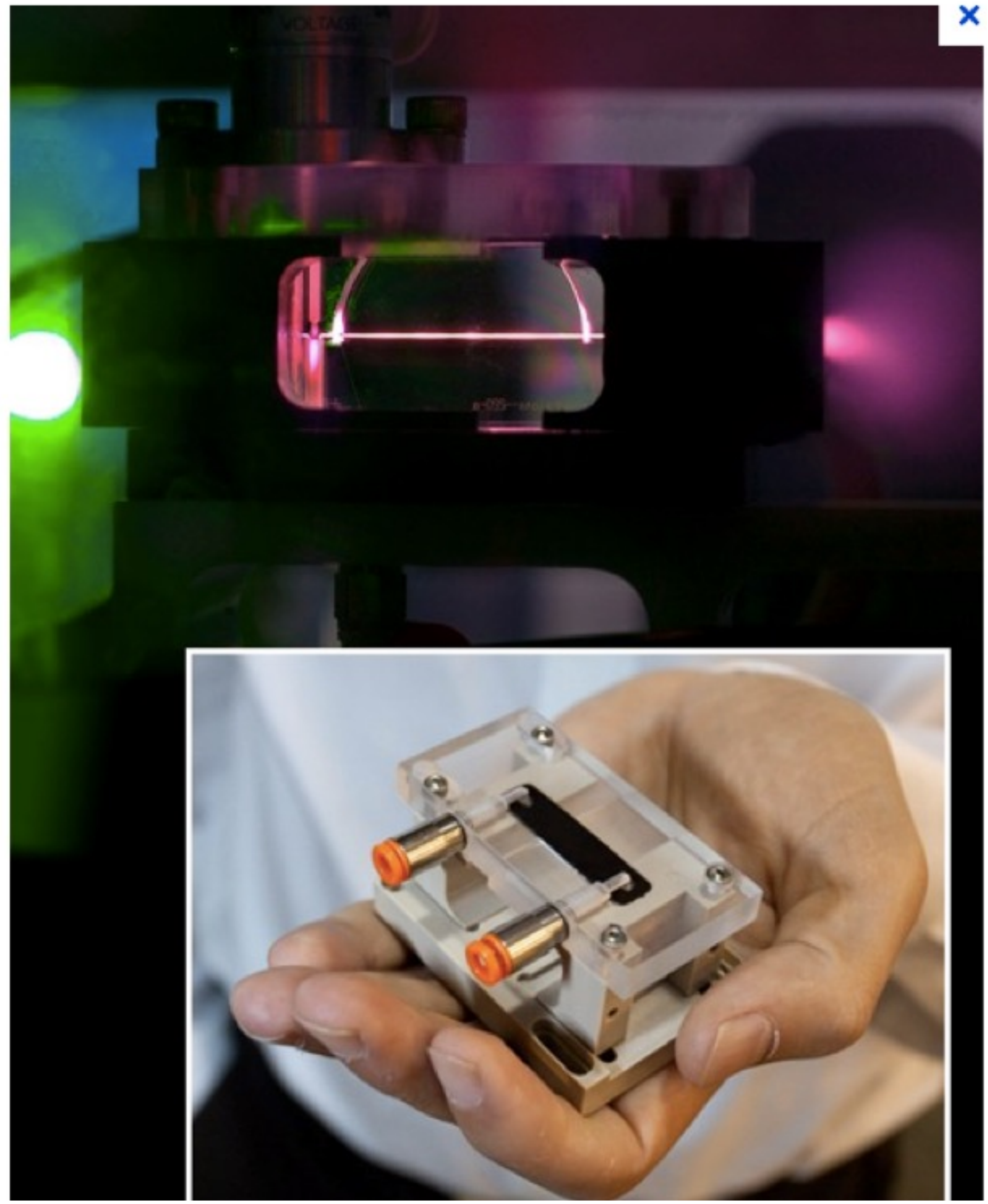
Relativistic Microlens



(Kando et al 2007)

GeV in the Palm

First GeV on few cm
(W. Leemans et al)



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)


LWFA led the High Field Science
also,
LWFA opened up applications
→ see part 2

International Committee for Ultra Intense Lasers

International promotion
of highest intensity lasers
and its applications (Oxford, 2004)

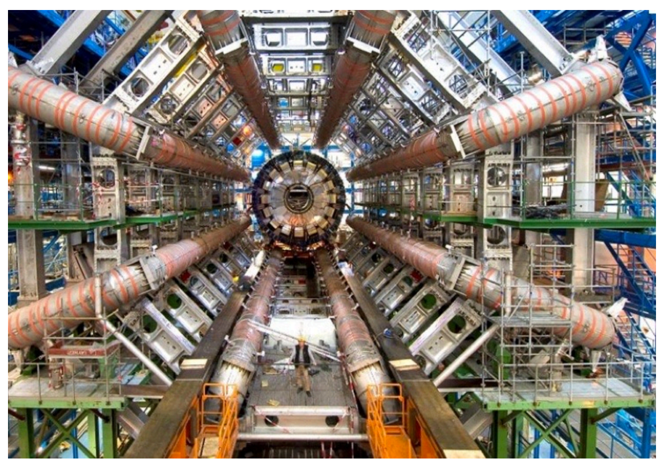
We ignited world-wide interest: s.a.

IZEST (International Center for Zepto- and Exawatt science and Technology)

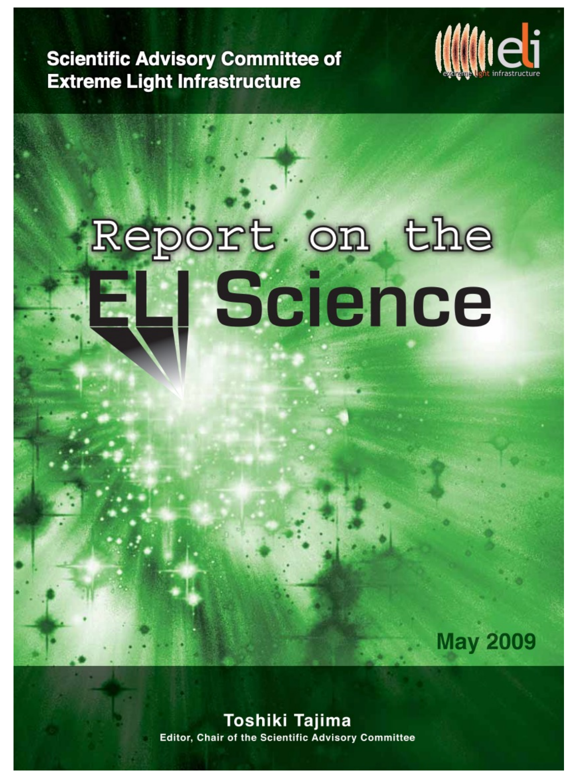
ELI (Extreme Light Intrastructure)

High Energy Physic (and intense laser) interests:

Young-Kee Kim
Then-Fermilab Deputy Director
former President, APS

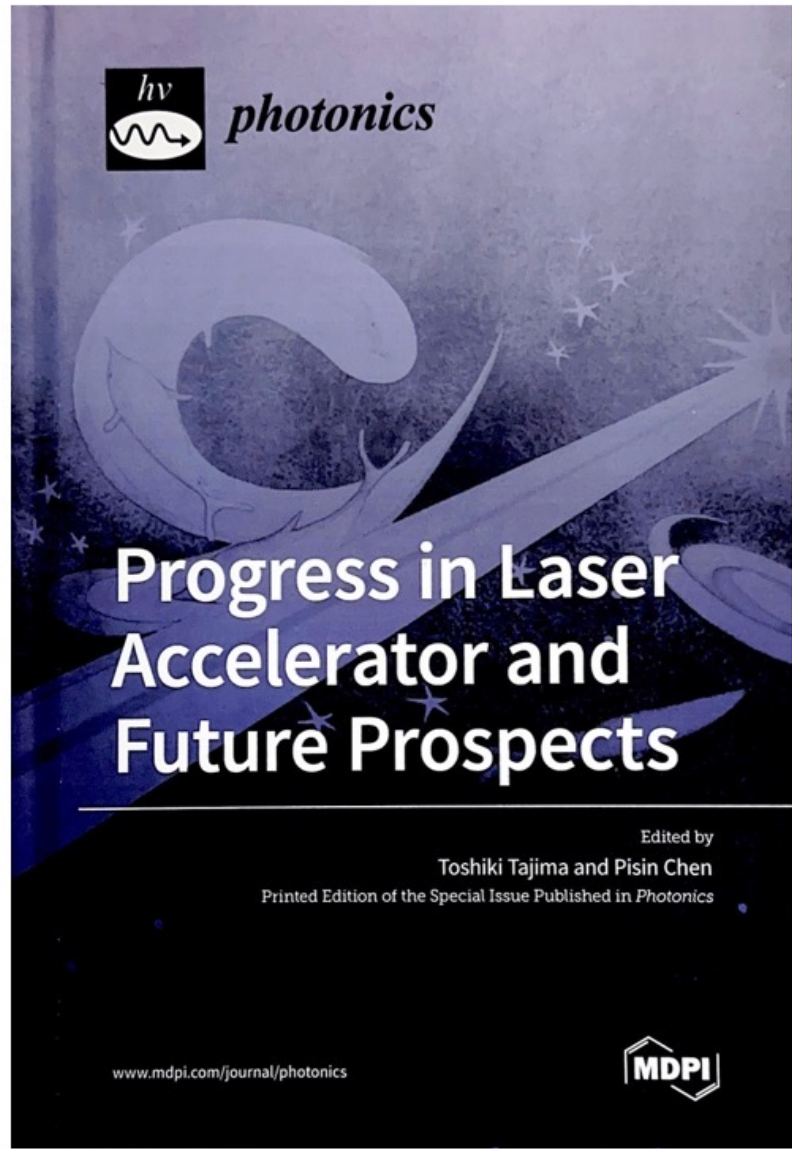


CERN



Thank you!

A latest book



discussions and inspirations from:

G. Mourou, D. Strickland, late J. Dawson, late Norman Rostoker, K. Nakajima, B. Barish, T. Ebisuzaki, the late Y. Takahashi, K. Shibata, S. Bulanov, M. Downer, Y. K. Kim, T. Esirkepov, R. Heuer, G. Huxtable, C. Seiders, D. Fisher, Y. Papamastorakis