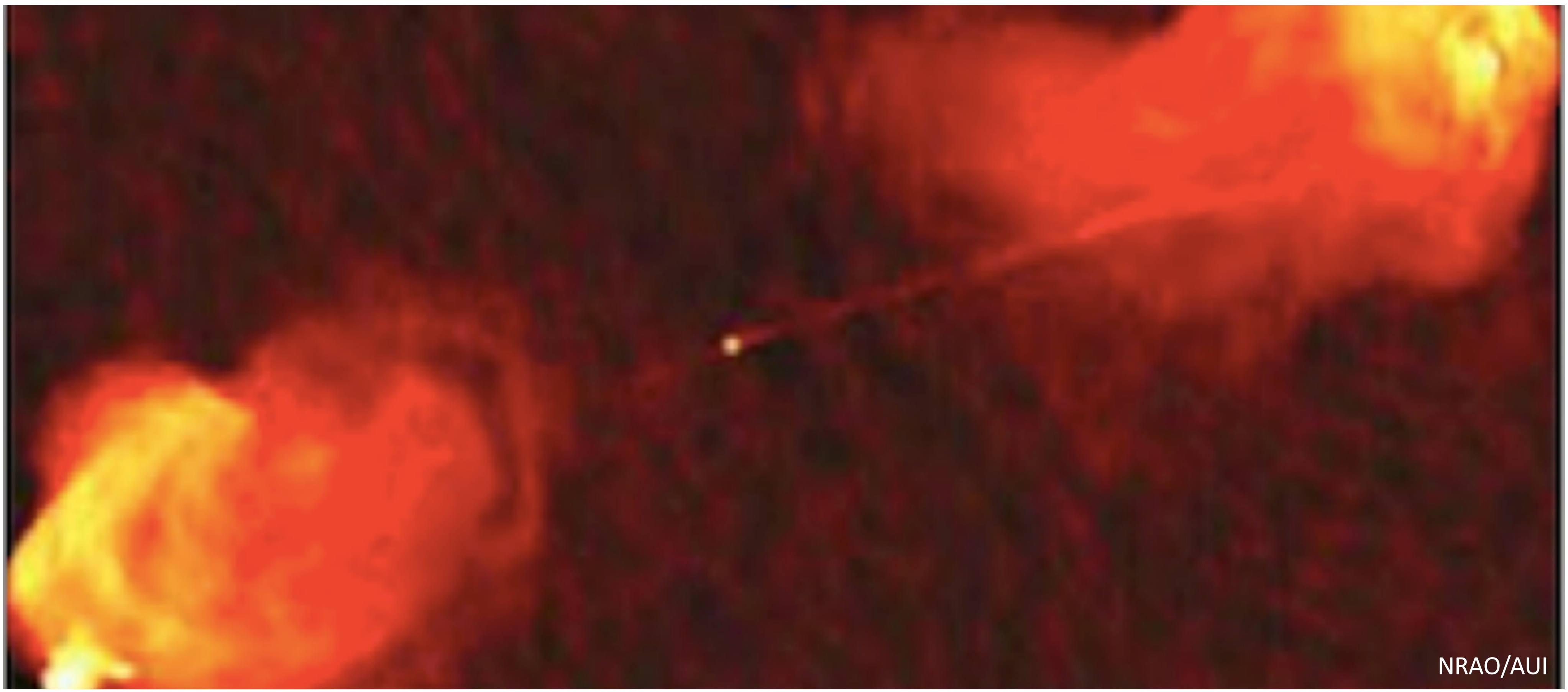
Plasma Accelerator Physics

Toshiki Tajima, Norman Rostoker Chair Professor, UCI

Class 1:PHY249 (2021Fall)



Syllabus (tentative)

PHY249: special topics in plasma physics (also remotely connected as [possibly UCLA PHY250, UCSD PHY239], UCI #48510)

Plasma Accelerator Physics

(Fall Quarter 2021: TTh 12:30-2:00pm , UCI FRHall 4179

also connected by Zoom: personal ID number 743-986-9093:

https://zoom.us/j/7439869093

[contact Assistant: Greg Huxtable huxtablg@uci.edu])

Instructor: Professor Toshiki Tajima

Norman Rostoker Chair Professor, UCI

(Reines Hall 4164; ttajima@uci.edu)

I will connect laser accelerators with other fundamental fields of physics here. First t
accelerator physics and high energy physics. Then to laser physics (such as CPA, CA
impact on laser cancer therapy. Finally we connect recent impact of WFA in high ene
messenger astrophysics.

I. Introduction
- Collective acceleration
- Why plasma is unstable? How can plasma be not unstable?

II. Strong banging
- intense lasers, intense beams
- progress of laser intensity---CPA revolution (1985, Mourou* et al.)
- introduction to laser matter interaction and nonlinear optics
- atomic cohesion (quantum coherence), plasma amorphousness, and bey
- high field---breaks matter, yet can create order
- relativistic coherence
- relativistic optics

III. Wakefield Acceleration
- Veksler-Rostoker problem (1956-1970's)
- What are wakefields? Why are they so stable? Comparison with tsunam
- Tajima-Dawson theory and relativistic coherence
- LWFA (laser wakefield acceleration, 1979, UCLA)
- High Density LWFA
- LWFA-driven nuclear physics
- Laser Acceleration of Ions
- CAN (coherent amplification network) laser (2013, Mourou* et al.)
- ultrahigh energy accelerator with WFA
- ultrafast medical laser surgery, laser-driven beam therapy of cancer

Plasma Accelerator Physics
PHY249 (UCI)
(Fall, 2021)
(I need to check the following)
https://canvas.eee.uci.edu/courses/48510

Now UCI Canvas Zoom number has been assigned:

Address: 48510-f21@classmail.eee.uci.edu
Archive: https://classmail.eee.uci.edu/

IV. Astrophysical plasma acceleration
- Astrophysical jets and disks: coherent structures and engines in nature
- EHECR (extreme high energy cosmic rays) and neutrino astrophysics (again UC Irvine's for
- ZeV neutrino physics and TeV gamma astrophysics
- gravitational waves (LIGO by Barry Barish **) and gamma bursts from neutron star collisio

Overall reference:

T. Tajima, X. Q. Yan, and T. Ebisuzaki, Rev. Mod. Plas. Phys.**4**, 7 (2021).

Refs. (additional):

G. Mourou*, T. Tajima, and S. Bulanov, Rev. Mod. Phys. **78**,309 (2006).

T. Tajima, K. Mima, and H. Baldis, eds. *High Field Science* (Kluwer/Plenum, NY, 2000).

(More to come)

Assignments:

To be discussed in the class: HW: 20%; Proposal for the term project: 20%; Term Report: 60%.

**) 2017 Nobel Laureate in Physics.
*) 2018 Nobel Laureate in Physics.

examples of the term projects in UCI _PHY249 (Winter 2014; Winter 2019):

C. Lau, P. C. Yeh, O. Luk, J. McClenaghan, T. Ebisuzaki, and T. Tajima, Phys. Rev. STAB **18**, 024401 (2015).

B.S. Nicks, S. Hakimi, E. Barraza-Valdez, K.D. Chestnut, G.H. DeGrandchamp, K.R. Gage, et al., Photonics **8**, 216 (2021).

In the Term Report, in addition to your term project work description, you have to identify what the instr
indicated as to how and why we can avoid plasma instabilities in wakefields, or alternativel
have to discover new mechanism for stability

Accelerators

- Conventional accelerators

  electron (or ion) surrounded by a metal in vacuum

  → the upper field (below ionizational force on a metal ~ MeV /cm)

- Plasma accelerators

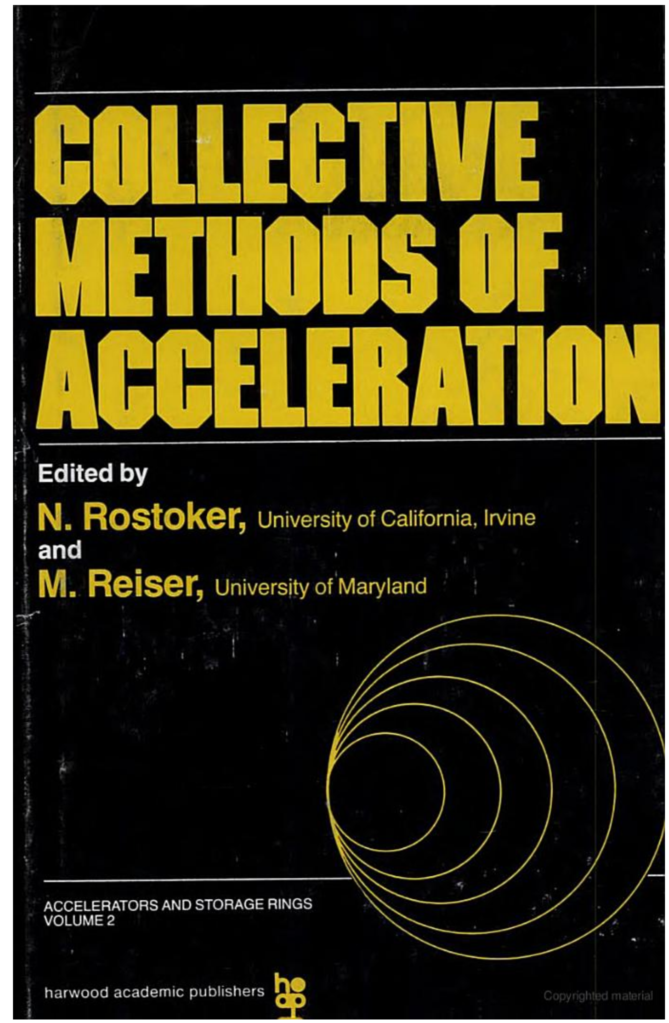
  Veksler (1956),

  Rostoker (in 1960's -70's)

  Tajima-Dawson (1979)

  CPA laser (Mourou, Strickland, 1985)

  First wakefield acceleration (Nakajima, …., Tajima, 1994)



(UCI: one of the epicenters!)

Why is plasma unstable?

- Atoms and solids:

  nucleus vs. bound electrons

  (and applied large enough fields (~MeV/cm)

  → ionization → plasma

  no binding force*)

  solids: more than atomic forces →

  lattice forces, van der Waals force

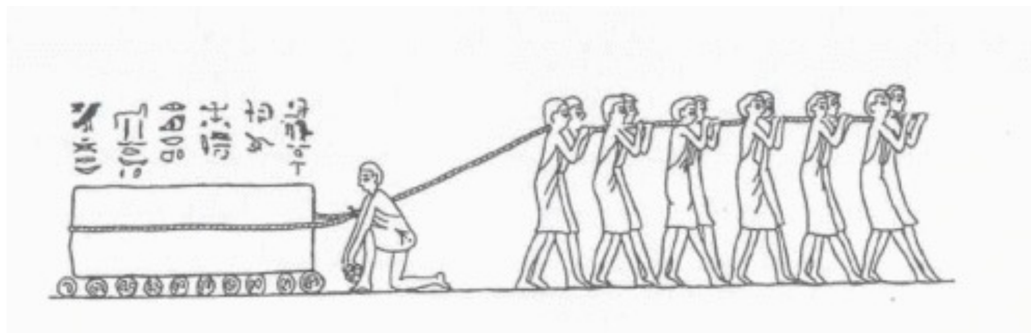
- Gravitational system:

  Sun vs. planets, asteroids and comets

*) Additionally, **collective forces**

What is *collective force*?

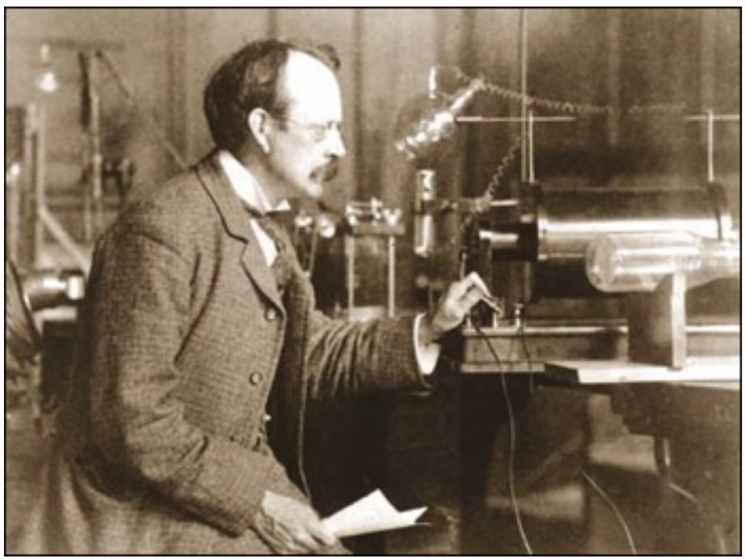
How can a Pyramid have been built?

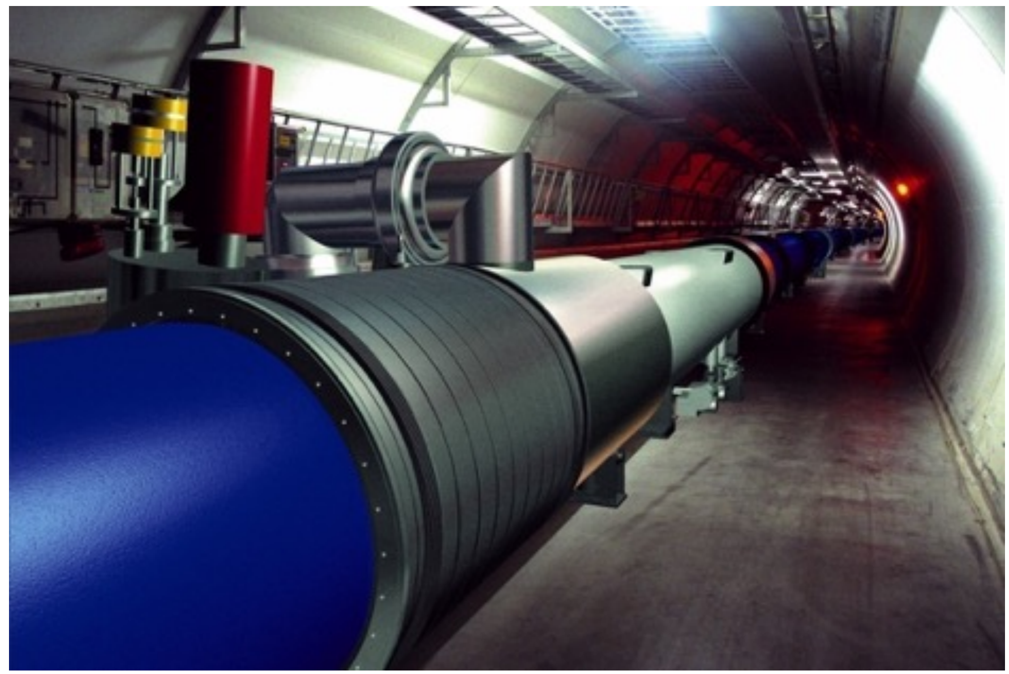


Individual particle dynamics → Coherent and collective movement

Collective acceleration (Veksler, 1956; Tajima & Dawson, 1979)
Collective radiation (N^2 radiation)
Collective ionization (N^2 ionization)
Collective deceleration (Tajima & Chao, 2008；Ogata, 2009)

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



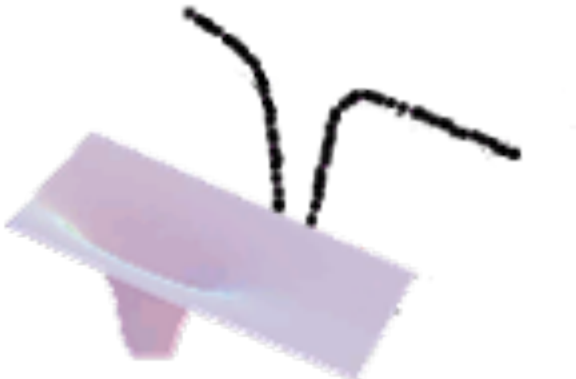


J. J. Thomson

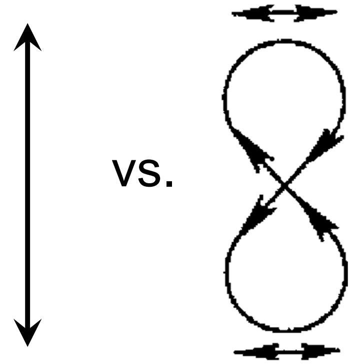

Wakefields = Collective force

<u>Nonlinearities</u> in atom, plasma, and vacuum

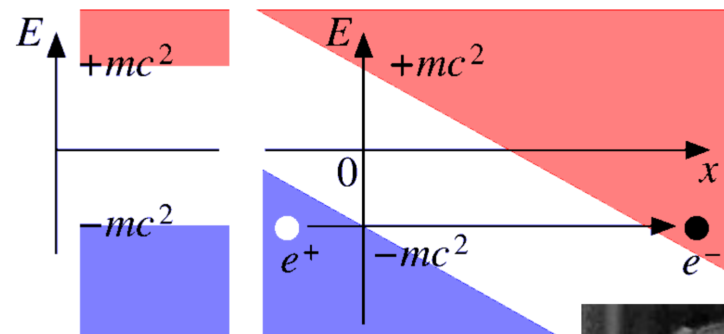
Atomic nonlinear potential



Plasma electron nonlinear relativistic motion



Vacuum nonlinearity



Keldysh field for laser atomic ionization

Laser wakefield

Schwinger field for vacuum breakdown

Compact high energy colliders
Compact accelerator applications
PeV acceleration for quantum gravity →

Nonlinear QED fields
General relativistic effects
Vacuum probe (s.a. Dark energy)

Relativistic nonlinearity under intense laser

Tajima-Dawson suggested this
to erect a robust construct **Wakefields**

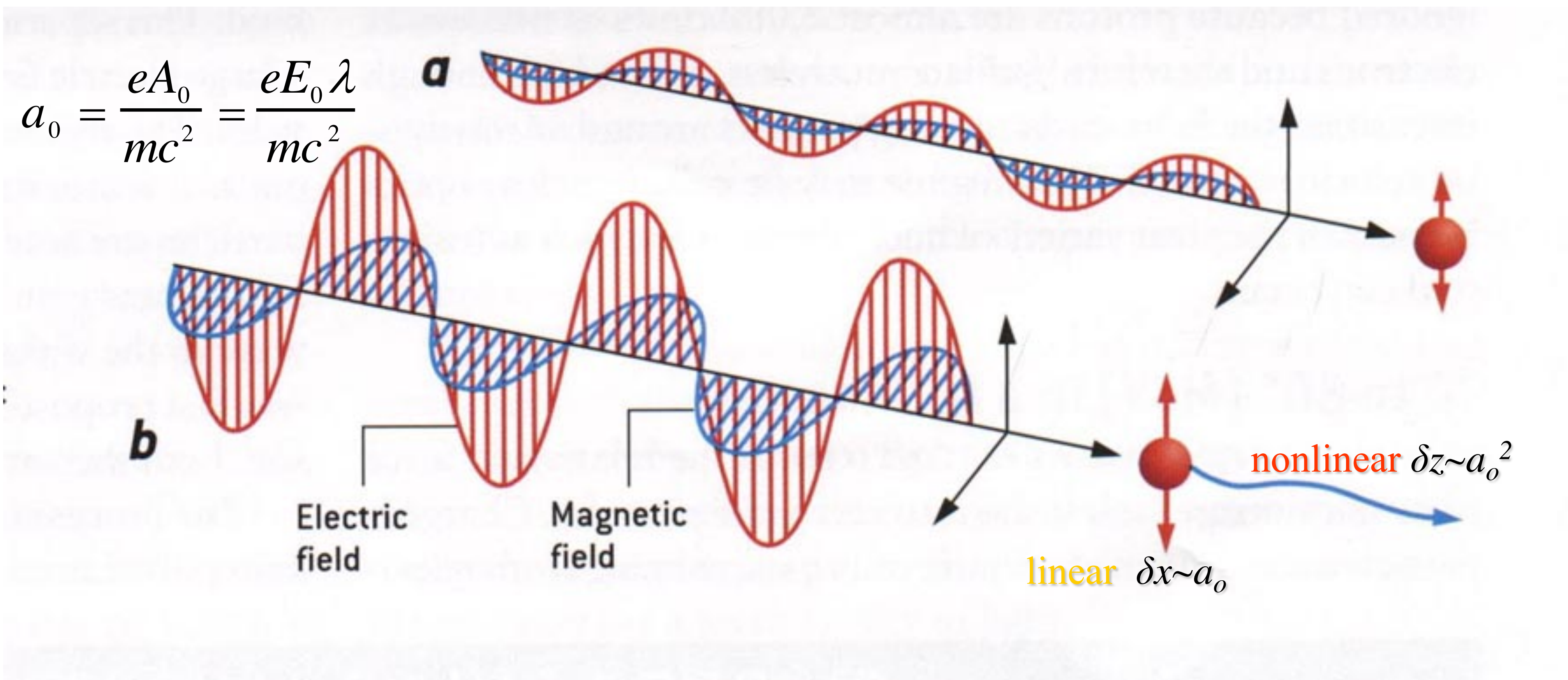
a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v\sim c$

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

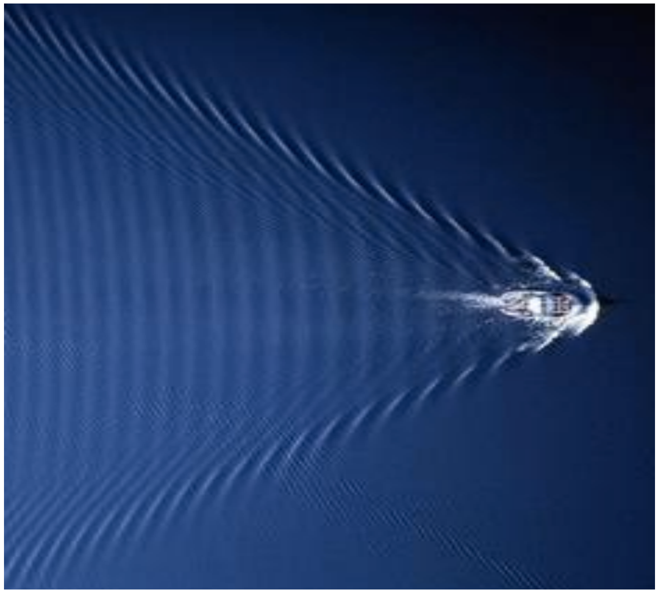
$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$



Laser Wakefield (LWFA) (1979):

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

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

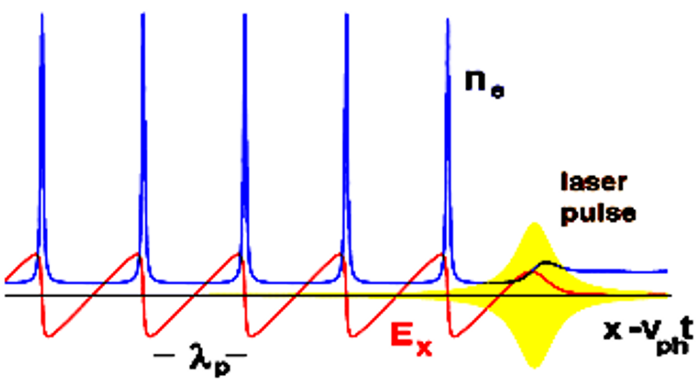


vs

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

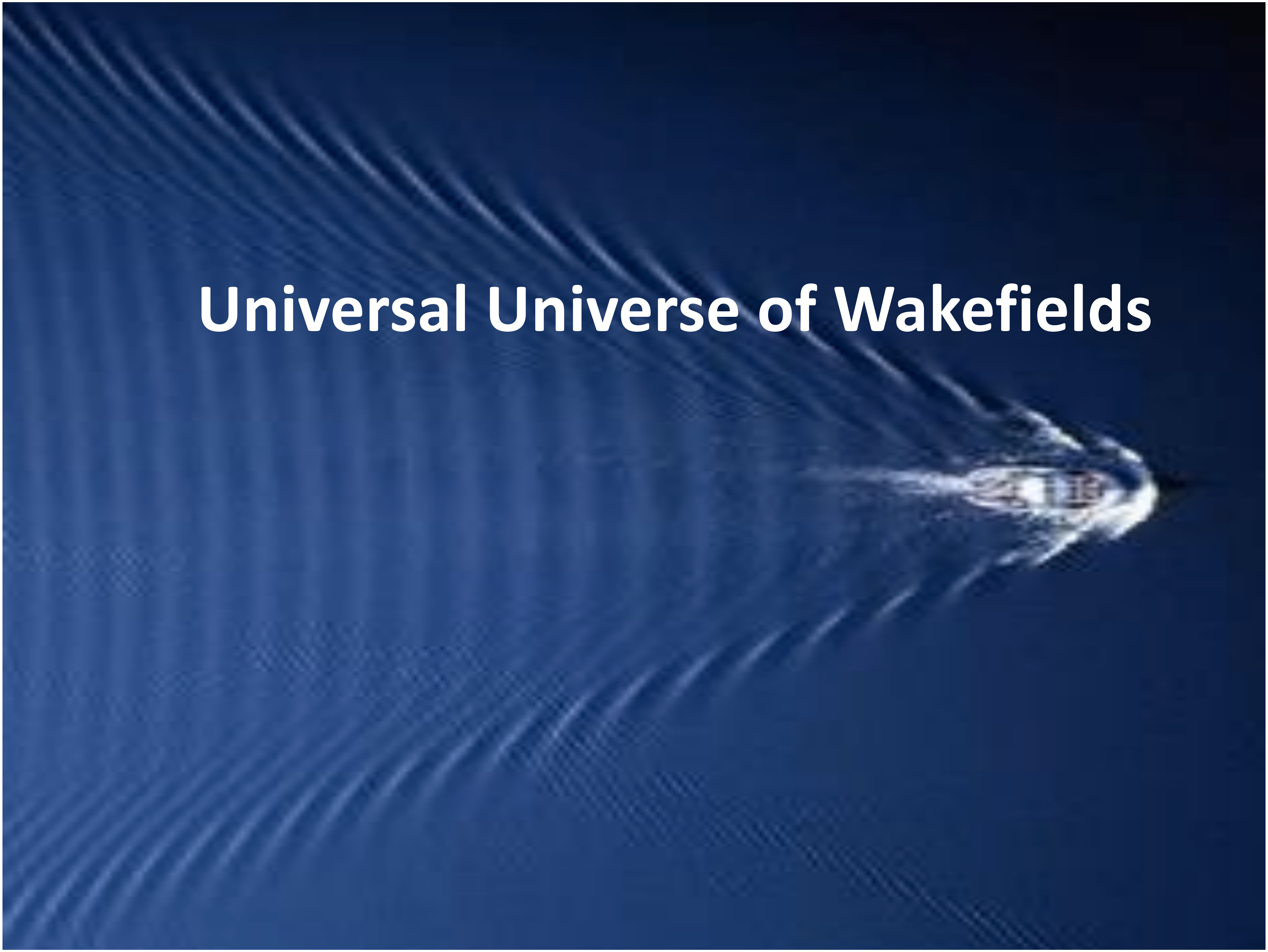
Wave **breaks** at v<c



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

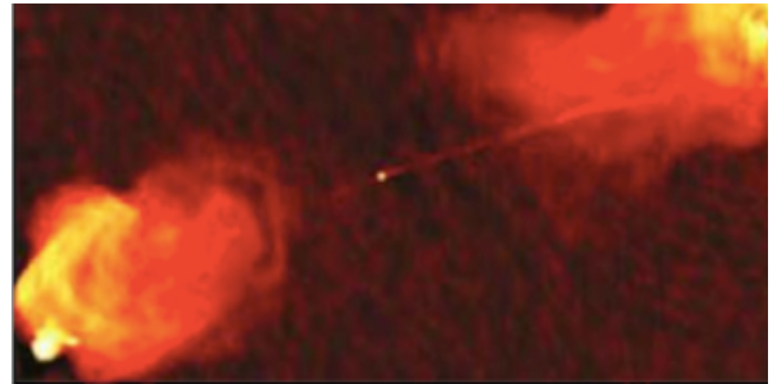
Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c /e$ (~ GeV/cm)

Universal Universe of Wakefields

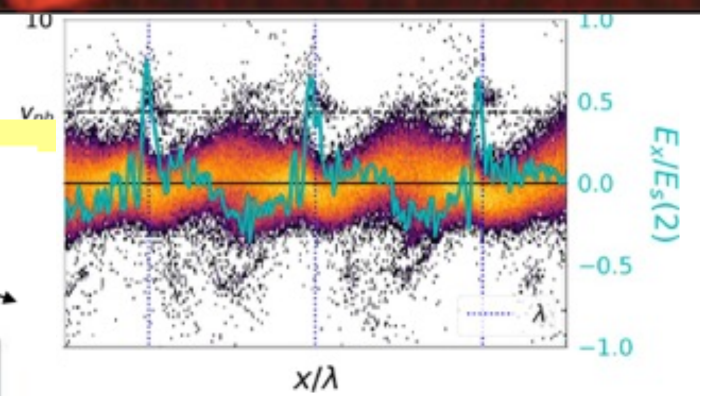


Ranges of wakefields

λ : 10^{-13} cm ← → 10^{19} cm

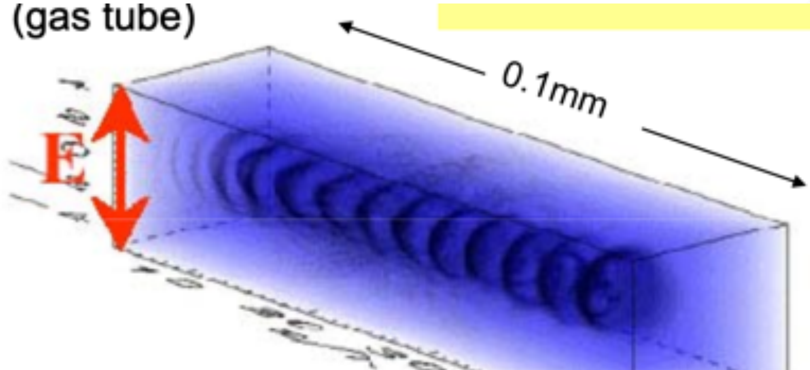


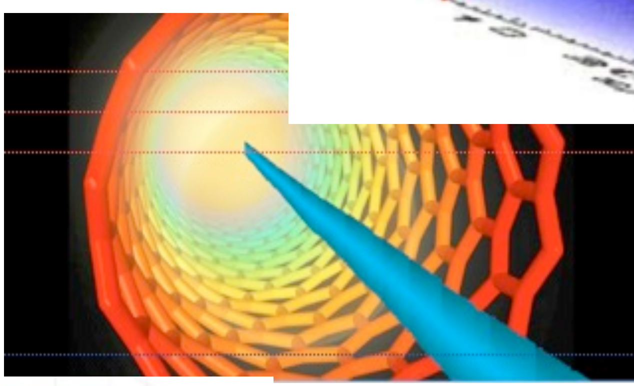
$\lambda = 10^{19}$ cm
(AGN jets)



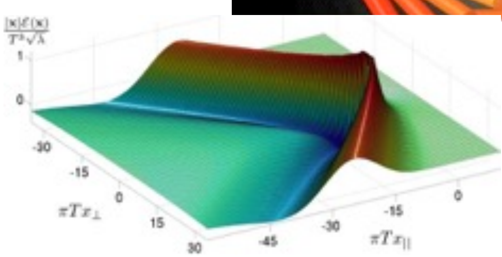
λ = 1 cm (fusion plasma)

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





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



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

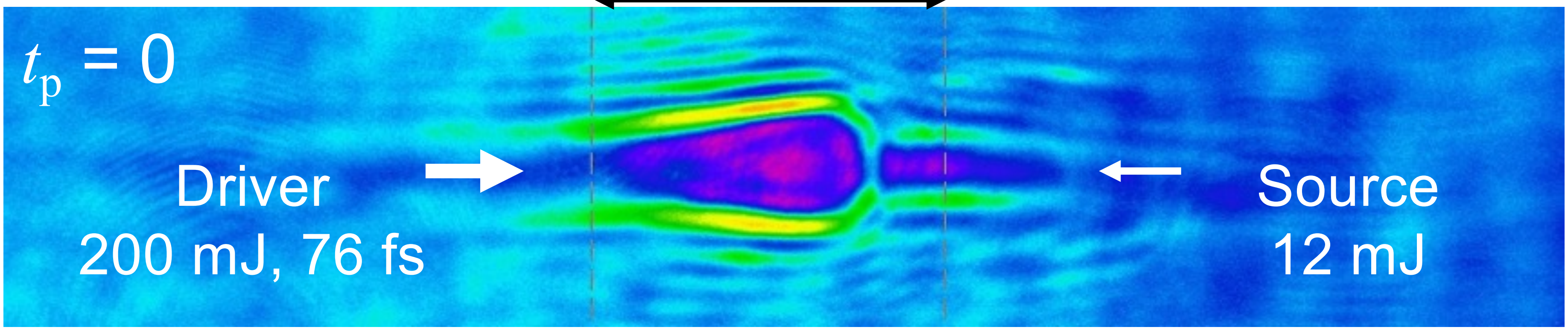
Space-Time Overlapping
of Driver and Source pulses

Side View

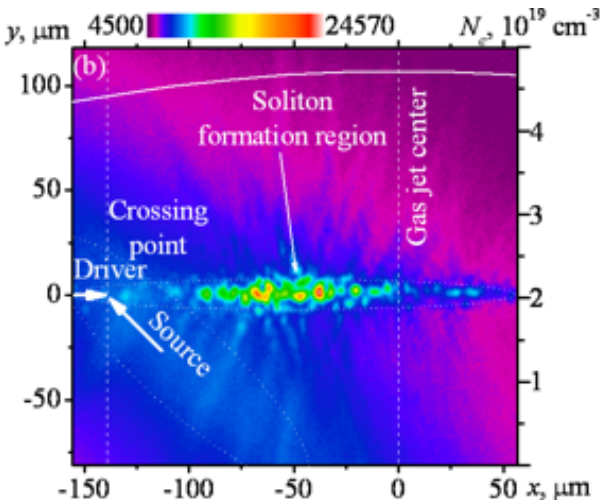
Vacuum focus

630 μm

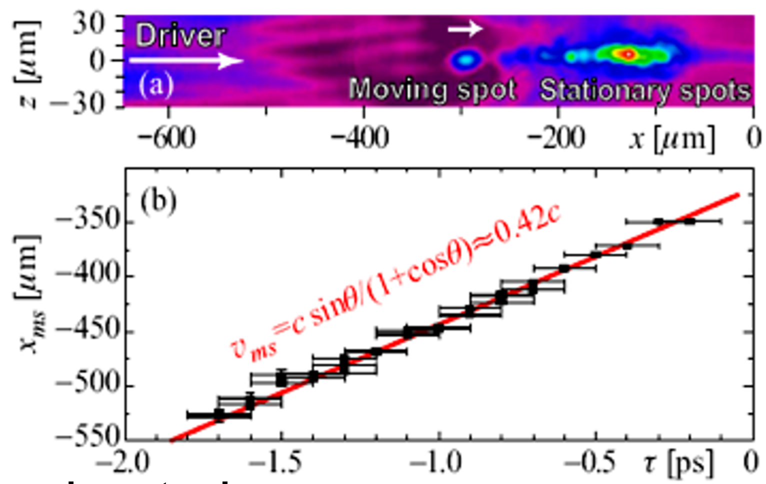
Jet center

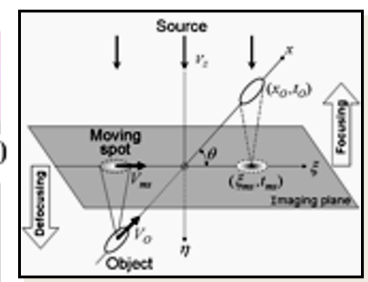


Top View



Relativistic Microlens





(Kando et al

Paradigm Shift in Plasma Physics

- Instabilities dominant in plasma science
  (*something to despise*)

↓

- Structure formation via nonlinear dynamics (e. g. structure called wakefields)

new organizational principle

Philosophy espoused in
Tajima et al., RMPP 4, 7 (2020)
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)]

Instabilities vs Played-out Structures

Examples:

- Two-stream instability (see p. 334 T. Tajima, Computational Plasma Physics, 1989) (or bump-in-tail instabilities, or drift wave instabilities)

- Wakefield driven by a pulse of laser

  Wakefield

  "hide-and-seek"

  Jets (astrophysical, largest structure of the world)

The late Prof. Abdus Salam

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

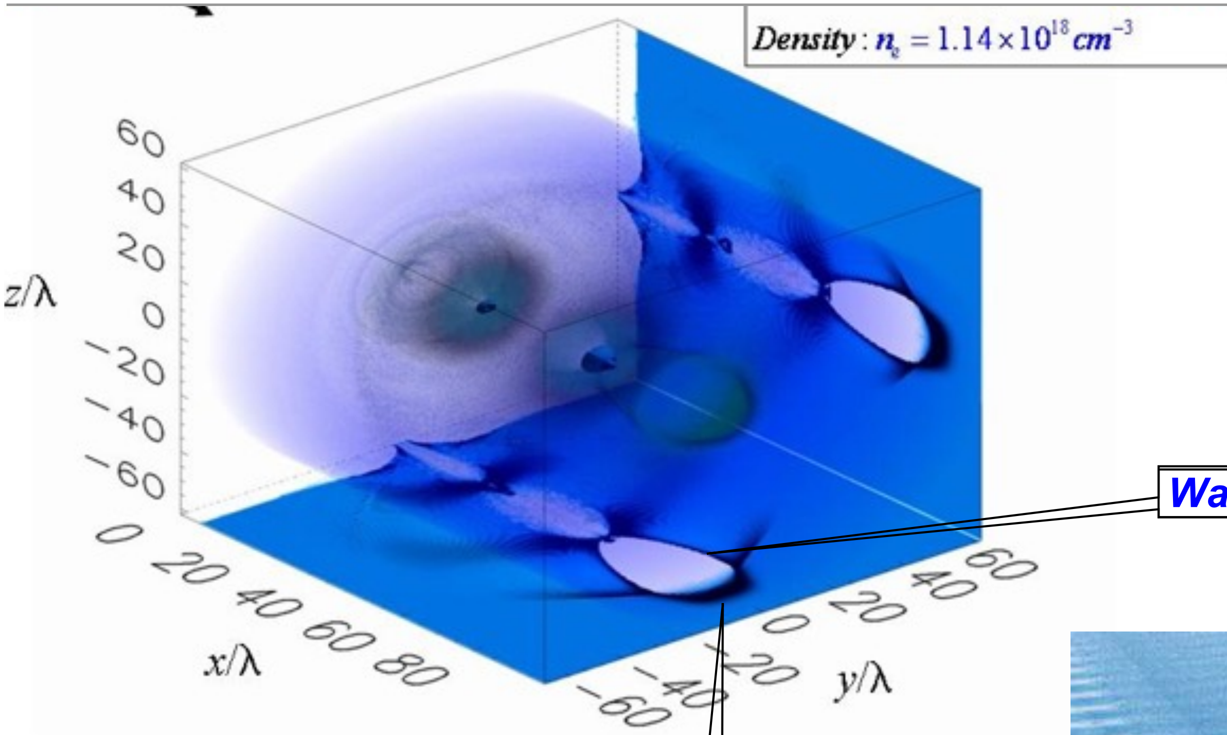
Salam: *'Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged'*. (1981)

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

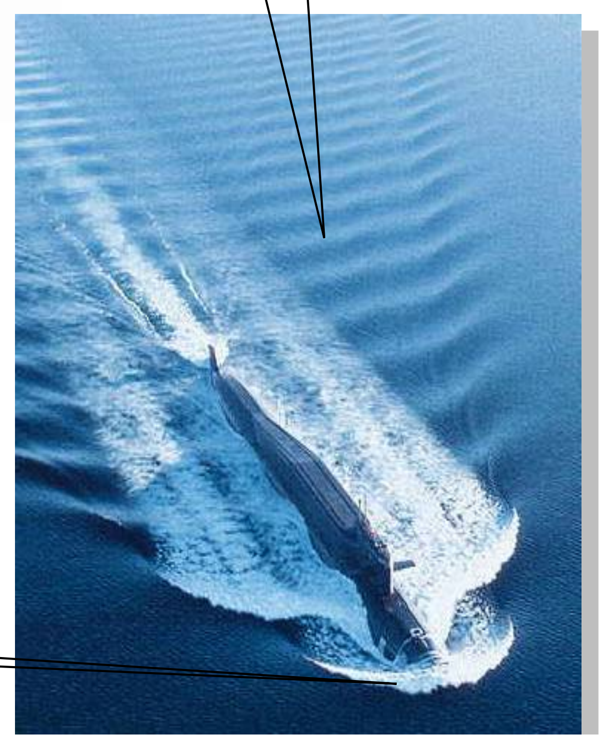
Effort: many scientists over many years to realize his vision / dream
High field science: spawned

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

Laser-driven Bow and Wake



(Bulanov, Esirkepov)



Wakefield acceleration

Wake Wave

Bow Wave

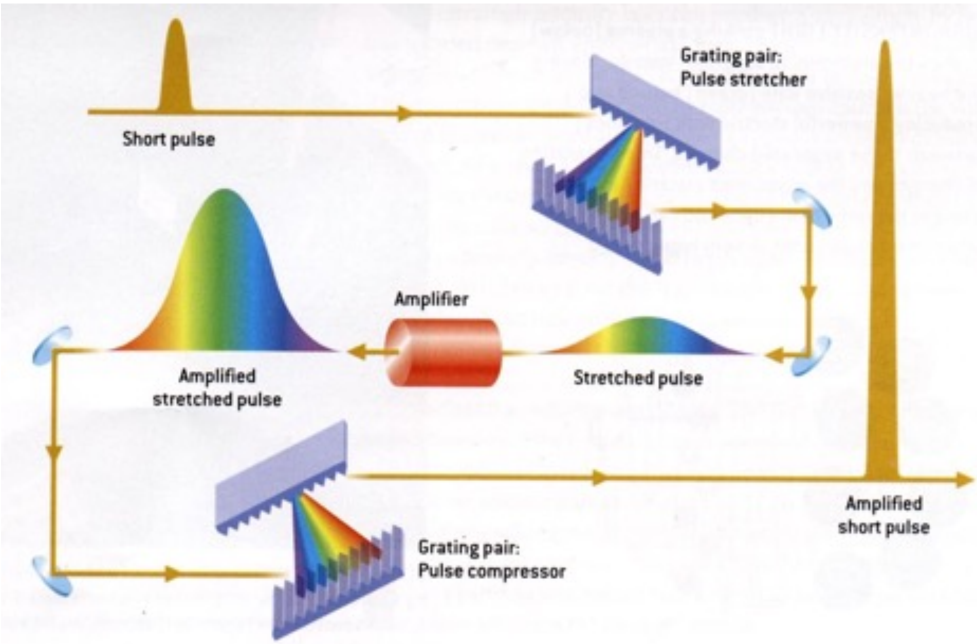
Ponderomotive acceleration

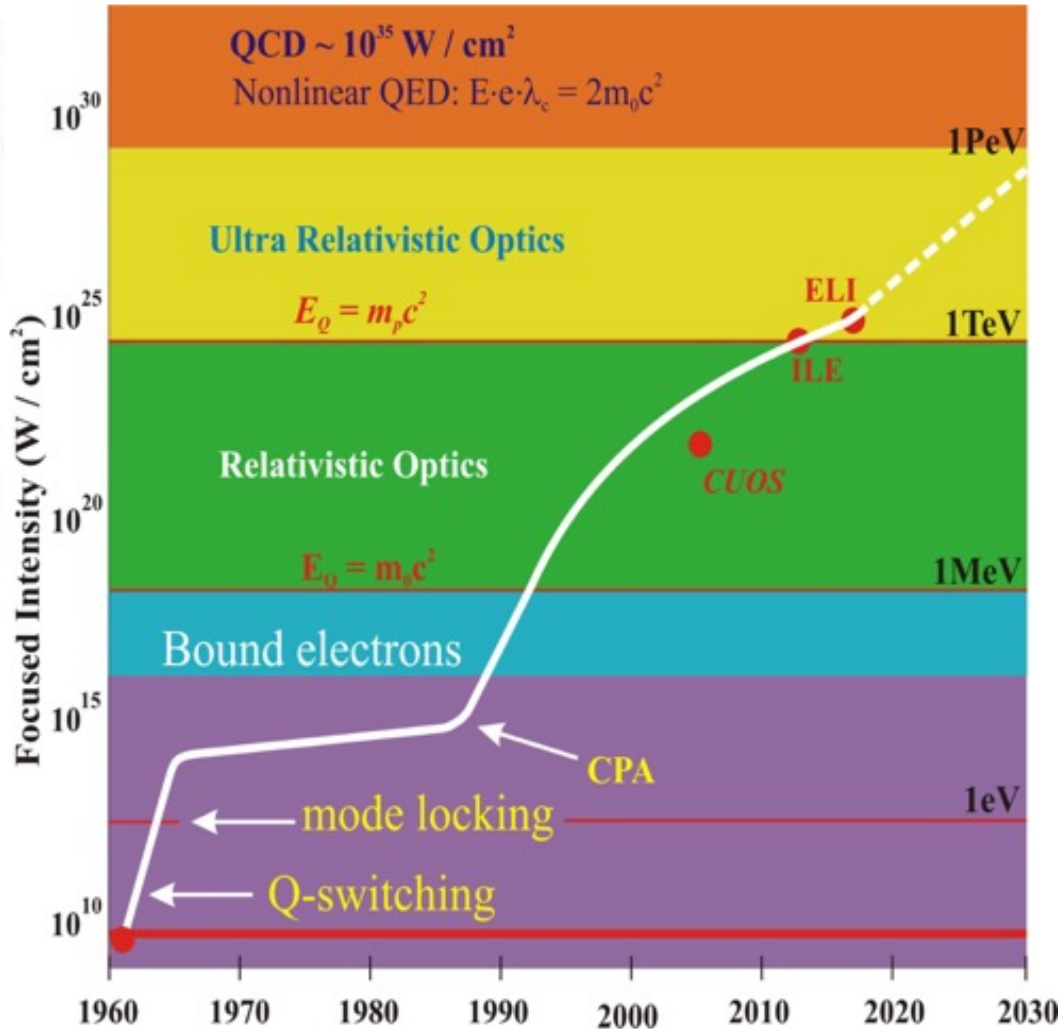
21st Century; the Photon Century
Could basic research be driven
by the massless and chargeless particles; Photons?

C. Townes (laser invention) →

G. Mourou (Inst. Zetta- Exawatt
Science and Technology)

Enabling technology: laser revolution





G. Mourou invented Chirped Pulse Amplification (1985)

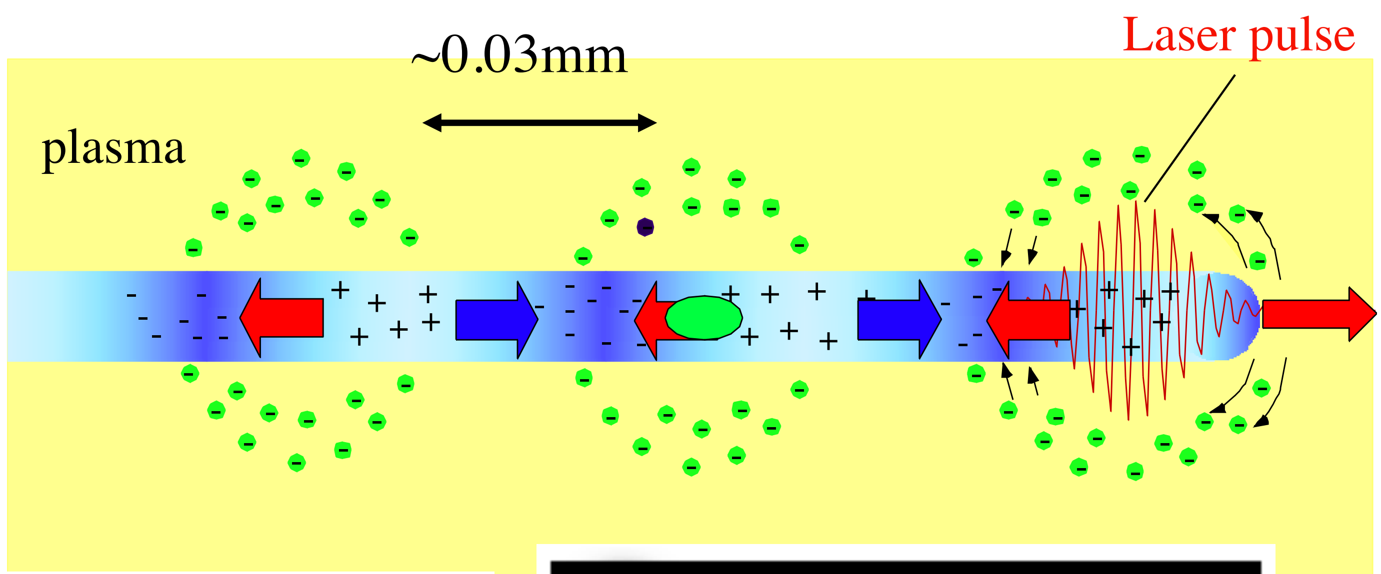
Laser intensity exponentiated since,

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

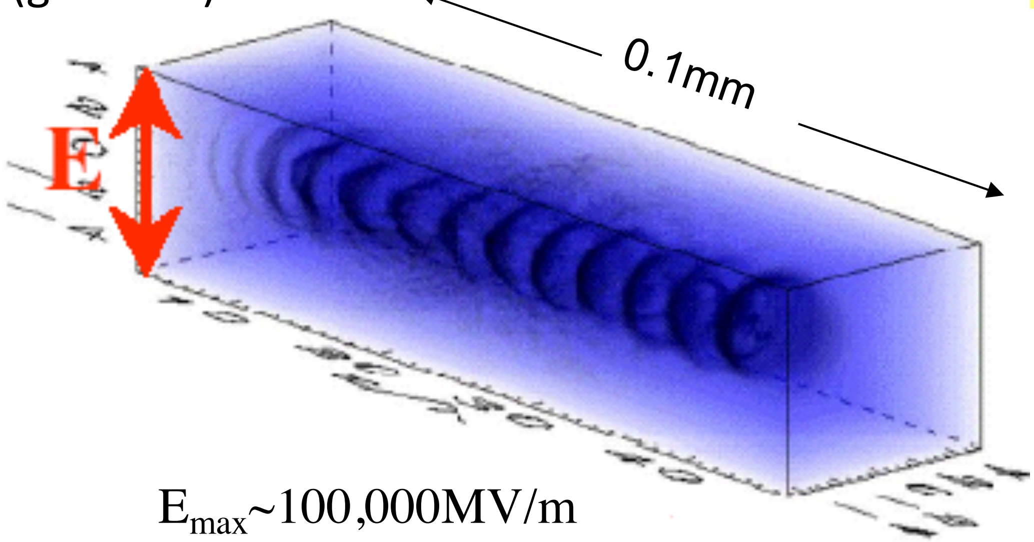
Thousand-fold Compactification

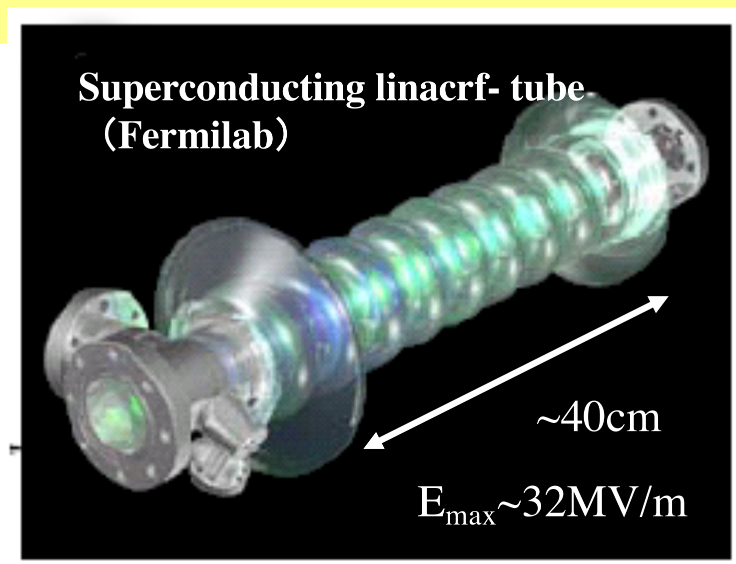
Laser wakefield: thousand folds gradient (and emittance reduction)

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



(gas tube)

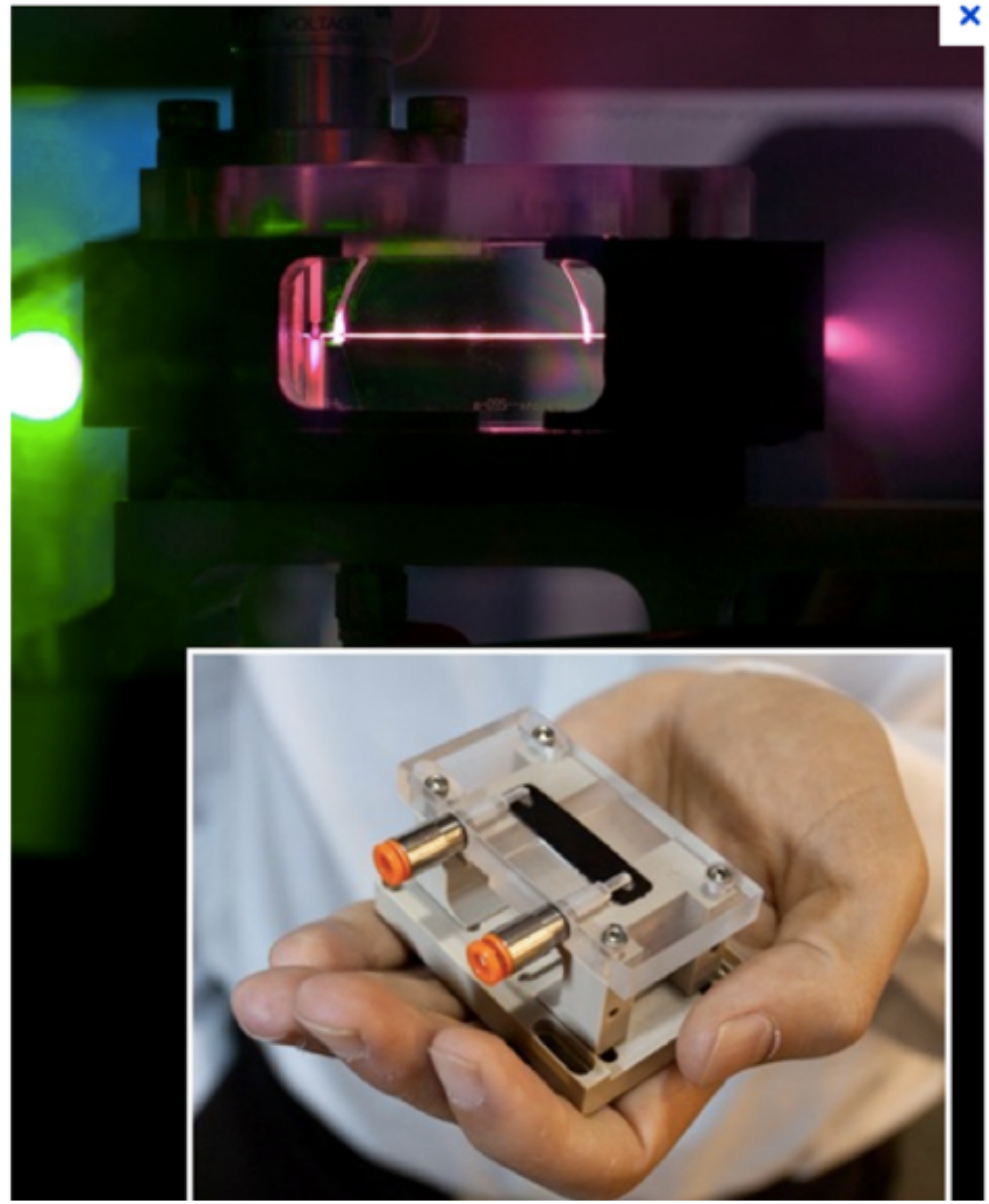




GeV in the Palm

First GeV on few cm

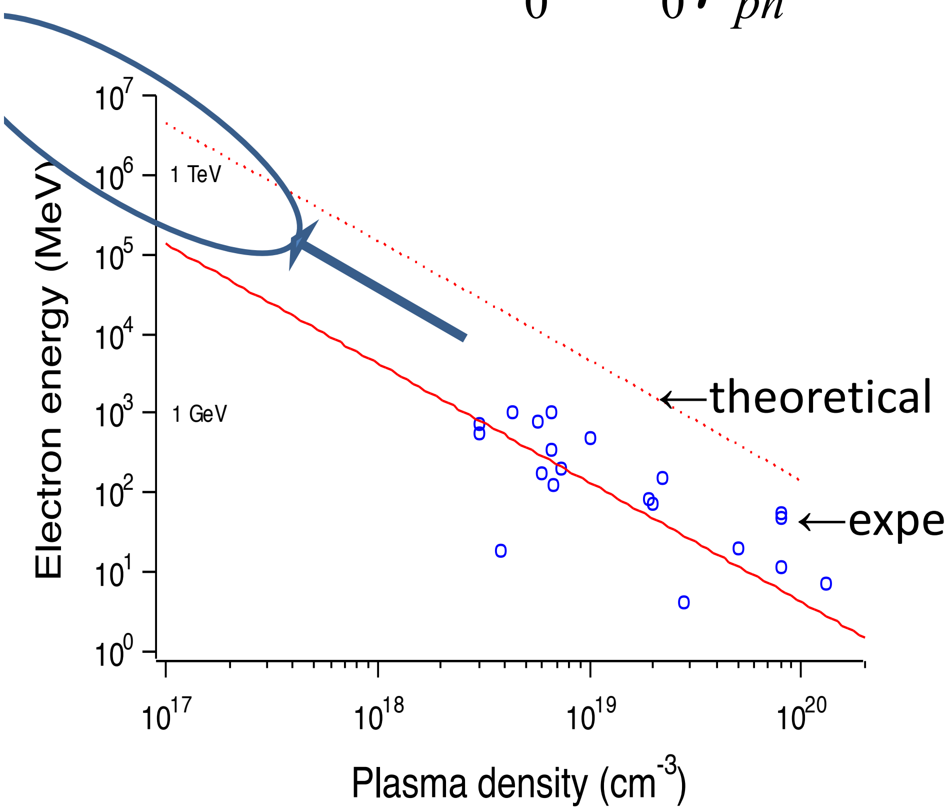
(W. Leemans et al)



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
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)

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

dephasing length

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

pump depletion length

Wakefields

nonlinear optics even in nuclear QCD plasma

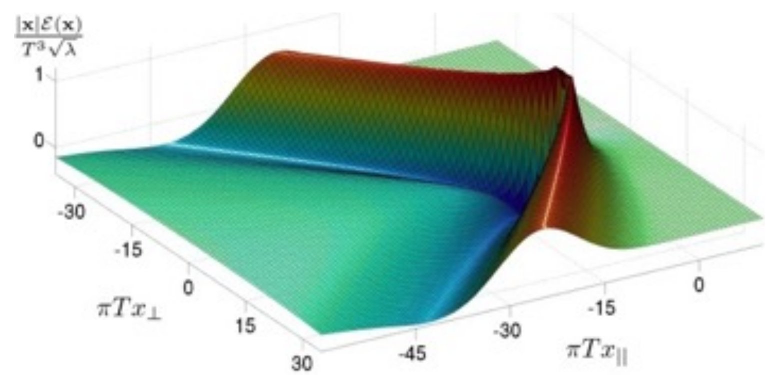
Kelvin wake

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

Hokusai

Maldacena

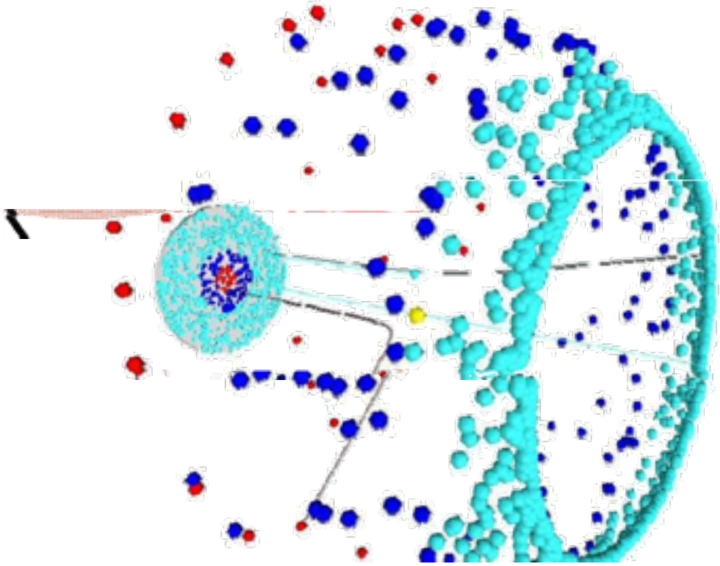
(Plasma physics vs.
String theory)

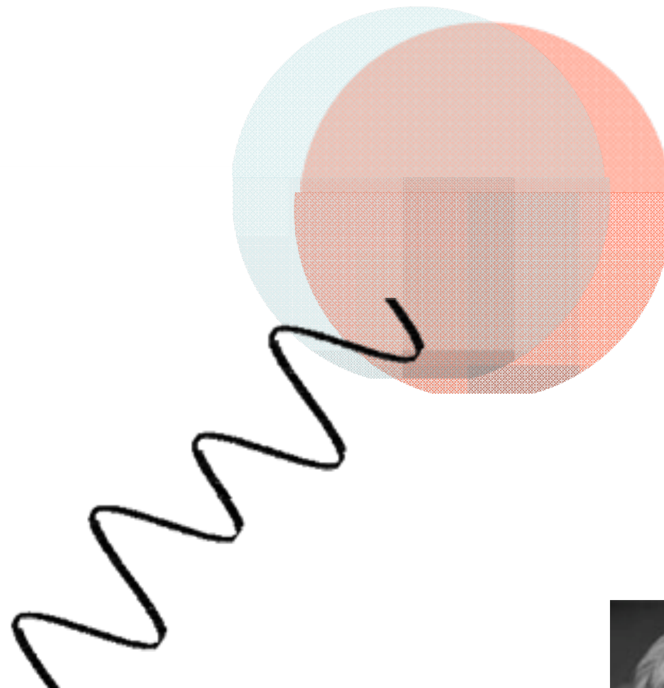


Traditional approaches :

conventional accelerator vs. conventional laser spectroscopy

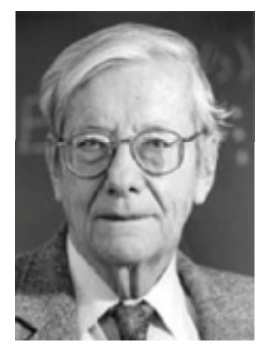
Accelerator (Rutherford) approach vs. Nonlinear optics Spectroscopy





Rutherford

Franken



Bloembergen

We ignited world-wide interest: s.a. IZEST

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

(G. Mourou, Director; T. T., Deputy Director): since 2010- working with the wishes of

High Energy Physic (and intense laser)

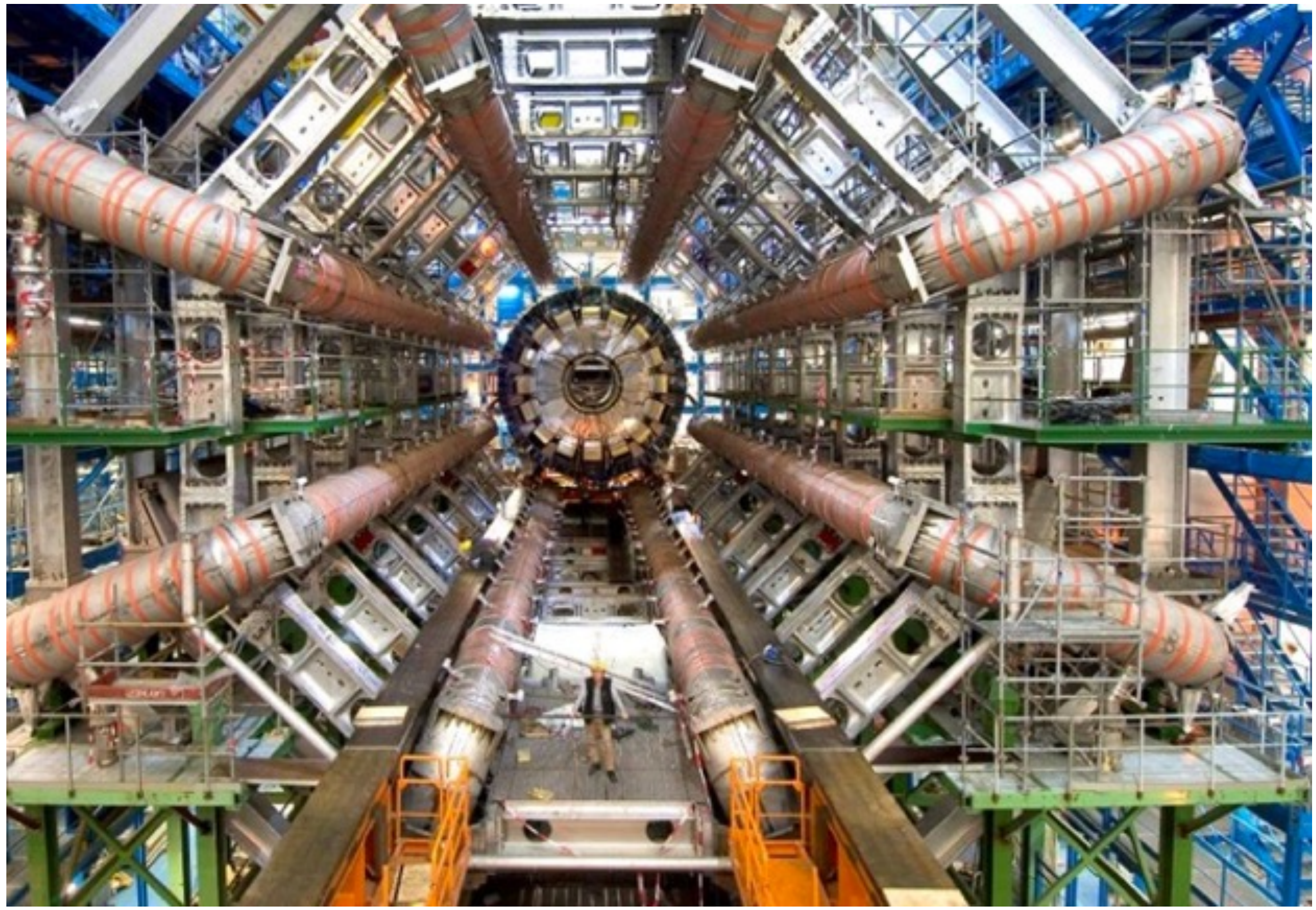
Supporters: s. a.

Young-Kee Kim
Then-Fermilab Deputy Director
Now Vice Preisdent, APS

IZEST

Fermilab

CERN



Rolph Heuer
CERN then-Director General

ELI (2010), now <u>Mega Project</u> on Extreme **Laser** (2011)

Extreme Light Infrastructure: EU decided (2010) at Czech, Hungary, and Romania
Now, Russia announced July 5, 2011: 6 Mega Projects (3-4B Euro) include **Extreme Laser**

Beyond Exawatt
Beyond 10kJ

ELI: serving Chair, Scientific Advisory Committee
Extreme Laser Mega Project (in budget negotiation): Chief Scientific Advisor/ Mega Grant Honorary Director (suggested)
International team being formed: IZEST (International Center for Zetawatt / Exawatt Science and Technology)

IZEST

S&TRF
НАУКА И ТЕХНОЛОГИИ РФ

Евразийский открытый институт, используя обучение через интернет, реализует 18 программ ба..

По диаметру отверст можно определить и веществ у ..

05.07.11
Σ Стерлигов Иван
Правительственная комиссия по высоким технологиям и инновациям; Обсуждение

Обсуждение
Версия для печати
добавить ссылку

Сверхмощный лазер как интегратор науки

В числе меганаучных проектов, которые будут реализованы на территории России, – Международный центр исследований экстремальных световых полей на основе сверхмощного лазерного комплекса в Нижнем Новгороде. Руководит центром всемирно известный физик Жерар Муру при поддержке Минобрнауки России. STRF.ru подробно рассказывал об этой работе в статье «Российские учёные строят сверхмощный лазер». Насколько значим этот проект для мировой науки, мы выяснили у Тосики Тадзимы, заведующего кафедрой физического факультета Университета Людвига Максимилиана в Мюнхене, председателя Международного комитета по сверхмощным лазерам (International Committee on Ultra-High Intensity Lasers, ICUIL).


Тосики Тадзиме не терпится поучаствовать в российском мегапроекте по созданию сверхмощного лазера

Справка STRF.ru:
Международный комитет по сверхмощным лазерам – подразделение Международного союза фундаментальной и прикладной физики, основанное в 2003 году. Задача ICUIL – продвижение науки и технологии сверхмощных лазеров и координация исследований и разработок в этой области. Под сверхмощными лазерами в комитете понимают лазеры с интенсивностью 10^{19} ватт на см^2 и мощностью около 10 тераватт

На Ваш взгляд, что примечательного произошло в области сверхмощных лазеров в последнее время?

– Прошлый год стал эпохальным для нас благодаря решению Евросоюза о запуске проекта Extreme Light Infrastructure [ELI, включает целый ряд сверхмощных лазеров в нескольких регионах Европы], а также началу реальной работы National Ignition Facility в США – альтернативный токамакам проект термоядерной энергетики, основанный на лазерном нагреве и инерционном удержании плазмы. Мы предполагаем, что развитие сверхмощных лазеров и сопутствующих областей науки значительно ускорится, и стараемся способствовать

http://strf.ru/