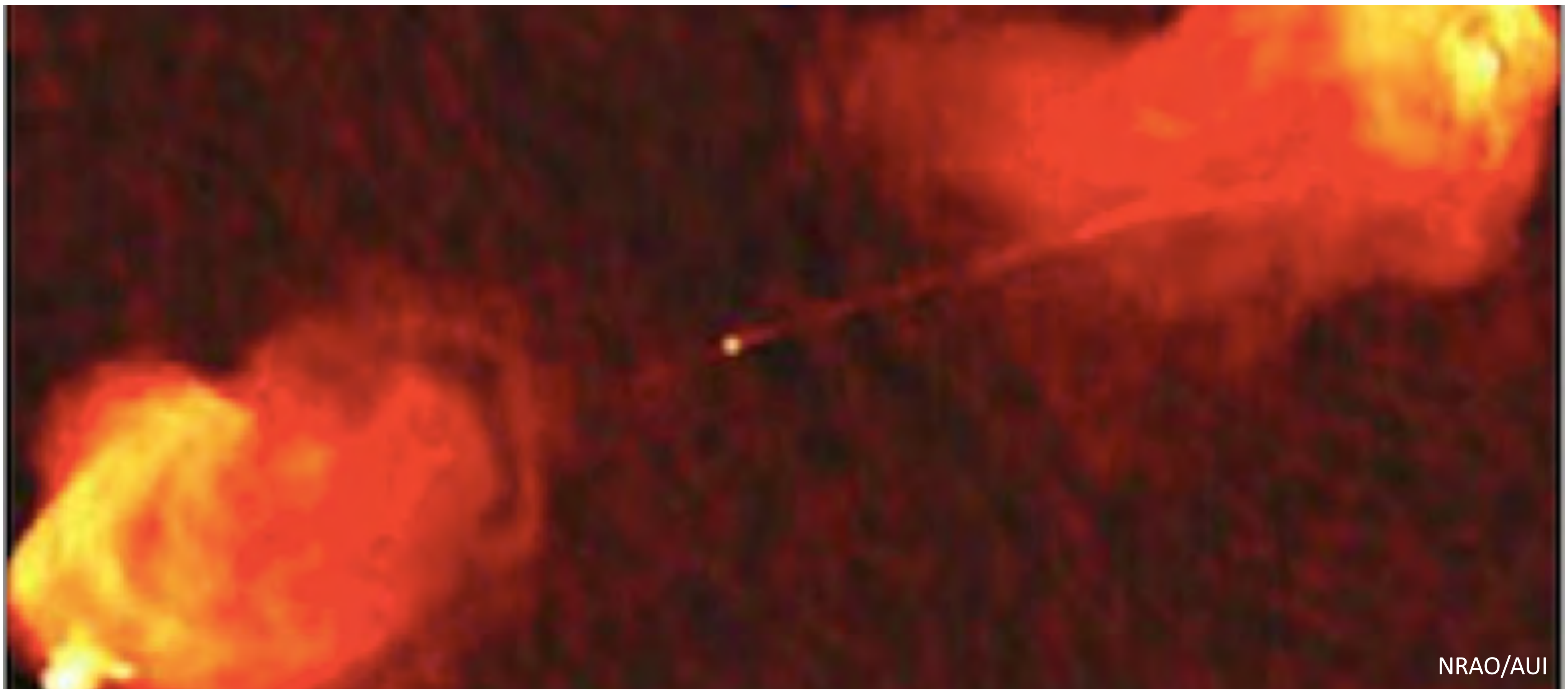
Plasma Accelerator Physics

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, CAI
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):

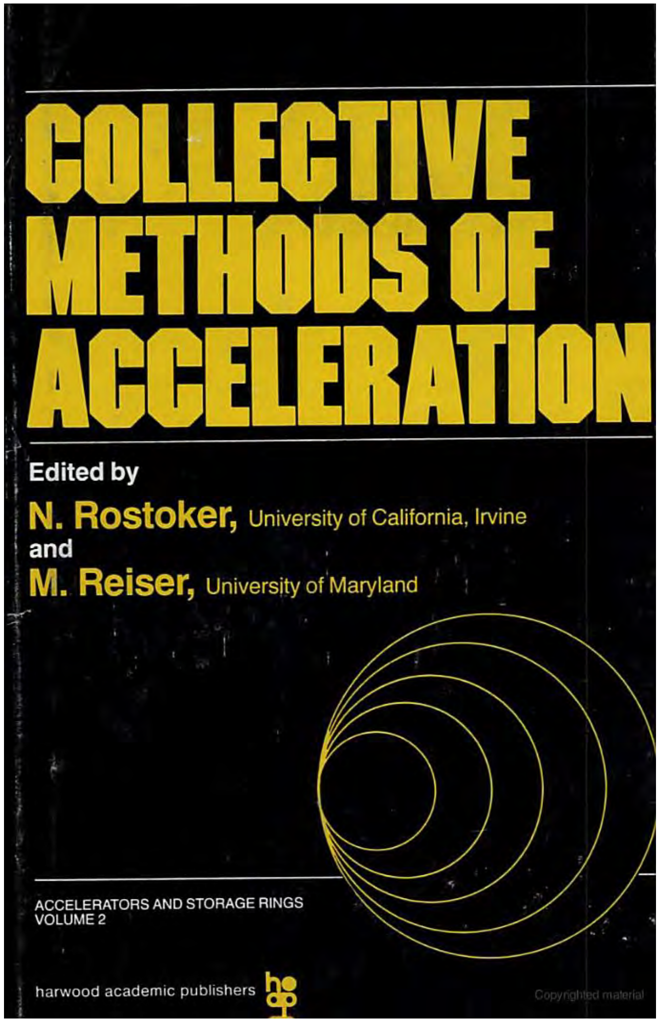
C. Lau, P. C. Yeh, O. Luk, J. McClenaghan, T. Ebisuzaki, and T. Tajima, Phys. Rev. STAB **18**, 024401 (2015).

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*?

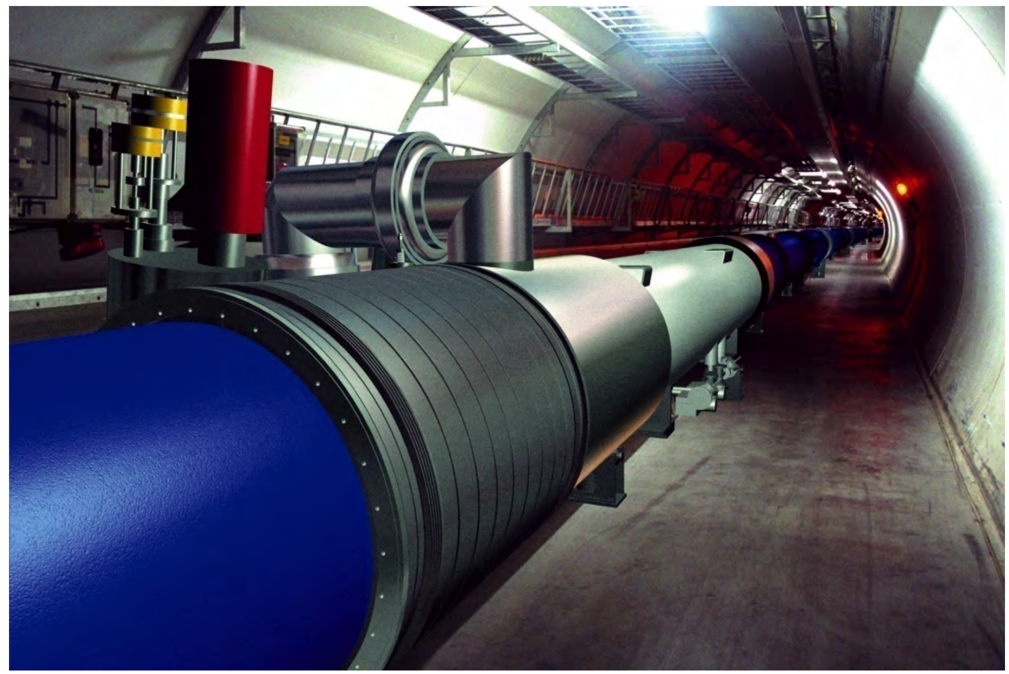
How can a Pyramid have been built?

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

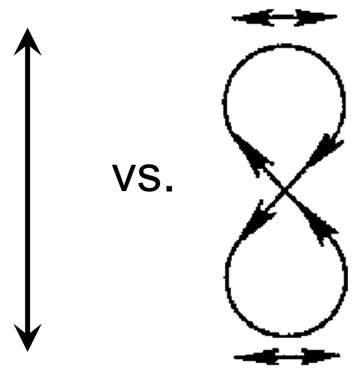



Wakefields = Collective force

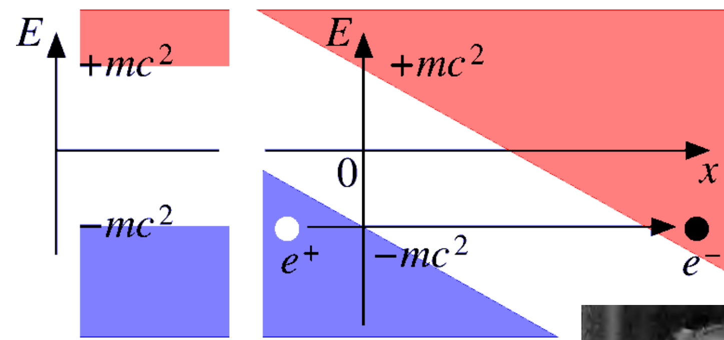
Nonlinearities in atom, plasma, and vacuum

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**

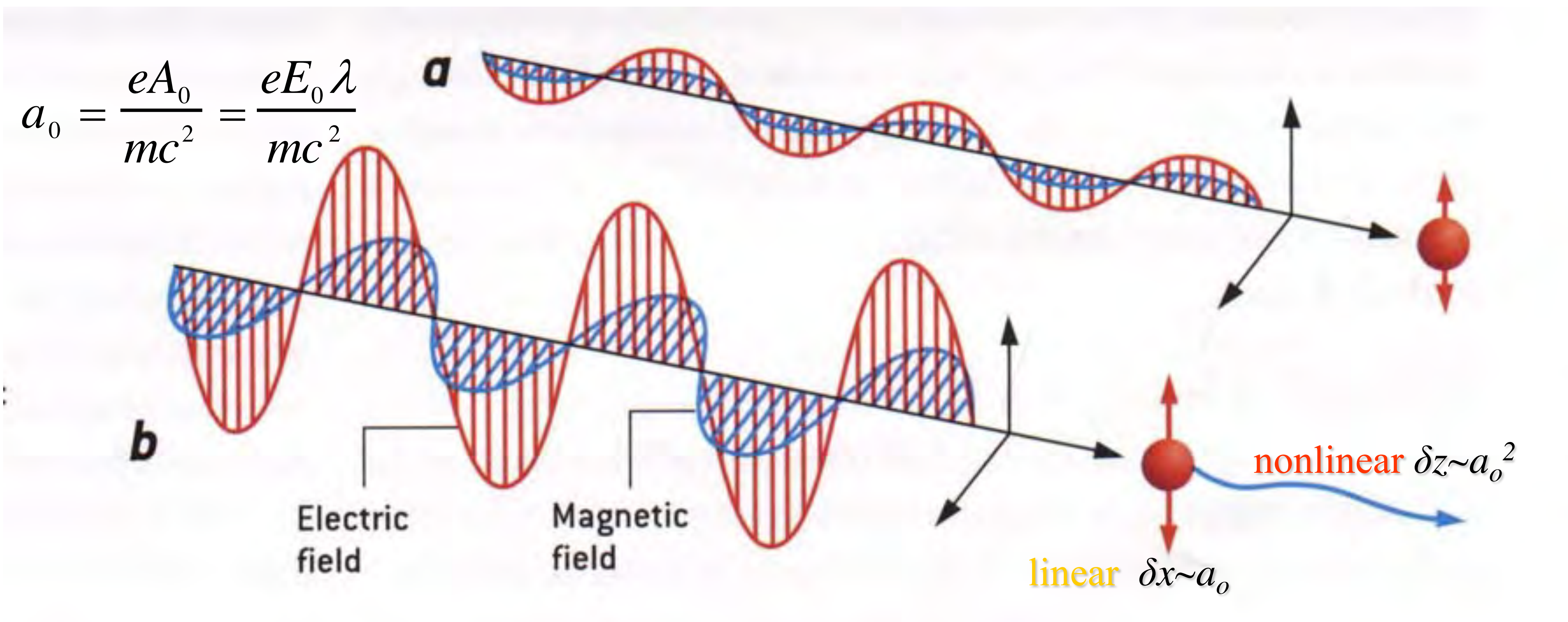
a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v \sim c$

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

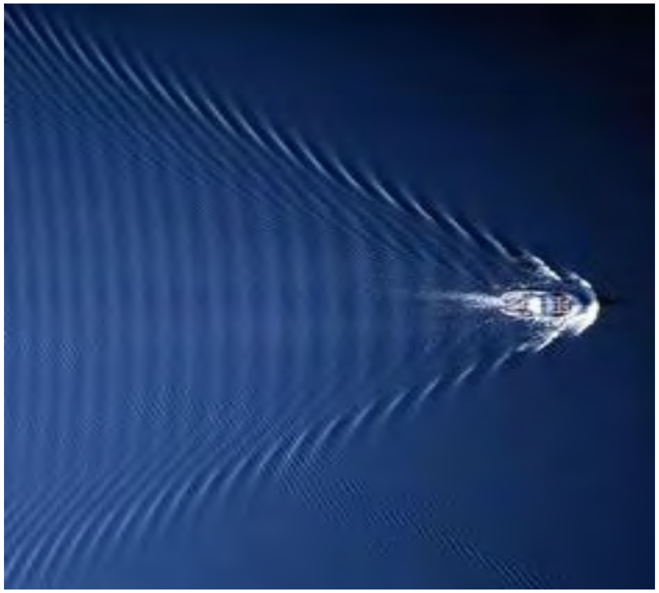
$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$



relates to **HW#1**

Laser Wakefield (LWFA) (1979):

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

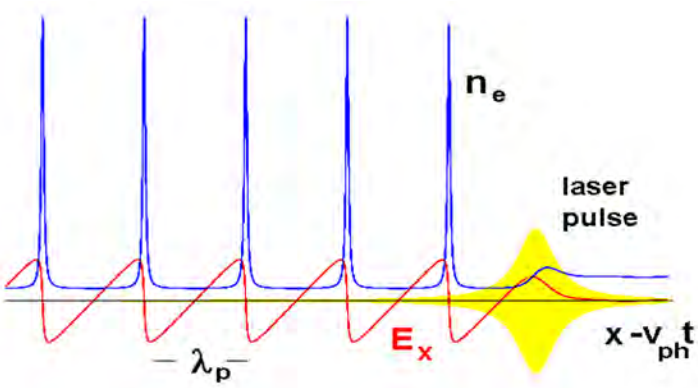


vs

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

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



← relativity regularizes (*relativistic coherence*)

Wave **breaks** at v<c

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

Basic Concepts

- Ponderomotive force ← magnetic Lorentz force of laser, a_0 v_g)
- Wakefields ← triggered by ponderomotive force (charge separation----plasma waves, ω_p v_p)
  ← resonance condition: positive side of wave (π / k_p)
  → collective accelerating field (Irvine 1972-) embedded in plasma
- Plasma instability: **how to avoid?**
- Wave trapping of particles: trapping width v_{tr} (O'Neil, 1965)
- **Tajima-Dawson Field** (1979) ← trapping, ← wave breaking

Wave particle interaction

Landau damping

infinitesimal amplitude

1946

O'Neil's trapping concept:

P. Fluids 8, 2255 (1965)

→

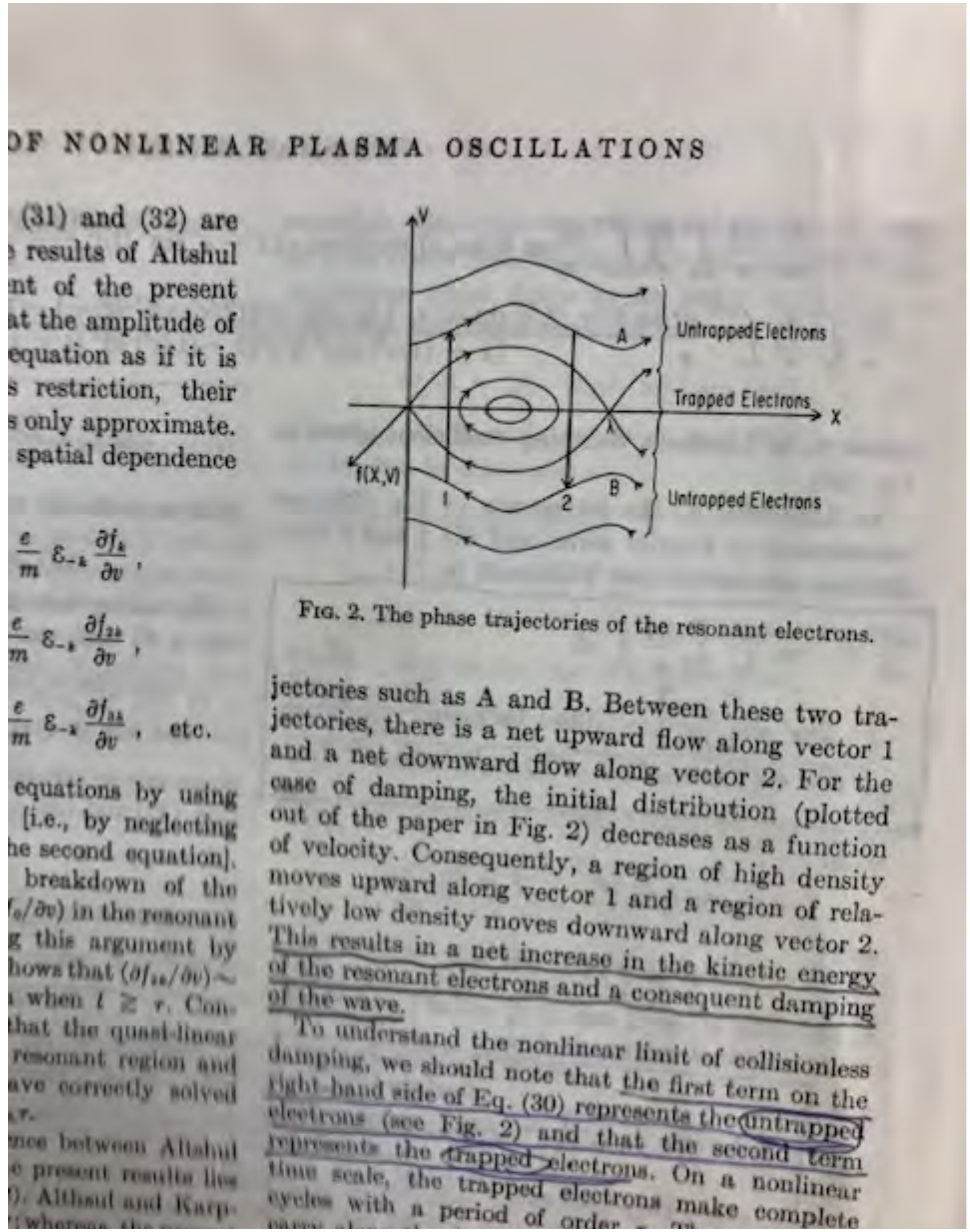
Tajima-Dawson's wakefields

1979

→

Tajima-Dawson field in Alfven wave (Nicks et al)

2020



OF NONLINEAR PLASMA OSCILLATIONS

(31) and (32) are
results of Altshul
nt of the present
at the amplitude of
equation as if it is
s restriction, their
s only approximate.
spatial dependence

$\frac{e}{m}\,\mathcal{E}_{-k}\,\frac{\partial f_k}{\partial v}$,

$\frac{e}{m}\,\mathcal{E}_{-k}\,\frac{\partial f_{2k}}{\partial v}$,

$\frac{e}{m}\,\mathcal{E}_{-k}\,\frac{\partial f_{3k}}{\partial v}$, etc.

equations by using
[i.e., by neglecting
he second equation].
breakdown of the
$f_0/\partial v$) in the resonant
g this argument by
hows that $(\partial f_{1k}/\partial v)\sim$
when $t \gtrsim \tau$. Con-
that the quasi-linear
resonant region and
ave correctly solved
τ.
nce between Altshul
e present results lies
). Altshul and Karp-
whereas the

FIG. 2. The phase trajectories of the resonant electrons.

jectories such as A and B. Between these two trajectories, there is a net upward flow along vector 1 and a net downward flow along vector 2. For the case of damping, the initial distribution (plotted out of the paper in Fig. 2) decreases as a function of velocity. Consequently, a region of high density moves upward along vector 1 and a region of relatively low density moves downward along vector 2. This results in a net increase in the kinetic energy of the resonant electrons and a consequent damping of the wave.

To understand the nonlinear limit of collisionless damping, we should note that the first term on the right-hand side of Eq. (30) represents the untrapped electrons (see Fig. 2) and that the second term represents the trapped electrons. On a nonlinear time scale, the trapped electrons make complete cycles with a period of order

Wakefield saturation (relates to HW #2)

Wakefields excited: stay robust

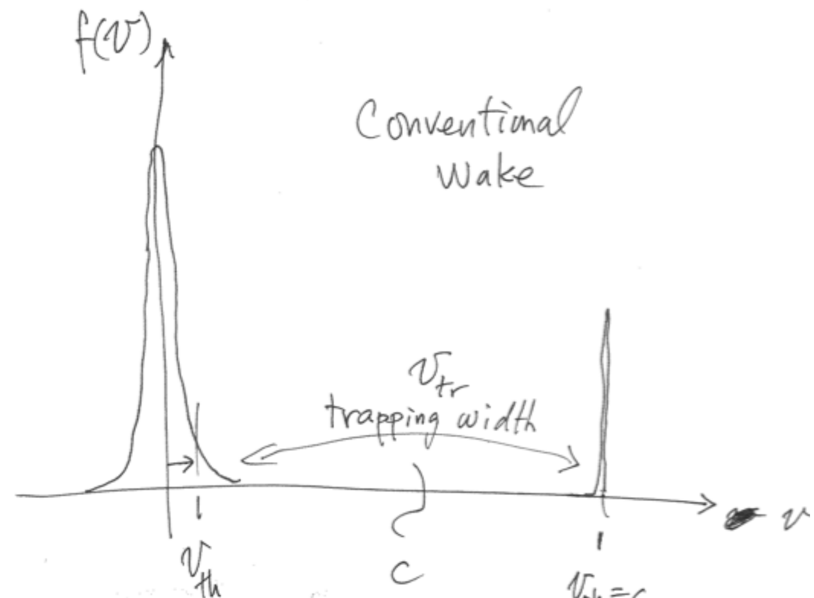
← large phase velocity

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

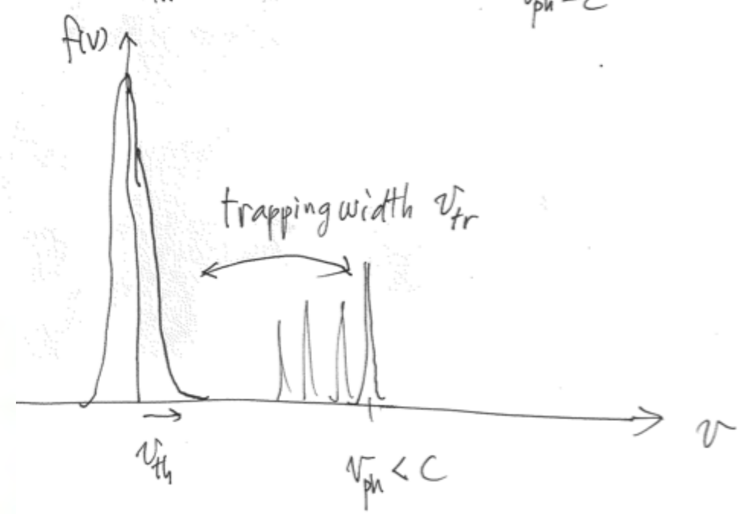
Show [Homework #2] with $v_{ph} = c$: $v_{tr} = \sqrt{eE/mk}$

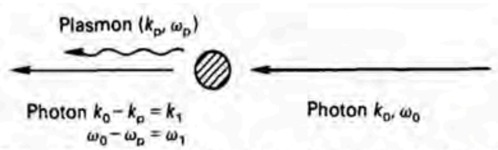
$v_{tr} = v_{ph}$ → saturation field

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

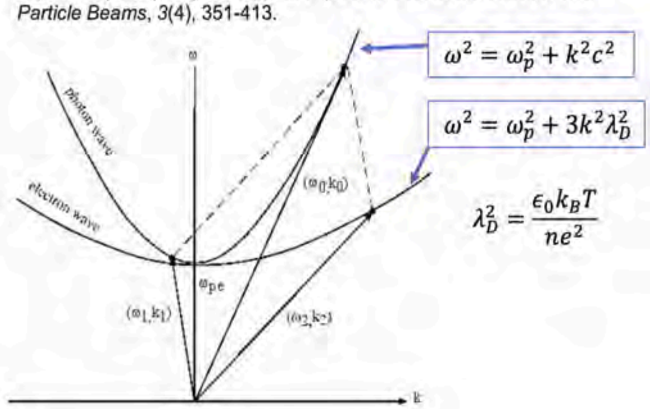


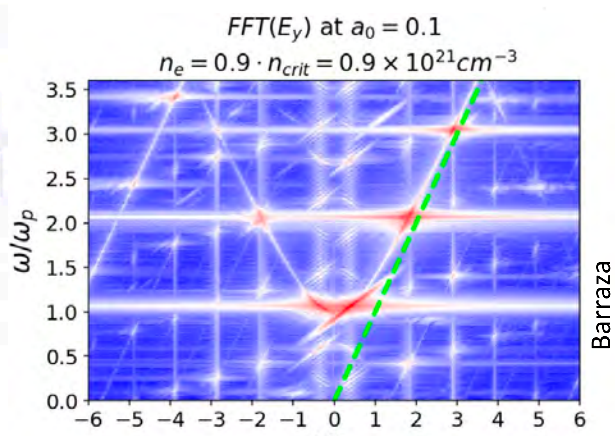
When $v_{ph} < c$, → $v_{tr} = \sqrt{eE/mk} < c$ → $E < E_{TD}$



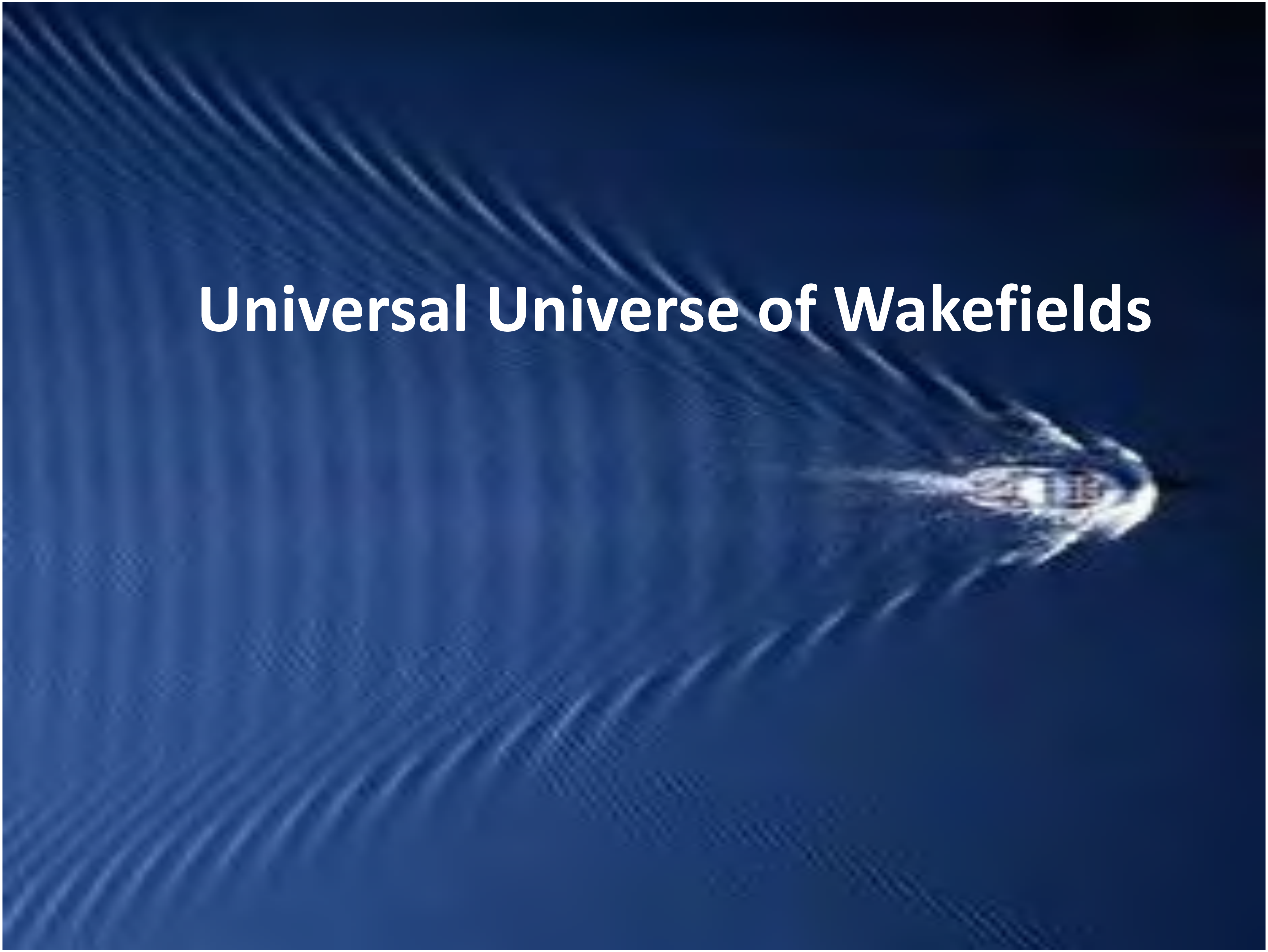


Tajima, T. (1985). High energy laser plasma accelerators. *Laser and Particle Beams*, 3(4), 351-413.



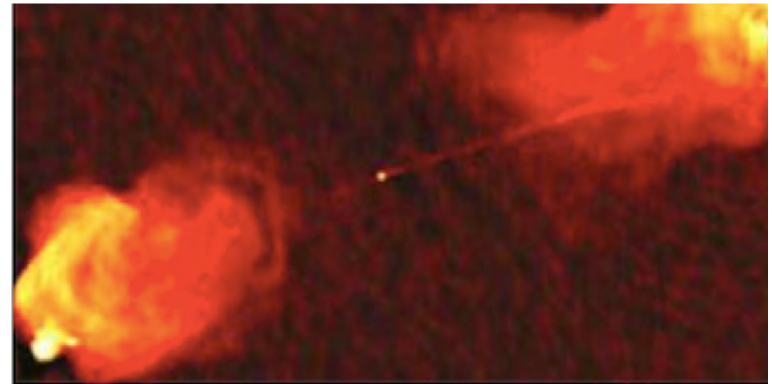


Universal Universe of Wakefields

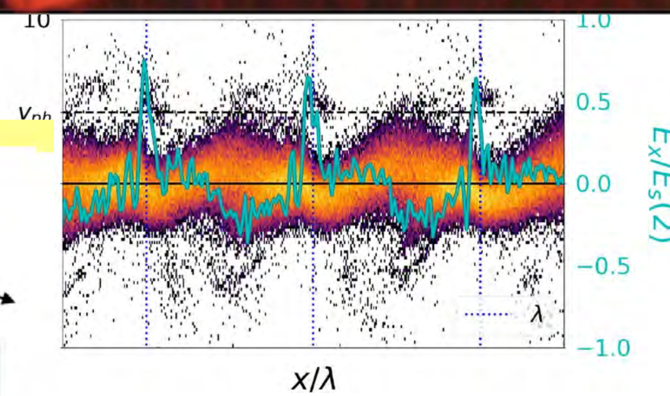


Ranges of wakefields

λ : 10^{-13} cm ← → 10^{19} cm

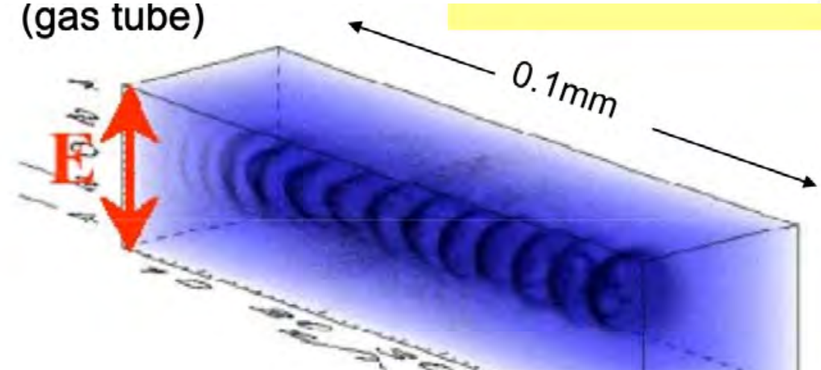


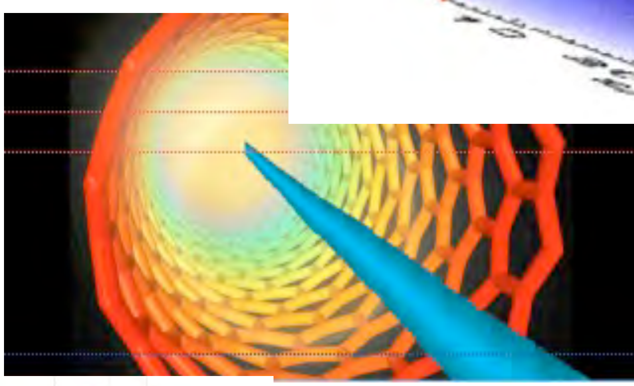
$\lambda = 10^{19}$ cm
(AGN jets)



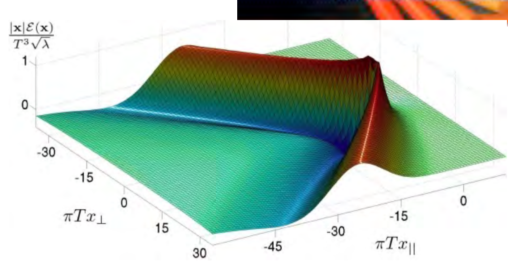
λ = 1 cm (fusion plasma)

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





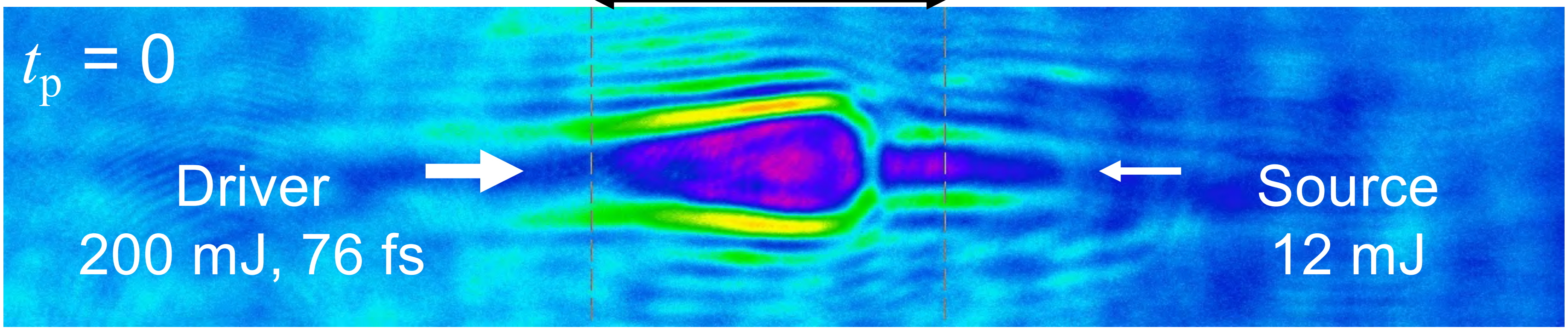
$\lambda = 10^{-7}$ cm
(nanotube)



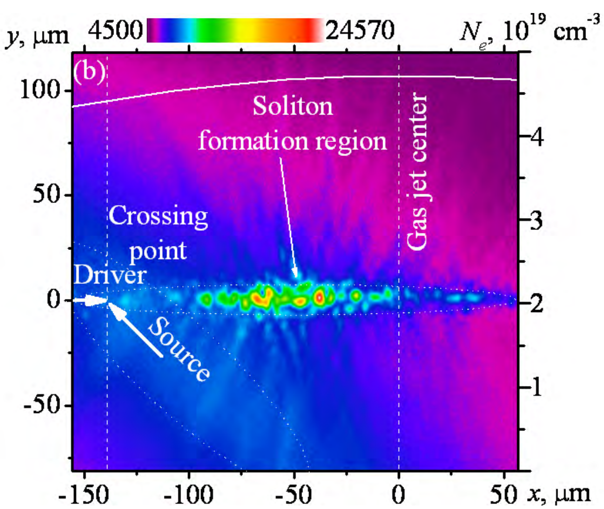
$\lambda = 10^{-13}$ cm (nuclear QCD plasma)

Space-Time Overlapping of Driver and Source pulses

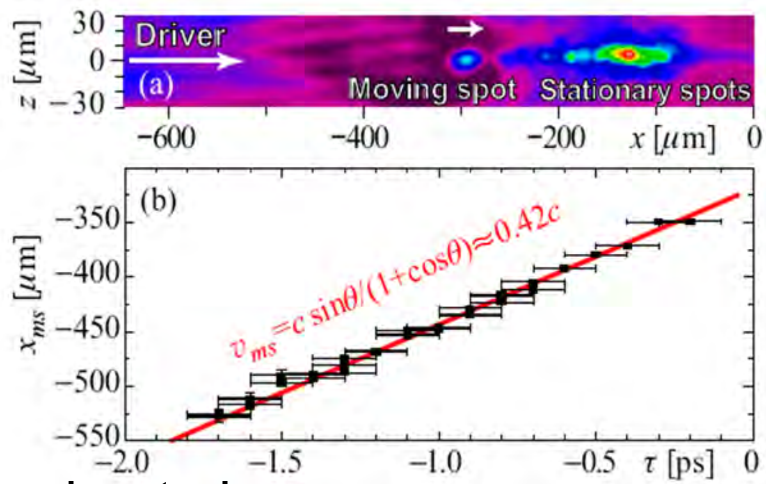
Side View

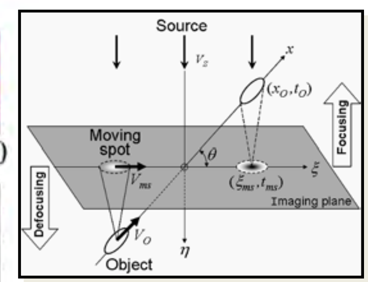


Top View



Relativistic Microlens





(Kando et al

Paradigm Shift in Plasma Physics

- Instabilities dominant in plasma science

↓

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

new organizational principle: High Phase Velocity Principle(HPVP), ….
(dynamical stability)

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

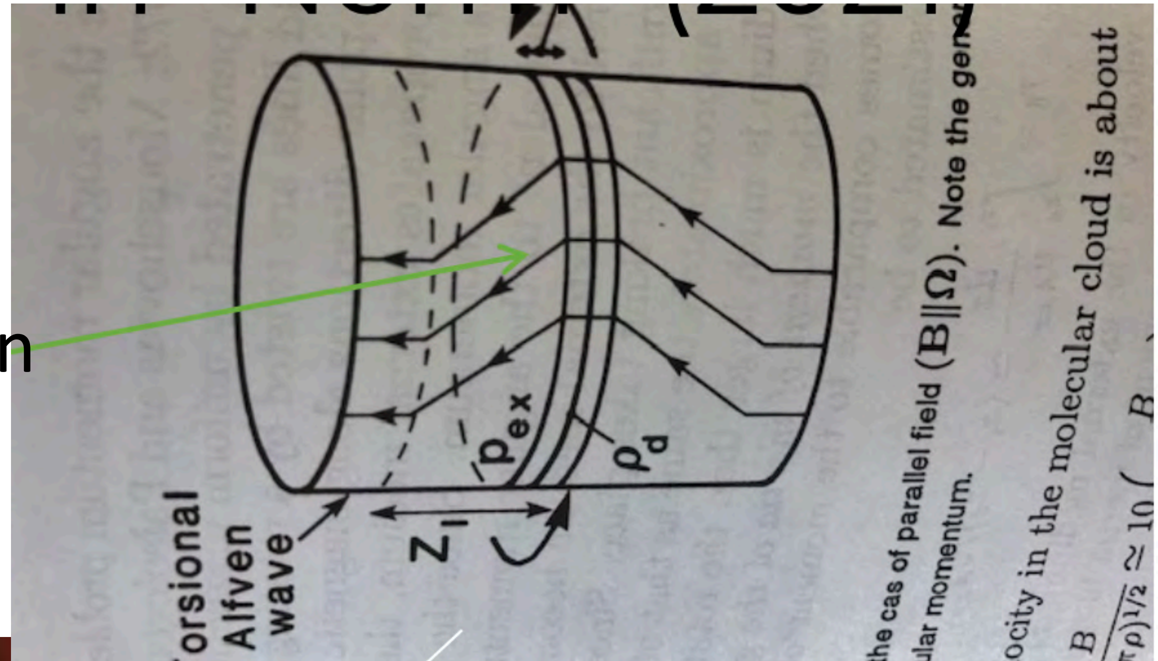
  "hide-and-seek"

  Jets (astrophysical, largest structure of the world)

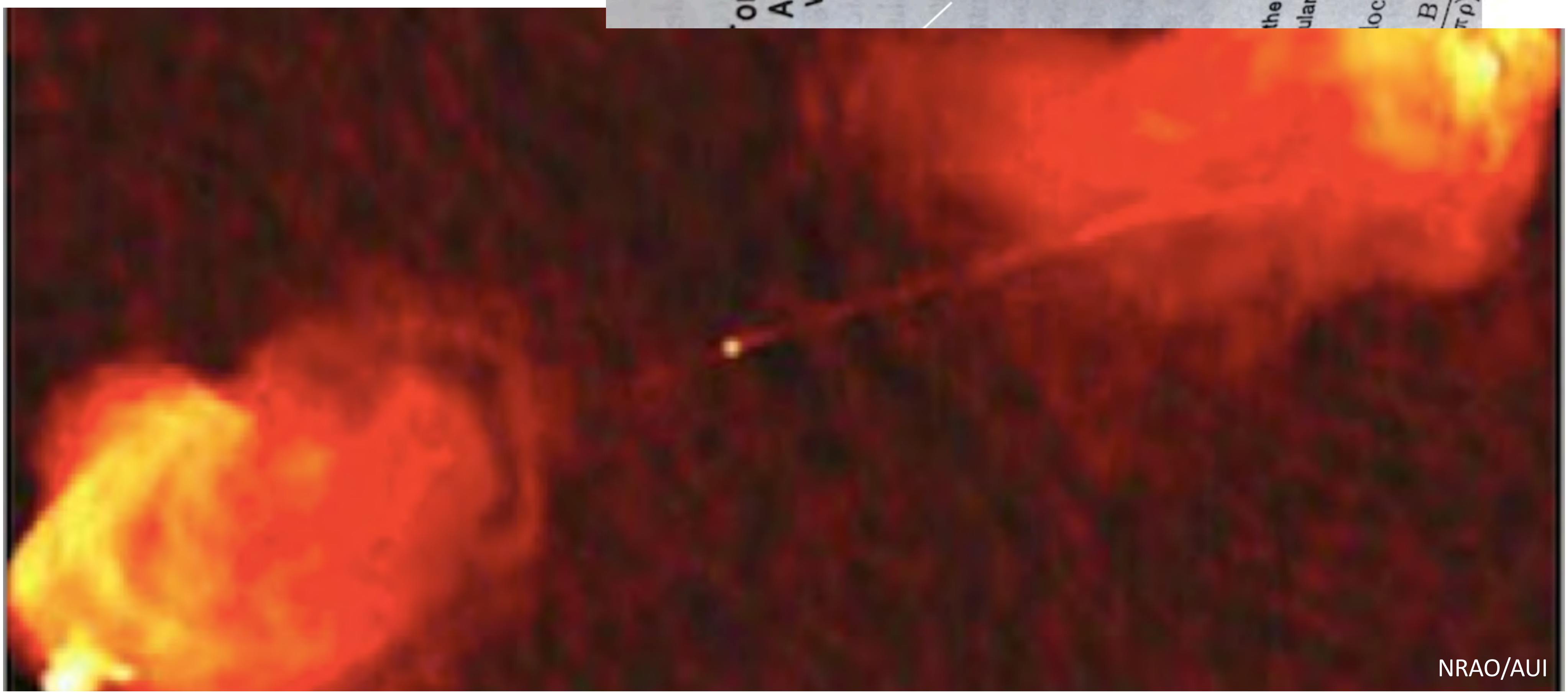
Rotation al twist onto magnetic field →

Jets and thei relongation

structure formation



Tajima-Shibata (199'



The late Prof. Abdus Salam

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

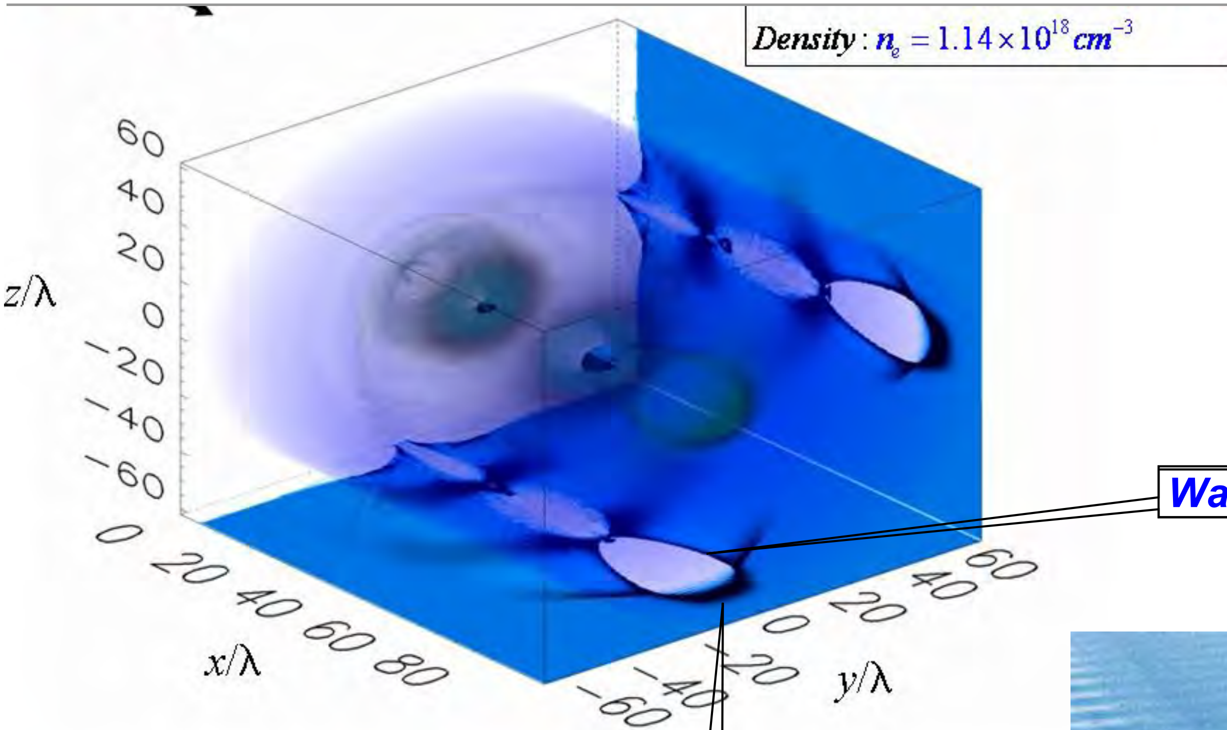
Salam*: ‘Scientists like me began feeling that we had less means to test our theory. However, with your laser acceleration, I am encouraged’*. (1981)

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)

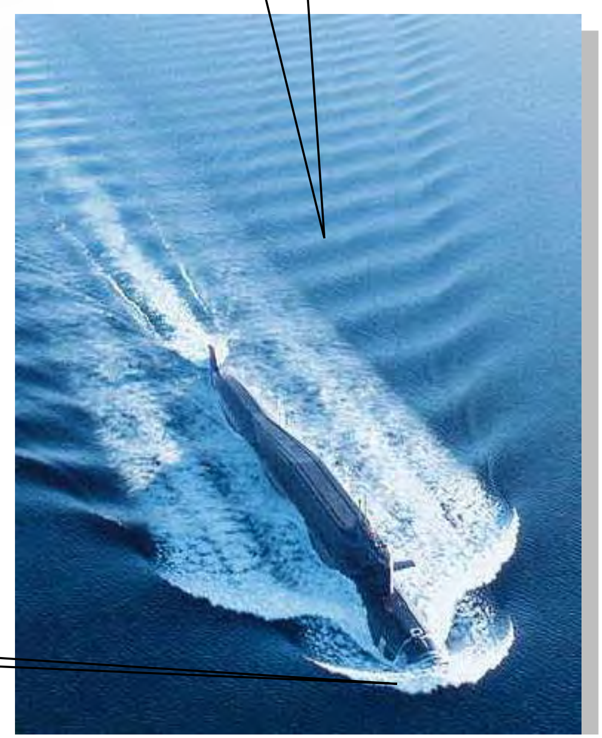
Laser-driven Bow and Wake



(Bulanov, Esirkepov)

Wakefield acceleration

Wake Wave



Bow Wave

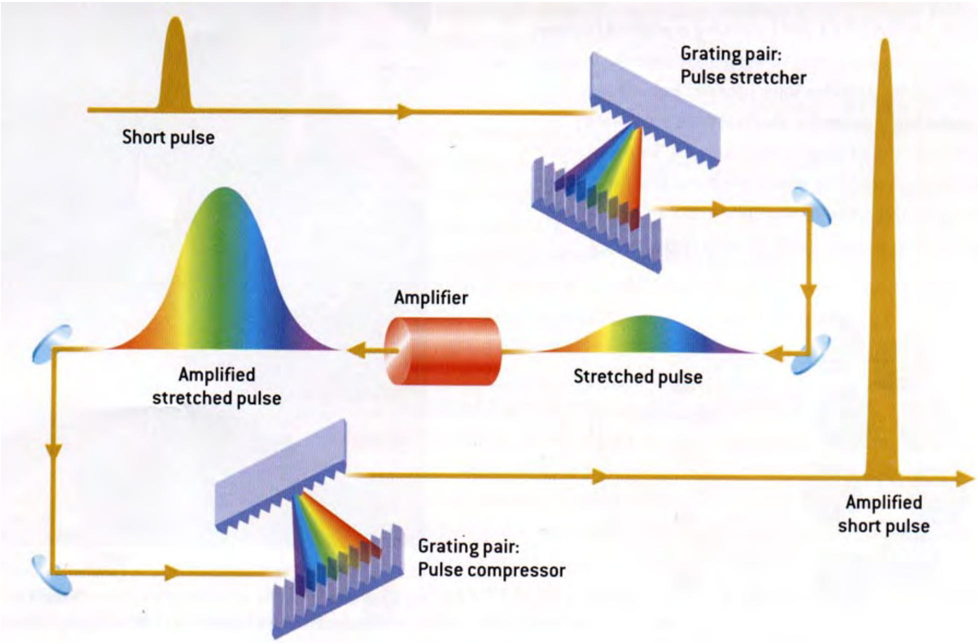
Ponderomotive acceleration

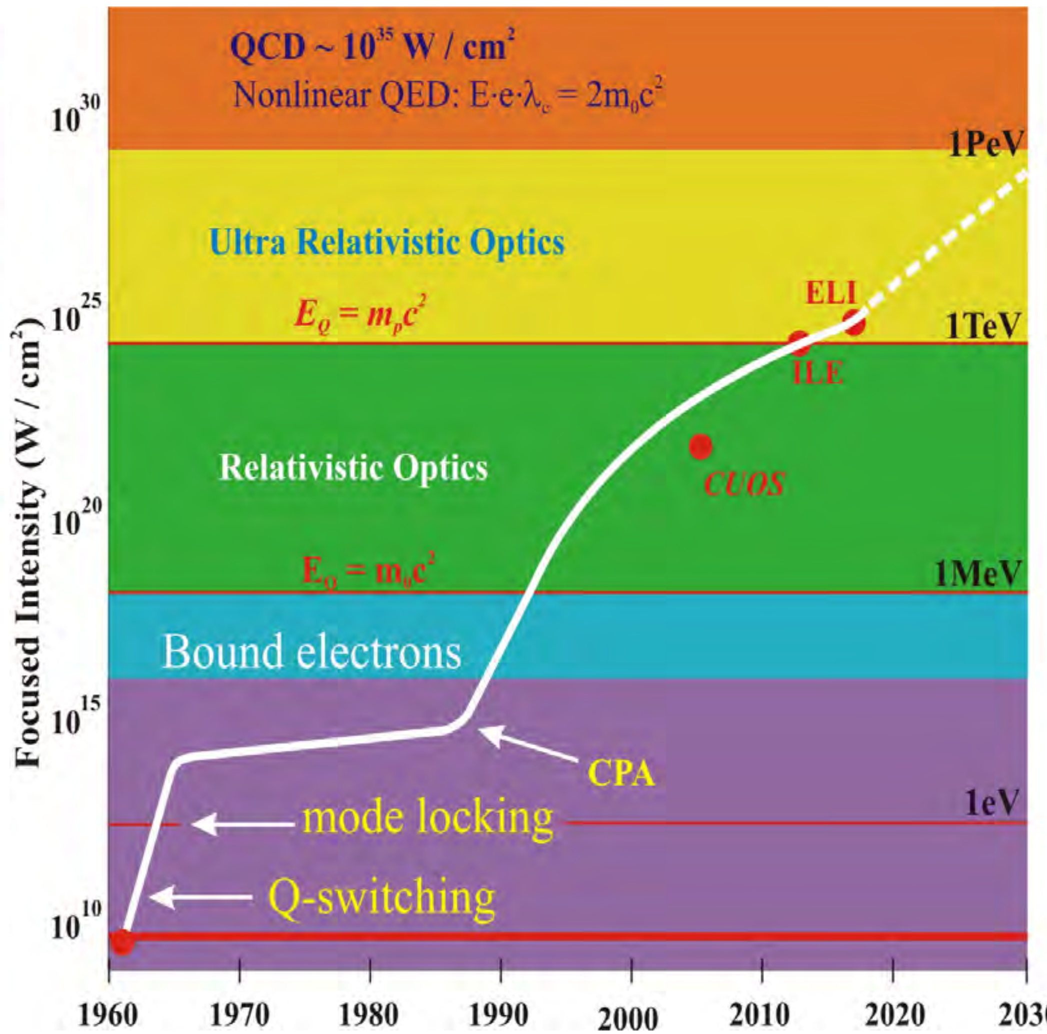
21st Century; the Photon Century
Could basic research be driven by the massless and chargeless particles; Photons?

C. Townes (laser invention) →

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

Enabling technology: laser revolution





G. Mourou invented Chirped Pulse Amplification (1985)

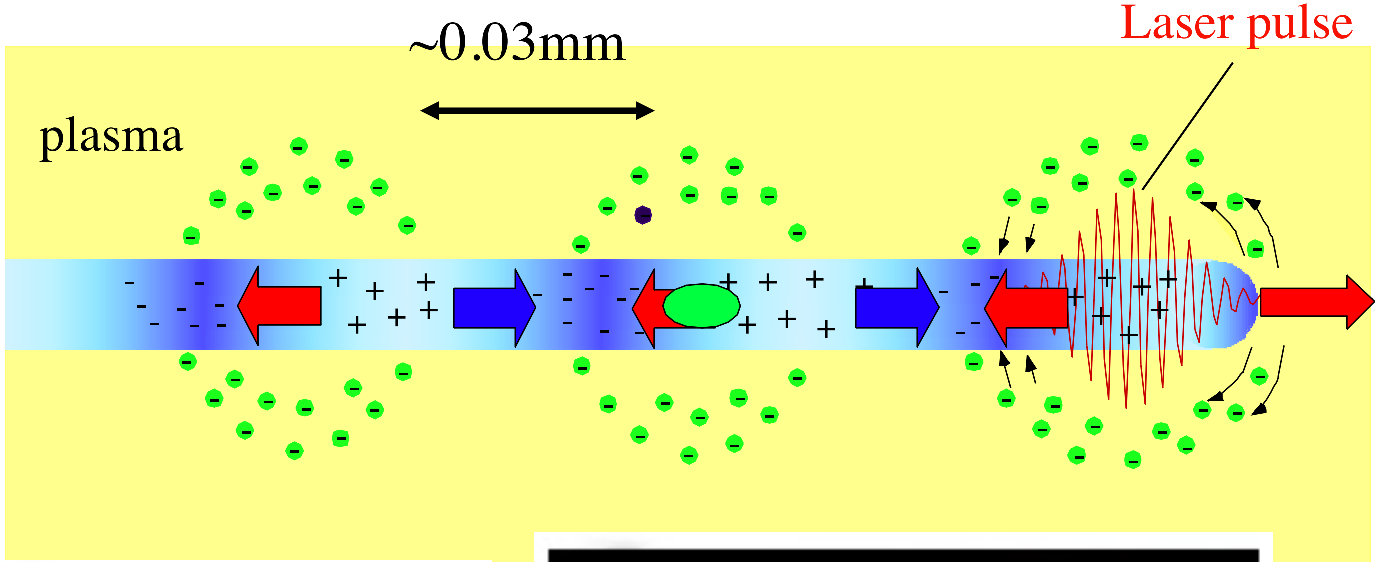
Laser intensity exponentiated since,

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

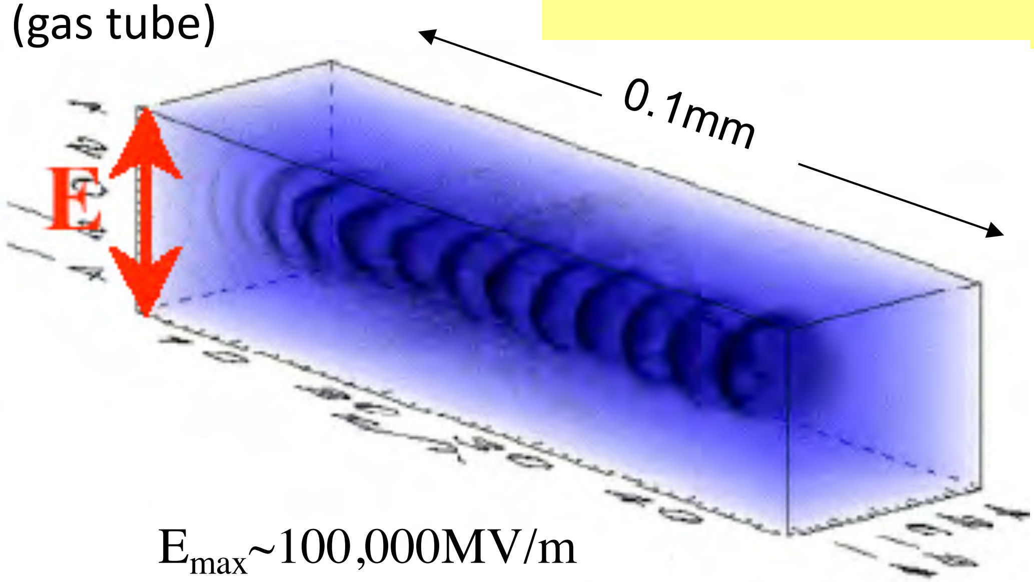
Thousand-fold Compactification

Laser wakefield: thousand folds gradient (and emittance reduction)

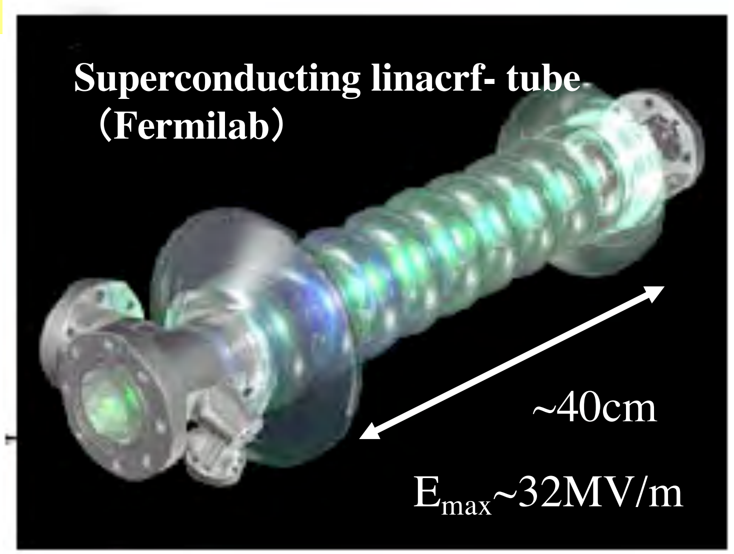
First experimental realization: Nakajima,….., Tajima, (1994)



(gas tube)

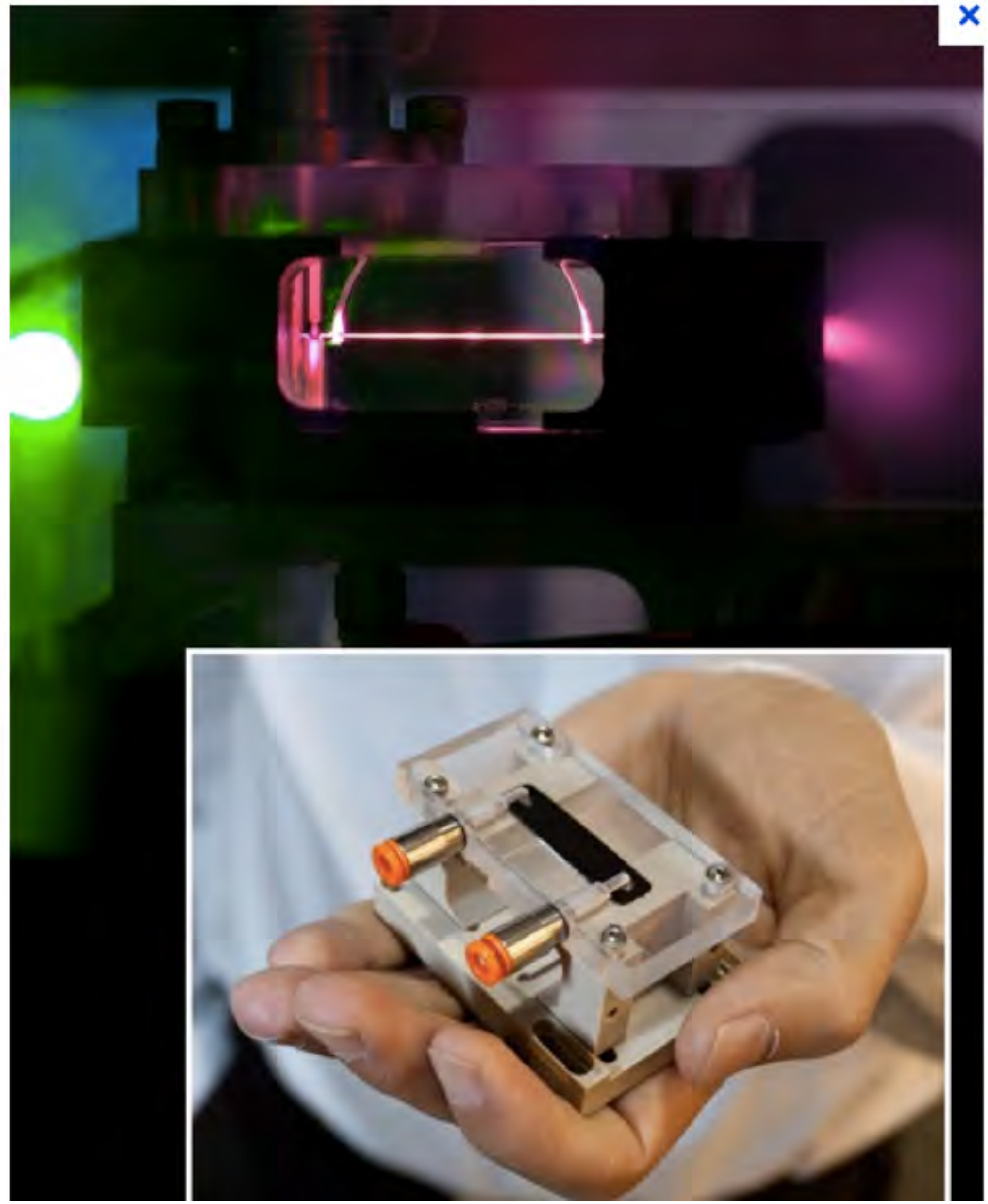


E_{max}~100,000MV/m



GeV in the Palm

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

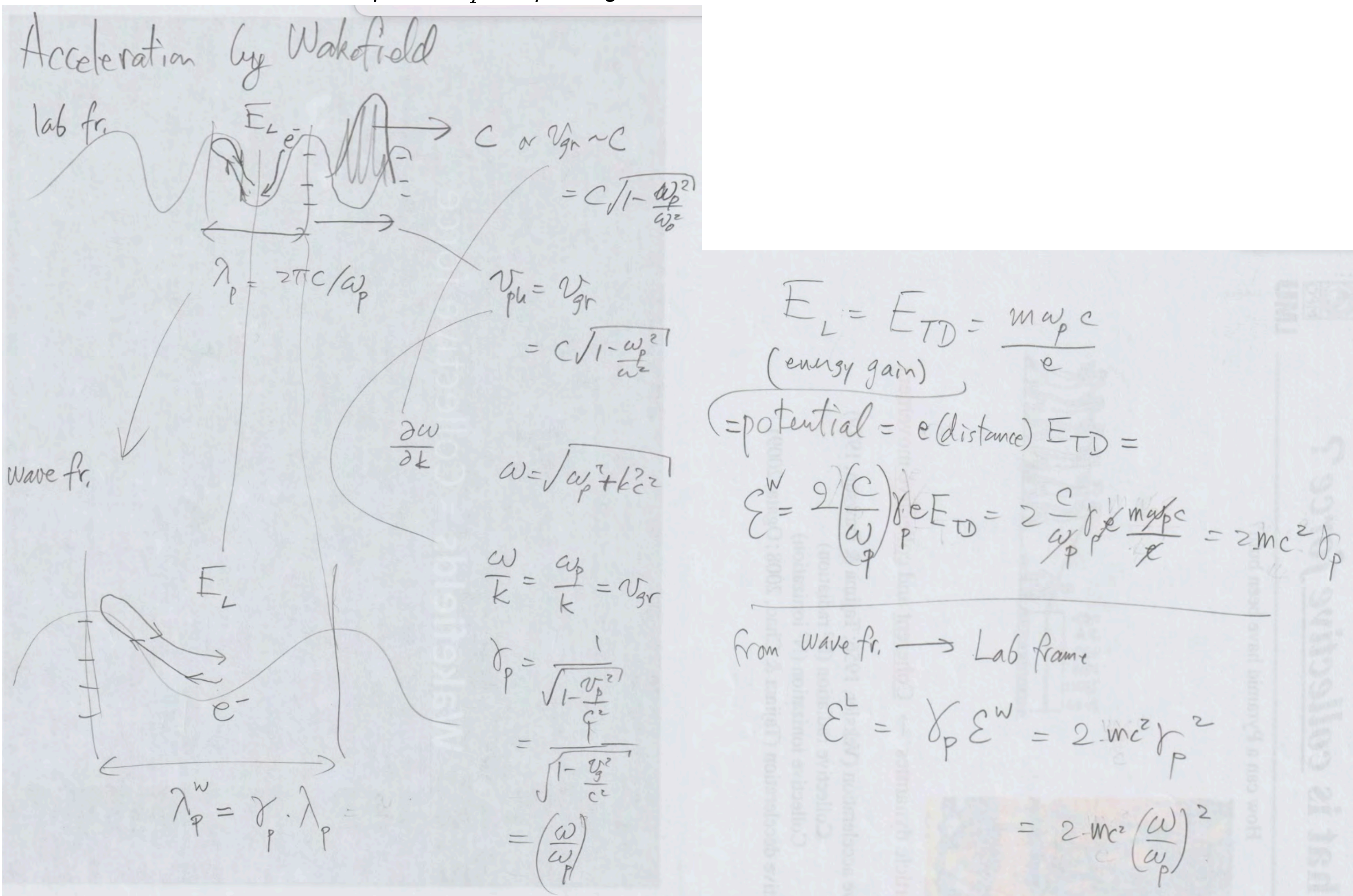


Acceleration by wakefields

Accelerating wave:

driven by laser pulse (group velocity of the photon: $v_{gr} = c\sqrt{1-\omega_p^2/\omega^2}$)

wakefield phase velocity $v_{ph} = \omega_p / k_p = v_{gr}$



Acceleration length:
Dephasing length

Dephasing length

$$\Delta v = c - v_{gr} = c - c\left(\sqrt{1-\frac{\omega_p^2}{\omega^2}}\right)$$

$$\simeq \left(c \times \frac{1}{2}\frac{\omega_p^2}{\omega^2}\right)$$

$$L_{dp} = \left(\frac{\pi c}{\omega_p}\frac{1}{\Delta v}\right)\times c$$

$(a_0 = 1)$

$$= \frac{\pi c}{\omega_p}\frac{1}{c}\frac{\omega^2}{\frac{1}{2}\omega_p^2}c = \frac{2\pi c}{\omega_p}\frac{\omega^2}{\omega_p^2}$$

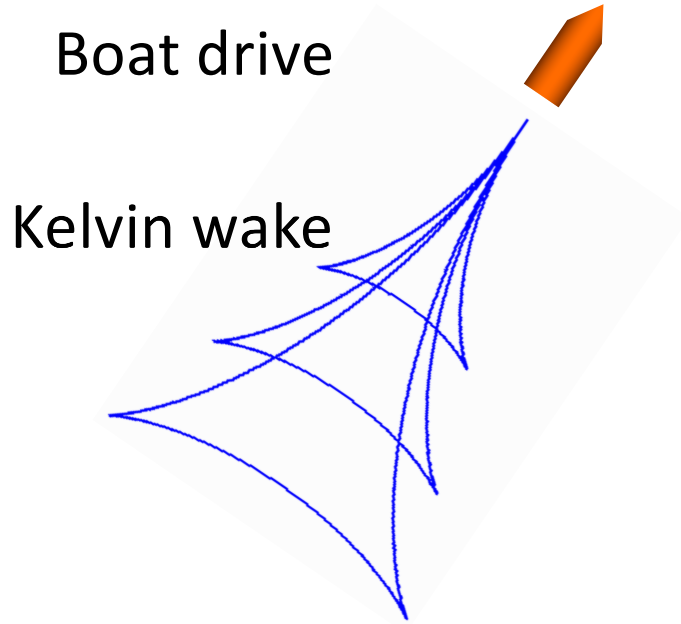
---

correction : class 1 p. 13

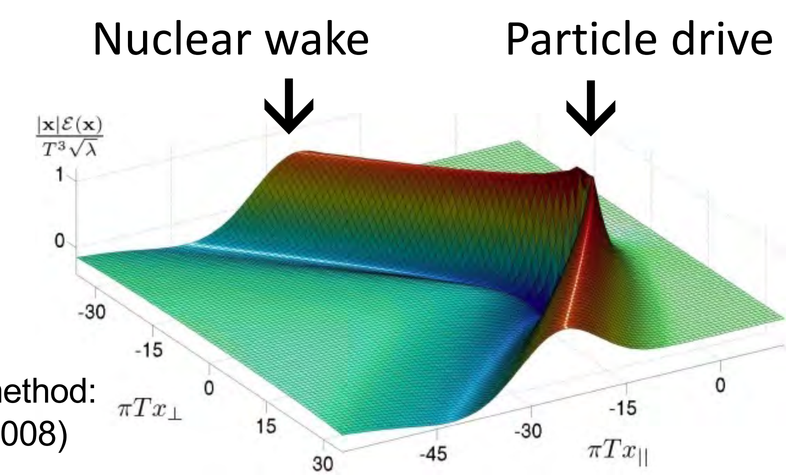
$$\omega^2 = \omega_p^2 + 3\lambda_D^2 k^2 \rightarrow \omega_p^2(1 + 3\lambda_D^2 k^2)$$

Wakefields

group velocity of the driver vs. phase velocity of wake



Maldacena

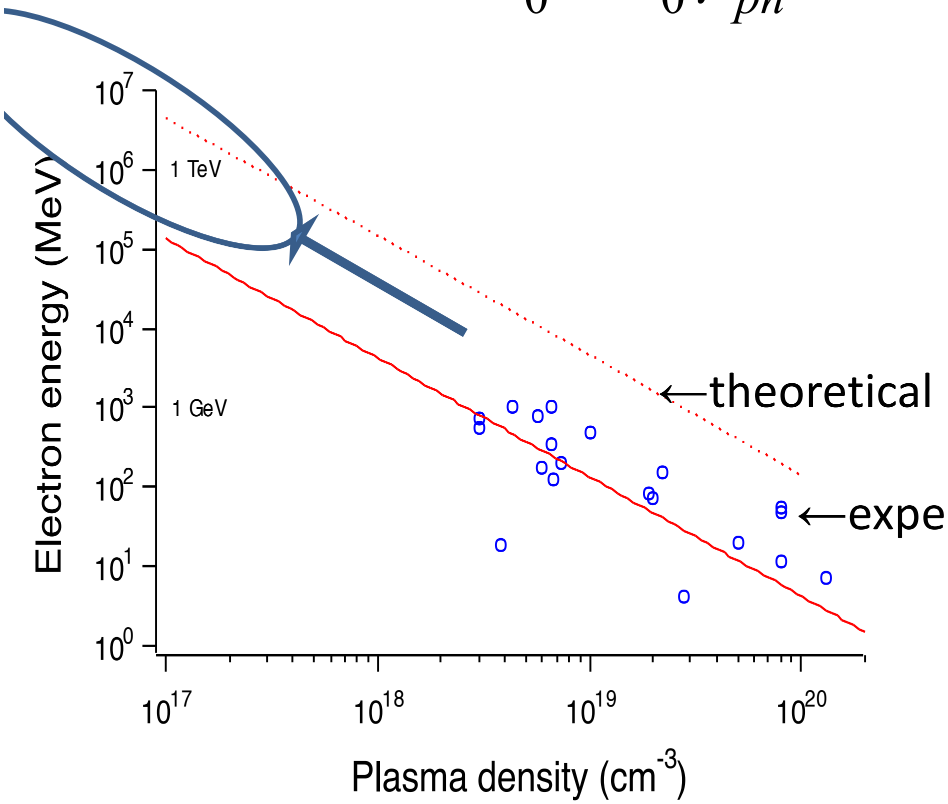


Maldacena (string theory) method:
QCD **wake** (Chesler/Yaffe 2008)

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

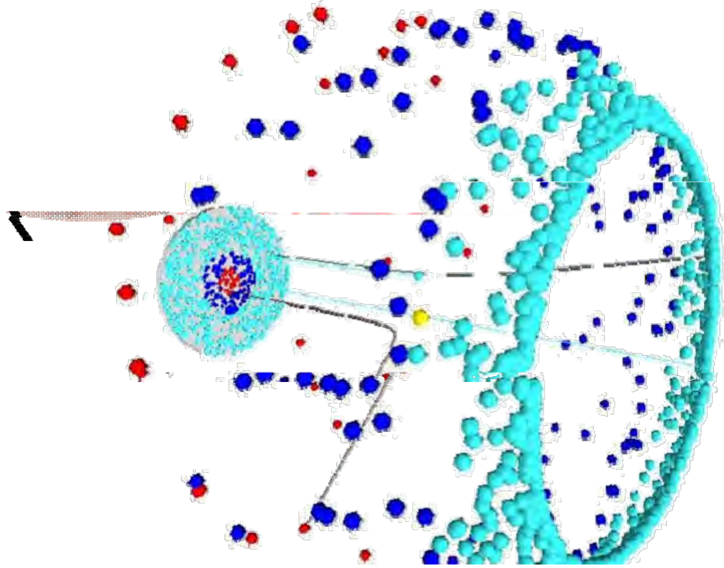
$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

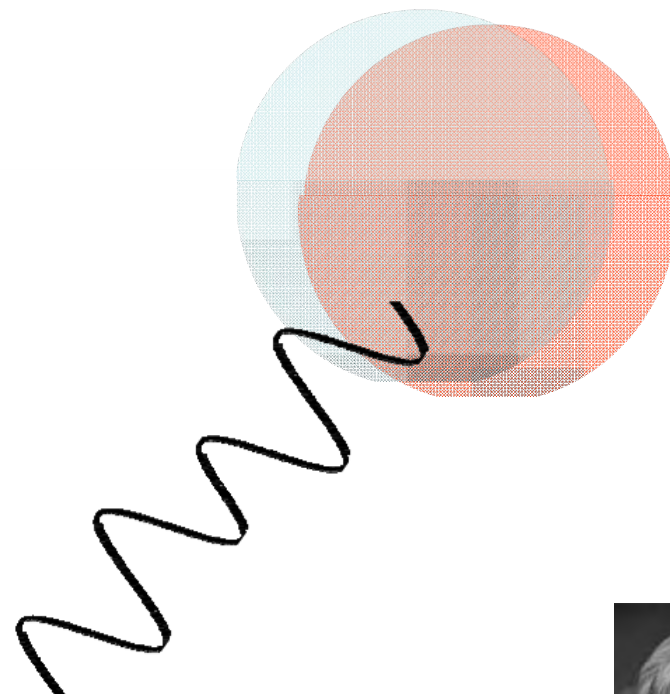
pump depletion length

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

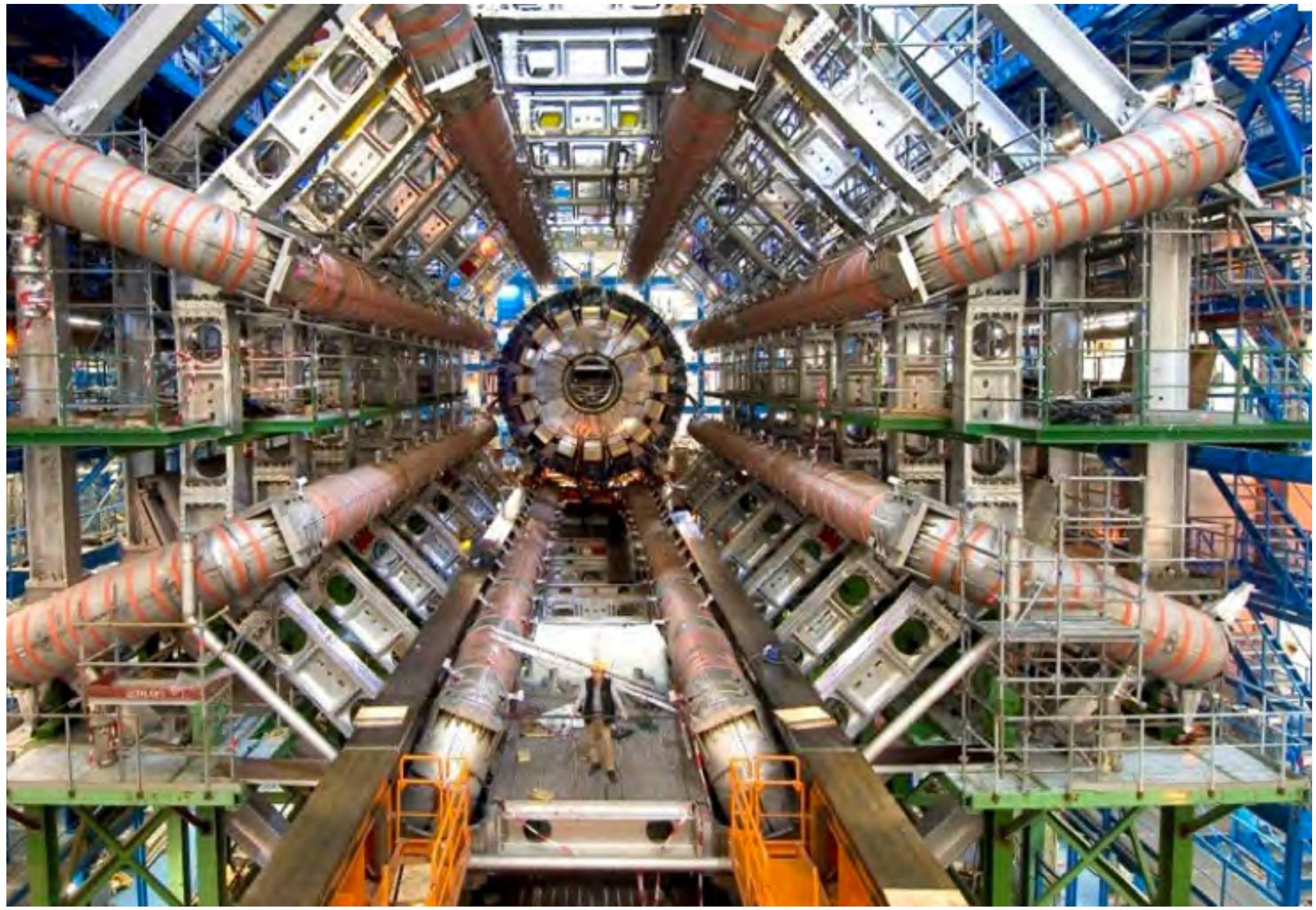
High Energy Physic (and intense laser)

Supporters: s. a.

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

Fermilab

CERN



Rolph Heuer
CERN then-Director General

ELI (2010), now Mega Project 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
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/