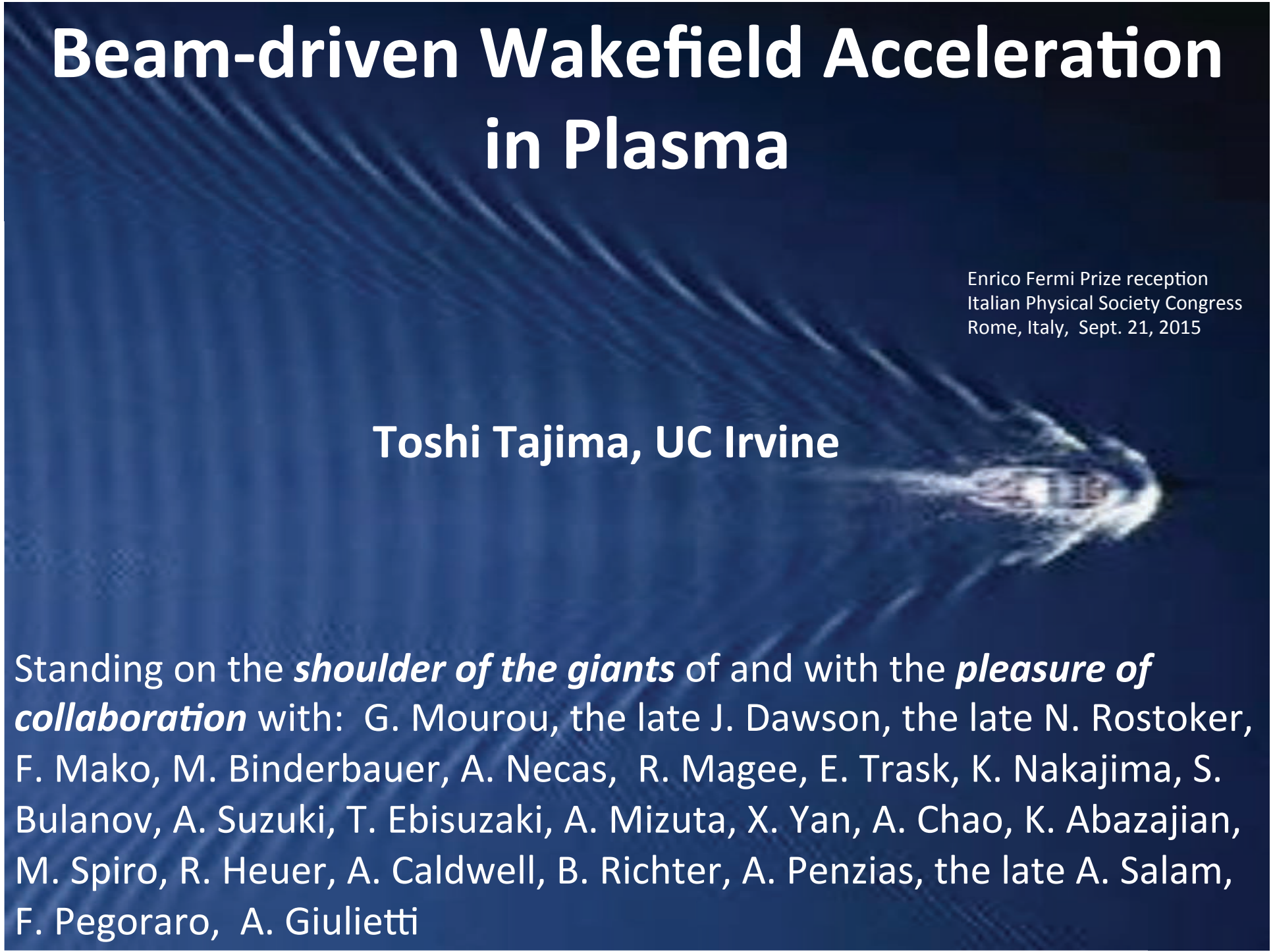


Beam-driven Wakefield Acceleration in Plasma



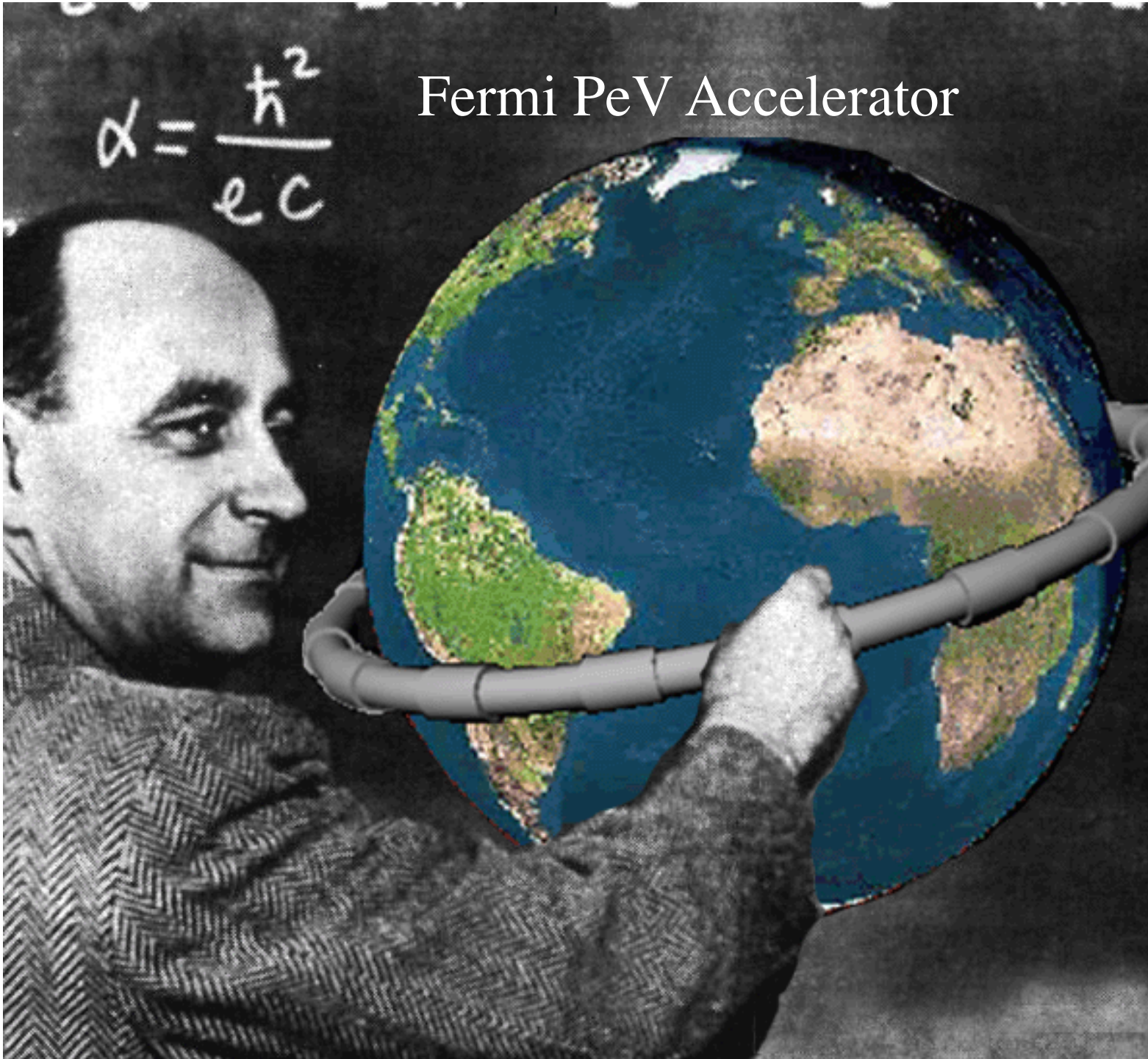
Enrico Fermi Prize reception
Italian Physical Society Congress
Rome, Italy, Sept. 21, 2015

Toshi Tajima, UC Irvine

Standing on the *shoulder of the giants* of and with the *pleasure of collaboration* with: G. Mourou, the late J. Dawson, the late N. Rostoker, F. Mako, M. Binderbauer, A. Necas, R. Magee, E. Trask, K. Nakajima, S. Bulanov, A. Suzuki, T. Ebisuzaki, A. Mizuta, X. Yan, A. Chao, K. Abazajian, M. Spiro, R. Heuer, A. Caldwell, B. Richter, A. Penzias, the late A. Salam, F. Pegoraro, A. Giulietti

$$\alpha = \frac{\hbar^2}{e c}$$

Fermi PeV Accelerator

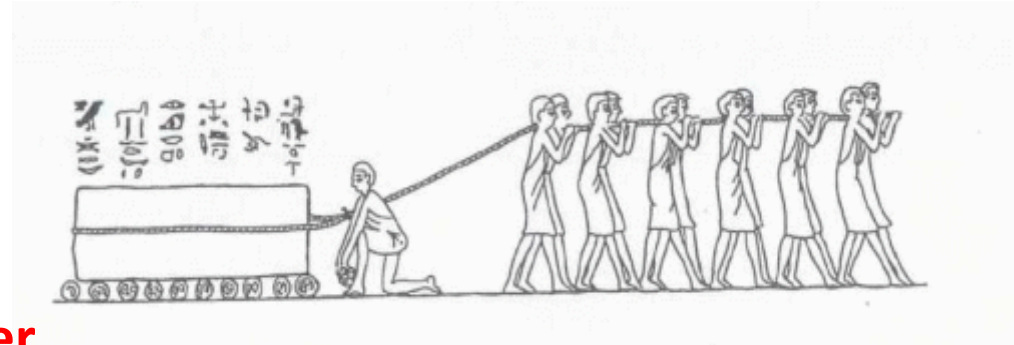


Alpha is the artist's equation, not Fermi's.

Plasma accelerator driven by beam

Collective force $\sim N^2$ ($\leftarrow$ linear force $\sim N$)

Coherent and smooth structure



- Plasma accelerator driven by **laser**

$\leftarrow$ [**Fermi**'s challenge for PeV accelerator]

compactification by $10^3 - 10^4$ (even by 10^6) over conventional accelerators
enabled by **laser** technology (intense ultrafast **laser** compression)

- Cosmic manifestation of **laser wakefield** acceleration

$\leftarrow$ [beyond the applicability of **Fermi**'s Stochastic Acceleration]

AGN (active galactic nuclei) disk-jet system:

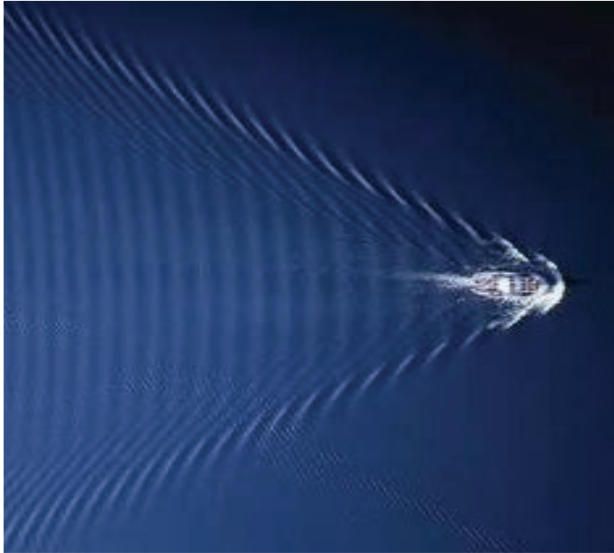
nature's preferred **wakefield** accelerators; telltale signature phenomena observed

- Beam-driven **wakes** in plasma enhance fusion reactions

$\leftarrow$ [from **Fermi**'s neutron-driven fission reaction (the Chicago pile) to beam-plasma wake enhancement of fusion reaction]

Laser Wakefield (LWFA):

Wake phase velocity $\gg$ water movement speed
maintains **coherent** and **smooth** structure



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

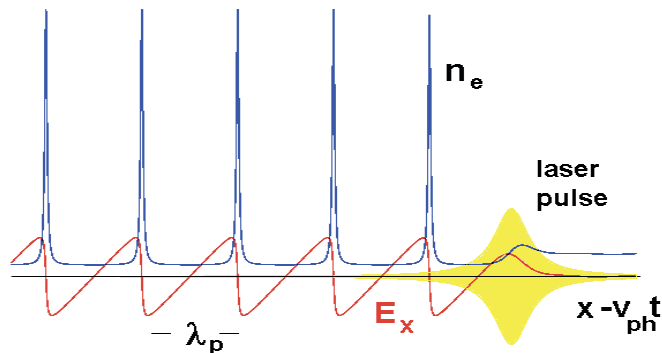


VS

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

No wave breaks and wake **peaks** at $v \approx c$

Wave **breaks** at $v < c$

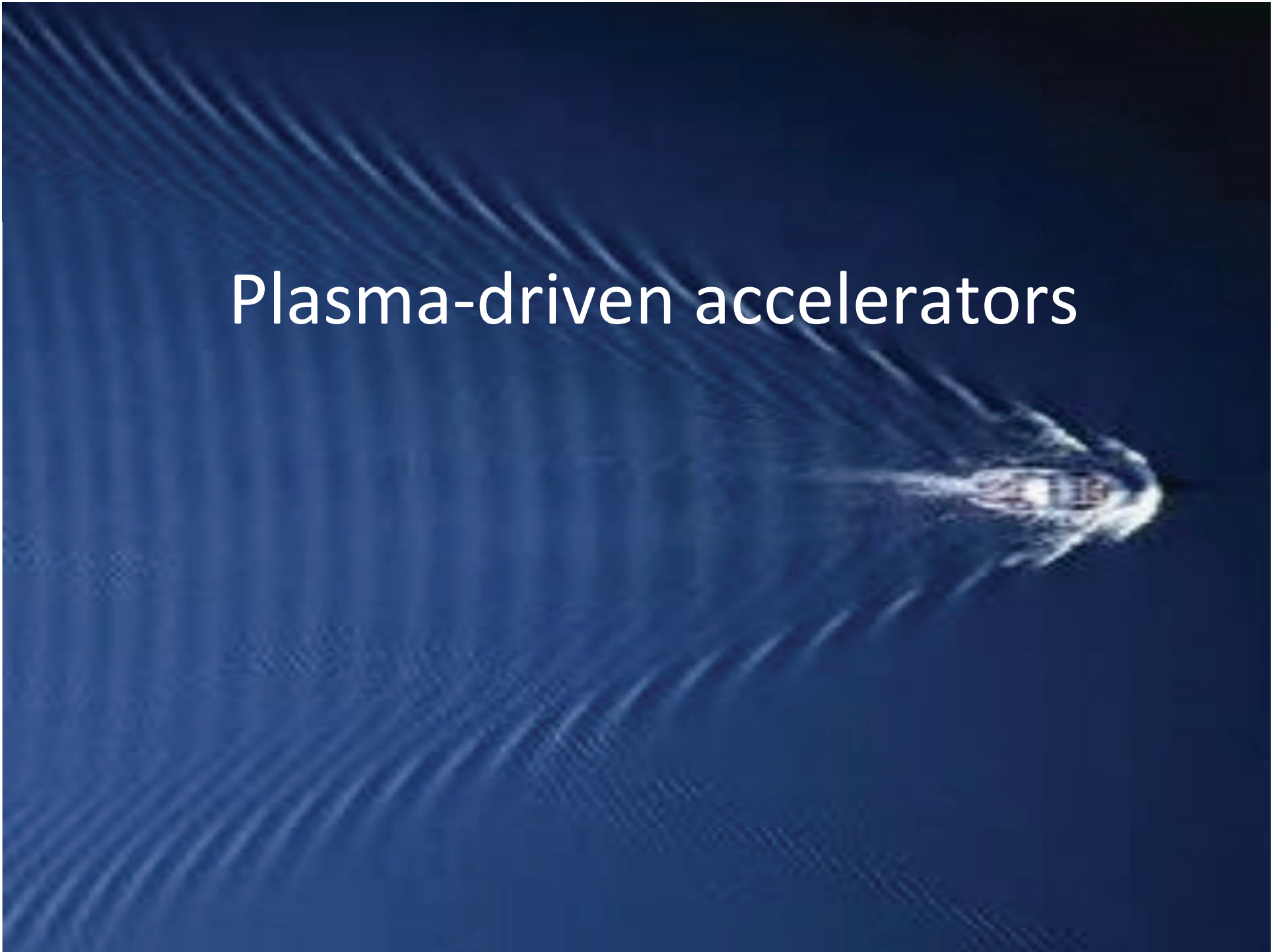


← relativity
regularizes
(*relativistic coherence*)



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

Plasma-driven accelerators



Acceleration by plasma **wake** waves: History



V. Veksler

Collective acceleration suggested:

Veksler (1956, CERN)

Driven by electron beam

(ion energy) $\sim (M/m)(\text{electron energy})$

Many experimental attempts of plasma acceleration (~60's - '70s, Rostoker's lab UCI included)

led to no such amplification

(ion energy) $\sim (2\alpha+1)x(\text{electron})$ | **Mako-Tajima (UCI) analysis** (1978;1984)

sudden acceleration, ions untrapped,

electrons return, while some run away

→ #1 **gradual acceleration necessary**

→ **Tajima-Dawson (1979, UCLA) wakefield**

#2 **electron acceleration** possible

with **trapping** (with the Tajima-

Dawson field) with **laser**, **more tolerant** for

sudden process



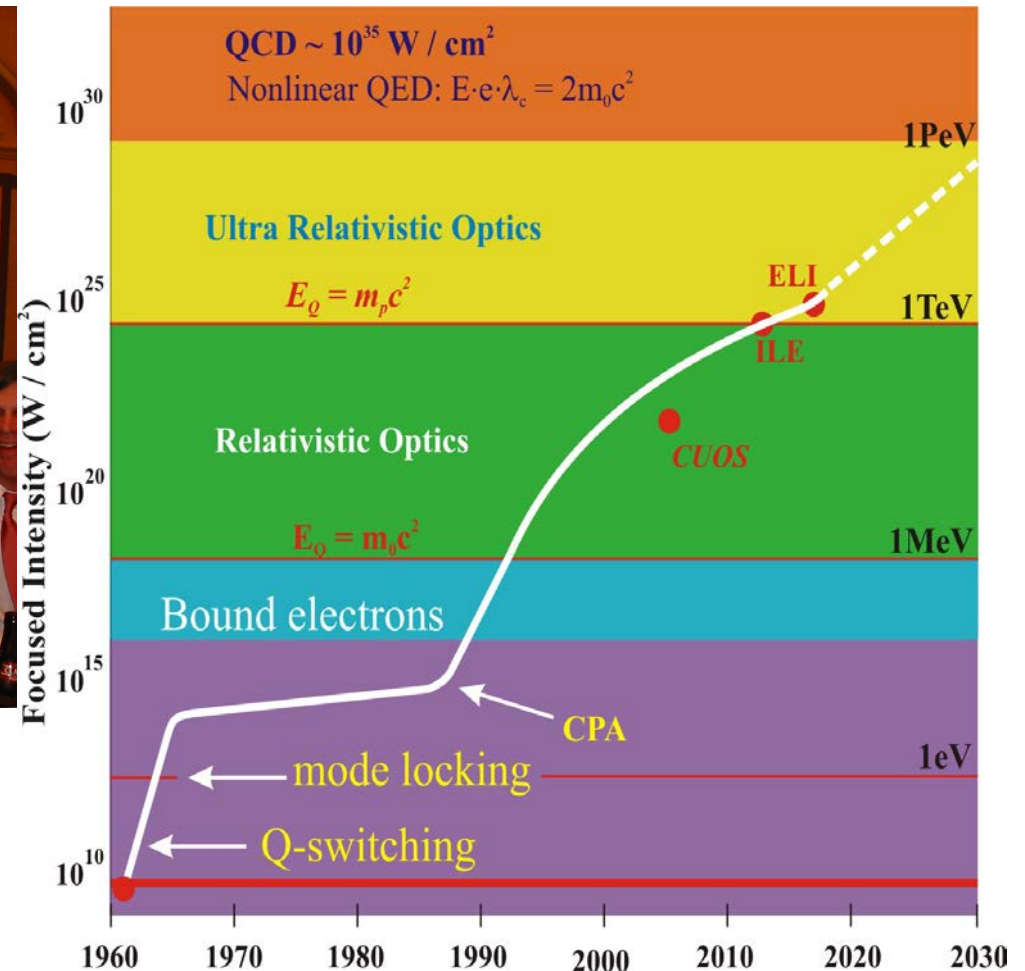
J. Dawson

Target Normal Sheath Acceleration

laser-driven ion acceleration (LLNL,2000)

sudden acceleration, ions untrapped

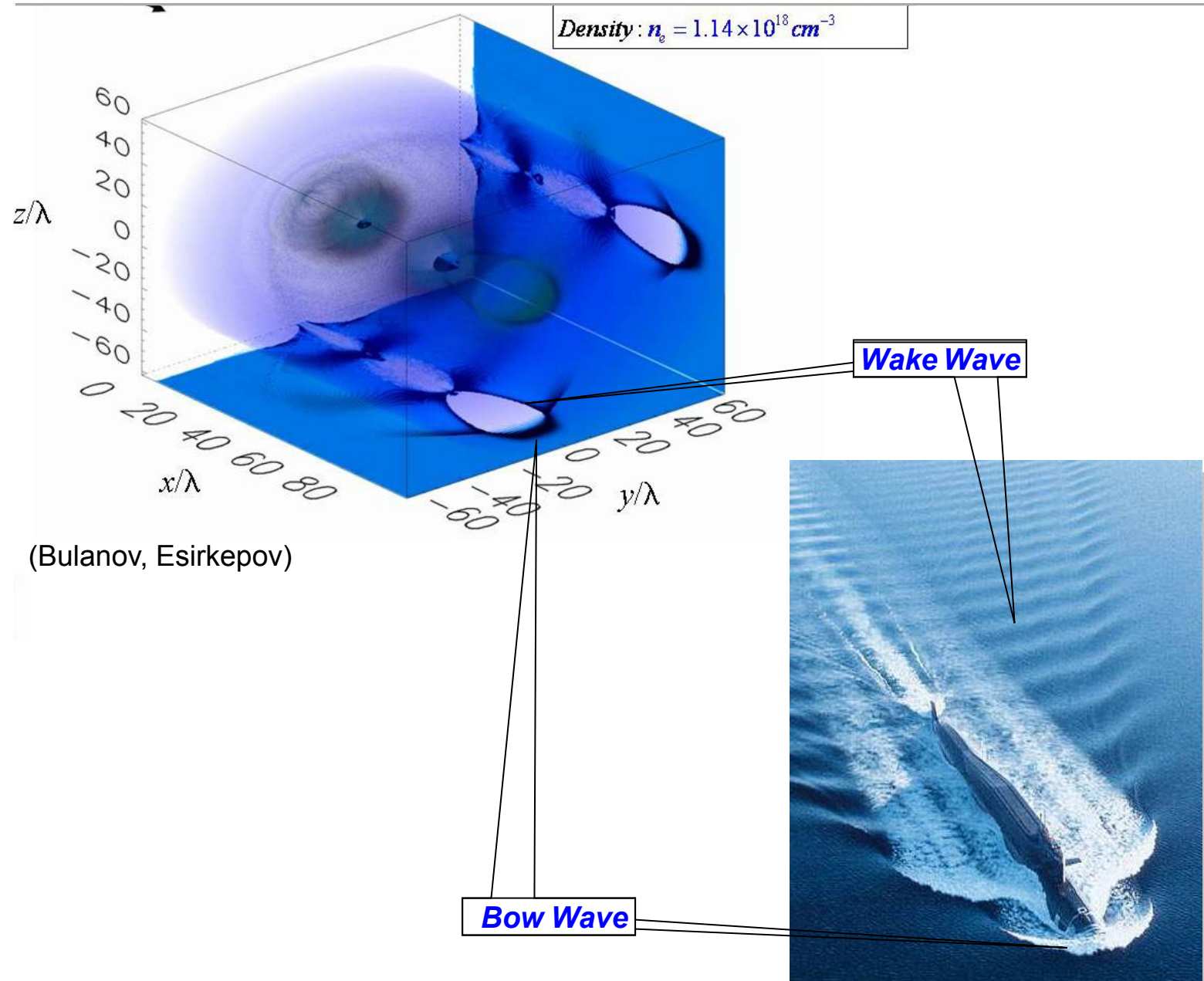
Enabling technology: **laser** revolution



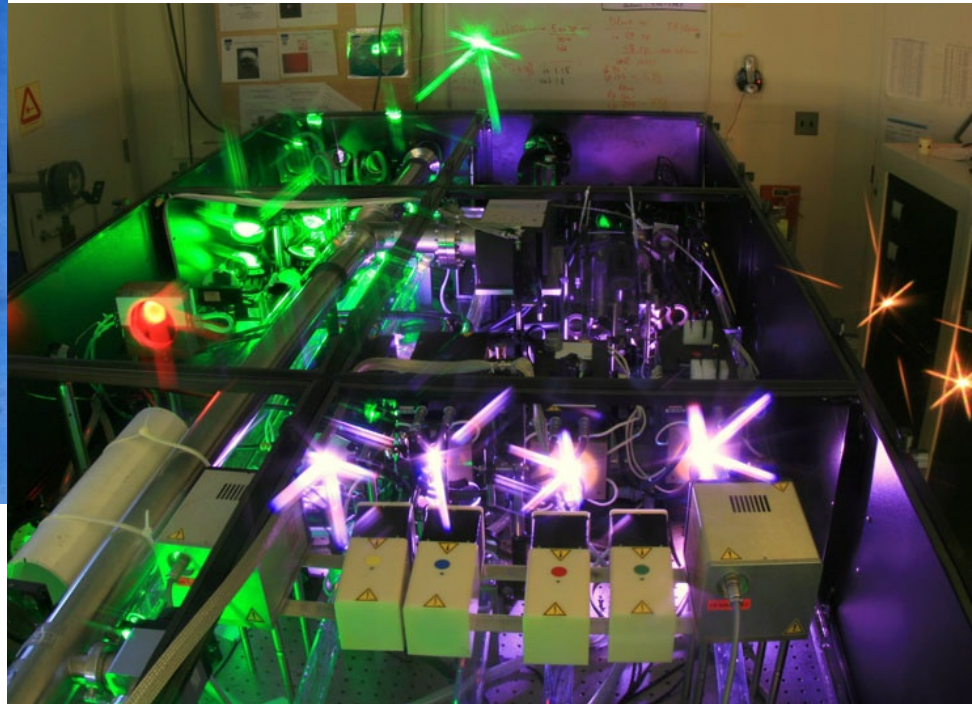
G. Mourou invented **Chirped Pulse Amplification** (1985)

Laser intensity exponentiated since,
to match the required intensity for Tajima-Dawson's **LWFA** (1979)

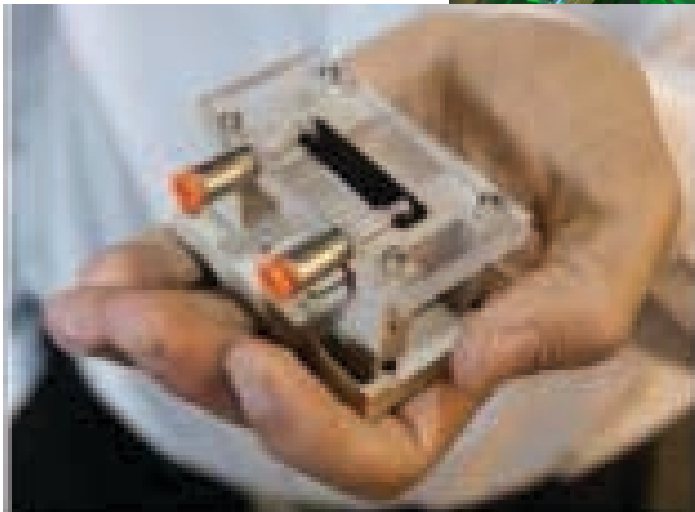
Laser-driven Bow and Wake



Demonstration, realization, and applications of **laser wakefield** accelerators



(Michigan)



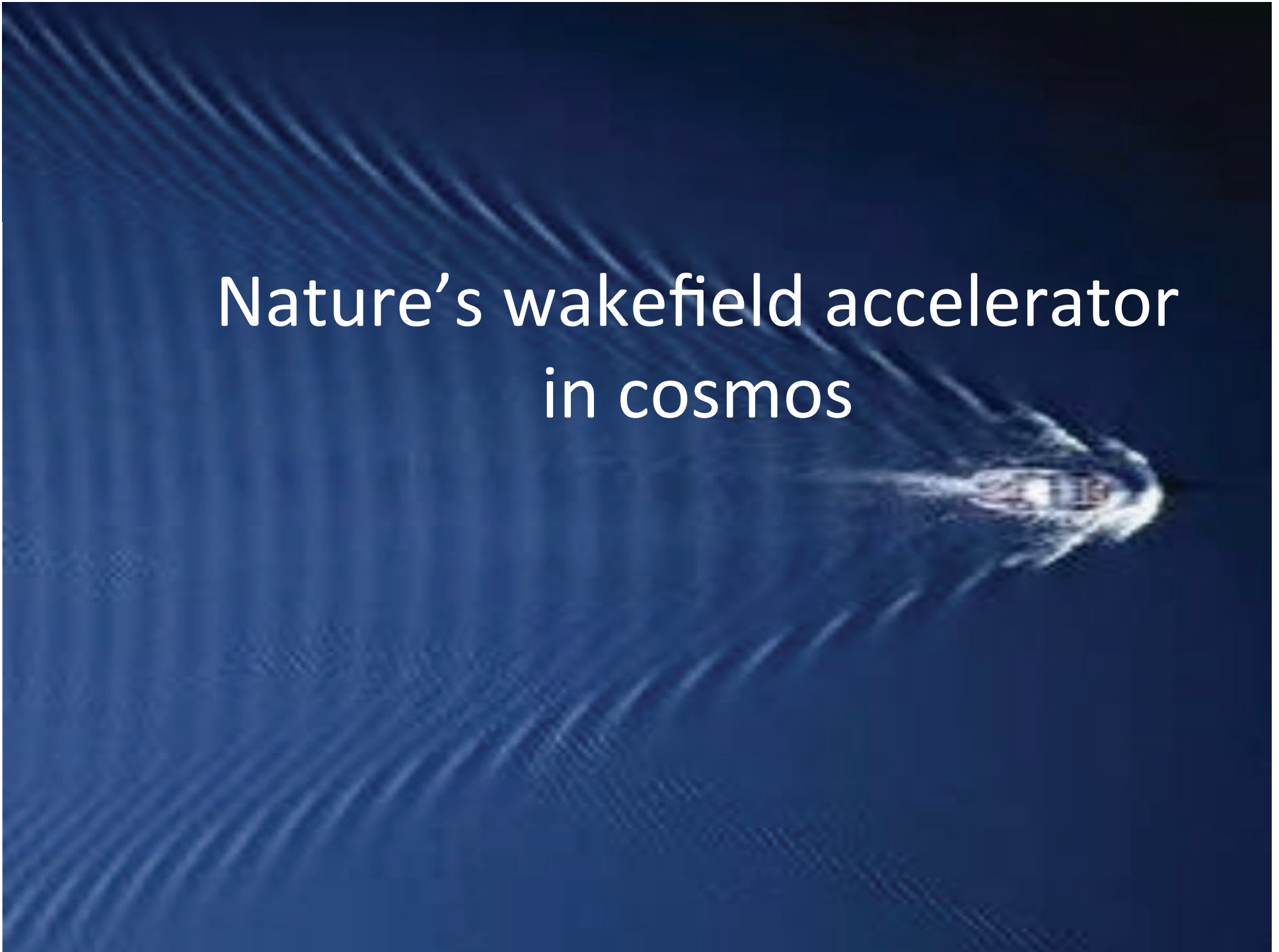
4 GeV **laser accelerator** LBL



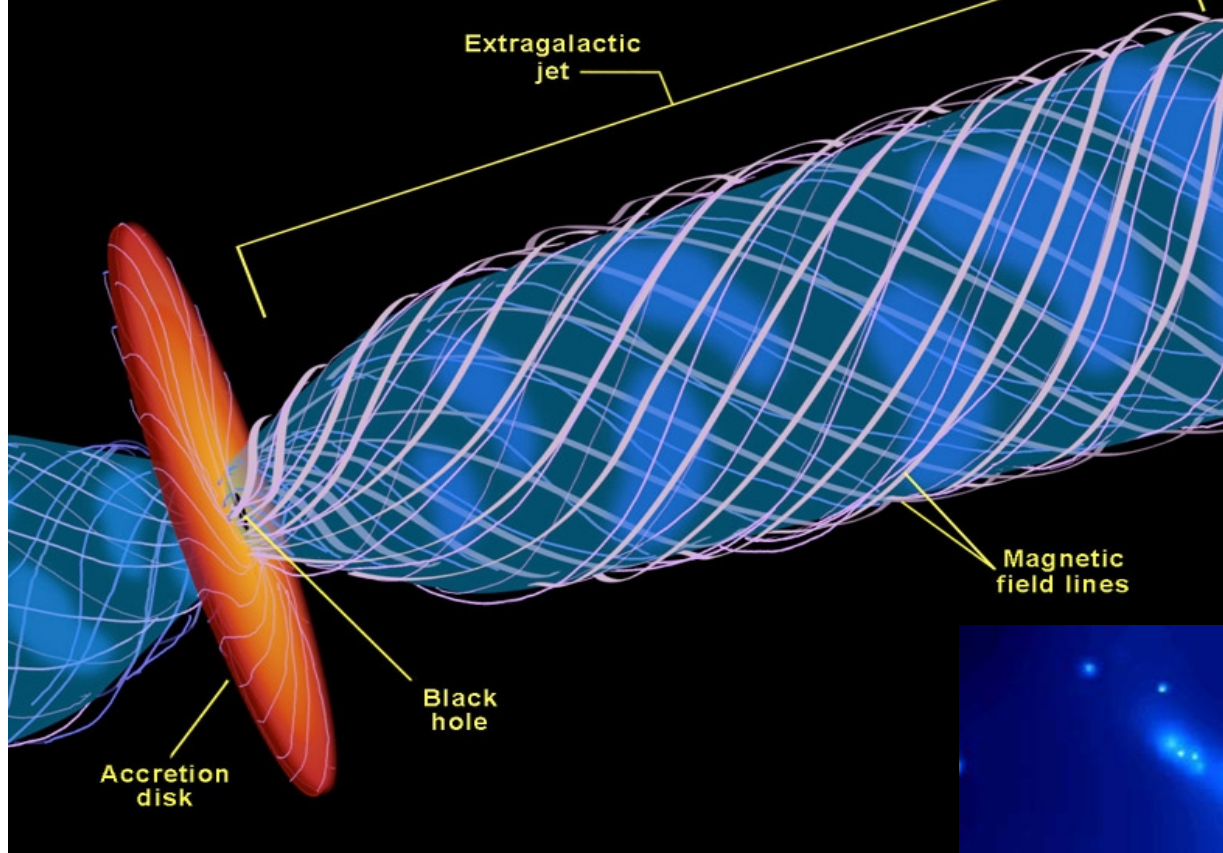
3 GeV Synchrotron SOLEIL



Nature's wakefield accelerator in cosmos



Formation of extragalactic jets from black hole accretion disk



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



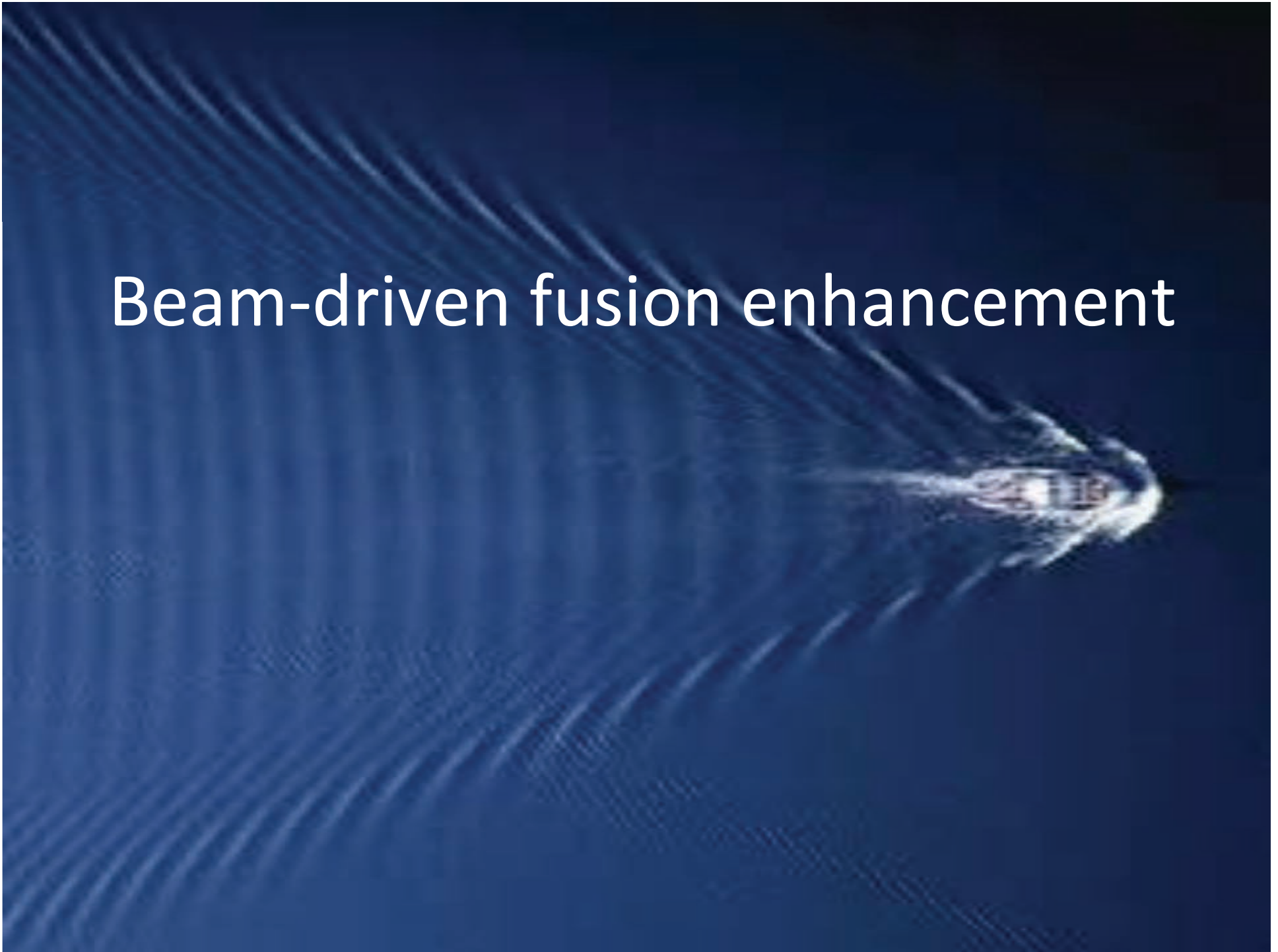
Coherent **wakefield** acceleration
(no limitation of the energy)

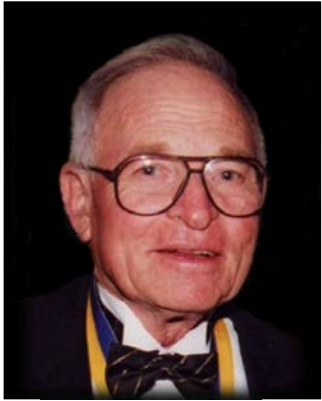
Nature's **LWFA** : Blazar jets

extreme high energy cosmic rays ($\sim 10^{21}$ eV)
episodic γ -ray bursts observed
consistent with **LWFA** theory



Beam-driven fusion enhancement

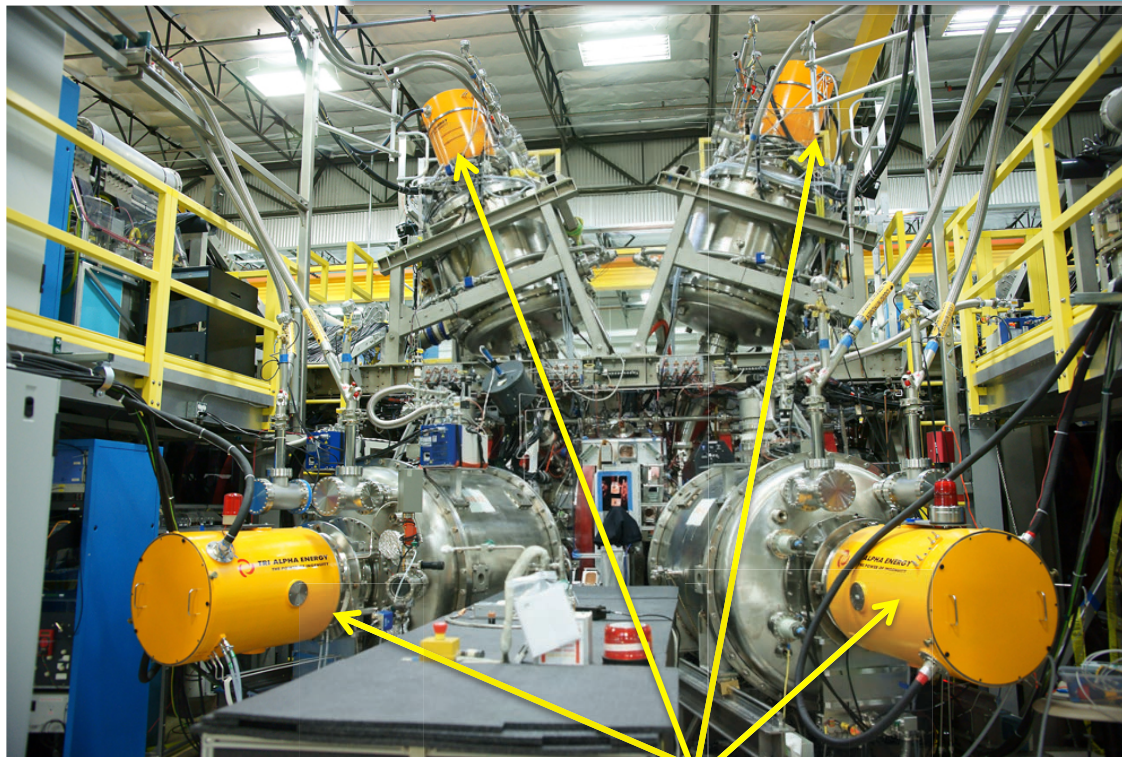




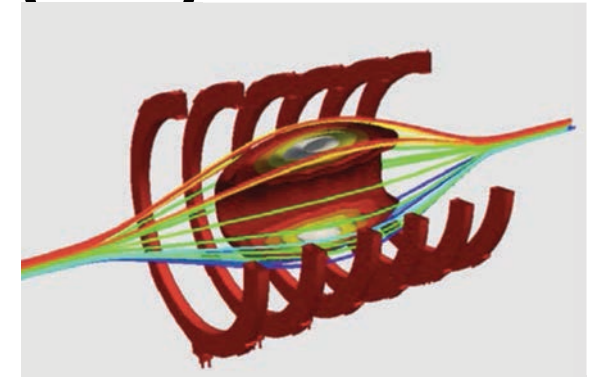
N. Rostoker

Beam-driven fusion plasma (FRC)

TAE's machine + beams



Beams



FRC plasma + coils

6 beam systems
15 keV
10+ MW
20 degree angle
Operate with:

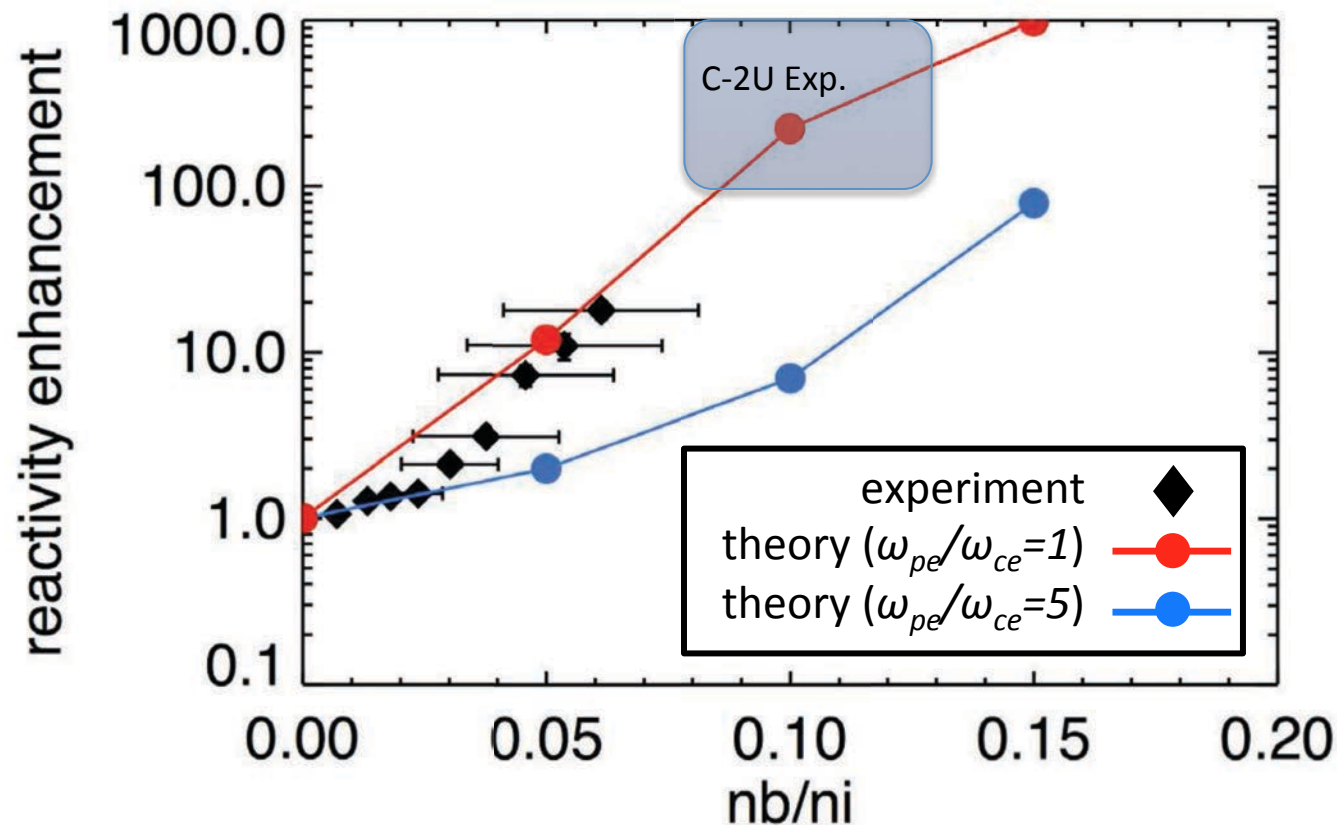
- Hydrogen beam – H
- Deuterium plasma – D

Fermi's Chicago pile

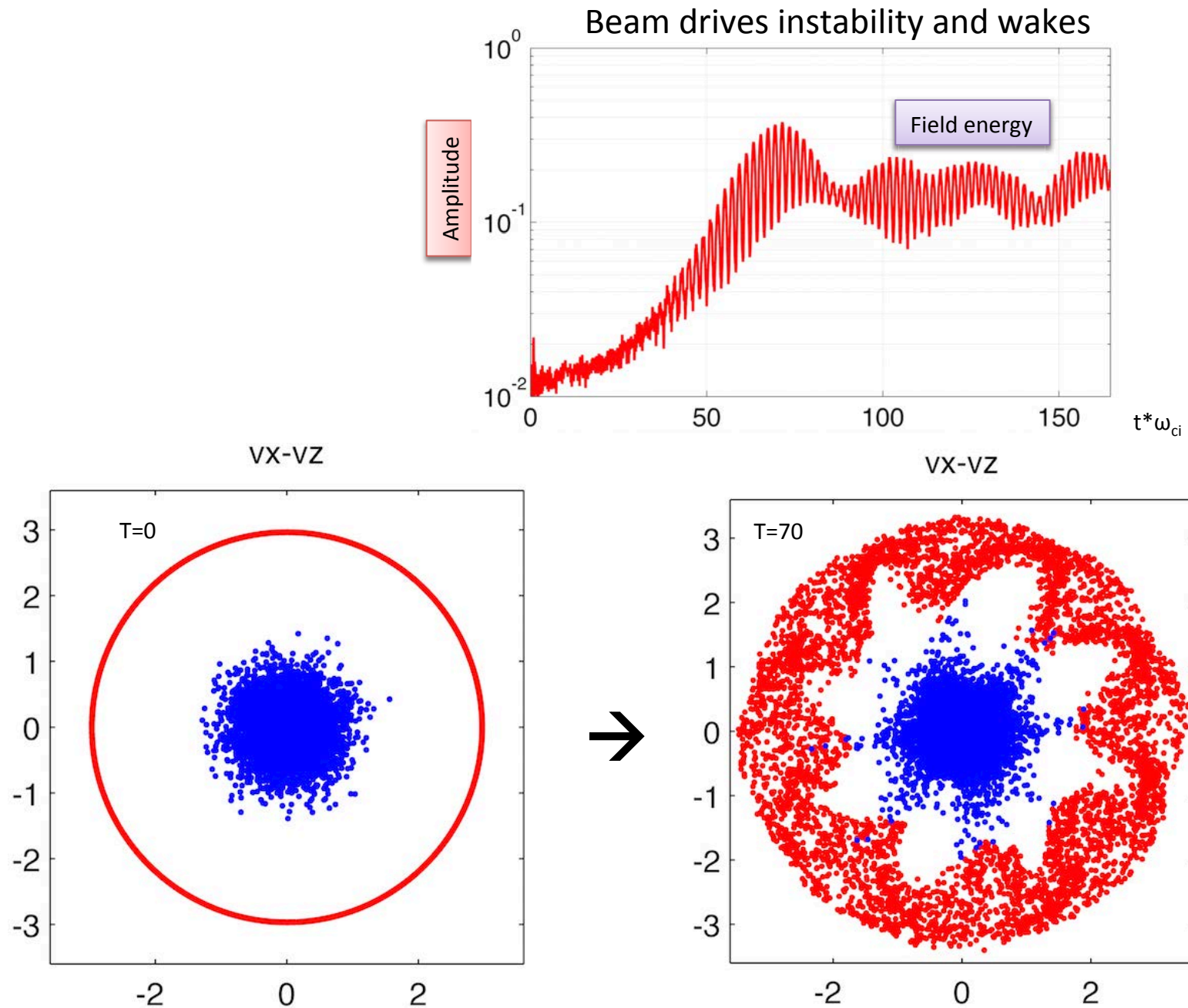


D-D fusion enhanced by 100-1000 times driven by H-beam in TAE fusion plasma :

- ❑ TAE hydrogen beam-driven FRC deuteron plasma: fusion reactivity enhanced by 100 -1000 over thermonuclear expected value, when beam is sufficiently strong
- ❑ Beam-driven plasma wakes can enhance fusion



Beam drives small plasma **tails** → fusion **enhancement**



(computation by A. Necas)

Conclusions

- Demonstrated: Using ultrafast pulses (of **laser** or particle beams), coherent collective (robust) **wakefield** (GeV/cm) excitable
- Applications: ultrafast radiolysis, intraoperative electron therapy, compact **X-ray** sources/**XFEL**,....
- **Wakefield** acceleration: Nature's natural accelerators to EHECR, **gamma ray** bursts
- Beam-driven **wakes** in FRC: enhance fusion reactivity

Grazie!