A Journey: from Wakefields to Astrophysics and Fusion

Toshi Tajima
UC Irvine

Symposium
University of California, Irvine
Jan. 25, 2018

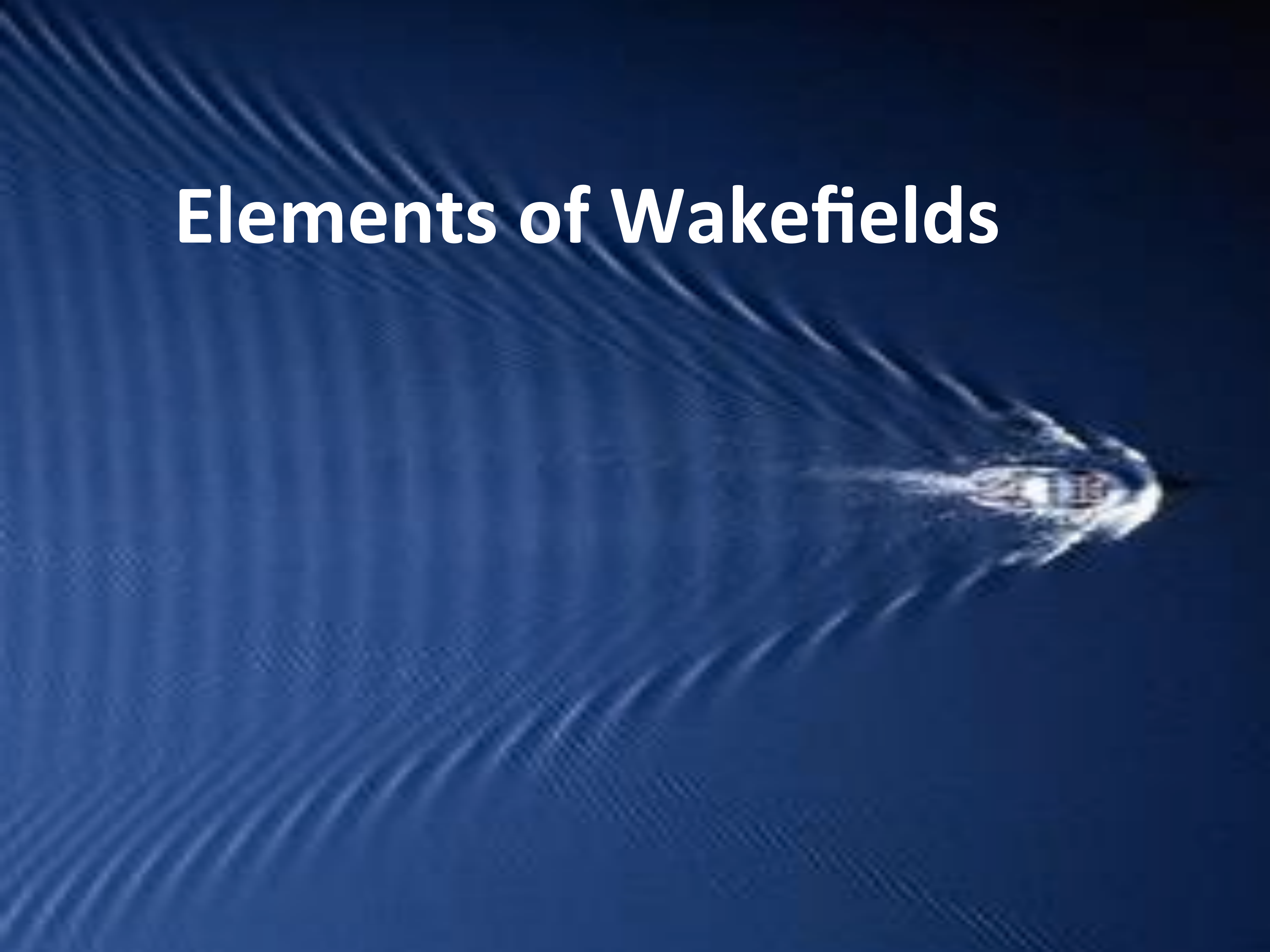
abstract

1. Wakefield: robustly elevated energy state, relativistic coherence, Higgs' state of plasma ←→Field Reversed Configuration: robustly elevated energy state (elevation → Landau-Ginzburg-like potential)

2. Nature prevarently creates wakefields: AGN accretion disk and jets
   Fermi acceleration → Wakefields
3. Gamma-ray bursts (Blazars): signature of wakefields
4. Gamma-ray bursts: sometimes accompanied by GW

5. New technology thin film compression (TFC) →
   Leading to a new innovation X-ray LWFA
6. "TeV on a chip" (X-ray LWFA); coherent γ-ray laser; new
   zeptosecond science; medical (and other compact) accelerators

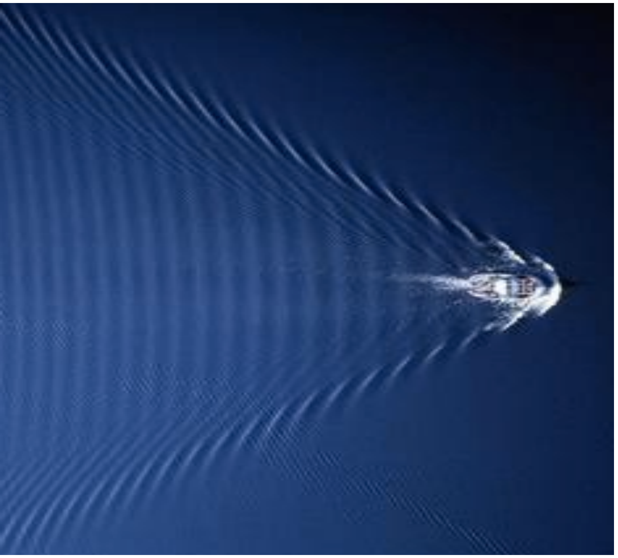
Elements of Wakefields



Laser Wakefield (LWFA):

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

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

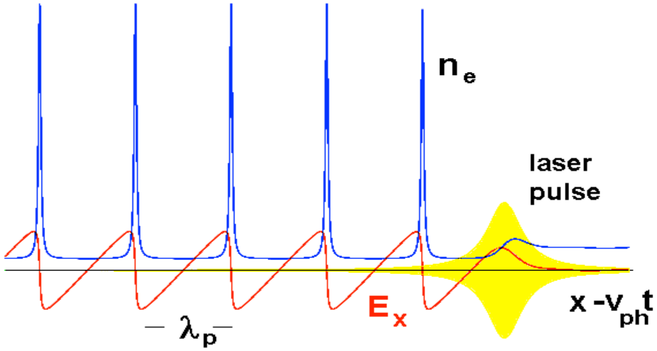


vs

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*)

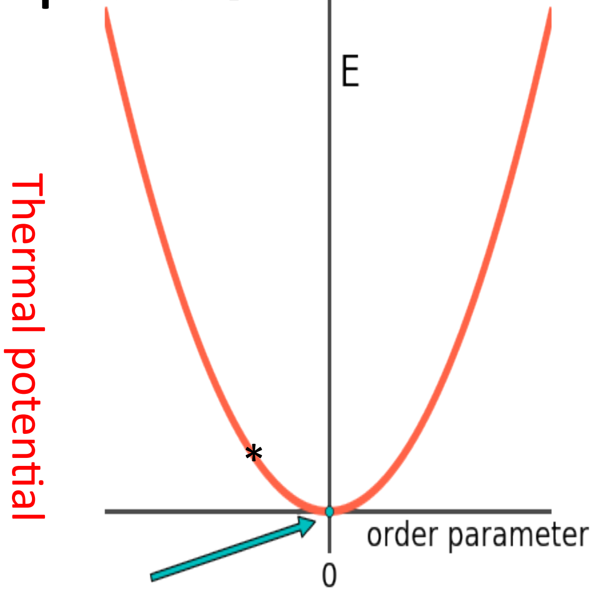
Relativistic coherence enhances beyond the Tajima-Dawson field $E = m\omega_p c /e$ (~ GeV/cm)

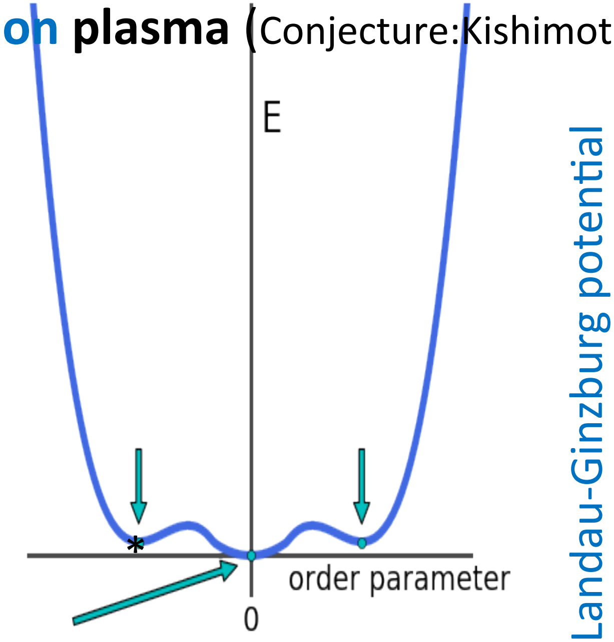
Thermal plasma vs. Wakefields and Higgs

Trivial vacuum vs. Laundau-Ginzburg potential → BCS → Nambu → Higgs vacuum

Thermal plasma and Landau damping → wakefields , plasma with elevated energy

Thermal plasma → Field Reversed Configuration plasma (Conjecture:Kishimoto et al. 2018)





[**Landau damping**: decay of excited waves to equilibrium (left picture)]

Wakefield: no damping; distinct excited <u>stable state </u>←no particles to resonate (@ $v = c$)

= plasma's elevated Higgs state

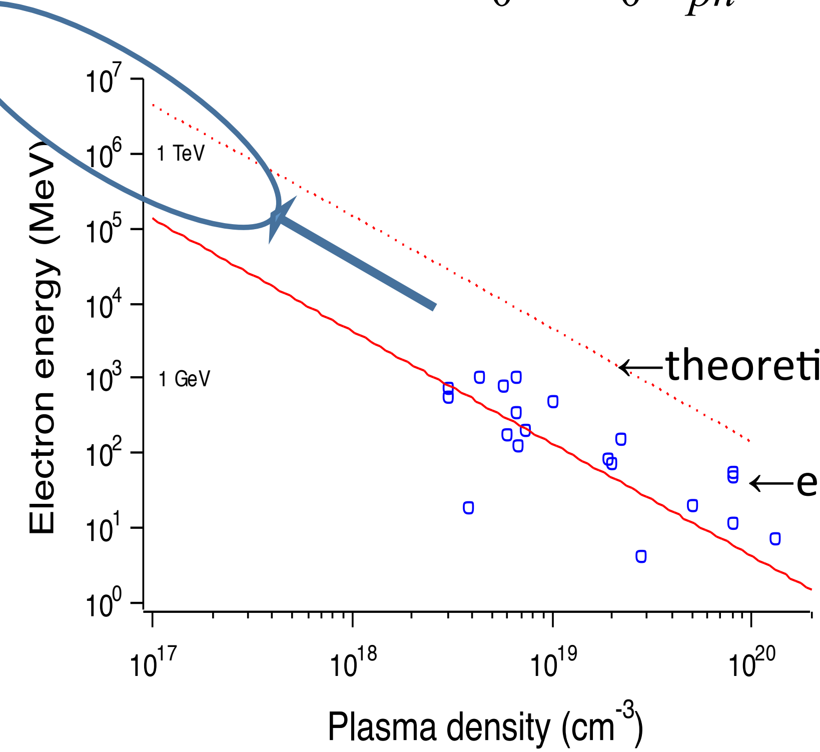
| 0 >   vs. | H >   (cf . | H >   → | 0 >)

thermo-equilibrium   wakefield state   tsunami onshore

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)



←theoretical

←experimental

In order to avoid wavebreak,

$$a_0 < \gamma_{ph}^{1/2},$$

where

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

$n_{cr} = 10^{21}$

$n_e = 10^{16}$

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

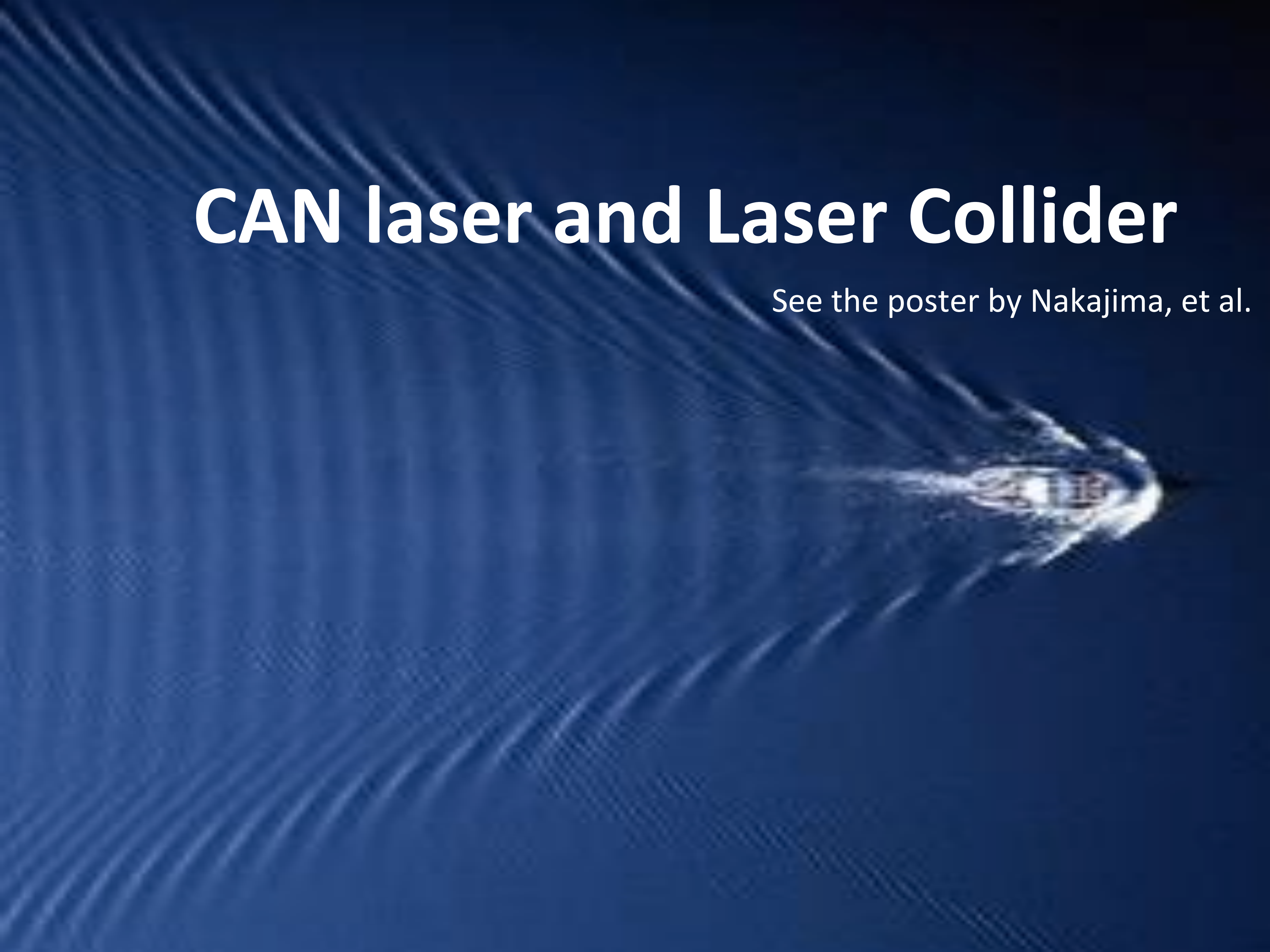
dephasing length

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

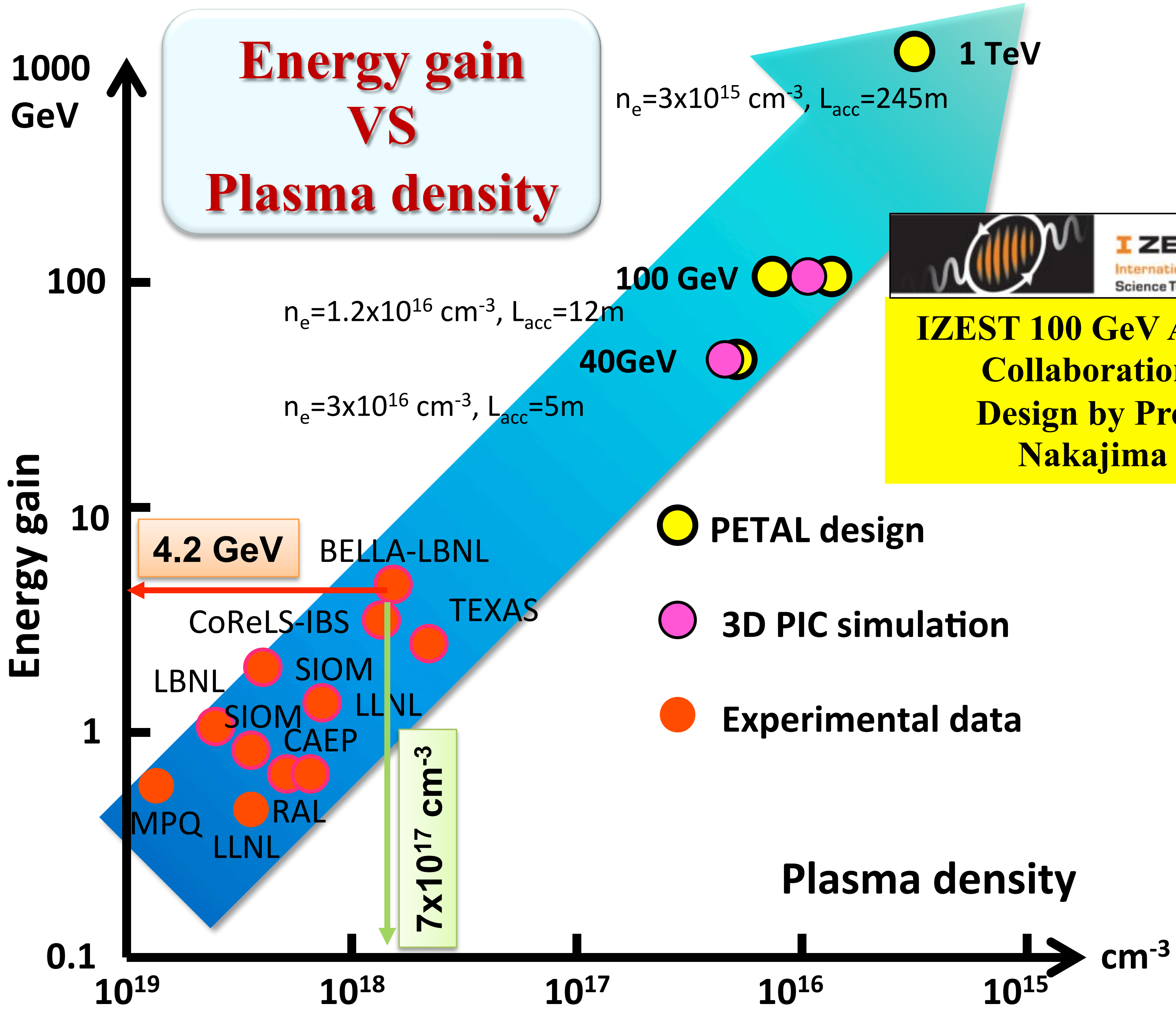
pump depletion length

CAN laser and Laser Collider

See the poster by Nakajima, et al.



Energy gain VS Plasma density



IZEST International Zeta-Exawatt Science Technology

IZEST 100 GeV Ascent Collaboration: Design by Prof. Nakajima

IZEST

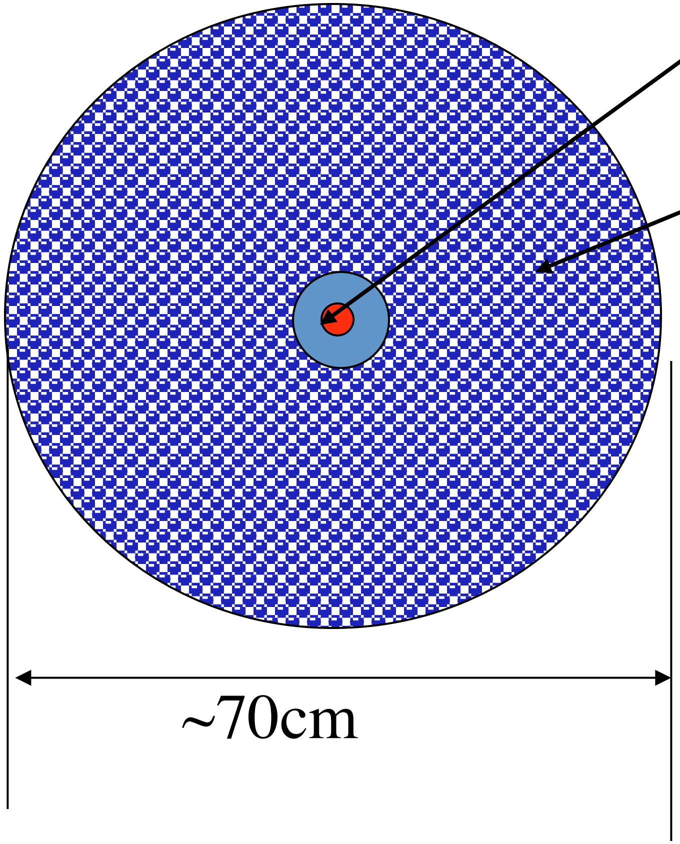
ican
International Coherent
Amplification Network

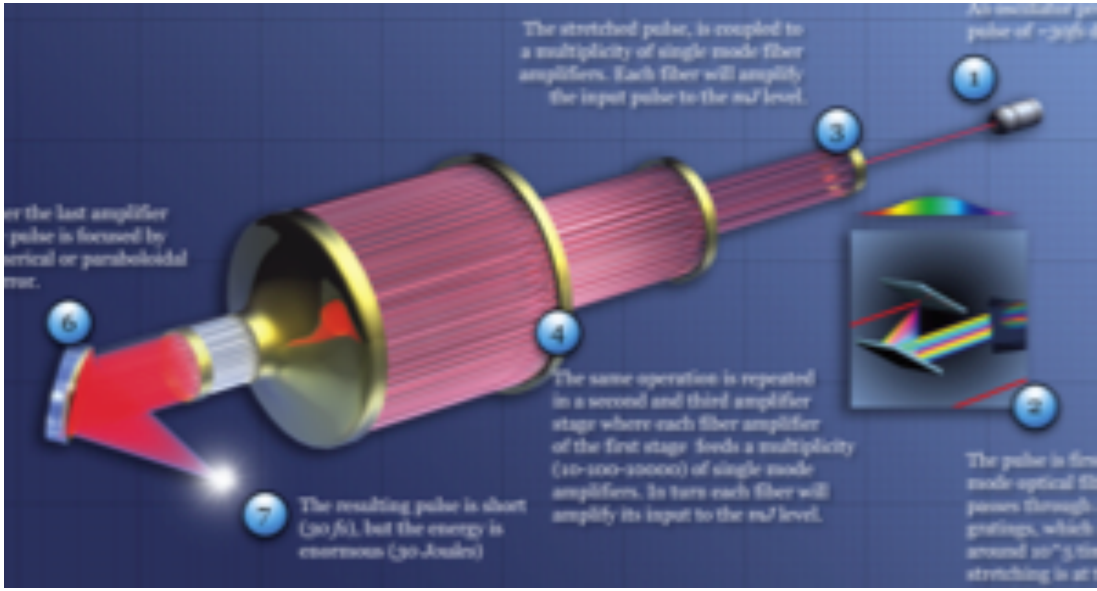
Coherent Amplification Network

Efficient (>30%), high rep rated (~kHz –MHz),
light, digitally controllable

CAN laser makes laser collider possible

See Nakajima et al. poster (2018)

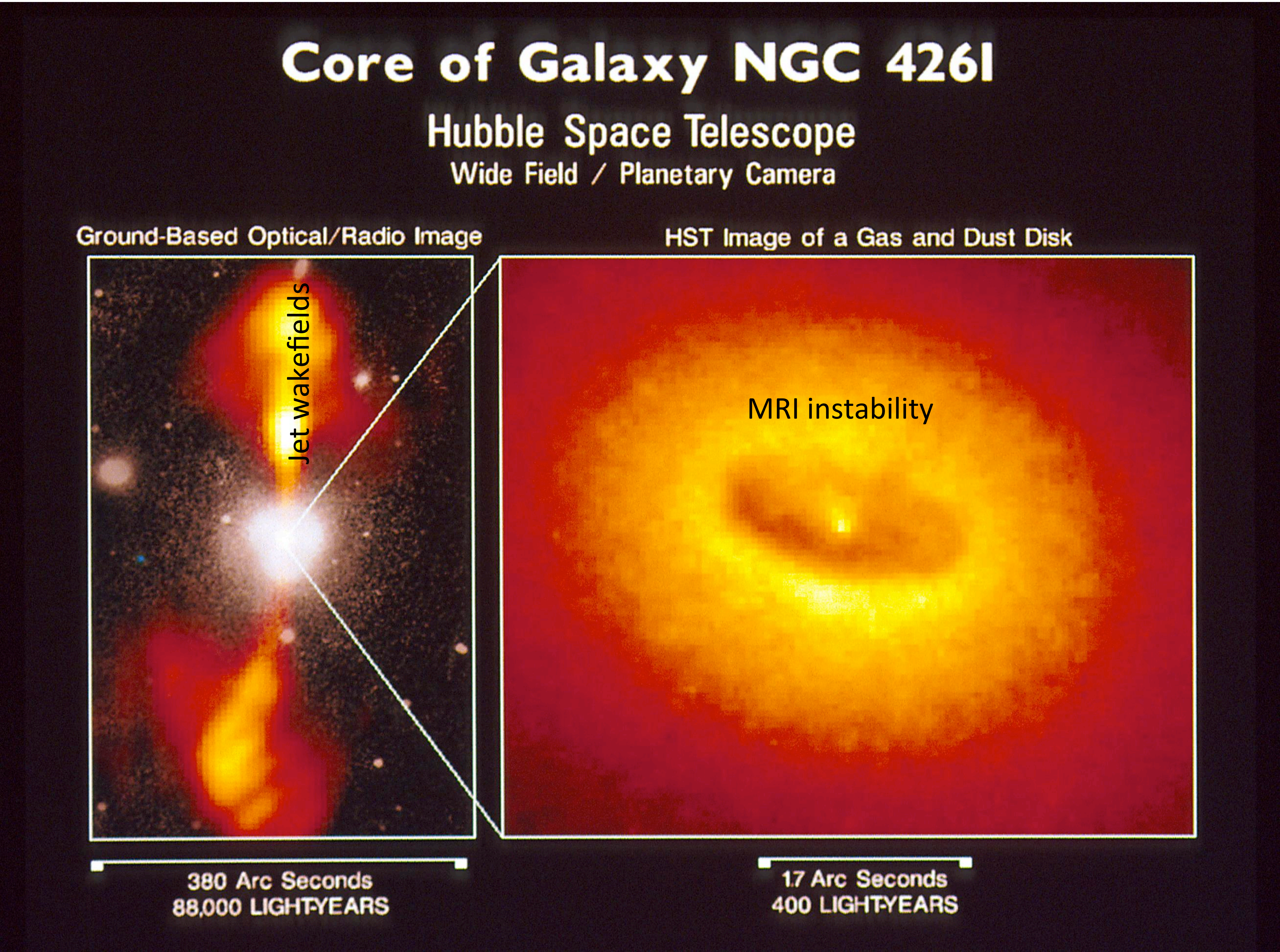


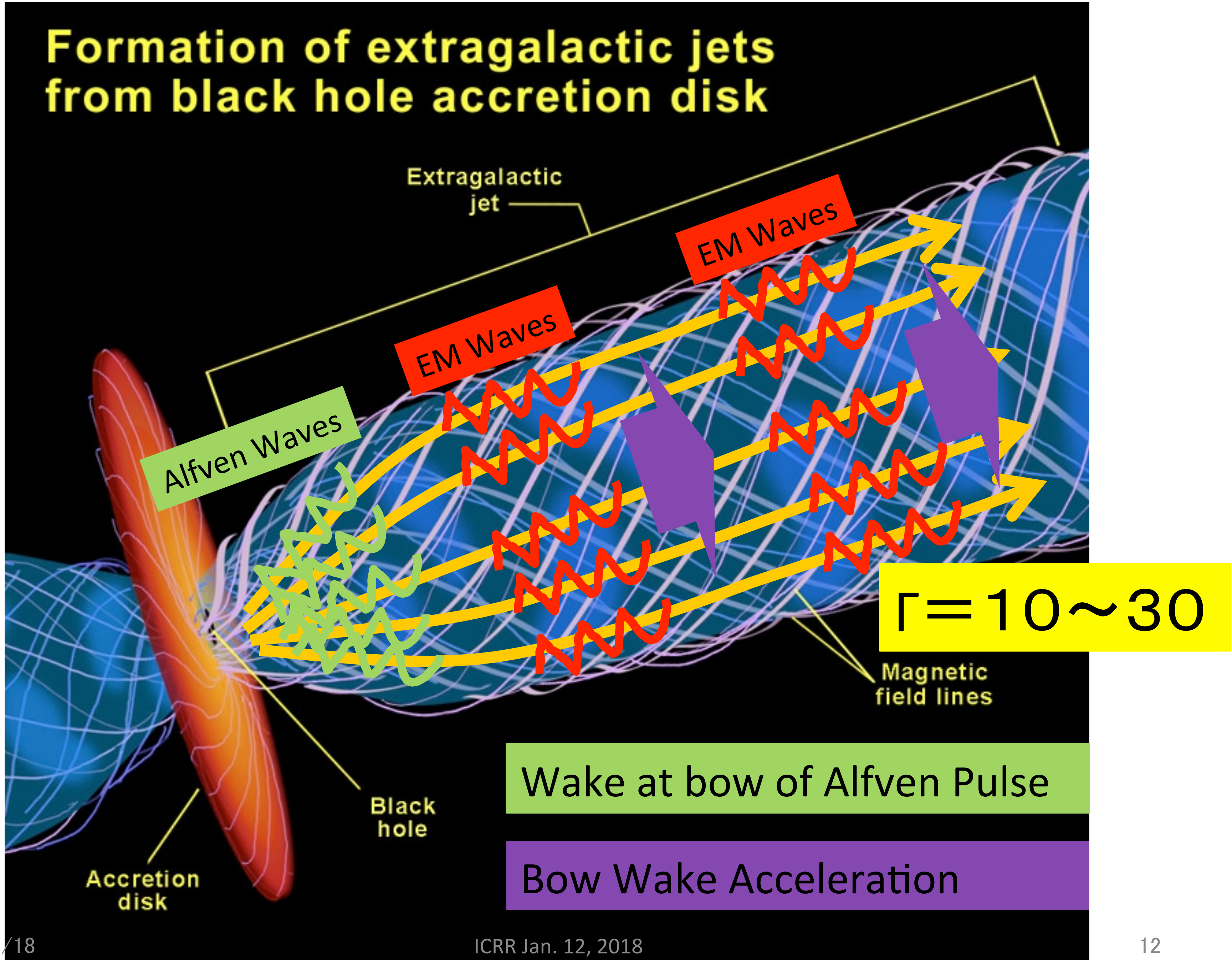


Mourou, Brocklesby, Tajima, Limpert,
Nature Photonics (2013)

Nature’s Natural Wakefields: jet wakfields driven by disk MRI instability

Ebisuzaki et al. Astropart. Phys. (2014)





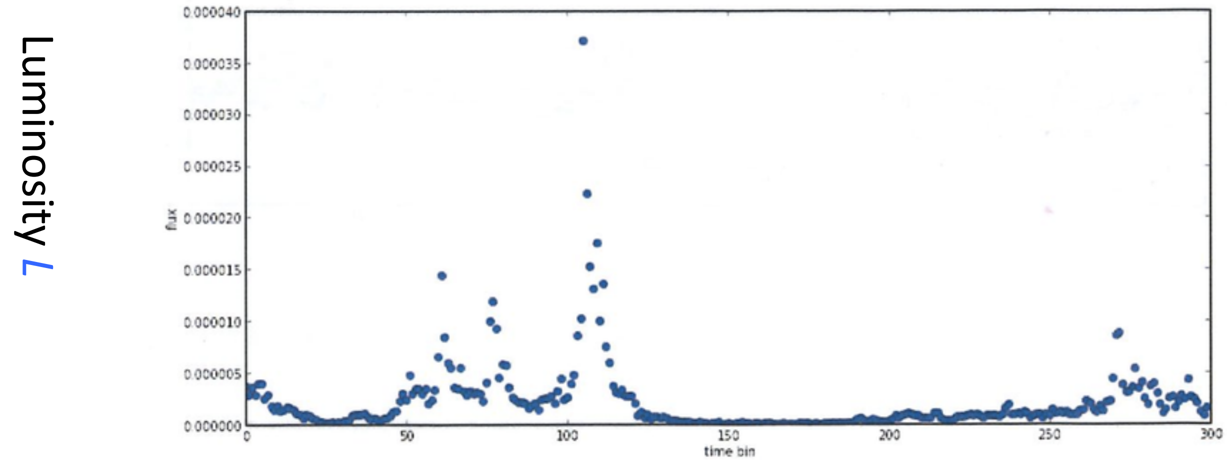
Γ＝10～30

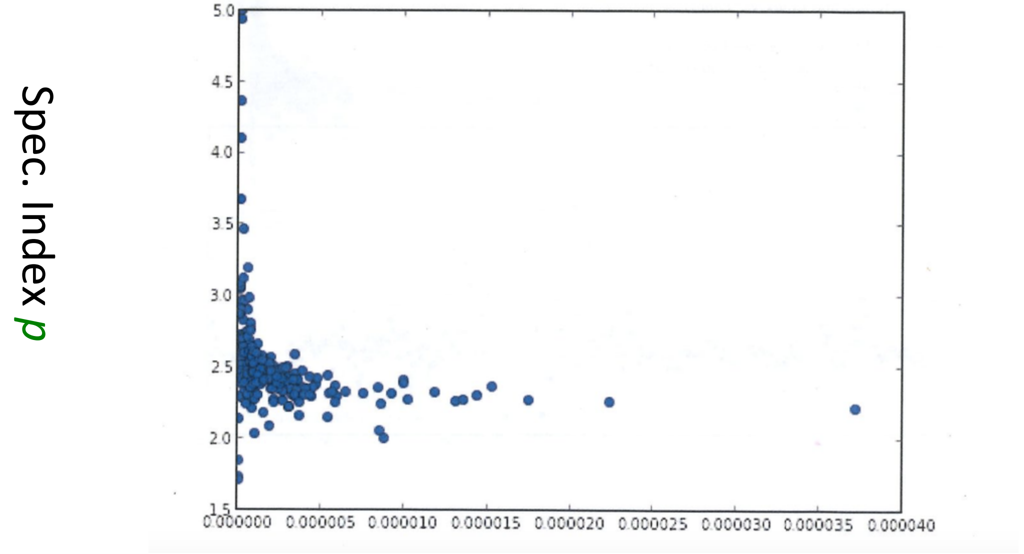
Wake at bow of Alfven Pulse

Bow Wake Acceleration

Luminosity of gamma ray emission and the spectrum AGN 3C454.3 with $M = 10^7 M_\odot$

Strong accretion
→ strong wakefield





Luminosity L

Ideal episode for wakefield:
index $p = 2$,
Otherwise $p > 2$
(Mima et al. 1991; Ebisuzaki et al. 2014)

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

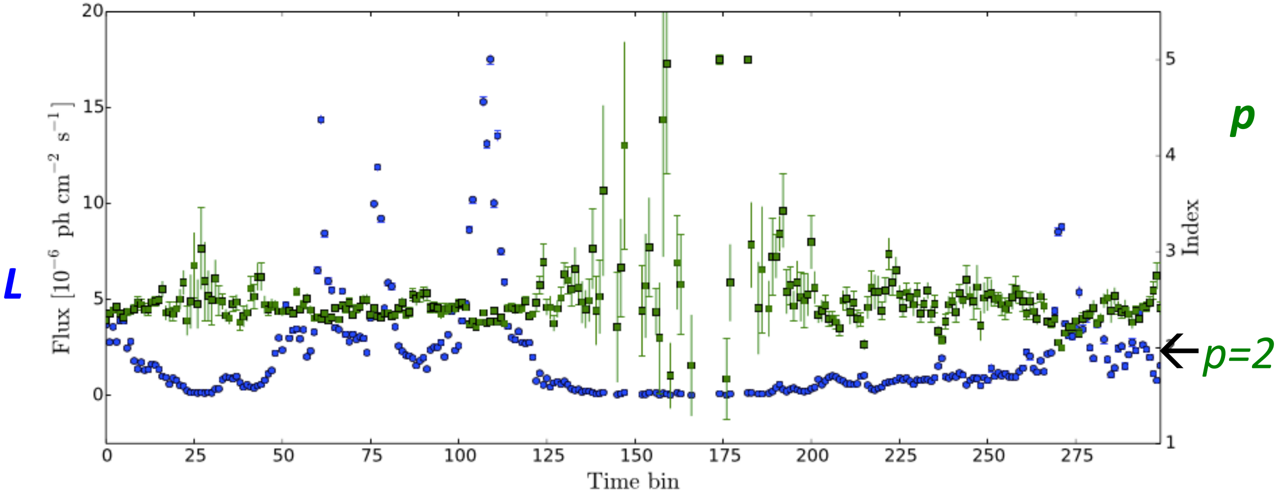
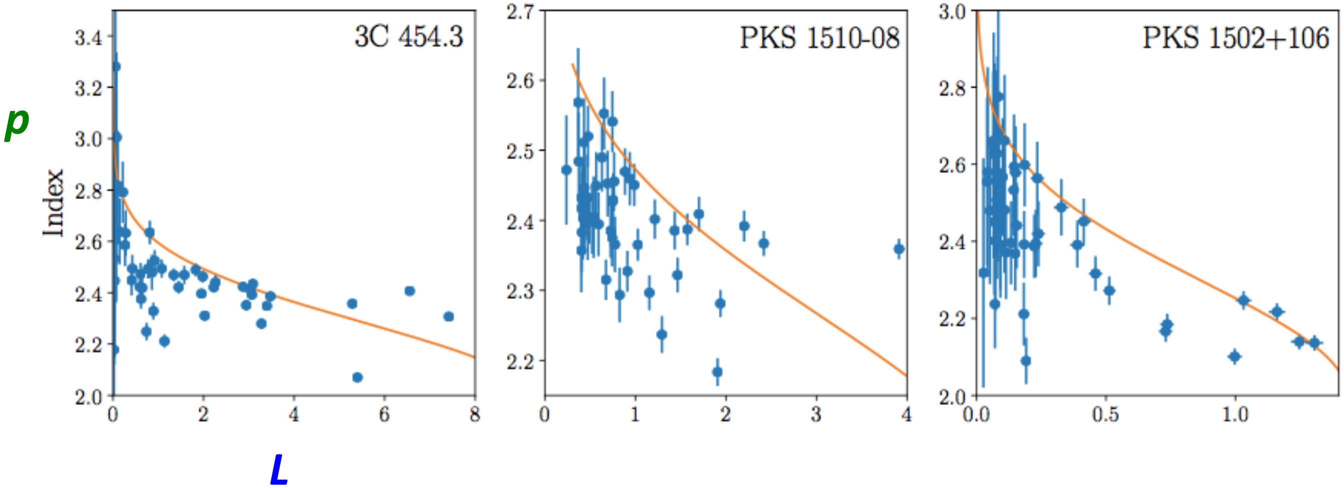


FIG. 2.— Shown are the flux (blue circles, left axis) and spectral index (green squares, right axis) for 3C 454.3 in 300 time bins of 7.9 days duration. An anti-correlation can be seen: the peaks in flux correspond to dips in the spectral index and vice versa.



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

Gravitational wave and Gamma bursts

Fermi satellite x LIGO

- gamma bursts synchronize with GW
- GW precedes gamma bursts

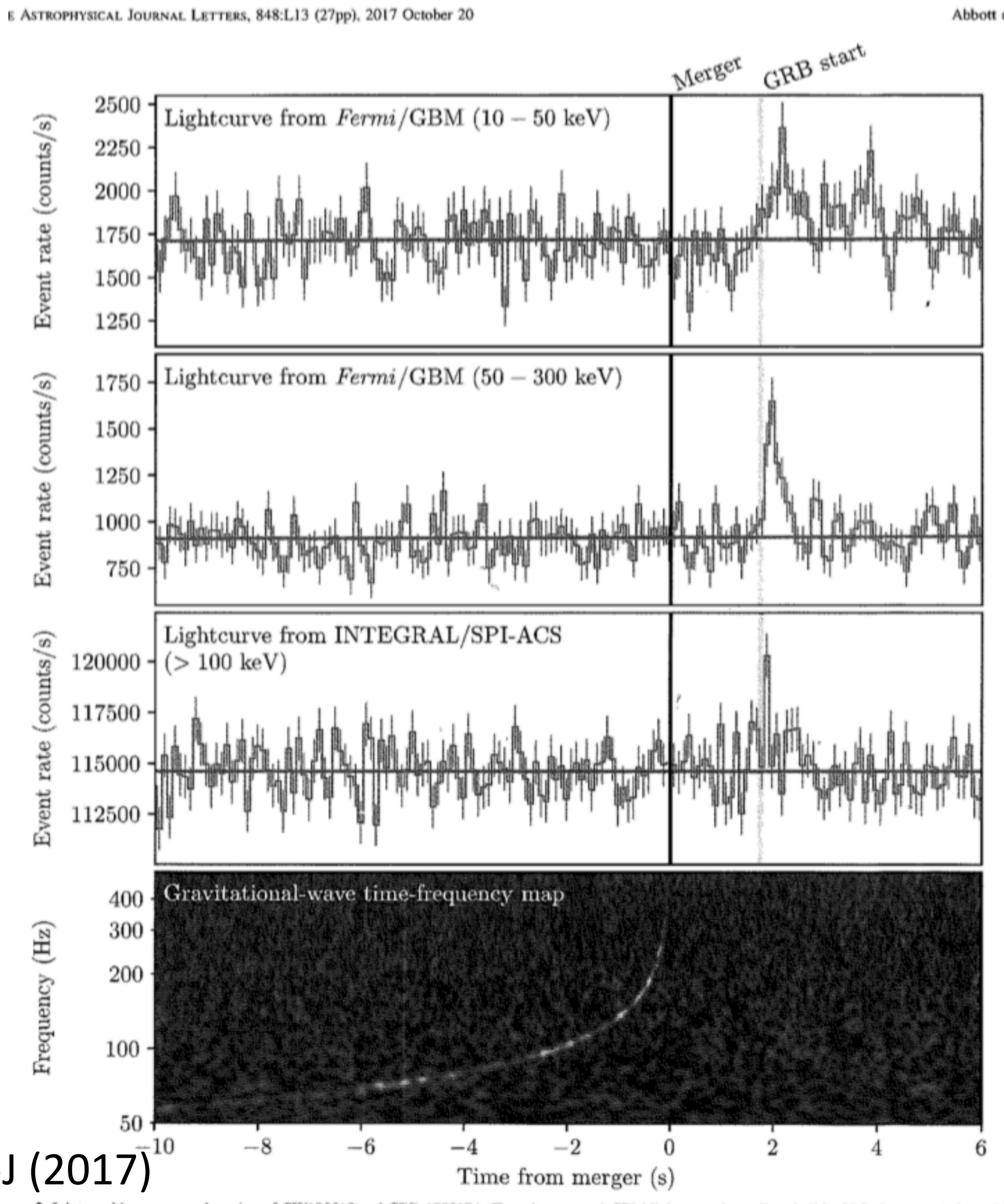
see (Ebisuzaki's talk)

Neutron star-Neutron star collision

→ similar wakefields

(Takahashi et al. 2000)

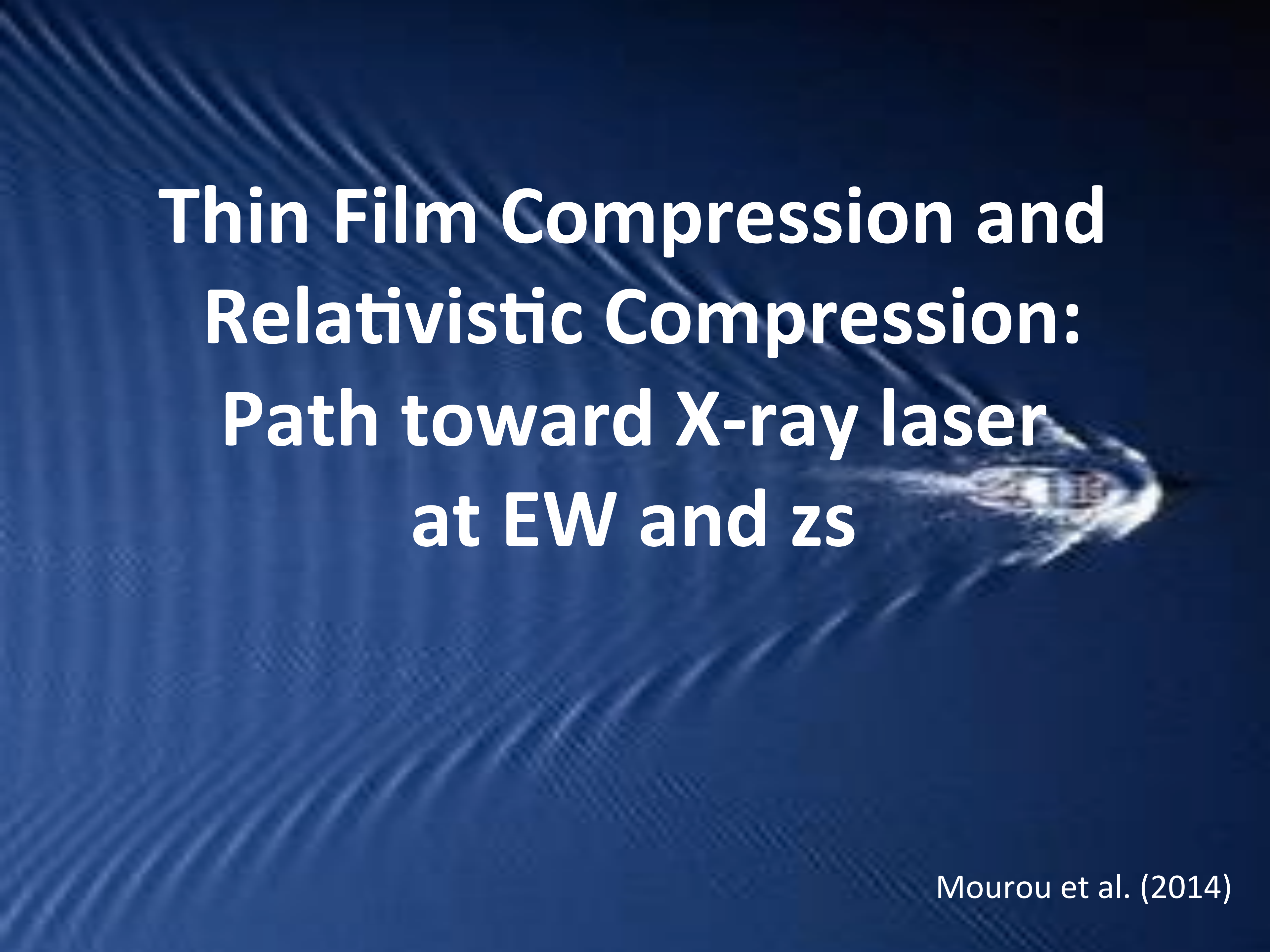
Wait for (Barish's talk)



E Astrophysical Journal Letters, 848:L13 (27pp), 2017 October 20

Abbott

Abbott et al. ApJ (2017)



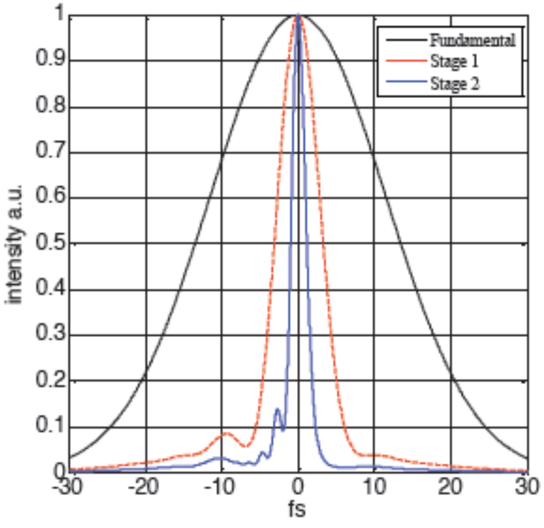
Thin Film Compression and Relativistic Compression: Path toward X-ray laser at EW and zs

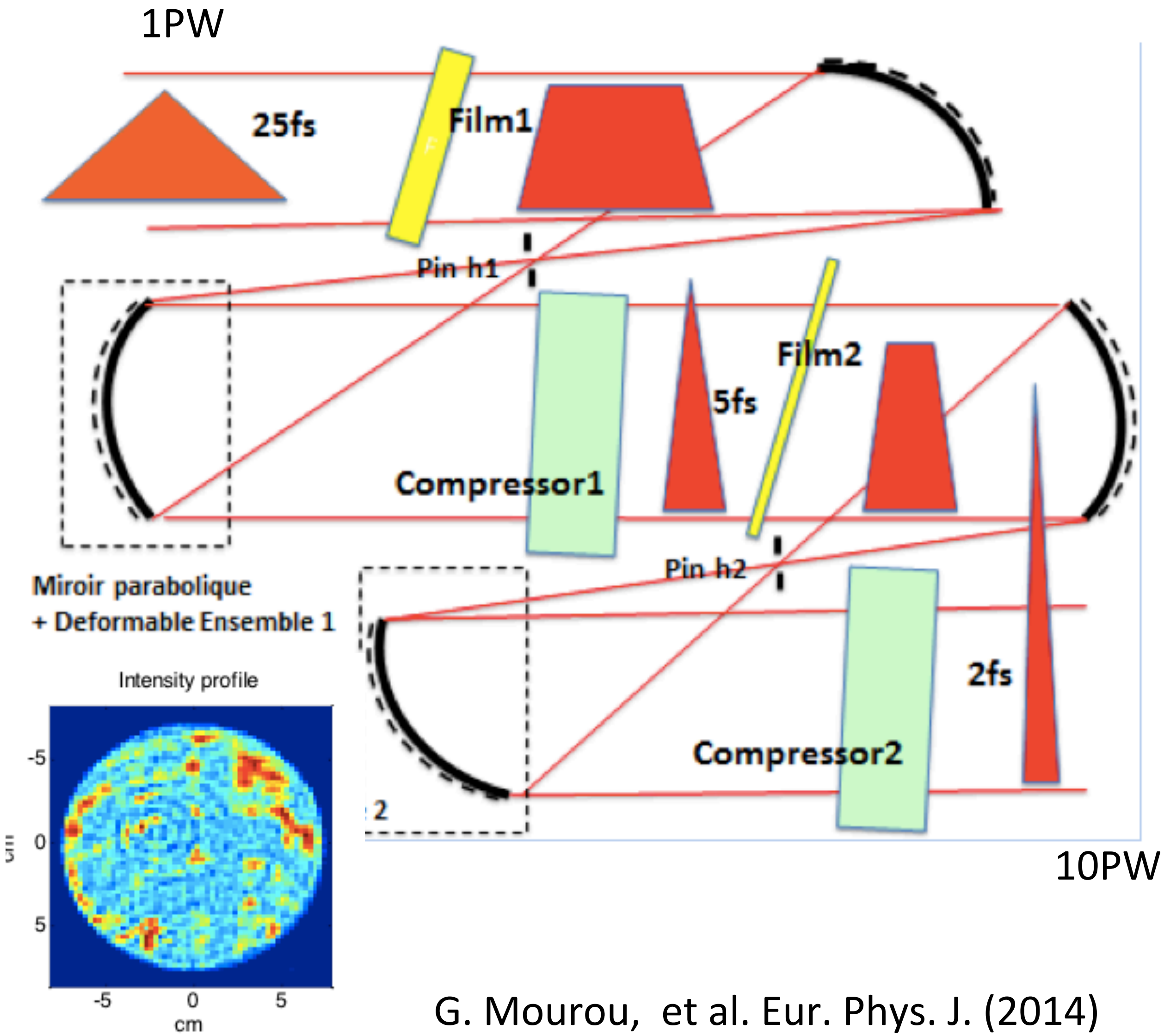
Mourou et al. (2014)

Single-cycle laser (new Thin Film Compression)

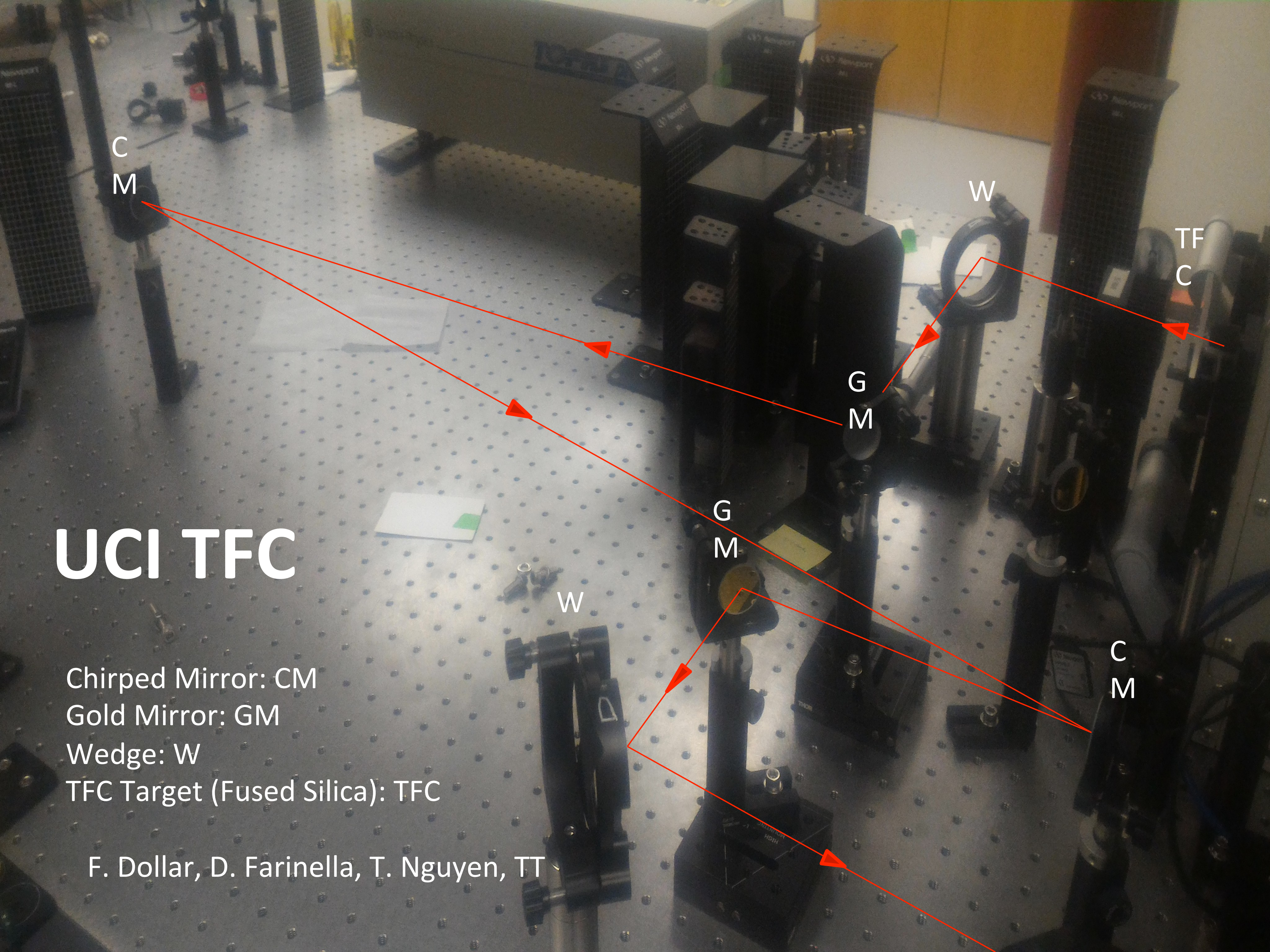
Laser power = energy / pulse lnegth

Optical nonlinearity of thin film → pulse frequency width bulge, pulse compression





G. Mourou, et al. Eur. Phys. J. (2014)

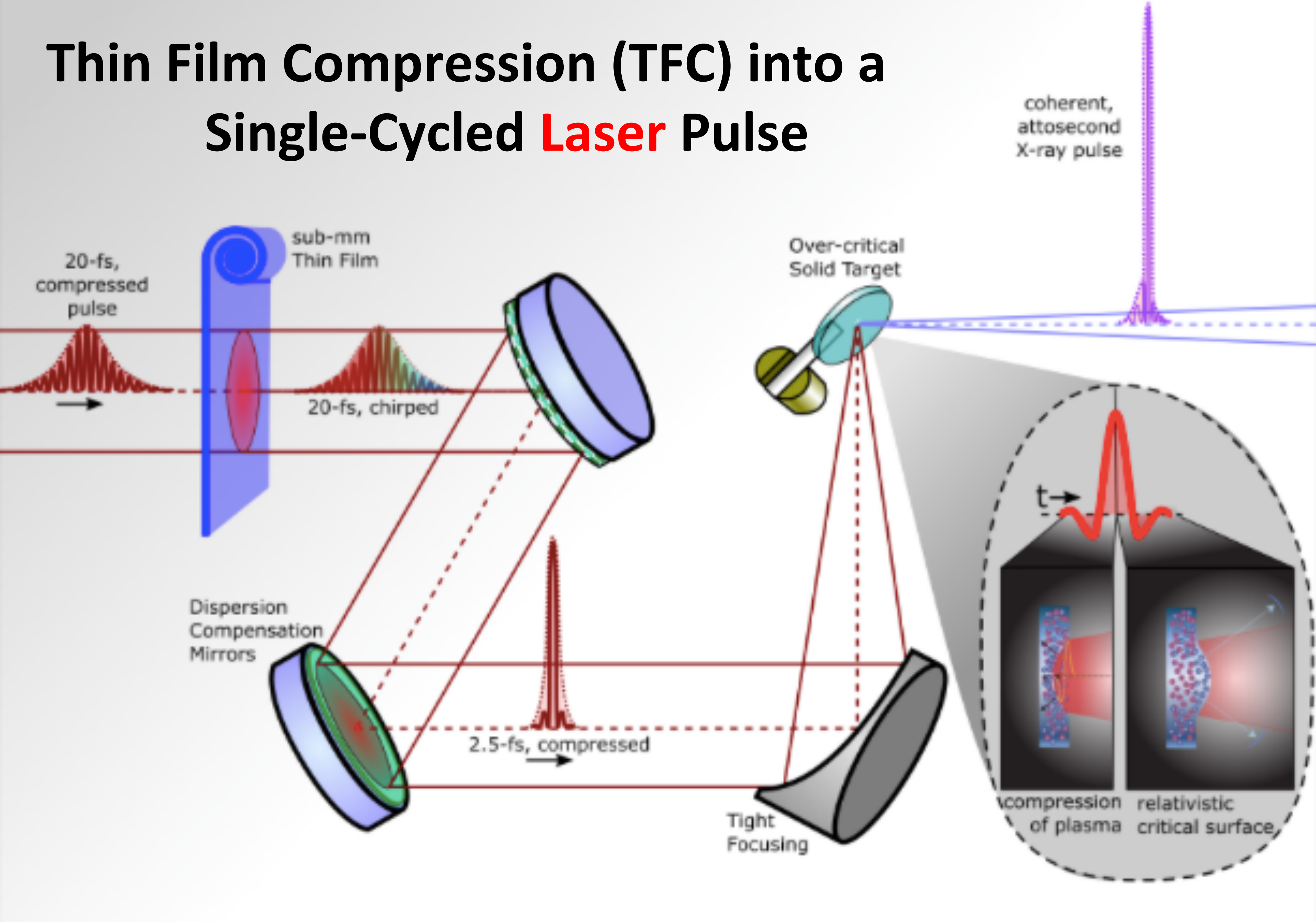


UCI TFC

Chirped Mirror: CM
Gold Mirror: GM
Wedge: W
TFC Target (Fused Silica): TFC

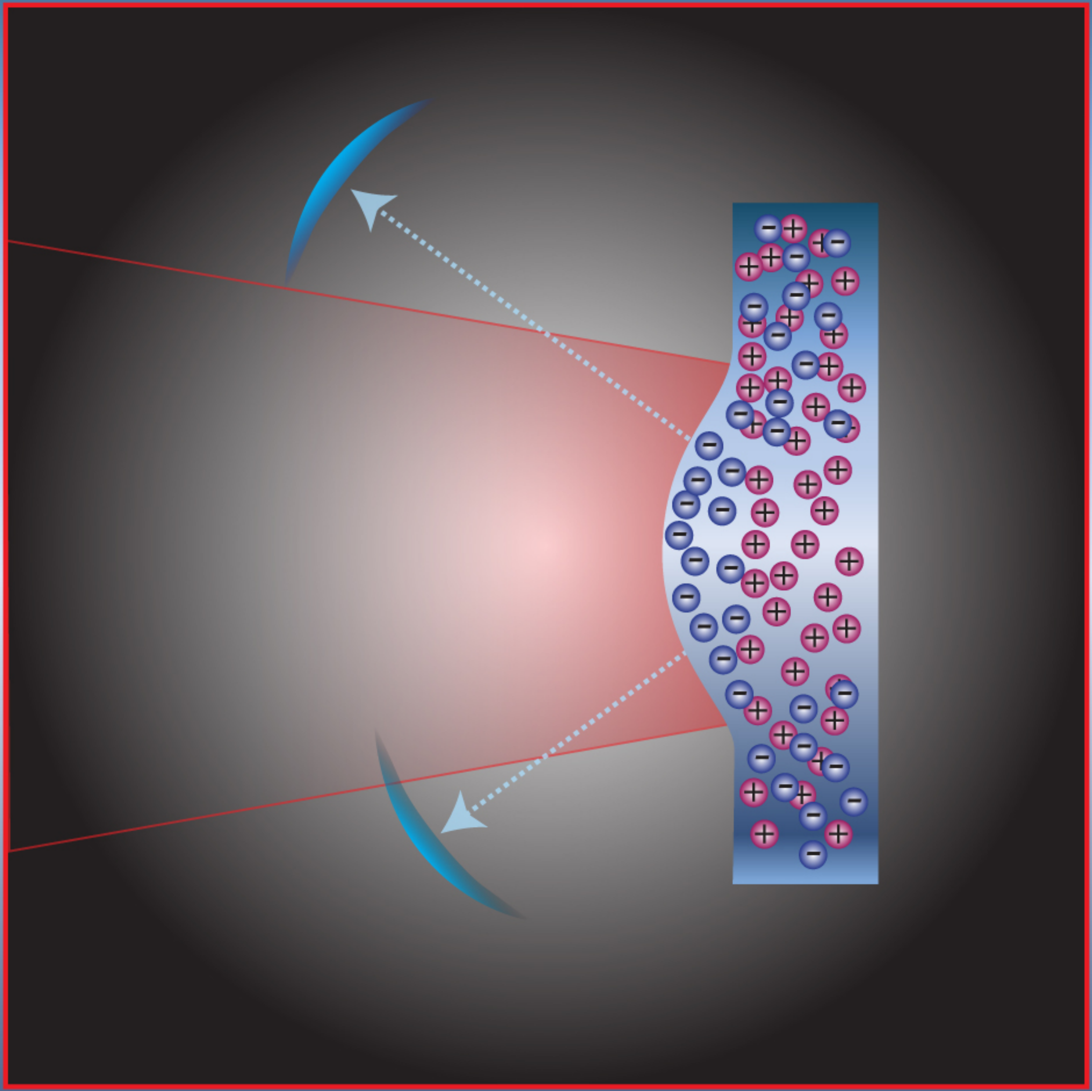
F. Dollar, D. Farinella, T. Nguyen, TT

Thin Film Compression (TFC) into a Single-Cycled Laser Pulse



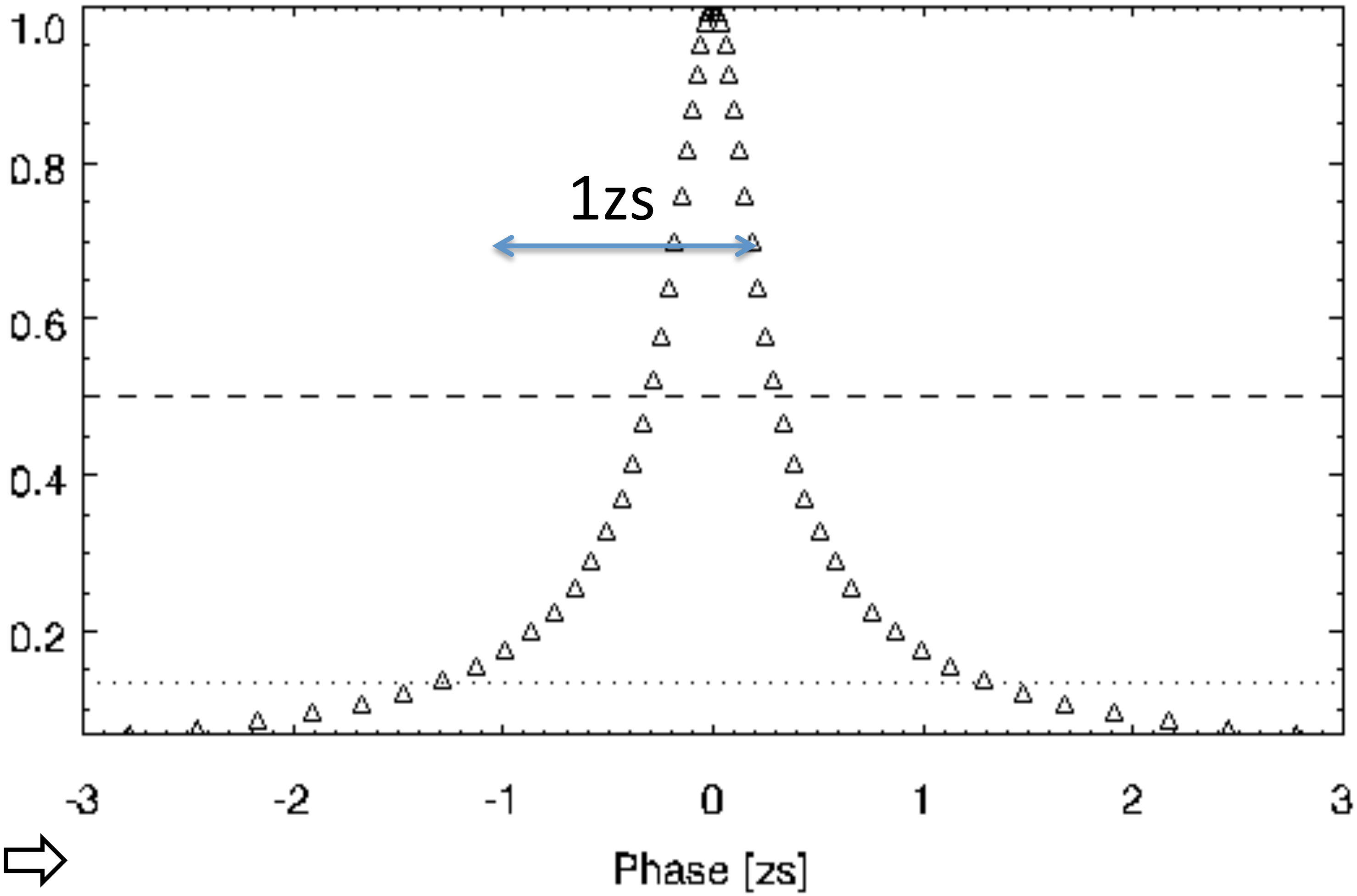
Mourou et al. (2014)

Relativistic Compression



Even,isolated zeptosecond X-ray laser pulse possible

(simulation by N. Naumova, et al., 2014)



⇨

1PW optical laser → 10PW single osc. Optical laser

→ EW single osc. X-ray laser

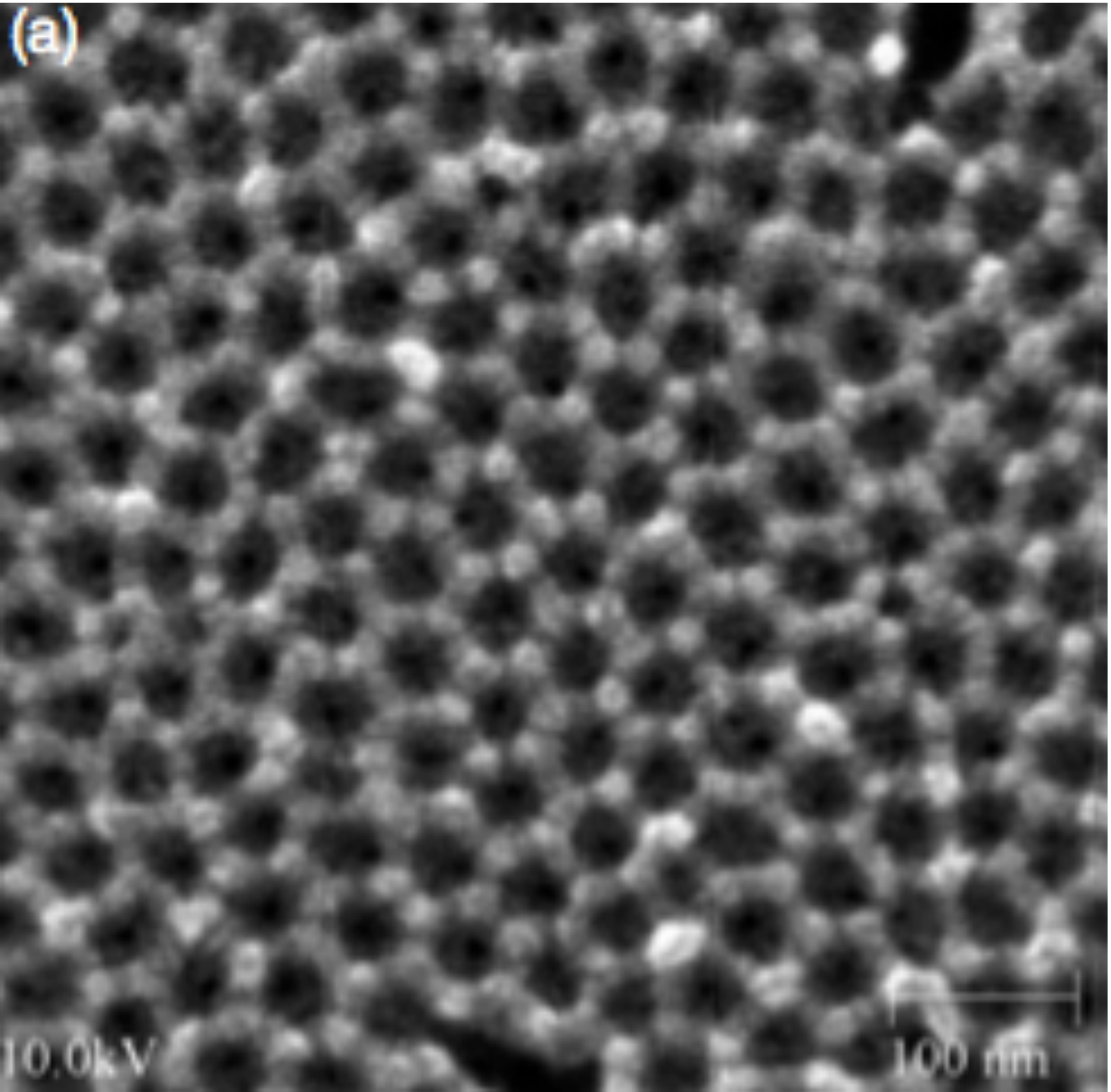
Consistent with “Intensity-pulse-width Conjecture” (Mourou-Tajima, Science **331** (2011))

X-ray LWFA in Nanostructure

Tajima, EPJ 223 (2014)
Hakimi, et al, Zhang, Posters

Porous Nanomaterial:

rastering possible



Nano holes:
reduce the stopping power
keep strong wakefields

➔ Marriage of *nanotech* and *high field science*

Spatia (nm), time(as-zs), density 10^{24} /cc), photon (keV) scales:
Transverse and longitudinal **structure of nanotubes**: act as e.g., accelerator structure (the structure intact in time of ionization, material breakdown times fs > x-ray pulse time zs-as)

Porous alumina on Si substrate
Nanotech. **15**, 833 (2004);
P. Taborek (UCI): porous alumina (2007)

UCI/Fermilab efforts on nanostructure wakefield acceleration

16th Advanced Accelerator Concept Workshop (AAC2014)

TeV/m Nano-Accelerator

Current Status of CNT-Channeling Acceleration Experiment

Y. M. Shin[1,2], A. H. Lumpkin[2], J. C. Thangaraj[2], R. M. Thurman-Keup[2], P. Piot[1,2], and V. Shiltsev[2]

Thanks to X. Zhu, D. Broemmelsiek, D. Crawford, D. Mihalcea, D. Still, K. Carlson, J. Santucci, J. Ruan, and E. Harms

[1]Northern Illinois Center for Accelerator and Detector Development (NICADD), Department of Physics, Northern Illinois University

[2]Fermi National Accelerator Laboratory (FNAL)

X-ray wakefield acceleration in nanomaterials tubes

T. Tajima, EPJ (2014)

X-ray laser with short length and small spot:

NB: electrons in outers-shell bound states, too, interact with X-rays

Simulation:

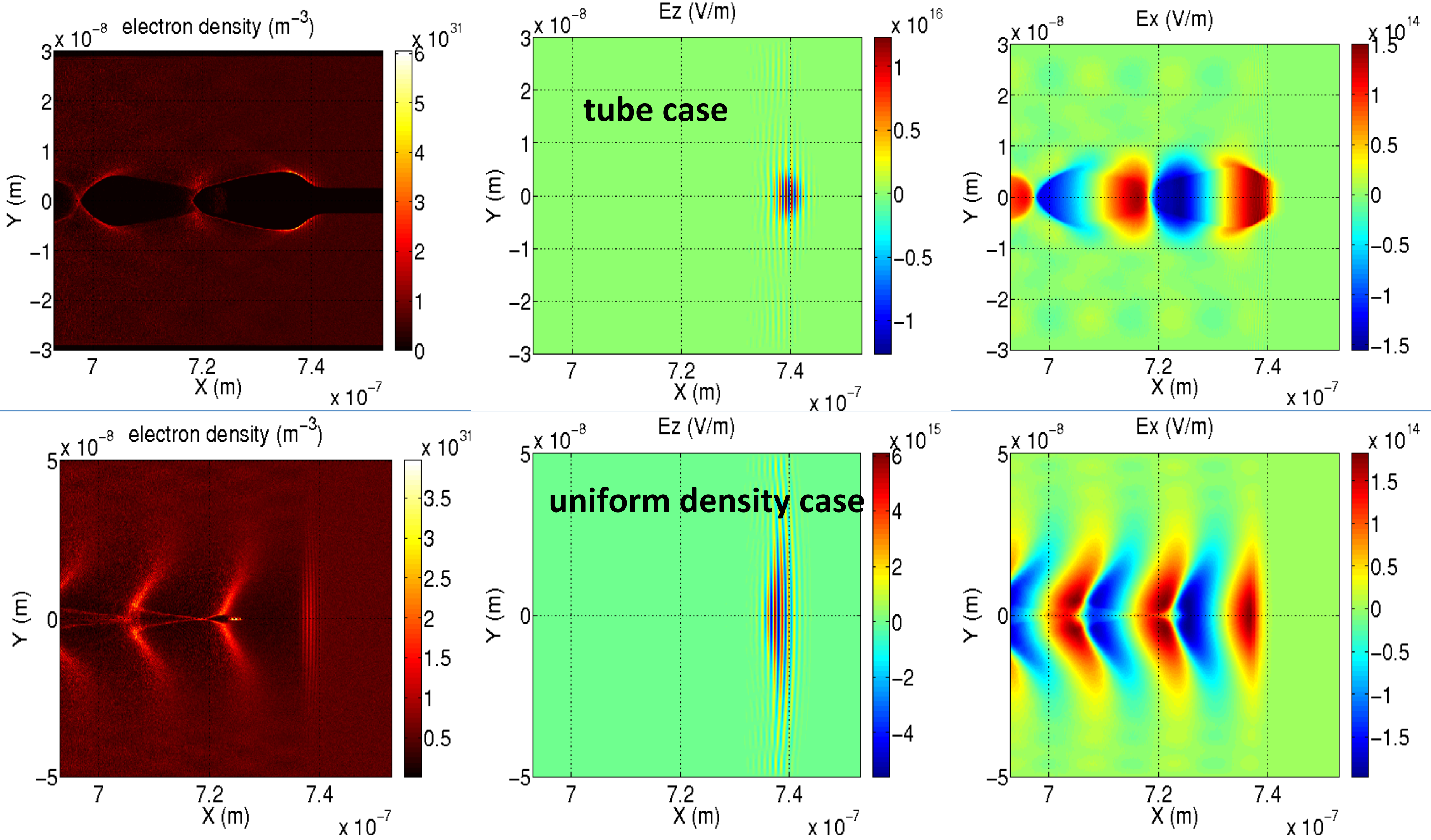
X.M. Zhang, et al.PR AB (2016)

Laser pulse with small spot can be well controlled and guided with a tube. Such structure available e.g. with **carbon nanotube,** or **alumina nanotubes** (typical simulation parameters)

$$\lambda = 1nm, a_0 = 4, \sigma_L = 5nm, \tau_L = 3nm / c$$

$$n_{tube} = 5 \times 10^{24} / cm^3, \sigma_{tube} = 2.5nm$$

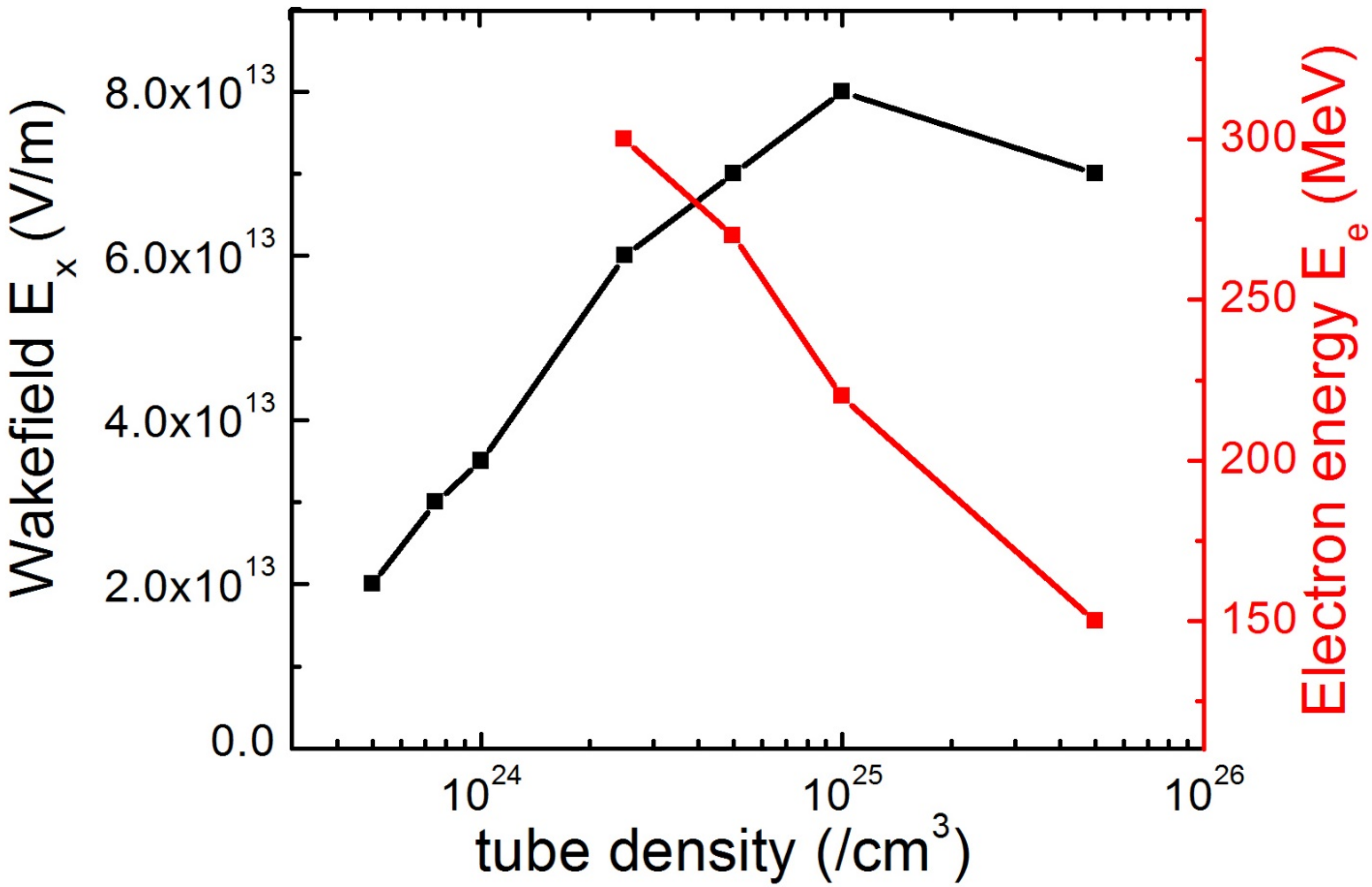
Wakefield comparison between the cases of a tube and a uniform density



X. M. Zhang

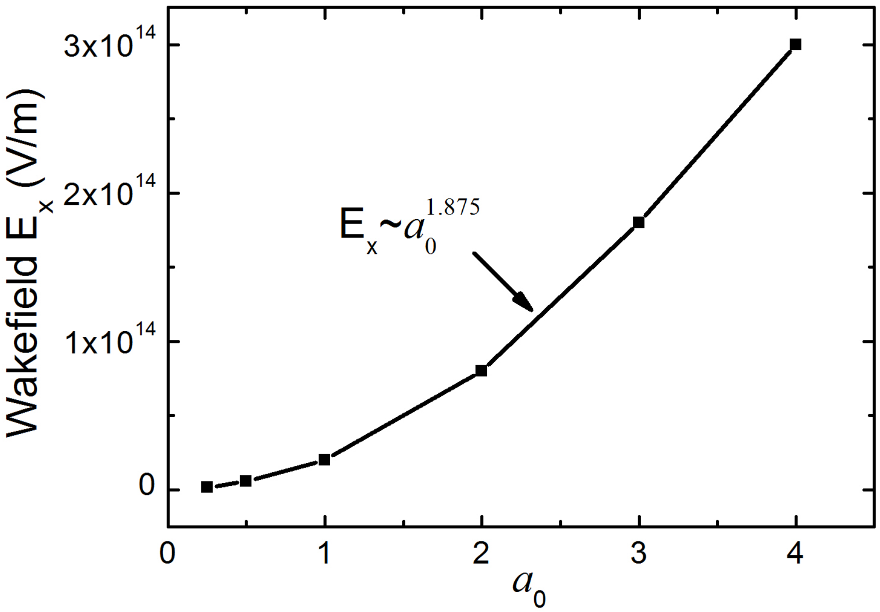
PIC simulation of X-ray wakefields in a nanomaterial tube: Density scaling

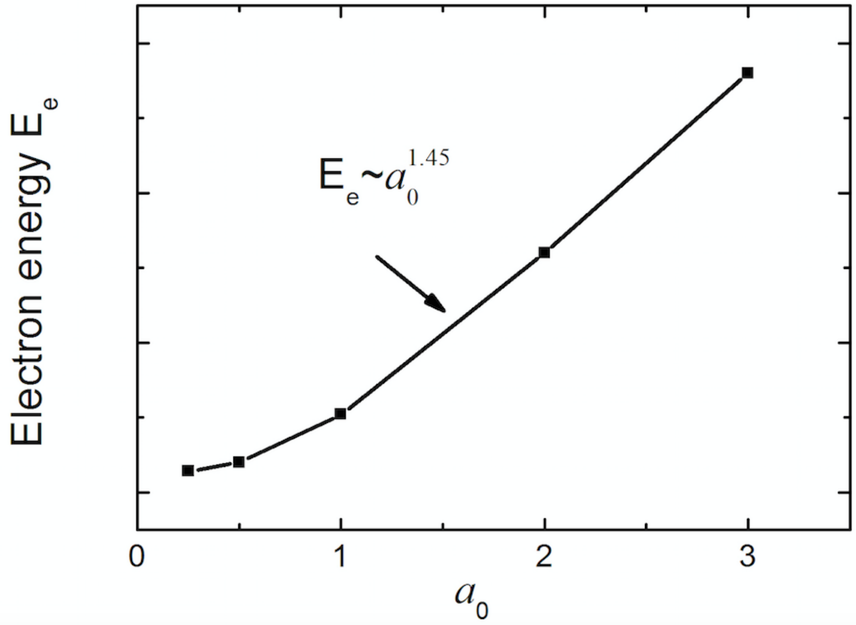
Photon energy = 1keV,tube radius = 5nm, a_0=4, a few-cycled laser (around n_{cr} / n = 200)



X. M. Zhnag (2016)

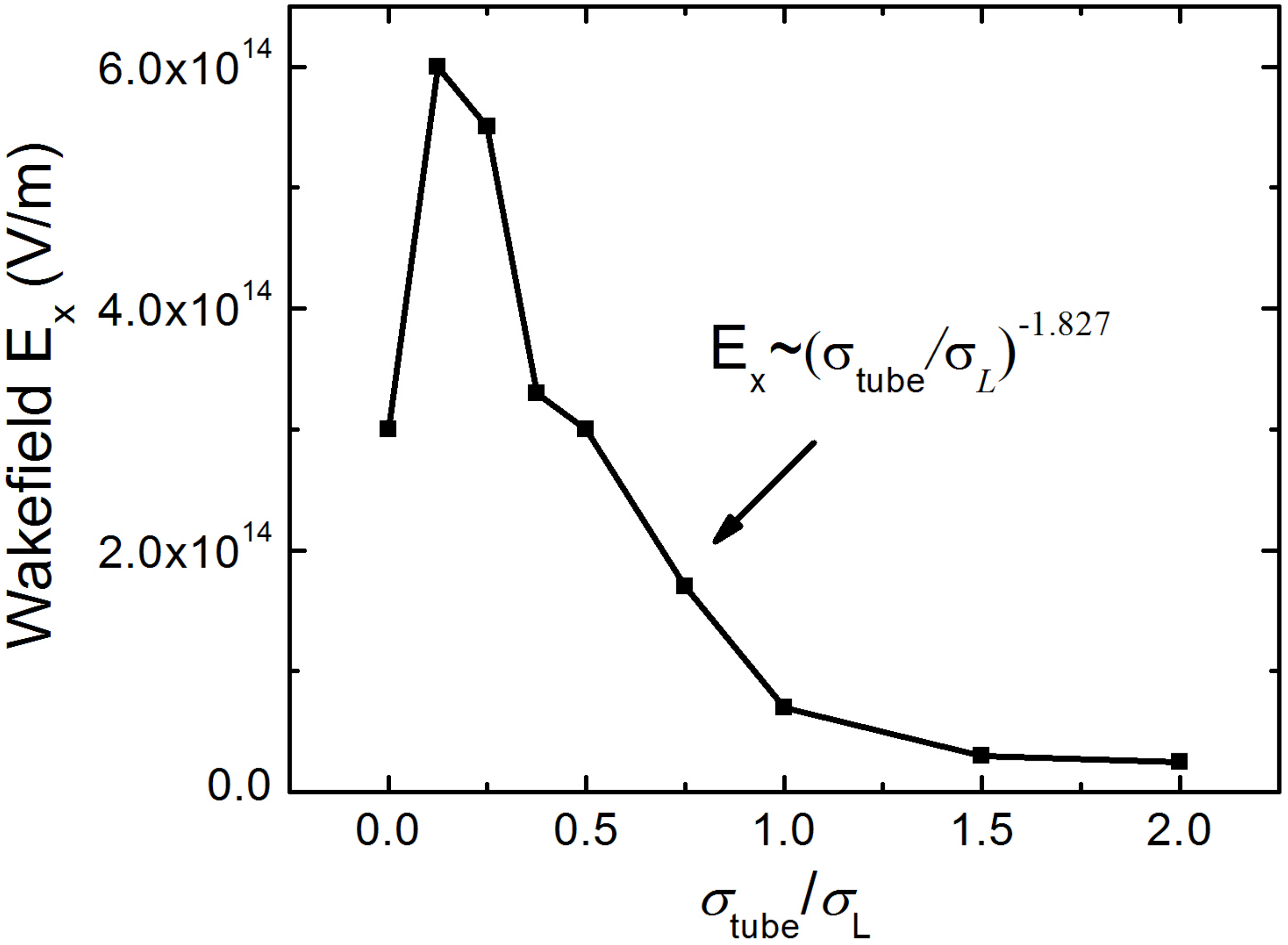
Wakefield scaling to the X-ray laser amplitude





X. M. Zhnag (2016)

Wakefields and the tube geometry



X. M. Zhang (2016)

With and without **optical phonon branch**

Model of optical phonon branch: *T. Tajima and S. Ushioda, PR B (1978)*

→ nanoplasmonics in X-ray regime

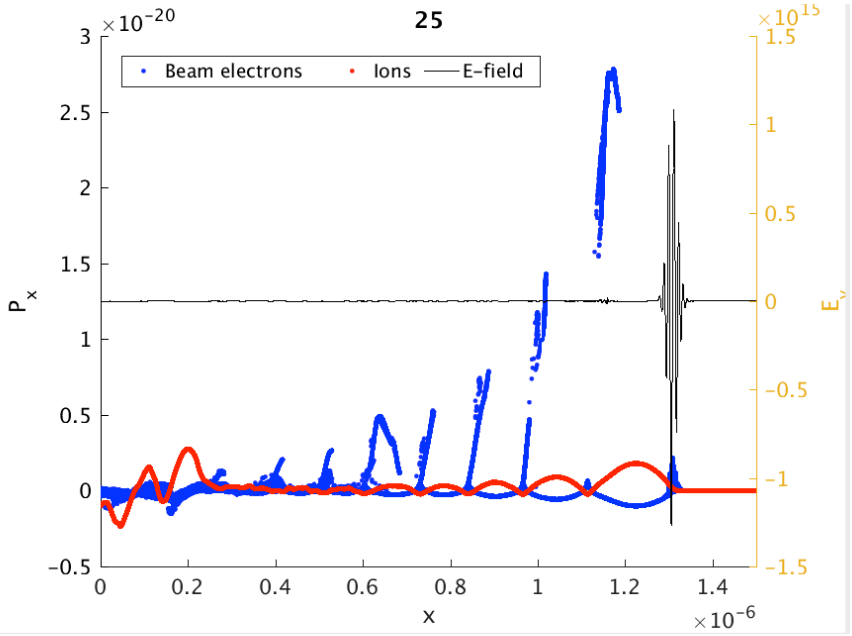
Without lattice force (i.e. plasma)

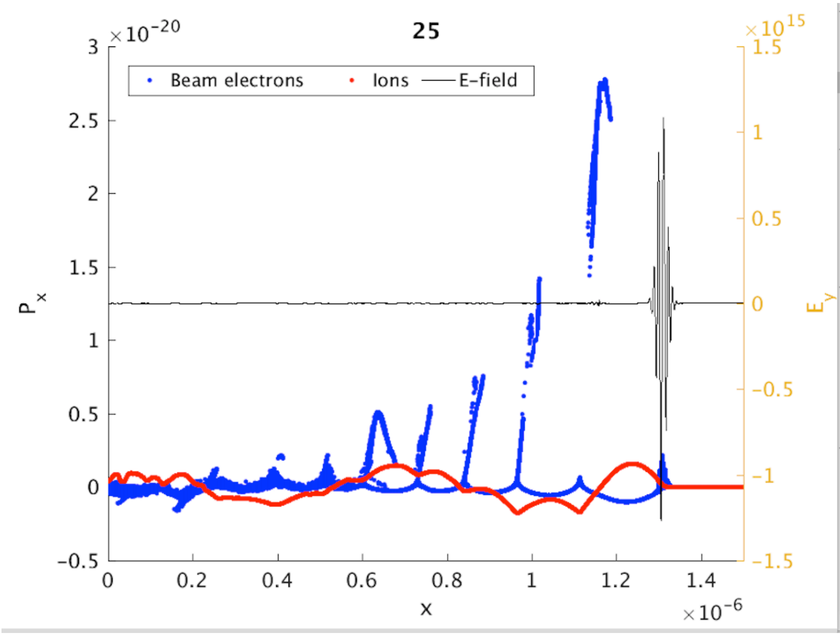
(when ω_{TO} is much smaller than ω_{pe}, there is no noticeable difference from the below where $\omega_{TO} = 0$)

With lattice force (optical phonon branch present)

$$\epsilon = 1 - \frac{\omega_{pe}^2}{\omega^2} - \frac{\Omega_p^2}{\omega^2 - \omega_{TO}^2}$$

$$\frac{\omega_{TO}}{\omega_{pe}} \simeq 0.75 \qquad \frac{\Omega_p}{\omega_{pe}} \simeq \frac{1}{43}$$

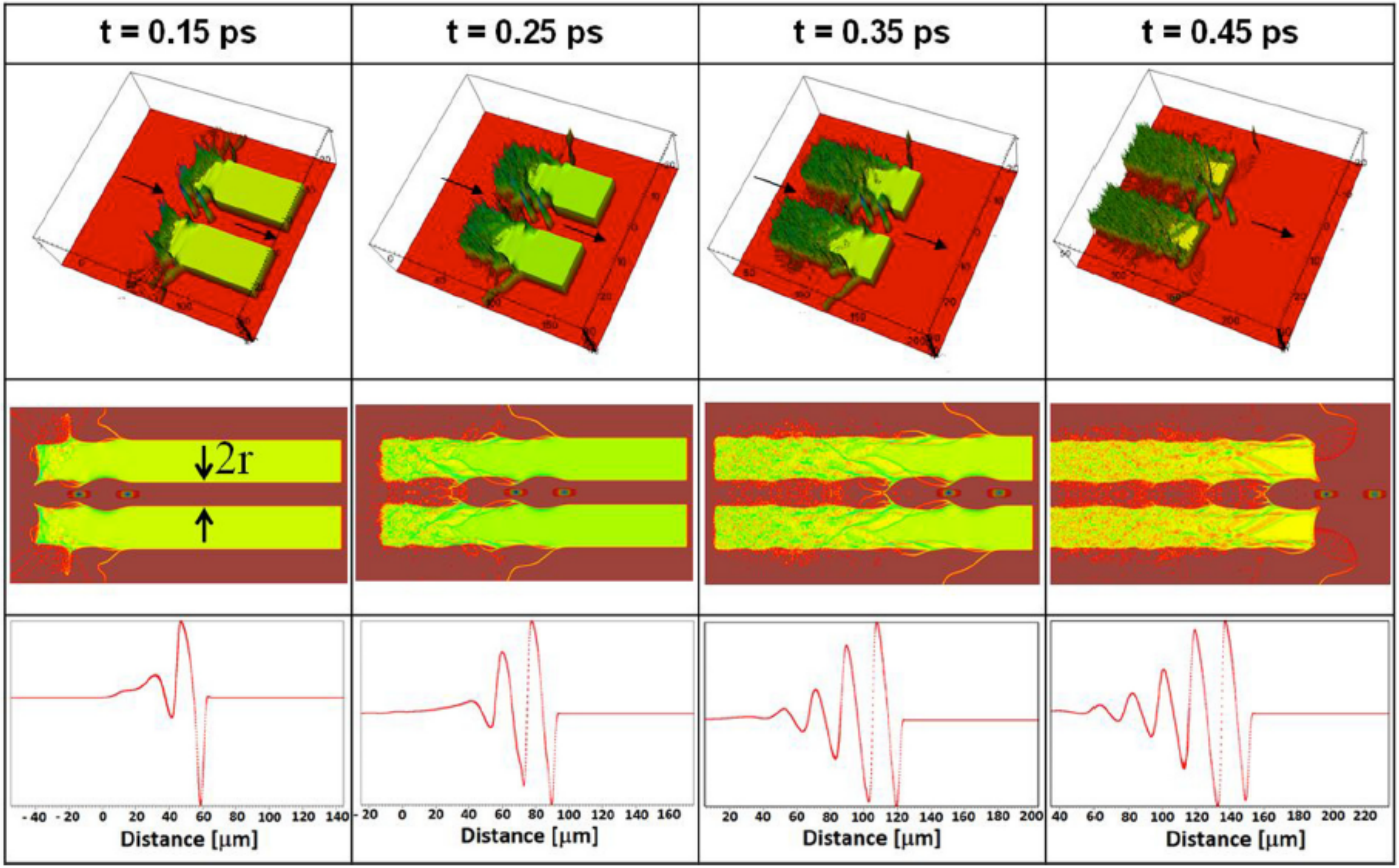




S. Hakimi, et al. (2017)

Wakefield on a chip

toward TeV over cm (beam-driven)



Y. Shin (2014)

Conclusions

- **Robust** heightened energy state of plasma, Higgs' state: Wakefields
- In fusion plasma: **FRC** (Field Reverse Configuration), a Higgs' state (or Landau-Ginzburg excited stable state)

- Wakefields: **Nature creates** naturally and ubiquitously: jets from Blackhole (AGN) driven by **MRI instability** of the accretion disk, NS-NS collsions
- **Gamma rays bursts** (TeV), **Cosmic rays** (ZeV): simultaneous

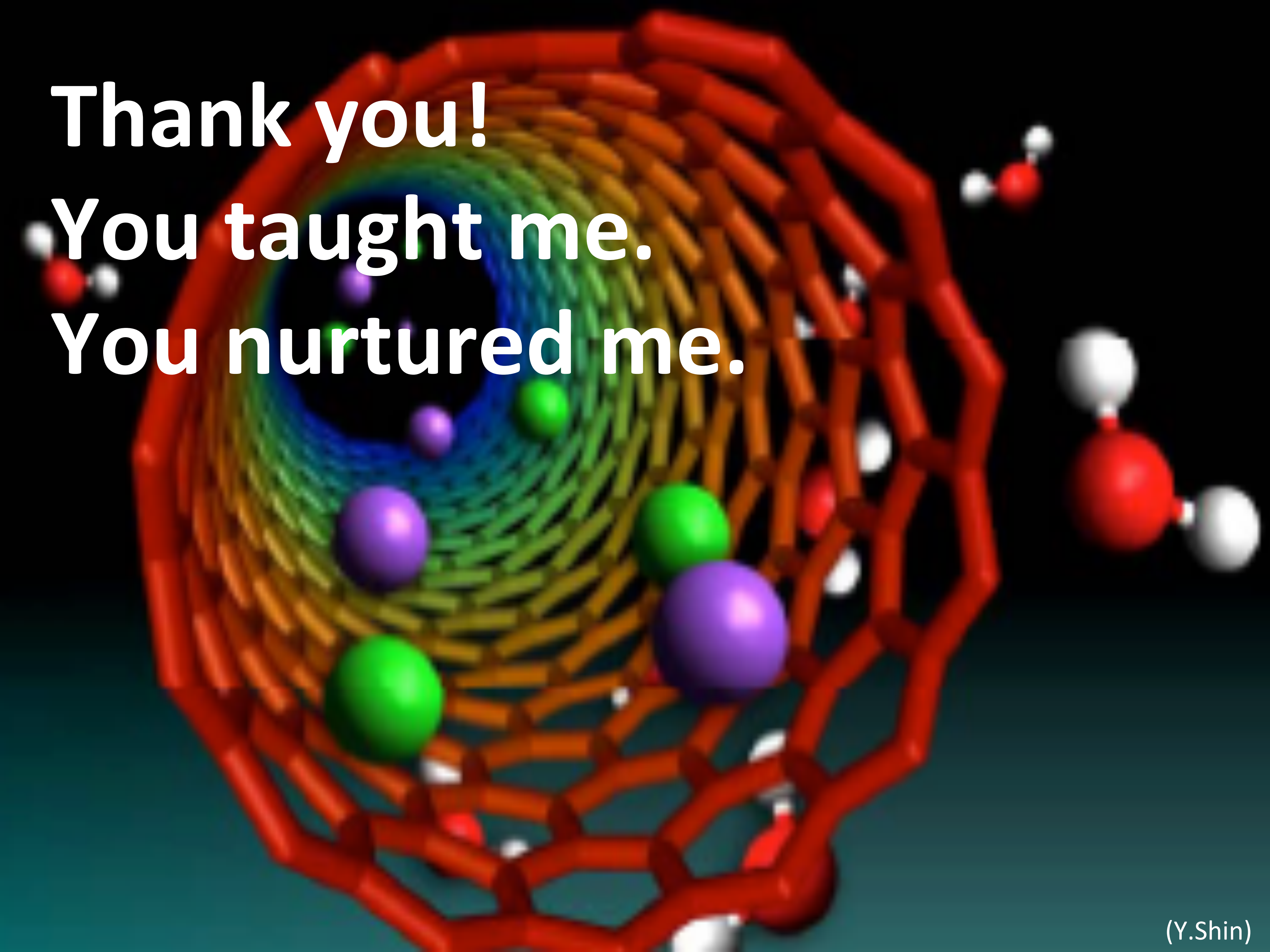
  (sometimes with GW → Barish's talk)

- A new direction of ultrahigh intensity: **zeptosecond lasers**
- **EW 10keV X-rays laser** from 1PW optical laser
- Single-cycled X-ray laser pulse (relativistic compression)
- **X-ray LWFA in crystal**: accelerating gradient (from GeV/cm) →TeV/cm
- **Crystal nanoengineering**: s.a. nanoholes, arrays, focus nano-optics for nano-accelerator
- Start of **zeptoscience**: ELI-NP zeptoproject (collaboration)---

  laser tools fit for nuclear phys. (←→attoseconds for atoms)

- **Scale revolution**: eV→keV; PW→EW; as→zs; μm→nm; GeV/cm→TeV/cm; 100m→cm; μ-beam→nanobeam; 10^{18}/cc → 10^{24}/cc

  →**societal impact**



Thank you!

You taught me.

You nurtured me.

(Y.Shin)