Wakefields:
Laser, toilet science, and gamma-ray bursts

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Kanazawa, Japan
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* 2018 Nobel, ** 2017 Nobel

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. Laser acceleration drove (1979) laser innovations:

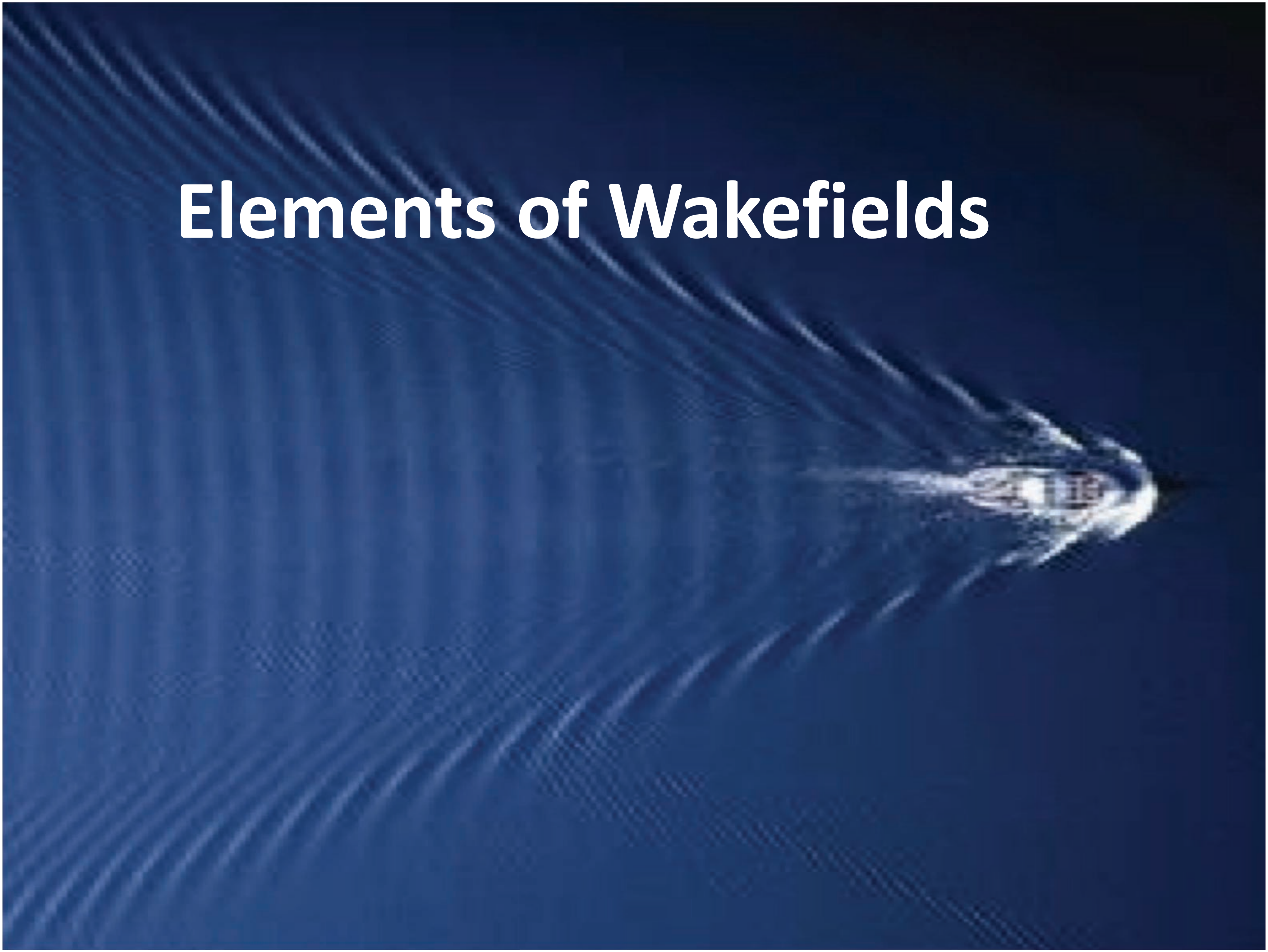
   CPA (1985)*, RC (2004), CAN laser (2013), TFC (2014)
3. Nature prevalently creates wakefields: AGN accretion disk and jets

   Fermi acceleration → Wakefields acceleration
4. Gamma-ray bursts (Blazars): signature of wakefields

   GRB : sometimes accompanied by Gravitational Waves (GW)**
5. CAIL and Toilet Science
6. New technology thin film compression (TFC) →

   Leading to a new innovation X-ray LWFA
7. "TeV on a chip" (X-ray LWFA); coherent γ-ray laser; new zeptosecond science; medical (and other compact) accelerators

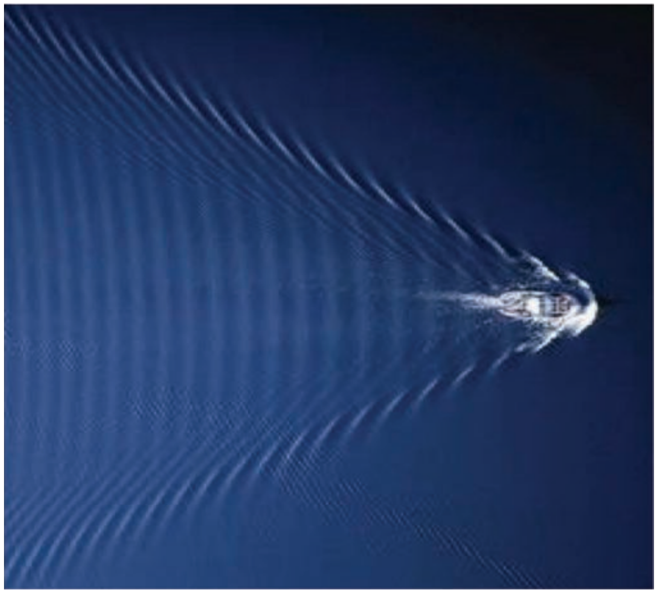
Elements of Wakefields



Laser Wakefield (LWFA, 1979):

Wake phase velocity >> thermal speed ($v_{ph} >> v_{th}$) maintains **coherent** and **smooth** structure

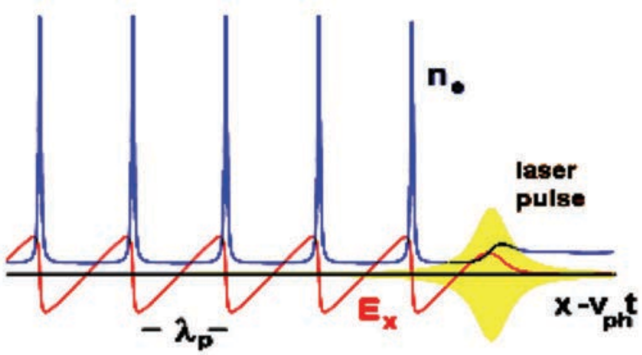
Tsunami phase velocity becomes ~0, causes **wavebreak** and **turbulence**



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 $v \approx c$



← 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)

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

(1979)

Plasma free of binding potential , but its electron responses forms its sturdy “spine”:

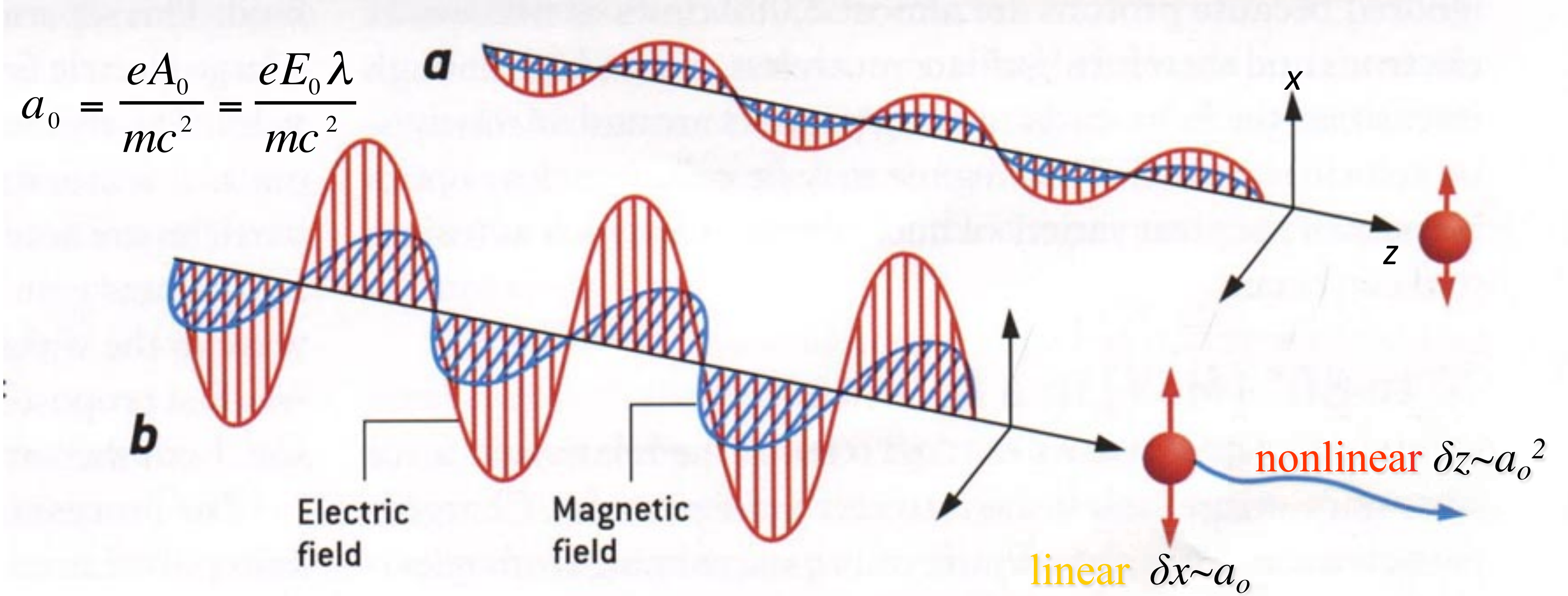
a) Classical EM : $v_{os} << c$,

$a_0 << 1$: δx only

b) <u>Relativistic</u> EM: $v_{os} \sim c$

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

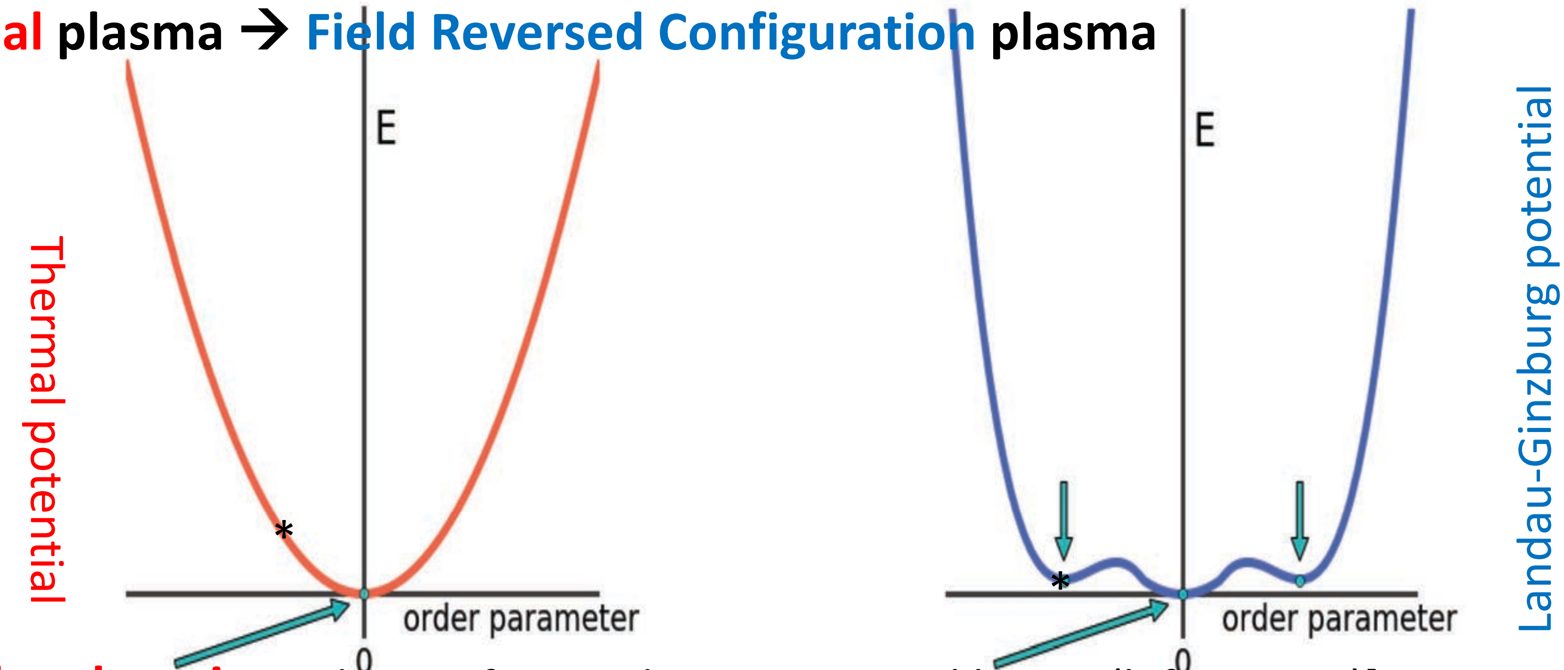
$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$



Needs for relativistic laser intensity $a_0 = eE / m\omega c > 1$ (1979) → high field science CPA* (1985)

Thermal plasma vs. Wakefields (and Higgs)

Trivial vacuum vs. Laundau-Ginzburg potential → BCS → Nambu → Higgs vacuum
Thermal plasma w/ Landau damping → wakefields , plasma with elevated energy
Thermal plasma → Field Reversed Configuration plasma



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

Wakefield: no damping; distinct excited <u>stable state</u> ←no particles to resonate (@ $v_{ph} >> v_{th}$)
= plasma's elevated Higgs state , "onigokko (hide 'n seek)" state , or "spined" state

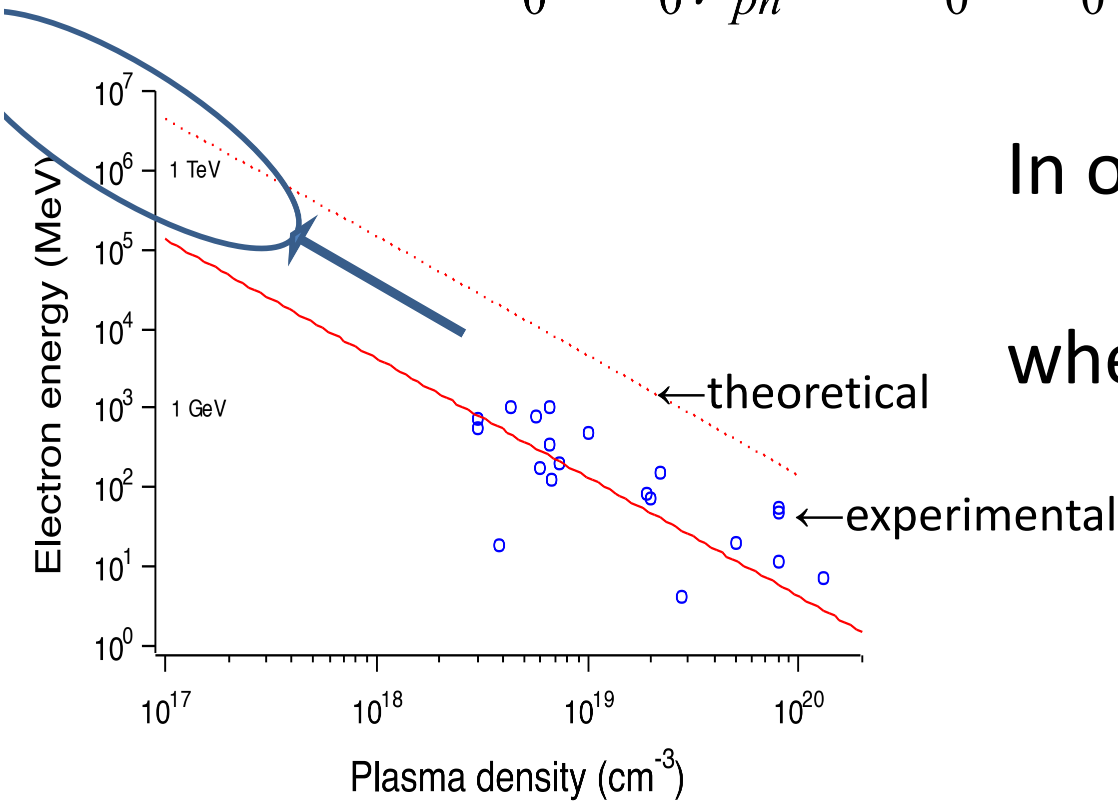
| 0 > vs. | *H* > (cf . | *H* > → | 0 >)

thermo-equilibrium — wakefield state — tsunami onshore

Tajima, Nakajima, Mourou*, RNC (2017)

Theory of wakefield toward extreme 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)



In order to avoid wavebreak,

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

where

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

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

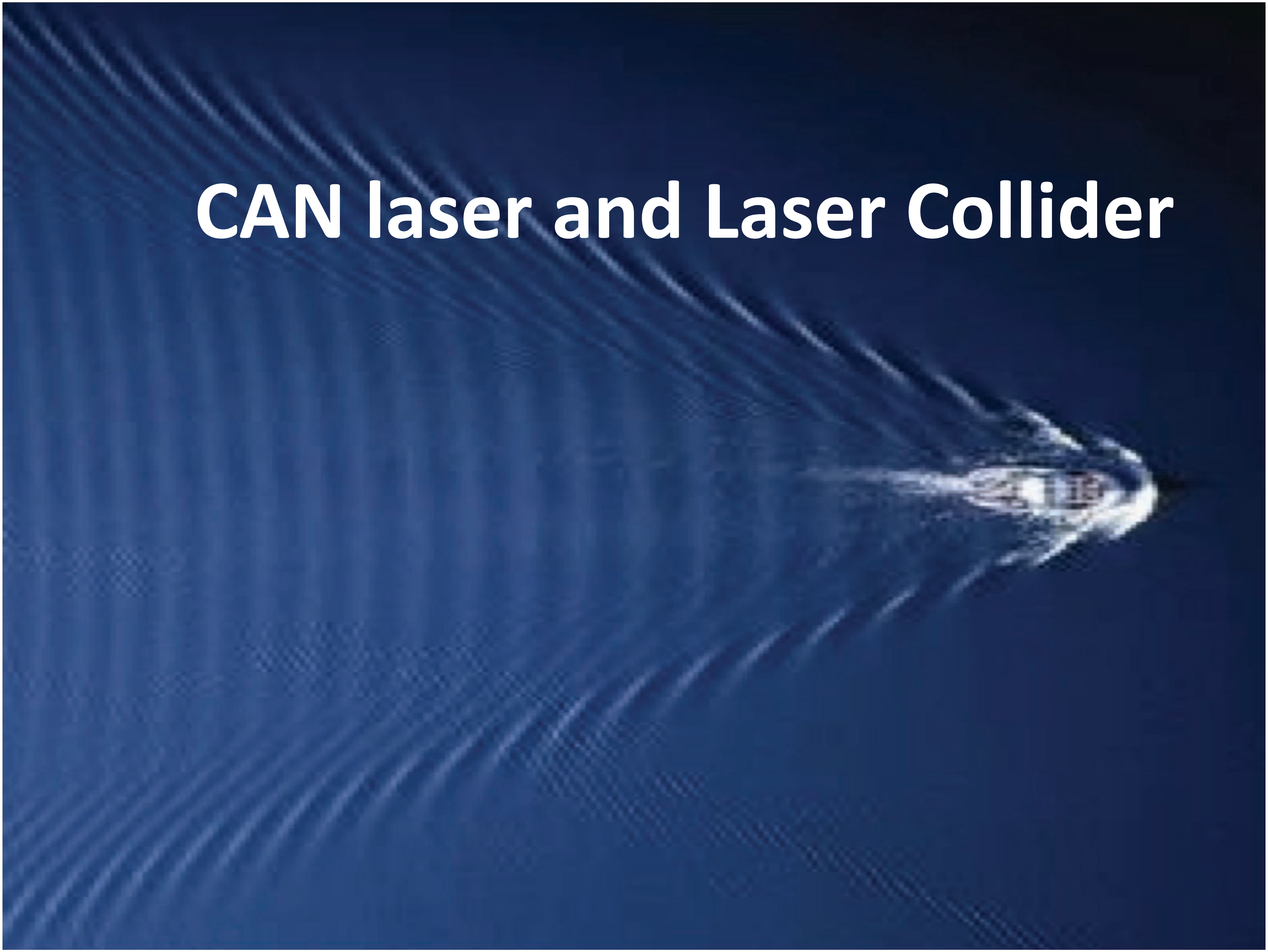
$n_e = 10^{16}$

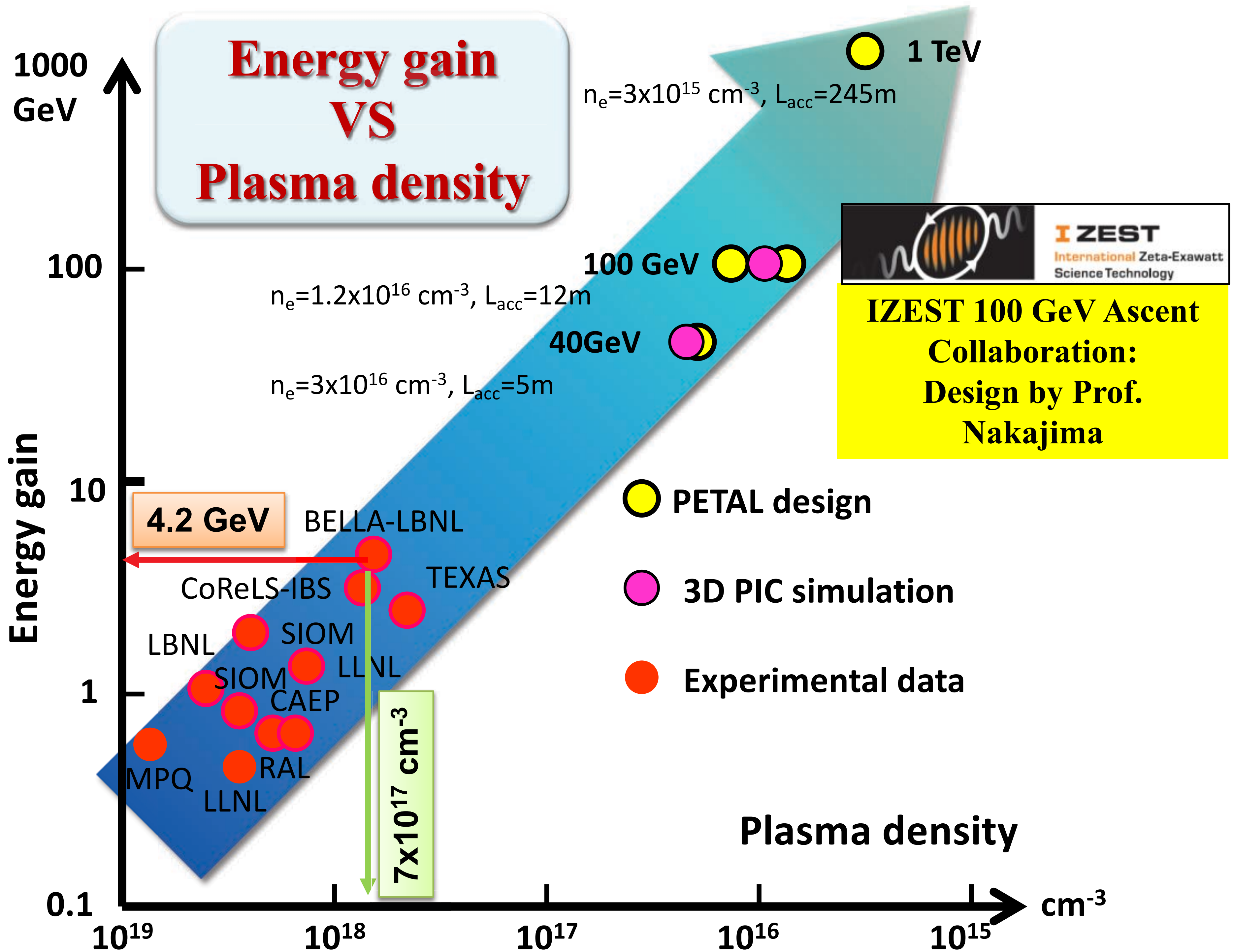
$$L_d = \frac{2}{\pi}\lambda_p a_0^2\left(\frac{n_{cr}}{n_e}\right),$$

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



Energy gain
VS
Plasma density
1000 GeV
100
10
1
0.1
Energy gain
1 TeV
n_e=3x10^{15} cm^{-3}, L_{acc}=245m
100 GeV
n_e=1.2x10^{16} cm^{-3}, L_{acc}=12m
40GeV
n_e=3x10^{16} cm^{-3}, L_{acc}=5m
IZEST
International Zeta-Exawatt Science Technology
IZEST 100 GeV Ascent Collaboration: Design by Prof. Nakajima
4.2 GeV
BELLA-LBNL
CoReLS-IBS
TEXAS
LBNL
SIOM
LLNL
SIOM
CAEP
MPQ
RAL
LLNL
7x10^{17} cm^{-3}
PETAL design
3D PIC simulation
Experimental data
Plasma density
10^{19}
10^{18}
10^{17}
10^{16}
10^{15}
cm^{-3}

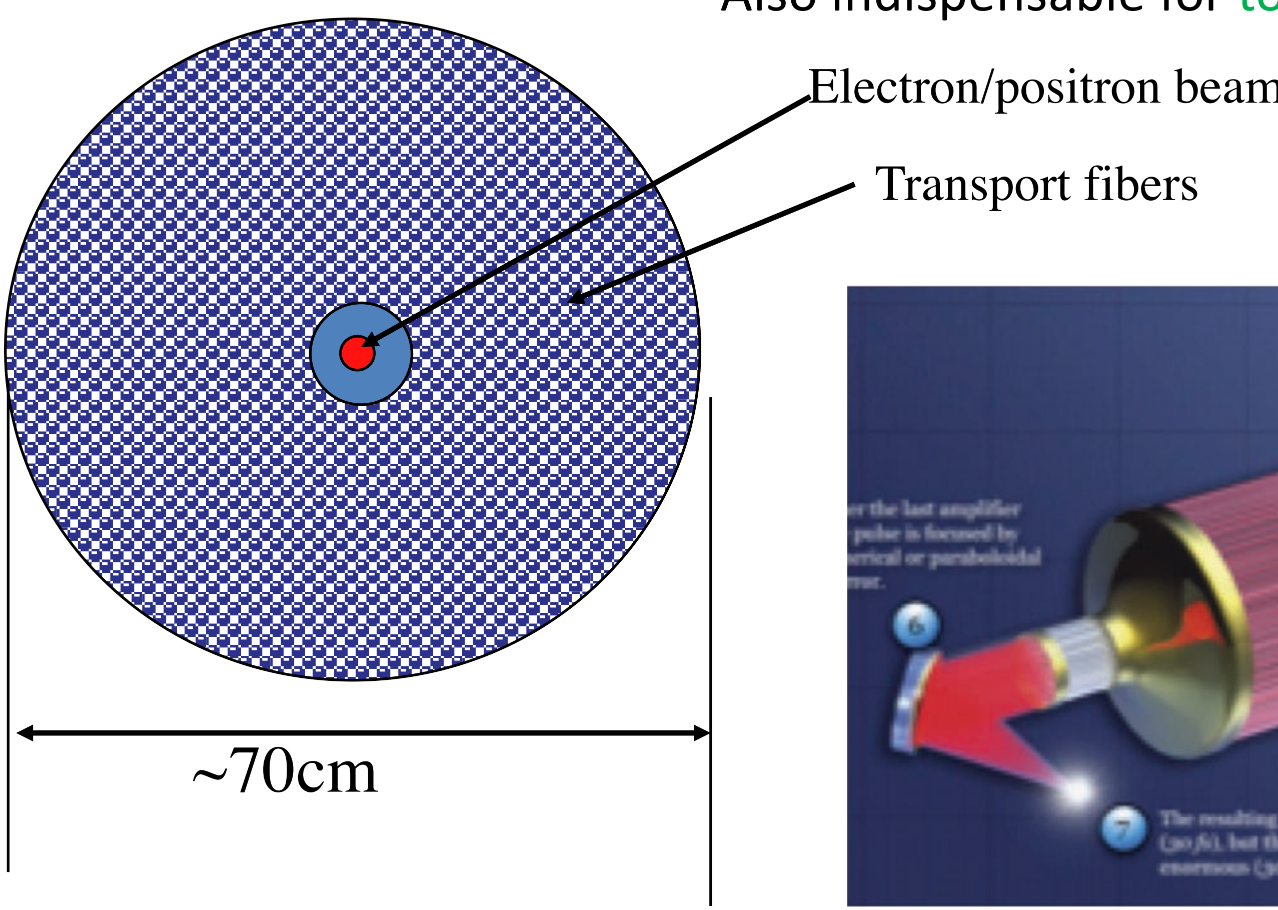
Coherent Amplification Network

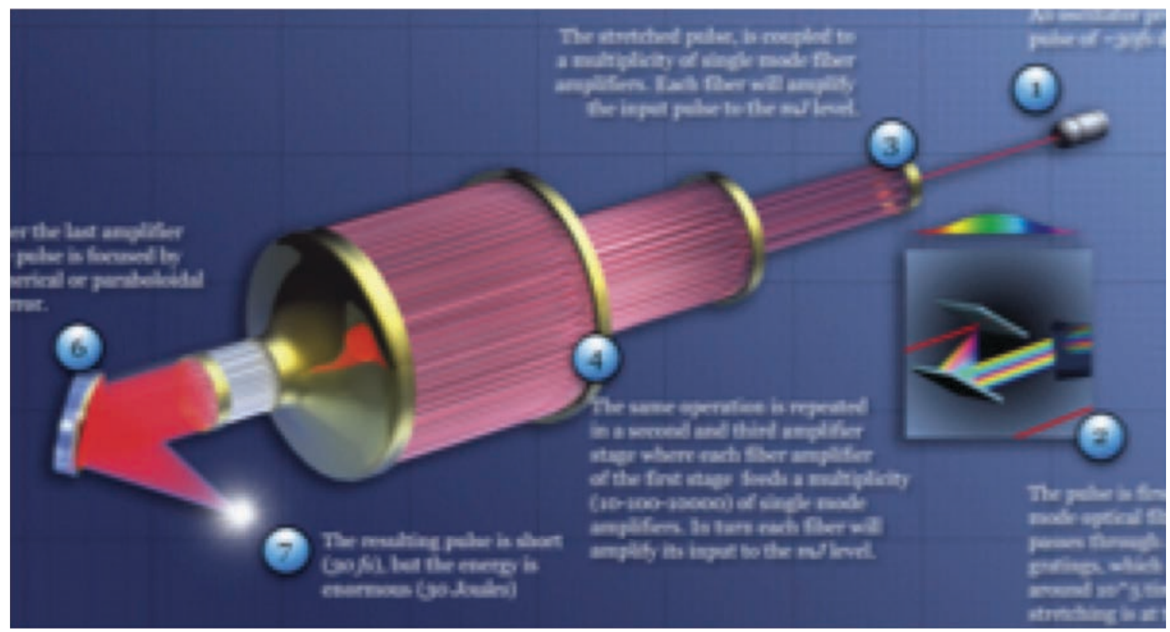
Efficient (>30%), high rep rated (~kHz –MHz), light, digitally controllable

CAN laser makes laser collider possible

See Nakajima et al. (2018)

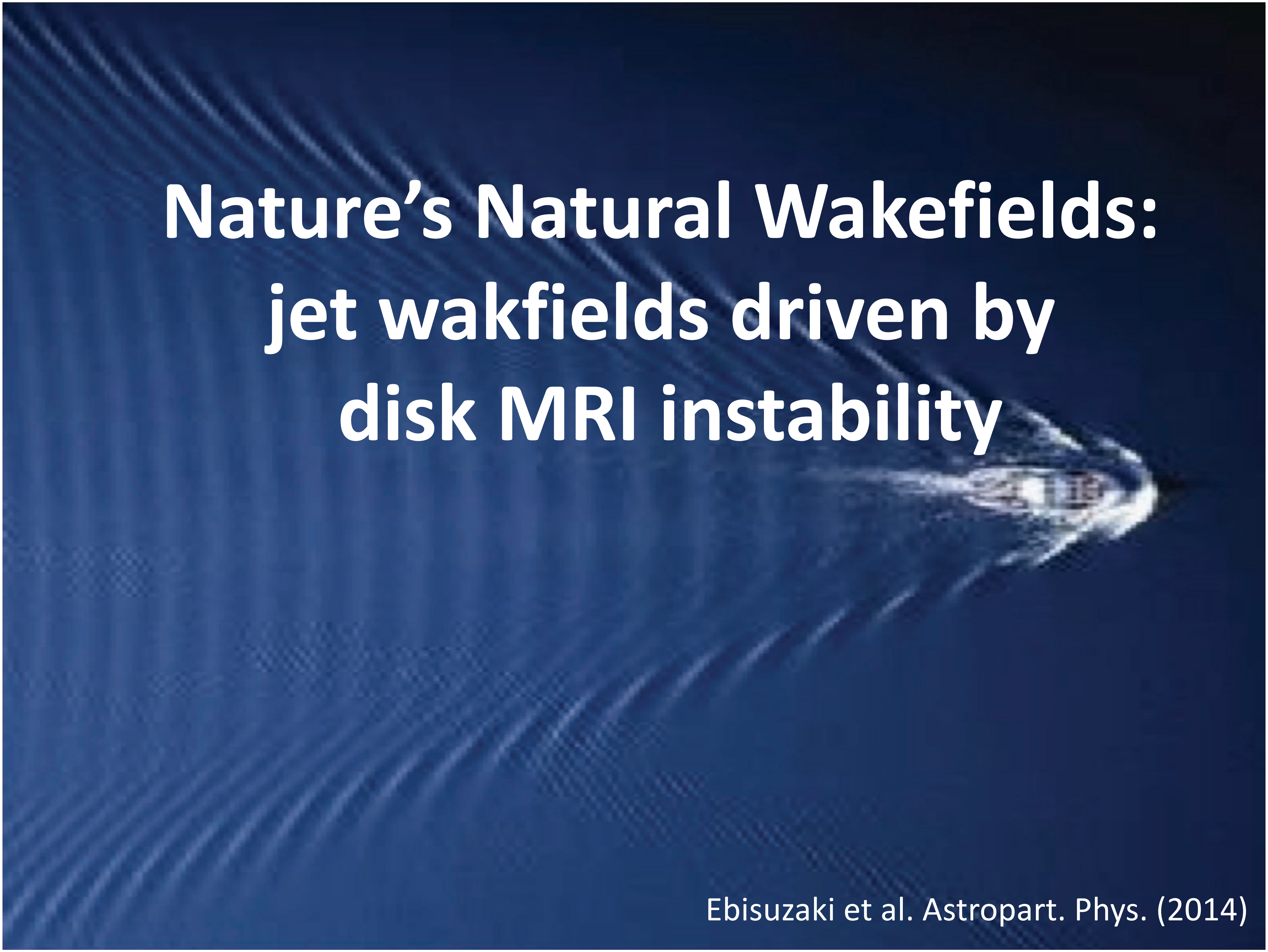
Also indispensable for toilet science (later)



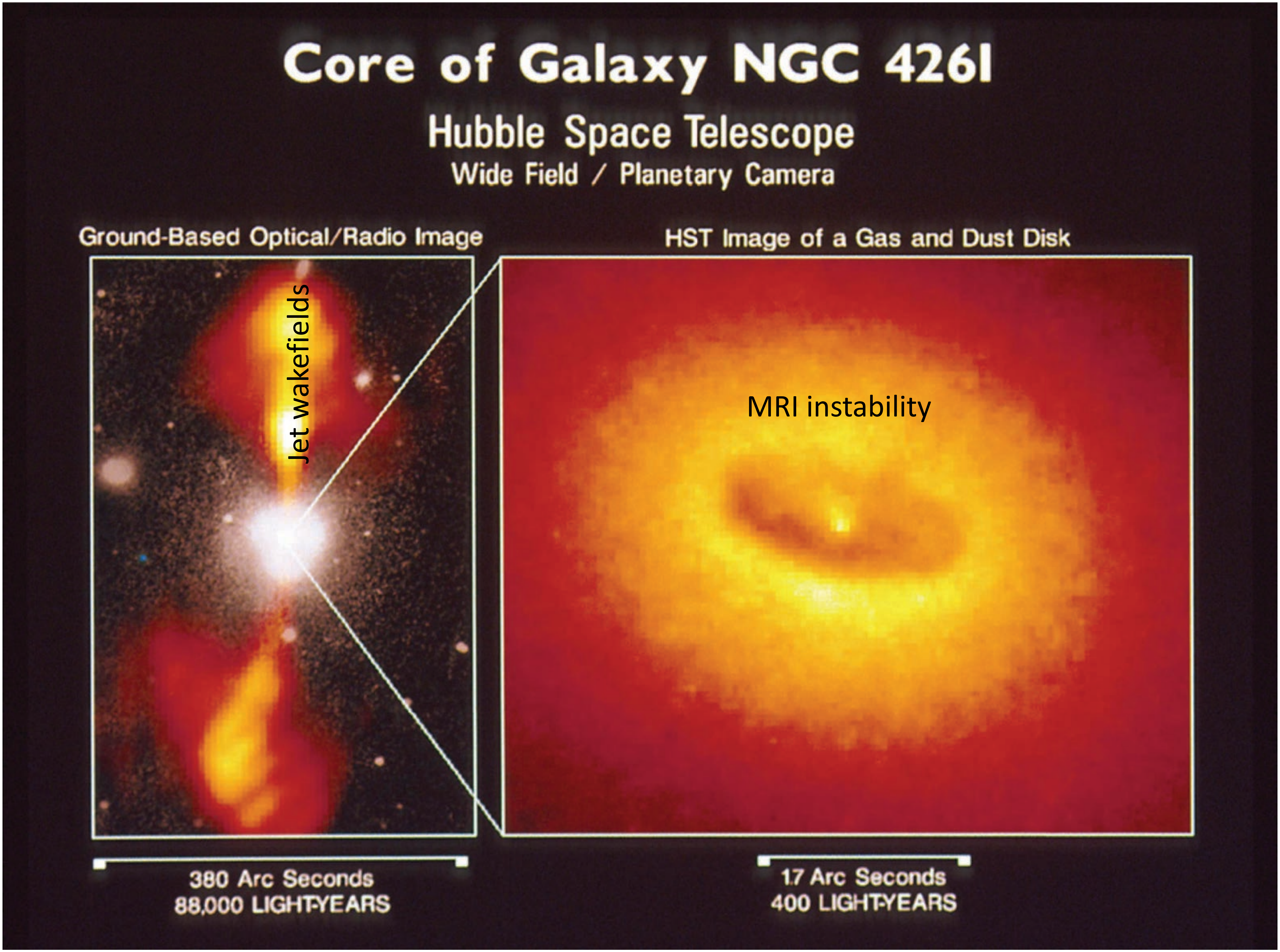


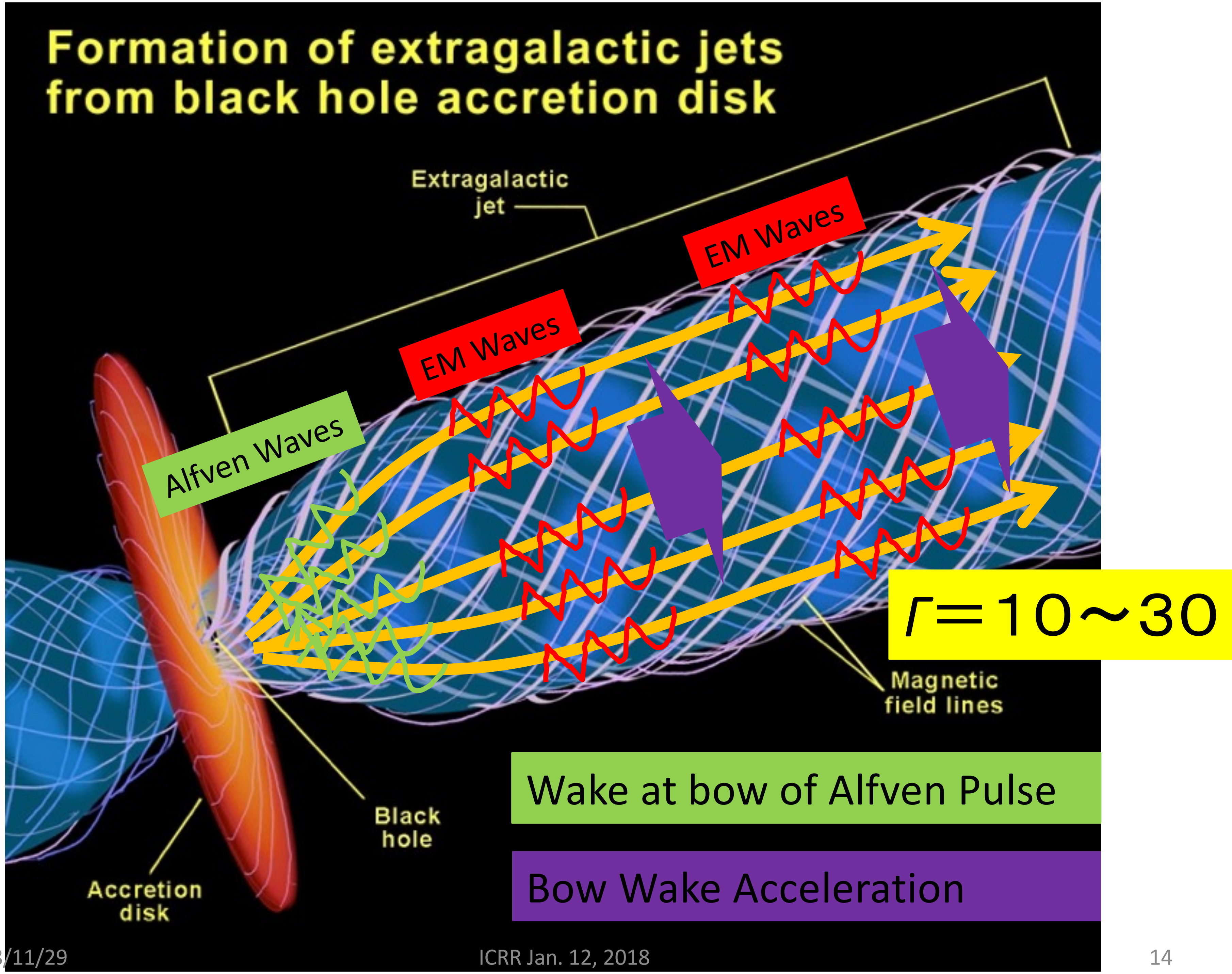
Mourou*, Brocklesby, Tajima, Limpert, Nature Photonics (2013)

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



Ebisuzaki et al. Astropart. Phys. (2014)


Core of Galaxy NGC 4261
Hubble Space Telescope
Wide Field / Planetary Camera
Ground-Based Optical/Radio Image
HST Image of a Gas and Dust Disk
Jet wakefields
MRI instability
380 Arc Seconds
88,000 LIGHT-YEARS
1.7 Arc Seconds
400 LIGHT-YEARS


Formation of extragalactic jets from black hole accretion disk
Extragalactic jet
EM Waves
EM Waves
Alfven Waves
Γ=10～30
Magnetic field lines
Black hole
Accretion disk
Wake at bow of Alfven Pulse
Bow Wake Acceleration

Anti-correlation between **Luminosity** and **Power index** from **Blazars**

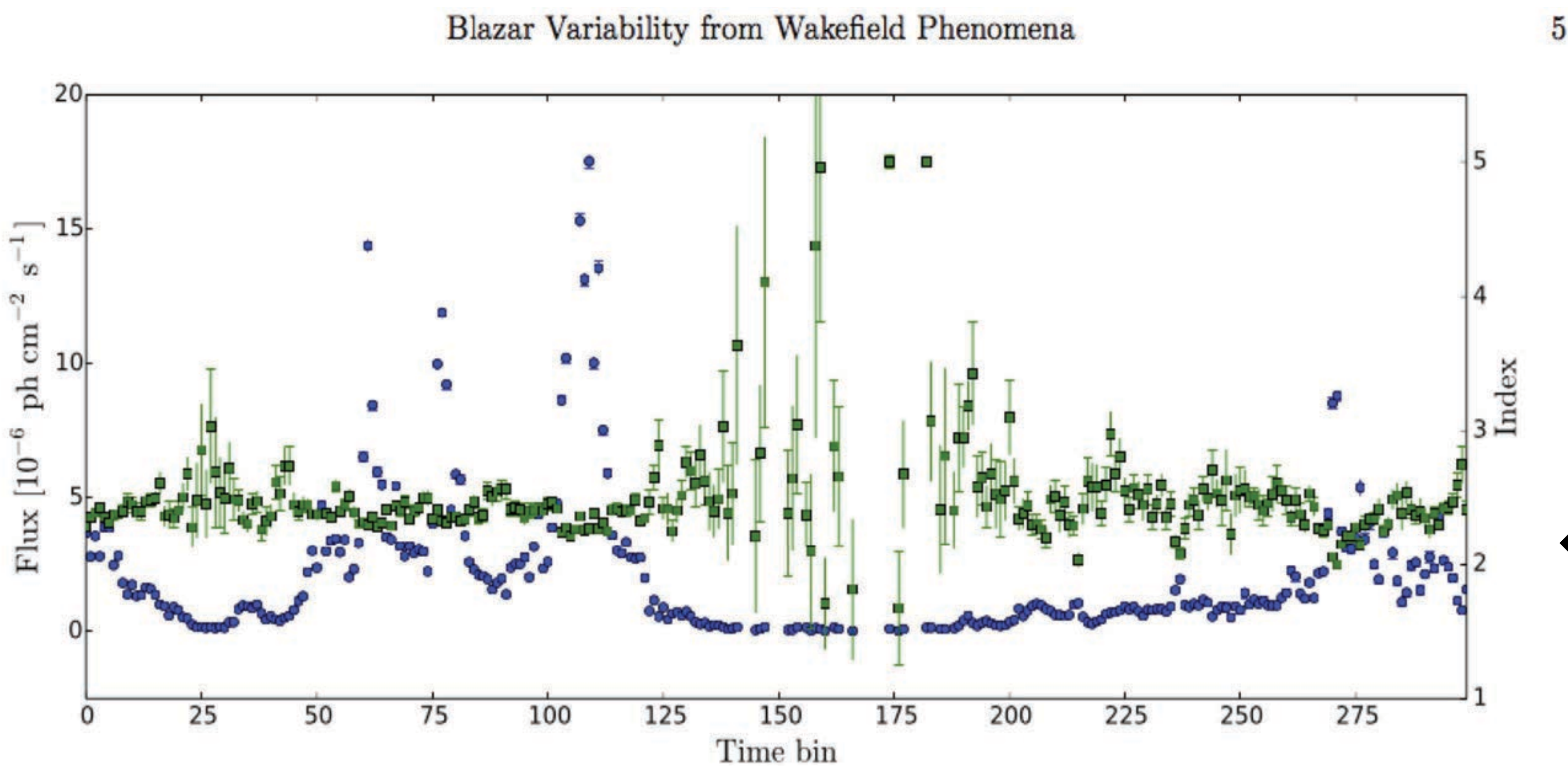
Anti-correlation of
Luminosity ***L*** of gamma-ray and
Power index ***p*** in time

↑

Wakefield theory anticipated(Ebisuzaki-Tajima 2014)

Power index ***p*** vs.
Luminosity ***L*** for several
Blazars (more in **Abazajian**
et al. arXiv **2018**)

L



p

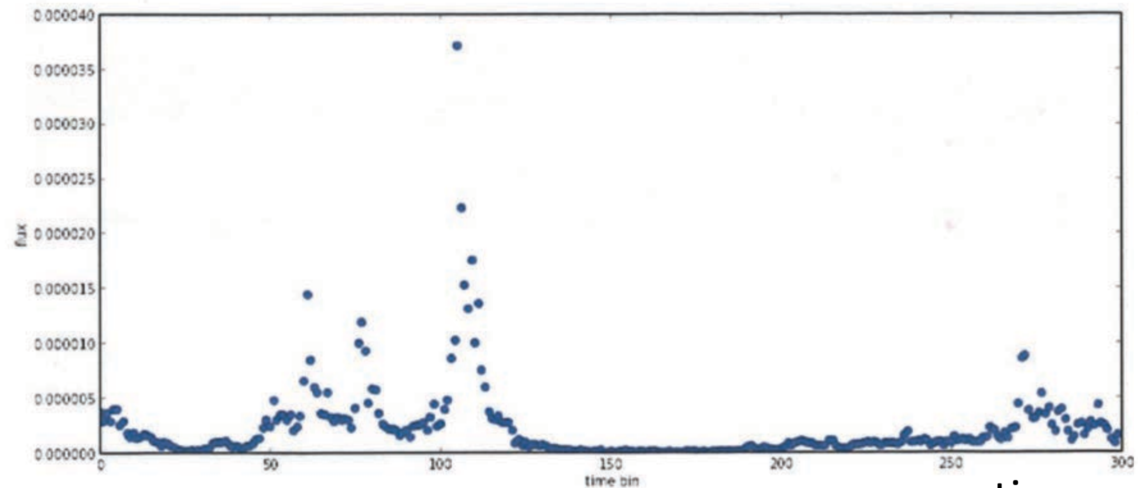
← *p=2*

Luminosity of gamma ray emission and spectrum

AGN 3C454.3 with M = $10^7 M_{\odot}$

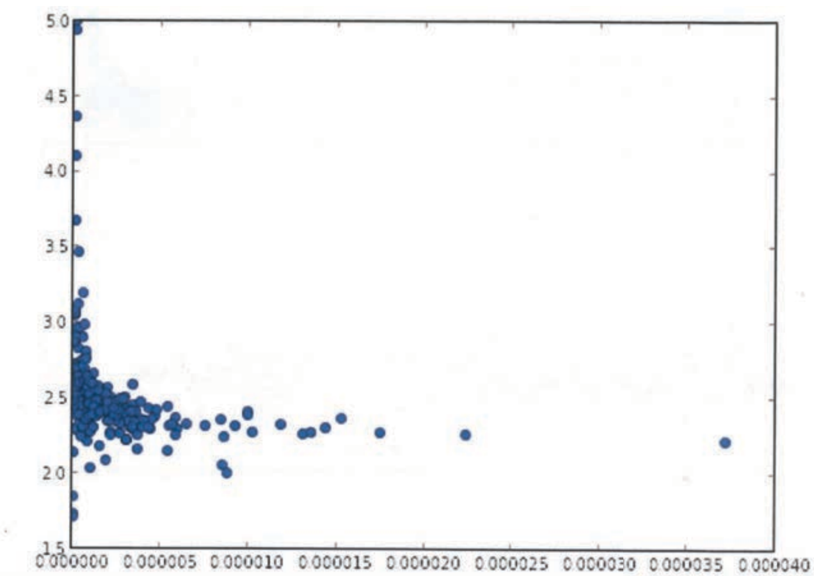
Strong accretion
→ strong wakefield

Luminosity L



time

Spec. Index p



← $p=2$

Luminosity L

Ideal episode for wakefield:
index $p = 2$,
Otherwise $p > 2$
(Mima, Tajima, Hasegawa 1991; Takahashi, Hillman, Tajima 2000, Ebisuzaki, Tajima 2014)

Gravitational wave and Gamma bursts

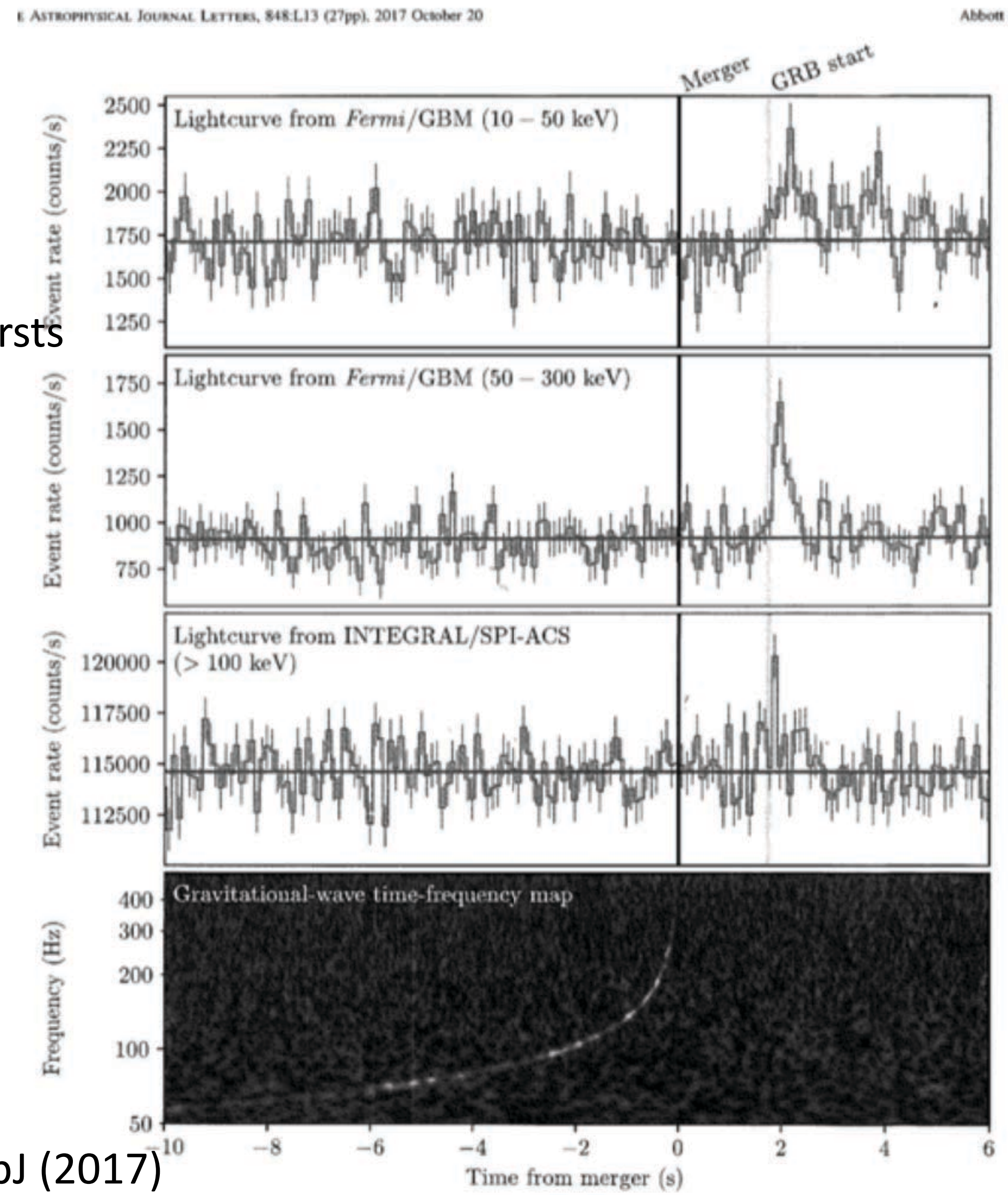
Fermi satellite x LIGO

- gamma bursts →
- **GW** synchronize precedes gamma bursts

see (Ebisuzaki et al, 2014)
Neutron star-Neutron star collision
→ similar wakefields
(Takahashi et al. 2000)

Simultaneous **Gravitational Waves****
(Barish** at UCI, 2018) →
(delayed by ~ 1 sec)

**) Nobel in Physics (2017)



Abbott et al. ApJ (2017)

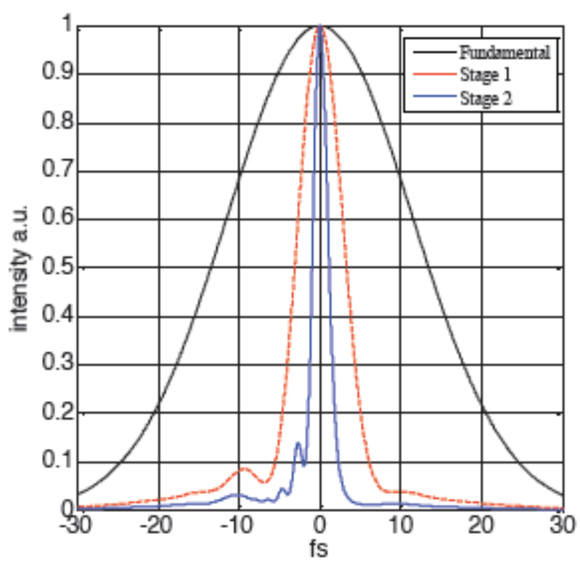
Thin Film Compression and CAIL, and Toilet Science

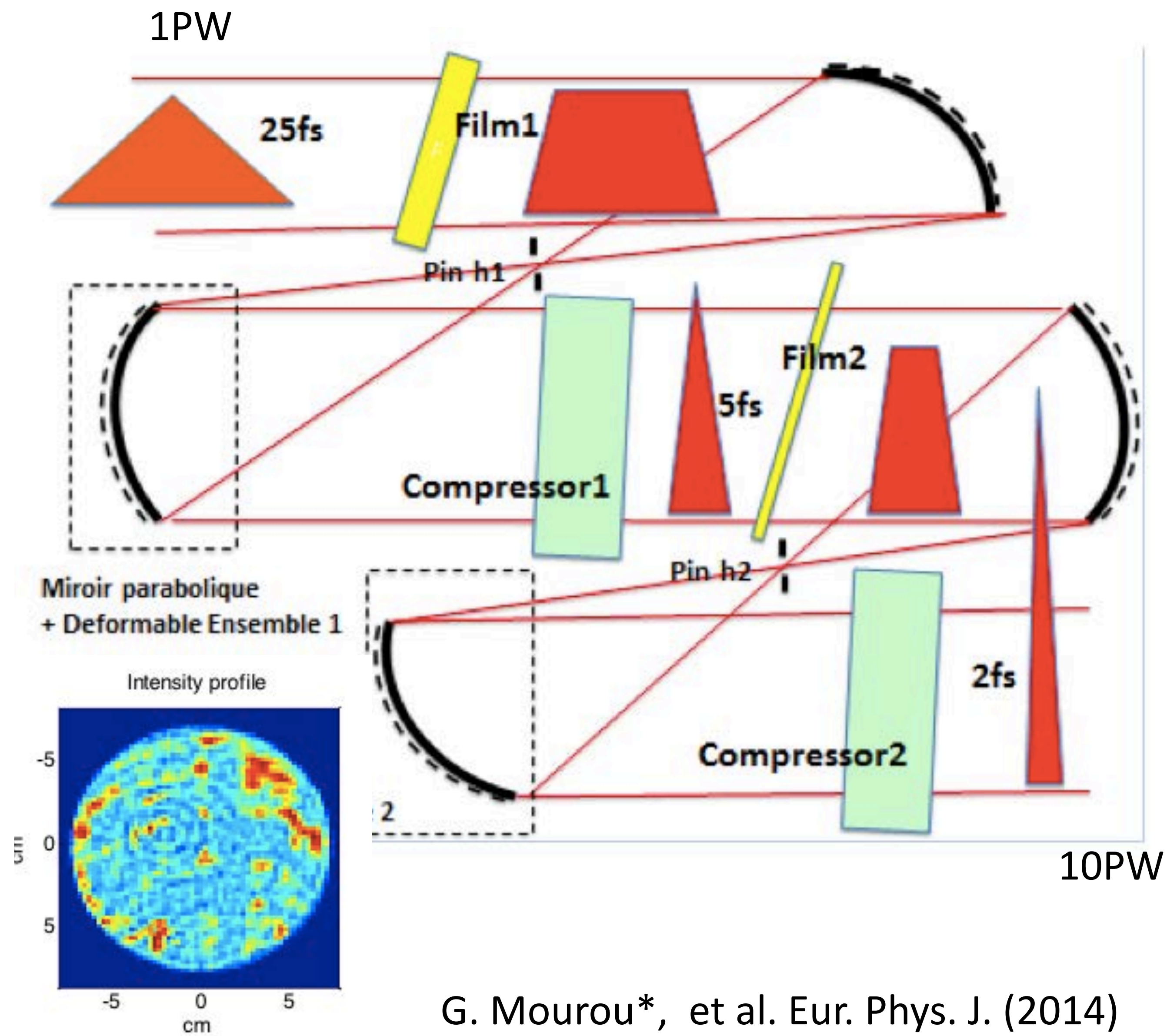
Mourou* et al. (2014)

Single-cycle laser (new Thin Film Compression)

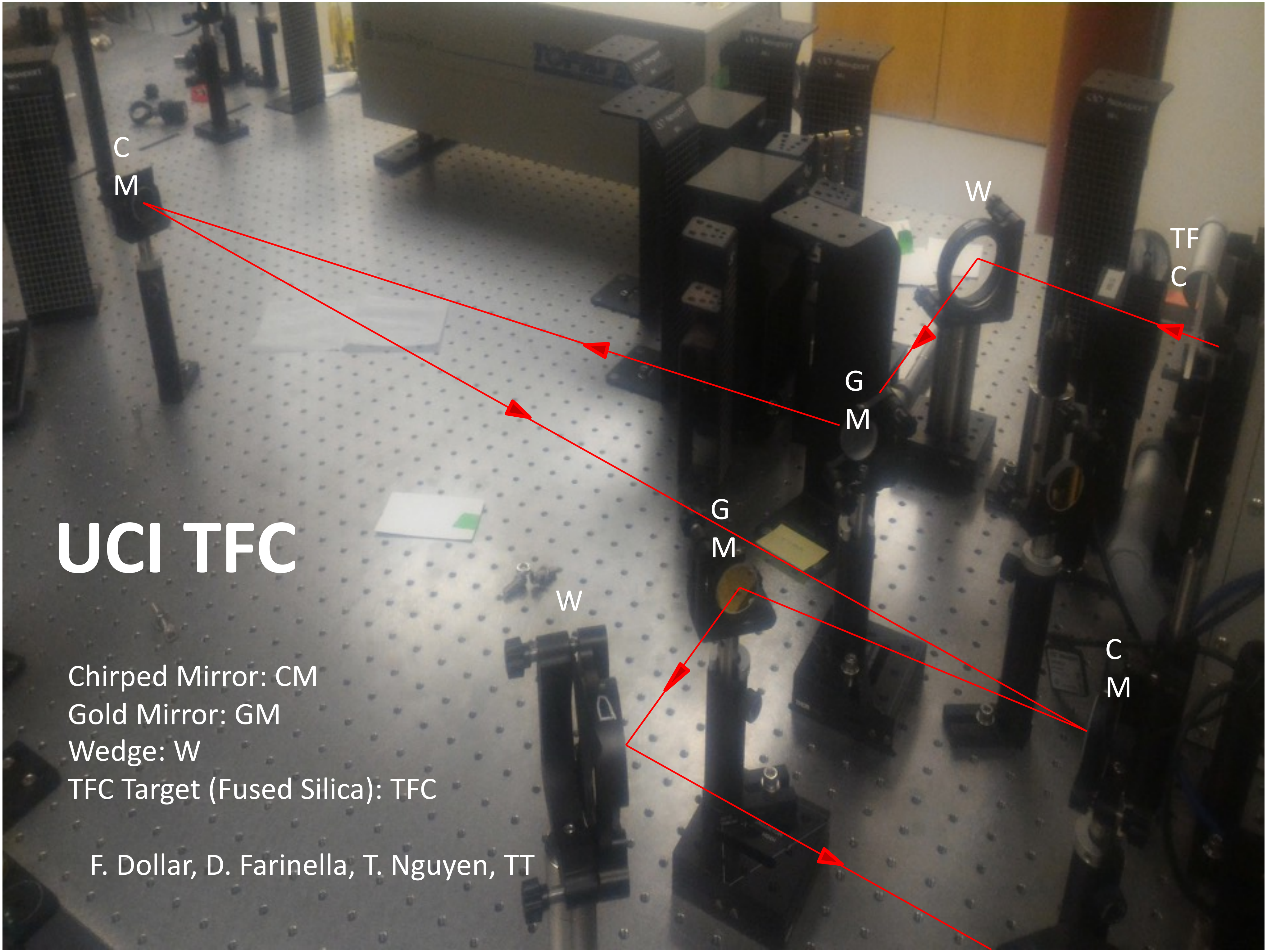
Laser power = energy / pulse lnegth

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



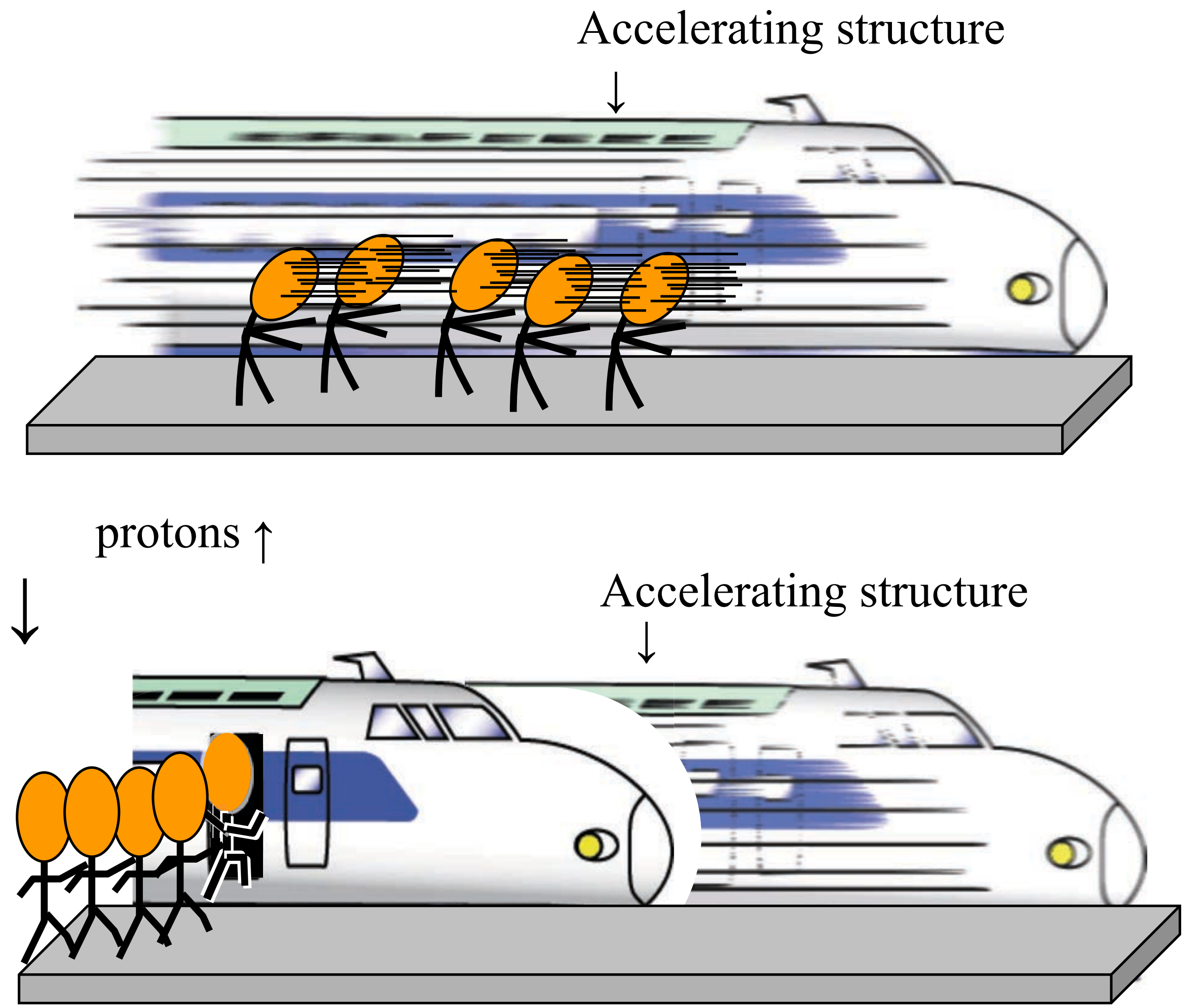


G. Mourou*, et al. Eur. Phys. J. (2014)


UCI TFC
C
M
W
TF
C
G
M
G
M
W
C
M
Chirped Mirror: CM
Gold Mirror: GM
Wedge: W
TFC Target (Fused Silica): TFC
F. Dollar, D. Farinella, T. Nguyen, TT

Adiabatic (Gradual) Acceleration

from #1 lesson of Mako-Tajima problem (1978)

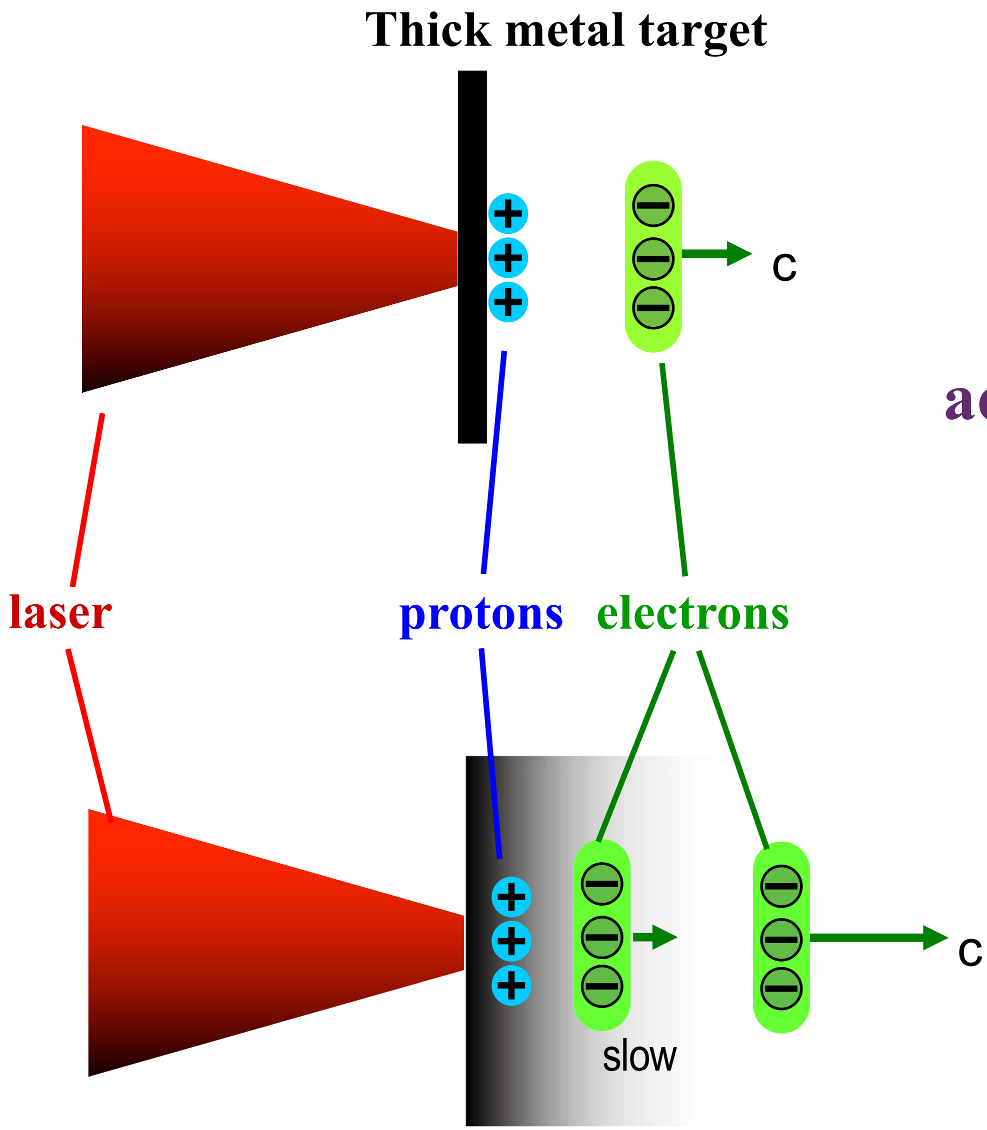


Inefficient if <u>suddenly</u> accelerated

Efficient when <u>gradually</u> accelerated

Lesson #1: gradual acceleration → Relevant for ions

Adiabatic (Shinkansen) acceleration (2)



Graded, thin (nm), or clustered target and/or circular polarization

Most experimental configurations of proton acceleration(2000-2009)

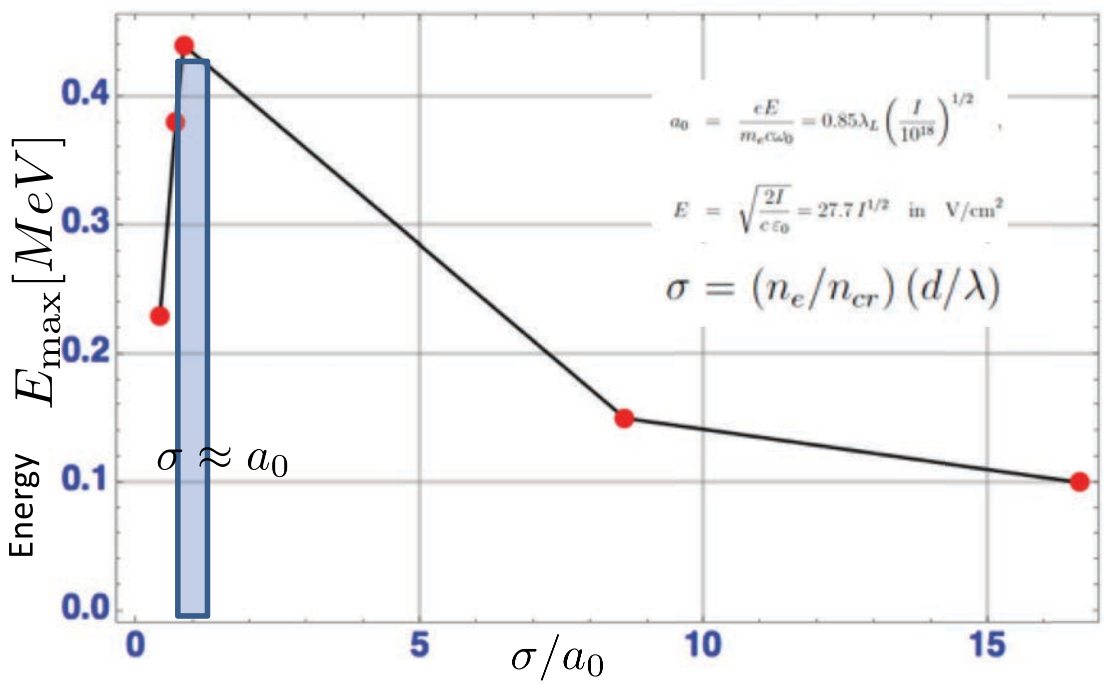
Innovation ("Adiabatic Acceleration")
(CAIL, 2009-)

= Method to make the electrons within ion trapping width

Target thickness scales with a_0

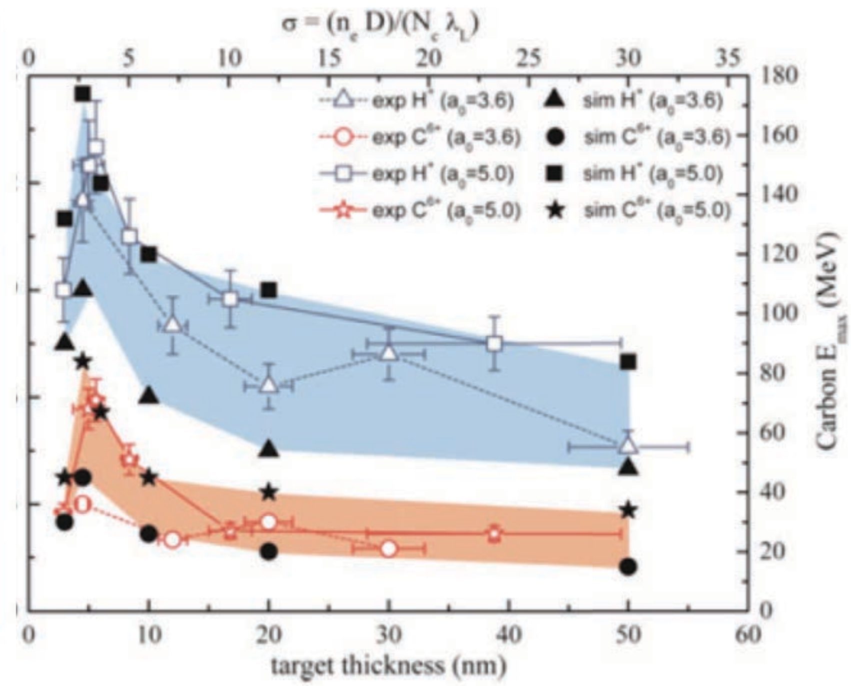
Coherent Acceleration of Ions by Laser (CAIL)

Deuteron energy vs. thickness of foil



target thickness [normalized to laser intensity]

Our simulation



Experiment: Steinke (2010)

Optimum parameters (sweet-spot) for ion acceleration at $\sigma \approx a_0$

Necas (2018)

自己責任を果たす新しい哲学とサイエンス

New Philosophy and Science to Fulfill Self-responsibility

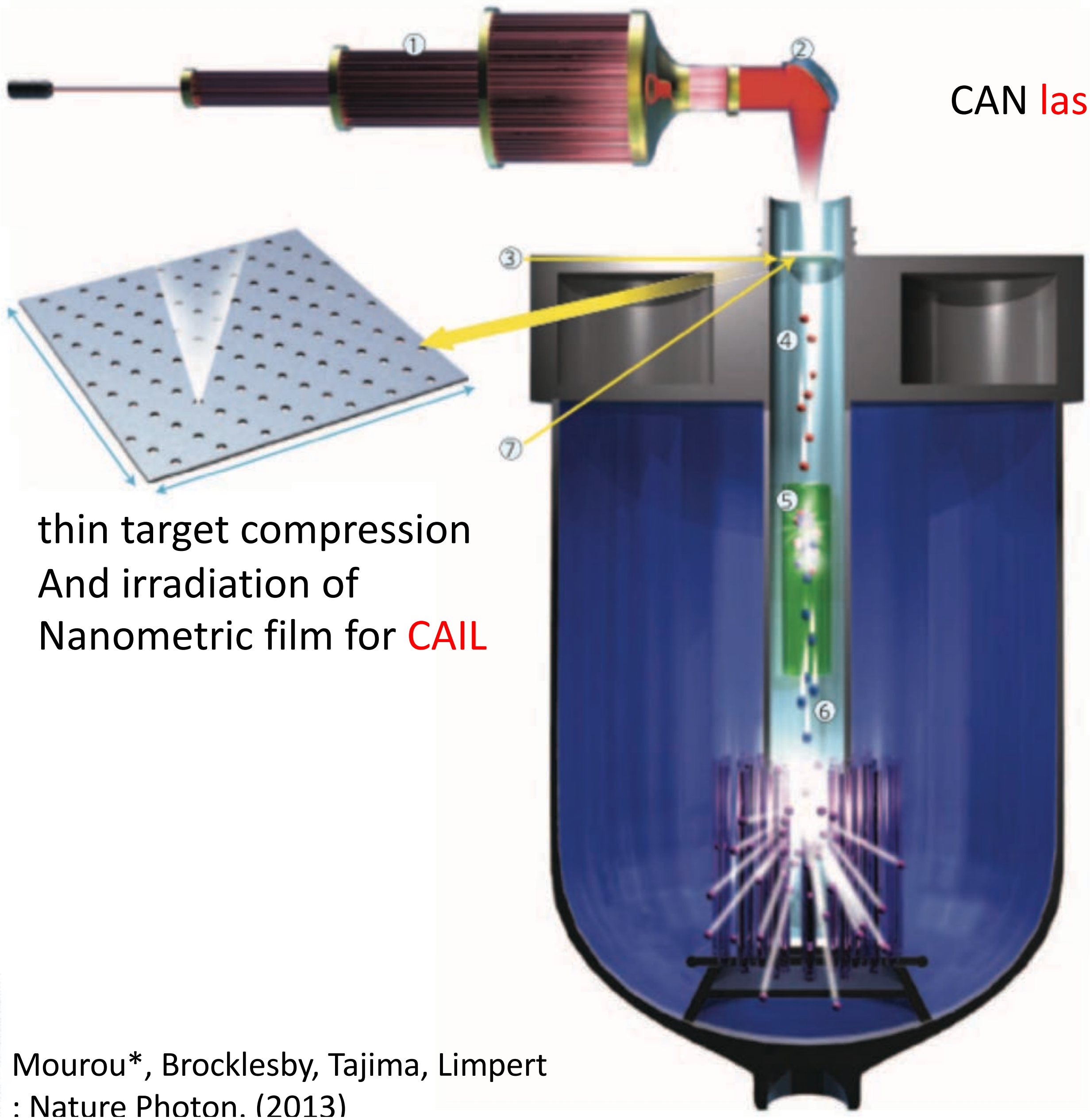
20^{th} Century:
Science of Discovery

↓

21^{st} Century:
Toilet Science:
Responsive to societal issues self-inflicted

Tajima
(Jan. 18,2005)

Toilet Science with CAN laser :
Coherent Acceleration of Ions by Laser (CAIL)



CAN laser

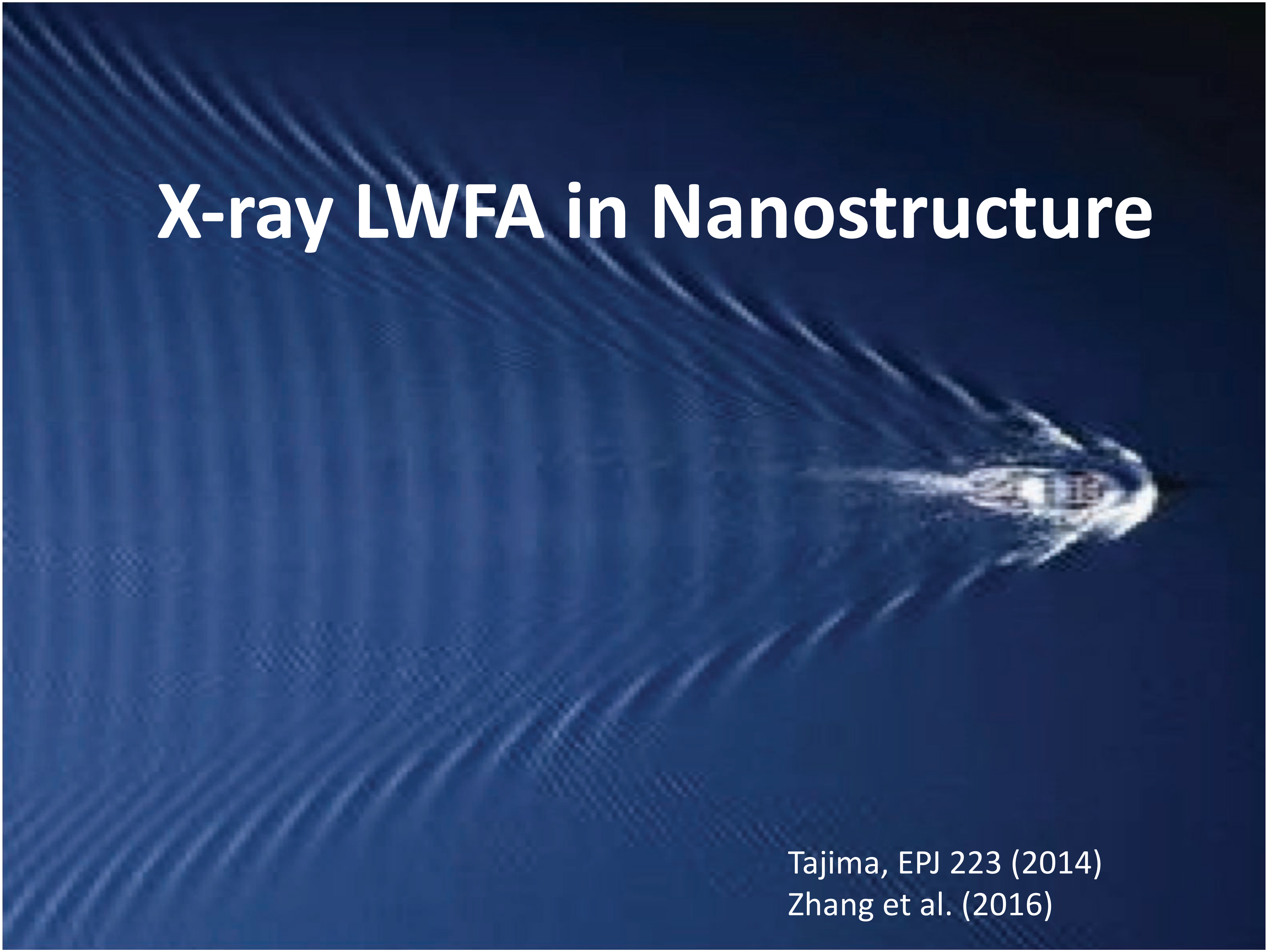
thin target compression
And irradiation of
Nanometric film for CAIL

Transmutator of nuclear waste
by neutrons
(Tajima, Necas, Mourou*, Gales,
Leroy, 2018)

generated with deuteron
acceleration by CAIL
(Tajima, Yan, Habs, 2010)

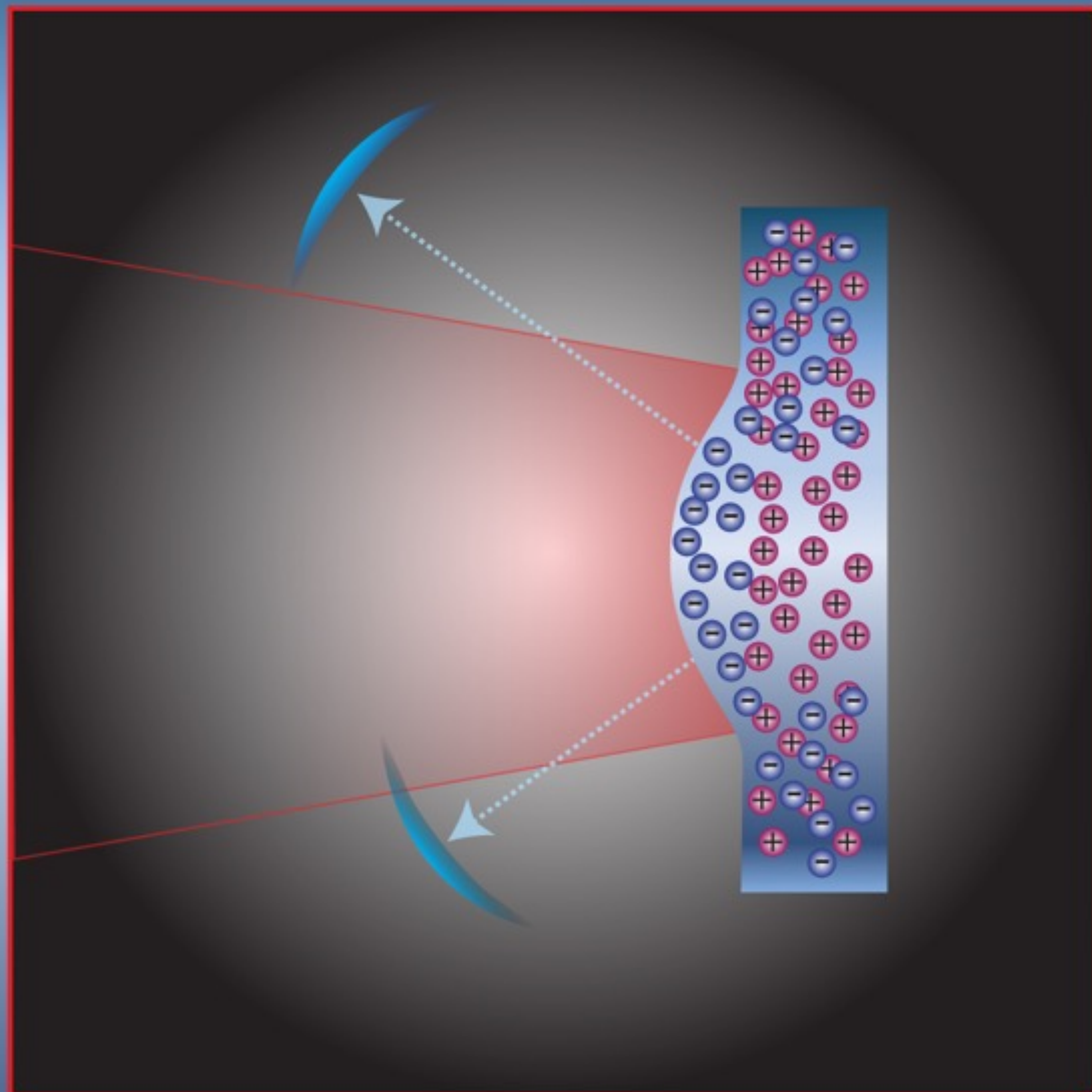
Mourou*, Brocklesby, Tajima, Limpert
: Nature Photon. (2013)

X-ray LWFA in Nanostructure

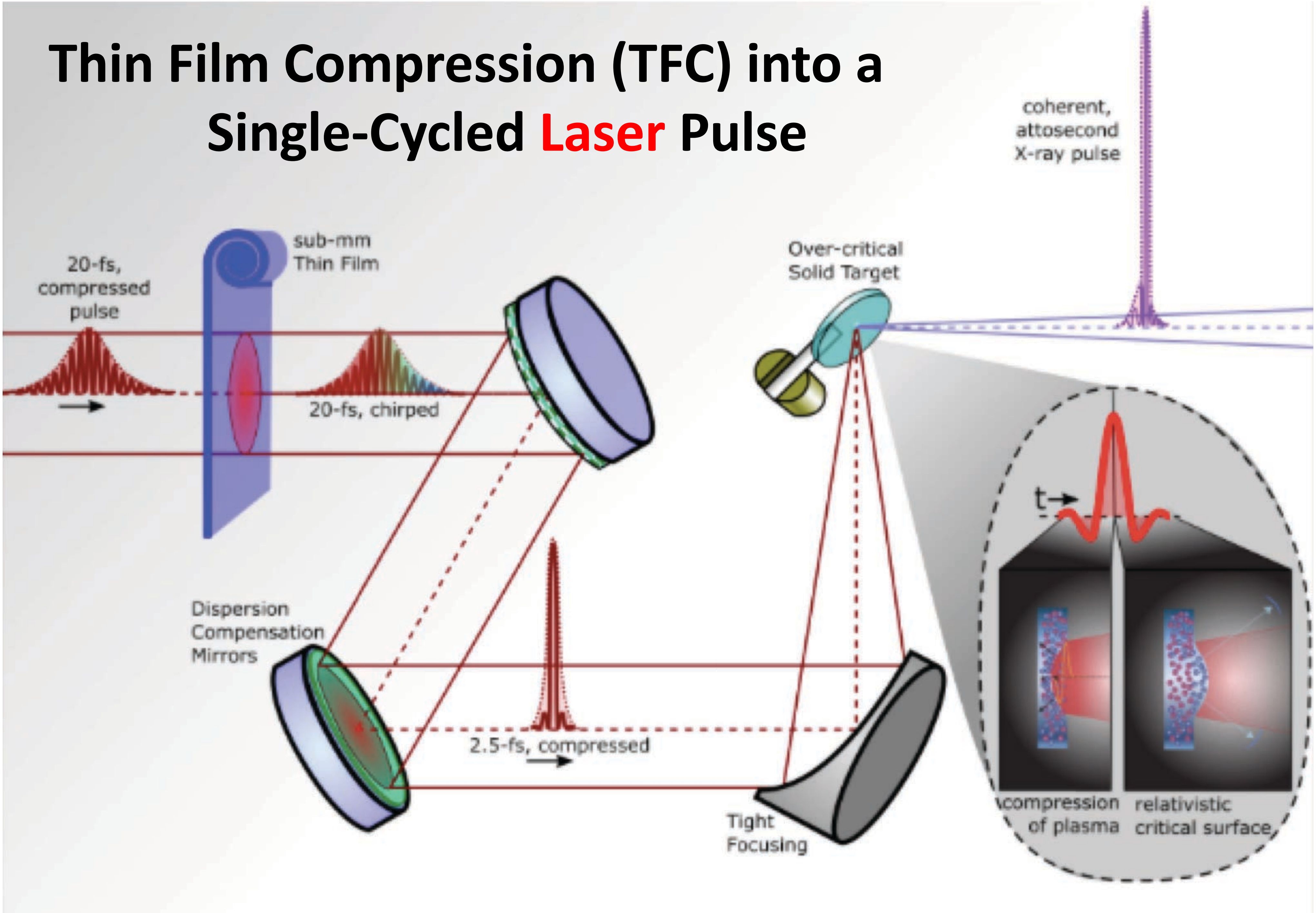


Tajima, EPJ 223 (2014)
Zhang et al. (2016)

Relativistic Compression



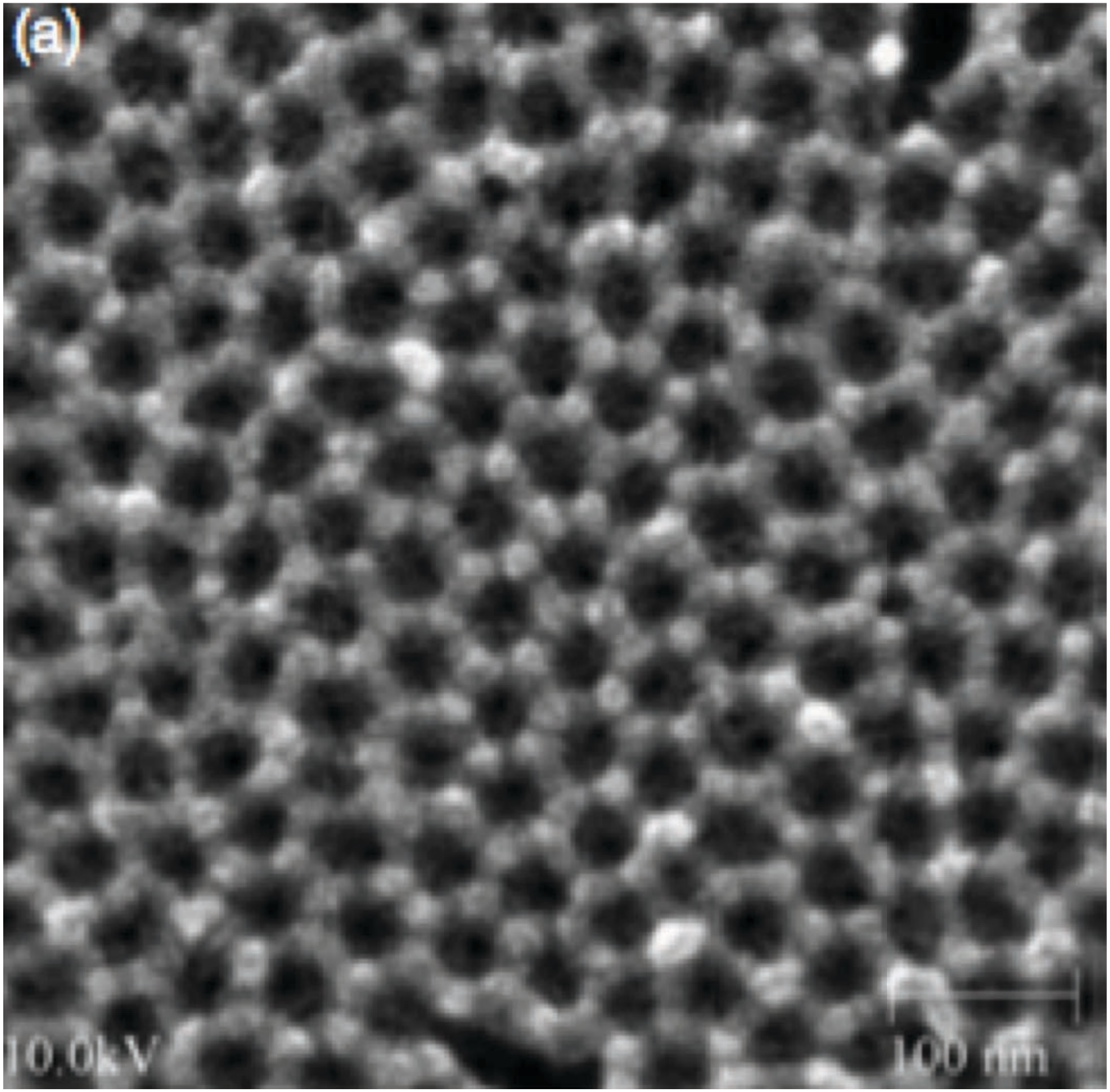
Thin Film Compression (TFC) into a Single-Cycled Laser Pulse



Mourou* , Brocklesby, Tajima, Limpert (2014)

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 alimina on Si substrate Nanotech. **15**, 833 (2004);

P. Taborek (UCI): porous alumina (2007)

Fermilab/UCI 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:

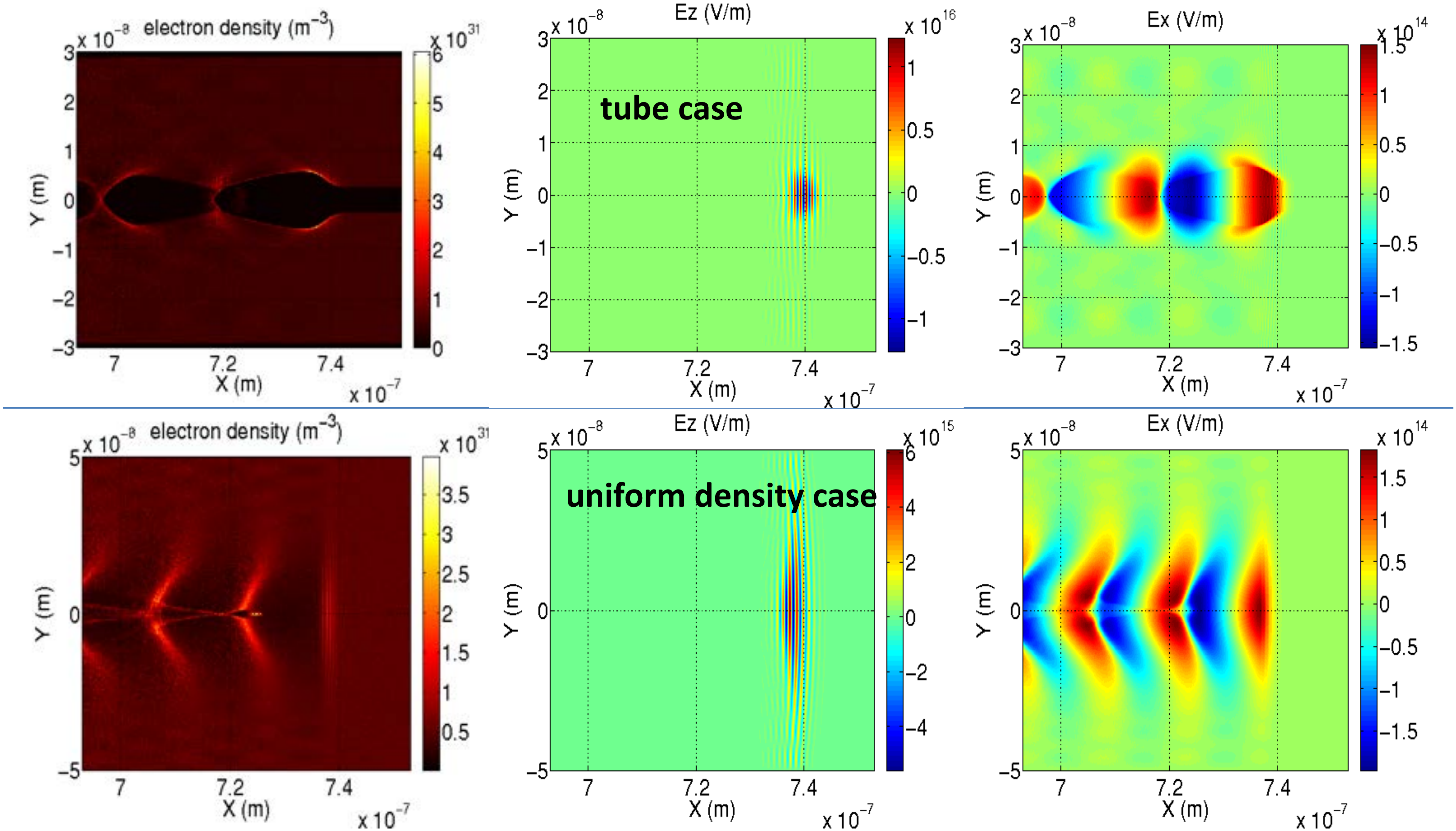
X.M. Zhang, et al.PR AB (2016)

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, Tajima,…Mourou*,… (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

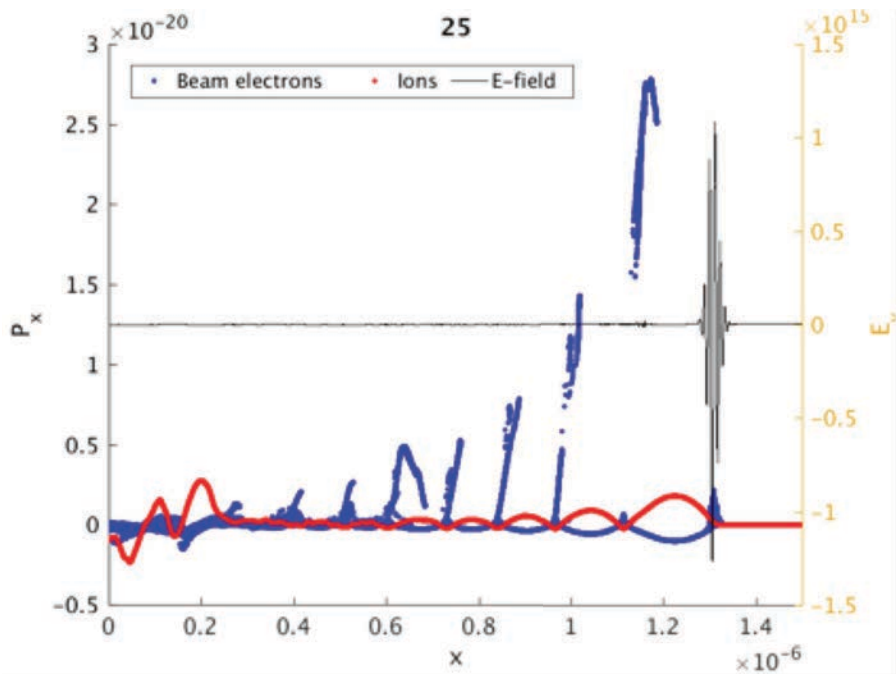
Without lattice force (i.e. plasma)

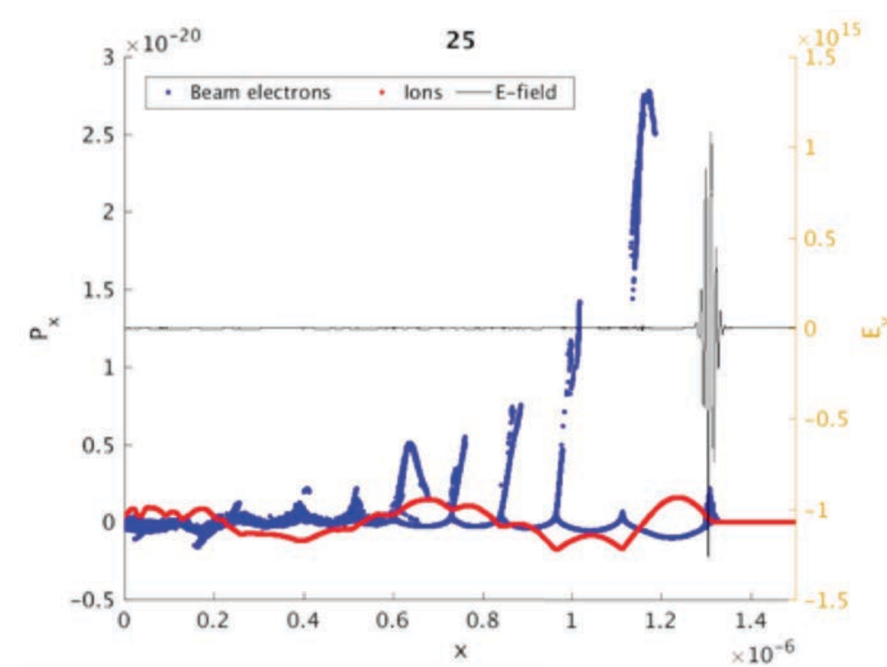
(when ω_{TO} is much smaller than ω_{pe}, there is no noticeable difference from the below where $\omega_{TO} = 0$)

With lattice force (optical phonon branch present)

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

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

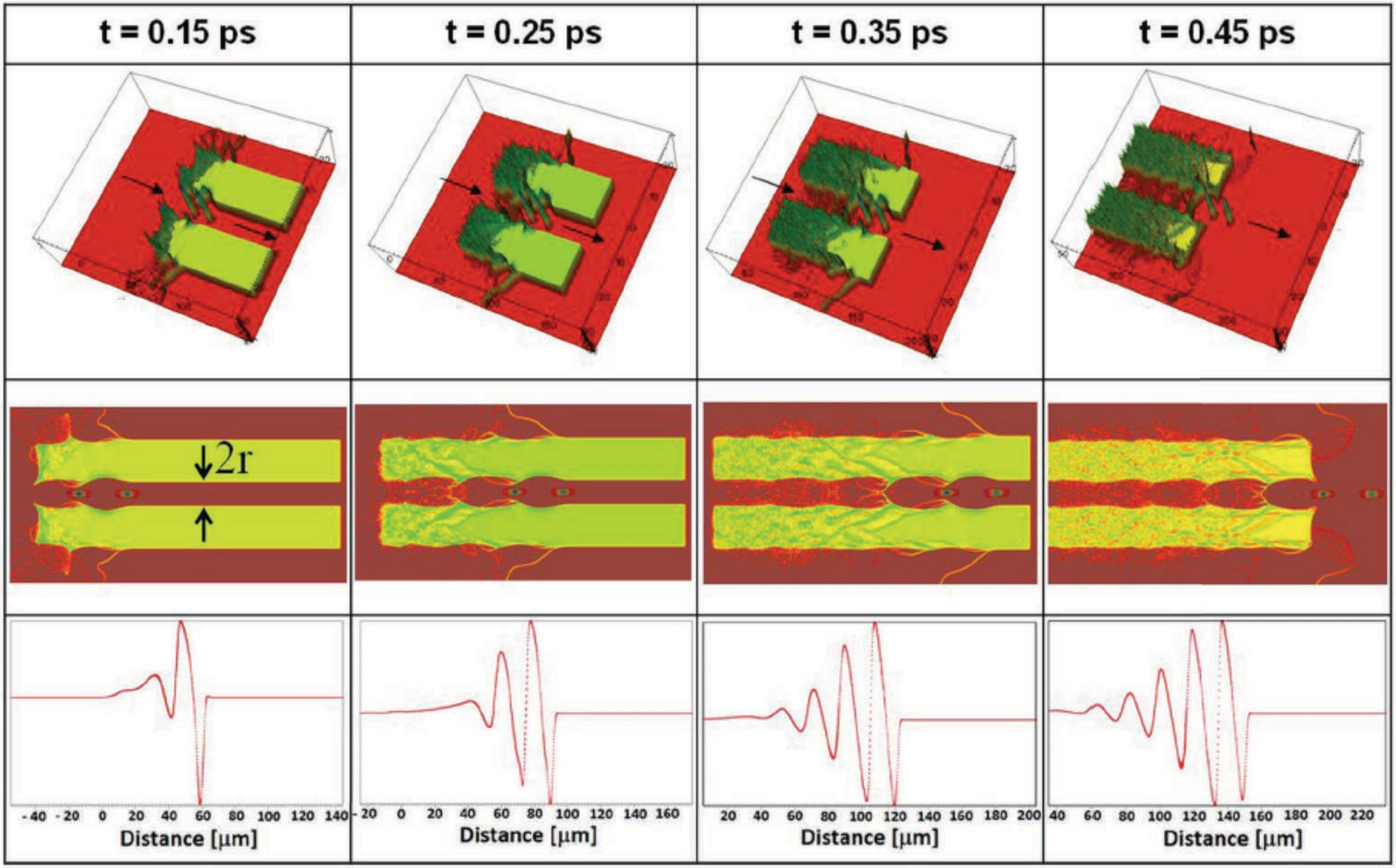




S. Hakimi, et al. (2017)

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's** natural and **ubiquitous** creation: jets from Blackhole (AGN) driven by **MRI instability** of the accretion disk, NS-NS collisions
- **Gamma rays bursts** (TeV), flares, **Cosmic rays** (ZeV): simultaneous observations

  (sometimes with **GW** → Barish**'s **LIGO** observation of GW)
- Toilet Science: efficient ion acceleration for **transmutation**
- 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
- **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 (medical, Toilet Science,…)
- **Laser acceleration**: stimulated high field science laser technologies (**CPA***, **RC, CAN**, **TFC**, …)


Thank you!
You taught me.
You nurtured me.
兼六の
十月桜
吾を迎ふ
感謝と誓ひ
砂利踏みしめたり
（11/11/2018,俊樹）