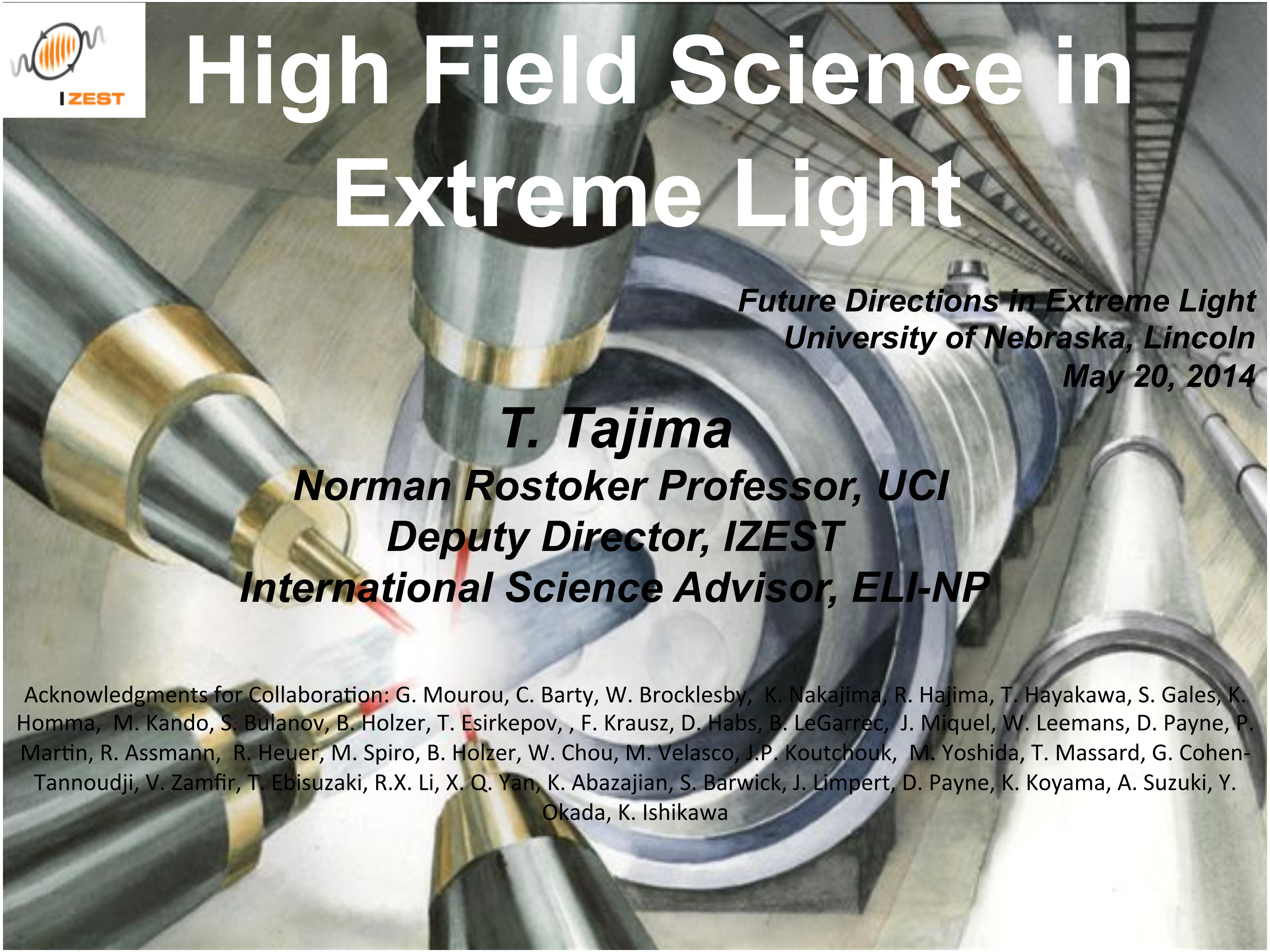


High Field Science in Extreme Light

Future Directions in Extreme Light
University of Nebraska, Lincoln
May 20, 2014

T. Tajima

Norman Rostoker Professor, UCI
Deputy Director, IZEST
International Science Advisor, ELI-NP

Acknowledgments for Collaboration: G. Mourou, C. Barty, W. Brocklesby, K. Nakajima, R. Hajima, T. Hayakawa, S. Gales, K. Homma, M. Kando, S. Bulanov, B. Holzer, T. Esirkepov, , F. Krausz, D. Habs, B. LeGarrec, J. Miquel, W. Leemans, D. Payne, P. Martin, R. Assmann, R. Heuer, M. Spiro, B. Holzer, W. Chou, M. Velasco, J.P. Koutchouk, M. Yoshida, T. Massard, G. Cohen-Tannoudji, V. Zamfir, T. Ebisuzaki, R.X. Li, X. Q. Yan, K. Abazajian, S. Barwick, J. Limpert, D. Payne, K. Koyama, A. Suzuki, Y. Okada, K. Ishikawa

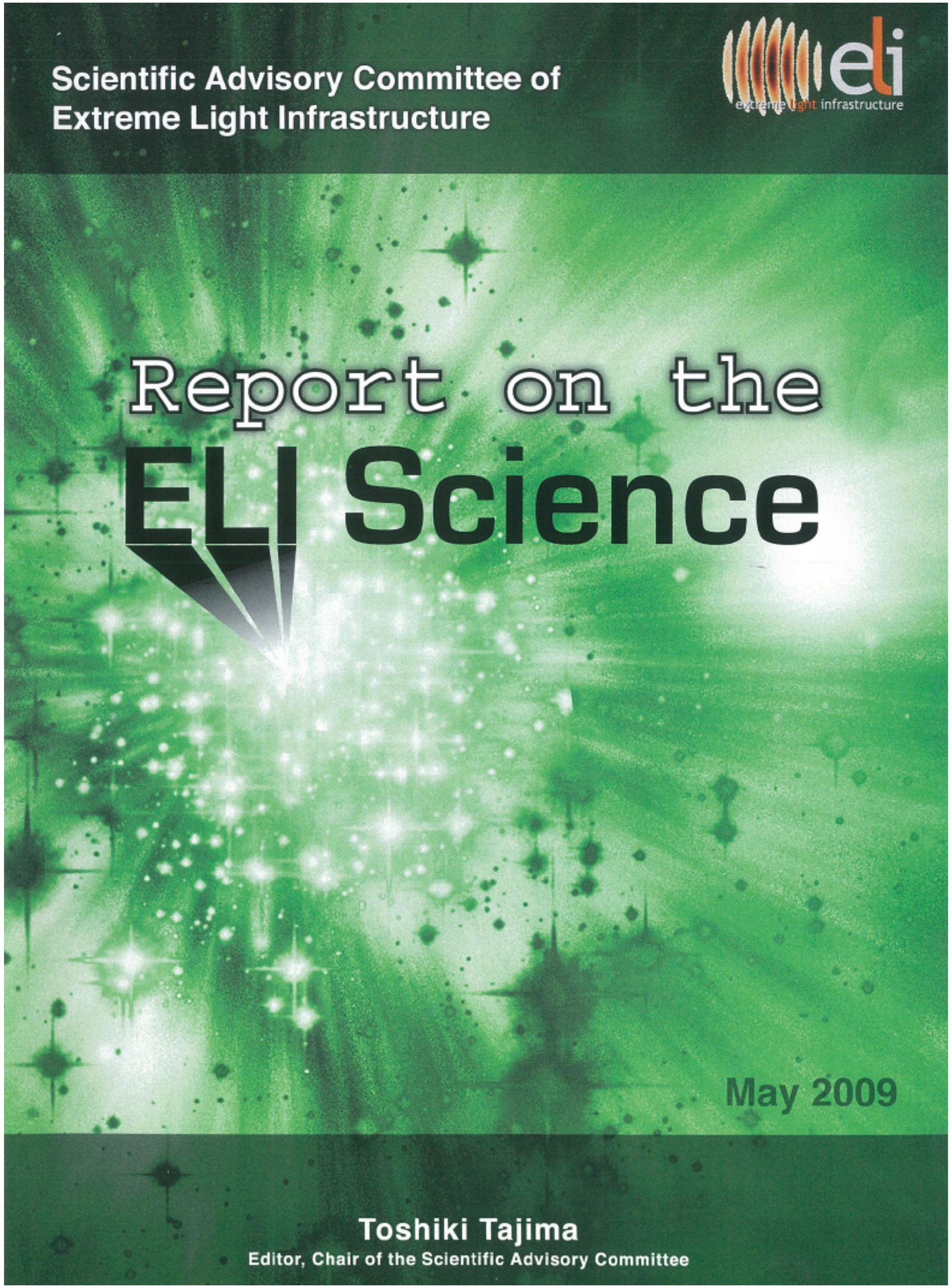
content

- High fields that break matter, but keep order

  Guiding principle for order: not atomic cohesion (quantum coherence), but relativistic coherence (and plasma's collective eigenmodes)

  →laser plasma acceleration, plasma decelerator, plasma optics,…
- Extreme laser : intensity and frequency [from optics to **X-rays**]
- Extreme laser: high rep rate and high efficiency [fiber laser (CAN)]
- European challenges: ELI (Extreme Light Infrastructure), IZEST (International Center for Zetta- Exawatt Science and Technology)
- Extreme light applications: all written in ELI SAC Report + plus novel applications------

  EW 10keV zs X-ray lasers, compact crystal LWFA, crystal ion accelerators, crystal neutron sources, portable crystal muon / neutrino sources, crystal gamma ray sources, vacuum acceleration



Scientific Advisory Committee of
Extreme Light Infrastructure

Report on the
ELI Science

May 2009

Toshiki Tajima
Editor, Chair of the Scientific Advisory Committee

ELI science:

GeV acceleration of e^-, ions
fs intense X-rays / γ-rays
attosecond science
high field science

→ integration of science, rather than splitting into narrower subdisciplines

→ broadening of geographical bases in frontier science

Approval of ELI: 2011
Start of ELI centers: 2012

ELI (Extreme Light Infrastructure)-DC

ELI: € 850M ESFRI
project (2012~)

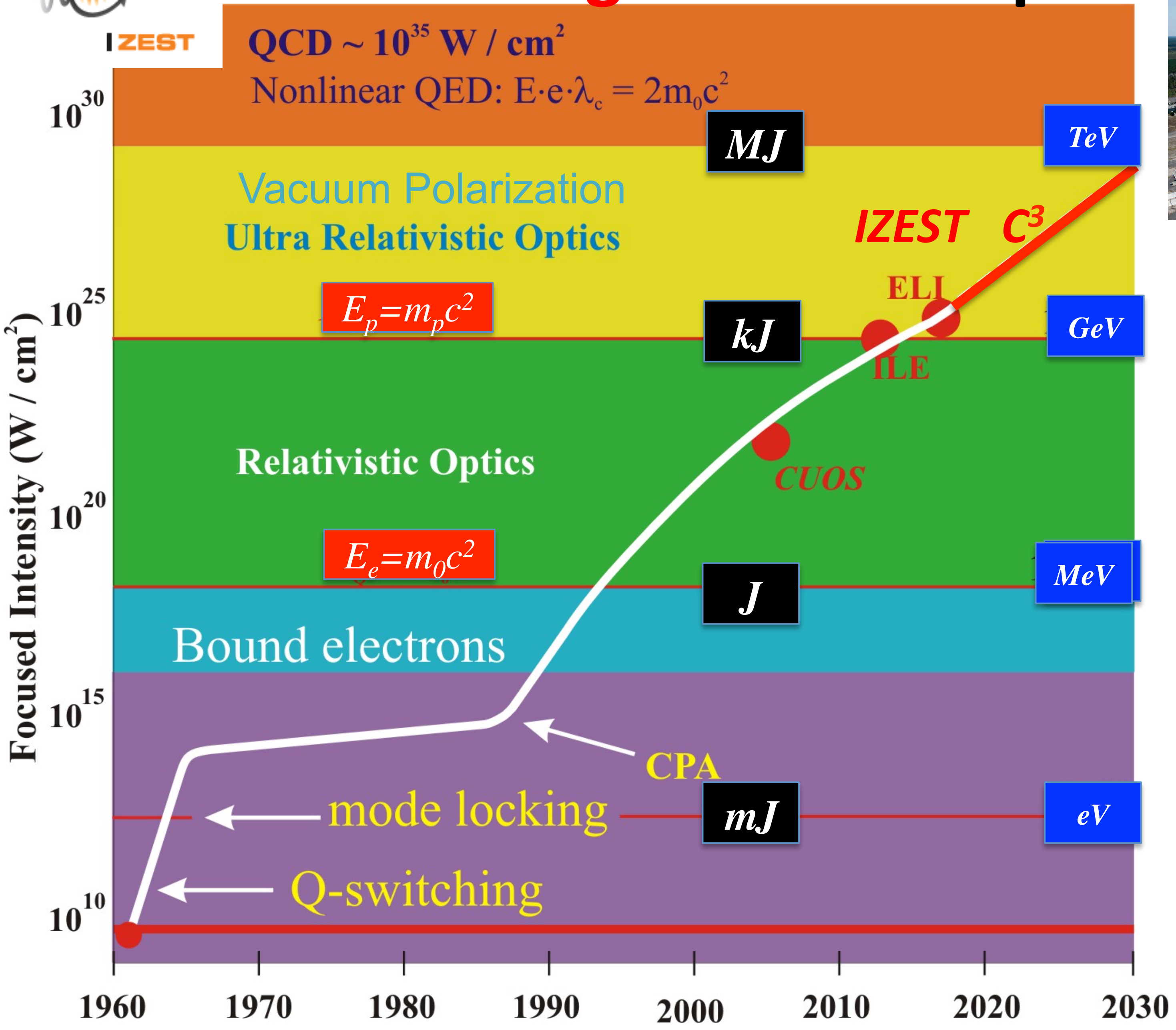
up to sub-exawatt
laser

ELI-Delivery Consortium
IA : 2013~

2014 ICUIL Greetings (excerpt):

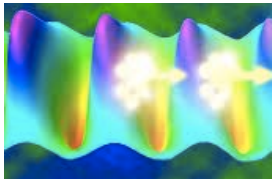
Year 2013 started with a bang to us the high intensity laser community as well. **The Extreme Light Infrastructure (ELI)-Delivery Consortium (DC) International Association** has been founded on April 11, 2013 and as Director General and CEO appointed as of July, 2013 was Professor Wolfgang Sandner, our former Co-Chair of ICUIL. As among the early birds of European ESFRI roadmap projects, ELI has started at 850M Euro budget and as of 2018 it is expected to be operational. **ELI-Beamlines, ELI-Nuclear Physics, and ELI-ALPS (attosecond science pillar)** have now already started construction and well into their way. Also in a serious launching stage is the **XCELS (Extreme Center for Exawatt Laser Science)** at the level of subexawatt (200PW). They have launched an impressive workshop "Laser Ascent to Subatomic and Applications" in Moscow as a step toward this realization in Russia. This aspires to be the fourth and final pillar of ELI, ELI-High Field Science.

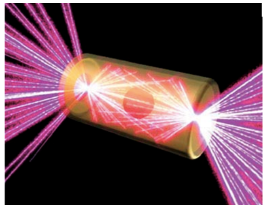
Extreme Light Road Map

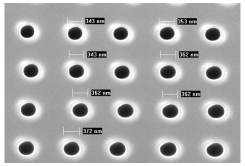



LMJ/NIF, 2MJ, 3B€

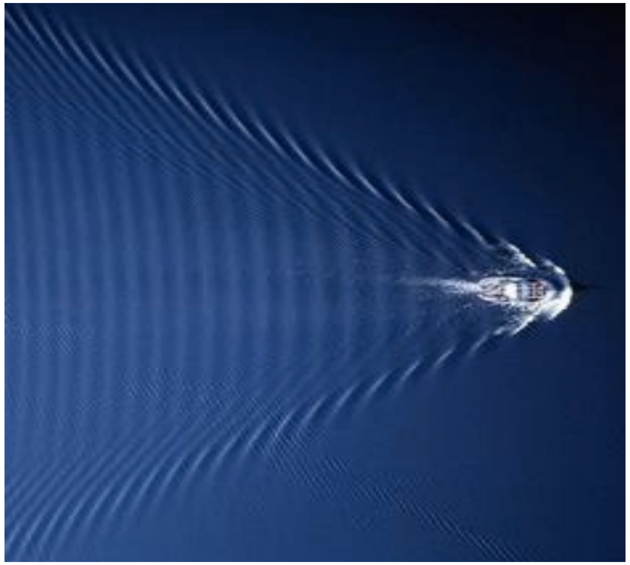

ELI, kJ 0.3 B€







Laser Wakefield (LWFA):
nonlinear optics in plasma

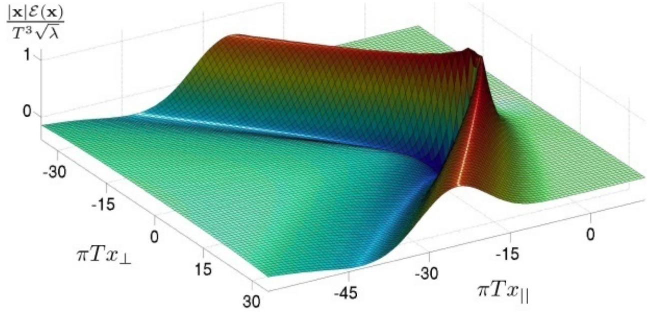


Bow ('ponderomotive')

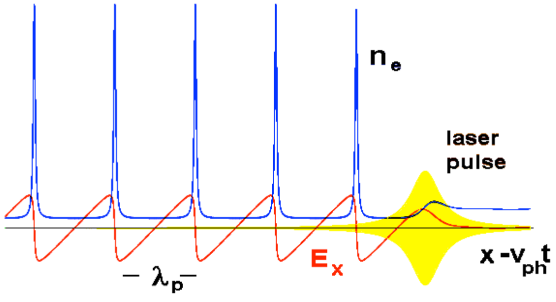
and Kelvin **wake** waves

No wave breaks and wake **peaks** at v≈c

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



Wave **breaks** at v<c



← relativity regularizes

(relativistic coherence)

(The density cusps.
Cusp singularity)

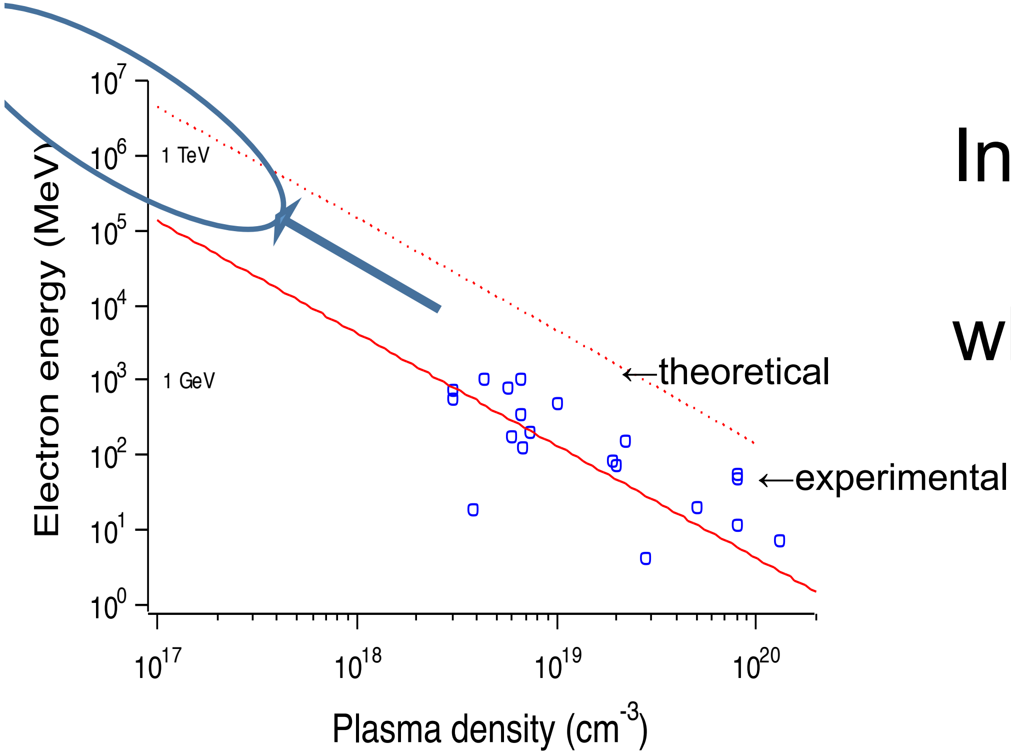
Hokusai

Maldacena

(Plasma physics vs.
Superstring theory)

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)



In order to avoid wavebreak,

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

where

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

Three ways to increase energies:

(1) Reduce density n_e

(2) Increase laser frequency or n_{cr}

(3) Increase laser intensity a_0

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

dephasing length

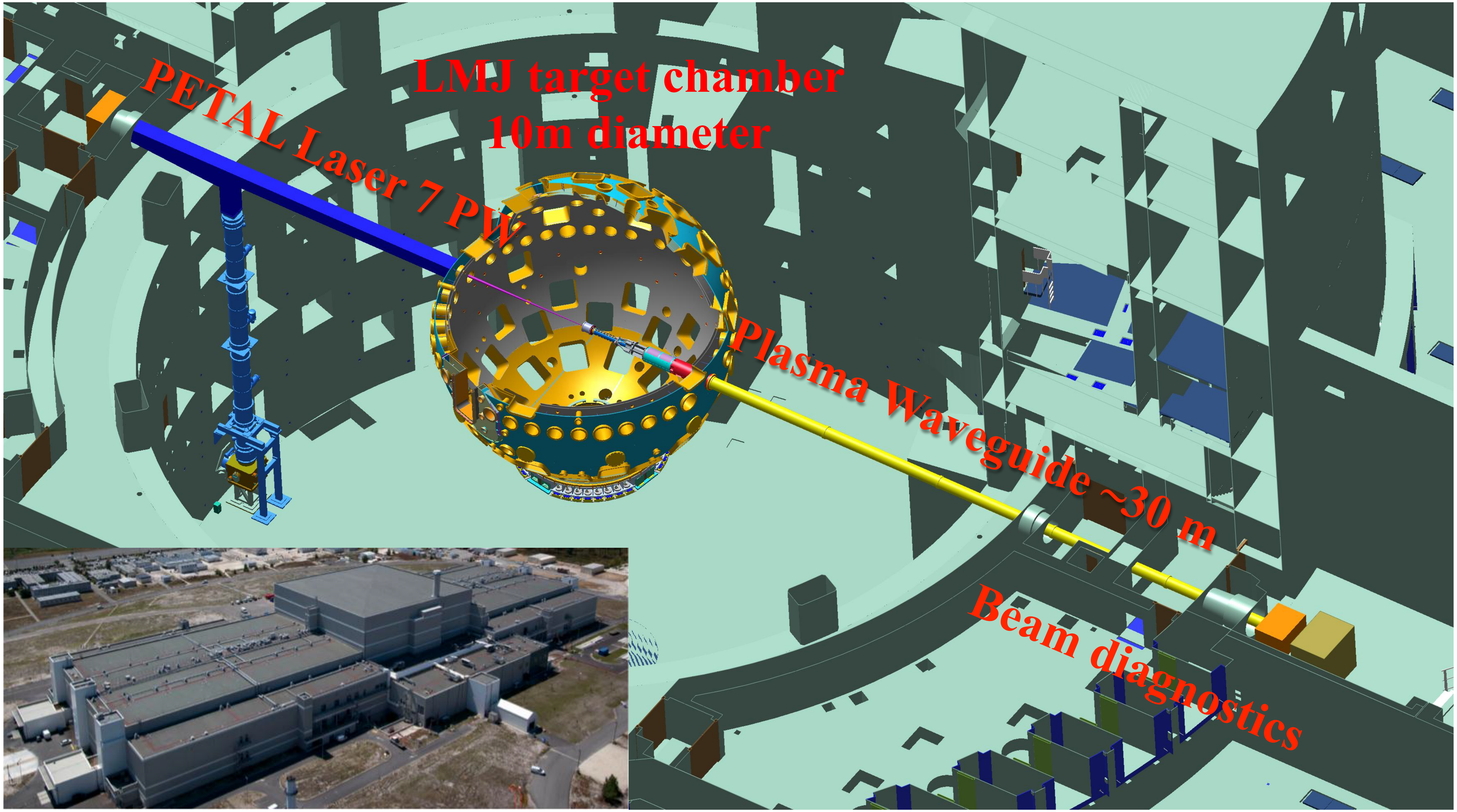
$$L_p = \frac{1}{3\pi}\lambda_p a_0\left(\frac{n_{cr}}{n_e}\right),$$

pump depletion length

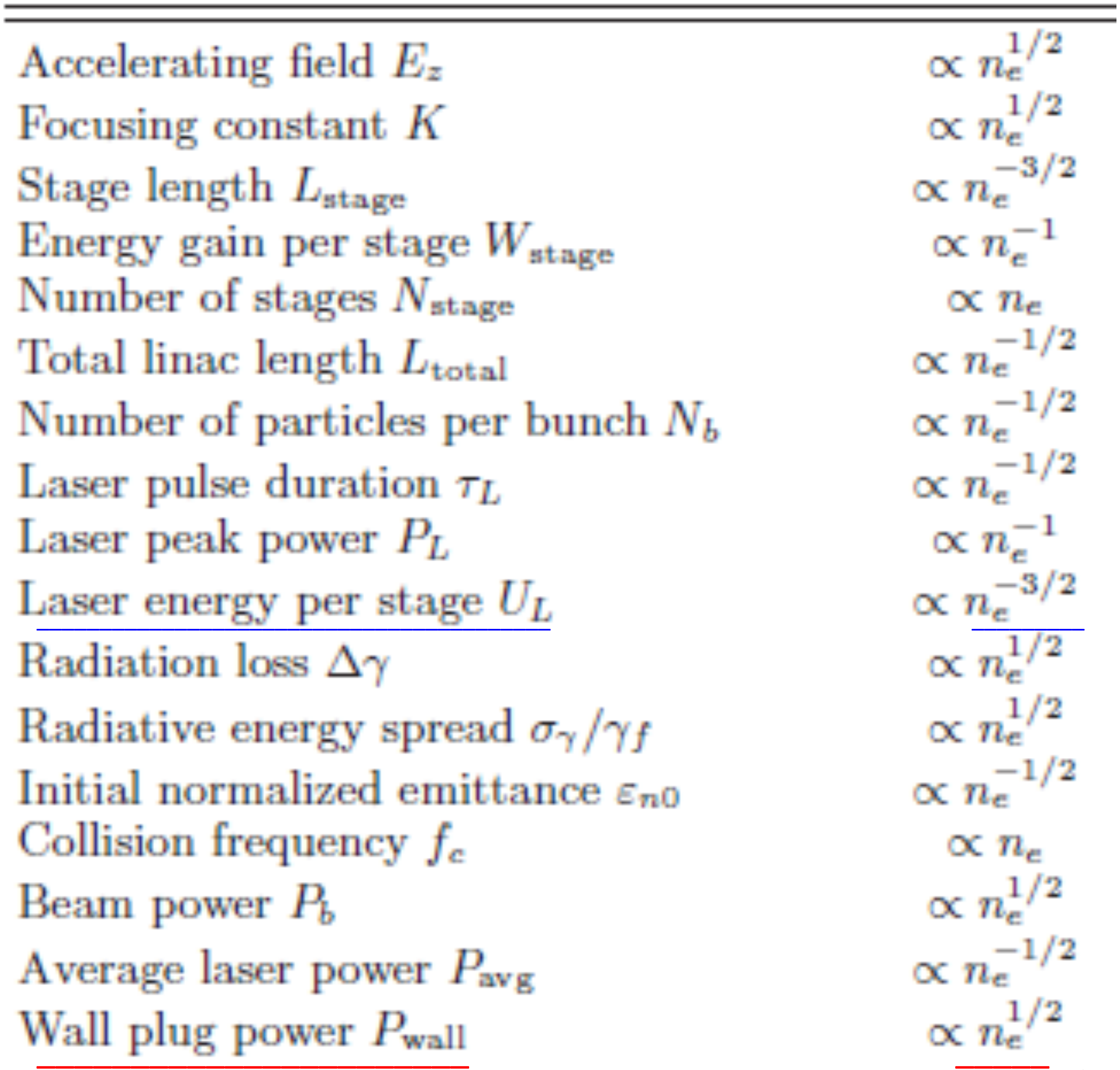
Method(1) to decrease density

IZEST propose 100 GeV Ascent Experiment using 3.5 kJ, 500fs, 7 PW PETAL laser

Nakajima(IZEST 2014)



Density scalings of **LWFA** for collider



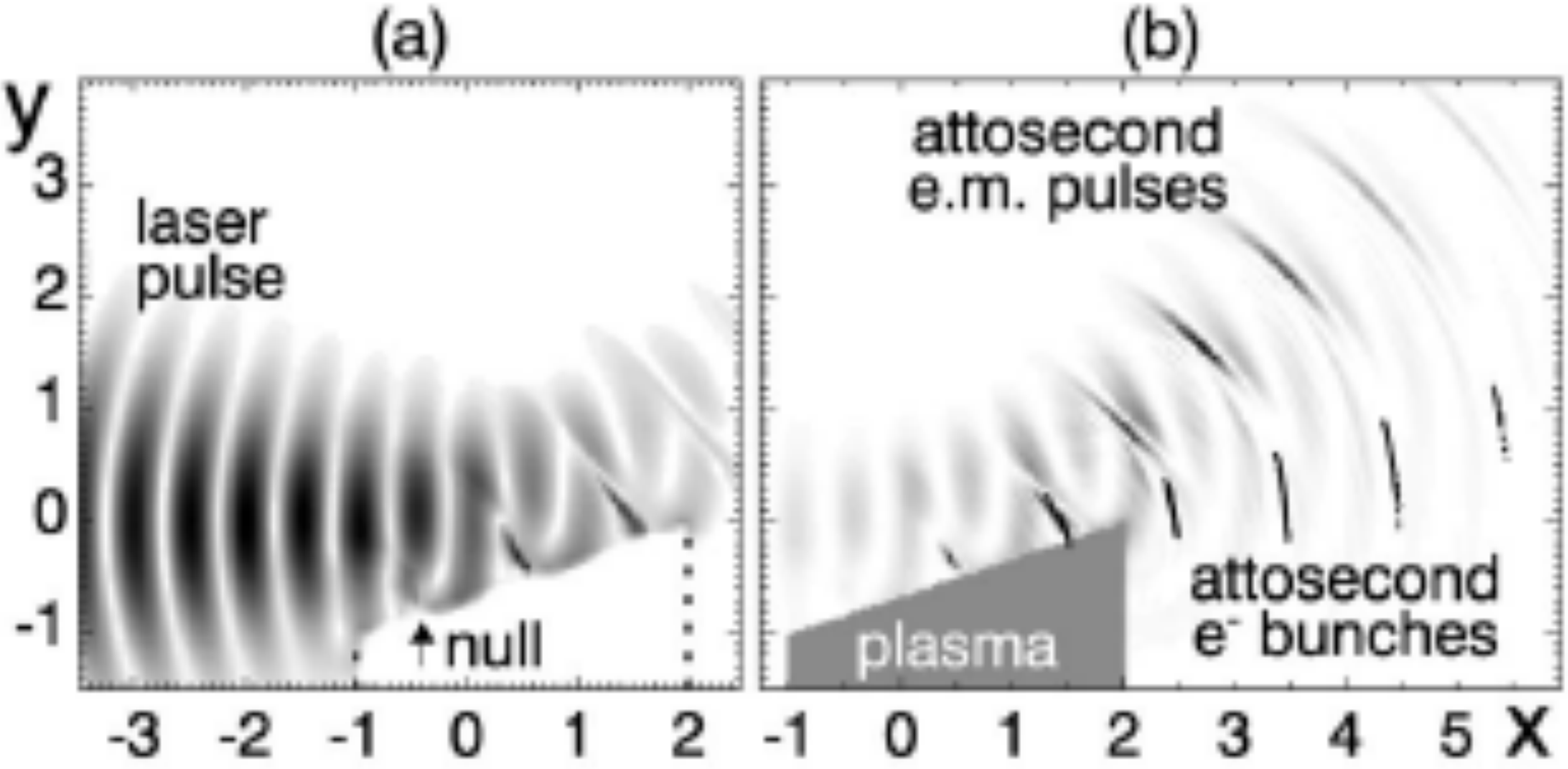
Accelerating field E_z	$\propto n_e^{1/2}$
Focusing constant K	$\propto n_e^{1/2}$
Stage length L_{stage}	$\propto n_e^{-3/2}$
Energy gain per stage W_{stage}	$\propto n_e^{-1}$
Number of stages N_{stage}	$\propto n_e$
Total linac length L_{total}	$\propto n_e^{-1/2}$
Number of particles per bunch N_b	$\propto n_e^{-1/2}$
Laser pulse duration τ_L	$\propto n_e^{-1/2}$
Laser peak power P_L	$\propto n_e^{-1}$
Laser energy per stage U_L	$\propto n_e^{-3/2}$
Radiation loss $\Delta\gamma$	$\propto n_e^{1/2}$
Radiative energy spread σ_γ/γ_f	$\propto n_e^{1/2}$
Initial normalized emittance ε_{n0}	$\propto n_e^{-1/2}$
Collision frequency f_c	$\propto n_e$
Beam power P_b	$\propto n_e^{1/2}$
Average laser power P_{avg}	$\propto n_e^{-1/2}$
Wall plug power P_{wall}	$\propto n_e^{1/2}$

(Nakajima, PR STAB, 2011)

10^{18} /cc (conventional) → 10^{16} /cc

Conversion of laser into X-ray laser pulse

Naumova et al. PRL (2004)



Even better:
Single osc. laser pulse (Mourou et al. 2014) converted into single osc. X-ray laser
by the above Naumova 's method (Tajima, 2014)
→ **EW** (1-10)**keV attosecond** zeptosecond **X-ray laser** (single osc. Pulse) from PW laser

Crystal Acceleration by X-ray Laser

→Method (2): increase frequency

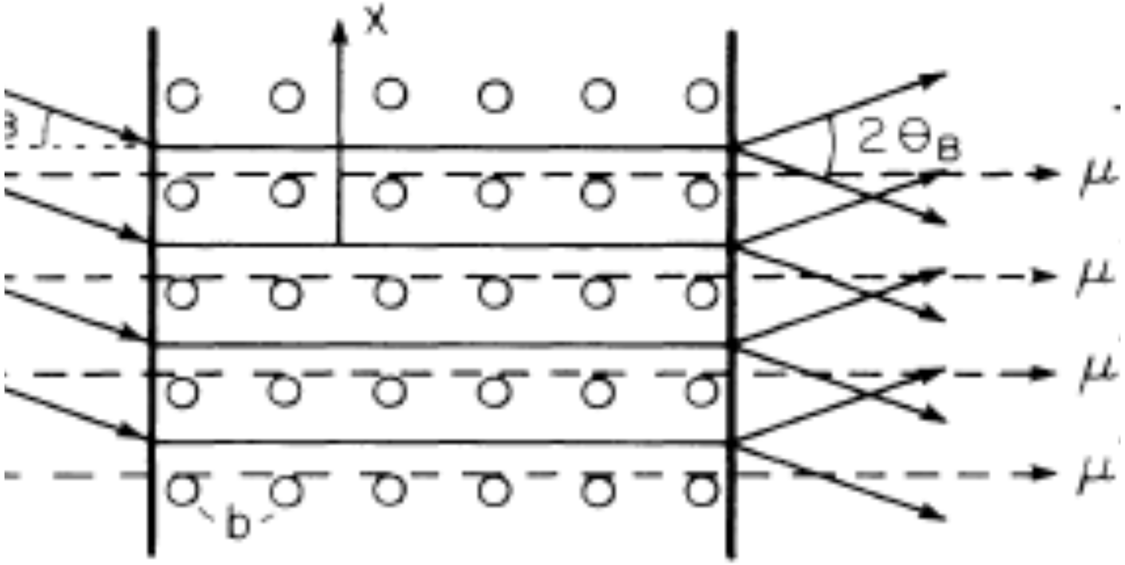
When laser ω_0 ↗,
we can ↗ n_e, E_{acc}
length L_{acc} ↘ *(*)*
(typically 10^2-10^3 smaller than plasma LWFA)

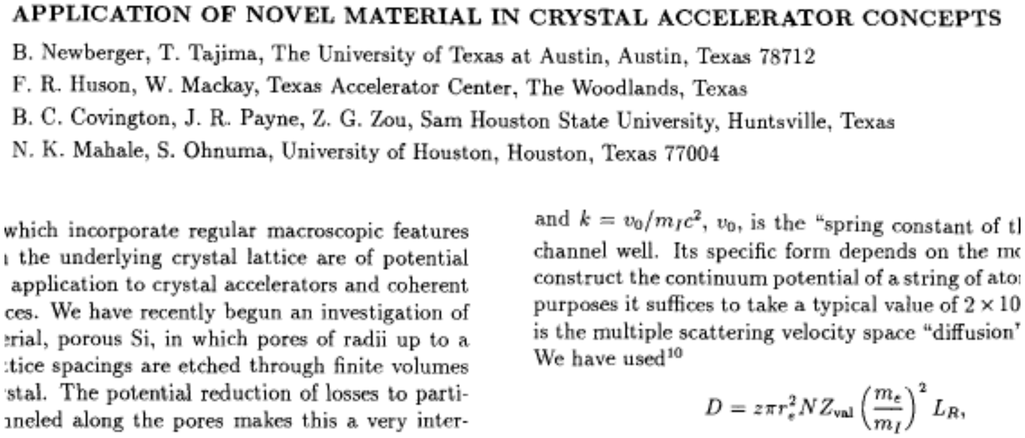
more compact accelerator
smaller emittance

Need to reduce electron friction:
crystal <u>nano-channels</u>
(see previous works right)

NB (*):
$L_p \sim 1/(6\pi)\ c/\omega_p\ E_e\ /a_0\, mc^2$
$[L_d \sim 1/\pi\ c/\omega_p\ E_e / mc^2\ ]$

→ For given energy E_e, L ↘, as n_e ↗




APPLICATION OF NOVEL MATERIAL IN CRYSTAL ACCELERATOR CONCEPTS

B. Newberger, T. Tajima, The University of Texas at Austin, Austin, Texas 78712
F. R. Huson, W. Mackay, Texas Accelerator Center, The Woodlands, Texas
B. C. Covington, J. R. Payne, Z. G. Zou, Sam Houston State University, Huntsville, Texas
N. K. Mahale, S. Ohnuma, University of Houston, Houston, Texas 77004

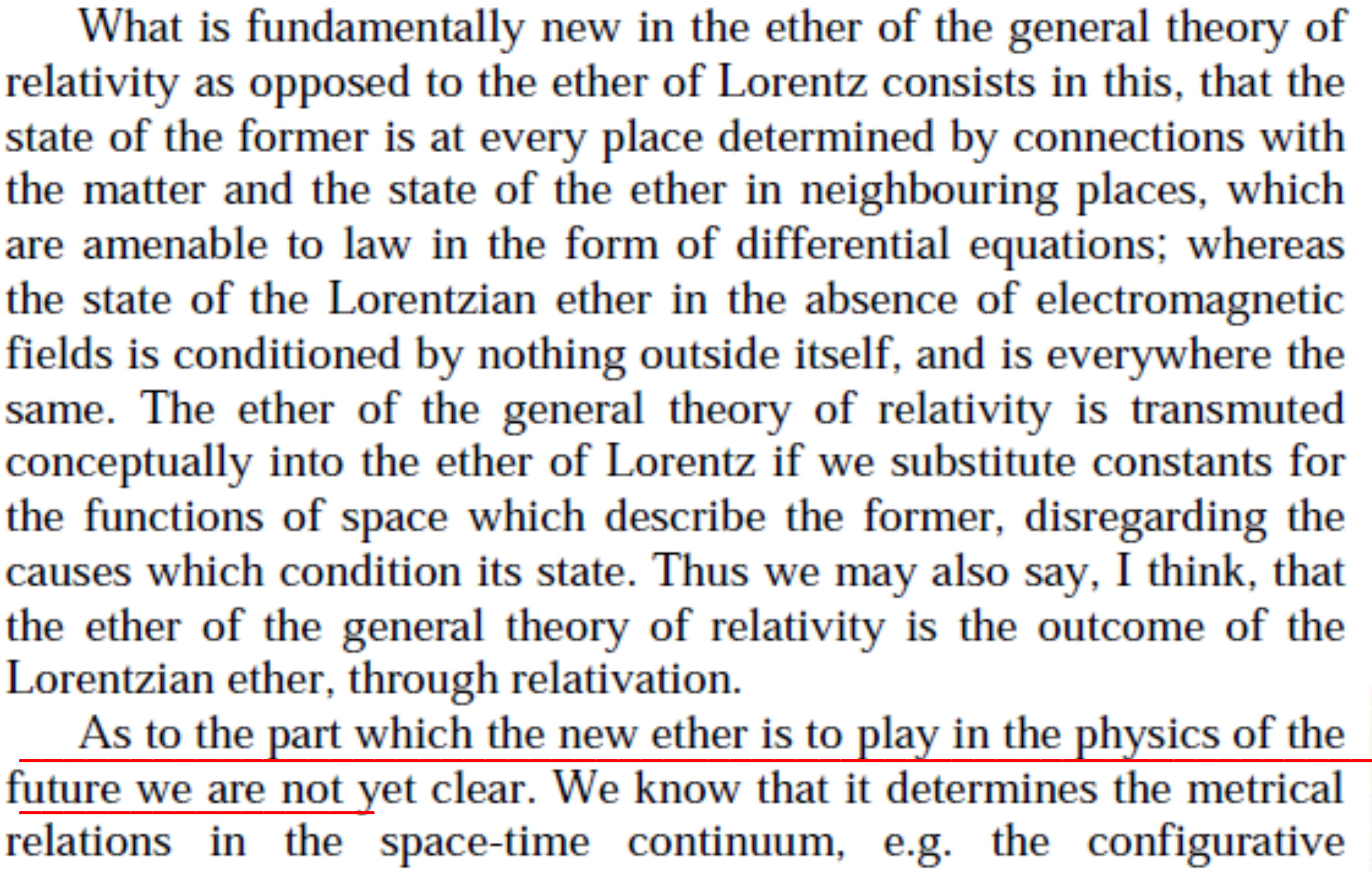
which incorporate regular macroscopic features
the underlying crystal lattice are of potential
application to crystal accelerators and coherent
ces. We have recently begun an investigation of
erial, porous Si, in which pores of radii up to a
tice spacings are etched through finite volumes
stal. The potential reduction of losses to parti-
nneled along the pores makes this a very inter-

and $k = v_0/m_I c^2$, v_0, is the "spring constant of t
channel well. Its specific form depends on the m
construct the continuum potential of a string of ato
purposes it suffices to take a typical value of 2×10
is the multiple scattering velocity space "diffusion"
We have used[10]

$$D = z\pi r_e^2 N Z_{\rm val} \left(\frac{m_e}{m_I}\right)^2 L_R,$$

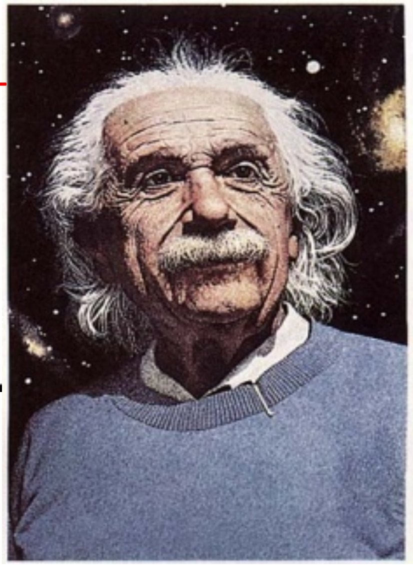
→Method (3) : increase intensity ↗ onto tighter spots↘, when wavelength ↘

Einstein and Ether



What is fundamentally new in the ether of the general theory of relativity as opposed to the ether of Lorentz consists in this, that the state of the former is at every place determined by connections with the matter and the state of the ether in neighbouring places, which are amenable to law in the form of differential equations; whereas the state of the Lorentzian ether in the absence of electromagnetic fields is conditioned by nothing outside itself, and is everywhere the same. The ether of the general theory of relativity is transmuted conceptually into the ether of Lorentz if we substitute constants for the functions of space which describe the former, disregarding the causes which condition its state. Thus we may also say, I think, that the ether of the general theory of relativity is the outcome of the Lorentzian ether, through relativation.

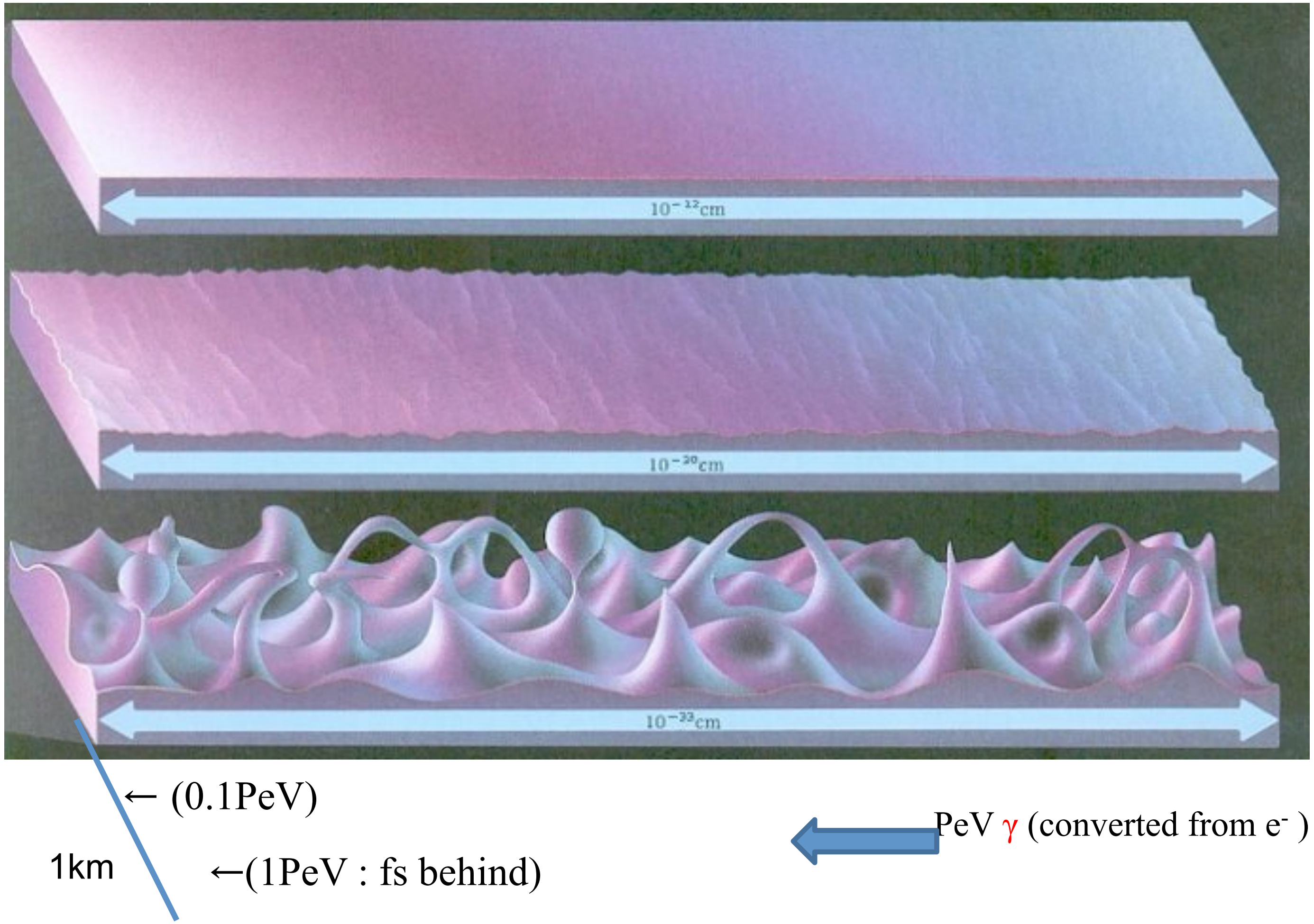
As to the part which the new ether is to play in the physics of the future we are not yet clear. We know that it determines the metrical relations in the space-time continuum, e.g. the configurative



(A. Einstein, 1922)

Feel vacuum texture: PeV energy γ

Laser acceleration → controlled laboratory test to see quantum gravity texture on photon propagation (Special Theory of Relativity: c_0)



Coarser, lower energy texture

Finer, higher energy texture

$c < c_0$

← (0.1PeV)

1km

←(1PeV : fs behind)

PeV γ (converted from e^-)

γ-ray signal from primordial GRB

LETTERS NATURE

(Abdo, et al, 2009)

←lower energy

higher→

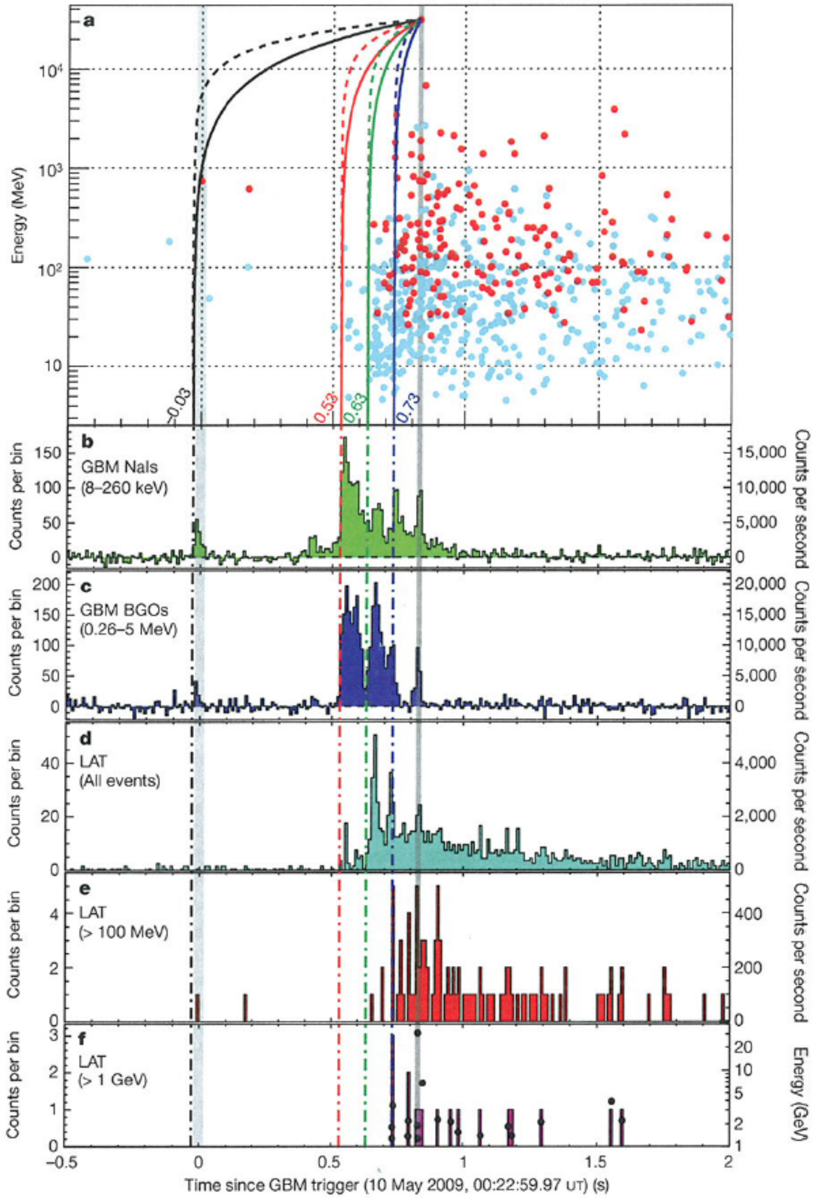


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy

lowest to highest energies. **f** also overlays energy versus arrival time for each

Energy-dependent **photon speed ?**

Observation of primordial Gamma Ray Bursts (GRB)

(limit is pushed up close to Planck mass)

Lab PeV γ (from e-) can explore this with control

Brief History of *ICUIL* – *ICFA* Joint Effort

- *ICUIL* Chair (Tajima) sounded on A. Wagner (Chair *ICFA*) and Suzuki (incoming Chair) of a common interest in laser driven acceleration, Nov. 2008
- *ICFA* GA invited Tajima for presentation by *ICUIL* and endorsed initiation of joint efforts on Feb. 13, 2009
- *Joint Task Force* formed of *ICFA* and *ICUIL* members, W. Leemans, Chair, Sept, 2009
- First Workshop by *Joint Task Force* held @ GSI, Darmstadt, April, 2010
- Report to *ICFA* GA (July,2010) and *ICUIL* GA (Sept, 2010) on the findings
- *EuroNNAc* Workshop on Novel Accelerators (CERN, May, ’11)
- Publication of *Joint Task Force* Report (Dec. 2011)
- Start of *ICAN* Workshop Series @ CERN (Feb., 2012)
- US DOE *AAC* Workshop on advanced laser tech (2013)
- Final *ICAN* Conference @ CERN (June, 2013) → next phase *WE-CAN*

High Luminosity

➔ Extreme laser : **high rep rate, high efficiency laser**

= Coherent Amplification Network Laser (2013)

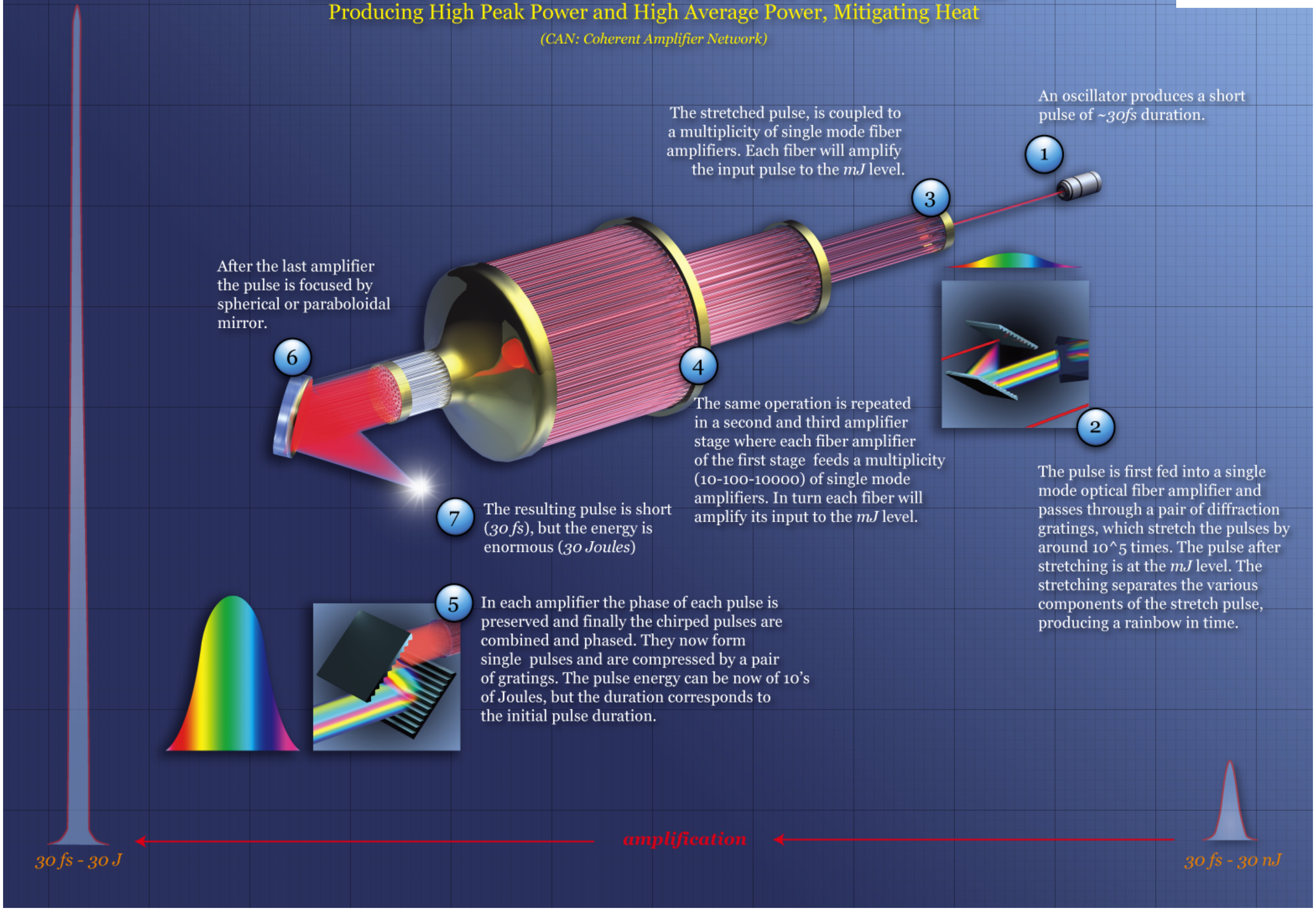
ican
International Coherent
Amplification Network

CAN Laser

HOW A “CAN” LASER AMPLIFIER WORKS

Producing High Peak Power and High Average Power, Mitigating Heat

(CAN: Coherent Amplifier Network)



① An oscillator produces a short pulse of ~*30fs* duration.

② The pulse is first fed into a single mode optical fiber amplifier and passes through a pair of diffraction gratings, which stretch the pulses by around 10^5 times. The pulse after stretching is at the *mJ* level. The stretching separates the various components of the stretch pulse, producing a rainbow in time.

③ The stretched pulse, is coupled to a multiplicity of single mode fiber amplifiers. Each fiber will amplify the input pulse to the *mJ* level.

④ The same operation is repeated in a second and third amplifier stage where each fiber amplifier of the first stage feeds a multiplicity (10-100-10000) of single mode amplifiers. In turn each fiber will amplify its input to the *mJ* level.

⑤ In each amplifier the phase of each pulse is preserved and finally the chirped pulses are combined and phased. They now form single pulses and are compressed by a pair of gratings. The pulse energy can be now of 10’s of Joules, but the duration corresponds to the initial pulse duration.

⑥ After the last amplifier the pulse is focused by spherical or paraboloidal mirror.

⑦ The resulting pulse is short (*30 fs*), but the energy is enormous (*30 Joules*)

Beyond QED photon-photon interaction

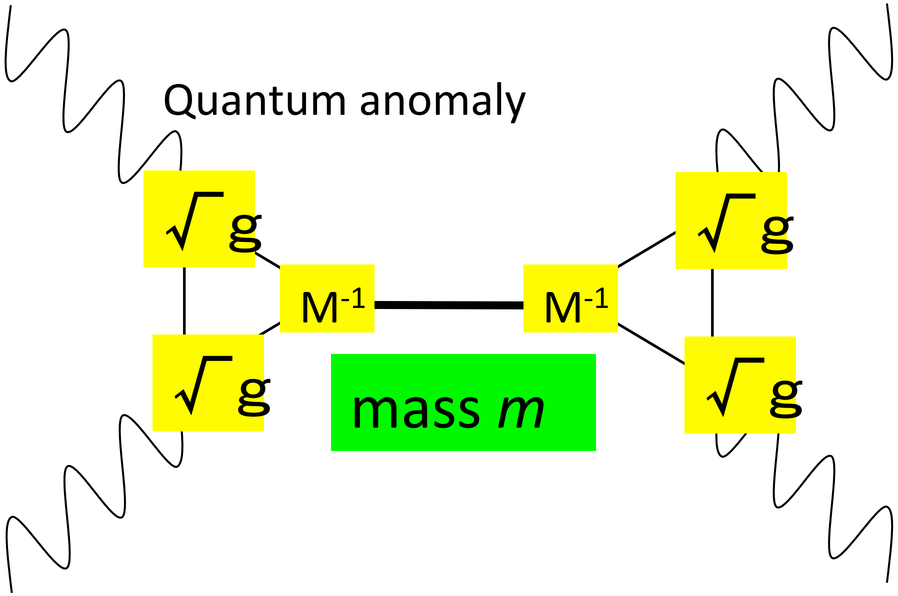
$$L_{QED} = \frac{1}{360}\frac{\alpha^2}{m^4}[4(F_{\mu\nu}F^{\mu\nu})^2 + 7(F_{\mu\nu}\tilde{F}^{\mu\nu})^2]$$

$$\Updownarrow \qquad\qquad\qquad \Updownarrow$$

$$\phi F_{\mu\nu}F^{\mu\nu} \qquad \sigma F_{\mu\nu}\tilde{F}^{\mu\nu}$$

Away from 4 : 7 = QCD , low-mass scalar ϕ , or pseudoscalar σ
(unlike Higgs, which is heavy fields for photon-photon interaction,)

Resonance in quasi-parallel collisions in low cms energy



If M~M_{Planck}, Dark Energy

$$gM^{-1}F^{\mu\nu}F_{\mu\nu}\phi$$

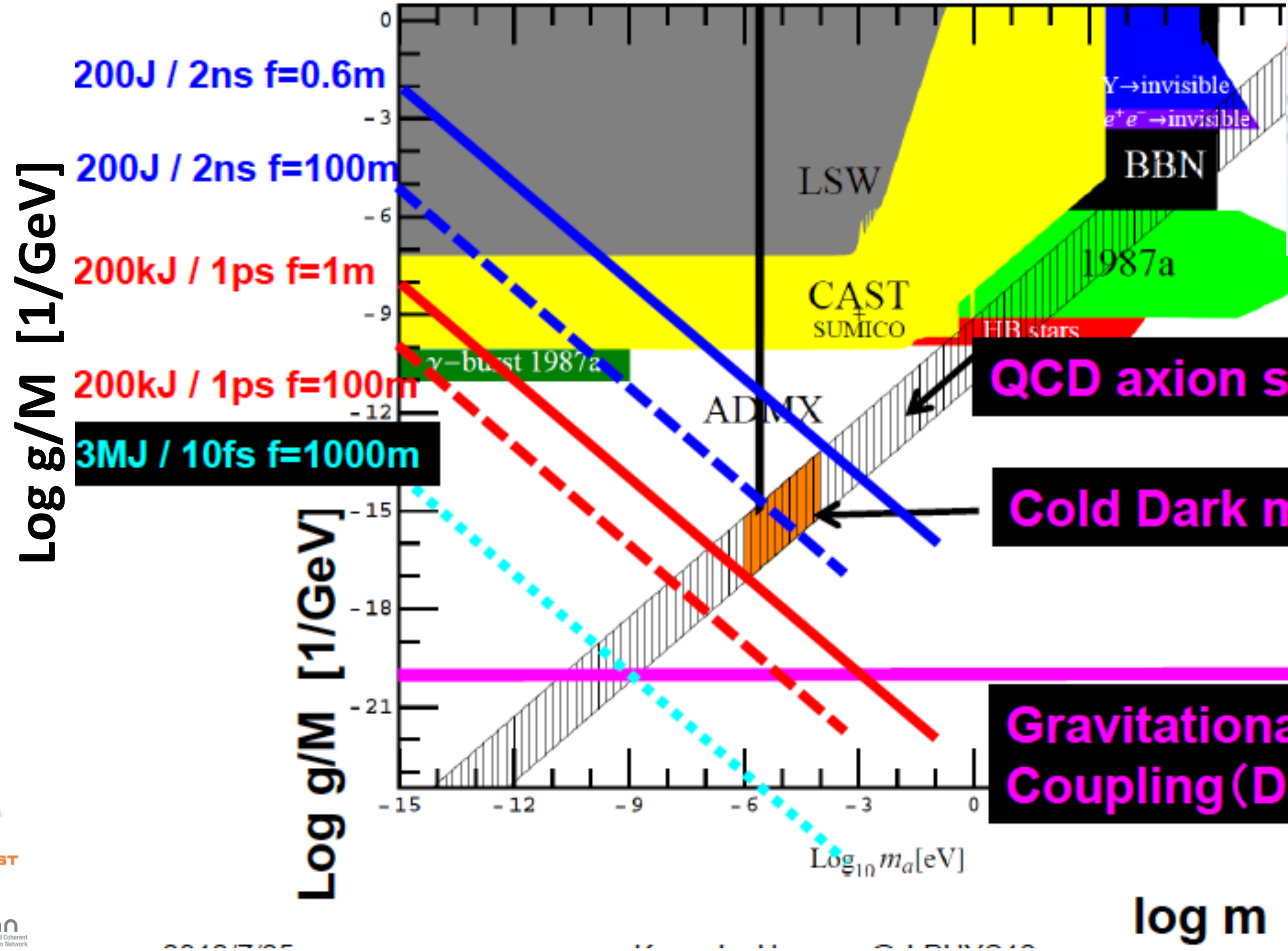
arXiv:1006.1762 [gr-qc]
Y. Fujii and K.Homma

QCD-instanton, Dark Matter

$$gM^{-1}F^{\mu\nu}\tilde{F}_{\mu\nu}\sigma$$

K.Homma, D.Habs,
T.Tajima (2011)

Photon mixer's road to unknown fields: Dark Matter and Dark Energy



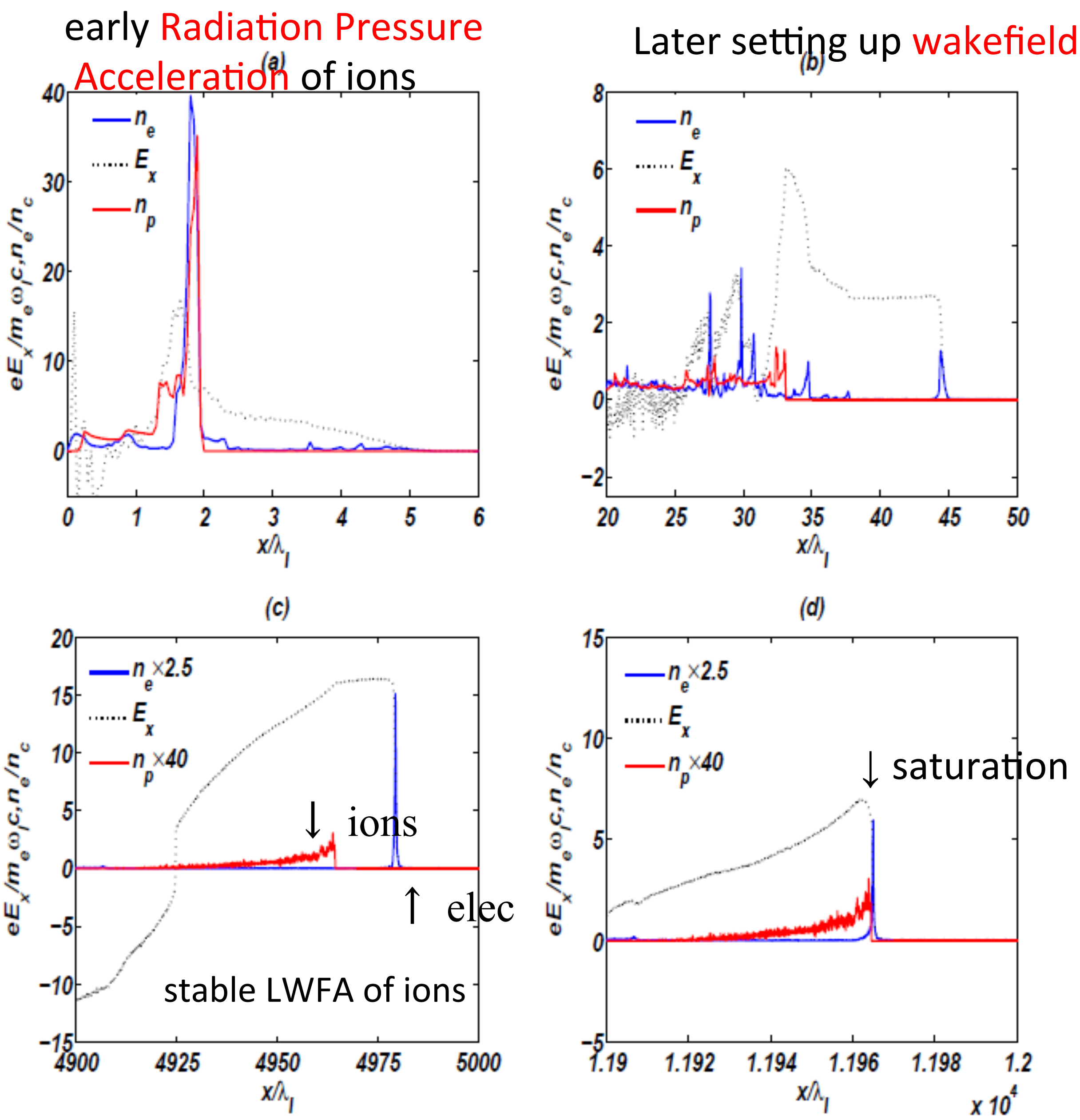
(Court. A. Oeftinger)

K.Homma, D.Habs, T.Tajima (2011)

Mountain of Radioactive Junk at Nuclear Facility

B. Carluec
(Court. A. Oeftinger(CERN))

TeV proton acceleration by LWFA


early Radiation Pressure Acceleration of ions

Later setting up wakefield

↓ ions

↑ elec

stable LWFA of ions

↓ saturation

High Intensity regime

$I = 10^{23}$ W/cm^2

(using ELI type laser)

$$E_i = (1/6)\, a_0^2\, (n_c/n_e)\, mc^2$$

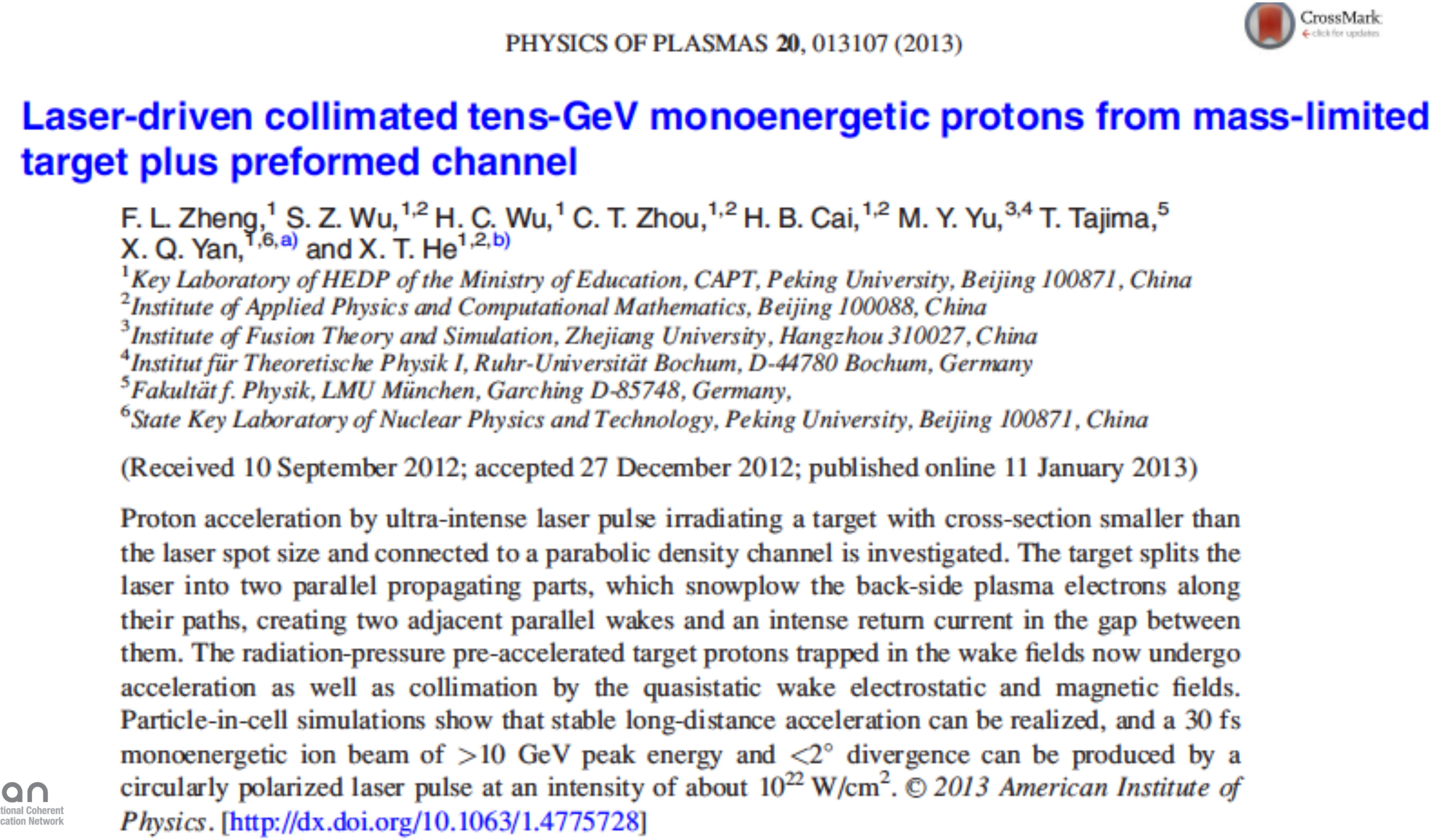
Snowplow LWFA
of ions injected by RPA
as injector at multi-GeV

0.5TeV over
dephasing length of 1cm

Zheng et al., 2011

GeV-TeV proton Energy Scalings(RPA x LWFA)

TeV over cm @ 10^{23}W/cm^2 (Zheng et al, 2012)
10GeV over mm @ 10^{22}W/cm^2 (Zheng et al, 2013)
200MeV @10^{21}W/cm^2 (Wang et al, 2013)



PHYSICS OF PLASMAS **20**, 013107 (2013)

Laser-driven collimated tens-GeV monoenergetic protons from mass-limited target plus preformed channel

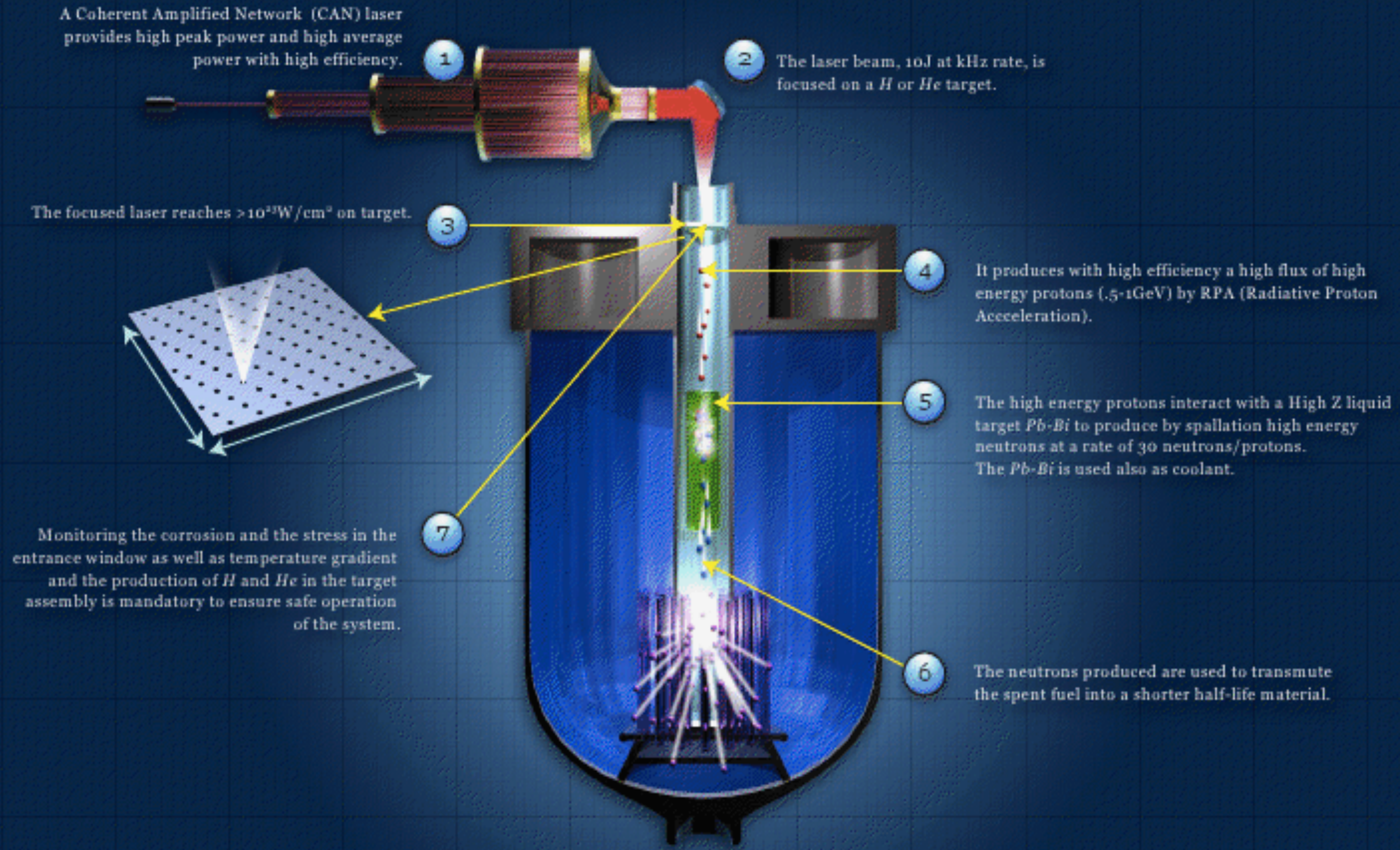
F. L. Zheng,[1] S. Z. Wu,[1,2] H. C. Wu,[1] C. T. Zhou,[1,2] H. B. Cai,[1,2] M. Y. Yu,[3,4] T. Tajima,[5]
X. Q. Yan,[1,6,a)] and X. T. He[1,2,b)]
[1]*Key Laboratory of HEDP of the Ministry of Education, CAPT, Peking University, Beijing 100871, China*
[2]*Institute of Applied Physics and Computational Mathematics, Beijing 100088, China*
[3]*Institute of Fusion Theory and Simulation, Zhejiang University, Hangzhou 310027, China*
[4]*Institut für Theoretische Physik I, Ruhr-Universität Bochum, D-44780 Bochum, Germany*
[5]*Fakultät f. Physik, LMU München, Garching D-85748, Germany,*
[6]*State Key Laboratory of Nuclear Physics and Technology, Peking University, Beijing 100871, China*

(Received 10 September 2012; accepted 27 December 2012; published online 11 January 2013)

Proton acceleration by ultra-intense laser pulse irradiating a target with cross-section smaller than the laser spot size and connected to a parabolic density channel is investigated. The target splits the laser into two parallel propagating parts, which snowplow the back-side plasma electrons along their paths, creating two adjacent parallel wakes and an intense return current in the gap between them. The radiation-pressure pre-accelerated target protons trapped in the wake fields now undergo acceleration as well as collimation by the quasistatic wake electrostatic and magnetic fields. Particle-in-cell simulations show that stable long-distance acceleration can be realized, and a 30 fs monoenergetic ion beam of >10 GeV peak energy and <2° divergence can be produced by a circularly polarized laser pulse at an intensity of about 10^{22} W/cm^2. © *2013 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4775728]

CAN Laser

THE LASER DRIVEN TRANSMUTATOR CONCEPT



A Coherent Amplified Network (CAN) laser provides high peak power and high average power with high efficiency. ①

② The laser beam, 10J at kHz rate, is focused on a *H* or *He* target.

The focused laser reaches $>10^{23}$W/cm^2 on target. ③

④ It produces with high efficiency a high flux of high energy protons (.5-1GeV) by RPA (Radiative Proton Acceleration).

⑤ The high energy protons interact with a High Z liquid target *Pb-Bi* to produce by spallation high energy neutrons at a rate of 30 neutrons/protons.
The *Pb-Bi* is used also as coolant.

Monitoring the corrosion and the stress in the entrance window as well as temperature gradient and the production of *H* and *He* in the target assembly is mandatory to ensure safe operation of the system. ⑦

⑥ The neutrons produced are used to transmute the spent fuel into a shorter half-life material.

Nature Photon. (2013)

Conclusions

- **Novel Extreme Laser frontiers:**
    (1) EW keV zs laser;
    (2) kHz kW average power laser
- Laser-driven accelerators : (a) far higher energies (PeV); (b) far smaller length / width / emittance; (c) respectable ave. power
- Compact ion accelerators: protons, neutrons, muons, etc.
    Nuclear transmutation by laser-driven neutron sources, ADS, ADR; portable neutrino source
- Huge vacuum nonlinearity: vacuum self-focusing, Schwinger field, super-Schwinger fields, vacuum accelerators, etc.
- Industrial applications (auto-industry, chemical industry, mechanical industry, medical, military, etc.) with
    (1) compact crystal; or (2)large fluence with CAN laser