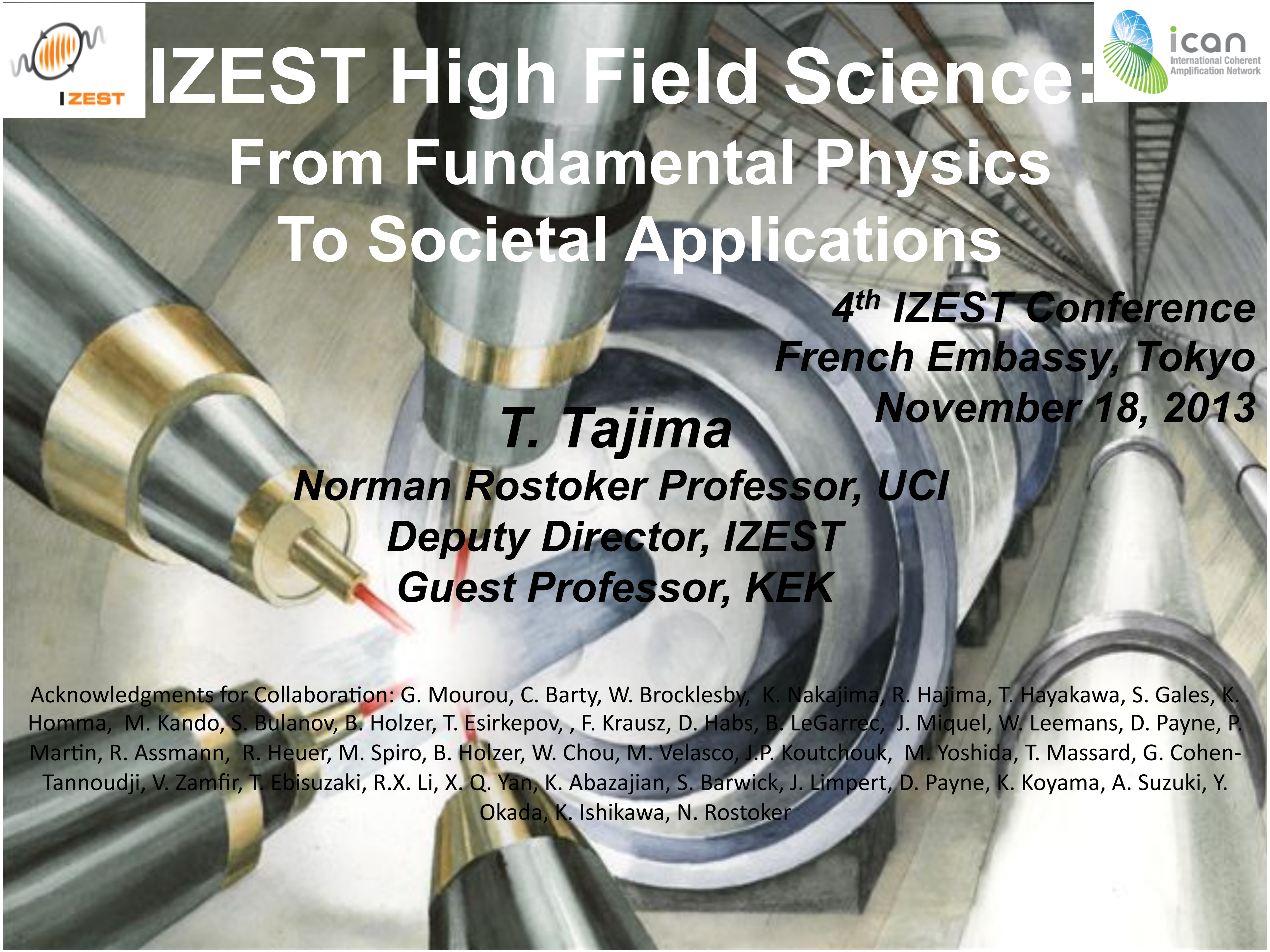


IZEST High Field Science:
From Fundamental Physics
To Societal Applications

4th IZEST Conference
French Embassy, Tokyo
November 18, 2013

T. Tajima
Norman Rostoker Professor, UCI
Deputy Director, IZEST
Guest Professor, KEK

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, N. Rostoker

content

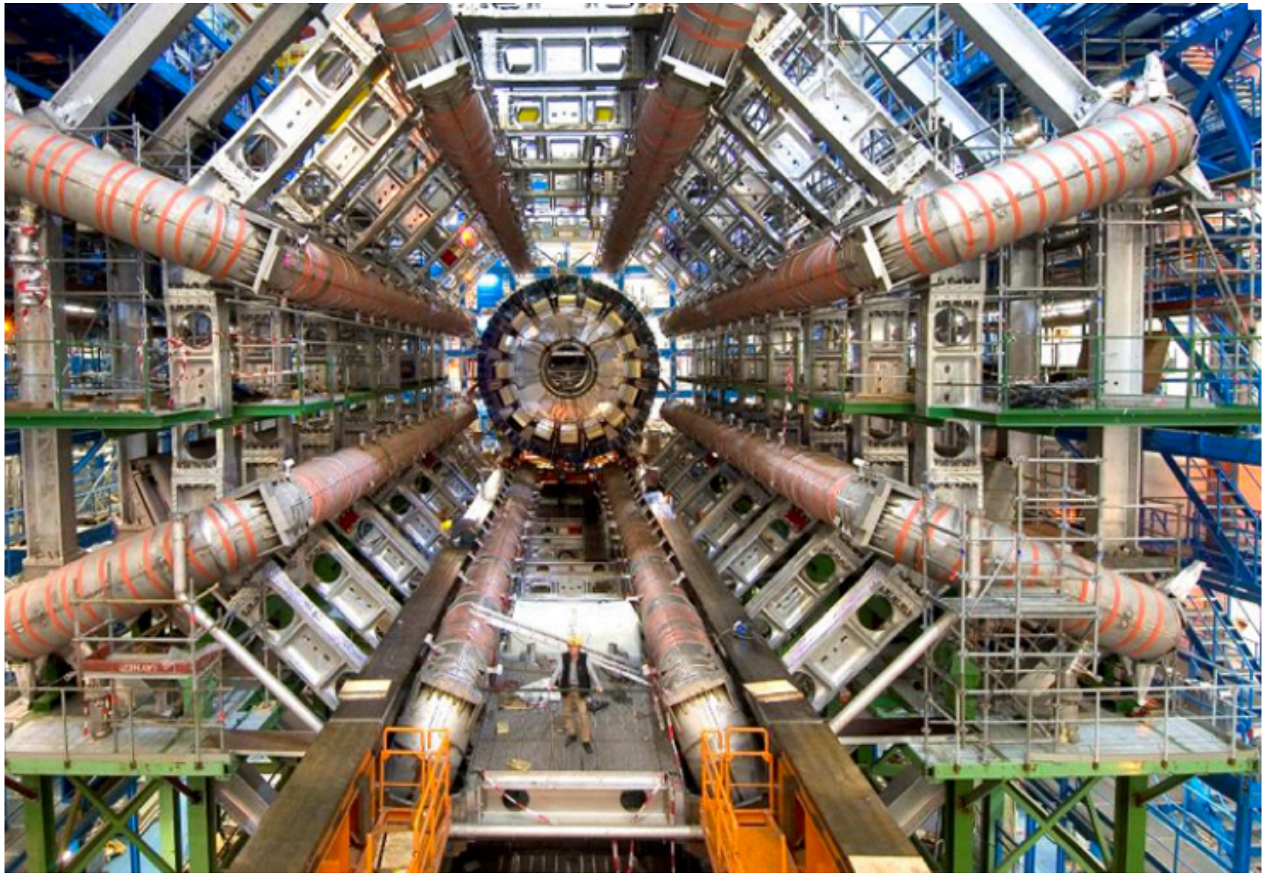
- High fields that break matter, but keep order

  Guiding principle for order: not atomic cohesion (quantum coherence), but relativistic coherence (and plasma's collective eigenmodes) (Lesson learned in N. Rostoker's lab, 1973-75)

  →laser plasma acceleration, plasma decelerator, plasma optics,…
- High energy accelerators by laser
- Luminosity issue for collider---*ICUIL-ICFA Joint Task*
- Answer to high rep rate and high efficiency → **fiber laser (CAN)**
- Laser (not charged particles) collider for Dark Fields search
- CAN lasers : enabling technology also for industrial and societal applications: compact radiation oncology, directed gamma beams (nuclear medicine and pharmacology), homeland security, transmutation of nuclear wastes (ADS, etc.) , ….

High Field Science Supporters: CERN

Rolf Heuer
CERN Director General



IZEST's Mission: Responding to Suzuki's Challenge

Atsuto Suzuki:
KEK Director General,
Former ICFA Chair

New Paradigm

PeV

Leptogenesis
SUSY breaking

Extra dimension
Dark matter
Supersymmetry

TeV

Standard Model
Quarks
Leptons

Greetings from Michel Spiro

(Former) President of CERN Council

As President of the CERN Council, I would like to express our interest and warm support in developing new ultra high gradient techniques of particle acceleration.

Plasma acceleration seems a very promising avenue.

The IZEST project is a bold and fierce adventure. It will open the way to a new generation of ultra high energy and compact accelerator and give access to totally new physics like probing quantum vacuum and testing the basic laws of physics.

I wish great success to the IZEST conference and to the IZEST project.

Best wishes,
Michel

[Court. A. Oeftinger(CERN)]

IZEST Associate Laboratories

Ecole Polytechnique - Palaiseau, France ①

CEA - Commissariat à l'Energie Atomique et aux énergies alternatives, Bordeaux, France ②

PPPL - Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA ③

FERMILAB - Fermi National Accelerator Laboratory, Chicago, Illinois, USA ④

LLNL - Lawrence Livermore National Laboratory, Livermore, California, USA ⑤

CUOS - Center for Ultrafast Optical Science, Ann Arbor, Michigan, USA ⑥

ALLS - Advanced Laser Light Source, Montreal, Canada ⑦

JAI - John Adams Institute for accelerator science, Oxford, UK ⑧

TOPS - TeraHertz to Optical Pulse Source, Strathclyde, UK ⑨

HHU - Heinrich Heine Universität, Düsseldorf, Germany ⑩

MEPhI - Moscow Engineering Physics Institute, Moscow, Russia ⑪

⑫ **IAP -** Institute of Advanced Physics, Nizhy Novgorod, Russia

⑬ **GIST -** Gwangju Institute of Science and Technology, Gwangju, Republic of Korea

⑭ **KEK -** High Energy Accelerator Research Organization, Tsukuba, Japan

⑮ **KPSI -** Kansai Photon Science Institute, Kansai, Japan

⑯ **LeCosPa -** Leung Center for Cosmology and Particle Astrophyics, Taipei, Taiwan

⑰ **CLPU -** Centro de Láseres Pulsados Ultracortos Ultraintensos, Salamanca, Spain

⑱ **CERN -** Organisation Européenne pour la Recherche Nucléaire, Genève, Switzerland

⑲ **SIOM -** Shanghai Institute of Optics and Fine Mechanics, Shanghai, China

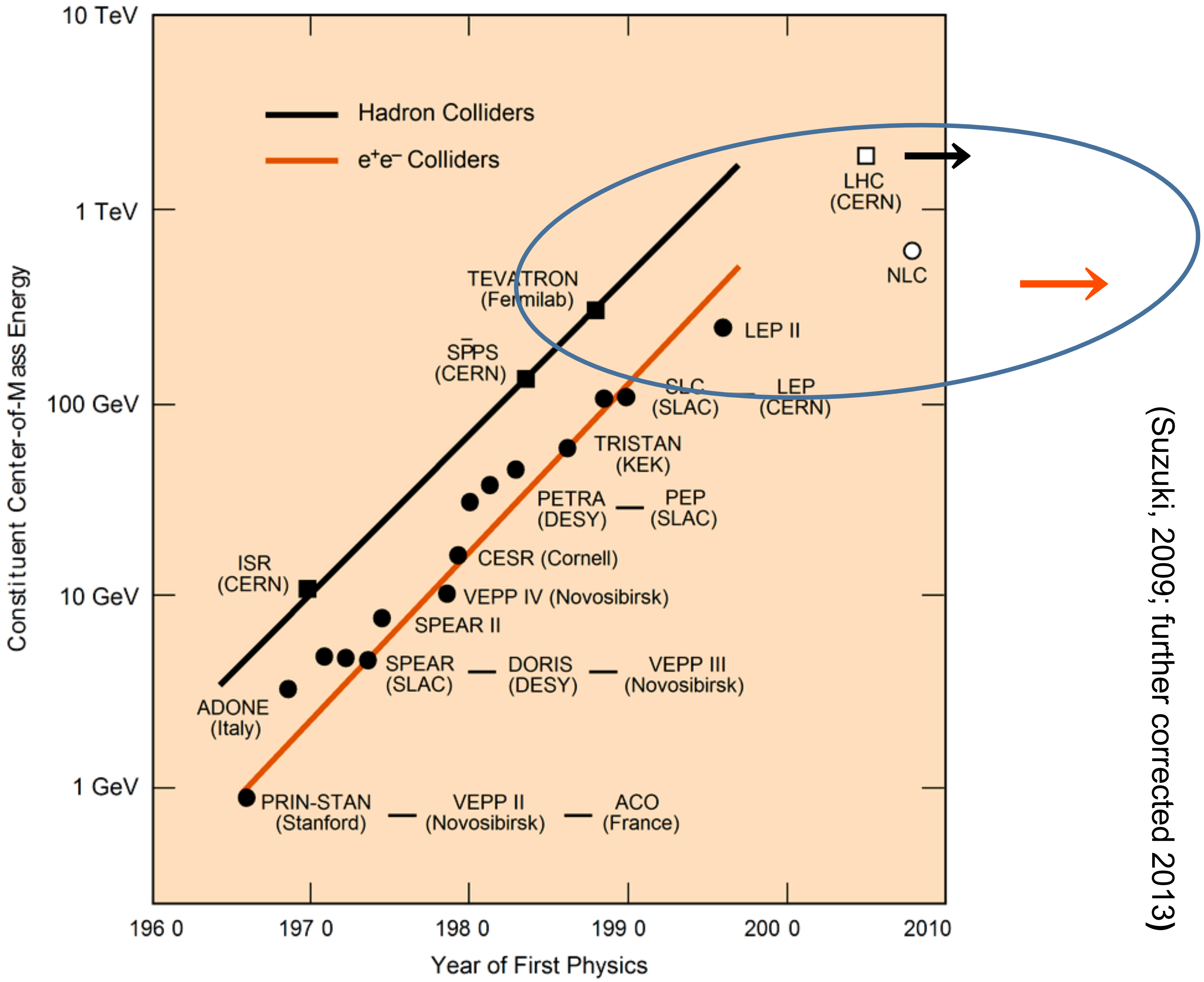
⑳ **Kyoto University -** Kyoto, Japan

㉑ **ELI-NP -** Extreme Light Infrastructure - Nuclear Physics, Magurele, Romania

㉒ **Beijing University** - Beijing, China

㉓ **TCHILS** - Texas Center for High Intensity Laser Science, Austin, USA

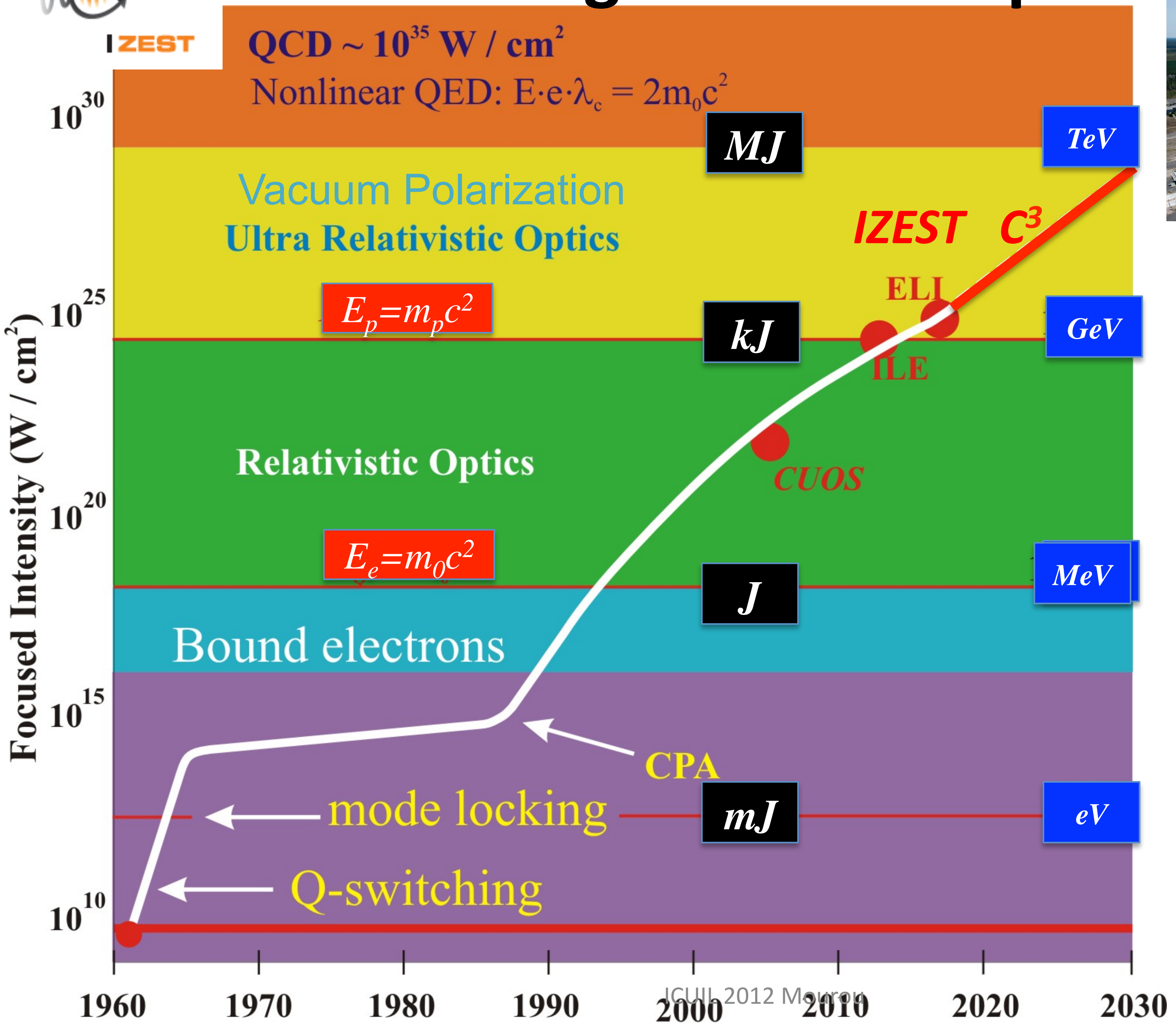
Livingston Chart and Recent Saturation

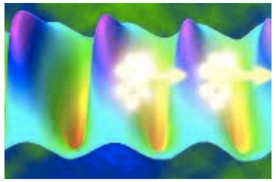


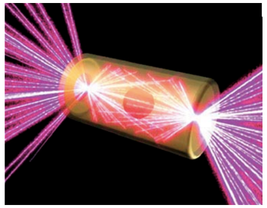
(Suzuki, 2009; further corrected 2013)

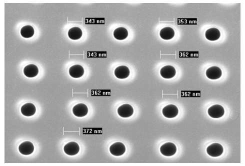
(http://tesla.desy.de/~rasmus/media/Accelerator%20physics/slides/Livingston%20Plot%202.html)

Extreme Light Road Map







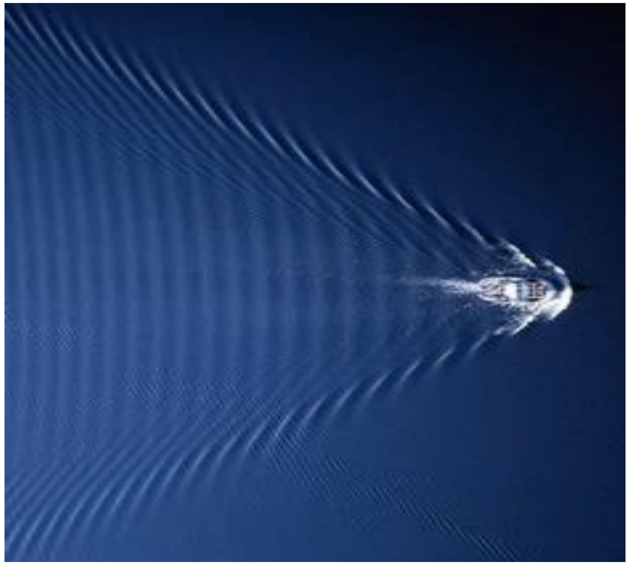


Brief History of *ICUIL* – *ICFA* Joint Effort

- *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*

ican
International Coherent
Amplification Network

Laser Wakefield (LWFA): nonlinear optics in plasma

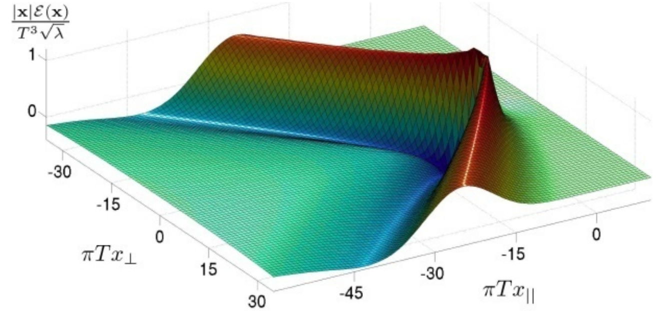


Bow ('ponderomotive')

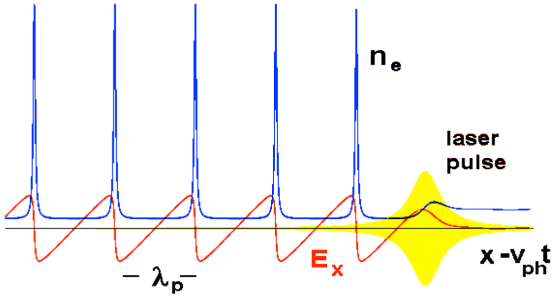
and Kelvin **wake** waves

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)

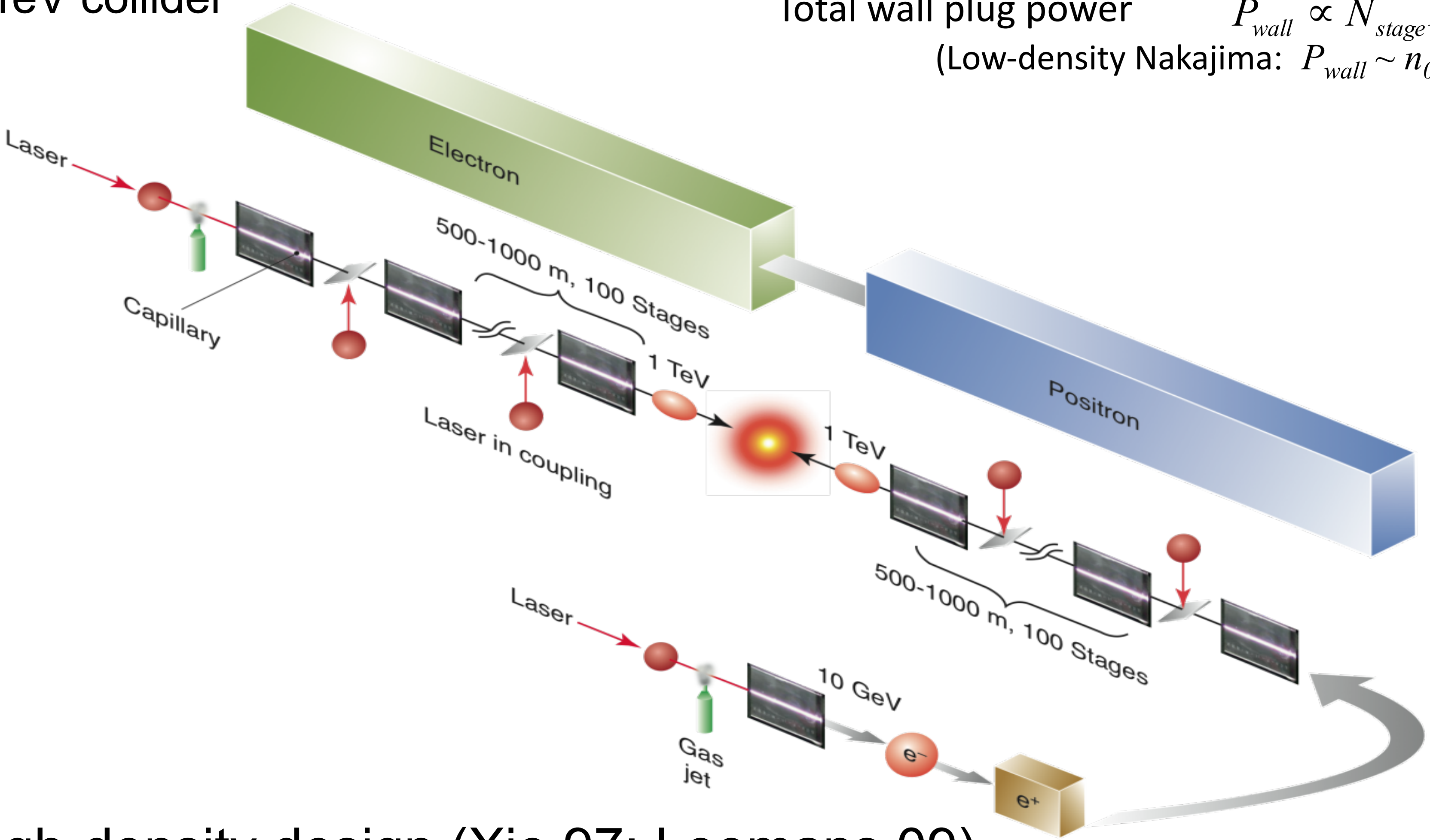
Laser driven collider concept

Laser energy: $U_L \sim n_0^{-3/2}$

Total wall plug power $P_{wall} \propto N_{stage} P_{avg} \propto n_0^{1/2}$

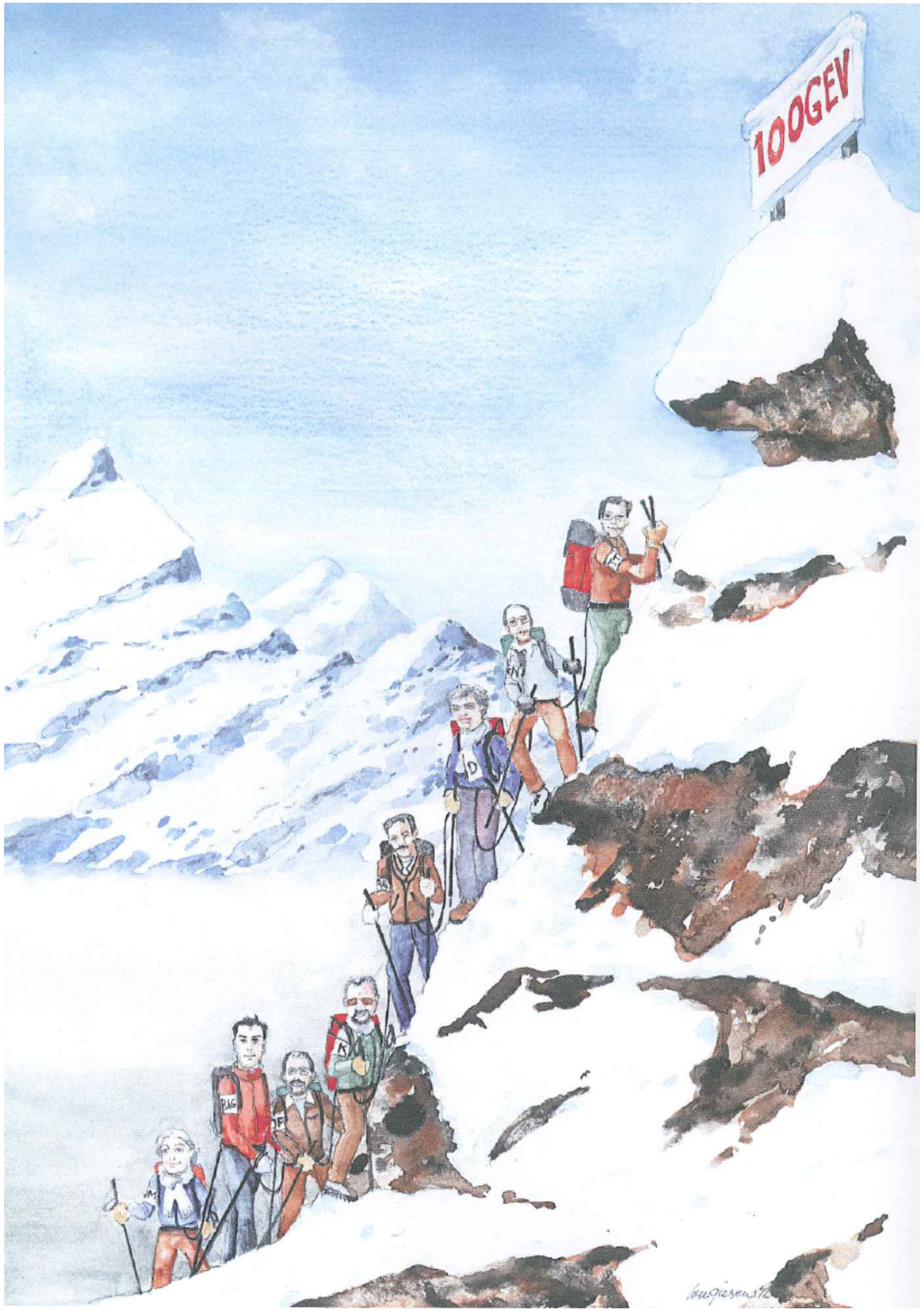
(Low-density Nakajima: $P_{wall} \sim n_0^{3/2}$)

a TeV collider



High-density design (Xie,97; Leemans,09)

ICFA-ICUIL Joint Task Force on Laser Acceleration(Darmstadt,10)



100 GeV (~Higgs energy) ascent:

Challenging!

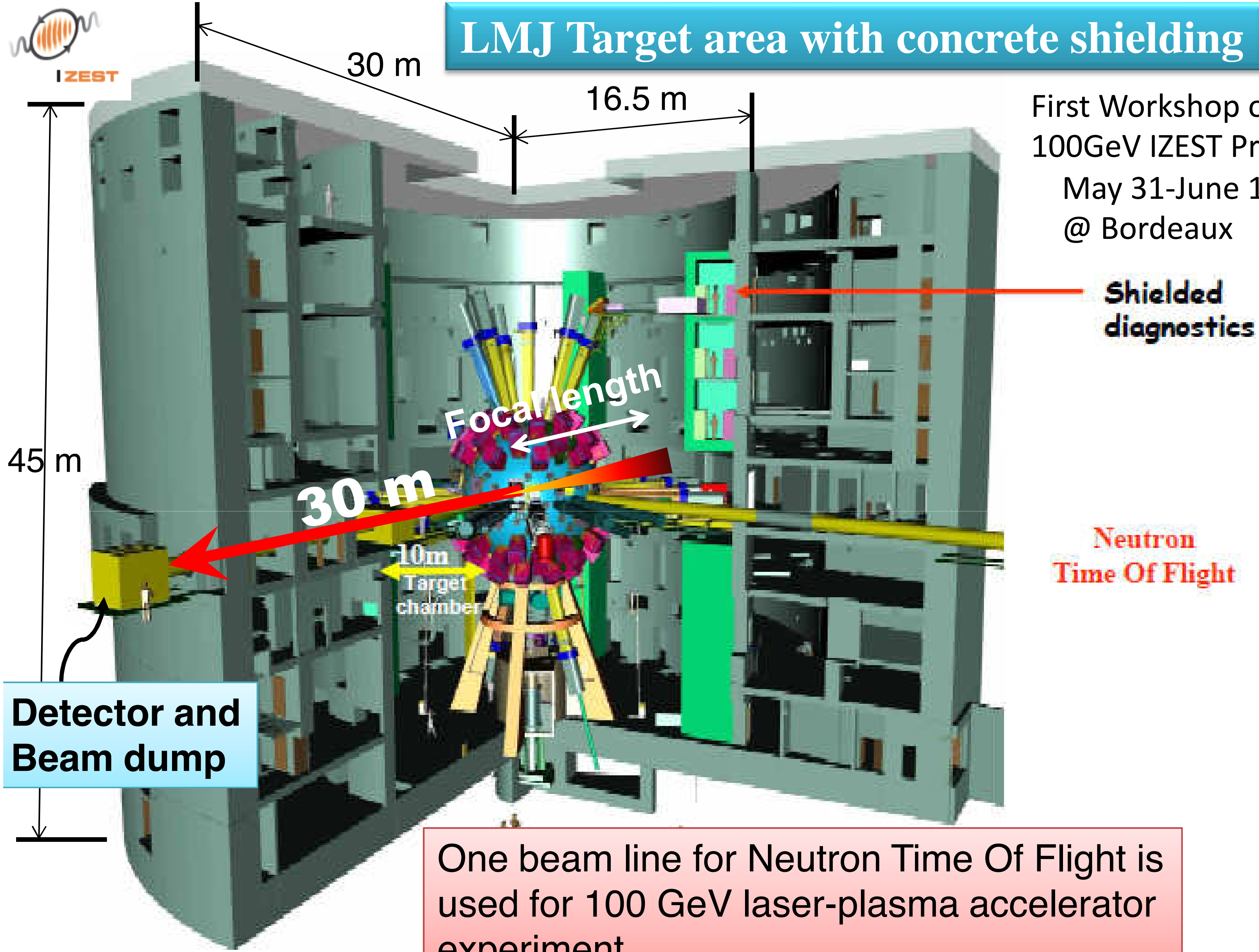
Inspirational

Needs international teamwork!

Please join us!

LMJ Target area with concrete shielding

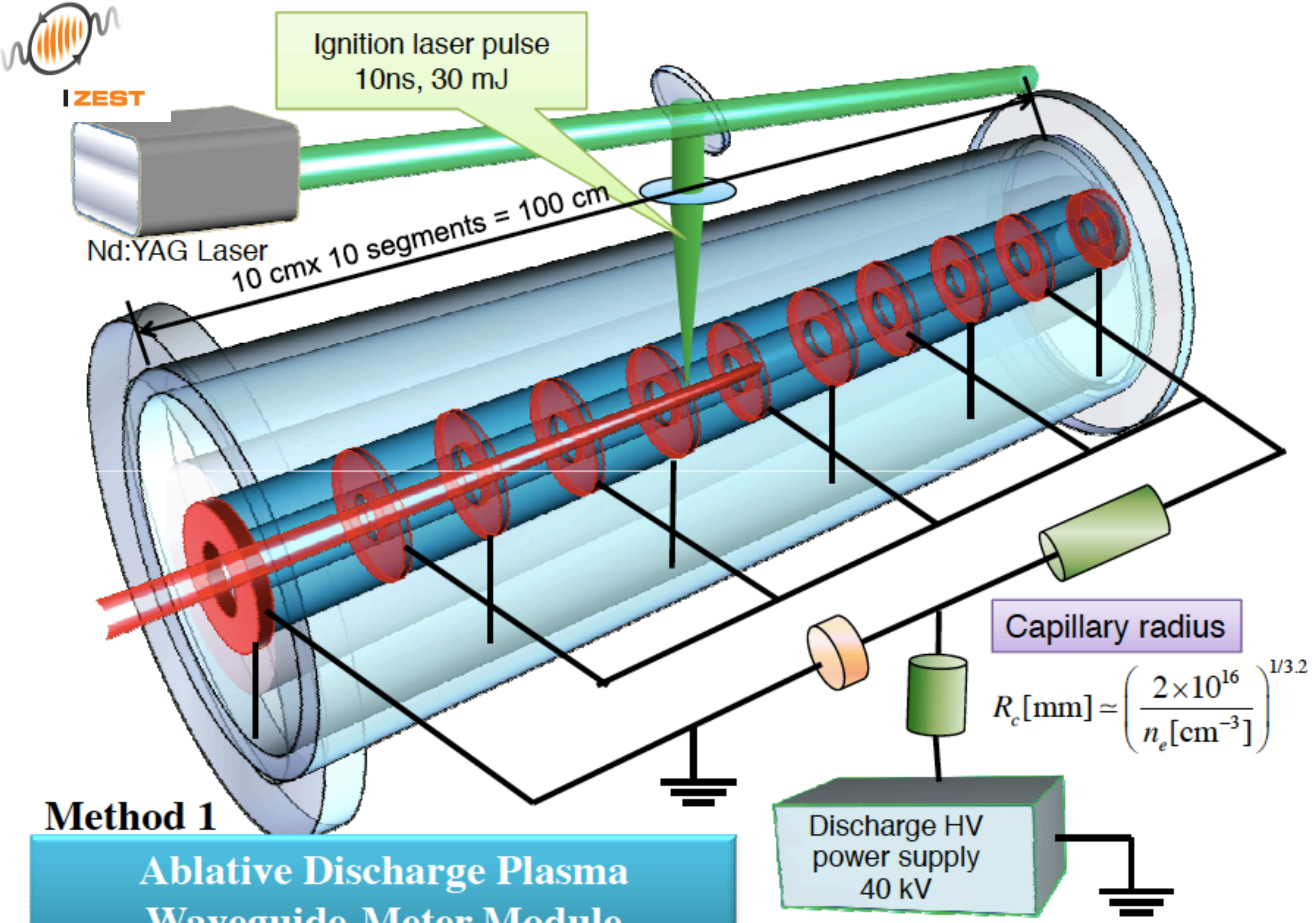
First Workshop on
100GeV IZEST Project:
May 31-June 1, ’12
@ Bordeaux



One beam line for Neutron Time Of Flight is used for 100 GeV laser-plasma accelerator experiment.

Nakajima, LeGarrec

Courtesy of PETAL



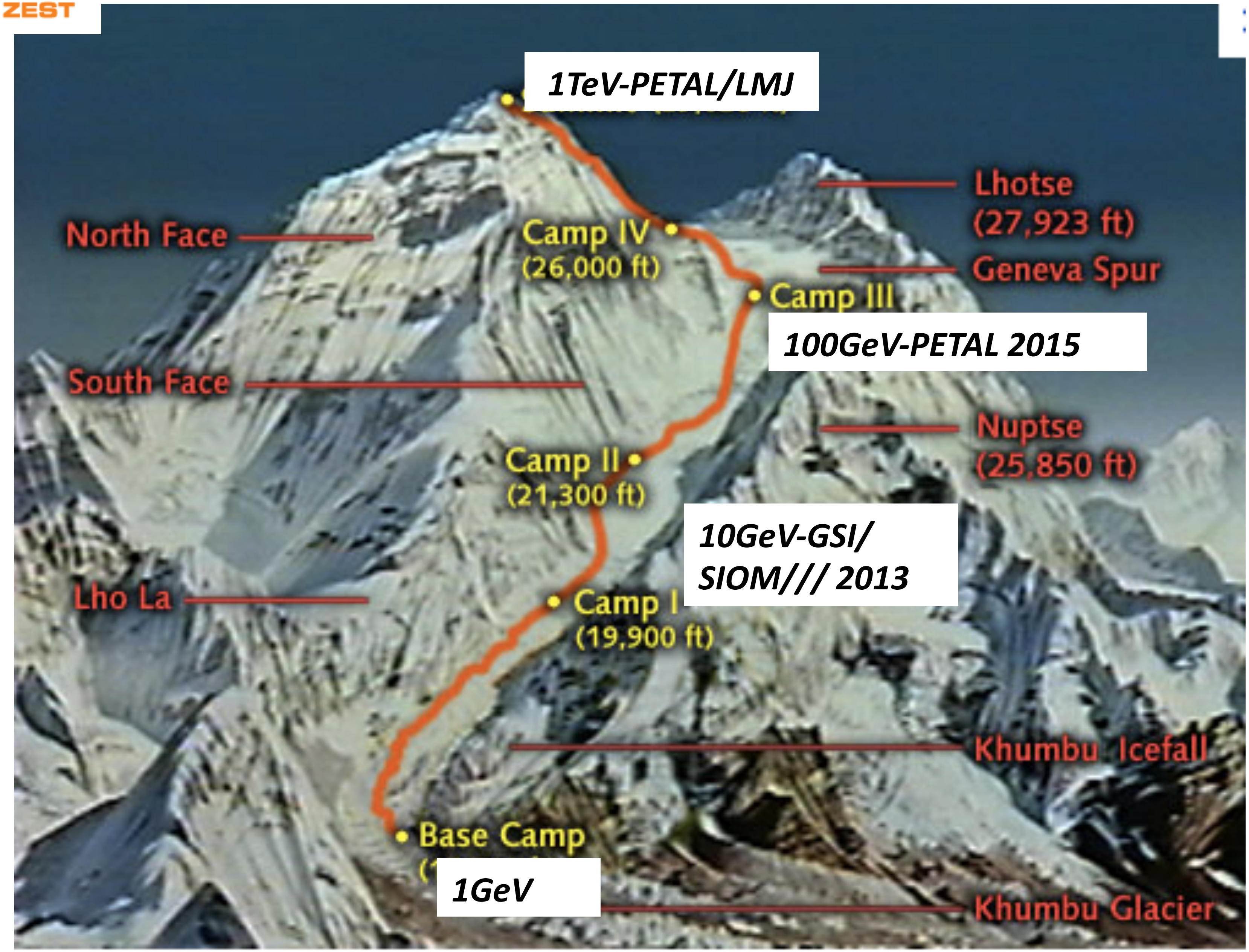
Capillary radius

$$R_c[\mathrm{mm}] \simeq \left(\frac{2\times10^{16}}{n_e[\mathrm{cm}^{-3}]}\right)^{1/3.2}$$

Method 1

Ablative Discharge Plasma Waveguide-Meter Module

IZEST 100GeV Ascent



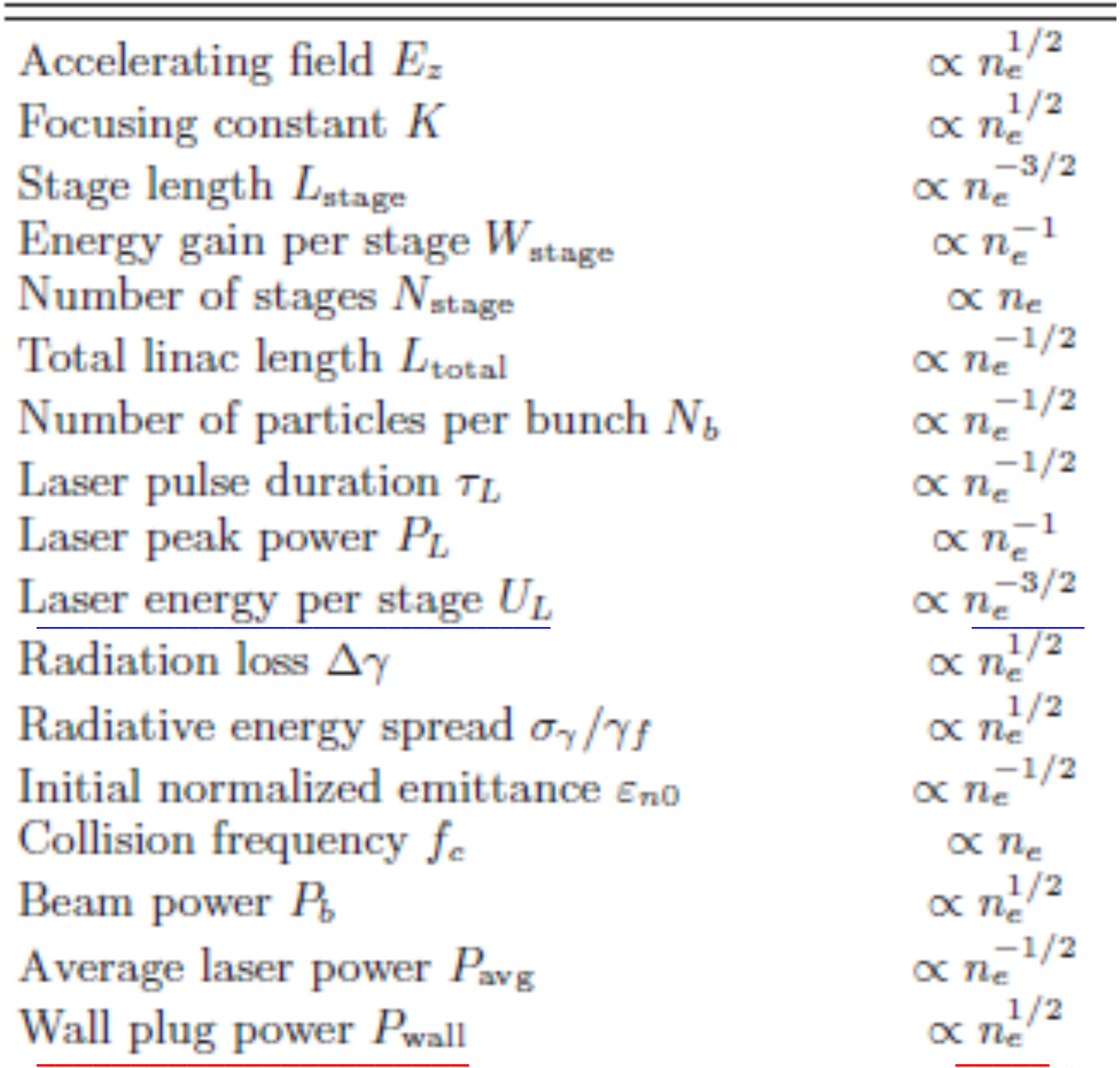
1TeV-PETAL/LMJ

100GeV-PETAL 2015

10GeV-GSI/ SIOM/// 2013

1GeV

Density scalings of **LWFA** for collider



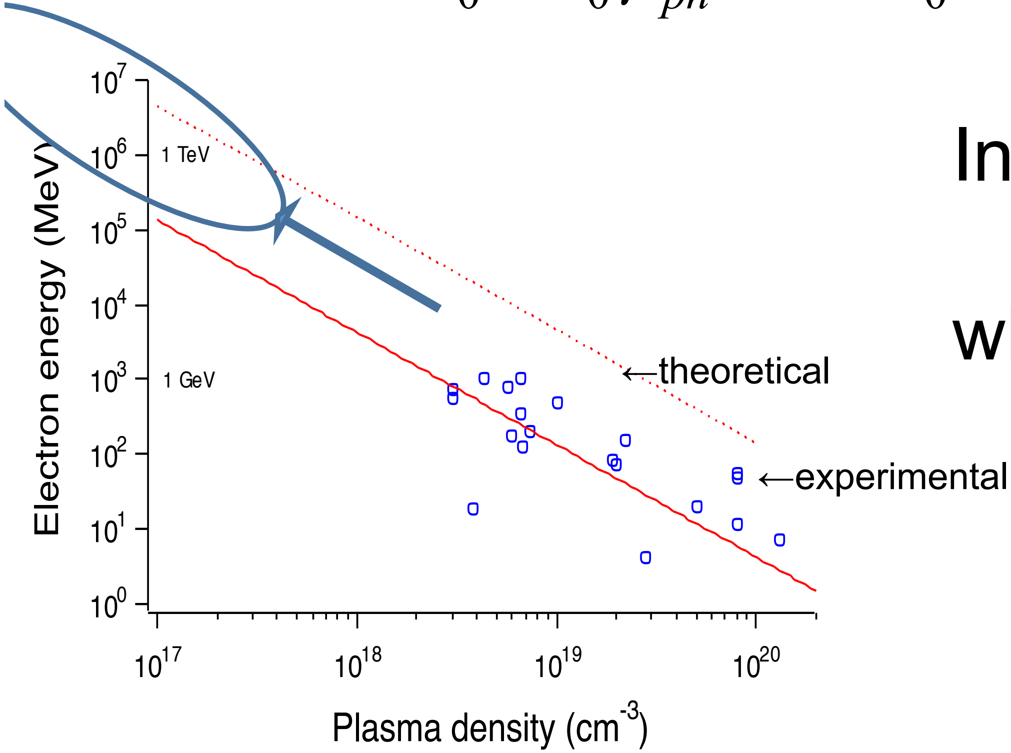
Accelerating field E_z	$\propto n_e^{1/2}$
Focusing constant K	$\propto n_e^{1/2}$
Stage length L_{stage}	$\propto n_e^{-3/2}$
Energy gain per stage W_{stage}	$\propto n_e^{-1}$
Number of stages N_{stage}	$\propto n_e$
Total linac length L_{total}	$\propto n_e^{-1/2}$
Number of particles per bunch N_b	$\propto n_e^{-1/2}$
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

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

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

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

dephasing length

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

pump depletion length

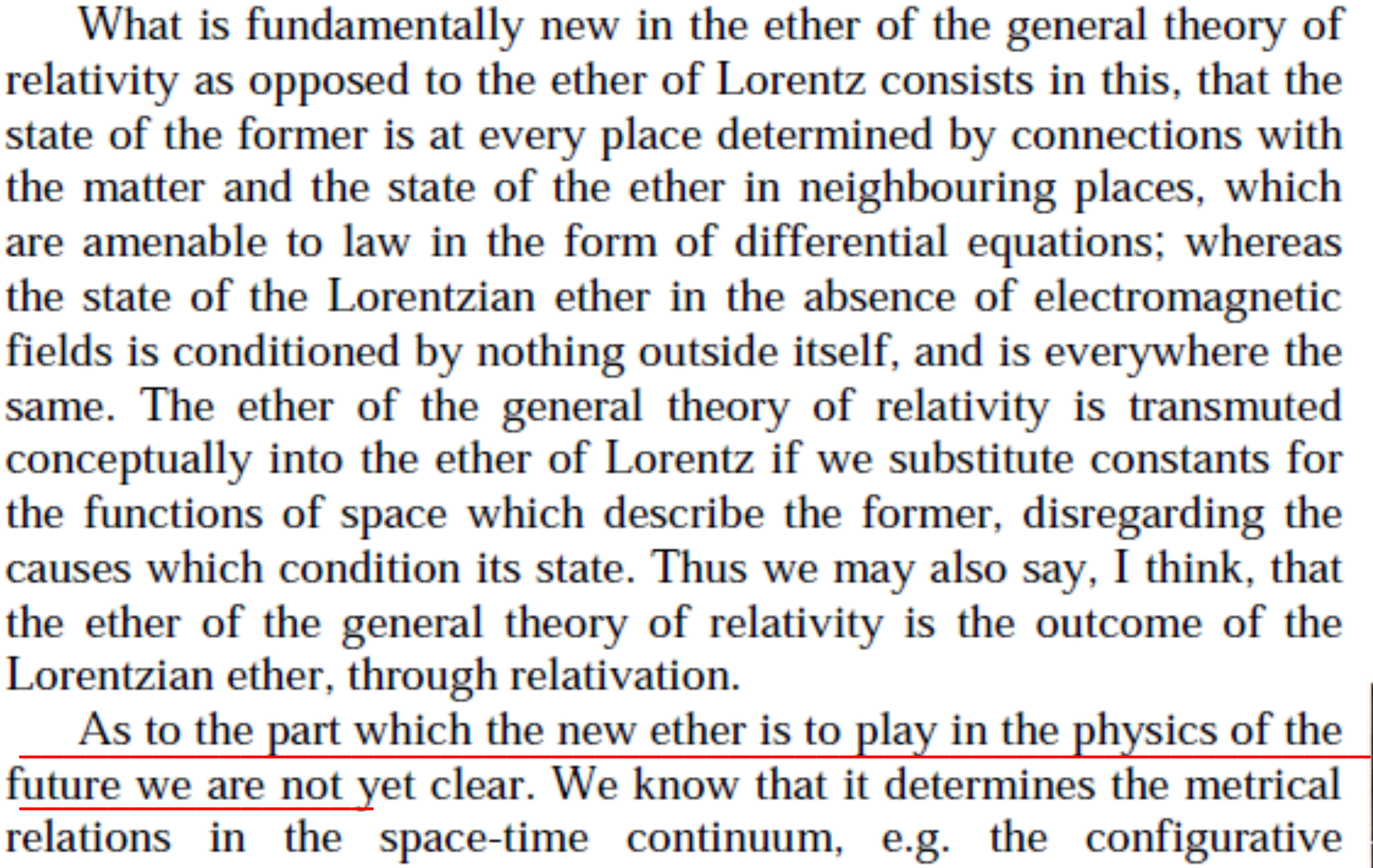
Adopt:

NIF laser (3MJ)

→ 0.7PeV

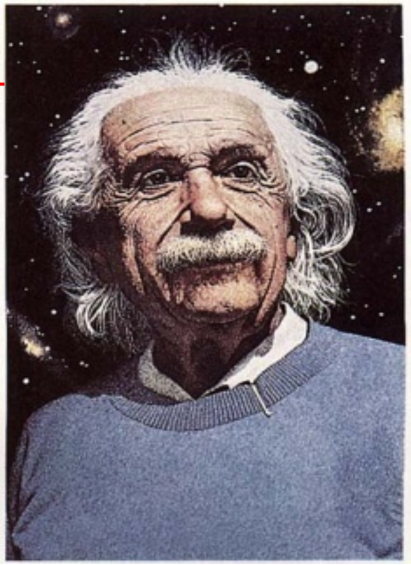
(with Kando, Teshima)

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.

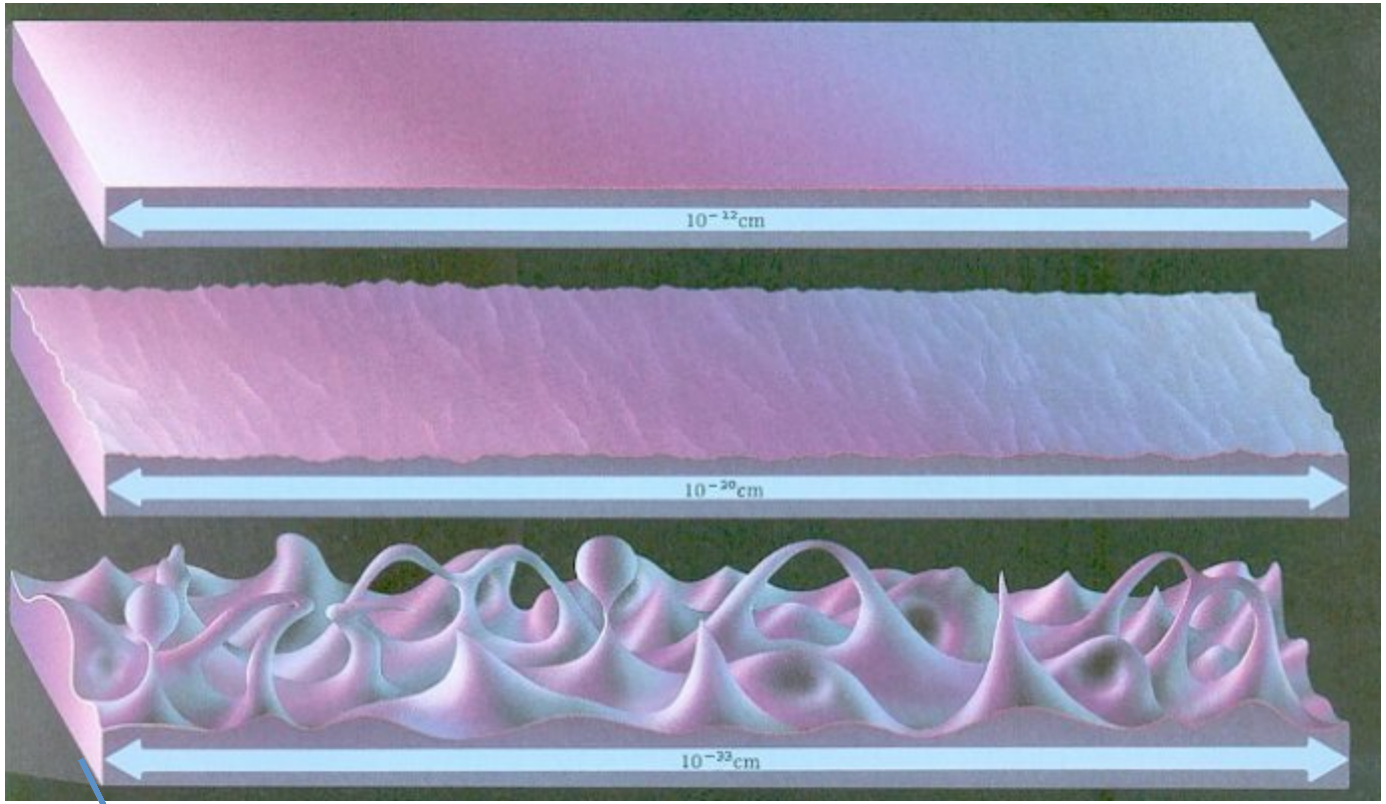
As to the part which the new ether is to play in the physics of the future we are not yet clear. We know that it determines the metrical relations in the space-time continuum, e.g. the configurative



(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)

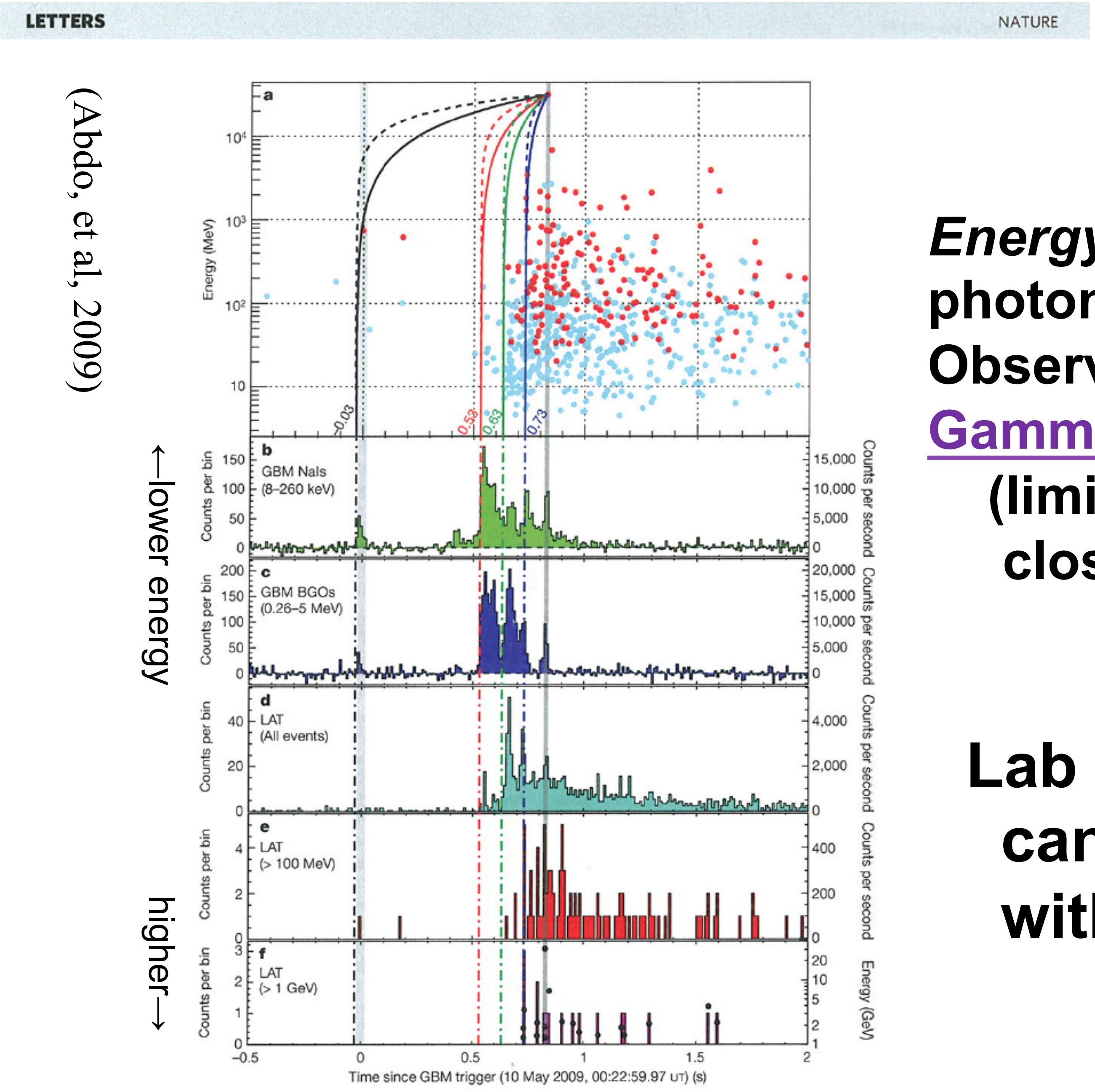
1km

←(1PeV : fs behind)

PeV γ (converted from e^-)

γ-ray signal from primordial GRB

(Abdo, et al, 2009)



←lower energy

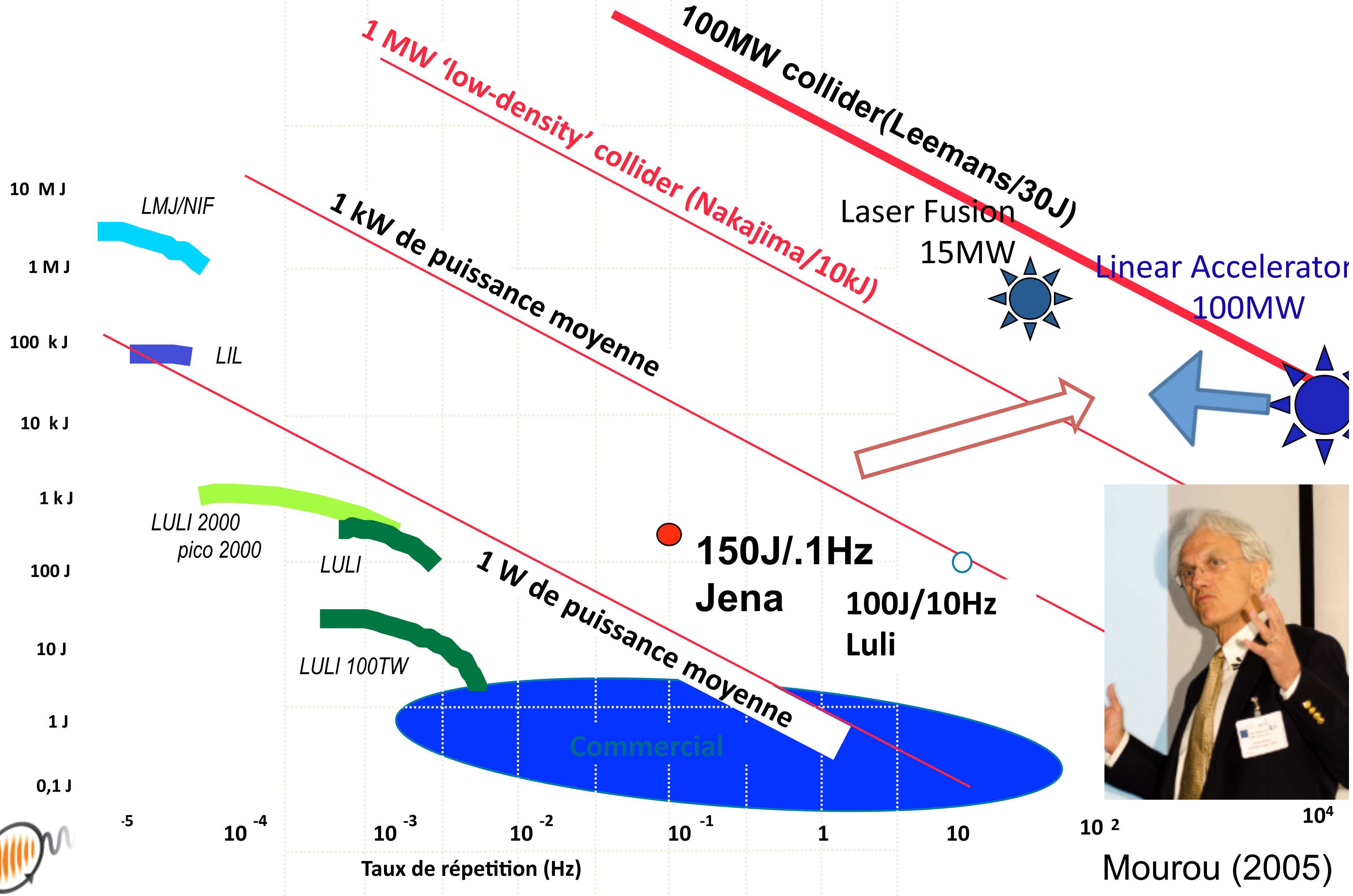
higher→

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

Etat de l’Art *(HEEAUP 2005): collider consideration*



Mourou (2005)

Mourou/ICAN (2013); Nakajima (2011)

IZEST

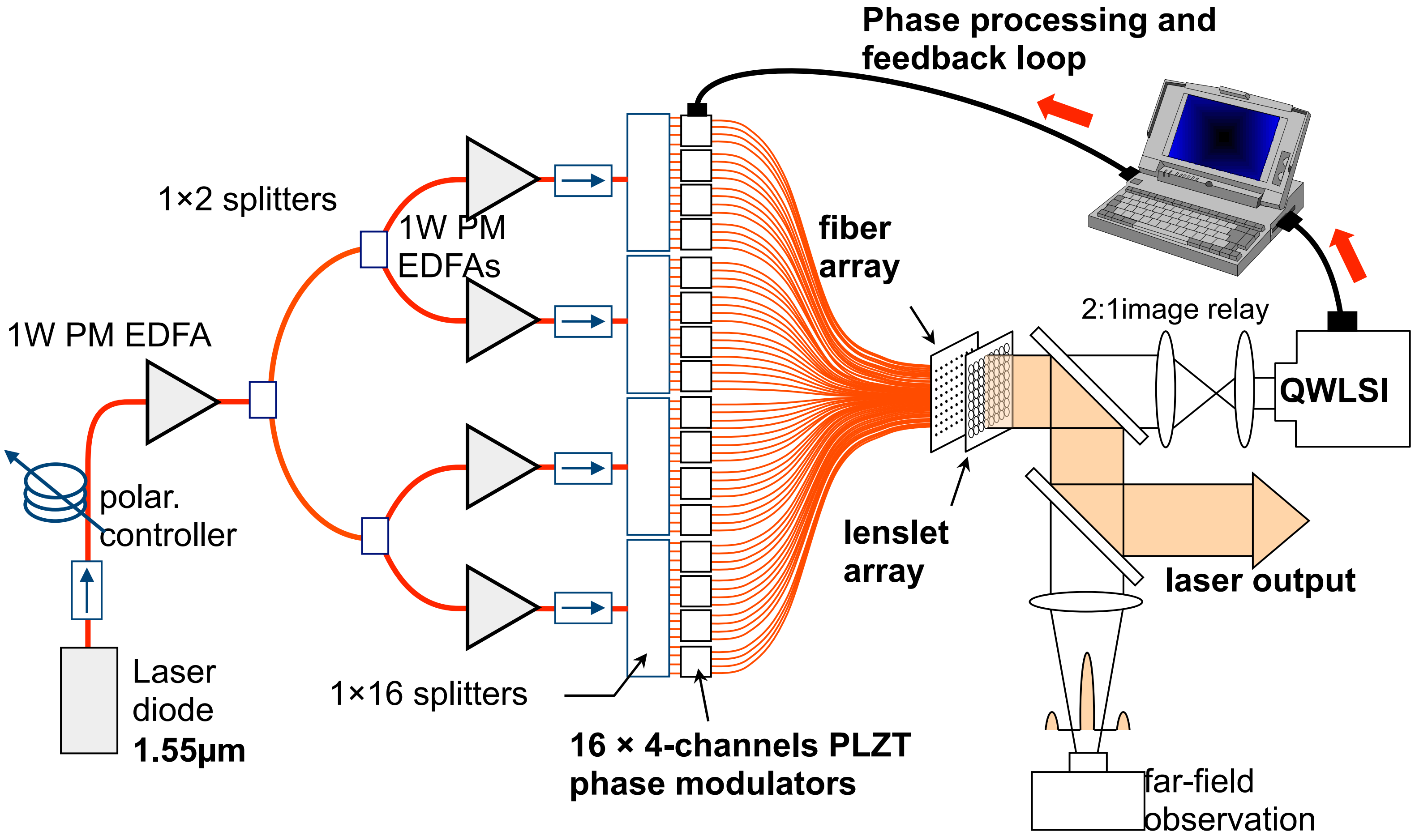
(International Center for Zetta- Exawatt Science and Technology)

aspires to push the average power
of ultraintense laser from **Watt** to **MW**

(*ICAN-International Coherent Amplification Network*)

J. Bourderionnet, A. Brignon (Thales), C. Bellanger, J. Primot (ONERA)

Coherent Fiber Combining

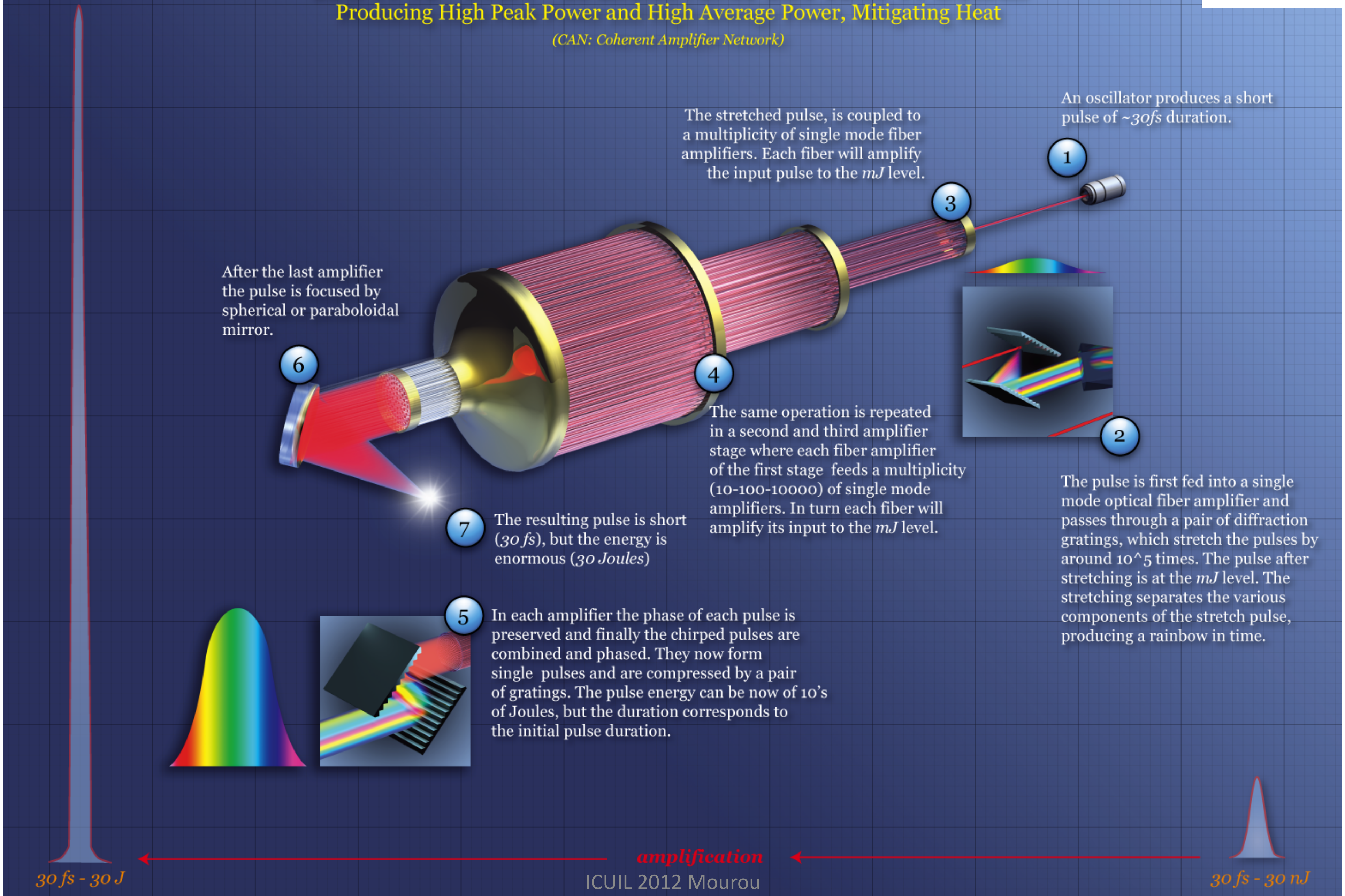


Achievement 2011
→ 64 phase-locked fibers

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*)

ICUIL 2012 Mourou

Smart control of laser

Emittance (and thus luminosity) of the particle beam

rapidly increases with the jitters of laser [in multi-stage acceleration]

smart control of laser →contains jitters

We see:

CAN laser property of **smartness**

higher rep rate, easier to operate CAN laser

higher rep rate, easier to feed-forward control

feedforward control → quality of beams

CAN laser : coherently connected (both in *parallel*, but also in *tandem*)

each fiber (digital unit): coherently and digitally controllable

→ digitally controlled **smart laser :** a new paradigm

ICAN Applications

Scientific :

- **Laser acceleration toward TeV**
- **Higgs factory with γ-γ collider**
- **Physics beyond the Standard Model: Dark Matter search with laser**
- **ZeV astrophysics (astrophysical manifestation of wakefields)**

(see T. Ebisuzaki and T. Tajima.: arXiv: 1306.0970 [astro-ph.HE])

Societal:

- **Laser proton acceleration and applications:**
  - Neutron sources
  - Accelerator Driven System(ADS) for transmutation of nuclear waste
  - Accelerator Driven Reactor(ADR) for safer energy production
- **Laser-driven gamma beam applications:**
  - Fukushima
  - Homeland security

ican International Coherent Amplification Network

Opportunities Enabled by CAN

Commission européenne

CAN Fiber Laser

Average power → luminosity

rep rate x peak power

Efficiency → cost

Smartness (digital control) → emittance

Intensity → gradient

Collider requirements

R. Aleksan (Court. A. Oeftinger(CERN))

γ-γ collider requirements

1-50kHz rep rate (other reqs are easier)

Dark matter search

average power → luminosity

Proton acceleration

intensity (energy of beam), smartness (beam quality), average power (fluence)

UNIVERSITY OF Southampton

Fraunhofer IOF

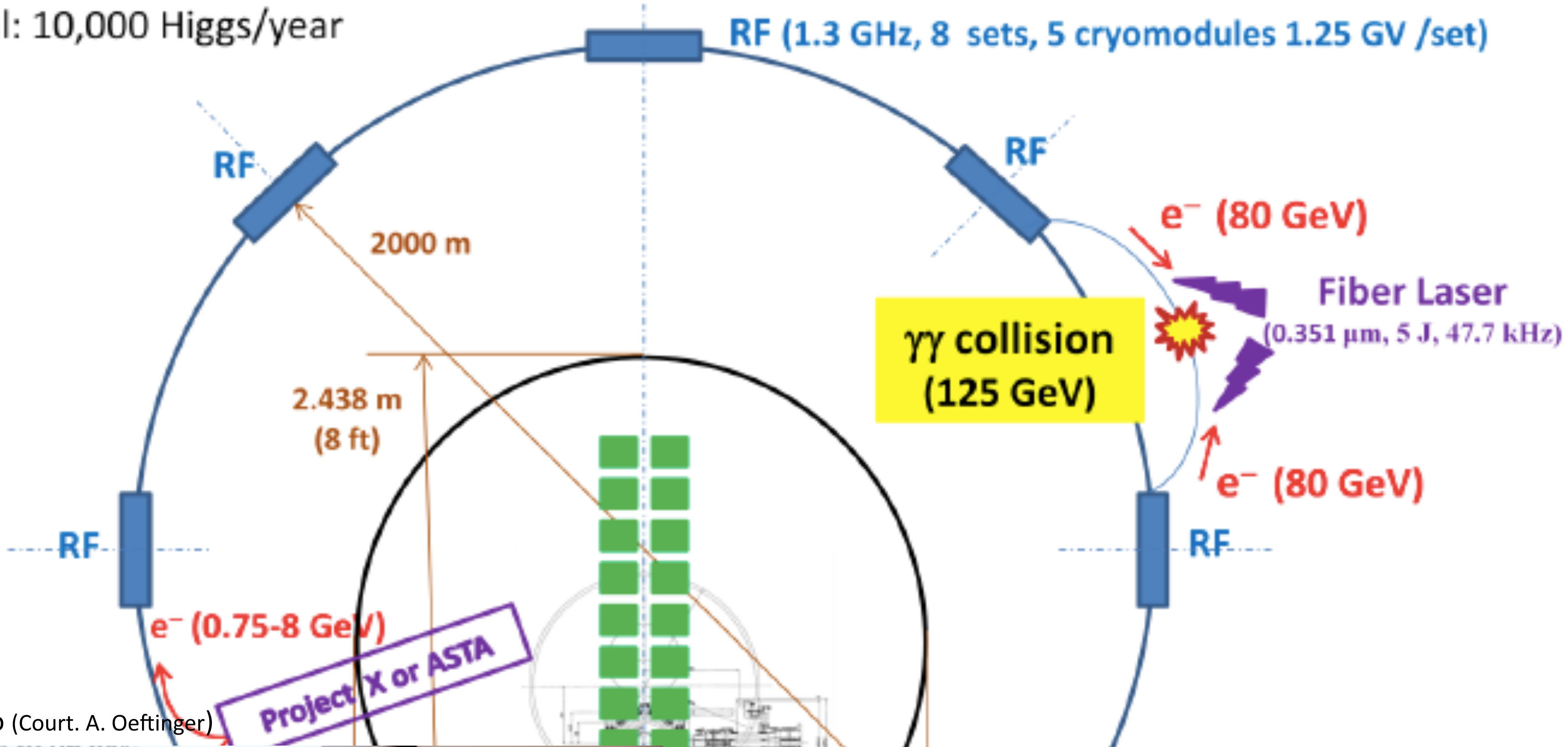
CERN

HFiTT – Higgs Factory in Tevatron Tunnel

(γγ collider)

(W. Chou et al.)

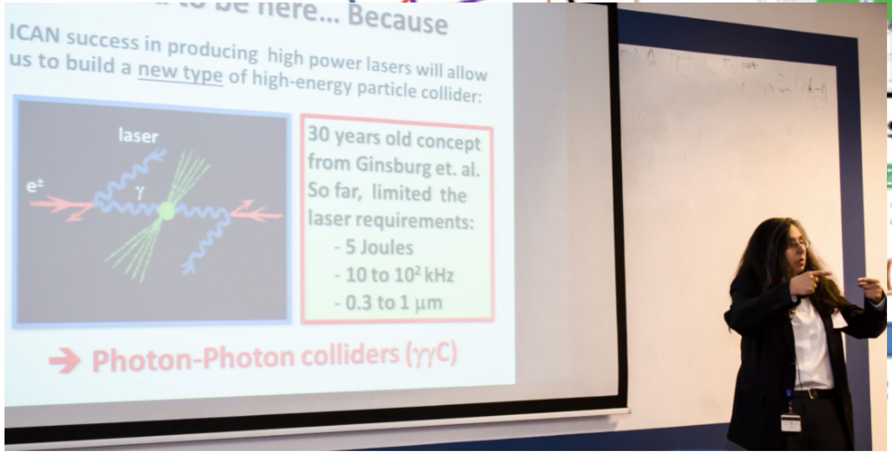
Goal: 10,000 Higgs/year



E = 80 GeV
ρ= 800 m
U = 4.53 GeV/turn

I = 0.15 mA x 2
P(rf) = 27 MW

M. Velasco (Court. A. Oeftinger)



…to be here... Because

ICAN success in producing high power lasers will allow us to build a new type of high-energy particle collider:

30 years old concept from Ginsburg et. al. So far, limited the laser requirements:
- 5 Joules
- 10 to 10² kHz
- 0.3 to 1 µm

➔ Photon-Photon colliders (γγC)

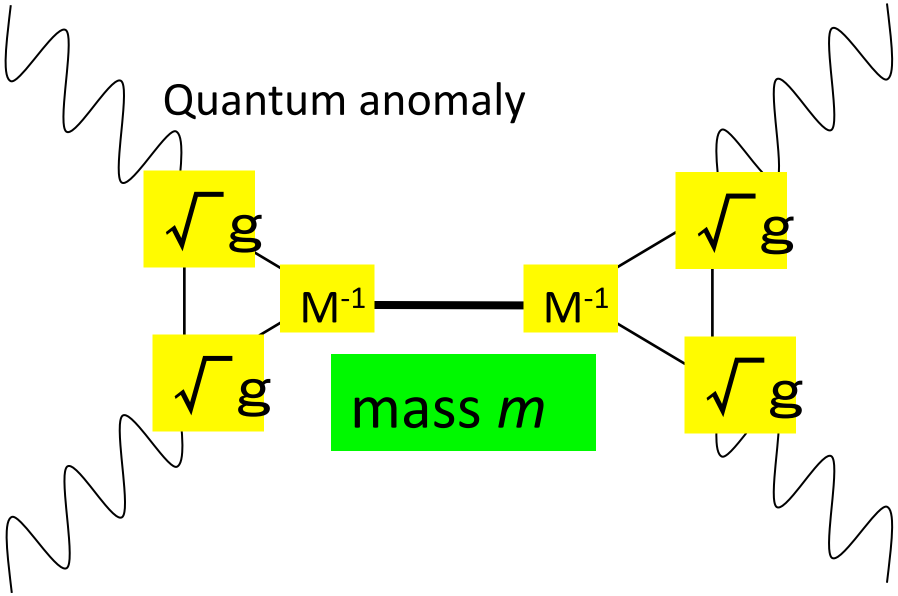
Beyond QED photon-photon interaction

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

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

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$_{\text{Planck}}$, 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)

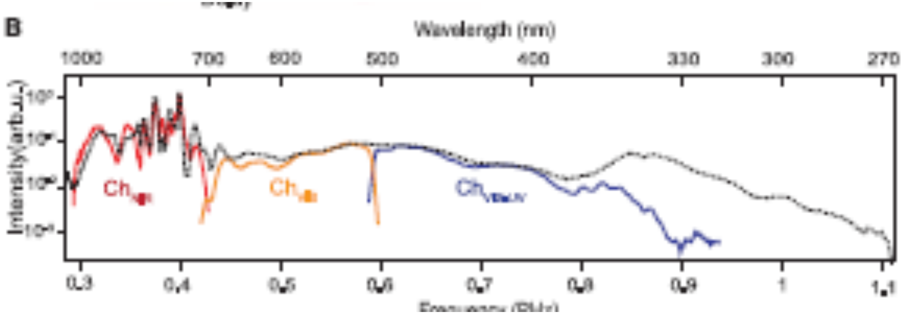
Degenerate Four-Wave Mixing (DFWM)

Laser-induced nonlinear optics in vacuum (cf. Nonlinear optics in crystal)

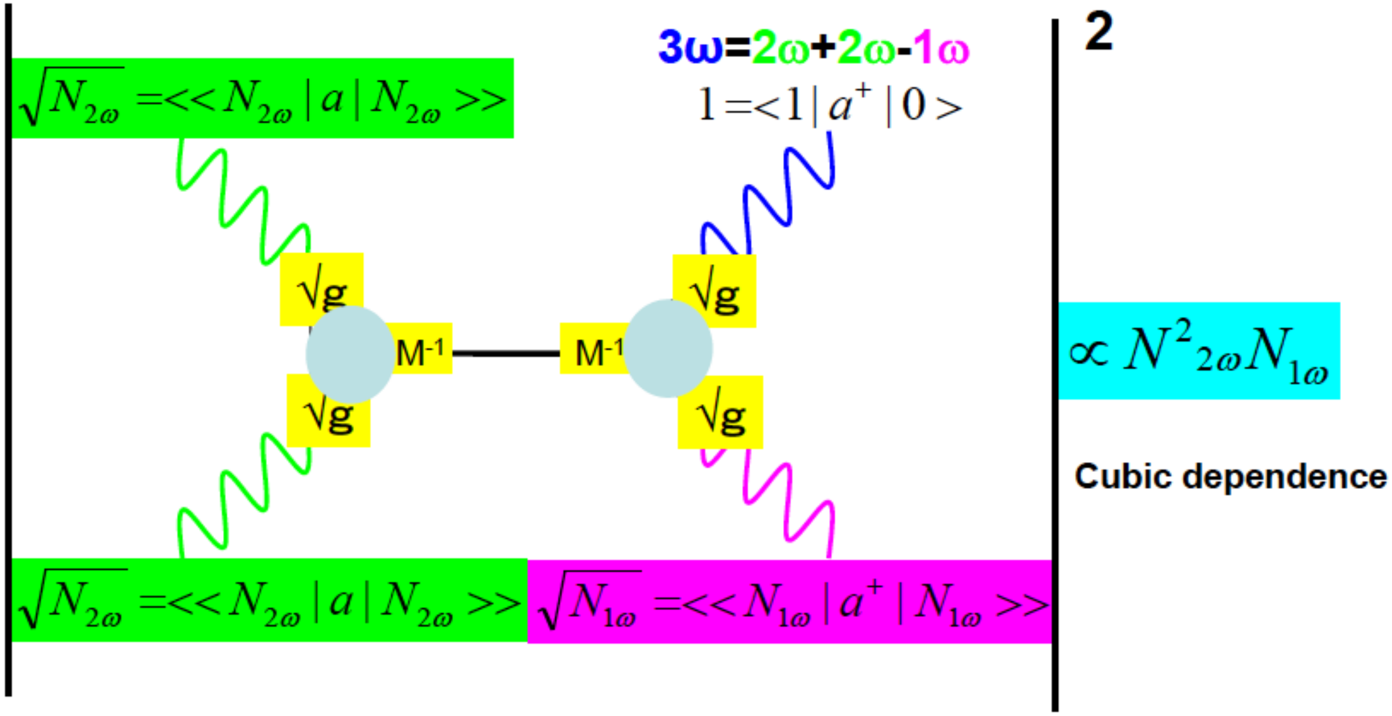
Decay into (4-x)ω can be induced by frequency-mixing

Sweep by arbitrary frequency **xω**

e.g. xω = 1ω



Wirth et al. (Science 2011: synthesized light transients)



3ω=2ω+2ω-1ω

$$1 = <1|a^{+}|0>$$

$$\sqrt{N_{2\omega}} = << N_{2\omega}|a|N_{2\omega} >>$$

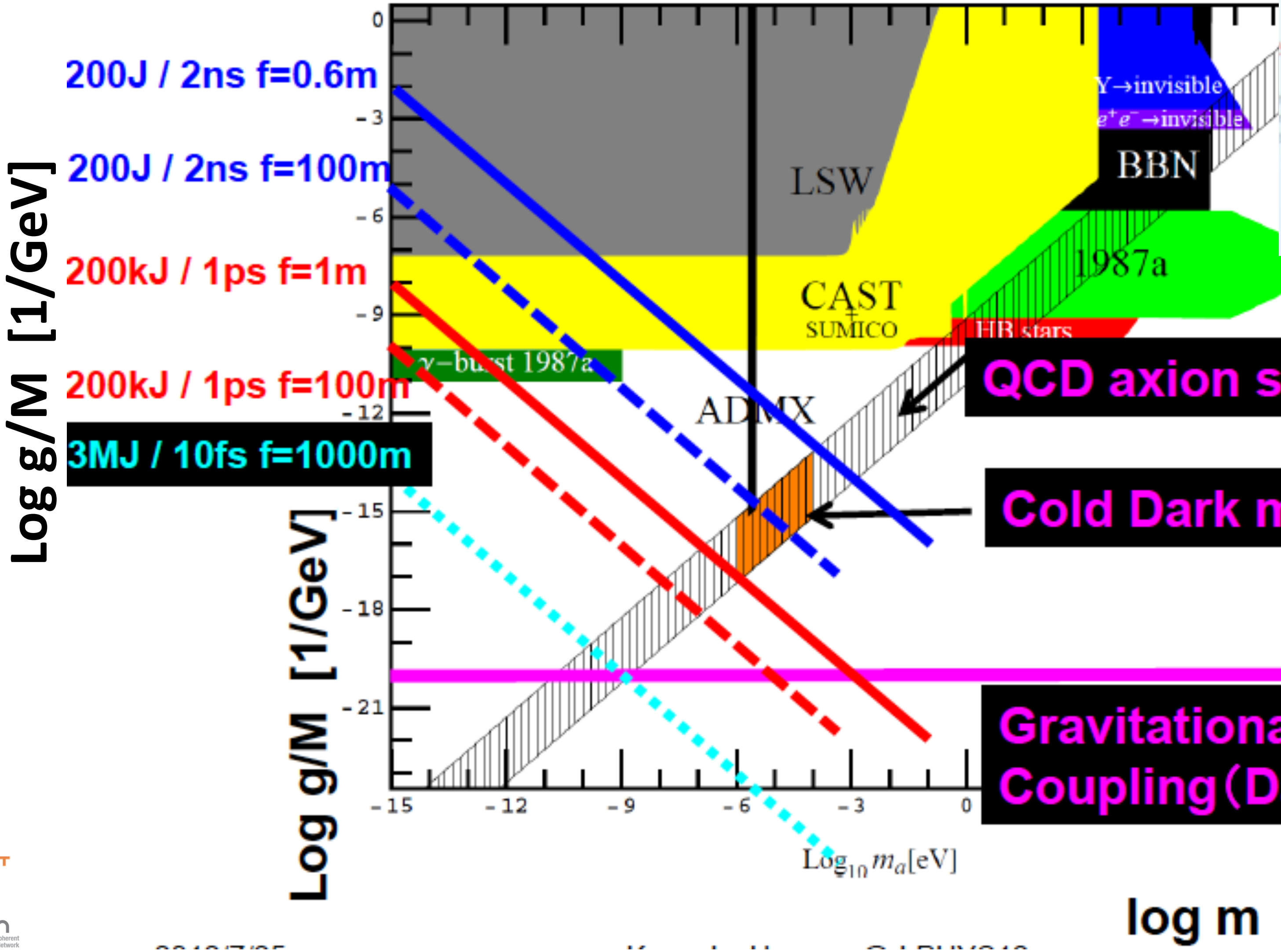
$$\sqrt{N_{2\omega}} = << N_{2\omega}|a|N_{2\omega} >> \sqrt{N_{1\omega}} = << N_{1\omega}|a^{+}|N_{1\omega} >>$$

$$\propto N^{2}{}_{2\omega} N_{1\omega}$$

Cubic dependence

K.Homma, D.Habs, T.Tajima
Appl. Phys. B (2011)

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



(Court. A. Oeftinger)

QCD axion scenario

Cold Dark matter

Gravitational Coupling (Dark Energy)

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

Mountain of Radioactive Junk at Nuclear Facility

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

Sharp discriminatory capability of monoenergetic gamma rays

Nuclear Resonance fluorescence signal


2 MeV e-Brem X-Ray image simulation

Bremsstrahlung gamma rays

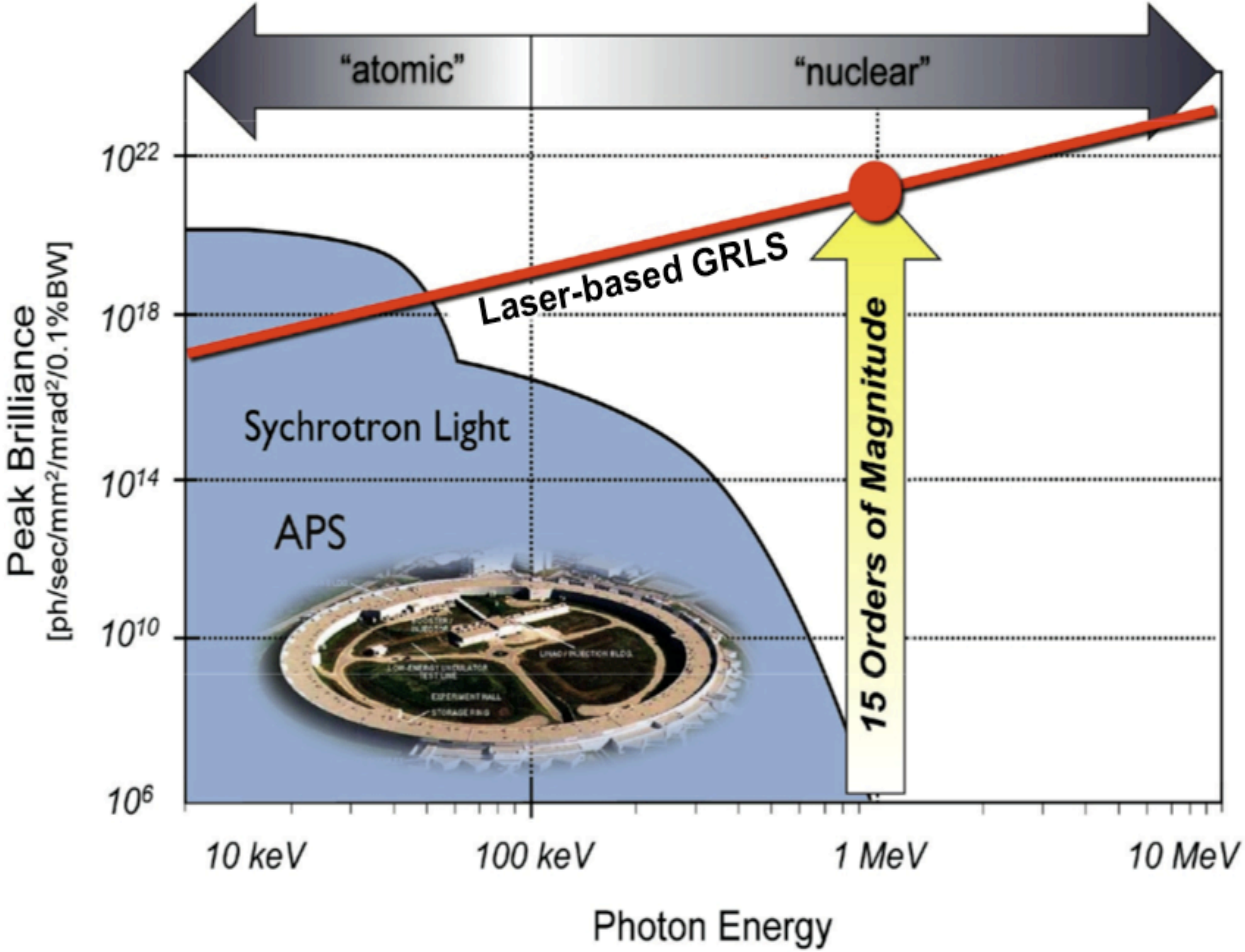
vs


1.734 MeV NRF image simulation

Laser Compton gamma rays

C. Barty and T. Tajima (2008)

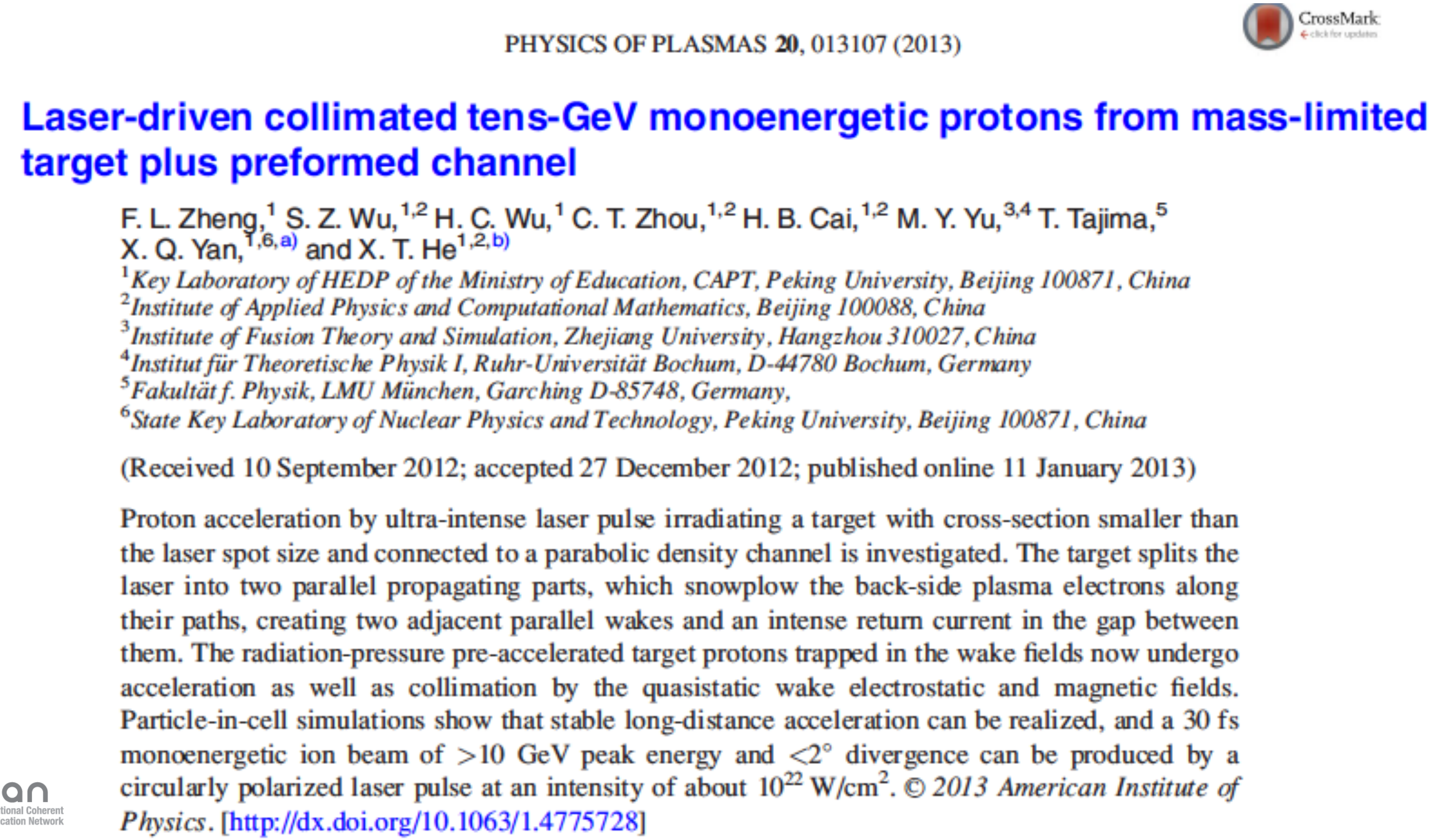
Brilliance of Laser Compton gamma source



Barty and Tajima, 2008

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

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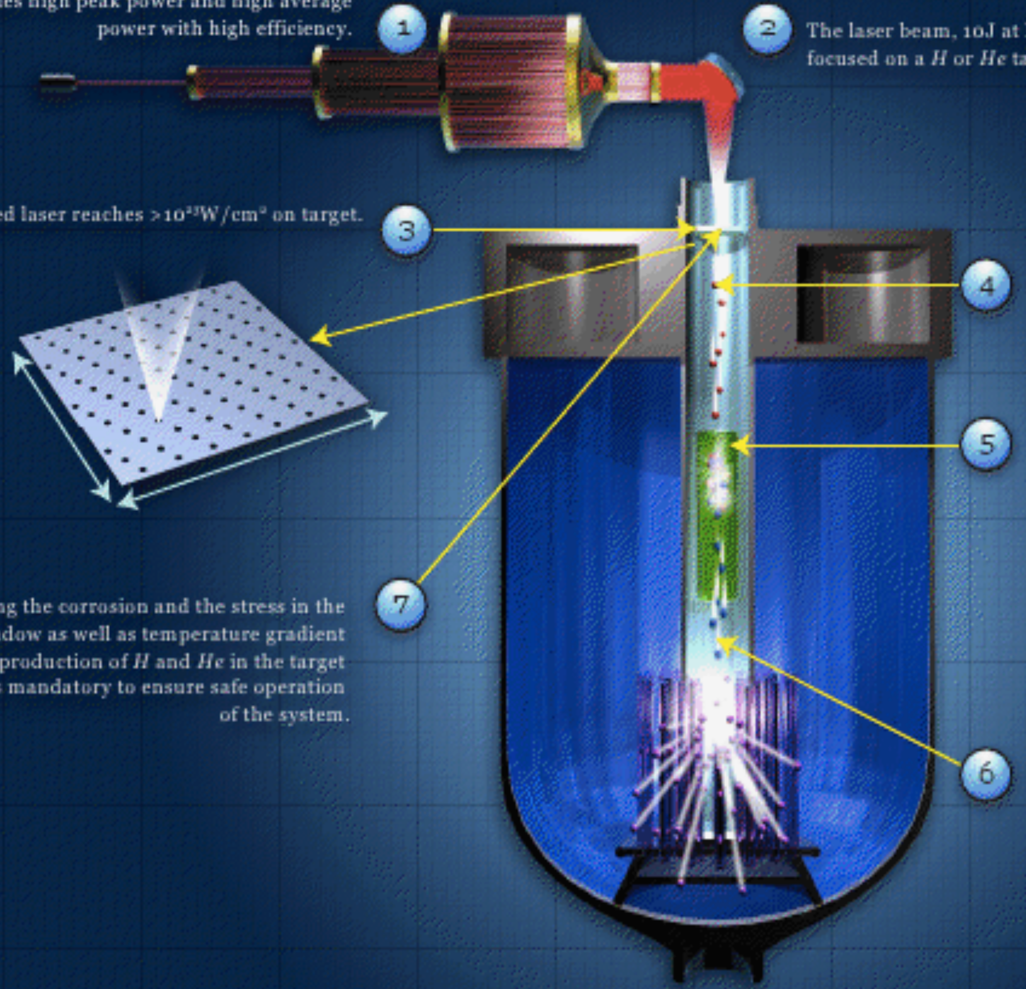
Proton acceleration by ultra-intense laser pulse irradiating a target with cross-section smaller than the laser spot size and connected to a parabolic density channel is investigated. The target splits the laser into two parallel propagating parts, which snowplow the back-side plasma electrons along 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]

ican
International Coherent
Amplification Network

IZEST

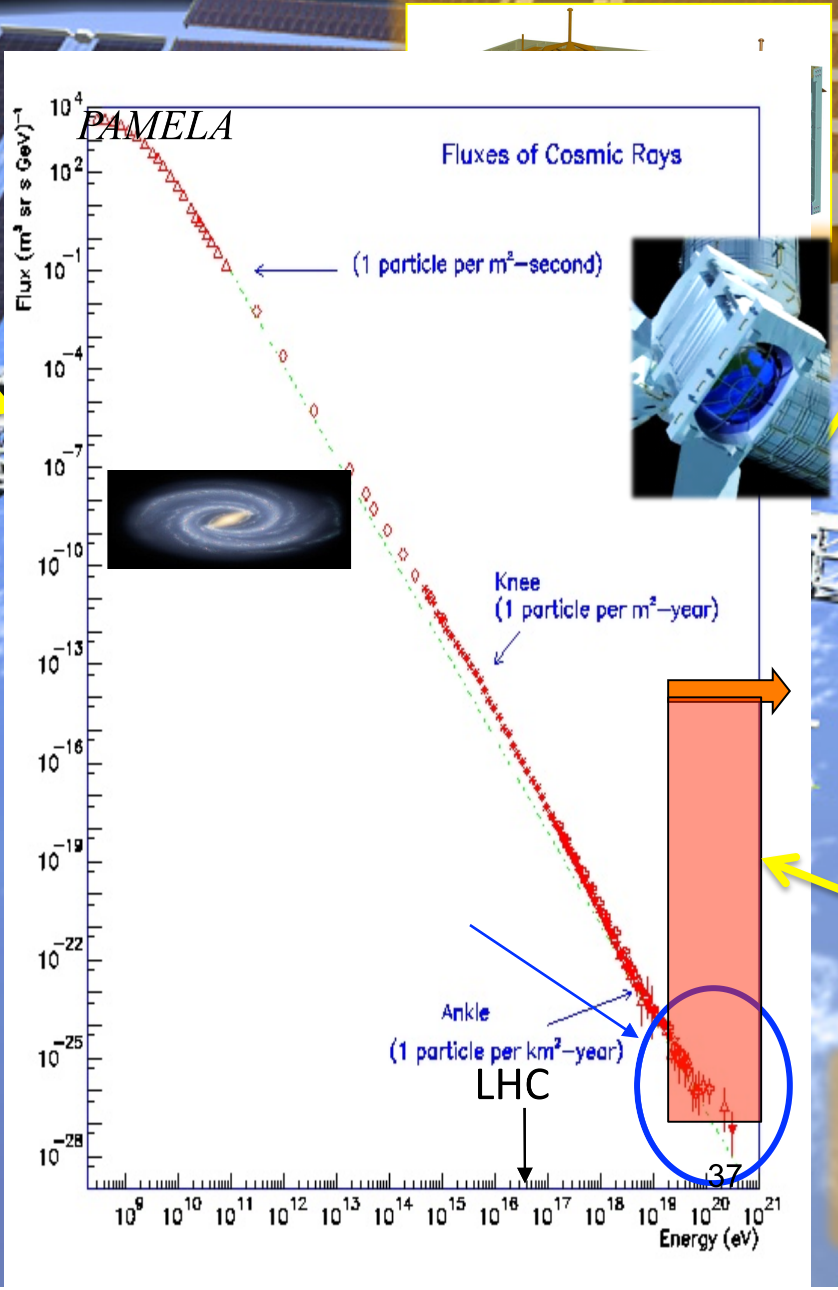
THE LASER DRIVEN TRANSMUTATOR CONCEPT

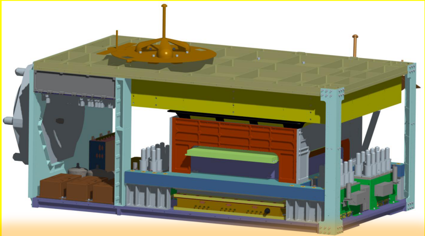


1. A Coherent Amplified Network (CAN) laser provides high peak power and high average power with high efficiency.
2. The laser beam, 10J at kHz rate, is focused on a *H* or *He* target.
3. The focused laser reaches $>10^{23}$W/cm² on target.
4. It produces with high efficiency a high flux of high energy 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.
6. The neutrons produced are used to transmute the spent fuel into a shorter half-life material.
7. 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.

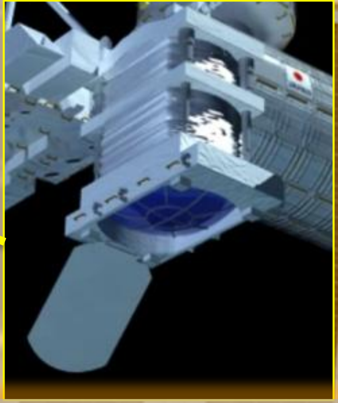
Extreme High Energy Cosmic Rays (EHECR)

AMS Launch
May 16, 2011





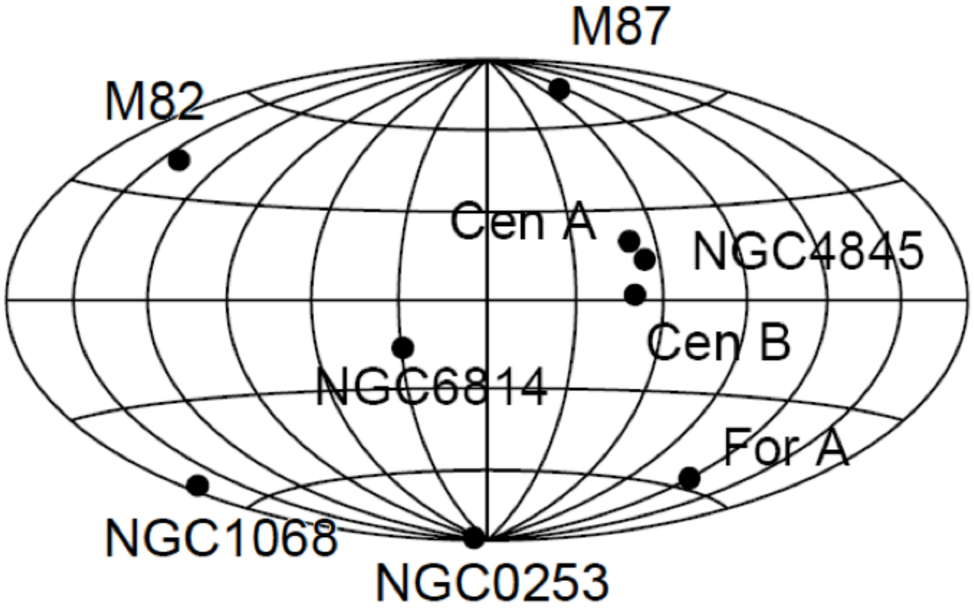
ISS-CREAM
Sp-X Launch 2014



JEM-EUSO
Launch Tentatively
planned for 2017

Cen A: an example of AGN

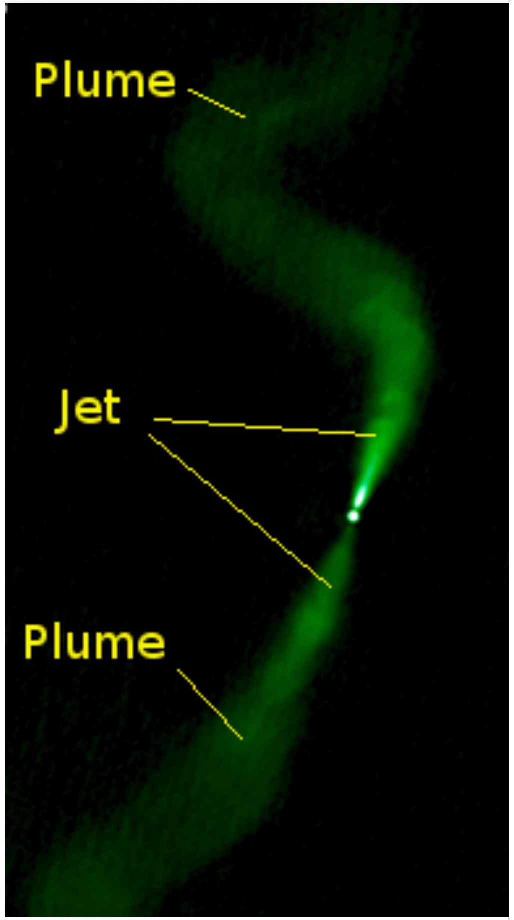
- Distance：3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source (collective oscillations!)
- Elliptical Galaxy
- Disk, AGN jets, halos: visible
- Other AGN: similar



Brightest AGNs

Conclusions

- **High field science** frontier expanding
- Laser-driven accelerators for high energy physics collider in particular
- Large fluence, high efficiency of CAN lasers important for many new scientific and societal applications
- CAN laser = smart laser : highly controllable
- Higgs factory by γ-γ collider emerging
- New weak-coupling field search of vacuum by laser
- Nuclear transmutation by laser-driven neutron sources, ADS, ADR; compact neutrino source
- Non-contact detection of nuclear isotopes via laser Compton gamma rays (Fukushima)
- Other industrial applications (auto-industry, chemical industry, mechanical industry, medical, etc.) with large fluence and high efficiency lasers
- EHECR <--> terrestrial laser acceleration



Blazar: Cosmic laser wakefield linac?

ありがとうございます!