

*The Einstein Lecture(4)*  
*Peking University*  
*September 12, 2013*

# Prospect for High Field Science

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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\***



\* I dedicate this lecture to my mentor, Professor Norman Rostoker



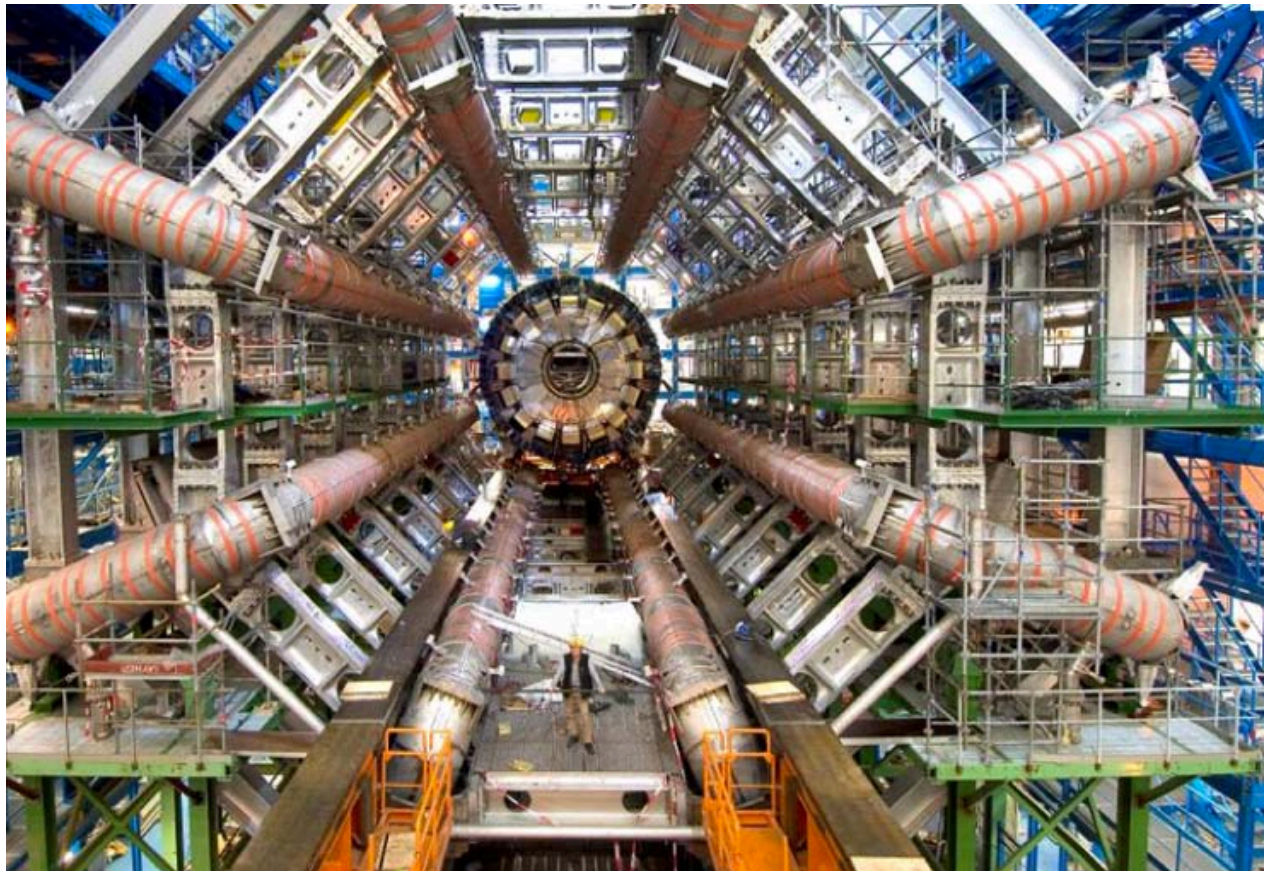
# content



- **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



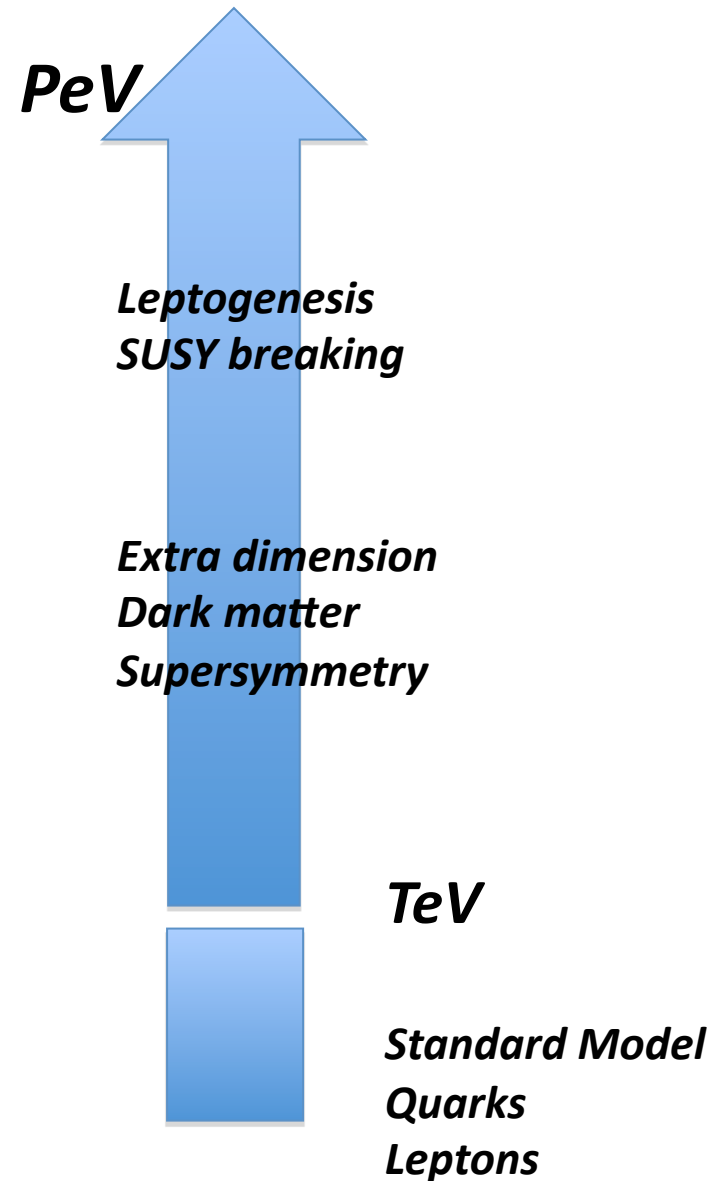
***Rolf Heuer***  
***CERN Director General***

# ***IZEST's Mission:*** **Responding to Suzuki's** **Challenge**



***Atsuto Suzuki:***  
***KEK Director General,***  
***Former ICFA Chair***

## **New Paradigm**





# 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)]

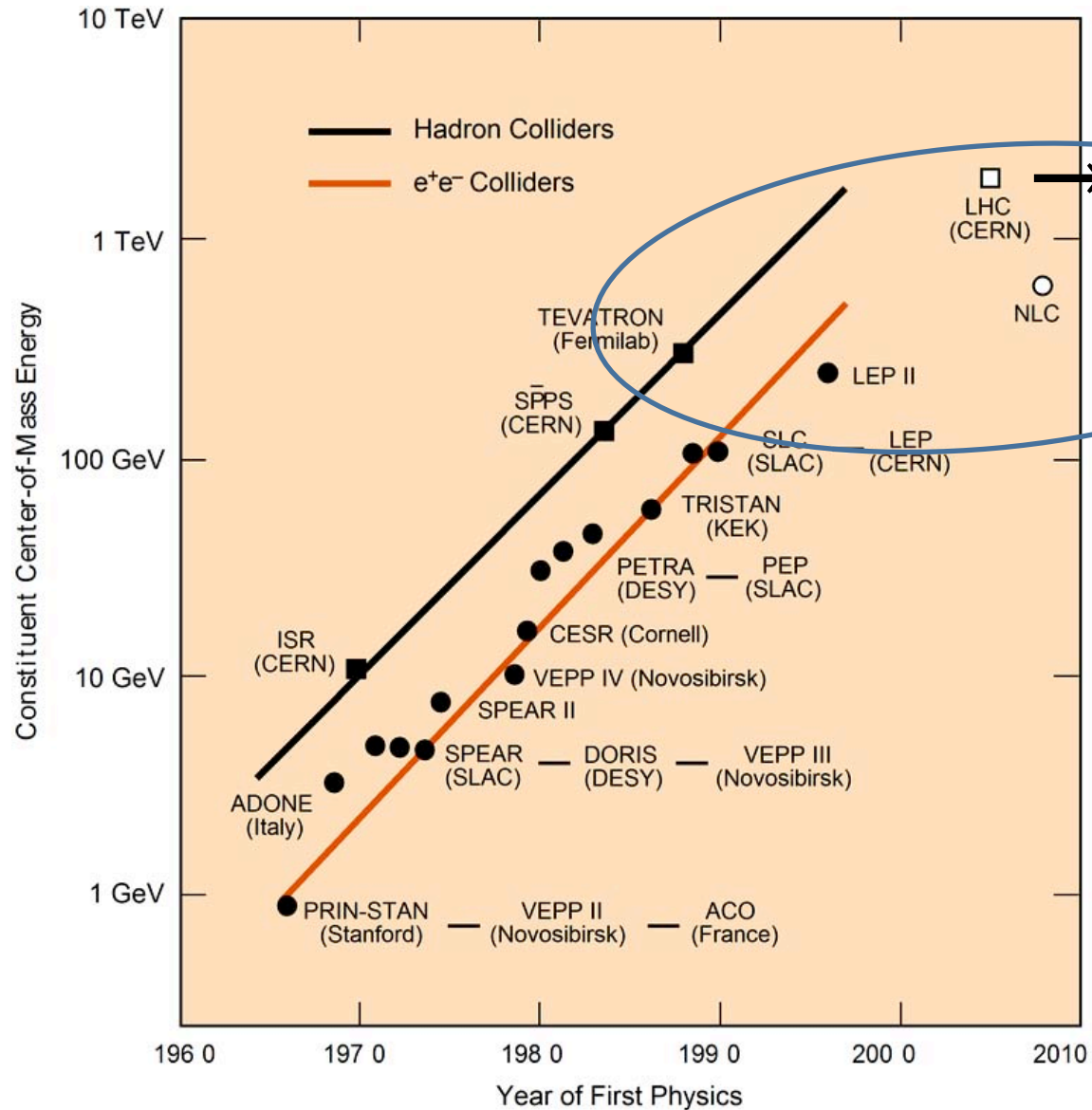


# IZEST Associate Laboratories



- |   |    |    |  |
|---|----|----|--|
| <b>Ecole Polytechnique</b> - Palaiseau, France  | 1  | 12 | <b>IAP</b> - Institute of Advanced Physics, Nizhy Novgorod, Russia                     |
| <b>CEA</b> - Commissariat à l'Énergie Atomique et aux énergies alternatives, Bordeaux, France | 2  | 13 | <b>GIST</b> - Gwangju Institute of Science and Technology, Gwangju, Republic of Korea  |
| <b>PPPL</b> - Princeton Plasma Physics Laboratory, Princeton, New Jersey, USA                 | 3  | 14 | <b>KEK</b> - High Energy Accelerator Research Organization, Tsukuba, Japan             |
| <b>FERMILAB</b> - Fermi National Accelerator Laboratory, Chicago, Illinois, USA               | 4  | 15 | <b>KPSI</b> - Kansai Photon Science Institute, Kansai, Japan                           |
| <b>LLNL</b> - Lawrence Livermore National Laboratory, Livermore, California, USA              | 5  | 16 | <b>LeCosPa</b> - Leung Center for Cosmology and Particle Astrophysics, Taipei, Taiwan  |
| <b>CUOS</b> - Center for Ultrafast Optical Science, Ann Arbor, Michigan, USA                  | 6  | 17 | <b>CLPU</b> - Centro de Láseres Pulsados Ultracortos Ultraintensos, Salamanca, Spain   |
| <b>ALLS</b> - Advanced Laser Light Source, Montreal, Canada                                   | 7  | 18 | <b>CERN</b> - Organisation Européenne pour la Recherche Nucléaire, Genève, Switzerland |
| <b>JAI</b> - John Adams Institute for accelerator science, Oxford, UK                         | 8  | 19 | <b>SIOM</b> - Shanghai Institute of Optics and Fine Mechanics, Shanghai, China         |
| <b>TOPS</b> - TeraHertz to Optical Pulse Source, Strathclyde, UK                              | 9  | 20 | <b>Kyoto University</b> - Kyoto, Japan   |
| <b>HHU</b> - Heinrich Heine Universität, Düsseldorf, Germany                                  | 10 | 21 | <b>ELI-NP</b> - Extreme Light Infrastructure - Nuclear Physics, Magurele, Romania      |
| <b>MEPhi</b> - Moscow Engineering Physics Institute, Moscow, Russia                           | 11 | 22 | <b>Beijing University</b> - Beijing, China   |
|   |    | 23 | <b>TCHILS</b> - Texas Center for High Intensity Laser Science, Austin, USA             |

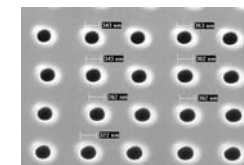
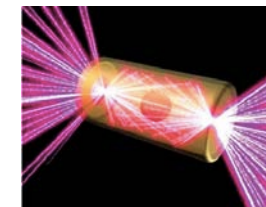
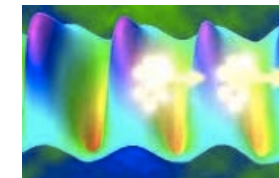
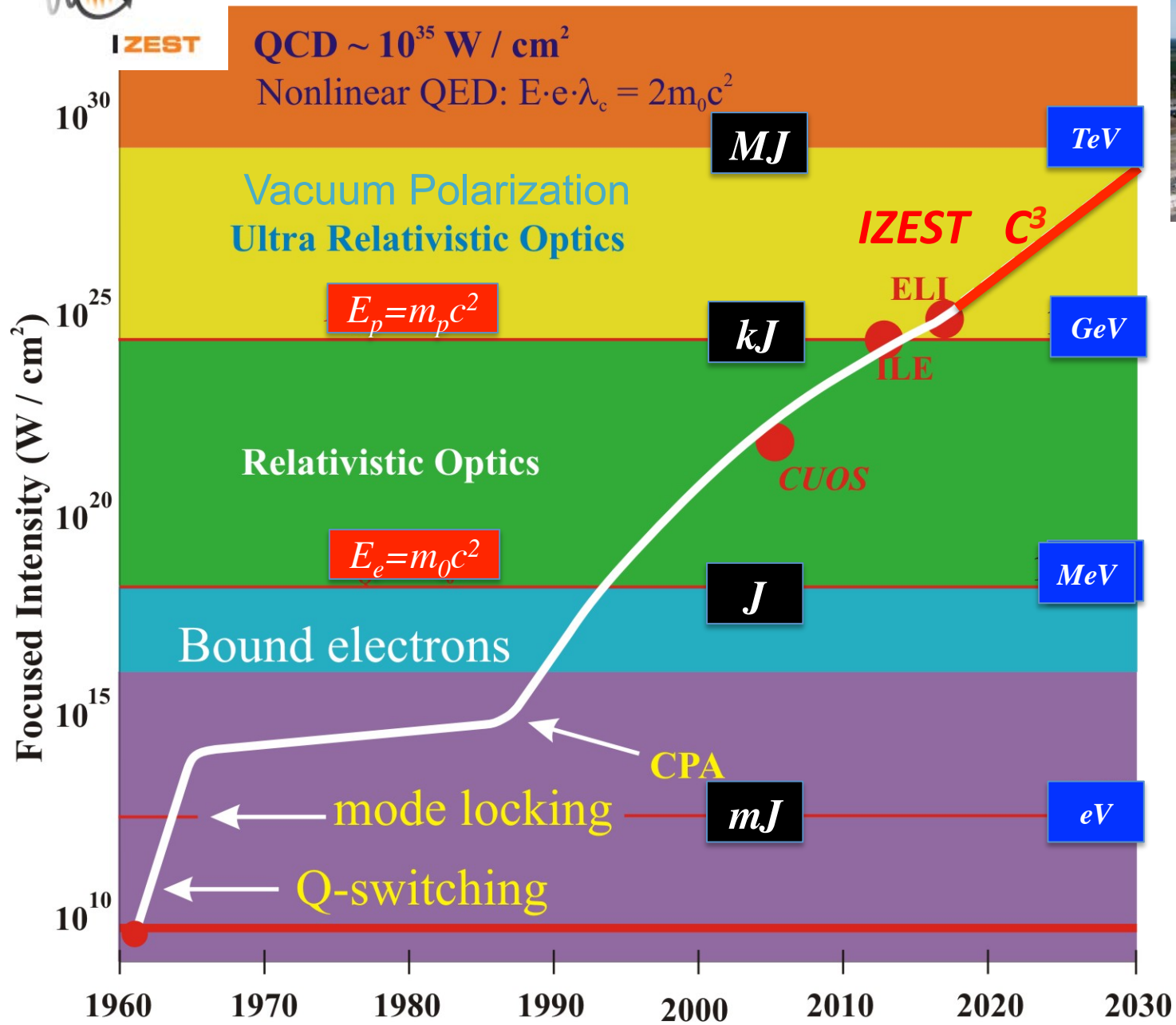
# Livingston Chart and Recent Saturation



(Suzuki, 2009; further corrected 2013)



# Extreme Light Road Map





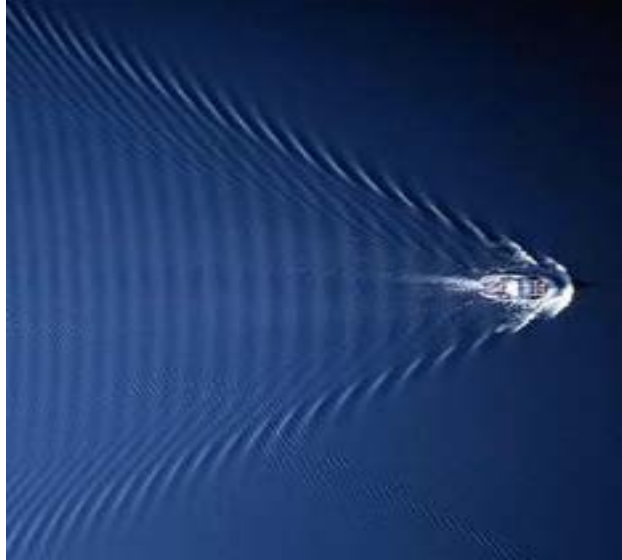
# Brief History of **ICUIL** – ICFA Joint Effort

- 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



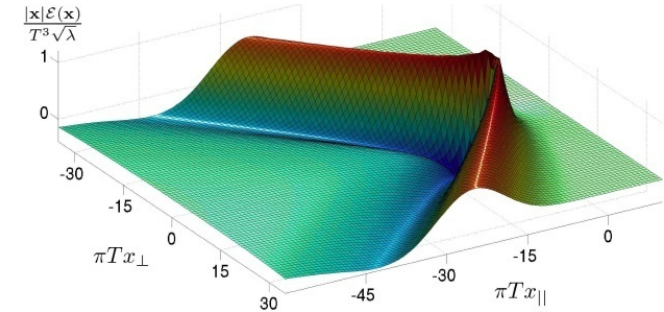


# Laser Wakefield (LWFA): nonlinear optics in plasma



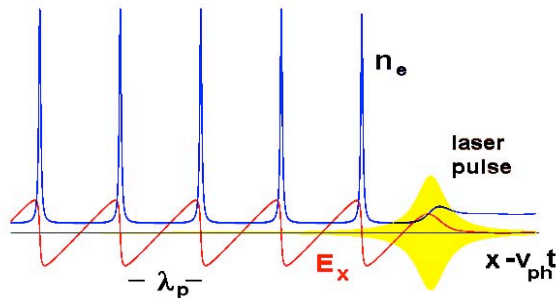
Bow ('ponderomotive')  
and Kelvin **wake** waves

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



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

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



← relativity  
regularizes  
(*relativistic coherence*)

(The density cusps.  
Cusp singularity)



Hokusai



Maldacena



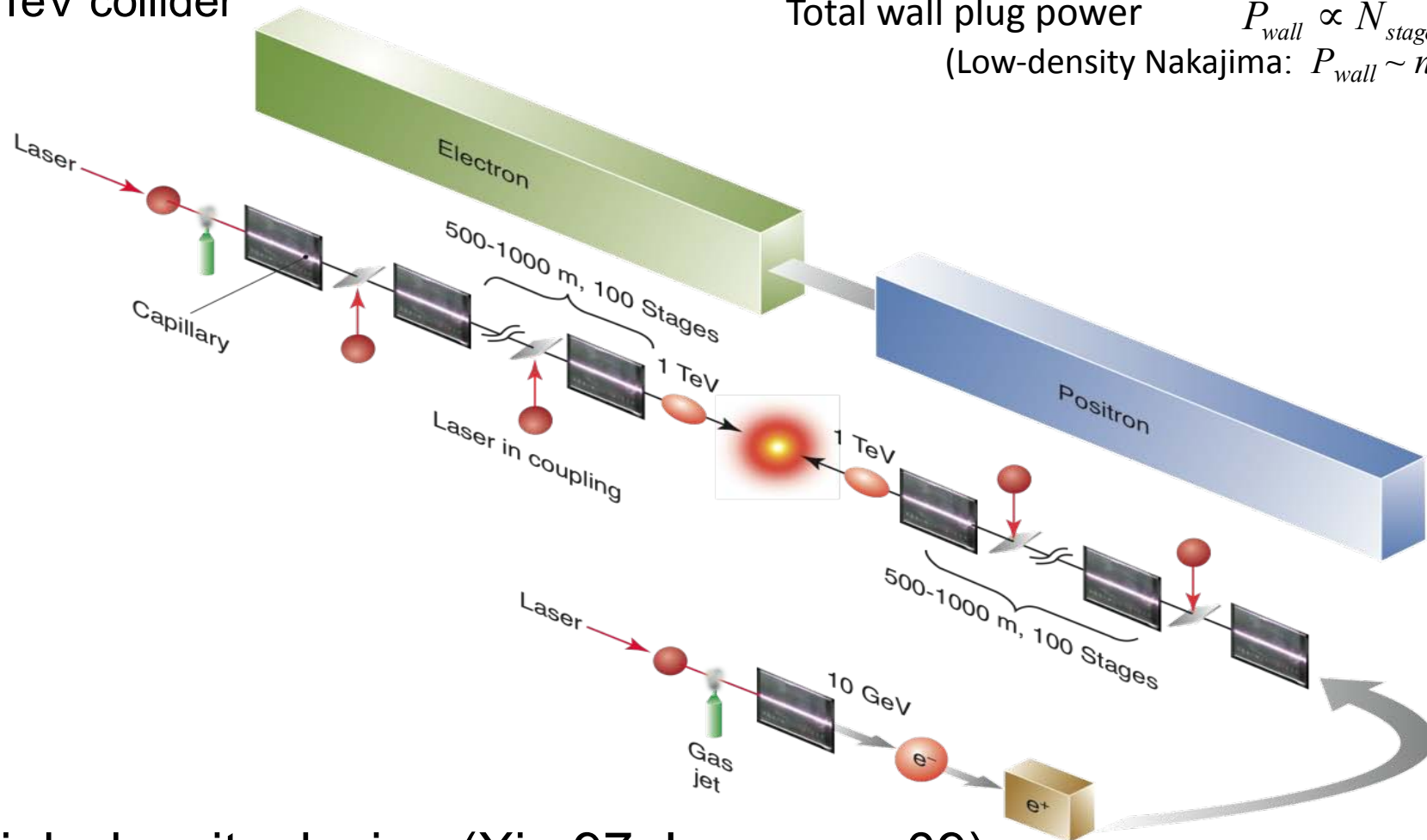
(Plasma physics vs.  
Superstring theory)

# Laser driven collider concept

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

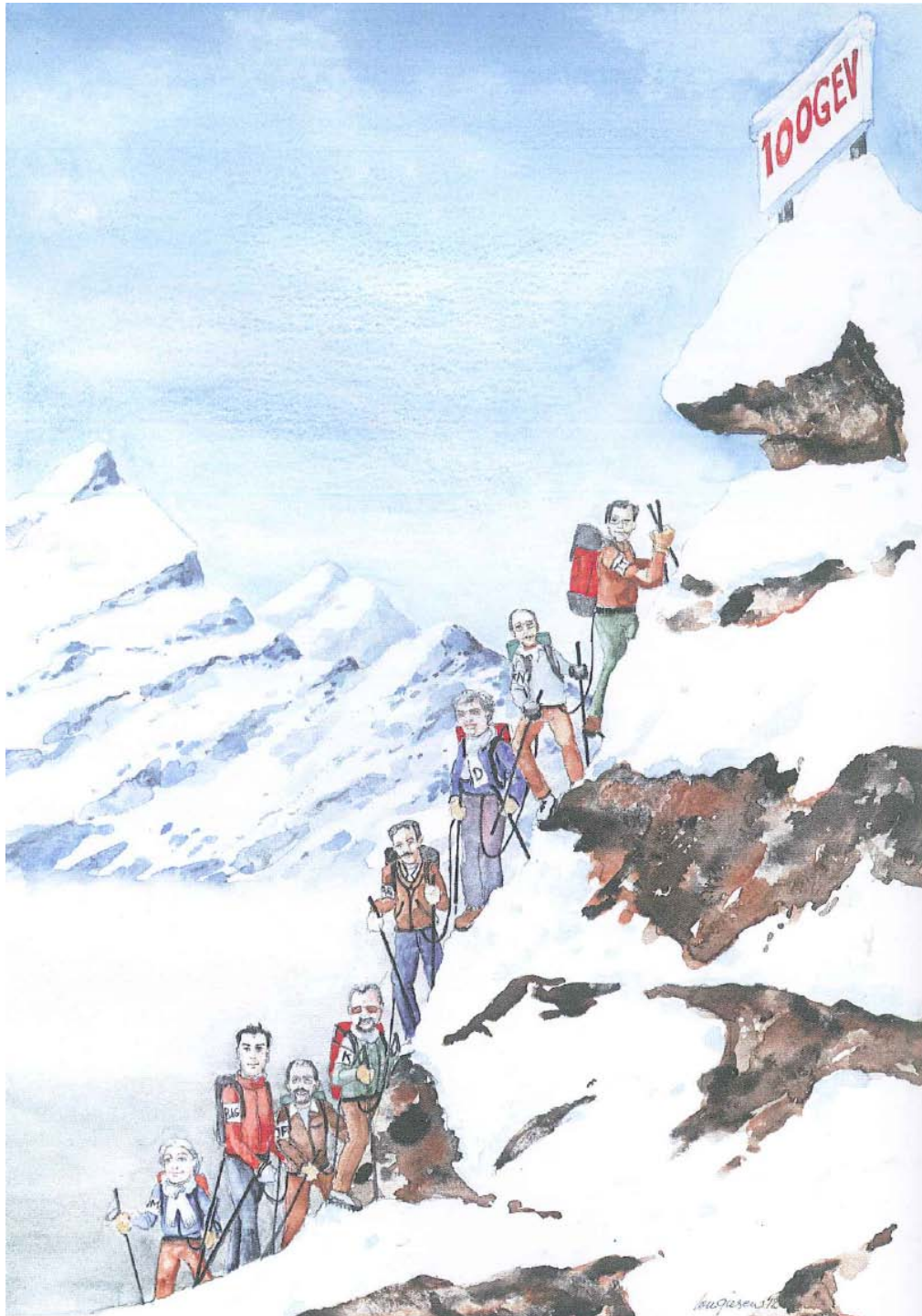
a TeV collider

Total wall plug power  $P_{wall} \propto N_{stage} P_{avg} \propto n_0^{1/2}$   
(Low-density Nakajima:  $P_{wall} \sim n_0^{3/2}$ )



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

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



**100 GeV (~Higgs energy)  
ascent:**

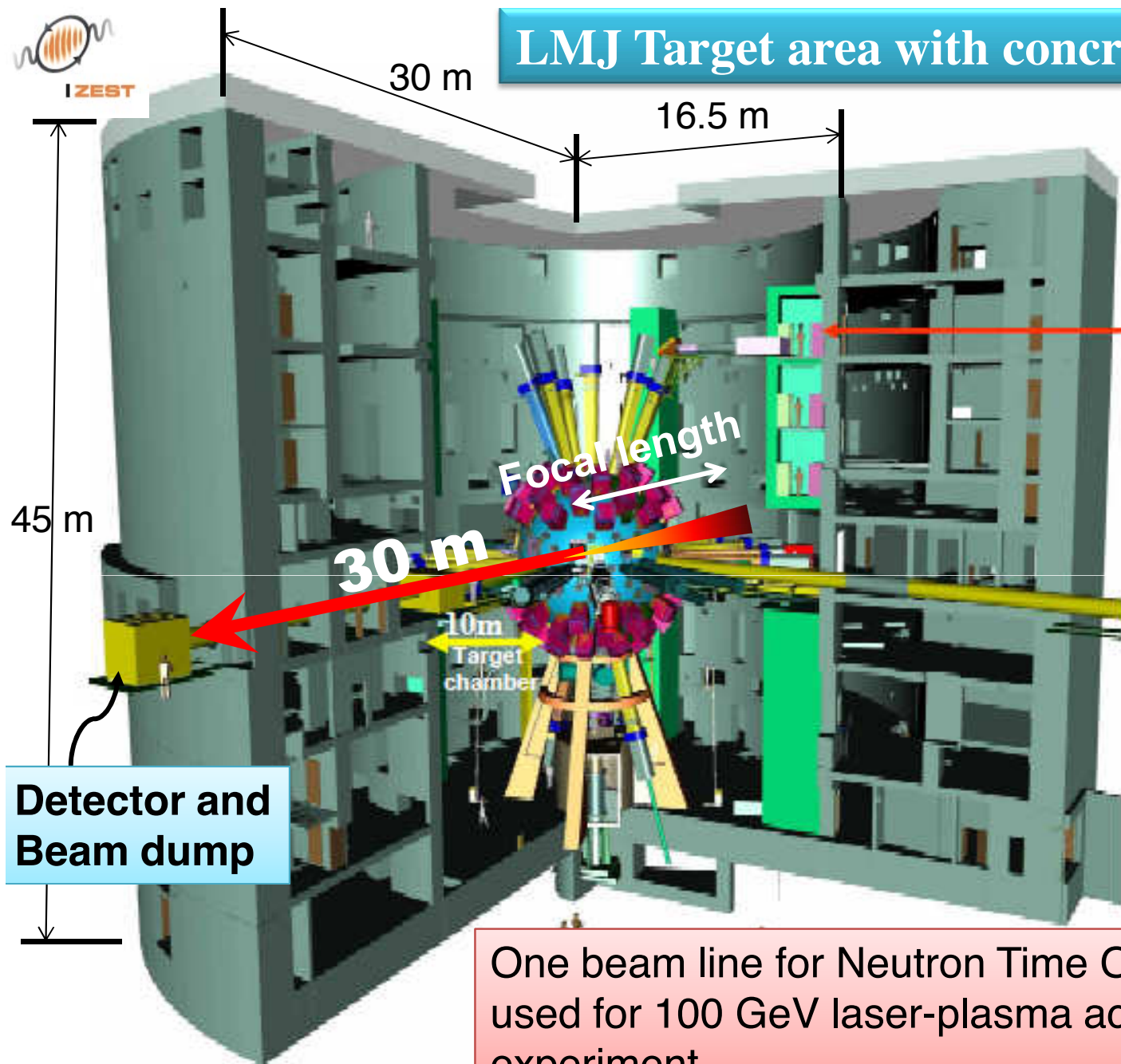
**Challenging!  
Inspirational  
Needs international  
teamwork!**

**Please join us!**



# LMJ Target area with concrete shielding

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

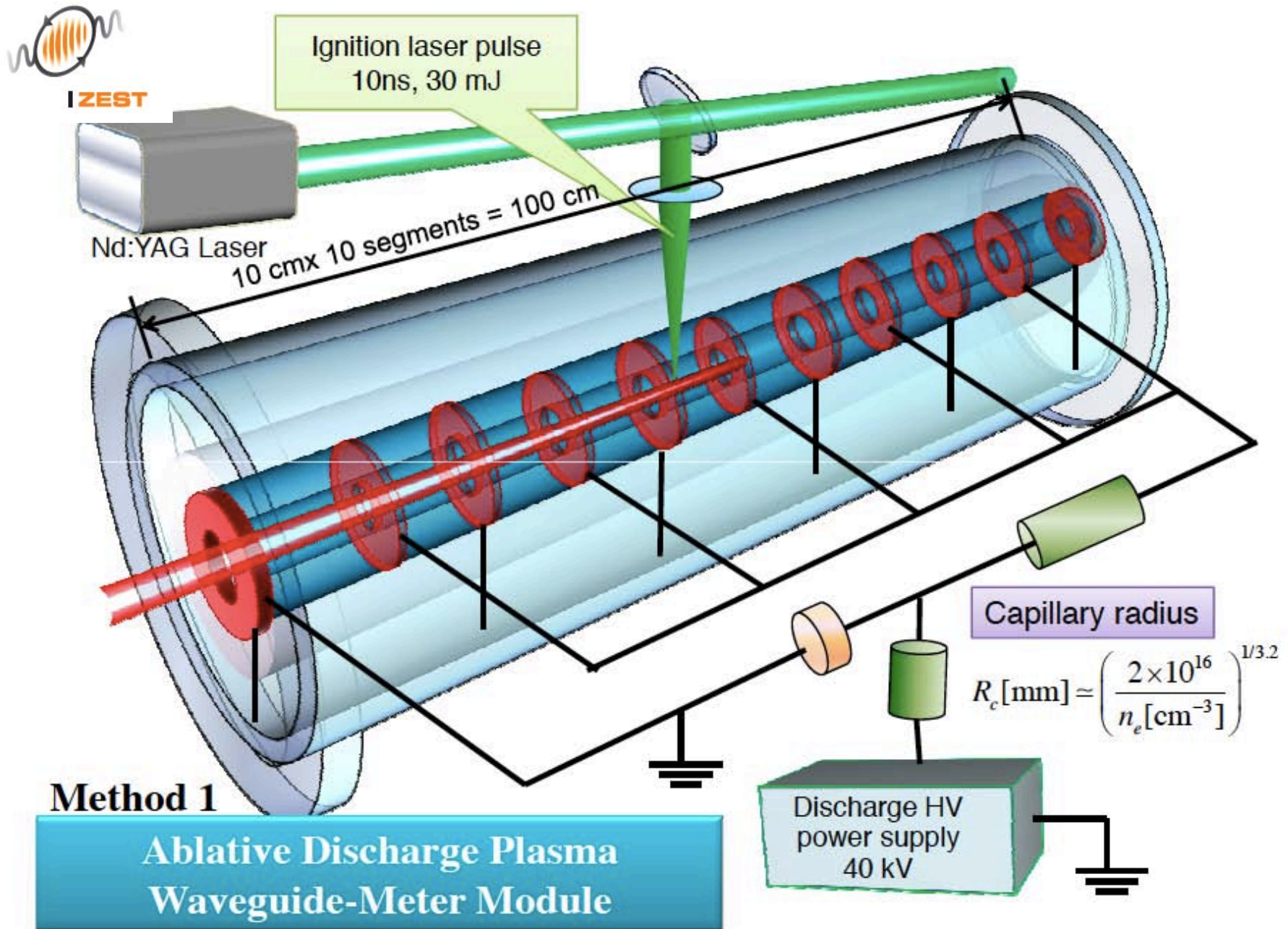


Shielded diagnostics

Neutron Time Of Flight

Detector and Beam dump

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





IZEST

# IZEST 100GeV Ascent





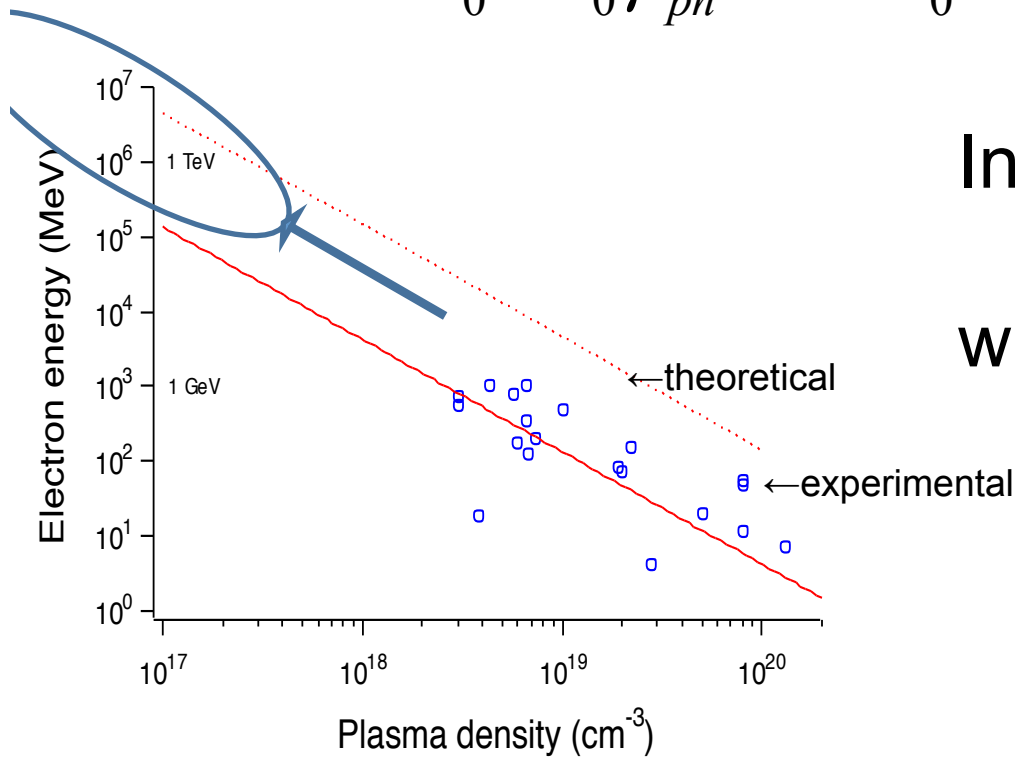
Density scalings of **LWFA**  
for collider

Accelerating field $E_z$	$\propto n_e^{1/2}$
Focusing constant $K$	$\propto n_e^{1/2}$
Stage length $L_{\text{stage}}$	$\propto n_e^{-3/2}$
Energy gain per stage $W_{\text{stage}}$	$\propto n_e^{-1}$
Number of stages $N_{\text{stage}}$	$\propto n_e$
Total linac length $L_{\text{total}}$	$\propto n_e^{-1/2}$
Number of particles per bunch $N_b$	$\propto n_e^{-1/2}$
Laser pulse duration $\tau_L$	$\propto n_e^{-1/2}$
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 $\sigma_\gamma/\gamma f$	$\propto n_e^{1/2}$
Initial normalized emittance $\varepsilon_{n0}$	$\propto n_e^{-1/2}$
Collision frequency $f_c$	$\propto n_e$
Beam power $P_b$	$\propto n_e^{1/2}$
Average laser power $P_{\text{avg}}$	$\propto n_e^{-1/2}$
Wall plug power $P_{\text{wall}}$	$\propto n_e^{1/2}$



# Theory of **wakefield** toward extreme energy

$$\Delta E \approx 2m_0c^2 a_0^2 \gamma_{ph}^2 = 2m_0c^2 a_0^2 \left( \frac{n_{cr}}{n_e} \right), \text{ (when 1D theory applies)}$$



In order to avoid wavebreak,

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

where

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

$$L_d = \frac{2}{\pi} \lambda_p a_0^2 \left( \frac{n_{cr}}{n_e} \right), \quad L_p = \frac{1}{3\pi} \lambda_p a_0 \left( \frac{n_{cr}}{n_e} \right),$$

dephasing length                      pump depletion length

Adopt:

**NIF laser (3MJ)**

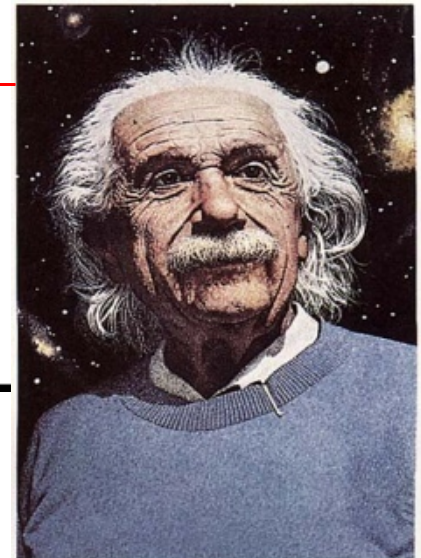
→ **0.7PeV**

(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

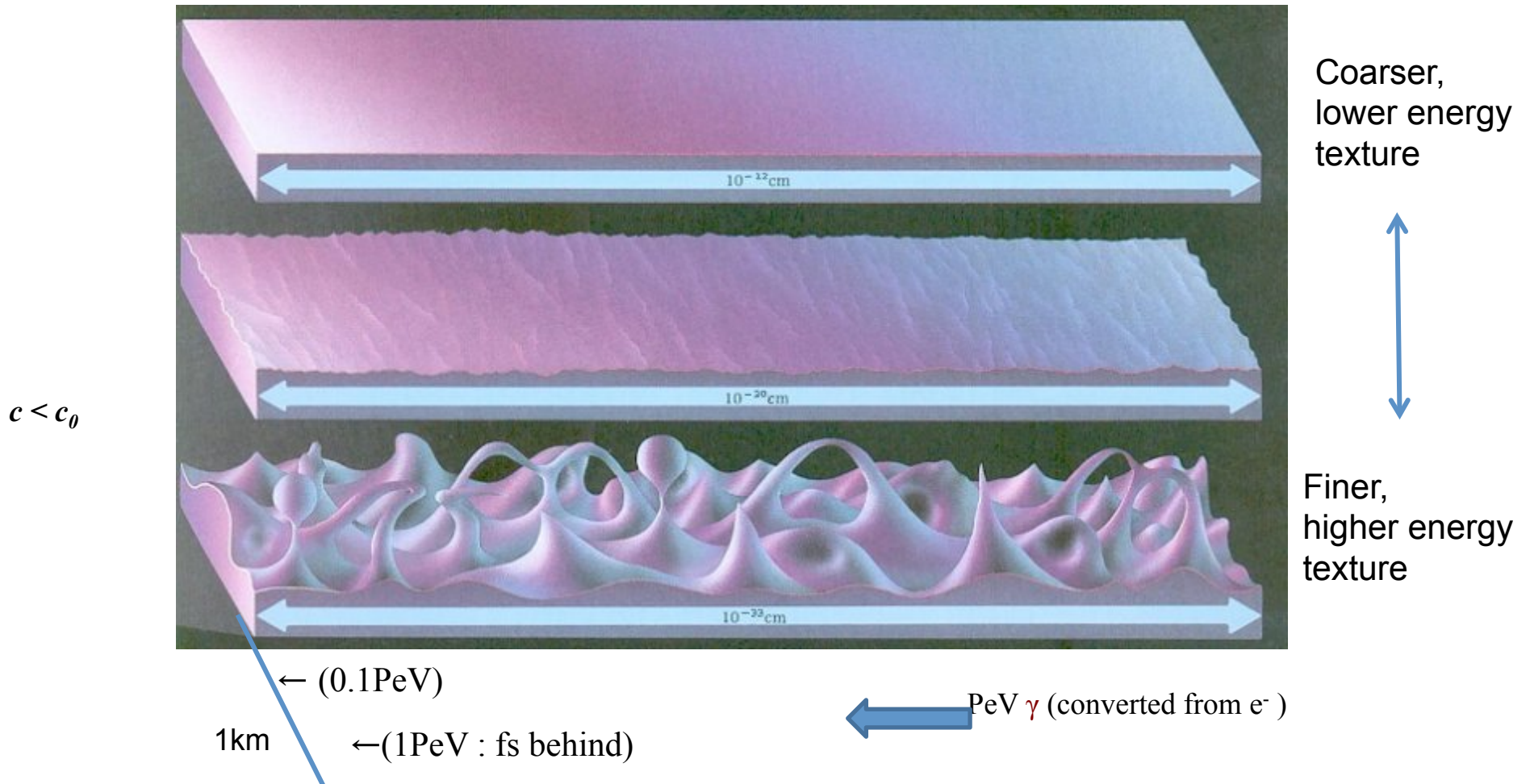


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(A. Einstein, 1922)

# Feel vacuum texture: PeV energy $\gamma$

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

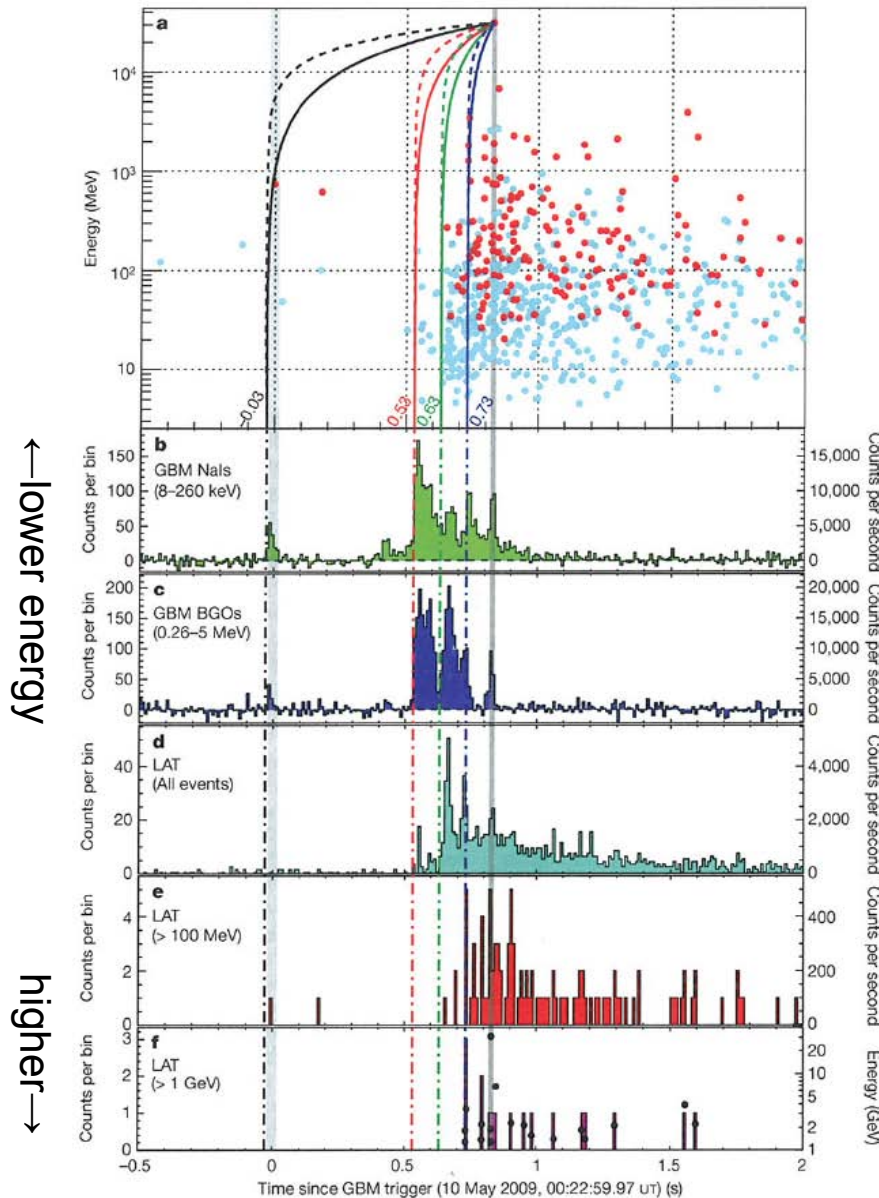


# $\gamma$ -ray signal from primordial GRB

LETTERS

NATURE

(Abdo, et al, 2009)



← lower energy

higher →

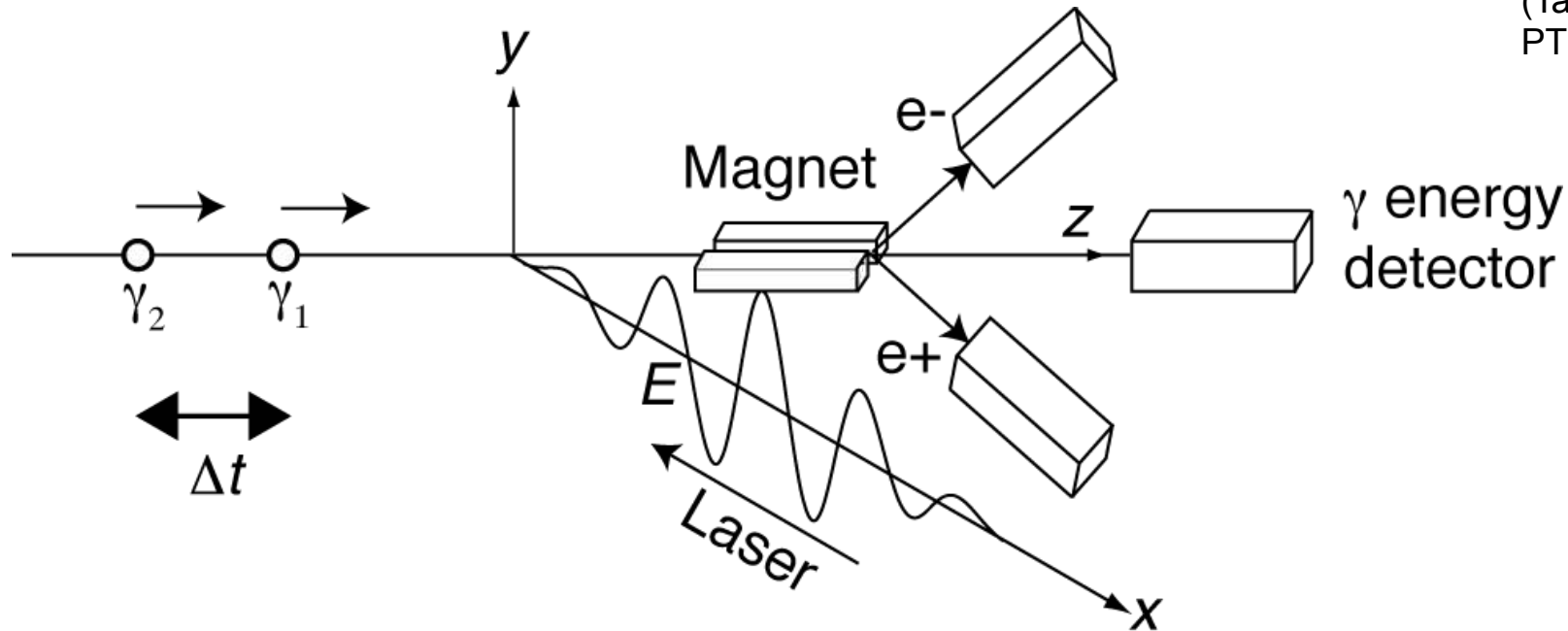
**Energy-dependent  
photon speed ?  
Observation of primordial  
Gamma Ray Bursts (GRB)  
(limit is pushed up  
close to Planck mass)**

**Lab PeV  $\gamma$  (from e-)  
can explore this  
with control**

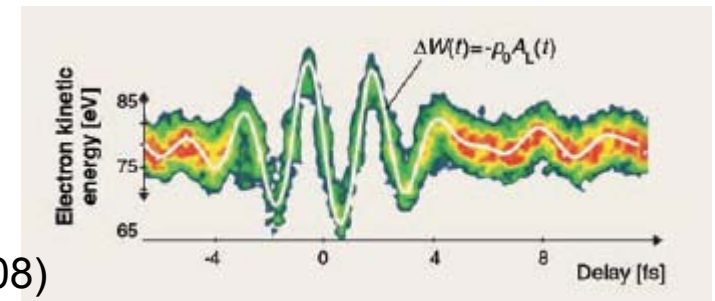
Figure 1 | Light curves of GRB 090510 at different energies. a, Energy lowest to highest energies. f also overlays energy versus arrival time for each

# Attosecond Metrology of PeV $\gamma$ Arrivals

(Tajima, Kando,  
PTP, 2011)

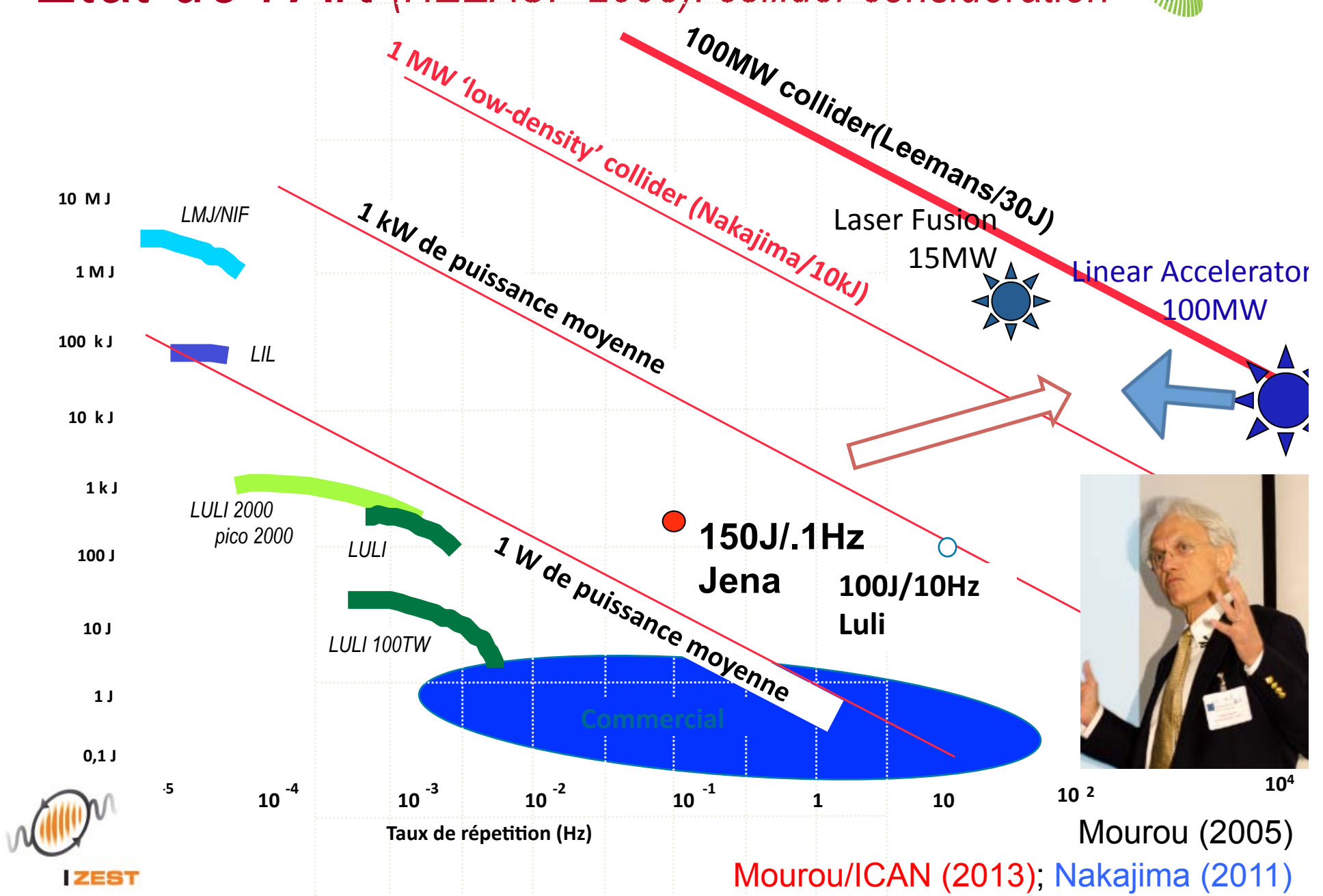


High energy  $\gamma$ - induced Schwinger breakdown (Narozhny, 1968)  
CEP phase sensitive electron-positron acceleration  
Attosecond electron streaking  
 $\gamma$ - energy tagging possible



Goulielmakis(2008)

# Etat de l'Art (HEEAUP 2005): collider consideration

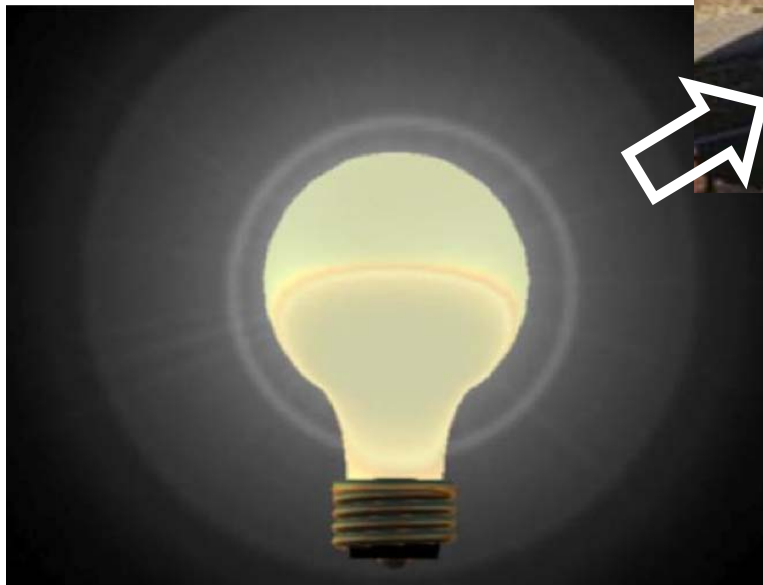


Mourou (2005)

Mourou/ICAN (2013); Nakajima (2011)

# A Leap of **Laser** Technology

*It's a light bulb!*



*To a power of TGV!*

# *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)*





**IZEST**  
International Zeta-Exawatt  
Science Technology

# Can the Future of Accelerator Be Fibers?



*"The discovery of this particle is potentially the beginning of another road, which is to explore what lies beyond the Standard Model"*

- Peter Higgs



*"I realized there would be many applications for the laser, but it never occurred to me that we'd get such power from it!"*

- Charles H. Townes

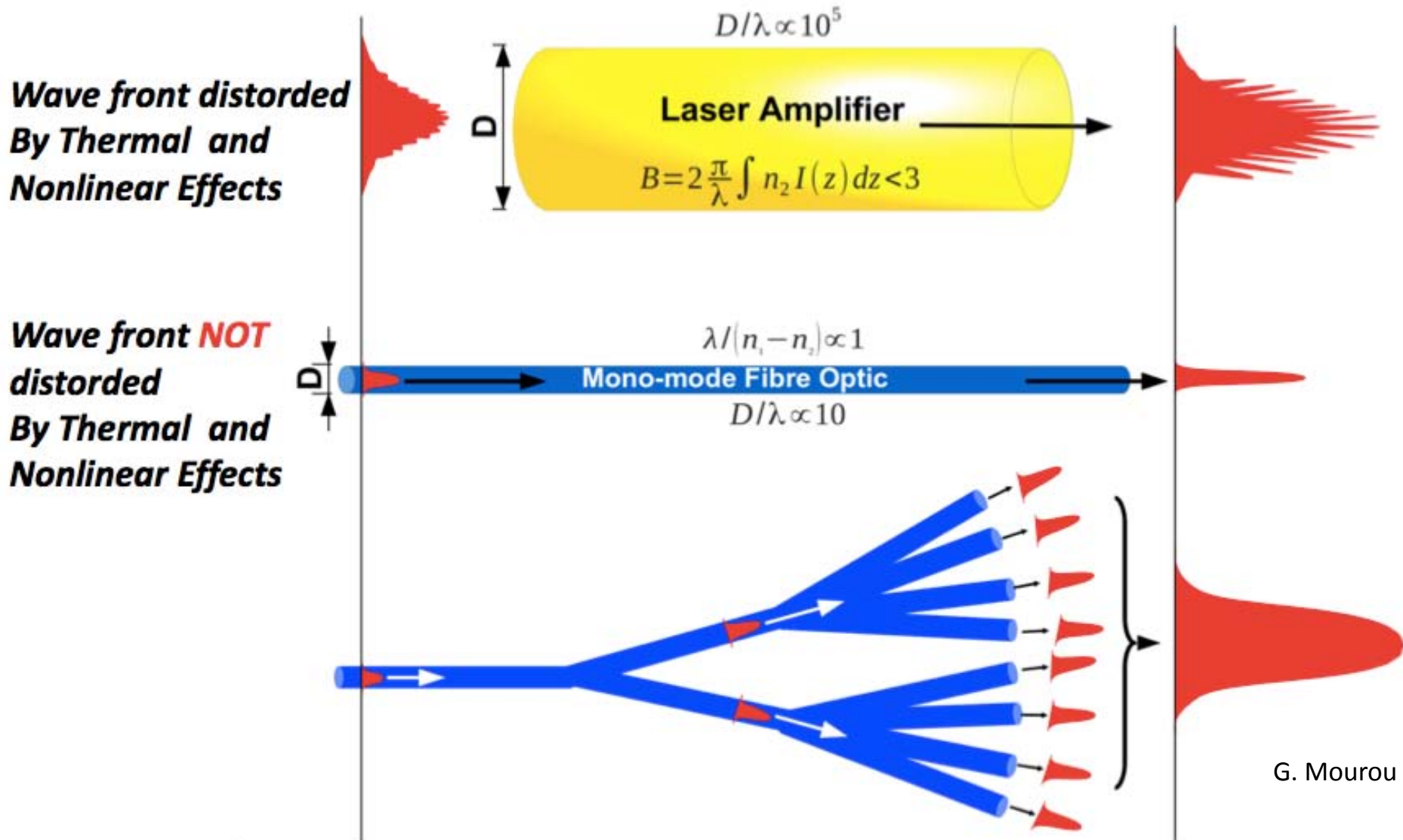
**Gerard Mourou**

**IZEST Ecole Polytechnique – Paris – France**

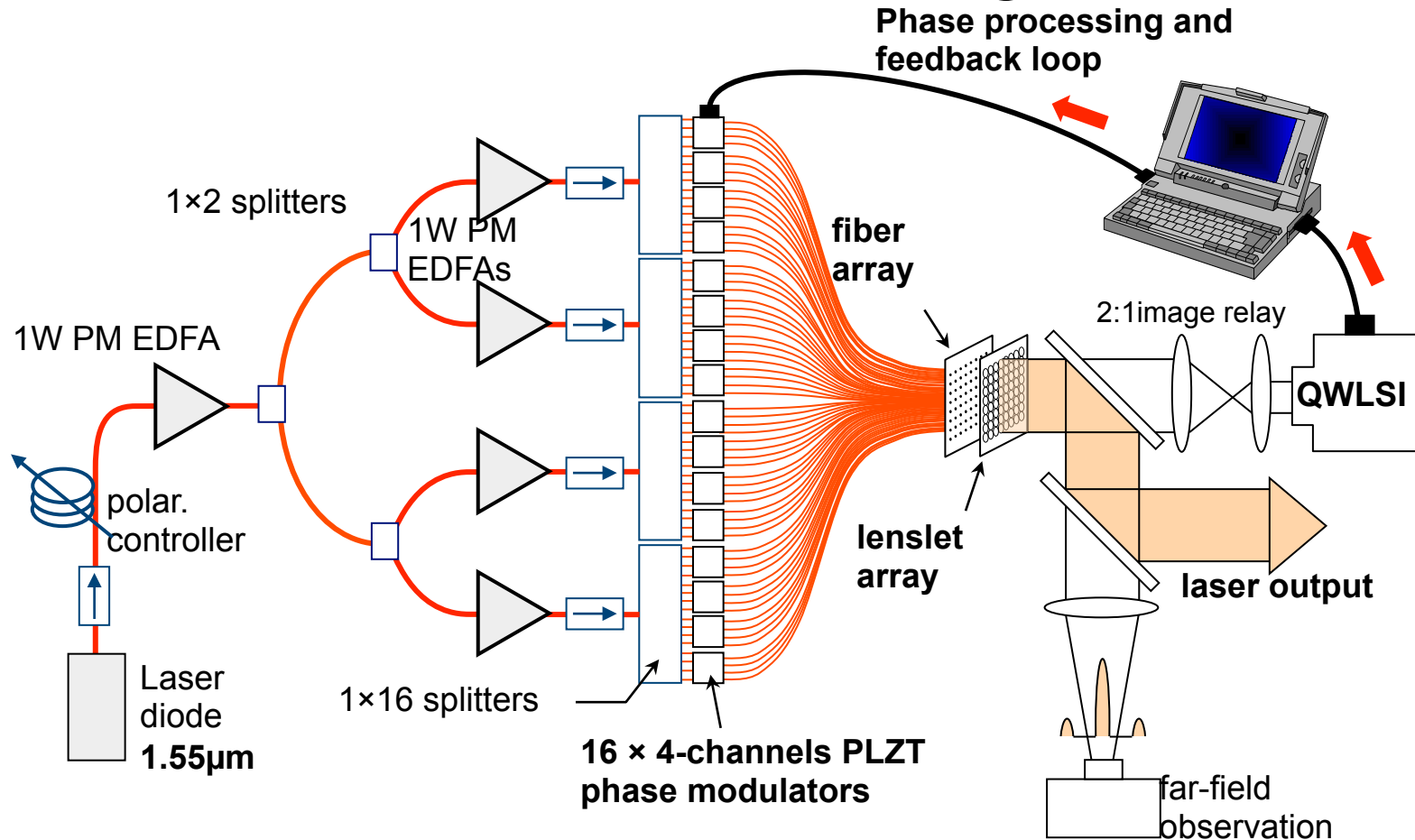
150th Anniversary of Politecnico di Milano

Gerard Mourou S.L Chin, Laval

# Laser beam quality: bulk vs. fiber



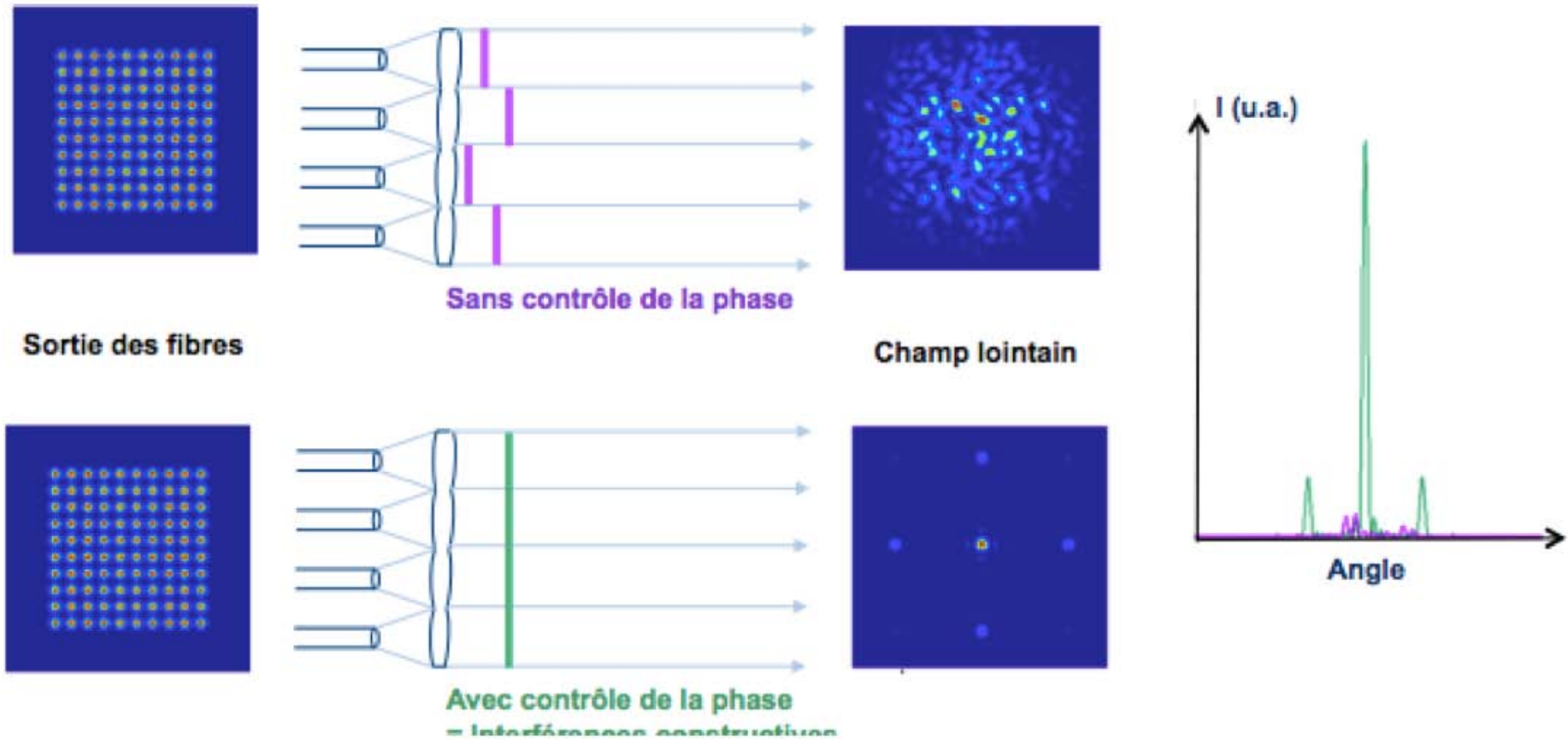
# Coherent Fiber Combining



**Achievement 2011**  
**→ 64 phase-locked fibers**

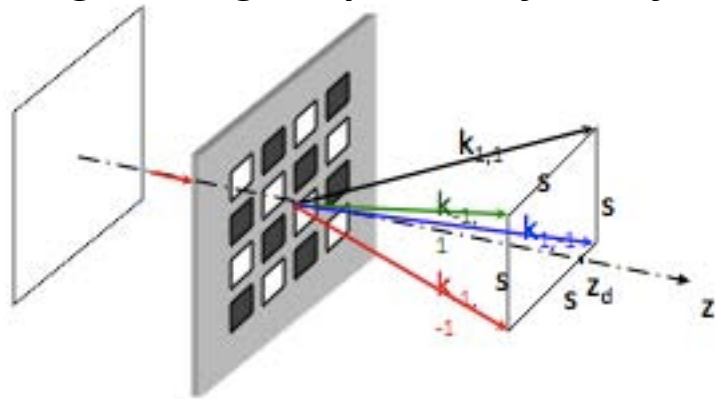
# Coherent amplification

After attosecond phase control discussed before, voila!  
= pristine **laser**

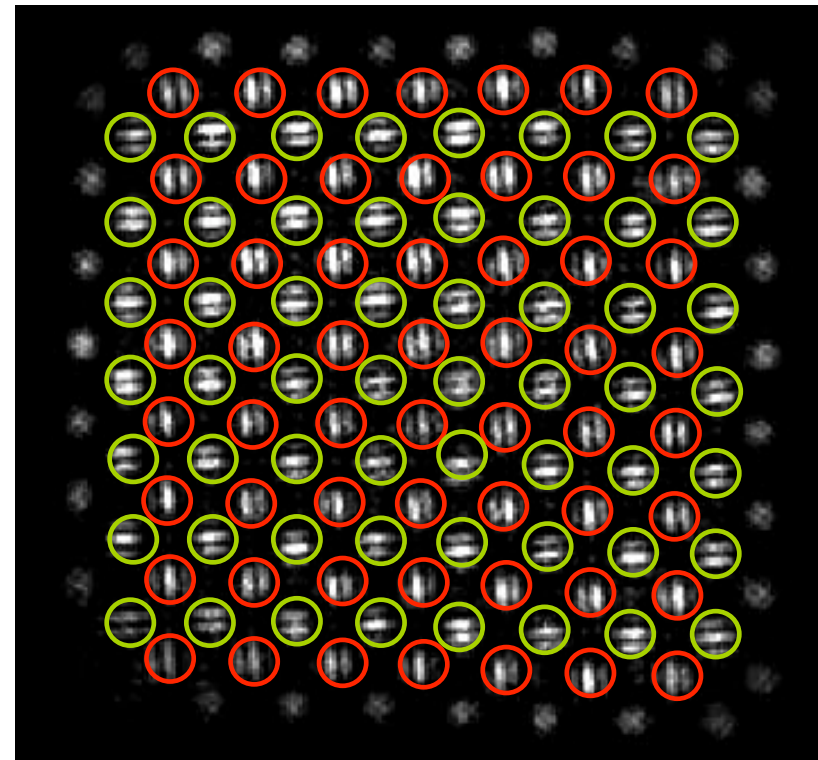
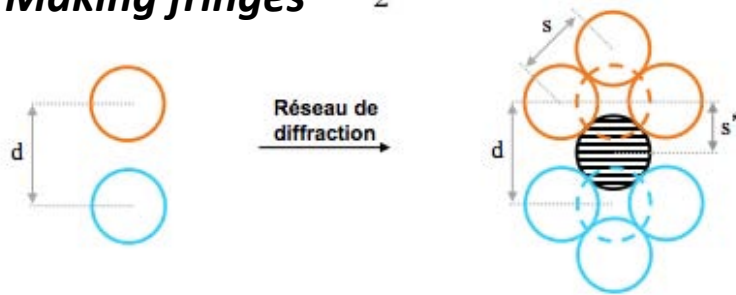


# Phase Noise Measurement with a Quadrilateral Shearing Interferometer

1) *Grating Making 4 replicas  $s$  of each fiber*



2) *Neighbor fibers interfere with replicas  
Making fringes*



3) *A phase map is captured every  $\sim 30$ ms  
making possible phase correction with phase  
modulator*

# HOW A "CAN" LASER AMPLIFIER WORKS

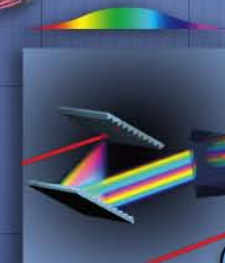
Producing High Peak Power and High Average Power, Mitigating Heat

(CAN: Coherent Amplifier Network)

An oscillator produces a short pulse of  $\sim 30\text{fs}$  duration.



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



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.



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.



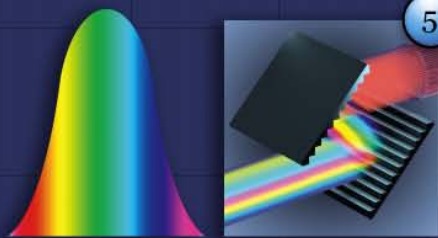
After the last amplifier the pulse is focused by spherical or paraboloidal mirror.



The resulting pulse is short ( $30\text{fs}$ ), but the energy is enormous ( $30\text{ Joules}$ )



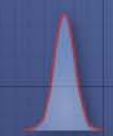
In each amplifier the phase of each pulse is preserved and finally the chirped pulses are combined and phased. They now form single pulses and are compressed by a pair of gratings. The pulse energy can be now of 10's of Joules, but the duration corresponds to the initial pulse duration.



$30\text{fs} - 30\text{J}$

amplification

$30\text{fs} - 30\text{mJ}$



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

## Linear collider (ILC @ 250GeV x 250GeV)

~8MW (in beams), cost for accelerators ~ 4GEuro

→ ~500Euro / W (beam)

## Laser-driven collider (if we design @ 250GeV x 250GeV)

same at 8MW (in beams)

diode 7\*Euro / W x 3 (to give total optics) = 21Euro/W

assume efficiencies: laser/wallplug =0.5, compressor=0.4, excitation of  
wake=0.4, acceleration=0.5. → total efficiency = 0.04

→ ~500Euro/W (beam)

however, (1) far less other cost s.a. civil eng., (2) \*could come down substantially

(a) yet to be demonstrated. [laser path after the current plan]

## Laser-driver for $\gamma$ - $\gamma$ collider (@80 x 80GeV)

5J x 100kHz → ~50MEuro (times ~2 for the total system)



## Scientific :

- **Laser** acceleration toward TeV
- Higgs factory with  $\gamma$ - $\gamma$  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

## CAN **Fiber Laser**

Average power  
 rep rate x peak power  
 Efficiency  
 Smartness (digital control)  
 Intensity

## Collider requirements

→ luminosity  
 → cost  
 → emittance  
 → gradient

## $\gamma$ - $\gamma$ 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)



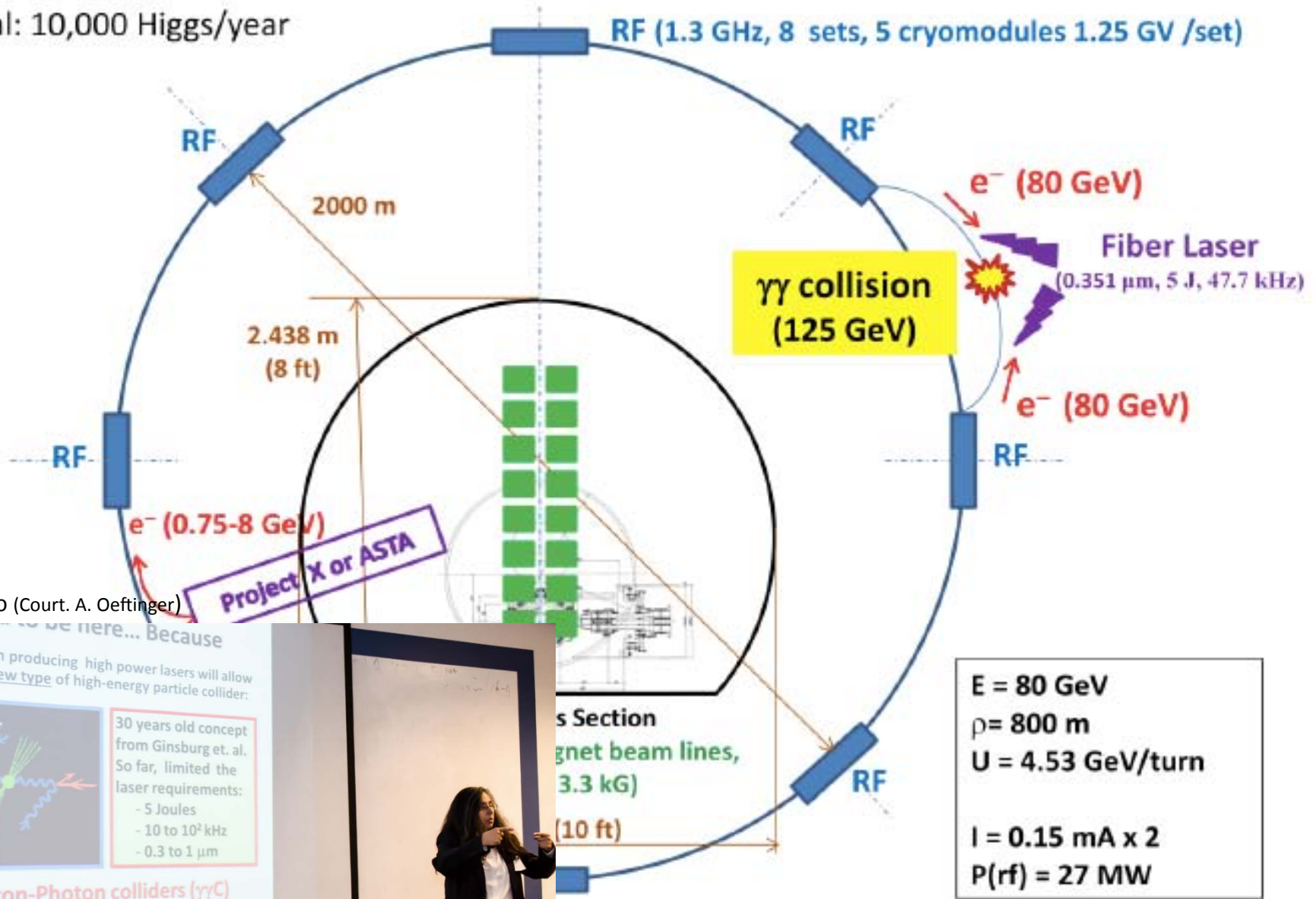
R. Aleksan (Court. A. Oeftinger(CERN))

# HFITT – Higgs Factory in Tevatron Tunnel

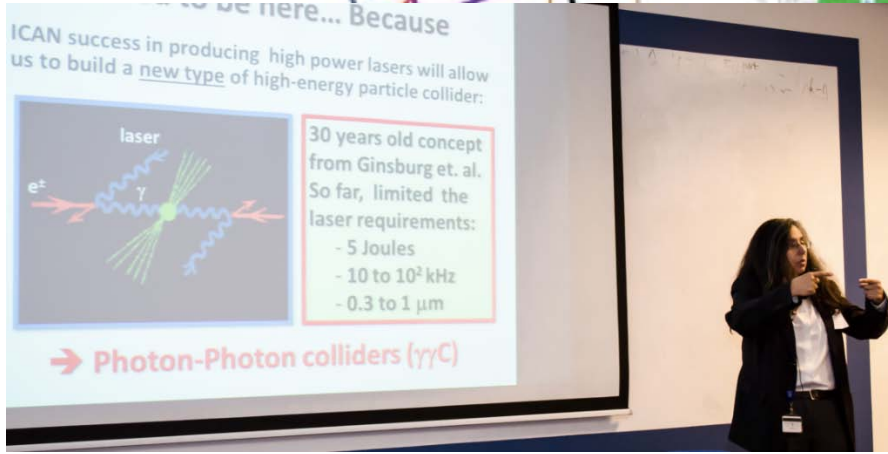
( $\gamma\gamma$  collider)

(W. Chou et al.)

Goal: 10,000 Higgs/year



M. Velasco (Court. A. Oeftinger)



$E = 80 \text{ GeV}$   
 $\rho = 800 \text{ m}$   
 $U = 4.53 \text{ GeV/turn}$   
 $I = 0.15 \text{ mA} \times 2$   
 $P(\text{rf}) = 27 \text{ MW}$

# Beyond QED **photon-photon** interaction

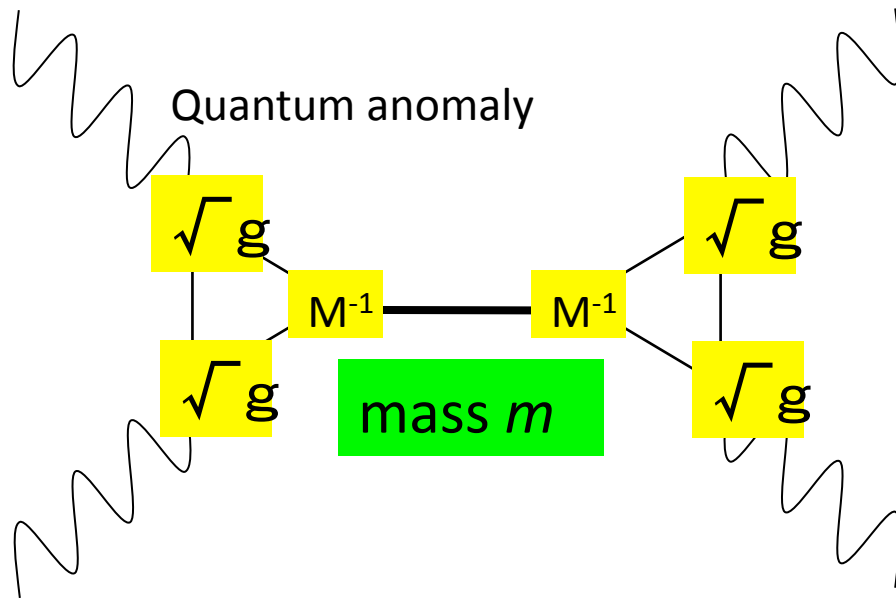
$$L_{QED} = \frac{1}{360} \frac{\alpha^2}{m^4} [4(F_{\mu\nu} F^{\mu\nu})^2 + 7(F_{\mu\nu} \tilde{F}^{\mu\nu})^2]$$

$\updownarrow$   
 $\phi F_{\mu\nu} F^{\mu\nu}$

$\updownarrow$   
 $\sigma F_{\mu\nu} \tilde{F}^{\mu\nu}$

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

**Resonance in quasi-parallel collisions in low cms energy**



If  $M \sim M_{\text{Planck}}$ , **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)

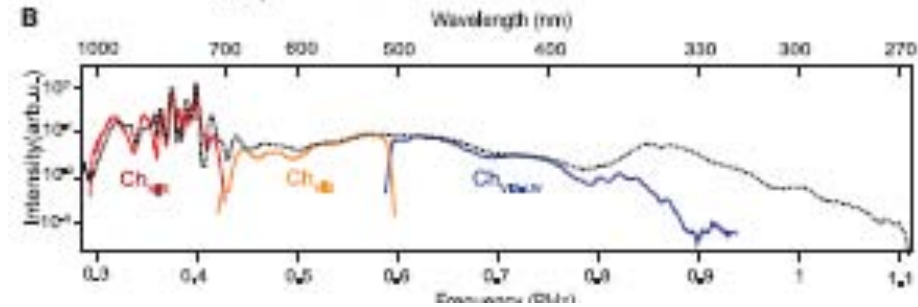
# Degenerate Four-Wave Mixing (DFWM)

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

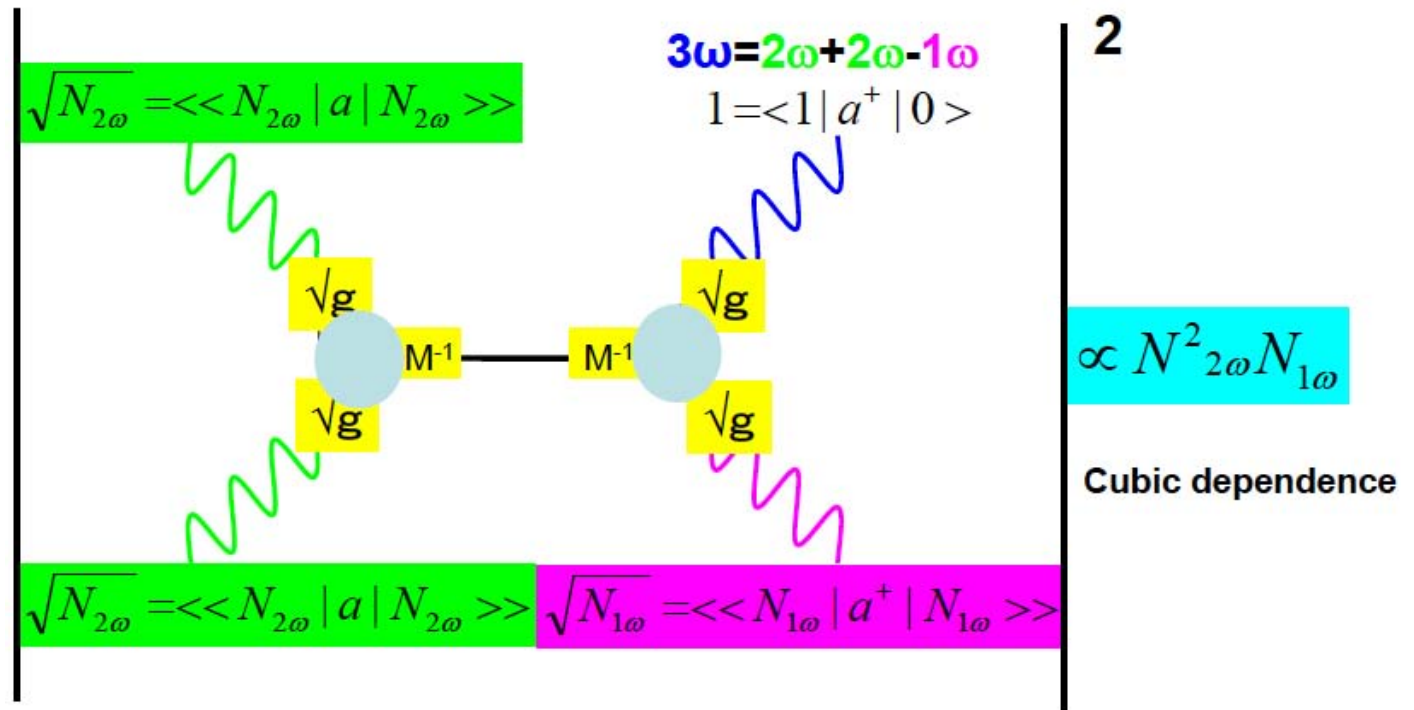
Decay into  $(4-x)\omega$  can be induced by frequency-mixing

Sweep by arbitrary frequency  $x\omega$

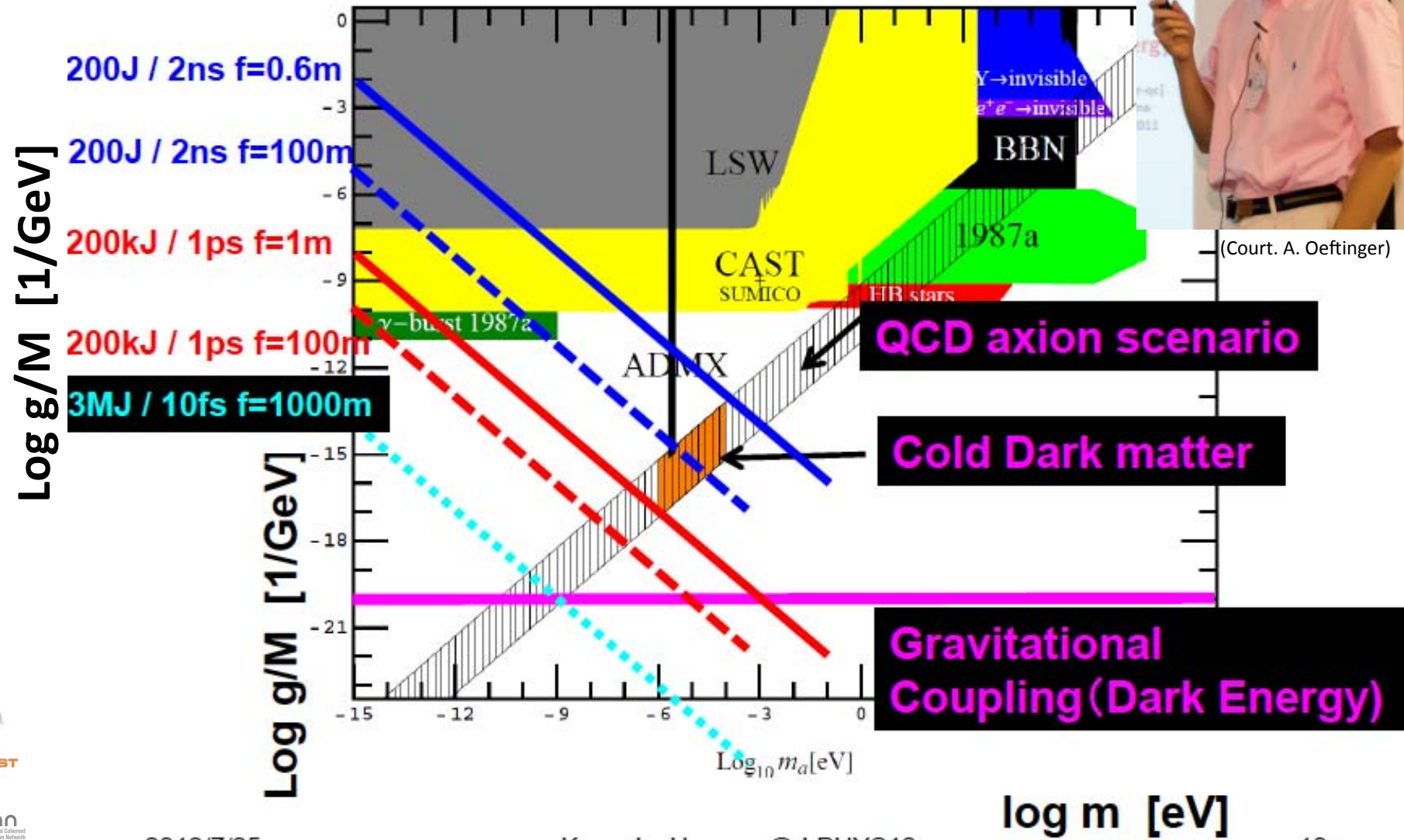
e.g.  $x\omega = 1\omega$



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



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

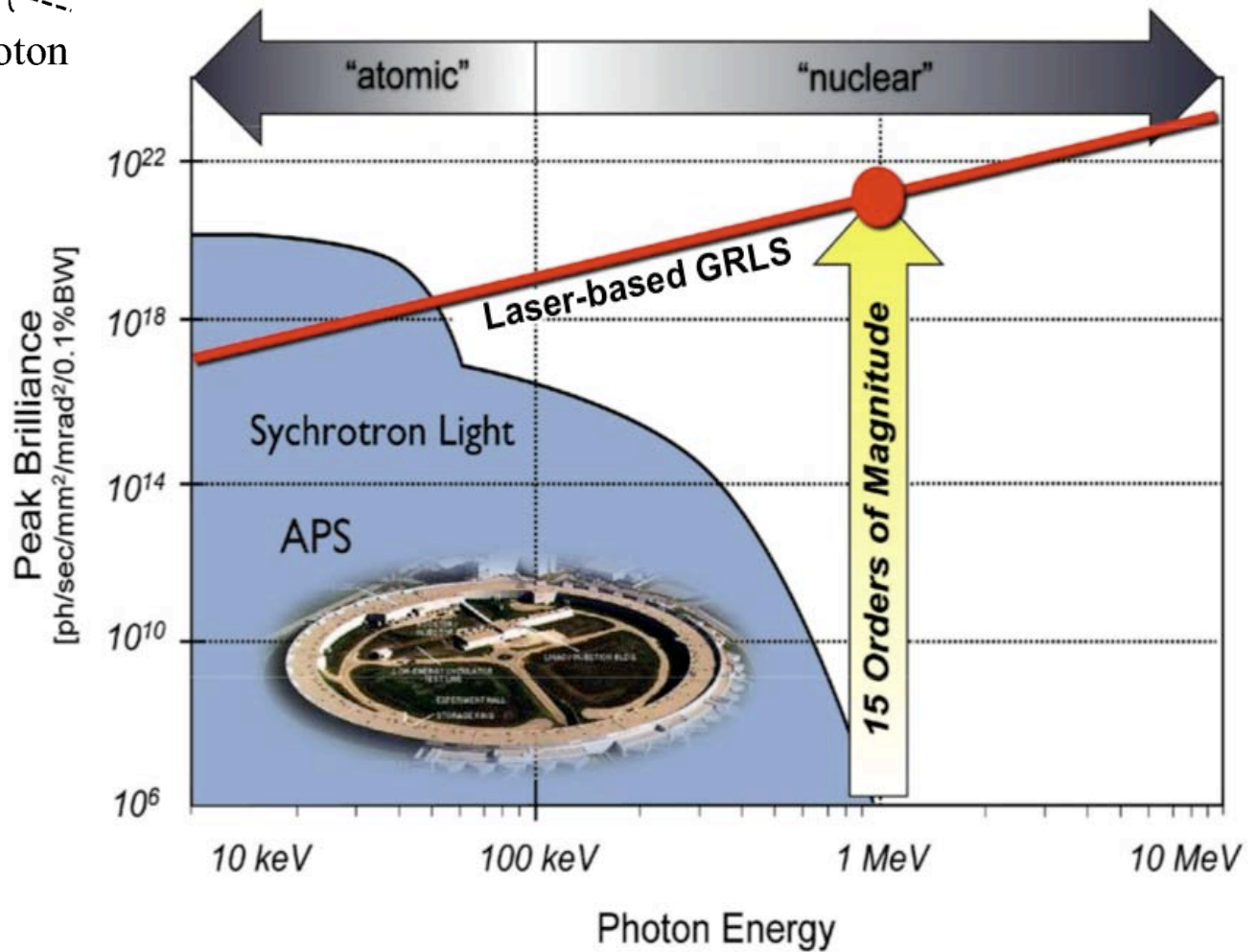
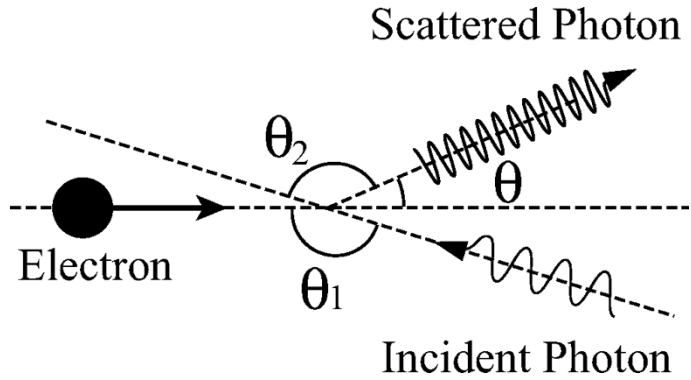


(Court. A. Oeftinger)



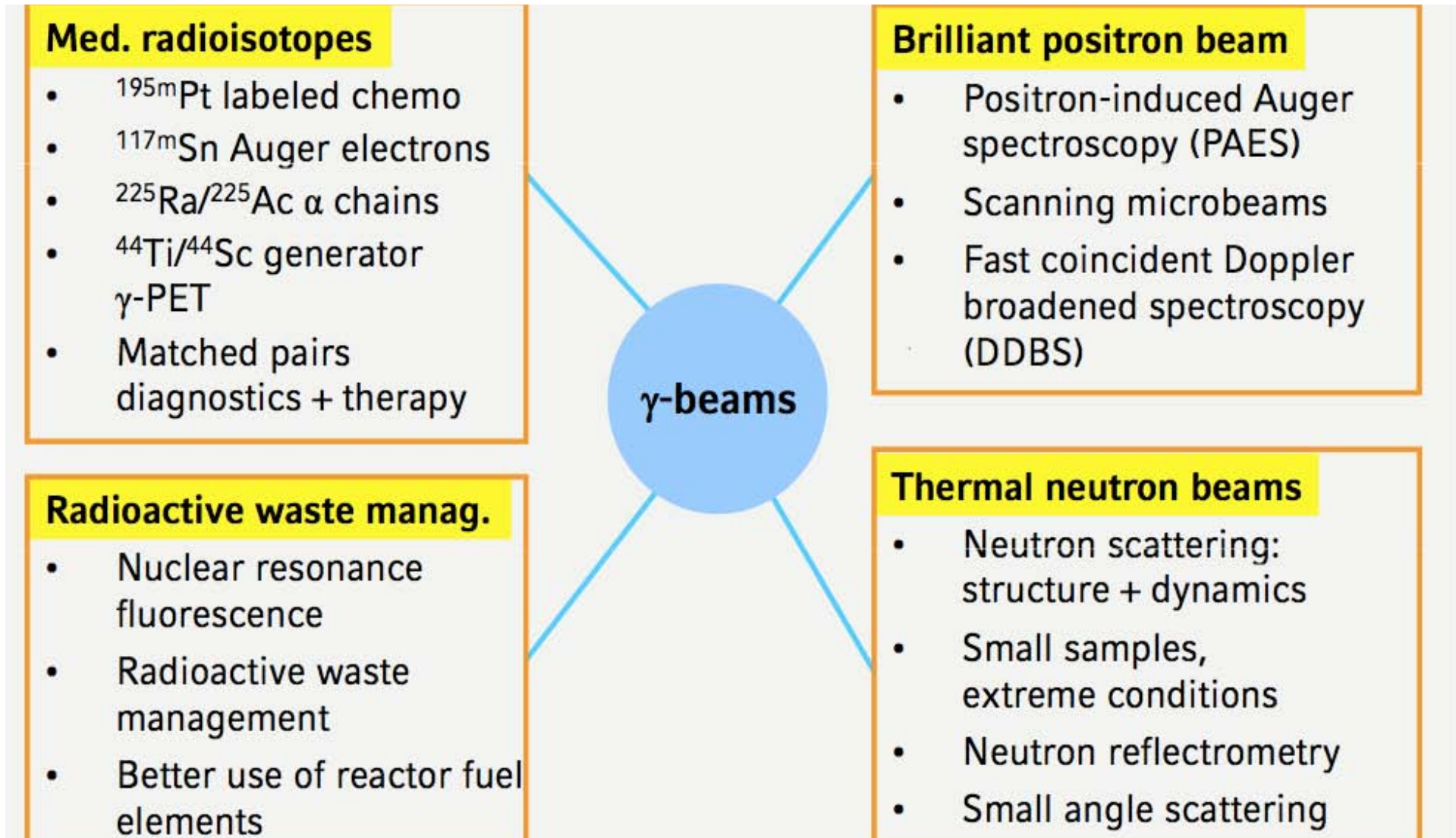
K.Homma, D.Habs, T.Tajima  
(2011)

# Laser Compton gamma source



Barty and Tajima, 2008

# Applications of **laser** Compton $\gamma$ -beams







# Mountain of Radioactive Junk at Nuclear Facility



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

# Sharp discriminatory capability of monoenergetic $\gamma$ rays



Bremsstrahlung  $\gamma$  rays

VS



Laser Compton  $\gamma$  rays

C. Barty and T. Tajima (2008)

# Paradigm Shift: 20<sup>th</sup> Century Science to 21<sup>st</sup> Century One

Physiology

Manufacturing

Consumption

Energy production

Discovery and  
conquering

Food stock cooking

Individual

Linear

Kitchen function

Pathology

Resource recycling

Waste treatment

Entropy minimization

Ethics and societal solution

Garbage management

Collective

Nonlinear

Toilet function

***Kitchen Science***

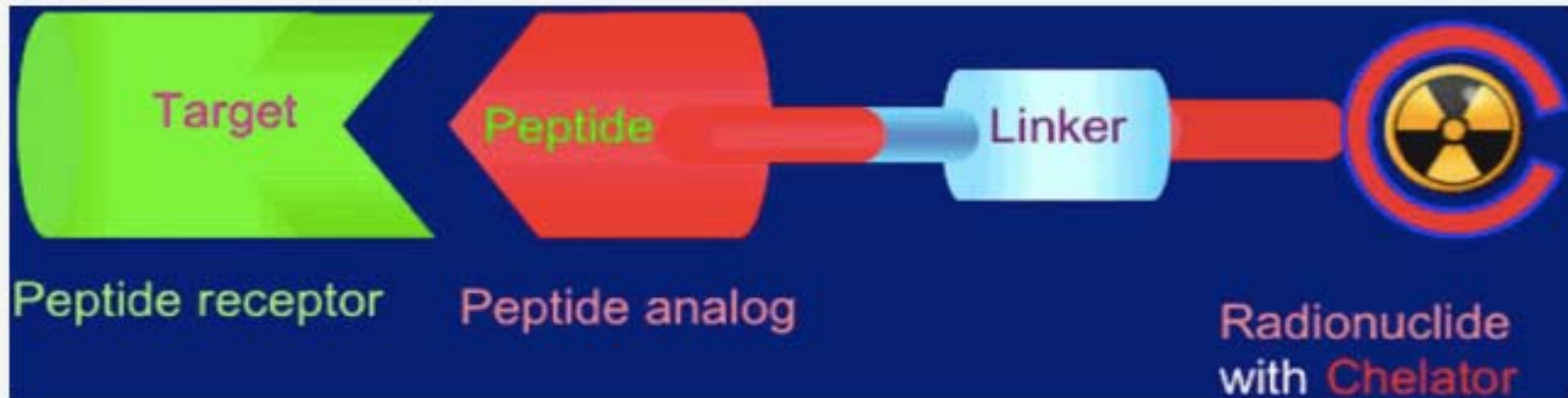
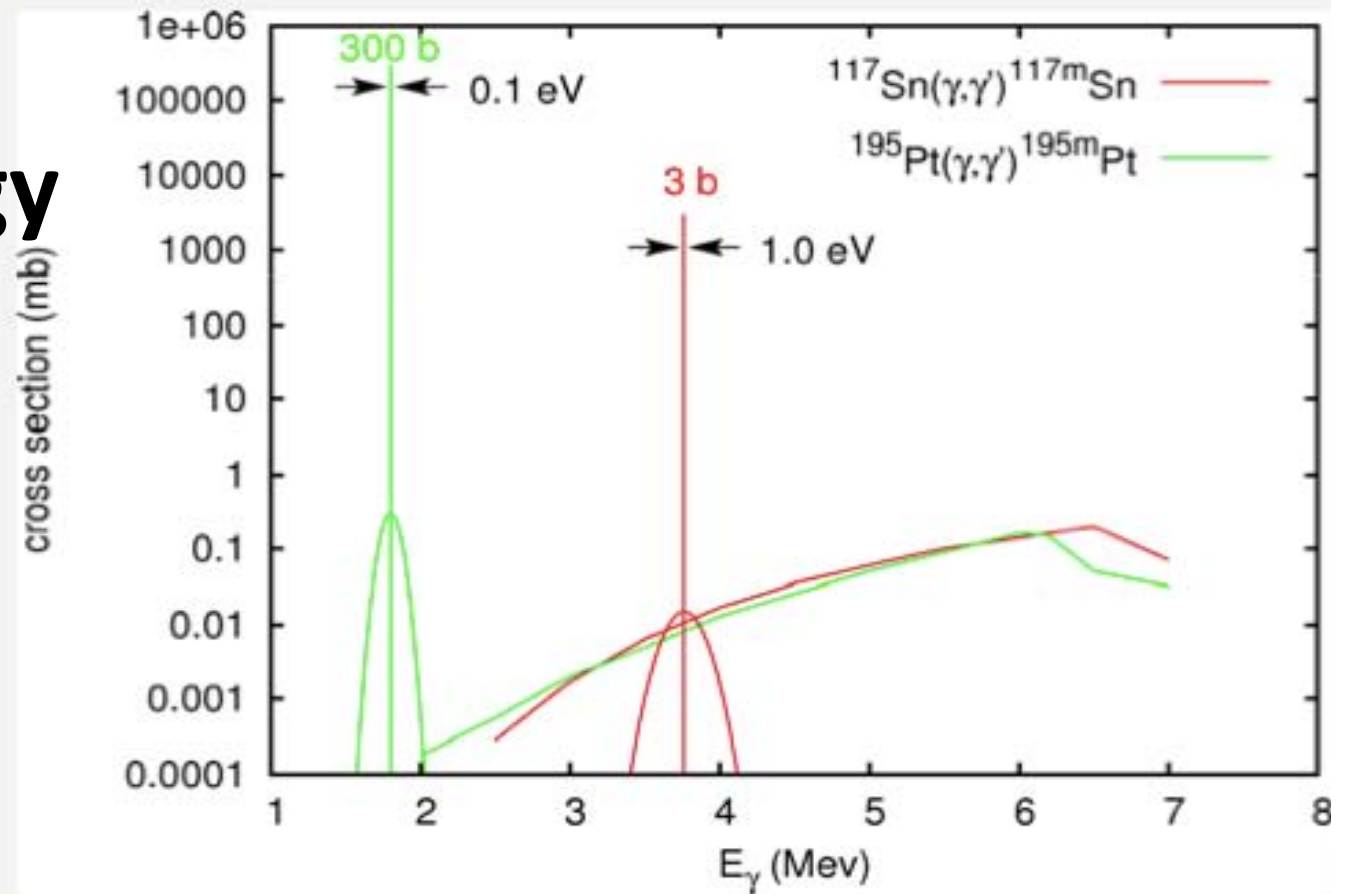


***Toilet Science***

# Nuclear Pharmacology

e.g.  $^{195m}\text{Pt}$   
label chemotherapy and  
study anti-tumor efficiency

(Habs, Tajima, Koester, 2011)



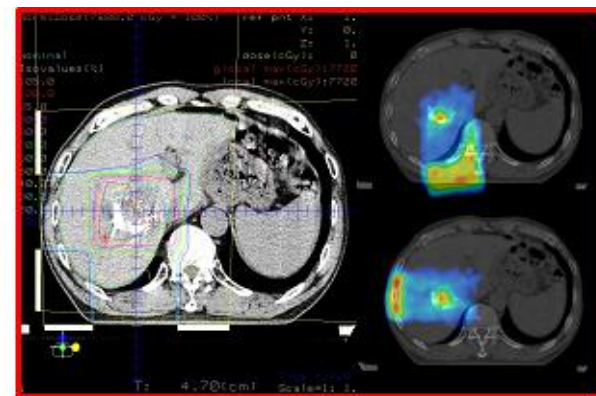
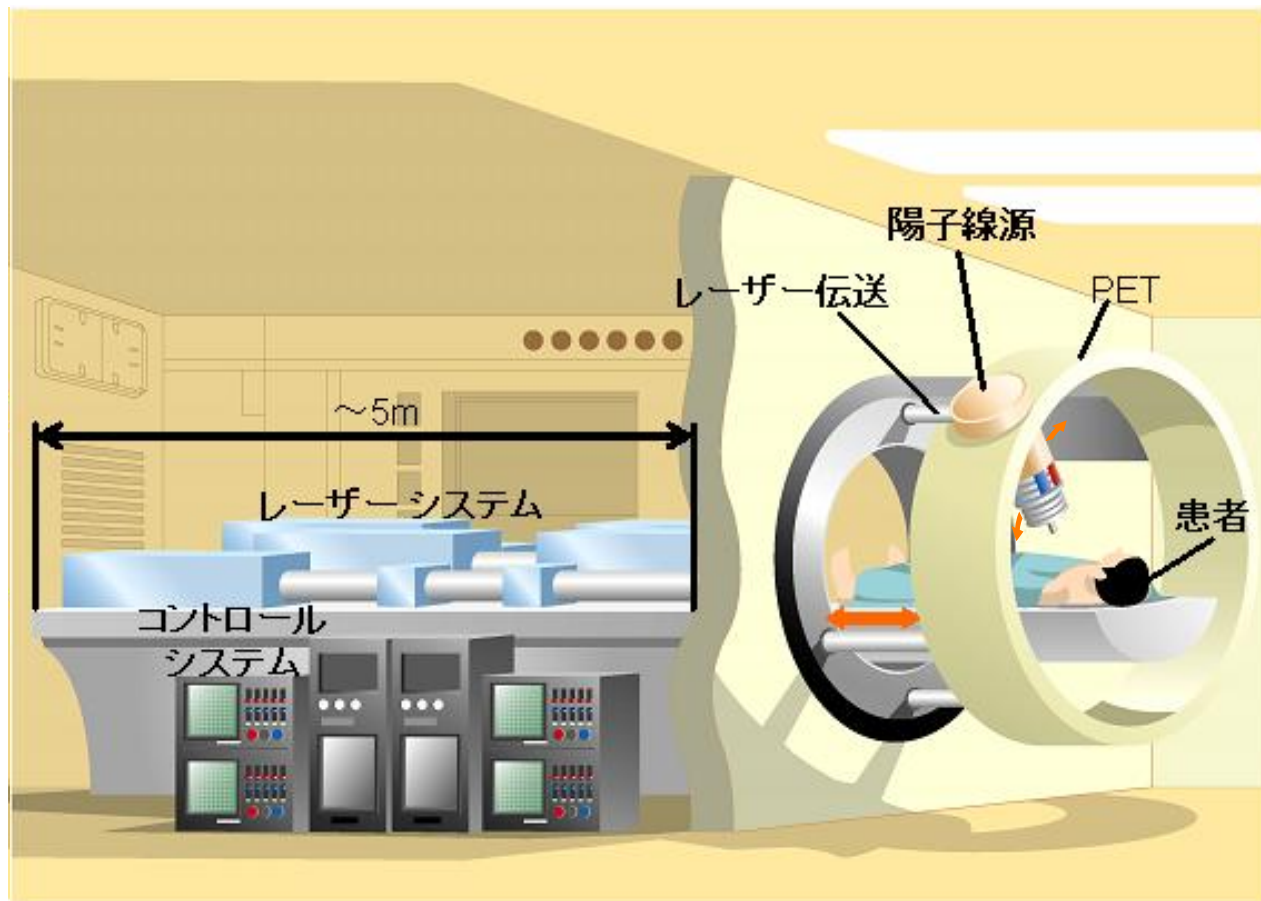
Habs, 2

# Conventional ion accelerator



The superconducting RF proton linac at the SNS at Oak Ridge National Laboratory is providing valuable experience for a future ADS accelerator.  
Image credit: ORNL.

# Concept of **Laser**-Driven Ion therapy



治療計画 (診断と照射)

# Toward more adiabatic acceleration of ions

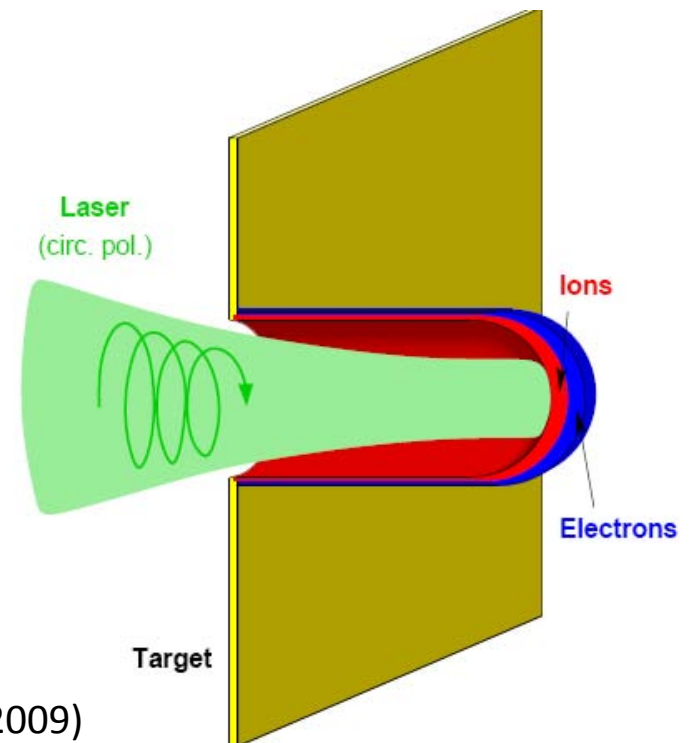
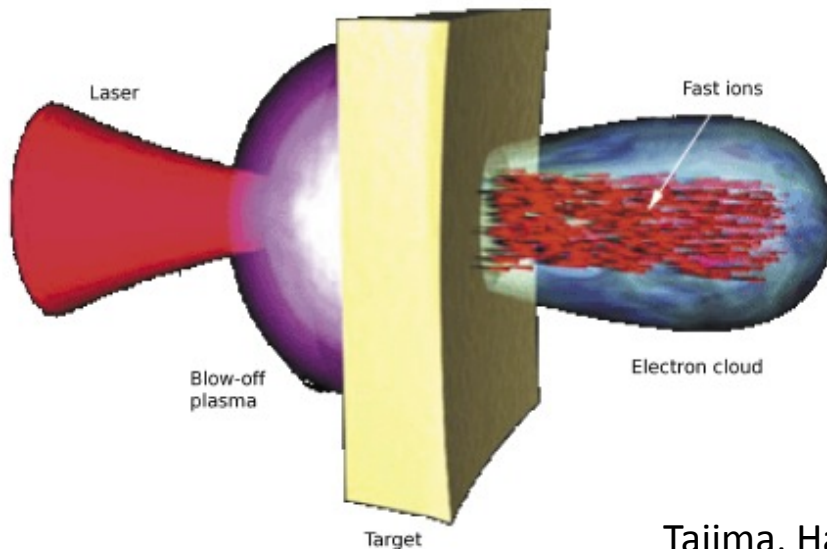
From **incoherent (or heating)** of electrons

to **Coherent drive** of them



**CAIL** (Coherent Acceleration of Ions by **Laser**)

**TNSA** (Target Normal Sheath Acceleration)

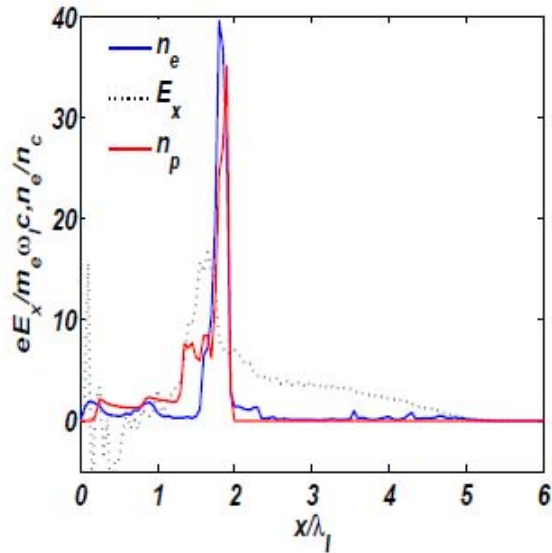


Tajima, Habs, Yan: RAST (2009)

# TeV proton acceleration by **LWFA**

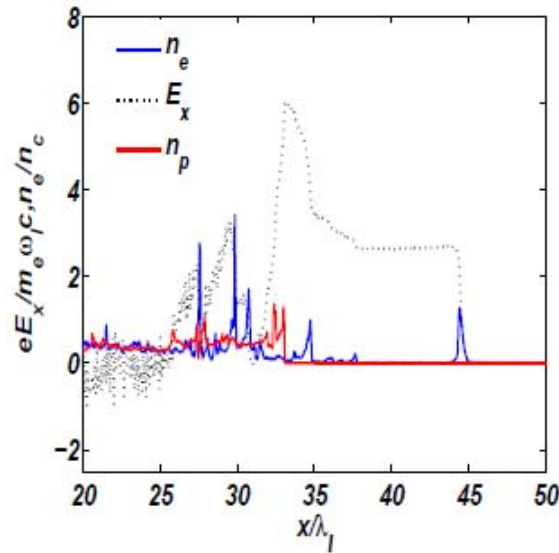
Early **RPA** of ions

(a)



Later setting up **wakefield**

(b)



High Intensity regime

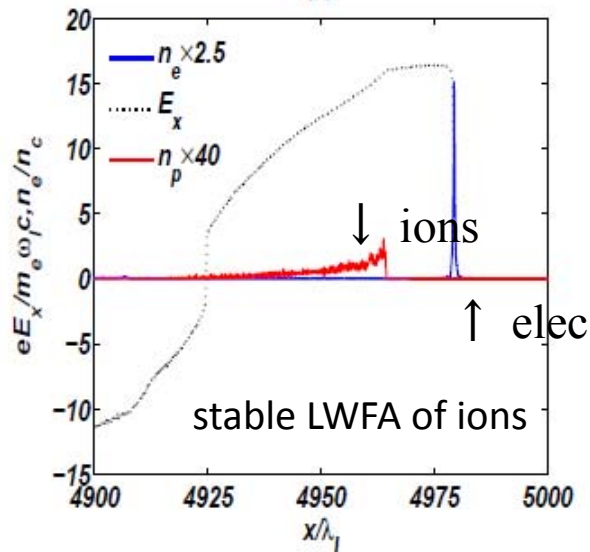
$$I = 10^{23} \text{ W/cm}^2$$

(using **ELI** type laser)

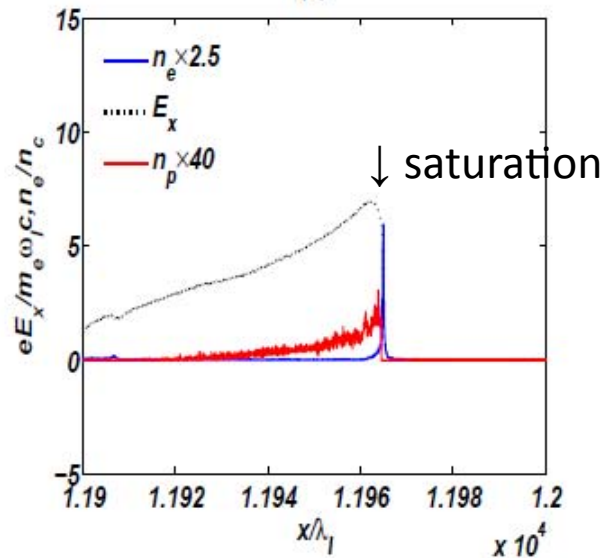
$$E_i = (1/6) a_0^2 (n_c / n_e) mc^2$$

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

(c)



(d)



0.5 TeV over  
dephasing length of 1 cm





# GeV-TeV proton Energy Scalings(**RPA** x **LWFA** )

TeV over cm @  $10^{23}$ W/cm<sup>2</sup> (Zheng et al, 2012)  
10GeV over mm @  $10^{22}$ W/cm<sup>2</sup> (Zheng et al, 2013)  
200MeV @  $10^{21}$ W/cm<sup>2</sup> (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,<sup>1</sup> S. Z. Wu,<sup>1,2</sup> H. C. Wu,<sup>1</sup> C. T. Zhou,<sup>1,2</sup> H. B. Cai,<sup>1,2</sup> M. Y. Yu,<sup>3,4</sup> T. Tajima,<sup>5</sup>  
X. Q. Yan,<sup>1,6,a)</sup> and X. T. He<sup>1,2,b)</sup>

<sup>1</sup>Key Laboratory of HEDP of the Ministry of Education, CAPT, Peking University, Beijing 100871, China

<sup>2</sup>Institute of Applied Physics and Computational Mathematics, Beijing 100088, China

<sup>3</sup>Institute of Fusion Theory and Simulation, Zhejiang University, Hangzhou 310027, China

<sup>4</sup>Institut für Theoretische Physik I, Ruhr-Universität Bochum, D-44780 Bochum, Germany

<sup>5</sup>Fakultät f. Physik, LMU München, Garching D-85748, Germany,

<sup>6</sup>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  $<2^\circ$  divergence can be produced by a circularly polarized laser pulse at an intensity of about  $10^{22}$  W/cm<sup>2</sup>. © 2013 American Institute of Physics. [<http://dx.doi.org/10.1063/1.4775728>]



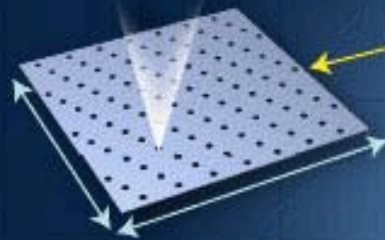
# THE LASER DRIVEN TRANSMUTATOR CONCEPT

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.

The focused laser reaches  $> 10^{13} \text{W/cm}^2$  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.

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.

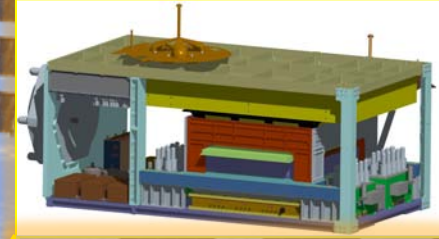
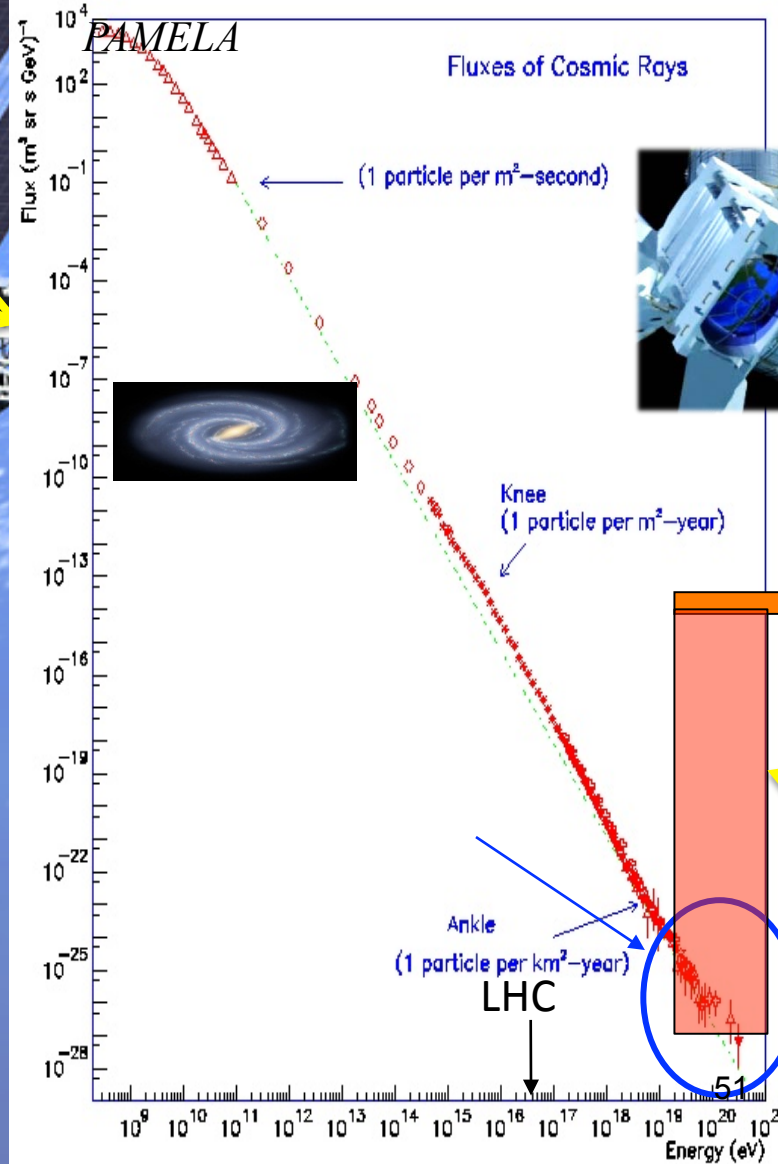
6

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

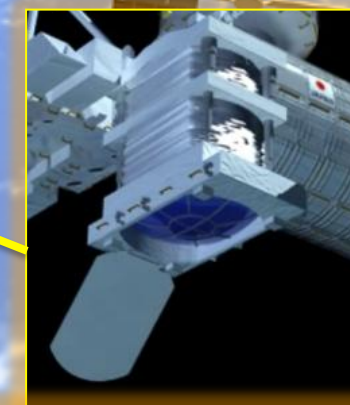
# Extreme High Energy Cosmic Rays (EHECR)



AMS Launch  
May 16, 2011

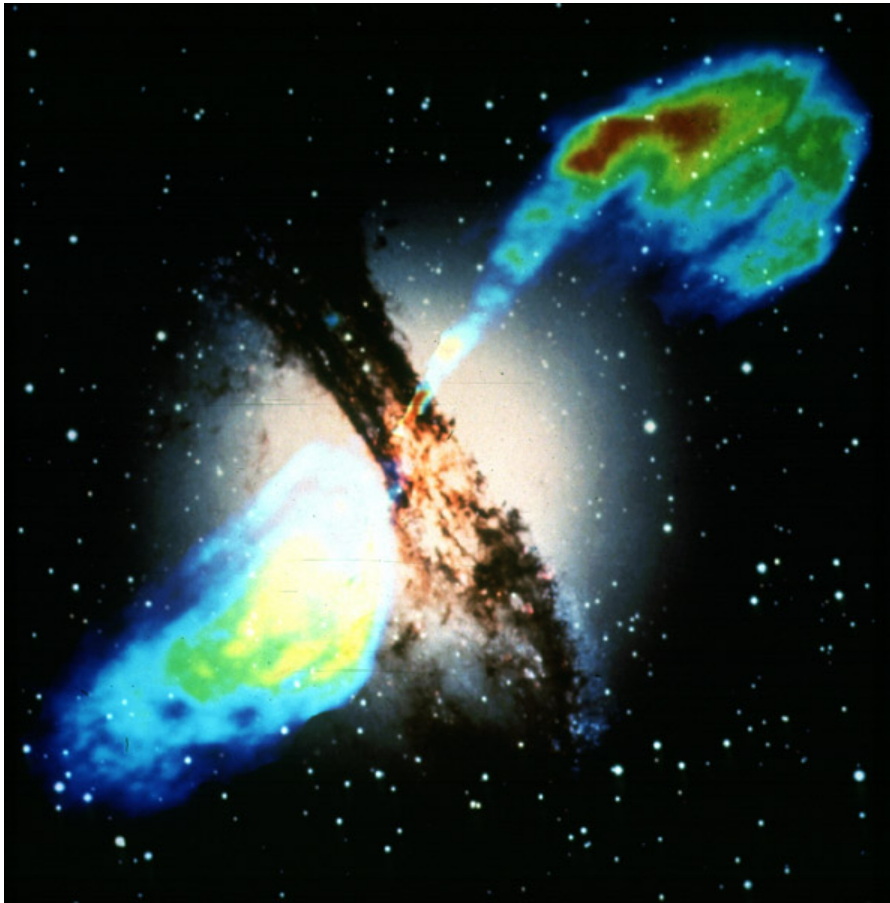


ISS-CREAM  
Sp-X Launch 2014



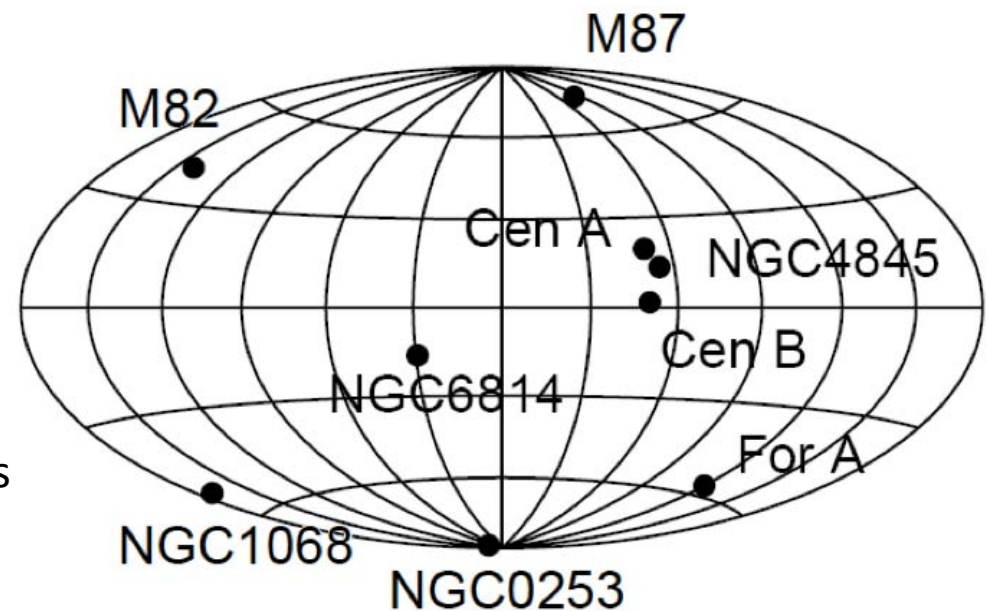
JEM-EUSO  
Launch Tentatively  
planned for 2017

# Cen A: an example of AGN

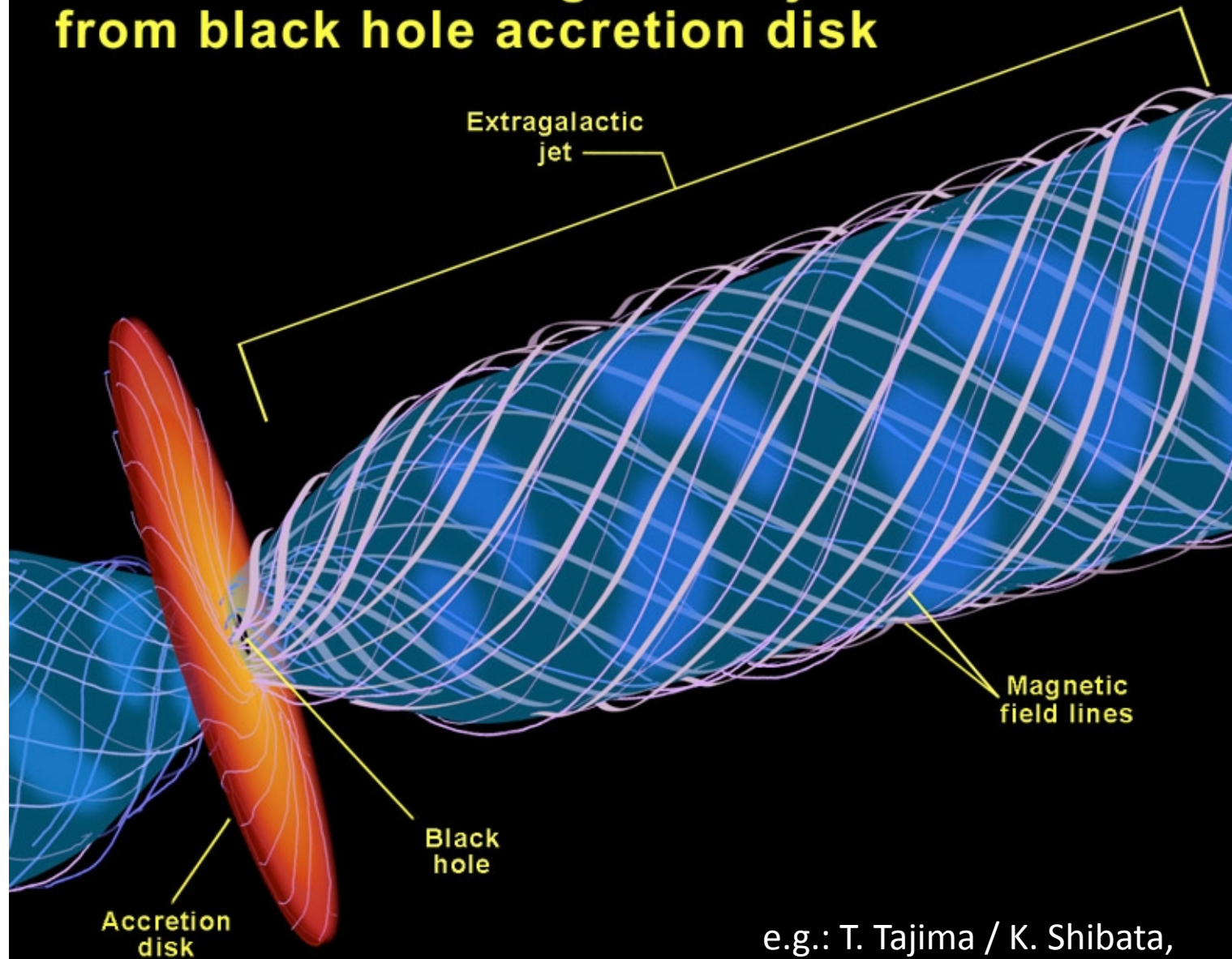


- Distance : 3.4Mpc
- Radio Galaxy
  - Nearest
  - Brightest radio source (collective oscillations!)
- Elliptical Galaxy
- Disk, AGN jets, halos: visible
- Other AGN: similar

Brightest AGNs

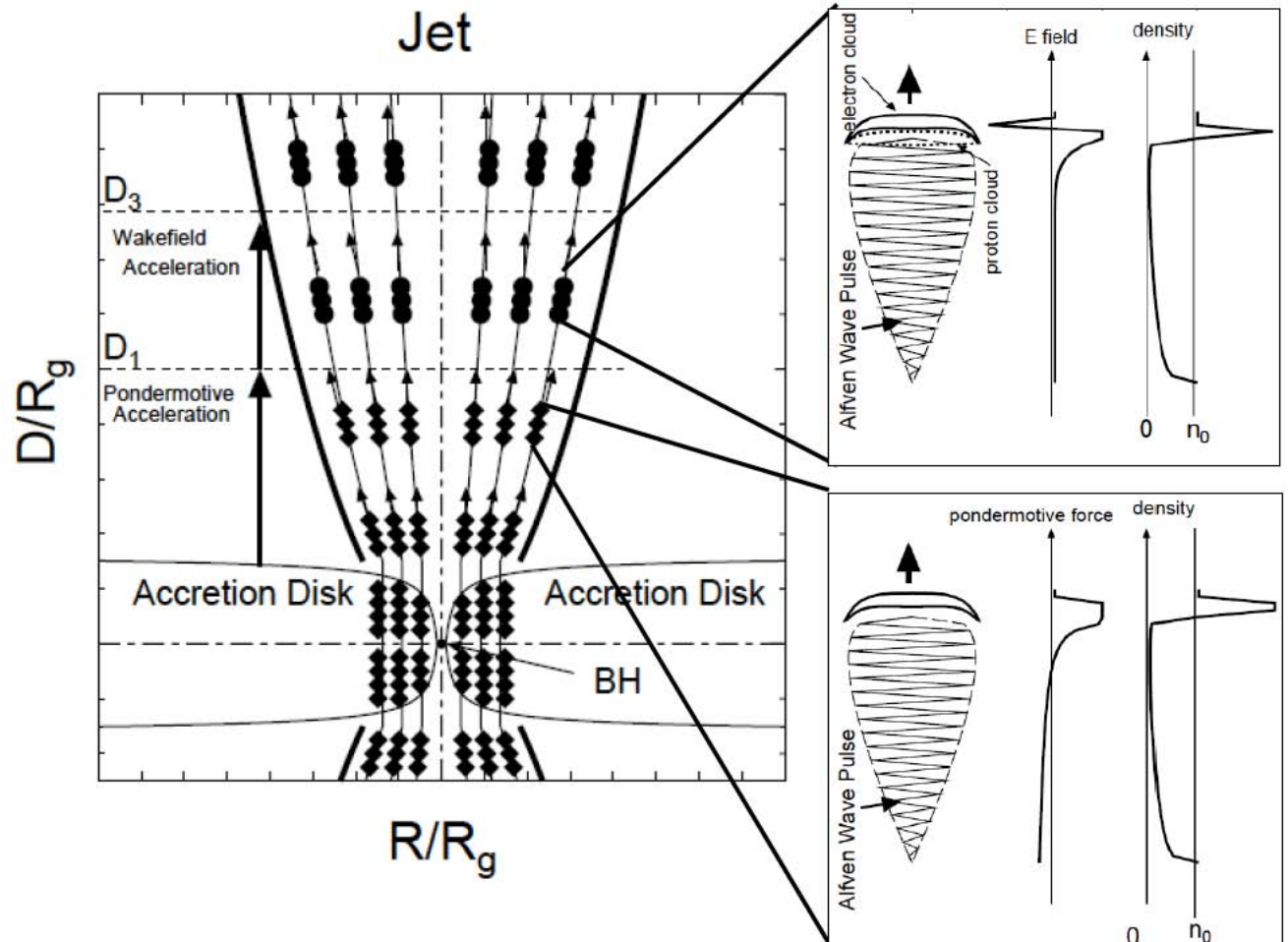
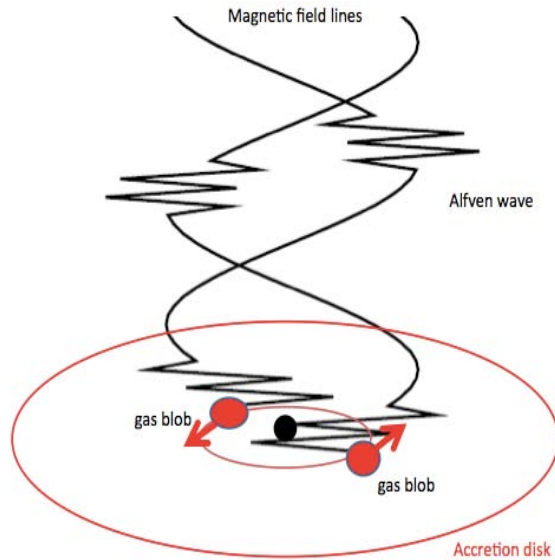


# Formation of extragalactic jets from black hole accretion disk

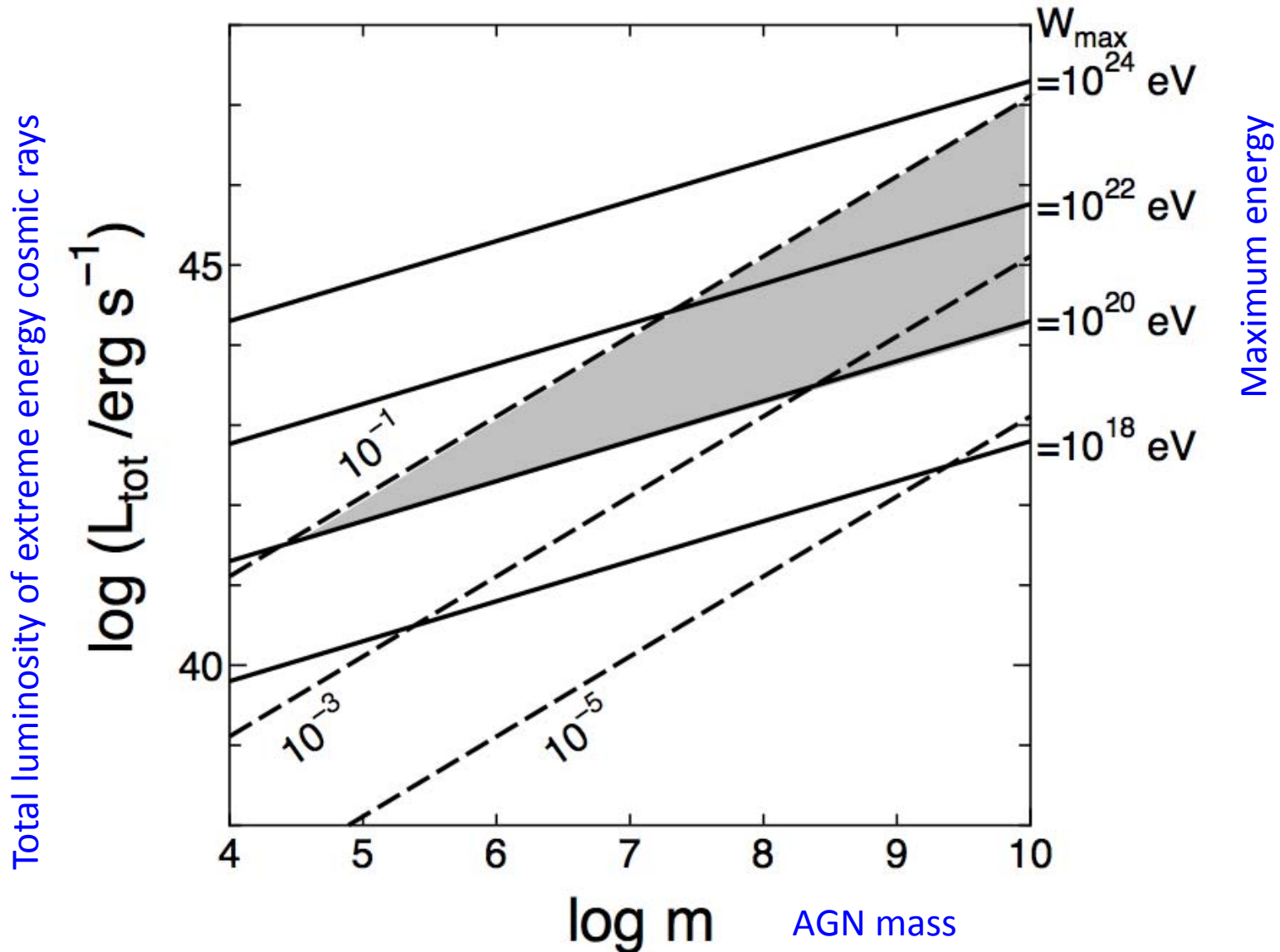


e.g.: T. Tajima / K. Shibata,  
"Plasma Astrophysics" (1997)

# Superintense **Alfven Shock** in the Blackhole Accretion Disk **Bow (Snowplow) Acceleration** toward ZeV Cosmic Rays



# Max Energy $W_{max}$ and Luminosity $L_{tot}$ of Extreme Energy Cosmic Rays as a Function of AGN Masses $m$



# Brightest $\gamma$ rays from AGNs: Flux and spectral power index

Table 2: Nearby gamma-ray emitting AGNs detected by Fermi satellite (Ackermann et al. (2011))

Counterpart	LII	BII	Redshift	Flux (1GeV-100GeV) $10^{-10}$ erg cm $^{-2}$	Spectral Index
NGC 0253	97.39	-87.97	0.001	$6.2 \pm 1.2$	2.313
NGC 1068	172.10	-51.04	0.00419	$5.1 \pm 1.1$	2.146
For A	240.15	-56.70	0.005	$5.3 \pm 1.2$	2.158
M82	141.41	40.56	0.001236	$10.2 \pm 1.3$	2.280
M87	283.78	74.48	0.0036	$17.3 \pm 1.8$	2.174
Cen A Core	309.51	19.41	0.00183	$30.3 \pm 2.4$	2.763
NGC 4945	305.27	13.33	0.002	$7.5 \pm 1.7$	2.103
Cen B	209.72	1.72	0.012916	$18.6 \pm 3.5$	2.325
NGC 6814	29.35	-16.02	0.0052	$6.8 \pm 1.6$	2.544





# 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  $\gamma$ - $\gamma$  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  $\leftrightarrow$  terrestrial **laser** acceleration

謝謝!



Blazar: Cosmic **laser wakefield** linac?