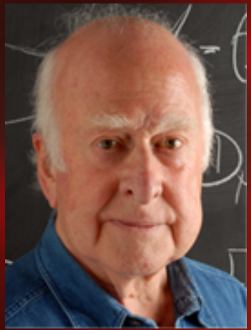
I ZEST
International Zeta-Exawatt Science Technology

Extreme Light Beyond the Horizon: *X-ray Wake Field Acceleration Route to TeV/cm*

Gérard Mourou,



"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!"

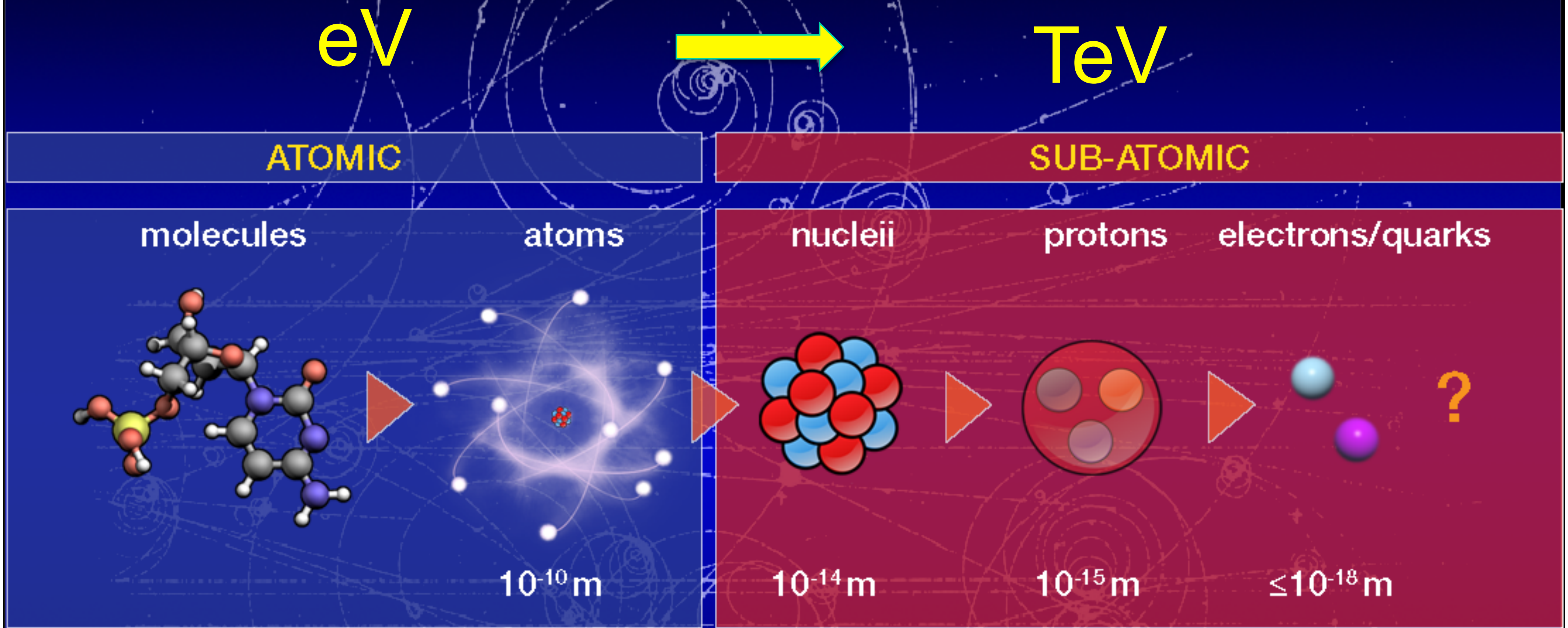
- Charles Townes

INFN Frascati 13/2/2017

IZEST Ecole Polyetechnique

International Year of Light 2015

Laser Exploration : From Atomic to Sub-Atomic



1PW, is 1000 times the world grid power (10^{-15} secondes)

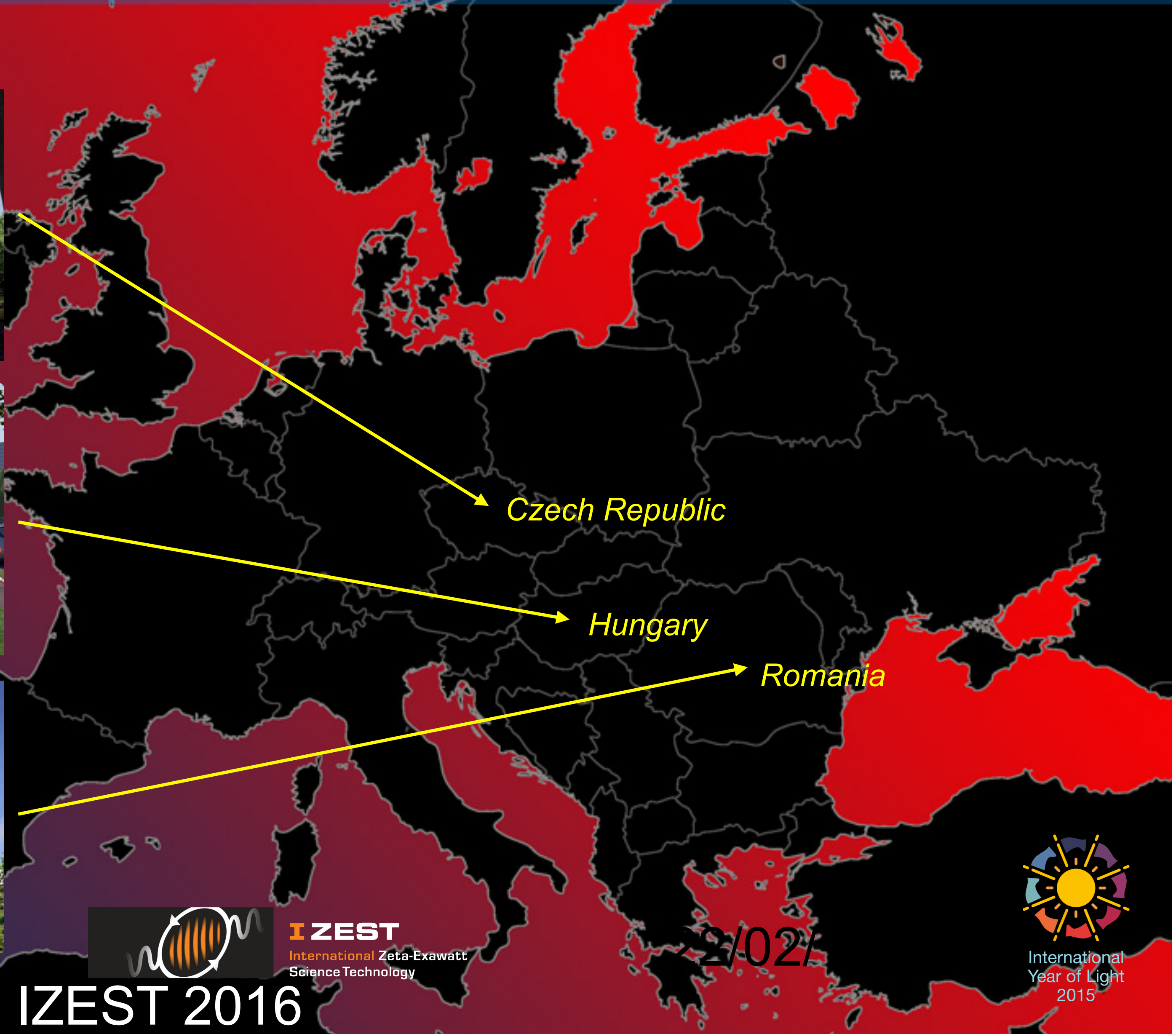
International Zeta-Exawatt Science Technology

IZEST 2016

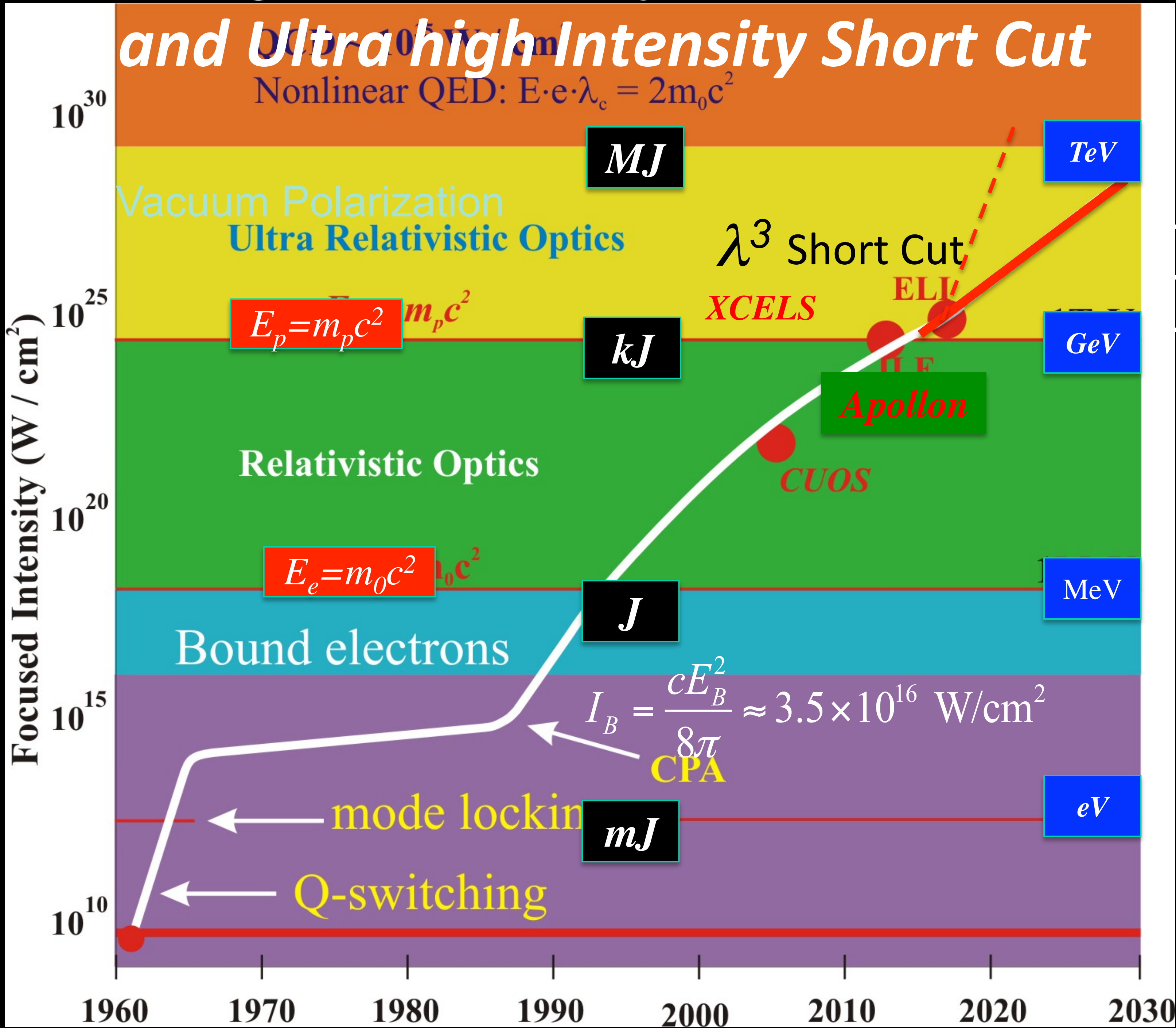
22/02/17

Extreme Light Infrastructure - ELI

The Largest Civilian Laser Infrastructure
Initiated and Coordinated(PP) by, G. Mourou (EP)
ELI (Delivery Consortium) W. Sandners



Extreme Light Road Map
and Ultrahigh Intensity Short Cut



1EW
1Joule in
1 attosec

Pulse compression to the single cycle Atto-Zeptosecond Exawatt Pulse

1. High Energy Single Cycle Pulse Compression in the Visible

2. High Energy Atto-Zeptosecond Pulse Compression X-ray, γ– ray Regime

4. Giant Wake Field Acceleration TeV/cm

5. Relativistic Proton generation

6. Table Top Cosmology

7. Solving the High Average Power Quandary

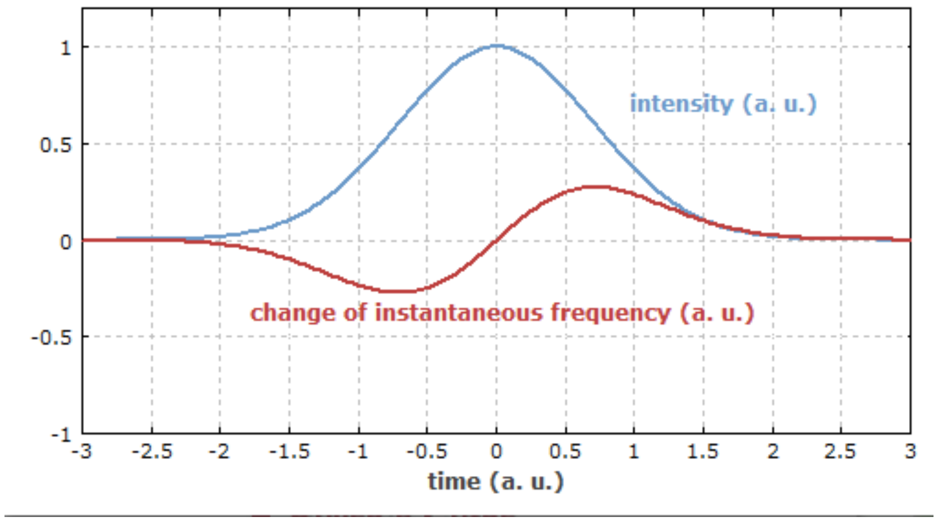
Pulse Compression in the Visible

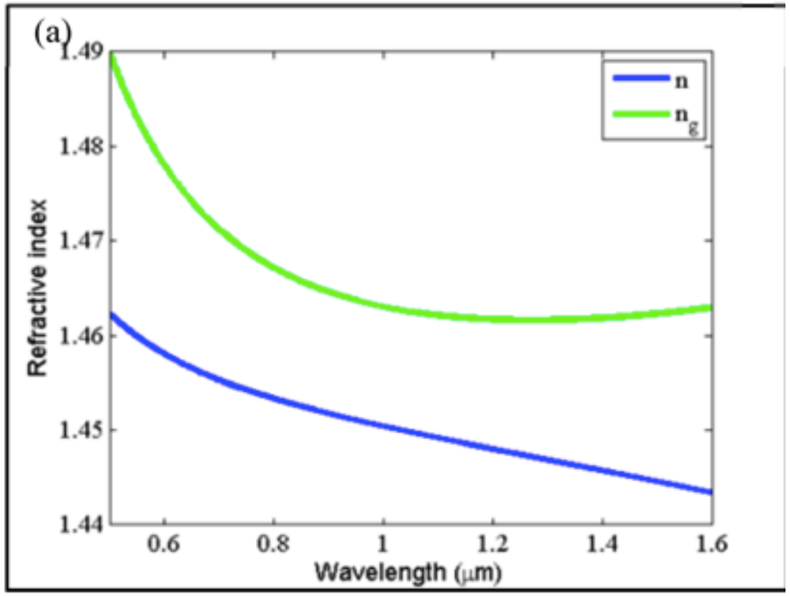
The laser pulse duration is limited by the gain bandwidth.
To go shorter, we need to produce a pulse:

1. with larger spectrum by self-phase modulation
2. and stretching it GVD before compression.

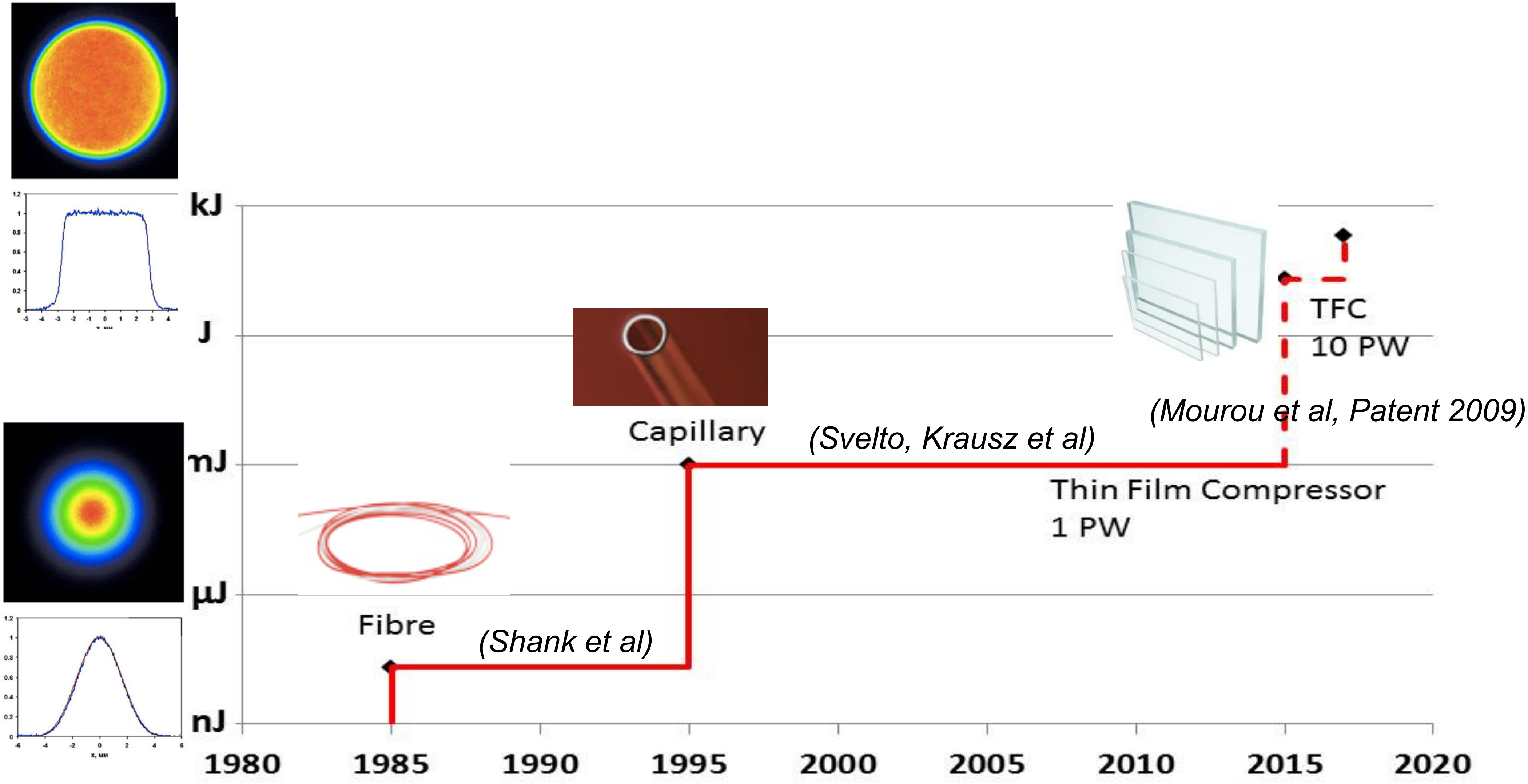
1) $$n(x,t) = n_0 + n_2 I(x,t)$$

2) $$\frac{\partial n(x,t)}{\partial t} = n_2 \frac{\partial I(x,t)}{\partial t}$$



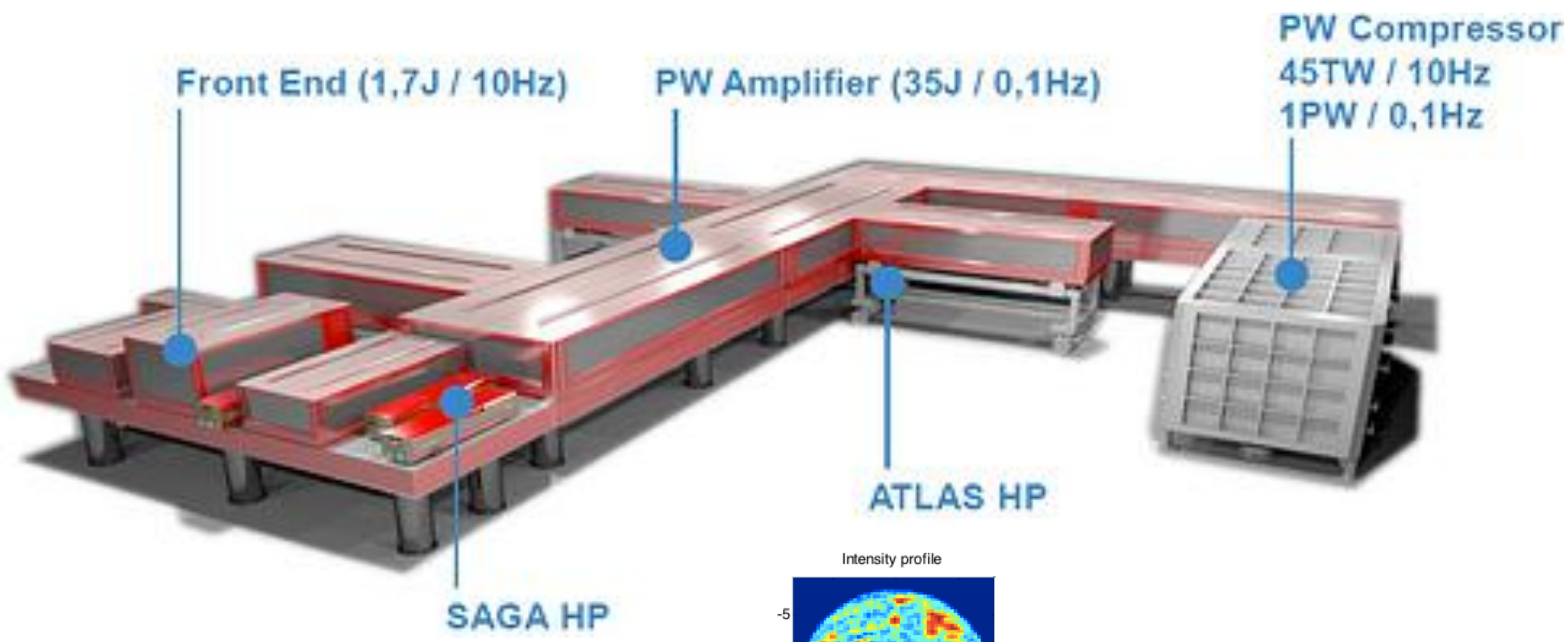


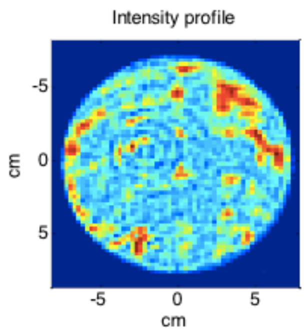
Pulse Compression and Single Cycle History



Gérard Mourou, Gilles Cheriaux, Christophe Radier,Device for generating a short duration laser pulse US 20110299152 A1

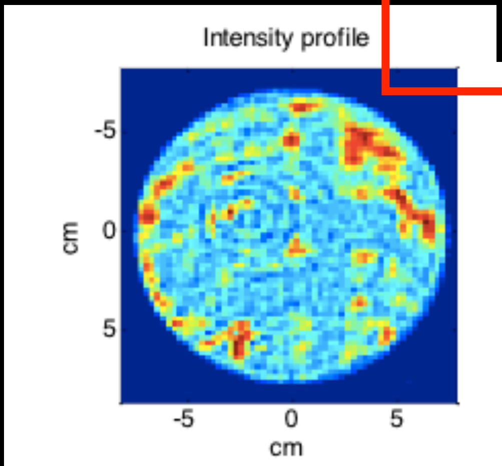
Petawatt Laser Provides A 10-1000J Uniform wave front in ***Phase and Amplitude***

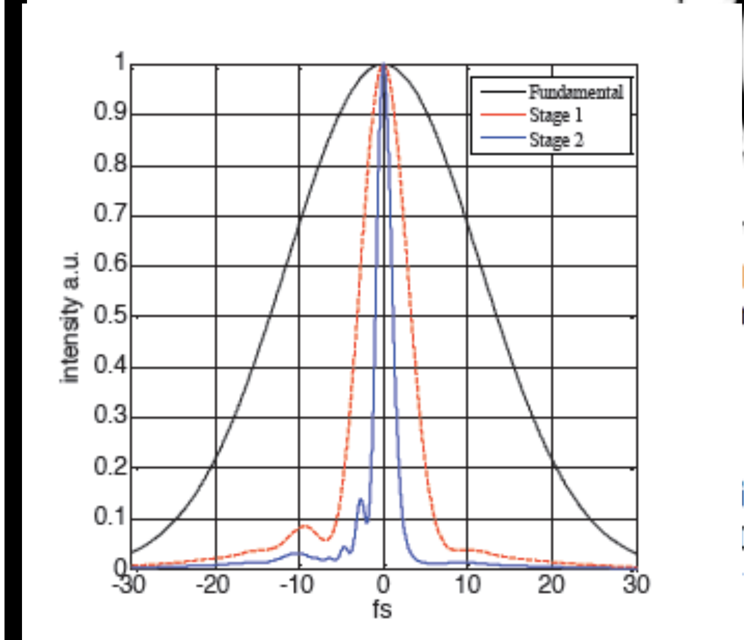


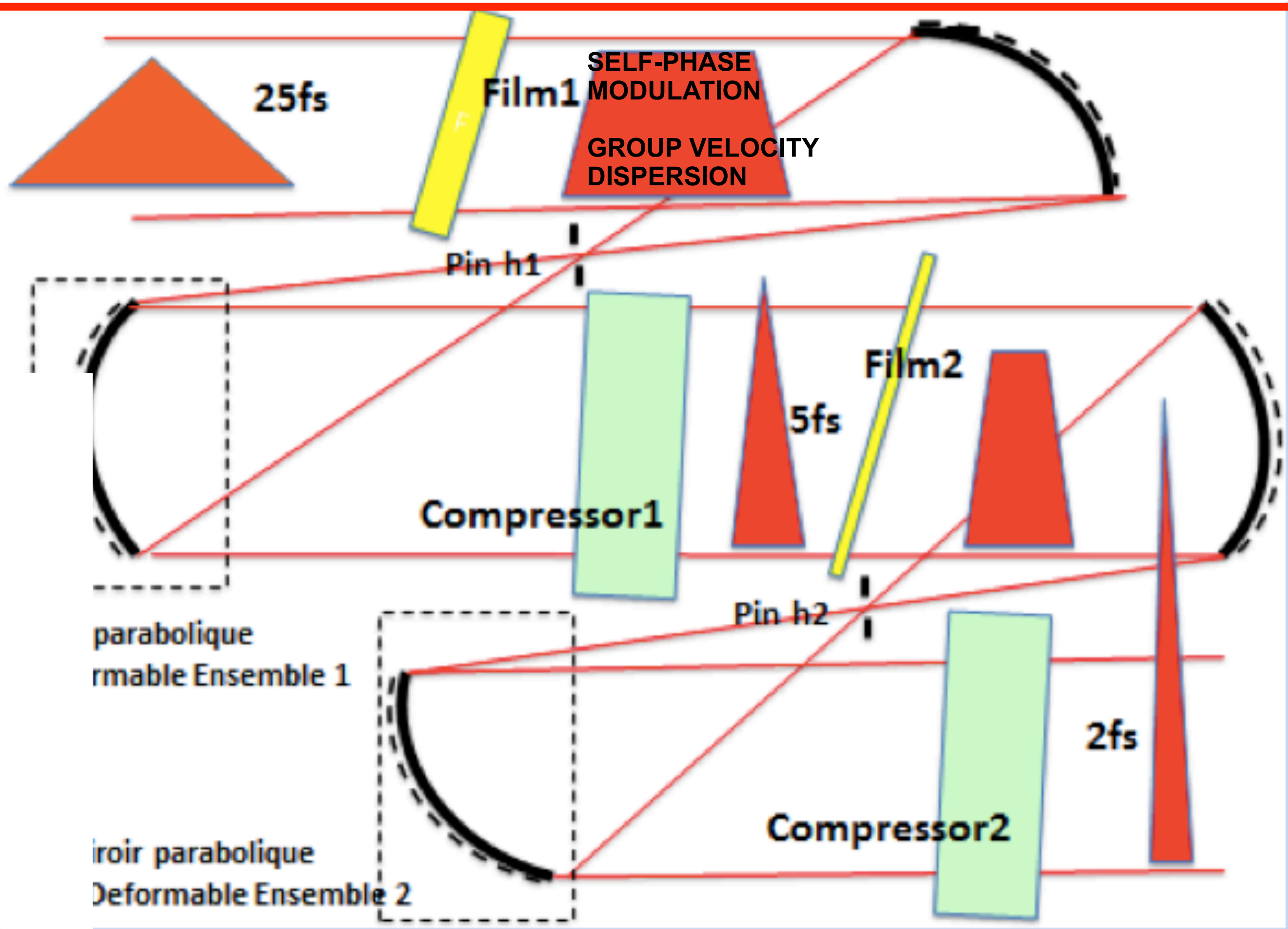


International Year of Light 2015

Single Cycle Thin Film Compressor TFC







G. Mourou, S. Mironov, E. Khazanov and A. Sergeev, Single cycle Physics , Eur. Phys. J. Special Topics, 223, 1181(2014)
A.A. Voronin, A.M. Zheltikov, T. Ditmire, B. Rus and G. Korn Optics. Com. 2011
G. Mourou, G. Cheriaux, C. Radier Patent 2009

Thin Film Pulse Compression

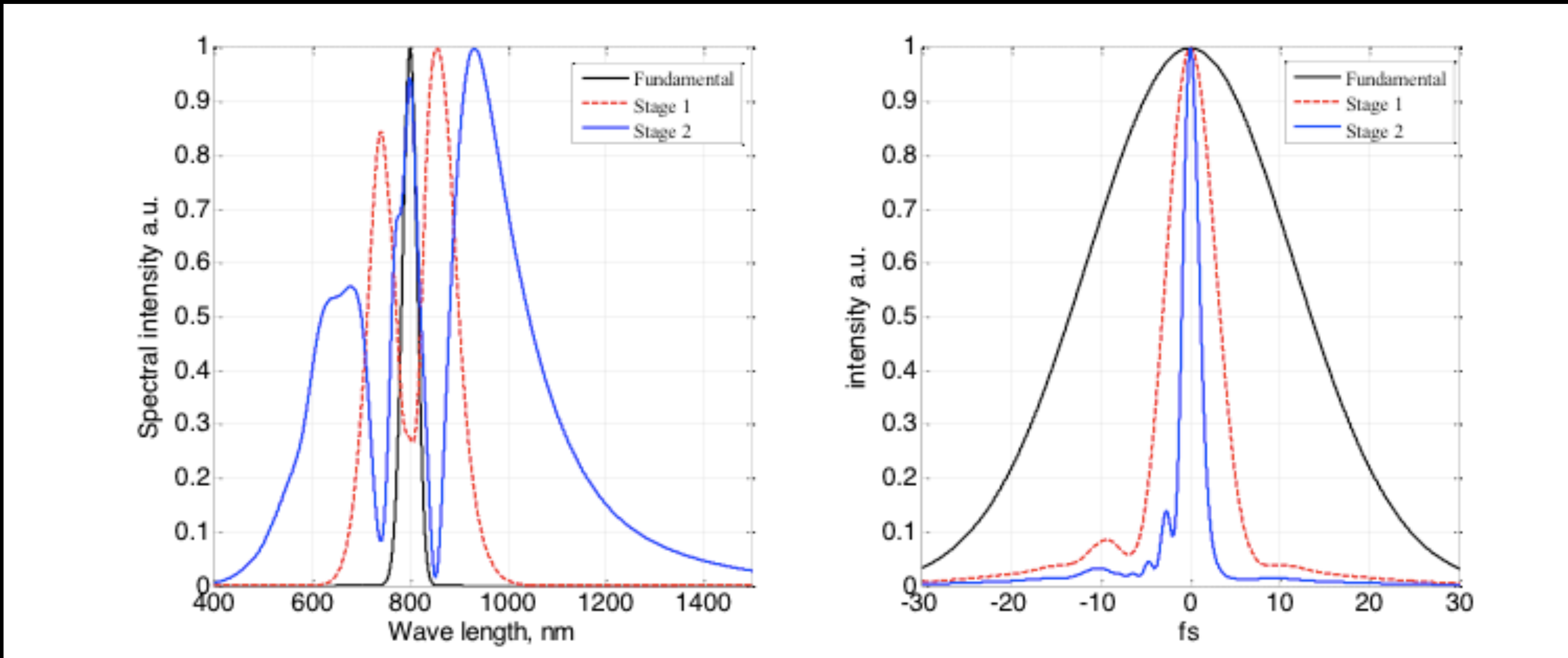
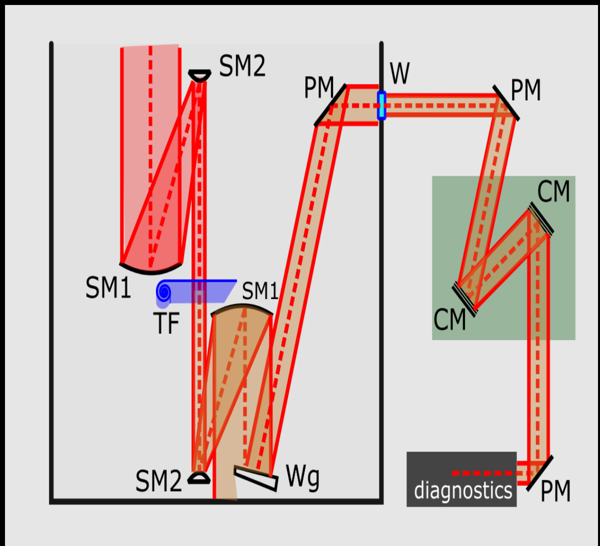
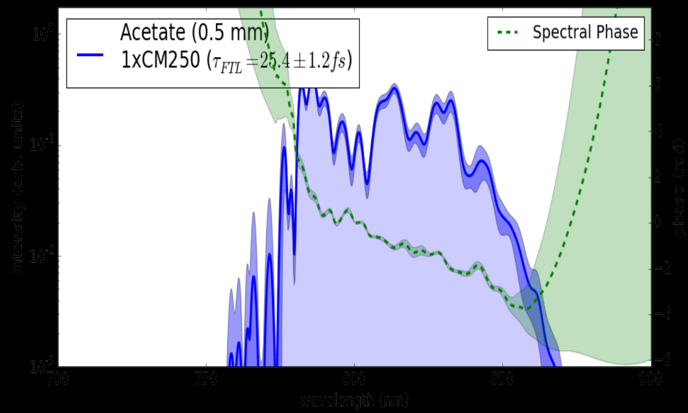
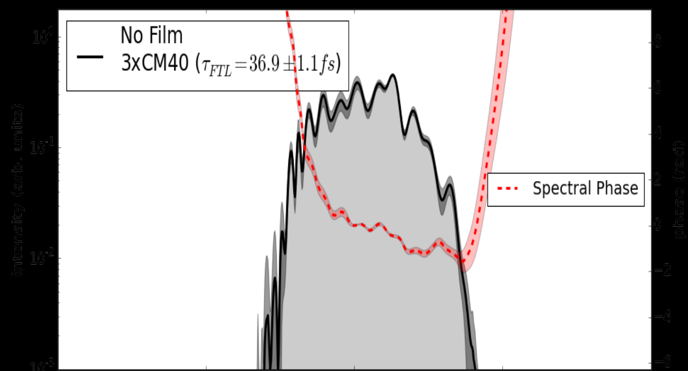


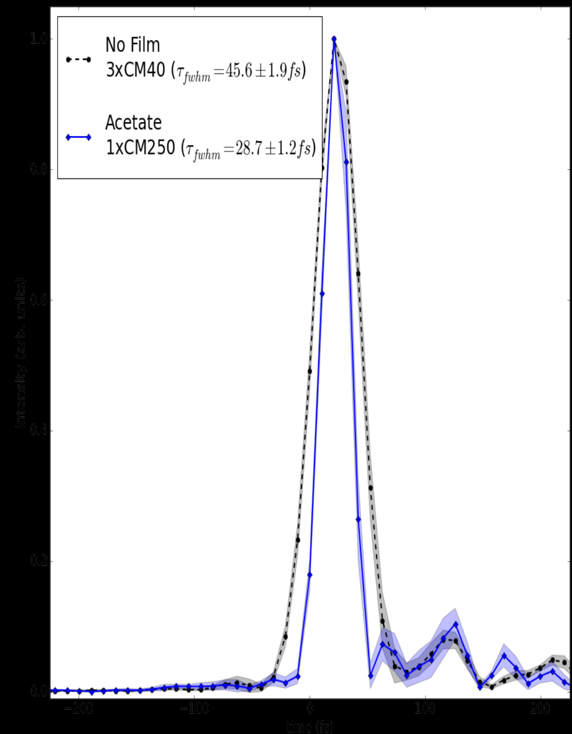
Fig. 4 shows the successive spectra and pulse durations corresponding to the laser out put, after the first stage and second stage. After the first stage the pulse 6.4fs, after the second stage the pulse is shrunk to 2.1fs



Cellulose Acetate (0.5 mm)







45 fs to 25 fs (at diagnostic limit)
Using 0.5mm films of 2 materials
Single chirped mirror pair

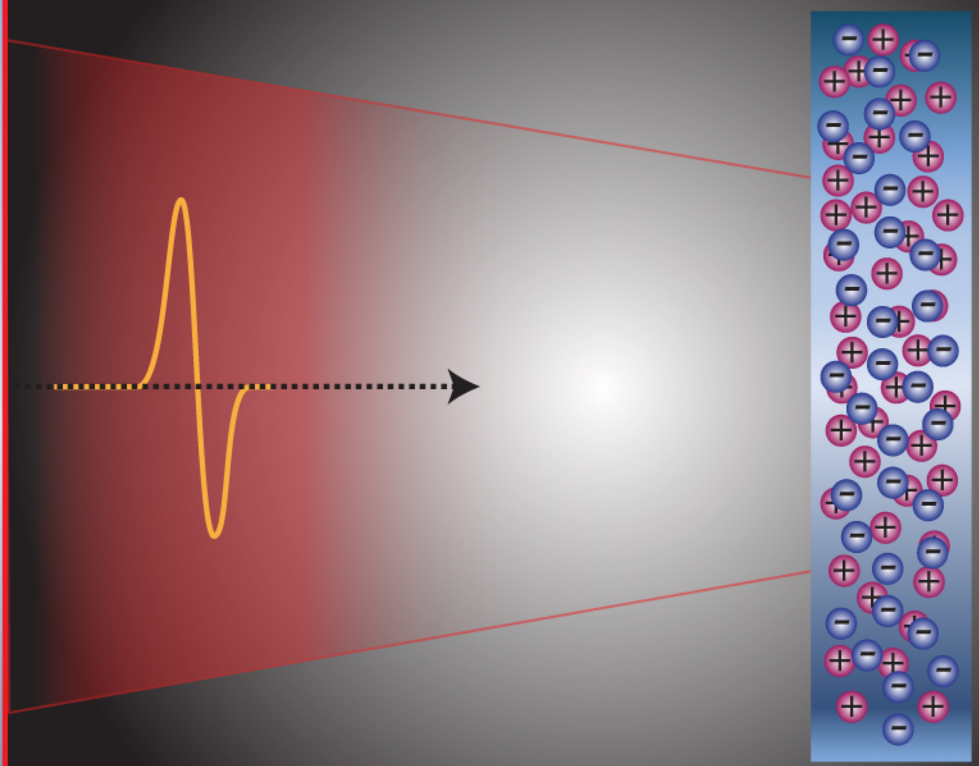
Low Hanging Fruits

Relativistic Compression
Scalable Isolated Attosecond Pulses

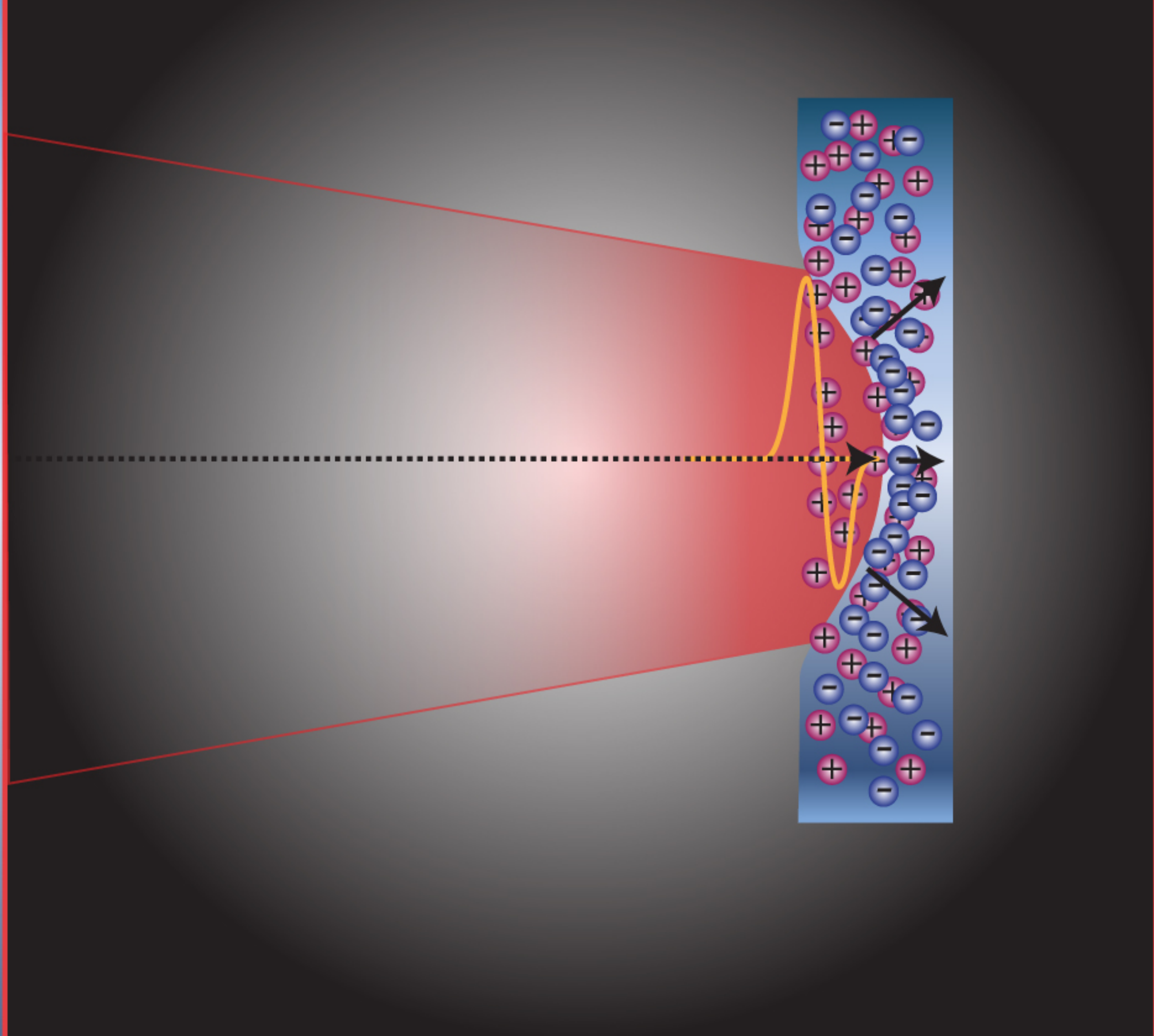
N. M. Naumova, J. A. Nees, I. V. Sokolov, B. Hou, and G. A. Mourou,

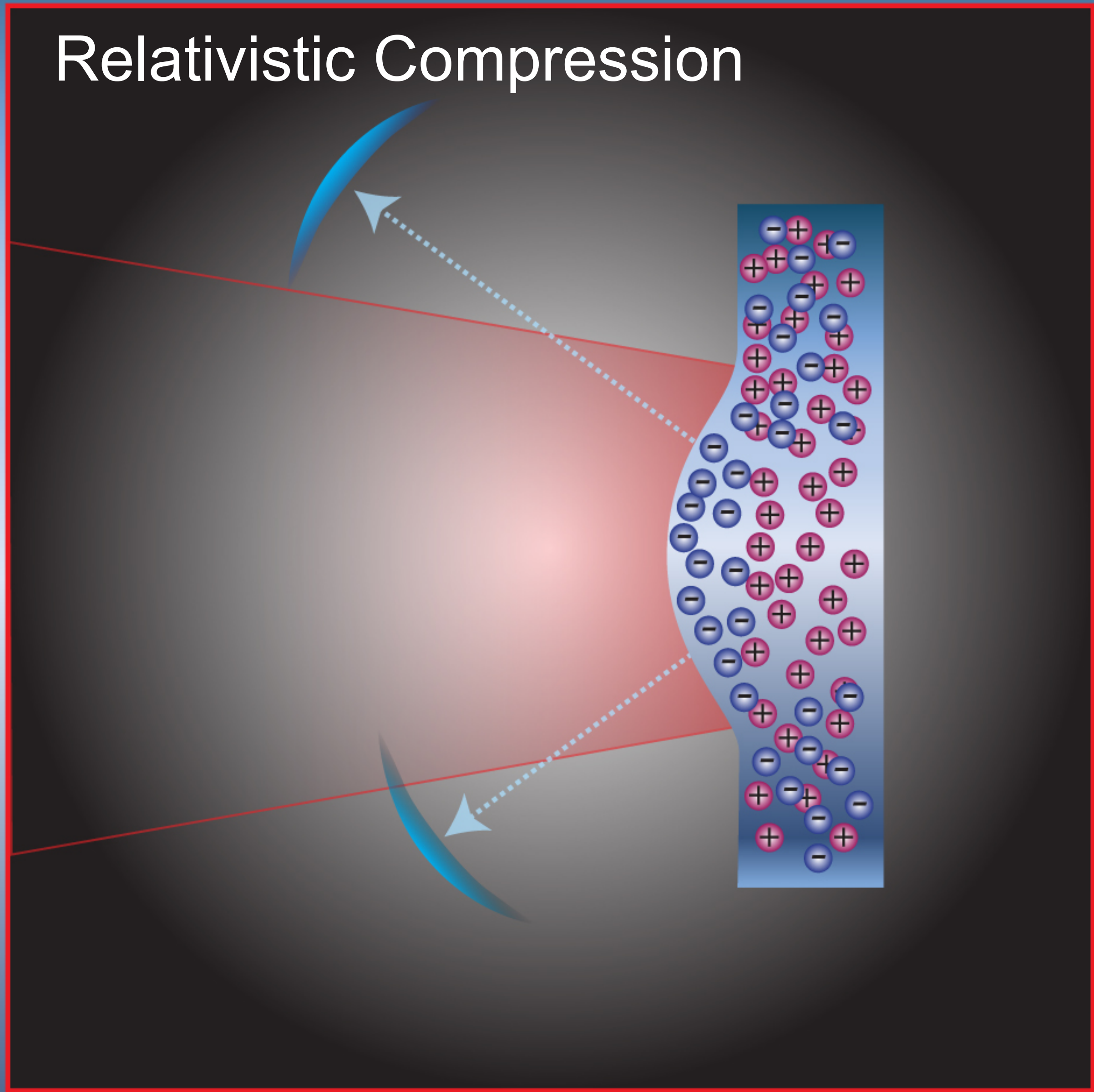
Relativistic generation
of isolated attosecond pulses in a λ^3 focal volume, Phys. Rev. Lett.
92, 063902-1 (2004).

Relativistic Compression



Relativistic Compression




Relativistic Compression

Scalable Isolated Attosecond Pulses

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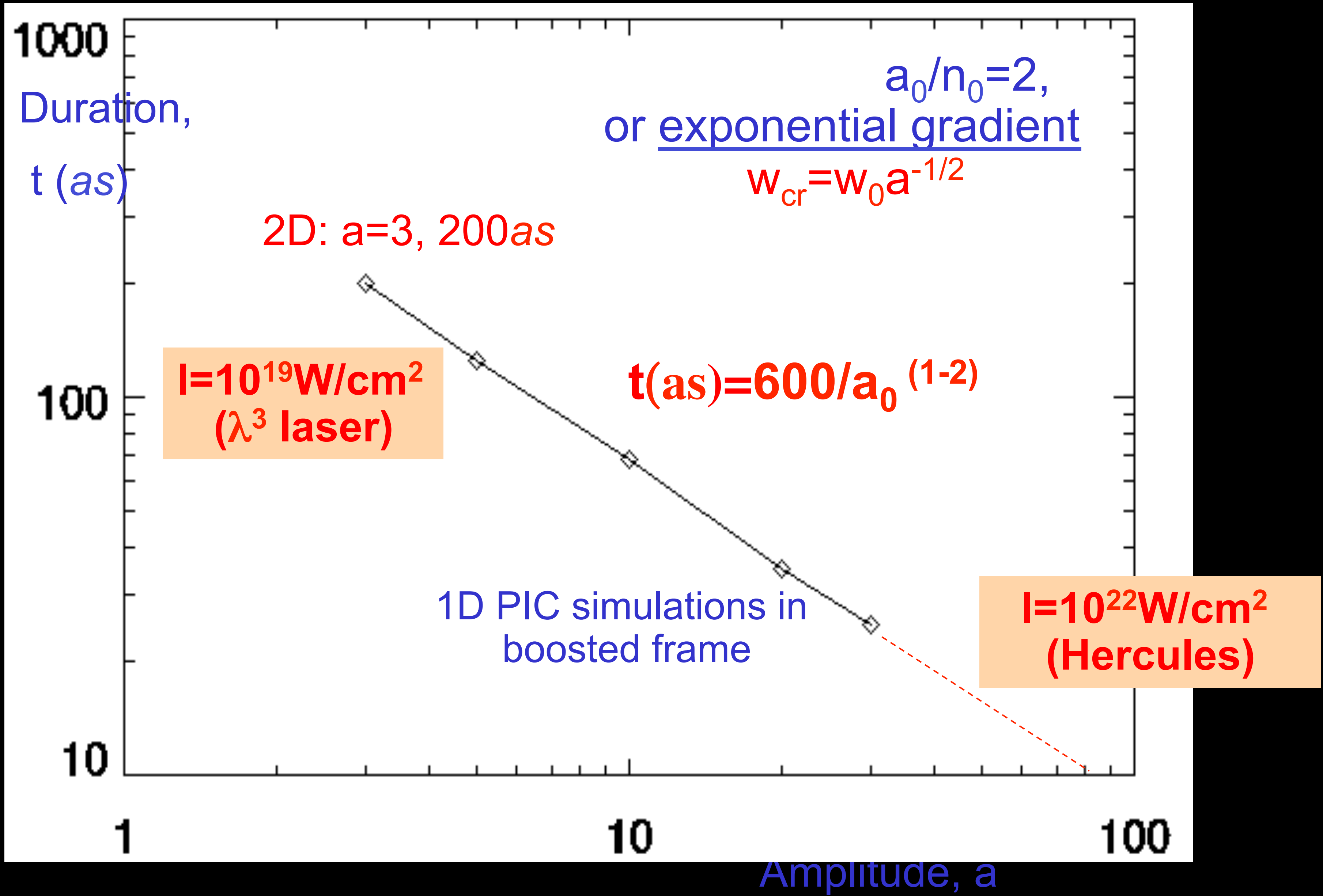
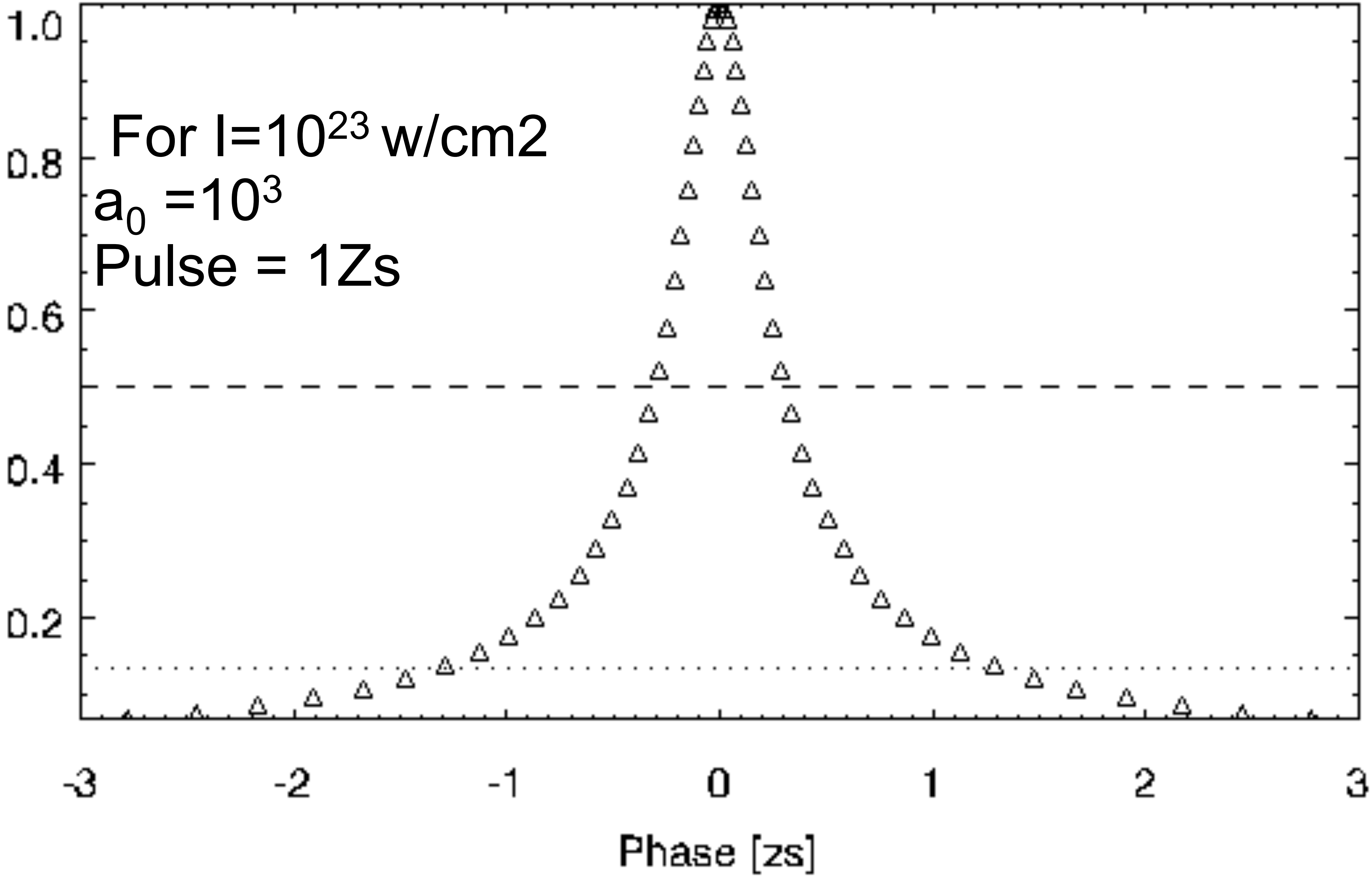


Zeptosecond pulses, (N. Naumova, I. Sokolov, G. Mourou)
(Preliminary Result)



But a zeptosecond pulse is also:

1. 1J in a Zs (10^{-21}s) is a Zettawatt Zw (10^{21}W)
2. A Zs (10^{-21}s) is a 1MeV Coherent Gamma-ray

Giant Laser Acceleration in solid: TeV/cm (CERN on a Dime) towards ZeV

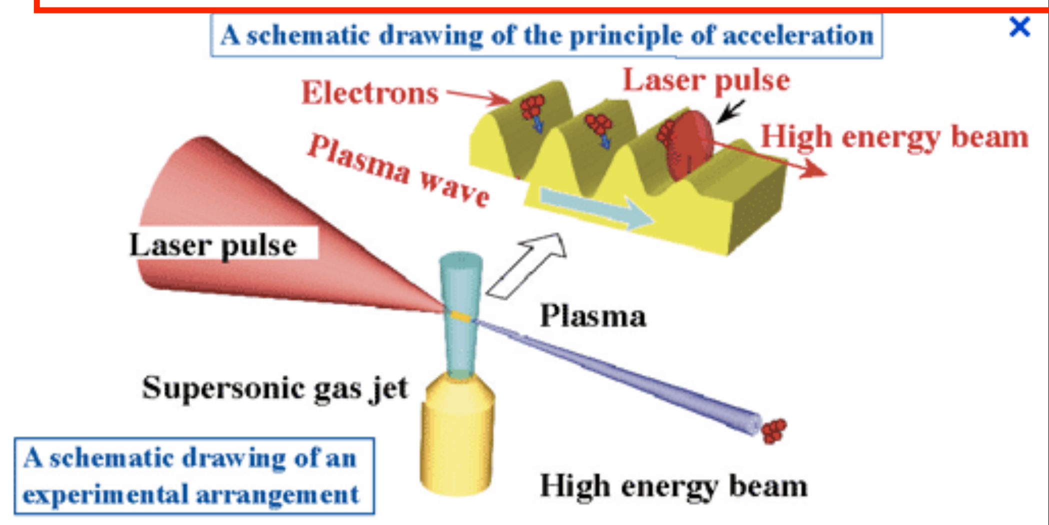
3. 1Zw over λ^2 spot size is 10^{29} W/cm^2 Schwinger Intensity:

Light Turns into Matter and Antimatter

Low Hanging Fruits
TeV/cm Acceleration

Giant Wake Field Acceleration in Gas and Solid

Femtosecond Visible Light Driver in Gas ***Tajima et Dawson 1979***



Plasma Acceleration Energy Gain

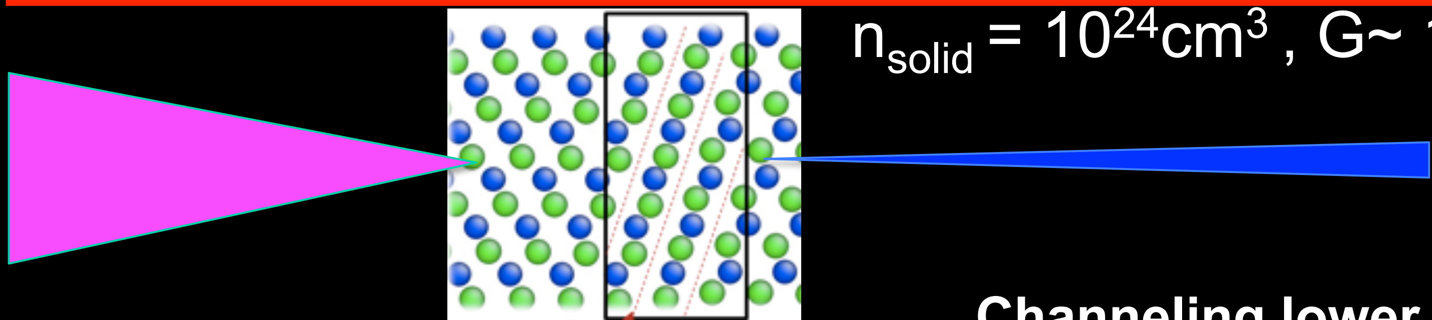
$G \alpha\ n^{1/2}$ eV/cm

1eV light $n_c \sim 10^{21} cm^{-3}$

$n_{gas} = 10^{18}\ cm^{-3}$, $G \sim 10^{9}$, GeV/cm

Atto-zepto, X-ray Driver, Solid, ***Tajima et Cavenago 1987***

$n_{solid} = 10^{24} cm^{3}$, $G \sim 10^{12}$ eV/cm, TeVcm

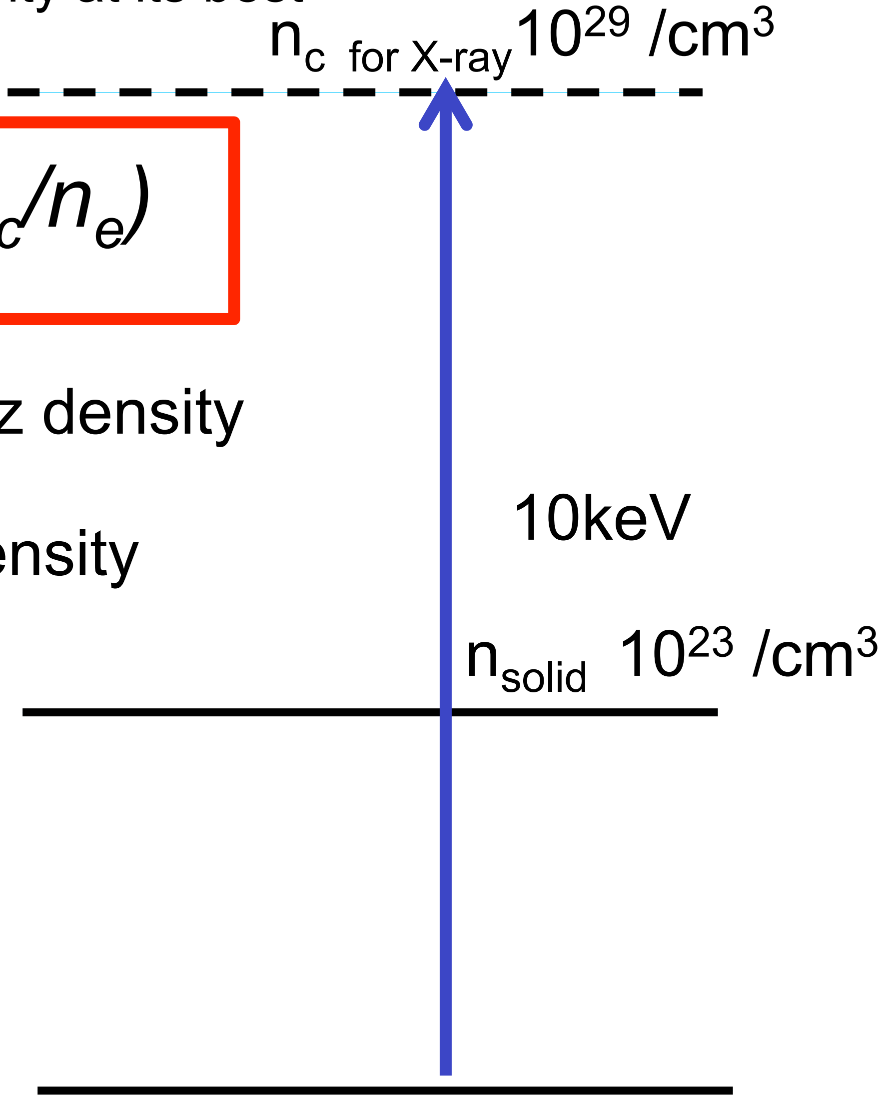


Drive pulse X-Ray, 600zs + as electron pulse

Channeling lower the emittance
Valid for electron, muons, heavy ions

Laser-Wake-Field Acceleration
Gas/Light vs Solid/ X-Ray

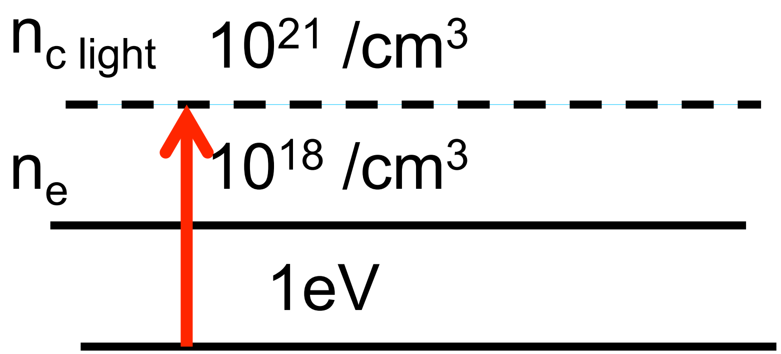
Serendipity at its best



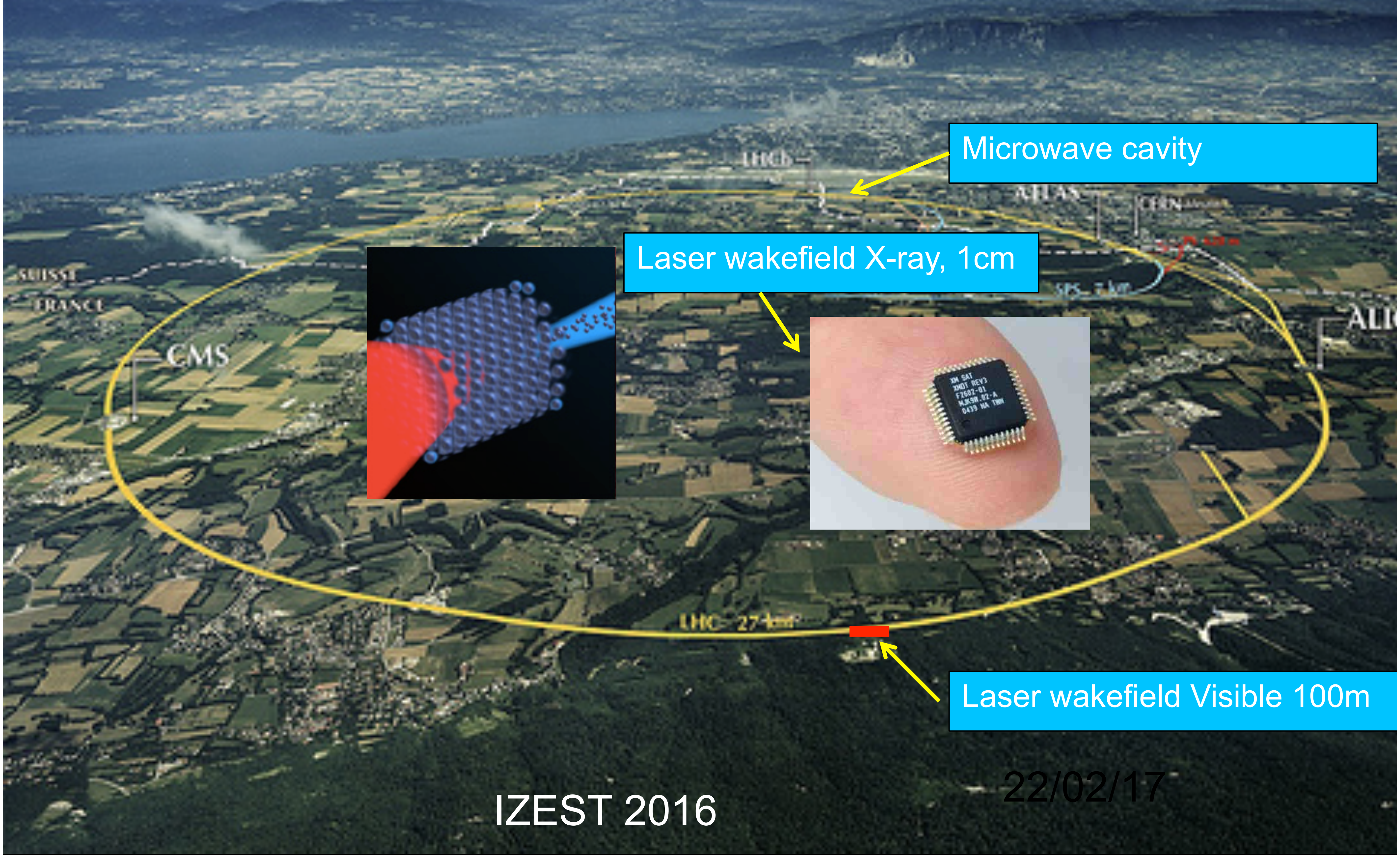
Energy Gain $E=a_0^2 m_o c^2 (n_c/n_e)$

In the visible $n_c = 10^{21}$/cm^3 Low gaz density

In the X-ray, $n_c = 10^{29}$/cm^3 Solid density

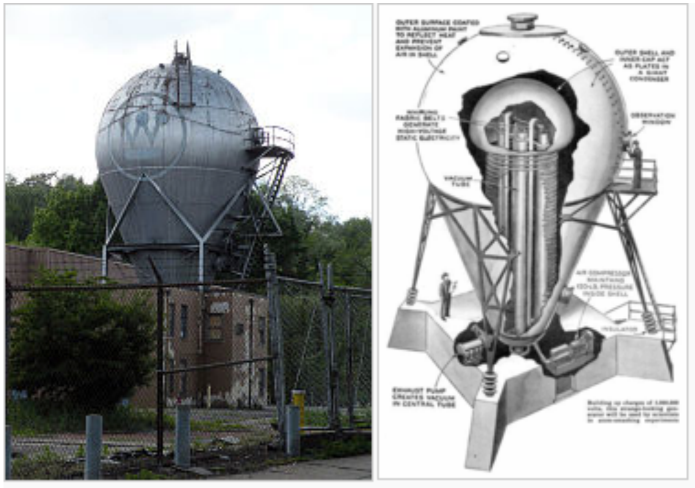


Outlook for
Laser-Particle acceleration TeV

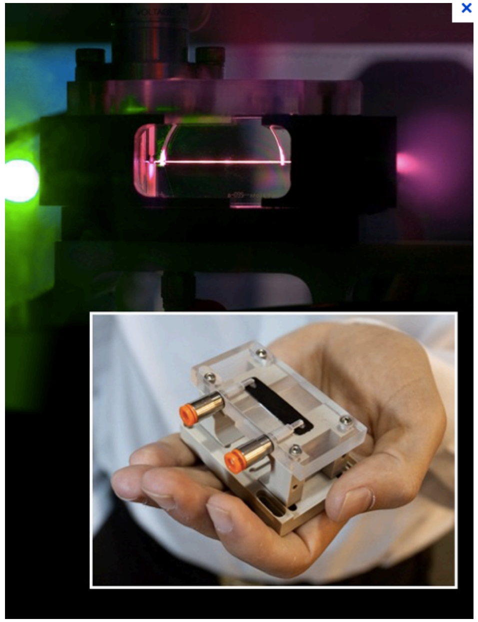


Historical Trend in Particle Acceleration From DC to X-ray

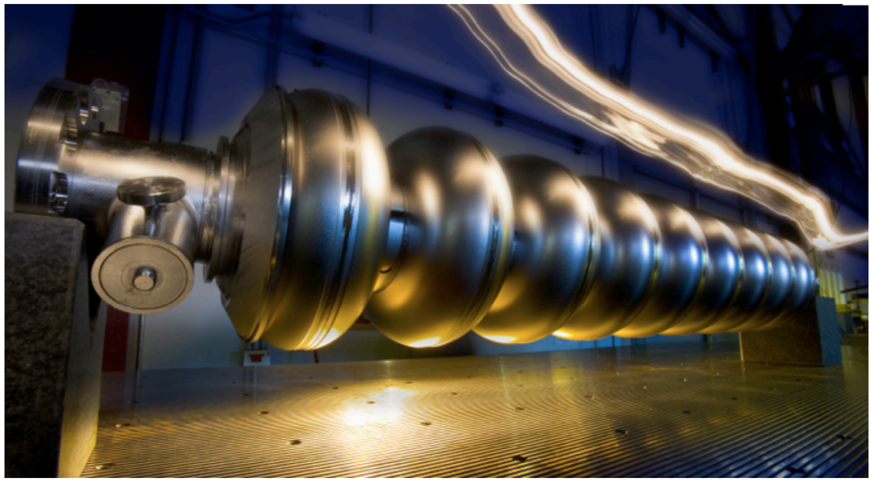
0 Hz   Van de Graff, MeV



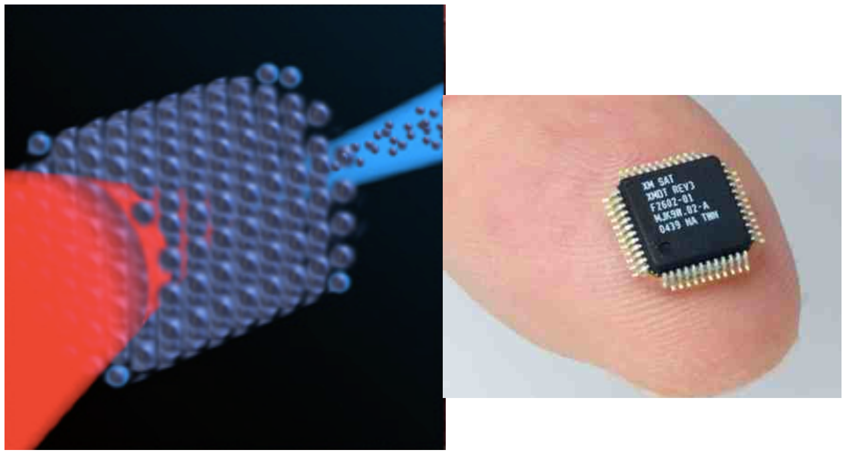
LWA , Visible 10^{14} Hz, GeV/cm



RF Cavity 10^{9} Hz, MeV/cm

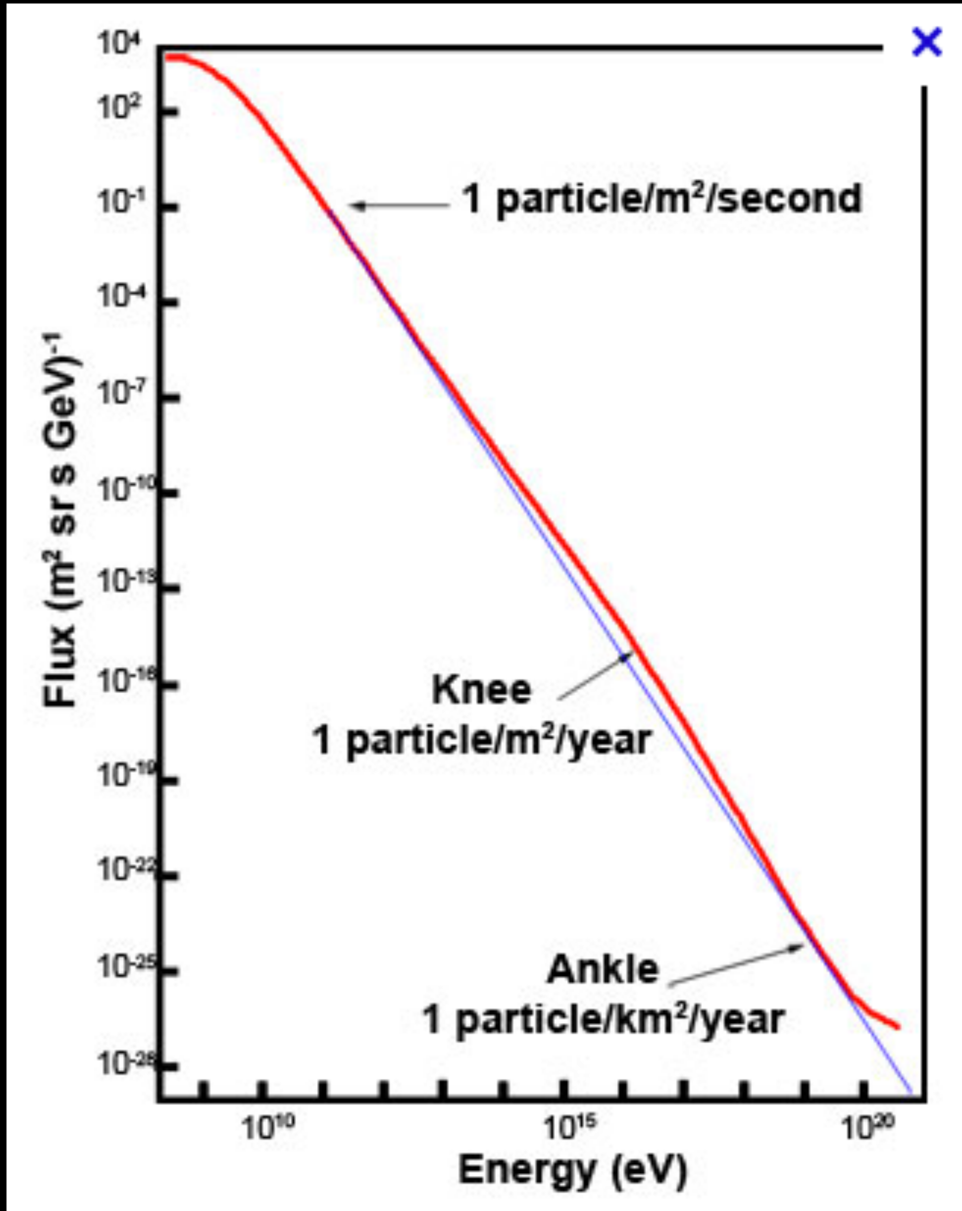


LWA – X-ray 10^{18} Hz, TeV/cm



TeV Particle Astrophysics

Cosmic Ray Spectrum



Cosmos on a Table
Lorentz Invariance

Light Dispersion
From quantum Vacuum

Gamma Ray Burst
mn Duration

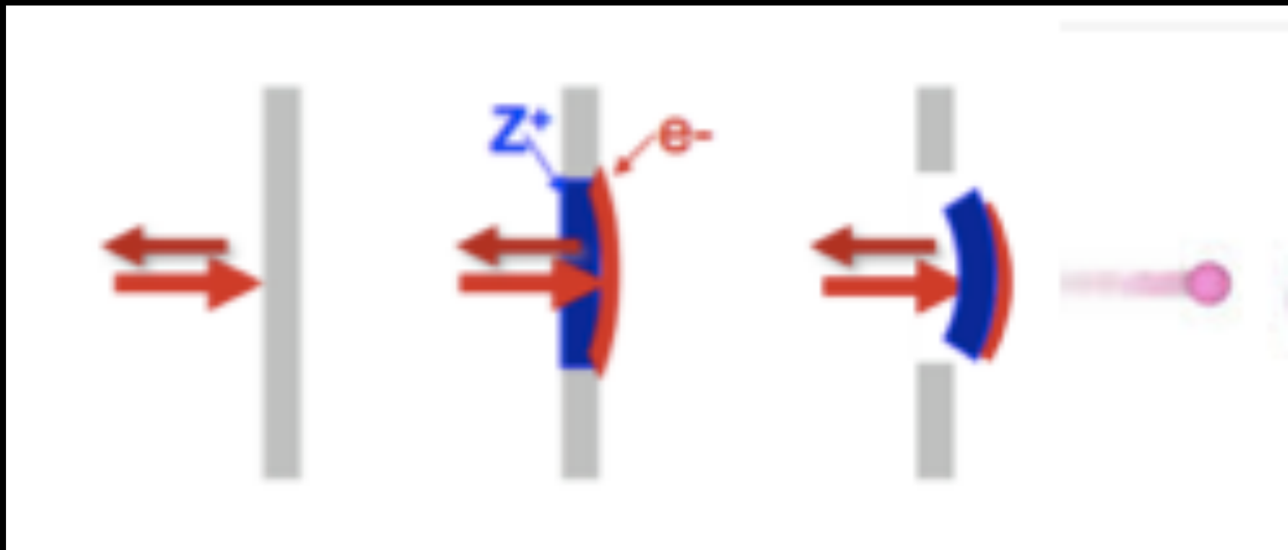
1billion years,

,
10mn spread

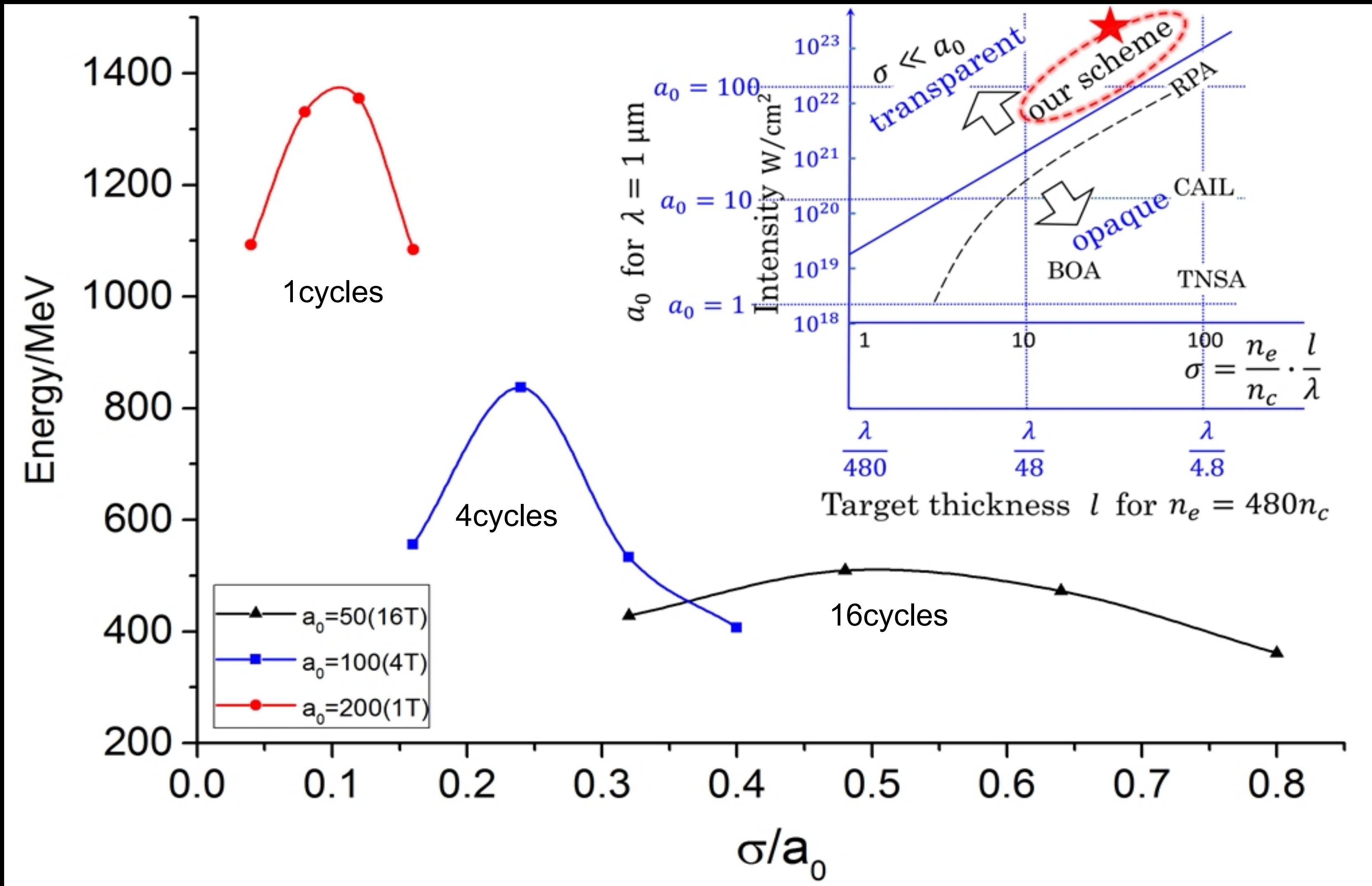
Low Hanging Fruits
High Energy Proton Generation

Low Hanging Fruit:

GeV Proton Generation



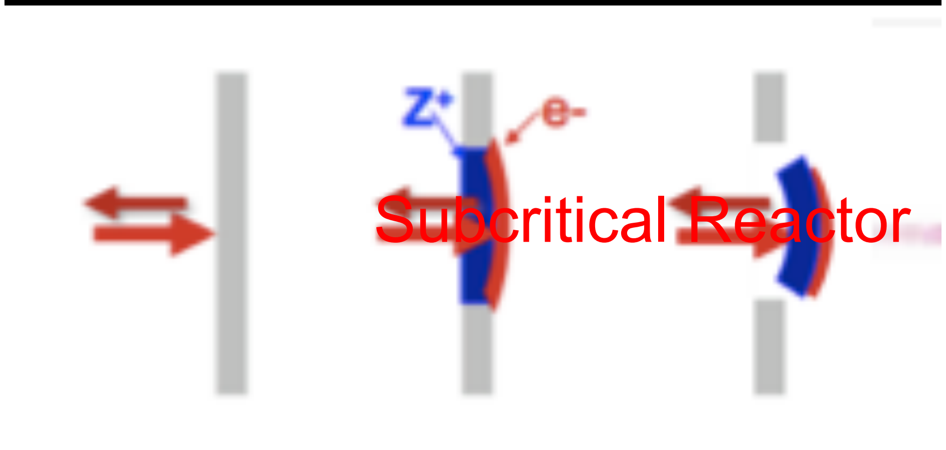
Applications of Single Cycle to Proton Generation vs a_0



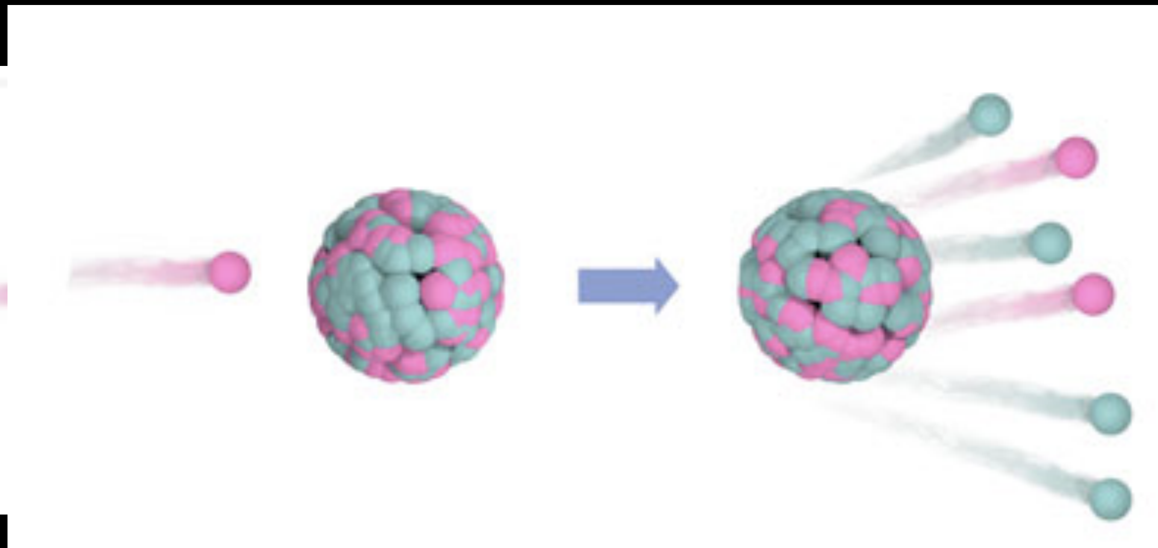
High Energy Proton Applications

GeV Proton Generation

Neutron source

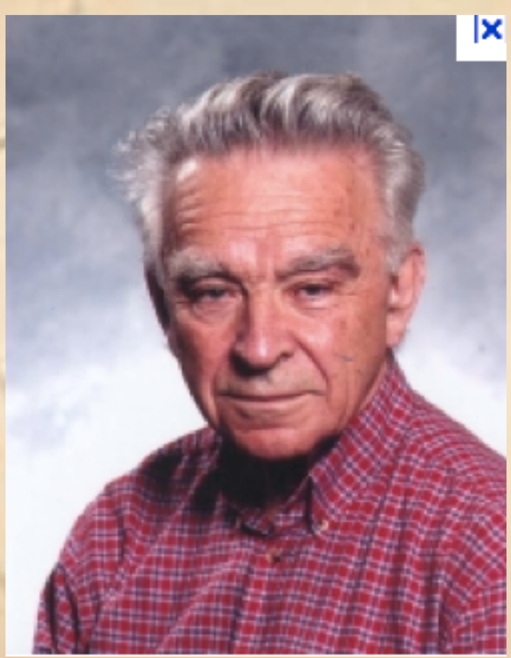


Subcritical Reactor

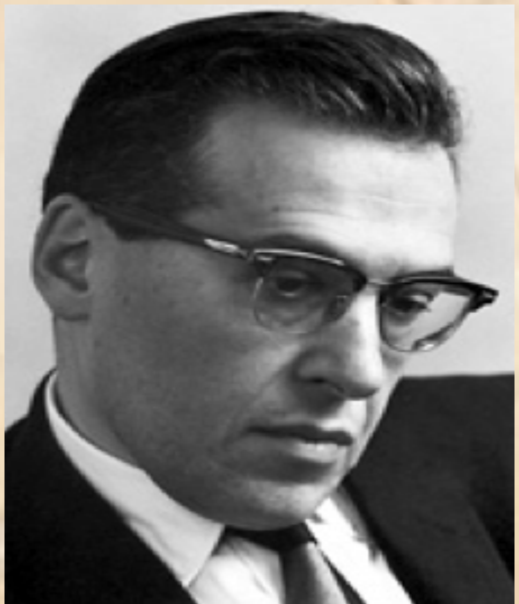


Extreme Light Societal Applications

Vacuum Polarization
Pair Generation
Vacuum breakdown



L. Keldish



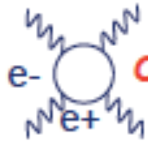
J. Schwinger

From N. Narozhny

Birefringence by QED in eV range

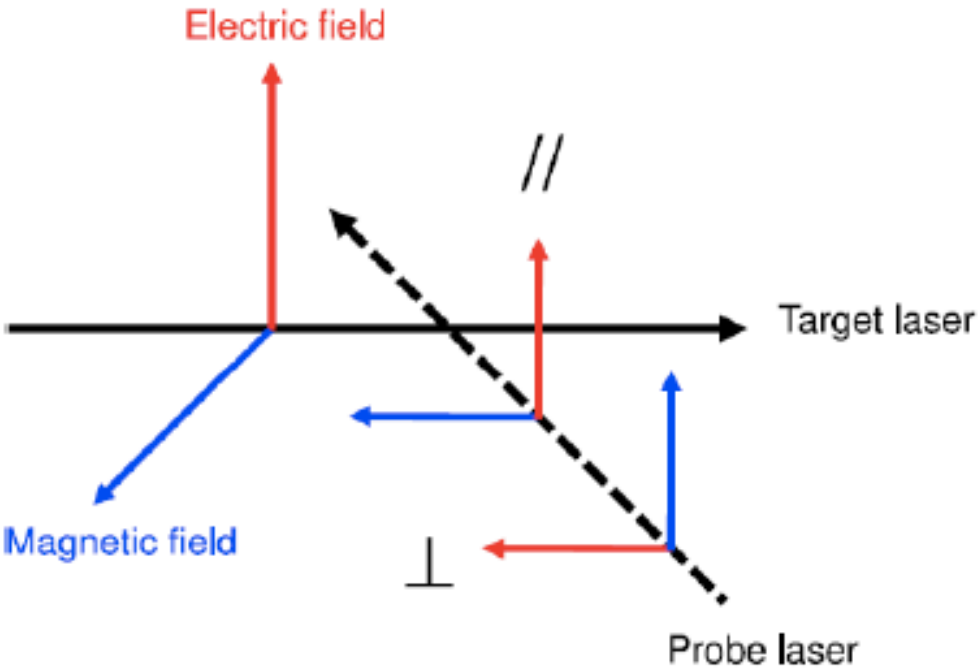
Euler-Heisenberg one-loop Lagrangian

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



$O(10^{-42}\text{b})$

Refractive index depends on polarizations



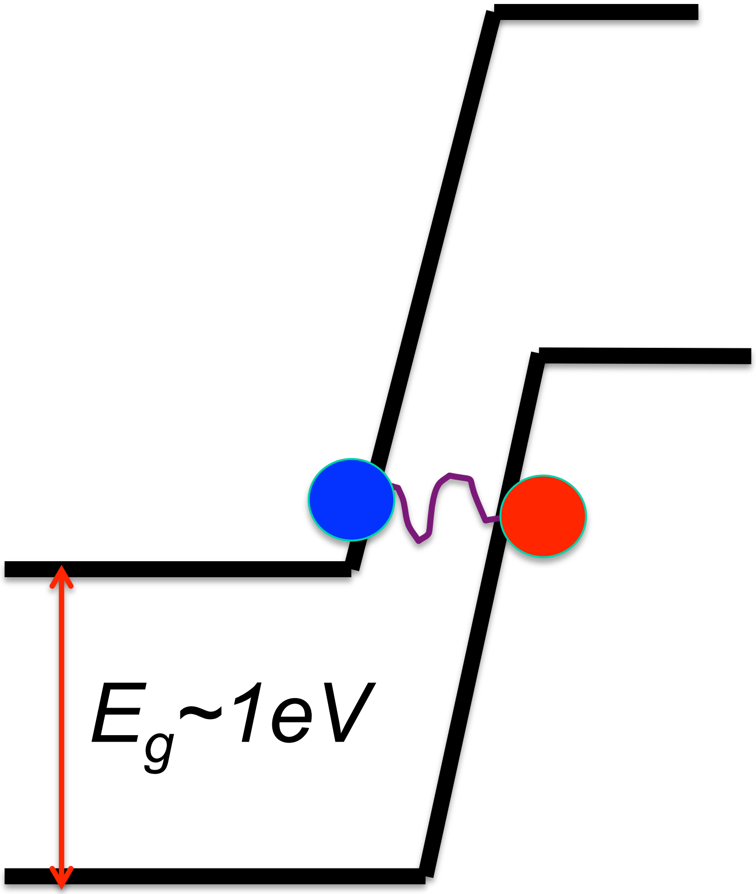
$$n_{\parallel} = 1 + \frac{16}{45}\frac{\alpha^2 U}{U_e}, \quad n_{\perp} = 1 + \frac{28}{45}\frac{\alpha^2 U}{U_e}$$

$$U_e = m_e^4 c^5/\hbar^3 \approx 1.42\text{x}10^6\ \text{J}/\mu\text{m}^3$$

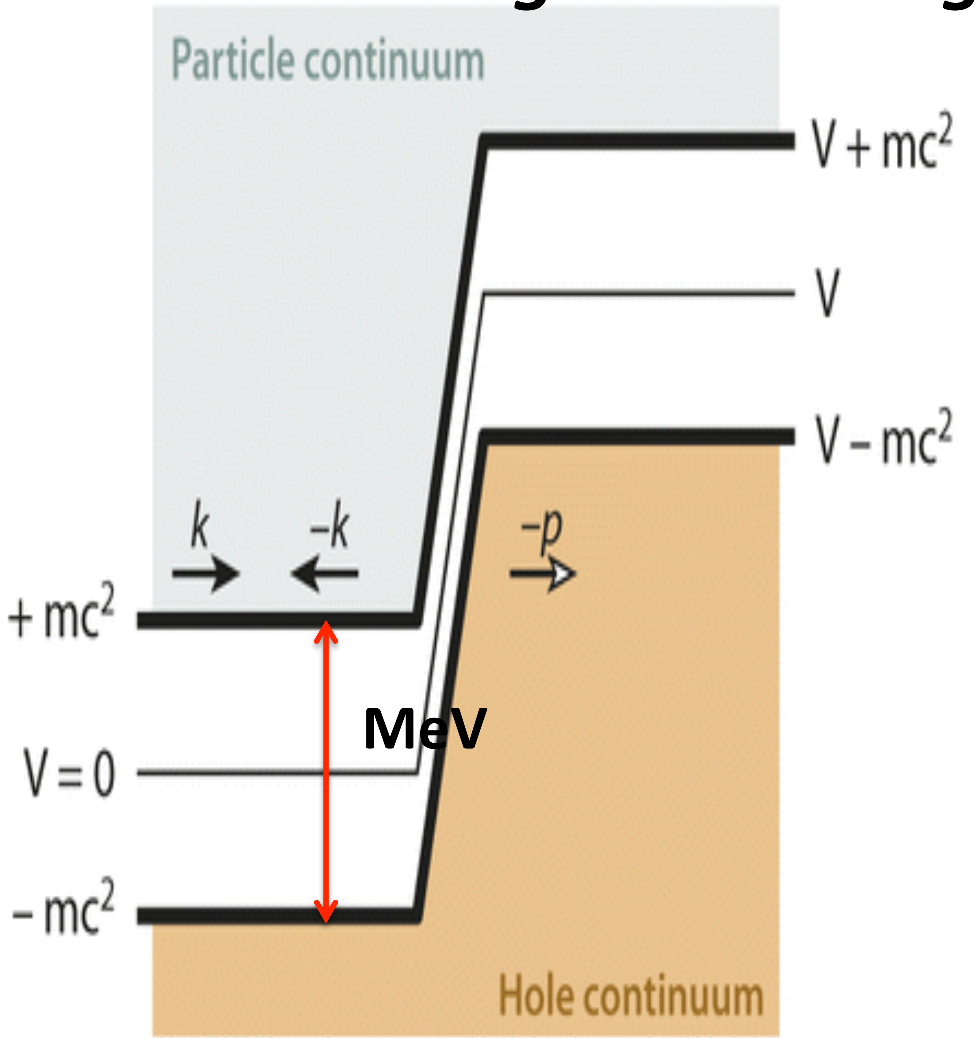
ELI(~200J per ~20fs) can reach $\Delta n \sim 10^{-9} \sim 10^{-10}$

(Homma, Habs, Tajima)

Keldysh Tunneling



Schwinger Tunneling



Keldysh Tunneling Hydrogen

$$W \propto \exp\left(-\frac{2}{3}\frac{E_a}{|E|}\right)$$

$$E_a = \frac{m^2 e^5}{\hbar^4}$$

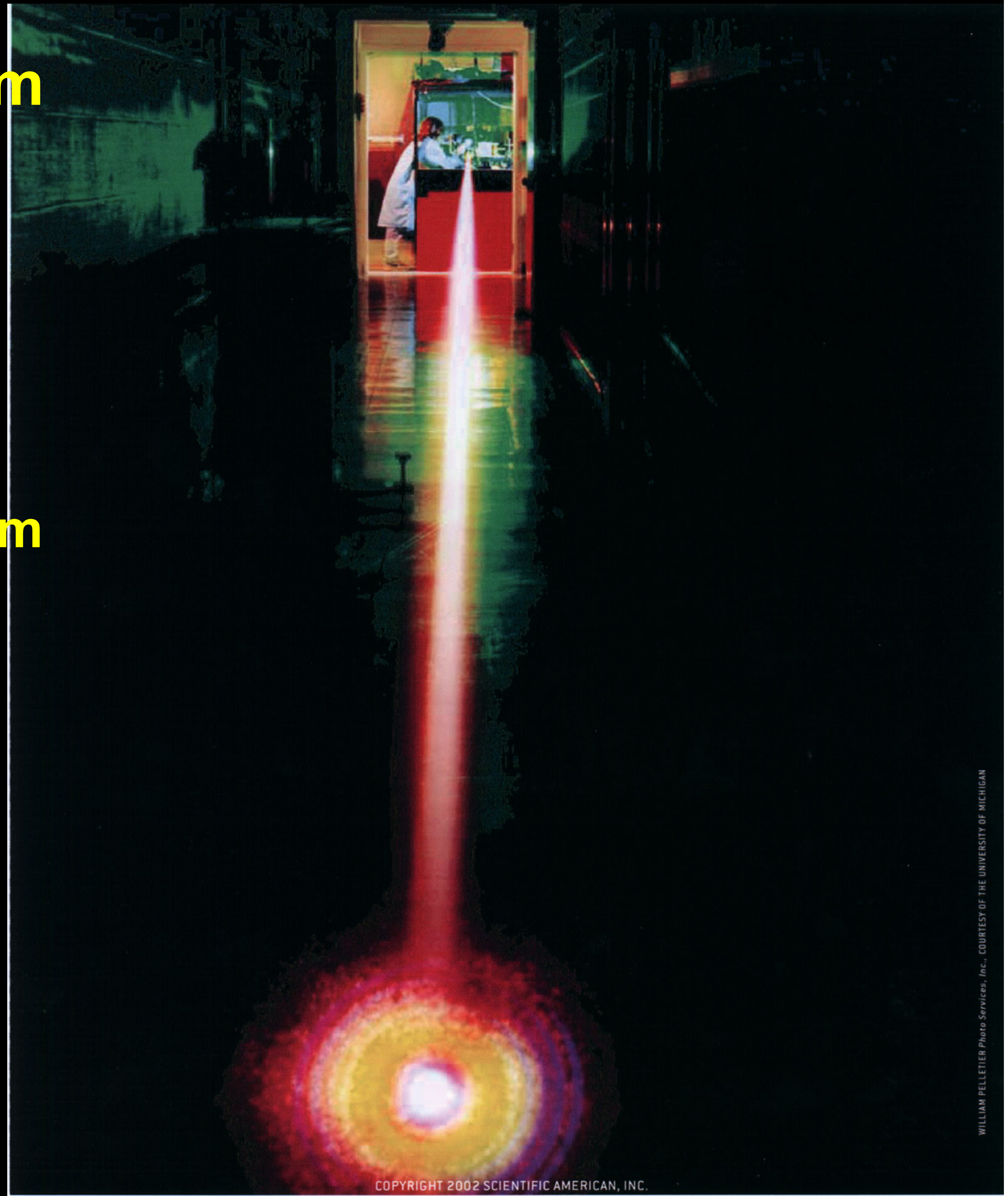
Schwinger Tunneling

$$W \propto \exp\left(-\frac{8E_s}{3E}\right)$$

$$E_s = \frac{m^2 c^3}{e\hbar}$$

$$\frac{E_a}{E_s} = \alpha^3 = \left(1/137\right)^3 \Rightarrow \frac{I_a}{I_s} = \left(1/137\right)^6 \approx 10^{13}$$

Nonlinear Filament in Vacuum



Critical Power Pc $= \lambda^2/n_2$

For zepto second pulse $\lambda = 10^{-10}$ **cm**

n_{2vac} 10^{-18} of $n_{2\ material}$

$Pc_{vac} = 10^{14}$ W

Size filament $=\lambda_{compton} = 10^{-10}$ cm

Energy per filament= 1 μJ

Extreme Light
Sub-critical Reactor
Transmutation of Nuclear Waste

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Science Technology

International
Year of Light
2015

Extreme Light Grand Challenges: Scientific and Societal Applications

Scientific Applications

Laser Astrophysics and Cosmology

Polarization of Vacuum, Materialization of Light

Beyond the Standard Model

Higgs Factory

Dark Matter

Societal Applications

Transmutation of Nuclear Waste

Under Critical Reactor

Nuclear Pharmacology

Proton Therapy

Orbital Debris Elimination by Deorbitation

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The Next Step: Solving the Laser Peak and Average Power Quandary

High Peak Power PW

High average power >100kW

High Repetition Rate 10kHz

Efficiency 30%

Single mode fiber can handle >10kW average Power

Coherent Amplifying Network

G. A. Mourou, D. Hulin and A. Galvanauskas, "The road to High Peak Power and High Average Power Laser: Coherent Amplification Network (CAN), AIP Conference Proceedings, Third International Conference on Superstrong Fields in Plasmas, vol. 827, Dimitri Batani and Maurizio Lontano, 152-163 (2006).

Study group sponsors by EC called ICAN to evaluate the concept mainly to try to decrease the number of fibers.

CAN Basic Brick
The Yb-doped Fiber (continued)

Yb:fiber transforms efficiently (70%) of low quality inexpensive ($10/W) light from a diode laser into a high quality single mode light with outstanding beam quality.

Fiber provides the highest beam quality with the highest laser efficiency.

The fiber can be precisely reproduced and pumped with 0.1% pump power precision/fluctuation

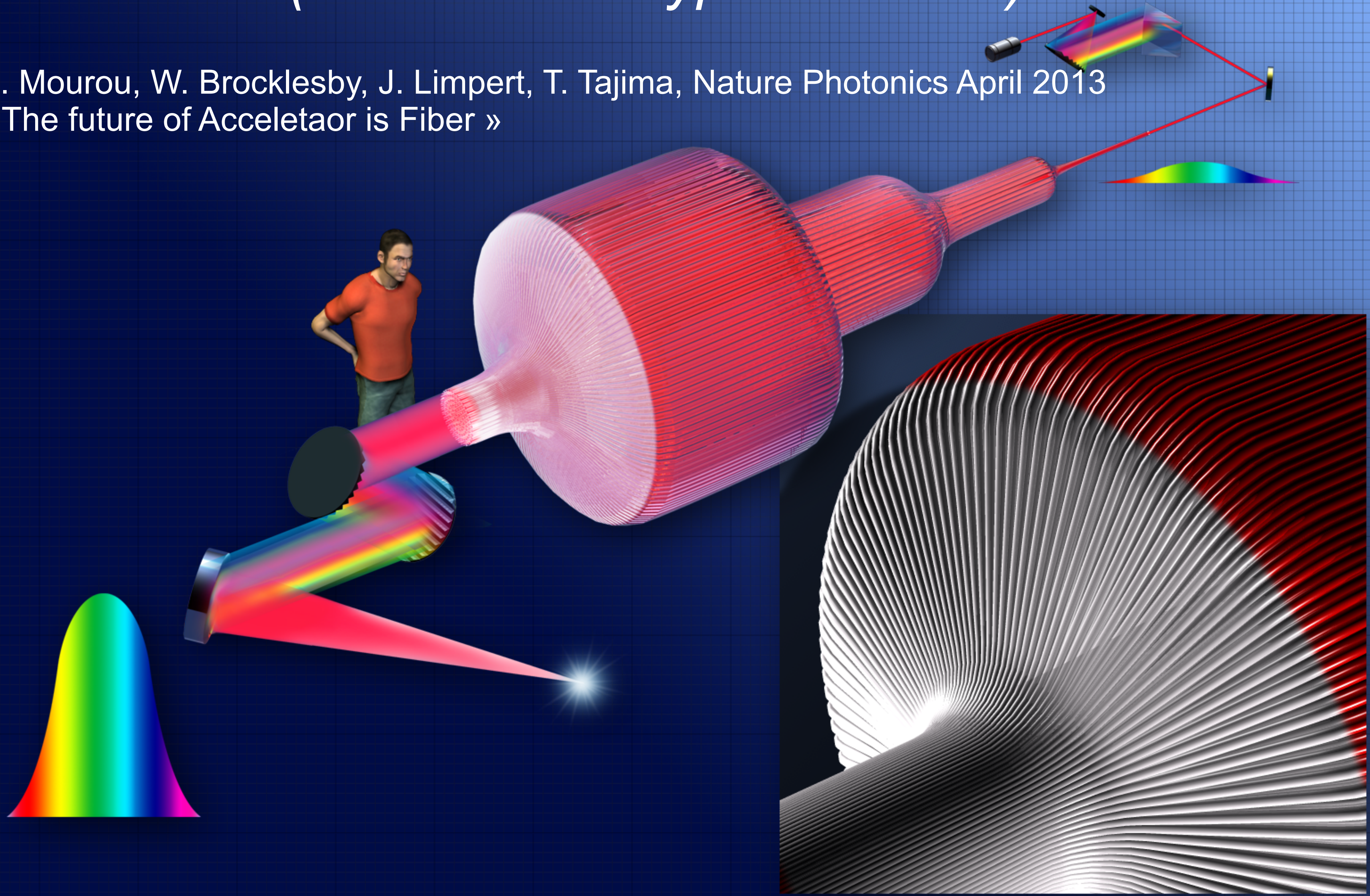
Single fiber can produce up to 2mJ, 200fs pulse with an average power ~ 800W, 40kHz (Jena Group)

A Phased-Fiber-Array emitting 50J, 50fs will be composed of 2 10^4 fibers.

Is it conceivable?

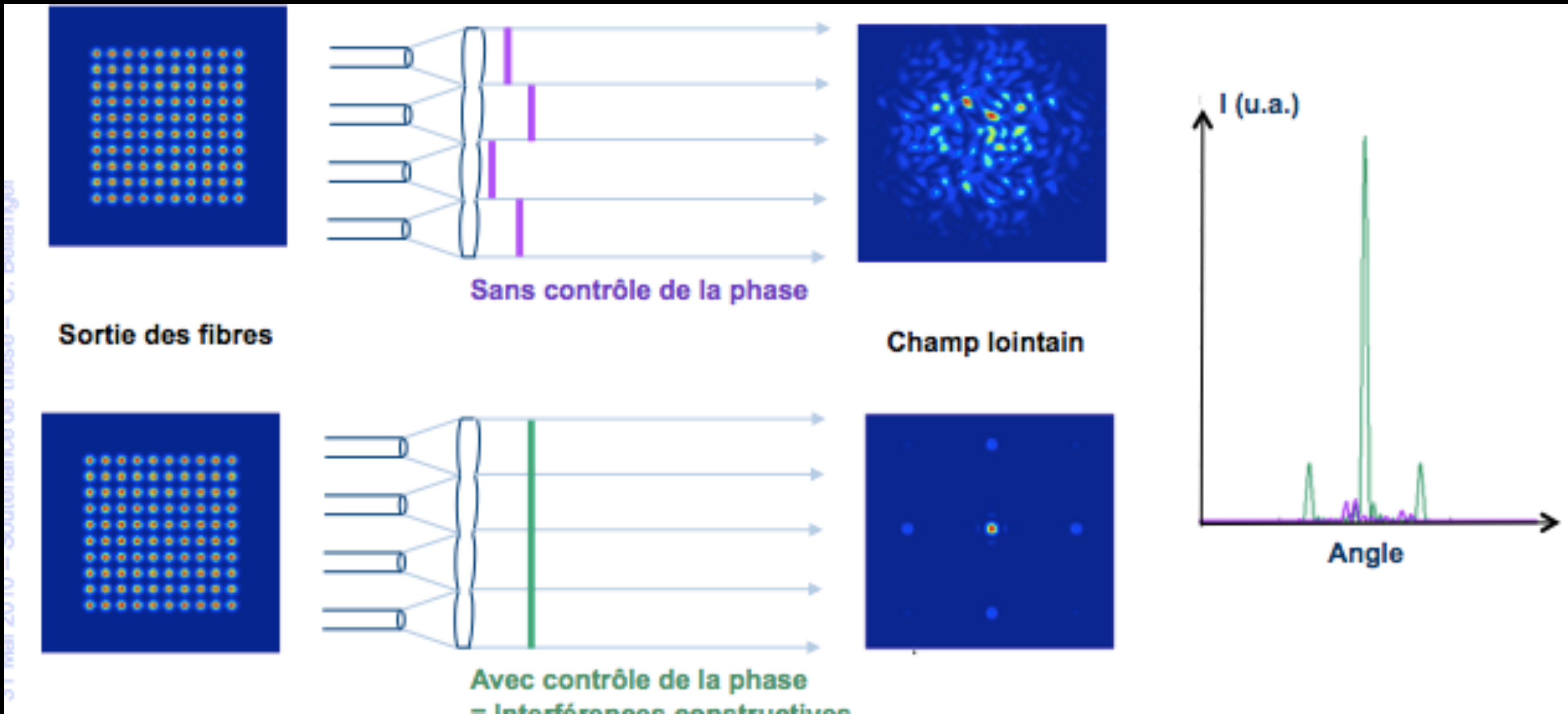
CAN Coherent Amplification Network
(X-CAN Prototype 61 fibers)

G. Mourou, W. Brocklesby, J. Limpert, T. Tajima, Nature Photonics April 2013
« The future of Acceletaor is Fiber »



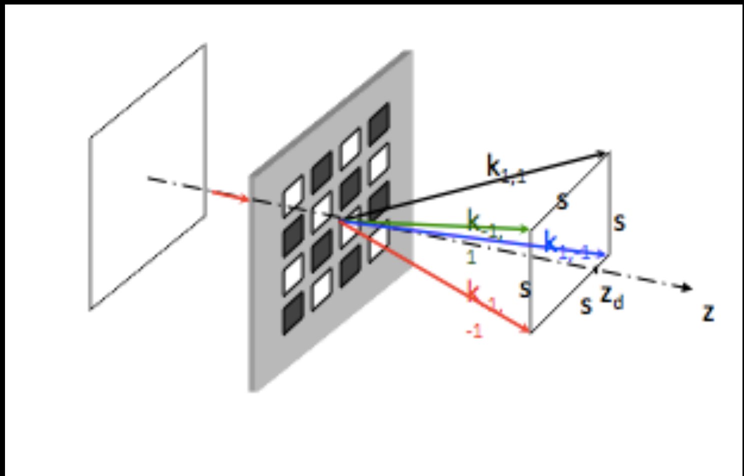
64 CW fibers have been phased

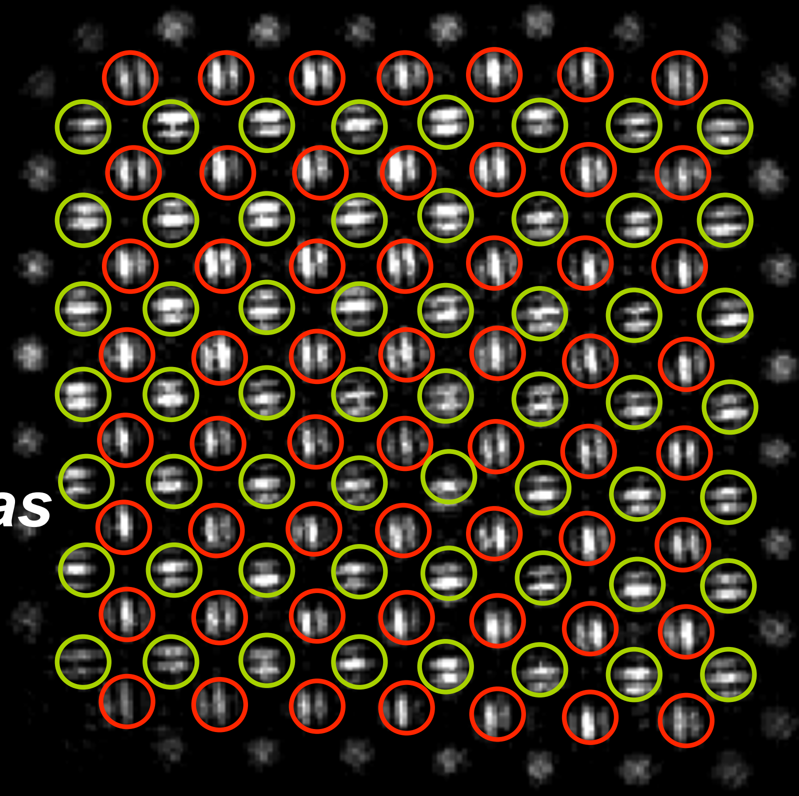
(This experiment in fact validates an extension possible to >10^4 phased fibers at 1kHz)



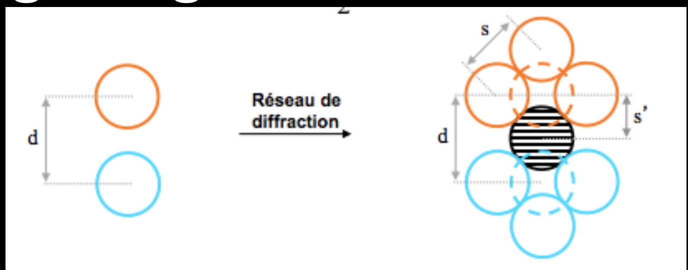
Coherent combining of 64 fibers with a Quadrilateral Shearing Interferometer (10^4 fibers with λ/60 precision at kHz)

1) Grating Making 4 replicas of each fiber





2) Neighbor fibers interfer with replicas Making fringes



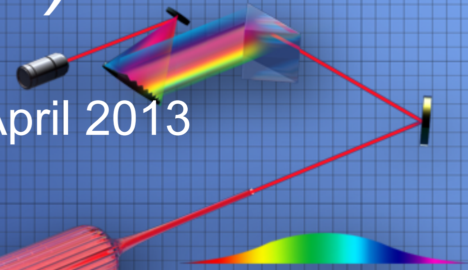
3) A phase map is captured every ms, making possible phase correction with phase modulator

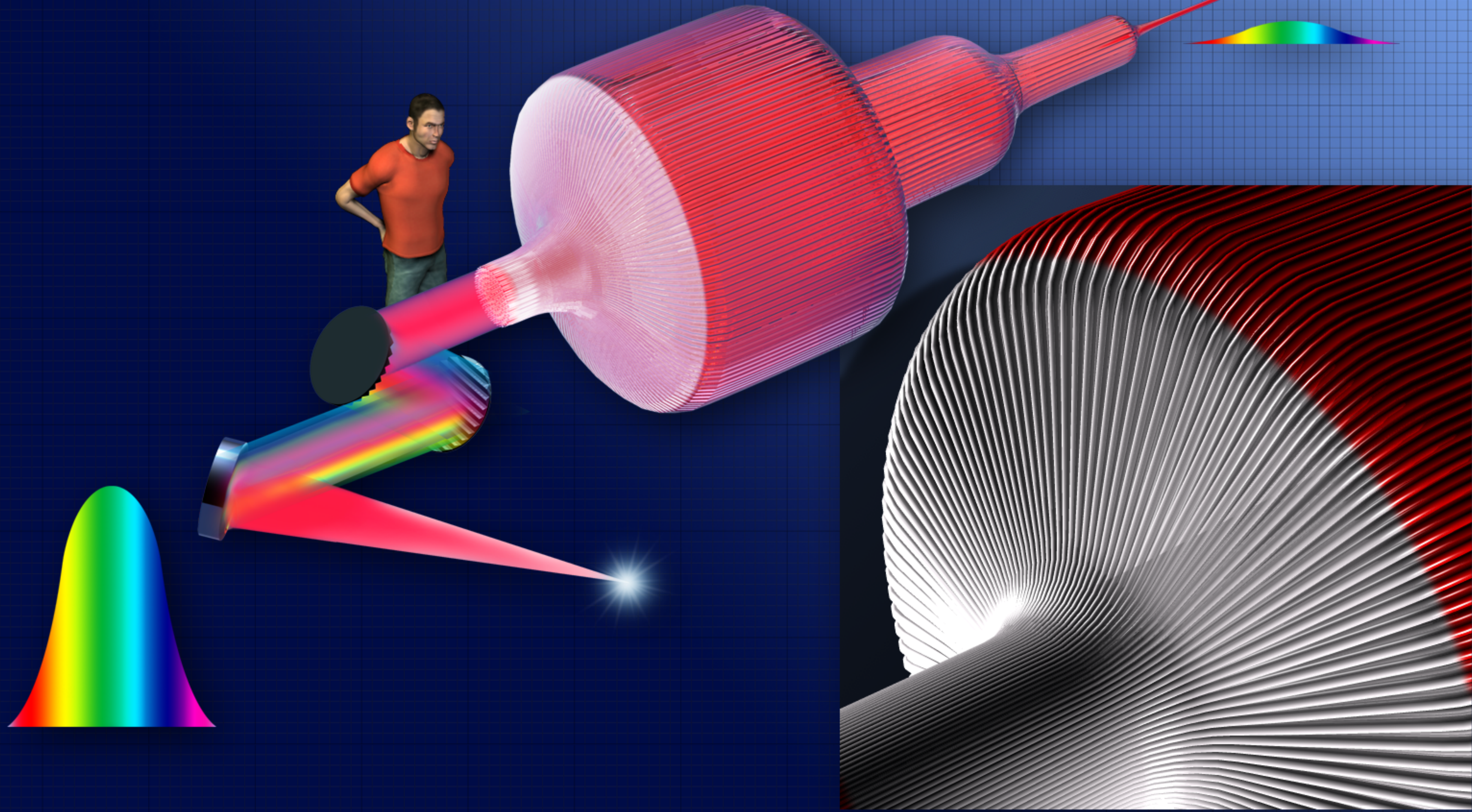
Only 6 pixels are necessary to λ/60 precision.

G. Mourou

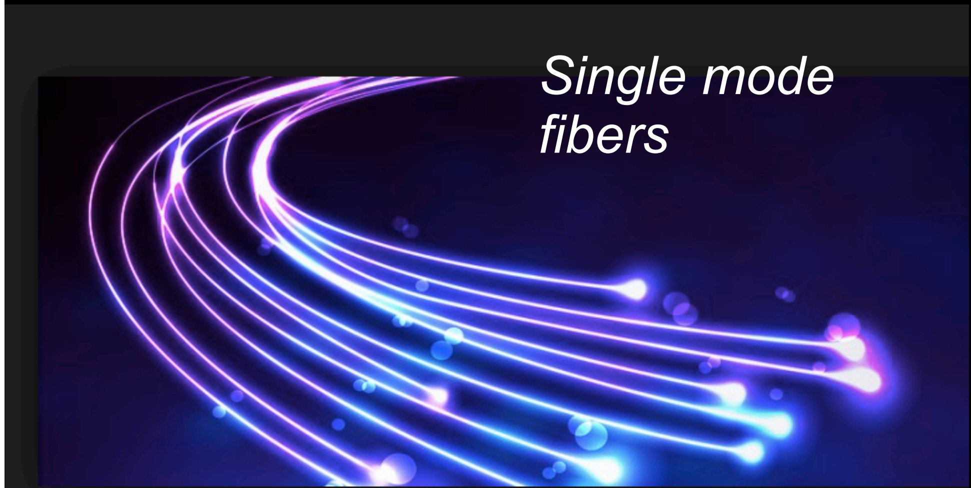
CAN Coherent Amplification Network
(X-CAN Prototype 61 fibers)

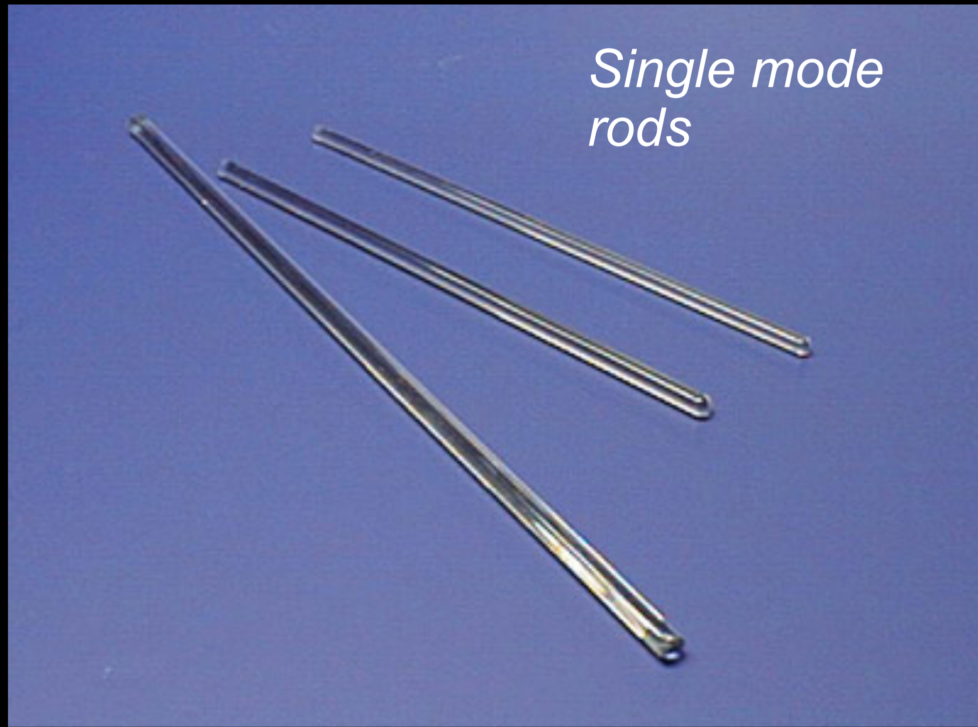
G. Mourou, W. Brocklesby, J. Limpert, T. Tajima, Nature Photonics April 2013
« The future of Acceletaor is Fiber »

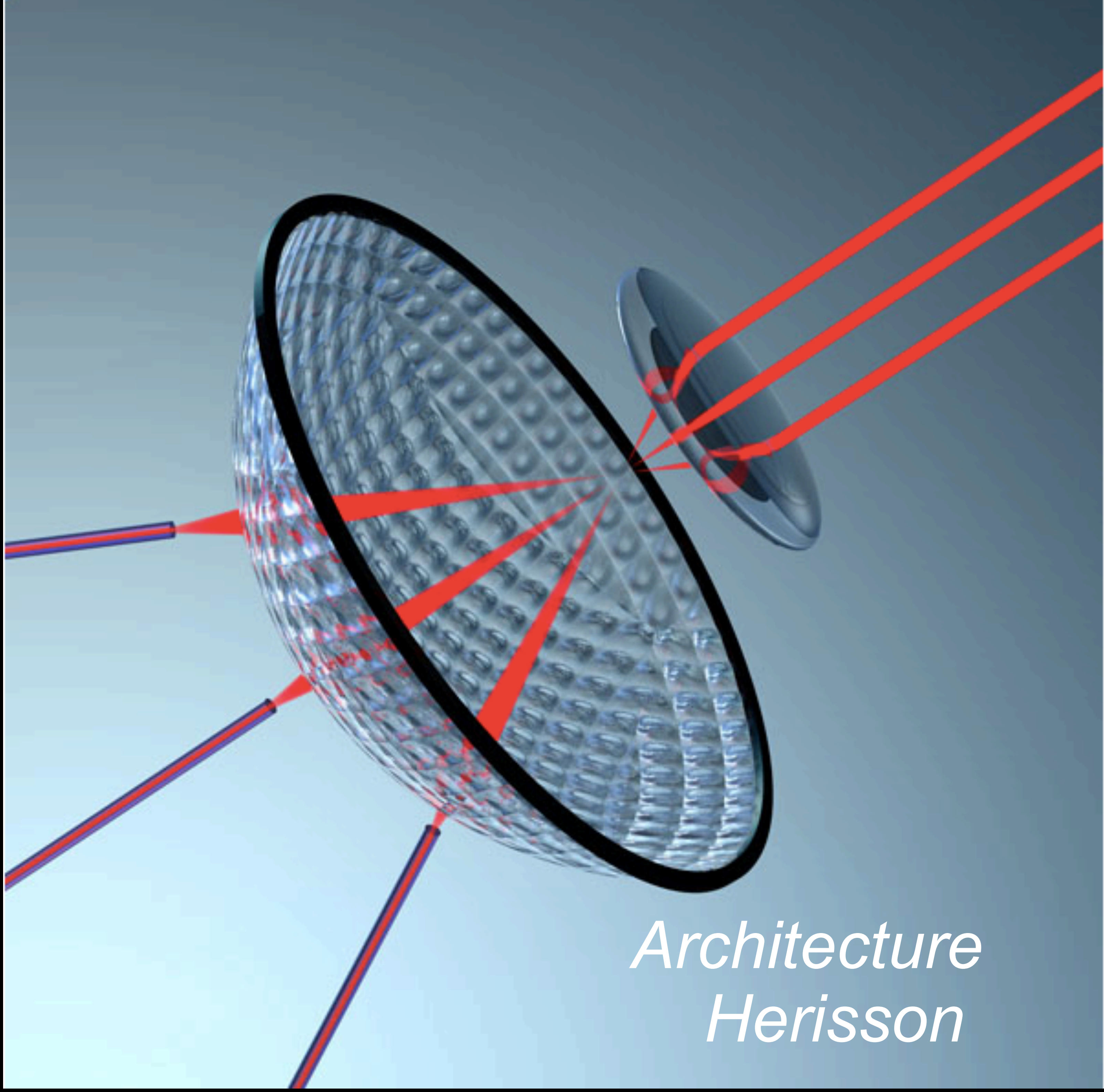


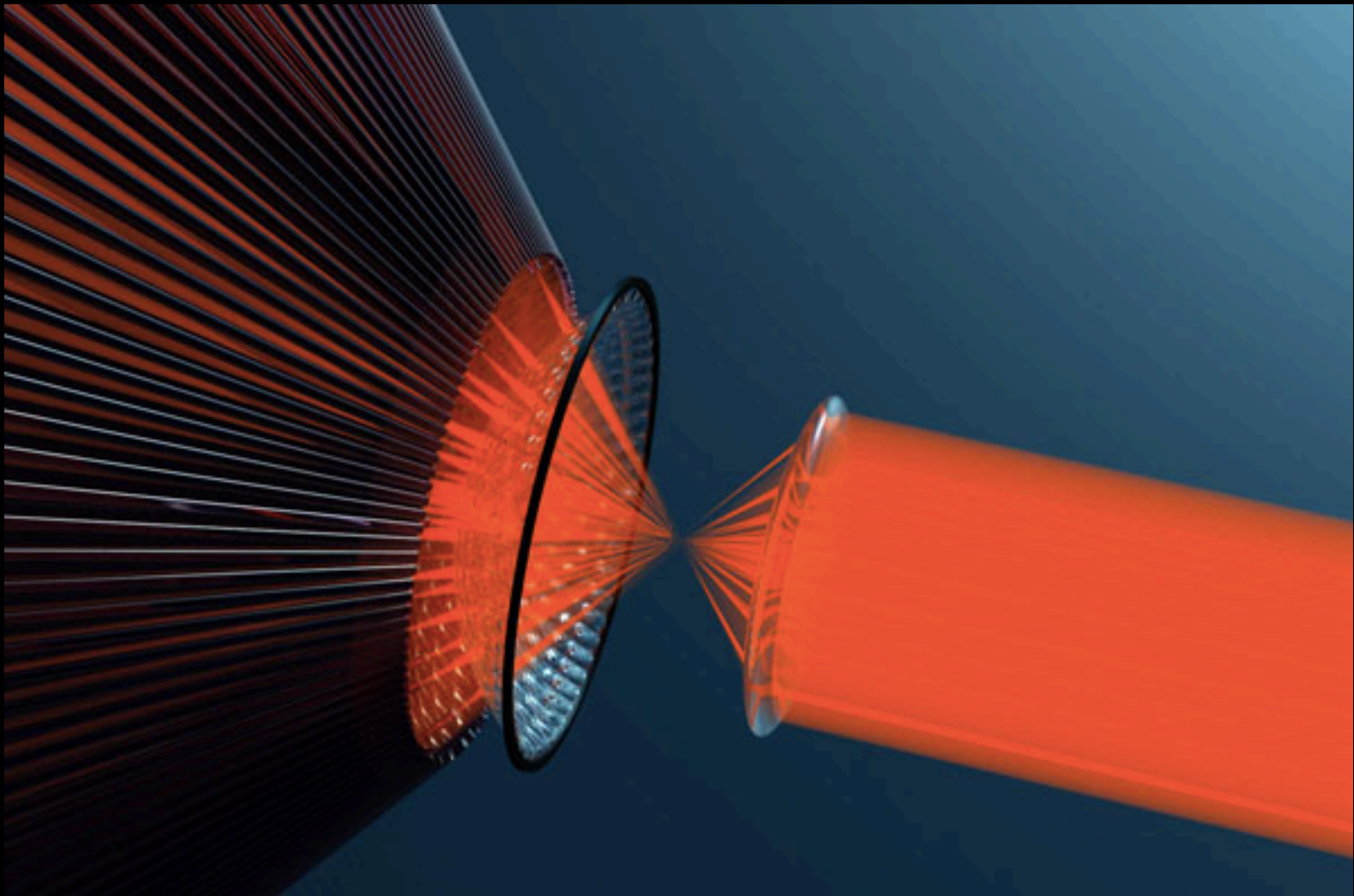


Moving from sub-mJ/ fiber to 10mJ /Rod

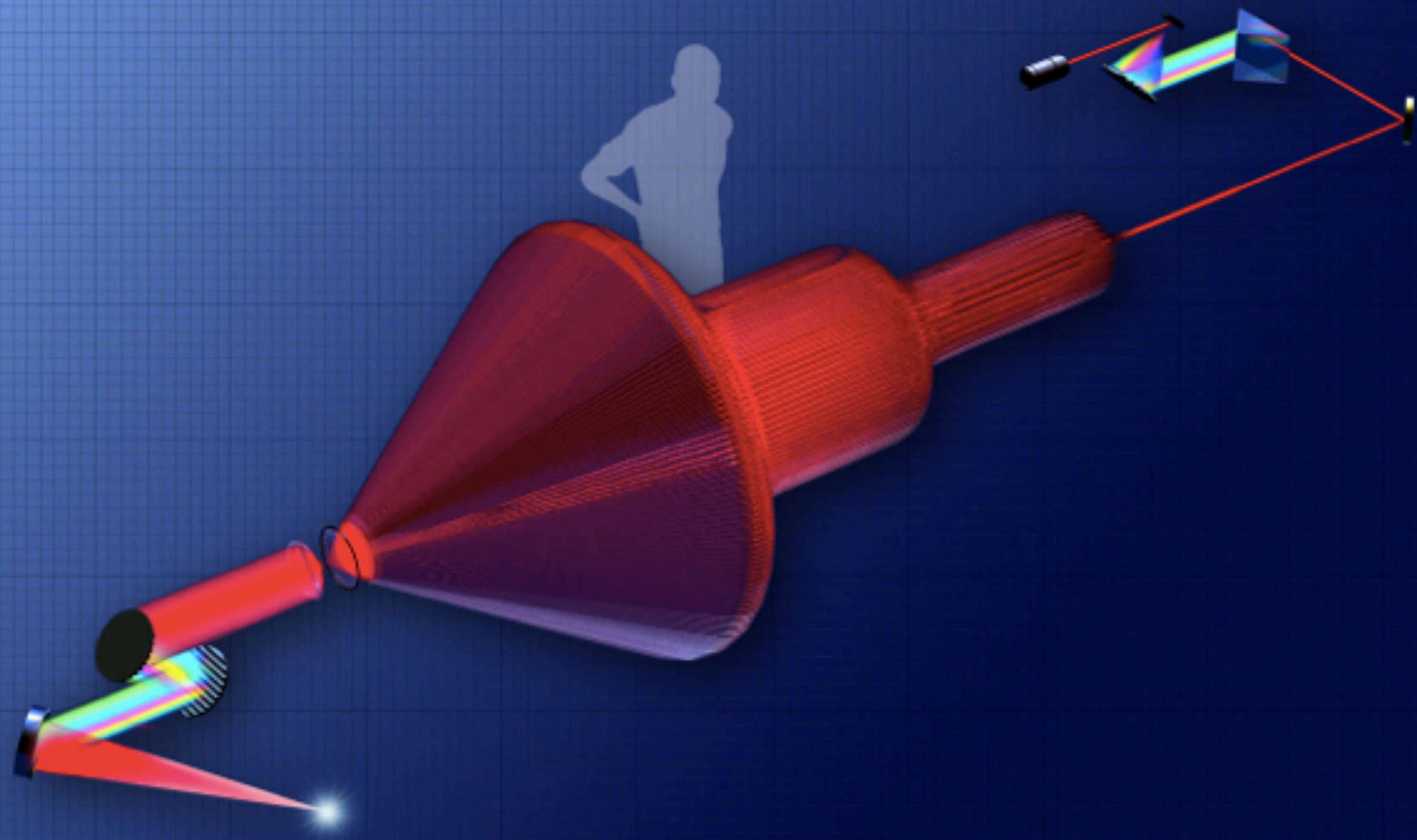





Architecture
Herisson



Coherent Amplification System Using Rod



After a ICAN study of 3 years the conclusions have been:

No simple way has been found to decrease the number of fibers without sacrifying: reliability, pulse quality, beam quality, simplifity, robustness, agility(bandwidth)

The initial design with 10^3 to 10^4 independent using Rods at few mJ/fiber can work at 1KHz and offers the unique properties :

The large number N of independent fibers(beams) makes possible:

1. superior beam quality, stability because of the number SQRT (N)
2. Provide flexibility pulse shape in time and space
3. superior beam pointing SQRT (N)
4. easy to align and maintain
5. it can work at kHz bandwidth.

A CAN system is heuristic at kHz. Ideally suited for multistage LWA, FEL, ….

Xcan

Coherent Amplification Network

POLYTECHNIQUE / THALES

From Prototype to Large Scale Applications

X CAN is an Ecole Polytechnique - Thales consortium to demonstrate that the CAN concept is capable to provide:

High Peak Power 100TW

High Average power in the 100kW

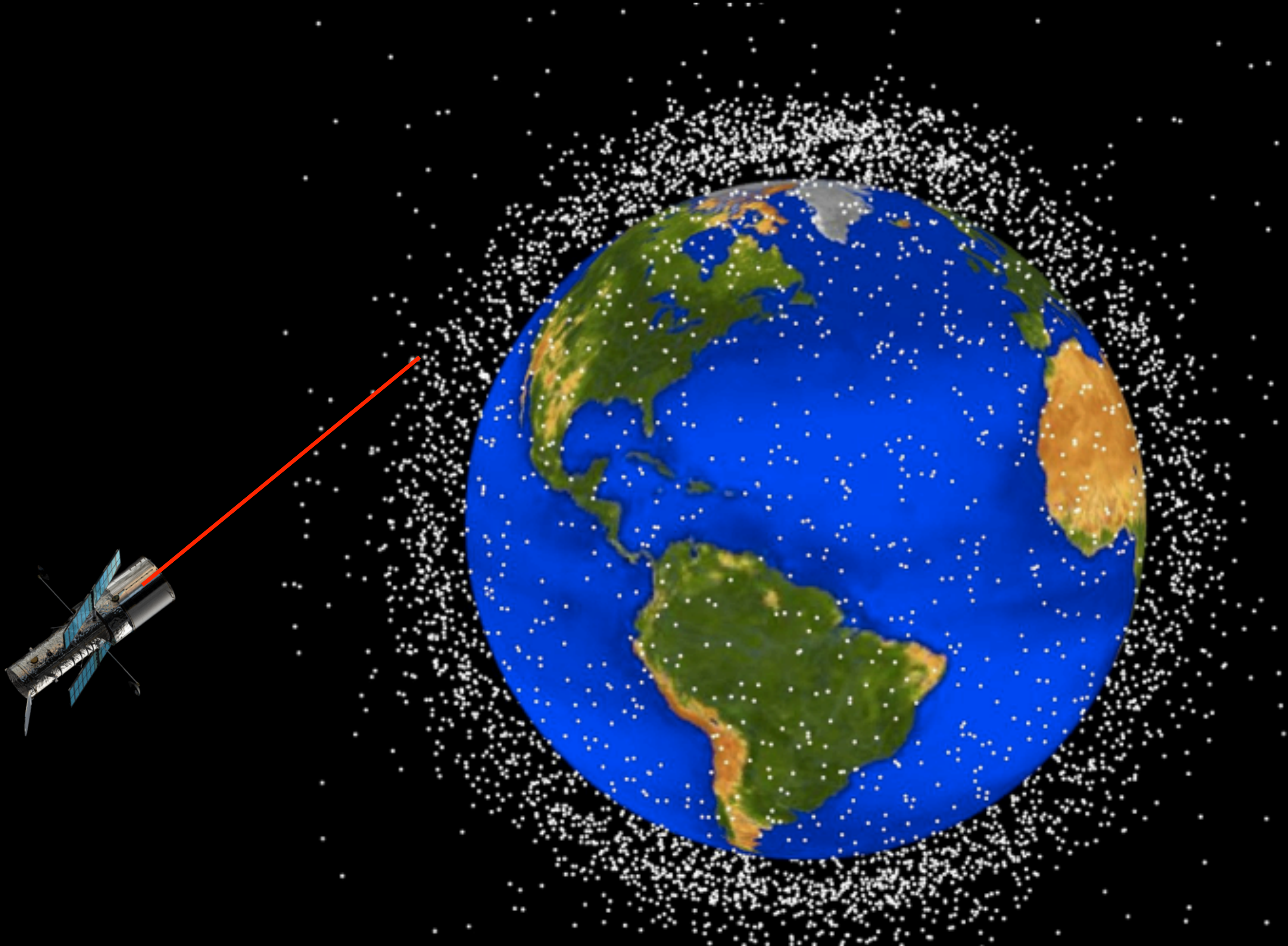
High Eficiency >30%

A budget of 3M€ has been allocated to build a 61 high energy fiber prototype that will validate the construction a 10^4 fiber unit for grand scale applications.

ICAN Space Debris

Millions of orbital debris are cluttering space

ark Quinn,Remi Soulard, G. Mourou, IZEST-EP



Mourou Korea 2014

Conclusion

F. Sinatra

'The Best is yet to come'.

Thank you

I ZEST
International Zeta-Exawatt
Science Technology

International
Year of Light
2015

Aknowledgements

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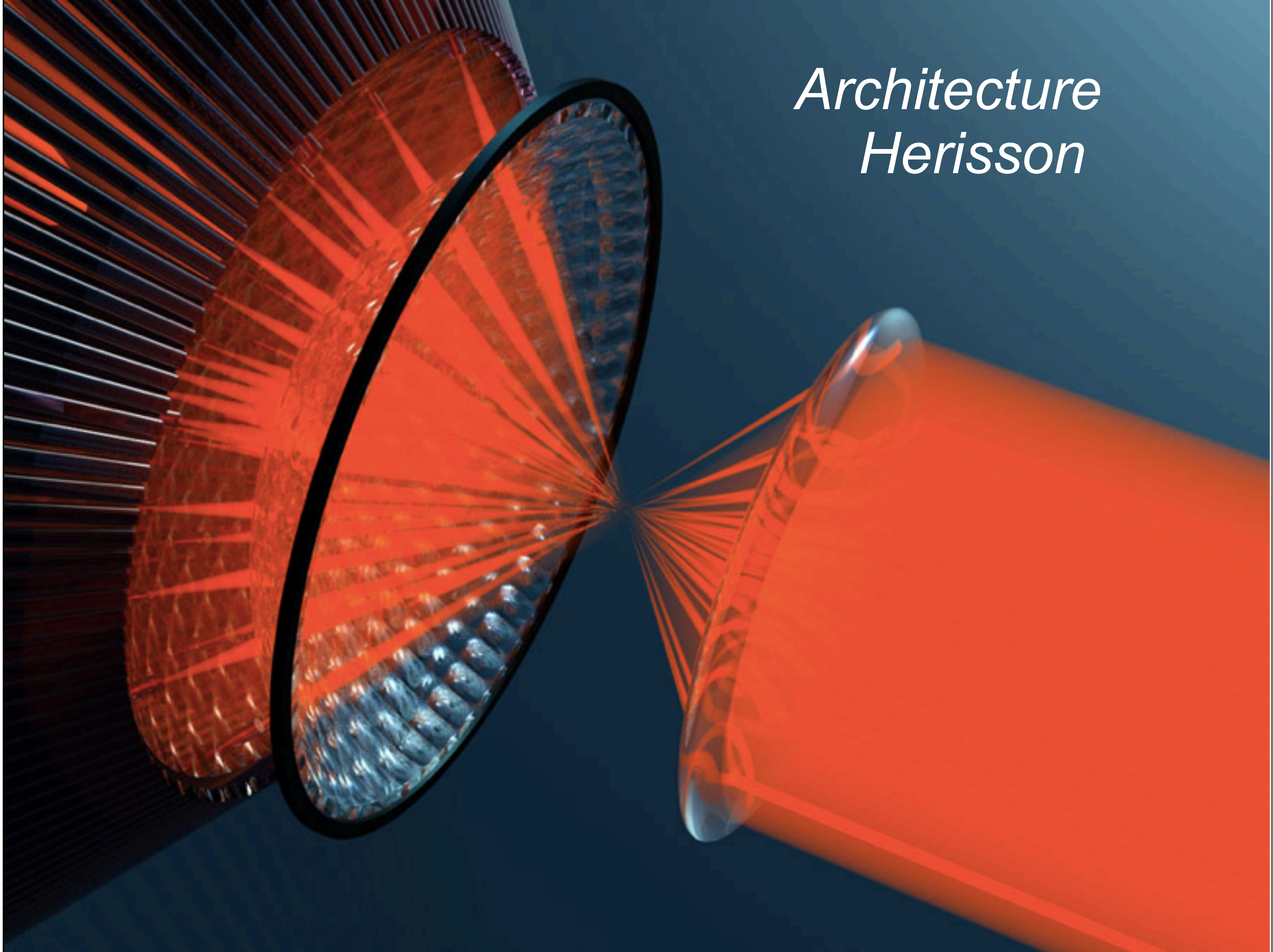

Architecture
Herisson

CAN Basic Brick
The Yb-doped Fiber (continued)

Yb:fiber transforms efficiently (70%) of low quality inexpensive ($10/W) light from a diode laser into a high quality single mode light with outstanding beam quality.

Fiber provides the highest beam quality with the highest laser efficiency.

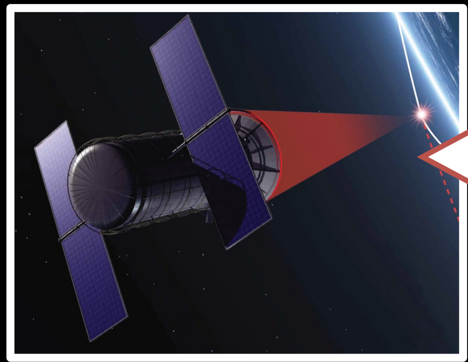
The fiber can be precisely reproduced and pumped with 0.1% pump power precision/fluctuation

Single fiber can produce up to 2mJ, 200fs pulse with an average power ~ 800W, 40kHz (Jena Group)

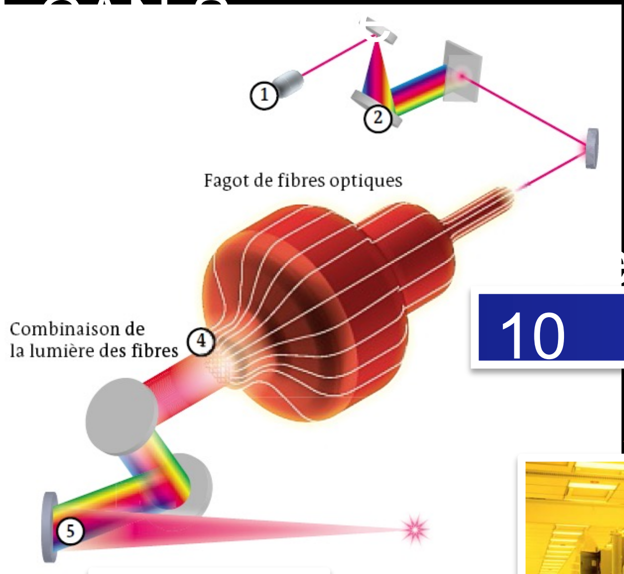
A Phased-Fiber-Array emitting 50J, 50fs will be composed of 2 10^4 fibers.

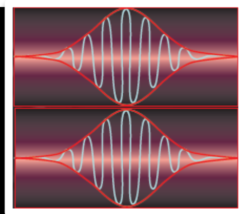
Is it conceivable?

Orbital debris removal



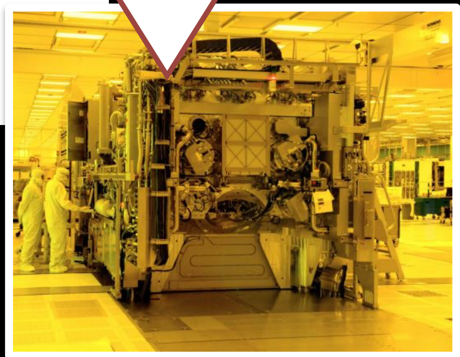
Particles Acceleration



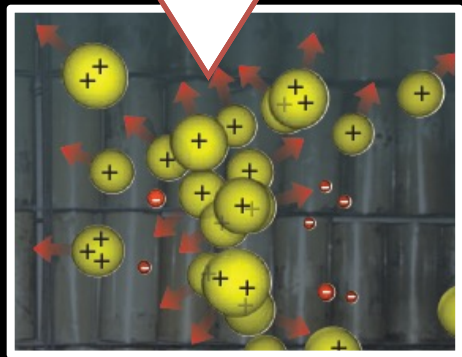


er number

10 100 1 000 10 000 100 00



XUV Photolithography



Chemical agent Neutralization

Nuclear waste transmutati


The Pressure of Light?
I = 10^23 w/cm^2
10 millions Eiffel Towers on the tip of your finger!
IZEST 2016
I ZEST
International Zeta-Exawatt Science Technology
22/02/17
International Year of Light 2015

Serendipity again!
Bridging Extreme Light and Space Applications

Thin Plastic/Glass Optical Elements Can Have Good Optical Quality And Nonlinear Properties.

Unlimited size and very low cost

. Polyethylene terephthalate 0.7mm, 1.5TW/cm², B=3-4

. Very large aspect ratio, surface over thickness, Unlimited aperture inexpensive.

. Uniformity within a fraction of λ .

se Noise Measurement with a Quadrilateral Shea Interferometer
(10^4 fibers with $\lambda/60$ precision at kHz)

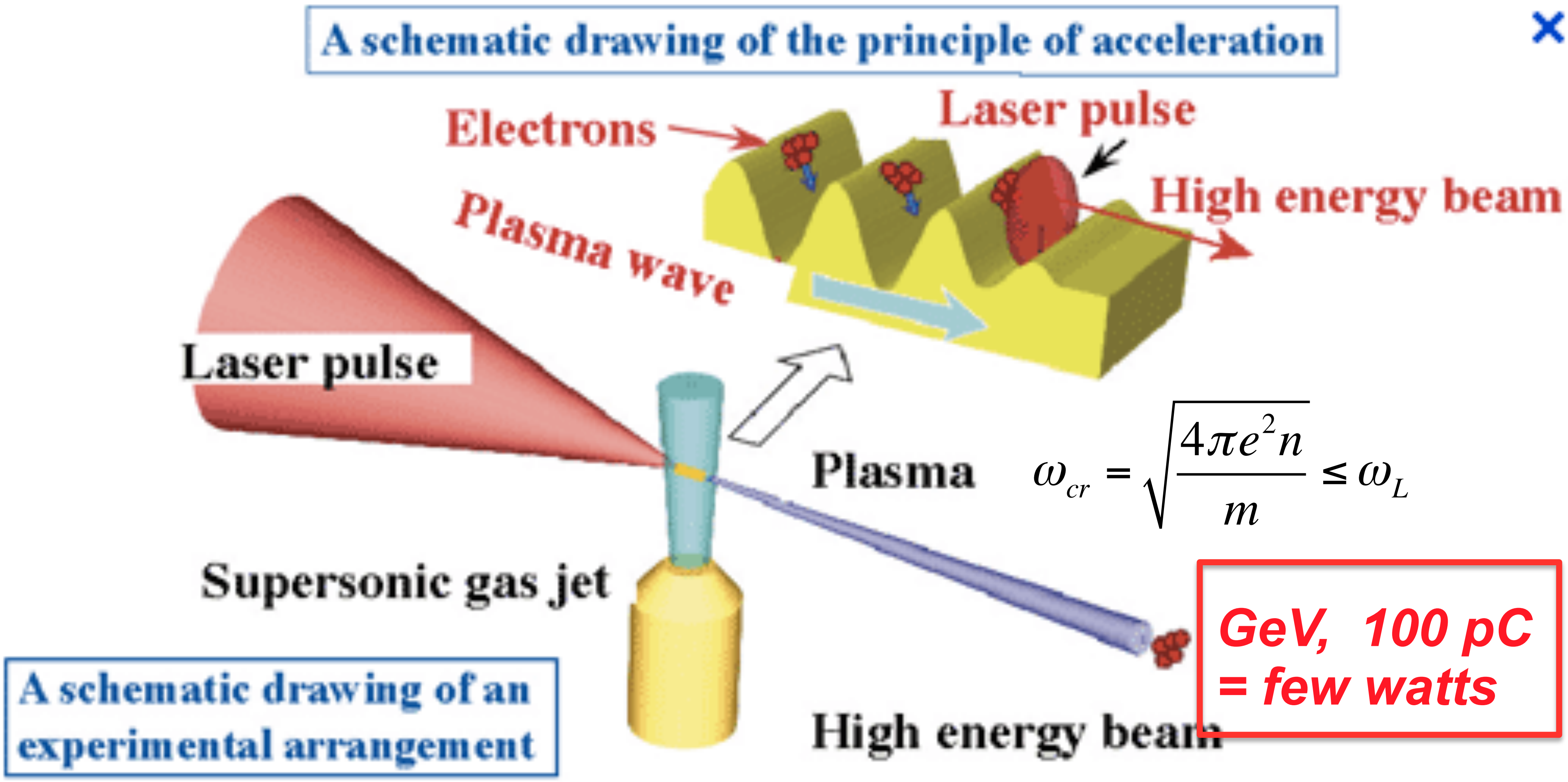
For 10^4 fibers , 6 pixels per fiber for a resolution of $\lambda/60$ @ 1kHz, off-the-shelf camera with 10^6 /1kHz are available.

Algorithm to control the phase distribution of fibers 40Gops Possible with a GPU.

G. Mourou

Laser Wake Field Acceleration GeV/cm

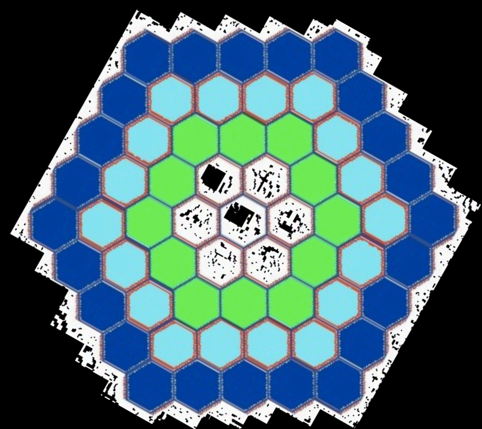
Tajima and Dawson 1979



$$\omega_{cr} = \sqrt{\frac{4\pi e^2 n}{m}} \leq \omega_L$$

GeV, 100 pC = few watts

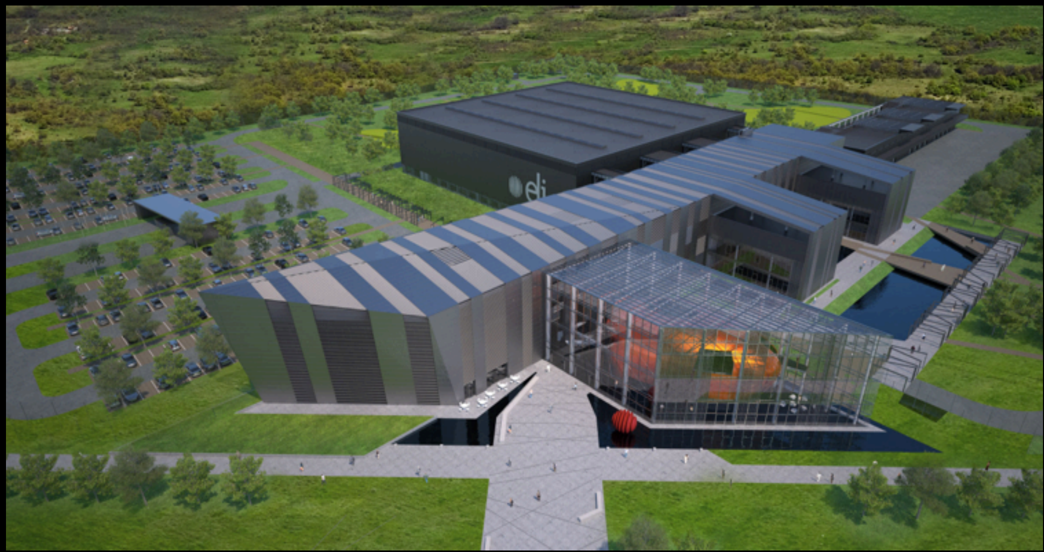
61 channels
350 fs
>10 mJ
50 kHz

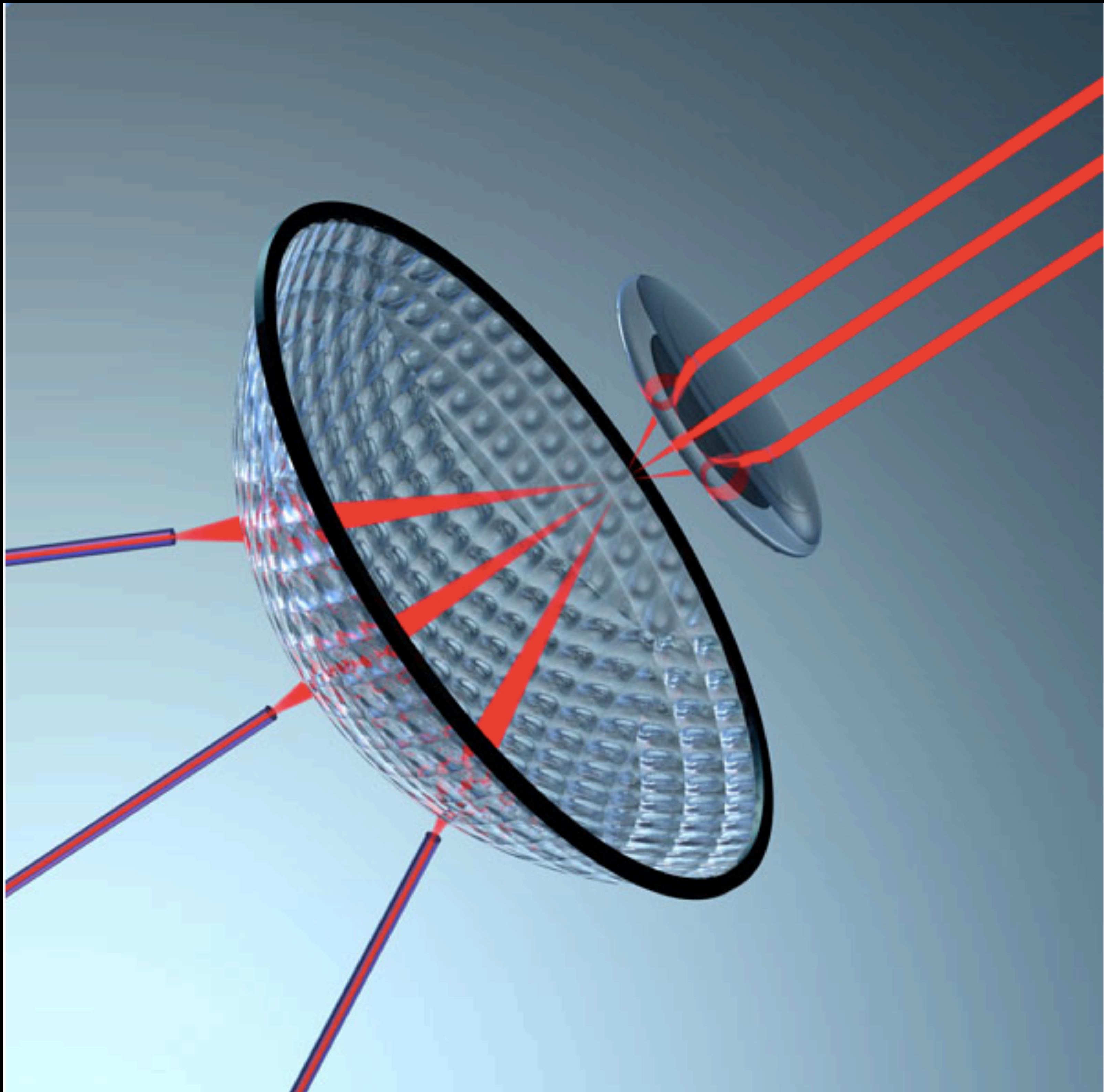


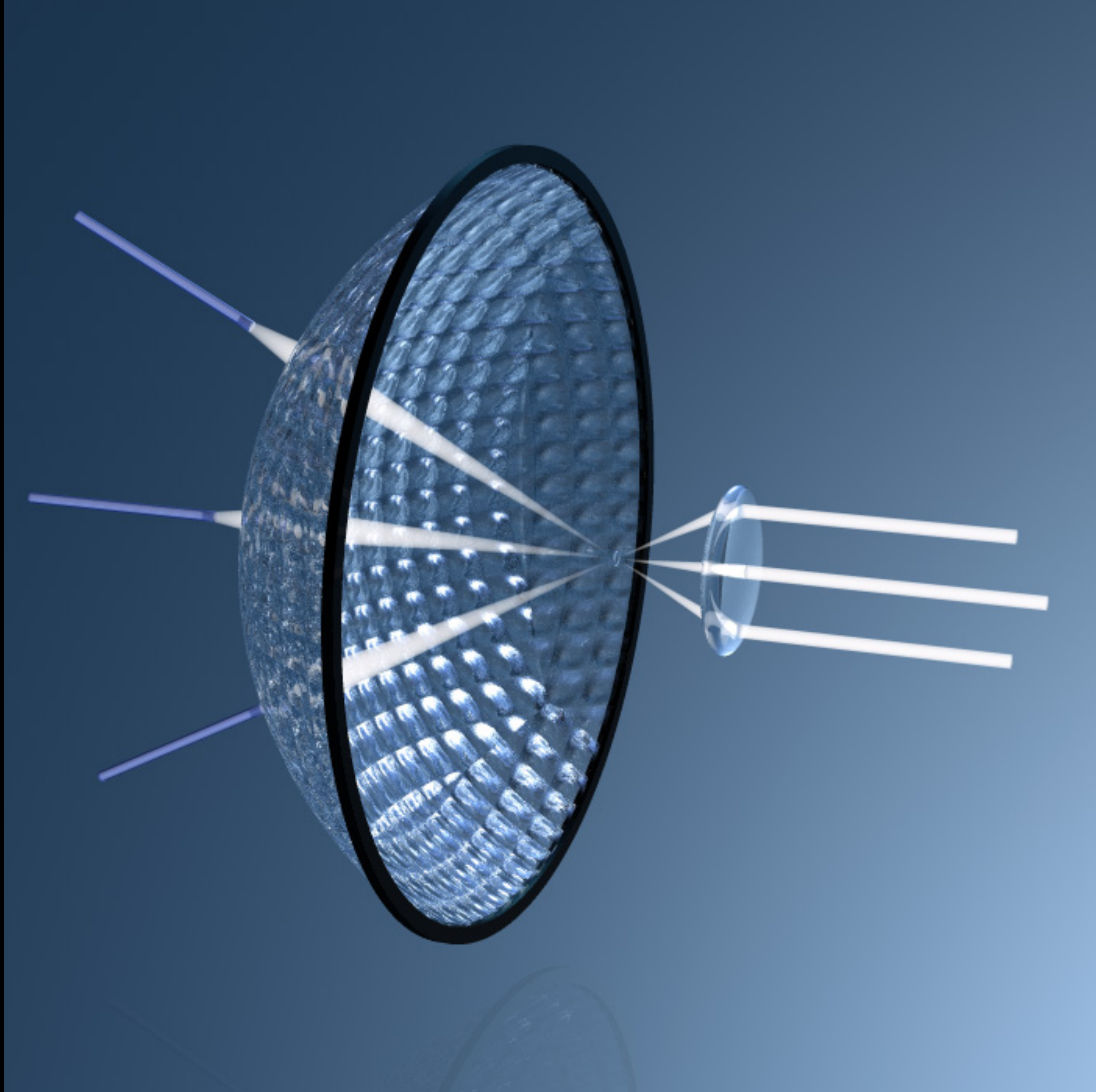
Where will the 4th Pillar be?

The 4th Pillar

Palaiseau (Apollon)
Nizny Novgorod (XCEL)
Kizu
Guanju
Shanghai
USA…Texas, MI. Ca,

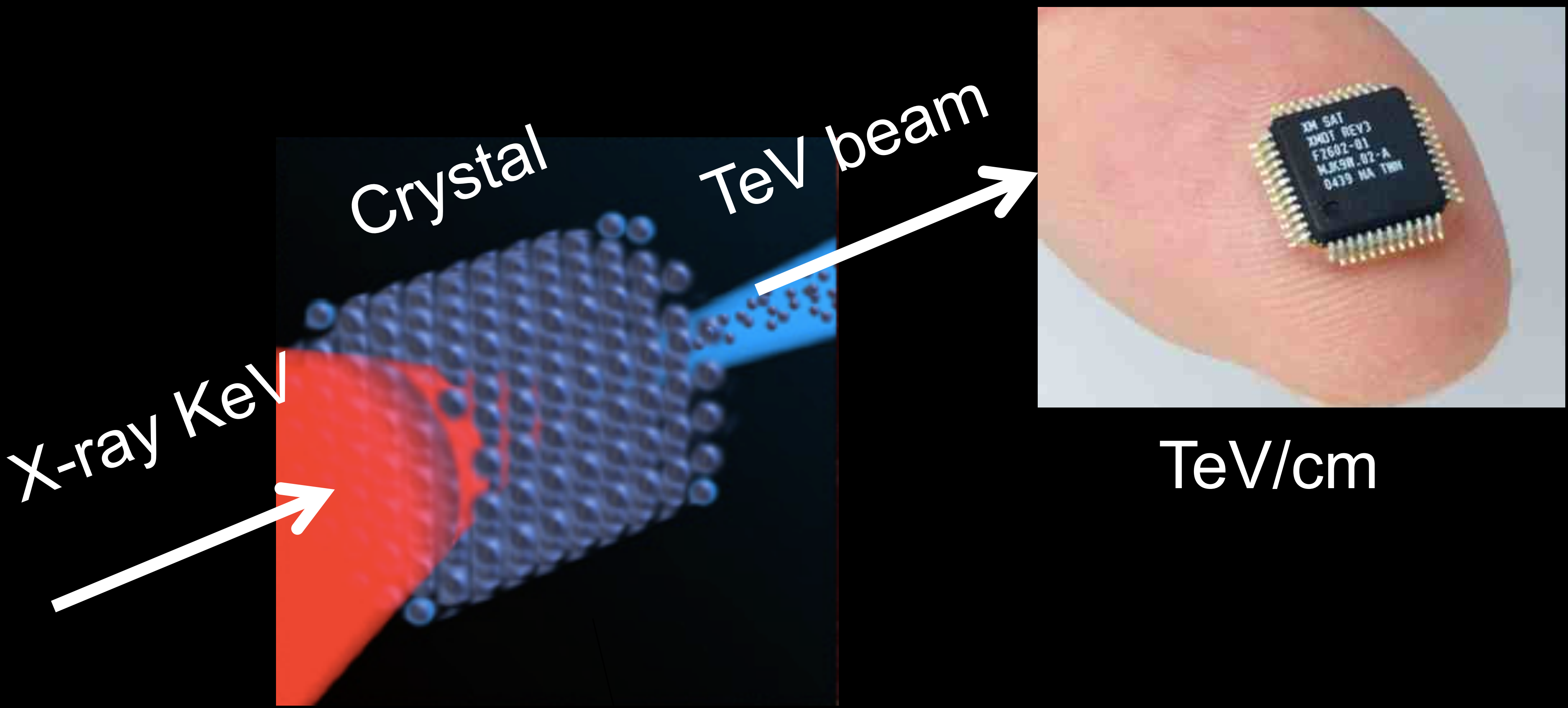






X-ray-Driven Crystal Accelerator

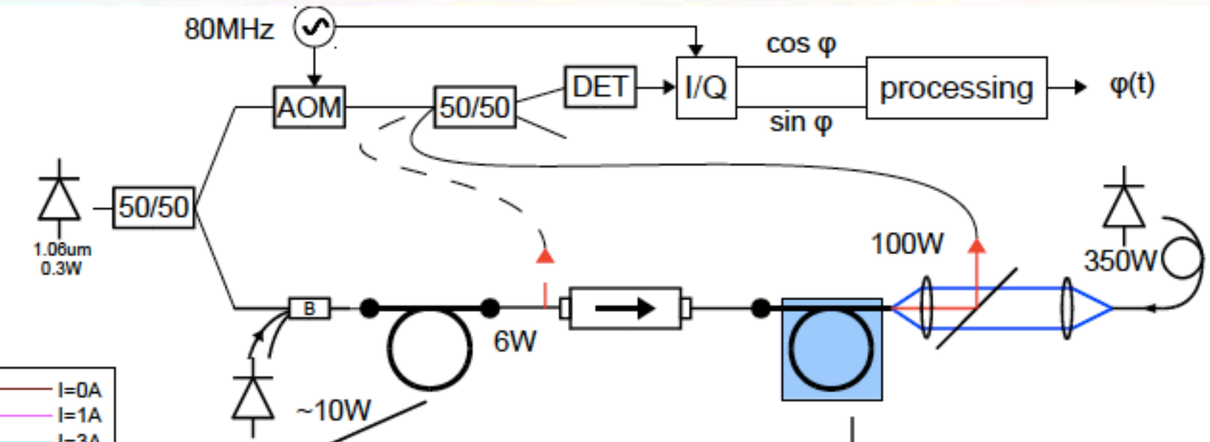
Increase of 10^6 in density
10^3 in Energy gain

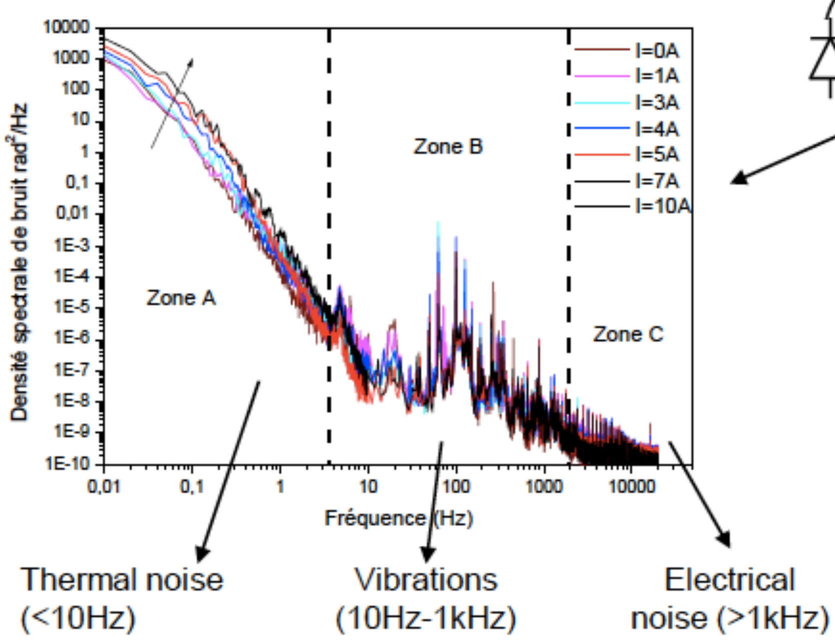


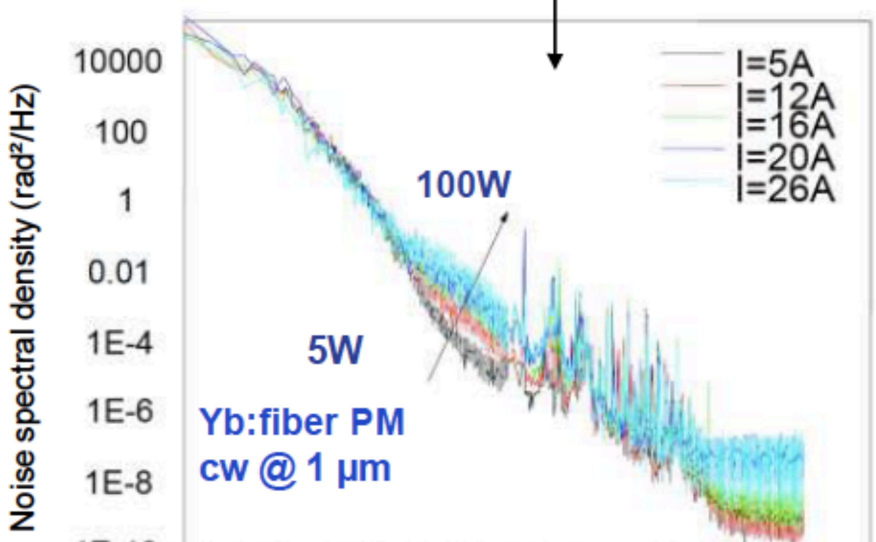
TeV/cm

ICAN
Sources of Phase Nois

What are the main sources of phase noise?







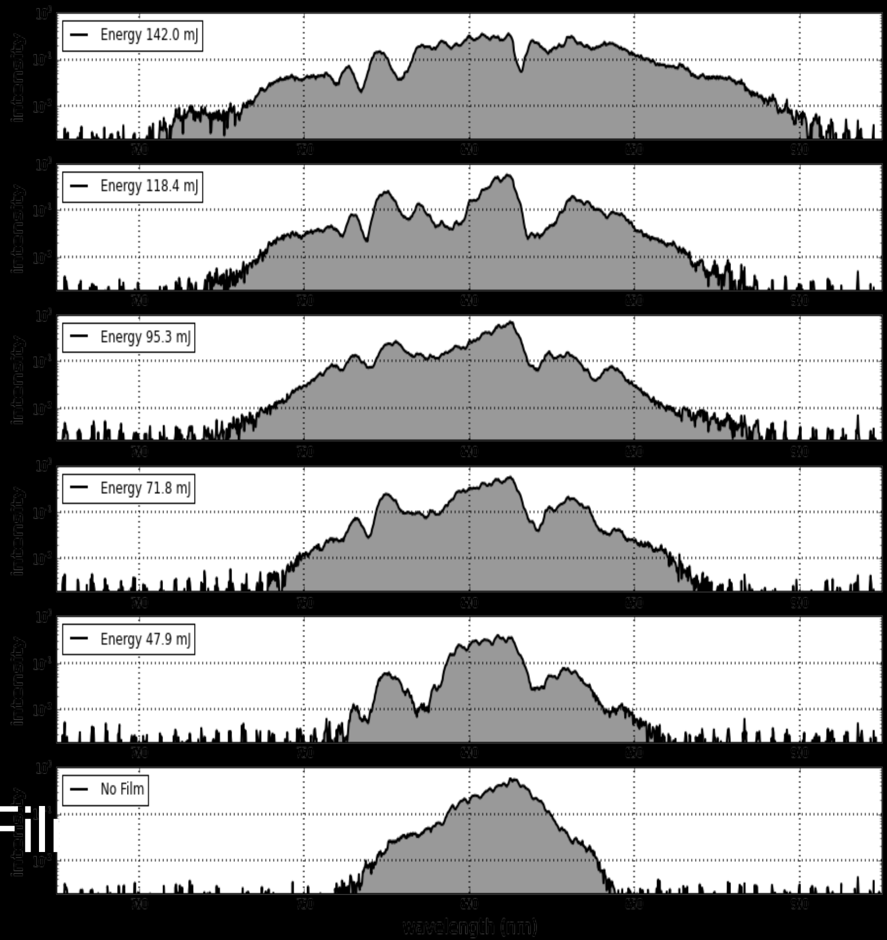
ICAN KOM

- Impact of high power -> mostly increase of thermal noise

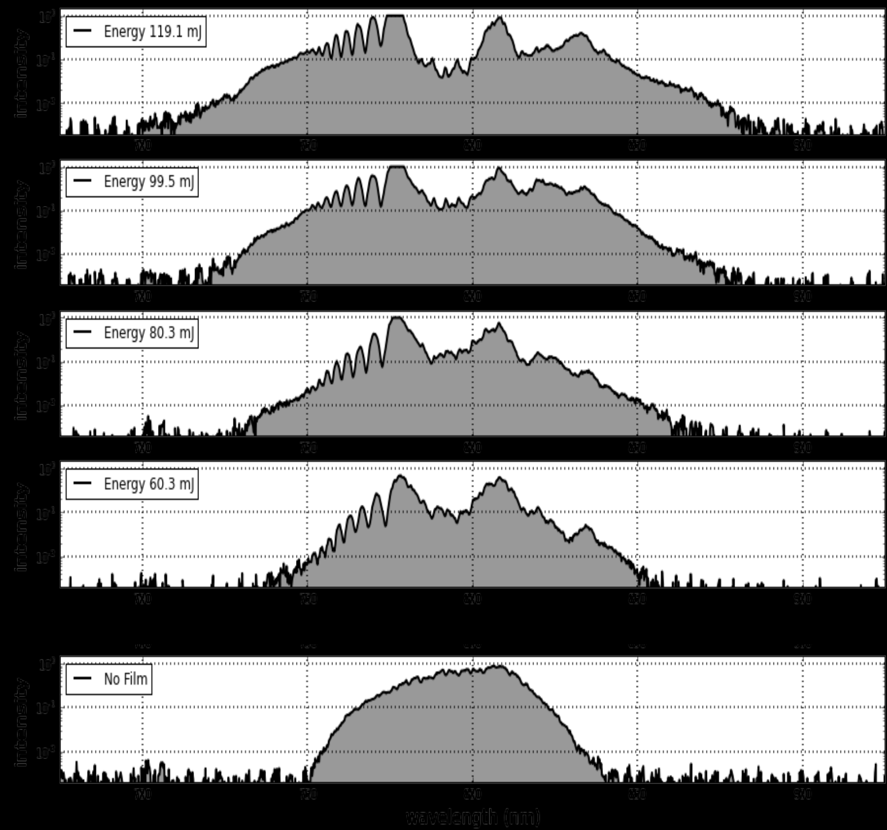
G. Mourou

Preliminary Experiment on PW CETAL (J. Wheeler et al)

Cellulose Acetate (0.5 mm)



PMMA (0.5 mm)



Intensity

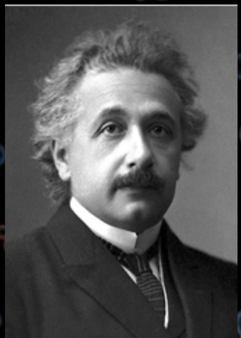
No Fil

Vacuum is not nothingness but is full of activity i.e Quantum Fluctuations

Fritz Sauter

Werner Heisenberg

Julian Schwinger

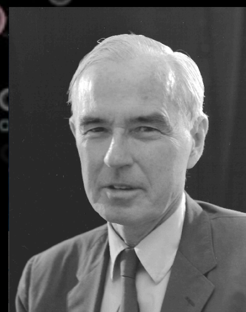


A. Einstein

H. Casimir

L. Hertz

J. Maxwell



W. Lamb

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