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CERN
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Plasma Acceleration

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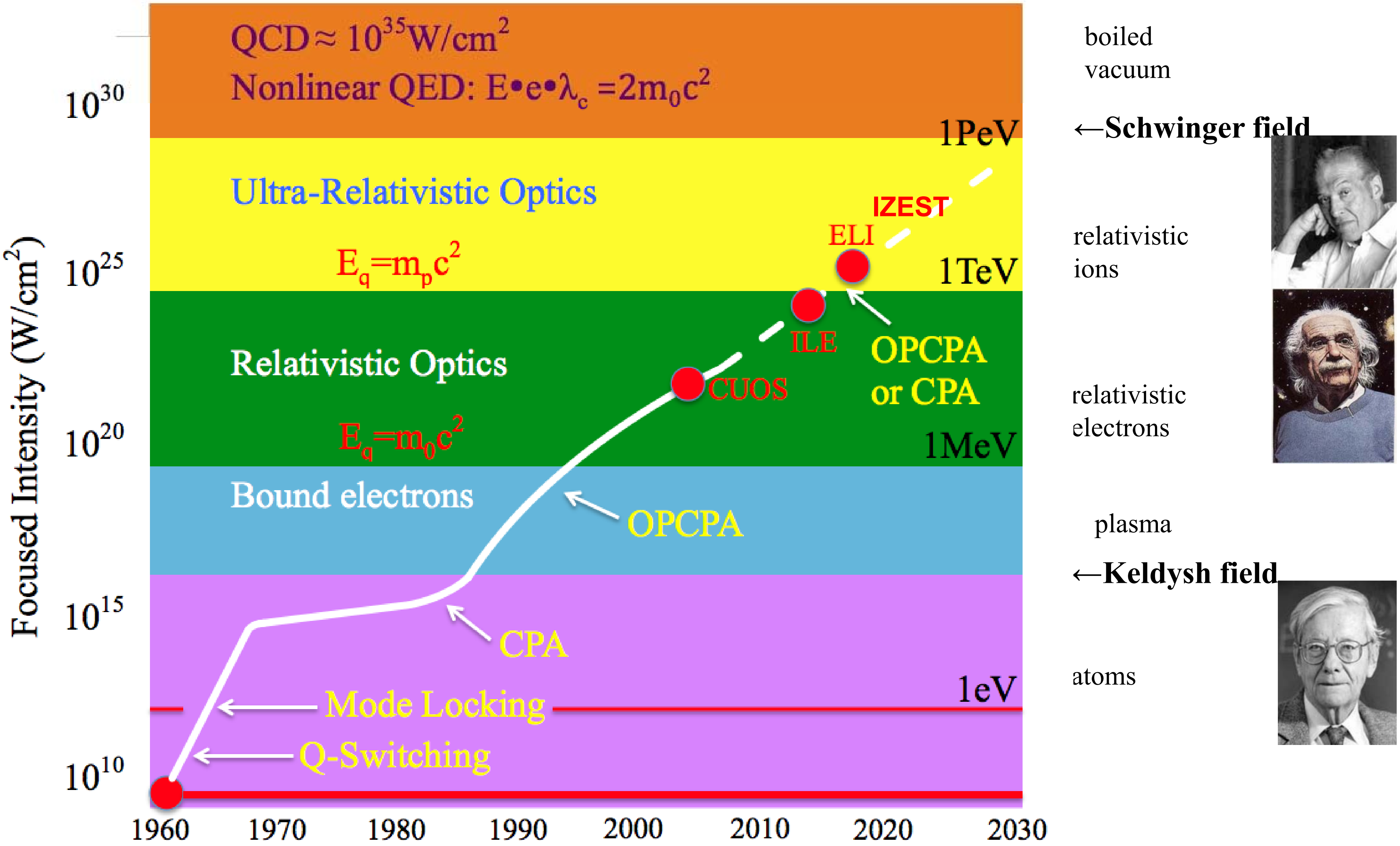


Leap in Laser Intensity

Relativistic nonlinearity under intense laser

(relativistic charged particle bunch does similar)

Ponderomotove force arising from v x B/c

↓

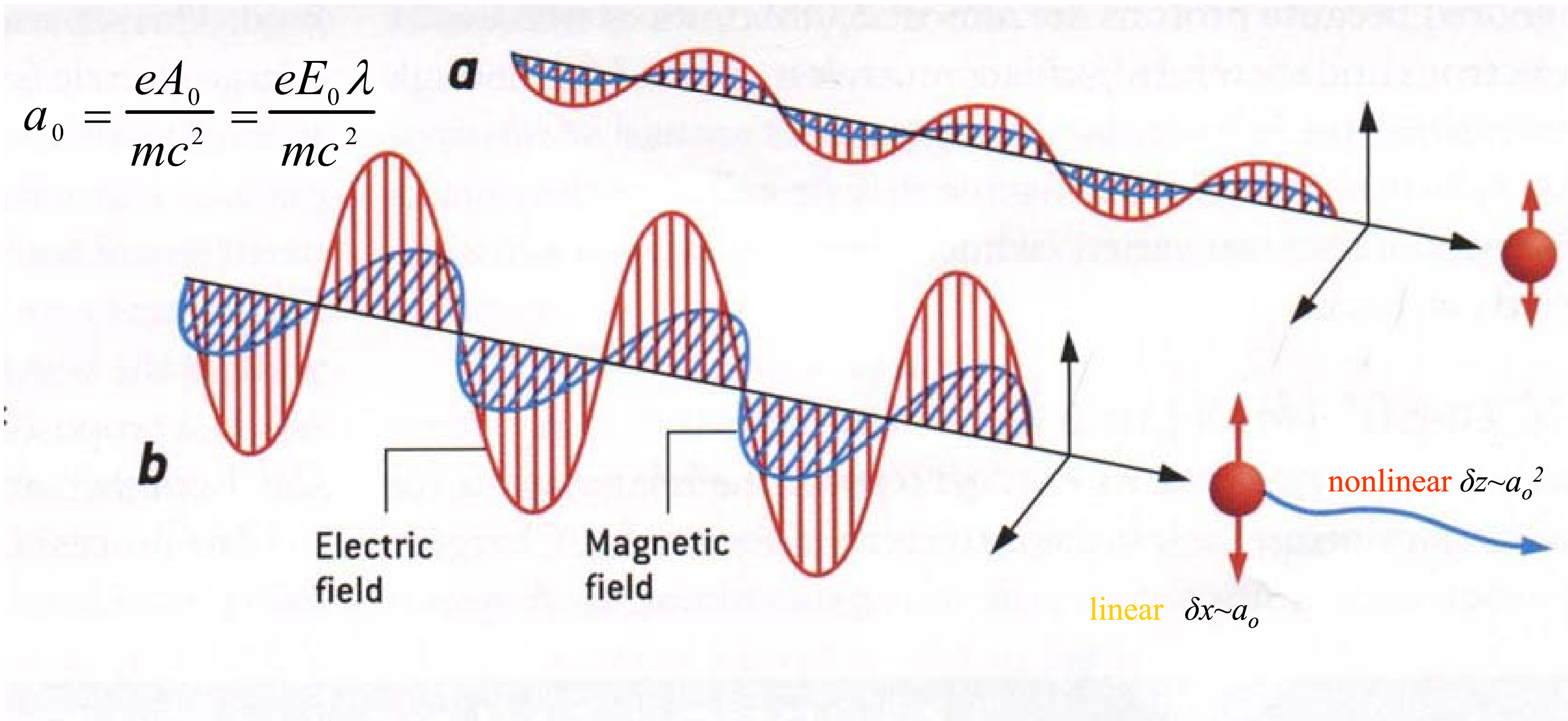
a) Classical optics : $v<<c$,

$a_0<<1$: δx only

b) Relativistic optics: $v \sim c$

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

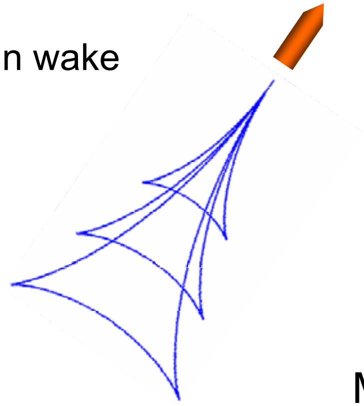
$$a_0 = \frac{eA_0}{mc^2} = \frac{eE_0\lambda}{mc^2}$$

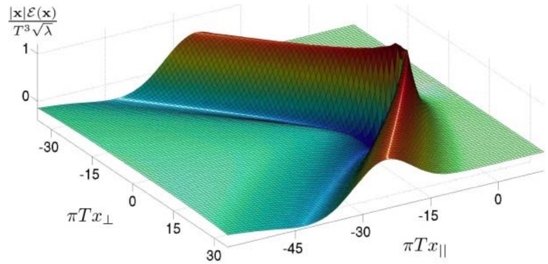


Wakefield ← relativistic nonlinearity

All particles in the medium participate = collective phenomenon

Kelvin wake

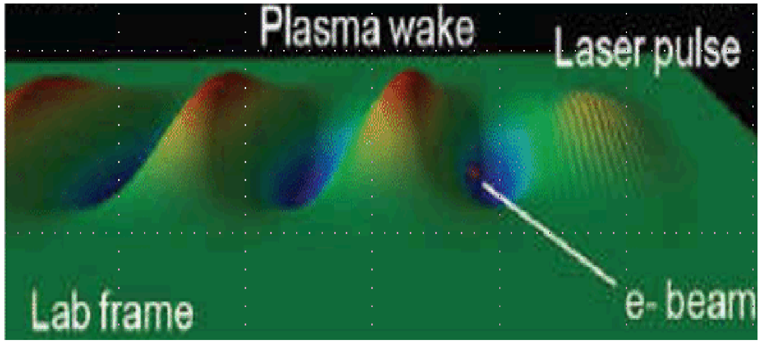




Maldacena (string theory) method:
QCD **wake** (Chesler/Yaffe 2008)

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

[Laser (LWFA) as well as charged beam excite wakefield]



← relativity regularizes

(The density cusps.
Cusp singularity)

Wave **breaks** at v<c

Hokusai

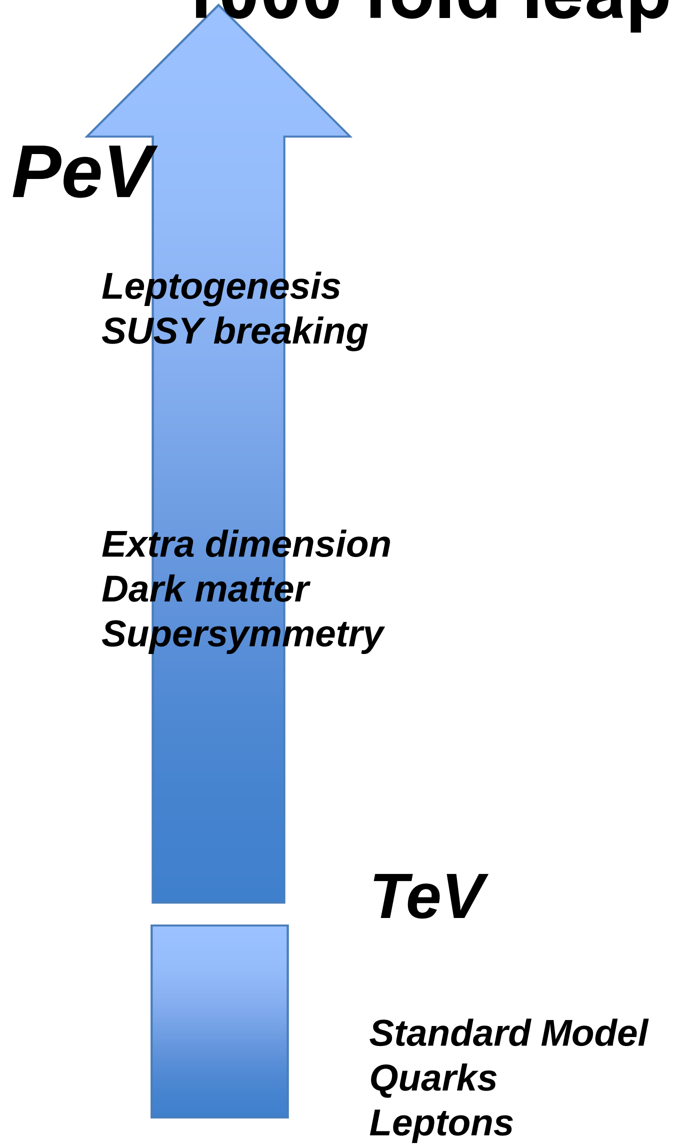
Maldacena

(Plasma physics vs.
String theory)

Responding to Suzuki's Challenge

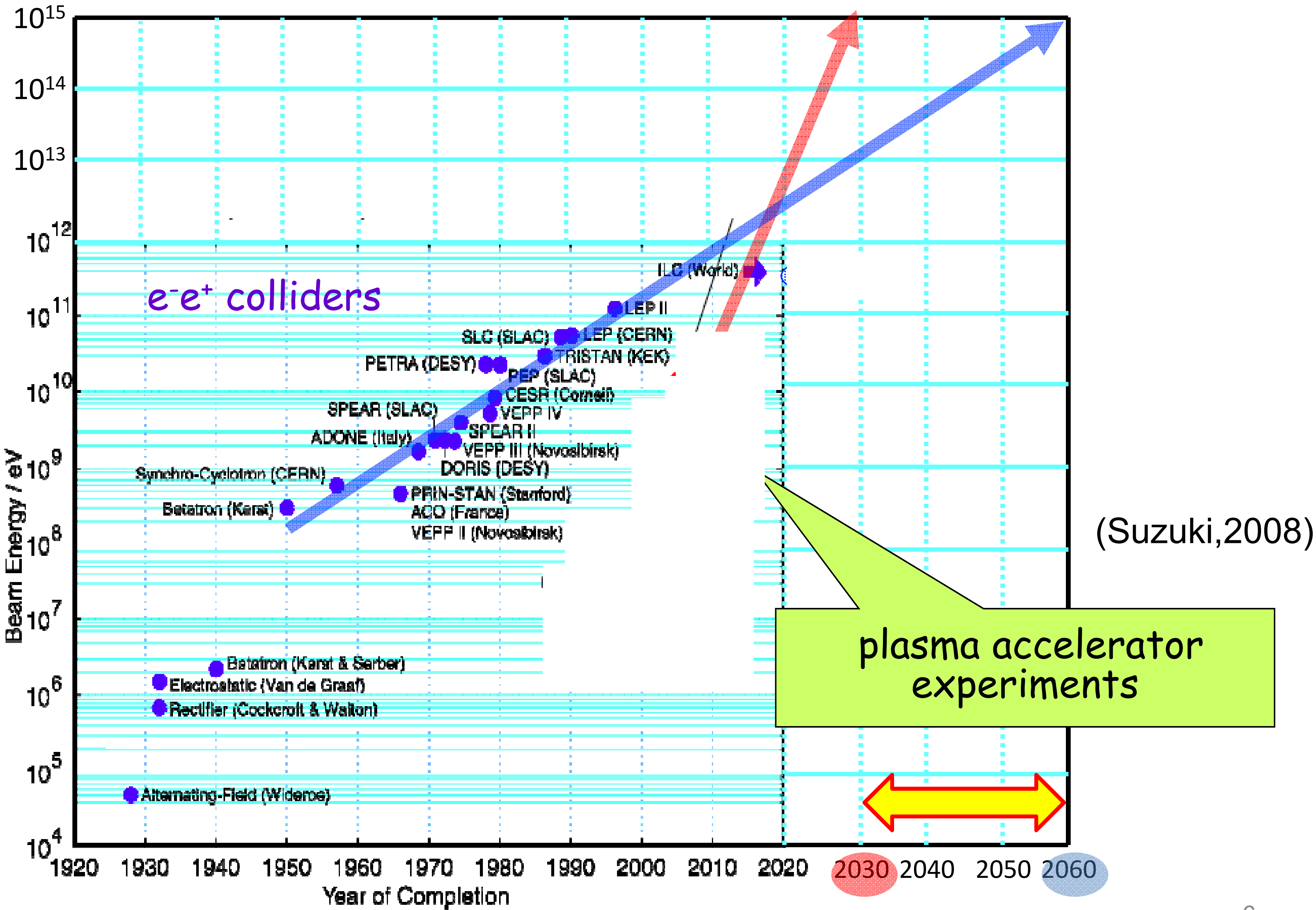
Atsuto Suzuki:
***KEK* Director General,**
***ICFA* Chair**

New Paradigm: 1000 fold leap



Suzuki (2008)

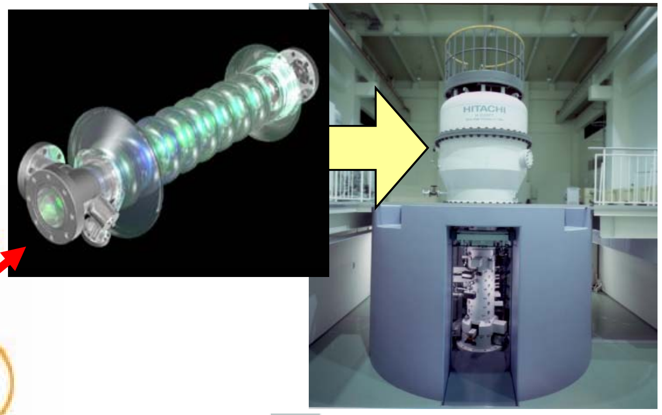
‘When can we reach PeV ?’: one of Suzuki Challenges



V. Yakimenko (BNL) and R. Ischebeck (SLAC), AAC2006 Summary report of WG4

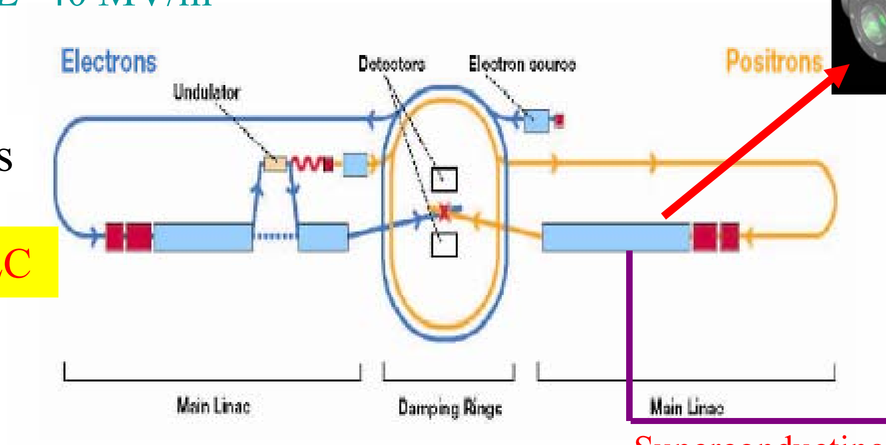
Accelerator

Evolution of Accelerators and their Possibilities (Suzuki,2008)



Ultra-High Voltage STEM with Superconducting RF cavity

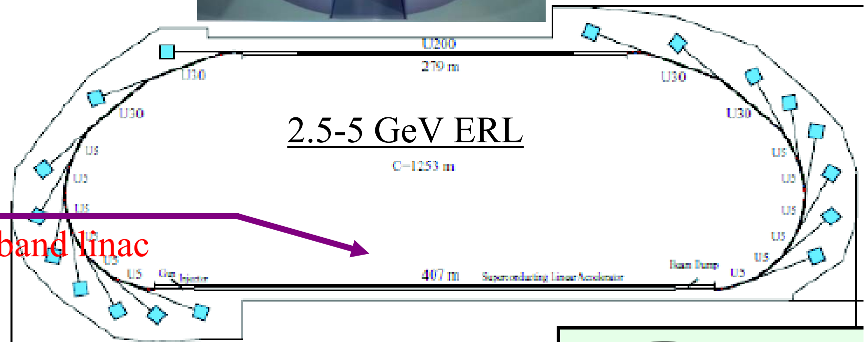
E=40 MV/m



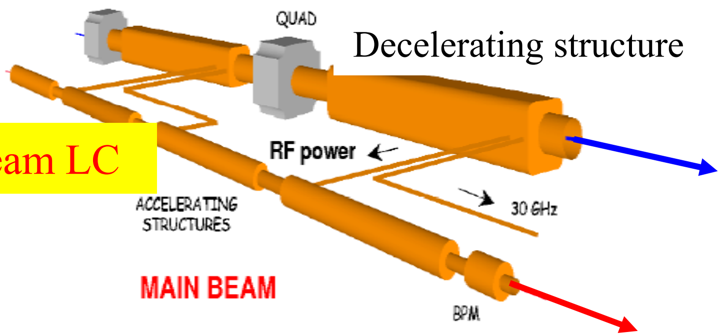
2020s

ILC

Superconducting L-band linac

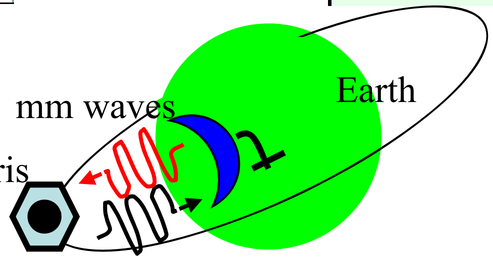


E=200 MV/m



2030s

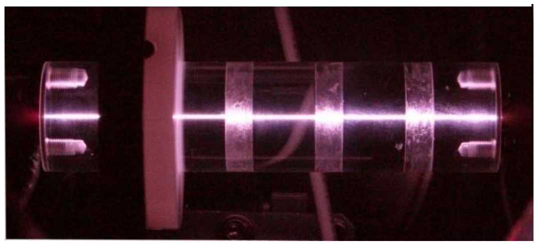
Two-beam LC



Earth-based space debris radar

E=10 GV/m

10cm-10GeV Plasma Channel Accelerator



2040s

Laser-plasma LC

Table-top high energy accelerator

Brief History of *ICUIL – ICFA* Joint Effort

- *ICUIL* Chair sounded on A. Wagner ,Chair *ICFA*, and Suzuki ,incoming Chair, of a common interest in laser driven acceleration (Nov. 2008)
- Leemans appointed (November 2008) to lay groundwork for joint standing committee of *ICUIL*
- *ICFA* GA invited Tajima for presentation by *ICUIL* and endorsed initiation of joint efforts (Feb. 13, 2009)
- *ICFA* GA endorsed *Joint Task Force* (Aug. 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
- 'Bridgelab Symposium' at L'Orme (Jan., 2011)
- *EuroNNAc* Workshop at CERN (coordinator) (May, 2011)
- 2nd *ICFA-ICUIL Joint Task Force* Workshop at LBL (Sept. 2011)
- Formation of *IZEST* (Sept., 2011)
- Report to this *ICFA* Seminars on Plasma Acceleration (Oct. 2011)

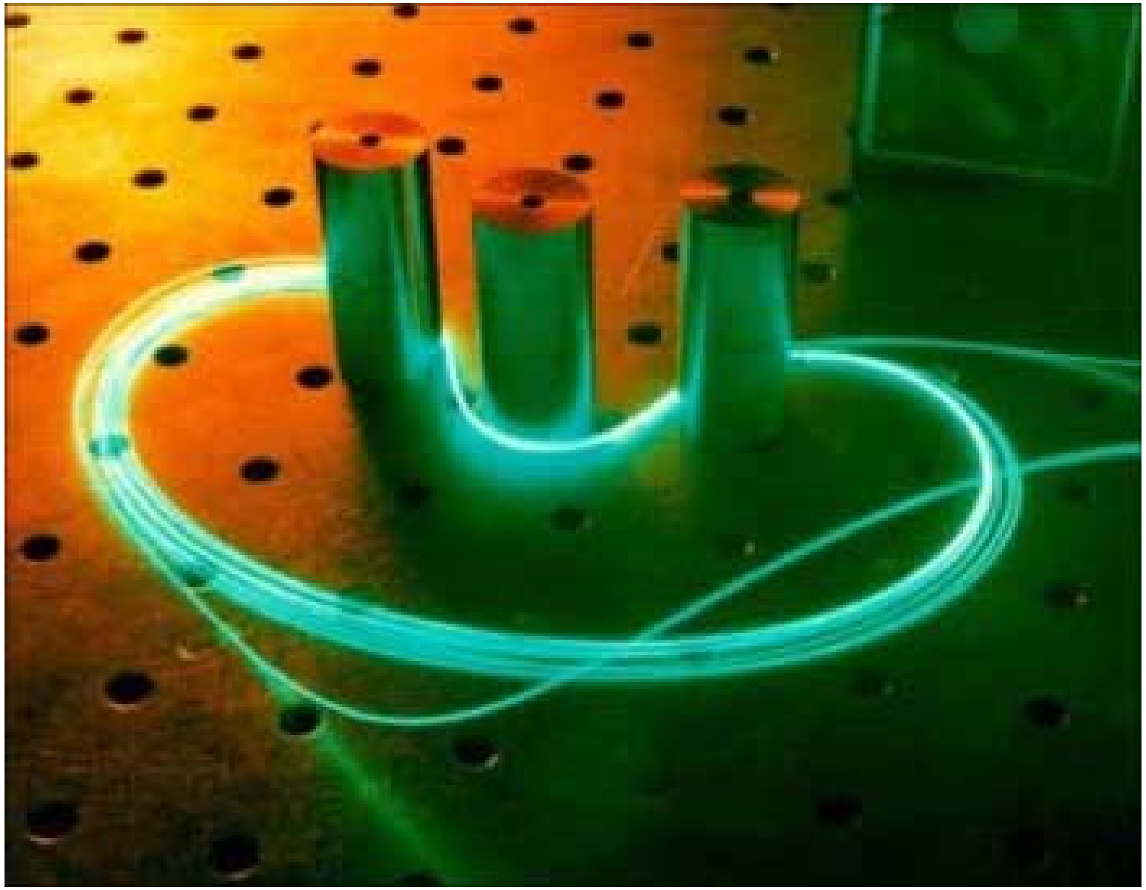
Density scalings for **LWFA** collider **low density operation**

Accelerating field E_z	$\propto n_e^{1/2}$
Focusing constant K	$\propto n_e^{1/2}$
Stage length $L_{\rm stage}$	$\propto n_e^{-3/2}$
Energy gain per stage $W_{\rm stage}$	$\propto n_e^{-1}$
Number of stages $N_{\rm stage}$	$\propto n_e$
Total linac length $L_{\rm total}$	$\propto n_e^{-1/2}$
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 $P_{\rm avg}$	$\propto n_e^{-1/2}$
Wall plug power $P_{\rm wall}$	$\propto n_e^{1/2}$

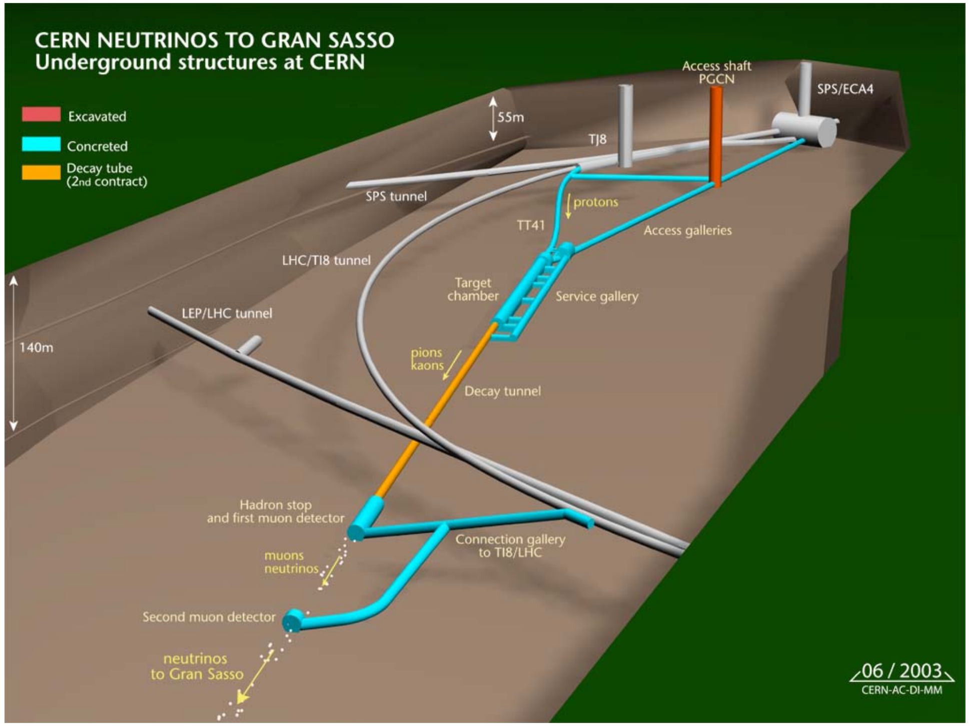
(Nakajima, PR ST AB 2011)

Fiber (vs. Bulk) Lasers

- High Gain fiber amplifiers allow ~ **40%** total plug-to-optical output **efficiency**
- Single mode fiber amplifier have reached **multi-kW** optical power.
- large bandwidth (**100fs**)
- **immune against thermo-**
optical problems
- excellent beam quality
- efficient, **diode-pumped**
operation
- high single pass gain
- mass-produced at **low cost**.



(G. Mourou)



Neutrino speeding faster than *c* ?

(*OPERA* collaboration, 2011)

<u>microsec rise time </u> vs.
ns advance time:
room for a large error

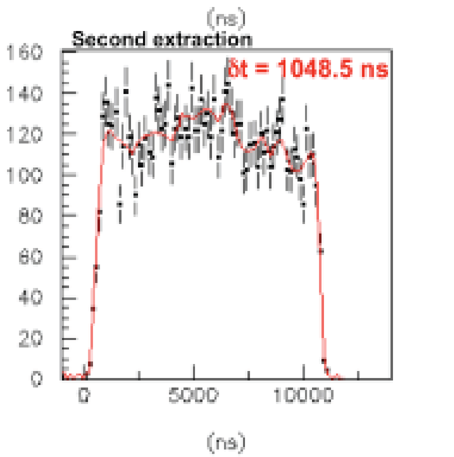
↓

IZEST initiative:

LWFA with RPA (Zheng et al. 2011)

TeV proton accelerated over cm
<u>fs pulse</u>, far narrower rise time

T. Adams (OPERA) 2011



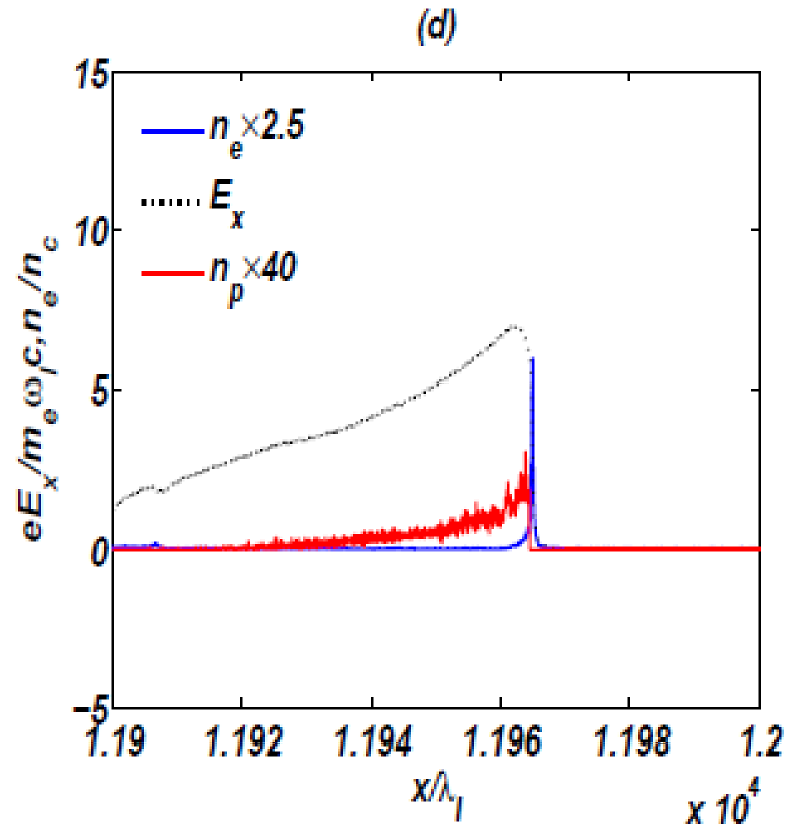
. time distributions (data points) and the proton PDF (red
tom) correcting for δt (blind) resulting from the maximum

to account all the effects related to DAQ and TT
ıe of Δt_{clock} determined in 2006 from a test-bench

TeV proton acceleration by LWFA

early Radiation Pressure Acceleration of ions → Later setting up wakefield

High Intensity regime
$I = 10^{23}$ W/cm^2
(using *IZEST* type laser)



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

0.5TeV over length of 1cm
<u>100fs</u> proton pulse

↓

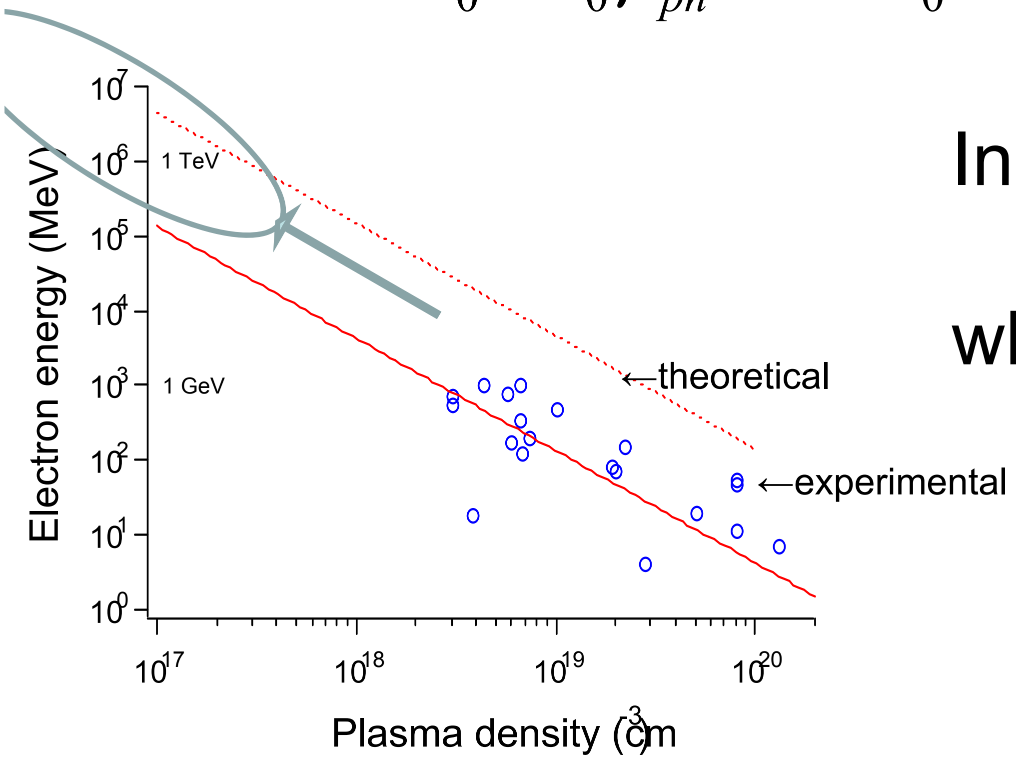
Can we use this to test with sharply pulsed superluminous neutrinos?

Zheng et al., 2011

stable LWFA of protons

Wakefield toward extreme (PeV) energy: Electrons (TeV /stage)

$$\Delta E \approx 2m_0c^2a_0^2\gamma_{ph}{}^2 = 2m_0c^2a_0^2\left(\frac{n_{cr}}{n_e}\right),$$ (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
(Tajima, Kando, Teshima, 2011)

γ-ray signal from primordial GRB

LETTERS NATURE

(Abdo, et al, 2009)

←lower energy

higher→

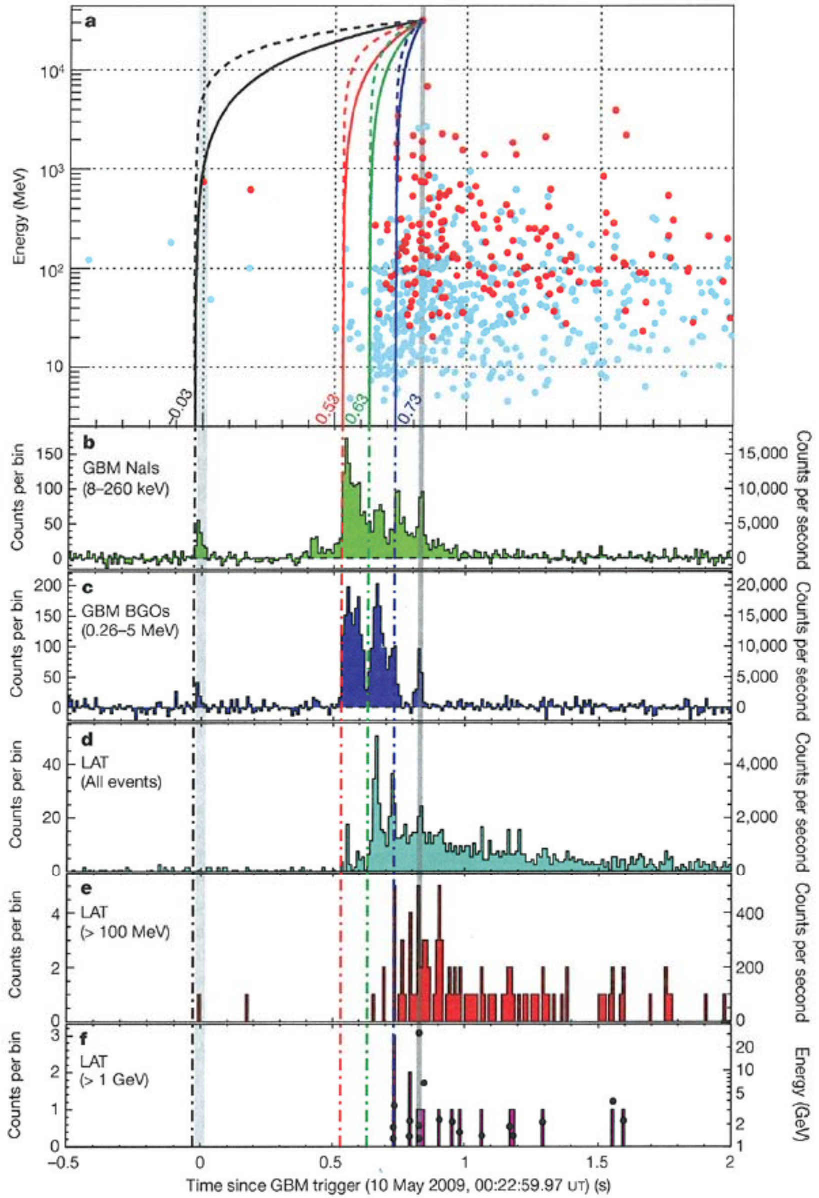


Figure 1 | Light curves of GRB 090510 at different energies. a, Energy ... lowest to highest energies. **f** also overlays energy versus arrival time for each

High energy astrophysics

***c(E): Lorentz violation*?**

Observation of primordial Gamma Ray Bursts (GRB)

(limit is pushed up close to Planck mass)

↓

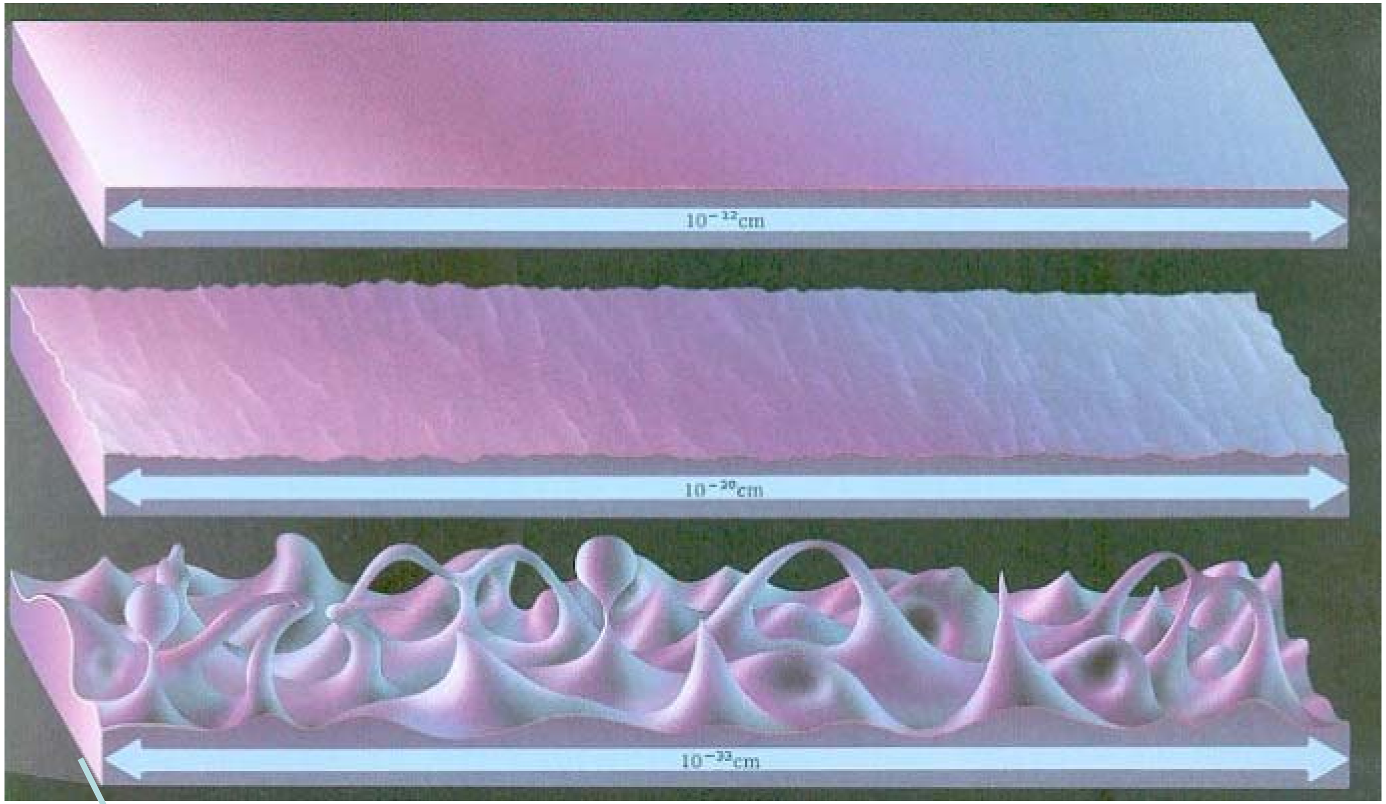
LWFA PeV γ (from e-) can explore this with control

Feel vacuum texture: PeV energy γ

needs fs to as metrology

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

$c < c_0$



Coarser, lower energy texture

Finer, higher energy texture

← (0.1PeV)

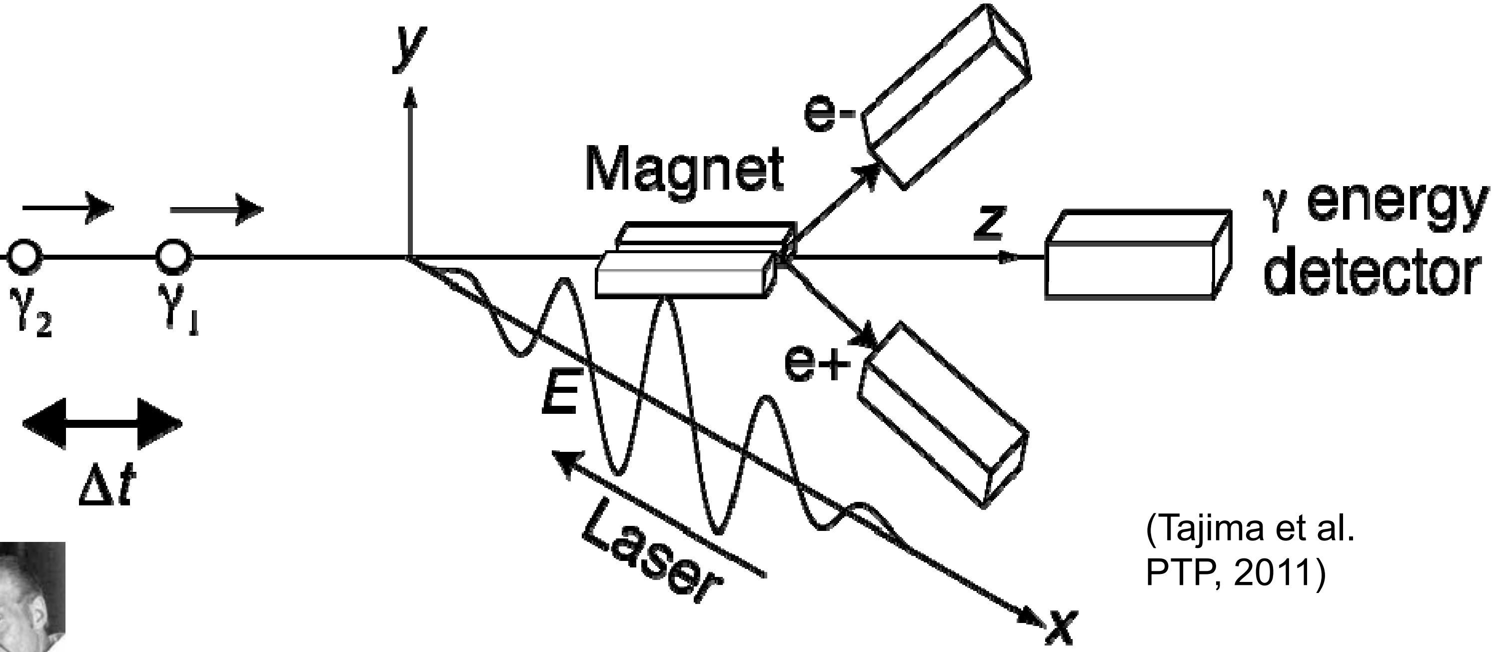
1km

←(1PeV : fs behind)

PeV γ (converted from e^-)

fs/as metrology of PeV γ Arrivals

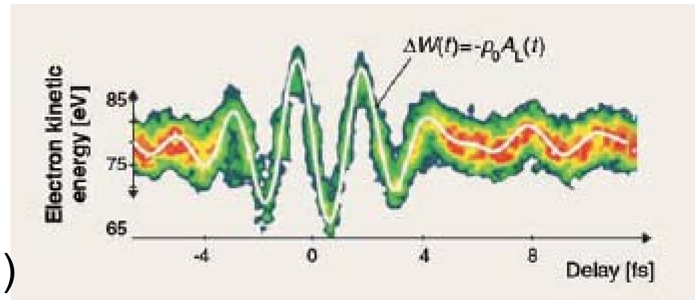
γ-triggered CEP laser goal-line



(Tajima et al. PTP, 2011)

High energy γ- induced Schwinger breakdown (Nishishov, 1964, Narozhny, 1968)
CEP phase sensitive electron-positron acceleration
Attosecond electron streaking
γ- energy tagging possible

Goulielmakis et al. @MPQ(2008)



Extreme High Energy and Synchrotron Radiation

E > 30TeV: untested territory for Lorentz invariance

(B. Altschul, 2008)

with a modified Lorentz factor

$$\tilde{\gamma} = \frac{1}{\sqrt{1 + 2\delta_{\gamma}(\hat{v}) - v^2}}. \qquad (13)$$

The power radiated would then be $P = \frac{e^2 a^2}{6\pi m^2}\tilde{\gamma}^4$.] For ultrarelativistic particles, $\gamma \approx [2(1 - v)]^{-1/2}$ increases very rapidly as a function of v, since $\frac{d\gamma}{dv} = v\gamma^3 \approx \gamma^3$. The modified expression for $\vec{v}(\vec{p})$ changes the radiated power $P(\vec{p})$ to

$$P(\vec{p}) = P_0(\vec{p})\{1 + 4\gamma^2[\delta(\hat{p}) - \delta_{\gamma}(\hat{p})]\}, \qquad (14)$$

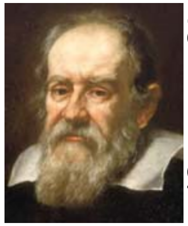
Synchrotron radiation
radiation

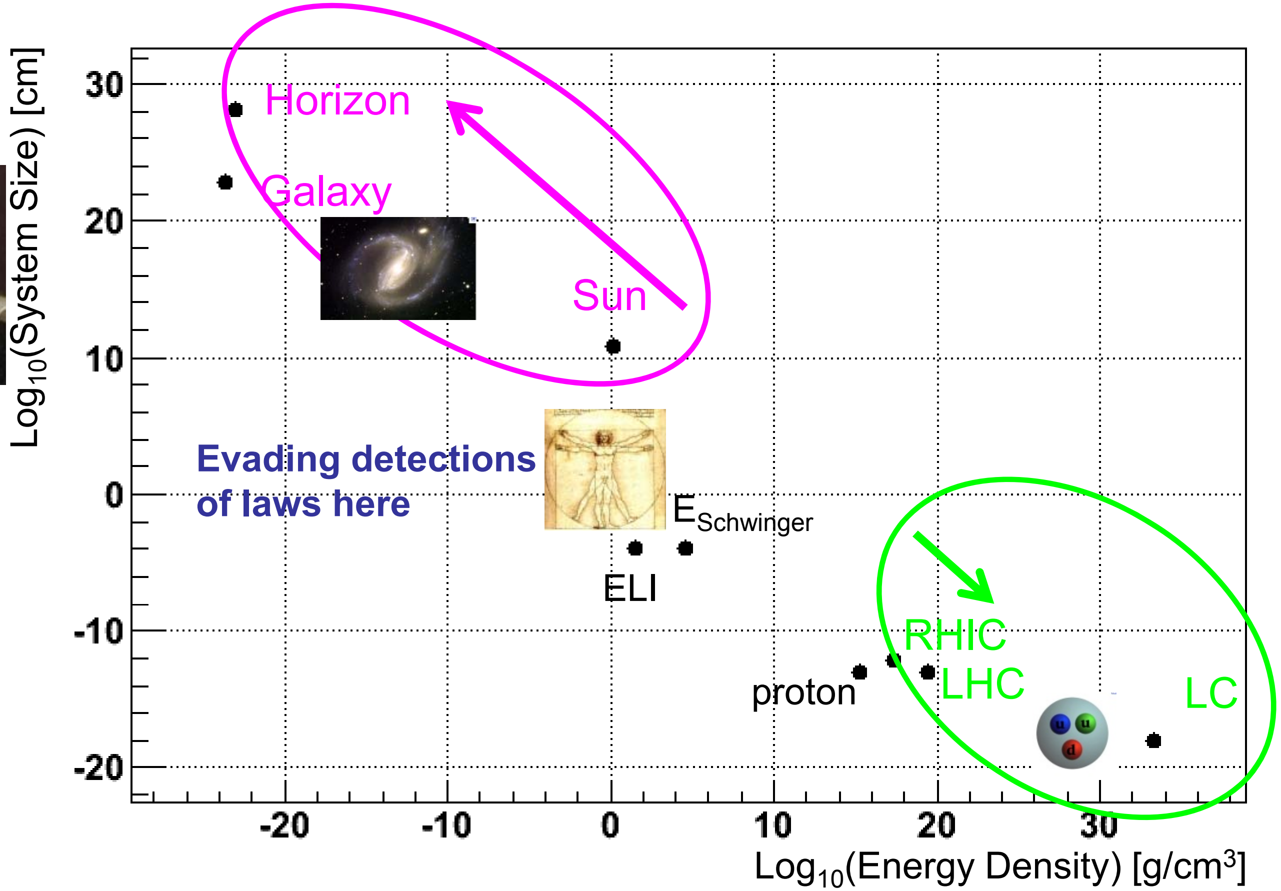
↑ Lorentz violating term

Laser fits the gaping hole

in search of unknown fields:
dark matter/dark energy

Cosmological observation





High energy collider

Domains of physical laws

Homma, Habs, Tajima (2011)

Beyond photon-photon interaction in QED

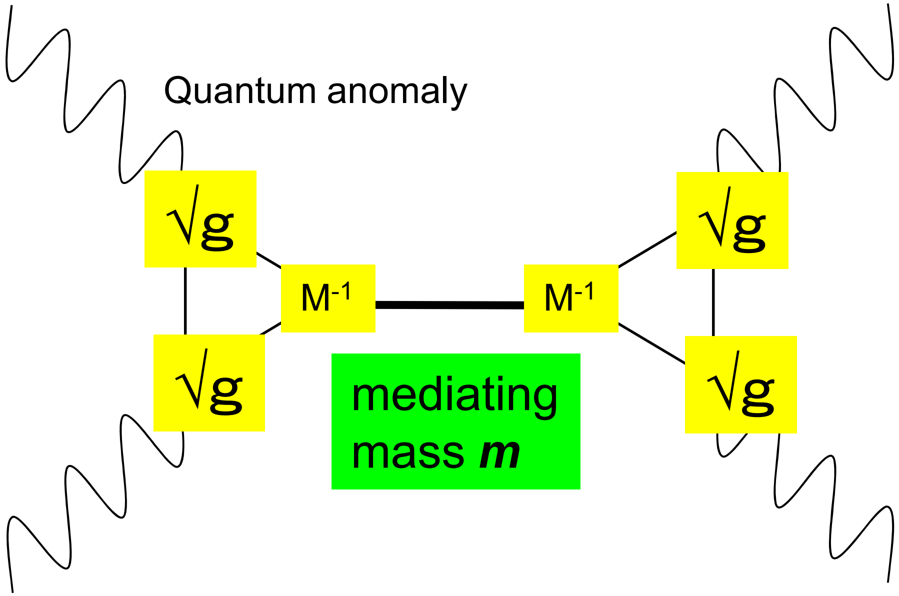
Heisenberg-Euler

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

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

QCD and low-mass scalar ϕ and pseudoscalar σ may change 4 : 7

Resonance in quasi-parallel collisions in low cms energy



If M~M$_{Planck}$, Dark Energy

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

QCD-instanton, Dark Matter

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

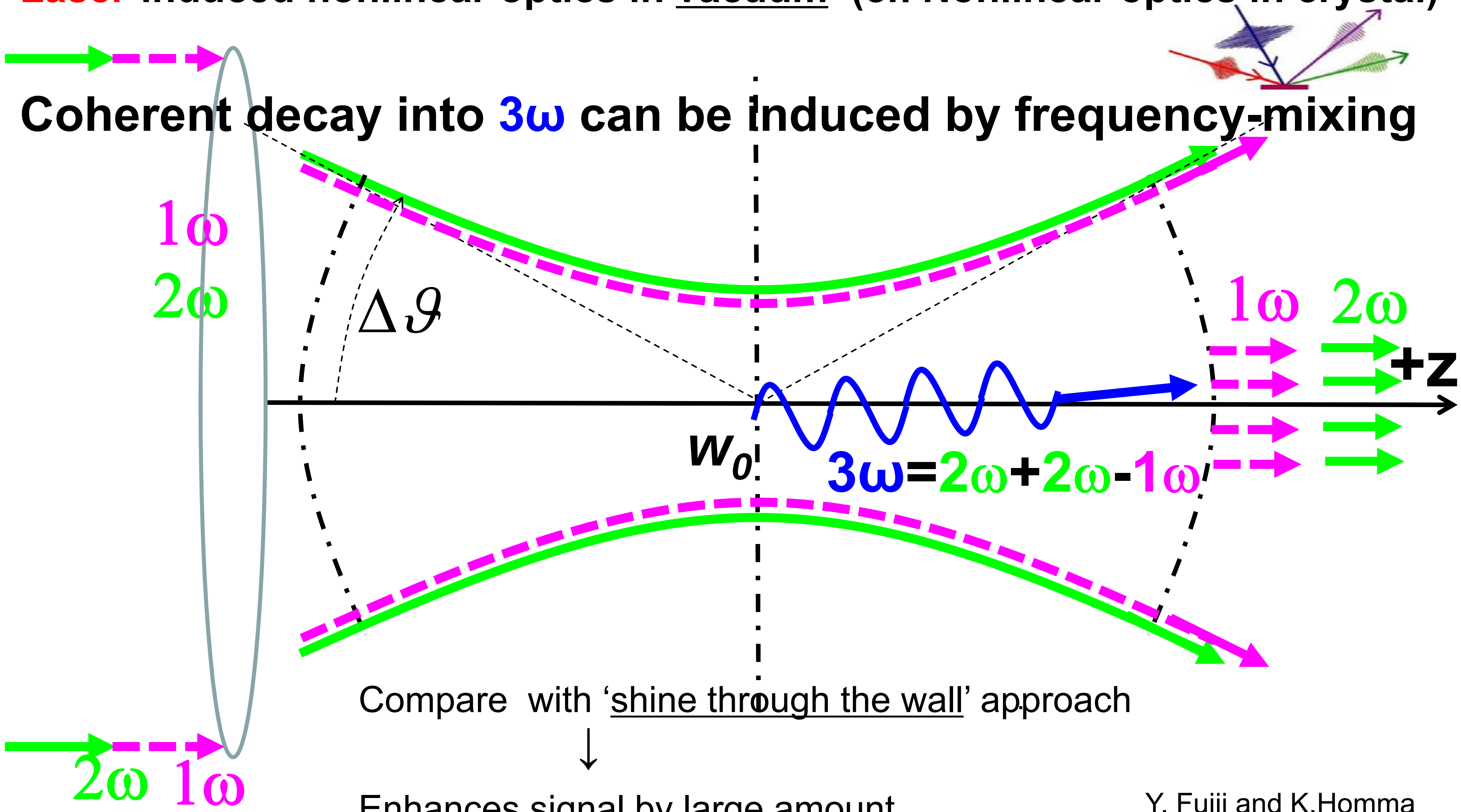
Y. Fujii and K.Homma
Prog. Theo. Phys.

K.Homma, D.Habs, T.Tajima
Appl. Phys. B

Degenerate Four-Wave Mixing (DFWM)

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

Coherent decay into 3ω can be induced by frequency-mixing



Compare with 'shine through the wall' approach

↓

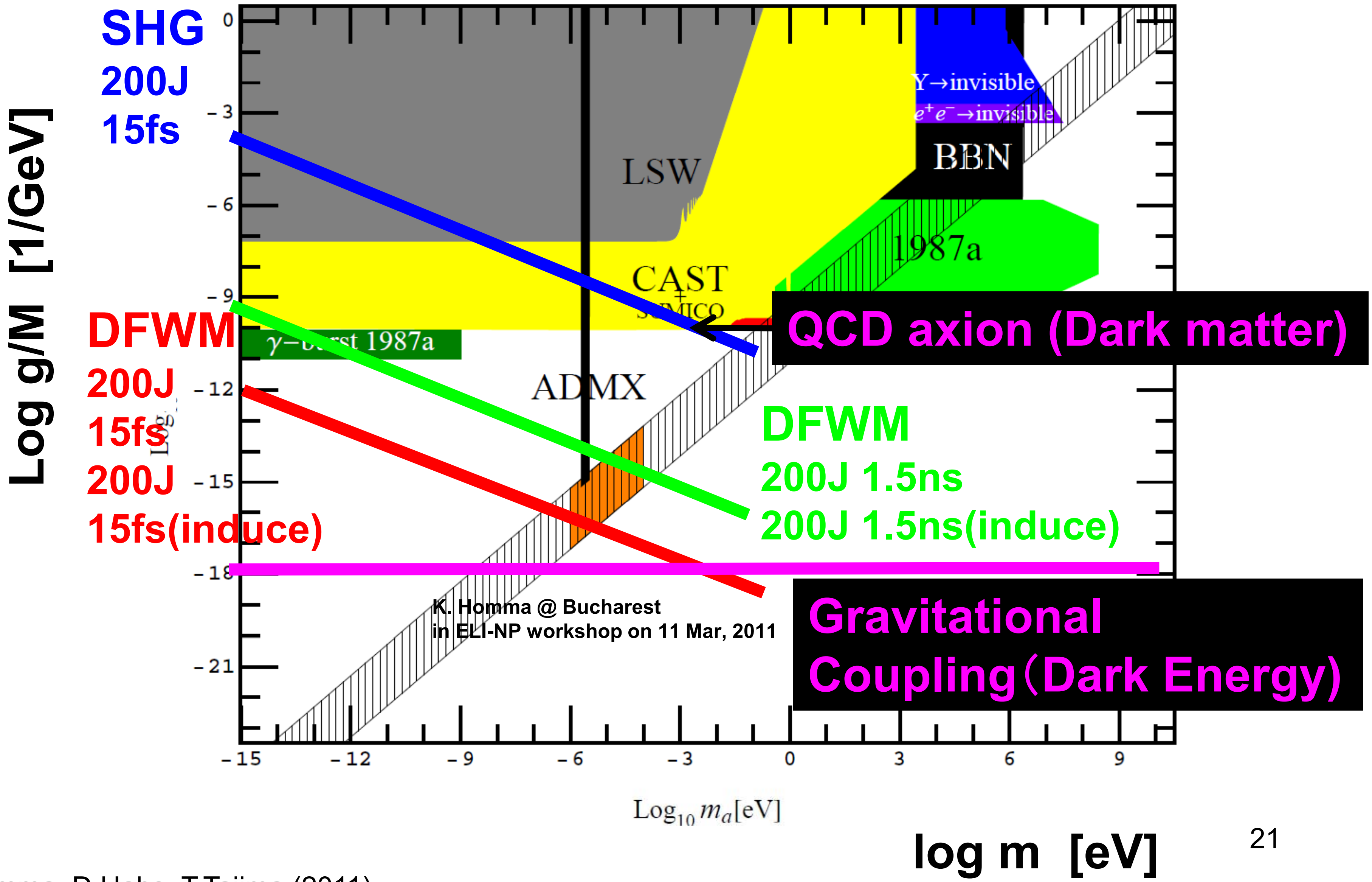
Enhances signal by large amount

$$N_{3\omega} \propto N_{2\omega}{}^{2} N_{1\omega} / \tau$$

Y. Fujii and K.Homma
Prog. Theo. Phys.

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

High Field road to unknown fields: dark matter and dark energy



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

IZEST

International Center for Zetta-Exawatt Science and Technology

* Highest intensity using existing / near future lasers with the world brainpower
* TeV (and PeV) energy frontier, with non-collider paradigm (such as Lorentz invariance check)
* High field approach (as opposed to high momentum) of fundamental physics
* Works with ICUIL and ICFA, in a shorter timeline than a generation

Under the Aegis of
CEA, Ecole Polytechnique and
Ministry of Research and Education

Conclusions

- Bridge between accelerator and laser communities
  necessary and ongoing (*ICFA-ICUIL Joint Task Force*)
- Collider physics requirements:
  ==➔ low density operation of LWFA suggested
- High efficient, high average power driver laser technology:
  ICAN Project (*CERN, Fermi, KEK* collaborating)
- Non-collider paradigm:
  Energy frontier with attosecond precision w/ a few shots
  e.g. Lorentz invariance test (in TeV and PeV)
- High field science approach: coherent production of new fields :
  dark matter; dark energy

IZEST promotes this science in response to Suzuki's challenge
in collaboration with *ICFA*