Invited Talk
International Conference 'Nonlinear Optics: East-West Reunion' (NLO50 2011)
Suzdal, Russia
Friday 23 September, 2011

Nonlinear Optics of Vacuum

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LMU and MPQ, Garching, Germany

Acknowledgments for Collaboration and advice: G. Mourou, F. Krausz, E. Goulielmakis, W. Leemans, K. Nakajima, K. Homma, D. Habs, P. Chomaz, H. Videau, T. Esirkepov, S. Bulanov, M. Kando, W. Sandner, A. Suzuki, M. Teshima, R. Assmann, R. Heuer, S. Karsch, F. Gruener, W. Chou, F. Takasaki, M. Nozaki, A. Chao, P. Bolton, J.P. Koutchouk, K. Ueda, Y. Kato, X. Q. Yan, R. Li, A. Ringwald, H. Ruhl, T. Ostermayr, S. Petrovic, C. Klier, B. Altschul, Y. K. Kim, M. Spiro, A. Seryi, A. Sergeev, A. Livak, K. Iqbal, C. Robilliard, J. Taran

1. Suzuki's challenge in high energy physics
   High energy frontier: TeV and beyond
   A collider?
2. Non-collider paradigm
   Vacuum texture and synchrotron radiation
   in high energy
   Energy frontier at PeV with attosceond metrology
   without luminosity
3. High Field explores low energy new fields:
   high field of laser (cf. high momentum)
   Dark matter and dark energy fields in vacuum
   2nd harmonic, degenerate 4 wave mixing
4. zs streaking of vacuum by laser and γ photon
5. New initiative : IZEST = LIL compression, XCELS in Russia, etc.

IZEST's Mission: Responding to Suzuki's Challenge

Atsuto Suzuki:
KEK Director General,
ICFA Chair

New Paradigm

PeV

Leptogenesis
SUSY breaking

Extra dimension
Dark matter
Supersymmetry

TeV

Standard Model
Quarks
Leptons

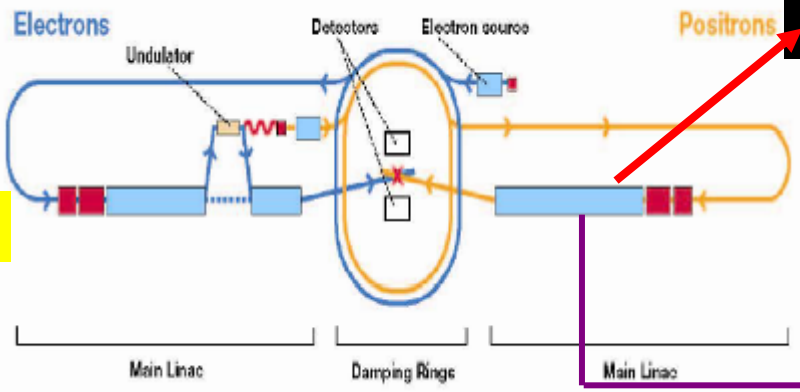
Accelerator

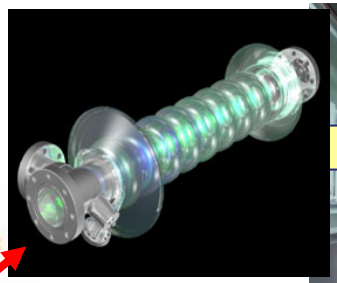
Evolution of Accelerators and their Possibilities (Suzuki,2008)

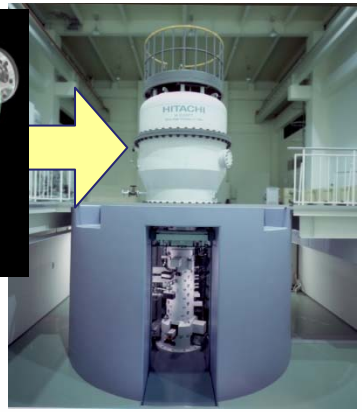
E=40 MV/m

2020s

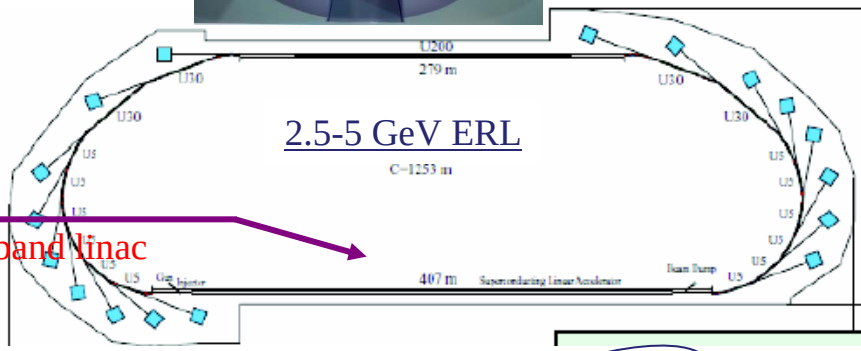
ILC







Ultra-High Voltage STEM with Superconducting RF cavity



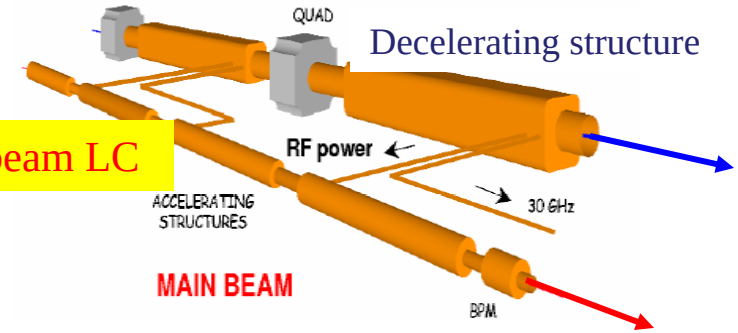
Superconducting L-band linac

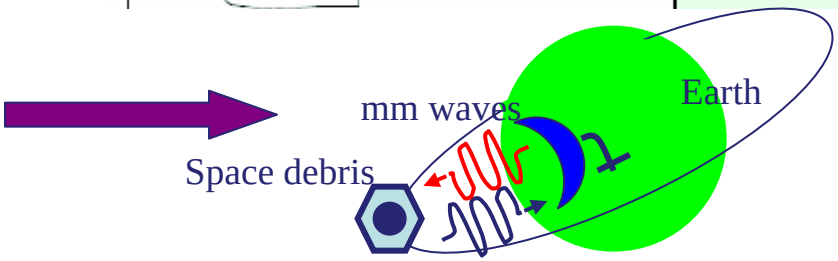
E=200 MV/m

DRIVE BEAM

2030s

Two-beam LC





Earth-based space debris radar

E=10 GV/m

10cm-10GeV Plasma Channel Accelerator

2040s

Laser-plasma LC

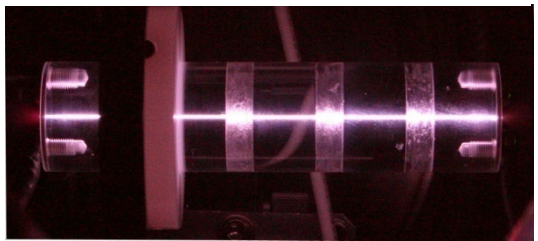
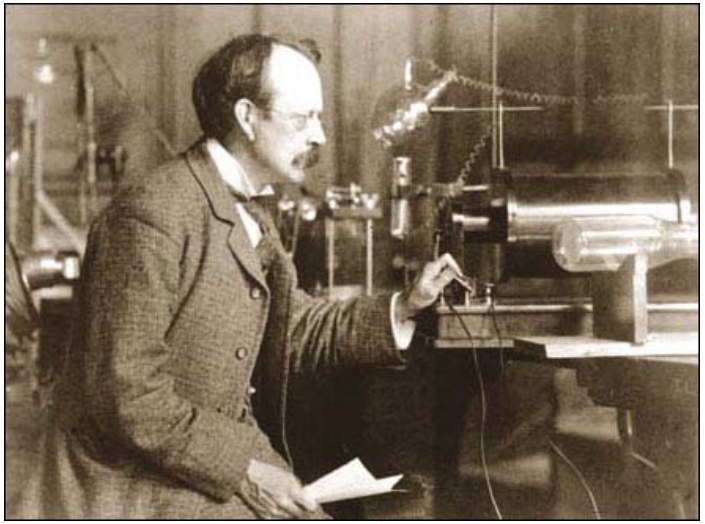
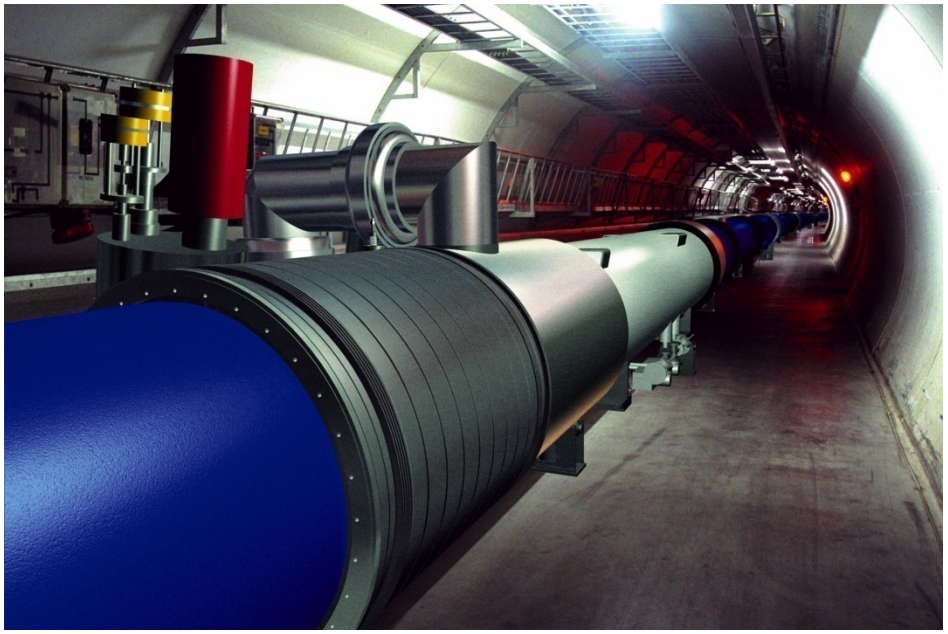


Table-top high energy accelerator

20th Century, the Electron Century
Basic Research Dominated by Massive and Charged Particles



J. J. Thomson



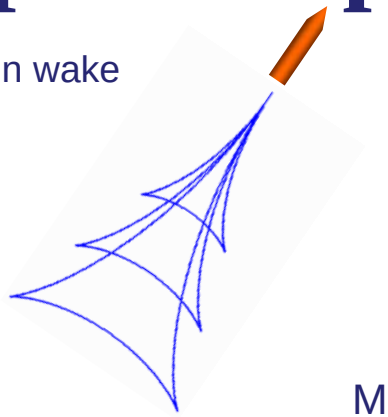
IZEST

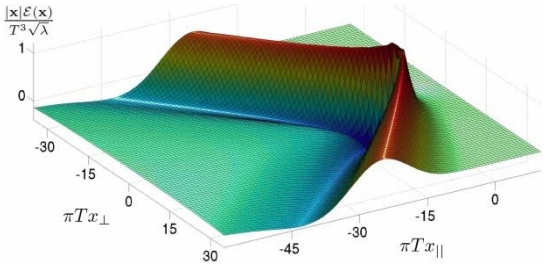
21st Century; the Photon Century
Could basic research be driven by the massless and chargeless particles; Photons?

C. Townes

Laser Wakefield (LWFA): nonlinear optics in plasma

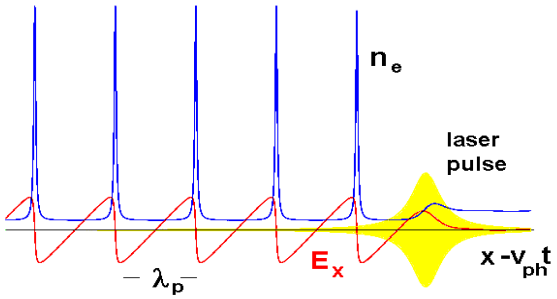
Kelvin wake





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

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



← relativity regularizes

Wave **breaks** at v < c

Hokusai

Maldacena

(The density cusps.
Cusp singularity)

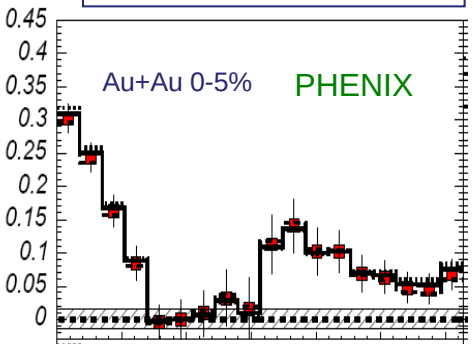
(Plasma physics vs.
String theory)

Nuclear Wake?

- BNL (and CERN) heavy ion collider: **"monojet"**
- Could be caused by:
  - Large angle gluon radiation (Vitev and Polsa and Salgado).
  - Deflected jets, due to flow (Armesto, Salgado and Wiedemann) and/or path length dependent energy loss (Chiu and Hwa).
  - Hydrodynamic conical flow from mach cone shock-waves (Stoecker, Casalderrey-Solanda, Shuryak and Teaney, Renk, Ruppert and Muller).
  - Cerenkov gluon radiation (Dremin, Koch).
- Jet quenching: collective deceleration by wakefield?
  - LWFA method, or Maldacena method?

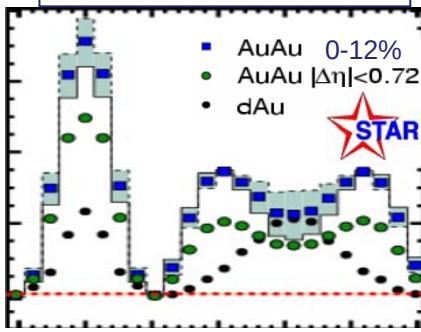
PHENIX PRL 97, 052301 (2006)

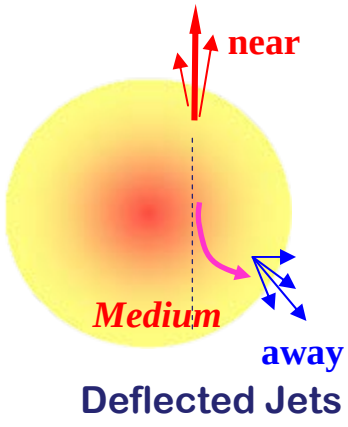
$2.5<p_T^{Trigger}<4$ GeV/c
$1<p_T^{Assoc}<2.5$ GeV/c



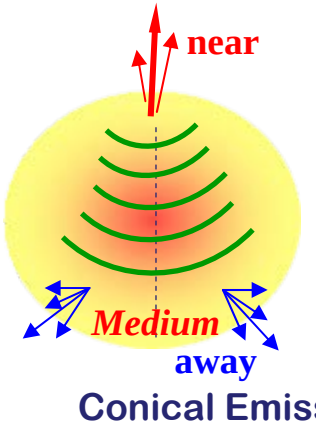
Horner (STAR) QM2006

$3<p_T^{Trigger}<4$ GeV/c
$1<p_T^{Assoc}<2.5$ GeV/c





Deflected Jets



Conical Emission

Density scalings of LWFA for collider

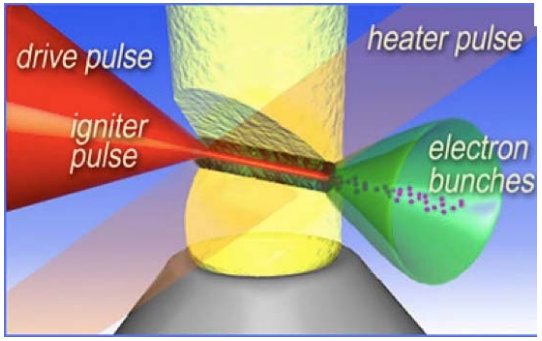
Accelerating field E_z	$\propto n_e^{1/2}$
Focusing constant K	$\propto n_e^{1/2}$
Stage length $L_{\rm stage}$	$\propto n_e^{-3/2}$
Energy gain per stage $W_{\rm stage}$	$\propto n_e^{-1}$
Number of stages $N_{\rm stage}$	$\propto n_e$
Total linac length $L_{\rm total}$	$\propto n_e^{-1/2}$
Number of 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, 2011)

PeV Accelerator

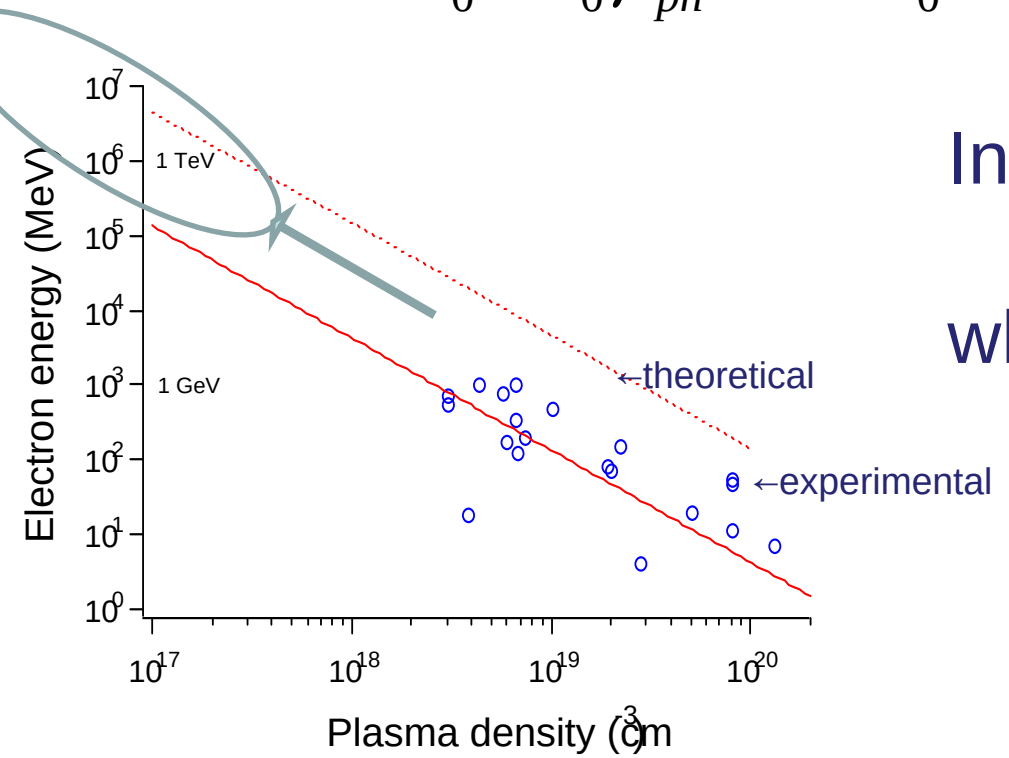
With conventional Technology
The accelerator would Girdle the Earth:
Fermi's vision (1954)

1km laser plasma accelerator
with LIL or LMJ
(Vision 2011)



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

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

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

dephasing length

pump depletion length

Adopt:

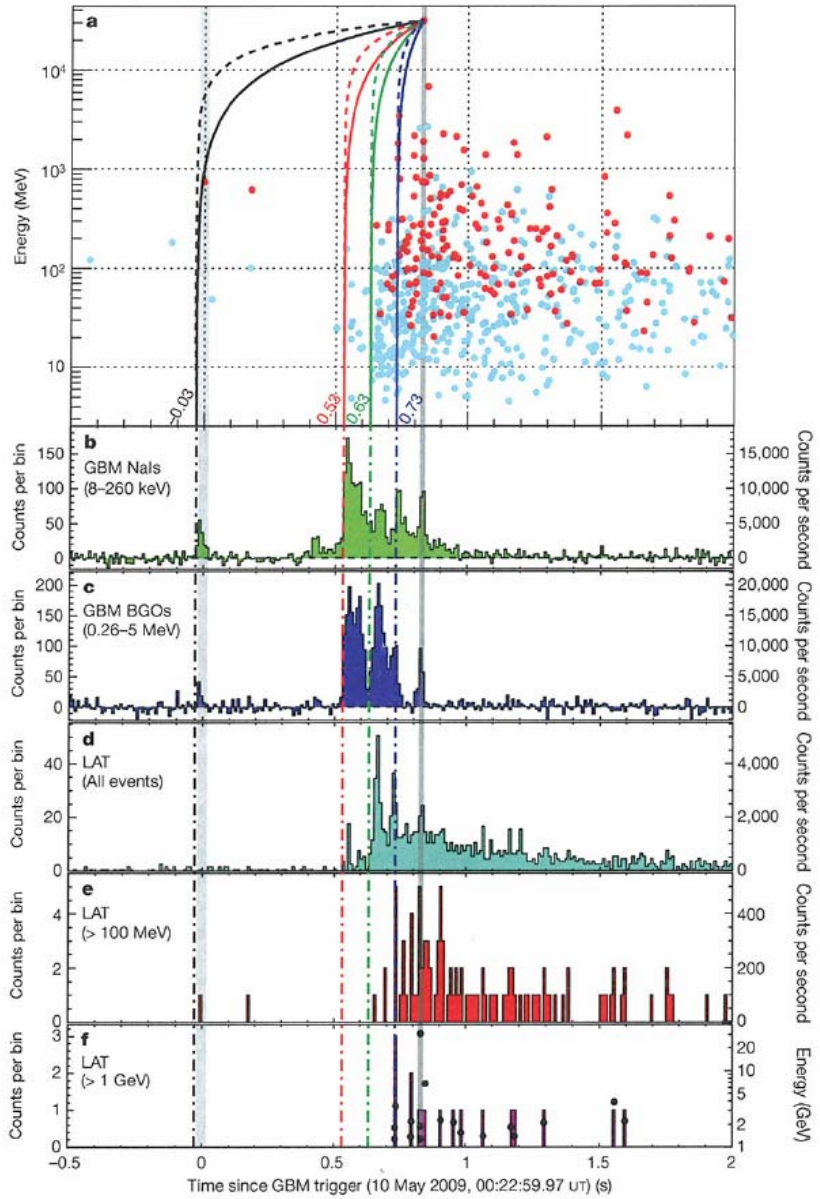
LMJ laser (3MJ)

→ 0.7PeV

(with Kando, Teshima)

γ-ray signal from primordial GRB

(Abdo, et al, 2009)



←lower energy

higher→

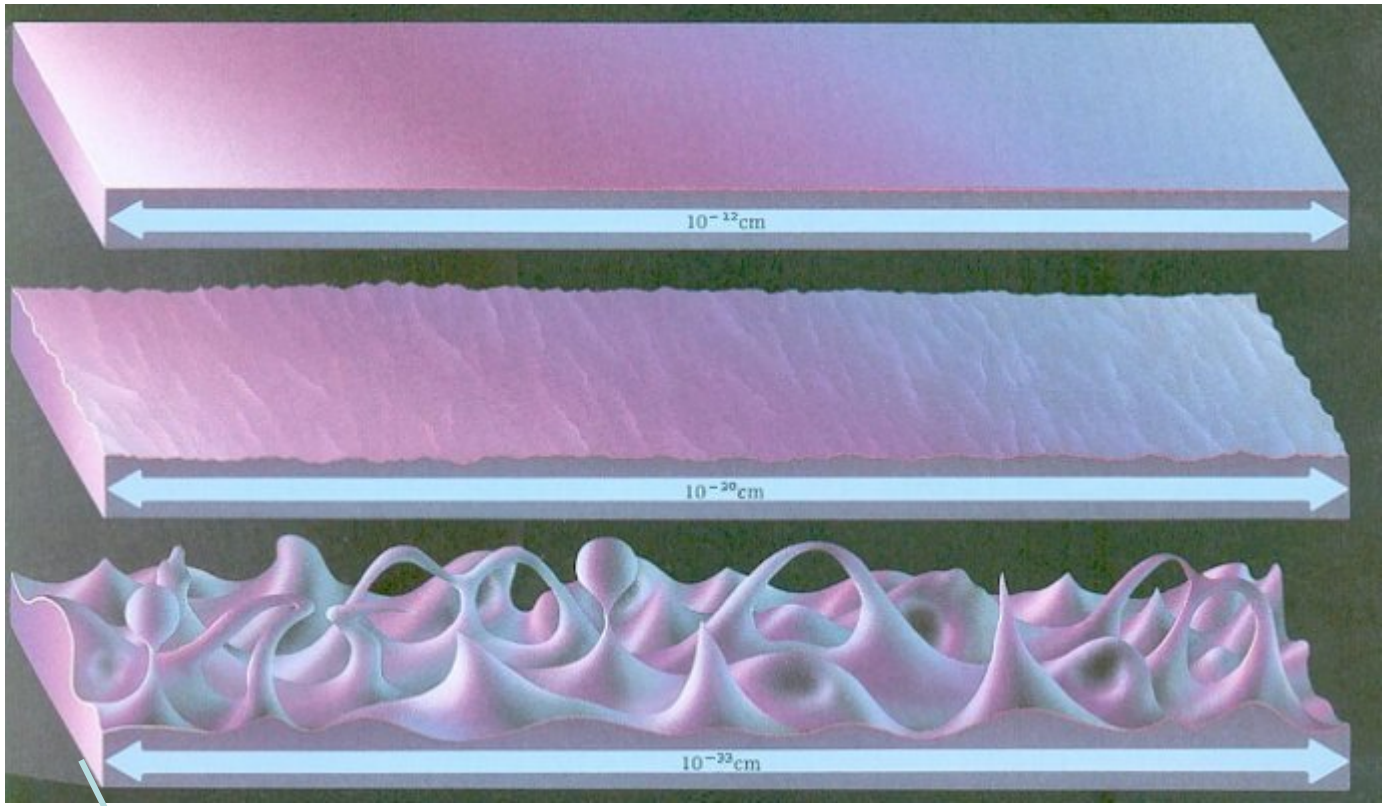
Figure 1 | Light curves of GRB 090510 at different energies. a, Energy lowest to highest energies. f also overlays energy versus arrival time for each

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

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)



$c < c_0$

Coarser, lower energy texture

Finer, higher energy texture

← (0.1PeV)

1km

←(1PeV : fs behind)

PeV γ (converted from e^-)

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

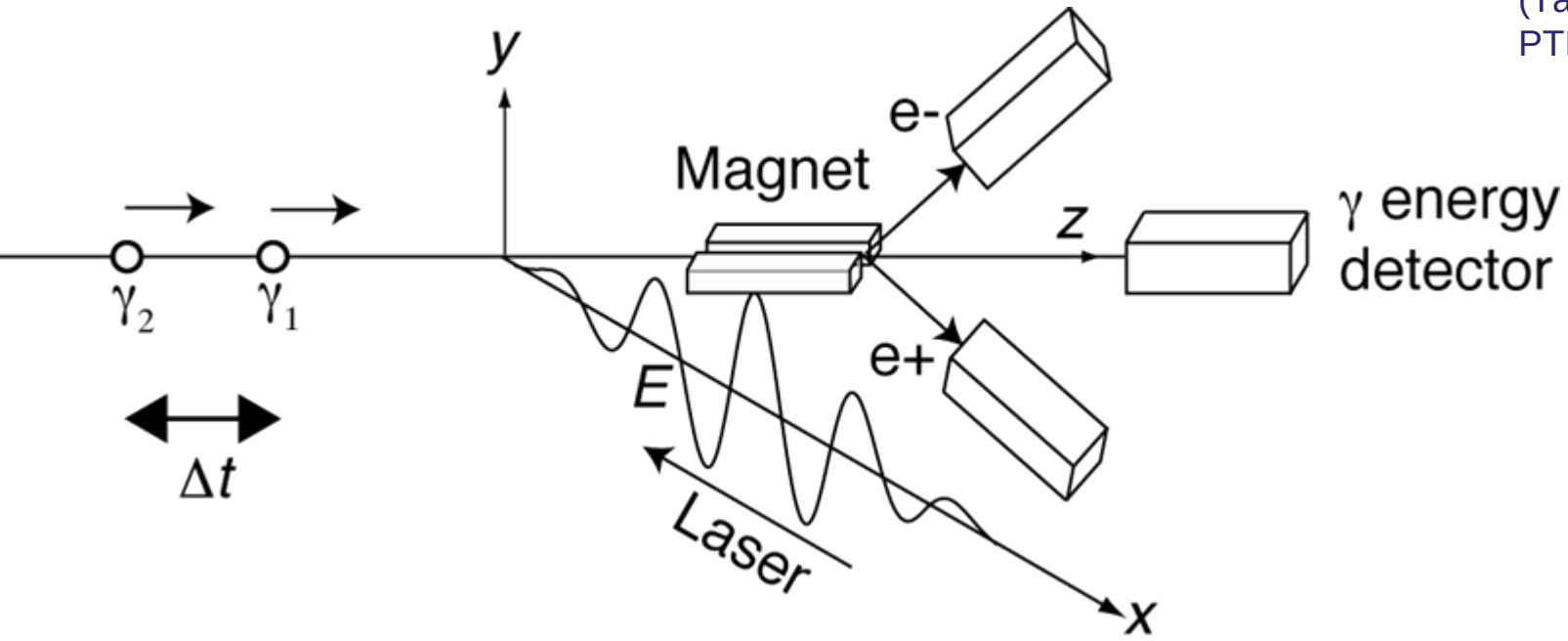
$$P(\vec{p}) = P_0(\vec{p})\{1 + 4\gamma^2[\delta(\hat{p}) - \delta_\gamma(\hat{p})]\}. \qquad (14)$$

Synchrotron radiation
radiation

↑ Lorentz violating term (>30TeV)

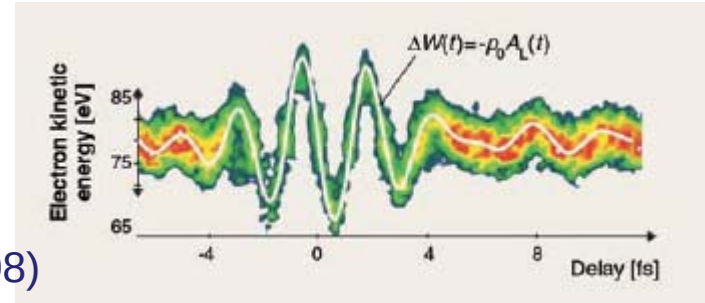
Attosecond Metrology of PeV γ Arrivals

(Tajima, Kando, PTP, 2011)



Narozhny, Nikisho, Ritus

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

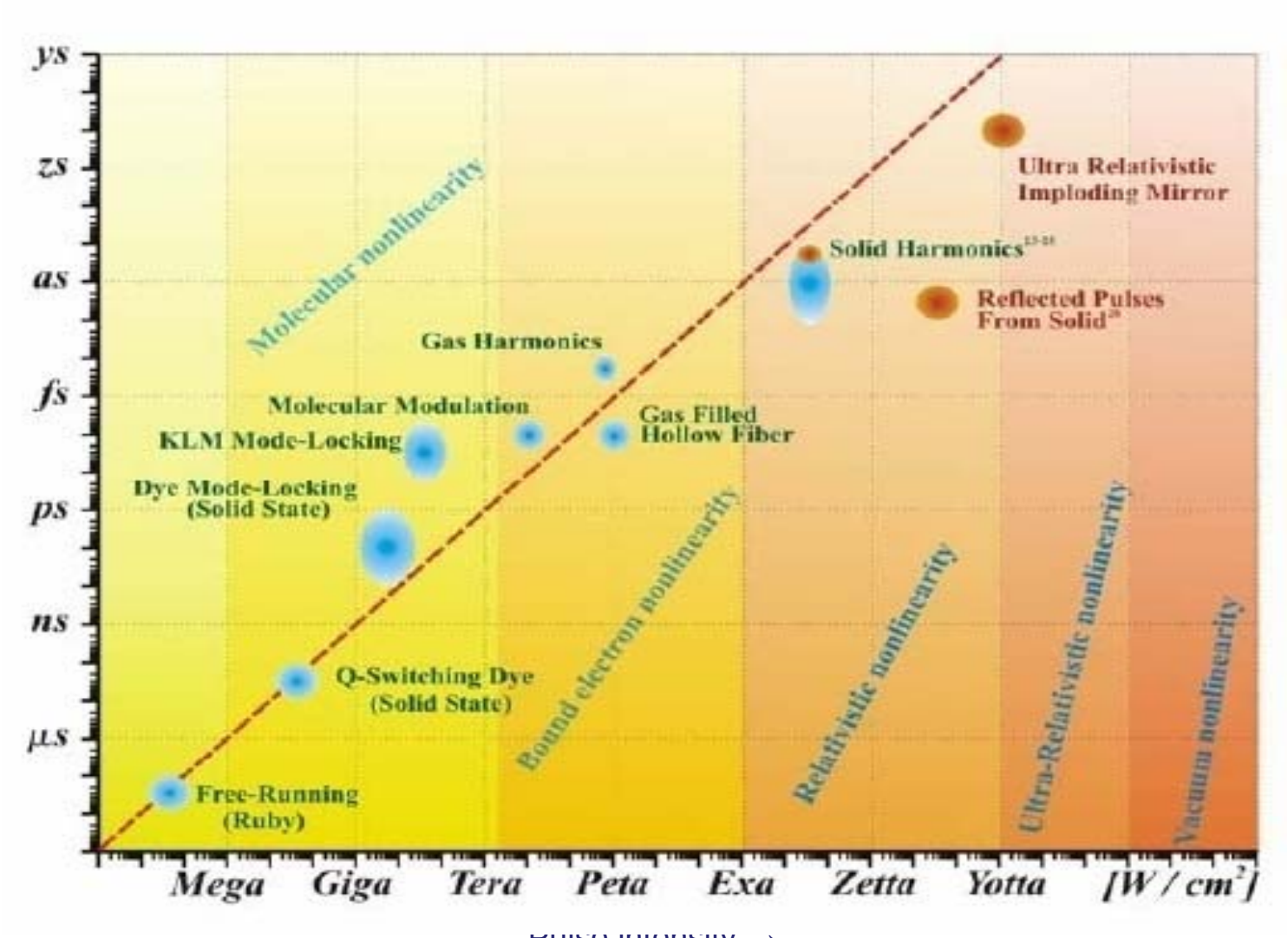


Goulielmakis(2008)

The Conjecture

(← physics: "Matter is nonlinear"

"The more rigid nonlinearity, the more intense to manipulate it";
rigidity vs. pulse length)



(Mourou / Tajima, science, 2011)

Streaking Vacuum

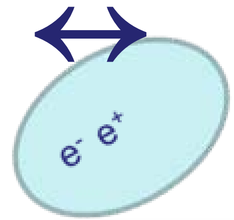
(from atomic physics to QED vacuum physics)

vacuum

Gamma photon ‘ionization’
XUV streaking
→zeptosecond dynamics

$E_S/E_K = \alpha^3; \ \ P_{c\,vac}/P_c = \alpha^6$

size
$\lambda_C = \alpha a_B$



depth of potential
$\Phi = \alpha^2 W_B$

$$R_{e^+e^-} \propto \exp\left(-\left(\frac{8}{3}\right)\left(\frac{m}{\omega}\right)\left(\frac{E_S}{E}\right)\right)$$

Nikishov(1964)

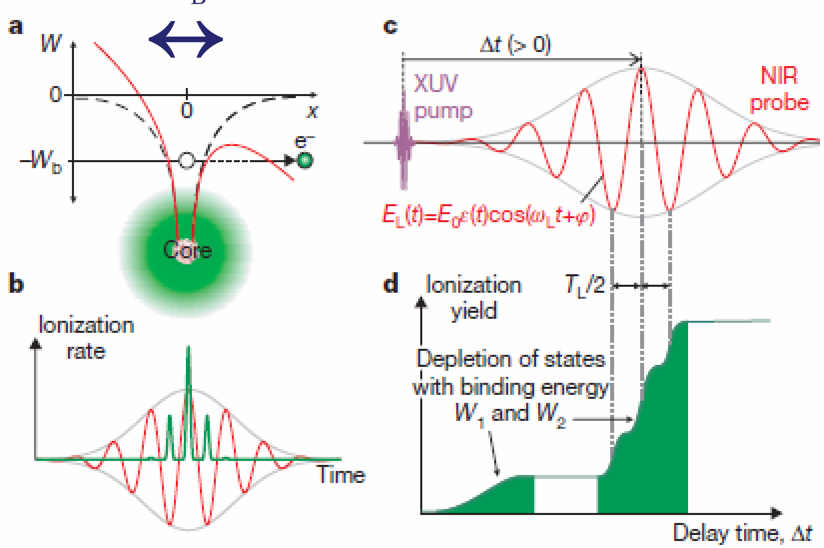
Nonperturbative: $W_\parallel =$ [illegible] $, \quad W_\perp = 2W_\parallel, \quad \varkappa \ll 1.$ (36')

For large values of ϰ we essentially have u ≫ 1 in the integrals (36). Using this fact, we obtain

Multiphoton: $W_\parallel =$ [illegible] $, \quad W_\perp = \frac{3}{2} W_\parallel, \quad \varkappa \gg 1.$ (36'')

Uiberacker et al. (2007)

a_B



XUV photon ionization
Laser streaking
→ attosecond dynamics

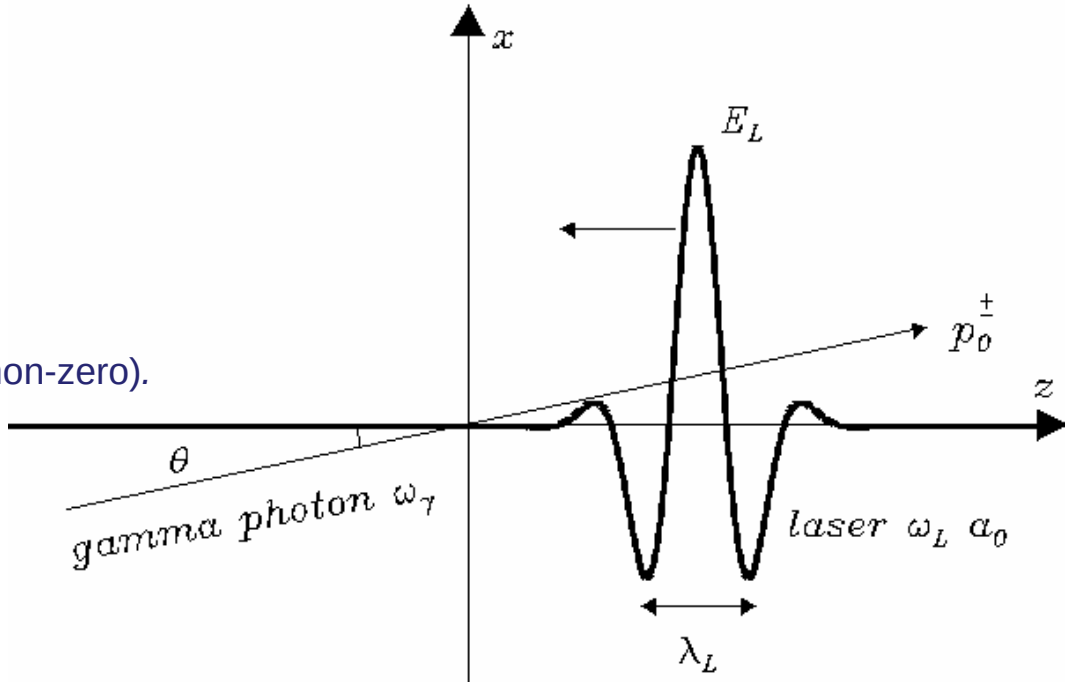
atom

γ-photon induced vacuum streaking by lasers

Schwinger-Nikishov amplitude

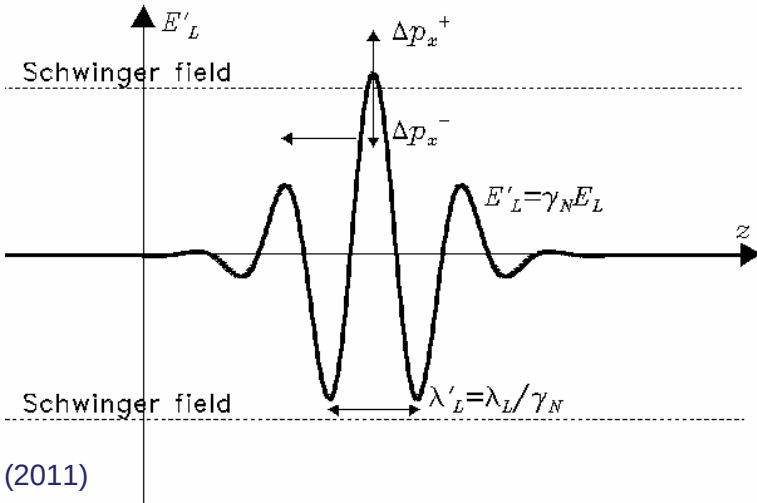
$a_0^{SN}=(mc^2/\hbar\omega_L)(mc^2/\hbar\omega_\gamma)$

(We need to make the Schwinger invariant non-zero).



time resolution of streaking on the Nikishov frame (the Nikishov $\gamma_N = \hbar\omega_\gamma/mc^2$)

$\Delta t' = [2(\hbar/mc^2)/(a_0^2\omega_L^2)]^{1/3}$.



Necessary laser amplitude:

$a_0^{res} = 2\ (mc^2/\hbar\omega_L')$.

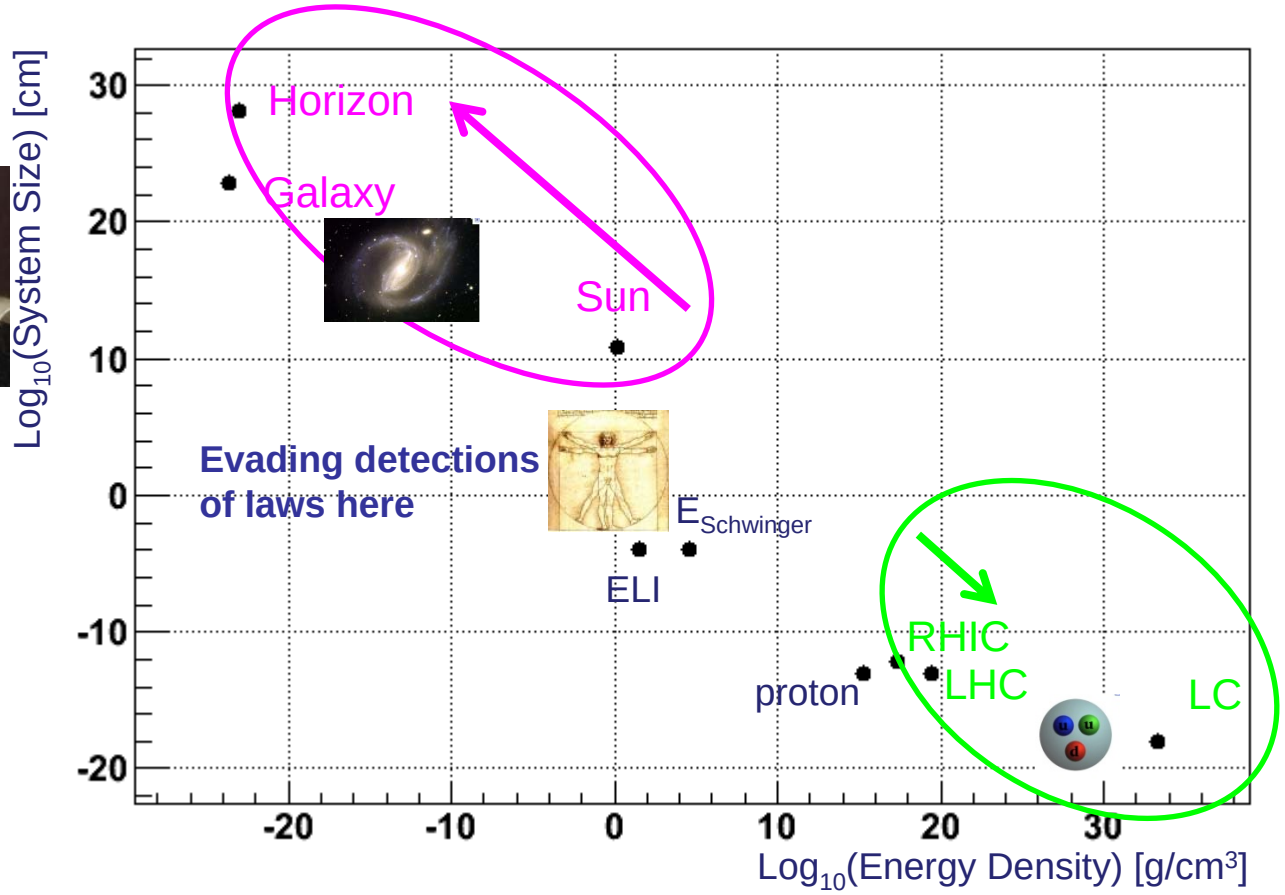
Tajima, Goulielmakis, Krausz, et al (2011)

Laser fits the gaping hole

in search of unknown fields:
dark matter/dark energy

IZEST

Cosmological observation



High energy collider

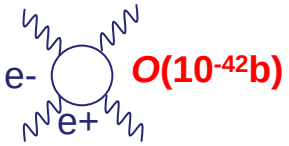
Domains of physical laws

Homma, Habs, Tajima (2011)

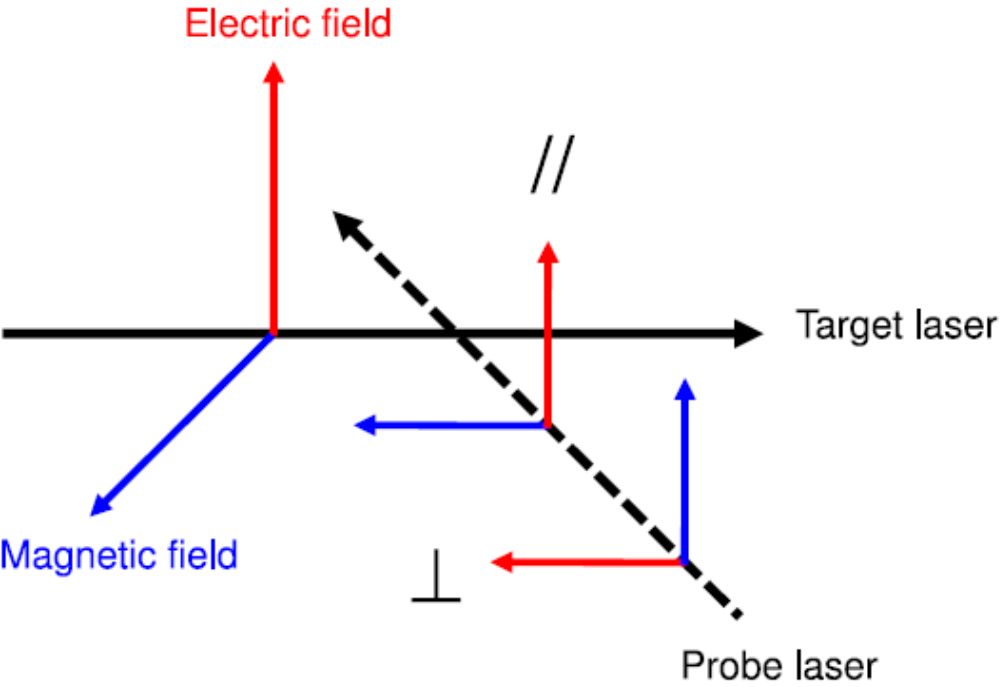
Birefringence by QED in eV range

Euler-Heisenberg one-loop Lagrangian

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



Refractive index depends on polarizations



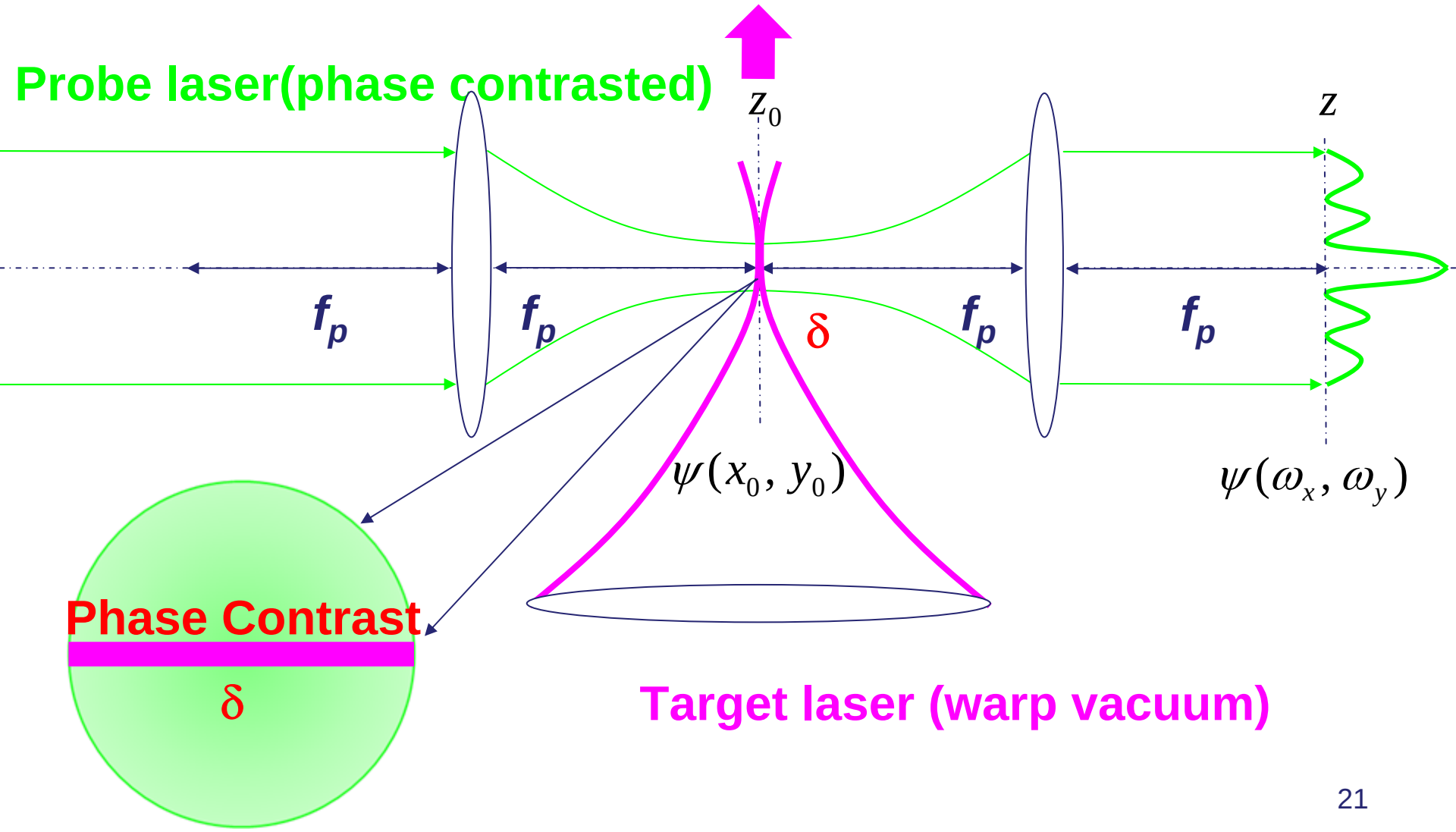
$$n_{\parallel} = 1 + \frac{16}{45}\frac{\alpha^2 U}{U_e}, \quad n_{\perp} = 1 + \frac{28}{45}\frac{\alpha^2 U}{U_e}$$

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

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

(Homma, Habs, Tajima)

Phase contrast imaging of vacuum



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

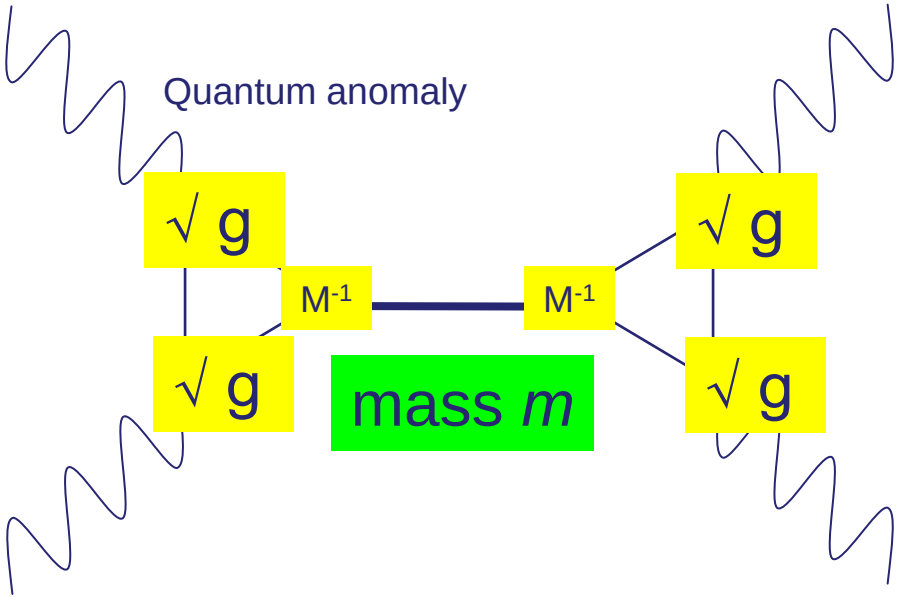
Beyond QED photon-photon interaction

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

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

Away from 4 : 7 = QCD , low-mass scalar ϕ , or pseudoscalar σ

Resonance in quasi-parallel collisions in low cms energy



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

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

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

QCD-instanton, Dark Matter

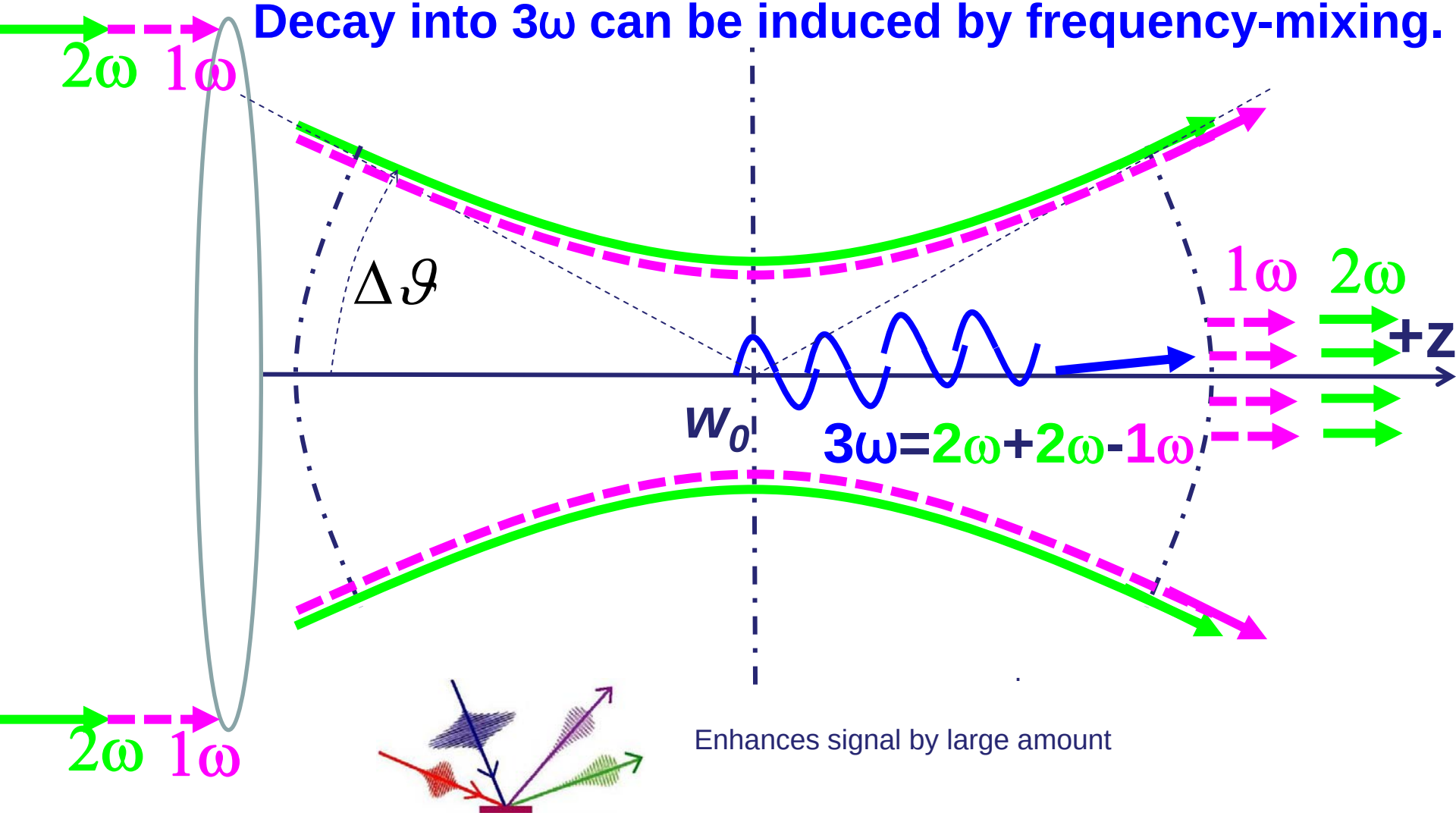
$$gM^{-1}F^{\mu\nu}\tilde{F}_{\mu\nu}\sigma$$

K.Homma, D.Habs, T.Tajima

Degenerate Four-Wave Mixing (DFWM)

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

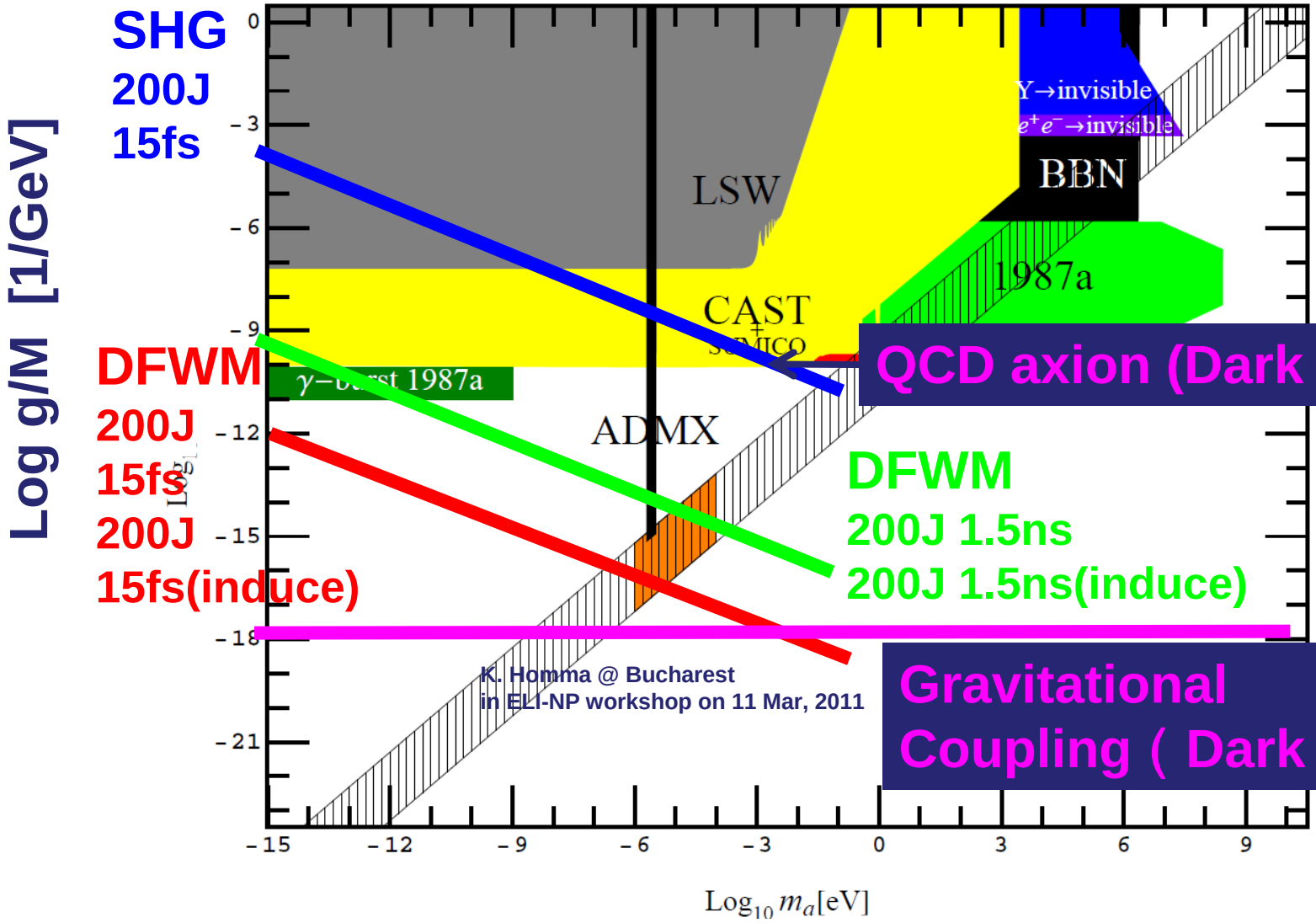
Decay into 3ω can be induced by frequency-mixing.



Enhances signal by large amount

K.Homma, D.Habs, T.Tajima

HFS road to unknown fields: dark matter and dark energy



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

Latest Development: CERN getting into the game

EuroNNAc Workshop on novel accelerators (May 3-6, 2011)

Tuesday 03 May 2011

Introductory Presentations - Kjell Johnsen Auditorium (08:30-10:30)

- Conveners: Dr. Collier, Paul (CERN)

time	title	presenter
08:30	Goals of Network and Workshop (00h15')	ASSMANN, Ralph (CERN)
08:45	Accelerator R & D as Driver of Innovation (00h45')	HEUER, Rolf (CERN)
09:30	History and Outlook for Plasma Acceleration (00h30')	TOSHI, Tajima (LMU Munich)
10:00	Modern Lasers for Novel Acceleration Methods (00h30')	MOUROU, Gerard (ILE)

Coffee Break - 30-7-012 (10:30-11:00)

Introductory Presentations - Kjell Johnsen Auditorium (11:00-12:30)

- Conveners: Dr. Collier, Paul (CERN)

time	title	presenter
11:00	Accelerator R & D for Particle Physics (00h30')	MYERS, Steve (CERN)
11:30	Status Report Asia (00h30')	SHENG, Zhengming (Shanghai Jiao Tong University)
12:00	Status and Plans US (beam driven) (00h15')	HOGAN, Mark (SLAC)
12:15	Status and Plans US (Laser driven) (00h15')	ESAREY, Eric (LBNL)

IZEST

International Center for Zetta-Exawatt Science and Technology

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

ELI (2010), now Mega Project on Extreme Laser (2011)

Extreme Light Infrastructure: EU decided (2010) at Czech, Hungary, and Romania
Now, Russia announced July 5, 2011: 6 Mega Projects (3-4B Euro) include **Extreme Laser**

Beyond Exawatt
Beyond 10kJ

ELI: serving Chair, Scientific Advisory Committee
Extreme Laser Mega Project (in budget negotiation):
Chief Scientific Advisor/
Mega Grant Honorary Director (suggested)
International team being formed:
IZEST (International Center for Zetawatt / Exawatt Science and Technology)

http://strf.ru/

S&TRF
НАУКА И ТЕХНОЛОГИИ РФ

Евразийский открытый институт, используя обучение через интернет, реализует 18 программ ба..

По диаметру отверст можно определить и веществ у ..

05.07.11
Σ Стерлигов Иван
Правительственная комиссия по высоким технологиям и инновациям: Обсуждение

Обсуждение
Версия для печати
добавить ссылку

Сверхмощный лазер как интегратор науки

В числе меганаучных проектов, которые будут реализованы на территории России, – Международный центр исследований экстремальных световых полей на основе сверхмощного лазерного комплекса в Нижнем Новгороде. Руководит центром всемирно известный физик Жерар Муру при поддержке Минобрнауки России. STRF.ru подробно рассказывал об этой работе в статье «Российские учёные строят сверхмощный лазер». Насколько значим этот проект для мировой науки, мы выяснили у Тосики Тадзимы, заведующего кафедрой физического факультета Университета Людвига Максимилиана в Мюнхене, председателя Международного комитета по сверхмощным лазерам (International Committee on Ultra-High Intensity Lasers, ICUIL).

Тосики Тадзиме не терпится поучаствовать в российском мегапроекте по созданию сверхмощного лазера

Справка STRF.ru:
Международный комитет по сверхмощным лазерам – подразделение Международного союза фундаментальной и прикладной физики, основанное в 2003 году. Задача ICUIL – продвижение науки и технологии сверхмощных лазеров и координация исследований и разработок в этой области. Под сверхмощными лазерами в комитете понимают лазеры с интенсивностью 10^{19} ватт на см^2 и мощностью около 10 тераватт

На Ваш взгляд, что примечательного произошло в области сверхмощных лазеров в последнее время?

– Прошлый год стал эпохальным для нас благодаря решению Евросоюза о запуске проекта Extreme Light Infrastructure [ELI, включает целый ряд сверхмощных лазеров в нескольких регионах Европы], а также началу реальной работы National Ignition Facility в США – альтернативный токамакам проект термоядерной энергетики, основанный на лазерном нагреве и инерционном удержании плазмы. Мы предполагаем, что развитие сверхмощных лазеров и сопутствующих областей науки значительно ускорится, и стараемся способствовать

XCELS (Russia)

Conclusions

- Optical approach: does it overtake the accelerator in high energy and fundamental physics?
- Collider physics requirements: ==➔ low density operation, laser with large energy per stage
- Energy frontier (beyond TeV) with precision w/ a few shots possible = non-collider paradigm of fundamental science

  e.g. Lorentz invariance test , quantum gravity
- High field science approach: capability to explore new fields (dark matter; dark energy): SHG, DFWM, learning from NLO (in matter); zs metrology
- Join us at *IZEST;* collaboration btw ISTC and IZEST

The Cabin in Suzdal
(a Waka poem)

「遥か来ぬ　ロシアの大地　夏残照
芳しきかな　丸太屋の宿」

“The distance I‘ve come
far to the land of Russia
at summer’s last cry
What fragrance and comfort
the logcabin lulls me in!”

Toshi Tajima
Sept, 2011

Спасибо!