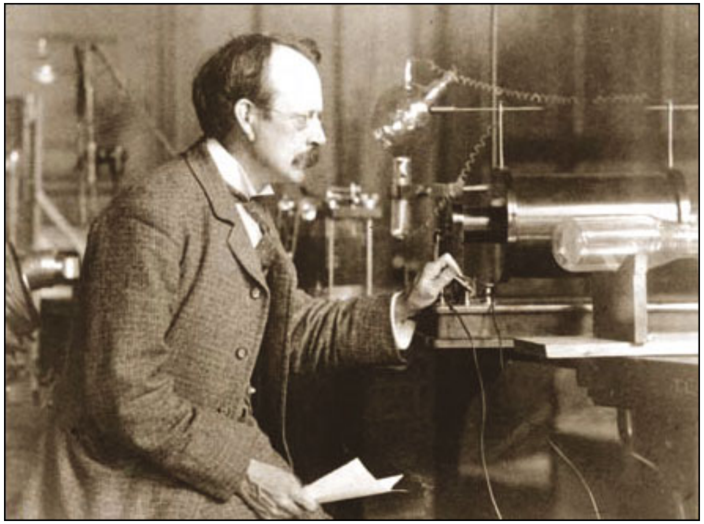
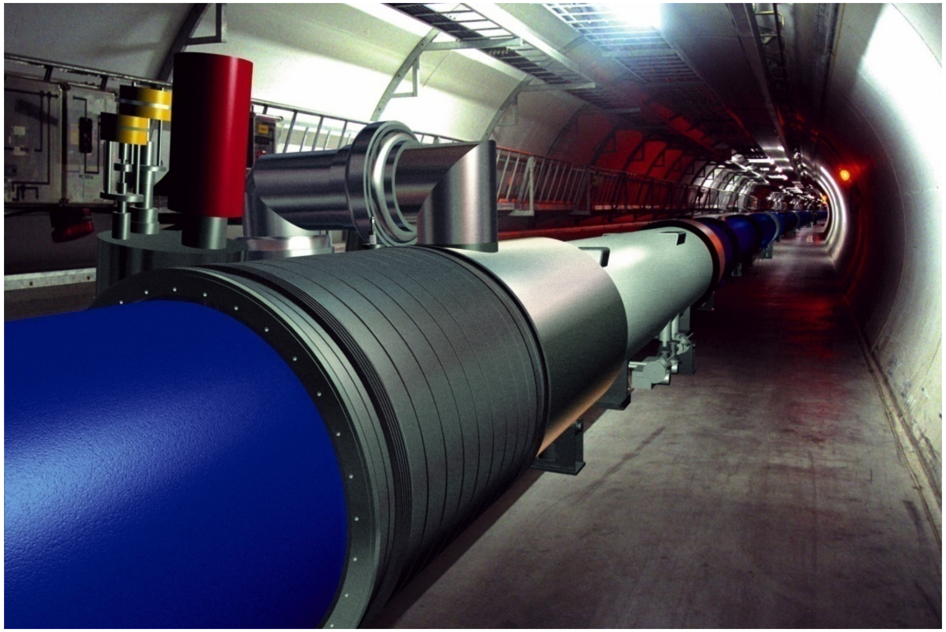
1. Fundamental physics with intense lasers
2. Isomorphism between atomic physics and vacuum physics
   - Keldysh field vs. Schwinger field
   - attosecond streaking of an atom → zeptosecond streaking of vacuum
3. Nonlinear QED as an entry to new field search:
   - Heisenberg-Euler Lagrangean---phase contrast imaging of vacuum
   - Detection of its possible deviation
4. Low energy new fields: Frontier of large number of coherent photons:
   - Dark Matter and Dark Energy fields in vacuum
   - 'Shake the vacuum', Degenerate 4 wave mixing
     - luminosity increases faster than N^2 with coherency
5. Mission of *IZEST:*
   - kJ [large photon number (=Avogadro number)] laser (*PETAL*)
   - + high average power laser (*ICAN*) toward fundamental physics in the international networking (with many willing labs to cover a wide range of parameters)

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



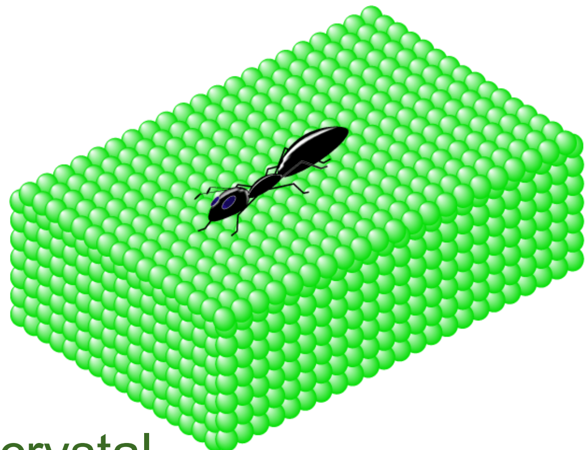
J. J. Thomson



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

C. Townes

What is vacuum?



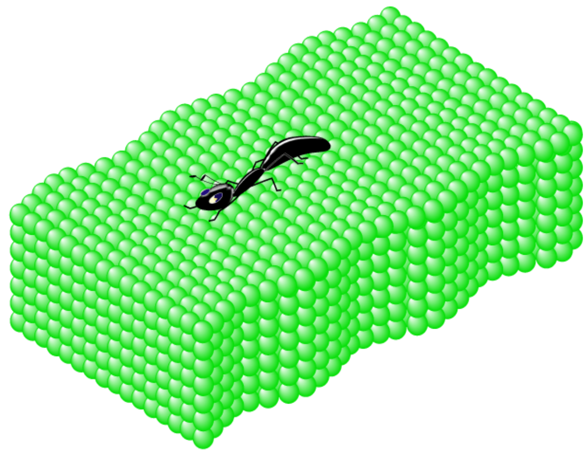
crystal

An observer (bug) in crystal looks at vacuum

↓

vacuum

「真(true)空(nothing)」

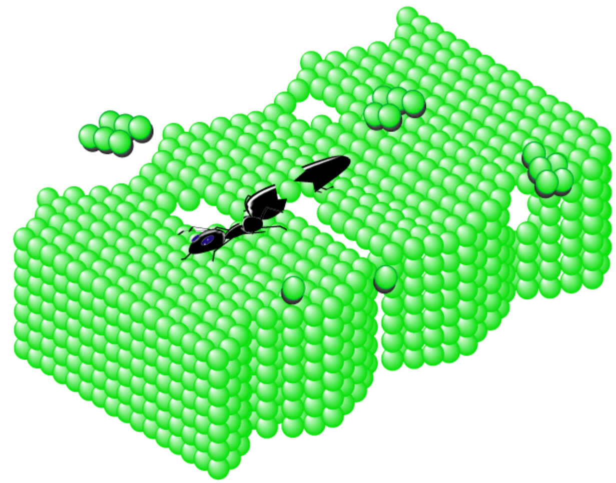


Phonon : excitation of vacuum

↓

Photon : distortion of vacuum

「色=(即是)空」



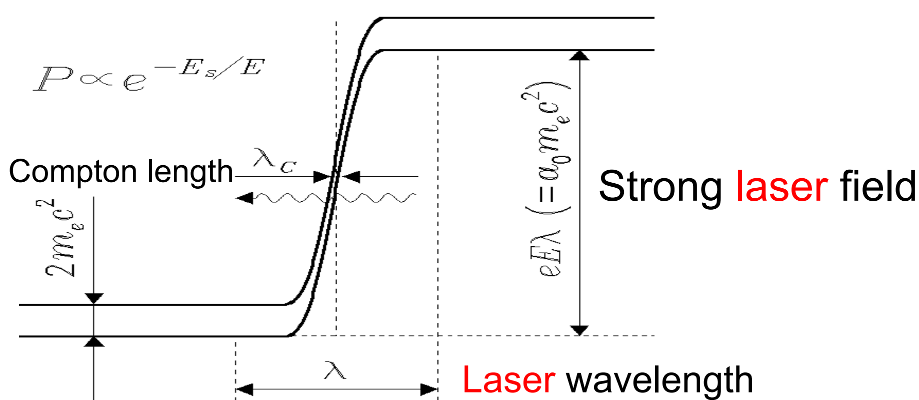
Strong field breaks vacuum

↓

vacuum produces e+e- pair

「空=(即是)色」

QED vacuum breakdown



Self-focusing in air to vacuum

Critical power for self-focusing in matter /plasma / vacuum:

χ_3 nonlinearity

$$P_{cr} = \lambda^2/(2\pi n_0 n_2) \sim \mathrm{GW}$$

relativistic plasma nonlinearity

$$P_{cr} = mc^5/e^2(\omega/\omega_p)^2 \sim 17\,(\omega/\omega_\mathrm{p})^2\ \mathrm{GW}$$

vacuum nonlinearity

$$P_{cr} = (90/28)\, c\, E_S^2\lambda^2/\alpha \sim 10^{15}\,(\lambda/\lambda_{1\mu})^2\ \mathrm{GW}$$

e.g. X-ray of 10keV, $P_{cr} \sim 10\mathrm{PW}$

‘ELI Long-term Ambition’ =

Studying the Atomic Structure to the Vacuum Structure

Does the atomic world repeat itself in vacuum?

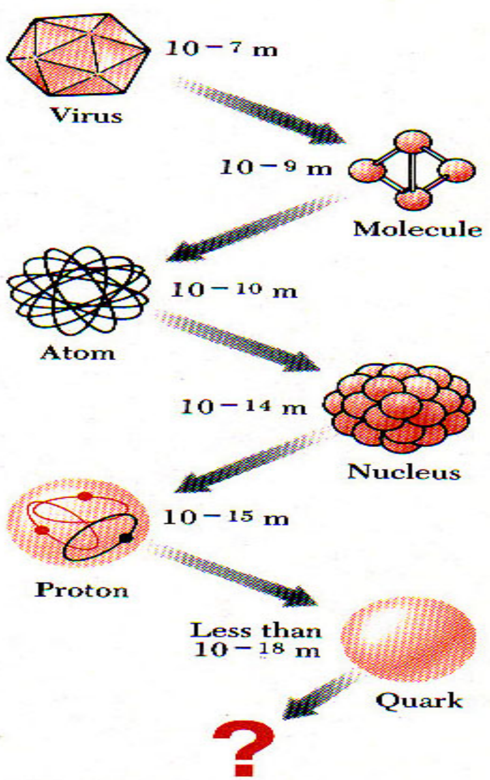
Isomorphism between atomic physics and vacuum QED exists,

However, not identical (atomic: non-relativistic);

(vacuum: relativistic, s.a. Schwinger invariants)

(Mourou)

= Path toward superSchwinger



Vacuum structure

Keldysh field

Keldysh parameter

$$\gamma_K = \omega\sqrt{2m\Phi}/eE,$$

Schwinger intensity / Keldysh intensity $= \alpha^{-6} \sim 10^{14}$

Vacuum self-focusing /χ_3 self-focusing power $\sim \alpha^{-6} \sim 10^{15}$

Vacuum parameter

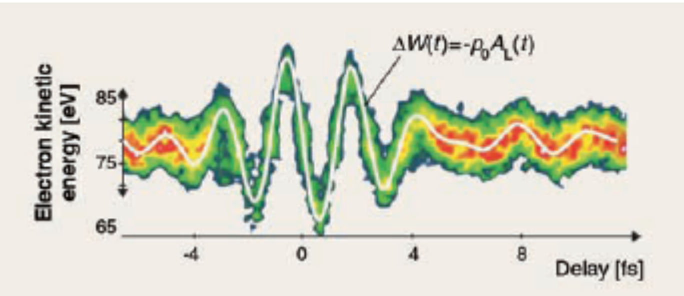
$$\gamma_V = 1/a_0.$$

Schwinger field

γ-photon induced vacuum streaking by lasers

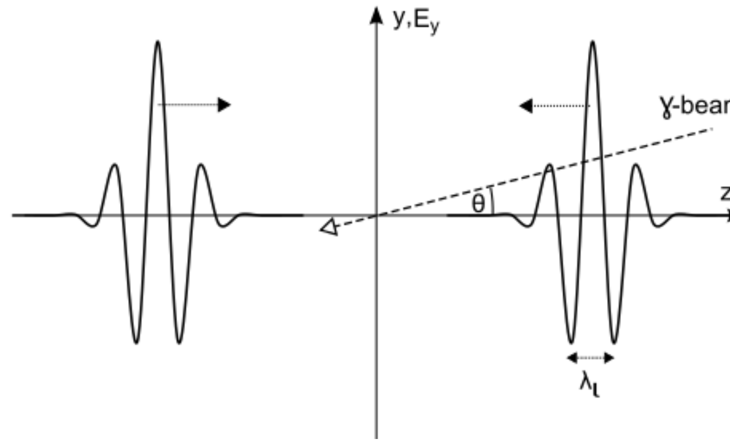
Tajima, Goulielmakis, Krausz, et al (2011); Ipp et al (2011)

Atomic as streaking



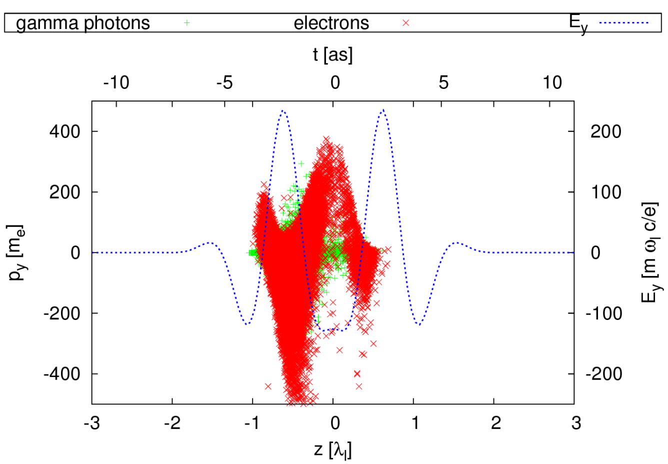
Goulielmakis(2008)

Laser field is compressed by factor $(h\nu/mc^2) \sim 10^{3\text{-}4}$ with the counterstreaming high energy γ

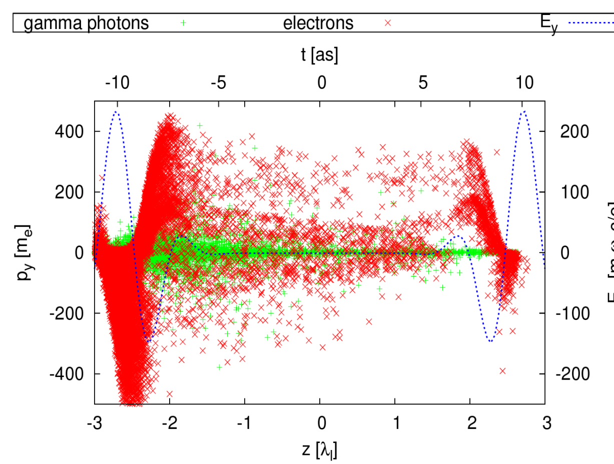


QED vacuum streaking

earlier

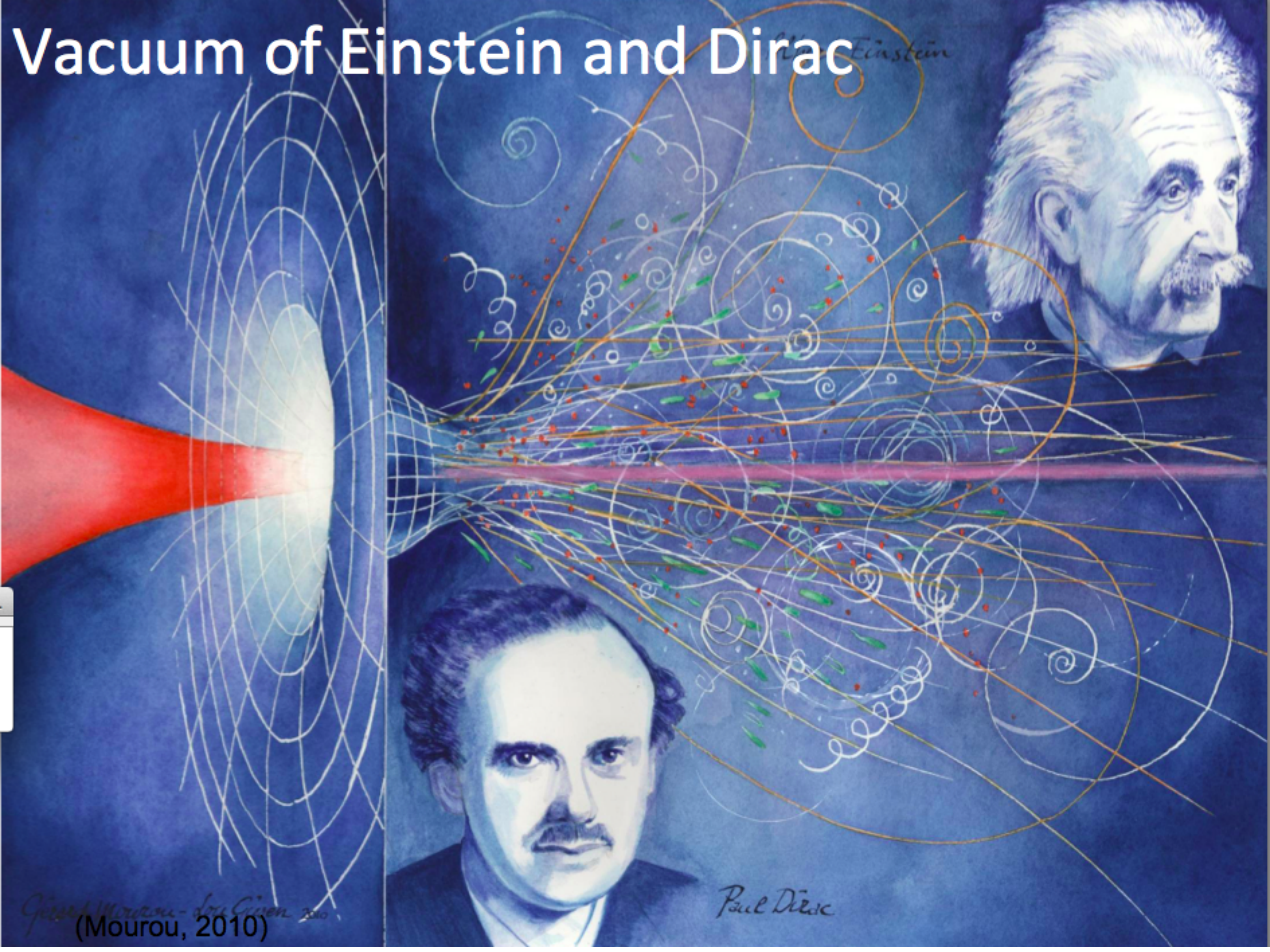


→ later; cascade effects



C. Klier et al (2011)

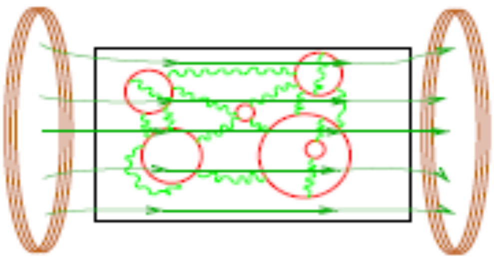
Vacuum of Einstein and Dirac

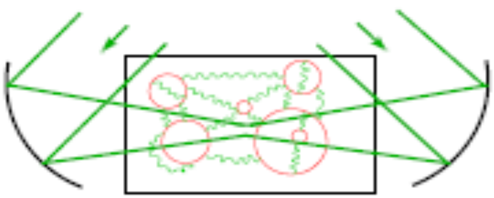


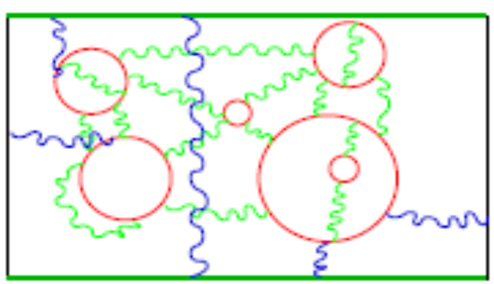
(Mourou, 2010)

Why quantum vacuum physics?

Vacuum nonlinearities







- Heisenberg-Euler/Casimir in mathematical physics
  - QFT in strong fields or with boundaries
  - functional determinants
- applied quantum vacuum physics
  - quantum fluctuations as a building block
  - dispersive forces in micro/nano machinery [DeKieviet @ ThisWorkshop]
- fundamental effect of QFT
  - ($\sim$ Lamb shift, $g-2$, ...)
- fundamental physics
  - search for new physics
  - new particles or forces

H. Gies (2008)

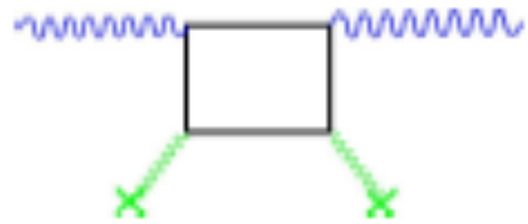
Light Propagation in a B field.

▷ quantum Maxwell equation for a "light probe" $f^{\mu\nu}$

$$0 = \partial_\mu f^{\mu\nu} - \frac{8}{45}\frac{\alpha^2}{m^4} F_{\alpha\beta} F^{\mu\nu} \partial_\mu f^{\alpha\beta} - \frac{14}{45}\frac{\alpha^2}{m^4} \tilde{F}_{\alpha\beta} \tilde{F}^{\mu\nu} \partial_\mu f^{\alpha\beta}$$

↑ vacuum nonlinearity ↑

Phase and group velocity



$$v_{\|} \simeq 1 - \frac{14}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

$$v_{\perp} \simeq 1 - \frac{8}{45}\frac{\alpha^2}{m^4} B^2 \sin^2\theta_B$$

(Toll'54)

(Baier, Breitenlohner'67; Narozhny'69)

(Bialynicka-Birula, Bialynicki-Birula'70)

(Adler'71)

$\Longrightarrow$ magnetized quantum vacuum induces birefringence

[DiPiazza @ ThisWorkshop]

▷ detection schemes: PVLAS, BMV, Q&A, OSQAR, TR18-B7

H. Gies (2008)

IZEST's Missions

- An international endeavor to unify the high Intensity laser and the high energy / fundamental physics communities to draw

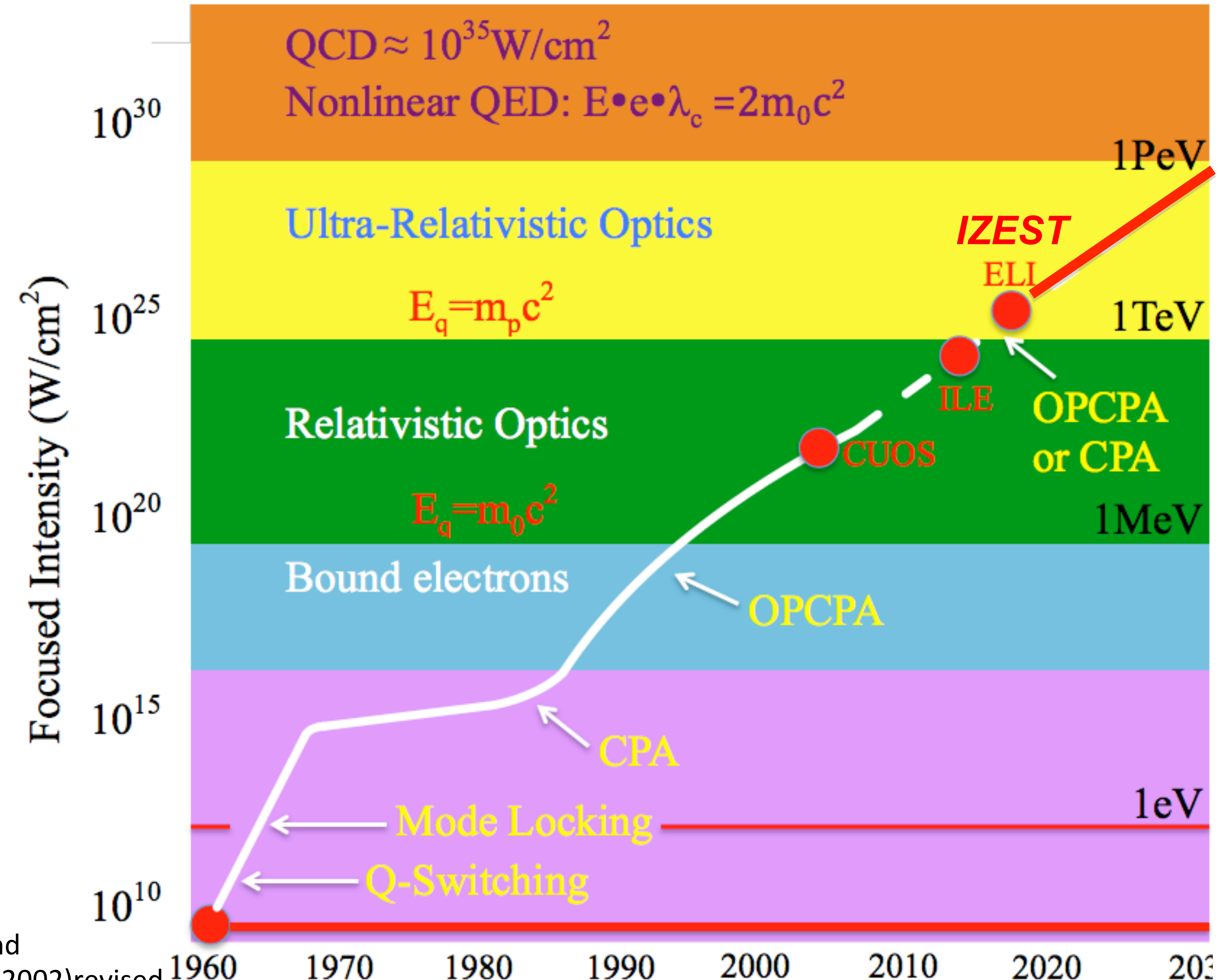
"The Roadmap of Ultra High Intensity Laser"
and apply it to
"Laser-Based Fundamental Physics"

- To form an international team of scientists that can foster and facilitate scientific missions of EW/ZW class lasers and high average power lasers (***ICAN***) comprised from ICFA and ICUIL communities (in collab)

See more:
www.int-zest.com/

Also: Tajima and Mourou PR STAB(2002)

Laser intensity exponentiates over years



Tajima and Mourou (2002)revised

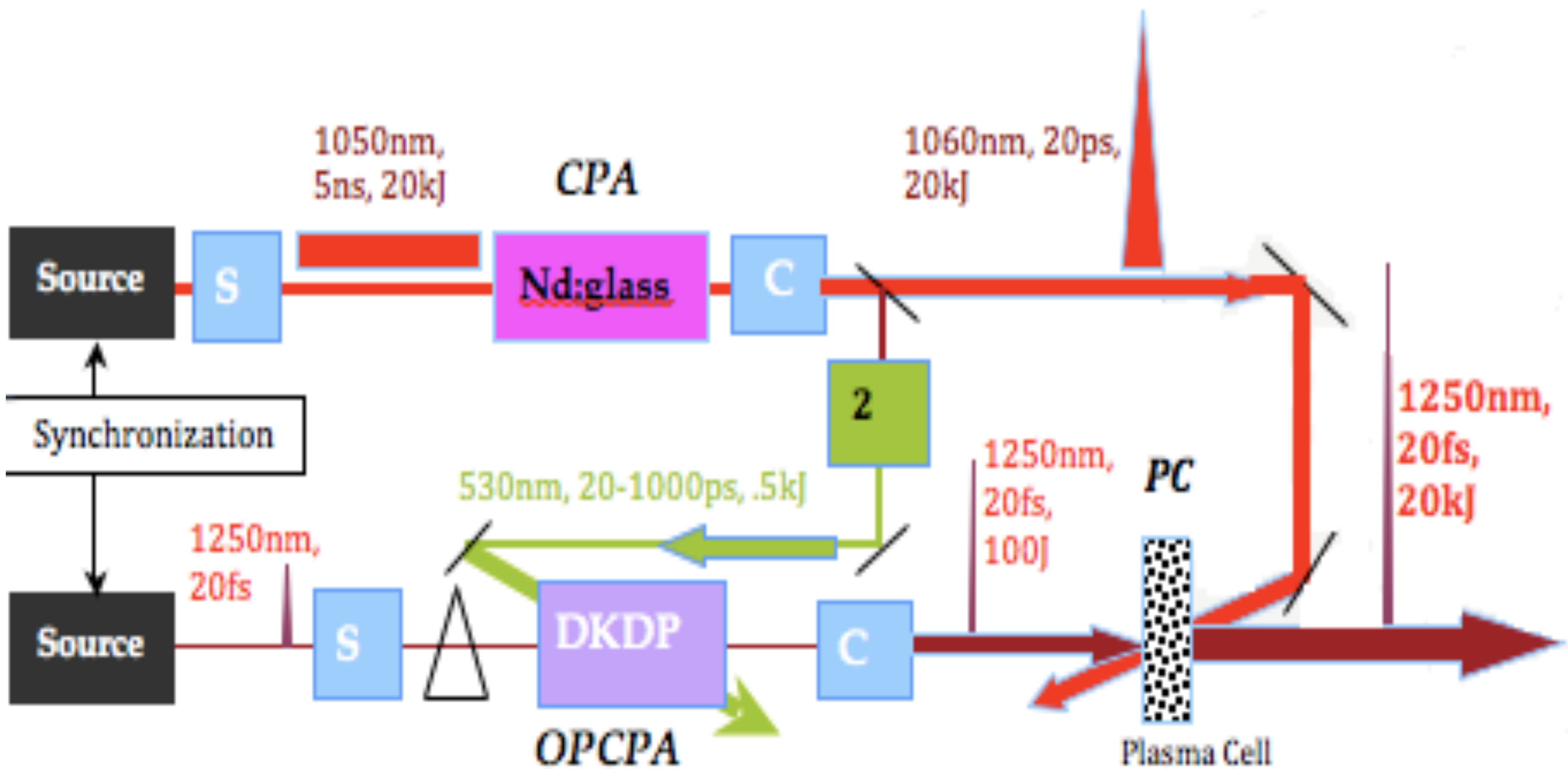
ELI : www.extreme-light-infrastructure.eu/

IZEST

New Laser Compression Concept C^3

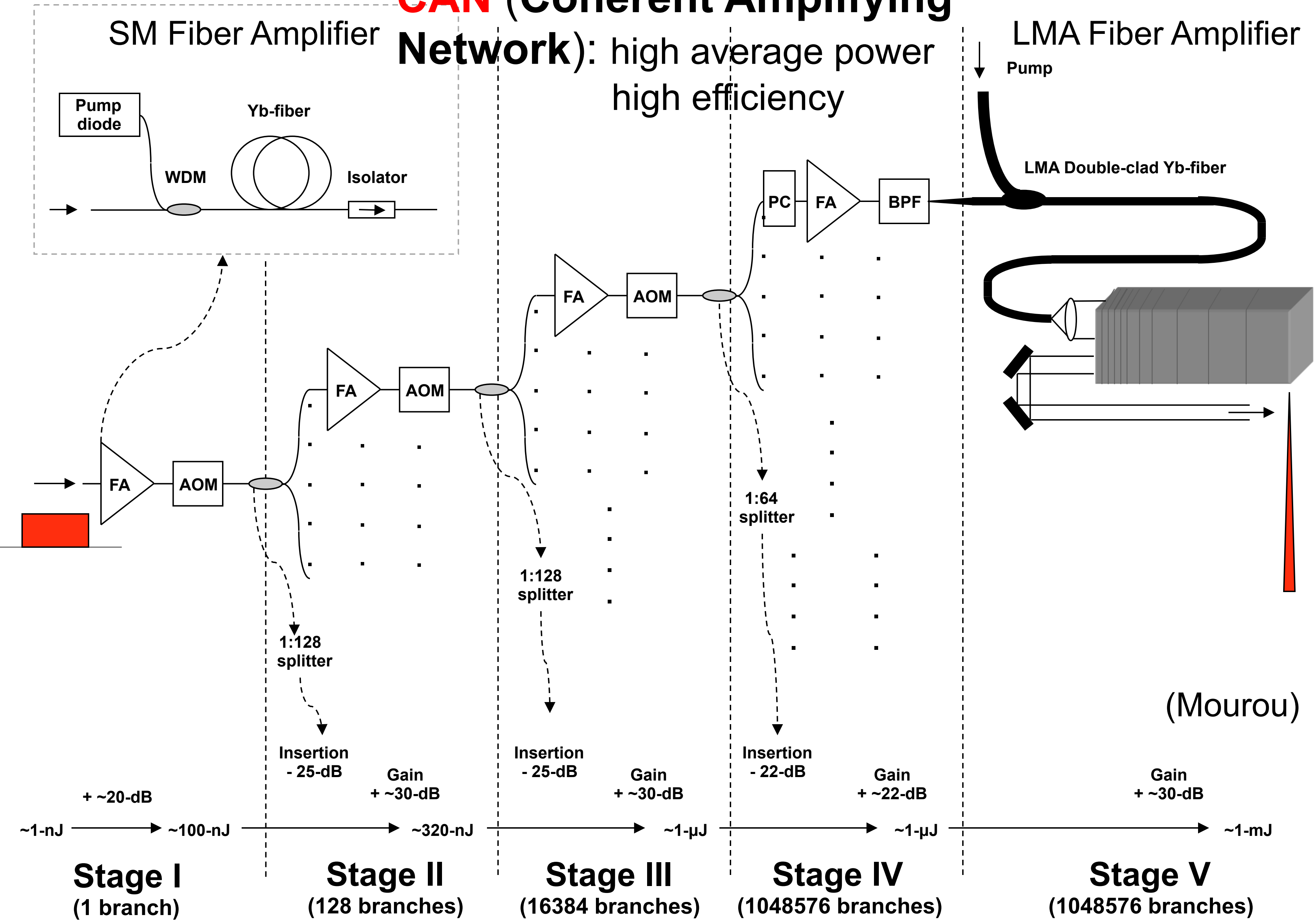
(Cascaded Compression Conversion)

to achieve intensity > 10^{23}W/cm^2



G. Mourou et al. Opt. Comm.(2012)

CAN (Coherent Amplifying Network): high average power high efficiency



(Mourou)

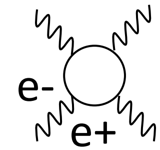
Dark Matter / Dark Energy (Quantum Gravity Vacuum)

- Weakly interacting particles like axion or axion-like, U(1) gauge bosons with low mass in the sub-electron volt?
- Nonlinear effect in large electromagnetic fields: light shinning through a wall → much more sensitive new technique.
- Ultralight ultraweak coupling fields of quantum gravity origin (Dark Energy candidate) in ~ nano-electron volts?

Birefringence by QED in eV range

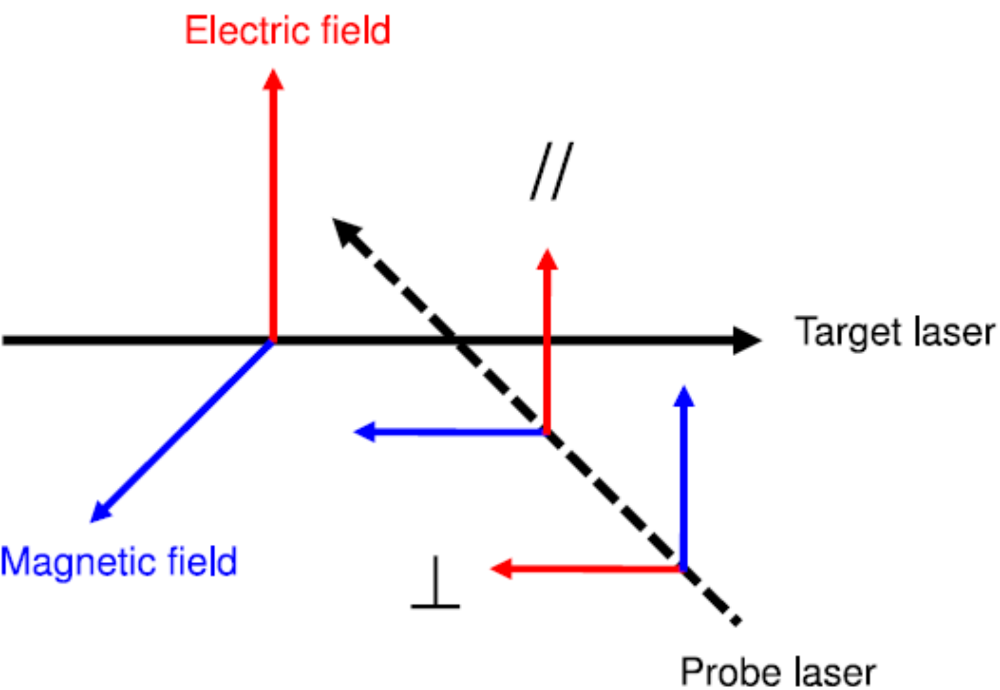
Euler-Heisenberg one-loop Lagrangian

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



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

Refractive index depends on polarizations



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

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

ELI(~200J per ~20fs)

can reach $\Delta n \sim 10^{-9} \sim 10^{-10}$

σ so small, never observed--→

fortune in disguise

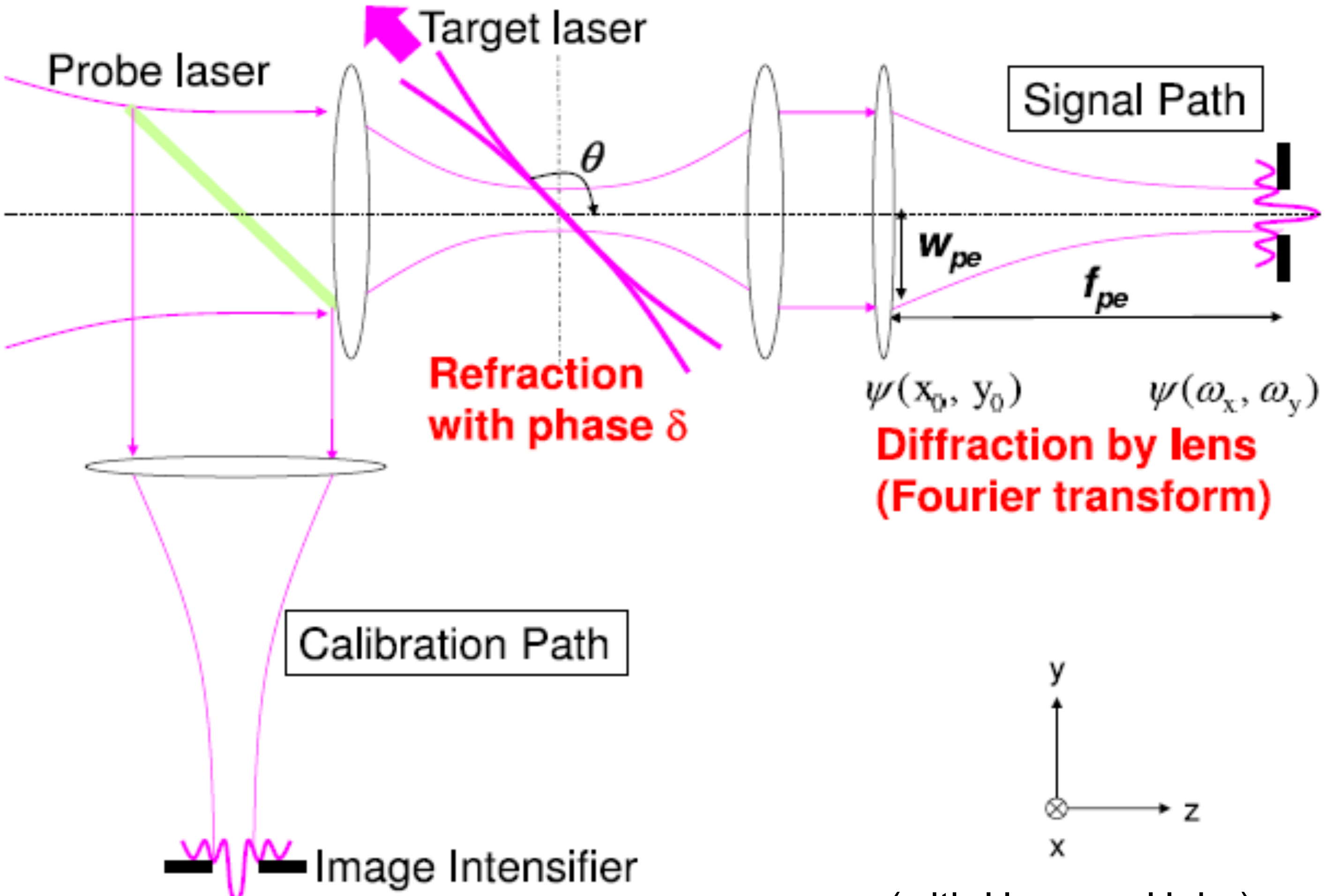
(Homma, Habs, Tajima, 2011)

QED vacuum probe by intense laser

Heisenberg-Euler Langrangian: tiny nonlinearity, never observed

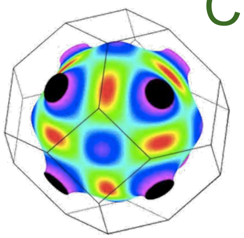
→ intense laser needed; sensitive probe, avoid blinding laser

Phase contrast imaging(refractive index →diffraction, noise reduction)

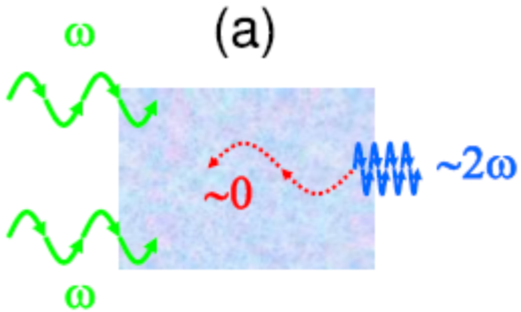


(with Homma, Habs)

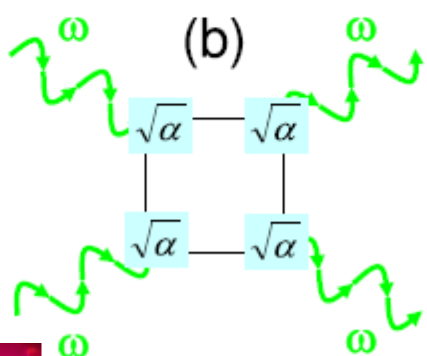
Intense laser probes matter /vacuum nonlinearity

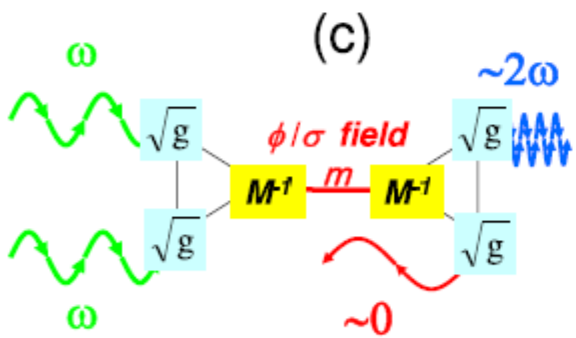


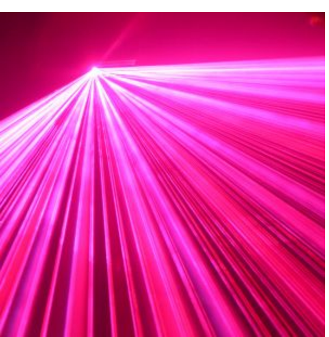
Crystal nonlinearity →
second harmonic generation (Franken et al, 1961)



Learn from **Nonlinear Optics** of matter for vacuum:







QED nonlinearity

Vacuum nonlinearity by light- mass field (dark energy, axion,..)
→ second harmonic

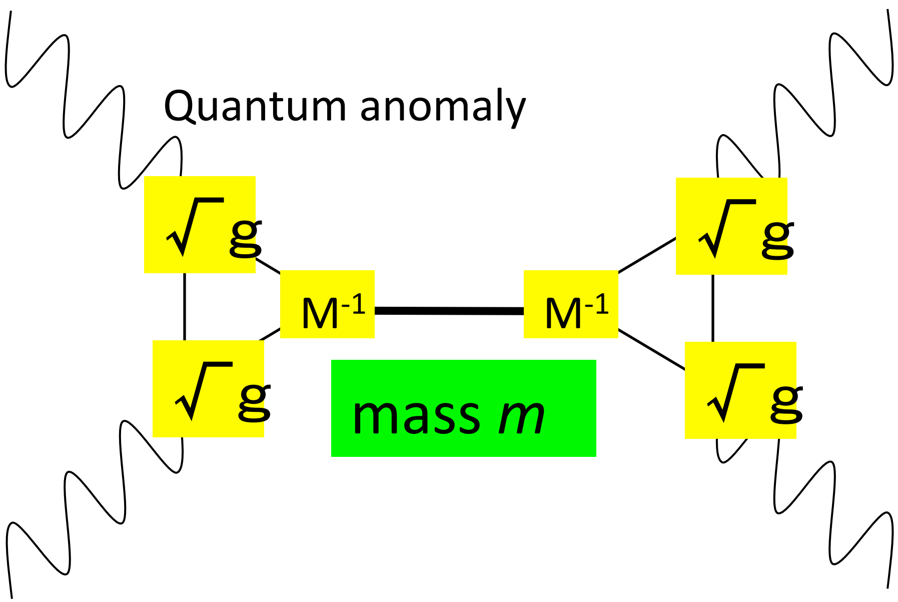
Beyond QED photon-photon interaction

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

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

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

Resonance in quasi-parallel collisions in low cms energy



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

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

QCD-instanton, Dark Matter

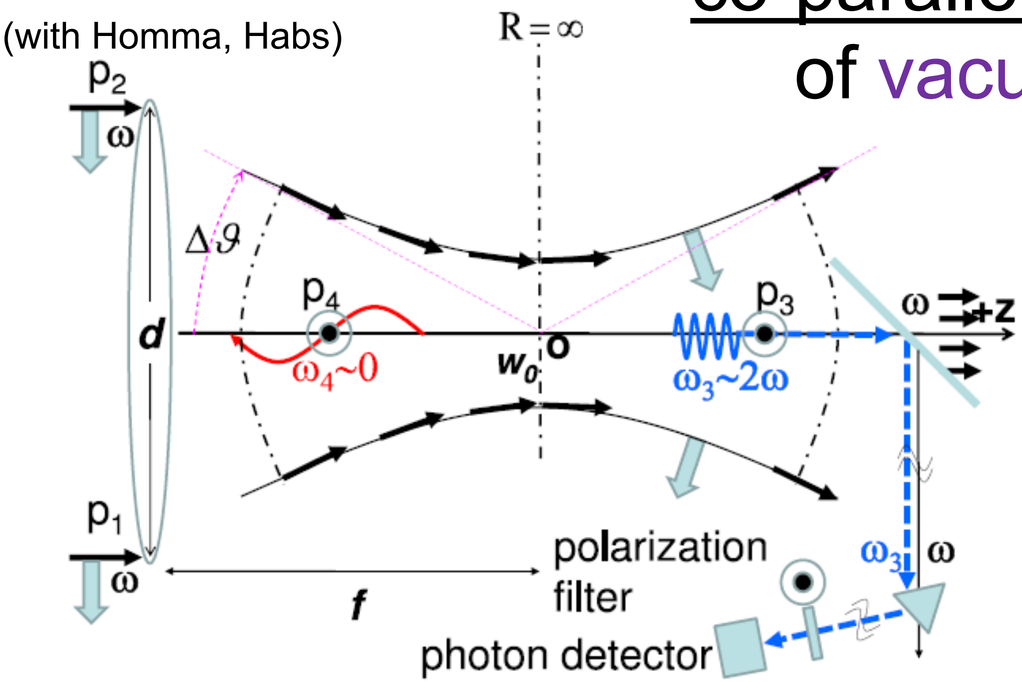
$$gM^{-1}F^{\mu\nu}\tilde{F}_{\mu\nu}\sigma$$

K.Homma, D.Habs,
T.Tajima (20121, 2012)

Learning from laser parametric scattering: low energy (meV - neV) fields (vacua)

co-parallel intense laser probe of vacuum

(with Homma, Habs)



Many orders of magnitude gain in resonant coupling and sensitivity over long interaction:

Nonlinearity of vacuum

$\omega + \omega \rightarrow 2\omega$ (SHG a la Franken)

or see next .

cf. Brillouin forward scattering beat / optical parametric excitation = phonon mediating (Nambu-Goldston boson)

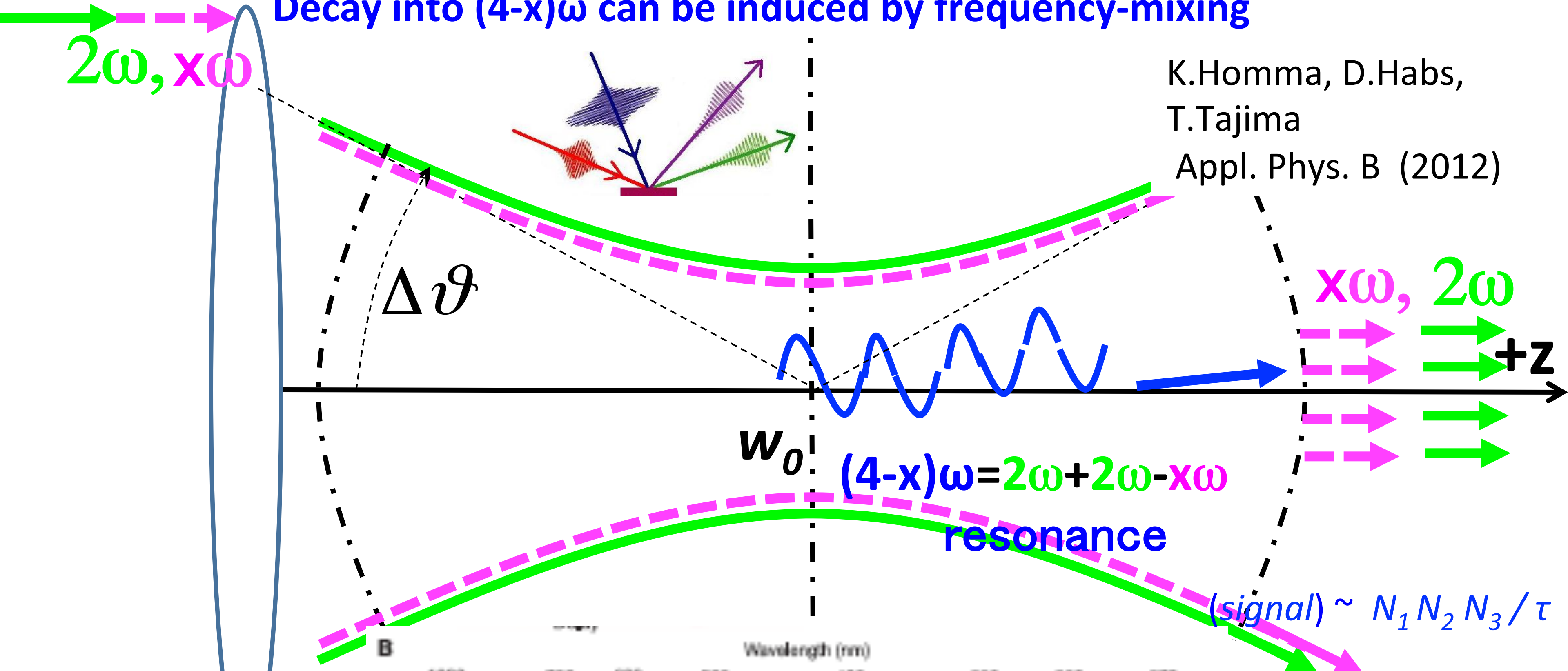
Mass of light fields(dark energy fields, axion-like fields) resonates with specific crossing angle of co-propagating lasers

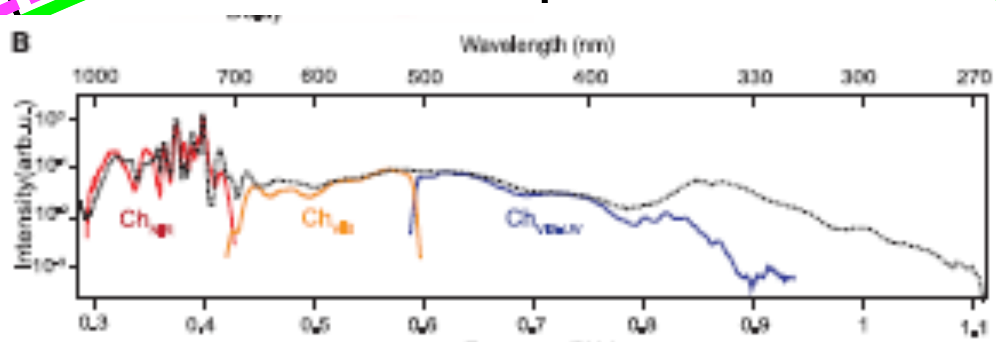
Degenerate Four-Wave Mixing (DFWM)

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

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

K.Homma, D.Habs, T.Tajima Appl. Phys. B (2012)



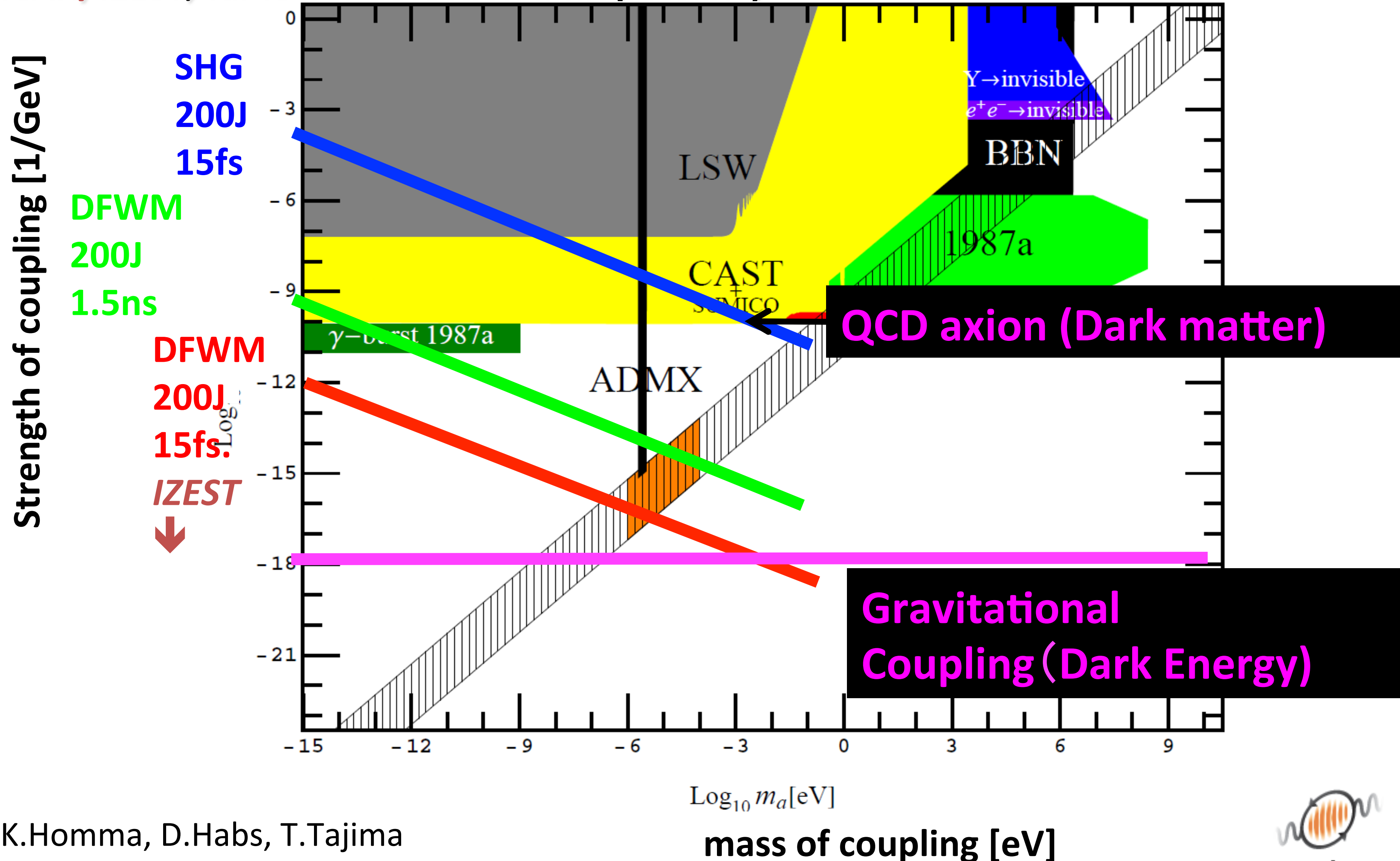


Sweep by arbitrary frequency xω

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

Photon mixer to new fields:

Dark Matter and Dark Energy in a single shot (with rep-rate such as *ICAN/IZEST*, far lower detection limit possible)

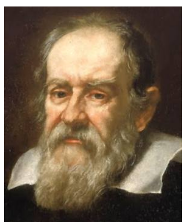


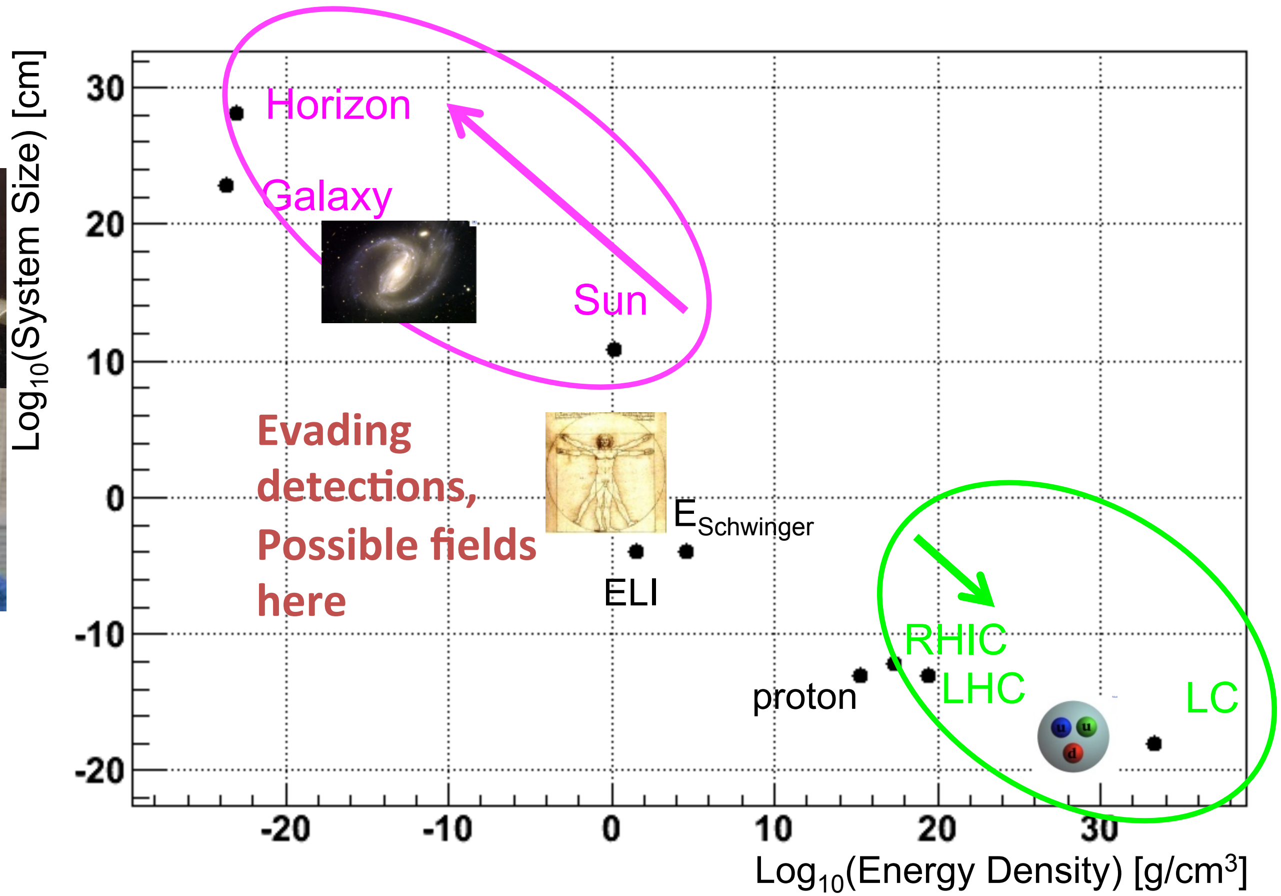
K.Homma, D.Habs, T.Tajima (2012)

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 (2012)

Conclusions

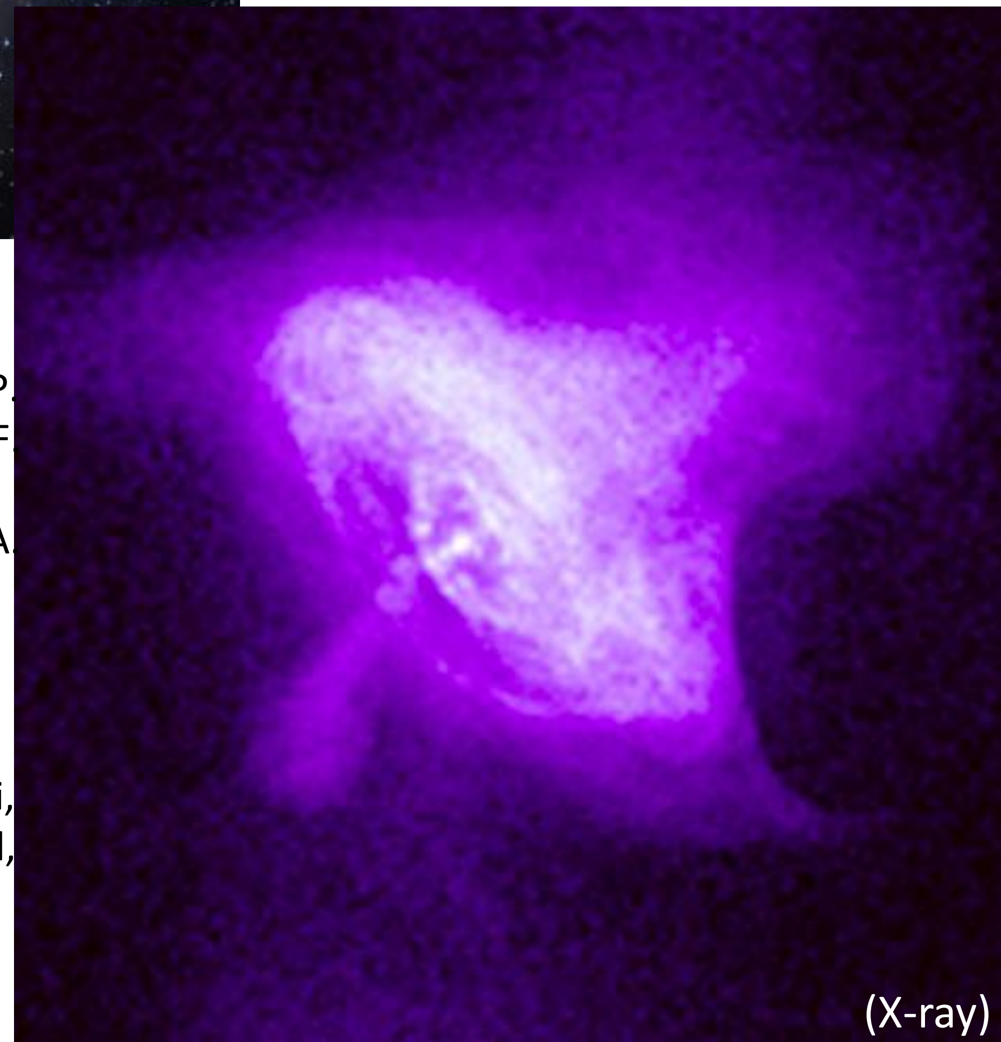
- Nonlinear optics (atoms) → Nonlinear optics (vacuum)
- Nonlinear QED: phase contrast imaging of vacuum---
  Heisenberg-Euler Lagrangean, Specific prediction
- Any deviation from above → new physics, new fields
- Proposed degenerate 4 wave mixing method:
  very sensitive to detect small-mass new fields such as
  Dark Matter(axion-like particles) and Dark Energy
- The sensitivity (and luminosity) of the coherent large photon number detection:
  luminosity (per shot) N^3/τ [N the number of laser photons (~Avogadro number), τ the pulse length]: $N^3/\tau \sim 10^{70}$ ($N^3 f/\tau$ when rep-rate f is applied, could be greater than 10^{80} per year)
- New way of exploring fundamental physics with intense and large photon number lasers emerging

Thank you!

Cosmic PeV accelerating machine

Crab nebula:

← optics ↓ X-rays



Acknowledgments for Collaboration:
G. Mourou, W. Leemans, K. Nakajima, K. Homma, P. Bolton, M. Kando, S. Bulanov, T. Esirkepov, J. Koga, F. Krausz, E. Goulielmakis, D. Habs, B. LeGarrec, C.. Barty, D. Payne, H. Videau, P. Martin, W. Sandner, A. Suzuki, M. Teshima, R. Assmann, R. Heuer, A. Caldwell, S. Karsch, F. Gruener, M. Somekh, J. Nilsson, W. Chou, F. Takasaki, M. Nozaki, D. Payne, A. Chao, J.P. Koutchouk, Y. Kato, X. Q. Yan, C. Robilliard, T. Ozaki, J. Kieffer, N. Fisch, D. Jaroszynski, A. Seryi, T. Kuehl, H. Ruhl, C. Klier, Y. Cao, B. Altschul, T. Seggebrock, K. Kondo, H. Azechi, K. Mima, M. Yoshida, T. Massard, A. Ipp