

# Nonlinear interaction of laser light with vacuum

- Introduction
- Nonlinear process in the laser–vacuum interaction
- Scattering of intense laser light in vacuum
- Feasibility of the experiment to detect the scattered light
- Summary

**Ryosuke Kodama**

# Research Subjects in PhoPs Osaka Univ.



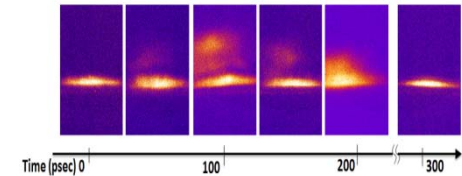
## HERMES project:

High Energy density Revolution of Matter in Extreme States

to explore high pressured condensed matter with combination of high power lasers and XFEL.

0.5PWx2+XFEL(2016)  
200J/10ns+XFEL(2017)

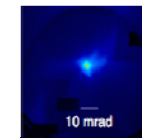
XFEL-diffraction patterns



## LAPLACIAN project:

Laser Acceleration PLAtform as a Coordinated Innovative Anchor

to develop laser-plasma accelerator and its applications for compact radiation sources.

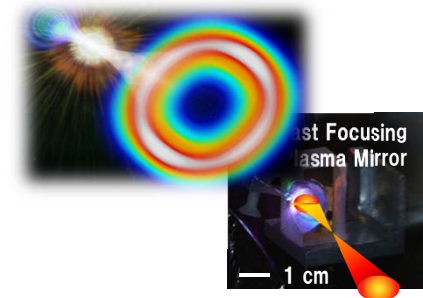


Pointing stability :  
<100-200 $\mu$ mrad



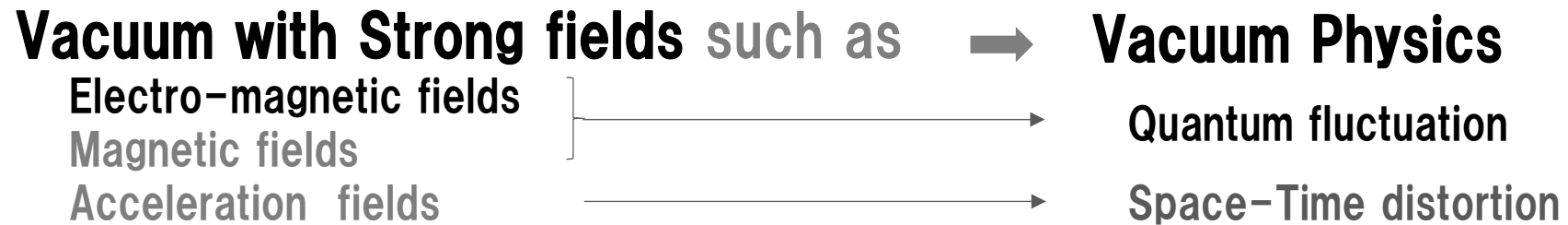
## Vacuum Quantum Optics:

to understand the Vacuum Physics



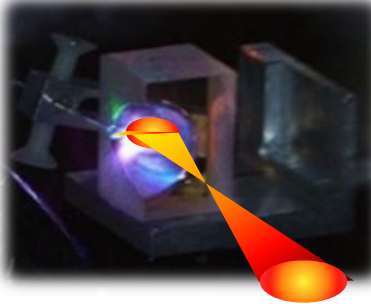
Exploration of Vacuum Quantum Optics with high power laser must be a new approach to understand the Vacuum Physics related to the Beginning of the Universe.

**Vacuum Quantum Optics:** EM Wave creation and propagation in vacuum affected by the strong field.



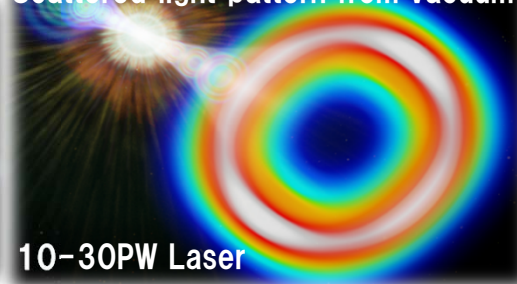
Scattered light from the Vacuum would be created by the vacuum polarization due to the **Quantum fluctuation**, which should be related to the beginning of the Universe

Focusing plasma mirror



Opt. Letts. 35, (2010) 2314

Scattered light pattern from vacuum



10-30PW Laser

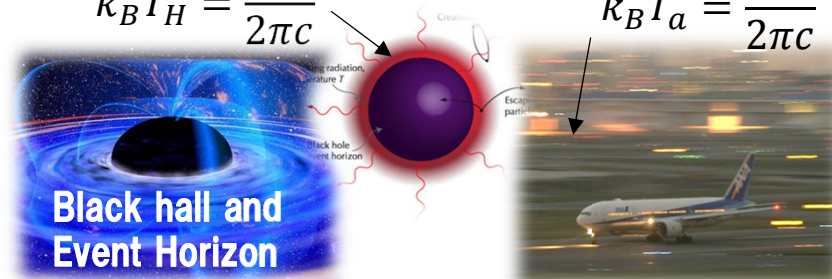
Phys. Rev. Letters 107, (2011) 073602

Investigation of the “Event Horizon” or **space-time distortion** in the Gravitational field would be made through the observation of “Unruh Effect”.

If Gravitational field = Acceleration field

$$k_B T_H = \frac{\hbar g}{2\pi c}$$

$$k_B T_a = \frac{\hbar a}{2\pi c}$$



Black hole and Event Horizon

for the equivalent principle in the general theory of relativity

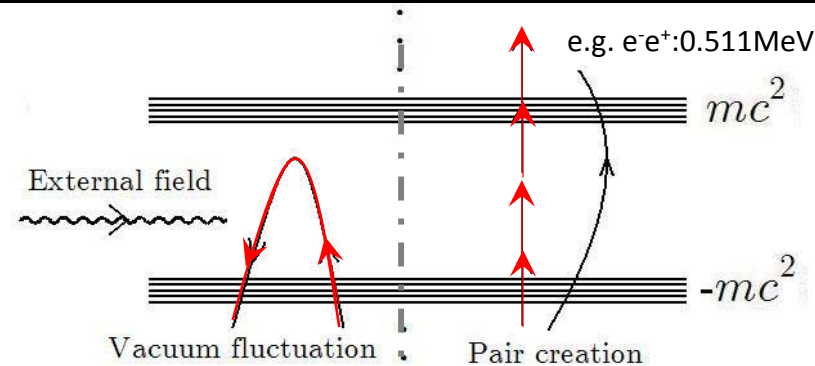
# Photon Interactions with Vacuum:

There are two different types of the interactions.

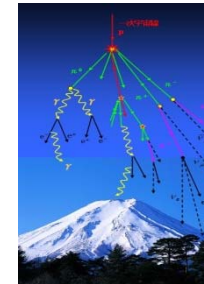
## ➤ Enhancement of the Vacuum quantum fluctuation with external fields

- Enhancement of the fluctuation and create the vacuum polarization with high fields:  
e.g. Scattering, Birefringence, high order harmonic generation • •

➡ **Optical Laser**



## ➤ Break of the Vacuum with photons



- Pair Creation with a Multi photon process  
➡ **High order harmonics or XFEL**
- High energy Photon-photon collider creates elementary particles from vacuum.  
e.g. observation of hadron jet

A cascade process of the pair creation initiated by a high energy photon or electron in the enhanced vacuum fluctuation.

➡ **Optical Laser + X-ray or E beam**

Ultra-intense Optical laser & Intense x-ray or electron beam will be required to explore the VQO.

# Nonlinear process in the strong electro-magnetic field in Vacuum is given by the Lorentz invariant.



To study the interaction of the laser light with vacuum, we calculate *Lagrangian density*  $L(F,G)$  of electromagnetic fields in a vacuum, which is represented by the sum of the densities due to the classical  $L_{class}$  and QED  $L'(F,G)$  terms.

$$\begin{aligned}
 L(F, G) &= L_{class} + L'(F, G) \\
 &= L_{class} + L_1(F, G) + L_2(F, G) + \dots \\
 &= L_{class} + \underbrace{\frac{\alpha(4F^2 + 7G^2)}{360\pi^2 E_{cr}^2} - \frac{\alpha F(8F^2 + 13G^2)}{630\pi^2 E_{cr}^4}}_{\text{Nonlinear term}} + \dots
 \end{aligned}$$

Fine structure constant:  $\alpha = e^2/\hbar c$  Schwinger critical field:  $E_{cr} = m^2 c^3 / e\hbar$

$$\mathbf{P}(F, G, \mathbf{E}, \mathbf{B}) = -\frac{\partial L'}{\partial F} \mathbf{E} + \frac{\partial L'}{\partial G} \mathbf{B}, \quad \mathbf{M}(F, G, \mathbf{E}, \mathbf{B}) = \frac{\partial L'}{\partial F} \mathbf{B} + \frac{\partial L'}{\partial G} \mathbf{E}.$$

**Lorentz invariants**

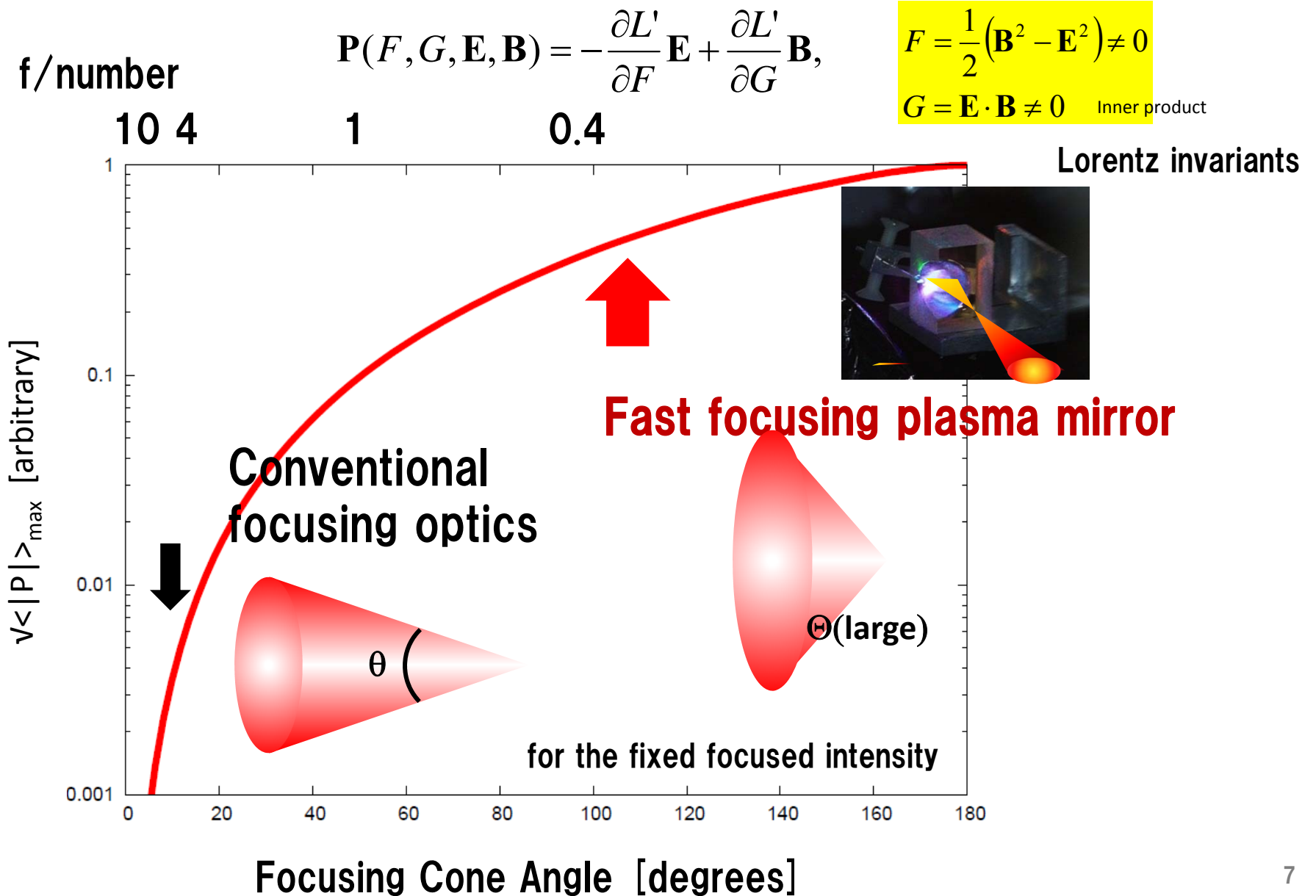
$$F = \frac{1}{2} (\mathbf{B}^2 - \mathbf{E}^2) \neq 0$$

$$G = \mathbf{E} \cdot \mathbf{B} \neq 0$$

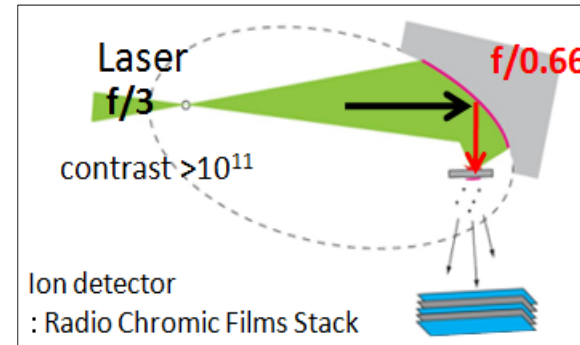
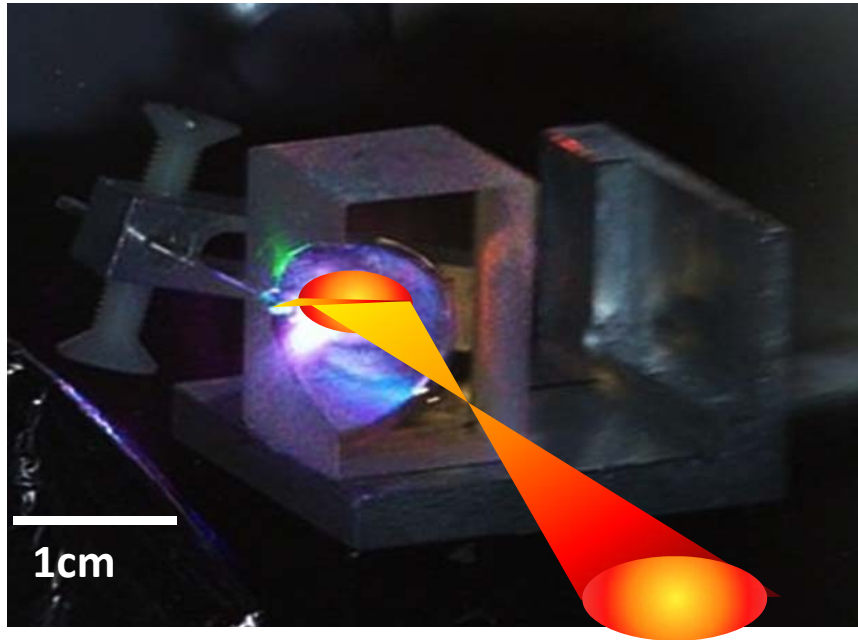
**Non-plane wave condition is required!**

$$F = \frac{1}{2}(\mathbf{B}^2 - \mathbf{E}^2) \neq 0$$
$$G = \mathbf{E} \cdot \mathbf{B} \neq 0$$

# Polarization due to the nonlinear process in Vacuum Depends on the Focusing Cone Angle

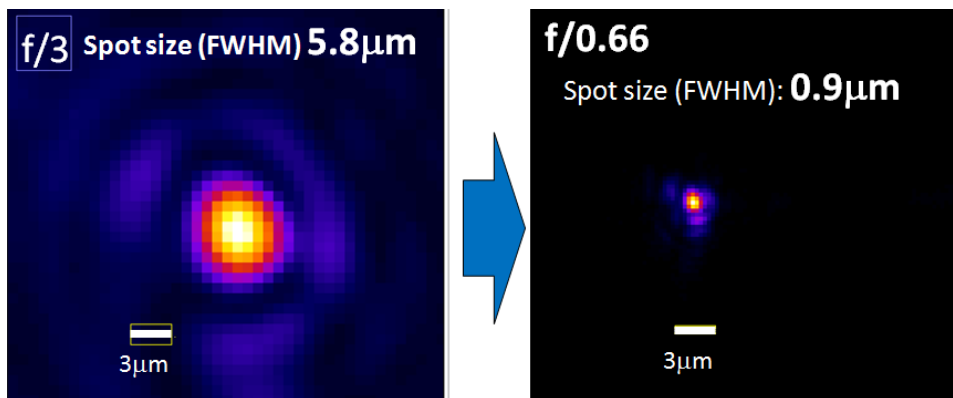


# Fast Focusing Optics $f/\lt 0.5$ can be Realized with a Spheroid Plasma Mirror in a Power Laser System



## Advantage of the Spheroid Plasma Mirror

- Realistic alignment geometry
- Realization of Fast Optics
- Preventing the prepulse effect



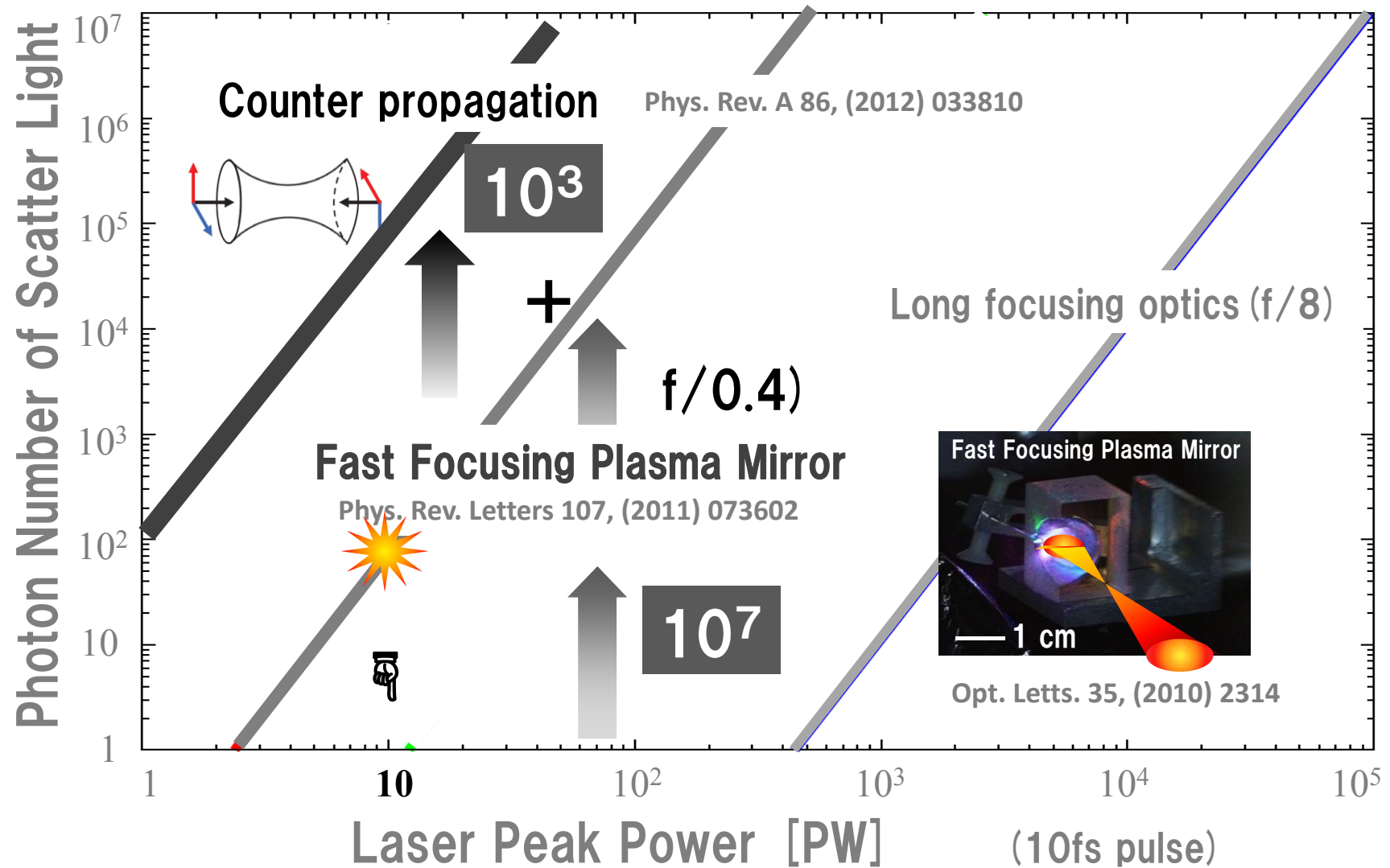
Realized the Fast Focusing of High Power Laser.

Focused laser intensities was enhanced by 10–20 with the focusing plasma mirror.

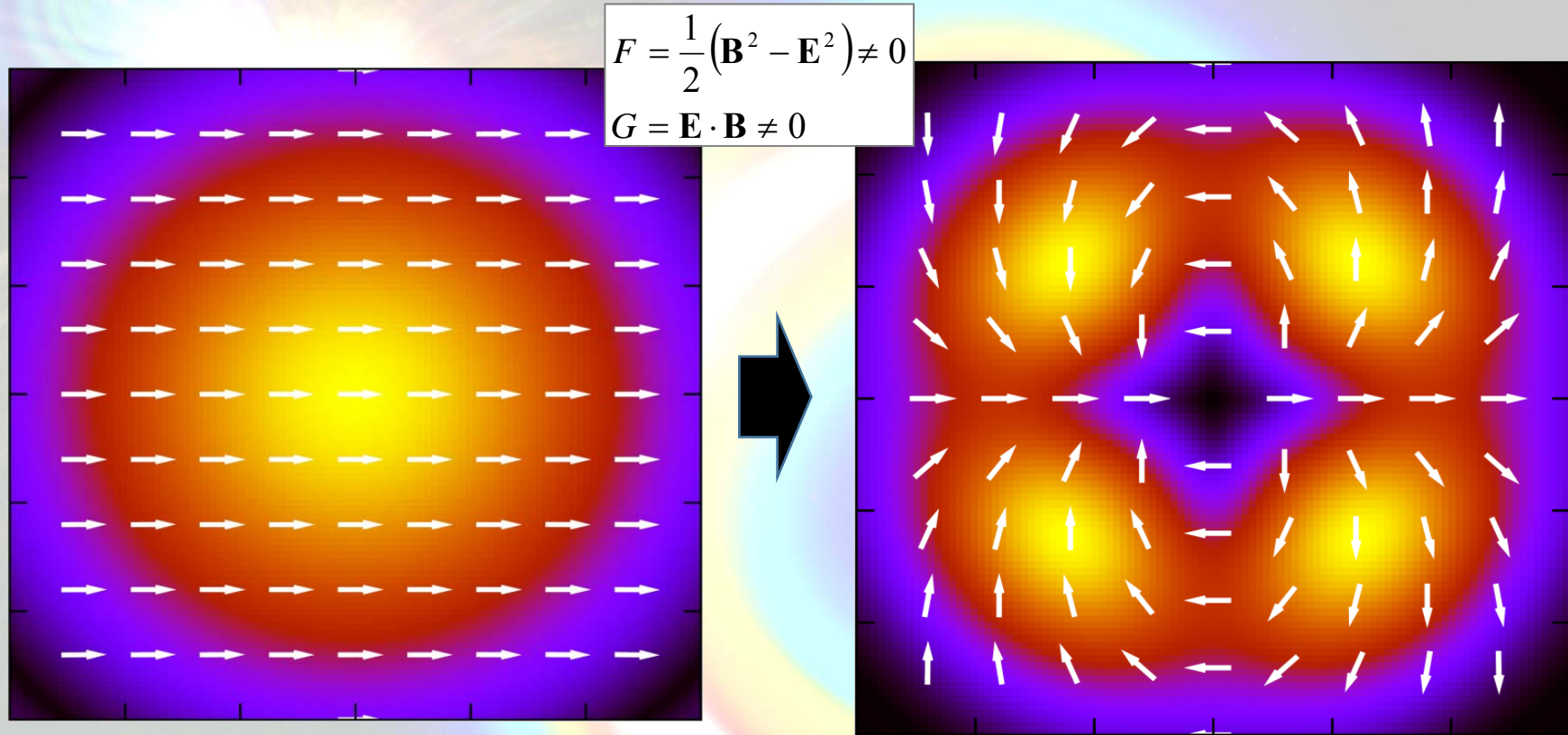
Conventional optics :30cmφ for PW



# Dependence of the Laser power and the Focusing geometry on the Scattered light from Vacuum



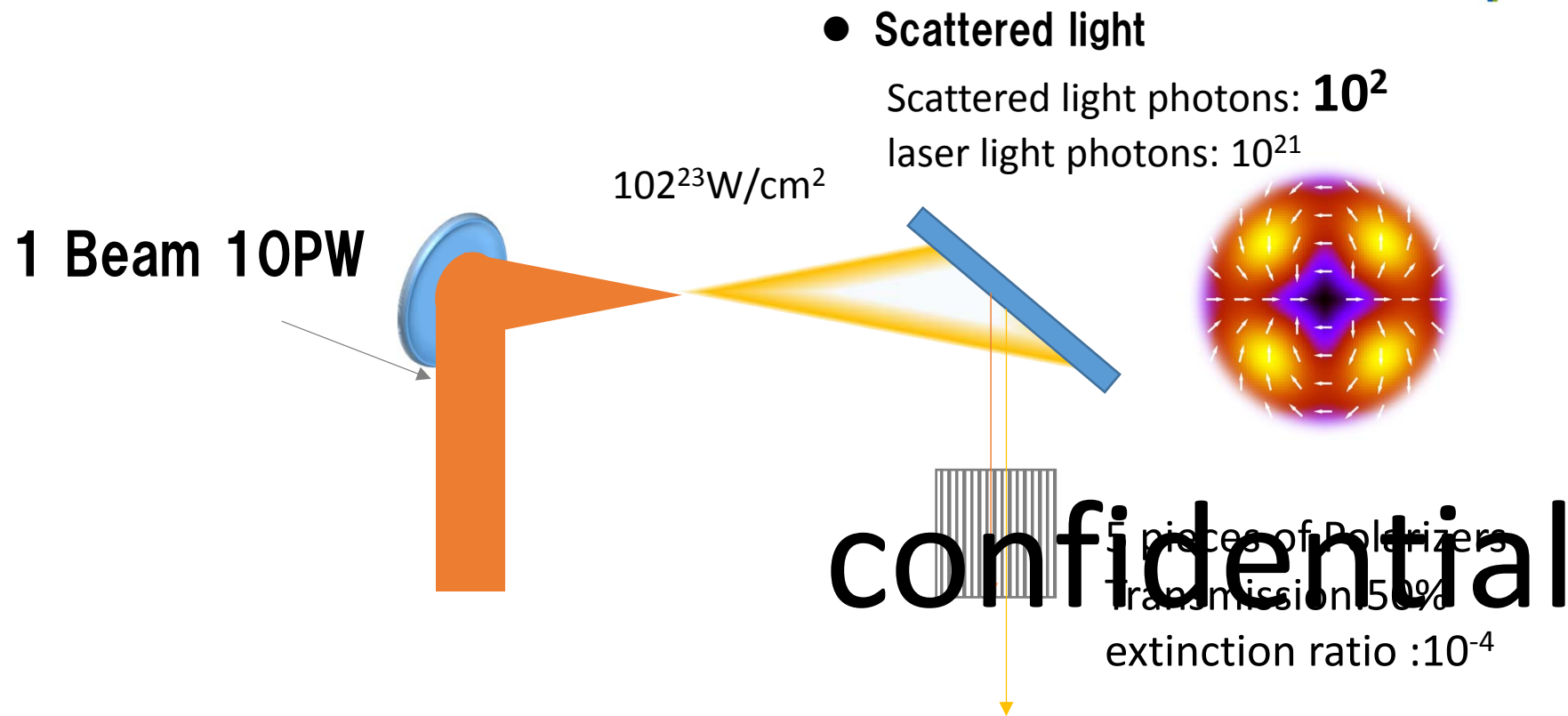
Polarization of the scattered light is totally different from the Incident one as well as that from matter



Y. Monden and R. Kodama Phys. Rev. Letters 107, 073602 (2011)

Feasibility of experiment to detect the scattered light?  
Noise sources: incident light and scattering from matter

# Signal to Noise ratio for the detection of the scattered light from Vacuum with 10PW laser light



**confidential**

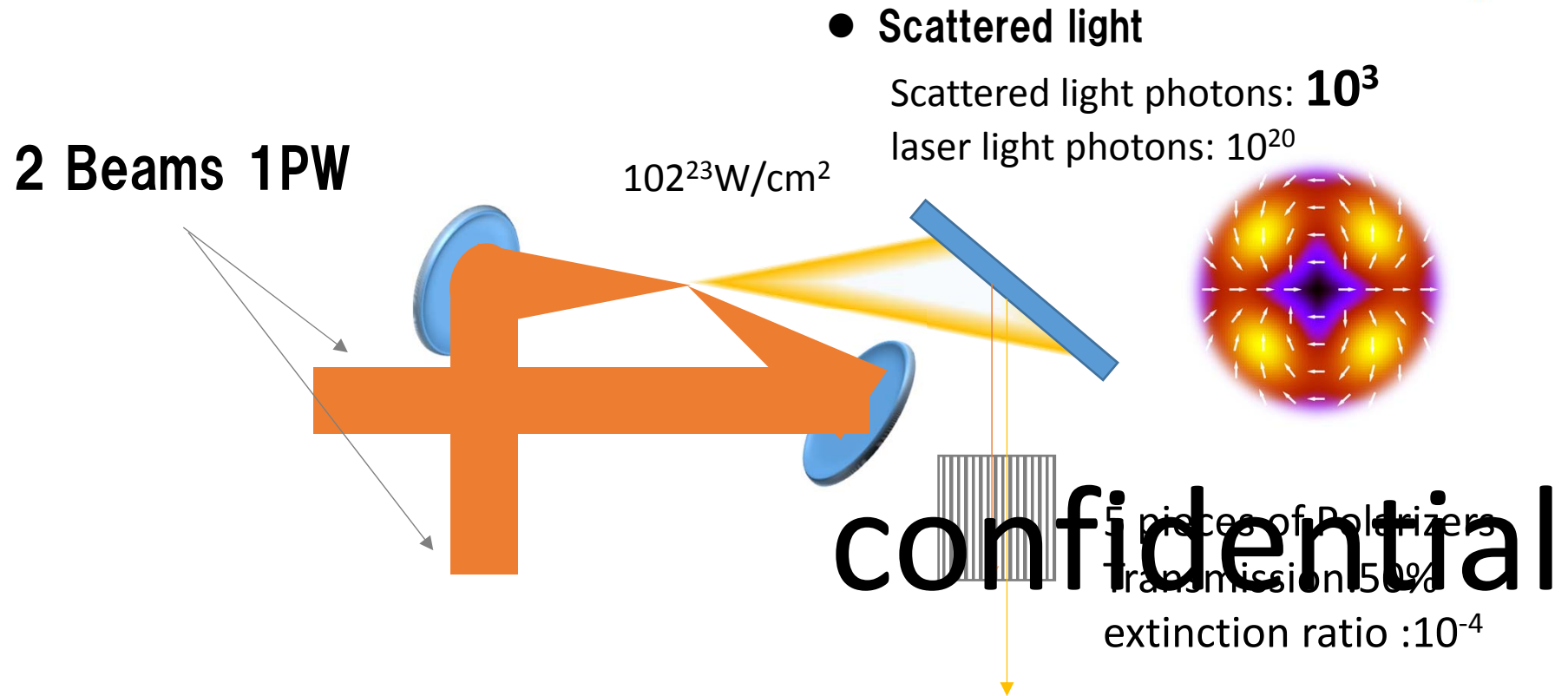
**>3photons/10 noise photons: S/N>0.3**

for single shot



>10 shot accumulation

# Signal to Noise ratio for the detection of the scattered light from Vacuum with 2 beams of 1PW laser light



**>30photons/1 noise photons: S/N>30**

for single shot

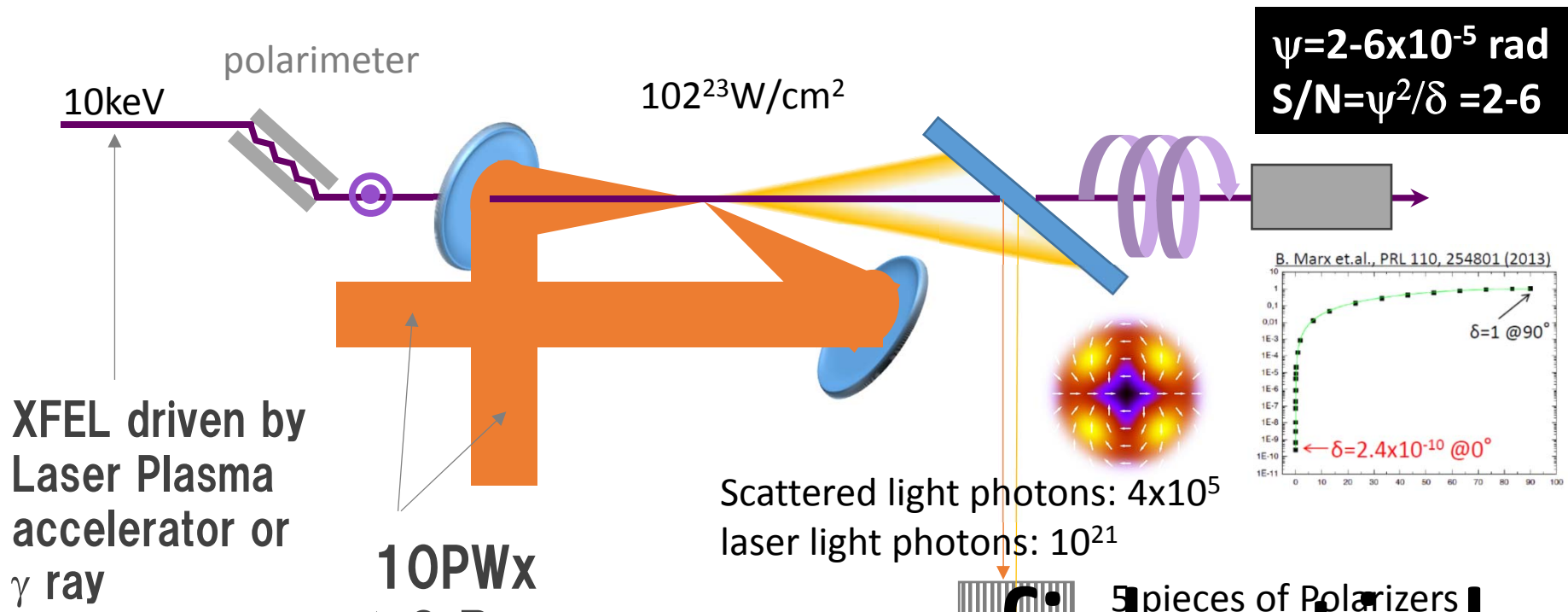


>10 shot accumulation for imaging?

The Perturbated Vacuum would be more cleared with the simultaneously applying the Passive and Active methods, if we had 20PW laser and PW laser driven X ray or Gamma ray .

- Vacuum Birefringence  $\psi = 2\pi \frac{L}{\lambda} \Delta n$

$\psi = 2-6 \times 10^{-5}$  rad  
 $S/N = \psi^2 / \delta = 2-6$



XFEL driven by Laser Plasma accelerator or  $\gamma$  ray

10PWx  
 >2 Beams

**confidential**

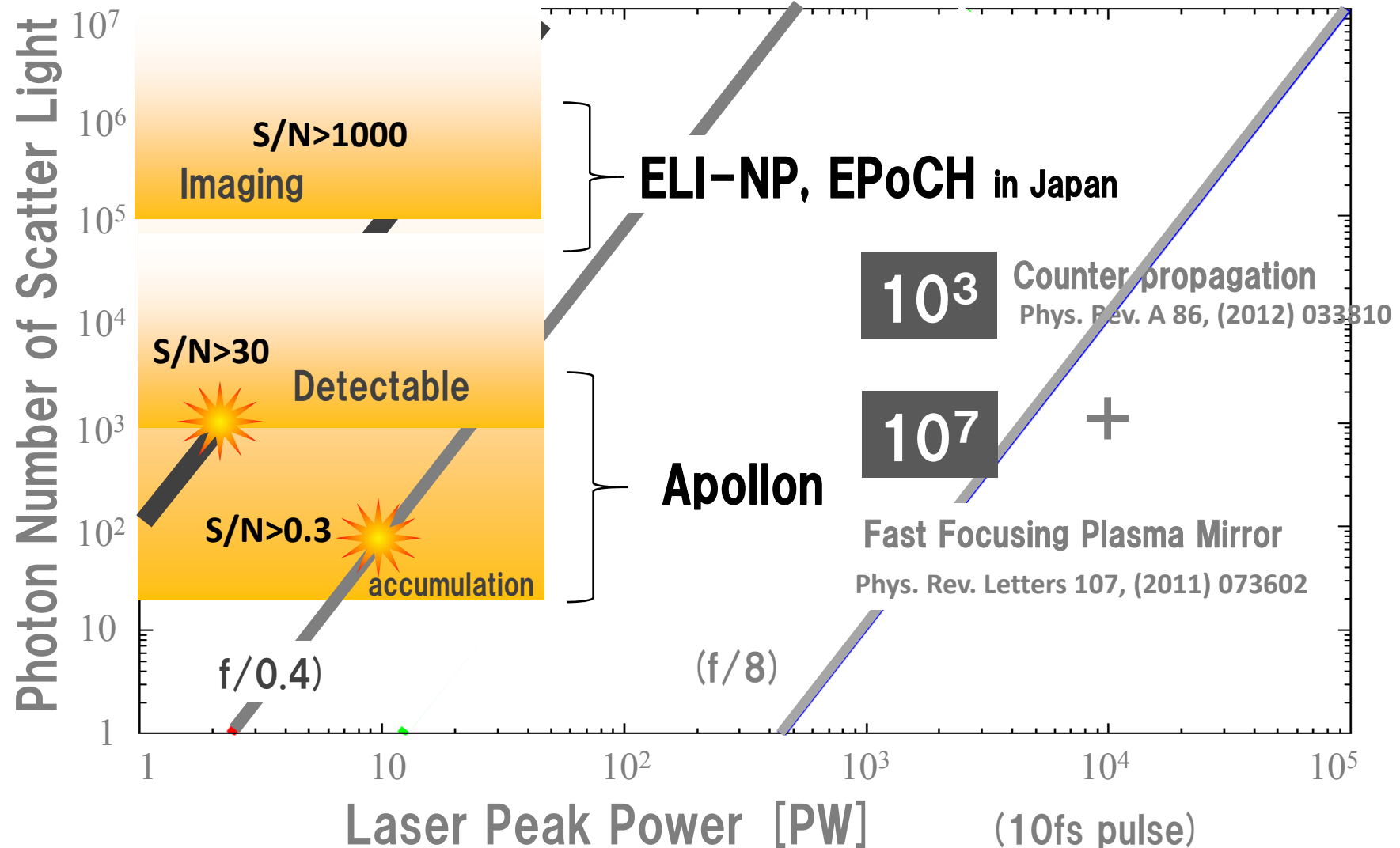
- Scattered light

5 pieces of Polarizers  
 Transmission: 5%  
 extinction ratio:  $10^{-4}$

**>10000 photons / 10 noise photons: S/N > 1000**

No accumulation for imaging?

# Scattered light from Vacuum could be detected in the near future, which would experimentally start the Vacuum Quantum Optics



# Two projects in Japan are now under progress in advance of the EPoCH project

Osaka Univ., and JAEA KPSI has coordinated the community meeting



## EPoCH laser

Establishment for Power-laser Community Harvest in Japan

200J/0.1Hz long pulse laser+XFEL(2016-)



High energy density  
solid matter and material



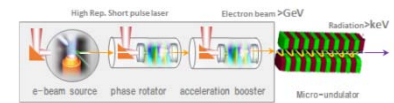
kJ-10kJ +  
PW laser for Laser-Accelerator XFEL

Tera Pascal Science  
Super diamond  
Metallic carbon  
Exotic structured material  
Planetary Physics  
:

30PW Laser (2-3beams) /10kJ long pulse laser  
+ <PW laser for Laser-Accelerator XFEL

Vacuum Quantum Optics  
Strong EM field and Magnetic field  
Strong acceleration field  
High Field Science  
Laboratory Astro physics

Laser -Accelerator XFEL



0.5PW Laser(x2beams 1Hz) + XFEL (2016-)

High field science  
by Osaka Univ. JAEA, RIKEN, other Univ.

200TW Laser (3beams) +  
Plasma devices+micro undurator (2017-)

LAPLACIAN Laser Plasma accelerator development  
by Osaka Univ. JAEA, RIKEN, KEK and other Univ.

# Summary

- Three subjects on high energy density sciences are carried out with high power lasers:
  - Laser plasma Accelerator and its application for XFEL
  - High pressured condensed matter as a new Solid states
  - Vacuum Quantum Optics for study the Vacuum physics
- **Scattered light from Vacuum could be detected in the near future in the Apollon Facility, ELI facilities or EPoCH in Japan, which would experimentally start the Vacuum Quantum Optics**
- Two projects are now under progress in advance of the 20–30PW+10kJ EPoCH laser system.
  - LAPLACIAN project  
to develop laser–plasma accelerator and its applications for compact radiation sources.
  - HERMES project  
to study high pressure condensed matter in the regime of >TPa with combination of high power lasers and conventional XFEL.



*I appreciate all the funds and the contributed members of  
the research groups in Osaka University and collaborators in the world :*



*Institute for Academic Initiatives (IAI), Osaka University  
Photon Pioneers Center (PhoPs), Osaka University  
Harima Center for Photon Sciences (HAPS), Osaka University*



*C-PhoST: Consortium for Photon Science and Technology in Kansai  
HERMES project: High Energy density Revolution of Matter in Extreme States  
LAPLACIAN project: Laser Acceleration Platform as a Coordinated Innovative Anchor  
International Alliance on HED matter (JSPS)*



*Photon Frontier Network program in Japan (MEXT JST)  
ImPACT: Impulsing Paradigm Change through disruptive Technologies (CAO JST )  
X-ray Free Electron Laser Priority Strategic Program (MEXT JST)  
JSPS Core to Core Program (MEXT JSPS)*



*Japan Science and Technology Agency (JST)  
Japan Society for the Promotion of Science (JSPS)  
Genesis Research Institute, Inc.*

**Thank you for your attentions!**

# Two projects in Japan are now under progress in advance of the EPoCH laser system to expand the field of HED states



Osaka Univ., and JAEA KPSI has coordinated the community meeting



## EPoCH laser

Establishment for Power-laser Community Harvest in Japan



200J/0.1Hz long pulse laser+XFEL(2016-)

High energy density  
solid matter and material



kJ-10kJ +  
PW laser for Laser-Accelerator XFEL

### Tera Pascal Science

Super diamond  
Metallic carbon  
Exotic structured material

### Planetary Physics

⋮

30PW Laser (2-3beams) / 10kJ long pulse laser  
+ PW laser for Laser-Accelerator XFEL

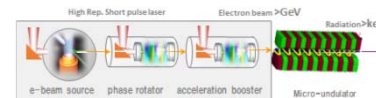
### Vacuum Quantum Optics

Strong EM field and Magnetic field  
Strong acceleration field

### High Field Science

Laboratory Astro physics

Laser -Accelerator XFEL



PW Laser(2beams 1Hz) + XFEL (2016-)

High field science

by Osaka Univ. JAEA, RIKEN, other Univ.



200TW Laser (3beams) +  
Plasma devices+micro undurator (2017-)

Laser Plasma accelerator development

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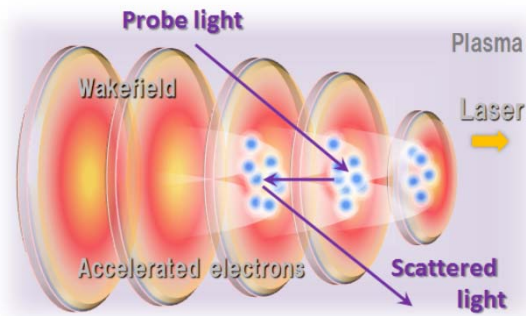


# Active Methods to detect the “Unruh Effect”

have been Proposed, which must be more realistic as compared with a passive method or measurements of the self-emission due to the Unruh effect

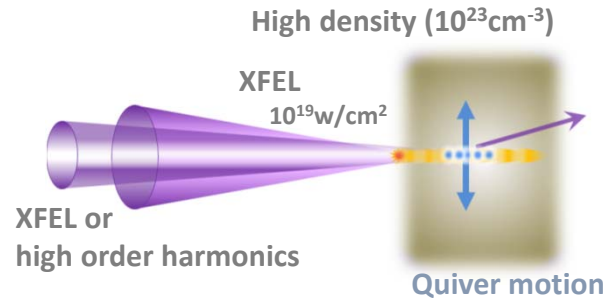


## Acceleration in Wakefield

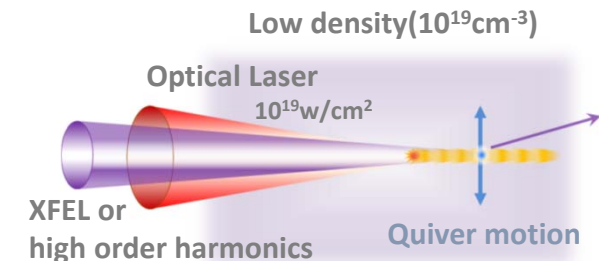


M. Yano *et al.*, to be submitted 2015

## Oscillation of Electron



M. Yano *et al.*, to be submitted 2015



R. Bingham *et al.*, SCIENTIFIC REPORTS,2,491(2012)

Photon Number of Scattered light:

5 /shot

$10^6$  /shot

55/shot

## Double Scattering method

- Electrons as a Emitter and a detector of the scattered light is in the same frame.
- We must detect the scattered light influenced by the acceleration field but the efficiency of scattering could be critical to be observed.
- We may expect scattering by the multi-bunched electrons in the multi-Wakefield packet .

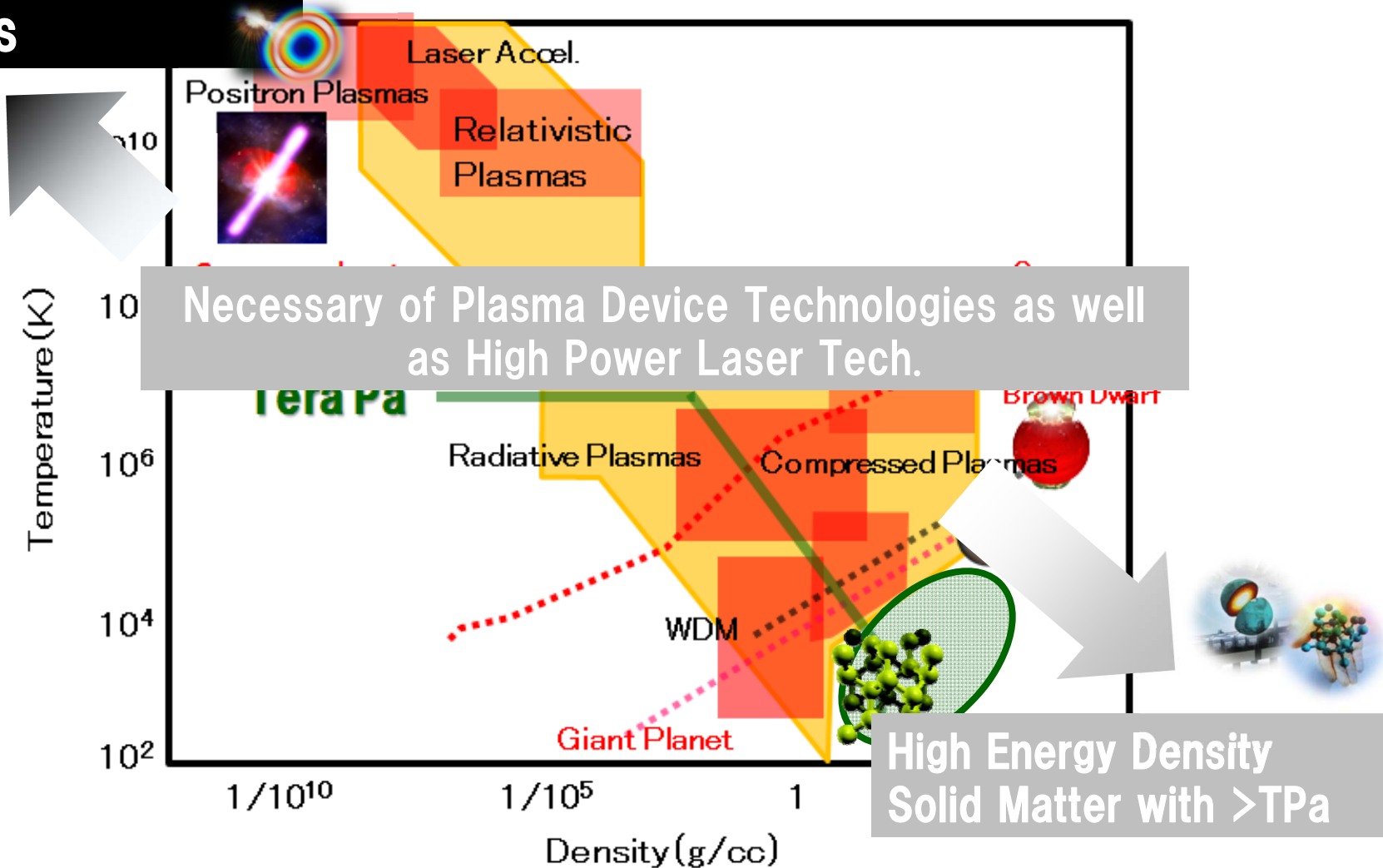
## Single Scattering method

- The detector is in the laboratory frame whereas the electrons as an emitter of the scattered light is in the different frame.
- Absorption and emission due to the dipole is not symmetry. Then we may expect detection of scattered light influenced by the acceleration field.

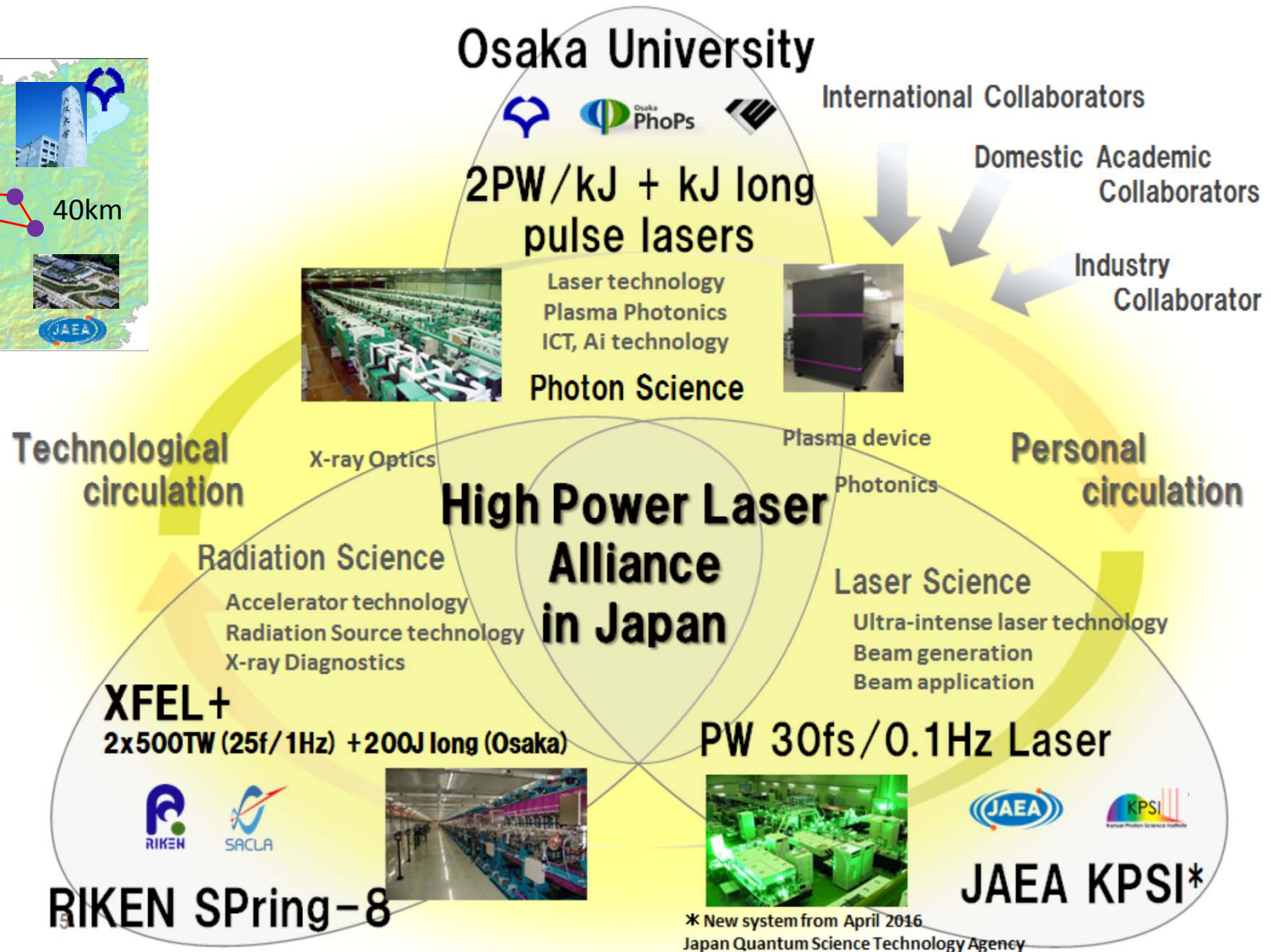


The Fields could be Expanding from the Plasma States to the Vacuum with a Strong Field and the Vacuum quantum Optics would be Explored .

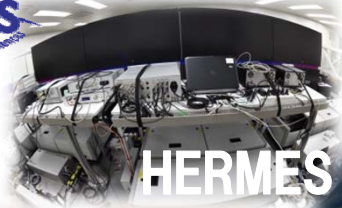
# Vacuum Quantum Optics



# High Power Laser Alliance in Japan or 100km High Power Laser Facility will be launched in 2016



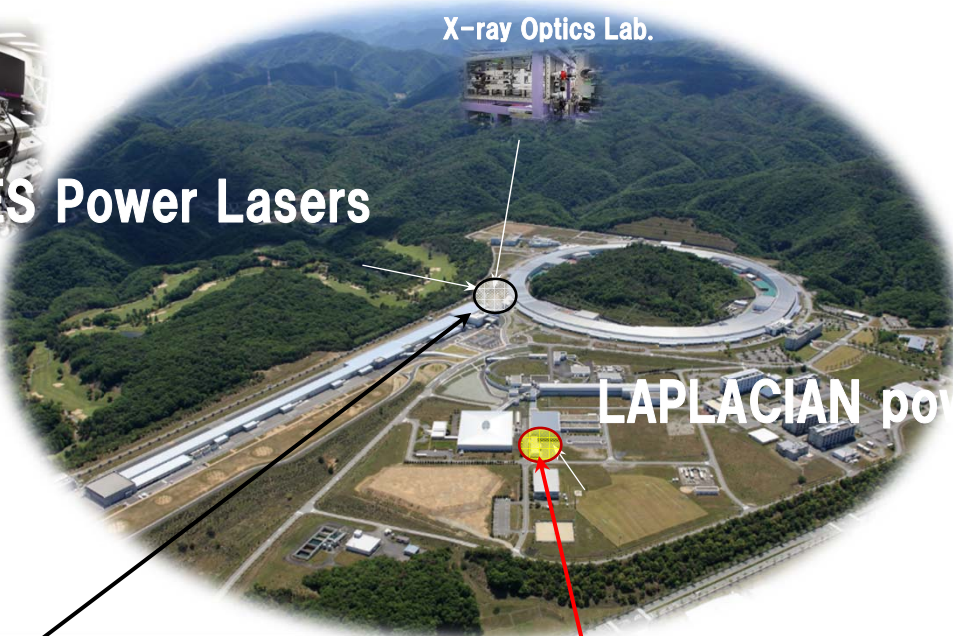
# Two Projects (HERMES and LAPLACIAN) on HEDS are carried out by Osaka University under collaboration with RIKKEN Spring-8



HERMES Power Lasers




X-ray Optics Lab.




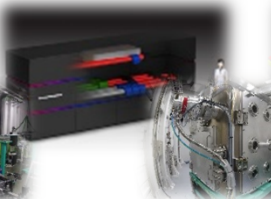
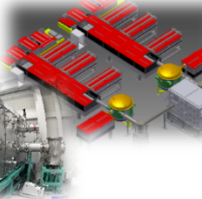
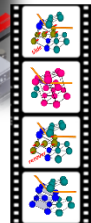
LAPLACIAN power supply





## HERMES Project


### with High Power Laser and XFEL

- 40TW short pulse (10Hz)
- 200–400J/530nm long tailored pulse (0.1Hz)
- 500TW short pulse (1Hz) x2bems

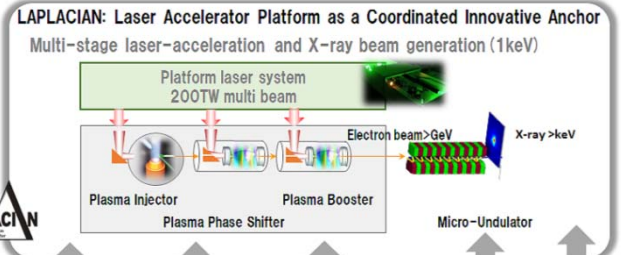
## LAPLACIAN Project


### Laser Accelerator Platform as a Coordinated Innovative Anchor




LAPLACIAN: Laser Accelerator Platform as a Coordinated Innovative Anchor

Multi-stage laser-acceleration and X-ray beam generation (1keV)

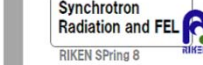





Osaka Univ. Photon Pioneers Center



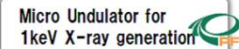
JAEA Kansai Photon Science Institutes




RIKEN Spring 8



Public offering



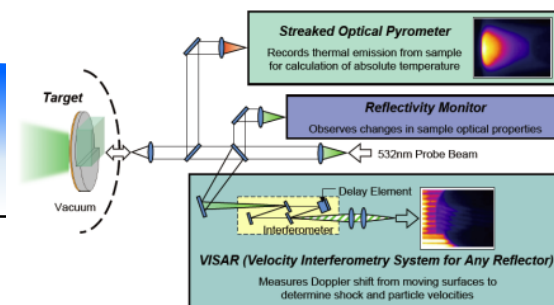
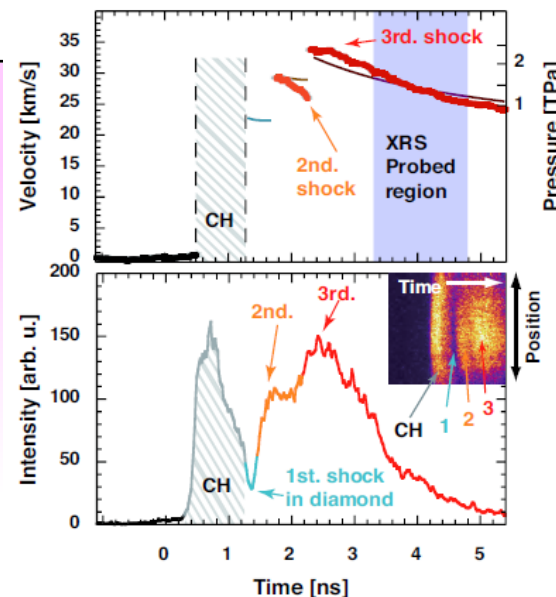
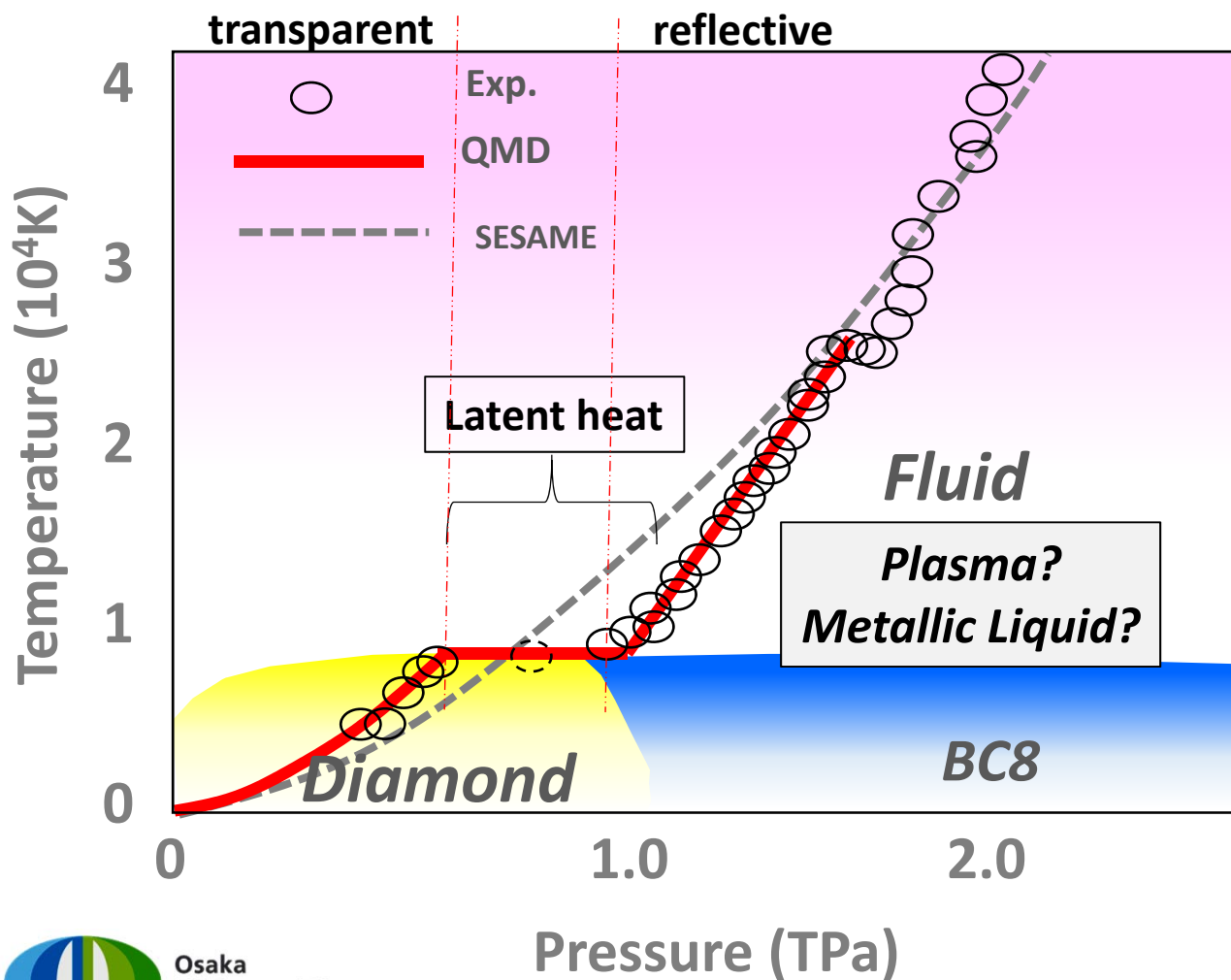
KEK-PF





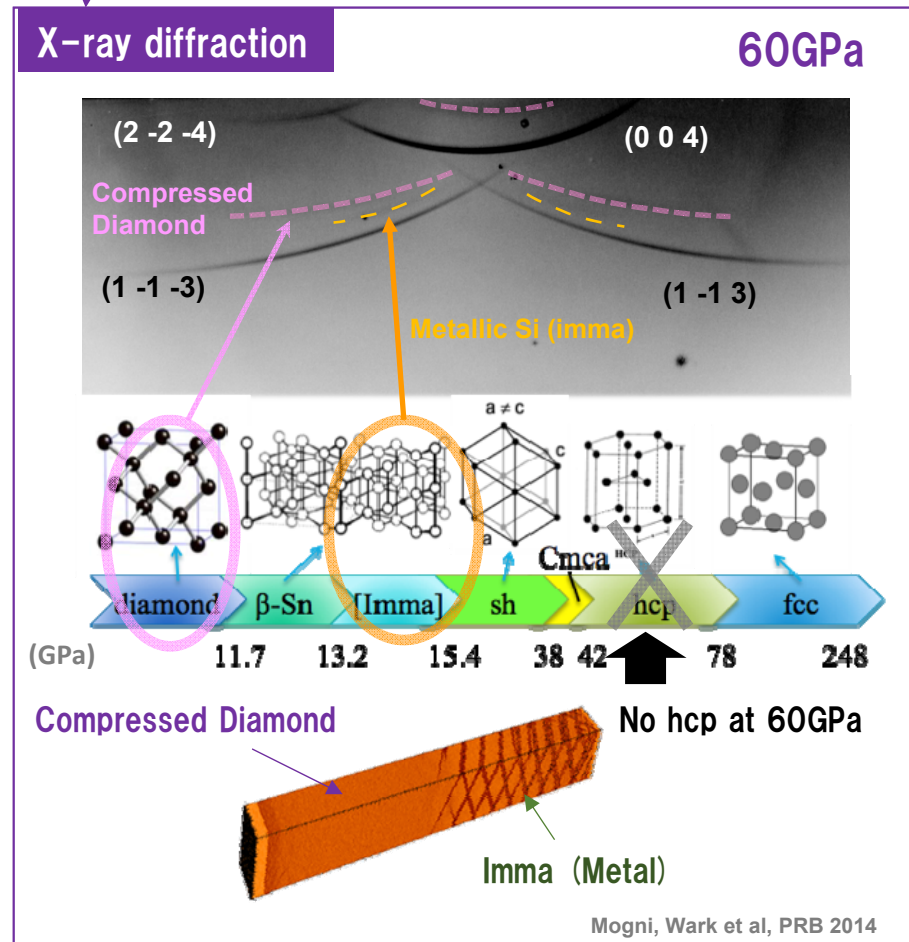
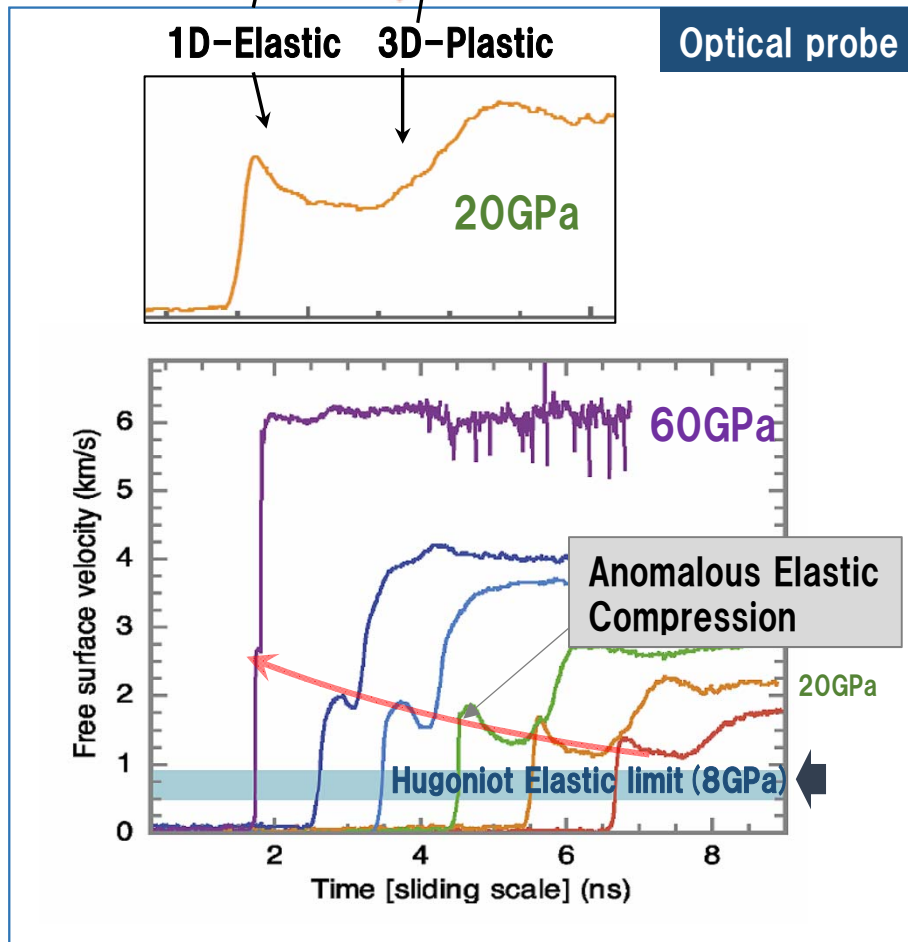
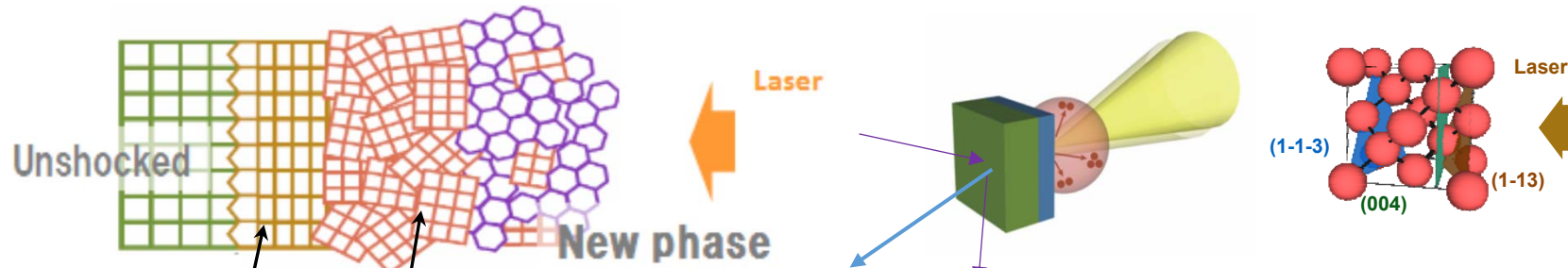
# Precise Estimation of the Temperature and Pressure of Carbon in the TPa regime from SOP and VISAR

The experiments are well consistent to the QMD model calculation at near the melting point



Chemical bonding energy of the diamond crystal: 357kJ/mol

# Anomalous Elastic Stress and Mixture of Metal and Semiconductor in the Dynamically Compressed Si



Mogni, Wark et al, PRB 2014

# Osaka University



**2PW/kJ + kJ long pulse lasers**

Laser technology  
Plasma Photonics  
ICT, Ai technology  
Photon Science



International Collaborators

Domestic Academic Collaborators

Industry Collaborator

Technological circulation

Personal circulation

## High Power Laser Alliance in Japan

X-ray Optics

Plasma device

Photonics

Radiation Science

Laser Science

Accelerator technology  
Radiation Source technology  
X-ray Diagnostics

Ultra-intense laser technology  
Beam generation  
Beam application

**XFEL+**

2x500TW (25f/1Hz) +200J long (Osaka)

**PW 30fs/0.1Hz Laser**



**RIKEN Spring-8**

**JAEA KPSI\***

\* New system from April 2016  
Japan Quantum Science Technology Agency



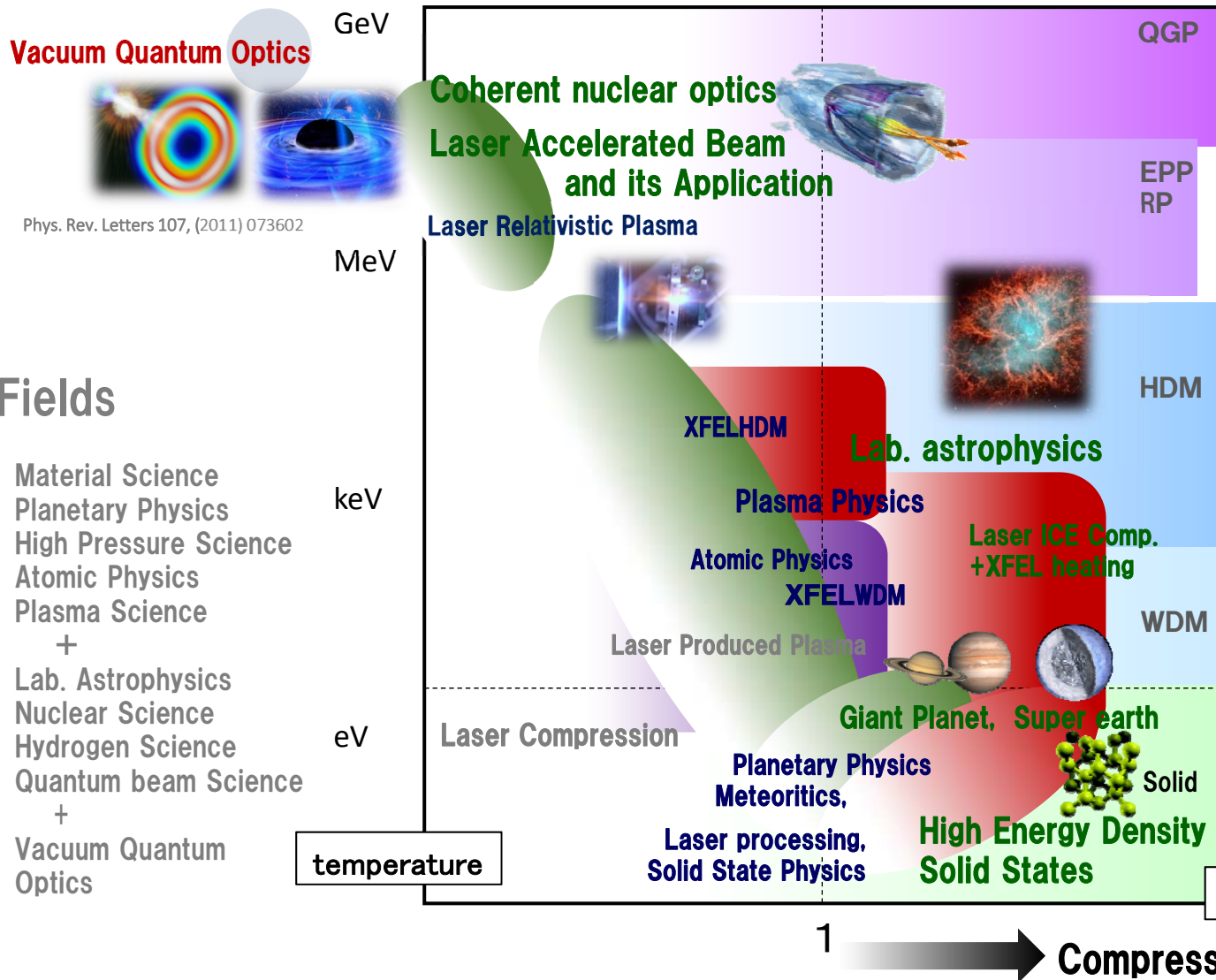
# Combination of high power laser and XFEL opens new fields of HEDS in the HERMES



**1<sup>st</sup>** 40TW laser  
40J long pulse laser  
Double XFEL beams

**2<sup>nd</sup>** Full coherent XFEL  
>2-400J long pulse laser  
>500TW laser

**3<sup>rd</sup>** Full coherent XFEL  
>kJ long pulse laser  
>10PW laser



## Subjects

- Laser processing
- Extreme condition material
- material in Planet
- WDM
- relativistic plasma
- +
- Core of Super earth
- metallization physics(>3TPa)
- Astro plasma
- laser-acceleration application
- nuclear coherent control
- +
- Vacuum polarization
- nonlinear QED