高強度場の物理と
そのハドロン物理への応用

板倉数記(KEK)
kazunori.itakura@kek.jp

2014 Jan. 14th @ RIKEN

本講演の目標

- **高強度場の物理**

  のなんたるかを紹介し、その重要性とともに、「学際性」と「今日性」を理解してもらう。

- **ハドロン物理**

  での重要な未解決問題（特にフロンティアでの）に高強度場の物理が関係することを示唆し、興味を持ってもらう。

Plan

- **Introduction** (20min)

  when, what, why, how ?

- **Examples of strong field physics** (20min)

  field dynamics, particles in strong fields

- **Strong field physics in hadron physics** (20min)

  heavy-ion collisions, compact stars

- **Summary**

References

- Greiner, Muller and Rafelski, ``*Quantum Electrodynamics of Strong Fields*,'' Berlin, Germany: Springer (1985) 594 P. (Texts and Monographs In Physics)

- Dunne, ``*Heisenberg-Euler effective Lagrangians: Basics and extensions*,'' In Shifman, M. (ed.) et al.: From fields to strings, vol. 1, 445-522 [hep-th/0406216].

- Mourou, Tajima, and Bulanov, “*Optics in the relativistic regime*” Rev. Mod. Phys. 78 (2006) 309

- Di Piazza, Muller, Hatsagortsyan and C.H. Keitel, ``*Extremely high-intensity laser interactions with fundamental quantum systems*,'' Rev. Mod. Phys. 84 (2012) 1177

- Itakura, “*Strong field physics and the early time dynamics in high-energy heavy ion collisions*” in preparation (J. Physics)

- 板倉 『衝突から熱平衡まで:強ゲージ場、不安定性、粒子生成』 原子核研究 52巻 Suppl.1 (2008) http://www.genshikaku.jp/52sp1PDF/itakura.pdf

- 板倉 『「強い場の物理」から見た高エネルギー重イオン衝突』 原子核研究 第57巻1号 （2012) 46

Introduction

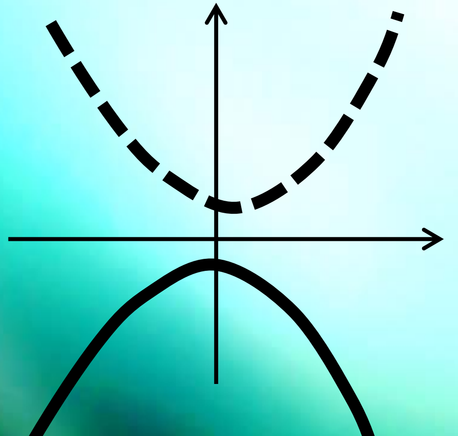
When is a field “strong”?

“strongness” depends on systems

- Consider an **external field** which couples to a system. Applying an external field drives the system at its ground state into “excited” states.
- A field is called “strong” when its energy is much larger than the **typical excitation energy** of the system (or “vacuum”).
- “**Critical field**” is defined by the typical excitation energy.

ex) In QED vacuum: electron-positron excitation

In condensed matter (in the presence of a gap) : electron-hole excitation



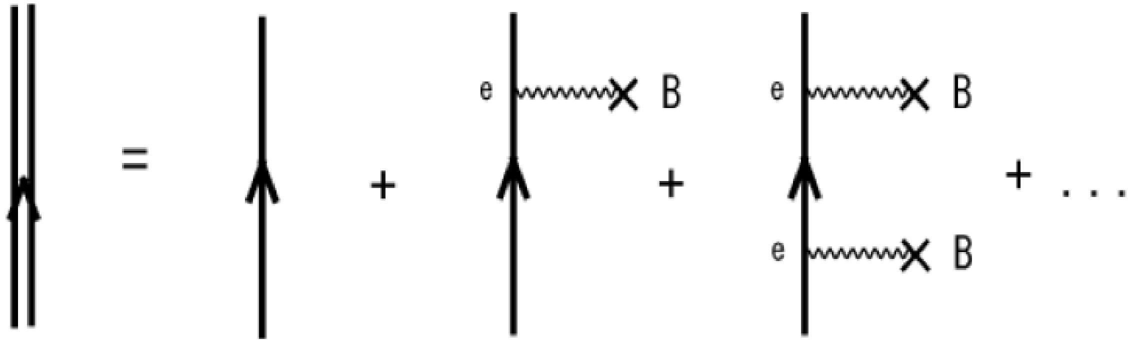
Conducting band (vacant)

Valence band (occupied)

What is "strong field physics"?

- **Characteristic phenomena that occur only under strong gauge fields** (EM fields and Yang-Mills fields)
- **Typically, weak-coupling but non-perturbative**

ex) electron propagator in a strong magnetic field



$$1 + O\left(\frac{eB}{m_e^2}\right) + O\left(\left(\frac{eB}{m_e^2}\right)^2\right)$$

must be resummed when $B >> B_c$

$$eB_c \equiv m_e^2$$

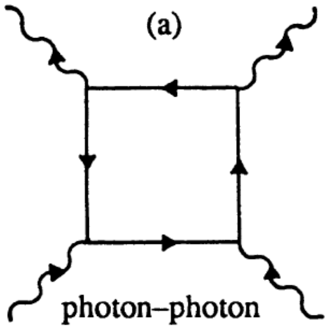
$$eE_c \sim m_e^2$$

Schwinger's critical field

→ "Nonlinear QED"

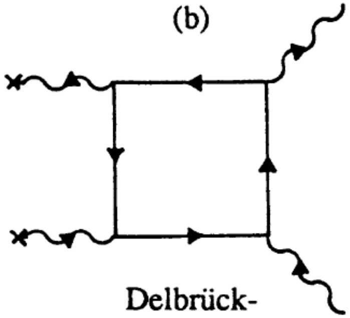
Photon-photon interaction occurs at higher orders in QED

(a)



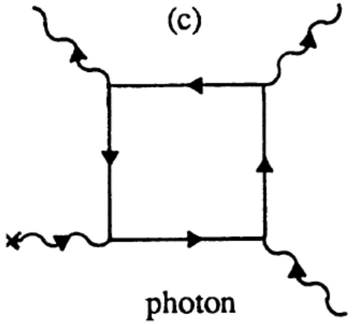
photon–photon scattering

(b)



Delbrück-scattering

(c)



photon splitting

- Photon-photon interaction possible only at higher orders (through quantum effects)

- In vacuum, its cross section is extremely small ~ $O(\alpha^4)$ hopeless to detect in experiments

- In the presence of strong fields (eg. atomic Coulomb field Ze), the same diagram leads to

  Delbrueck scattering ~ $O(Z^4\alpha^4)$

  Photon splitting ~ $O(Z^2\alpha^4)$

  Both were already observed in experiments.

  Milstein, Schumacher, Phys. Rep. 243 (1994) 183
  Akhmadaliev et al. PRL 89 (2002) 061802

- However, in extremely strong fields, the lowest order is not enough. Need to resum up to infinite order

- Similar things happen in QCD where coupling constant is larger. Need to understand “nonlinear QED” for better understanding of QCD dynamics.

1 Tesla = 10^4 Gauss

How strong?

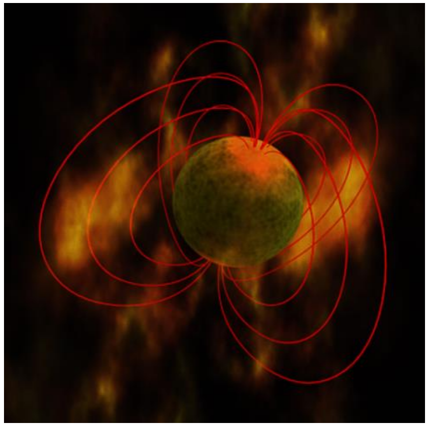
10^{17}—10^{18} Gauss

$\sqrt{eB} \sim 1 - 10\ m_\pi$

Noncentral heavy-ion collisions at RHIC and LHC

Also strong Yang-Mills fields

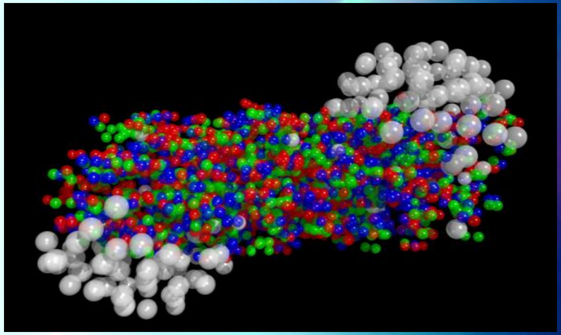
$\sqrt{gB} \sim 1 -$ a few **GeV**



10^{15}Gauss : Magnetars

4x10^{13} Gauss : "Critical" magnetic field of electrons

$\sqrt{eB_c} = m_e = 0.5\text{MeV}$



45 Tesla : strongest steady magnetic field

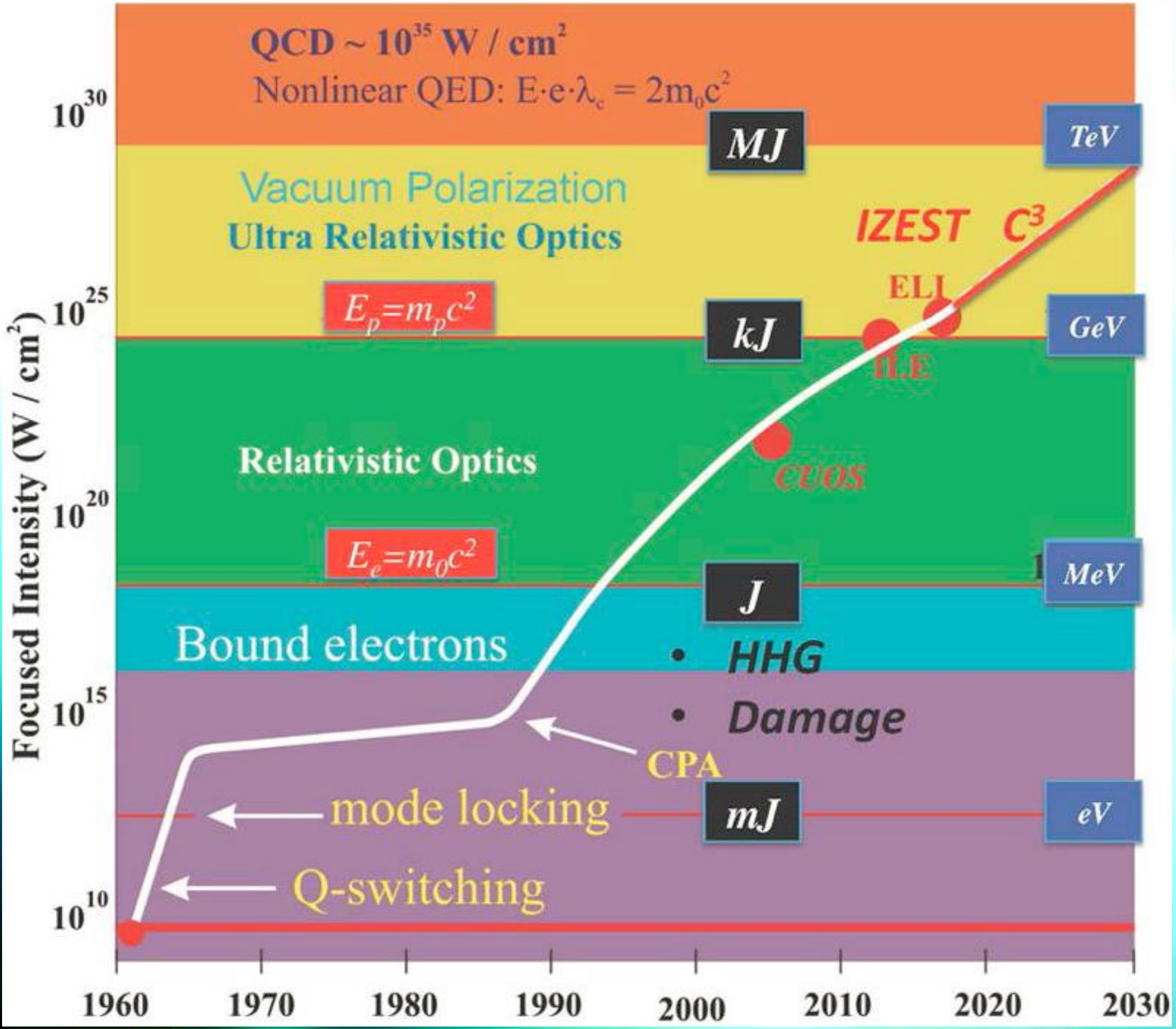
(High Mag. Field. Lab. In Florida)

10^8Tesla=10^{12}Gauss: Typical neutron star surface

Super critical magnetic field may have existed in very early Universe. Maybe after EW phase transition? (cf: Vachaspati '91)

8.3 Tesla : Superconducting magnets in LHC

Development of high-intensity laser

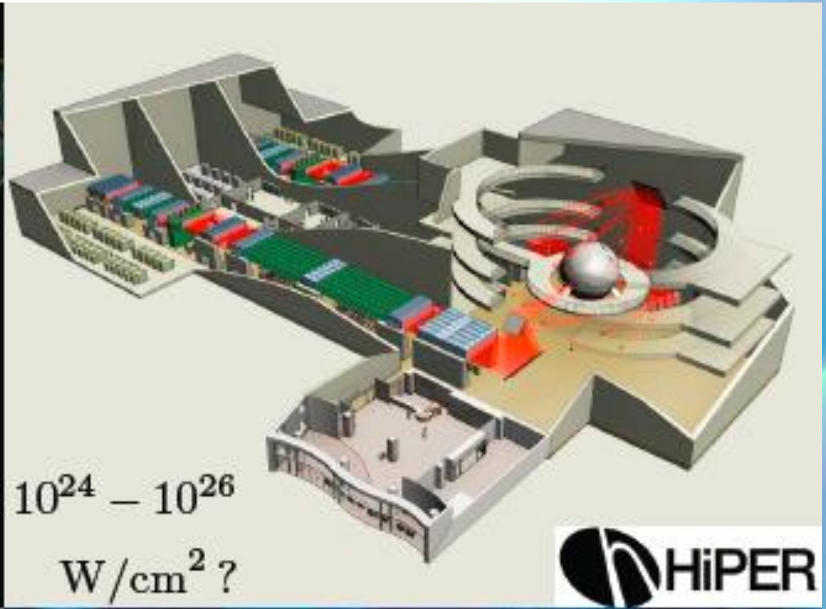


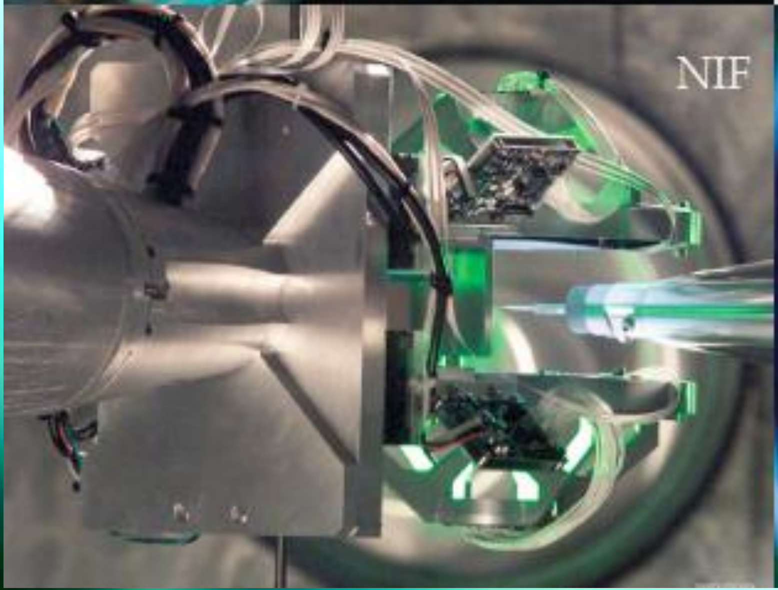
GEKKO-EXA (Japan)
XFEL, POLARIS, NIF, etc

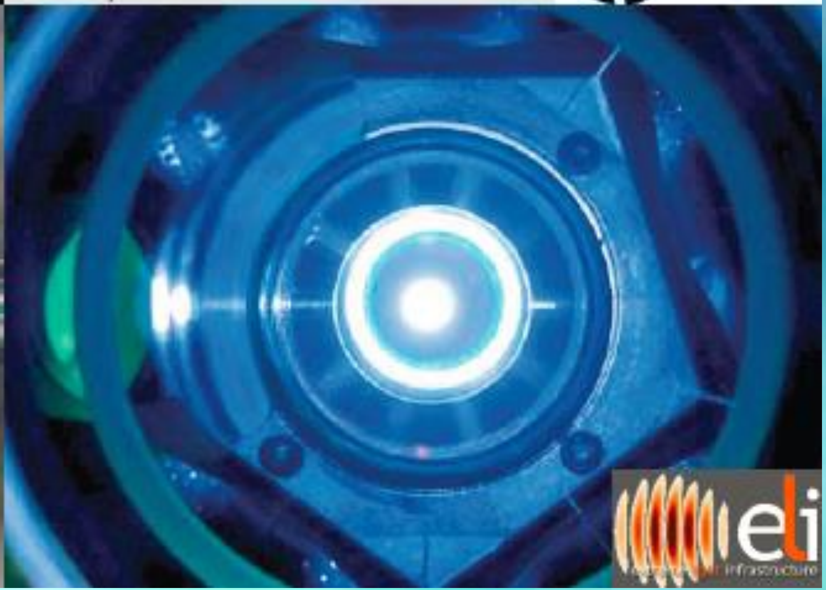
CUOS @ Michigan U.
(Center for Ultrafast
Optical Science)
Hercules has the world
Record 10^{22} W/cm^2

Mourou, Tajima

New facilities under construction







Many reasons

for studying strong field physics

- Because there exists in Nature
- Because we can learn something about "vacuum"
- Because it is a special tractable case of non-equilibrium physics (can be formulated in weak-coupling theory)
- Because it may allow for a new kind of universal picture in Nature
- Because it could give hints to unsolved problems.

Interdisciplinary field

- **Traditional ways of understanding physics**

  → based on classification of physical systems (in scale hierarchy)

  ex) elementary particle physics, nuclear physics, atomic physics, optics, condensed matter physics (metal, insulator, semiconductor), astrophysics

- **Interdisciplinary ways of understanding physics**

  → based on properties that are common in different systems

  ex) nonlinear physics, critical phenomena, non-equilibrium physics, etc

- **Strong field physics is one of such.**

  → we treat **extreme phenomena in many different systems** which could be hopefully described in "universal" ways.

Workshop series "Physics in Intense Fields"

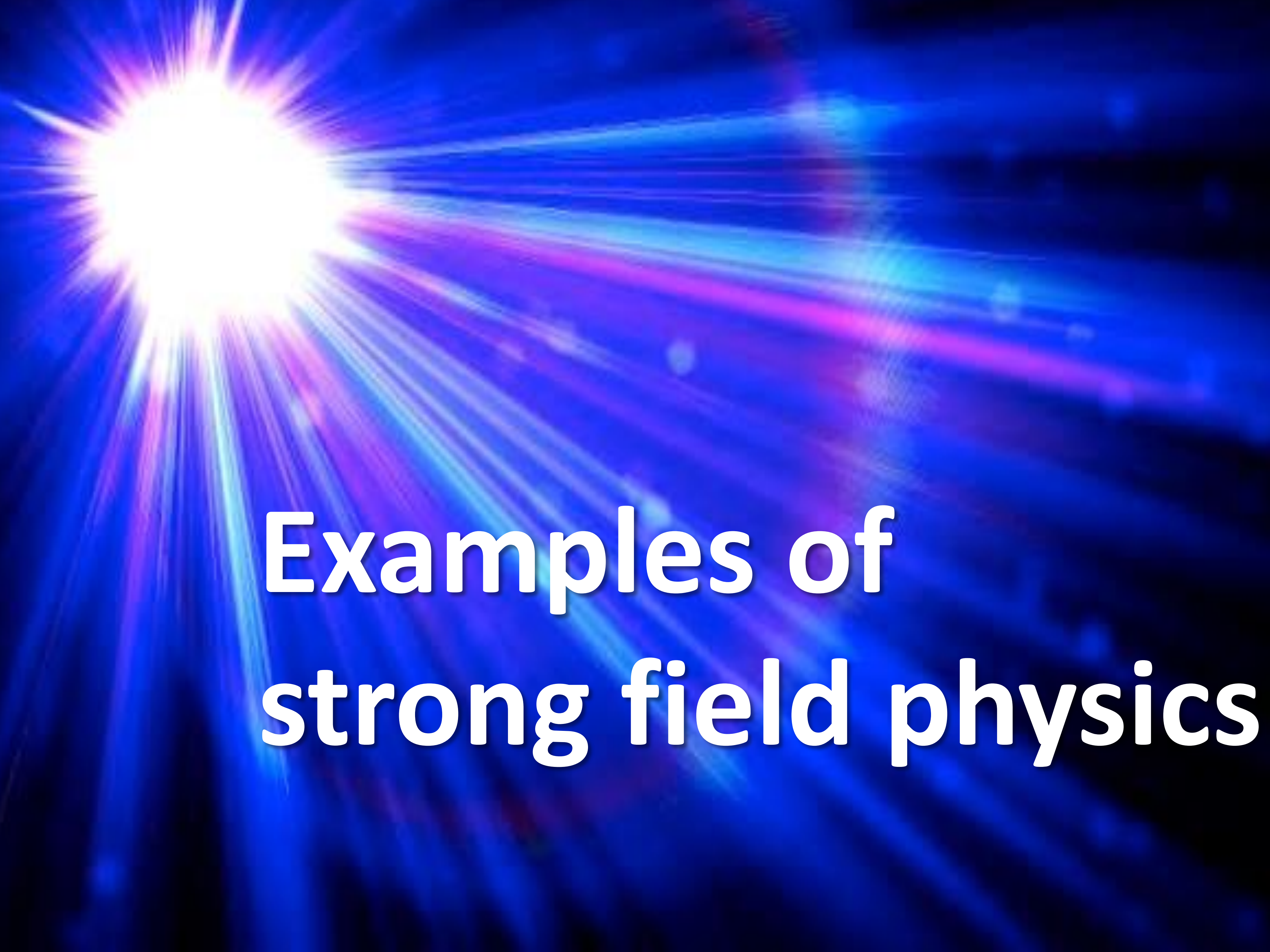
covered many areas in physics

(particle physics, nuclear-hadron physics, cond-mat physics, astrophysics, laser physics)

- **PIF2010 @ KEK** (# of participants ~100) chair of program committee

  http://atfweb.kek.jp/pif2010/
- **PIF2013 @ DESY** (# of participants ~60) one of organizers

  https://indico.desy.de/conferenceDisplay.py?confId=7155
- PIF2015 ? @ England?

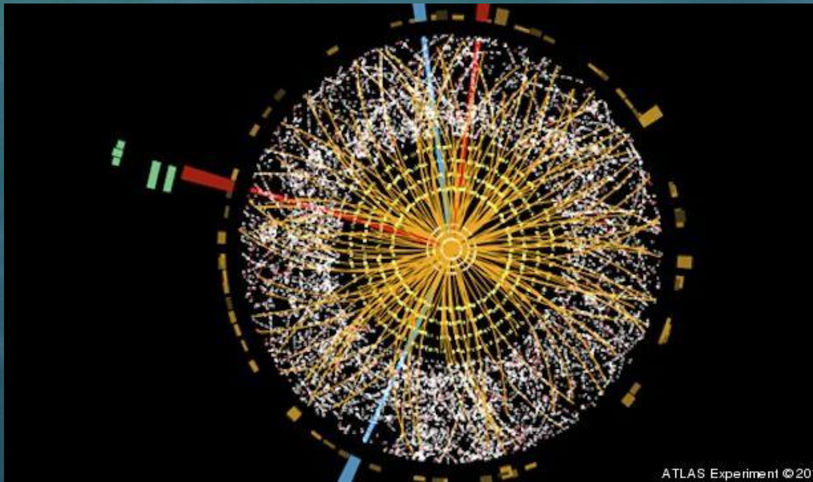


Examples of strong field physics

"Vacuum" in modern physics

- **Quantum Field Theory** is the basic language of modern physics
  → describes dynamics of oscillating degrees of freedom at each space point
- **"Vacuum"** = lowest energy state of the system having nontrivial structure. Always fluctuating.
- Unveiling the vacuum structure is the first step towards understanding the physical world.
  The same is true for condensed matter physics.

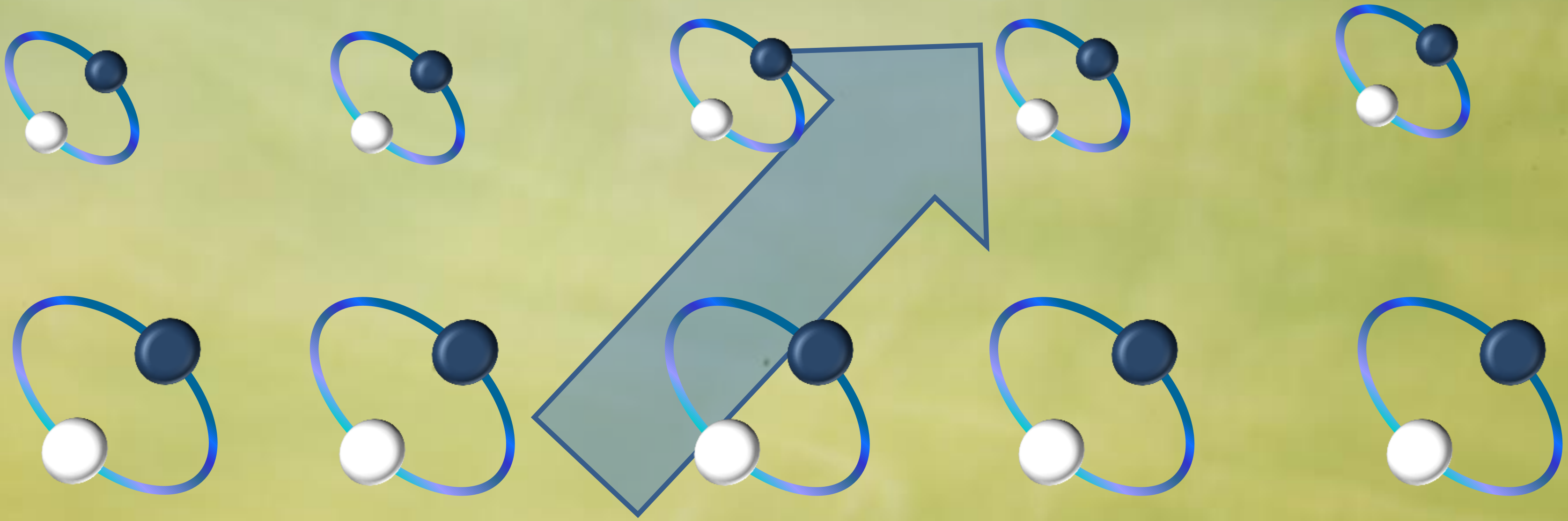
ex) "Higgs particle" is a fluctuation, excitation of the vacuum with nontrivial structure (condensed Higgs fields).



QED ------ A world of photons, electrons and positrons

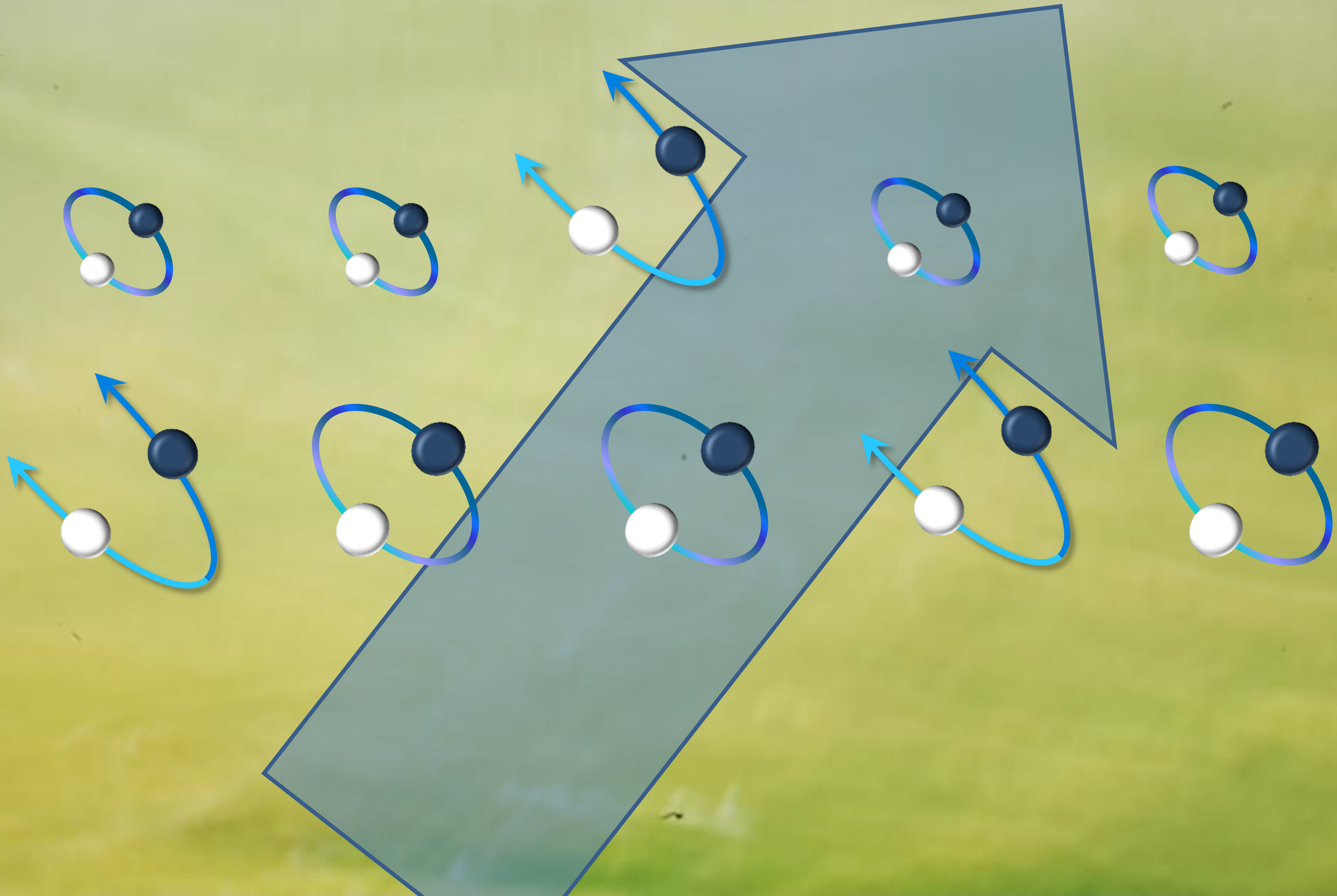
The vacuum is always fluctuating with virtual electron-positron pairs.

Random fluctuations align in external fields
→ they behave "coherently".

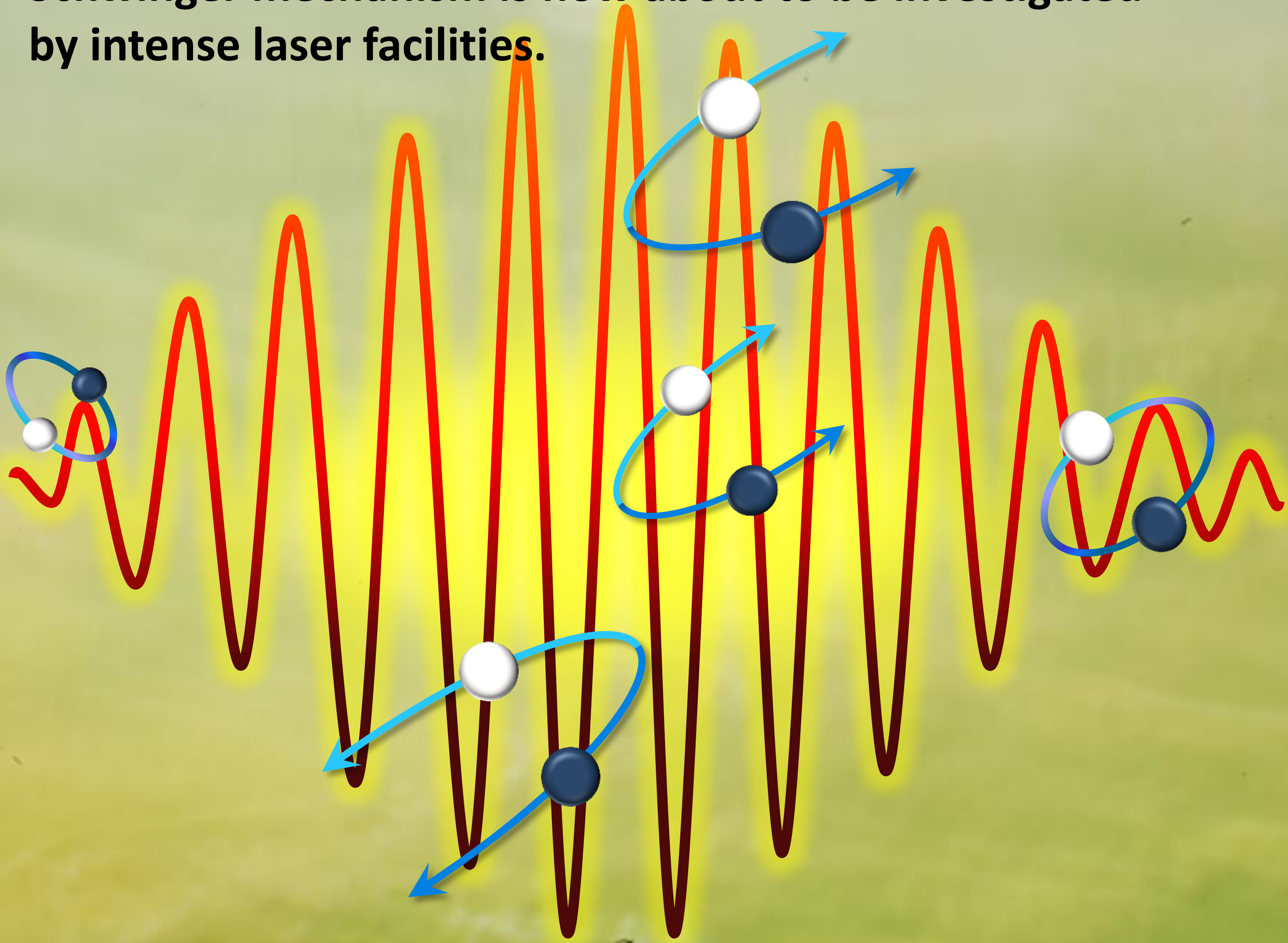


With increasing external electric fields, virtual pair becomes real.
Amplification of fluctuation!

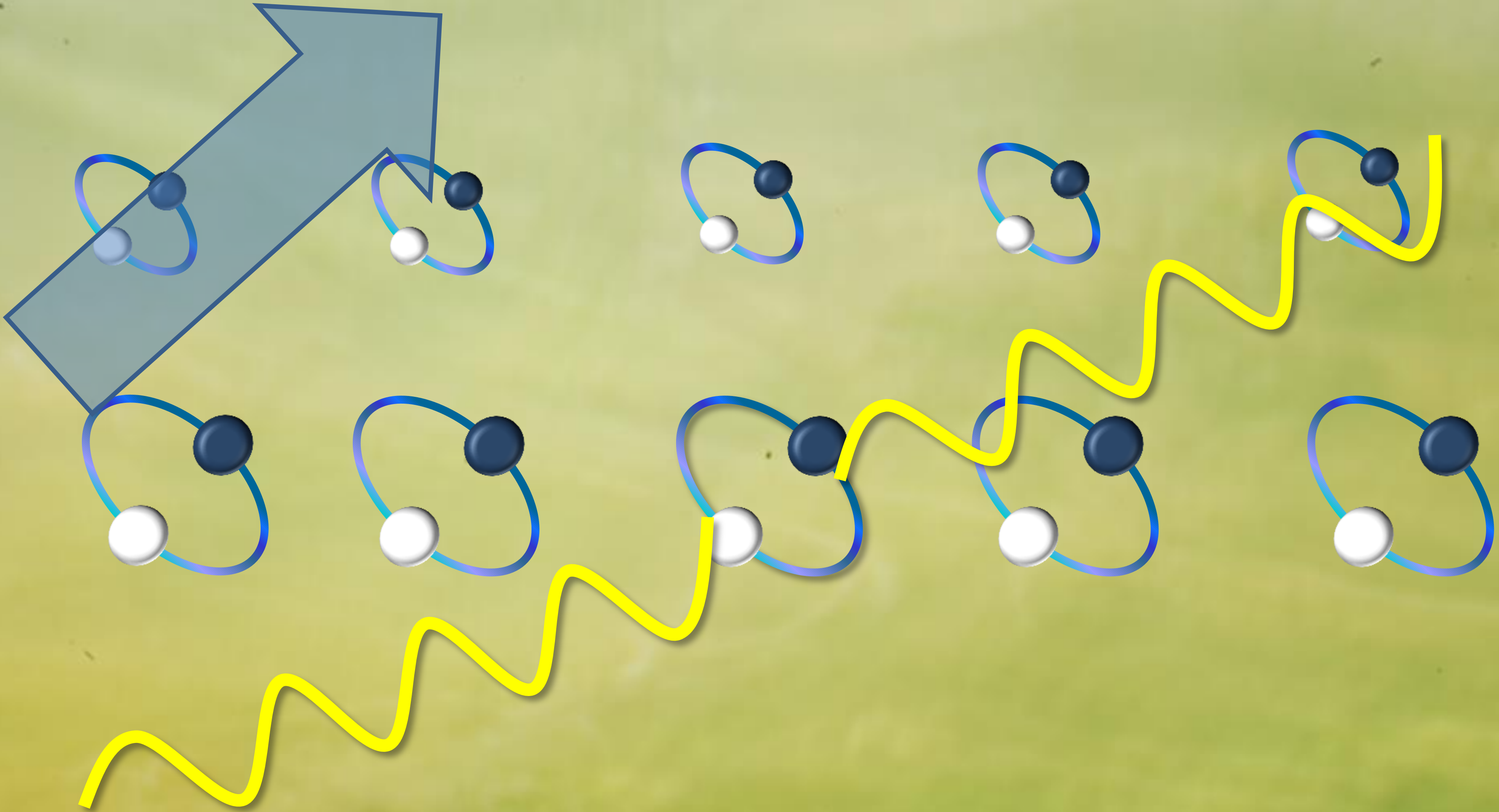
→ Vacuum “break-down” (Schwinger mechanism)



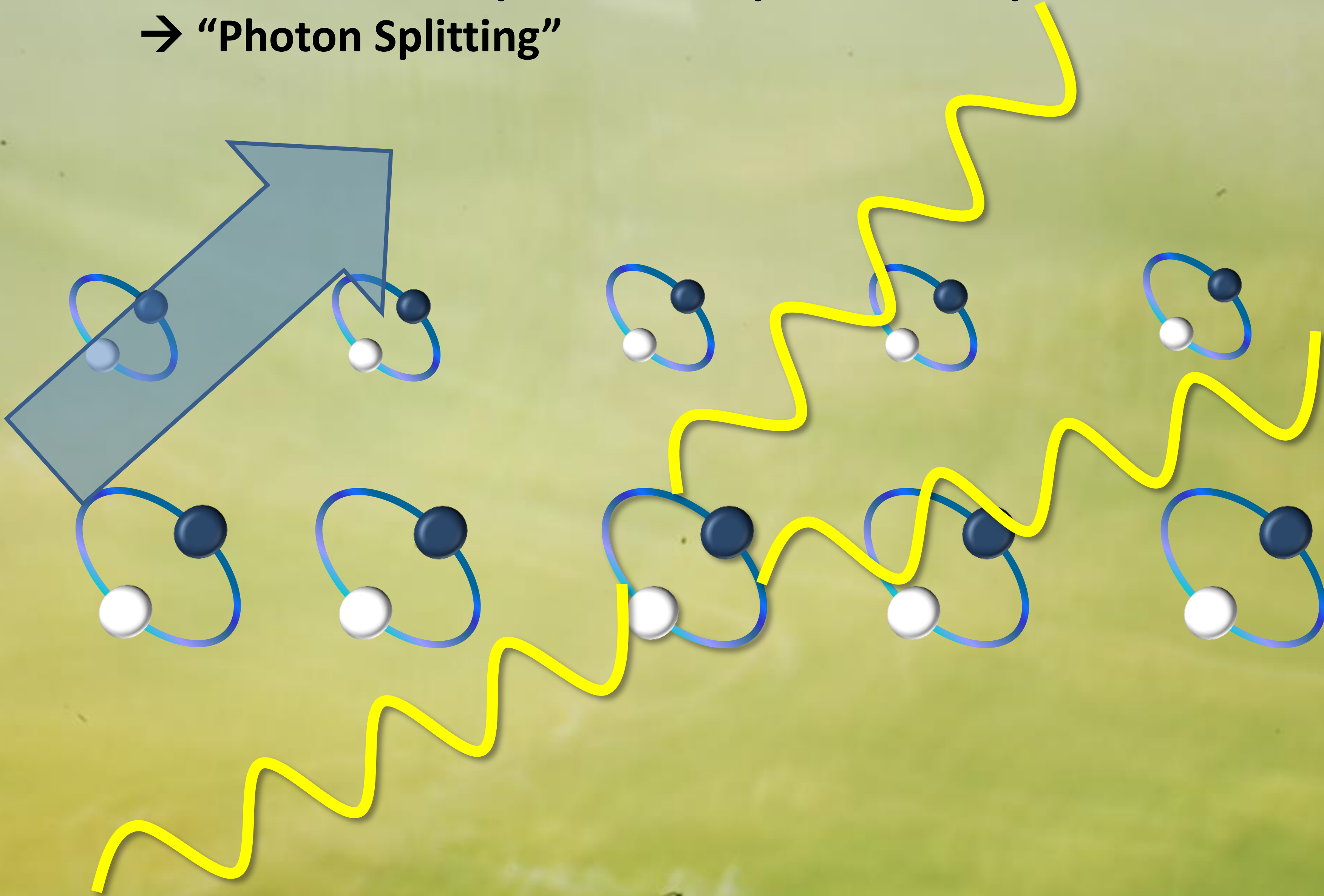
Schwinger mechanism is now about to be investigated by intense laser facilities.



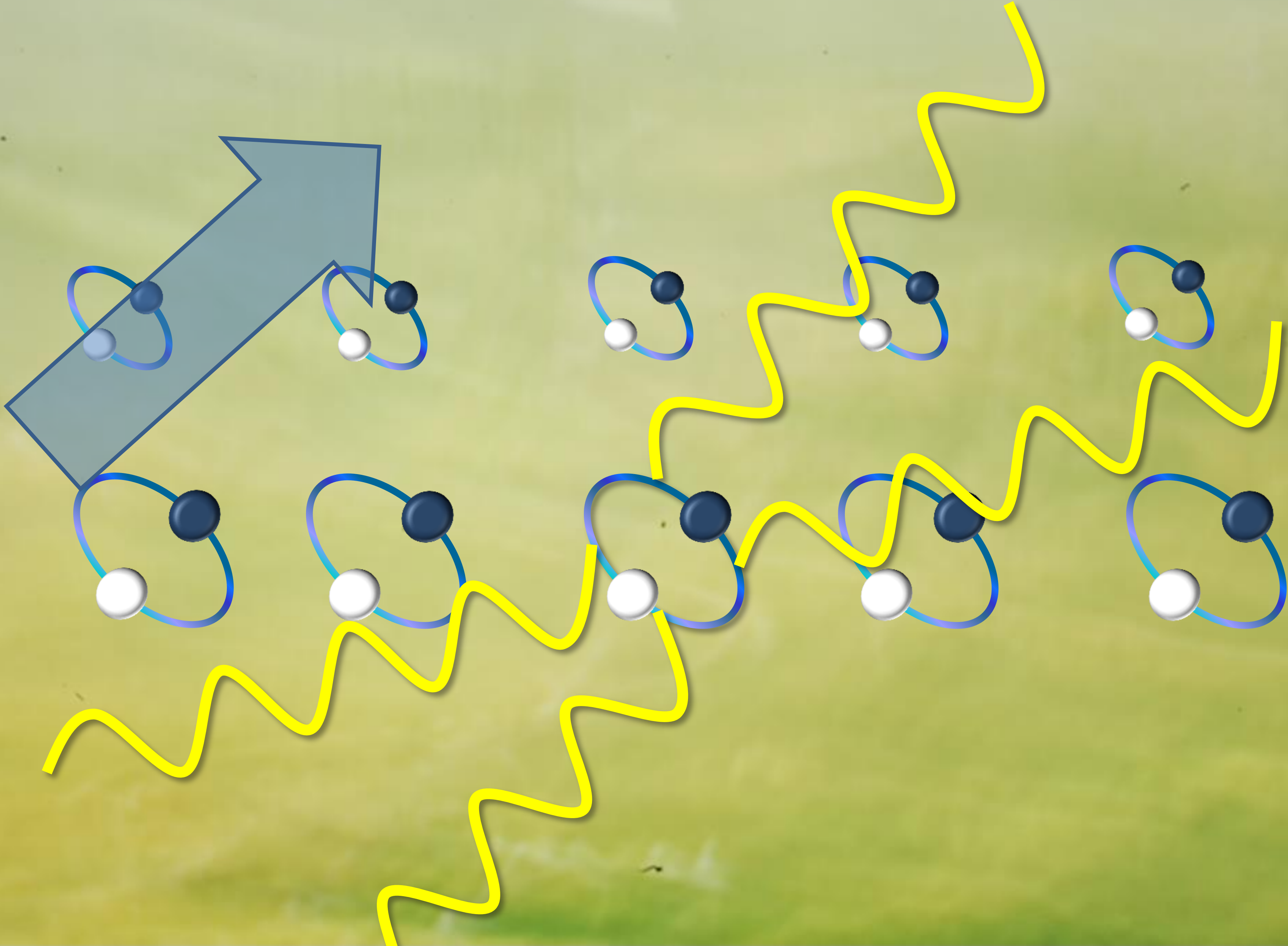
External photons easily couple to aligned (enhanced) fluctuations to change their properties.   cf) exiton-polariton



Sometimes a real photon can split into two photons
→ "Photon Splitting"



Photon-photon scattering is enhanced due to external fields



Examples

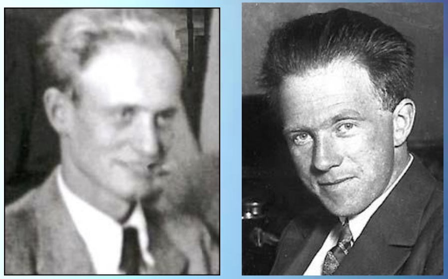
1. Field dynamics

- Euler-Heisenberg action
- Schwinger mechanism (1 loop)
- Schwinger mechanism (beyond 1 loop)

2. Interaction of a particle with strong fields

- Photons : birefringence and decay
- neutral pions : new decay mode

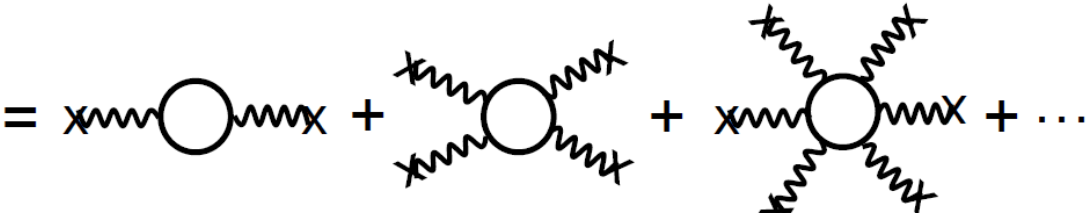
Euler-Heisenberg action



Z. Phys. 98, 714 (1936)
arXiv:physics/0605038

- Effective potential of constant EM fields
  is nonlinear inducing interactions among fields

$$\mathfrak{L} = \underbrace{\frac{1}{2}(\mathfrak{E}^2 - \mathfrak{B}^2)}_{\text{original}} + \frac{e^2}{h\,c}\int_0^\infty e^{-\eta}\,\frac{d\,\eta}{\eta^3}\left\{ i\,\eta^2(\mathfrak{E}\,\mathfrak{B})\cdot\frac{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2\,i\,(\mathfrak{E}\,\mathfrak{B})}\right)+\text{konj}}{\cos\left(\frac{\eta}{|\mathfrak{E}_k|}\sqrt{\mathfrak{E}^2-\mathfrak{B}^2+2\,i\,(\mathfrak{E}\,\mathfrak{B})}\right)-\text{konj}} + |\mathfrak{E}_k|^2 + \frac{\eta^2}{3}(\mathfrak{B}^2-\mathfrak{E}^2)\right\}$$



$$|\mathfrak{E}_k| = \frac{m^2c^3}{e\hbar}$$

$$= -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{\alpha^2}{360m^4}\left[4(F^{\mu\nu}F_{\mu\nu})^2 + 7(F^{\mu\nu}\tilde{F}_{\mu\nu})^2\right] + \cdots$$

Analog of photon photon scattering

- Imaginary part appears when E is greater than E_{crit}

J. Schwinger, 1951
W.Heisenberg, H.Euler, 1936

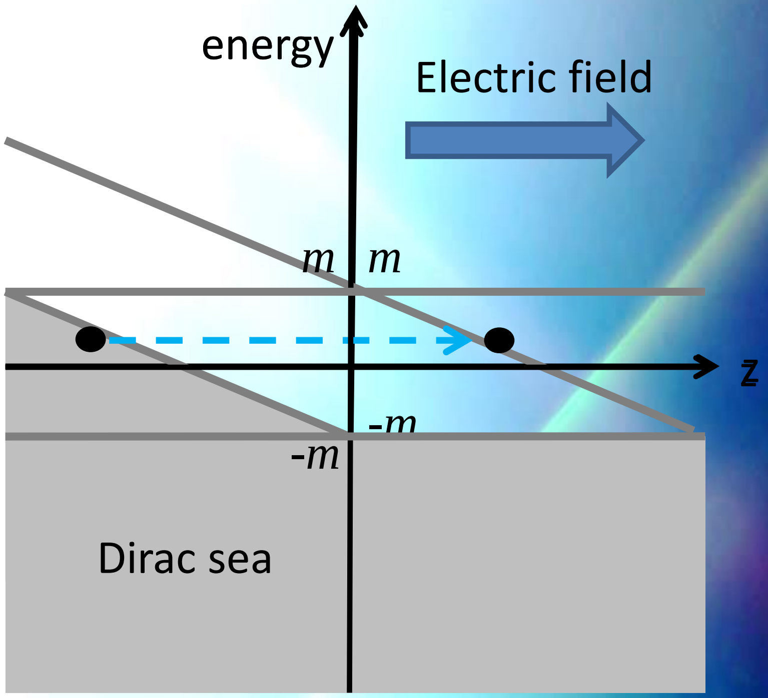
Schwinger mechanism

Electron-positron pair creation occurs under very strong electric field

- **Mass gap → tunneling**

Critical field $$E_c = \frac{m_e^2}{e}$$

tunneling probability $$P(p_T) = \exp\left(-2\int |p_z|\, dz\right)$$
$$= \exp\left(-\frac{\pi(m_e^2 + p_T^2)}{eE}\right)$$



- **Imaginary part of Euler-Heisenberg action**

weak-coupling, 1 loop, infinite order wrt external field

NONperturbative → impossible in fixed higher order

- **Not measured yet! P ~ exp {– π E_c/E }**

← analogy : laser ionization of atom,
electron-hole pair creation, etc

Beyond 1-loop Schwinger formula

- **Higher loop effects and strong coupling**

  two loop only in weak field limit (Lebedev-Ritus 1984)

  all order guess (Ritus 1987) ←→ strong coupling result (Affleck et al, 1982)

  weak field limit

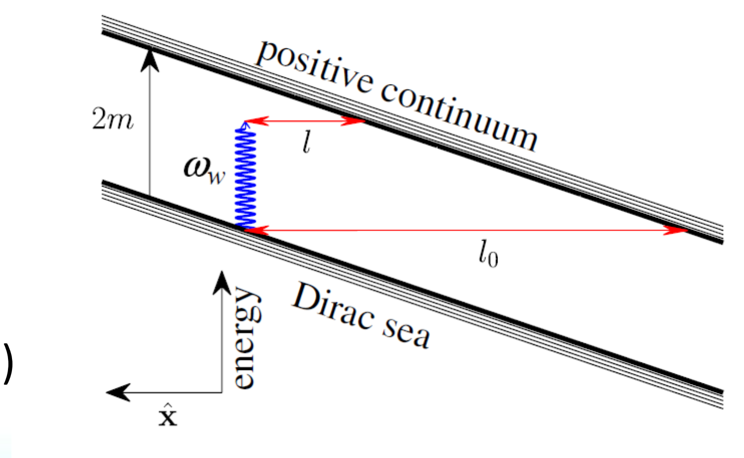
- **Enhanced by rapid fluctuation**

  (assisted Schwinger mechanism)

  rapid mode reduces tunneling barrier

  combination with multiphoton absorption

  (Schutzhold, Gies, Dunne, 2008)

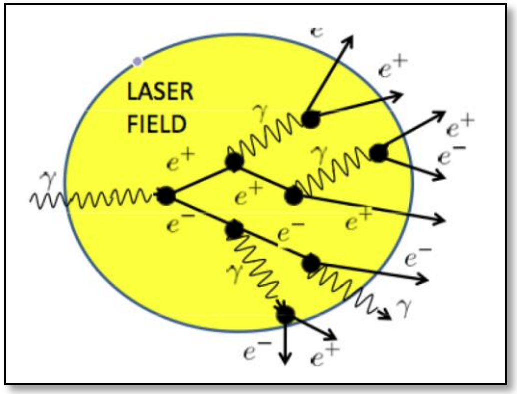


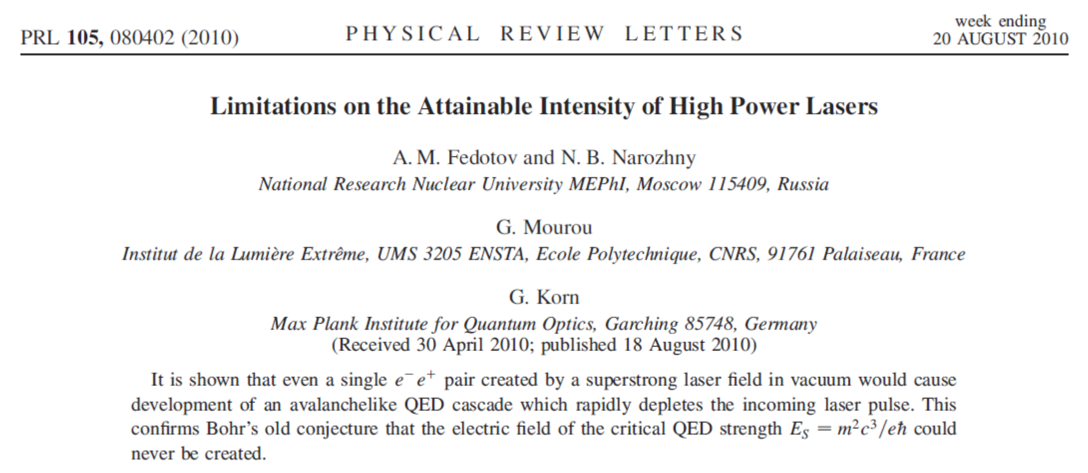
- **Finite volume effects**

  In order to create a pair, the extent must be larger than the Compton length

  It would make sense to discuss **supercritical electric field** only when we consider small volume cf Wang-Wong 1988

QED cascade




PRL **105,** 080402 (2010) PHYSICAL REVIEW LETTERS week ending 20 AUGUST 2010

Limitations on the Attainable Intensity of High Power Lasers

A. M. Fedotov and N. B. Narozhny
National Research Nuclear University MEPhI, Moscow 115409, Russia

G. Mourou
Institut de la Lumière Extrême, UMS 3205 ENSTA, Ecole Polytechnique, CNRS, 91761 Palaiseau, France

G. Korn
Max Plank Institute for Quantum Optics, Garching 85748, Germany
(Received 30 April 2010; published 18 August 2010)

It is shown that even a single e^-e^+ pair created by a superstrong laser field in vacuum would cause development of an avalanchelike QED cascade which rapidly depletes the incoming laser pulse. This confirms Bohr's old conjecture that the electric field of the critical QED strength $E_S = m^2c^3/e\hbar$ could never be created.

- We cannot go beyond Schwinger's critical field $E_s = m^2/e$.
- Once an e+e- pair creation occurs, electrons/positrons are accelerated by the laser field to emit hard photons (brems), which then decay into e+e- pairs. The original laser field will be screened by this cascade.
- Very short period < Schwinger mechanism
- Cascade itself occurs at lower electric field $E > \alpha E_s$ (α =1/137). Thus injection of an energetic electron will be enough for the cascade to occur even in subcritical electric field.

Prototype of cascade

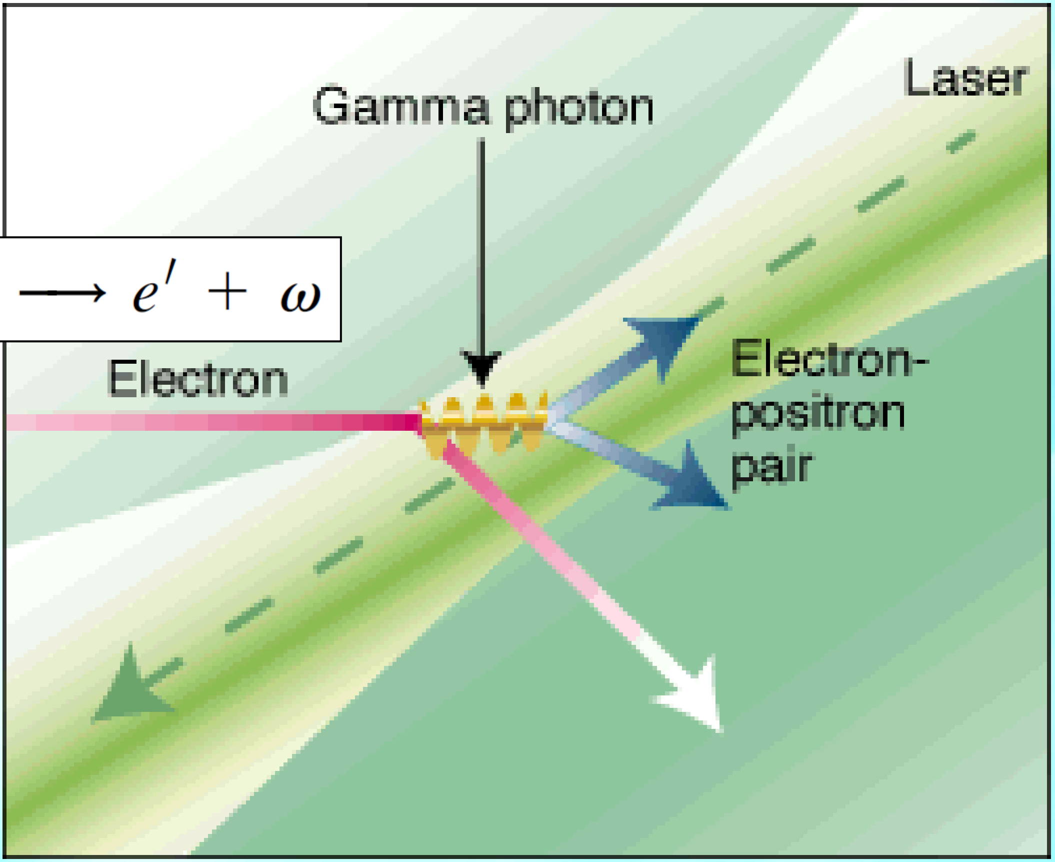
- Observation of photon emission and its decay in laser field

E144 @ SLAC

PRL76 (1996)
PRL79 (1997)

$$e + n\omega_0 \longrightarrow e' + \omega$$

Confirmed up to n=4



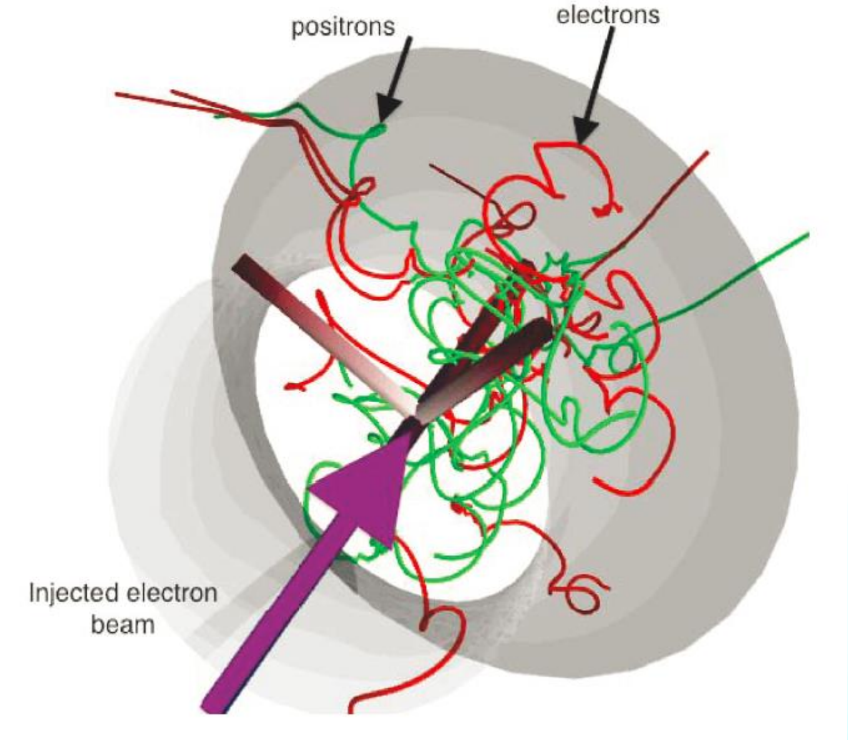
$$\omega + m\omega_0 \rightarrow e^- + e^+$$

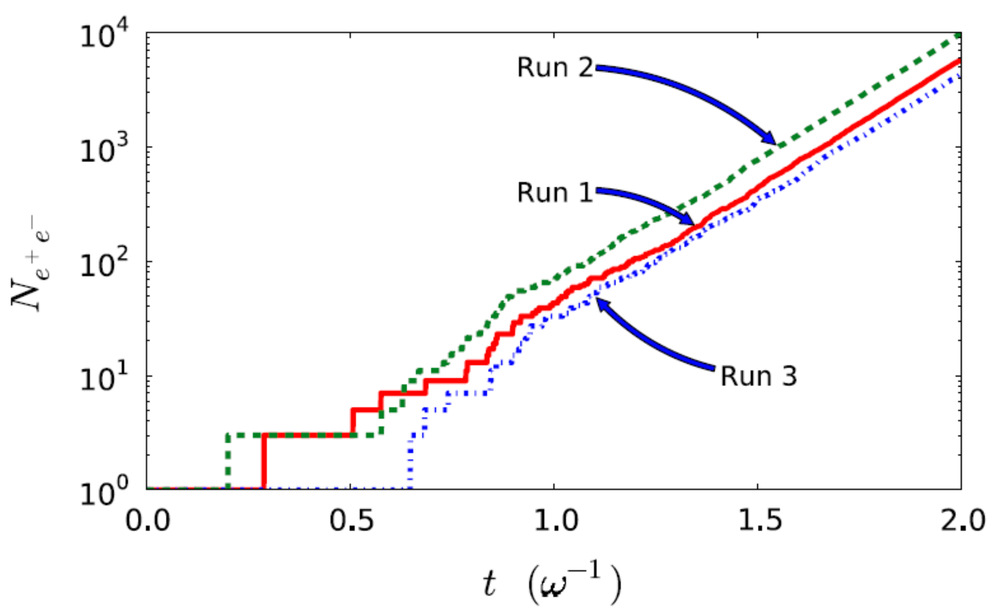
Electron energy 46.6 GeV
Laser Nd:glass 1054 and 527 nm
Peak intensity 10^{18} W/cm2

Numerical simulation

Elkina, et al. PRST 14 (2011)

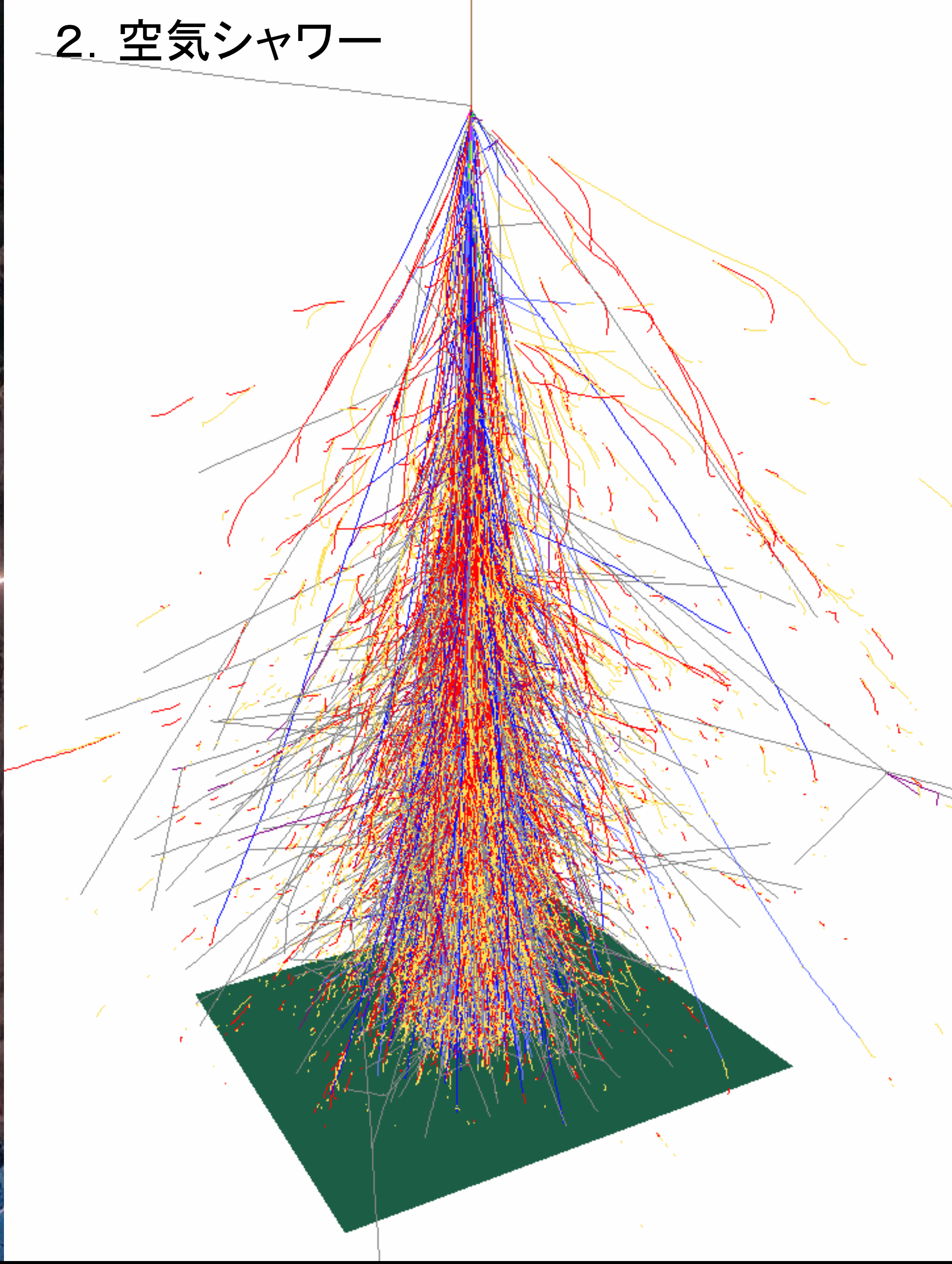
Monte-Carlo simulation of ***cascade equations***





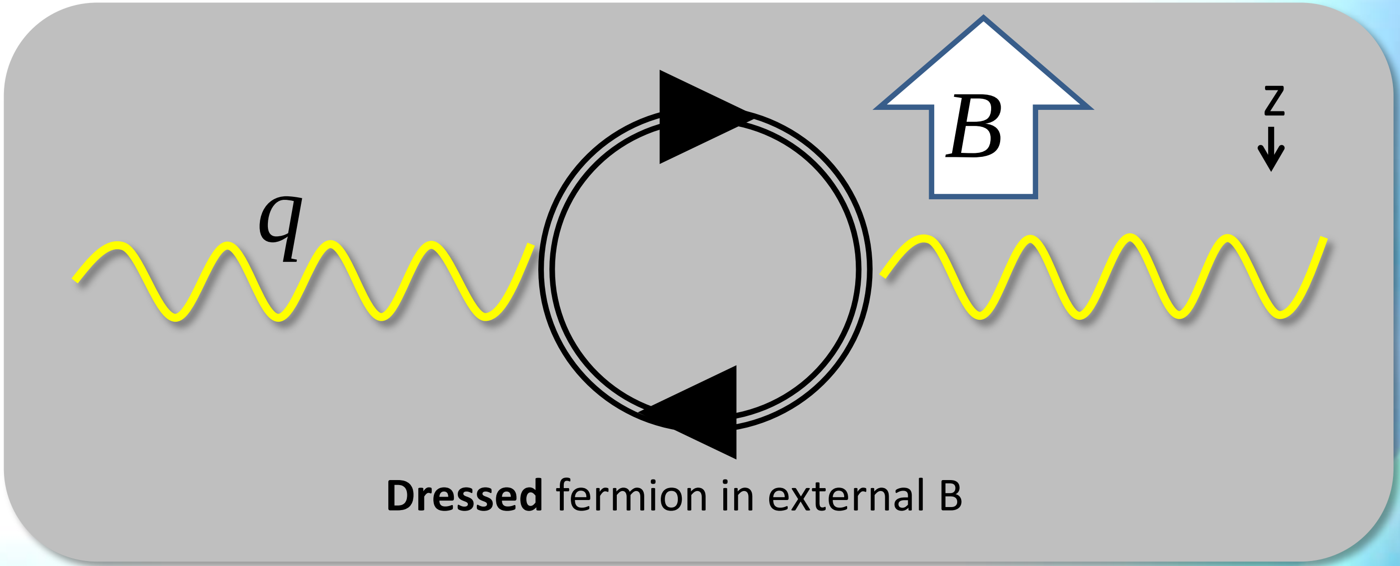
ω : laser frequency

Number of e+e- pairs grow exponentially in time.



1．空気（絶縁体）にかかった高電位差が、電子の雪崩的な生成に伴う雷で解消する。
2．高エネルギーの粒子が大気中の原子核に衝突し、生成粒子がさらに粒子を放出。

Photons in strong magnetic fields



Dressed fermion in external B

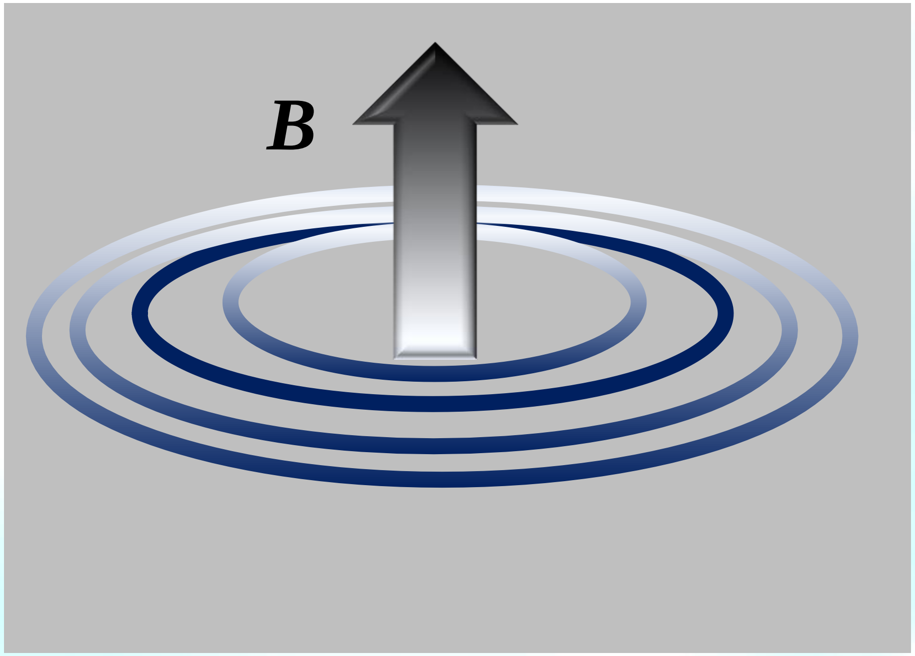
- **Properties of a photon propagating in a magnetic field**

  ← vacuum polarization tensor $\Pi^{\mu\nu}(q,B)$

- **Old but new problem** [Weisscopf 1936, Baier-Breitenlohner 1967, Narozhnyi 1968, Adler 1971]

  - Polarization tensor $\Pi^{\mu\nu}(q,B)$ has been known in *integral* form
  - Analytic representation obtained very recently [Hattori-Itakura 2013]

Charged fermion in magnetic fields

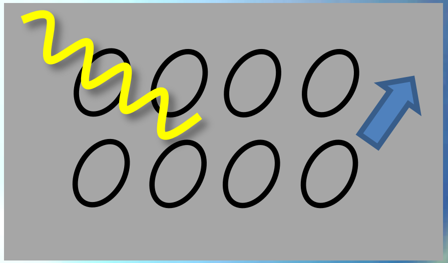


Anisotropic response

- Can freely move in parallel to the magnetic field.
- Transverse motion is quantized to the Landau levels.

(need to include the effects of magnetic fields to all orders)

Magnetic vacuum as a media



Propagating photon in strong magnetic field

= probing magnetic vacuum “polarized” by external fields

~ photon couples to virtual excitation of vacuum (cf: exciton-polariton)

***B* dependent anisotropic response of a fermion** (Landau levels)

- discretized transverse vs unchanged longitudinal motion
  - → Two different refractive indices : ***VACUUM BIREFRINGENCE***
- energy conservation gets modified
  - → Pol. Tensor can have imaginary part : ***PHOTON DECAY INTO e+e- PAIR***

(lots of astrophysical applications)

$$\Pi^{\mu\nu}_{\rm ex}(q) = \chi_0(q^2\eta^{\mu\nu} - q^\mu q^\nu) + \underline{\chi_1(q_\parallel^2\eta_\parallel^{\mu\nu} - q_\parallel^\mu q_\parallel^\nu) + \chi_2(q_\perp^2\eta_\perp^{\mu\nu} - q_\perp^\mu q_\perp^\nu)}$$

present only in external fields

II parallel to B

⊥ transverse to B

$$\eta_\parallel^{\mu\nu} = diag(1,0,0,-1)$$

$$\eta_\perp^{\mu\nu} = diag(0,-1,-1,0)$$

$$\begin{aligned} q^\mu &= (q^0, q_\perp, 0, q^3) \\ q_\parallel^\mu &= (q^0, 0, 0, \; q^3) \\ q_\perp^\mu &= (0, q_\perp, 0, 0) \end{aligned}$$

Vacuum birefringence

- **Maxwell eq. with the polarization tensor :**

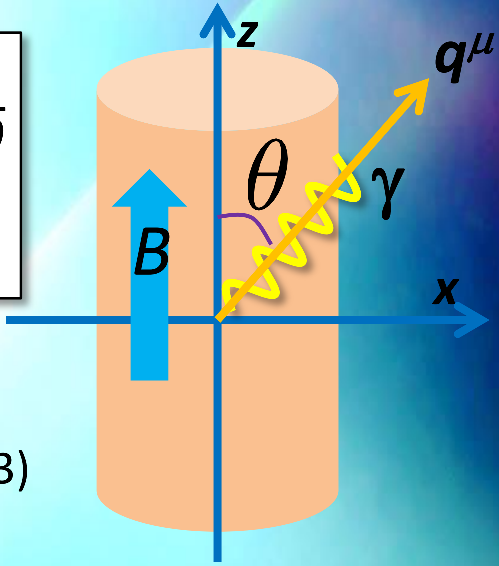
$$\left(q^2\eta^{\mu\nu} - q^\mu q^\nu + \hat{\Pi}^{\mu\nu}_{\rm ex}\right) A_\nu(q) = 0$$

$$\Pi^{\mu\nu}_{\rm ex}(q) = \chi_0(q^2\eta^{\mu\nu} - q^\mu q^\nu) + \chi_1(q_\parallel^2\eta_\parallel^{\mu\nu} - q_\parallel^\mu q_\parallel^\nu) + \chi_2(q_\perp^2\eta_\perp^{\mu\nu} - q_\perp^\mu q_\perp^\nu)$$

- **Dispersion relation of two physical modes gets modified**

→ Two refractive indices : "Birefringence"

$$n^2 \equiv \frac{|\boldsymbol{q}|^2}{\omega^2} \Rightarrow \begin{cases} n_1^2 = \dfrac{1+\chi_0+\chi_1}{1+\chi_0+\chi_1\cos^2\theta} \\ n_2^2 = \dfrac{1+\chi_0}{1+\chi_0+\chi_2\sin^2\theta} \end{cases}$$



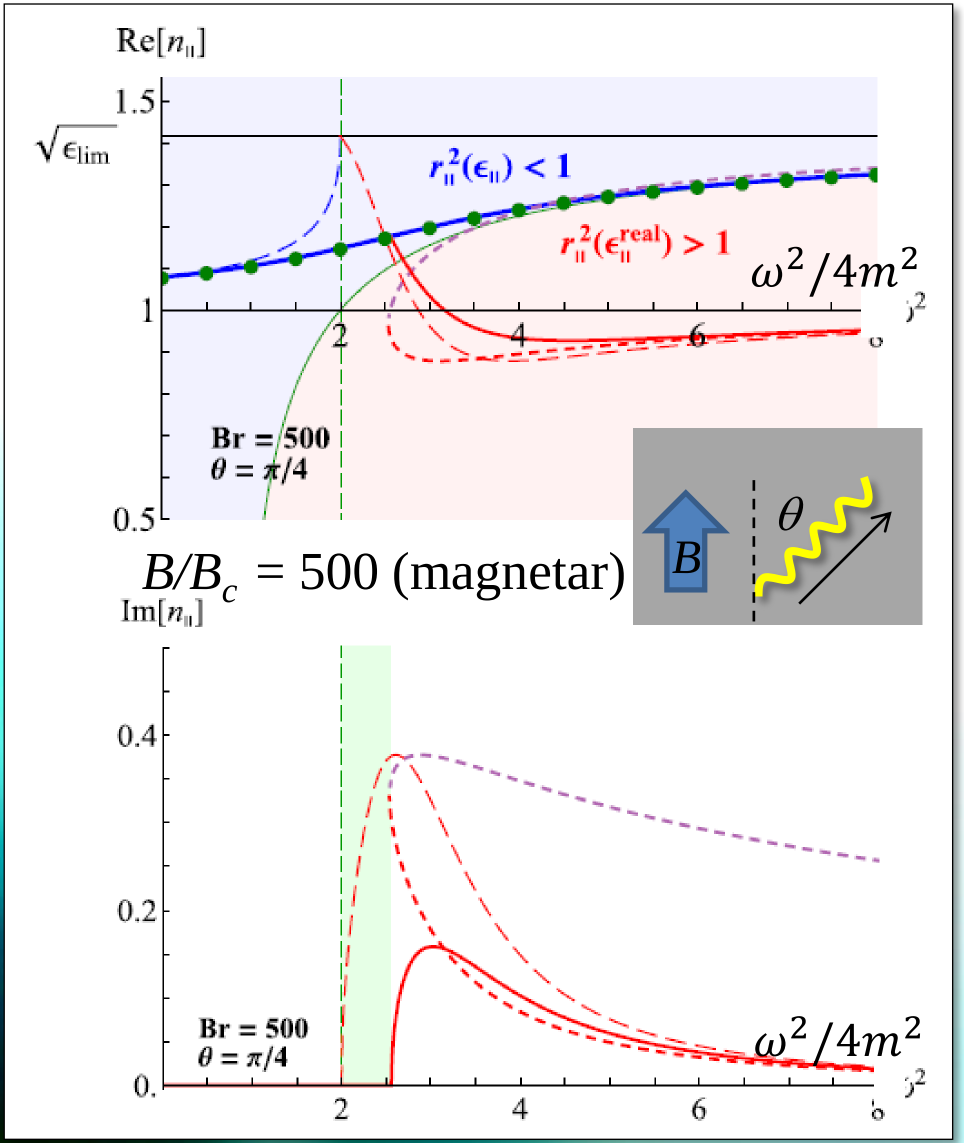
1. Compute χ_0, χ_1, χ_2 analytically at the one-loop level

Hattori-Itakura Ann. Phys. 330 (2013)

2. Solve them self-consistently w.r.t *n in LLL approx.*

Hattori-Itakura Ann. Phys. 334 (2013)

Refractive index

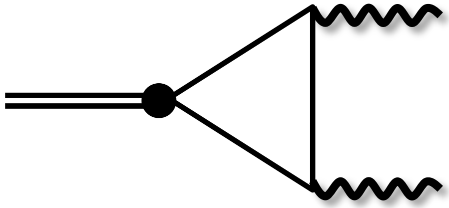


- **Use LLL solution for simplicity**
- **Refractive index $n_{||}$ deviates from 1 and increases with increasing ω**

  cf: air n = 1.0003, water n = 1.333
- **New branch at high energy is accompanied by an imaginary part → decay into an e+e- pair**

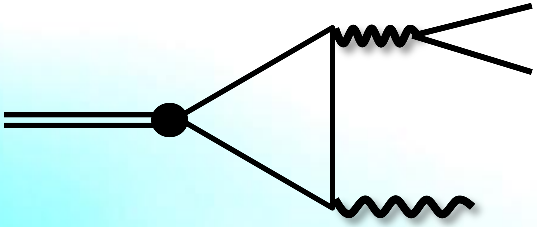
Neutral pion decay

- **Chiral anomaly** induces π^0 decay through triangle diagram



$$\pi^0 \to 2\gamma : \mathcal{O}\left(e^2\right)$$

Dominant (98.798 % in vacuum)



$$\pi^0 \to \gamma + e^+e^- : \mathcal{O}\left(e^3\right)$$

Dalitz decay (1.198 % in vacuum)
NLO contribution

99.996 %

- **Adler-Bardeen's theorem**

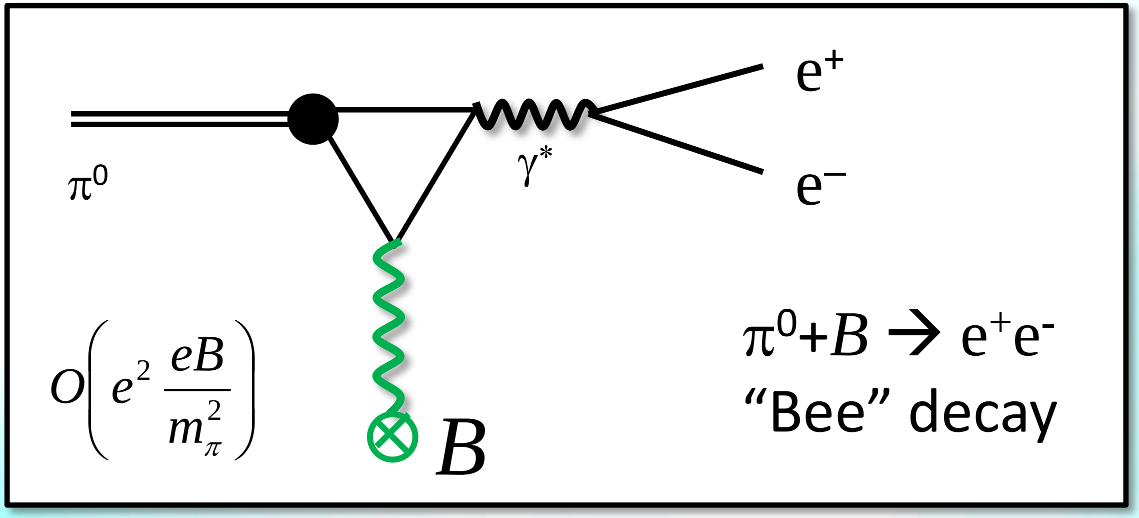
There is no radiative correction to the triangle diagram
Triangle diagram gives the exact result in all-order perturbation theory

→ only two photons can couple to π^0

Neutral pions in strong B

Hattori , KI, Ozaki, arXiv:1305.7224[hep-ph]

- There is only one diagram for a constant external field to be attached



$O\left(e^2 \frac{eB}{m_\pi^2}\right)$

$\pi^0 + B \rightarrow e^+e^-$
"Bee" decay

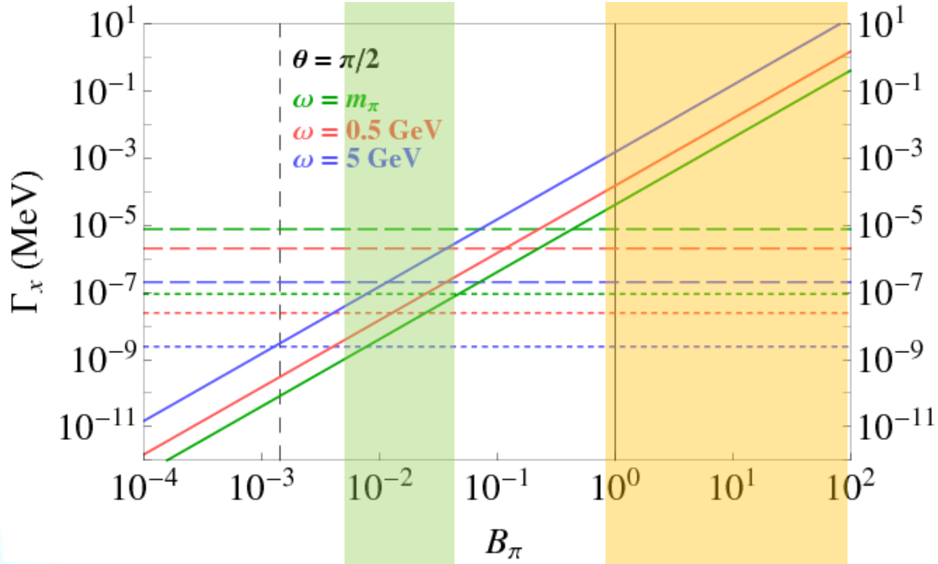
cf: axion
(very light, but
small coupling)

- Also implies

-- conversion into γ with space-time varying B
-- Primakoff process* ($\gamma^* + B \rightarrow \pi^0$): important in HIC
-- mixing of π^0 and γ

* observed in nuclear Coulomb field

Decay rates of three modes

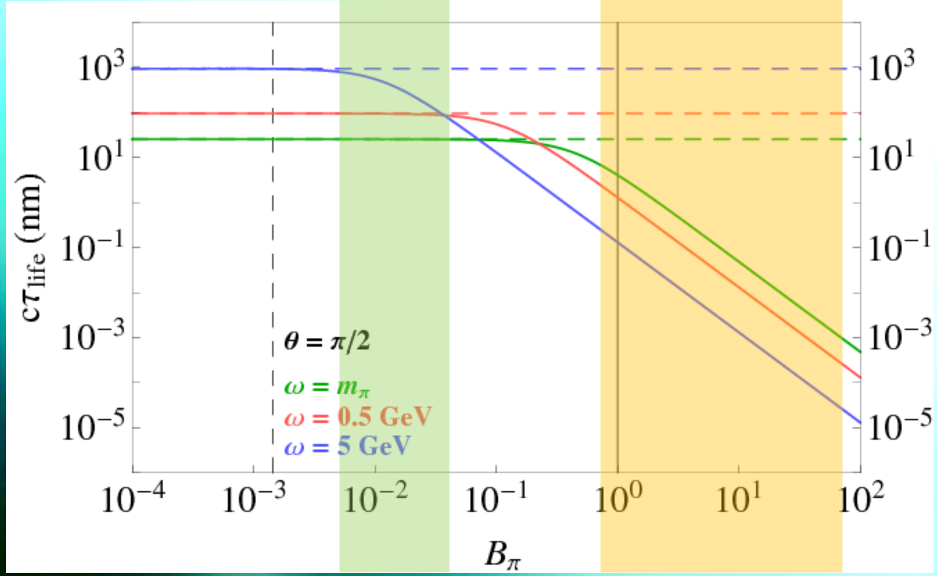


Solid : "Bee" decay
Dashed: 2γ decay
Dotted : Dalitz decay

$$\Gamma_{Be^+e^-} = \frac{q^2 q_\parallel^2}{12\pi\omega_\pi}\left(\lambda\frac{eB}{q^2}\right)^2\left(1+\frac{2m^2}{q^2}\right)\sqrt{1-\frac{4m^2}{q^2}}$$

$$B_\pi = B/m_\pi^2$$

Mean lifetime



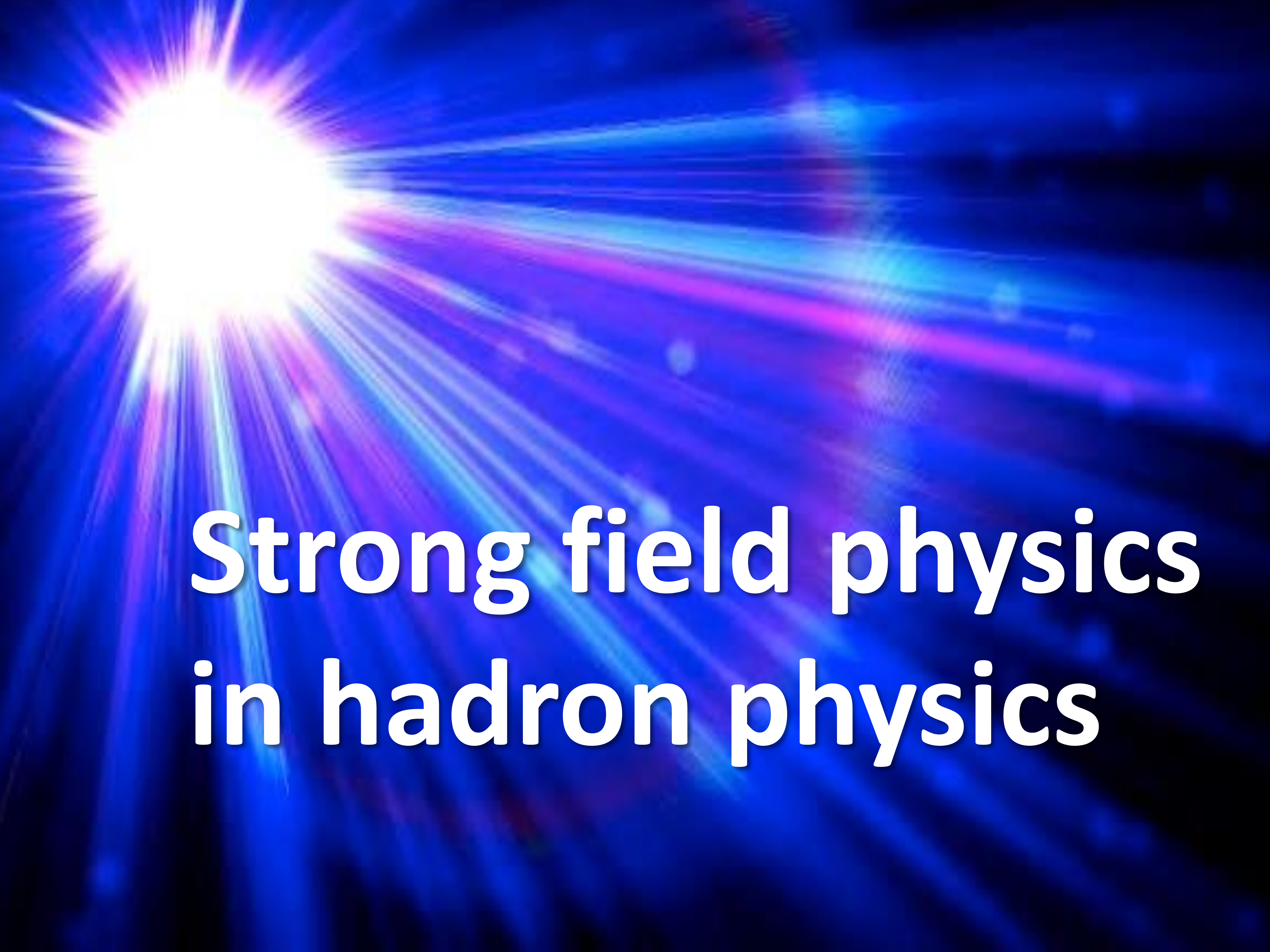
← Picometer

← femtometer

$$\tau_{life} = \Gamma_{total}^{-1}$$

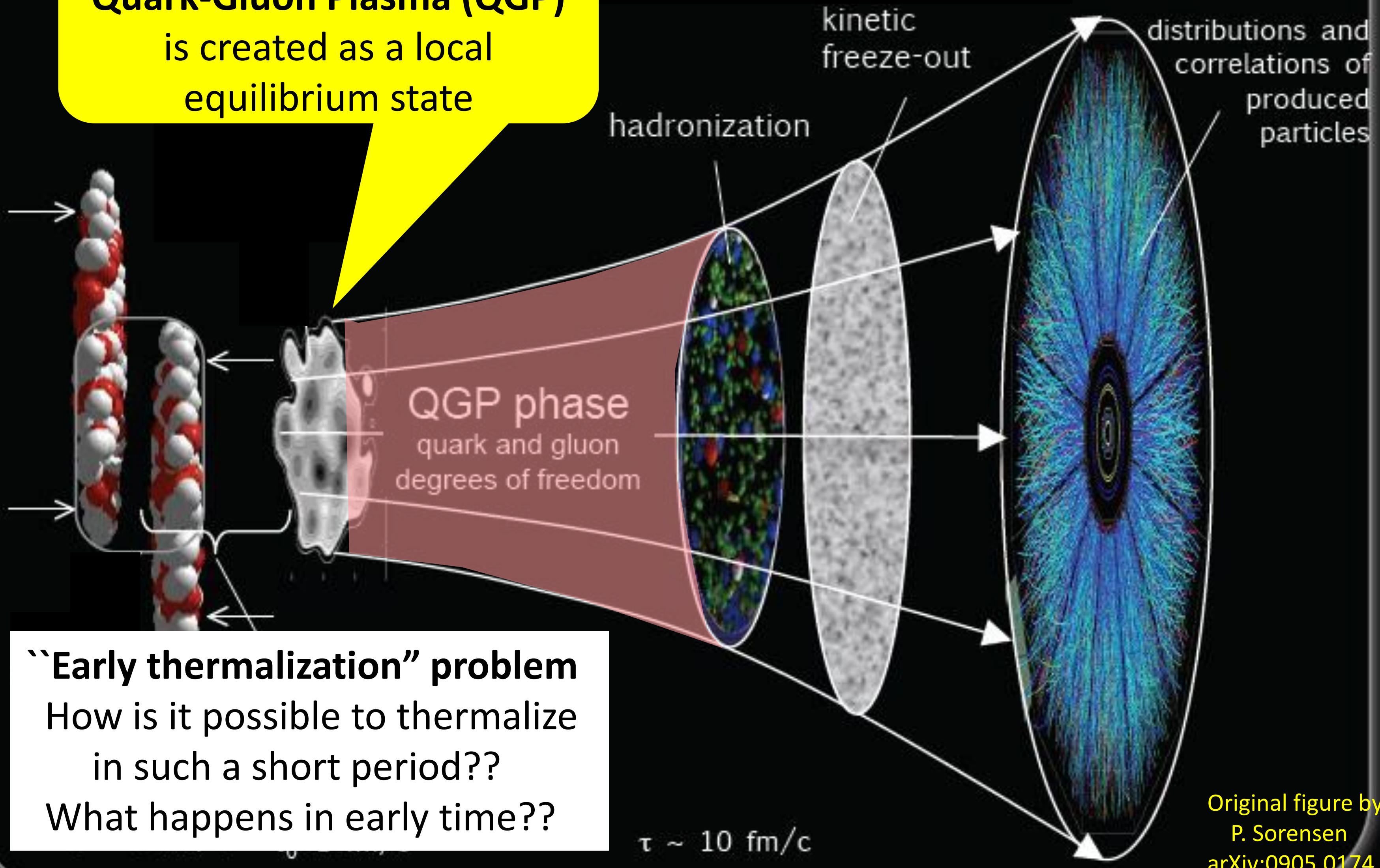
$$= \frac{1}{\Gamma_{2\gamma} + \Gamma_{Dalitz} + \Gamma_{Bee}}$$

Energetic pions created in cosmic ray reactions will be affected



Strong field physics in hadron physics

Heavy-ion Collisions: Little Bang



After a finite short time, **Quark-Gluon Plasma (QGP)** is created as a local equilibrium state

``Early thermalization" problem
How is it possible to thermalize in such a short period??
What happens in early time??

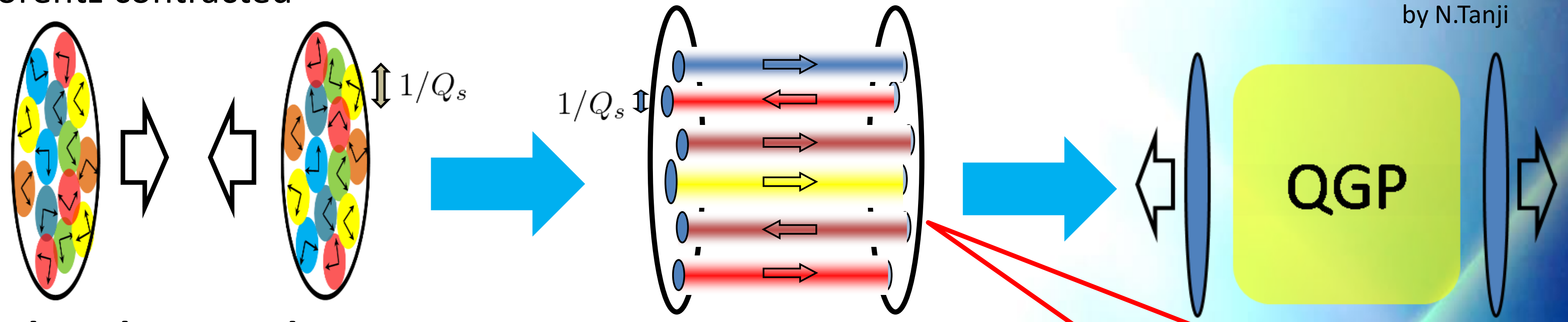
Original figure by P. Sorensen arXiv:0905.0174

A modern picture of HICs

Lorentz contracted

Gluon dominant

Original figure
by N.Tanji



Color Glass Condensate

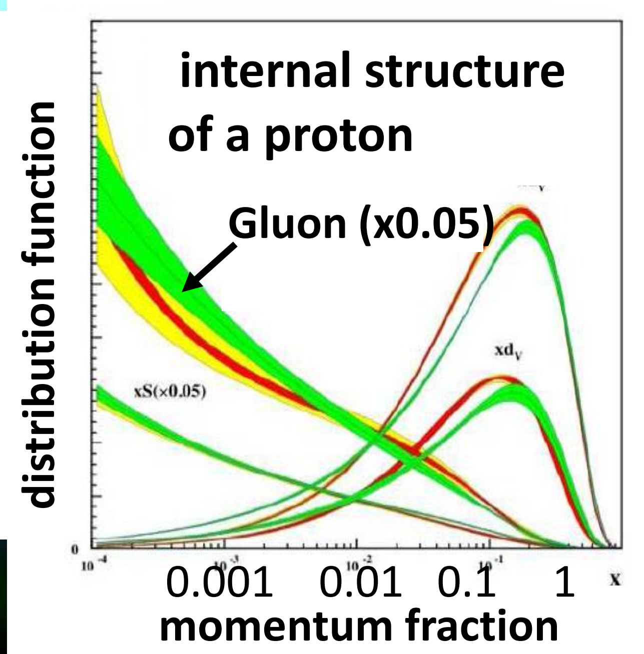
$$\mathbf{E}^a_\mathrm{T} \perp \mathbf{B}^a_\mathrm{T}$$

Glasma flux tubes

$$\mathbf{E}^a_\mathrm{L} \parallel \mathbf{B}^a_\mathrm{L}$$

non-Abelian Gauss's laws

$$\nabla \cdot \mathbf{E}^a = -g f^{abc} \mathbf{A}^b \cdot \mathbf{E}^c$$
$$\nabla \cdot \mathbf{B}^a = -g f^{abc} \mathbf{A}^b \cdot \mathbf{B}^c$$



After the collision: GLASMA

Very strong color SU(3) electromagnetic fields

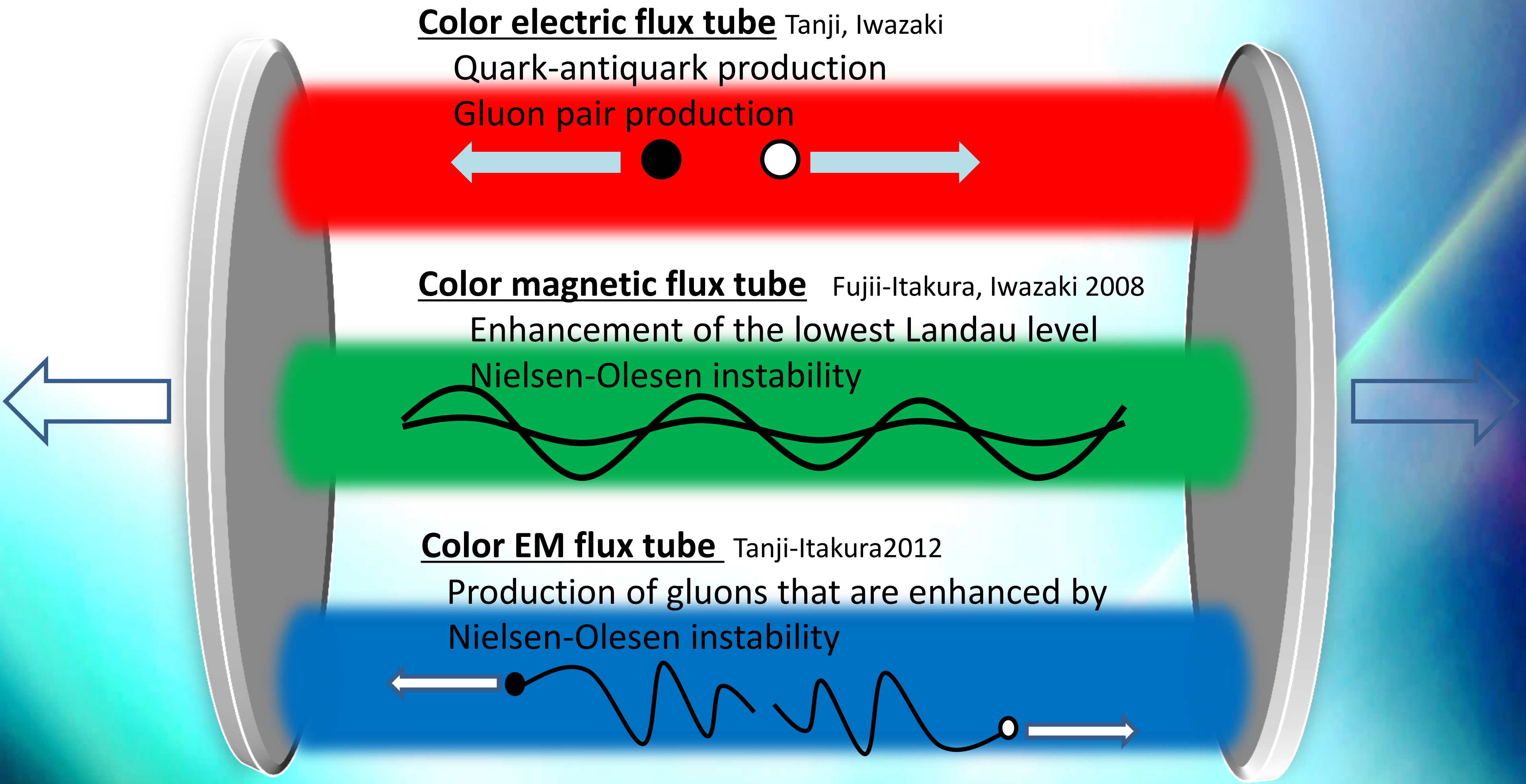
with flux structure

Both color ELECTRIC and MAGNETIC fields

$\sqrt{gB} \sim \sqrt{gE} \sim Q_s \sim$ 1- a few GeV $\gg m_q$

Strong fields, but weak coupling $Q_s \gg \Lambda_{QCD}$

Unstable Glasma



Color electric flux tube Tanji, Iwazaki

Quark-antiquark production

Gluon pair production

Color magnetic flux tube Fujii-Itakura, Iwazaki 2008

Enhancement of the lowest Landau level

Nielsen-Olesen instability

Color EM flux tube Tanji-Itakura2012

Production of gluons that are enhanced by Nielsen-Olesen instability

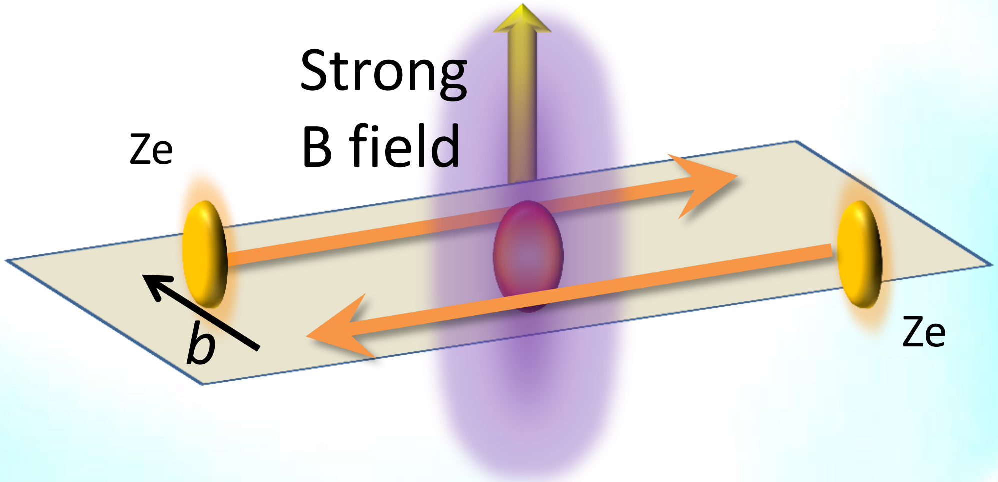
- Nonlinear time evolution of Glasma → Turbulent spectrum（≠ thermal）

→ **We definitely need more input from strong field physics**

Cascade for gluon dynamics? New info with EM probes?

Strong magnetic fields in HICs

- Two ions with **large electric charges** collide at high energy
- **Non-central** HICs at RHIC and LHC provide **STRONGEST** magnetic fields.



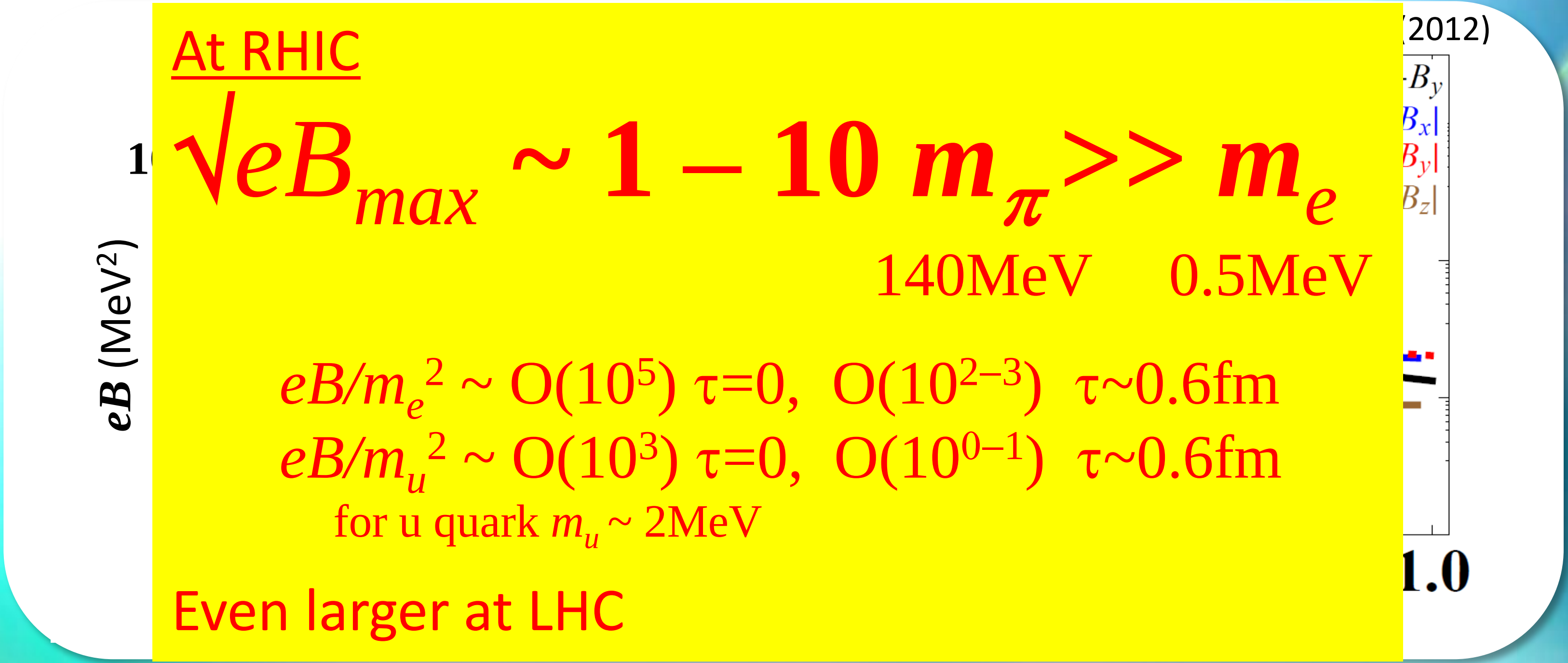
$$e\vec{B}(\vec{x}) = Z\alpha_{\rm EM}\sinh(Y)\frac{(\vec{x}'_\perp - \vec{x}_\perp)\times \vec{e}_z}{[(\vec{x}'_\perp-\vec{x}_\perp)^2+(t\sinh Y - z\cosh Y)^2]^{3/2}}.$$

$x'_\perp$, Y : transverse position and rapidity (velocity) of moving charge

Z=79 (Au), Y=6, b=4fm → eB (origin, t=z=0) ~ 10^4 –10^6 MeV^2

Strong magnetic fields in HICs

- Two ions with **large electric charges** collide at high energy
- **Non-central** HICs at RHIC and LHC provide **STRONGEST** magnetic fields.



At RHIC

$$\sqrt{eB}_{max} \sim 1 - 10\ m_\pi >> m_e$$

140MeV 0.5MeV

$eB/m_e^2 \sim O(10^5)$ $\tau=0$, $O(10^{2-3})$ $\tau\sim0.6$fm
$eB/m_u^2 \sim O(10^3)$ $\tau=0$, $O(10^{0-1})$ $\tau\sim0.6$fm
for u quark $m_u \sim 2$MeV

Even larger at LHC

- **Decay very fast**:

  Strong field physics will be most prominent in very early time!

  (though the fields are still strong enough even at QGP formation time)

Very strong fields exist at very early time in HIC

“Strong field physics”
works only at early time!
and thus can be a good probe
of early time dynamics in HICs

ex) EM probes

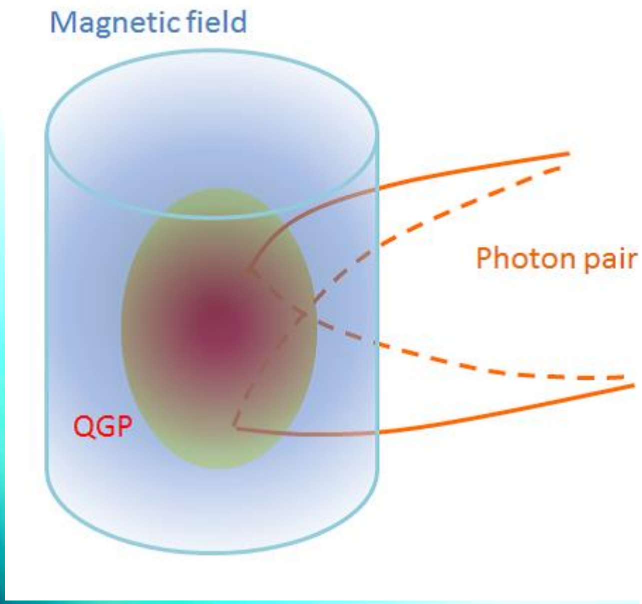
Photons are subject to birefringence and decay

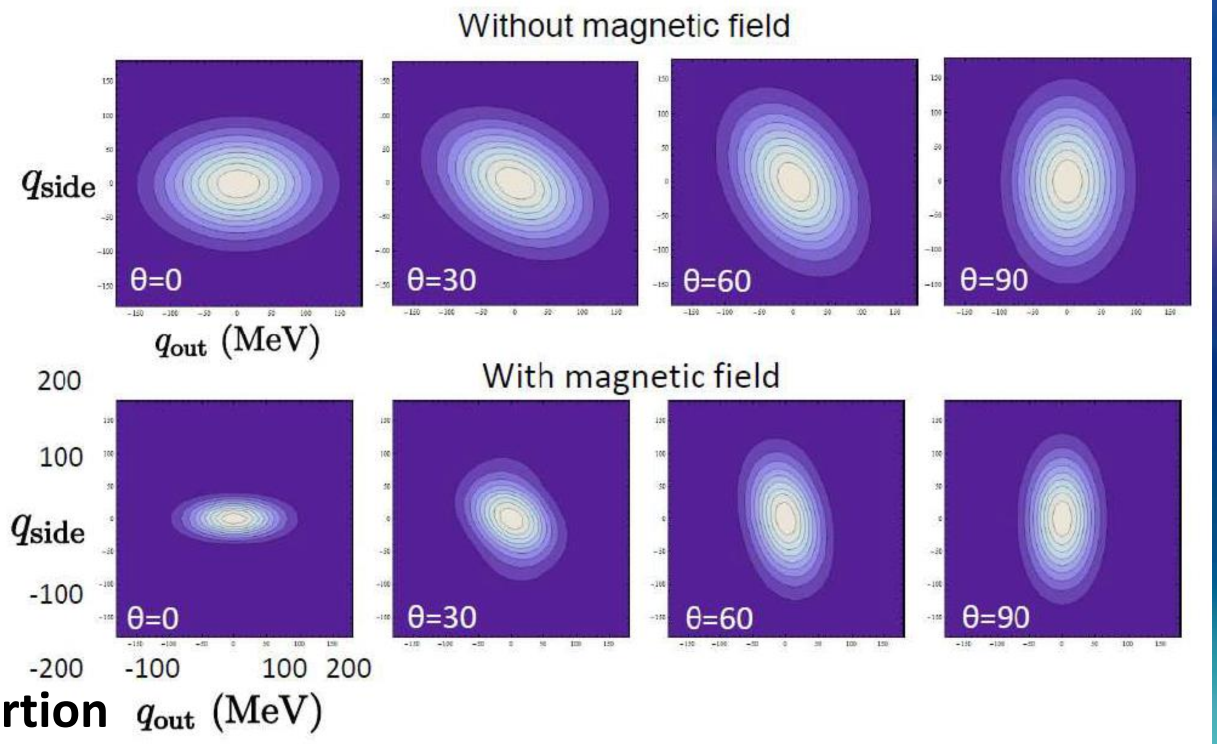
Photon's decay & birefringence in HIC

- **Generates elliptic flow (v_2) and higher harmonics (v_n)**
  (at very low momentum region)
- **Distorted photon "HBT image"**

Based on a simple toy model with moderate modification

Hattori & KI, arXiv:1206.3022



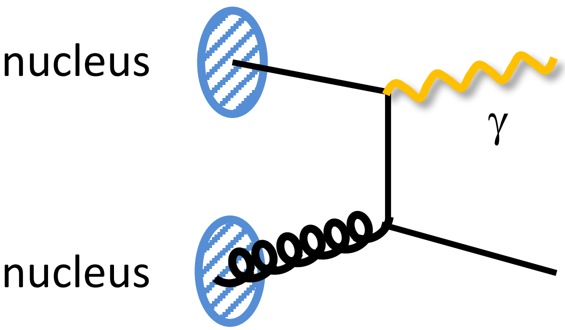


Magnification and distortion

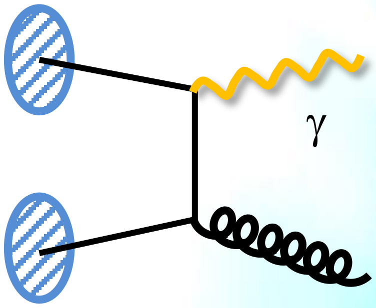
← can determine the profile of photon source if spatial distribution of magnetic field is known.

γ conversion into π^0 in HICs

HICs create many high energy γs

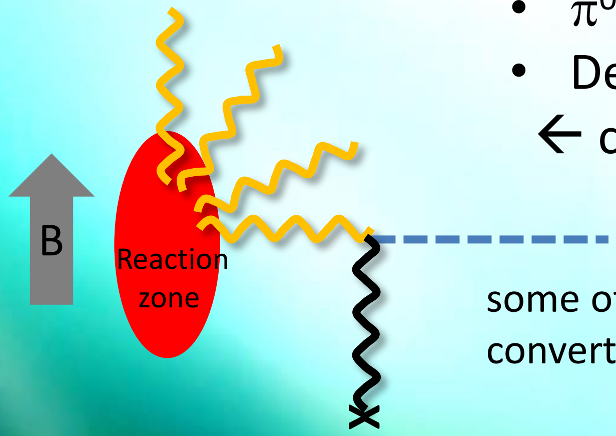


Gluon Compton scattering in LO



$q\bar{q}$ annihilation in LO

Conversion rate is strongest in perpendicular direction to B



- π^0 will get positive v2
- Depends on time profile of B fields

← can be used as probe of early time evolution

some of them
convert into π^0

Strong fields in astrophysics

- **Early universe**

  QCD phase transition?

  QGP in laboratory is really QGP in early universe?

- **Compact stars (neutron stars, magnetars)**

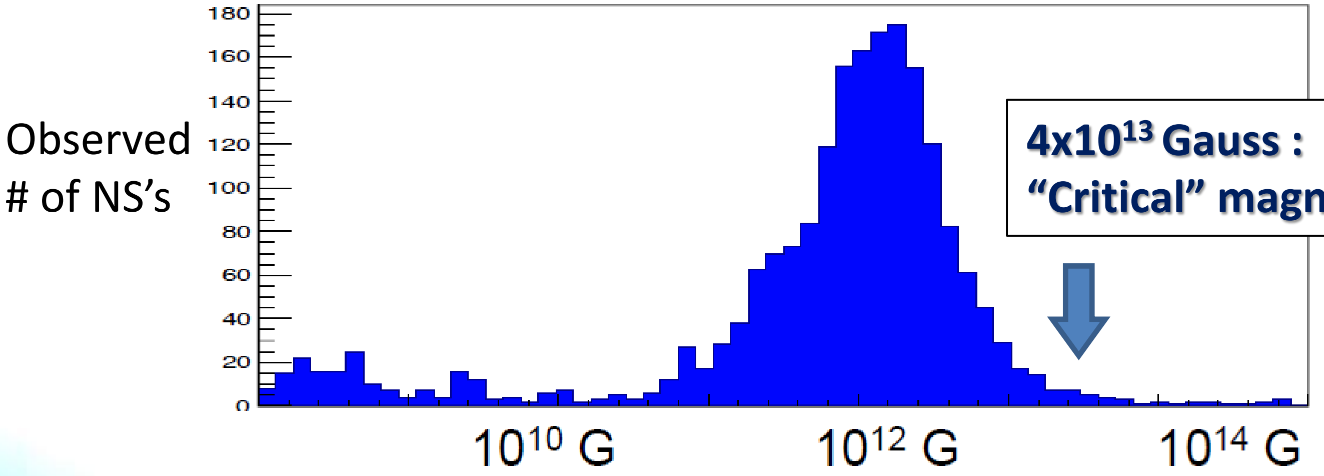
  inner region EOS?

  outer region mechanism of radiation?

- **Black Holes, Gamma-ray bursts**

  jet production?

Magnetic fields of neutron stars

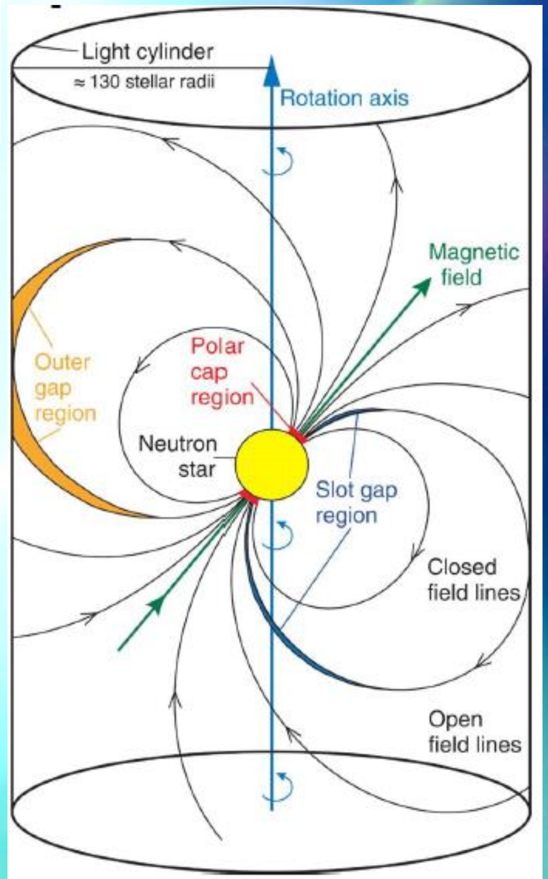


4x10^{13} Gauss : $\sqrt{eB_c} = m_e = 0.5\text{MeV}$
"Critical" magnetic field of electrons

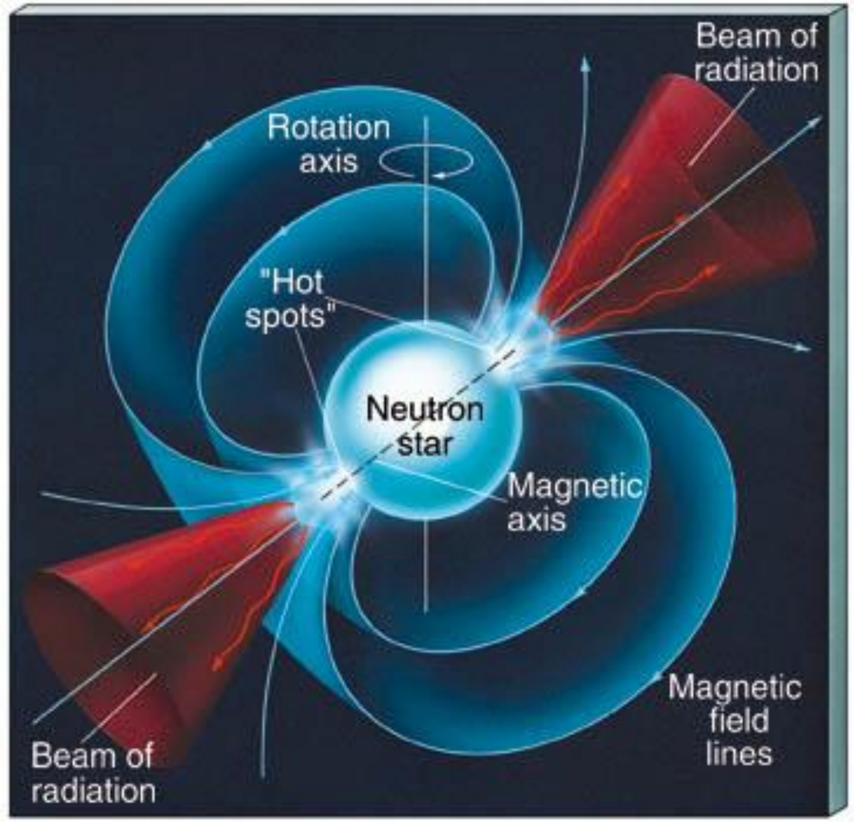
No ***static*** electric field
Pulsars → rapid rotation of magnetic field
→ Electric field is induced and strong too

<u>Magnetars</u>
Stronger magnetic fields exceeding the critical field

- **Generation mechanism unknown!**
- **Important to compare NS and magnetar**



Strong field physics in NS/magnetar



- **OUTSIDE of the star**

Both electric and magnetic fields are strong enough around the polar regions.

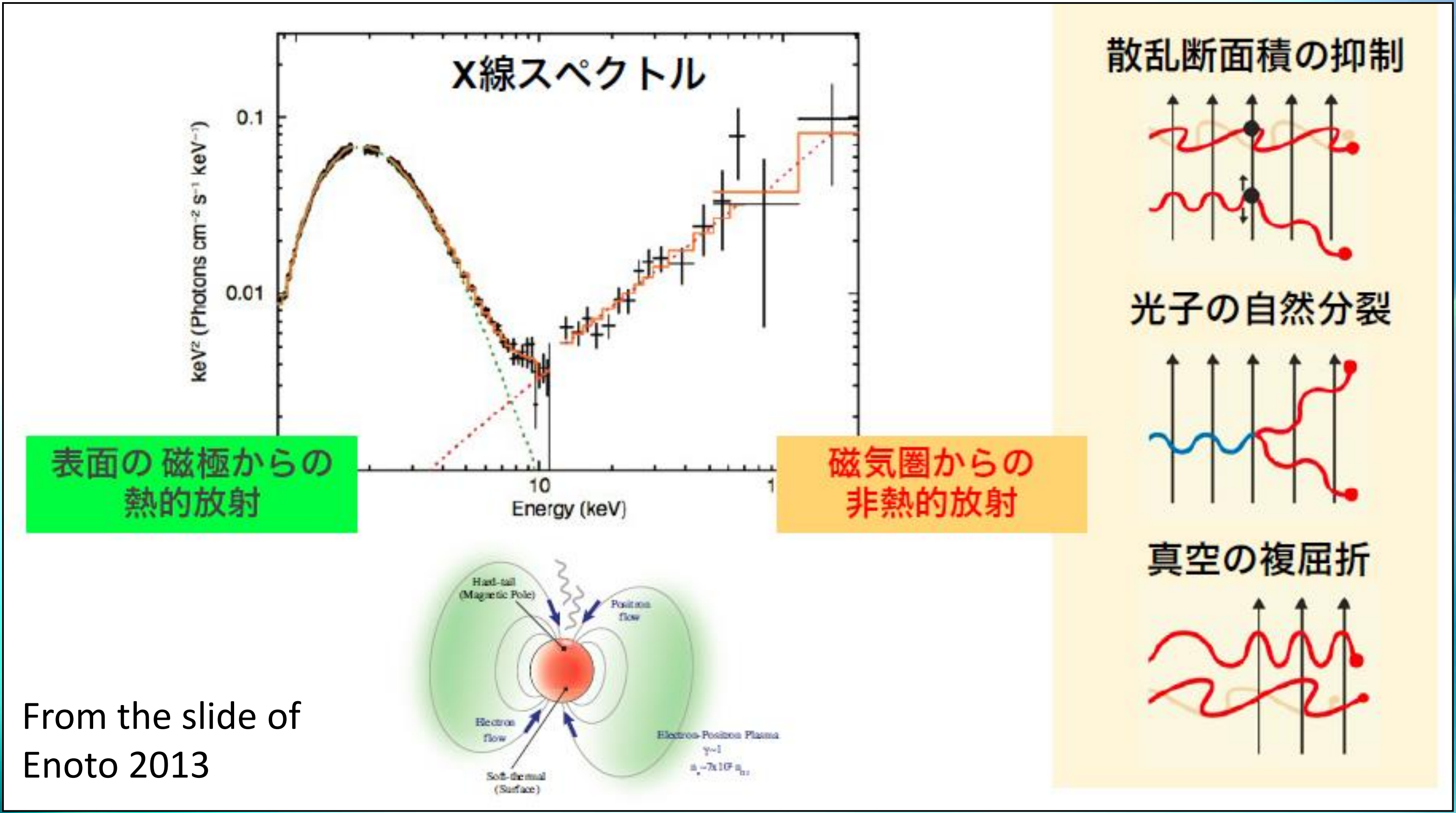
→ anomalous photon emission due to photon splitting and Schwinger mechanism?

→ origin of intense radiation ?

- **INSIDE of the star**

If the magnetic field is present in the stars, there must be a big effect on the equation of state of nuclear matter.

Unique X-ray spectrum in magnetars

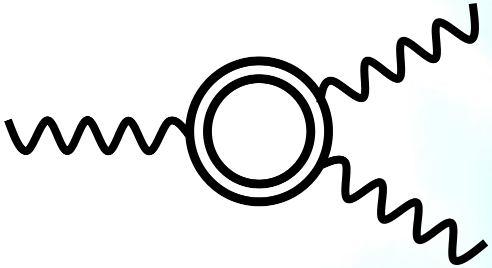


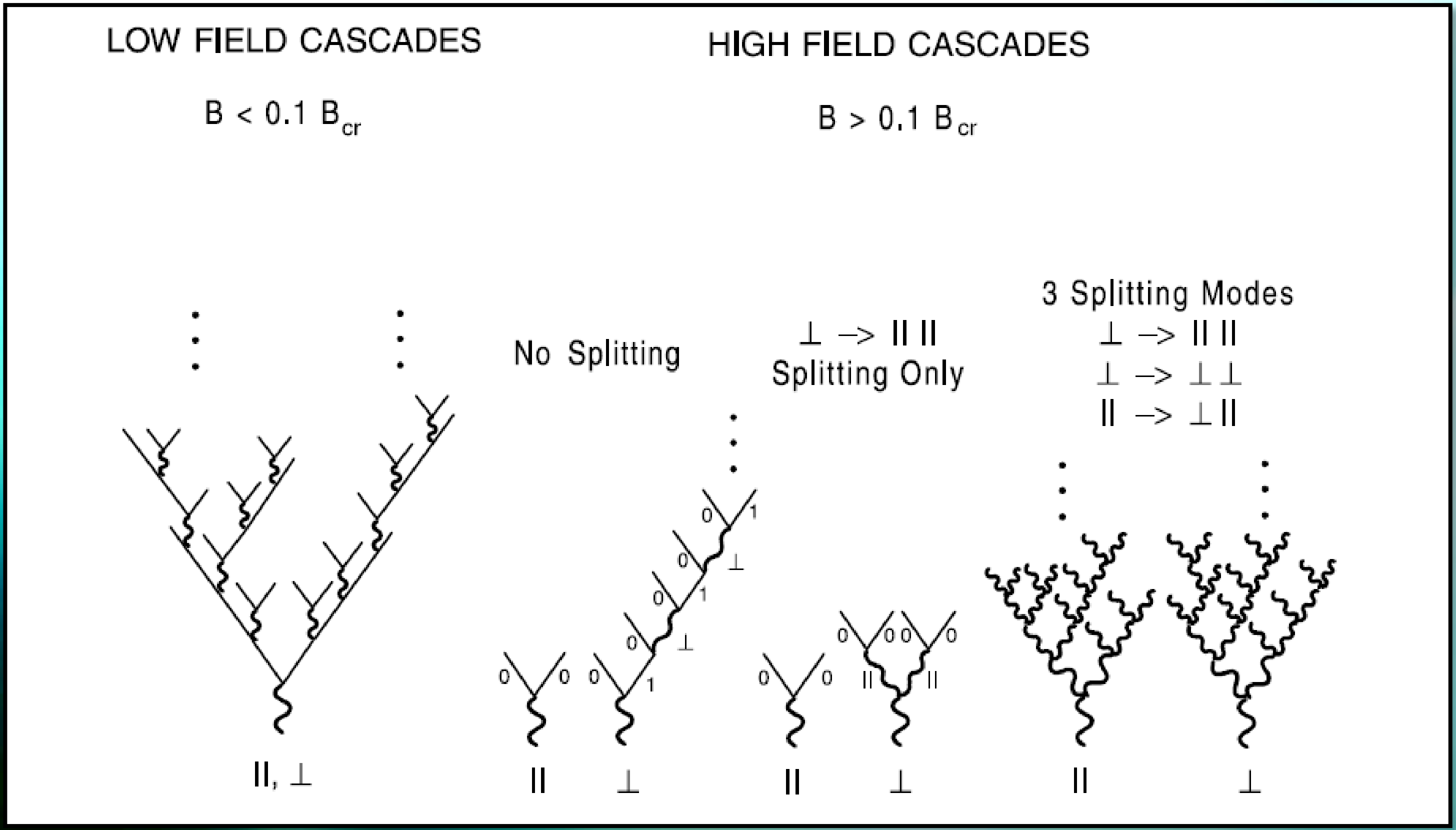
From the slide of
Enoto 2013

Magnetic field → anisotropy in photon spectrum → effects of polarization
High energy photons（E>500keV）split into low energy photons

Photon splitting

Impossible in vacuum



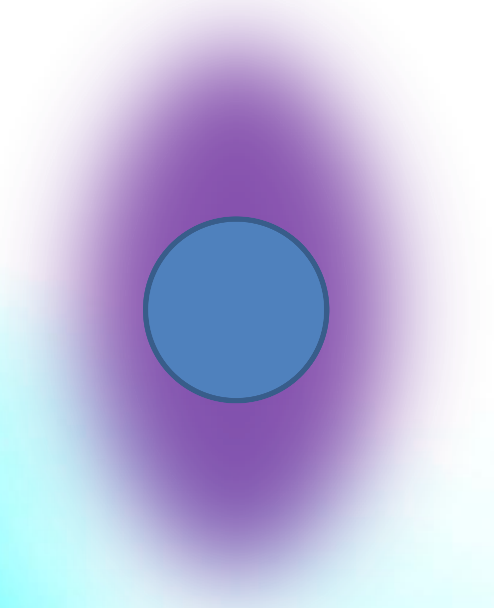


Baring, Harding
ApJ 547 (2001)

Jet production around magnetic poles

Lensing due to magnetic fields

- **Photon's refractive index varies in magnetic fields. Its magnitude is larger than in air, but smaller than in water.**



Distortion of the NS image and image in the background

Distortion of spoon image and background due to water

Need to consider rotating magnetic field (including the effects of electric field)

Response of hadrons to magnetic fields

- Naïve argument: spin *s*, magnetic moment *g,* charge *e*

$$E_n^2(p_z, s_z) = m^2 + p_z^2 + (2n+1)eB - gs_z eB$$

Landau levels spin-magnetic effect

- "Effective" mass in *B*

$$E_{n=0}^2(p_z = 0, s_z) = m^2 + (1 - gs_z)eB$$

- Spin 0 mesons : $m^2 + eB$ (pions) "heavier"
- Spin 1/2 , *g*=2 : m^2 (electron)
- Spin 1, *g*=2 : $m^2 - eB$ (rho meson) "lighter"

Effects of magnetic fields on EoS

- **Three possible effects to be considered**

1. **Landau quantization for electrons and protons** (not for neutron)

   → anisotropy of chemical potential (beta equilibrium)

2. **Mass shift of protons** (due to large anomalous magnetic moment)

   → new balance of beta equilibrium (more protons?)

3. **Mass shift of pions**

   → anisotropic nuclear force? Charge asymmetry?

- **Earlier attempt**

  Broderick, Prakash, and Lattimer, Astrophys. J 537 (2000) 351

  - reduction of electron μ → increase of proton fraction
  - softening of EOS due to Landau quantization
  - stiffening due to anomalous magnetic moment of nucleons

Summary

- When an external field is much larger than typical excitation energy of a system, one can find extraordinary non-perturbative phenomena called "strong field physics".
- Strong field physics reveals novel properties of ordinary particles such as photons and hadrons in strong external fields.
- Such extreme situations are seen in Nature, in particular, in the universe, and also realized in experiments with high-intensity laser or heavy-ion collisions.
- We need to incorporate strong field physics to understand the early time evolution of heavy-ion collisions and the properties of compact stars like neutron stars and magnetars.
- There are many topics that I couldn't cover in this talk. They include nonlinear Compton scattering, Synchrotron radiation, QCD phase transition in strong B, chiral magnetic effects, etc, etc