Nanoshots and Schwinger Sparks

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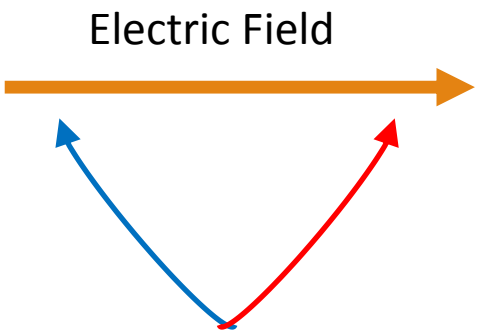
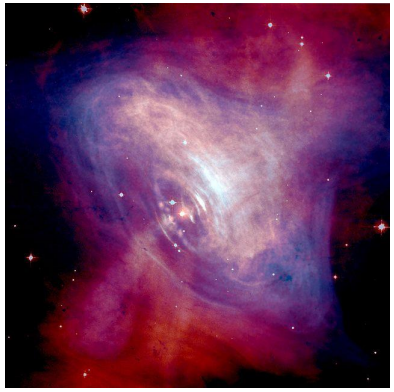
FNAL
Hojin Yoo

In collaboration with Albert Stebbins

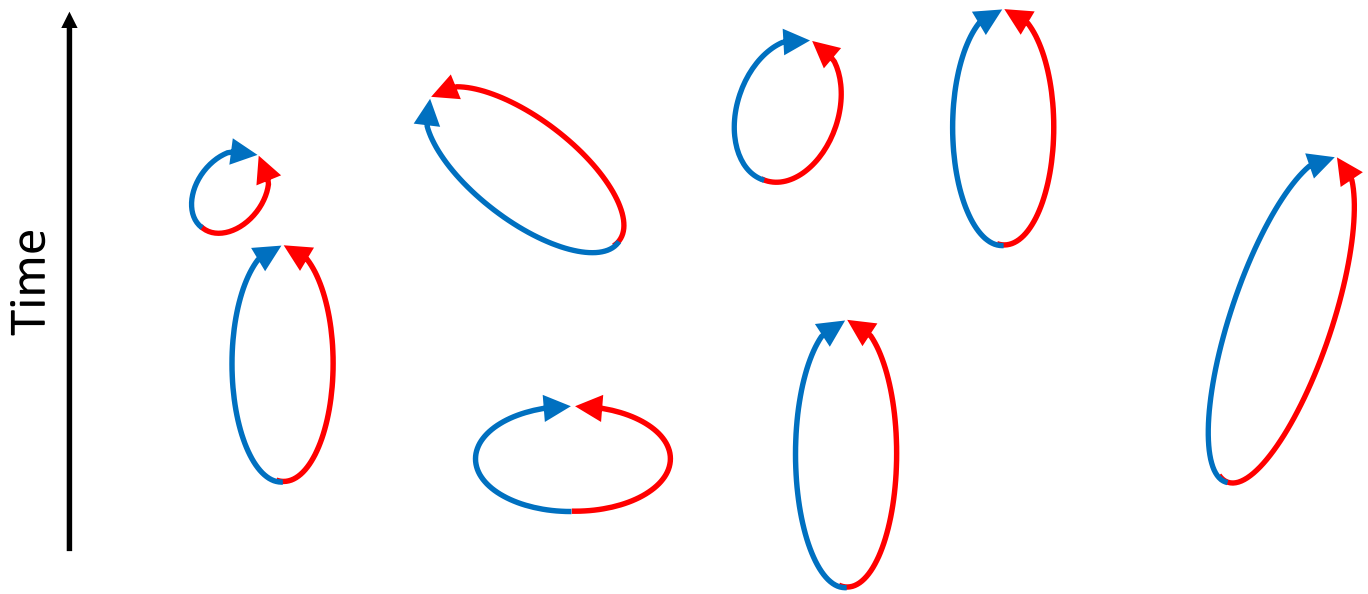
Outline

- Introduction
  - The Schwinger Effect
  - Laser Experiments
- Pulsars
  - Giant Pulses (nanoshots)
- Toy model for nanoshots
  - Quantum Kinetic Theory
  - Schwinger Spark Chamber



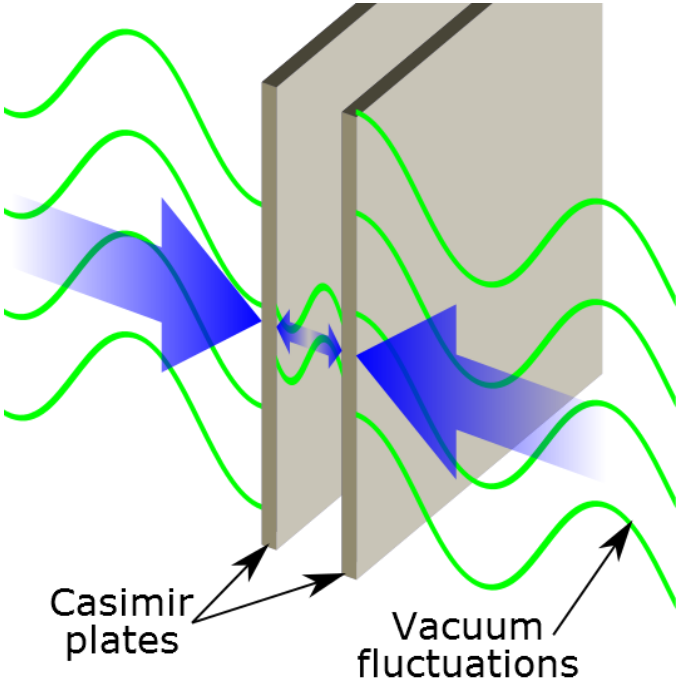


Quantum Vacuum



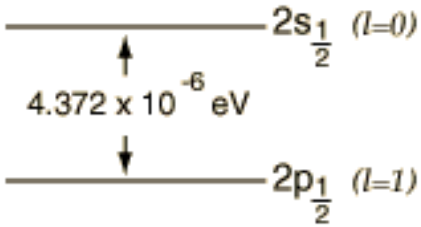
Existence of Virtual Particles

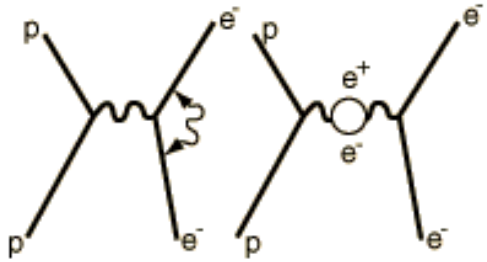
- Casimir effect



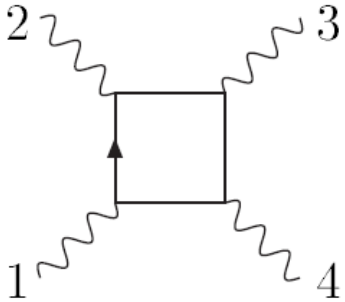
Existence of Virtual Particles

- Lamb shift



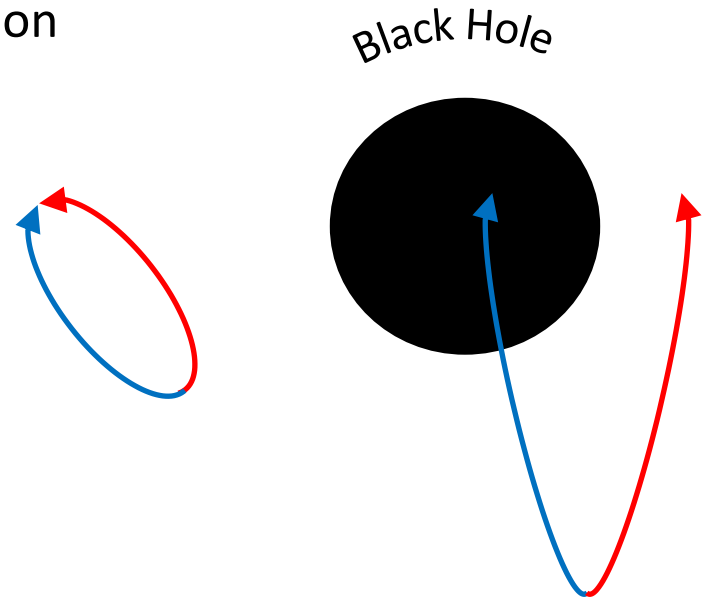


- Light-light Scattering



Existence of Virtual Particles

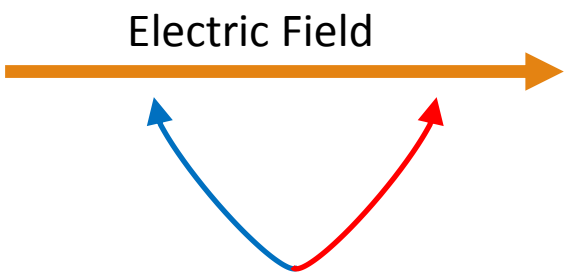
- Hawking Radiation



- Many more …

Schwinger Effect

- Instability of vacuum under strong external electric fields



- Electric field breaks electron-positron loop and separates them apart.
- Pair creation threshold

$$eE\delta l \sim eE\frac{\hbar}{mc} \gtrsim 2mc^2 \Rightarrow E_c \sim \frac{m^2c^3}{e\hbar} \sim 10^{16}\ V/cm$$

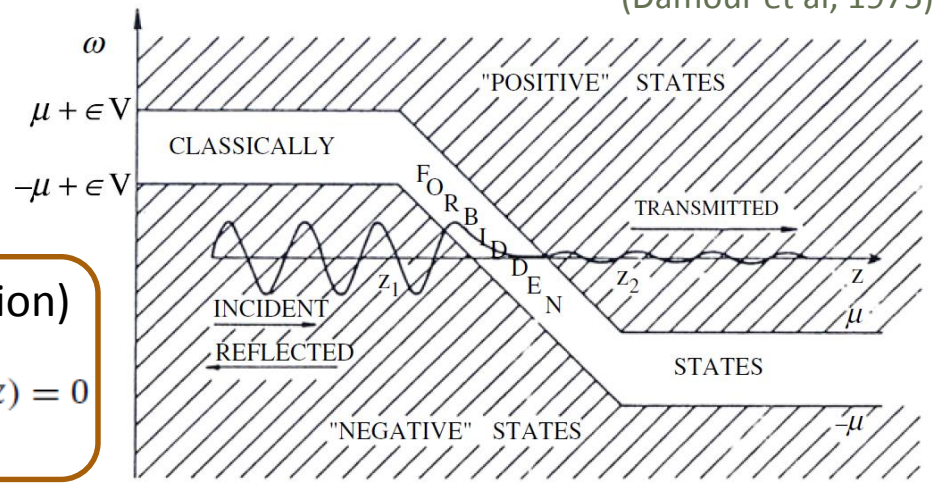
Schwinger Limit

Schwinger Effect

- Semi-classical picture: *Tunneling process*

Diagram from (Damour et al, 1975)

e. g. $A^\mu = (-zE, 0, 0, 0)$



Wave function (Klein-Gordon Equation)

$$\left[-\hbar^2 \frac{\mathrm{d}^2}{\mathrm{d}z^2} + p_\perp^2 + m_e^2 c^2 - \frac{1}{c^2}\left[\mathcal{E} - V(z)\right]^2\right]\phi(z) = 0$$

$$\mathcal{E}_\pm = |eE|z \pm \sqrt{(cp_z)^2 + c^2\mathbf{p}_\perp^2 + (m_e c^2)^2}$$

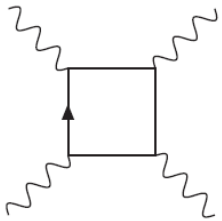
$$|T|^2 = \frac{|\text{transmission flux}|}{|\text{incident flux}|} \propto \exp -\frac{2}{\hbar}\int_{z_-}^{z_+} |p_z|\mathrm{d}z \sim \mathrm{e}^{-\pi\frac{m_e^2 c^3}{\hbar e E}}$$

(Sauter, 1931)

QED Effective Action

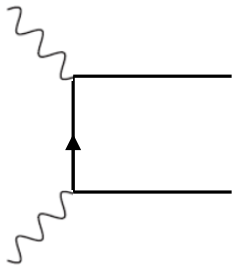
$$\langle \text{out}, 0 | 0, \text{in} \rangle_A = e^{\frac{i}{\hbar} W[A]}$$

- encodes

$Re[W] \ni$  $+ \cdots$ Dispersive effects, e. g. Vacuum birefringence

Euler–Heisenberg Lagrangian

$$\mathcal{L} = \frac{1}{2}\left(\mathbf{E}^2 - \mathbf{B}^2\right) + \frac{2\alpha^2}{45m^4}\left[\left(\mathbf{E}^2 - \mathbf{B}^2\right)^2 + 7\left(\mathbf{E}\cdot\mathbf{B}\right)^2\right]$$

$\text{Im}[W] \ni$  $+ \cdots$ Absorptive effects, e. g. Vacuum pair creation

c.f. Quantum Mechanics

$$|\Psi(t)|^2 \sim \exp\left[-\frac{2}{\hbar}\left(\text{Im}E\right)t\right]$$

QED Effective Action

Effective action for a given A

$$\langle \text{out}, 0|0, \text{in}\rangle_A = \int \mathcal{D}\psi\mathcal{D}\bar{\psi} \exp\left[\frac{i}{\hbar}\int dx^4 \mathcal{L}_{QED}\right] \equiv e^{\frac{i}{\hbar}W[A]}$$

$$\mathcal{L}_{QED} = \bar{\psi}\left(i\gamma^\mu\partial_\mu - e\gamma^\mu A_\mu - m\right)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \text{gf term}$$

$$\Rightarrow \quad W[A] = -i\text{Tr}\ln\left[\frac{i\gamma^\mu\partial_\mu - e\gamma^\mu A_\mu - m + i\epsilon}{i\gamma^\mu\partial_\mu - m + i\epsilon}\right] \equiv \int d^4x\, \mathcal{L}_{eff}$$

Using proper-time integral in the frame $\vec{E} \parallel \vec{B}$

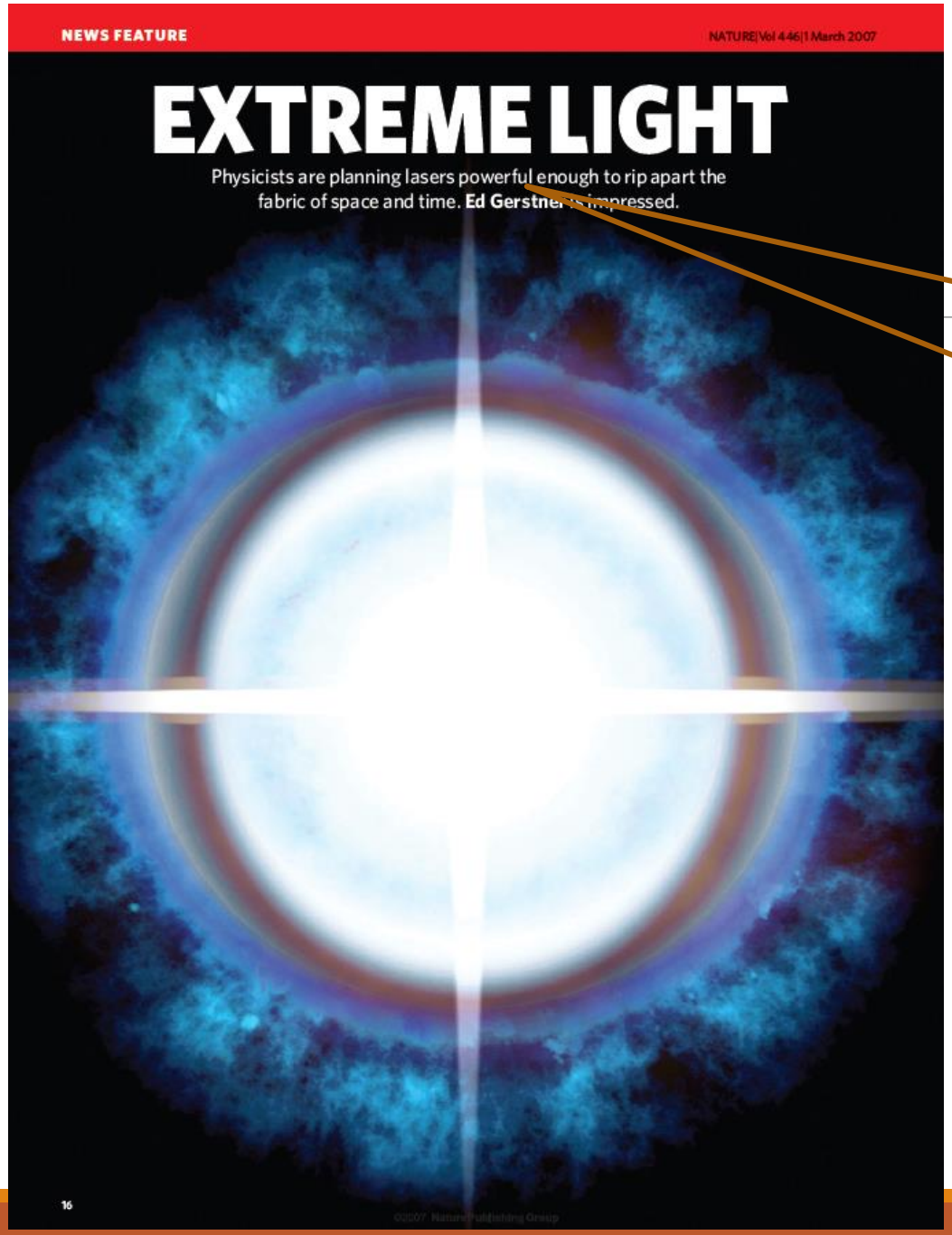
$$\mathcal{L}_{eff} = \frac{1}{8\pi^2}\int_0^\infty \frac{ds}{s^3} e^{-is\left[m^2 - i\epsilon\right]}\left[e^2 s^2 EB\coth(seE)\cot(seB) - 1 - \frac{e^2 s^2}{3}\left(E^2 - B^2\right)\right]$$

The vacuum decay rate per unit volume is

$$\boxed{\frac{\Gamma}{V} = 2\text{Im}\mathcal{L}_{eff} = \frac{e^2 EB}{4\pi^2}\sum_{n=1}^{\infty}\frac{1}{n}\coth\left(n\frac{\pi B}{E}\right)e^{-n\pi m^2/eE}}$$

(Schwinger, 1951)

In natural unit



Physicists are planning lasers powerful enough to rip apart the fabric of space and time.

"We're going to change the index of refraction of the vacuum, and produce new particles."
— Gérard Mourou

eXtreme light infrastructure

Schwinger Effect in lab?

Laser Experiments, e.g. ELI, IZEST, HiPER, …

Vacuum decay rate

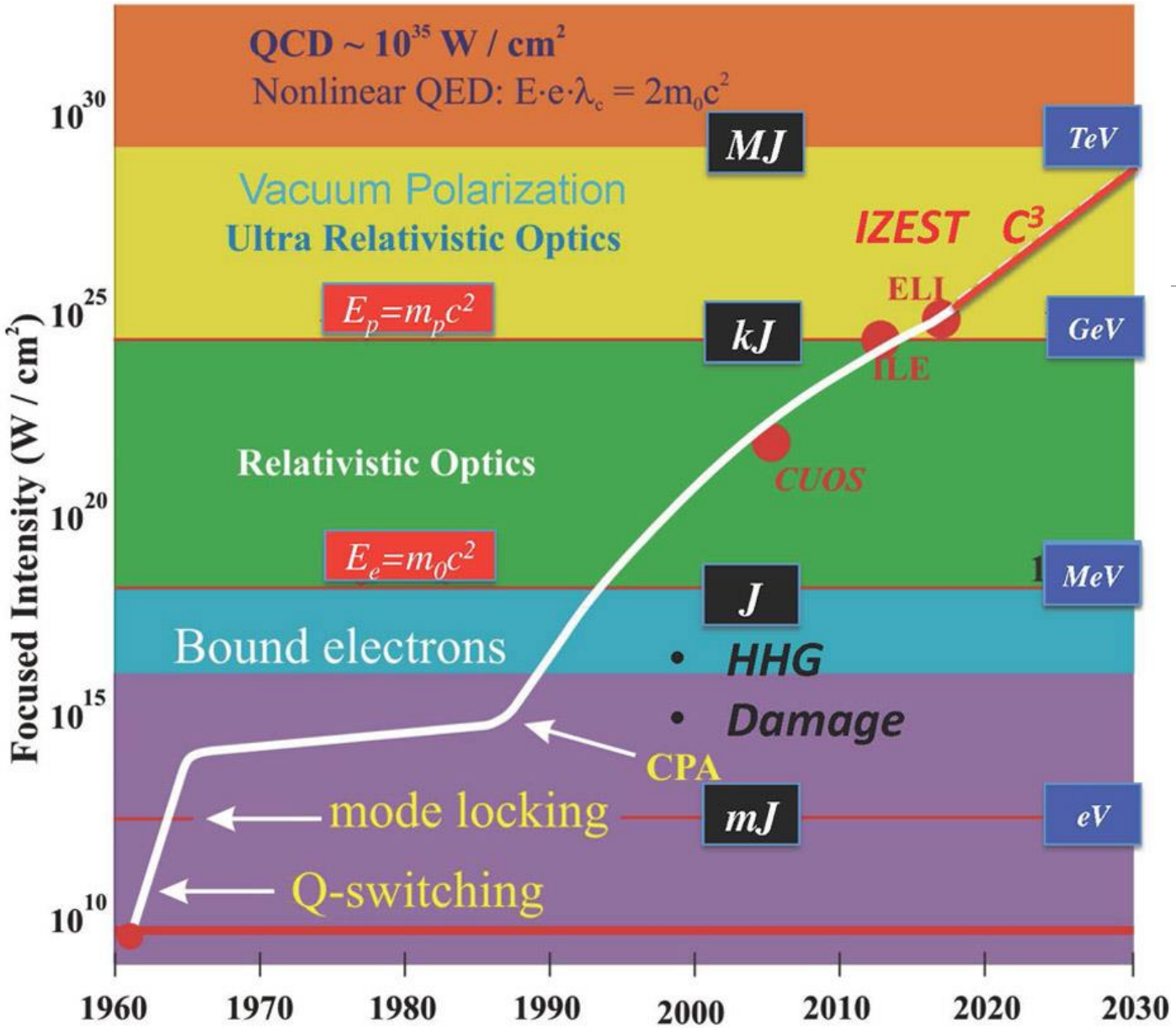
$$\Gamma \sim \exp\left[-\pi \frac{m_e^2 c^3}{e\hbar E}\right]$$

The Schwinger Limit

$$E_c = \frac{m_e^2 c^3}{e\hbar} \approx 10^{16} V/cm$$

Required intensity of coherent radiation

$$I_c \approx \frac{c}{8\pi} E_c^2 \sim 4 \times 10^{30} W/cm^2$$



Intensity evolution

(G. Mourou)

in high energy astrophysics?

(NASA)

Schwinger Effect in Pulsars?

The Crab pulsar (NASA)

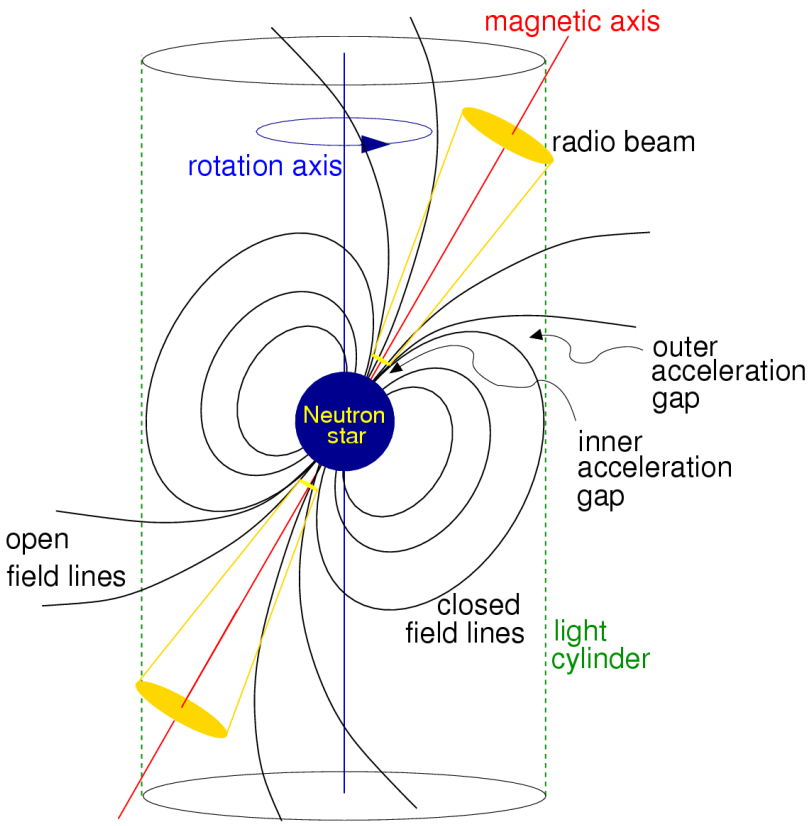
Pulsar?

- A rapidly rotating highly magnetized neutron star

Observational facts

- Very regular pulsed emission with periods ~ 1ms to 8s
- Period almost always increases slowly except occasional glitches
- Very high brightness temperature $T_b > 10^{25} - 10^{30} K$.

More about Pulsars



- Diameter ~ 20 km
- Mass m ~ $1.4 m_{\odot}$
- Charges flow along the open field line ⇒ Coherent radio emission along the axis of magnetic poles, "Light house"
- Spinning down mechanism = Magnetic Dipole Radiation

$$\left(\frac{B_p}{Gauss}\right) \sim 3 \times 10^{19} \left(\frac{P\dot{P}}{s}\right)^{1/2}$$

$P - \dot{P}$ diagram

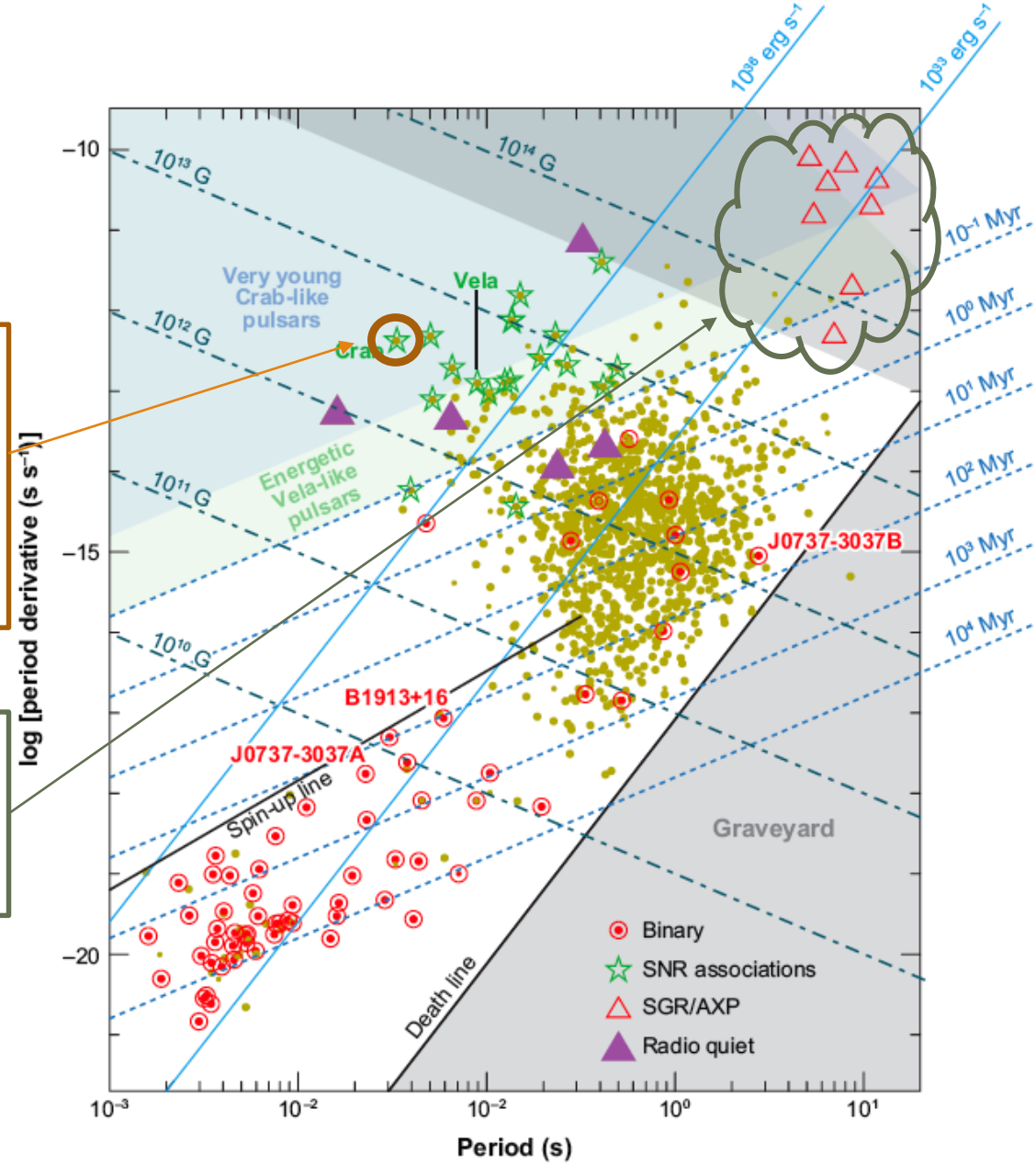
The Crab Pulsar

$B_{crab} \sim 5 \times 10^{12} G$

cf. $B_c = \frac{m_e^2}{e} \sim 4 \times 10^{13} G$

Magnetars

$B_{magnetar} \gtrsim 10^{14} G$



Is a Pulsar ideal place for the Schwinger effect?

PROS

- The presence of strong magnetic fields may imply the presence of strong electric fields.

- still possible without disturbing observables from pulsars.
- Many poorly understood pulsar phenomena

CONS

$$\varepsilon \equiv \frac{1}{2}\left[\sqrt{(FF)^2 + \left(F\tilde{F}\right)^2} - FF\right]^{1/2} \gtrsim E_c$$

$$\varepsilon \approx \frac{\left|\vec{B}\cdot\vec{E}\right|}{B} \text{ for } B \gg E$$

- Induced electric field from a rotating dipole

$$\varepsilon \sim \frac{R\Omega}{c} B_p \ll E_c \qquad \varepsilon_{crab} \lesssim 0.01 \times E_c$$

- MHD approximation (Force-free condition)

$$\vec{E} \approx -\frac{\left(\vec{\Omega}\times\vec{r}\right)}{c} \times \vec{B}$$

Rich Phenomenology of Pulsars: Giant Pulses

- Strong narrow pulses with a energy many times larger that of mean pulse energy

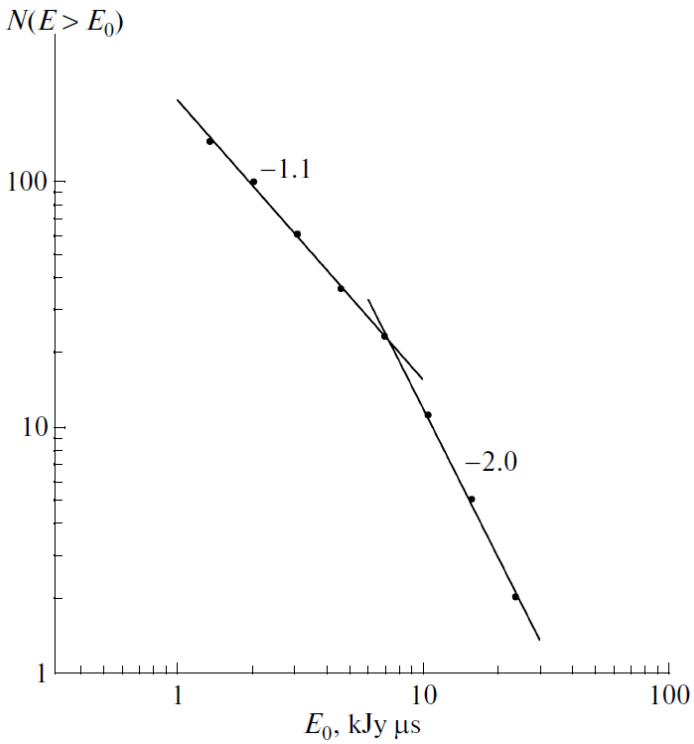
$$S_{GP} > 100 \times S_{MP}$$

- Very rare. Only ~14 of out ~2000 known pulsars including the Crab emit giant pulses.
- A power-law distribution of pulse energy

$$\mathrm{N}(\mathrm{E} > E_0) = K E_0^{-\alpha}$$

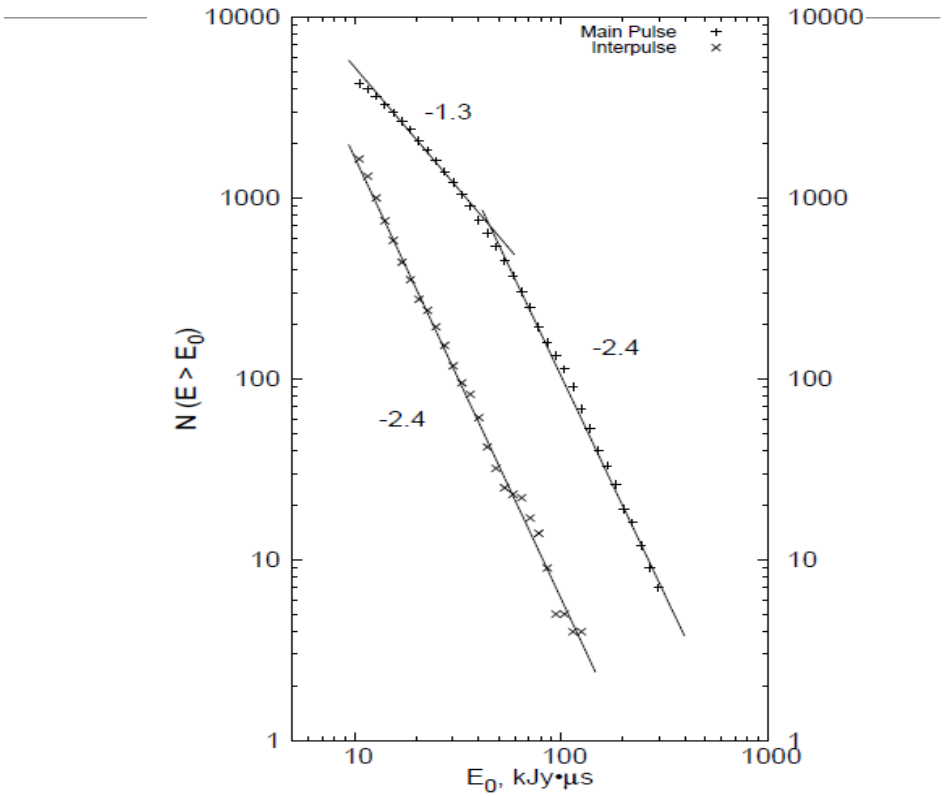
- occur in narrow phase-windows in pulse profile
- occasionally resolved into "nanoshots" (Hankins et al, '03)
  - Generally polarized (Jessner et al, '10)
  - Extremely bright, $T_b > 5 \times 10^{37} K$
  - ns duration -> 30 cm

Rich Phenomenology of Pulsars: Giant Pulses



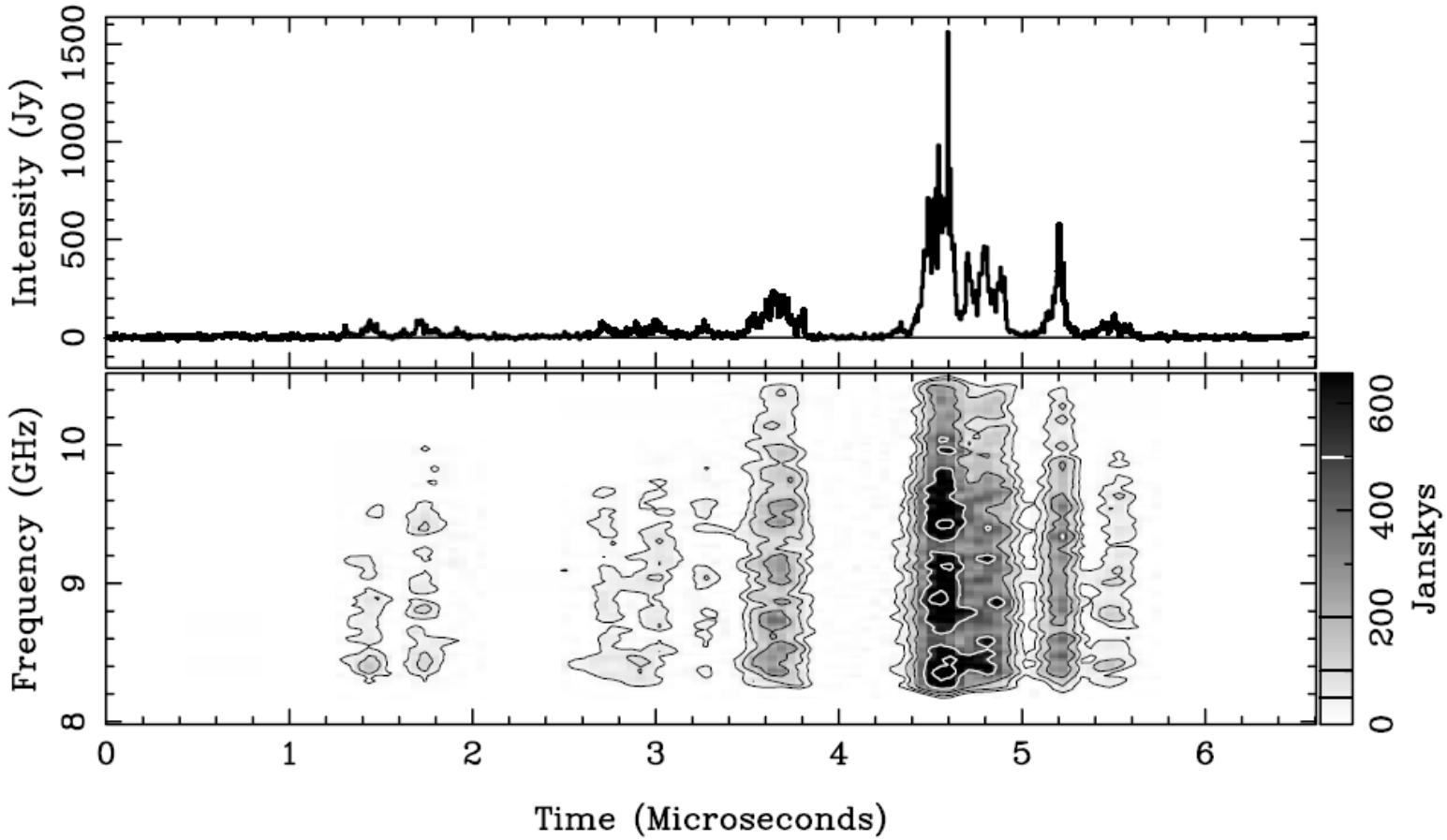
At a frequency of 2100 MHz

(Zhuravlev et al, '11)



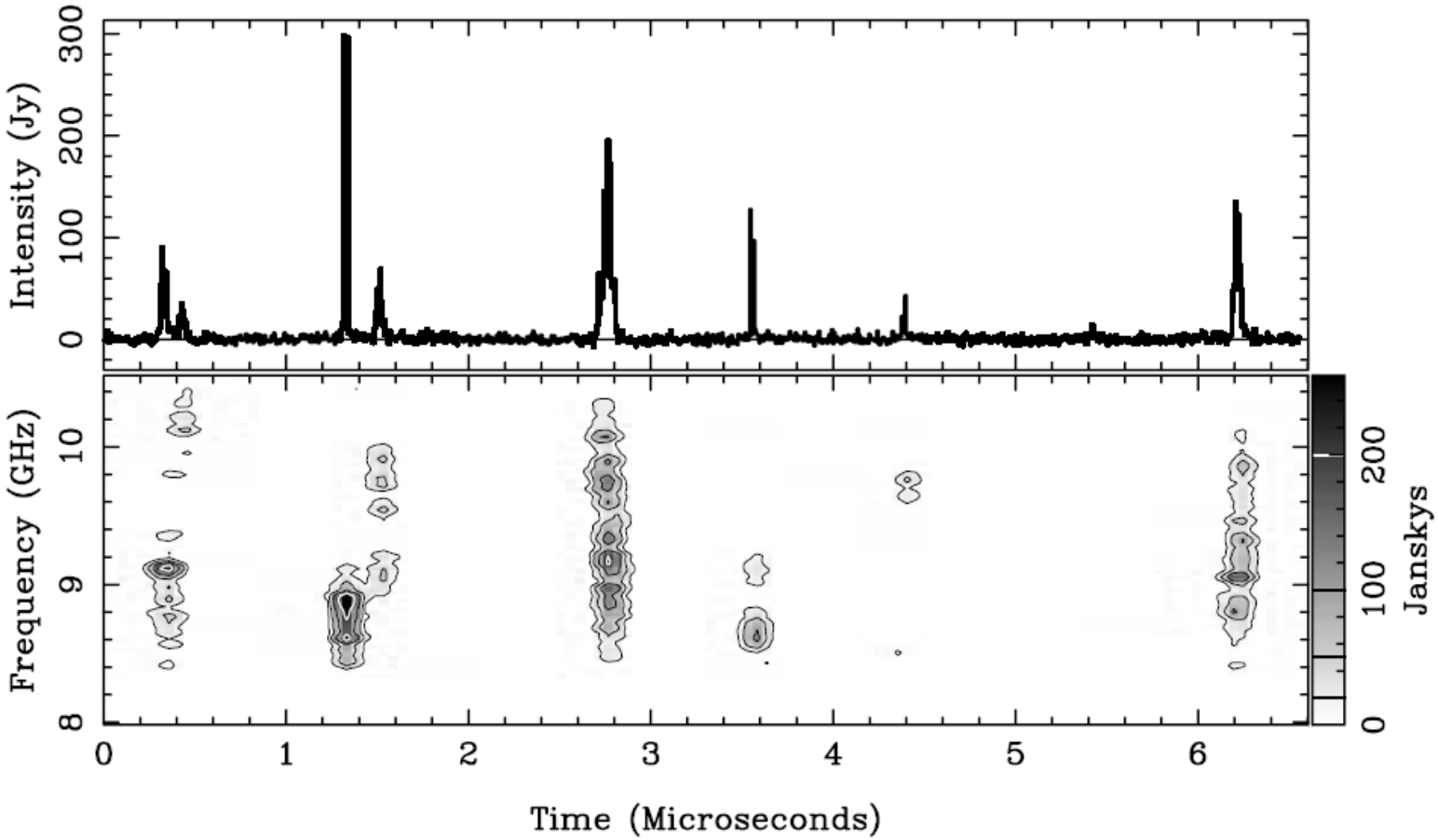
At 600 MHz (Popov et al, '09)

Energy distribution of the main-pulse GPs



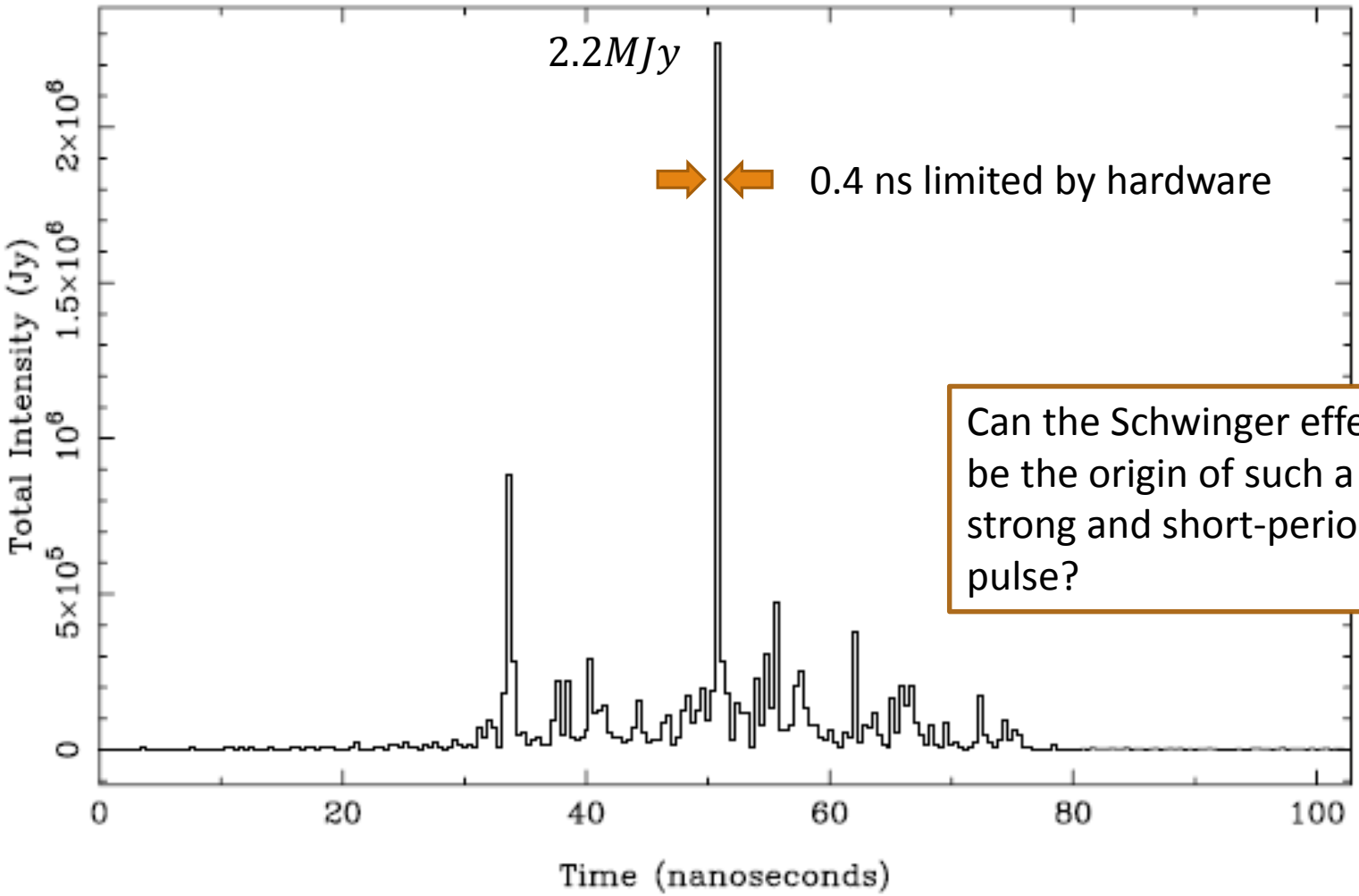
Example of a normal main pulse at 9GHz. (Hankins et al, 2007)

$$Jy \equiv 10^{-23} \frac{erg}{s \cdot cm^2 \cdot Hz}$$



Example of a sparse main pulse at 9.25 GHz. (Hankins et al, 2007)

A “Megapulse” from the Crab



Can the Schwinger effect be the origin of such a strong and short-period pulse?

a main pulse at 9.25 GHz. (Hankins et al, 2007)

Numerology

(Jassner, '10)

f (GHz)	Date (2007)	B (MHz)	SEFD (Jy)	T_{obs} (h)	δt (ns)	$\Delta\phi_{PA}$ (°)	N_{GP}	S_{max} (kJy)
15.1	Oct. 24–25	500	150	6	2.5	78	42	60
...	Nov. 4–5	500	150	11	2.5	78	43	40
8.5	Nov. 9–10	400	110	10	5.5	143	29	150

$$Jy \equiv 10^{-23} \frac{erg}{s \cdot cm^2 \cdot Hz} \quad L_\odot \approx 3.8 \times 10^{33} erg/s$$

Radio bolometric luminosity

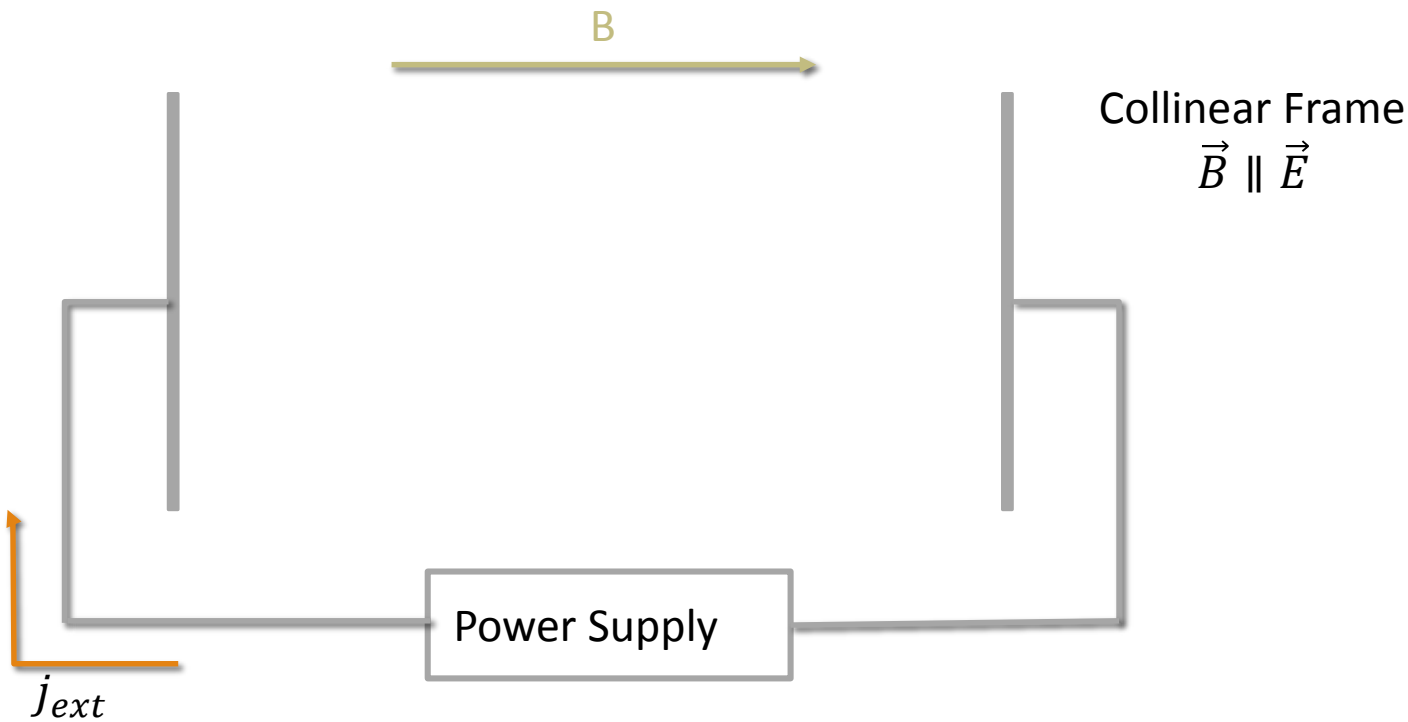
$$\dot{\mathcal{E}} \approx 4\pi D_{crab}^2 S_\nu \delta\nu \gtrsim 10^2 L_\odot$$

Electric field at emission

$$\delta E \approx \sqrt{\frac{8\pi \dot{\mathcal{E}} \delta t}{l^3}} \gtrsim 6 \times 10^{14}\, V/cm \sim 0.05\, E_c$$

Lower but close to the critical field, E_c

Toy model:
Schwinger Spark Chamber



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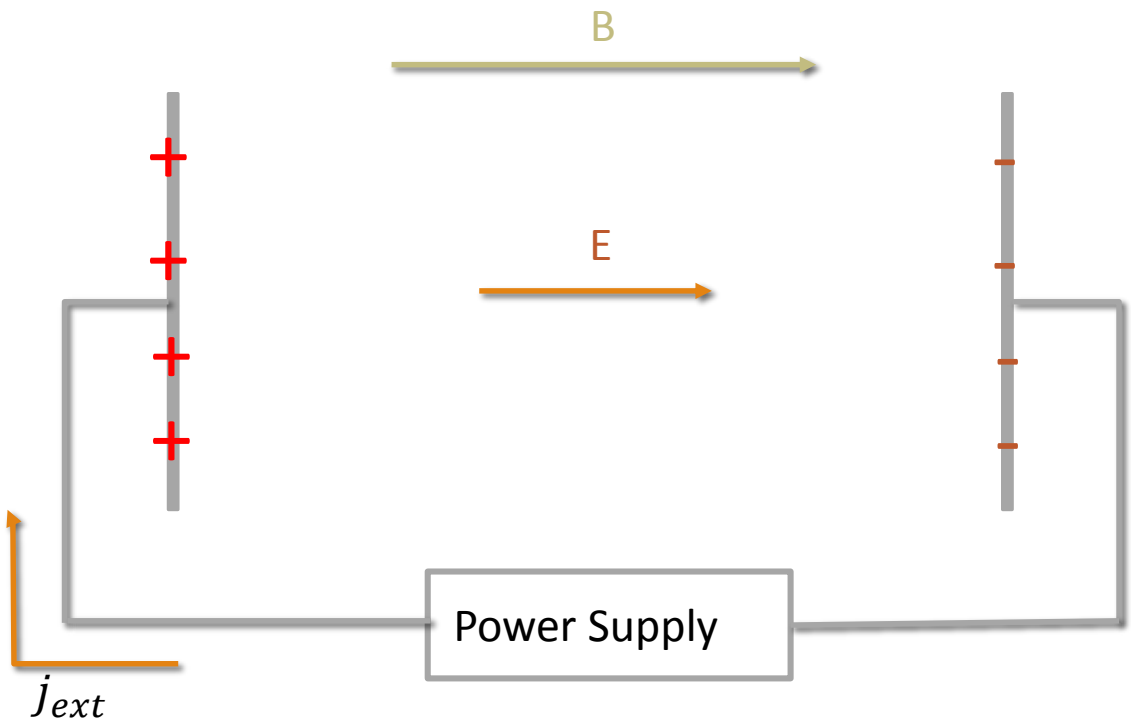

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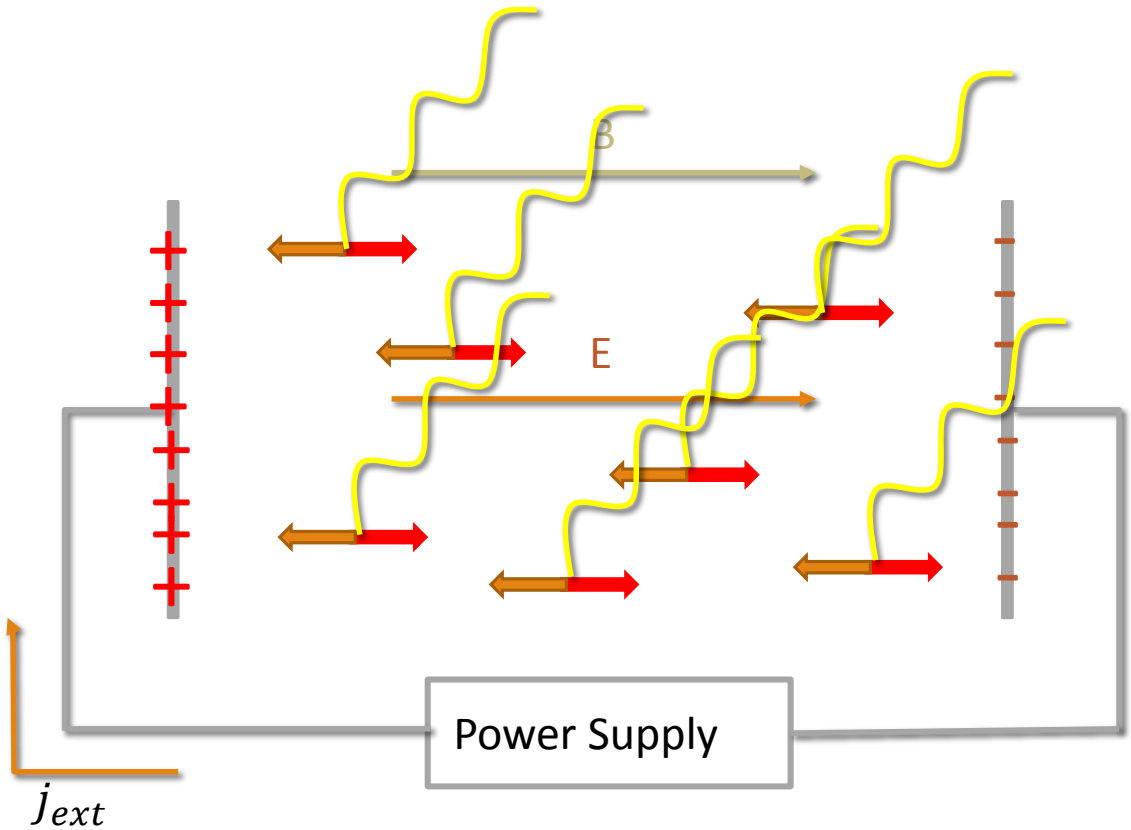


From QFT to Kinetic Theory

How to describe employ particle production and its back-reaction consistently?

Quantum Correlation Function

$$
\begin{aligned}
A^\mu(x) &= \langle A^\mu(x) \rangle \\
G^{\mu\nu}(x,y) &= \langle A^\mu(x) A^\mu(y) \rangle \\
S(x,y) &= \langle \psi(x) \bar{\psi}(y) \rangle \\
&\dots
\end{aligned}
$$

$\Rightarrow$

Boltzmann and Maxwell's Equation

$$\frac{\partial}{\partial t} f + \frac{\vec{p}}{m} \cdot \nabla f + \vec{F} \cdot \frac{\partial}{\partial \vec{p}} f = \mathcal{C}$$

$$\partial_\mu F^{\mu\nu} = j^\nu[f]$$

Close Time Path integral

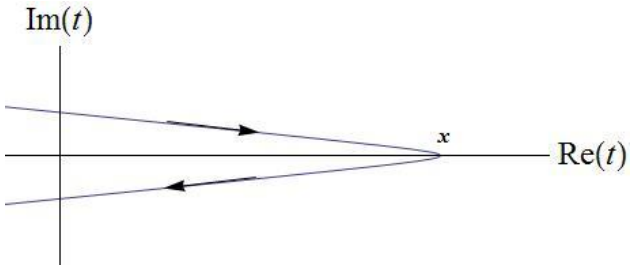
- One need to compute expectation value for a given quantum state.

$$\langle Q(t)\rangle = \left\langle \left[\bar{T}\exp\left(i\int_{-\infty}^{t} H_I(t)dt\right)\right] Q^I(t) \times \left[T\exp\left(-i\int_{-\infty}^{t} H_I(t)dt\right)\right]\right\rangle.$$

- Expressing the evolution operators using path integral, we get

$$\begin{aligned}\langle Q(t)\rangle &= \int D\Psi^+ D\Psi^- \exp\left[\frac{i}{\hbar}\int_{-\infty}^{t_f}\mathcal{L}(\Psi^+) - \frac{i}{\hbar}\int_{-\infty}^{t_f}\mathcal{L}(\Psi^-)\right] Q[t;\Psi^+] \\ &= \int D\Psi \exp\left[\frac{i}{\hbar}\int_C \mathcal{L}(\Psi)\right] Q[t;\Psi]\end{aligned}$$

where the time contour is:



From QFT to Kinetic Theory

From closed-time-path effective action

$$\Gamma[\psi,\bar{\psi},A,S,G] = S_{cl} + \frac{i}{2}\hbar \ln\det G^{-1} + \frac{i}{2}G^{-1}_{0,ba}G^{ab} - i\hbar\ln\det S^{-1} - iS^{-1}_{0,ba}S^{ab} + \Gamma_{2PI} + \hbar\delta$$

We obtain equations of motion (Kadanoff-Baym eq)

$$\begin{aligned}
\left(g_{\mu\nu}\partial^2 - (1-\lambda)\,\partial_\mu\partial_\nu\right)A^\mu(x) &= -e\mathrm{tr}\gamma^\mu S^F(x,x),\\
\left(g_{\mu\nu}\partial^2 - (1-\lambda)\,\partial_\mu\partial_\nu\right)G_F^{\nu\rho}(x,y) &= \int^{y_0} d^4z\,\Pi^F_{\mu\nu}(x,z)G^{\nu\rho}_\rho(z,y) - \int^{x_0} d^4z\,\Pi^\rho_{\mu\nu}(x,z)G_F^{\nu\rho}(z,y),\\
\left(g_{\mu\nu}\partial^2 - (1-\lambda)\,\partial_\mu\partial_\nu\right)G_\rho^{\nu\rho}(x,y) &= -\int_{y_0}^{x_0} d^4z\,\Pi^\rho_{\mu\nu}(x,z)G^{\nu\rho}_\rho(z,y),\\
\left[i\gamma^\mu\left(\partial + ieA\right)_\mu - m\right]S^F(x,y) &= \int^{y_0} d^4z\,\Sigma^F(x,z)S^\rho(z,y) - \int^{x_0} d^4z\,\Sigma^\rho(x,z)S^F(z,y),\\
\left[i\gamma^\mu\left(\partial + ieA\right)_\mu - m\right]S^\rho(x,y) &= -\int_{y_0}^{x_0} d^4z\,\Sigma^\rho(x,z)S^\rho(z,y).
\end{aligned}$$

Spectral functions

$$G_F^{\mu\nu}(x,y) = \frac{1}{2}\left\langle\{A^\mu(x),A^\nu(y)\}\right\rangle, G_\rho^{\mu\nu}(x,y) = \frac{i}{2}\left\langle[A^\mu(x),A^\nu(y)]\right\rangle,$$

$$S^F_{\alpha\beta}(x,y) = \frac{1}{2}\left\langle\left\{\psi_\alpha(x),\bar{\psi}_\beta(y)\right\}\right\rangle, S^\rho_{\alpha\beta}(x,y) = i\left\langle\left\{\psi_\alpha(x),\bar{\psi}_\beta(y)\right\}\right\rangle,$$

Statistical functions

From QFT to Kinetic Theory

In terms of Fourier modes

$$\frac{d}{dt}\tilde{S}_F(t,t;\vec{p}) + i\left(\vec{p} + e\vec{A}(t)\right)\left\{\gamma^0\vec{\gamma}, \tilde{S}_F\right\} + im\left[\gamma^0, \tilde{S}_F\right] \quad = \quad I_{col},$$

$$\begin{aligned} I_{col} \quad \equiv \quad & i\int^t dt' \left[\gamma^0\tilde{\Sigma}_\rho(t,t')\tilde{S}_F(t',t) + \tilde{S}_F(t,t')\tilde{\Sigma}_\rho(t',t)\gamma^0\right] \\ & -i\int^t dt' \left[\gamma^0\tilde{\Sigma}_F(t,t')\tilde{S}_\rho(t',t) + \tilde{S}_\rho(t,t')\tilde{\Sigma}_F(t',t)\gamma^0\right] \end{aligned}$$

QFT analogue of Boltzmann Equation

Parameterization

$$\tilde{S}_F(t_1,t_2;\vec{p}) = \frac{1}{4}\left(s(t_1,t_2) + \gamma^\mu v_\mu(t_1,t_2) + i\gamma_5 p(t_1,t_2) + \gamma^\mu\gamma_5 a_\mu(t_1,t_2) + \frac{i}{2}\left[\gamma^\mu,\gamma^\nu\right]t_{\mu\nu}(t_1,t_2)\right)$$

From QFT to Kinetic Theory

For $\vec{A} = A(t)\hat{z}$

$$\partial_t f = -\frac{\epsilon_\perp}{\omega^2}\dot{\vec{\pi}}\cdot\vec{g} + \frac{1}{2\omega}\left(mI_1 + \vec{\pi}\cdot I_{\vec{\gamma}}\right)$$

$$\partial_t g_z = \frac{\epsilon_\perp}{\omega^2}\dot{\pi}_z f - 2\omega h_z + \frac{1}{\epsilon_\perp\omega}\left(\left(mI_1 + \vec{\pi}\cdot I_{\vec{\gamma}}\right)\pi_z - \omega^2 I_{\gamma^3}\right)$$

$$\partial_t h_z = 2\omega g_z - \frac{m}{\epsilon_\perp} I_{\sigma^3}$$

$$\omega \equiv \sqrt{\vec{\pi}^2 + m^2}$$

$$\epsilon_\perp \equiv \sqrt{\vec{p}_\perp^2 + m^2}$$

$$n_{\vec{p}}(t) + \frac{1}{2} = f(t,\vec{p}) \equiv \frac{1}{2\omega}\left(ms + \vec{\pi}\cdot\vec{v}\right)$$

$$\vec{g}(t,\vec{p}) \equiv \frac{1}{\epsilon_\perp\omega}\left(\left(ms + \vec{\pi}\cdot\vec{v}\right)\vec{\pi} - \omega^2\vec{v}\right)$$

$$\vec{h}(t,\vec{p}) \equiv \frac{1}{\epsilon_\perp}\left(-\vec{\pi}\times\vec{a} - m\vec{b}\right)$$

Quantum Vlasov Equantion

(Kluger et al, '91)

$$\dot{n}_{\vec{k}}(t) = \frac{eE(t)\epsilon_\perp(t)}{\omega^2(t,\vec{k})}\int_{t_0}^{t} dt' \frac{eE(t')\epsilon_\perp(t')}{\omega^2(t',\vec{k})}\left(1 - n_{\vec{k}}(t')\right)\cos 2\Theta(t,t') \qquad \Theta(t,t_0) = \int_{t_0}^{t}\omega(t',\vec{p})dt'$$

From QFT to Kinetic Theory

Quantum Vlasov Equation

$$\dot{n}_{\vec{k}}(t) = \frac{eE(t)\epsilon_\perp(t)}{\omega^2(t,\vec{k})}\int_{t_0}^{t} dt' \frac{eE(t')\epsilon_\perp(t')}{\omega^2(t',\vec{k})}\left(1-n_{\vec{k}}(t')\right)\cos 2\Theta(t,t') \qquad \Theta(t,t_0) = \int_{t_0}^{t}\omega(t',\vec{p})dt'$$

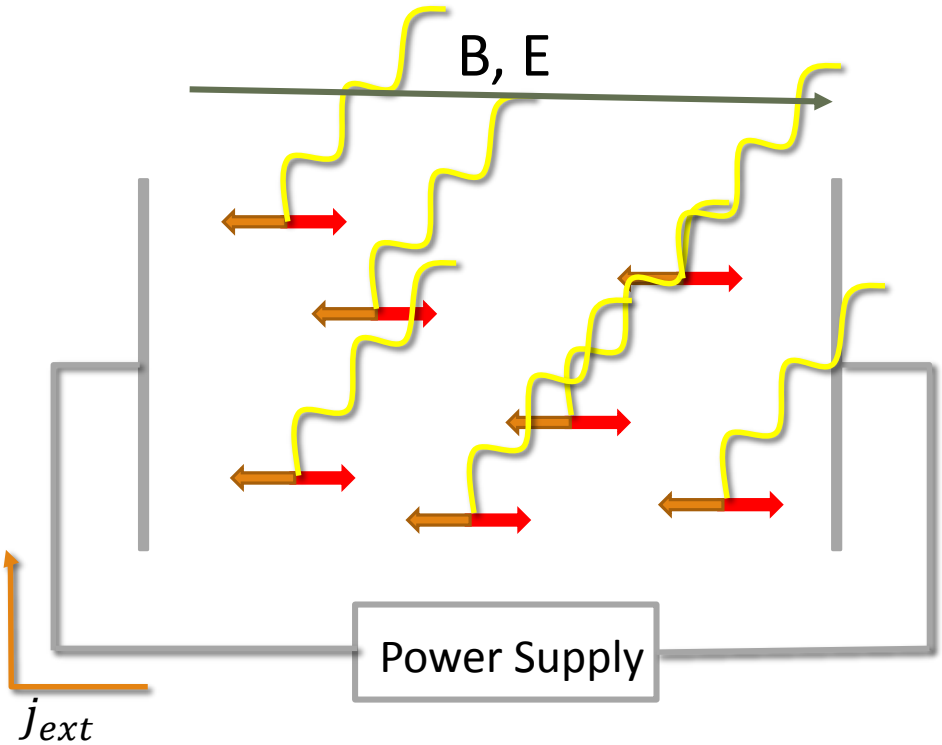
Maxwell's equation

$$\ddot{A}_z = j_{ext,z} + j_{pp,z} \qquad j_{pp,z} = e\int \frac{d^3k}{(2\pi)^3}\frac{\pi_z}{\omega_k}n_k + \frac{1}{E}\int\frac{d^3k}{(2\pi)^3}\omega_k\dot{n}_k$$

In the Markovian (semiclassical) Limit $\underbrace{\tau_{qm}}_{\text{Compton time}} \gg \underbrace{\tau_{cl}}_{\text{particle number}} \gg \underbrace{\tau_{pl}}_{\text{Plasma oscillation}}$ (Kluger et al, '98)

Occupation number $n_{\vec{k}}(t) \approx e^{-\pi E_c/E}\theta(\pi_z(t)) \qquad \vec{\pi} = \vec{k} - e\vec{A}$

Toy model: Schwinger Spark Chamber



Due to the strong magnetic field $B \gtrsim E$, only fermion pairs can be produced at the lowest Landau level.

Vacuum Decay rate

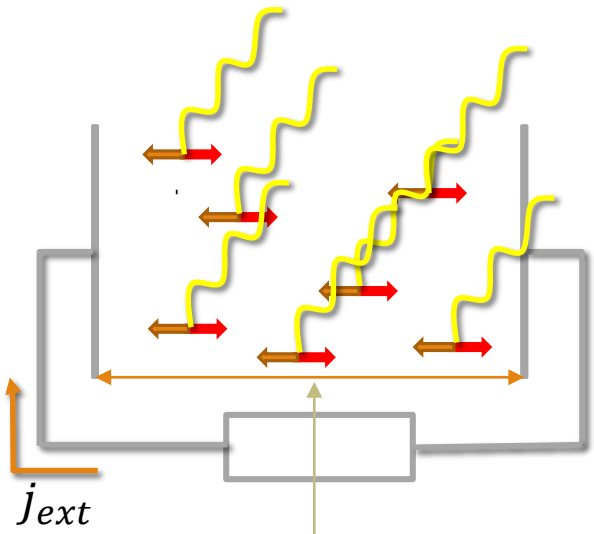
$$\frac{d}{dt}\mathcal{N} = \frac{d}{dt}\int_{k_z,n} n_{k_z,n}(t) \approx \frac{2e^2 EB}{(2\pi)^3} e^{-\pi E_c/E} \approx 2\Gamma\left[E, B\right]$$

Toy model: Schwinger Spark Chamber

Semiclassical 1D approximation

$$-\frac{d}{dt}E(t) = j_{pp}(t) + j_{ext}(t) \equiv j_{tot}(t)$$

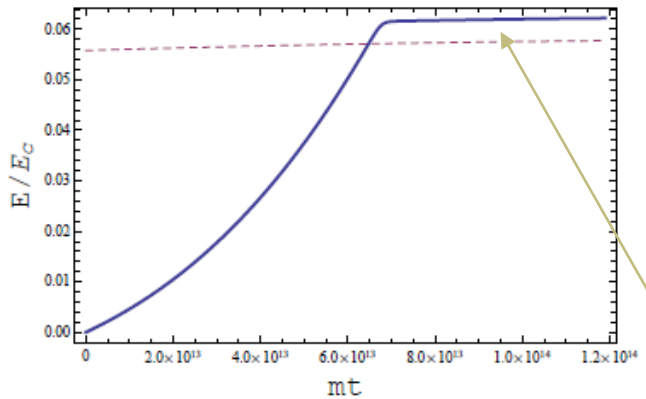
$$j_{pp}(t) \approx 2eS\left[E,B\right]w = 2\frac{e^3EB}{(2\pi)^2}we^{-\pi\frac{m^2}{eE}}$$

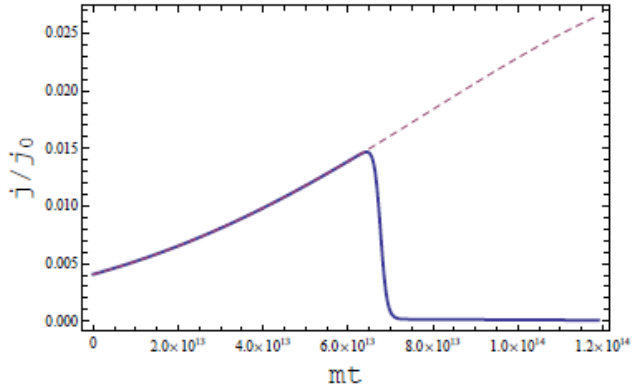


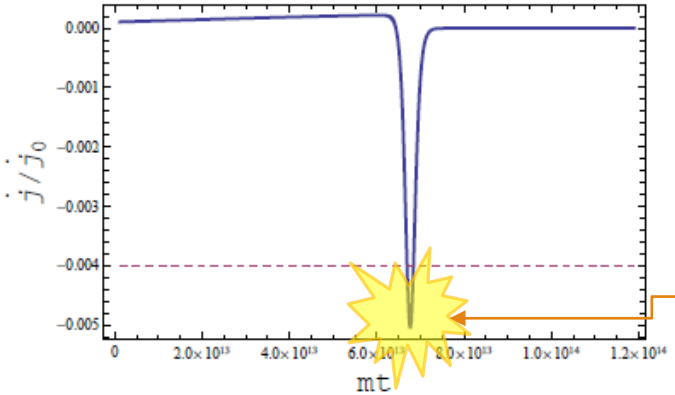
the width of the Chamber

Vacuum Decay Rate

Toy model: Schwinger Spark Chamber







The electric field limit $E_{lim} \sim 0.05 E_c$

$$1/\ln\left[\frac{mc}{\hbar}w\right] \sim 0.037$$

Schwinger spark!

Validity Conditions of The Spark Chamber

- Finite width to prevent the plasma oscillation

$$\left|\frac{E}{j_{pp}}\right| \gg w \implies \frac{1}{w^2} \gg 2\frac{e^3 B}{(2\pi)^2} e^{-\pi\frac{m^2}{eE}}$$

$$\boxed{w \ll 4 \times 10^4\, cm}$$

- Finite radius for small induced magnetic field

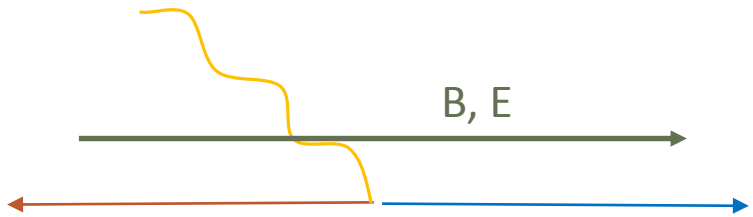
$$\left|\frac{B}{2\pi j_{pp}}\right| \gg r \implies \frac{1}{rw} \gg 2\frac{e^3 E}{(2\pi)} e^{-\pi\frac{m^2}{eE}}$$

$$\boxed{r \ll 8 \times 10^4\, cm}$$

$$\boxed{\text{the typical width for nanoshots } w \sim 30\, cm}$$

Validity Conditions of The Spark Chamber

- Negligible photon-induced pair production



For $r = \dfrac{\omega^2 - k_3^2}{4m^2}$ >> 1

Decay rate

$$W_i^{(SQA)} = -\frac{\mathrm{Im}\kappa_i}{\omega} = \frac{\alpha m^2}{3\sqrt{3}\pi\omega}\int_{-1}^{1}\frac{s_i}{1-v^2}K_{2/3}(z)\,dv, \quad z = \frac{8}{3(1-v^2)\kappa},$$

(Katkov, '11)

$$s_2 = 2(3-v^2), \quad s_3 = 3+v^2, \quad \kappa^2 = 4r(\mu^2+\nu^2) = -\frac{e^2}{m^6}\left(F^{\mu\nu}k_\nu\right)^2$$

Gamma-ray Flux density

$$\frac{d\Phi}{dE} = (3.37 \pm 0.47) \times 10^{-11} E^{-2.59\pm0.12} cm^{-2} s^{-1} TeV^{-1}$$

(HESS coll, '13)

Ratio

$$\frac{\Gamma_{schwinger}}{\Gamma_{\gamma\to e^\pm}} \sim 10^8 \text{ for } B \sim 0.1B_c \text{ and } E \sim 0.05E_c$$

Nanoshots from a Spark chamber

The Poynting vector at far distance

$$\vec{S} = \frac{1}{4\pi}\vec{E}\times\vec{B} = \frac{\hat{r}_0}{4\pi r_0^2}\left(\left(\vec{Q}\cdot\vec{Q}\right) - \left(\hat{r}_0\cdot\vec{Q}\right)^2\right) \qquad \vec{Q}(\hat{r}_0,\delta t) = \int d^3\delta x'\,\dot{\vec{j}}\left(\vec{x}_0' + \delta\vec{x}', t_0' + \delta t - \hat{r}_0\cdot\delta x'\right)$$

If a Schwinger spark chamber exists near the surface of the Crab pulsar,

luminosity and width of nanoshots

(In natural unit)

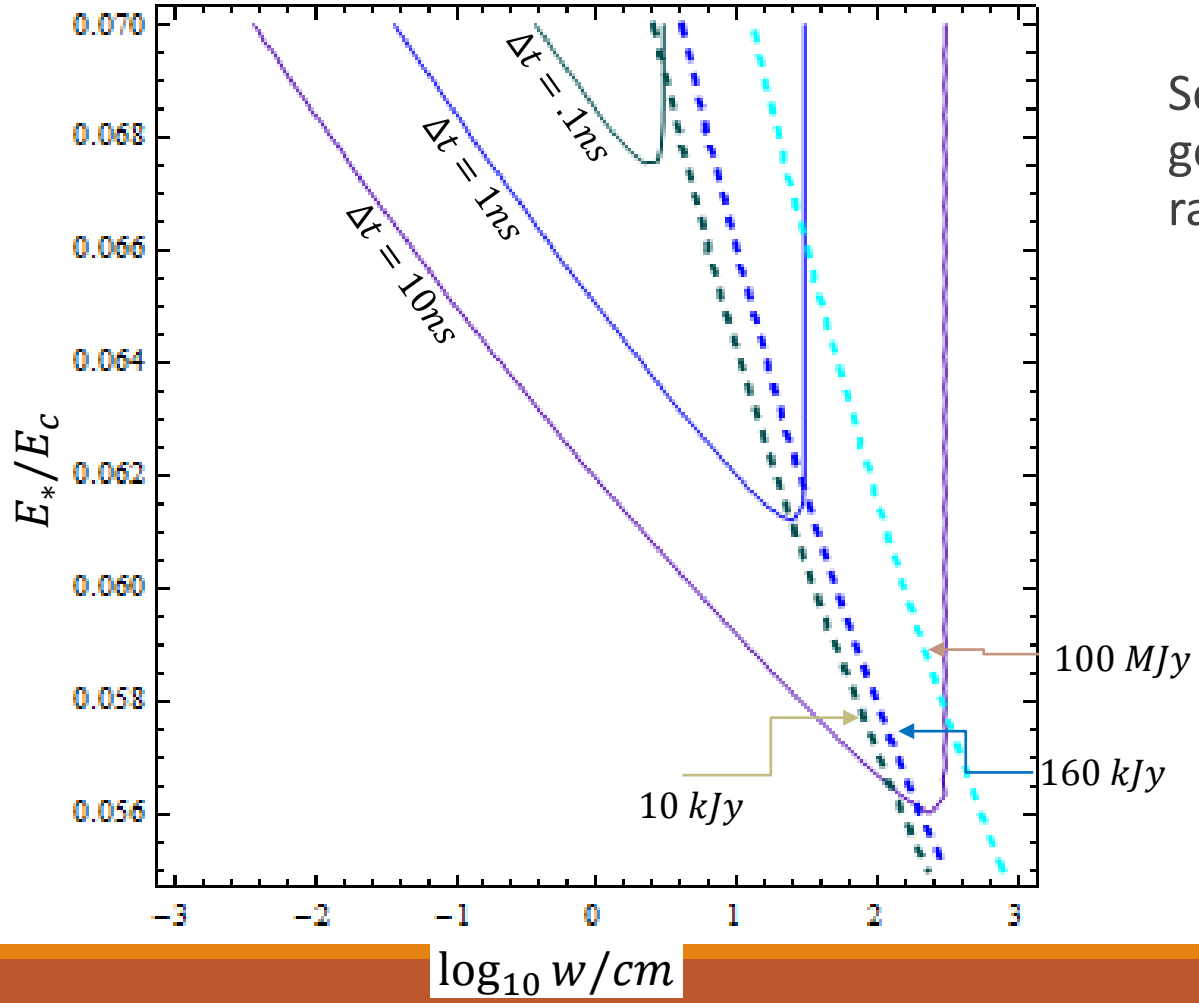
$$L_{max} \approx \frac{2}{3}\left(\frac{1}{\pi}\frac{E_*^2}{E_c\delta t_*}w^2\tanh\frac{w}{4\delta t_*}\right)^2$$

$$\Delta t \approx 2\delta t_*\cosh^{-1}\left[2+\cosh\frac{w}{2\delta t_*}\right]$$

$$\delta t_* \approx 2\left(\frac{E_c}{E_*}\right)^2\frac{e^{\pi E_c/E_*}}{e^3 B w}$$

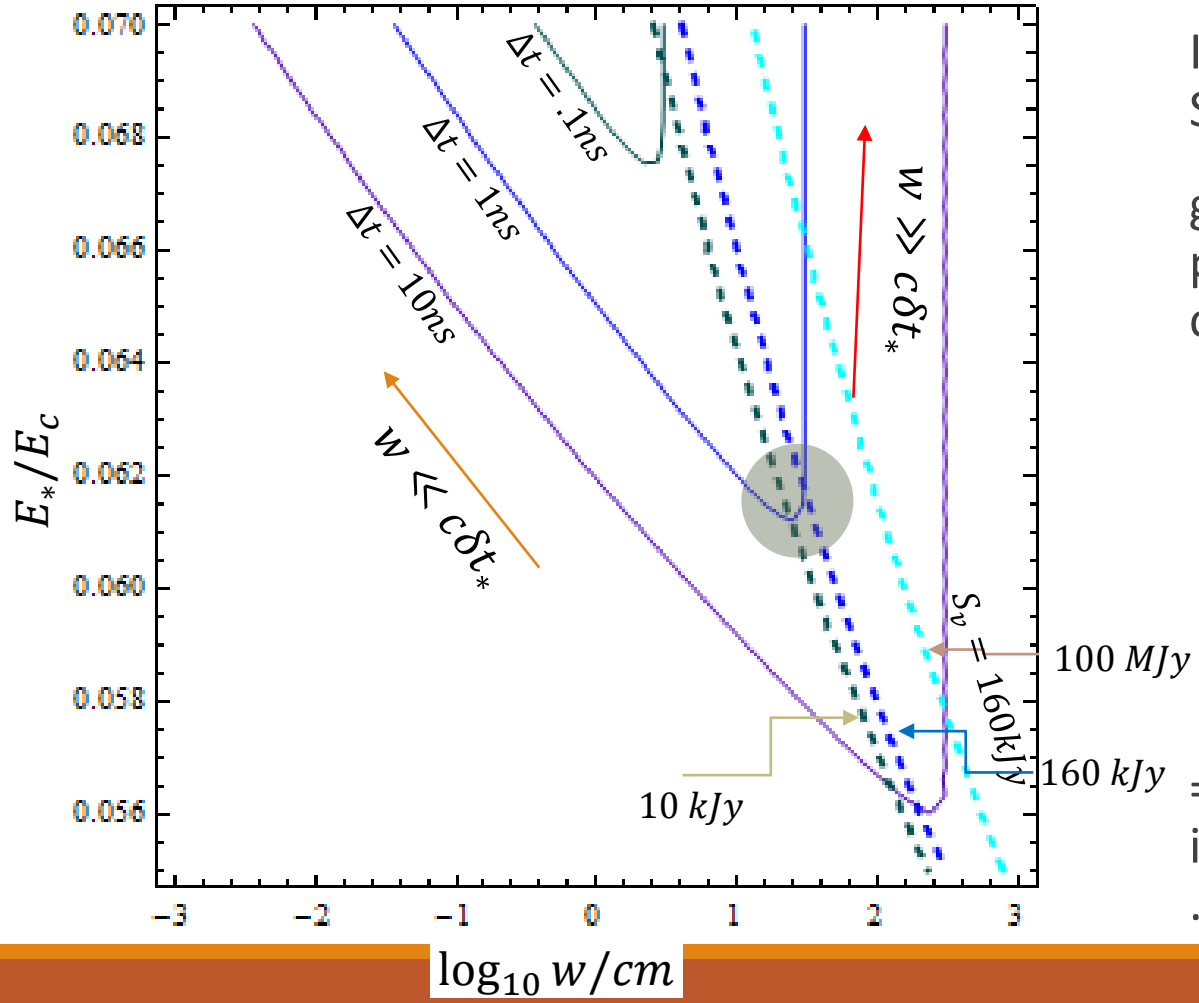
Width of a Schwinger spark

Schwinger sparks and Nanoshots from the Crab



Schwinger spark can generate a wide range of EM pulses.

Schwinger sparks and Nanoshots from the Crab



If nanoshots are from Schwinger spark, …

geometrical parameters are constrained.

3 length scales

- Nanoshot wid. $c\Delta t$
- Chamber wid. w
- Spark wid. $c\delta t_*$

=> Obs. Data indicates $c\Delta t \sim w \sim c\delta t_*$

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Summary & Outlook

- We construct a toy model that generates a narrow EM pulse from the Schwinger effect, a “Schwinger spark”.
- We derive the 1D evolution equation of field from QV equation and Maxwell’s equations for the toy model.
  - ⇒ Effects of collisional terms, validity conditions for QV equation?
- Schwinger spark can be a feasible origin of giant pulses (nanoshots) from the Crab pulsar.
- If so, the model suggests the existence of a region that has a strong electric field $E \sim 0.05 E_c$ and a size similar to the width of nanoshots $w \sim c\Delta t \sim 30cm$.
  - ⇒ High energy electron-positron pairs ($E \sim 10PeV$) are also generated.
    - pair cascade in the pulsar magnetosphere
    - PeV neutrinos

ELI-Nuclear Physics Facility

*In Magurele, Romania, the **ELI Nuclear Physics** (ELI-NP) facility will focus on laser-based nuclear physics. It will host two machines, a very high intensity laser, where beams from two 10 PW lasers are coherently added to get intensities of the order of 10^{23} - 10^{24} W/cm^2, and a very intense, brilliant gamma beam which is obtained by incoherent Compton back scattering of a laser light off a brilliant electron beam from a conventional linear accelerator. Applications include nuclear physics experiments to characterize laser – target interaction, photonuclear reactions, and exotic nuclear physics and astrophysics.*

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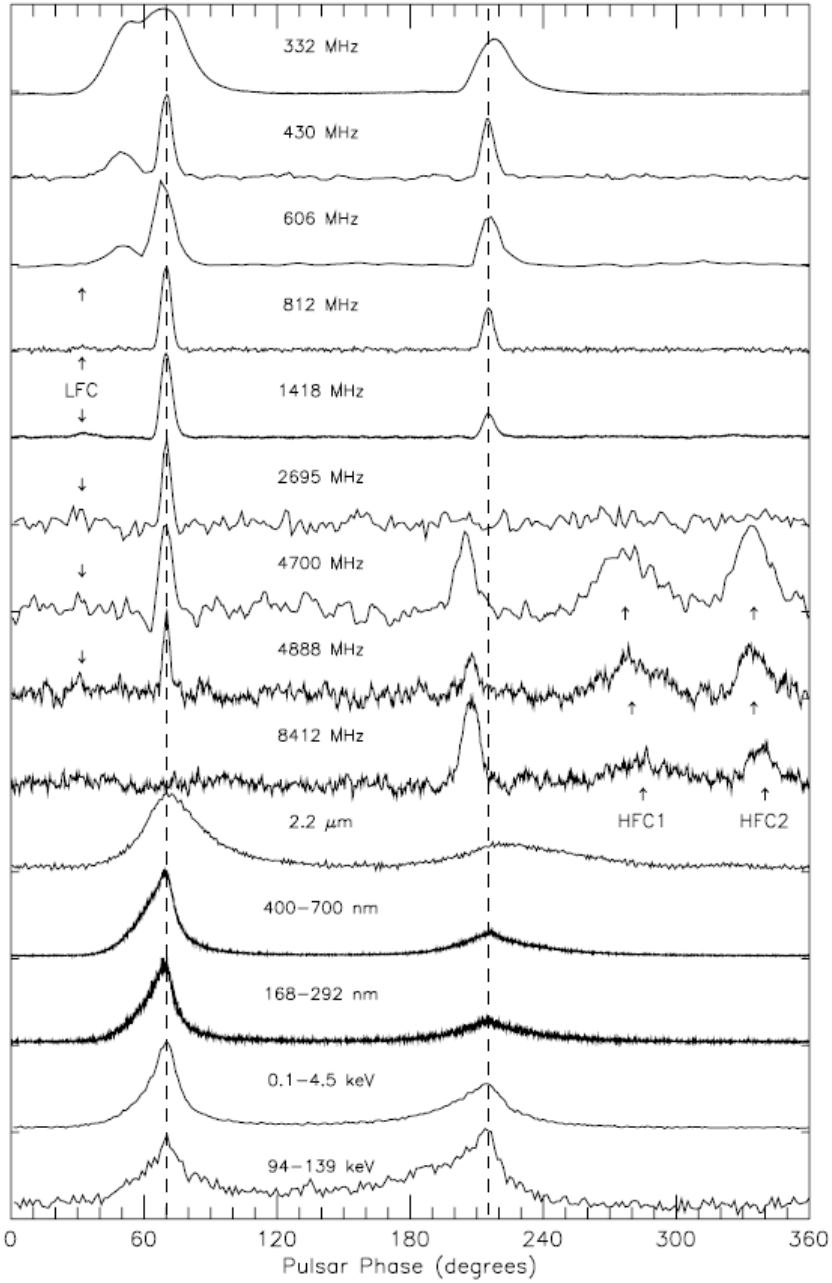
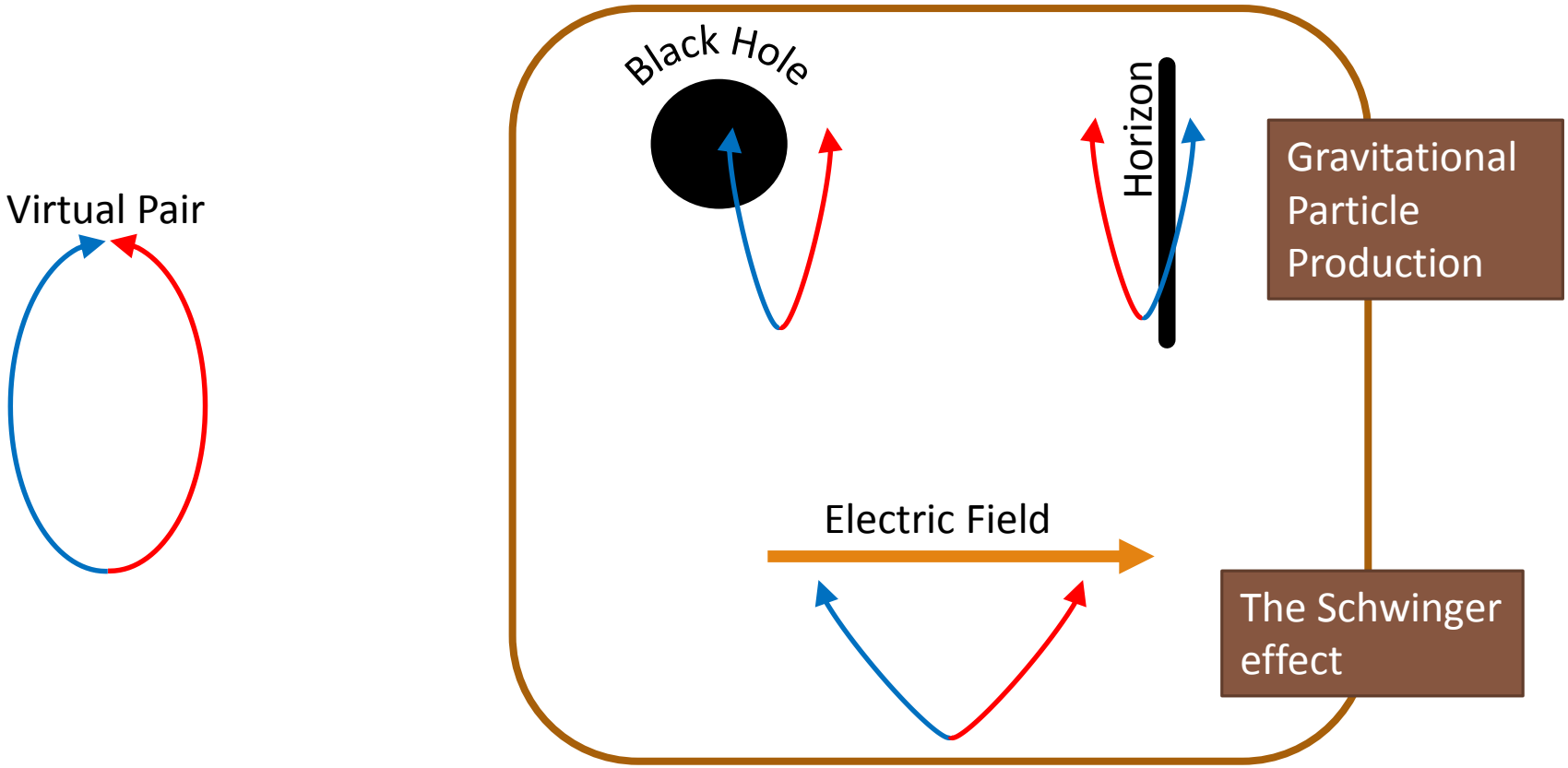


Mean Profile of the Crab Pulsar

(Hankins et al, '07)

Vacuum Pair Production