Astrophysical Origin of Positrons

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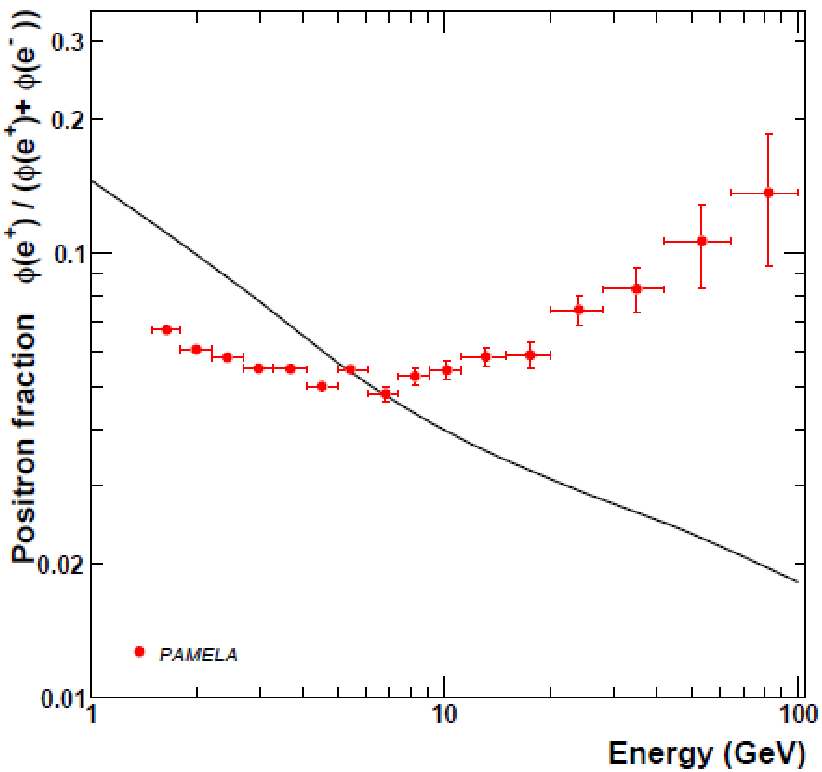
Outline

- Motivation
- Schwinger Mechanism from Astrophysical Objects
- Astrophysical Sources for Positrons
    - Black holes
    - Compact stars (quark stars, neutron stars, magnetars)
- Conclusion

Motivation

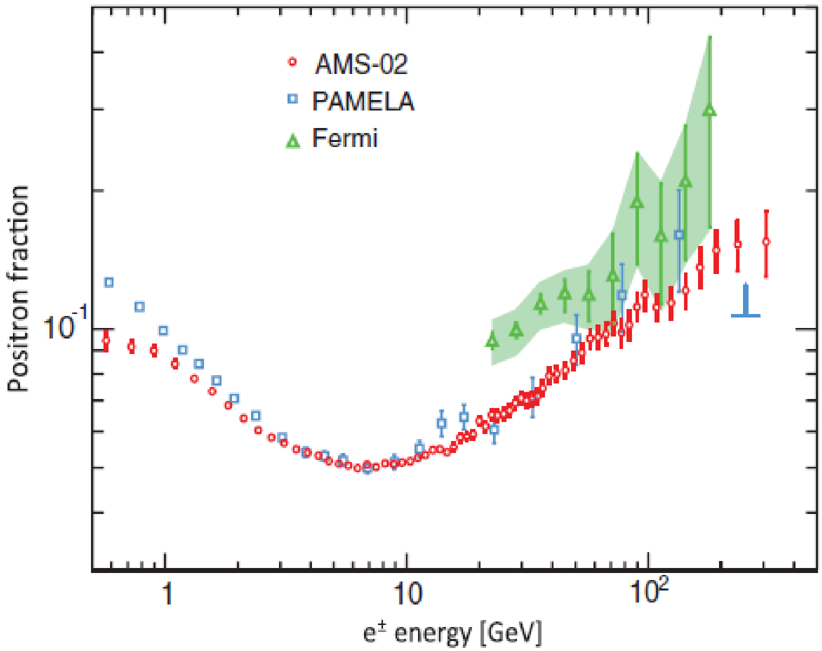
PAMELA



[Nature 458 (‘09) 607]

- Positron abundance in cosmic radiation for the energy range 1.5-100 GeV
- Deviation from secondary production (interaction between cosmic-ray nuclei and interstellar matter)

AMS-2



[Phys. Rev. Lett. 110 ('13) 141102]

- $e - e^+$: 6.6×10^6
- Measured positron fraction as a function of reconstructed energy:
  - Below 10 GeV, decreasing (secondary production from cosmic rays)
  - Steadily increasing from 10 to 250 GeV
- Neither fine structure nor observable anisotropy

Origin of Positrons?

- Dark matter origin?
  - Particle-antiparticle annihilation?
  - What kind of dark matter?

- Astrophysical origin?
  - Pulsar origin [Linden, Profumo, arXiv:1304.1791; Cholis, Hooper, arXiv:1304.1840]
  - Black holes or Compact stars (quark stars or neutron stars and/or magnetars)?

Astrophysical Origin of Positrons

- What mechanism produces positrons?
  - Many astrophysical mechanisms
  - Schwinger mechanism and/or Hawking mechanism
- What is the energy spectrum of positrons?
  - Schwinger pair production at finite temperature

$$N(\varepsilon, T) = \exp\left(-\pi \frac{\varepsilon^2 / m^2}{E / E_c}\right) \coth\left(\frac{\varepsilon}{T}\right)$$

- What does accelerate positrons to high energy?
  - Model-dependent, for instance, a constant electric field

$$\varepsilon = m \cosh\left(\sqrt{\frac{eE}{m}}\tau\right), \quad p_{\parallel} = m \sinh\left(\sqrt{\frac{eE}{m}}\tau\right)$$

Schwinger Mechanism from Astrophysical Objects

Astrophysical Objects Emit Pairs

Hawking radiation	Schwinger mechanism
Quantum (Dirac) vacuum	Quantum (Dirac) vacuum
Horizon	Electric field
KG or Dirac or Maxwell Eq	KG or Dirac Eq
Parametric interaction	Gauge interaction
One species of particles (charged or uncharged)	Charged pairs
Vacuum polarization (one-loop effective action)?	Heinsenberg-Euler/Schwinger vacuum polarization

Do charged black holes emit charged particles?

Heisenberg-Euler/Schwinger Effective Action

- Maxwell theory and Dirac/Klein-Gordon theory are gauge invariant:

$$F = \frac{1}{4} F^{\mu\nu} F_{\mu\nu} = \frac{1}{2}\left(\mathrm{B}^2 - \mathrm{E}^2\right), \quad G = \frac{1}{4} F^{\mu\nu} F^*_{\mu\nu} = \mathrm{B}\cdot\mathrm{E}$$

$$X = \sqrt{2(F + iG)} = X_r + iX_i$$

- Heisenberg-Euler/Schwinger effective action per four volume [J. Schwinger, "On gauge invariance and vacuum polarization," Phys. Rev. 82 ('51) 664]

$$L_{\mathrm{eff}} = -F - \frac{1}{8\pi^2}\int_0^\infty ds \frac{e^{-m^2 s}}{s^3}\left[(es)^2 G \frac{\mathrm{Re}\cosh(eXs)}{\mathrm{Im}\cosh(eXs)} - 1 - \frac{2}{3}(es)^2 F\right]$$

What is Schwinger Mechanism?

- QED action in a constant EM-field ($E \,/\!/\, B$, $X = B - iE$)

$$2\,\mathrm{Im}(L_{\mathrm{eff}}^{\mathrm{sp}}) = \frac{(eE)(eB)}{(2\pi)(2\pi)} \sum_{n=1}^{\infty} \frac{1}{n} \coth\left[\frac{n\pi B}{E}\right] \exp\left[-\frac{\pi m^2 n}{eE}\right]$$

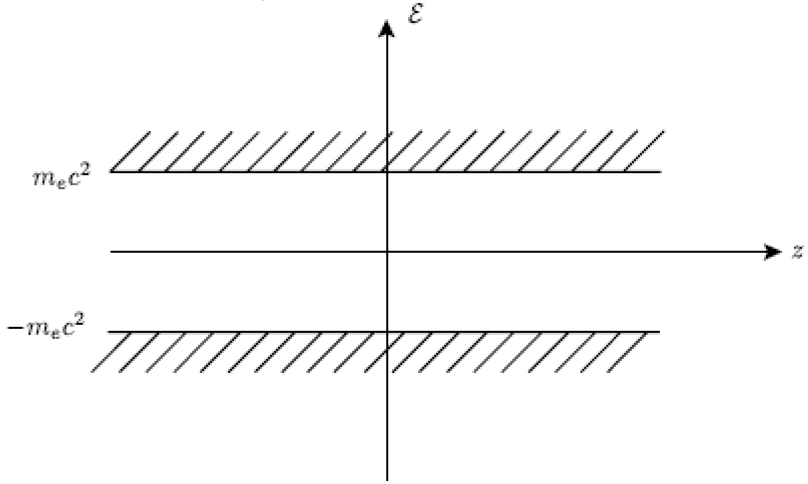
- Potential energy (Landau level) of an electron across a Compton wavelength in a constant E-field (B-field) equals to the rest mass of electron

$$eE_c \times \left(\frac{\hbar}{mc}\right) = mc^2 \Rightarrow E_c = \frac{m^2c^3}{e\hbar} = 1.3\times 10^{16}\mathrm{V}/cm$$

$$\hbar \times \left(\frac{eB_c}{mc}\right) = mc^2 \Rightarrow B_c = \frac{m^2c^3}{e\hbar} = 4.4\times 10^{13}G$$

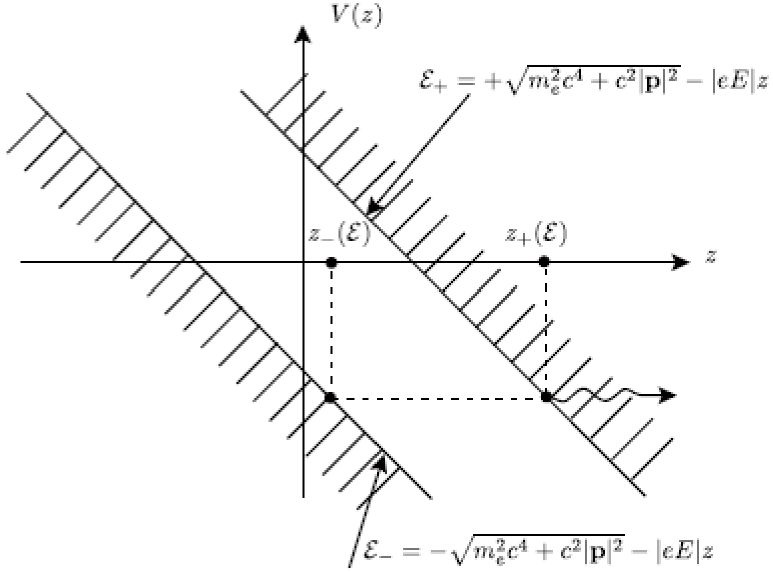
Schwinger Pair Production

Dirac Sea



[Fig. from Ruffini, Vereshchagin, Xue, Phys. Rep. 487 ('10)]

Dirac Sea in E-Field



Tunneling probability for particle-antiparticle pairs

$$N(\vec{p}_\perp) = \exp\left(-\pi\frac{m^2+\vec{p}_\perp^{\,2}}{|eE|}\right) = \exp\left(-\pi\frac{\varepsilon^2/m^2}{E/E_c}\right)$$

Duality between BH and QED

[W-Y P. Hwang, SPK, arXiv:1103.5264]

Notation	Schwarzschild BH	QED
$\frac{1}{\beta} = k_{\mathrm{B}} T$	$\frac{\kappa}{2\pi}$	$\frac{(qE/m)}{2\pi}$
# of States $\sum_J \int$	$\frac{1}{\beta} \sum_{l,m,p} \int \frac{d\omega}{2\pi}$	$\frac{m}{\beta} \sum_{\sigma} \int \frac{d^2 \mathrm{k}_{\perp}}{(2\pi)^2}$
Vac. Persistence	$\mp (\sum_J \int \;) \ln(1 \mp e^{-\beta\omega})$	$\pm (\sum_J \int \;) \ln(1 \pm e^{-\beta(\frac{k_\perp^2}{2m} + \frac{m}{2})})$
Vac. Polarization	$\mp \frac{1}{2} (\sum_J \int \;) \int_0^\infty \frac{ds}{s} e^{-\beta\omega \frac{s}{2\pi}} \frac{\{\cos(\frac{s}{2})\}}{\sin(\frac{s}{2})}$	$\pm (\sum_J \int \;) \frac{ds}{s} e^{-\beta(\frac{k_\perp^2}{2m} + \frac{m}{2}) \frac{s}{2\pi}} \frac{[\cos(\frac{s}{2})]}{\sin(\frac{s}{2})}$

Vacuum Persistence and Gravitational Anomalies

- Vacuum persistence = decay rate of vacuum due to Hawking radiation or Schwinger mechanism
- Trace anomalies = Hawking radiation [Christensen, Fulling, PRD 15 (‘77)] and Schwinger mechanism [Dittrich, Sieber, JPA 21 (‘88)]
- Vacuum persistence for bosons and fermions

$$2\,\mathrm{Im}(L_{\mathrm{red}}^{\mathrm{bos}}) = \sum_{l,m,p} \frac{\pi}{12}\frac{1}{\beta^2}, \quad 2\,\mathrm{Im}(L_{\mathrm{red}}^{\mathrm{fer}}) = \sum_{l,m,p} \frac{\pi}{24}\frac{1}{\beta^2}$$

equals to the total flux of Hawking radiation from gravitational anomalies [Robinson, Wilczek, PRL 95 (‘05); Iso, Umetsu, Wilczek, PRL 96 (‘06)].

Astrophysical Sources

Black Holes

Hawking Radiation

- Black holes emit thermal radiation with the Hawking temperature [Hawking, Nat. 248 ('74); CMP 43 ('75)].
- An uncharged and nonrotating Schwarzschild black hole with mass M

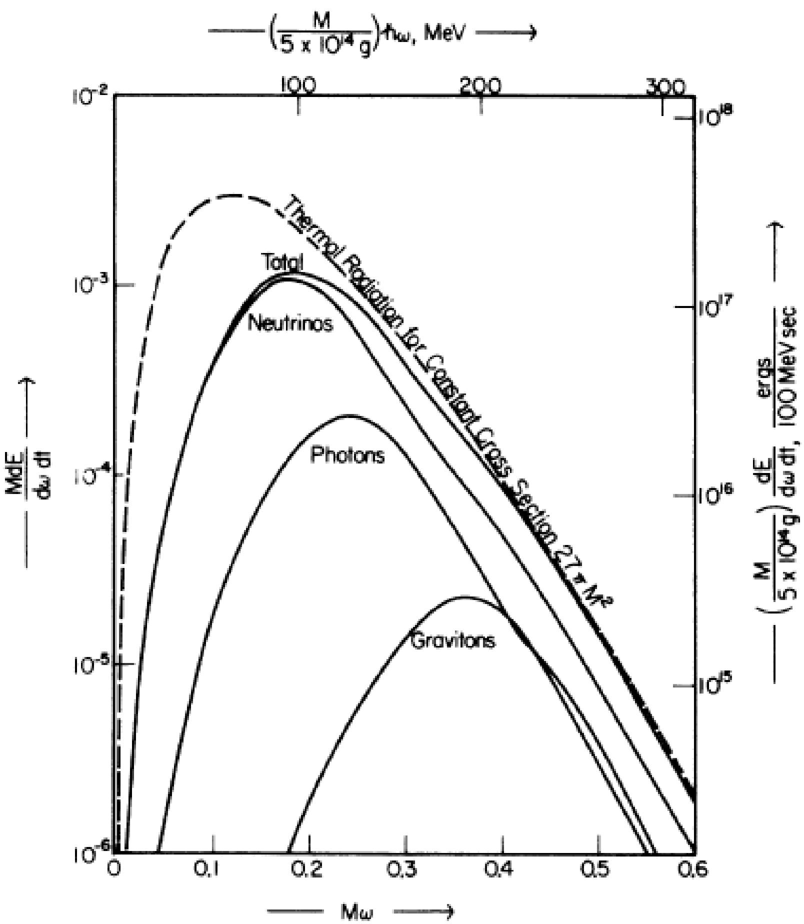
$$ds^2 = -\left(1 - 2GM/r\right)d(ct)^2 + \frac{dr^2}{1-2GM/r} + r^2 d\Omega_2^2$$

has the temperature $T_H = \hbar c^3 / 8\pi G M k_B = 10^{-6} (M_{\rm Sun}/M) K$

- Hawking radiation of bosons and fermions in a charged rotating black hole ($c = G = \hbar = 1$)

$$N_J(\omega) = \frac{1 - |R_J|^2}{e^{\beta(\omega - m\Omega_H - q\Phi_H)} \mp 1}, \quad \beta = \frac{1}{k_B T_H}, \quad T_H = \frac{\kappa}{2\pi},$$

Particle Emission Rate from BH



- Particle emission rate from an uncharged, nonrotating black hole [Page, PRD 13 ('75)].
- A hole of mass M >> 10^{17}g:
  - 81% neutrinos
  - 17% photons
  - 2% gravitons
- Particle emission rates from a charged, rotating black hole: discharge > angular momentum > neutral particle

Charged Black Holes

- A charged (Reissner-Nordstrom) black hole, gauge field, horizon, and the Hawking temperature

$$ds^2 = -\left(1 - 2M/r + Q^2/r^2\right)dt^2 + \frac{dr^2}{1 - 2M/r + Q^2/r^2} + r^2 d\Omega_2^2$$

$$A = (Q/r)dt \;, \qquad F = (Q/r^2)dt \wedge dr$$

$$r_H = M + \sqrt{M^2 - Q^2} \qquad T_H = \sqrt{M^2 - Q^2}/(2\pi r_H)$$

- Near horizon and near-extremal black hole geometry

$$ds^2 = -(\rho^2 - B^2/Q^2)d\tau^2 + Q^2/(\rho^2 - B^2)d\rho^2 + Q^2 d\Omega_2^2$$

$$r \to Q + \varepsilon\rho \qquad M \to Q + (\varepsilon B)^2/2Q \qquad t \to \tau/\varepsilon$$

Schwinger Emission from Near-extremal BH

- Schwinger emission (same charge) from a charged black hole [Zaumen, Nat. 247 ('74); Carter, PRL 33 ('74); Gibbons, CMP 44 ('75); Damour, Ruffini, PRL 35 ('75)]

$$N = m\left(\frac{eQ}{\pi m r_+}\right)^3 \exp\left[-\frac{\pi m^2 r_+^2}{eQ}\right] = m\left(\frac{eE_H r_+}{\pi m}\right)^3 \exp\left[-\frac{\pi m^2}{eE_H}\right]$$

- Charged particles from near-extremal black hole using the AdS geometry [Chen et al, PRD 85 ('12)]

$$N = \frac{\sinh(2\pi b)\sinh(\pi\tilde{a} - \pi a)}{\cosh(\pi a + \pi b)\cosh(\pi\tilde{a} - \pi b)}$$

$$a = qQ\ ,\ \ b = \sqrt{(q^2 - m^2)Q^2 - \left(l + 1/2\right)^2}\ ,\ \ \tilde{a} = \omega Q^2 / B$$

Kerr-Newman Black Hole

- Kerr solution ('63) and Newman et al ('65)

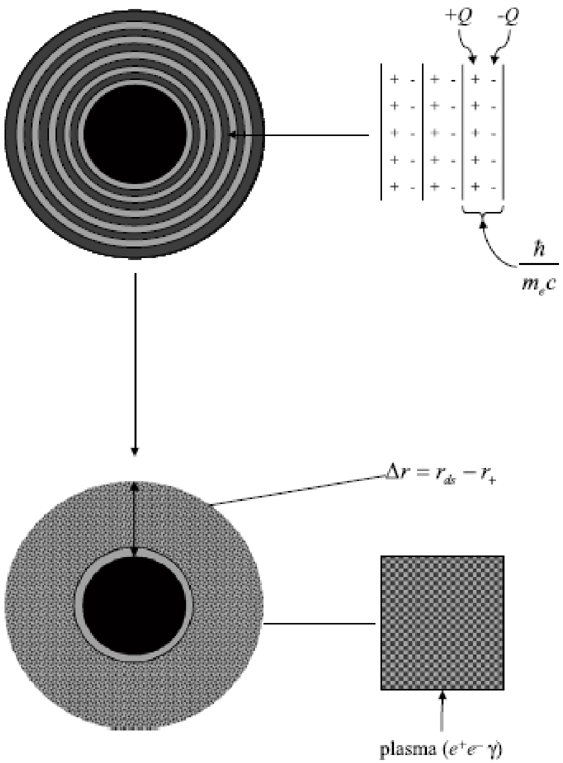
$$ds^2 = -\left(\frac{\Delta - a^2 \sin^2\theta}{\Sigma}\right)dt^2 - 2a\sin^2\theta\left(\frac{r^2 + a^2 - \Delta - a^2}{\Sigma}\right)dt\,d\phi$$
$$+\left(\frac{(r^2+a^2)^2 - \Delta a^2 \sin^2\theta}{\Sigma}\right)\sin^2\theta\, d\phi^2 + \frac{\Sigma}{\Delta}dr^2 + \Sigma d\theta^2$$

$$\Sigma = r^2 + a^2\cos^2\theta\ ,\quad \Delta = r^2 - 2Mr + a^2 + (Q^2 + P^2)\ ,\quad a = \frac{J}{M}$$

- The Maxwell 1-form

$$A = \frac{Qr(dt - a\sin^2\theta d\phi) - P\cos\theta(adt - (r^2 + a^2)d\phi)}{\Sigma}$$

Dyadosphere and Dyadotorus



[Fig. from Ruffini, Vereshchagin, Xue, Phys. Rep. 487 ('10)] *duados = pairs

- A GRB model based on the energetics ($10^{54} erg/M_{Sun}$) by Damour, Ruffini [PRL 35, ('75)].
- Dyadosphere: a region with supercritical E-field outside BH horizon [Ruffini ('98)]

$$r_H = 1.47\times 10^5 \mu\left(1+\sqrt{1-\xi^2}\right) cm$$

$$r_{ds} = 1.12\times 10^8 \sqrt{\mu\xi}\ cm$$

$$\mu = M / M_{Sun}\ ,\ \xi = Q/(M/\sqrt{G})$$

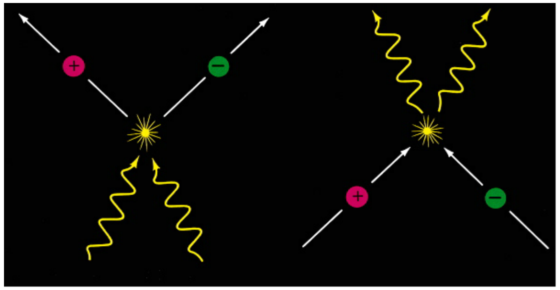
- Plasma of e^-e^+ pairs and photons

Positrons from Black Holes

- Enormous e^-e^+ pairs, at least one pair per each Compton volume, are produced, but electrons discharge a positively charged black hole, and some positrons may accelerate over L to gain an energy $\varepsilon = (eE_c)\left(\frac{L}{\lambda_c}\right) = \left(\frac{L}{\lambda_c}\right) MeV$.
- Annihilation and creation (Breit-Wheeler process) of e^-e^+ pairs and plasma state

$$e^- + e^+ \rightarrow \gamma_1 + \gamma_2 : \sigma_{e^-e^+} \approx \pi\left(\alpha\lambda_c \times \frac{mc^2}{\varepsilon_e}\right)^2 \frac{\varepsilon_e}{mc^2}\left[\ln\left(\frac{2\varepsilon_e}{mc^2}\right) - 1\right], (\varepsilon_e >> mc^2)$$

$$\gamma_1 + \gamma_2 \rightarrow e^- + e^+ : \sigma_{\gamma\gamma} \approx \pi\left(\alpha\lambda_c \times \frac{mc^2}{\varepsilon_\gamma}\right)^2, (\varepsilon_\gamma >> mc^2)$$



- Direct photon-photon scattering small

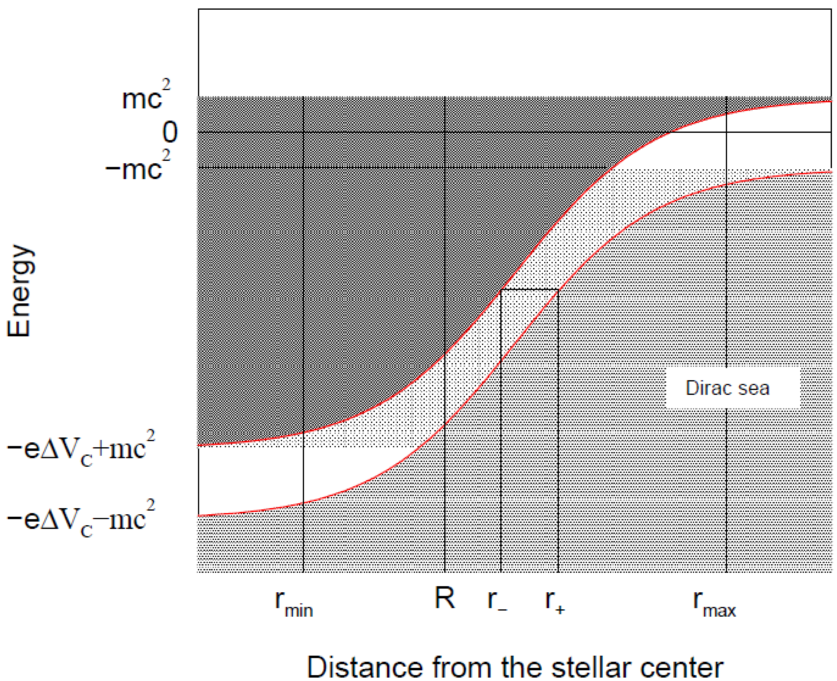
$$\sigma_{\gamma\gamma\rightarrow\gamma\gamma} = 7.4\times 10^{-66}(\omega^*[eV])^6$$

Dilemma for Black Hole Model

- However, pair production is a self-regulating process that would discharge a growing electric field and keep 26 order of magnitude lower than the dyadosphere value [D. N. Page, ApJ 653 ('06)].
- Then, how does ordinary matter gravitationally collapse to form a supercritically charged black hole?
- Strong interaction may bind charges beyond the critical strength (strange stars).
- But, black holes do not care about interactions: no hair theorem (mass, charge, and angular momentum).

Quark Stars

Strange Stars

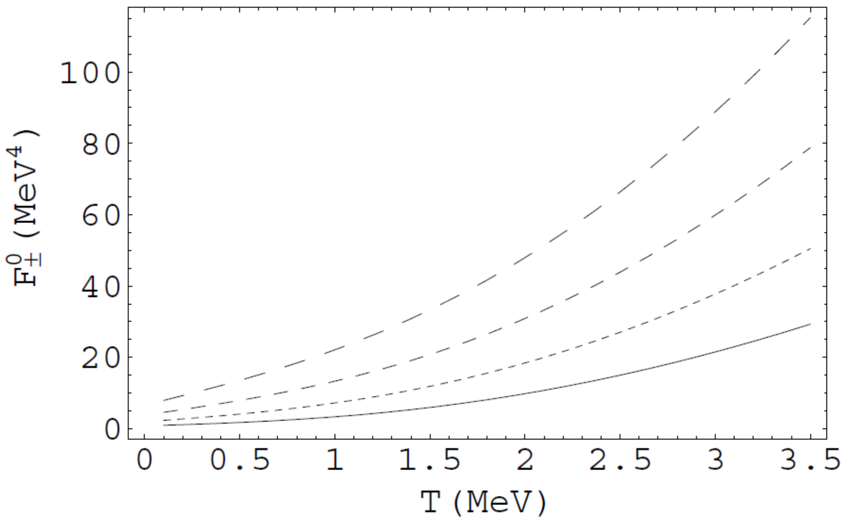


Tunneling of electrons from Dirac sea under Coulomb potential.

- Hypothesis: strange quark matter and star may be absolute minimum of strong interaction.
- Electrosphere of 10^3 fm above the quark surface induces a strong electric field of 5×10^{17} V/m for e^-e^+ pairs [Usov, PRL 80 ('98)].

Electron-Positron Pairs

Vacuum e-e+ pair flux



[Cheng, Harko, ApJ. 643 ('06)]

Strange star model

- Electrosphere:
  - thickness of 10^3 fm
  - surface temperature T (MeV)
  - electrostatic potential V_q
- Electrostatic potential V_q :
  - 8 MeV (solid curve)
  - 10 MeV (dotted curve)
  - 12 MeV (short dashed curve)
  - 14 MeV (long dashed curve)

Vacuum Polarization & Pair Production

- Purely thermal part of QED action [SPK, Lee, Yoon, PRD 82 ('10)]

$$\Delta L_{\text{eff}}(T,E) = L_{\text{eff}}(T,E) - L_{\text{eff}}(T=0,E)$$
$$= \mp i \sum_{k,\sigma} \left[\ln\left(1 \pm e^{-\beta(\omega_k - z_k)}\right) - \ln\left(1 \pm e^{-\beta\omega_k}\right) \right]$$

- Imaginary part of the effective action

$$\mathrm{Im}(\Delta L_{\text{eff}}) = \pm \frac{1}{2} i \sum_{k,\sigma} \sum_{j=1} \frac{(\mp n_{FD/BE}(k))^j}{j} \left[(e^{\beta z_k} - 1)^j + (e^{\beta z_k^*} - 1)^j \right]$$

- Real part of the effective action

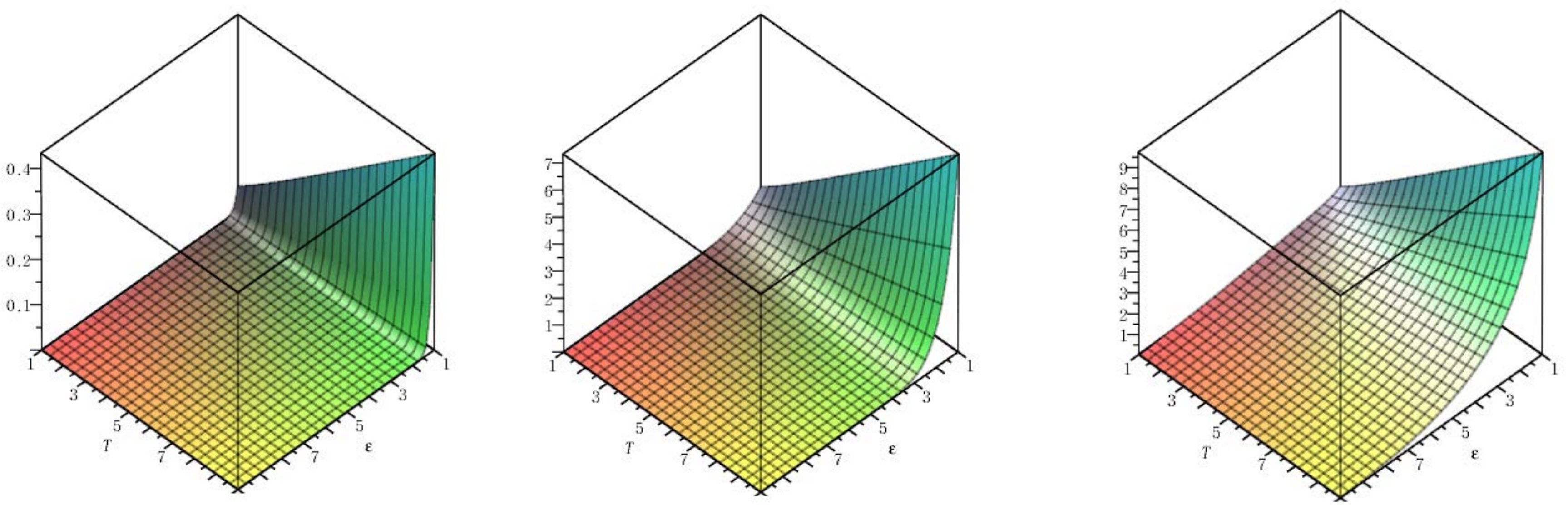
$$\mathrm{Re}(\Delta L_{\text{eff}}(T)) = \mp \sum_{k,\sigma} \arctan\left[\frac{\sin(\mathrm{Re}\, L_{\text{eff}}(T=0,k))}{e^{\beta\omega_k}\left(1 + |\beta_k|^2\right)^{(1+2|\sigma|)/2} \pm \cos(\mathrm{Re}\, L_{\text{eff}}(T=0,k))} \right]$$

Pair Production at T

- Pair-production rate at T [SPK, Lee, PRD 76 ('07); SPK, Lee, Yoon, PRD 82 ('10)]

$$2\,\mathrm{Im}\,\Delta L_{\mathrm{eff}}(T) \approx N^{\mathrm{sp/sc}}(T) = \begin{cases} \sum_k e^{-\pi \frac{\varepsilon_k^2/m^2}{E/E_c}} \tanh(\beta\omega_k/2) \\ \sum_k e^{-\pi \frac{\varepsilon_k^2/m^2}{E/E_c}} \coth(\beta\omega_k/2) \end{cases}$$

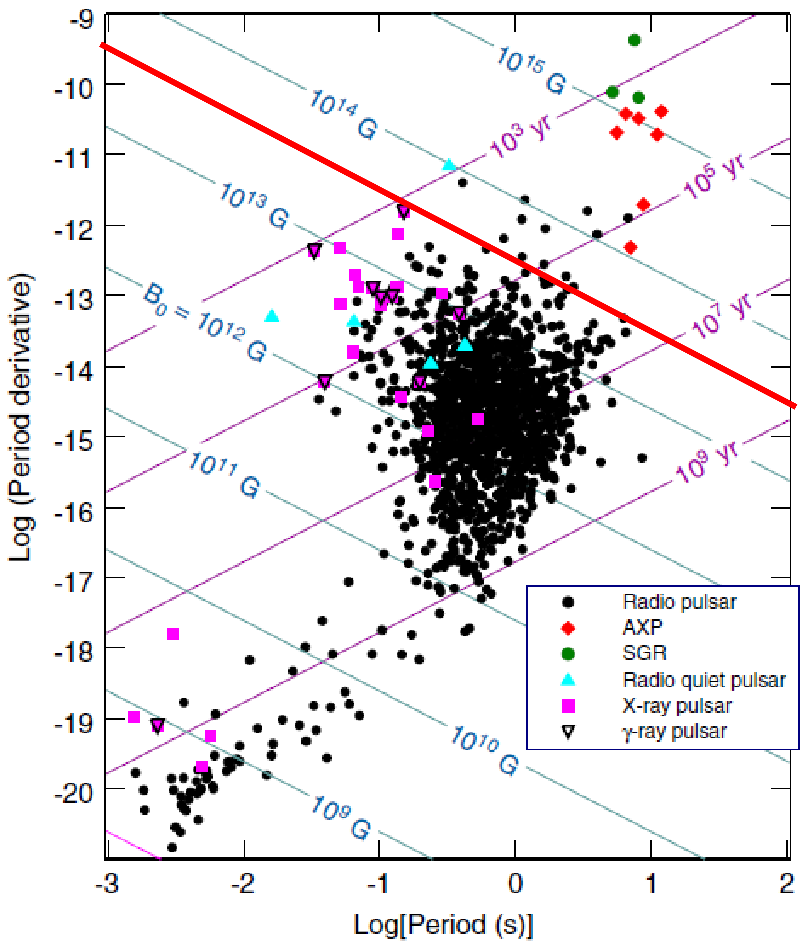
- e^-e^+pairs in $1E_c, 10E_c, 100E_c$ for $1MeV \le T, \varepsilon \le 10MeV$



Magnetars and Neutron Stars

Neutron Stars and Magnetars

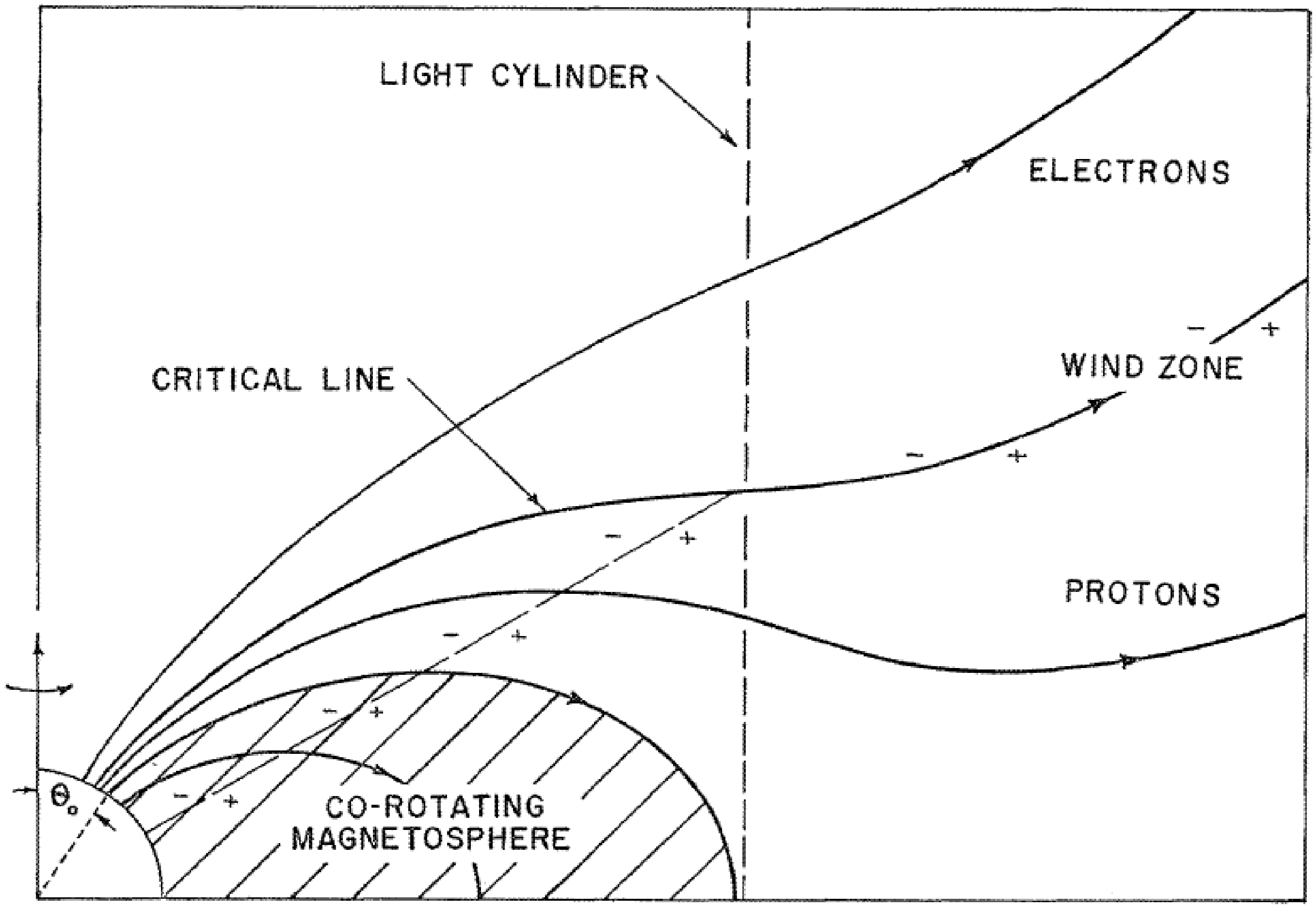
Schwinger Limit



- Compact stars
  - Weakly interacting quarks at core.
  - Strongly magnetized, magnetars surface B-field 10^{14}–10^{16} G (SGR, AXP observations).
  - Interior B-field: 10^{19} – 10^{20} G for quark matter core, 10^{18} G for nuclear matter core.

[Harding, Lai, Rep. Prog. Phys. 69 ('06)]

Pulsar Electrodynamics



[Goldreich and Julian, ApJ. 157 (‘69)]

Pair Production & Magnetized Vacuum

- The rotating magnetic field for pulsars or magnetars induces an electric field and changes the Landau levels

$$\vec{B}(t) = B_{\parallel}\vec{e}_{\parallel} + B_{\perp}(\cos\omega t\vec{e}_1 + \sin\omega t\vec{e}_2)$$

$$\vec{A} = \frac{1}{2}\vec{B}\times\vec{r} \Rightarrow \vec{E} = -\frac{1}{2}\dot{\vec{B}}\times\vec{r}$$

- The rotating magnetic field may produce e^-e^+ pairs [Di Piazza, Calucci, PRD 65 ('02); Heyl, Hernquist, MNRAS 326 ('05)].
- The Dirac vacuum in time-dependent magnetic field can break down (induces an electric field).

Instability of Magnetic Vacuum

- Breackdown from magnetic monopole production ($B_{max} = \alpha(m_m/m_e)^2 B_c$) [Duncan, arXiv:0002442]:
  - Planck scale: 10^{55} G
  - GUT scale: 10^{49} G
  - TeV quantum gravity from large extra dimensions: $10^{23}\ (m_m/TeV)^2$ G
- Dynamical breakdown: change of magnetic field greater than Landau energy [SPK,arXiv:1305.2577]

$$\left| d \ln(B(t)) / dt \right| \geq \omega(t)$$

Landau Levels in B(t)

- A charged spinless scalar in a homogeneous, time-dependent, magnetic field $\vec{A}(t) = \vec{B}(t) \times \vec{r} / 2$ governed by

$$\left[\frac{d^2}{dt^2} + \vec{p}_\perp^{\,2} + \left(qB(t)/2 \right)^2 \vec{x}_\perp^{\,2} - qB(t)\hat{L}_z + k_z^2 + m^2 \right] \Psi_{k_z \perp}(t, \vec{x} \perp) = 0$$

- Quantum motion transverse to the magnetic field is 2-dimensional, time-dependent, coupled oscillators

$$\hat{H}_\perp(t) = \vec{p}_\perp^{\,2} + \left(qB(t)/2 \right)^2 \vec{x}_\perp^{\,2} - qB(t)\hat{L}_z$$

- Time-dependent energy for the Landau levels (LL)

$$\omega^2(t) = qB(t)\left[2\hat{c}_-^{+}(t)\hat{c}_-(t) + 1 \right] + k_z^2 + m^2$$

Quantum Motion of Landau Levels

- Introduce a dimensionless measure that characterizes the quantum motion of the n-th LL during a time interval [SPK, arXiv:1305.2577]

$$R_n = \frac{(n/4)\left|\ln\left(B(t_f)/B(t_i)\right)\right|}{\int_{t_i}^{t_f} \omega(t',n)dt'}$$

- Classification of quantum motion of LLs and pair production

$$\begin{cases} \text{adiabatic change (exponential suppresion)}: & R_n << 1 \\ \text{sudden change (catastrophic production)}: & R_n >> 1 \\ \text{nonadiabatic change (moderate production)}: & \text{otherwise} \end{cases}$$

Pair Production in B(t)

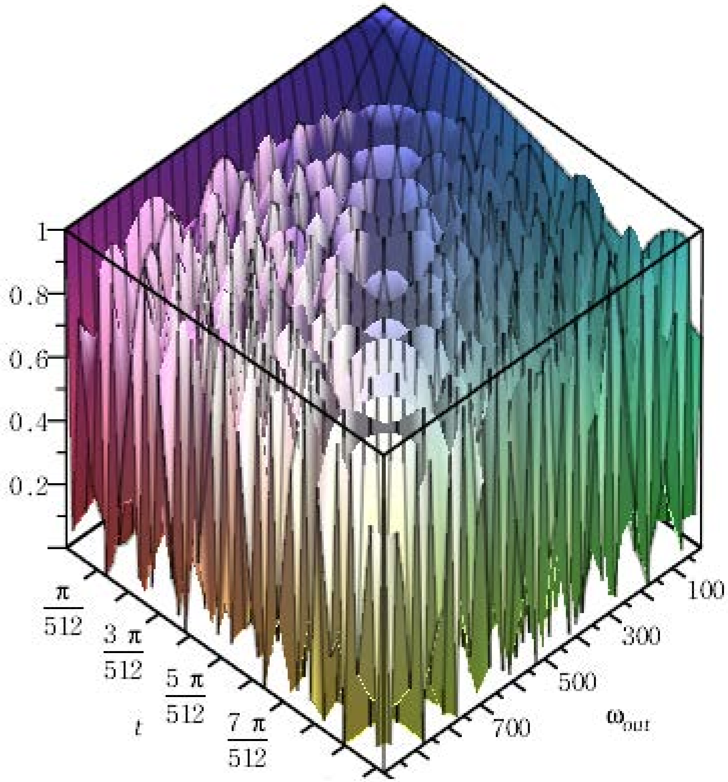
- Pair production in a sudden change of magnetic field

$$B(t) = \left(B_1 - B_0\right)\theta(t) + B_0$$

- Bogoliubov transformation between initial LL and final LL and its coefficients

$$\alpha = \frac{1}{2}\left(\sqrt{\frac{\omega_{out}}{\omega_{in}}} + \sqrt{\frac{\omega_{in}}{\omega_{out}}}\right)$$

$$\beta = \frac{1}{2}\left(\sqrt{\frac{\omega_{out}}{\omega_{in}}} - \sqrt{\frac{\omega_{in}}{\omega_{out}}}\right)$$



[Amplitude square for LL with initial energy =1 MeV & final energy =100 MeV –1 GeV]

Neutron Stars/ Magnetars

- Compton scales: length, time, and cyclotron frequency
  - $\lambda_c = 10^{-11} cm$
  - $t_c = 10^{-21} sec$
  - $\omega_c = 10^{21}/sec$
- Neutron stars/magnetars
  - $t_n = \frac{0.1}{\Omega} = 10^{-1} - 10^{-3} sec$
- Adiabatically changing fields exponentially suppress pair production.

Conclusion

- Critically reviewed astrophysical production of positrons (electron-positron pairs) via Schwinger mechanism and/or Hawking radiation
- Positively charged (rotating) black holes can create high energy positrons (cosmic origin like GRB), but a question is how such black holes can be formed from gravitational collapse in nature.
- Strong electromagnetic fields of compact stars (quark stars, magnetars or pulsars) may play a certain role in producing positrons (electron-positron pairs).