Schwinger Effect and Hawking Radiation in Charged Black Holes*

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*Similar talks at ICGC&4th GX, 12th ICGAC, 14th IK
1/3rd new material

Outline

- Introduction
- Effective Actions in In-Out Formalism
- Road to QED in Charged Black Holes
- Schwinger Effect in Near-Extremal BHs
- Extremal Micro-BH, Extremal BH Entropy and Evolution
- Conclusion

Spontaneous Pair Production and Vacuum Polarization

Hawking Radiation & Schwinger Effect

- Hawking emission formula in charged BH [CMP ('74)]

$$N_H = \frac{\Gamma_{j\omega lm}}{e^{\frac{\omega - q_j \Phi}{T_H}} \mp 1}$$

$$T_H = \frac{1}{2\pi} \frac{\sqrt{M^2 - Q^2}}{\left(M + \sqrt{M^2 - Q^2}\right)^2}$$

- No Hawking radiation when Q = M

- Schwinger emission formula in E-field [PR ('51)]

$$N_S = \exp\left(-\frac{m}{T_S}\right)$$

$$T_S = \frac{1}{2\pi}\left(\frac{qE}{m}\right)$$

- Heisenberg-Euler, Weisskopf, Schwinger QED actions

One-Loop Effective Actions:
Black Hole vs QED

[SPK, Hwang ('11)]

Notation	Schwarzschild BH	QED in E
$\frac{1}{\beta} = k_B T$	$\frac{\kappa}{2\pi}$	$\frac{(qE/m)}{2\pi}$
# of States $\sum_J \int$	$\frac{1}{\beta}\sum_{l,m,p}\int \frac{d\omega}{2\pi}$	$\frac{m}{\beta}\sum_{\sigma}\int \frac{d^2 k_\perp}{(2\pi)^2}$
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	$\mp\frac{1}{2}(\sum_J \int)\int_0^\infty \frac{ds}{s} e^{-\beta\omega\frac{s}{2\pi}} \frac{\{\cos(\frac{s}{2})\}}{\sin(\frac{s}{2})}$	$\pm(\sum_J \int)\frac{ds}{s} e^{-\beta(\frac{k_\perp^2}{2m}+\frac{m}{2})\frac{s}{2\pi}} \frac{[\cos(\frac{s}{2})]}{\sin(\frac{s}{2})}$

Schwinger Effect in Charged Black Holes

Zaumen, Nature ('74)

Carter, PRL ('74)

Gibbons, CMP ('75)

Damour, Ruffini ('76)

⋮

Khriplovich ('99)

Gabriel ('01)

SPK, Page ('04), ('05), ('08)

Ruffini, Vereshchagin, Xue ('10)

Chen et al ('12); Kerr-Newman BH, in preparation ('15)

Ruffini, Wu, Xue ('13)

SPK ('13)

Cai, SPK ('14)

SPK, Lee, Yoon ('15); SPK ('15)

Cai, SPK, in preparation ('15)

Spontaneous Emission of Bosons from Supercritical Point Charges

- Mean number of charged bosons produced from supercritical point charges [SPK ('13)]

$$N_C = e^{-2\pi(\bar{\lambda}-C)} \frac{1+e^{-4\pi C}}{1+e^{-2\pi(\bar{\lambda}-C)}}$$

$$C = Z\alpha\sqrt{1-\left(\frac{l+1/2}{Z\alpha}\right)^2}, \quad \bar{\lambda} = \frac{Z\alpha}{\sqrt{1-(m/\omega)^2}}$$

- Vacuum persistence (twice of the imaginary action)

$$W = \underbrace{\ln\left(1+e^{-2\pi(\bar{\lambda}-C)}\right)}_{\text{leading Schwinger formula}} - \underbrace{\ln\left(1+e^{-2\pi(\bar{\lambda}+C)}\right)}_{\text{charged vacuum}}$$

Boson Emission from Extremal RN BH

- Including only the leading terms (effective charge and angular momentum) for the KG equation in an RN BH

$$Q' = Q + \frac{m^2 M}{q\omega}$$

$$l' + \frac{1}{2} = \sqrt{\left(l + \frac{1}{2}\right)^2 + \frac{m^2 M}{\omega}\left(2qQ + \frac{m^2 M}{\omega}\right)}$$

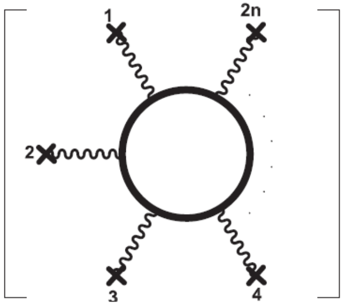
- Mean number is the same as that for the Coulomb field ($C' = C$ invariant), and that for extremal RN black hole.

Effective Actions in In-Out Formalism

In-Out Formalism for QED Actions

- In the in-out formalism, the vacuum persistence amplitude gives the effective action [Schwinger ('51); DeWitt ('75), ('03)] and is equivalent to the Feynman integral

$$e^{iW} = e^{i\int (-g)^{1/2} d^D x L_{\text{eff}}} = \langle 0,\text{out} \,|\, 0,\text{in}\rangle = \sum_{n=1}^{\infty}$$



- The complex effective action and the vacuum persistence for particle production

$$\left|\langle 0,\text{out} \,|\, 0,\text{in}\rangle\right|^2 = e^{-2\,\text{Im}W} \;, \quad 2\,\text{Im}W = \pm VT \sum_{\text{k}} \ln(1 \pm N_k)$$

Effective Actions at T=0 & T

- Zero-temperature effective actions in proper-time integral via the gamma-function regularization [SPK, Lee, Yoon ('08), ('10); SPK ('11)]; the gamma-function & zeta-function regularization [SPK, Lee ('14)]; quantum kinematic approach [Bastianelli, SPK, Schubert, in preparation ('15)]

$$W = \pm i \sum_{\mathrm{k}} \ln \alpha_{\mathrm{k}}^{*} = \pm i \sum_{l} \sum_{\mathrm{k}} \ln \Gamma\left(a_l + i b_l(\mathrm{k})\right)$$

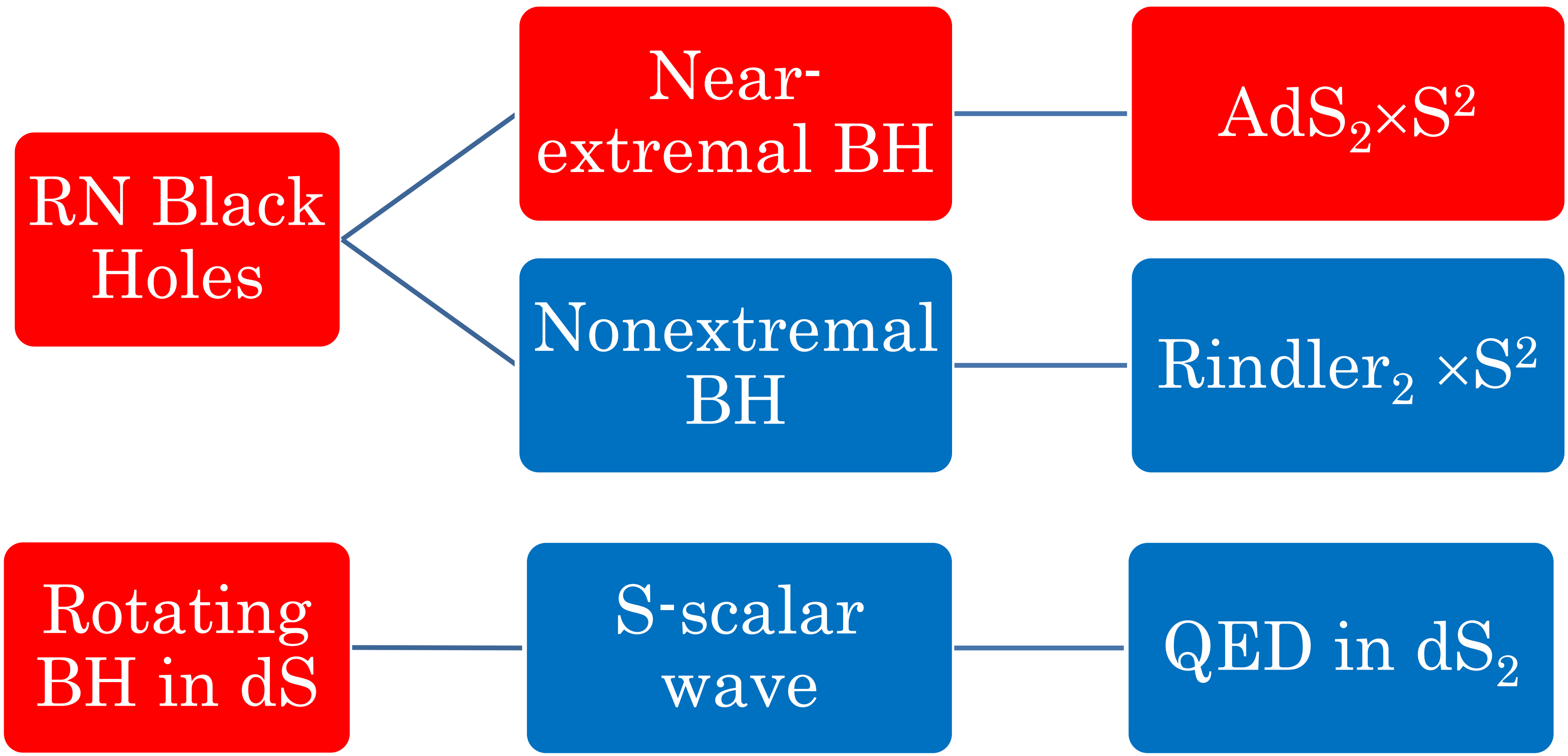
- finite-temperature effective action [SPK, Lee, Yoon ('09), ('10)]

$$\exp\left[i \int d^3x dt L_{\mathrm{eff}} \right] = \left\langle 0, \beta, \mathrm{in} \left| U^{+} \right| 0, \beta, \mathrm{in} \right\rangle = \frac{\mathrm{Tr}(U^{+} \rho_{\mathrm{in}})}{\mathrm{Tr}(\rho_{\mathrm{in}})}$$

Road to QED in Charged BHs

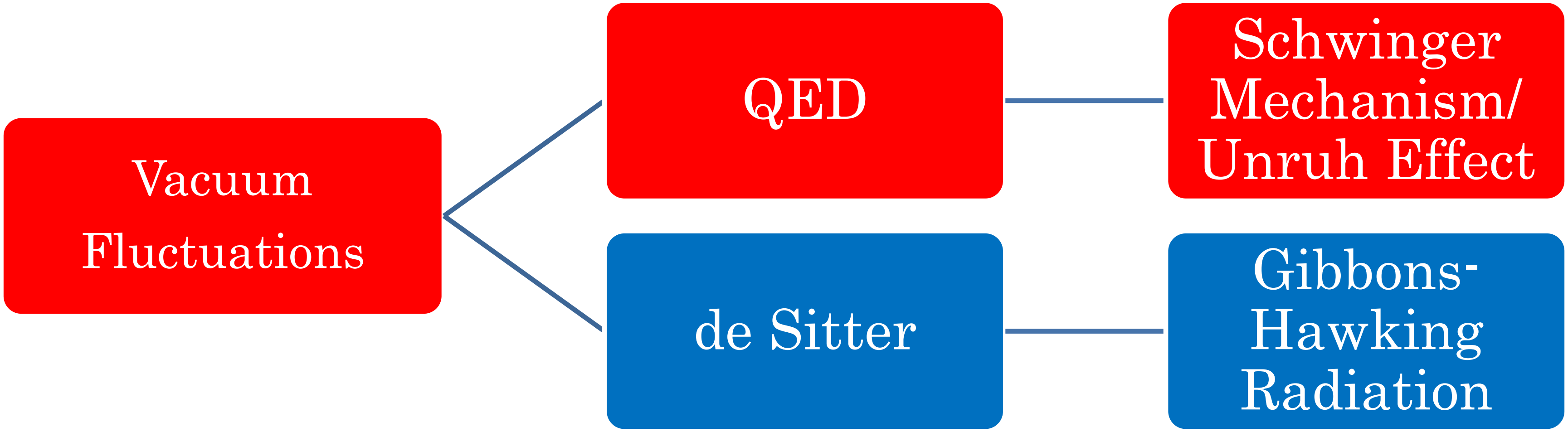
Why Schwinger Effect in (A)dS_2?

Near-Horizon Geometry of RN BHs



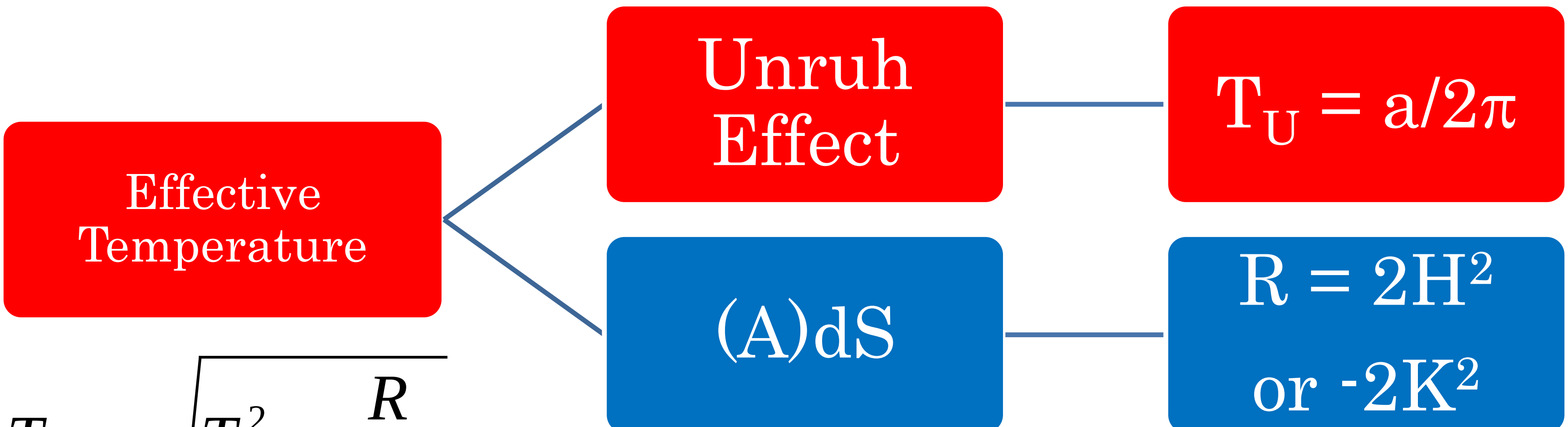
Schwinger Effect in (A)dS

[Cai, SPK ('14)]



Effective Temperature for Unruh Effect in (A)dS

[Narnhofer, Peter, Thirring (‘96); Deser, Levin (‘97)]



$$T_{\rm eff} = \sqrt{T_{\rm U}^2 + \frac{R}{8\pi^2}}$$

Schwinger formula in (A)dS

- (A)dS metric and the gauge potential for E

$$ds^2 = -dt^2 + e^{2Ht} dx^2, \quad A_1 = -(E/H)(e^{Ht} - 1)$$

$$ds^2 = -e^{2Kx} dt^2 + dx^2, \quad A_0 = -(E/K)(e^{Kx} - 1)$$

- Schwinger formula for scalars in dS_2 [Garriga ('94); SPK, Page ('08)] and in AdS_2 [Pioline, Troost ('05); SPK, Page ('08)]

$$N = e^{-S} \begin{cases} S_{dS} = \dfrac{2\pi}{H}\left[\sqrt{\left(\dfrac{qE}{H}\right)^2 + m^2 - \dfrac{H^2}{4}} - \dfrac{qE}{H}\right] \\ S_{AdS} = \dfrac{2\pi}{K}\left[\dfrac{qE}{K} - \sqrt{\left(\dfrac{qE}{K}\right)^2 - m^2 - \dfrac{K^2}{4}}\right] \end{cases}$$

Effective Temperature for Schwinger formula

- Effective temperature for accelerating observer in (A)dS [Narnhofer, Peter, Thirring ('96); Deser, Levin ('97)]

$$N = e^{-m/T_{\text{eff}}}\ , \ T_{\text{eff}} = \sqrt{T_{\text{U}}^2 + \frac{R}{8\pi^2}}\ , \ R = 2H^2(-2K^2)$$

- Effective temperature for Schwinger formula in (A)dS [Cai, SPK ('14)]

$$N = e^{-\overline{m}/T_{\text{eff}}}\ , \ \overline{m} = \sqrt{m^2 - \frac{R}{8}}\ , \ T_{\text{U}} = \frac{qE}{m}\ , \ T_{\text{GH}} = \frac{H}{2\pi}$$

$$T_{\text{dS}} = \sqrt{T_{\text{U}}^2 + T_{\text{GH}}^2} + T_{\text{U}}\ ; \ T_{\text{AdS}} = \sqrt{T_{\text{U}}^2 + \frac{R}{8\pi^2}} + T_{\text{U}}$$

Scalar QED Action in dS_2

- Pair production and vacuum polarization from the in-out formalism [Cai, SPK ('14)]

$$N_{\mathrm{dS}} = \frac{e^{-(S_\mu - S_\lambda)} + e^{-2S_\mu}}{1 - e^{-2S_\mu}}, \quad 2\,\mathrm{Im}\,W_{\mathrm{dS}}^{(1)} = \ln\left(1 + N_{\mathrm{dS}}\right)$$

$$L_{\mathrm{dS}}^{(1)} = \frac{H^2 S_\mu}{4(2\pi)^2} P\int_0^\infty \frac{ds}{s}\left[e^{-(S_\mu - S_\lambda)s/2\pi}\left(\frac{1}{\sin(s/2)} - \overbrace{\left(\frac{2}{s} + \frac{s}{12}\right)}^{\text{Schwinger subtraction}} \right) - e^{-S_\mu s/\pi}\left(\frac{\cos(s/2)}{\sin(s/2)} - \left(\frac{2}{s} - \frac{s}{6}\right)\right)\right]$$

$$S_\mu = 2\pi\sqrt{\left(\frac{qE}{H^2}\right)^2 + \left(\frac{m}{H}\right)^2 - \frac{1}{4}}, \quad S_\lambda = 2\pi\frac{qE}{H^2}$$

Scalar QED Action in AdS_2

- Pair production and vacuum polarization

$$N_{\mathrm{AdS}} = \frac{e^{-(S_\kappa - S_\nu)} - e^{-(S_\kappa + S_\nu)}}{1 + e^{-(S_\kappa + S_\nu)}}, \quad 2\,\mathrm{Im}\,W^{(1)}_{\mathrm{AdS}} = \ln\left(1 + N_{\mathrm{AdS}}\right)$$

$$L^{(1)}_{\mathrm{AdS}} = -\frac{K^2 S_\nu}{4(2\pi)^2} P\int_0^\infty \frac{ds}{s} e^{-S_\kappa s/2\pi} \cosh(S_\nu s/2\pi)\left[\frac{1}{\sin(s/2)} - \frac{2}{s} - \frac{s}{12}\right]$$

$$S_\nu = 2\pi\sqrt{\left(\frac{qE}{K^2}\right)^2 - \left(\frac{m}{K}\right)^2 - \frac{1}{4}}, \quad S_\kappa = 2\pi\frac{qE}{K^2}$$

Spinor QED Action in dS_2

- Pair production and vacuum polarization [SPK ('15)]

$$N_{\rm ds}^{\rm sp} = \frac{e^{-(S_\mu - S_\lambda)} - e^{-2S_\mu}}{1 - e^{-2S_\mu}}, \quad 2\,{\rm Im}\,W_{\rm dS}^{(1)} = -\ln\left(1 - N_{\rm ds}^{\rm sp}\right)$$

$$L_{\rm dS}^{\rm sp} = -\frac{H^2 S_\mu}{2(2\pi)^2} P\int_0^\infty \frac{ds}{s}\left(e^{-(S_\mu - S_\lambda)s/2\pi} - e^{-S_\mu s/\pi}\right)\left(\cot(\frac{s}{2}) - \frac{2}{s} + \frac{s}{6}\right)$$

$$S_\mu = 2\pi\sqrt{\left(\frac{qE}{H^2}\right)^2 + \left(\frac{m}{H}\right)^2}, \quad S_\lambda = 2\pi\frac{qE}{H^2}$$

Spinor QED Action in AdS_2

- Pair production and vacuum polarization [SPK ('15)]

$$N^{\rm sp}_{\rm AdS} = \frac{e^{-(S_\kappa - S_\nu)} - e^{-(S_\kappa + S_\nu)}}{1 - e^{-(S_\kappa + S_\nu)}}, \quad 2\,{\rm Im}\,W^{\rm sp}_{\rm AdS} = -\ln\left(1 - N^{\rm sp}_{\rm AdS}\right)$$

$$L^{\rm sp}_{\rm AdS} = -\frac{K^2 S_\nu}{2(2\pi)^2} P\int_0^\infty \frac{ds}{s}\left(e^{-(S_\kappa - S_\nu)s/2\pi} - e^{-(S_\kappa + S_\nu)s/2\pi}\right)\left(\cot(\frac{s}{2}) - \frac{2}{s} + \frac{s}{6}\right)$$

$$S_\nu = 2\pi\sqrt{\left(\frac{qE}{K^2}\right)^2 - \left(\frac{m}{K}\right)^2}, \quad S_\kappa = 2\pi\frac{qE}{K^2}$$

Bosonic or Fermionic Current in (A)dS$_2$

- Current in 2nd quantized field theory (in curved spacetime) = (2 charge: 2q) × (density of states along E: D/H) × (mean number: N)

$$J_{\rm dS} = (2q)\left(\frac{(2|\sigma|+1)HS_\mu}{4(2\pi)^2}\right)N_{\rm dS}$$

$$J_{\rm AdS} = (2q)\left(\frac{(2|\sigma|+1)KS_\nu}{4(2\pi)^2}\right)N_{\rm AdS}$$

- Consistent with the current from Frob et al (‘14); Stahl, Strobel (‘15); Stahl, Strobel, Xue (‘15) in D = 2.
- Magnetogenesis and IR hyperconductivity [Frob et al (‘14)].

Schwinger Effect in D-dimensional dS

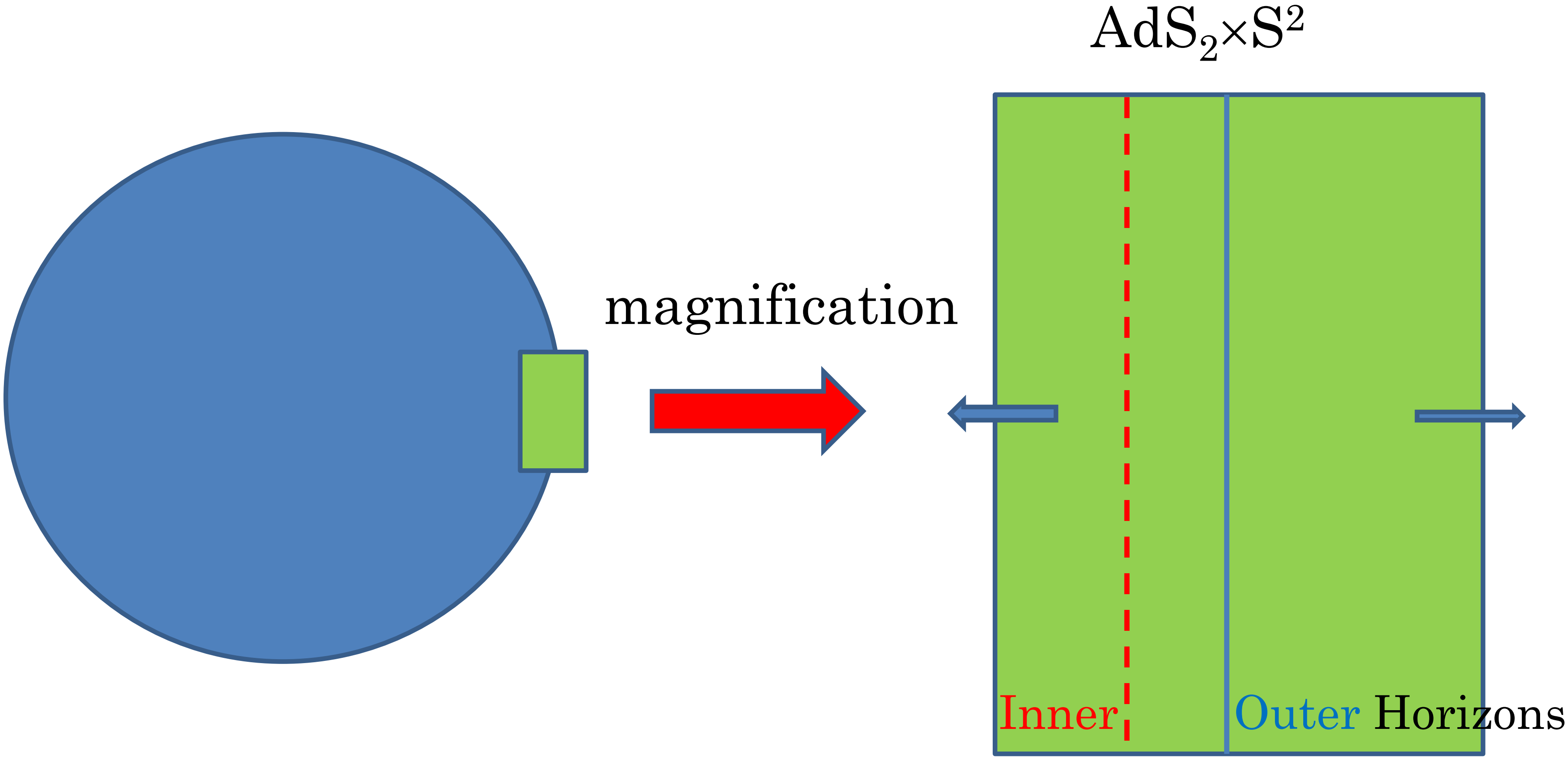
- The Schwinger effect in a constant E in a D-dimensional dS should be independent of t and $x_{\parallel}$ due to the symmetry of spacetime and the field, and the integration of $k_{\parallel}$ gives the density of states D.
- dS radiation in E=0 limit and Schwinger effect in H=0 limit

$$\frac{d^2 N_{\mathrm{dS}}}{dt dx_{\parallel}} = \frac{(2|\sigma|+1) H^2 S_{\mu}}{4(2\pi)^2} \int \frac{d^{D-2} k_{\perp}}{(2\pi)^{D-2}} \left(\frac{e^{-(S_{\mu}-S_{\lambda})} \pm e^{-2S_{\mu}}}{1-e^{-2S_{\mu}}} \right)$$

$$S_{\mu} = 2\pi \sqrt{\left(\frac{qE}{H^2}\right)^2 + \left(\frac{m}{H}\right)^2 - \left[\left(\frac{D-1}{2}\right)^2\right]}, \quad S_{\lambda} = 2\pi \frac{qE}{H^2} \left(\frac{qE/H}{\sqrt{(qE/H)^2 + \vec{k}_{\perp}^2}} \right)$$

Schwinger Effect in Near-Extremal Charged Black Hole

Near-Horizon Geometry of RN BH



G. t'Hooft & A. Strominger, "conformal symmetry near the horizon of BH," MG14, July 2015.

Near-Horizon Geometry

- Charged RN black hole: metric and potential

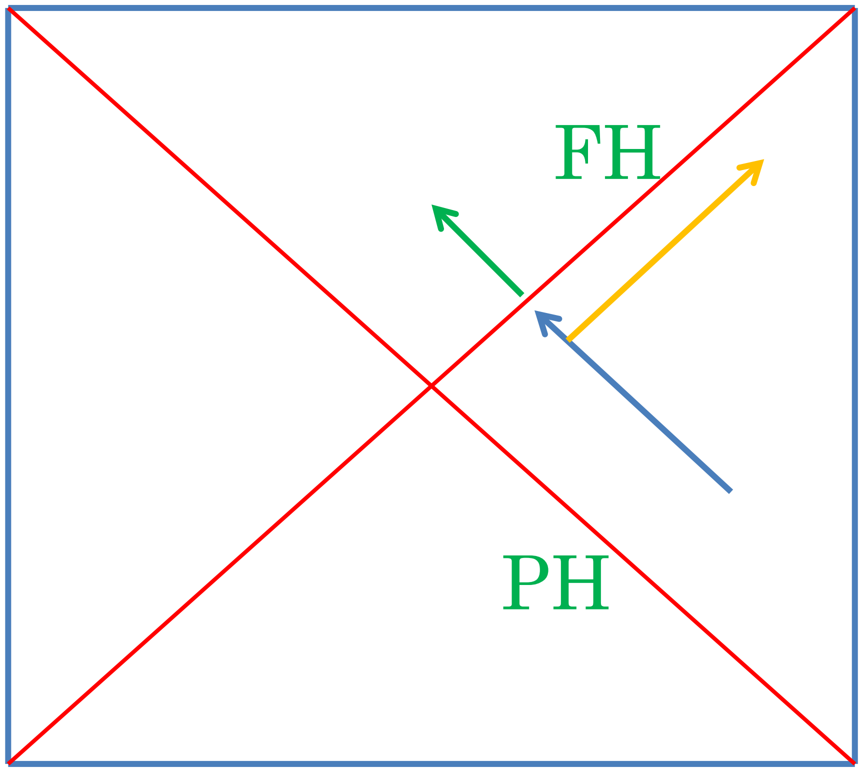
$$ds^2 = -f(r)dt^2 + \frac{dr^2}{f(r)} + d\Omega_2^2, \quad f(r) = 1 - \frac{2M}{r} + \frac{Q^2}{r^2}, \quad A_0 = \frac{Q}{r}$$

- Near-horizon geometry $AdS_2 \times S^2$ of near-extremal BH [Bardeen, Horowitz ('99)]

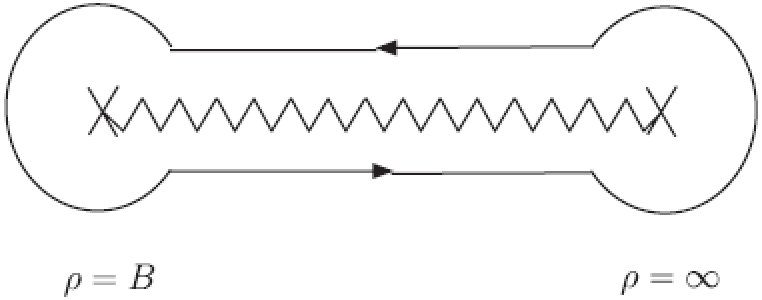
$$ds^2 = -\frac{\rho^2 - B^2}{Q^2} d\tau^2 + \frac{Q^2}{\rho^2 - B^2} dr^2 + Q^2 d\Omega_2^2,$$

$$r - Q = \varepsilon Q, \; t = \frac{\tau}{Q}, \; M - Q = \frac{(\varepsilon B)^2}{2Q}$$

Vacua for QED in AdS



- Boundary condition for quantum field for Schwinger effect in $AdS_2 \times S^2$
- Hamilton-Jacobi equation (or phase integral) $e^{-i\omega t} e^{iS(\rho)} Y_{lm}(\vartheta, \varphi)$



Hawking Radiation vs Schwinger Effect

- Hawking radiation (pole at outer horizon) suppressed:

$$N_H = e^{-\frac{\omega - qA_0}{T_H}}, \quad T_H = \frac{\sqrt{1/2 + M/2Q}}{4\pi\left(M + \varepsilon B\sqrt{1/2 + M/2Q}\right)^2}\varepsilon B$$

- Schwinger formula for charged scalars and fermions in spherical harmonics (poles at outer horizon and infinity) [Chen et al ('12); ('15)]

$$N_{NBH} = \left(\frac{e^{-S_a + S_b} - e^{-S_a - S_b}}{1 \pm e^{-S_a - S_b}}\right) \times \left(\frac{1 \mp e^{-S_c + S_a}}{1 + e^{-S_c + S_b}}\right),$$

$$S_a = 2\pi q Q, \quad S_b = 2\pi\sqrt{(q^2 - m^2)Q^2 - (l + 1/2)^2}, \quad S_c = 2\pi\frac{\omega Q^2}{B}$$

Interpretation of Schwinger Effect

- Thermal interpretation of Schwinger formula for charged scalars (upper signs) and fermions (lower signs) in spherical harmonics [SPK, Lee, Yoon ('15)]

$$N_{NBH} = \left(\frac{e^{-\frac{\bar{m}}{T_{RN}}} - e^{-\frac{\bar{m}}{\bar{T}_{RN}}}}{1 \pm e^{-\frac{\bar{m}}{\bar{T}_{RN}}}} \right) \times \left(\frac{1 \mp e^{-\frac{\omega - qA_0}{T_H}}}{1 + e^{-(\frac{\omega - qA_0}{T_H} + \frac{\bar{m}}{T_{RN}})}} \right),$$

$$T_{RN} = T_U + \sqrt{T_U^2 - (\frac{1}{2\pi Q})^2}, \quad \bar{T}_{RN} = T_U - \sqrt{T_U^2 - (\frac{1}{2\pi Q})^2}$$

$$T_U = \frac{qE_H / \bar{m}}{2\pi} = \frac{q}{2\pi \bar{m} Q}$$

Schwinger Effect and Hawking Radiation

- Thermal interpretation of Schwinger formula for charged scalars and fermions [SPK, Lee, Yoon ('15); SPK ('15)]

$$N_{NBH} = e^{\frac{\bar{m}}{T_{RN}}} \times \underbrace{\left(\frac{e^{-\frac{\bar{m}}{T_{RN}}} - e^{-\frac{\bar{m}}{\bar{T}_{RN}}}}{1 \pm e^{-\frac{\bar{m}}{\bar{T}_{RN}}}} \right)}_{\text{Schwinger Effect in AdS}_2} \times \underbrace{\left(\frac{e^{-\frac{\bar{m}}{T_{RN}}} \left(1 \mp e^{-\frac{\omega - qA_0}{T_H}}\right)}{1 + e^{-\frac{\omega - qA_0}{T_H}} e^{-\frac{\bar{m}}{T_{RN}}}} \right)}_{\text{Schwinger Effect in Rindler Space}}$$

Schwinger Effect in AdS_2
Cai & SPK JHEP ('14)

Schwinger Effect in Rindler Space
Gabriel & Spindel AP ('00)
Hawking Radiation of charges

Scalar QED Action in BH

- Vacuum polarization and persistence

$$W_{\rm sc}^{(1)} = -\sum_l (2l+1) P \int_0^\infty \frac{ds}{s} e^{-S_a s/2\pi} \sinh\left(\frac{S_b s}{2\pi}\right)\left(\frac{1}{\sin(s/2)} - \frac{2}{s} - \frac{s}{12}\right)$$

$$-\sum_l (2l+1) P \int_0^\infty \frac{ds}{s} e^{-S_c s/2\pi} \sinh\left(\frac{S_b s}{2\pi}\right)\left(\frac{1}{\sin(s/2)} - \frac{2}{s} - \frac{s}{12}\right)$$

$$2\,{\rm Im}\,W_{\rm sc}^{(1)} = \sum_l (2l+1) \ln\left(1 + N_{\rm sc}\right)$$

Spinor QED Action in BH

- Vacuum polarization and persistence

$$W_{\rm sp}^{(1)} = \sum_l (2l+1) P \int_0^\infty \frac{ds}{s} e^{-S_a s/2\pi} \sinh\left(\frac{S_b s}{2\pi}\right)\left(\frac{\cos(s/2)}{\sin(s/2)} - \frac{2}{s} + \frac{s}{6}\right)$$

$$+ \sum_l (2l+1) P \int_0^\infty \frac{ds}{s} e^{-S_c s/2\pi} \sinh\left(\frac{S_b s}{2\pi}\right)\left(\frac{1}{\sin(s/2)} - \frac{2}{s} - \frac{s}{12}\right)$$

$$2\,{\rm Im}\, W_{\rm sp}^{(1)} = -\sum_j (2j+1) \ln\left(1 - N_{\rm sp}\right)$$

Extremal Micro-BH, Extremal BH Entropy & Evolution

Micro-BH stable in QFT

- Breitenlohlner-Freedmann (BF) bound for boson (fermion) stability in AdS_2

$$\left(\frac{qE}{K}\right)^2 \leq m^2 + \left[\frac{K^2}{4}\right]$$

- Compton wavelength of charge ≥ horizon of extremal BH
  - Pairs cannot be created near the horizon (no Schwinger effect).
  - Extremal black holes emit neither Hawking radiation nor Schwinger pairs up to $\frac{l_{Pl}}{\sqrt{\alpha}}$.
  - Oppositely charged extremal BHs may form black atoms and remnants from Planckian regime.
  - Caveat: belongs to quantum gravity regime (loop gravity may check this).

Entropy of Extremal BH

- Hawking temperature of extremal BH, $T_H = \kappa/2\pi = 0$.
- But, all black holes have the entropy $S_{BH} = A/4$.
- Black hole thermodynamics $dM = (\kappa/8\pi)dA + \Phi_H dQ$ gives a null result: $dM = dQ$ since $\Phi_H = 1$.
- A question at ICGC & 4th GX [KITPC, Beijing ('15)] was whether the effective temperature T_{CK} gives the area-law and the answer is [SPK ('15)]

$$S_{BH} = \left(\frac{m}{e}\right) \times \left(\frac{A}{4}\right)$$

- Rong-Gen Cai opposed against this entropy since the Schwinger process is particle-dependent (m/e) while thermodynamics should rest on environmental quantities.

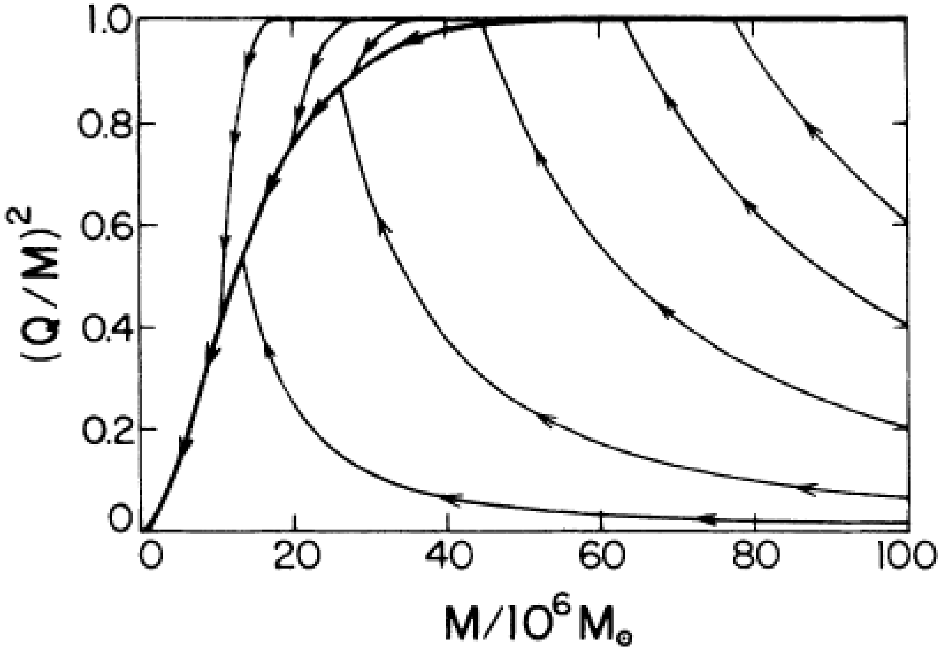
Evolution of RN BH
[Hiscock, Weems ('90)]

- Charge-loss rate? (Schwinger formula)

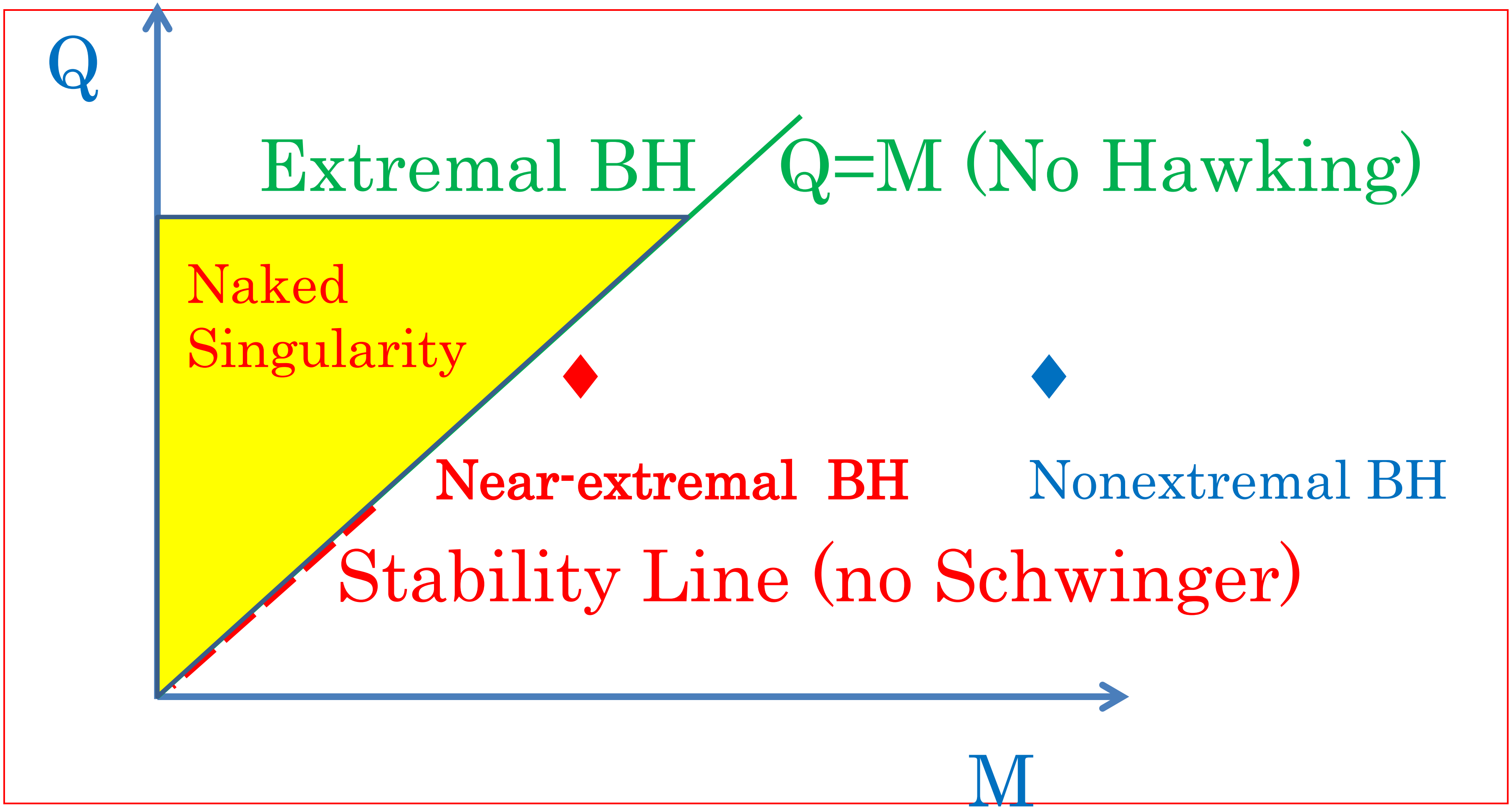
$$\frac{dQ}{dt} = -\frac{q^3}{\pi^2 r_H} \exp\left[-\frac{\pi m^2}{qQ/r_H^2}\right]$$

- Total rate of mass loss

$$\frac{dM}{dt} = -aT_H^4 \alpha \sigma_0 + \underbrace{\frac{Q}{r_H}\frac{dQ}{dt}}_{??}$$



Evolution of RN BH



Conclusion

- The production of charged particles from an RN black hole shows a strong interplay of the Schwinger effect and the Hawking radiation and has a thermal interpretation.
- Micro-black holes emit neither the Schwinger emission nor Hawking radiation and are stable due to BF bound for extremal black holes up to $l_{Pl}/\sqrt{\alpha}$ (quantum gravity models may check.)
- The vacuum polarization of QED in (A)dS and near-extremal RN black hole exhibits the gravity-gauge relation (or AdS/CFT).
- The evolution and phase diagram of RN black holes should properly include the Schwinger effect.
- The Schwinger effect in non-extremal black holes (Cai, SPK, in preparation.)

CosPA 2015

- When: October 12-16, 2015
- Where: KAIST, Daejeon, Korea
- **Plenary Speakers:**

Martin Bucher, Asantha Cooray, Daniel Eisenstein, Raphael Flauger, Xiao-Gang He, Christopher Hirata, Donghui Jeong, Xiangdong Ji, Yeongduk Kim, Hye-Sung Lee, Simona Murgia, Hans Peter Nilles, Carsten Rott, Yannis K. Semertzidis, Gary Shiu, Yi Wang, Yvonne Wong, Jun'ichi Yokoyama, Yu-Feng Zhou

- **International Organizing Comittee**

Pisin Chen, Kiwoon Choi, Richard Easther, Xiao-Gang He, Pauchy W-Y Hwang, Bo-Qiang Ma, Sandip Pakvasa, Raymond Volkas, David Wilshire, Jun'ichi Yokoyama

*Kiwoon Choi (Chair), Sang Pyo Kim (Cochair)