Accelerating Plasma Mirrors to Investigate Black Hole Information Loss Paradox

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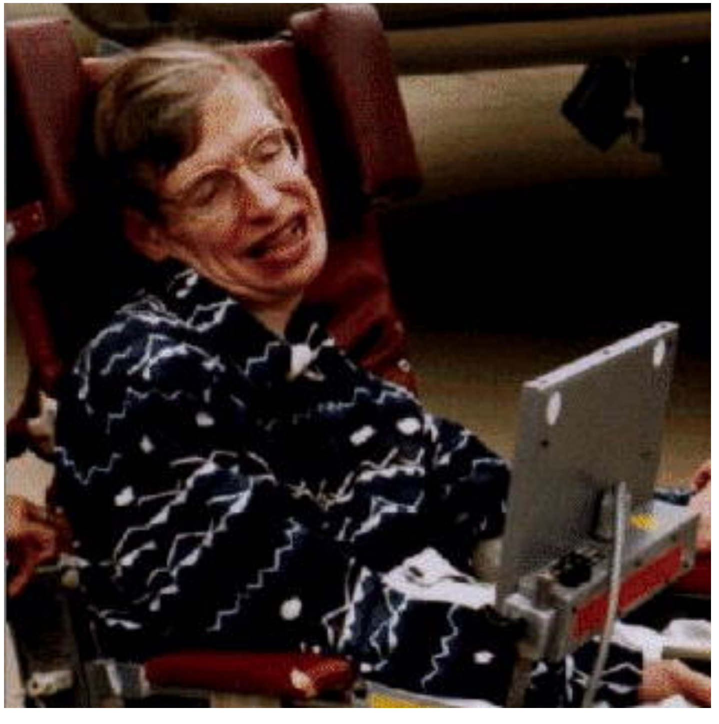
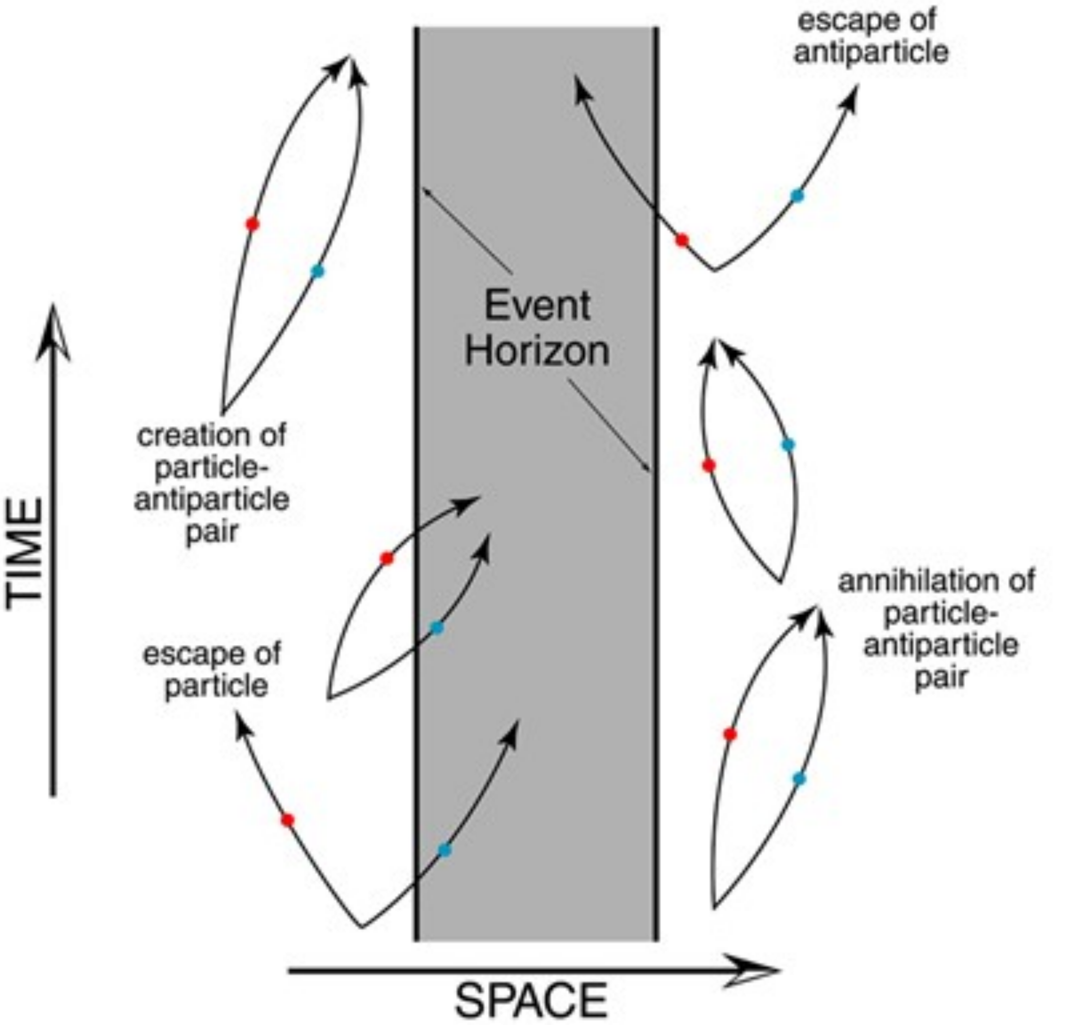
Black hole Hawking evaporation – Connecting GR, QM, SM in one stroke

$$r_s = \frac{2GM}{c^2} \qquad g = \frac{GM}{r_s^2}$$

$$k_B T_H = \frac{\hbar c^3}{8\pi GM} = \frac{\hbar g}{2\pi c}$$



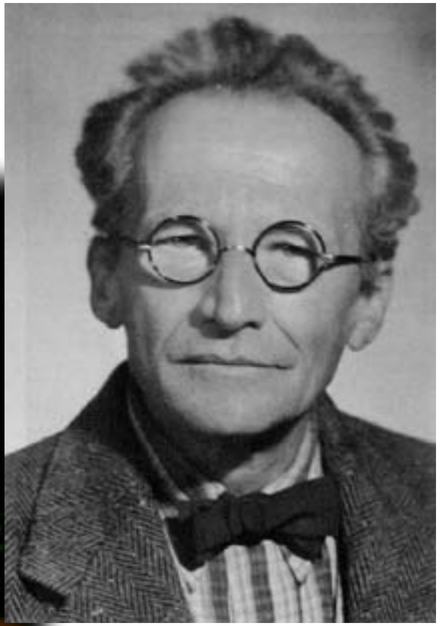


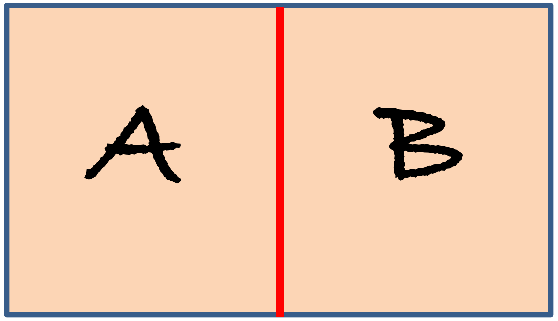
Hawking evaporation may result in the loss of information!

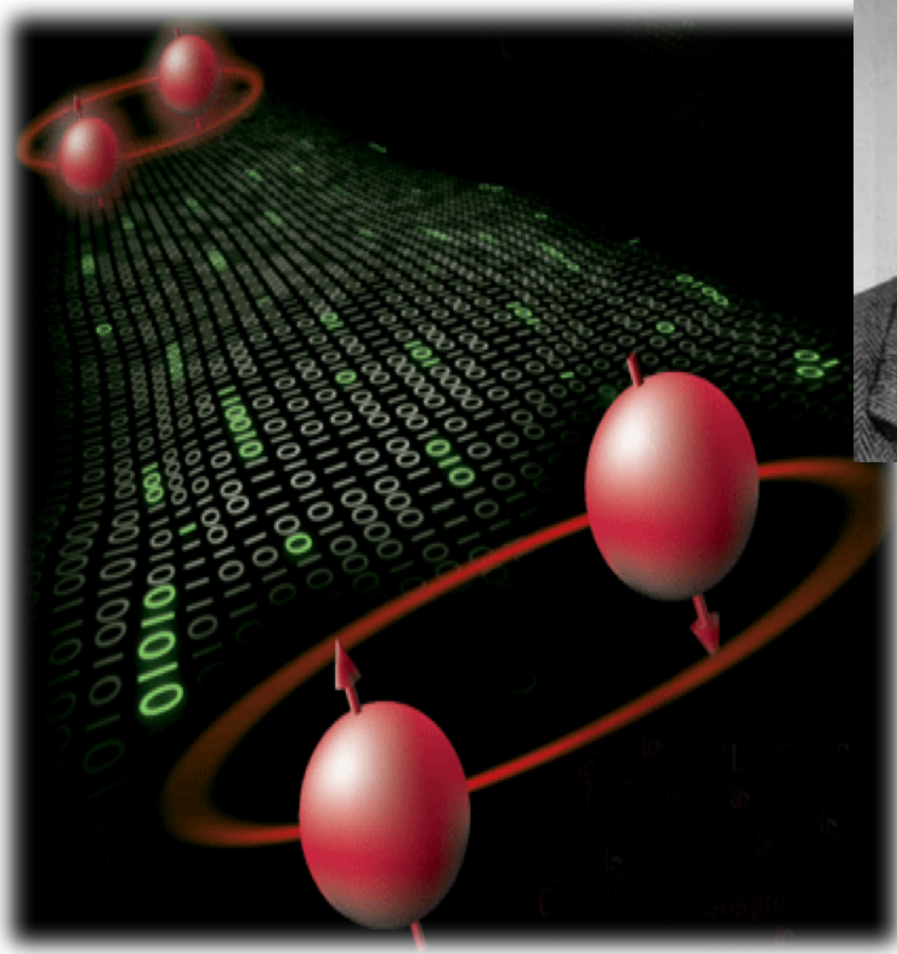
- First pointed out by Hawking himself in 1976
- Endless debates ever since
- Solutions include "black hole complementarity" (Susskind et al.), Firewall (AMPS, AMPSS), etc.
- Entanglement between Hawking radiation and partner particles Wilczek 1987, Schutzhold-Unruh 2010, Hotta-Schutzhold-Unruh (2015)
- Planck size black hole remnants (Chen-Ong-Yeom, Phys. Rep.2015)
- Naked black hole firewalls (Chen-Ong-Page-Sasaki-Yeom, PRL 2016)
- BMS Soft Hairs (Hawking-Perry-Strominger, 2016)
- No firewalls & nothing wrong w. information loss (Unruh-Wald 2017)
- An alternative hairdo based on Kac-Moody symmetry (Addazi-Chen-Marciano-Wu, 2017)

Quantum entanglement

Schrödinger: "*Verschrankung*" (1935) as a result of discussing with Einstein

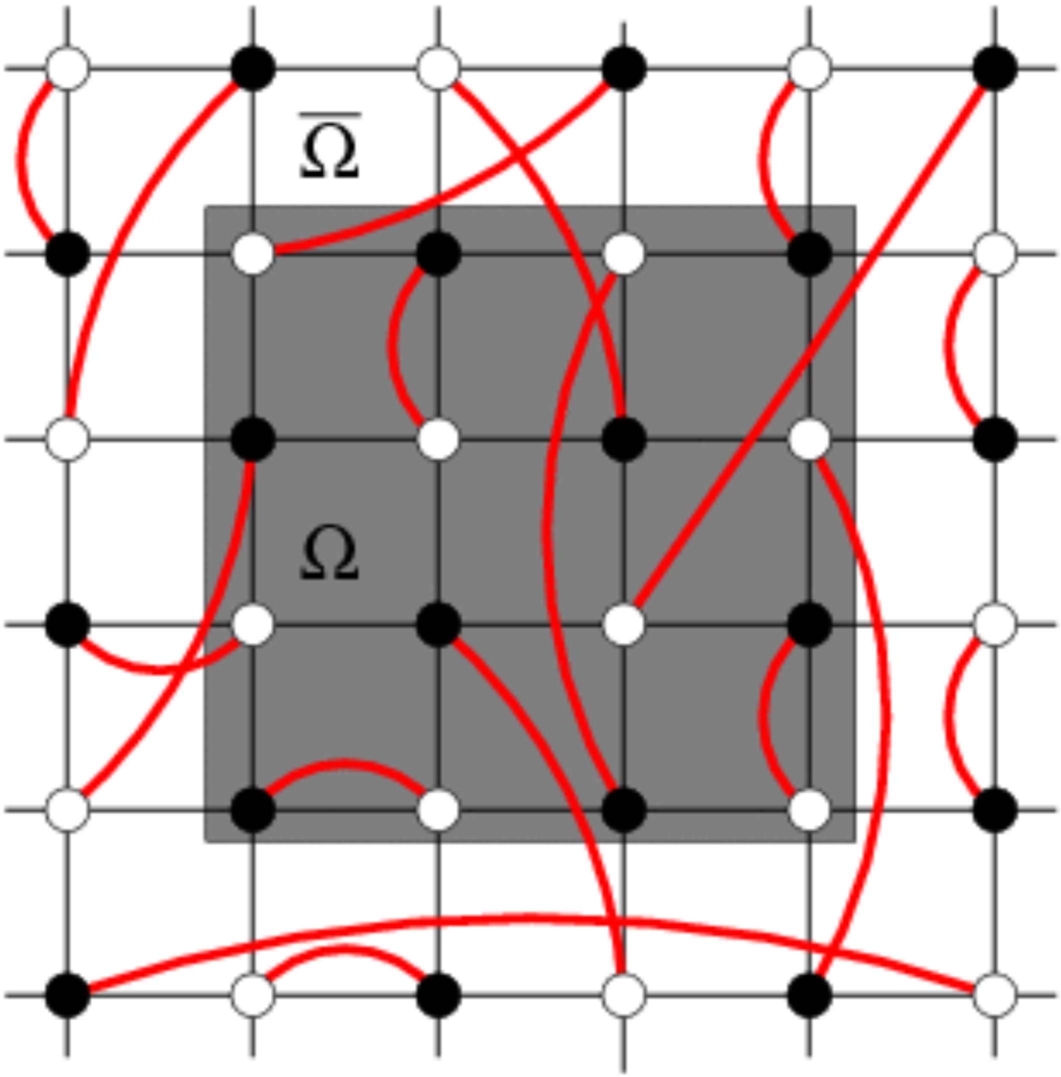






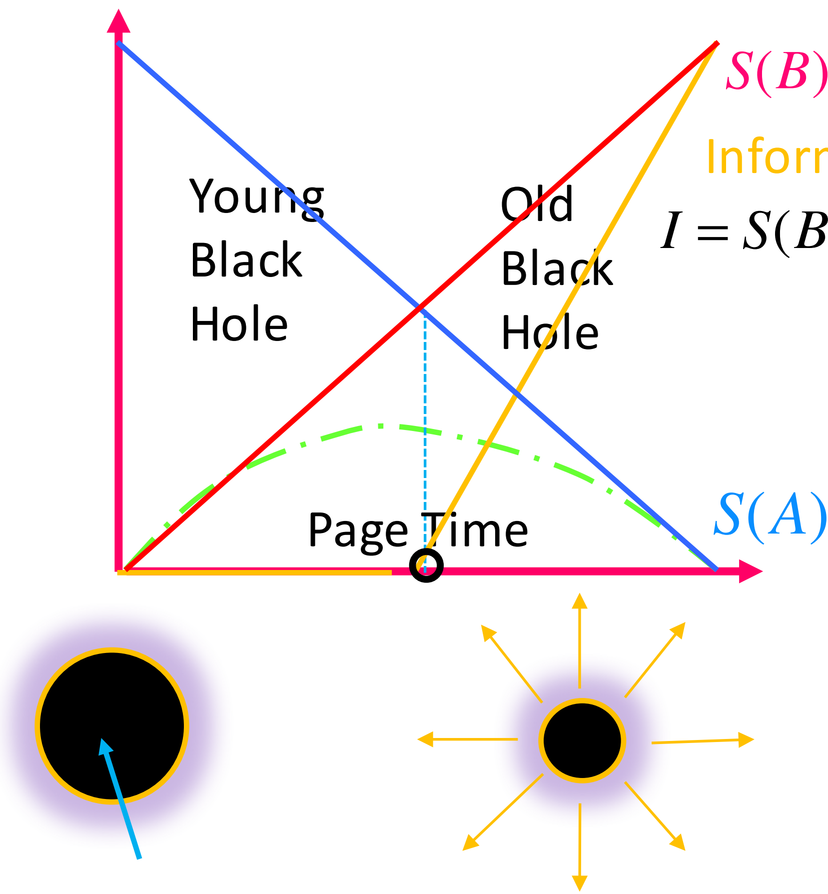
"Quantum entanglement is not just a property of QM, it is THE character of QM. It fundamentally breaks QM from classical physics." (E. Schrodedinger)

Monogamy of quantum entanglement



When would BH information come out?

$$S(A \cup B) = \log N = const$$



Information

$$I = S(B) - S(B|A)$$

$$S(B) = \log m$$

$$S(B|A) = \sum_{k=n+1}^{mn} \frac{1}{k} - \frac{m-1}{2n}$$

(For a pure and random system, Conjectured by Page, 1993; proved by Sen, 1996.)

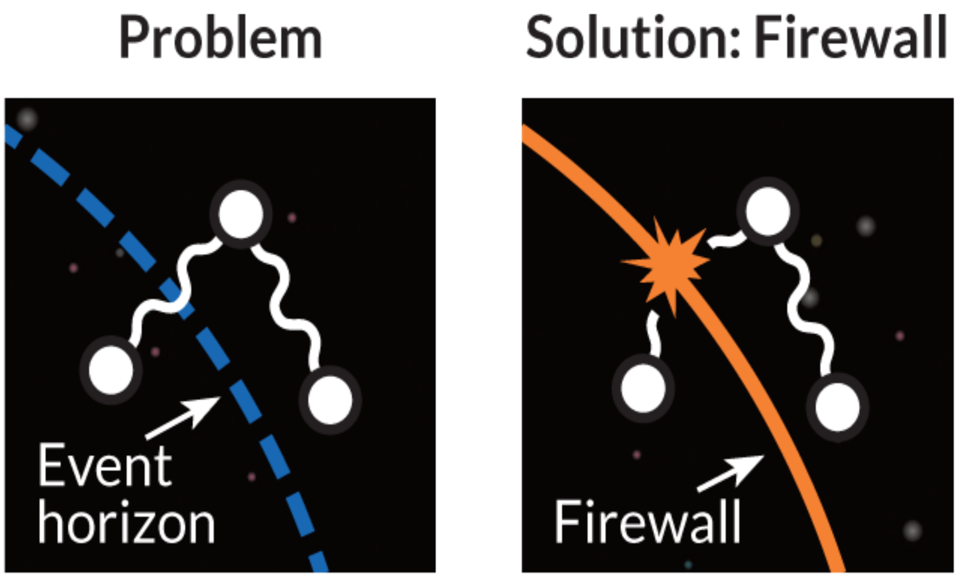
If $S(A) \propto Area$, then the information will come out when the black hole initial area decreases to half value. This is called the Page time.

In 2012, four physicists (AMPS) argued that the 3 basic assumptions that led to the BH complementarity principle, namely,

1. Unitarity
2. Local quantum field theory
3. No drama

cannot be all consistent. They suggested that the "most conservative" solution would be that there exists a firewall on the BH surface, anything falls into BH would be burned into ashes.

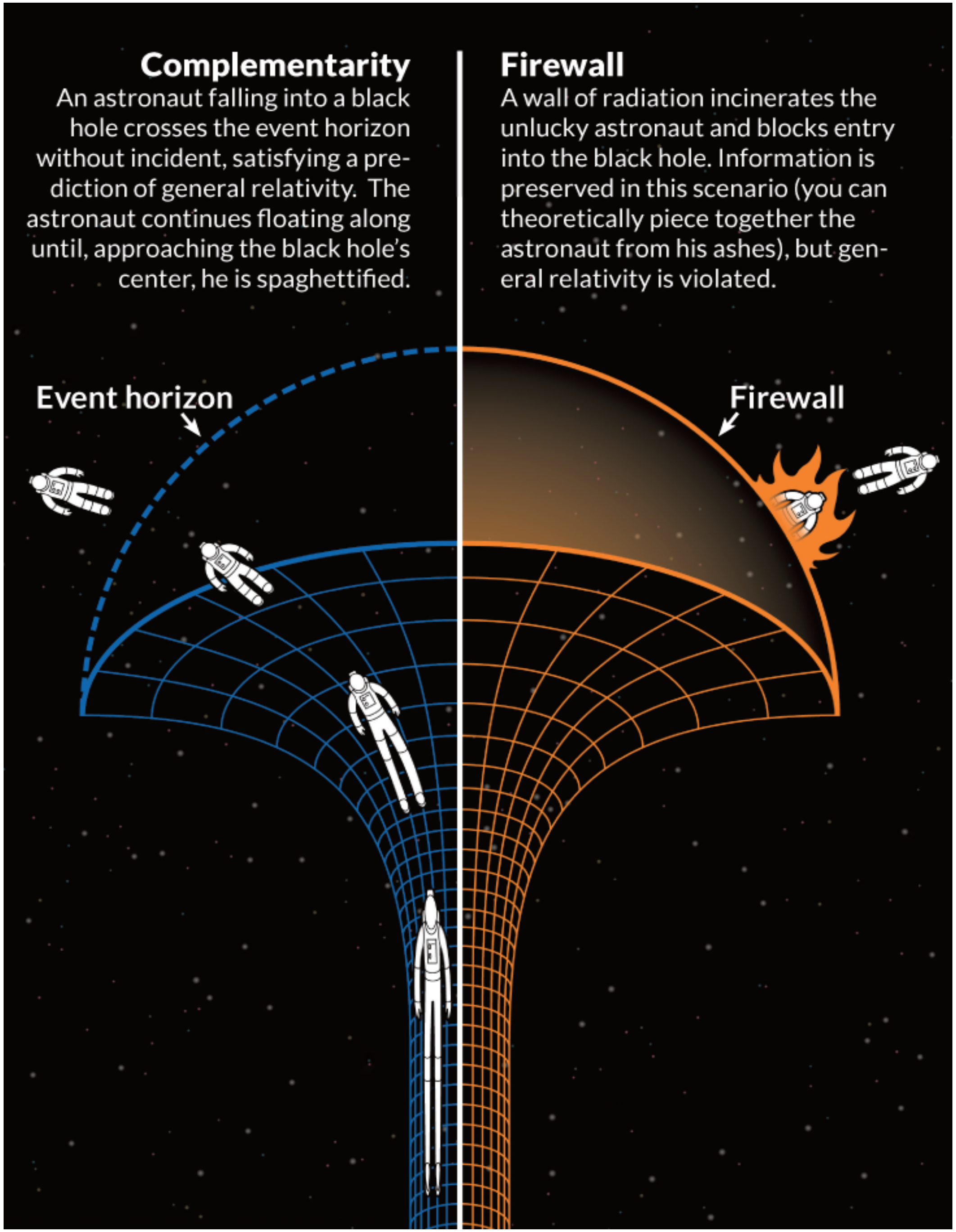
AMPS black hole firewall



- Ahmed Almheiri, Donald Marolf, Joseph Polchinski, James Sully, "Black Holes: Complementarity or Firewalls?",
- Ahmed Almheiri, Donald Marolf, Joseph Polchinski, Douglas Stanford, James Sully, "An Apologia for Firewalls",

The intensity of a quantum field is Determined by the rate of change of the field

For disconnected spacetimes, the magnitudes of the quantum field need not be continuous.



General relativity:

For a sufficiently large BH, whose curvature is small, objects should pass its horizon uneventfully — "No Drama"

AMPS firewall:

The requirement that Hawking radiation can bring information out from BH would result in the notion of firewall.

Yukawa Institute of Theoretical Physics, Kyoto University

The five authors of the paper with another colleague during the discussion at the Yukawa Institute for Theoretical Physics: (L to R) Dong-han Yeom, Yen Chin Ong, Pisin Chen, Don Page, Yasusada Nambu, and Misao Sasaki.

Chen-Ong-Page-Sasaki-Yeom: Why should firewalls be naked?

Phys. Rev. Lett. 116, 161304 (2016)

- Quantum fluctuations in Hawking radiation inevitable
- BH's backreaction to the quantum fluctuations leads to the exposure of the event horizon.
- Curvature of stellar-size BHs small, so GR should be satisfied
- Firewalls conjecture is not a conservative solution to the information paradox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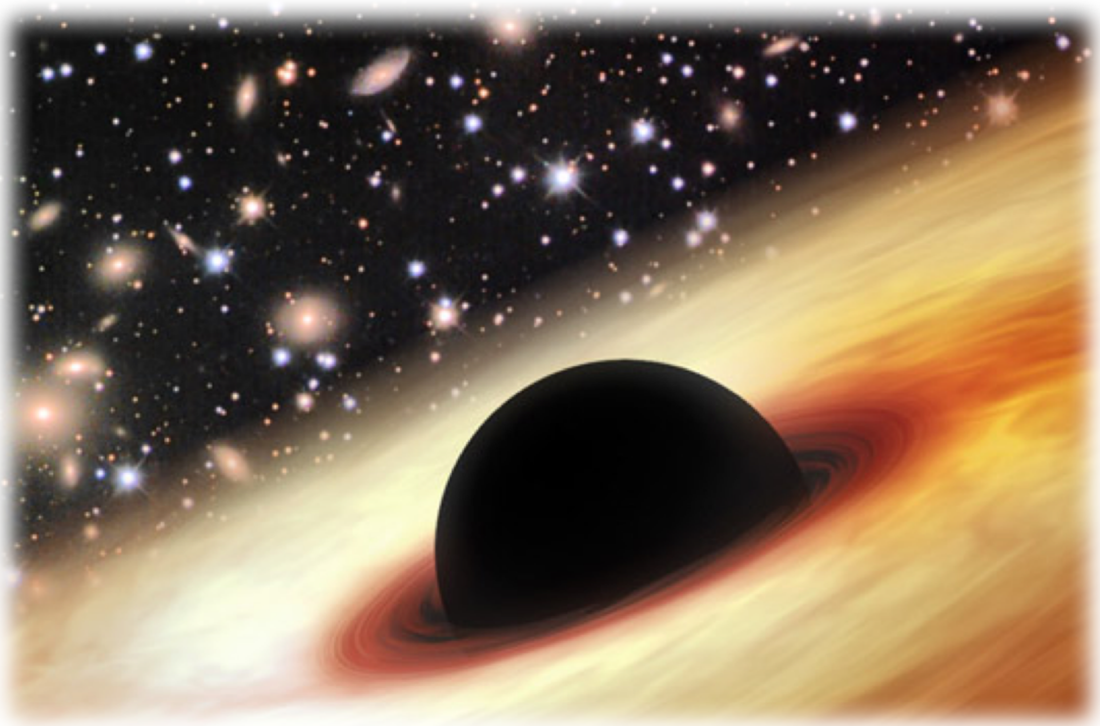
Investigations of ILP mostly theoretical
Astro black holes too cold and too young

Lifetime of solar mass BH: 10^{67} years
Age of the universe: 1.38×10^{10} years



Analog Black Holes

- Sound waves in moving fluids – "dumb holes"
  Unruh (1981, 1995)
- Traveling index of refraction in media
  Yablonovitch (1989)
- Violent acceleration of electron by lasers
  Chen-Tajima (1999)
- Electromagnetic waveguides
  Schutzhold-Unruh (2005)

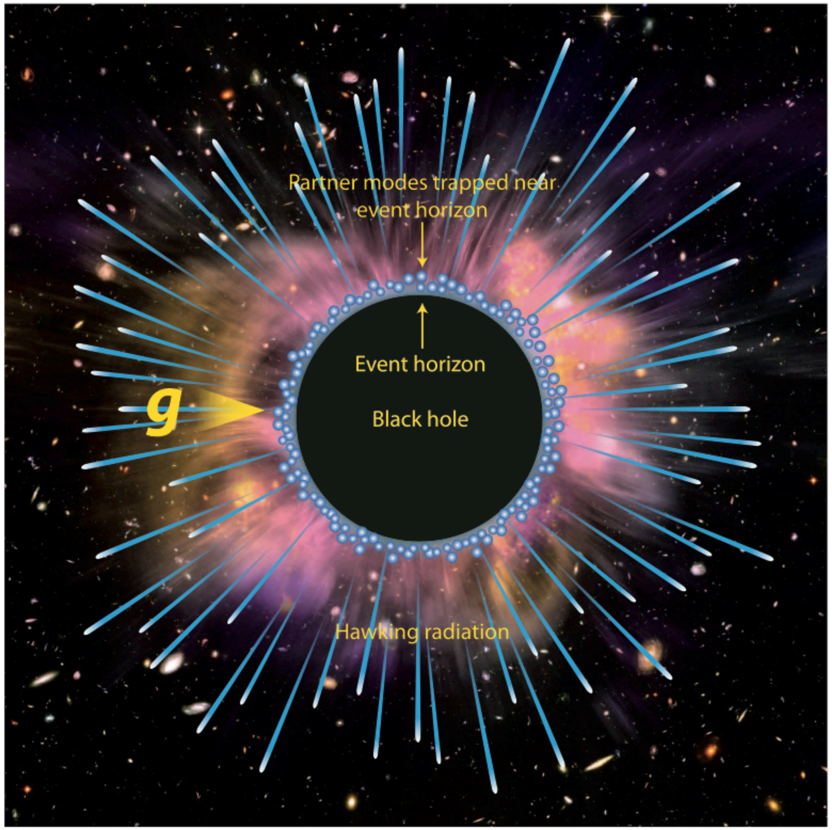
} Testing thermal nature of Hawking radiation

- Bose-Einstein condensate
  Steinhauer (2014)
- Accelerating mirror
  Fulling-Davies (1976), Davies-Fulling-Unruh (1977), Birrell-Davies (1982), Carlitz-Willey (1987), Hotta-Schutzhold-Unruh (2015), Chen-Mourou (2016), Chen-Yeom (2017)

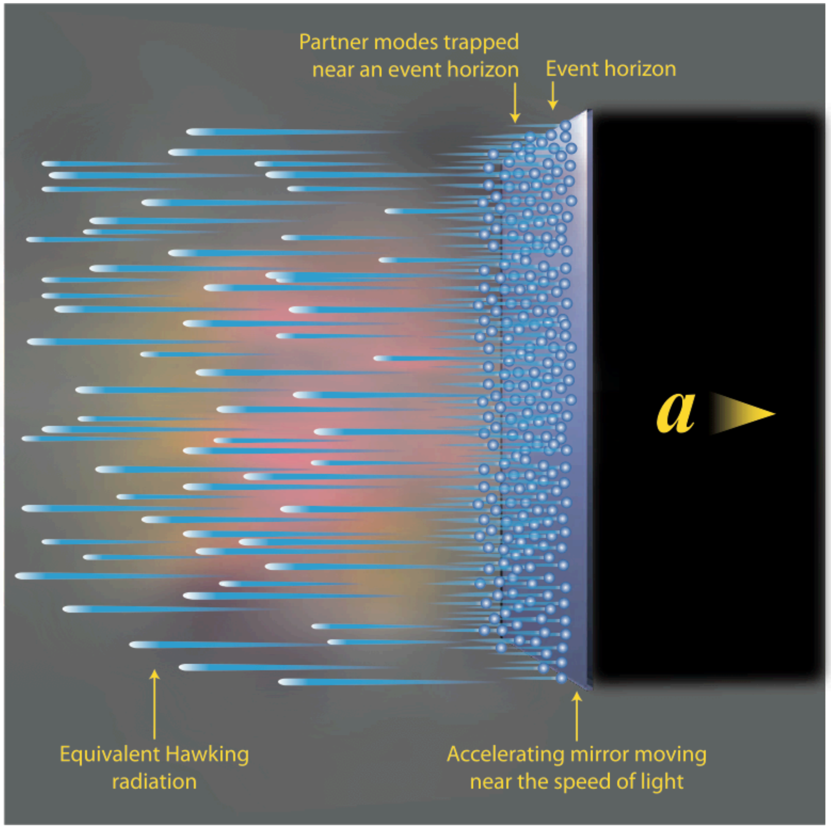
Accelerating mirror as an analog black hole

SIMULATING A BLACK HOLE ON A TABLE

New black hole simulator may shed more light on a contradiction in fundamental physics

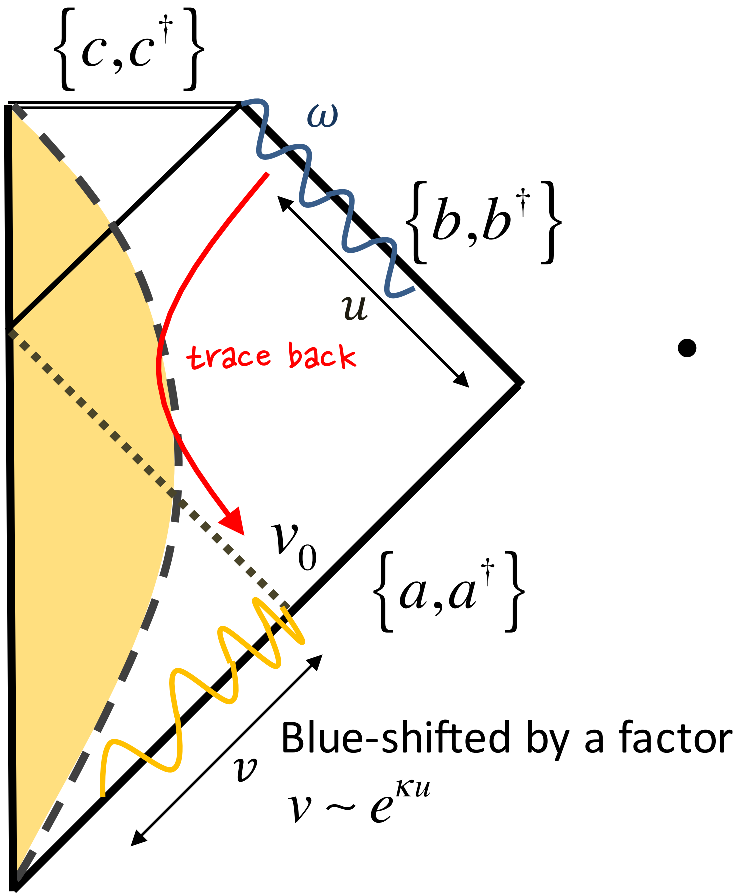


Black hole Hawking evaporation



Accelerating mirror as an analog black hole

Why is there a radiation?



- Hawking radiation is theoretically estimated by using the Bogoliubov transformation.

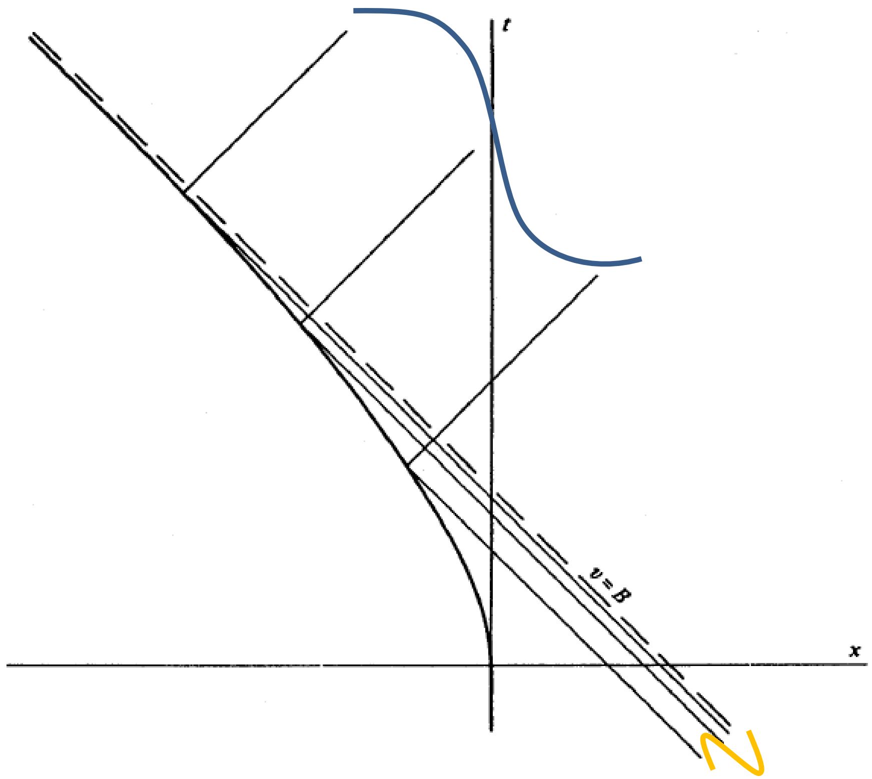
$$\langle n_\omega \rangle = \langle b_\omega^\dagger b_\omega \rangle = \sum_{\omega'} |\beta_{\omega\omega'}|^2$$

- A non-trivial Bogoliubov transformation is possible due to the **red-shift** of incoming modes by the horizon of a black hole.

$$p_\omega \sim e^{i\omega\kappa^{-1} \ln[(v_0 - v)/c]} \qquad (v > v_0)$$

$$= \sum_{\omega'} \left[\alpha_{\omega\omega'} f_{\omega'} + \beta_{\omega\omega'} f_{\omega'}^* \right]$$

Red-shift by a mirror

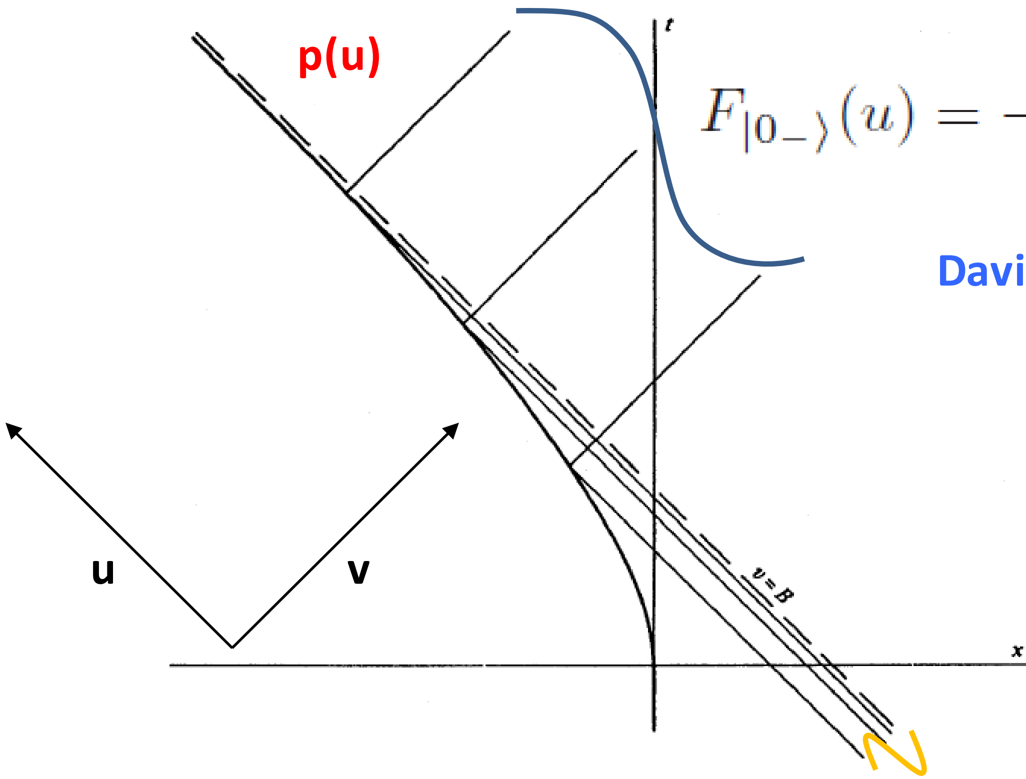


Fulling and Davies, 1976

Birrell and Davies, 1982

- **A moving mirror** is a surface that satisfies a reflecting boundary condition.
- If the mirror is moving with a constant acceleration, then it generates a thermal radiation.

Red-shift by a mirror

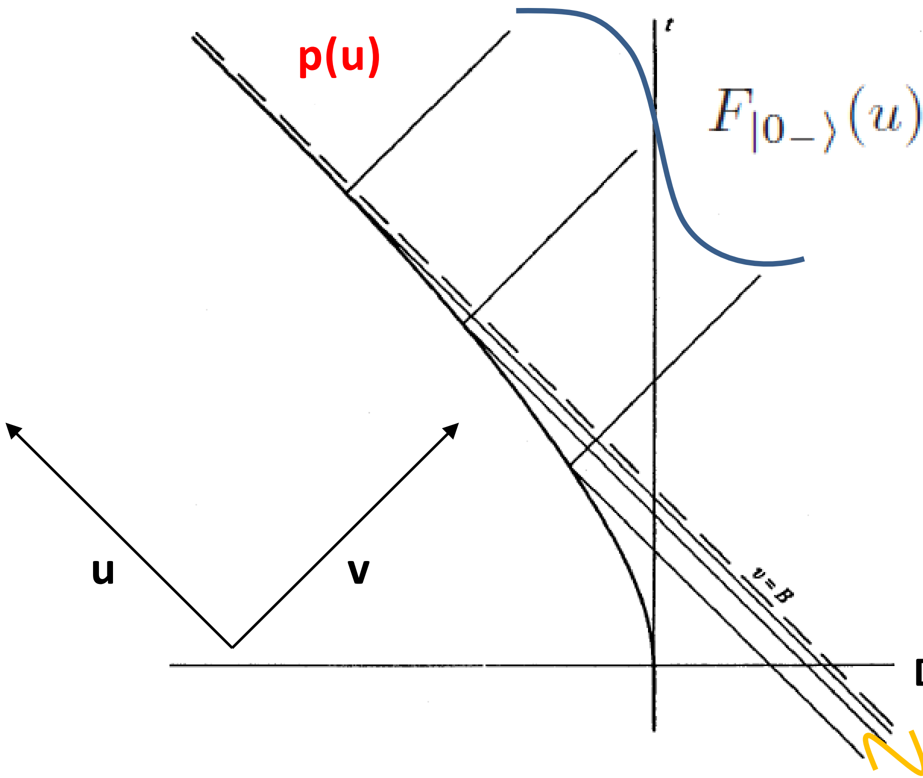


$$F_{|0_-\rangle}(u) = -\frac{c}{24\pi}\left(\frac{\dddot{p}(u)}{\dot{p}(u)} - \frac{3}{2}\frac{\ddot{p}(u)^2}{\dot{p}(u)^2}\right)$$

Davies, Fulling and Unruh, 1976

- One can calculate the **out-going energy flux** as a function of the mirror trajectory (for 2D spacetime).

Is there information loss?

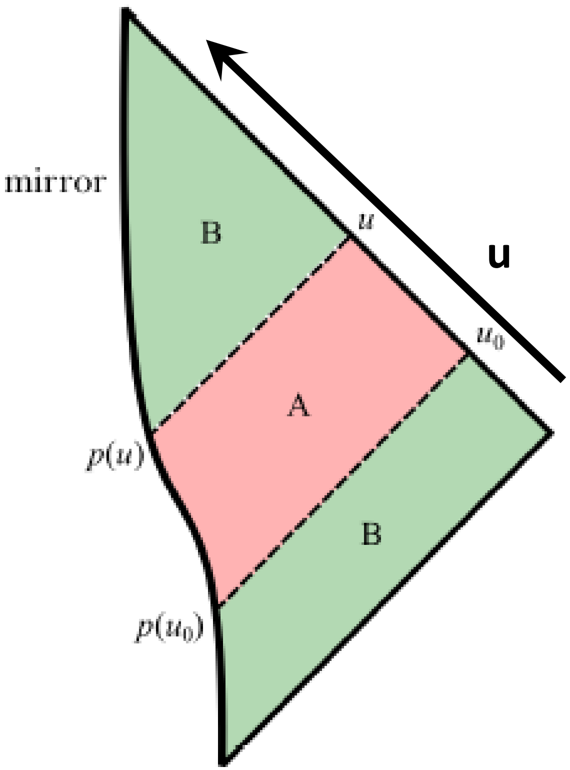


$$F_{|0_-\rangle}(u) = -\frac{c}{24\pi}\left(\frac{\dddot{p}(u)}{\dot{p}(u)} - \frac{3}{2}\frac{\ddot{p}(u)^2}{\dot{p}(u)^2}\right)$$

Davies, Fulling and Unruh, 1976

- Definitely, there should be no information loss in the mirror dynamics.
- Then what can we learn from the **entanglement entropy**?

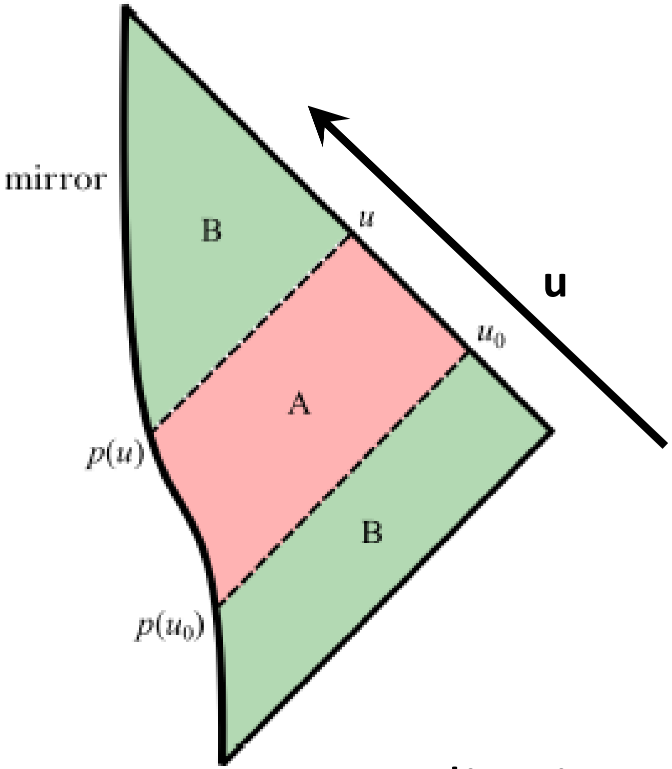
Entanglement entropy



$$S^{\epsilon}_{|0_+\rangle}(A) = \frac{c}{12} \log \frac{(u-u_0)^2}{\epsilon^2}$$

- In order to apply Page's argument, one can calculate the entanglement entropy as a function of u.
- In order to obtain a finite result, we need a **renormalization** of the cutoff .

Entanglement entropy formula



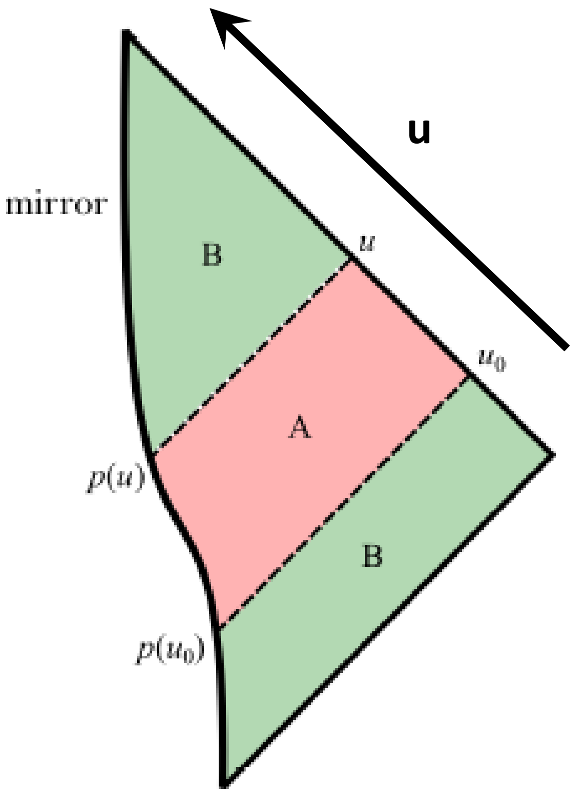
$$S(u) = -\frac{c}{12} \log \dot{p}(u)$$

- After a proper renormalization, we obtain the formula (Holzhey, Larsen and Wilczek, 1994; Bianchi and Smerlak, 2014).
- Several authors have tested the consistency of this paper, e.g., Abdolrahimi and Page, 2015.

Mirror trajectories

P Chen, D-h Yeom, “Entropy evolution of moving mirrors and the information loss problem”, arXiv:1704.08613 (Accepted for publication PRD)

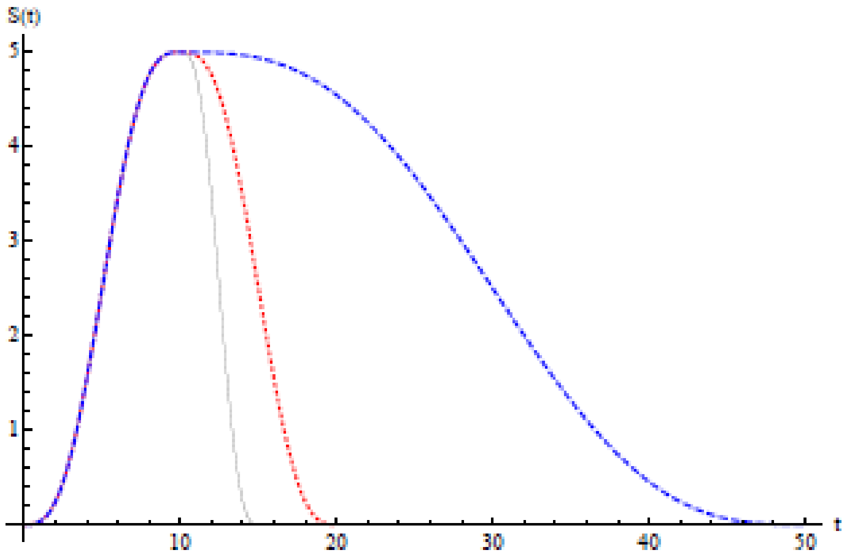
- Using this formula, we can test several candidate trajectories.

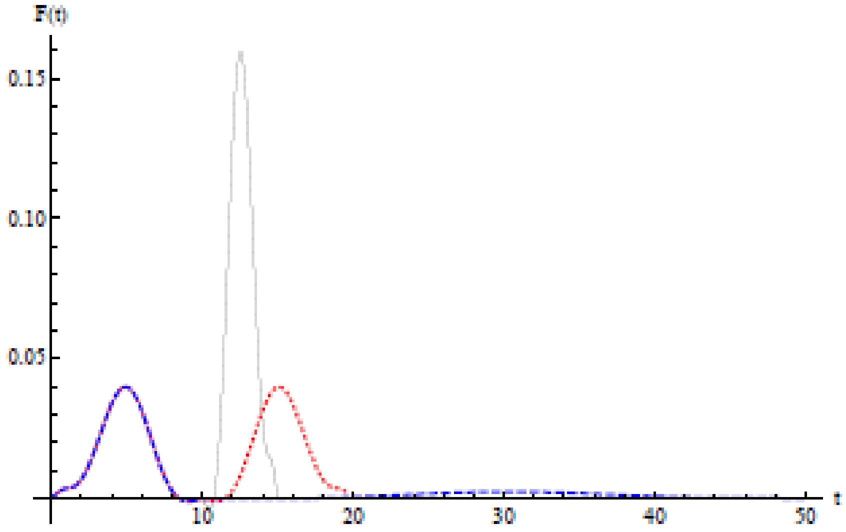


$$\frac{dS(t)}{dt} = A \sin^2 \pi \frac{t}{t_{\rm P}} \qquad 0 \leq t < t_{\rm P},$$
$$= -A \frac{t_{\rm P}}{t_{\rm f} - t_{\rm P}} \sin^2 \pi \frac{t - t_{\rm P}}{t_{\rm f} - t_{\rm P}} \qquad t_{\rm P} \leq t < t_{\rm f},$$

- Suddenly stopping mirror: $t_{\rm f} = 15$,
- Slowly stopping mirror: $t_{\rm f} = 20$,
- Long propagating mirror: $t_{\rm f} = 50$.

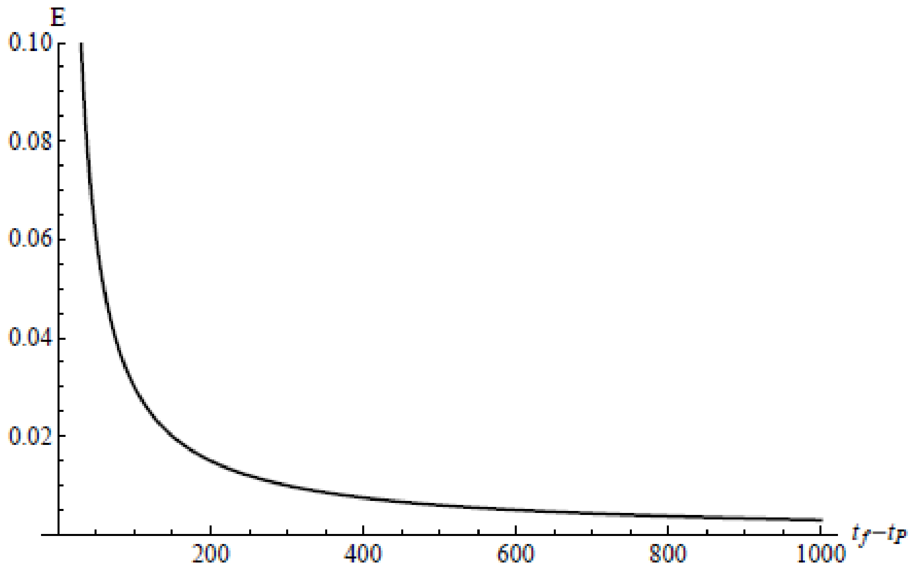
Test of scenarios





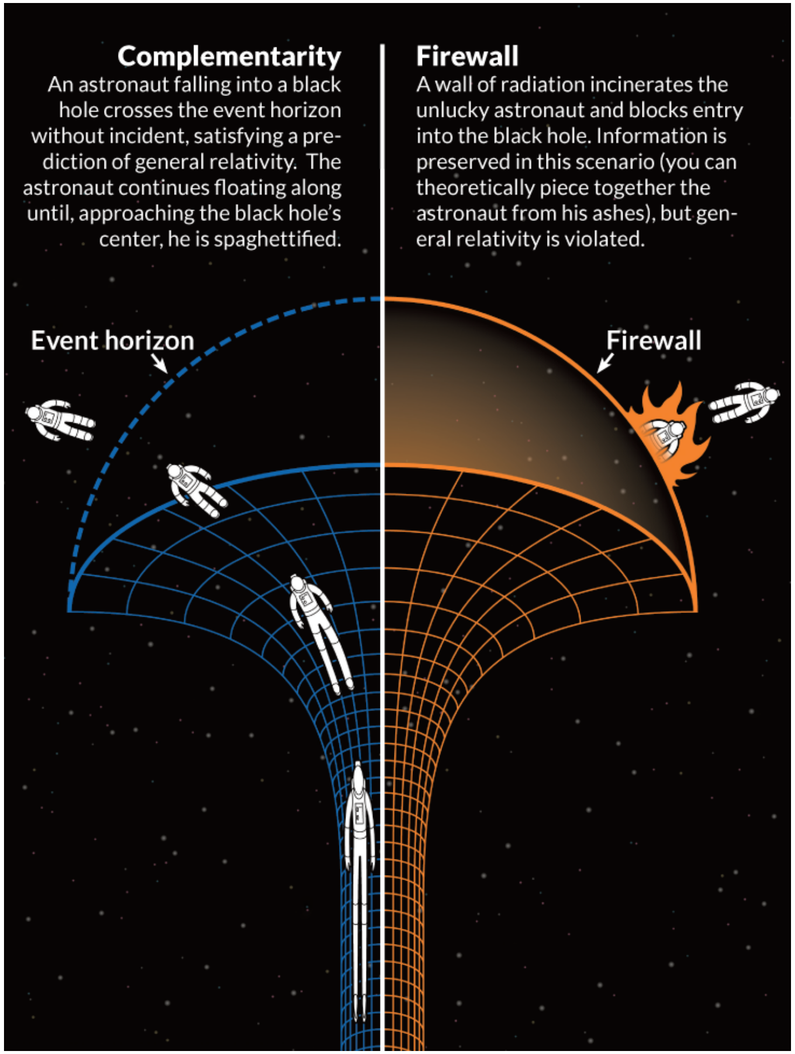
- For a suddenly stopping mirror, there is a large amount of energy emission. In general it is too large and hence it cannot mimic the last burst of a black hole.

Test of scenarios

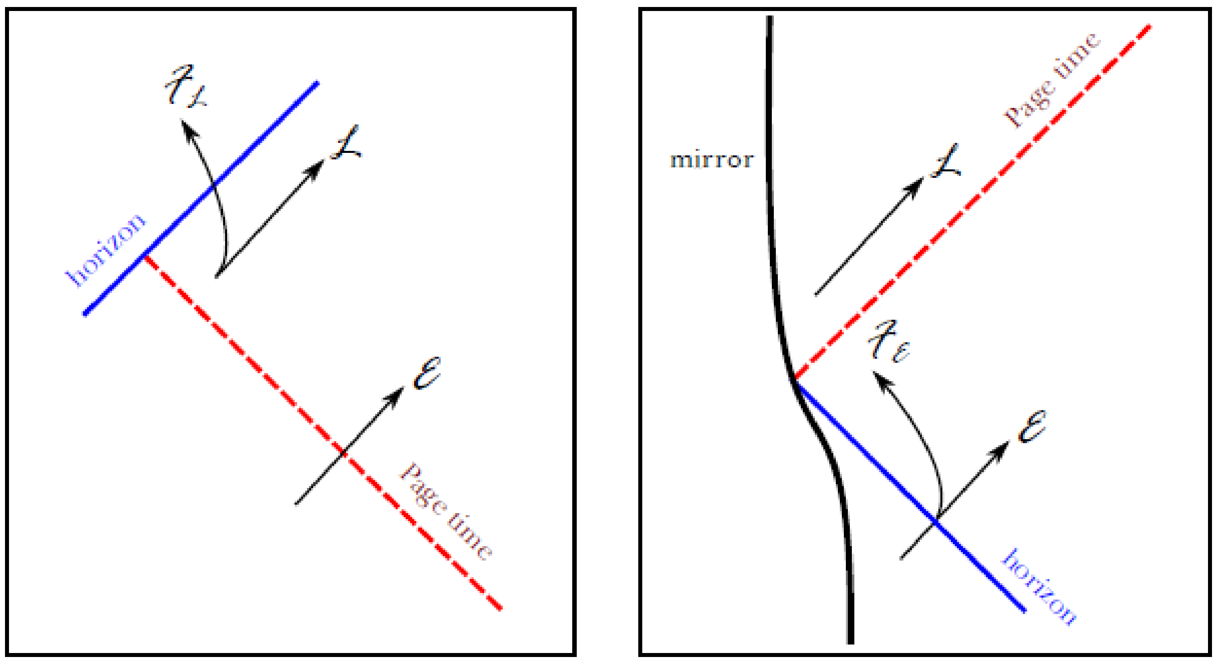


- For a mirror with very long lifetime, the emitted energy can be arbitrarily small.
- This mimics the possibility of correlation between vacuum and radiation or the remnant scenario.

Complementarity vs. Firewall

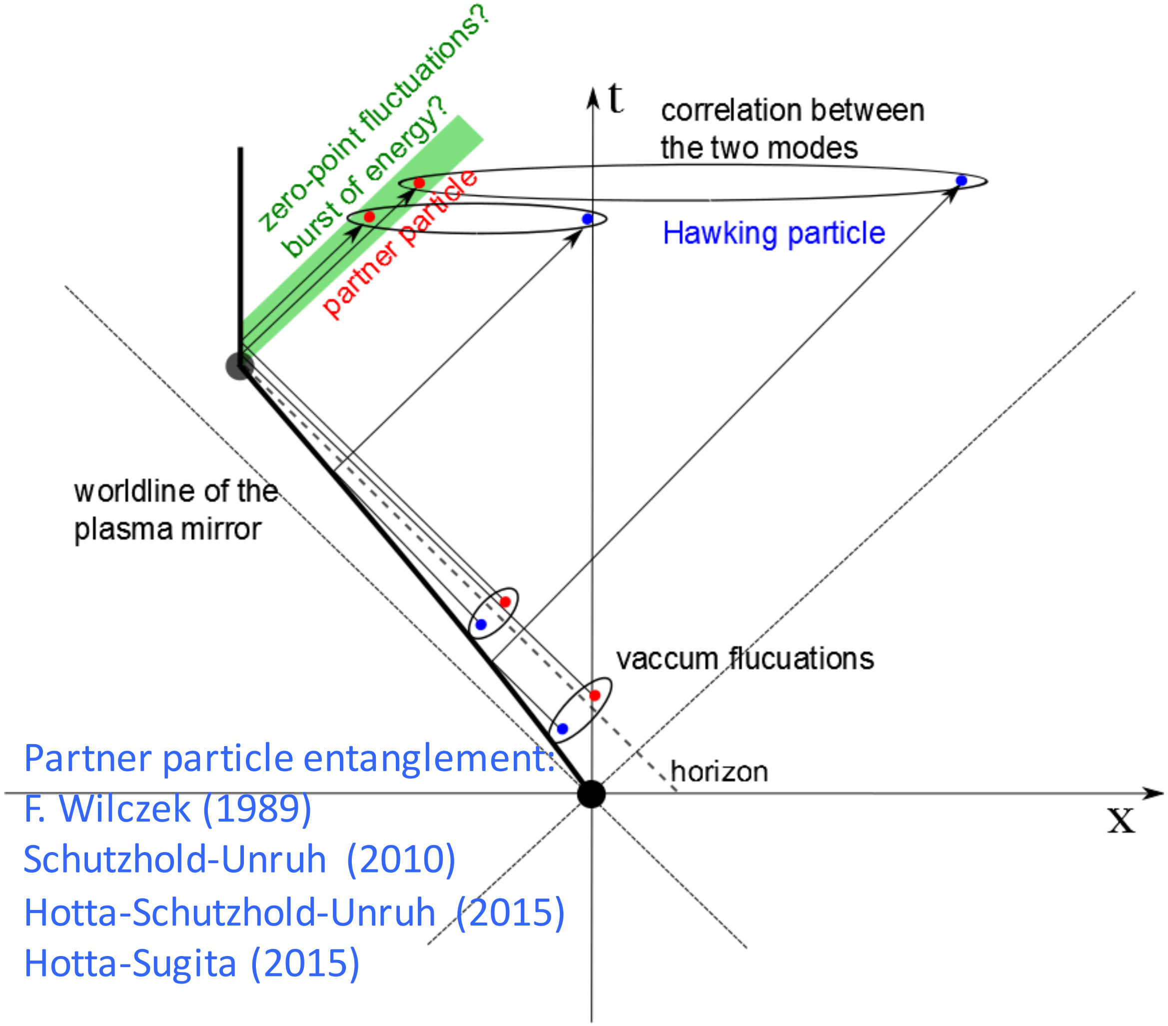


Consistency test: AMPS thought experiments



- Due to the monogamy of entanglements, there should be an effect that breaks one link.
- For a black hole case, this is called by (hypothetical) the **firewall**.
- There should be a violent effect from a **mirror**: a **firewall-like emission**?

Flying Mirror:
Entanglement between Hawking & partner particles
Final outburst of energy or not?

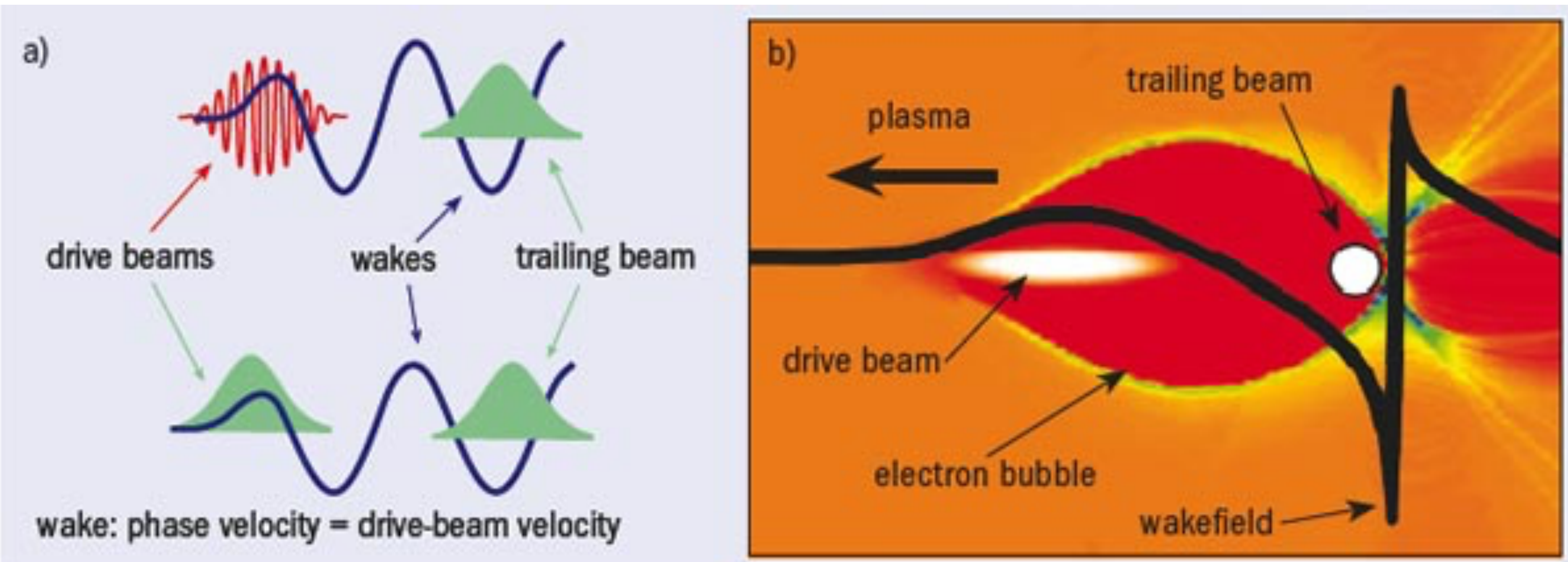


Partner particle entanglement:
F. Wilczek (1989)
Schutzhold-Unruh (2010)
Hotta-Schutzhold-Unruh (2015)
Hotta-Sugita (2015)

Plasma Wakefield Acceleration

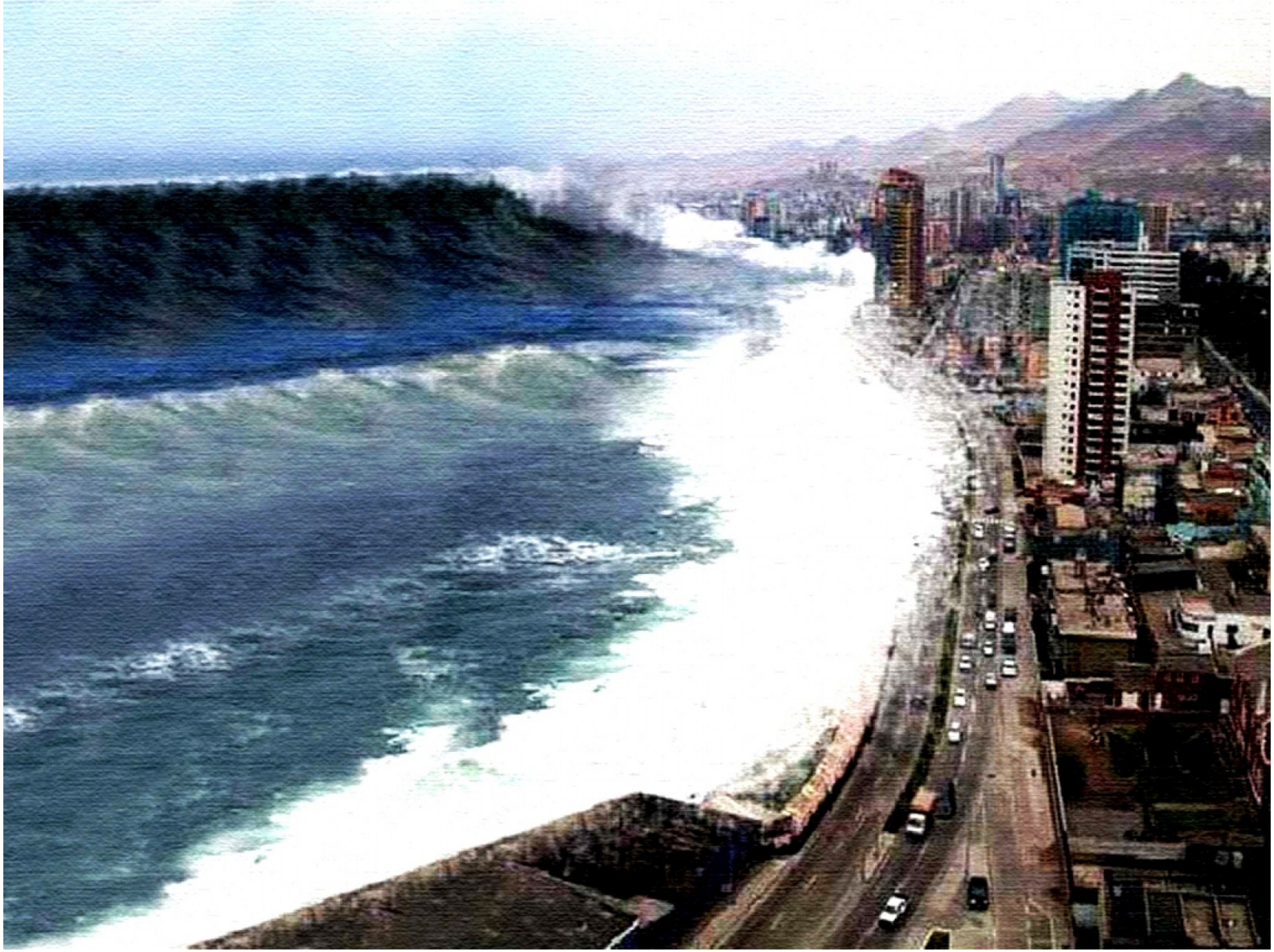
Tajima-Dawson (1979)- Laser driven (LWFA)

Chen-Dawson-Huff-Katsouleas (1985)- Particle beam driven (PWFA)



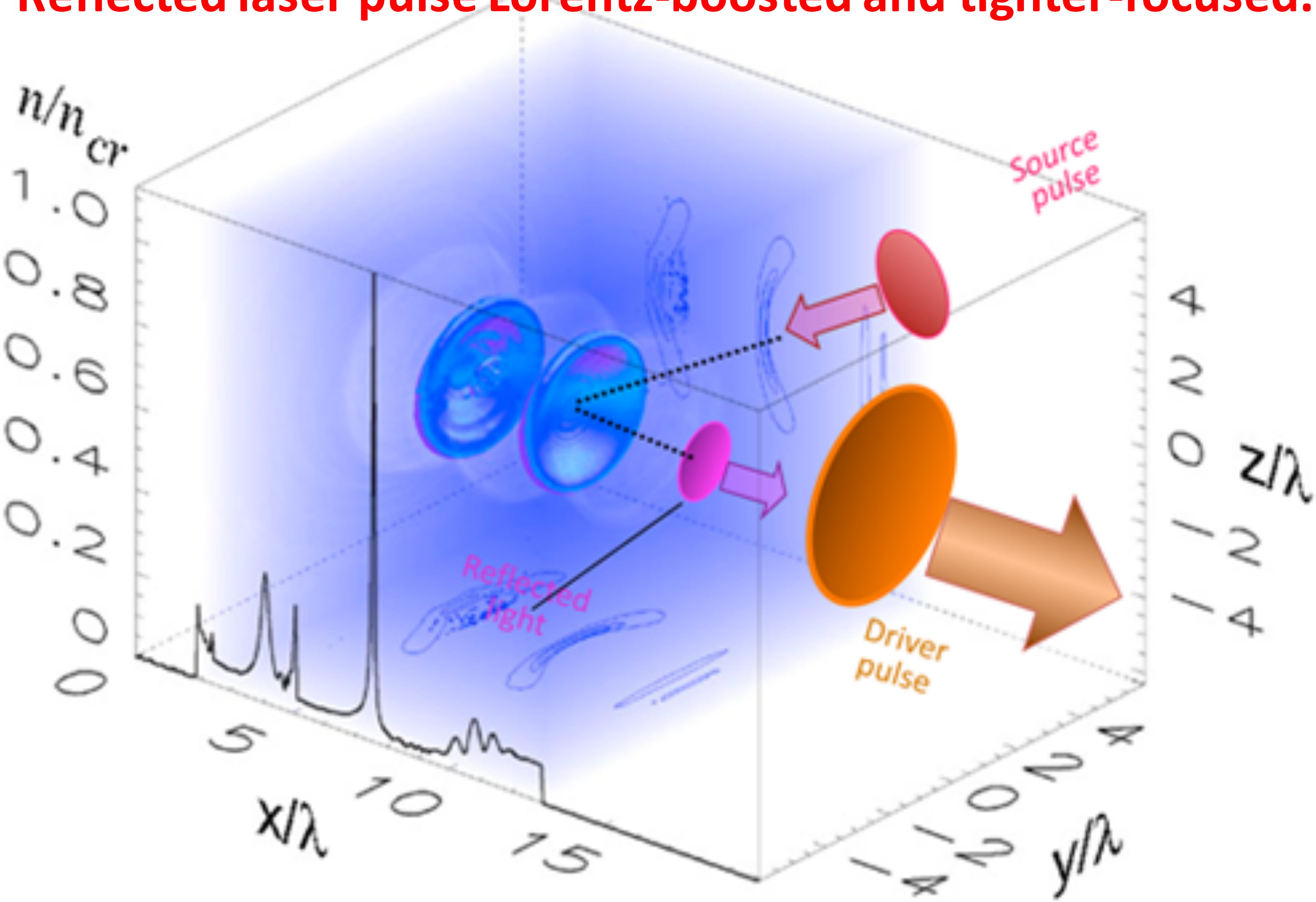
SLAC & LBL- Acceleration of O(100) GeV/m observed!

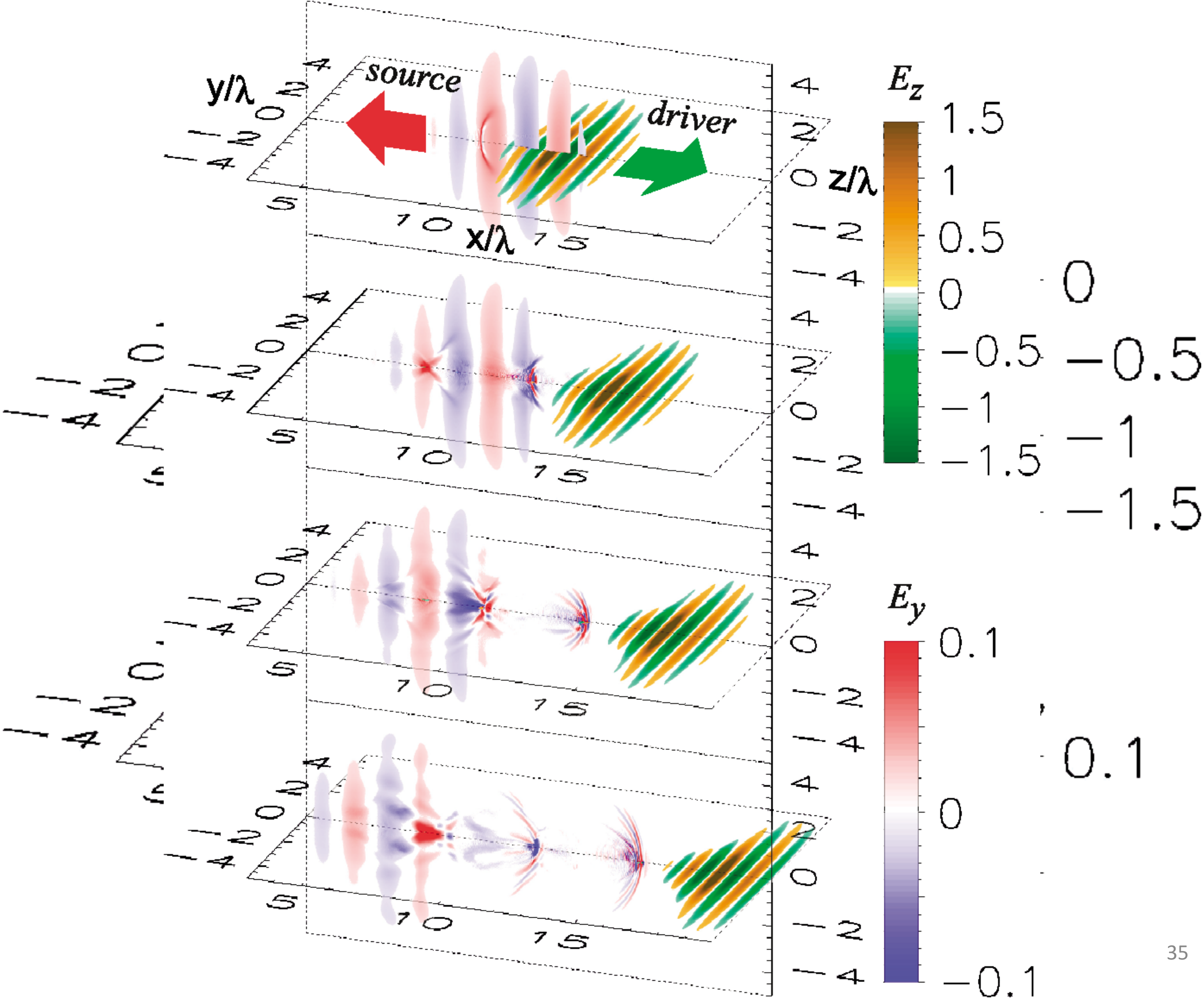
Plasma Wake is like a tsunami



Relativistic Plasma Mirror

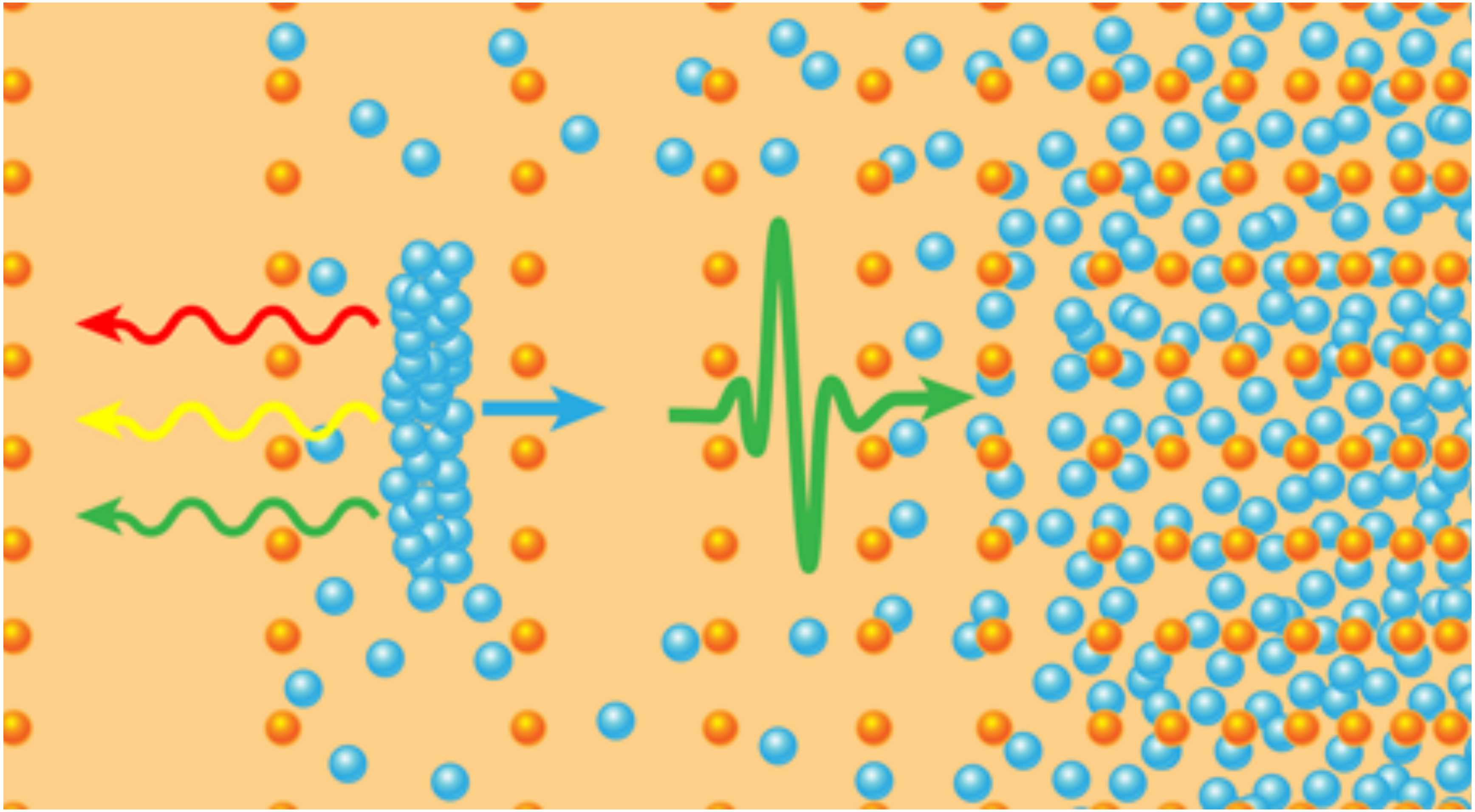
Reflected laser pulse Lorentz-boosted and tighter-focused.





source
driver
y/λ
x/λ
z/λ
E_z
1.5
1
0.5
0
−0.5
−1
−1.5
E_y
0.1
0
−0.1

Laser and plasma wakefield speed up as plasma density gradually increases



An accelerating plasma mirror

P Chen, G Mourou, "Accelerating plasma mirrors to investigate black hole information loss Paradox", Phys. Rev. Lett. 118, 045001 (2017).

- For uniform plasmas, the plasma wakefield, i.e., the relativistic mirror, is induced instantly by the impinging laser, under the "*Principle of Wakefield*"

Plasma wakefield follows behind the driver by one wavelength

- Nonlinear plasma wakefield is described by the (normalized) scalar and vector potentials ϕ and a by the coupled equations

$$\left[\frac{2}{c}\frac{\partial}{\partial\chi}-\frac{1}{c^2}\frac{\partial}{\partial\tau}\right]\frac{\partial a}{\partial\tau}=k_{p0}^2\frac{a}{1+\phi},$$

$$\frac{\partial^2\phi}{\partial\chi^2}=-\frac{k_{p0}^2}{2}\left[1-\frac{(1+a)^2}{(1+\phi)^2}\right].$$

Natural tendency of laser deceleration due to wakefield excitation

- The deceleration (or redshift) of the laser (and therefore the mirror) is governed by

$$\frac{\partial \omega}{\partial \chi} = -\frac{1}{2}\frac{\omega_p}{\omega}\frac{\partial}{\partial \chi}\frac{1}{1+\phi}.$$

- Let us model the laser envelope as

$$a_L(\chi) = a_{L0}\sin\left(\frac{\pi\chi}{L}\right), \qquad -L \le \chi \le 0.$$

Then the solution is

$$\phi \simeq \frac{a_{L0}^2 k_p^2}{8}\left\{\chi^2 - 2\left(\frac{L}{2\pi}\right)^2 [1-\cos(2\pi\chi/L)]\right\}.$$

and

$$\frac{\partial \phi}{\partial \chi} \simeq \frac{a_{L0}^2 k_p^2}{4}\left\{\chi - \frac{L}{\pi}\sin\left(\frac{2\pi\chi}{L}\right)\right\} < 0.$$

Acceleration of the plasma mirror

- Invoking the "wakefield principle",

$$\ddot{x}_M = \frac{dv_g}{dt} = v_g \frac{\partial v_g}{\partial x} = \eta c^2 \frac{\partial \eta}{\partial x}.$$

where the refractive index $\eta = \sqrt{1-(\omega_p^2/\omega^2)/(1+\phi)}$,

we find

$$v_M \simeq c\sqrt{1-\frac{\omega_{p0}^2}{\omega^2}\frac{1}{1+\phi}}\left(1+\frac{\partial \omega_p}{\partial x}\frac{t}{k_{p0}}\right).$$

Finally,

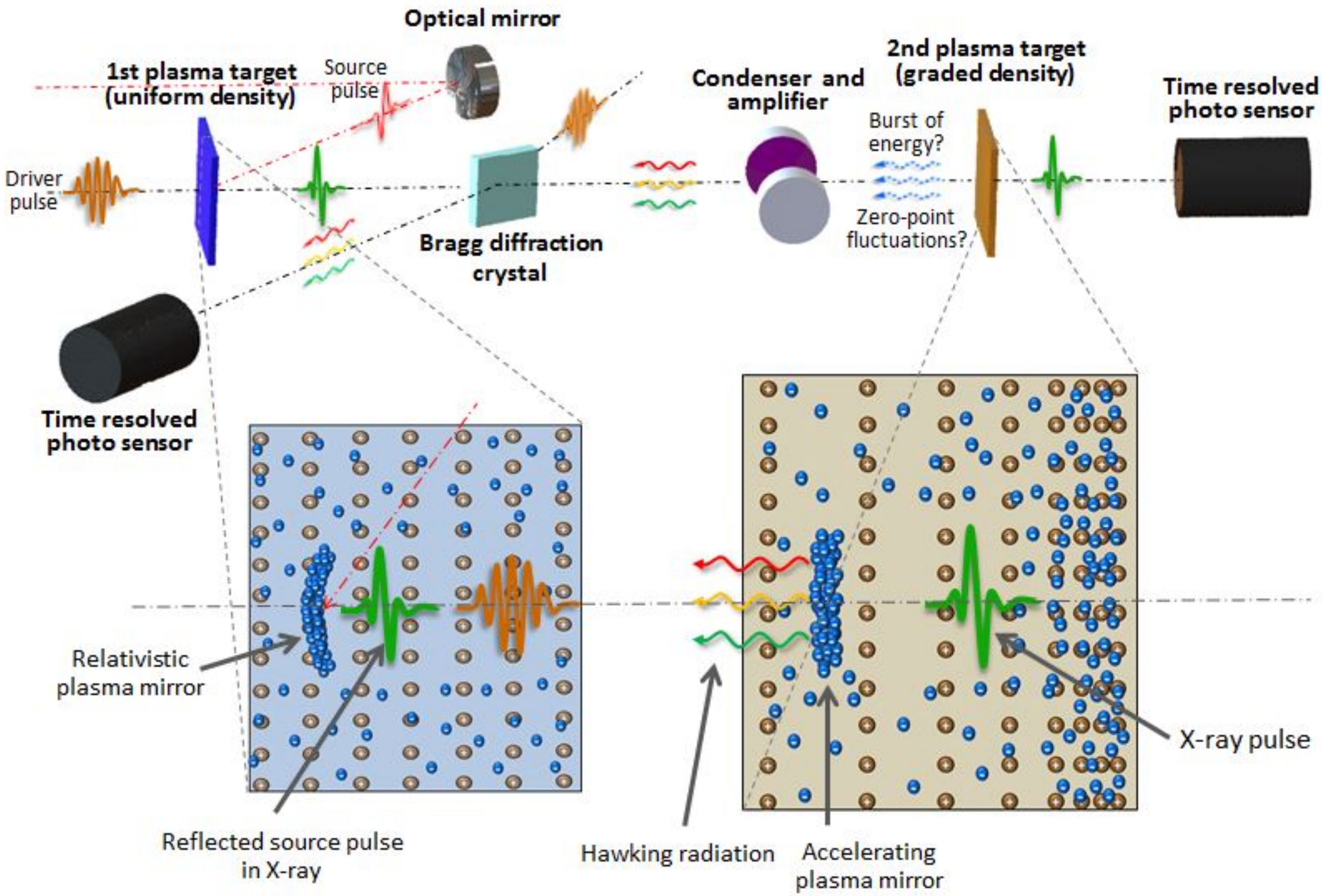
$$\ddot{x}_M = \frac{c}{2\eta_0}\left[v_g\left(1+\frac{\omega_{p0}^2}{\omega^2}\right)\frac{\omega_{p0}^2}{\omega^2}\frac{\partial}{\partial x}\frac{1}{1+\phi}\right]\left(1+\frac{\partial \omega_p}{\partial x}\frac{t}{k_{p0}}\right)$$

$$+c\eta_0\left(\frac{\partial \omega_p}{\partial x}\frac{1}{k_{p0}}+\frac{\partial^2 \omega_p}{\partial x^2}\frac{v_g t}{k_{p0}}\right).$$

Due to frequency redshift

Due to density gradient

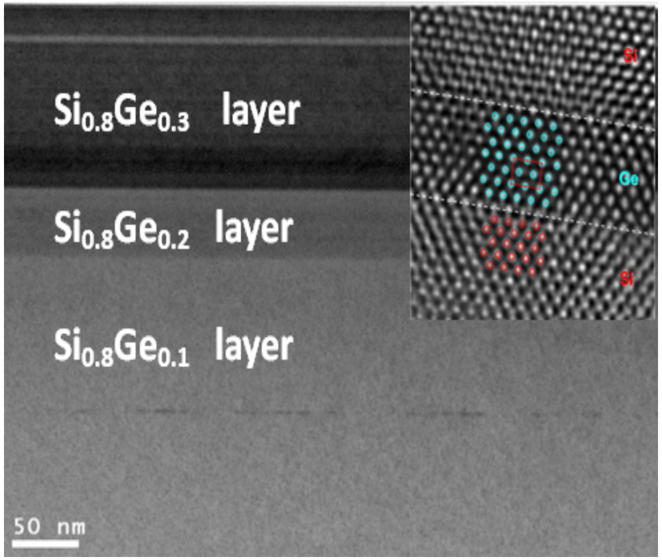
A conceptual design of the accelerating plasma mirror experiment



Plasma density variation

- Invoking nano-fabrication technology for solid plasma targets with, for example, a power-law increase of density:

$$n_{p0}e^{\pm x/D}, \begin{cases} n_{p0}(1+x/D)^{2(1-\eta_0)}, & 0 \le x \le X, \\ 0, & \text{otherwise} \end{cases}$$



- Then the acceleration is

$$\ddot{x}_M = \frac{(1-\eta_0)c^2}{D(1+x/D)^2}\exp\left(\frac{(1-\eta_0)x/D}{1+x/D}\right), \quad 0 \le x \le X.$$

Example

- The 4 length scales should satisfy the inequality:

$$\lambda_x \ll \lambda_p \ll D \ll X. \qquad (\lambda_x \simeq 7.79nm)$$

- Plasma target based on nanotechnology with

$\lambda_{p0} = 7.8nm$ $D = 10nm$, thickness $X = 2D$, and density $n_{p0} \sim 5\times 10^{23} cm^{-3}$ ⇒

- The mirror velocity: $v_M(0) \sim 0.01c$ ⇒ $v_M(2D) \sim 0.997c$
- Reflectivity of plasma mirror at this frequency: $Y \approx 1$

⇒ Corresponding Hawking temperature:

$$k_B T_H(x) \simeq \frac{\hbar c}{4\pi D} \frac{\omega_{p0}^2}{\omega_0^2} \frac{1}{(1+x/D)^2} \exp\left\{ \frac{(1-\eta_0)x/D}{1+x/D} \right\} \sim 1.6 - 0.1eV.$$

Background noise not severe

- One salient feature of this experiment:

  The Hawking signals propagate backward,

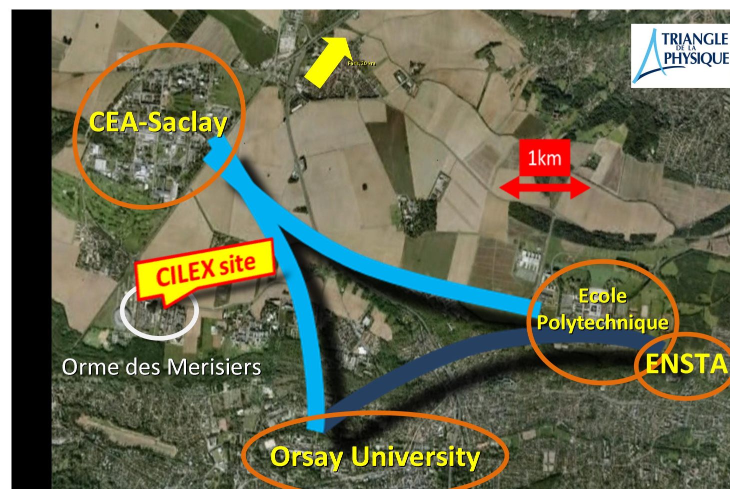
  whereas most x-ray or optical laser induced background

  particles would move forward.
- Since the x-ray energy 25 eV << m_e = 0.5 MeV, Compton backscattering induced by x-ray would have similar frequency at 25 eV
- Bragg diffraction crystal is designed to let pass the 25 eV but divert the 1-10 eV photons, these background signals would therefore be directed to a different path.
- In conclusion, the background in this experiment should be minute.

AnaBHEL Collaboration formed (Analog Black Hole Evaporation via Lasers)

National Taiwan University + Ecole Polytechnique + Kansai Photon Research Inst. + Shanghai Jiao Tong U.

- Two stages:
  1. Proof of principle at KPRI Laser facility, presently one of the most powerful lasers in the world @ PW
  2. Full scale expt. with 10PW APOLLON laser, Saclay when completed in 2018



What can we learn from AnaBHEL?

- First, if we can detect the **thermal radiation**, then in itself it confirms QFT in curved spacetime.
- Second, if we can experimentally measure the **entanglement entropy** of radiation (this is a challenge) before, during, and after the acceleration, then it can test the renormalization method for the entanglement entropy.
- Third, one can expect that as the mirror stops, there maybe violent effects on the mirror: **firewall-like burning mirror**?

Summary

- Hawking evaporation and information loss paradox is one of the fundamental problems in physics.
- So far investigations are essentially theoretical; Direct observation of black hole end-stage unlikely.
- Quantum entanglement between Hawking radiation and partner particle may reveal the secrete.
- Accelerating plasma mirrors may serve to address some aspects of this paradox experimentally.