Tabletop Analog Black Holes & Information Loss Paradox

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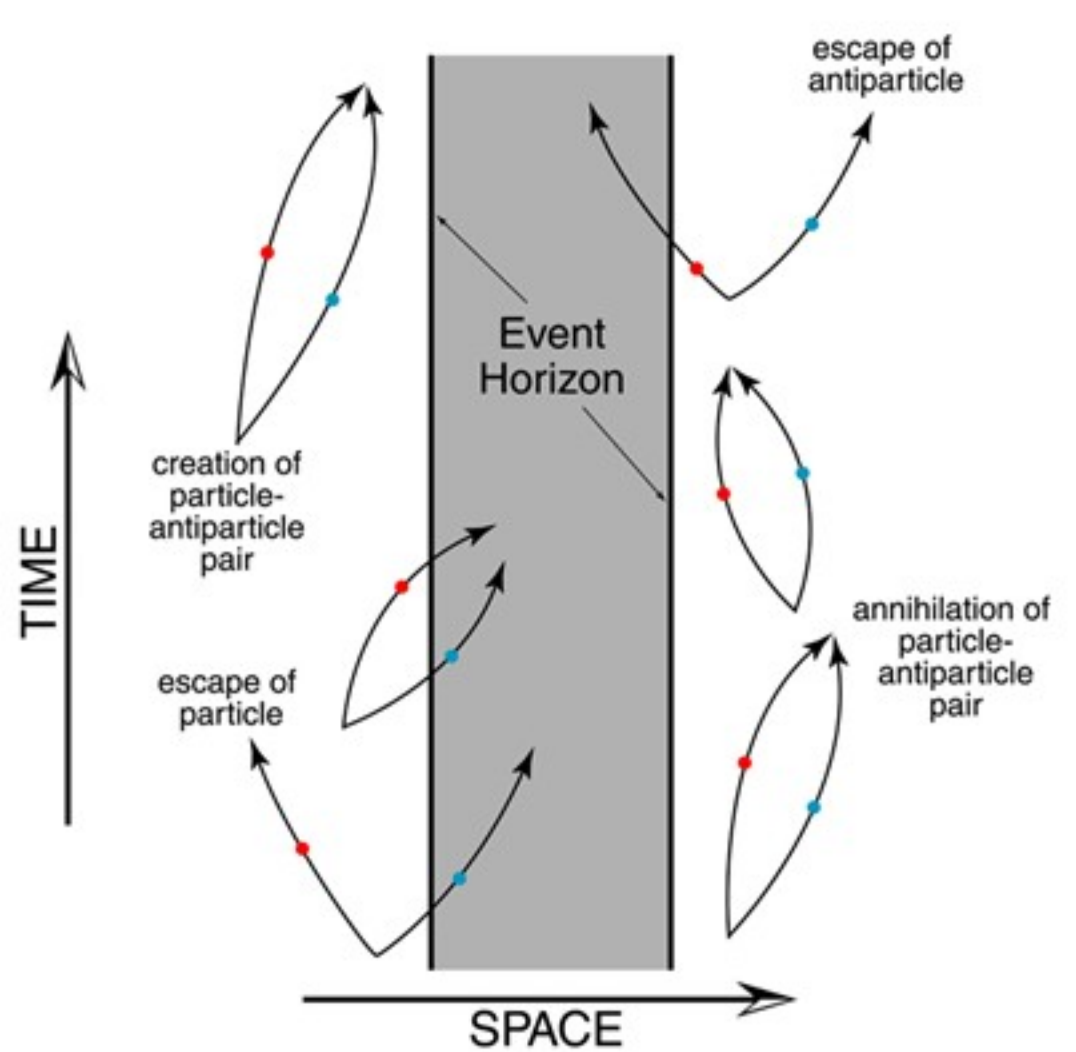
Black hole Hawking evaporation – Connecting GR, QM, SM in one stroke

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

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



Lifetime of black holes

- Hawking temperature:

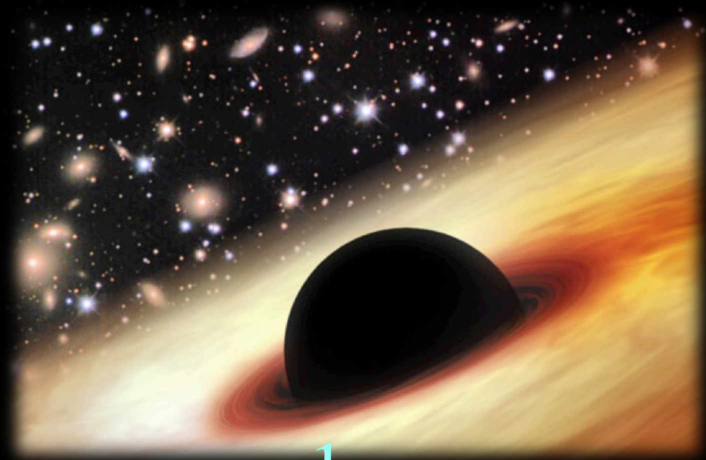
Planck's Constant [Quantum Mechanics]

Relativity

$$T = \frac{\hbar c^3}{8\pi G M k_B}$$

Boltzmann's Constant [Thermodynamics]

Newton's Constant [Gravity]



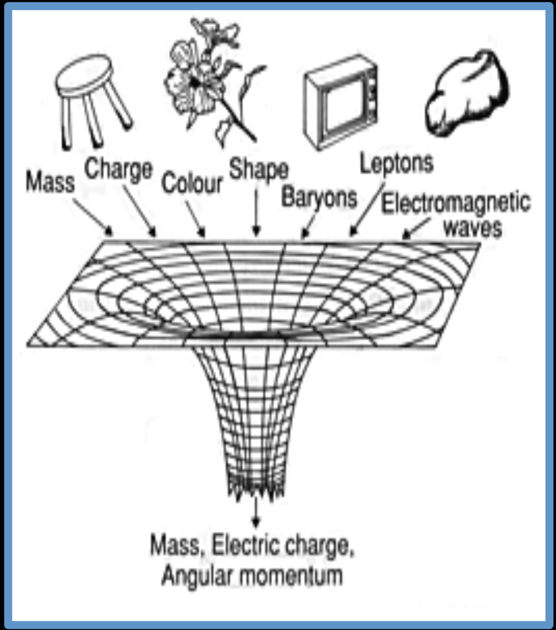
- Stefan-Boltzmann law: $$\frac{E}{A} = \sigma T^4 \propto \frac{1}{M^4}$$

Black hole surface area: $$A = 4\pi r_h^2 \propto M^2$$

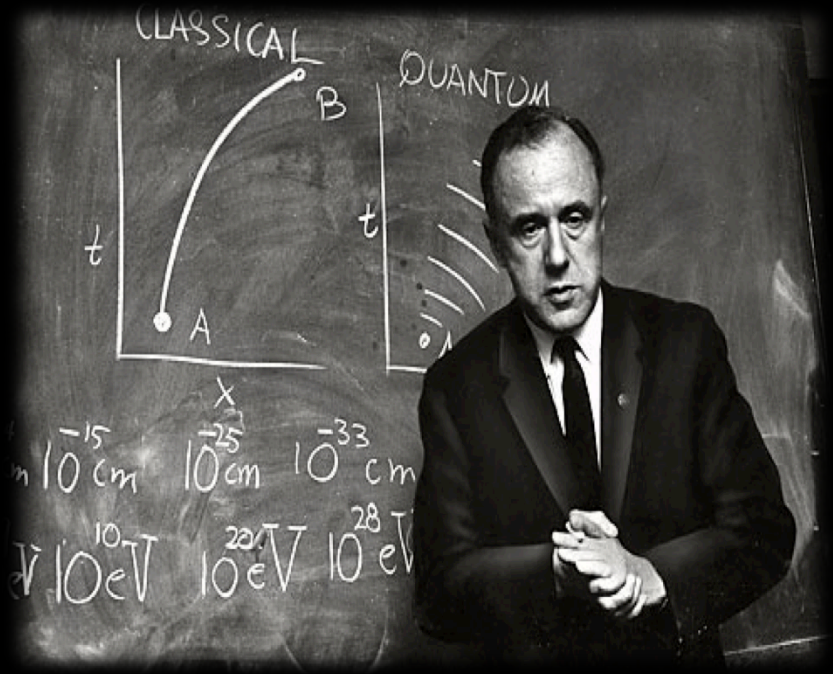
BH evaporation rate inversely proportional to mass squared: $$\frac{dM}{dt} \propto \frac{1}{M^2}$$

Lifetime of BH: Solar mass BH=10^{67} years

Age of the universe = 1.38×10^{10} years



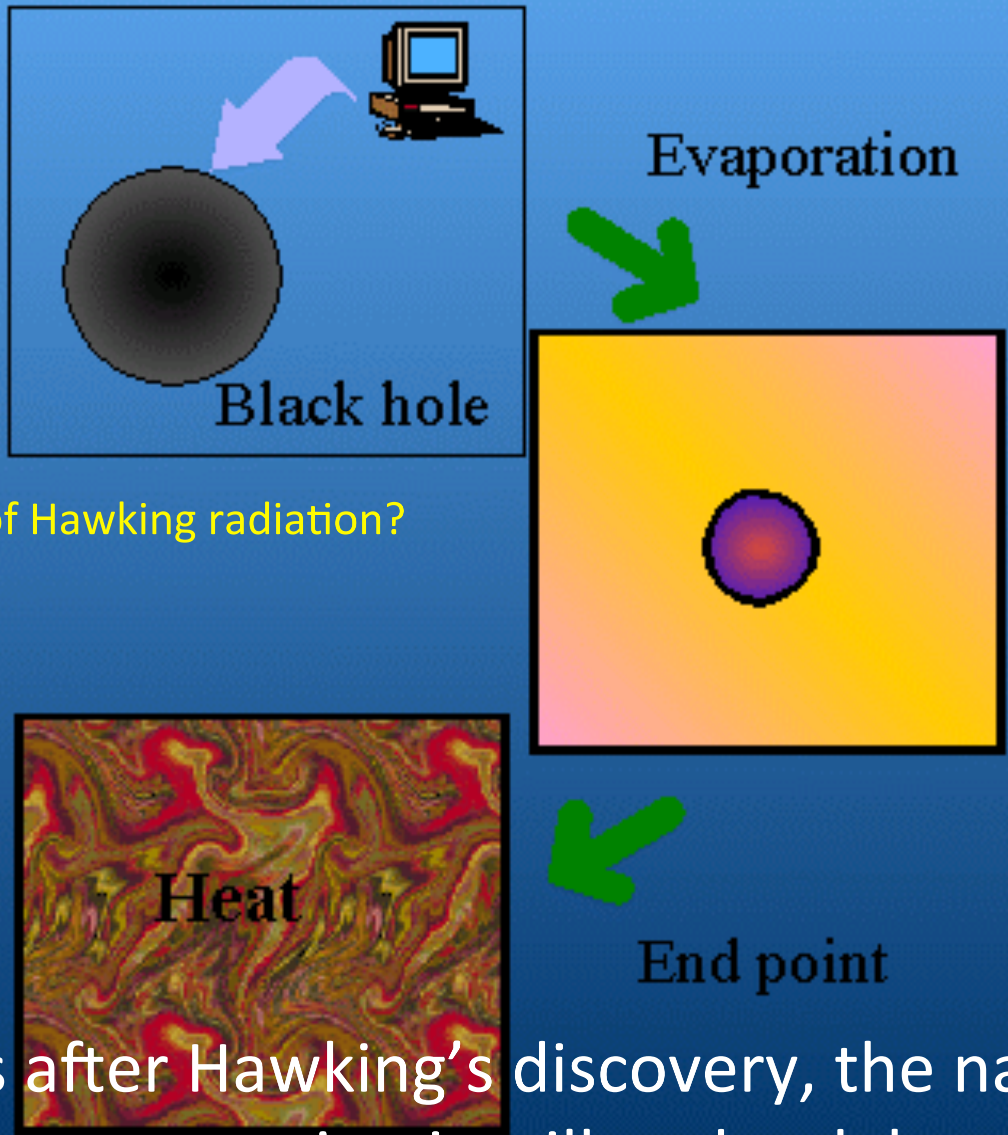
No-hair theorem



John Wheeler: What would happen if I dropped my coffee mug into a black hole?

Hawking-Perry-Strominger (2016): Its information would be stored around the horizon as soft hairs.

Information Loss



- Entanglement of Hawking radiation?
- Firewall?
- Fussball?
- Etc., etc., etc.

40 years after Hawking's discovery, the nature of BH evaporation is still under debate!

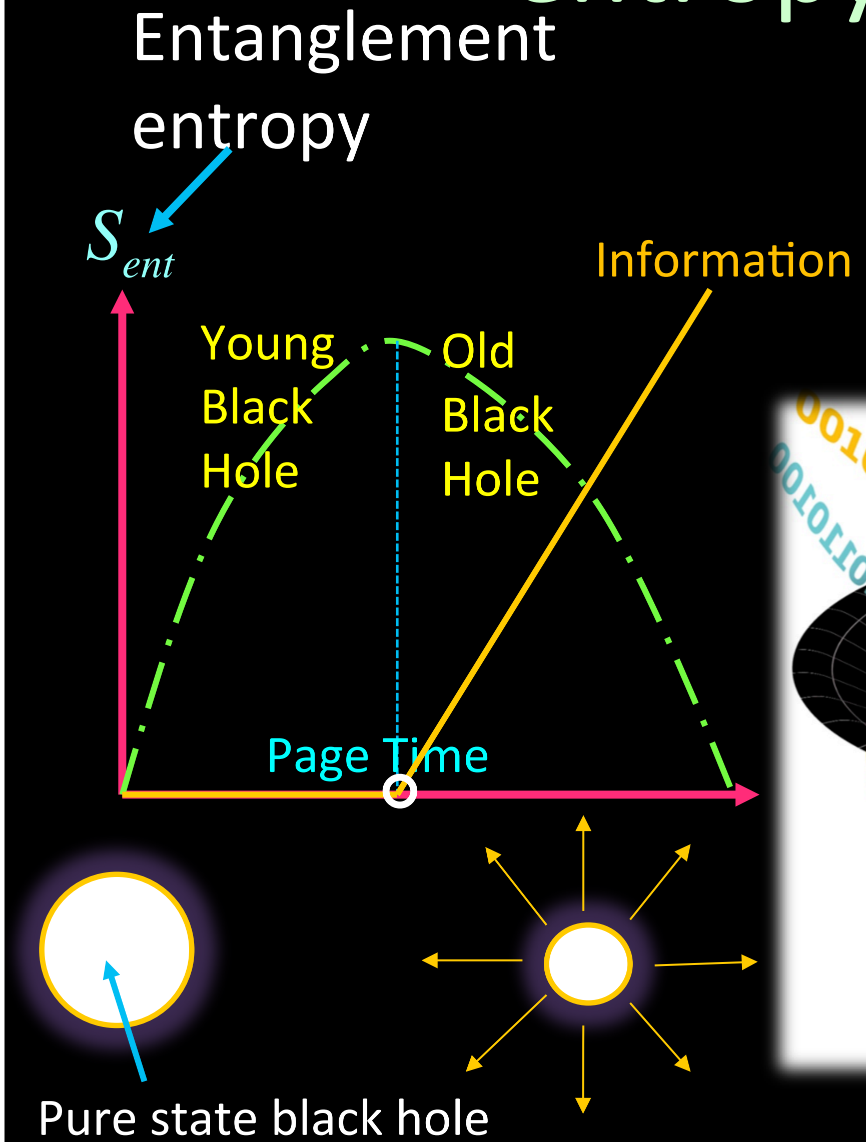
Hawking evaporation may result in the loss of information!

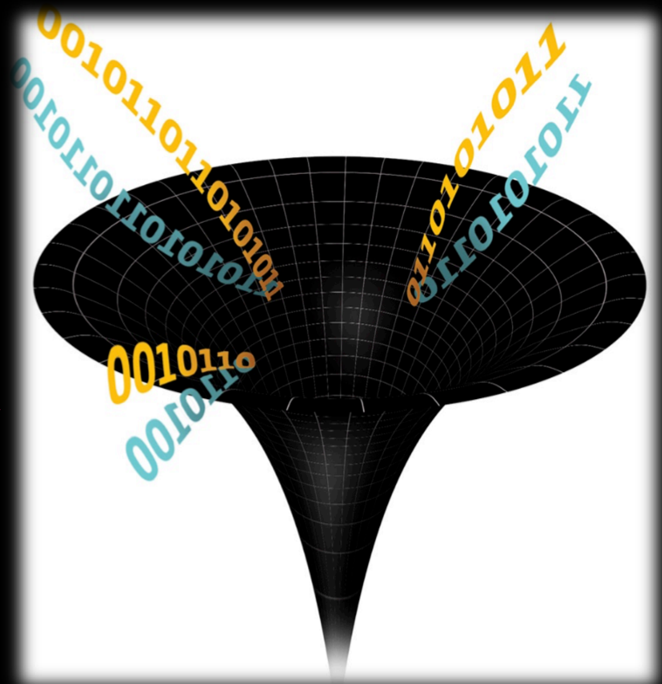
Fundamental conflict between general relativity and quantum field theory!!

- First pointed out by Hawking himself in 1978
- 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-Yeon, PRL 2016)
- Soft Hairs (Hawking-Perry-Strominger, 2016)
- No firewalls & nothing wrong w. information loss (Unruh-Wald 2017)
- etc., etc., etc.

Can Hawking radiation carry out information after all?

When would BH entanglement entropy come out?





Don Page

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)
- 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)

} Testing thermal nature of Hawking radiation

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Accelerating Plasma Mirrors to Investigate the Black Hole Information Loss Paradox

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The question of whether Hawking evaporation violates unitarity, and therefore results in the loss of information, has remained unresolved since Hawking's seminal discovery. To date, the investigations have remained mostly theoretical since it is almost impossible to settle this paradox through direct astrophysical black hole observations. Here, we point out that relativistic plasma mirrors can be accelerated drastically and stopped abruptly by impinging intense x-ray pulses on solid plasma targets with a density gradient. This is analogous to the late time evolution of black hole Hawking evaporation. A conception of such an experiment is proposed and a self-consistent set of physical parameters is presented. Critical issues, such as how the black hole unitarity may be preserved, can be addressed through the entanglement between the analog Hawking radiation photons and their partner modes.

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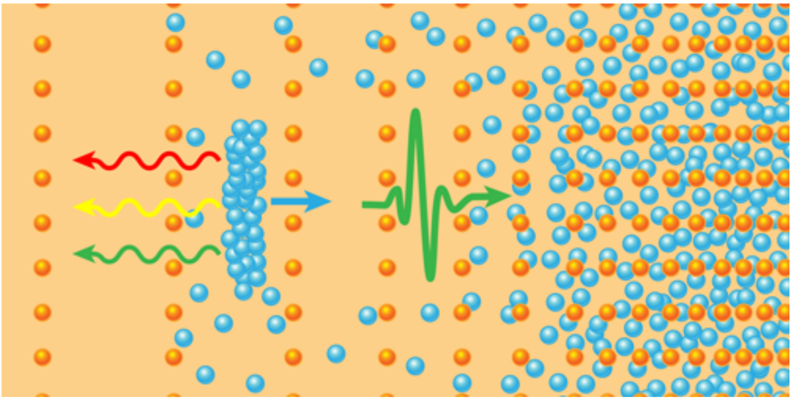
APS physics™

Synopsis: Plasma Mirror Mimics Evaporating Black Hole

January 23, 2017

A proposal for using an accelerated plasma mirror to study the black hole information paradox elevates a thought experiment into a potential reality.



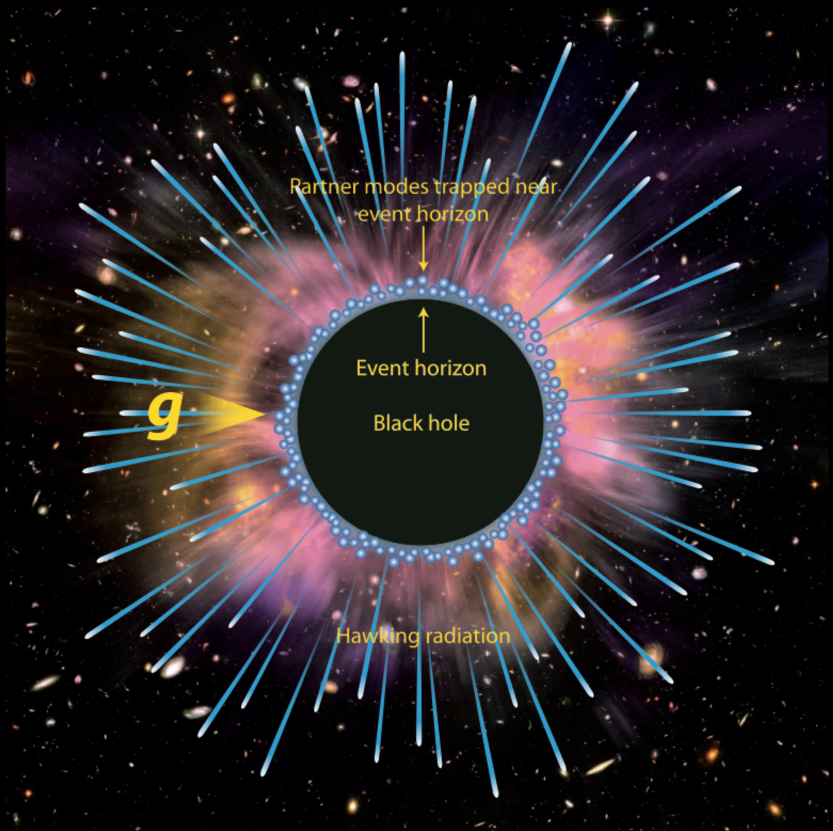
APS/Alan Stonebraker

If black holes radiate, as Stephen Hawking predicted in the 1970s, then the information inside them isn't as indestructible as quantum

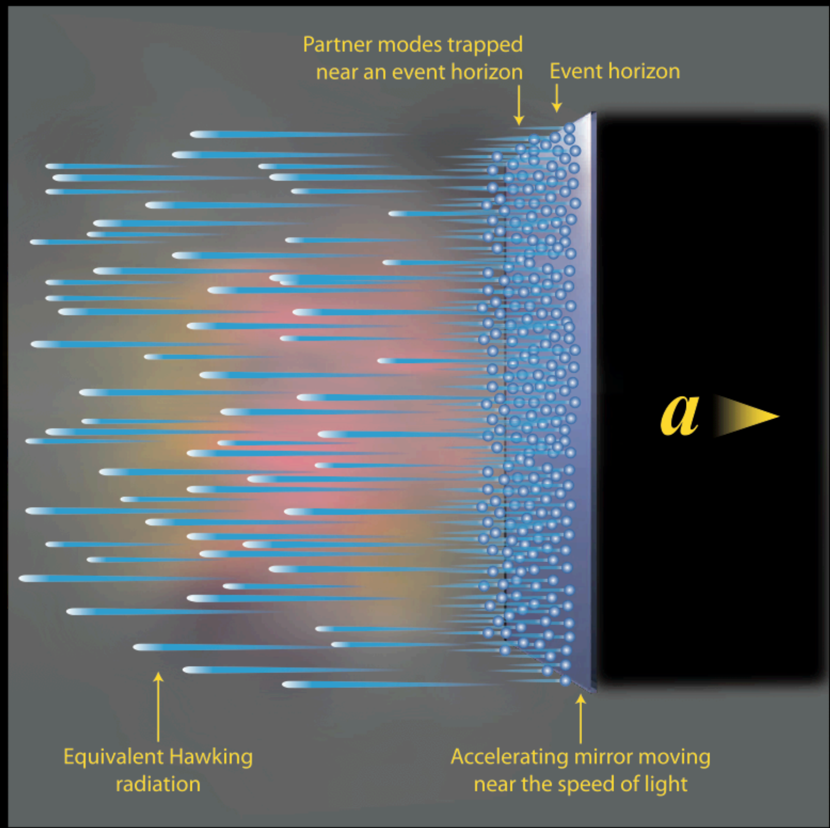
Accelerating mirror as an analog black hole

SIMULATING A BLACK HOLE ON A TABLE

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

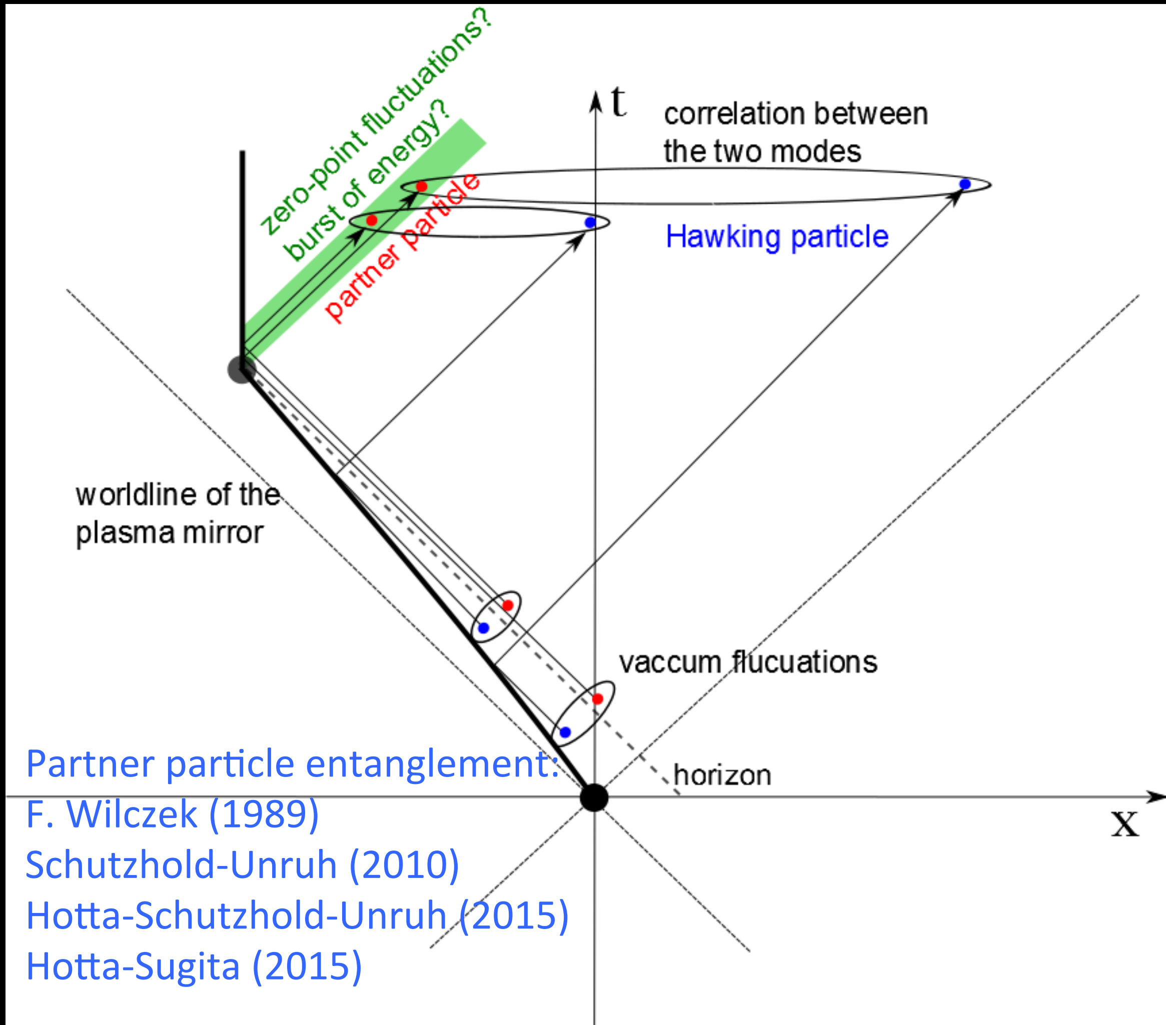


Black hole Hawking evaporation



Accelerating mirror as an analog black hole

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)

Accelerating plasma mirror

- Born relativistic
- Laser velocity in plasma can accelerate and thus its wakefield
- Acceleration can increase in time and stop abruptly

What can it offer?

- Investigation of HOW the Hawking particles correlate with the partner modes and possible final outburst of energy

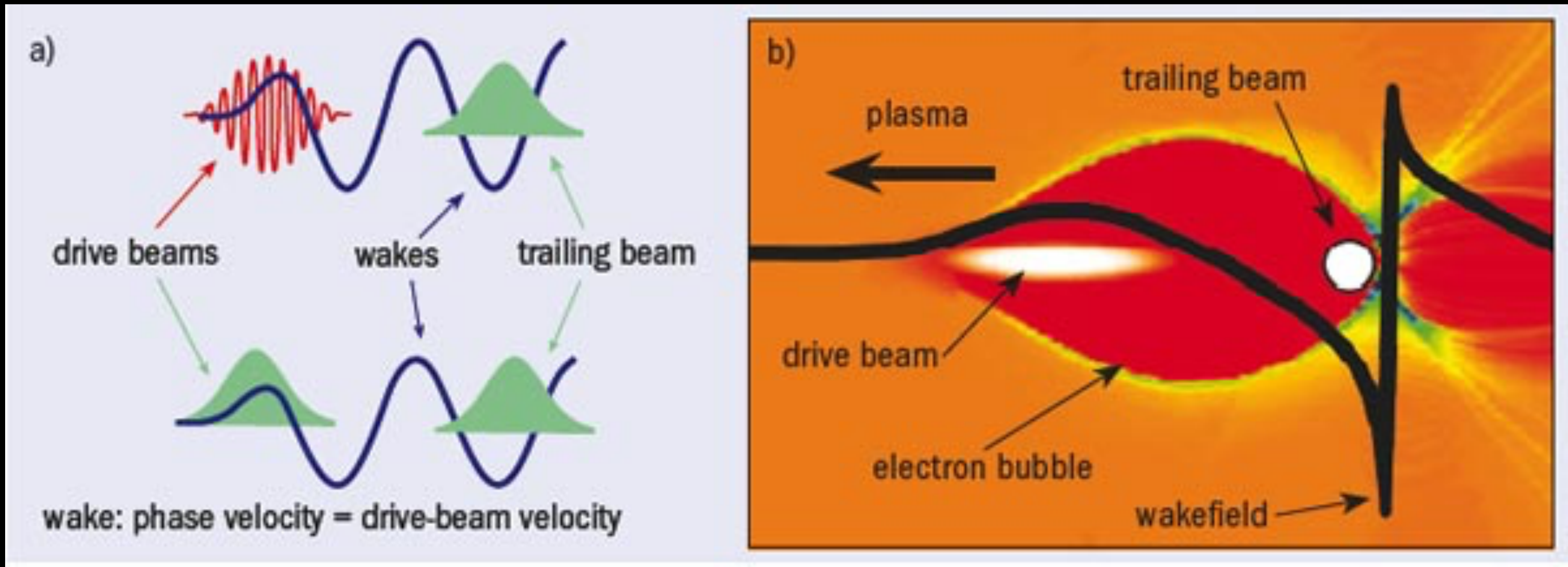
What it cannot offer?

- Being in flat space, unitarity preserved: no loss of information
- No singularity either

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!

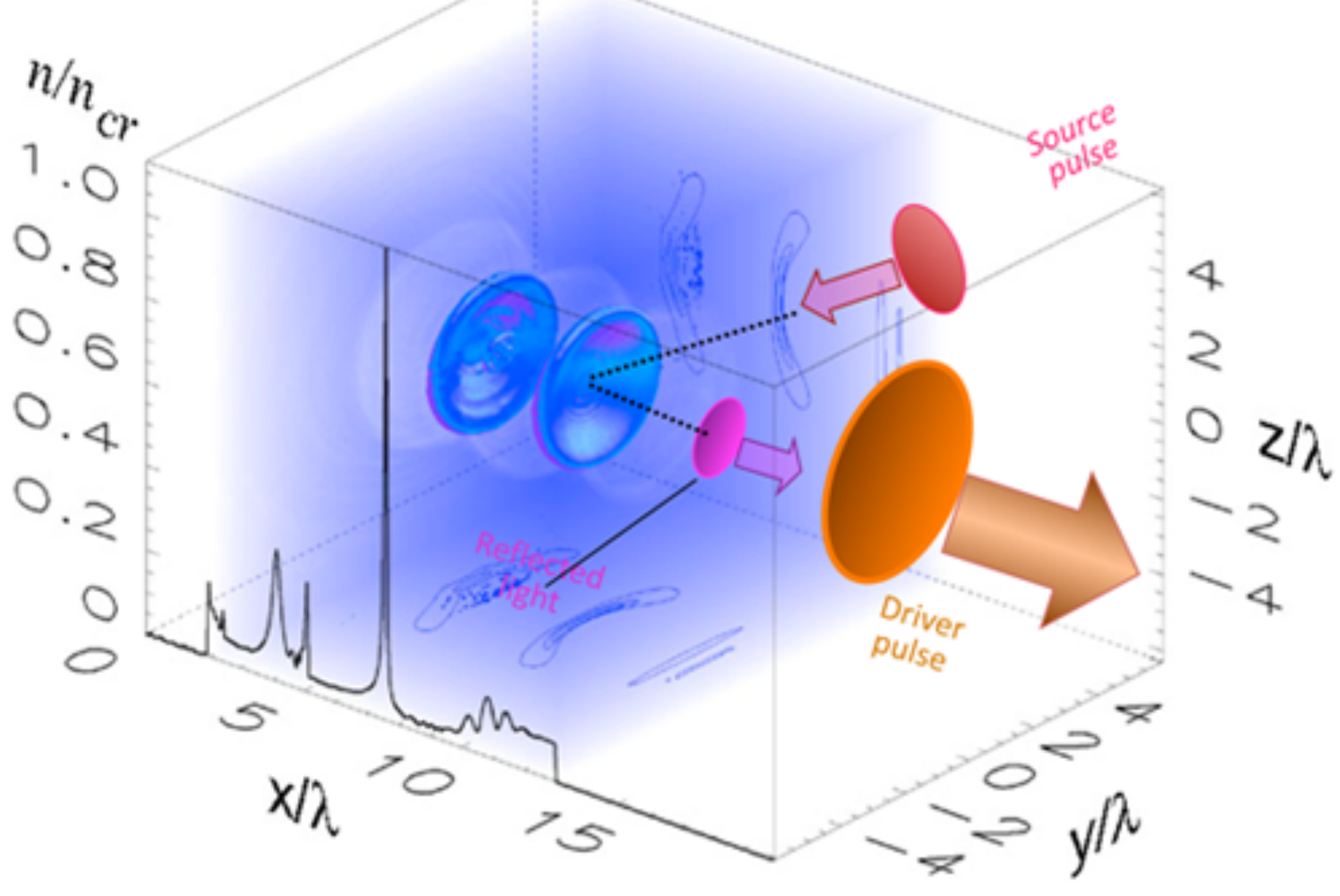
AWAKE- A new experiment at CERN

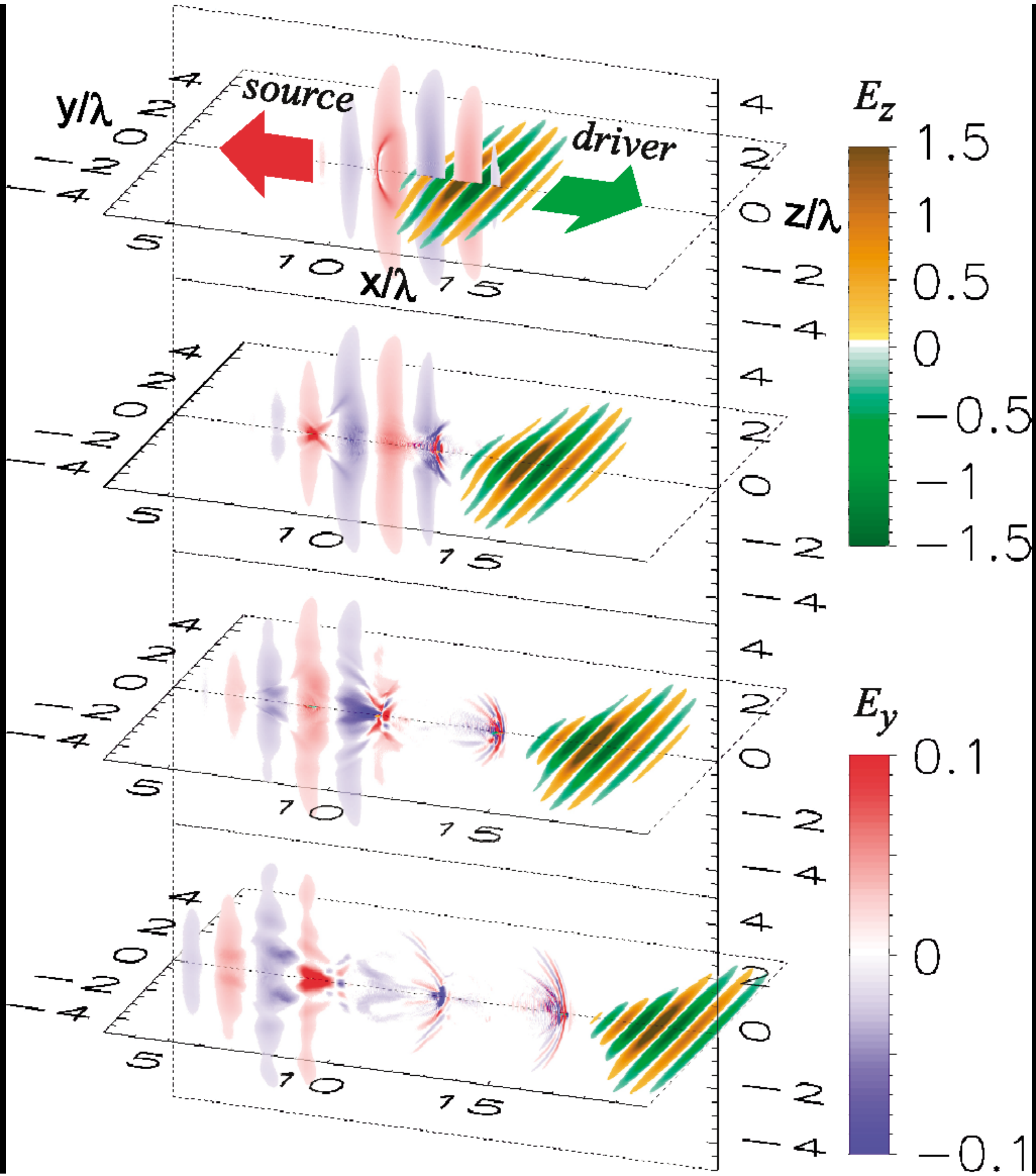
Plasma Wake is like a tsunami

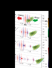
Relativistic Plasma Mirror

Bulanov (2001), Bulanov, Esirkepov, Tajima (2003), Mourou-Tajima-Bulanov (2006)

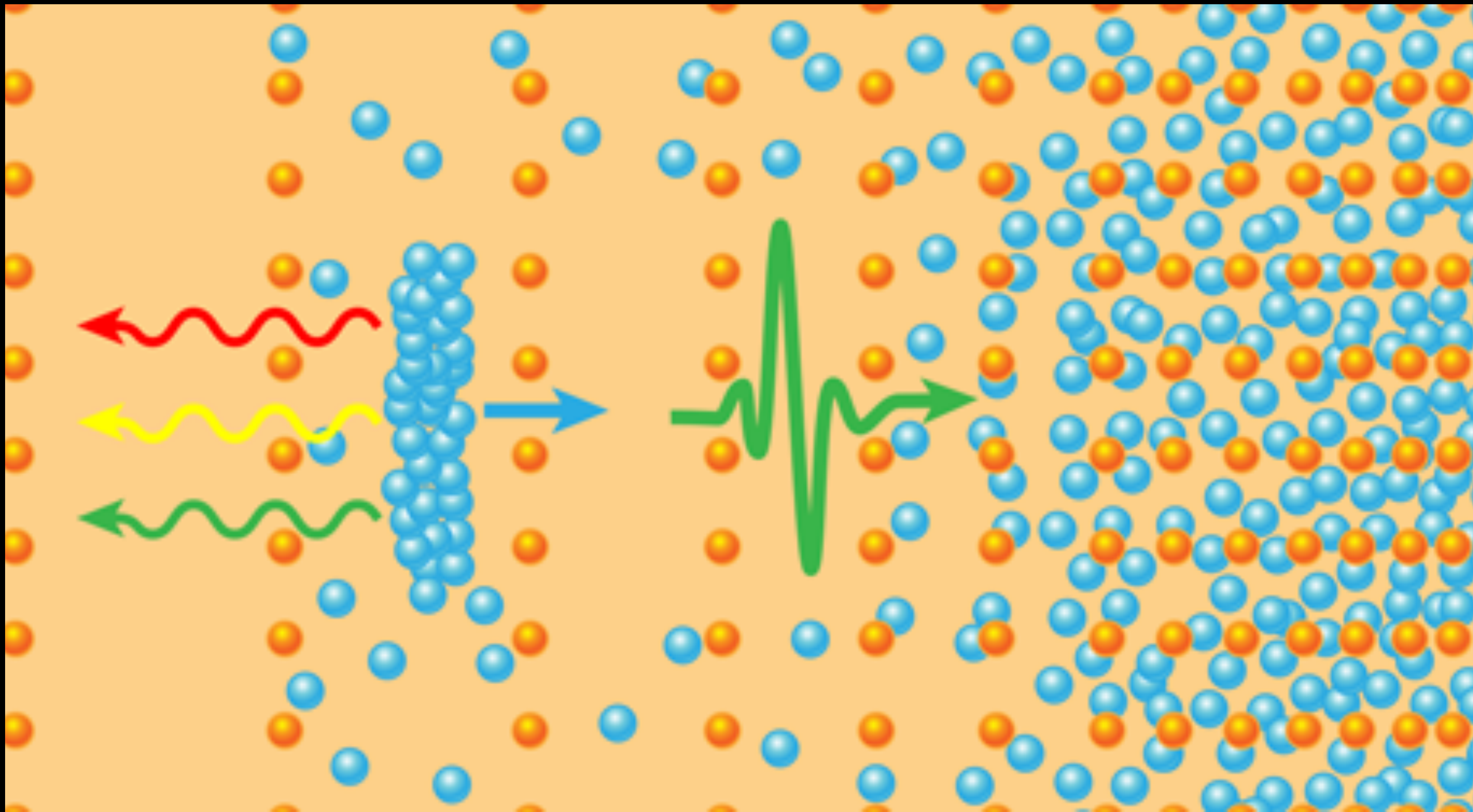
Reflected laser pulse Lorentz-boosted and tighter-focused.




source
driver
y/λ
x/λ
z/λ
Ez
1.5
1
0.5
0
−0.5
−1
−1.5
Ey
0.1
0
−0.1



Laser and plasma wakefield speed up as plasma density gradually increases



An accelerating plasma mirror

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

Phase velocity = group velocity: $v_M = v_{ph} = v_g$

- 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

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

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

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

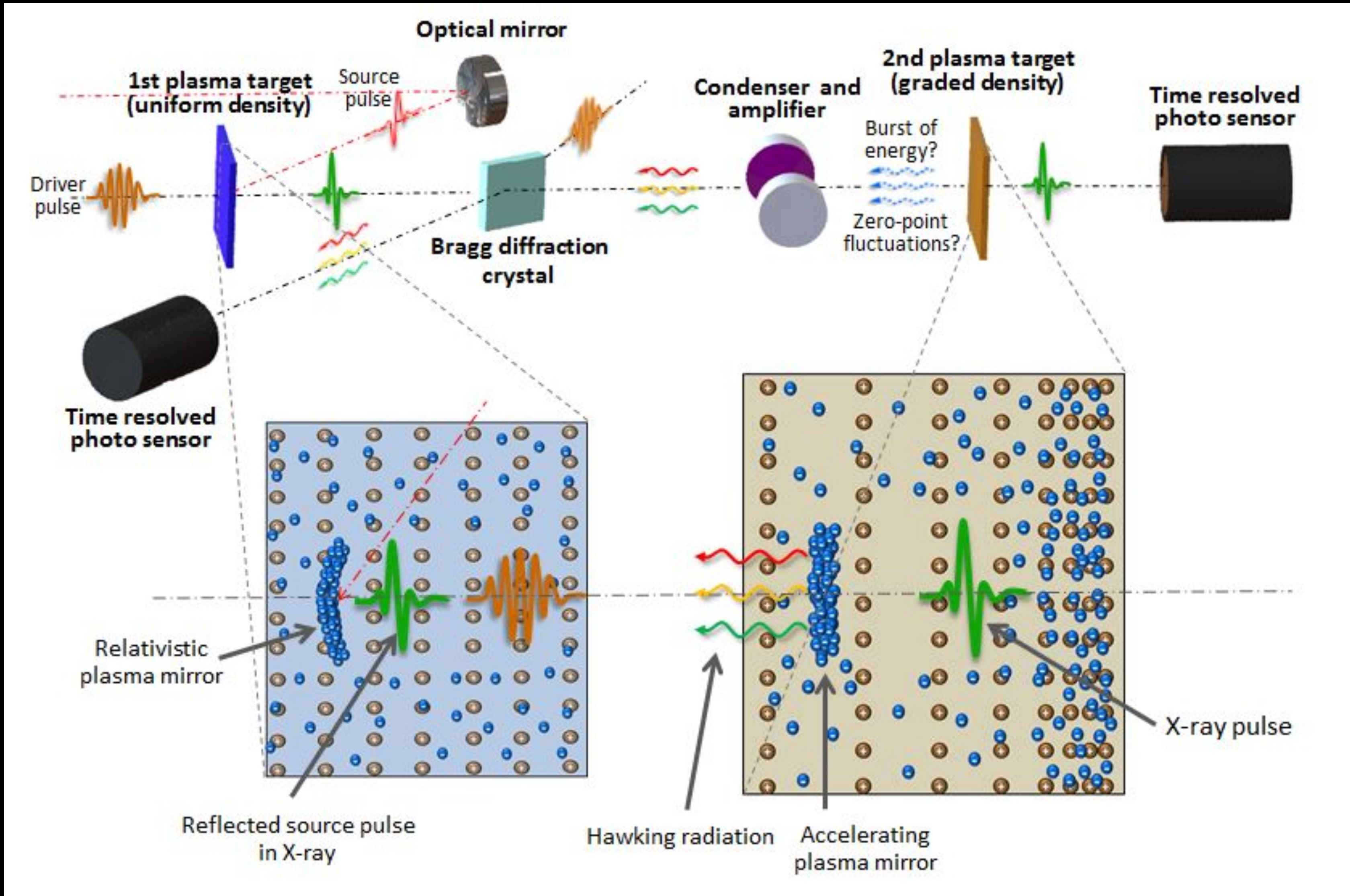
Finally,

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

Due to frequency redshift

Due to density gradient

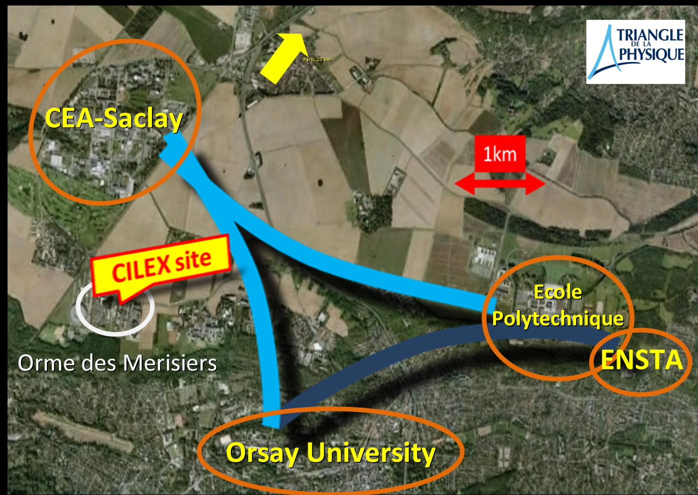
A conceptual design of the accelerating plasma mirror experiment



AnaBHEL (Analog Black Hole Evaporation via Lasers) Collaboration

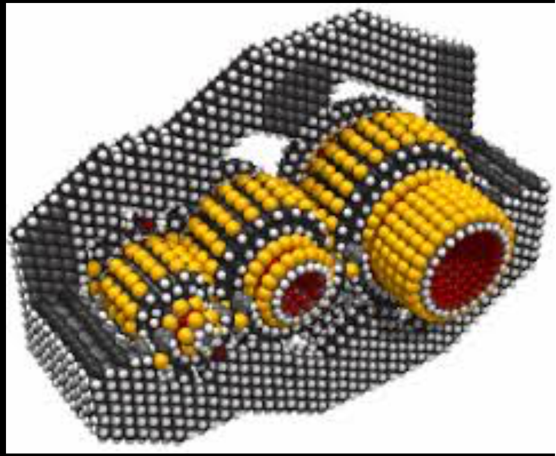
National Taiwan University + Ecole Polytechnique +
Kansai Photon Research Inst. + Shanghai Jiao Tong U.

- 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



Plasma density variation

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



- Invoking nano-fabrication technology for solid plasma targets with, for example, a power-law increase of density. Then the acceleration is

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

Example

- The 4 length scales should satisfy the inequality:

$$\lambda_{x-ray} \ll \lambda_p \ll D \ll X. \quad (\lambda_{x-ray} \simeq 1.2nm)$$

- Plasma target based on nanotechnology with

$D = \lambda_p = 100nm$, thickness $X = 5D$, and density

$$n_{p0} = 1.3\times 10^{25} - n_p(x = X) \sim 4.1\times 10^{25}\, cm^{-3}$$

- Laser power requirement: $10PW$ (100PW even better)
- Reflectivity of plasma mirror: $Y \approx 1$

→ Corresponding Hawking temperature:

$$k_B T_H(x) \simeq \frac{\hbar c}{4\pi D}\frac{\omega_{p0}^2}{\omega_0^2}\frac{1}{(1+x/D)^2}\exp\left\{\frac{(1-\eta_0)x/D}{1+x/D}\right\} \sim 0.1 - 0.004 eV.$$

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

Summary

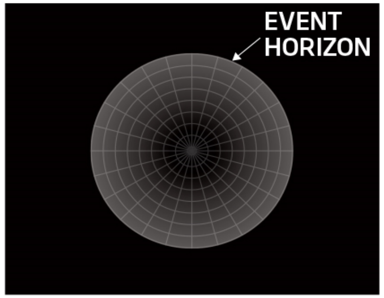
- Hawking evaporation and information loss paradox is one of the fundamental problems in physics.
- So far most investigations are limited to theoretical studies.
- Quantum entanglement between Hawking radiation and partner particle may reveal the secrete.
- Accelerating plasma mirrors may serve to address some aspects of this paradox experimentally.
- Extreme light can provide a unique tool to investigate General Relativity and black hole physics

A Brief History of BHs

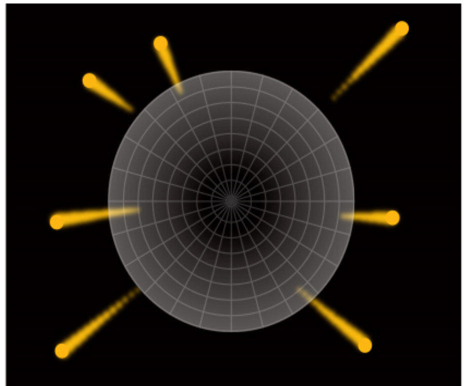
1916
General Relativity predicted the existence of BH

Brief history of black holes

1916
Black holes emerge from general relativity: nothing, not even light, escapes the event horizon

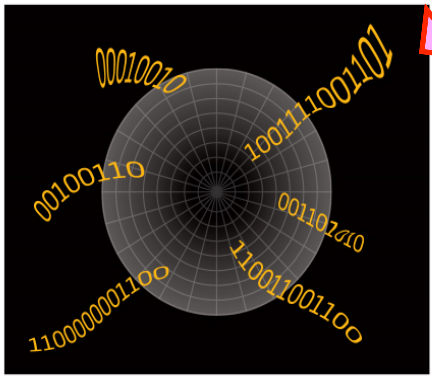


1974
Black holes emit **Hawking radiation** thanks to quantum mechanics



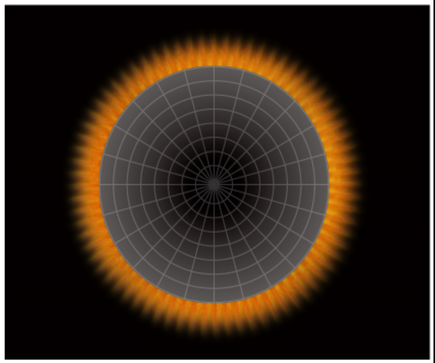
1974
Hawking theoretically discovered BH evaporation

2004
Hawking accepts that **information escapes** from black holes



2004
Hawking agreed that BH information is preserved

2012
Escaping information ignites **firewall,** which can't be reconciled with general relativity



2012
AMPS conjectured firewalls

Can the BH war be settled through experiments ?

2016
COPSY argued that firewalls are naked