Extreme Light Induced Plasma Mirrors to Investigate

Black Hole Information Loss Paradox

P. Chen & G. Mourou, arXiv:1512.04064

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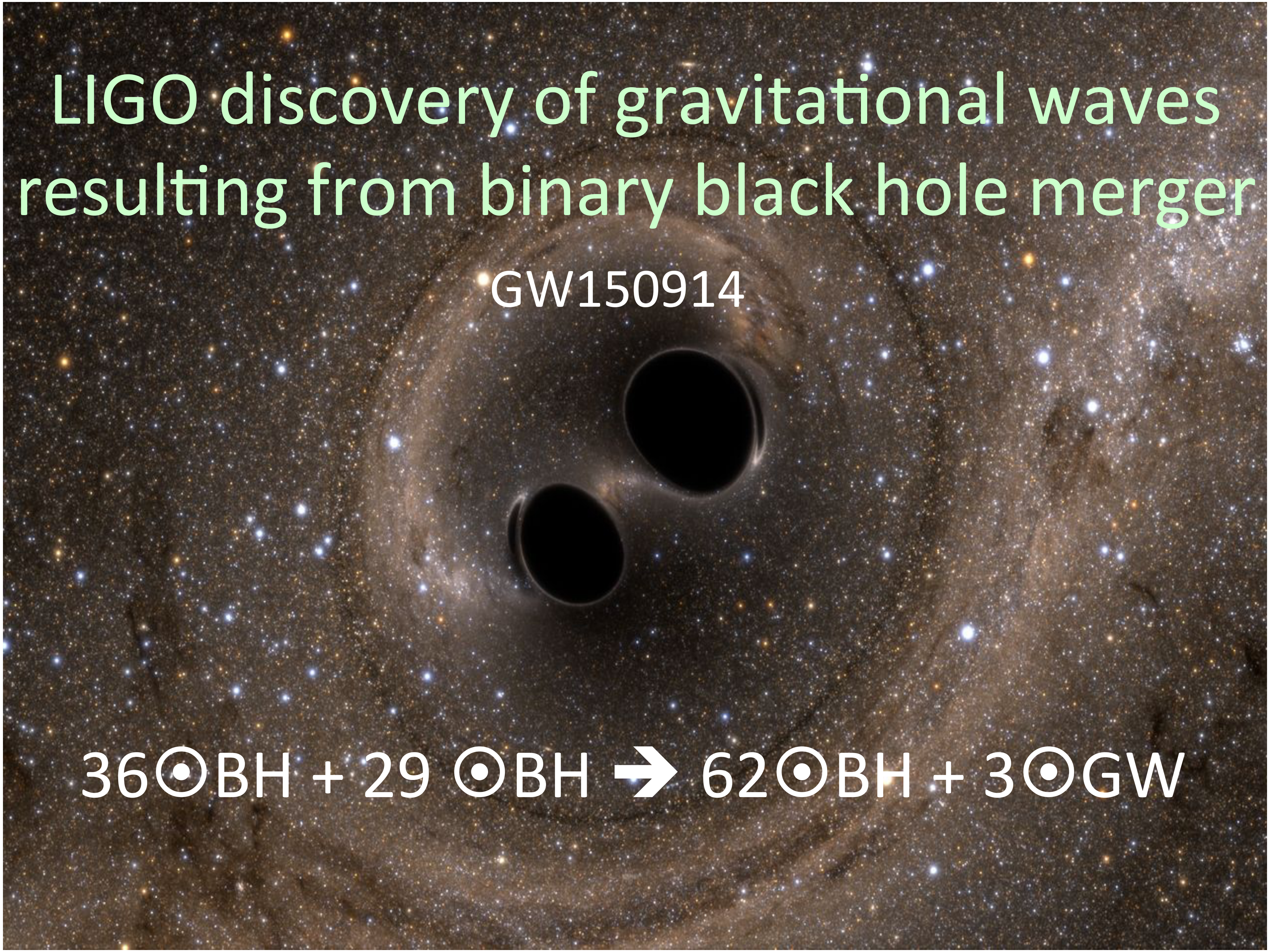
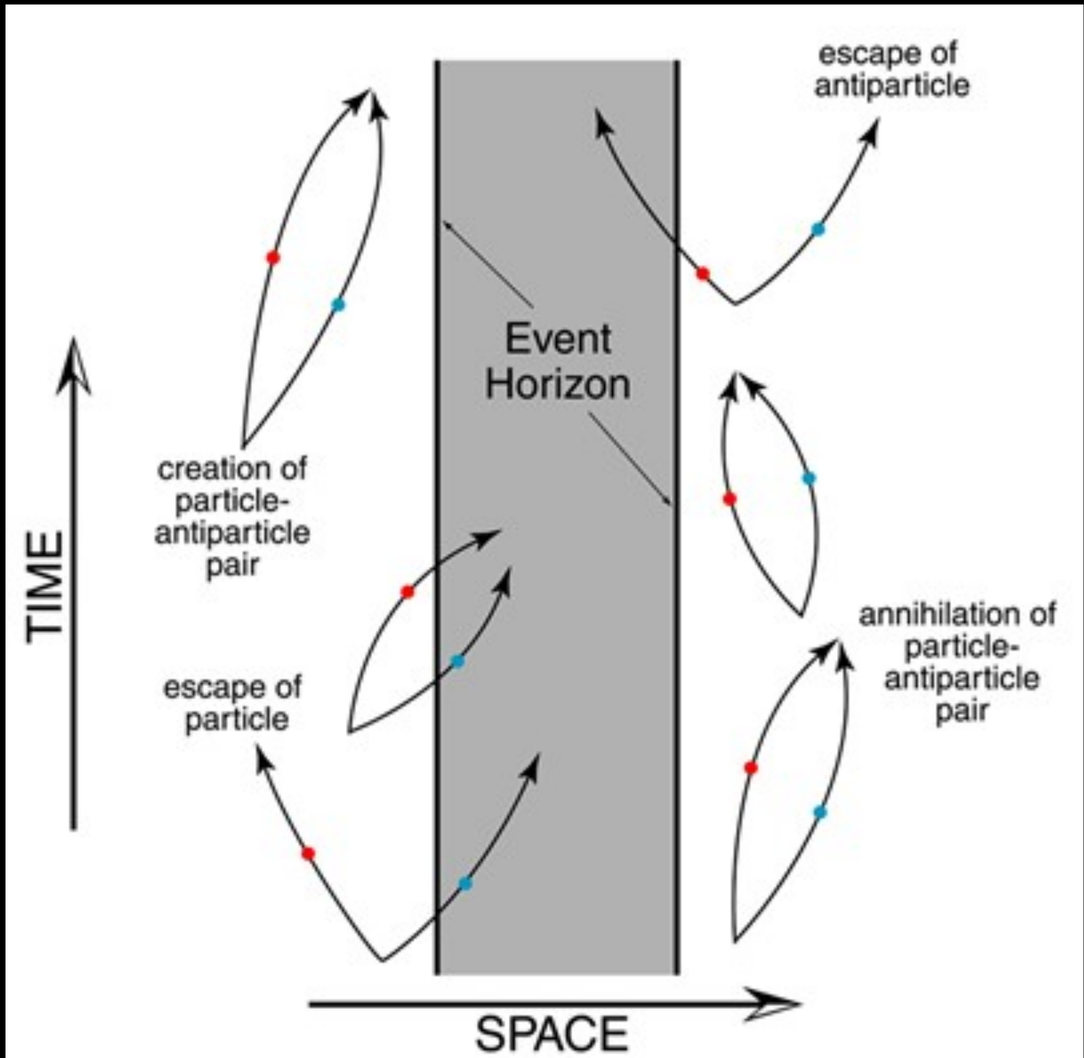

LIGO discovery of gravitational waves resulting from binary black hole merger
GW150914
36$\odot$BH + 29 $\odot$BH → 62$\odot$BH + 3$\odot$GW

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:

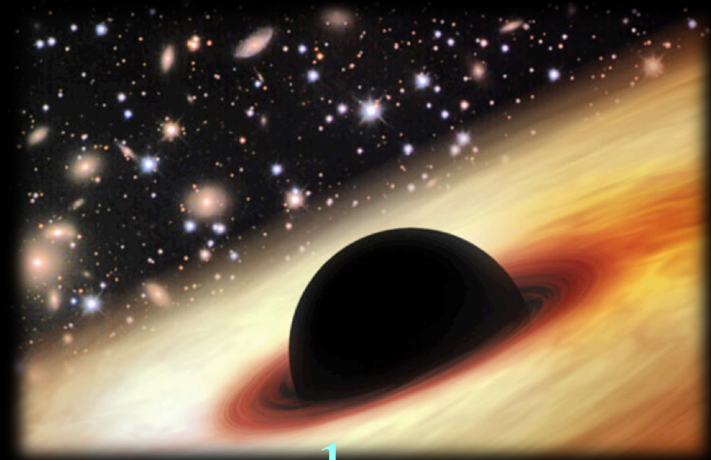
Planck's Constant [Quantum Mechanics]

Relativity

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

Boltzmann's Constant [Thermodynamics]

Newton's Constant [Gravity]



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

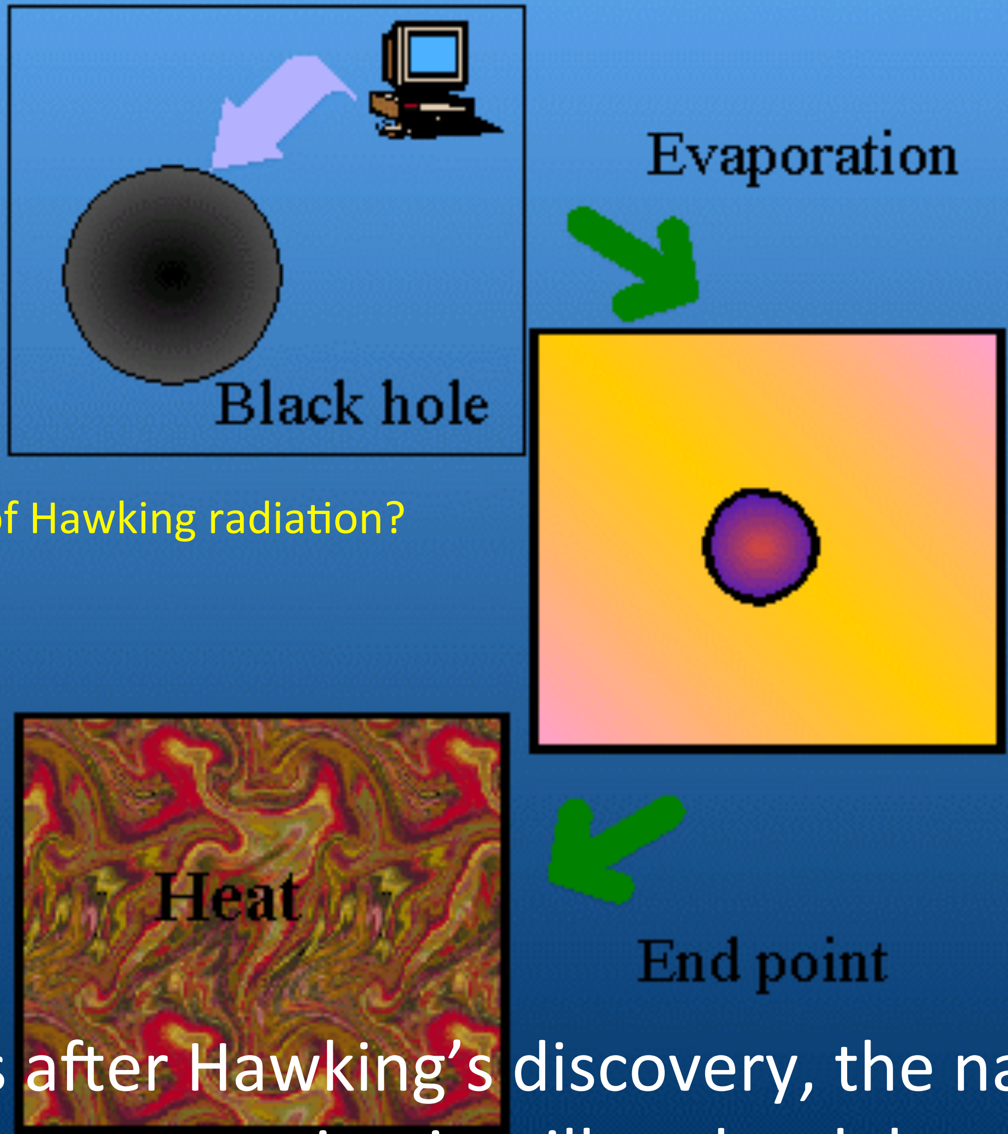
Black hole surface area: $A = 4\pi r_h^2 \propto M^2$

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 x 10^{10} years

Information Loss



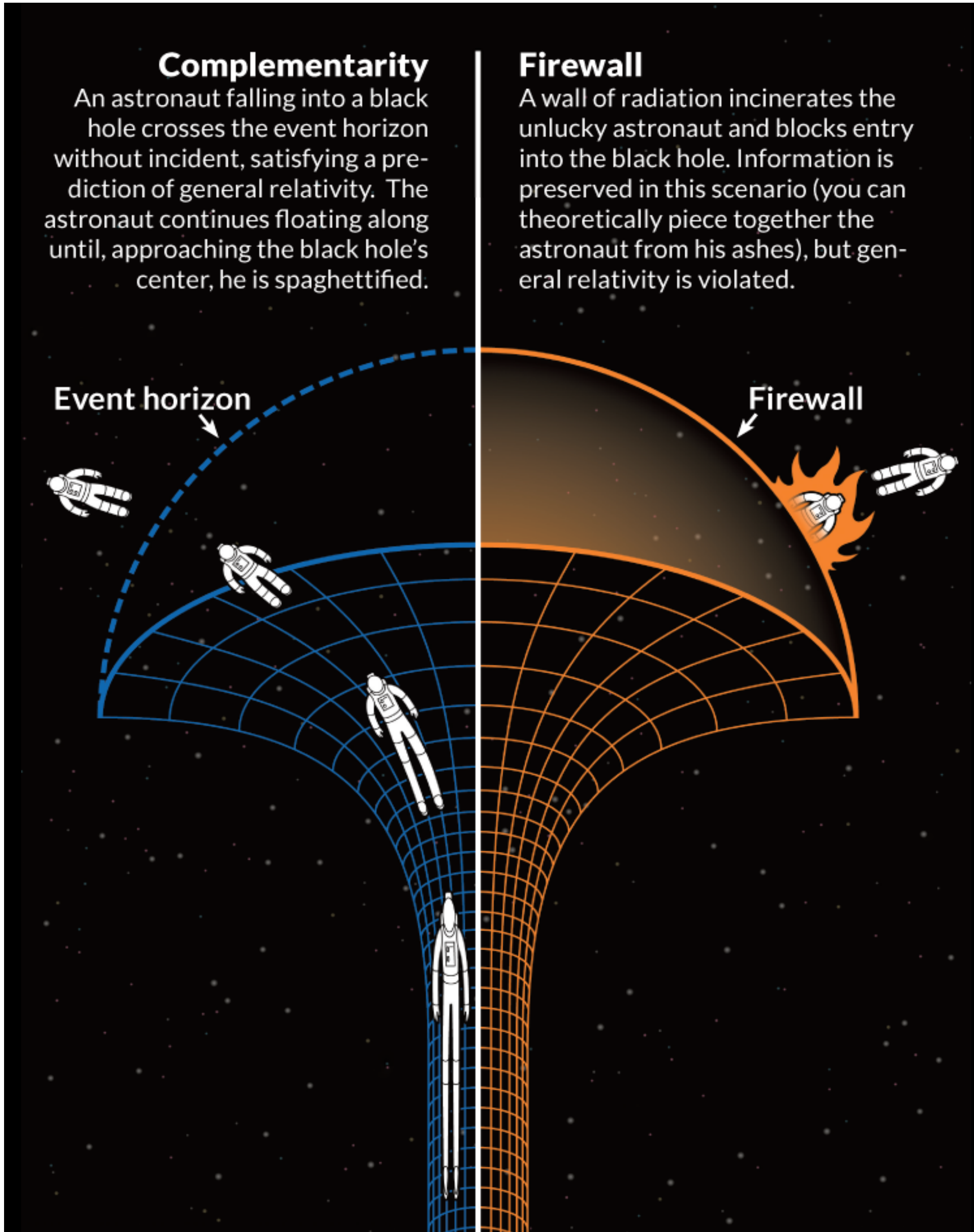
- Entanglement of Hawking radiation?
- Firewall?
- Fussball?
- Etc., etc., etc.

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)
- Latest: Soft hair (Hawking-Perry-Strominger, 2016)
- etc., etc., etc.



General relativity:

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

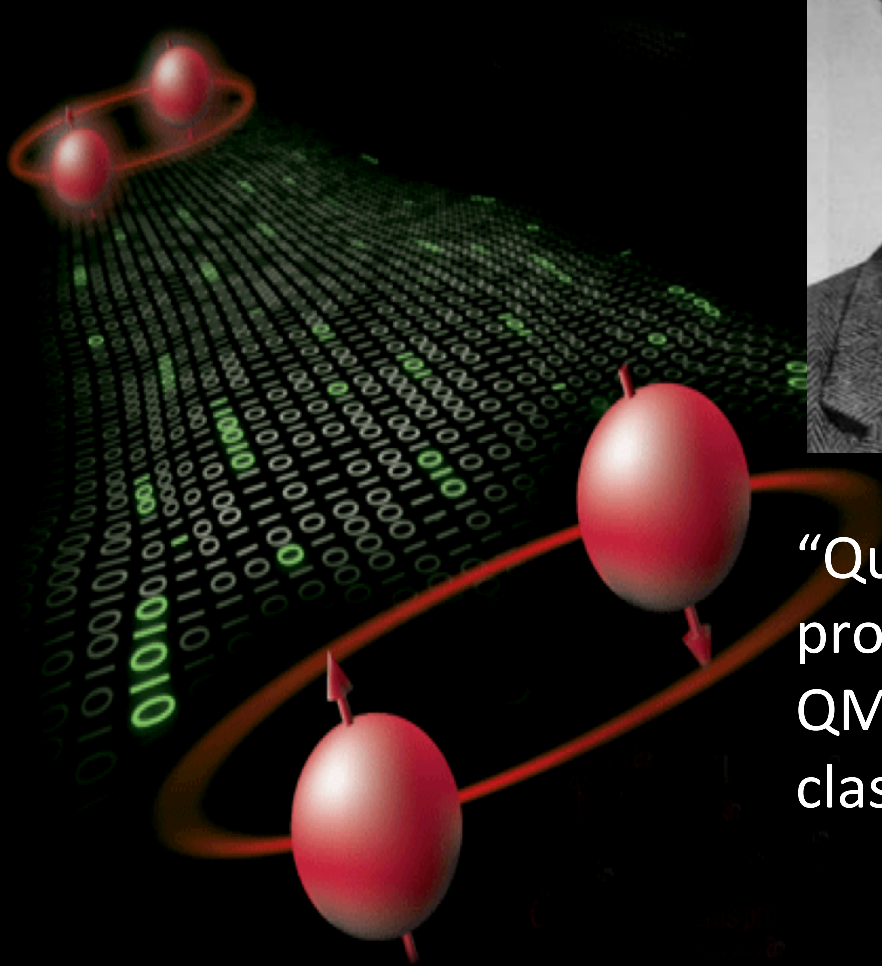
AMPS firewall:

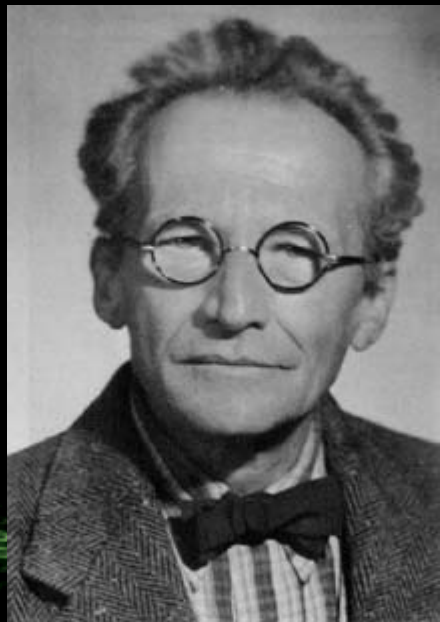
The requirement that Hawking radiation can bring information out from BH would result in the notion of firewall.

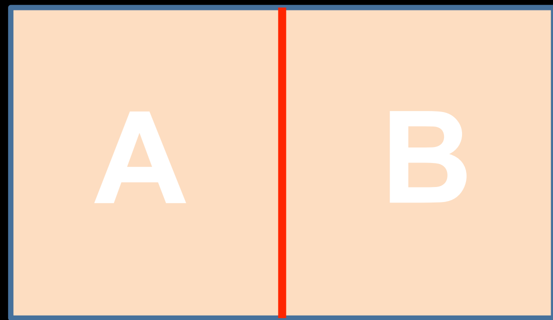
Can Hawking radiation carry out information after all?

Quantum entanglement

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

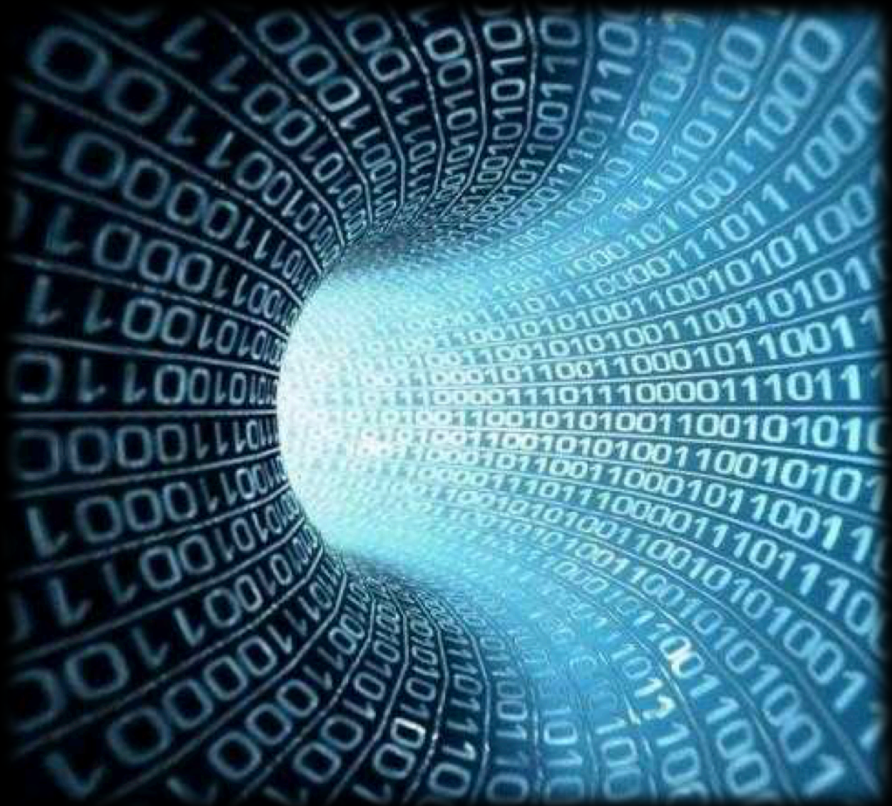






"Quantum entanglement is not just a property of QM, it is THE character of QM. It fundamentally breaks QM from classical physics.

What is quantum entanglement?



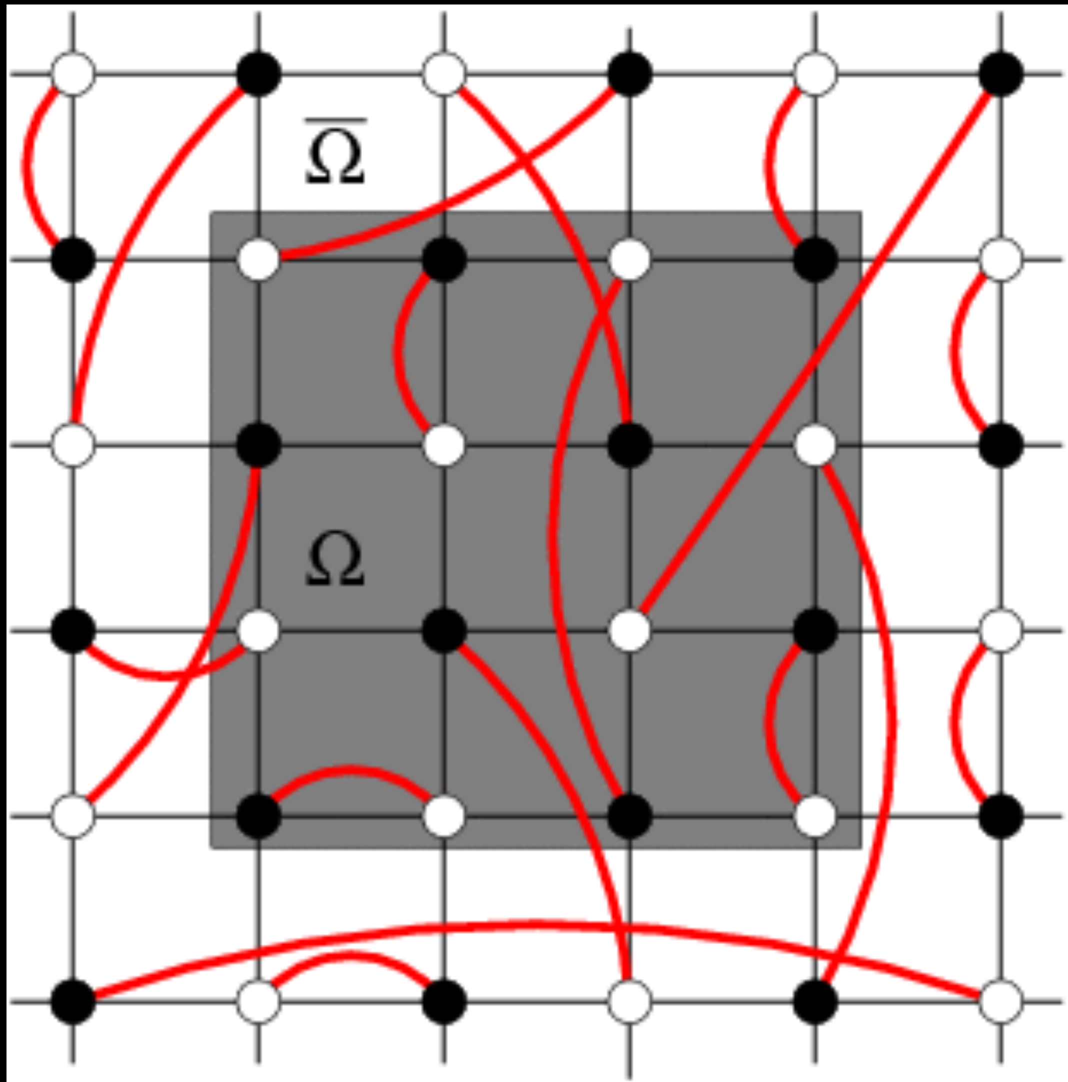
Thermodynamics:

Entropy ⟷ Disorder

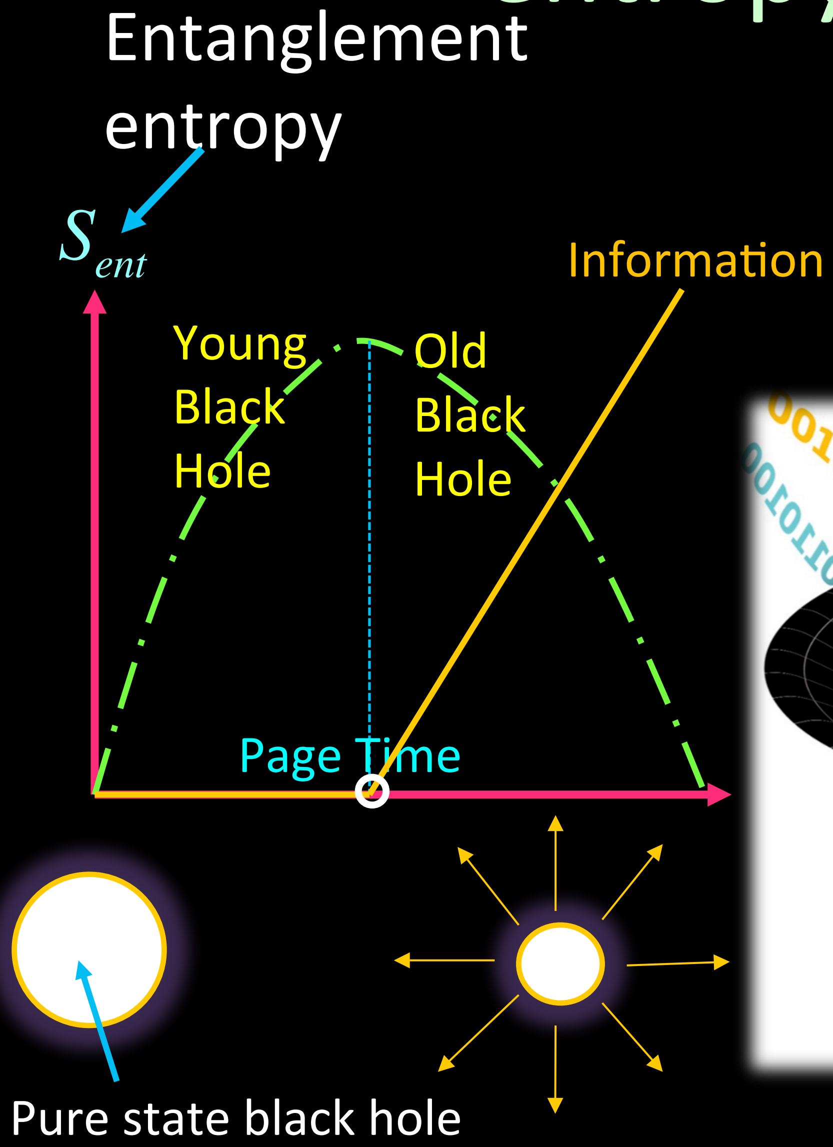
Quantum Informatics:

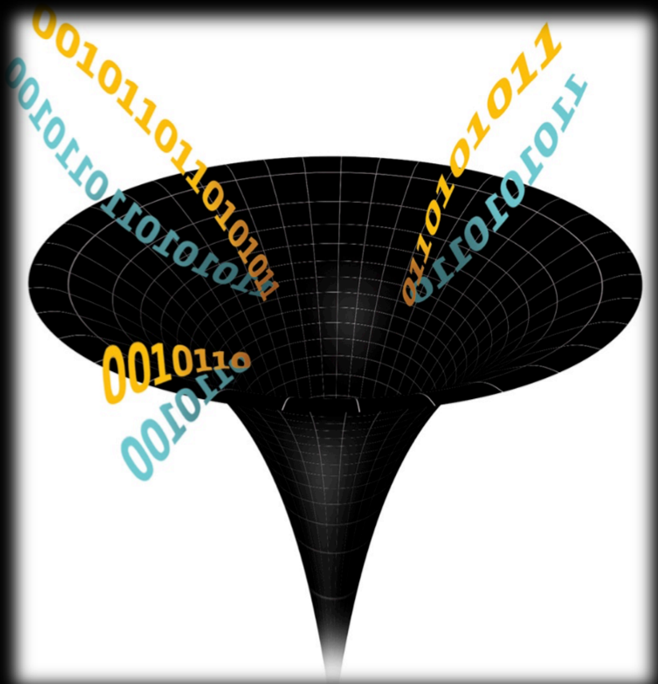
Entanglement Entropy ⟷ How tangled the system is

Monogamy of quantum entanglement



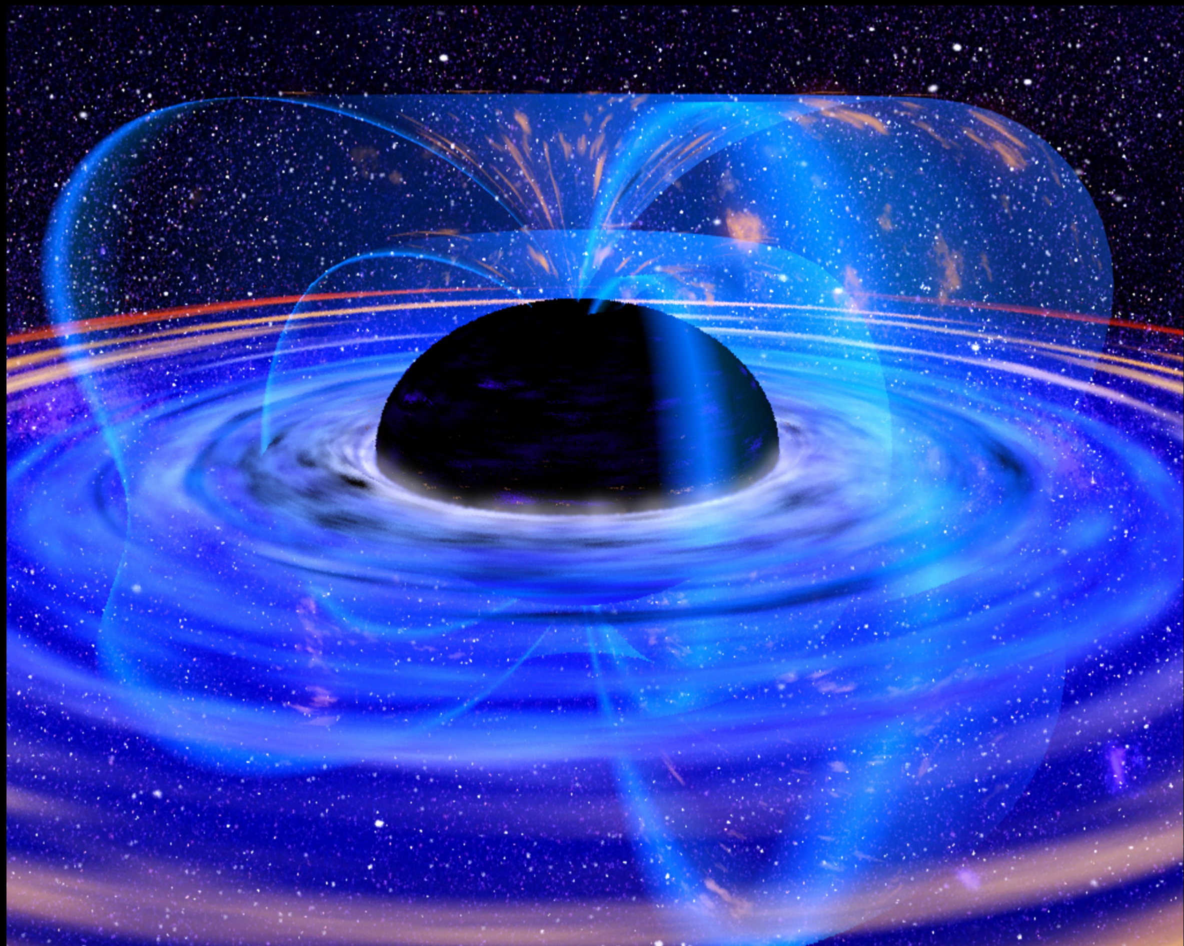
When would BH entanglement entropy come out?





Don Page

Investigations of ILP mostly theoretical. Astro black holes too cold and too young.



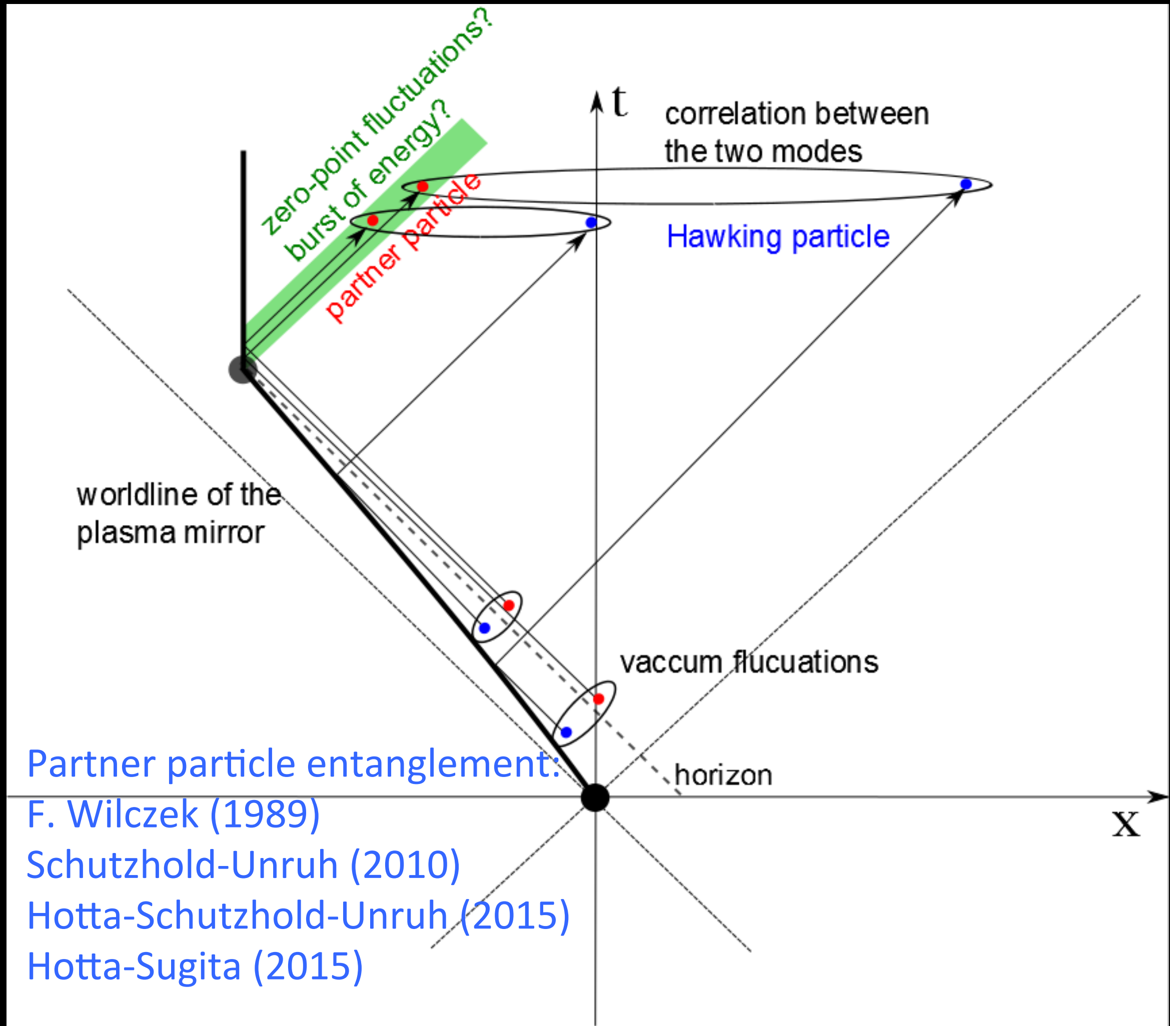
Analog Black Holes

- 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)

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

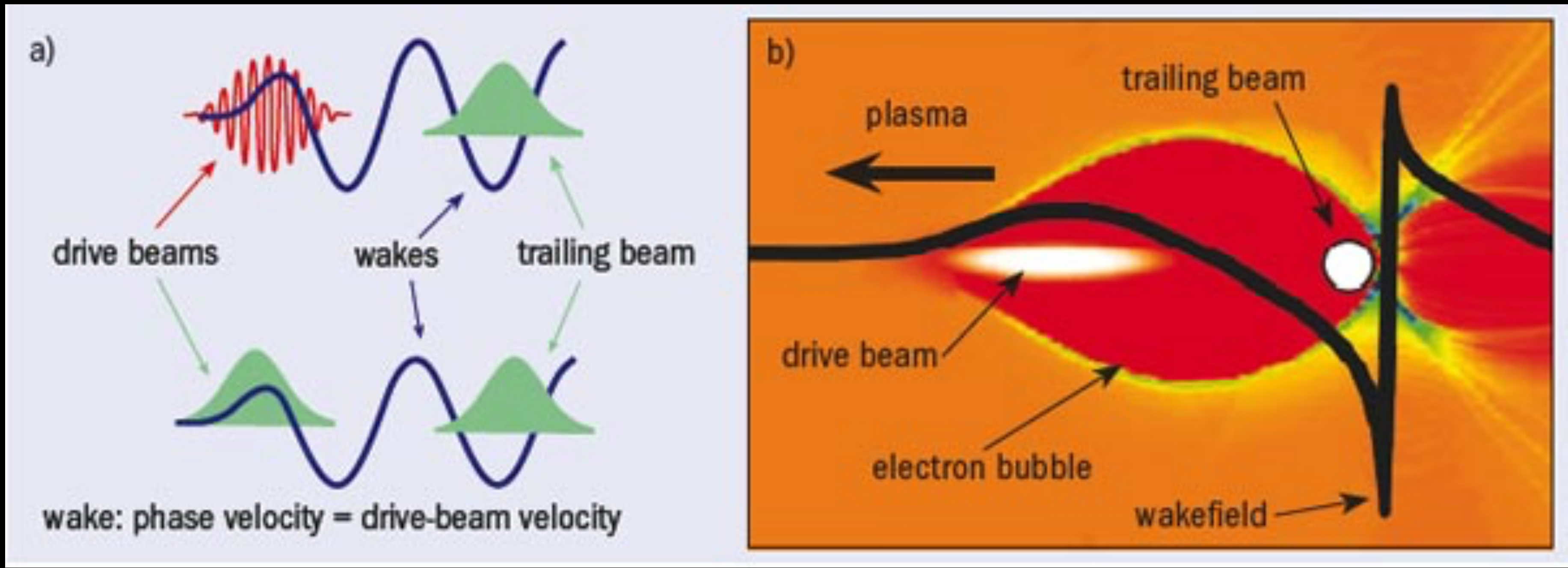


Partner particle entanglement:
F. Wilczek (1989)
Schutzhold-Unruh (2010)
Hotta-Schutzhold-Unruh (2015)
Hotta-Sugita (2015)

Plasma wakefield acceleration

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

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



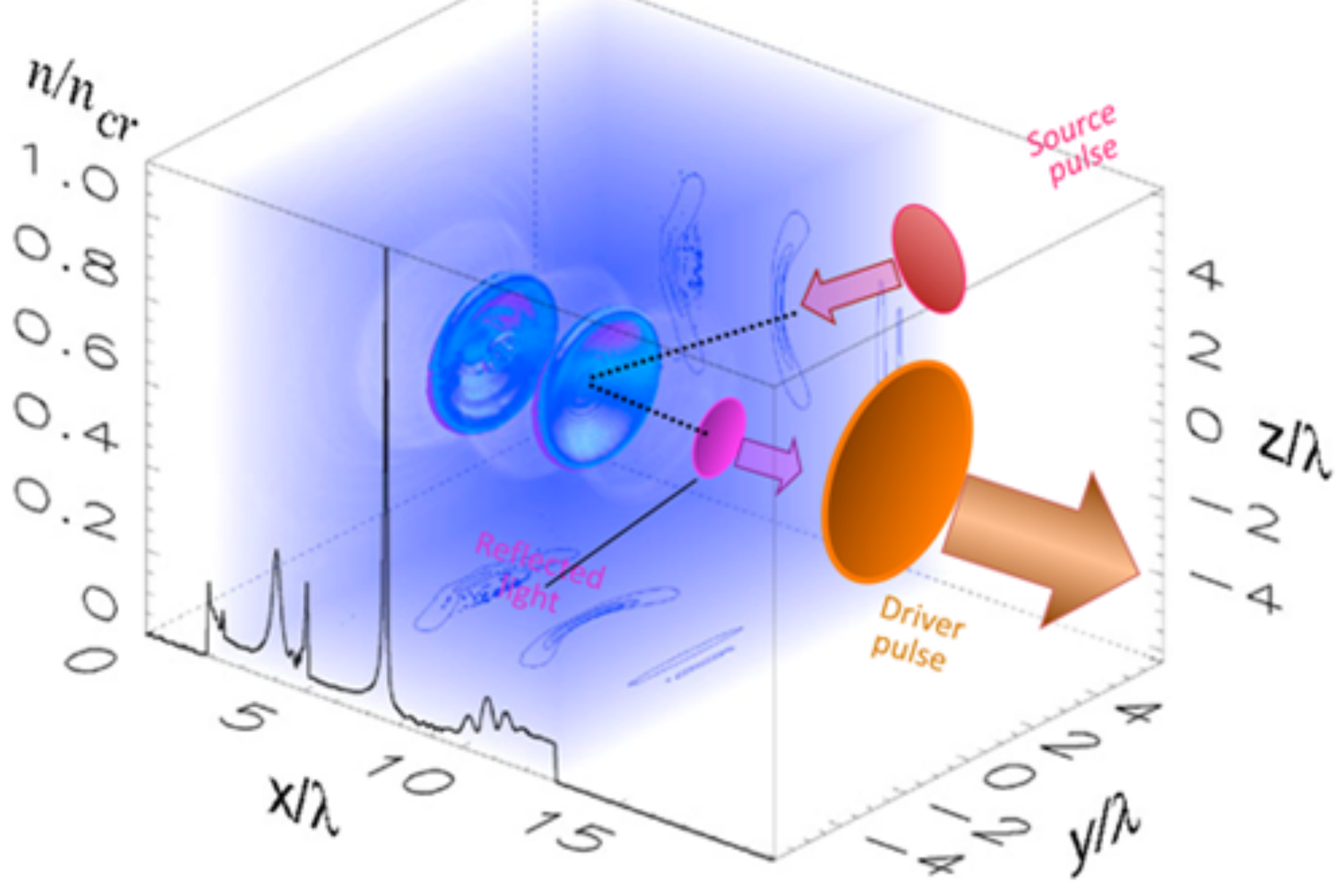
SLAC & LBL- Acceleration of O(100) GeV/m observed!

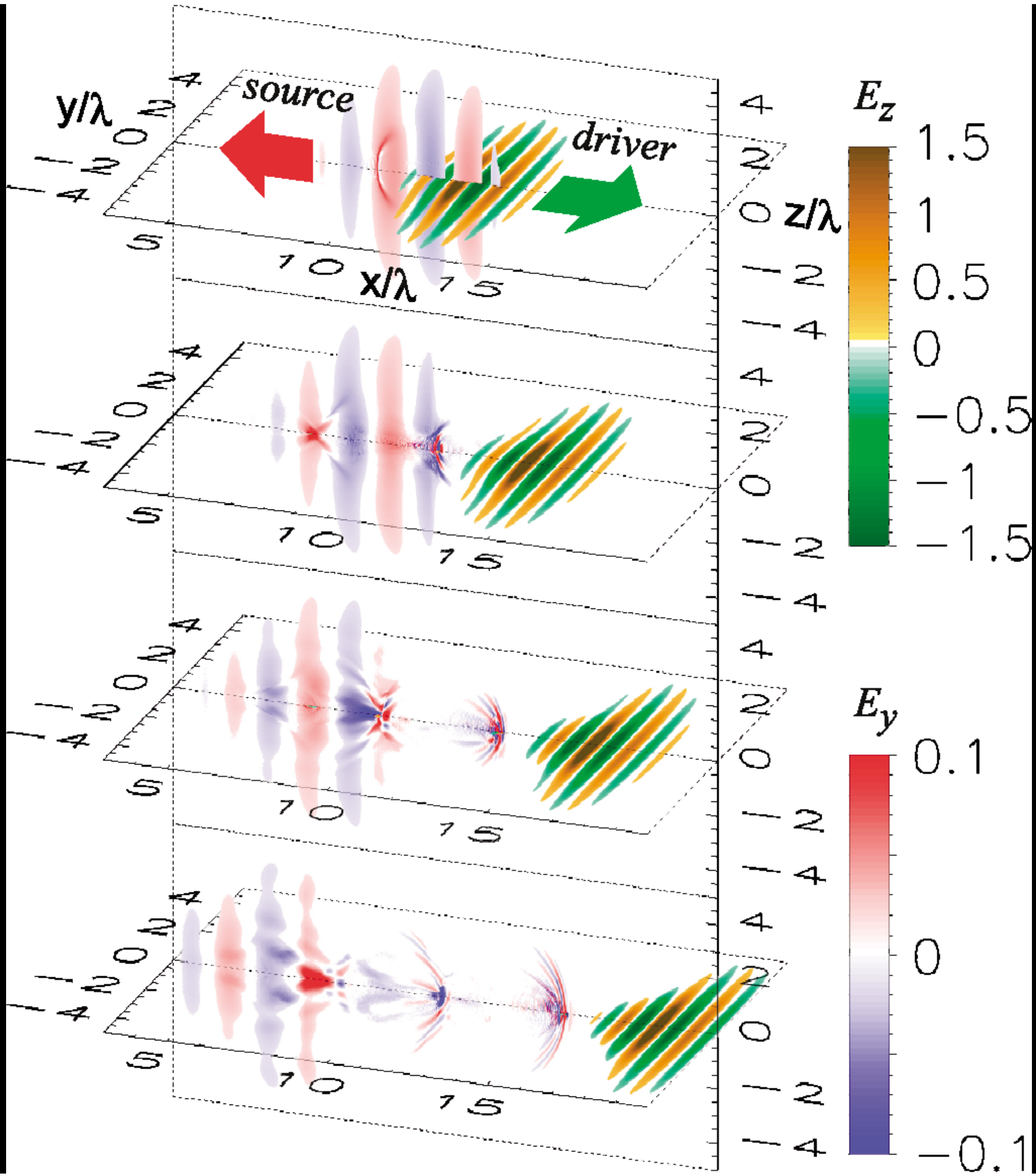
AWAKE- A new experiment at CERN

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
E_z
1.5
1
0.5
0
−0.5
−1
−1.5
E_y
0.1
0
−0.1
4
2
0
−2
−4
5
10
15

Accelerating plasma mirrors?

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

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

- Natural tendency of deceleration (redshift) of the laser (and therefore the mirror) due to wakefield excitation.
- But in nonuniform plasmas, the dispersion relation allows the laser group velocity, and therefore the plasma mirror phase velocity, to accelerate.

M. Lobet et al., Phys. Lett. A 377, 1114 (2013).

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

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

Finally,

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

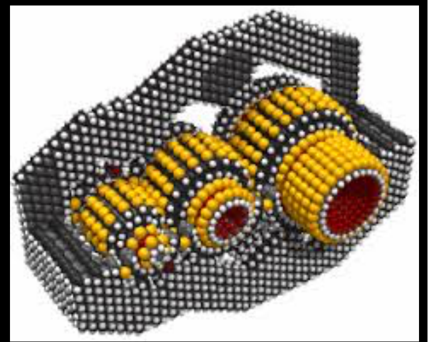
$$+c\eta_0 v_g\left(\frac{\partial \omega_p}{\partial x}\frac{1}{\omega_p}+\frac{\partial^2 \omega_p}{\partial x^2}\frac{x}{\omega_p}\right)\exp\left(\frac{\partial \omega_p}{\partial x}\frac{x}{\omega_p}\right).$$

Due to frequency redshift

Due to density gradient

Plasma density variation

- Invoking nano-fabrication technology for solid plasma targets with, for example, an exponential increase of density



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

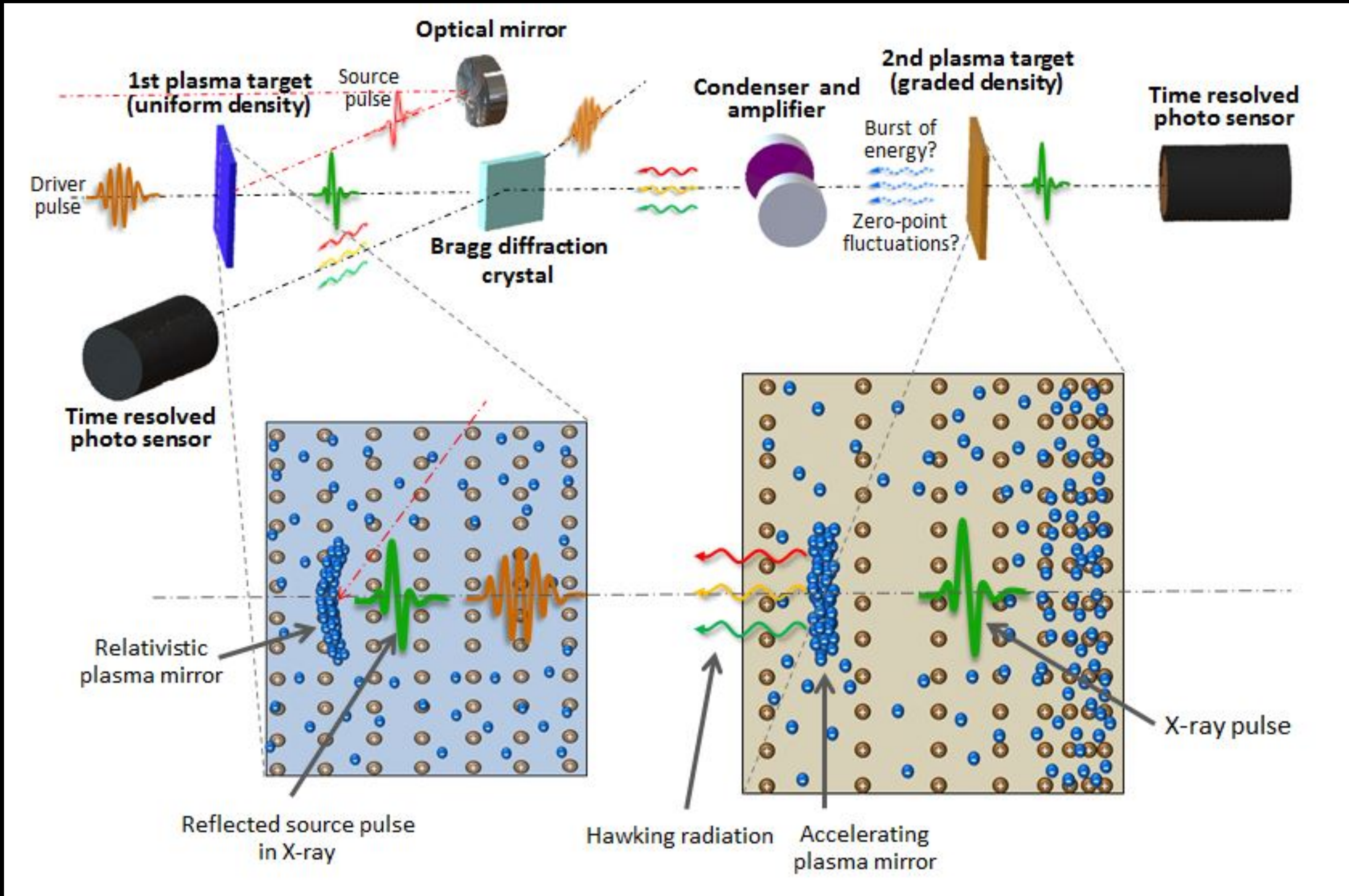
- Then the velocity approaches c asymptotically:

$$\frac{v_{ph}}{c} = 1 - \frac{1}{2}\frac{\omega_{p0}^2}{\omega_0^2}\left[1 - \frac{x/D}{1+x/D}\right] + O\left(\frac{\omega_{p0}^4}{\omega_0^4}\right).$$

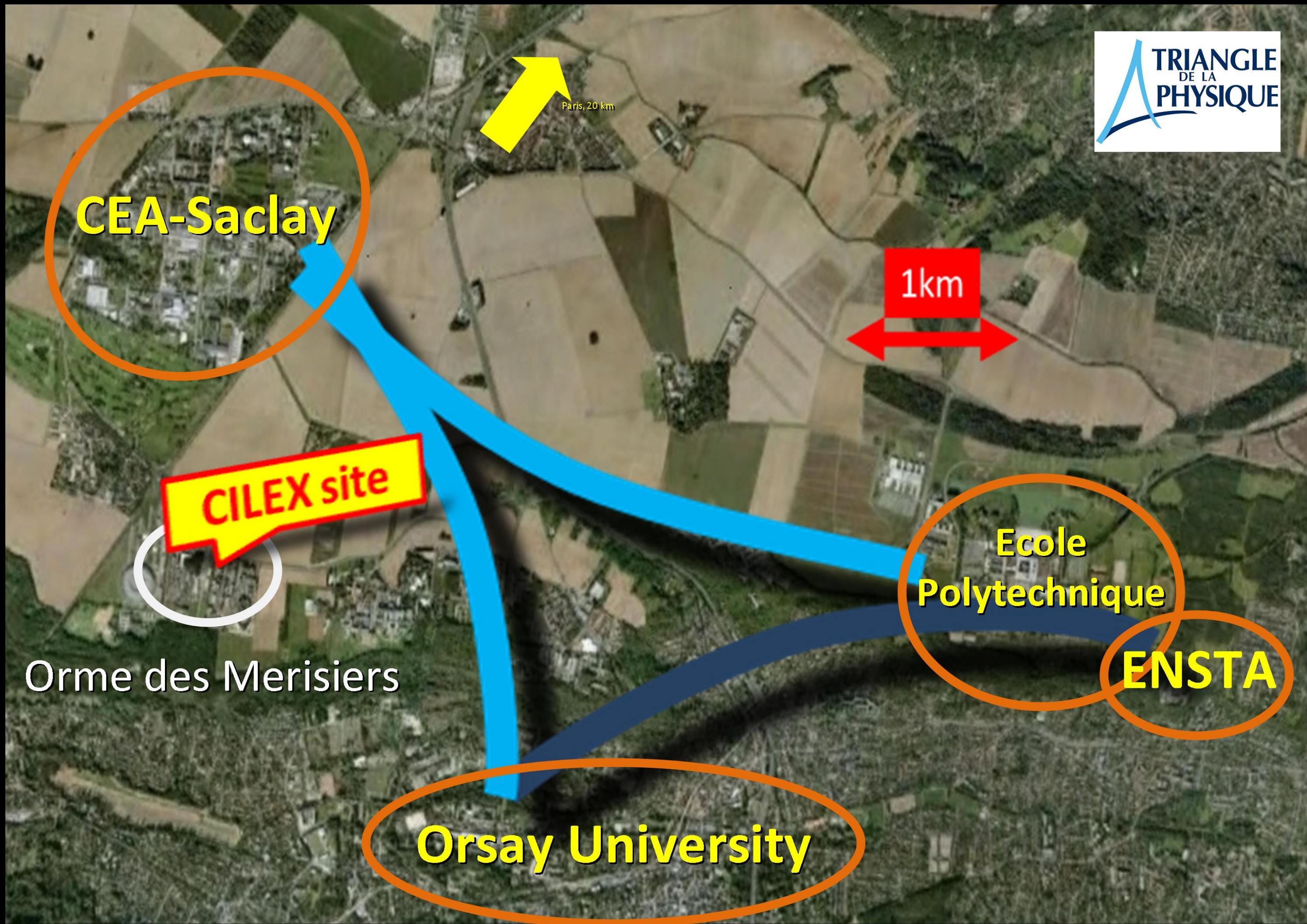
- This leads to the Hawking temperature

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

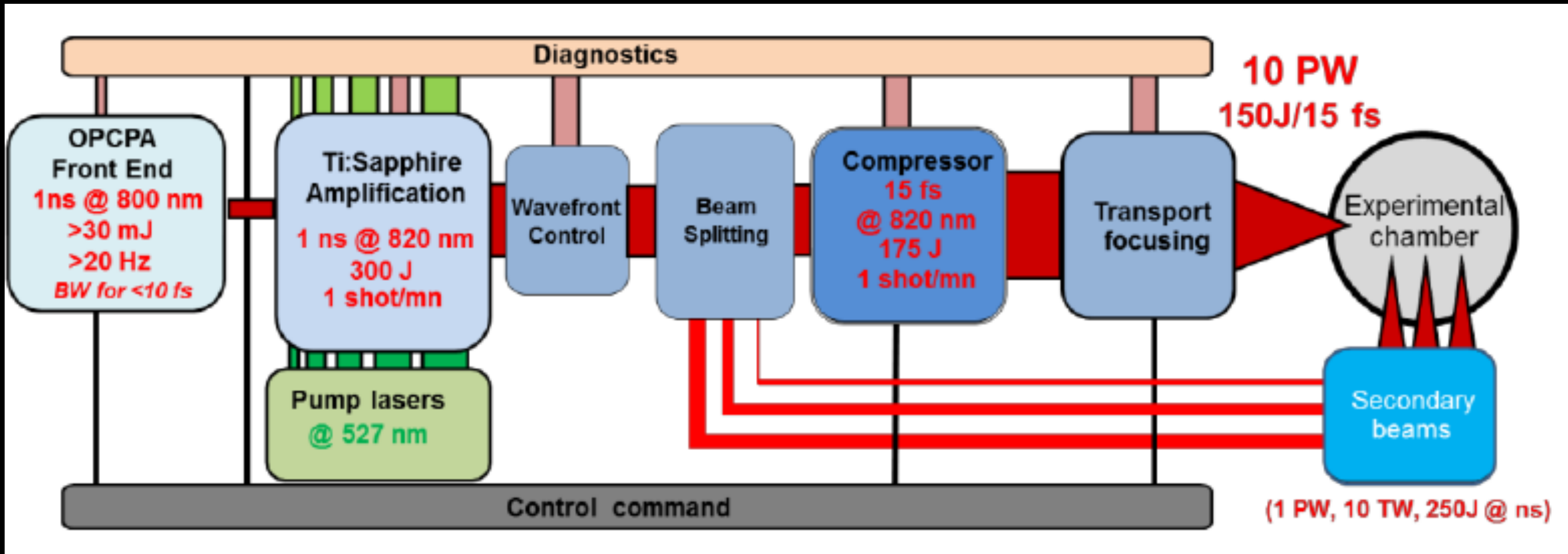
A conceptual design of the accelerating plasma mirror experiment



Cilex, Centre Interdisciplinaire Lumière Extrême – APOLLON Laser



APOLLON Laser



Design based on single cycle APOLLON

- Design principle: hierarchy of 4 key length parameters

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

- Plasma target based on nanotechnology with $D = 10\lambda_p = 100nm$, thickness $X = 5D = 500nm$, and density $n_{p0}(x=0) = 1.3\times 10^{25}\,cm^{-3}$ $n_{p0}(x=X) = 4.1\times 10^{25}\,cm^{-3}$
- Laser power requirement: $10PW$ A minor fraction used for creating the 1st mirror, with outcoming x-ray at $\sim 1keV$
- Impinging the 2nd, solid target, $a_x \sim 2.$

➡ Corresponding Hawking temperature:

$$k_B T_H(x) \sim 0.1 - 0.004 eV.$$

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