# Black Hole Information Loss Paradox and the AnaBHEL Experiment

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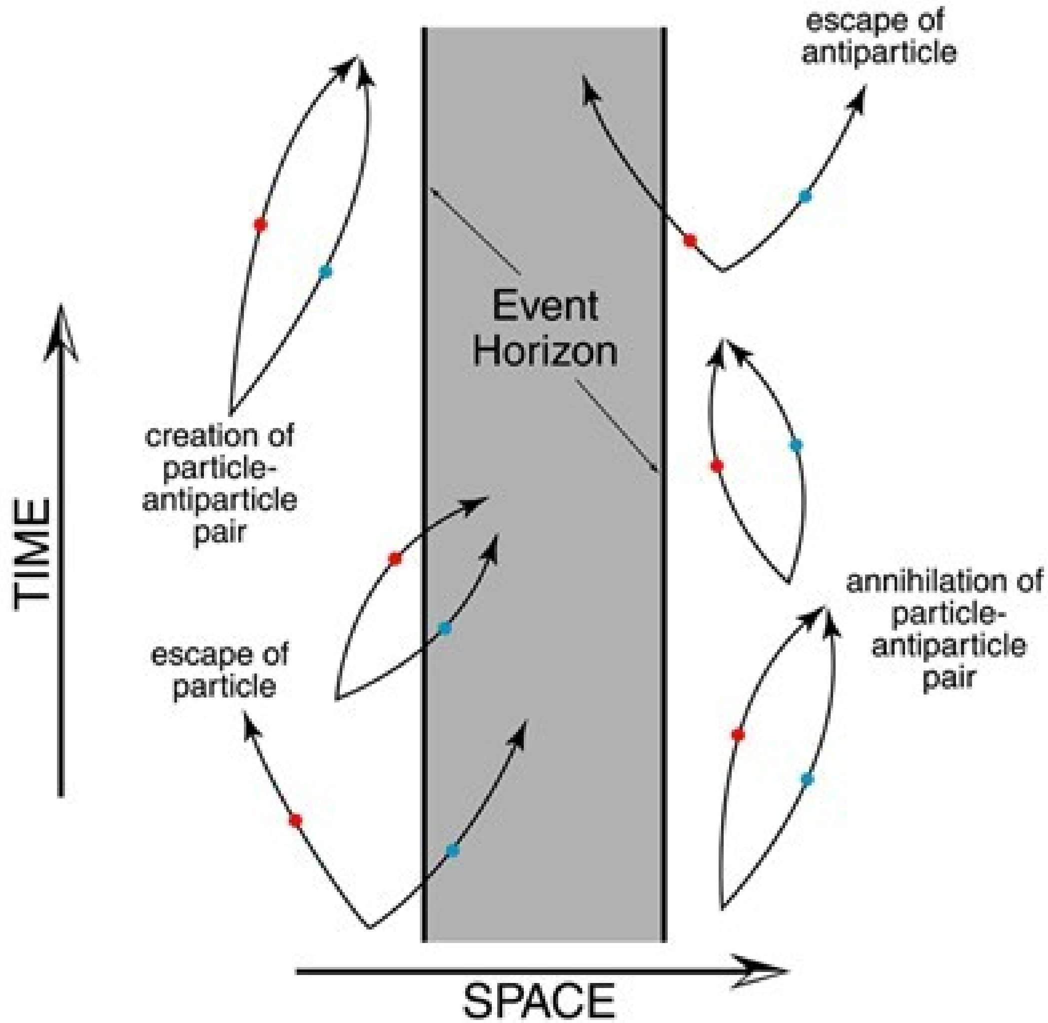
# Tribute to Stephen Hawking
## (1942-2018)

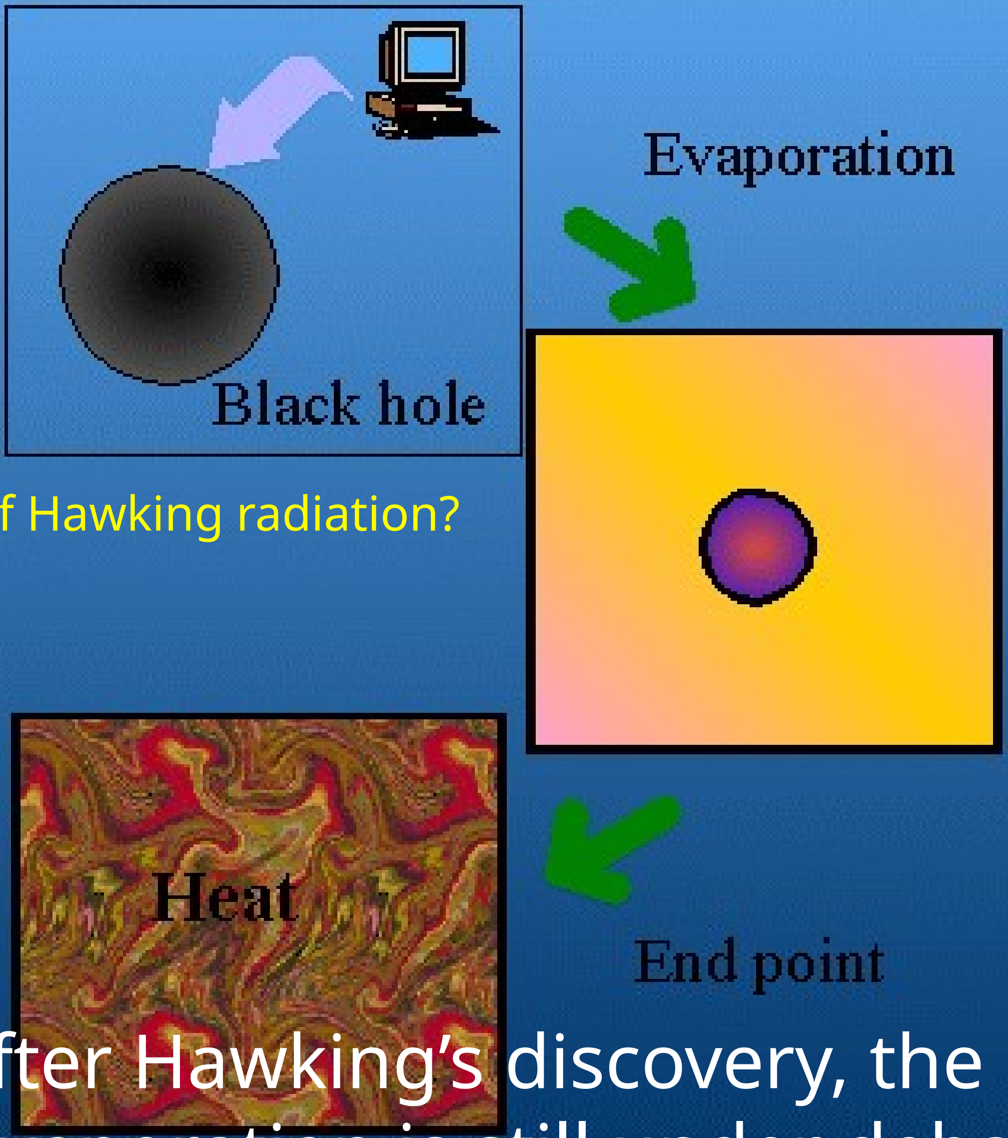
# Black hole Hawking evaporation – Connecting GR, QM, SM in one stroke

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

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



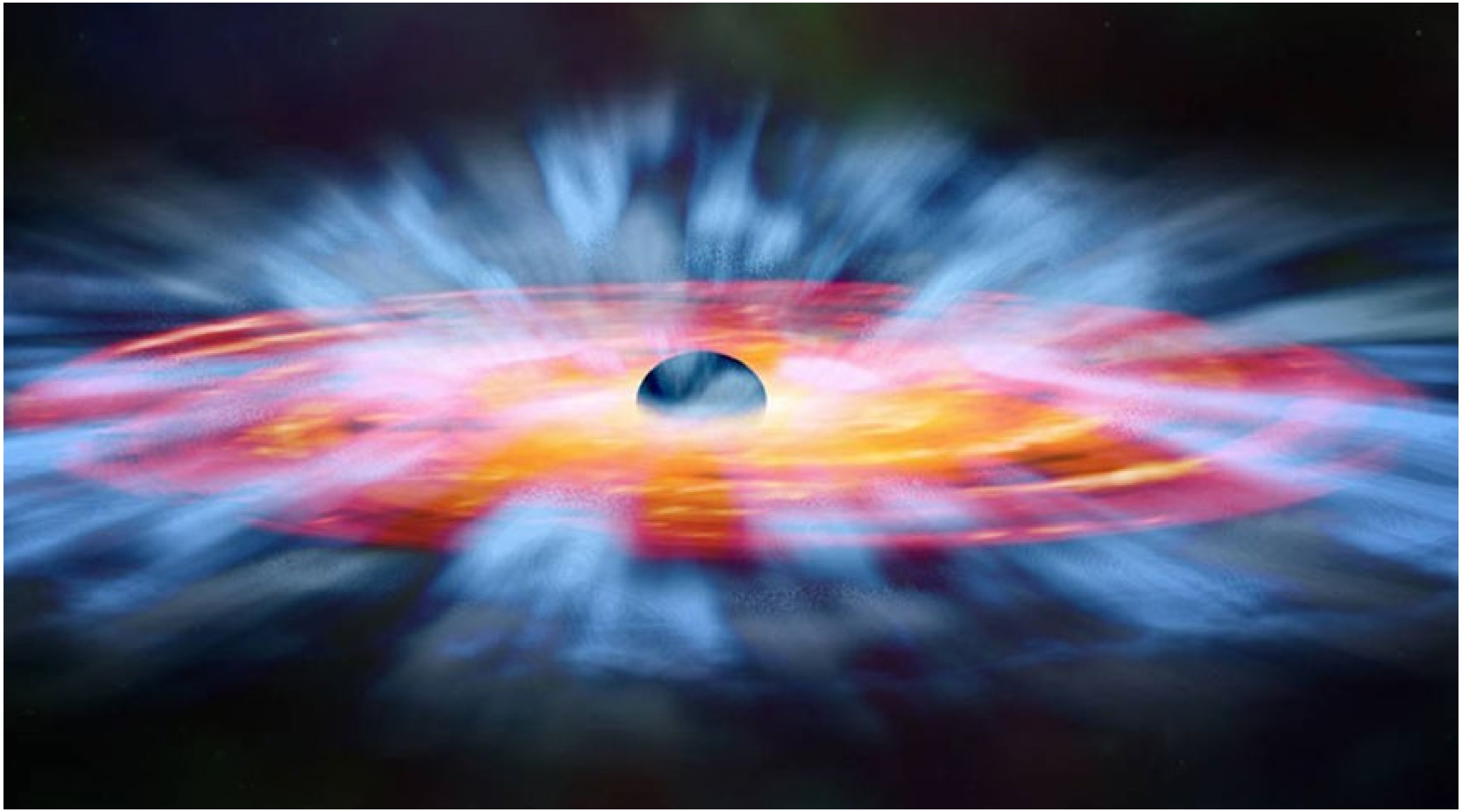
# Information Loss




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

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

# Can Hawking radiation carry information out after all? If so, how?

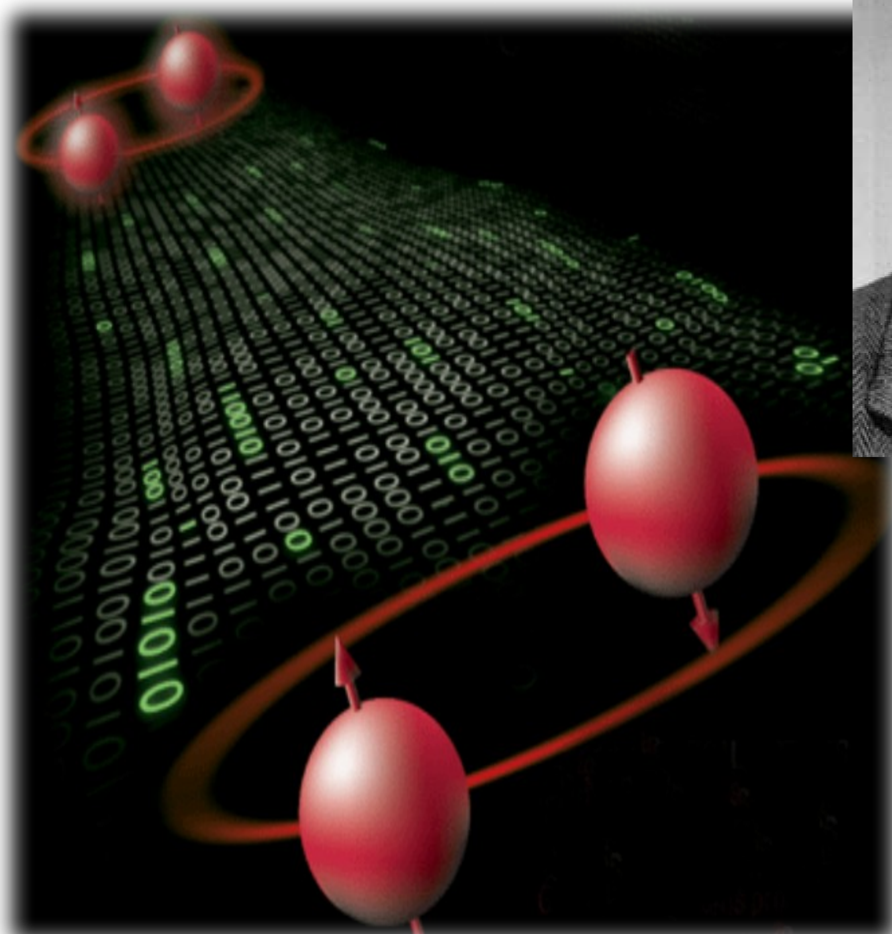


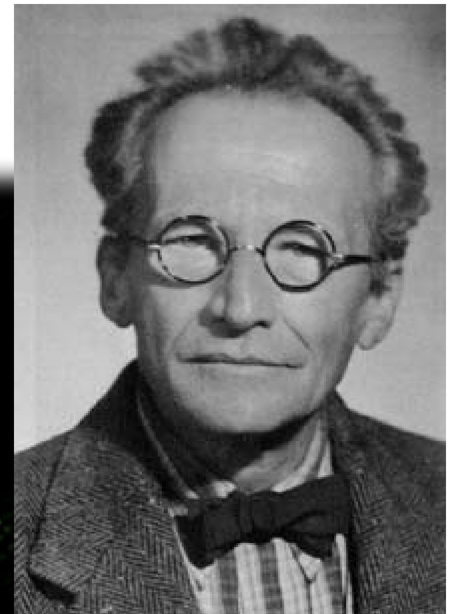
# Hawking evaporation may result in the loss of information!

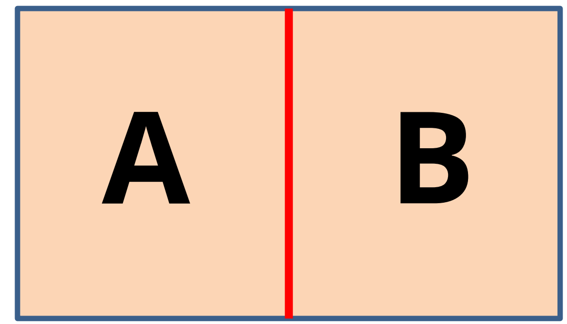
- First pointed out by Hawking himself in 1976
- Endless debates ever since
- Solutions include "black hole complementarity" (Susskind et al.), Firewalls (AMPS, AMPSS 2012), etc.
- Entanglement between Hawking radiation and partner particles (Wilczek 1987, Schutzhold-Unruh 2010, Hotta-Schutzhold-Unruh 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)
- Islands and replica wormholes based on string theory (Almheiri et al. 2019)
- Wave function of the universe and multi-histories (Chen-Sasaki-Yeom-Yoon 2021)

# Quantum entanglement

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

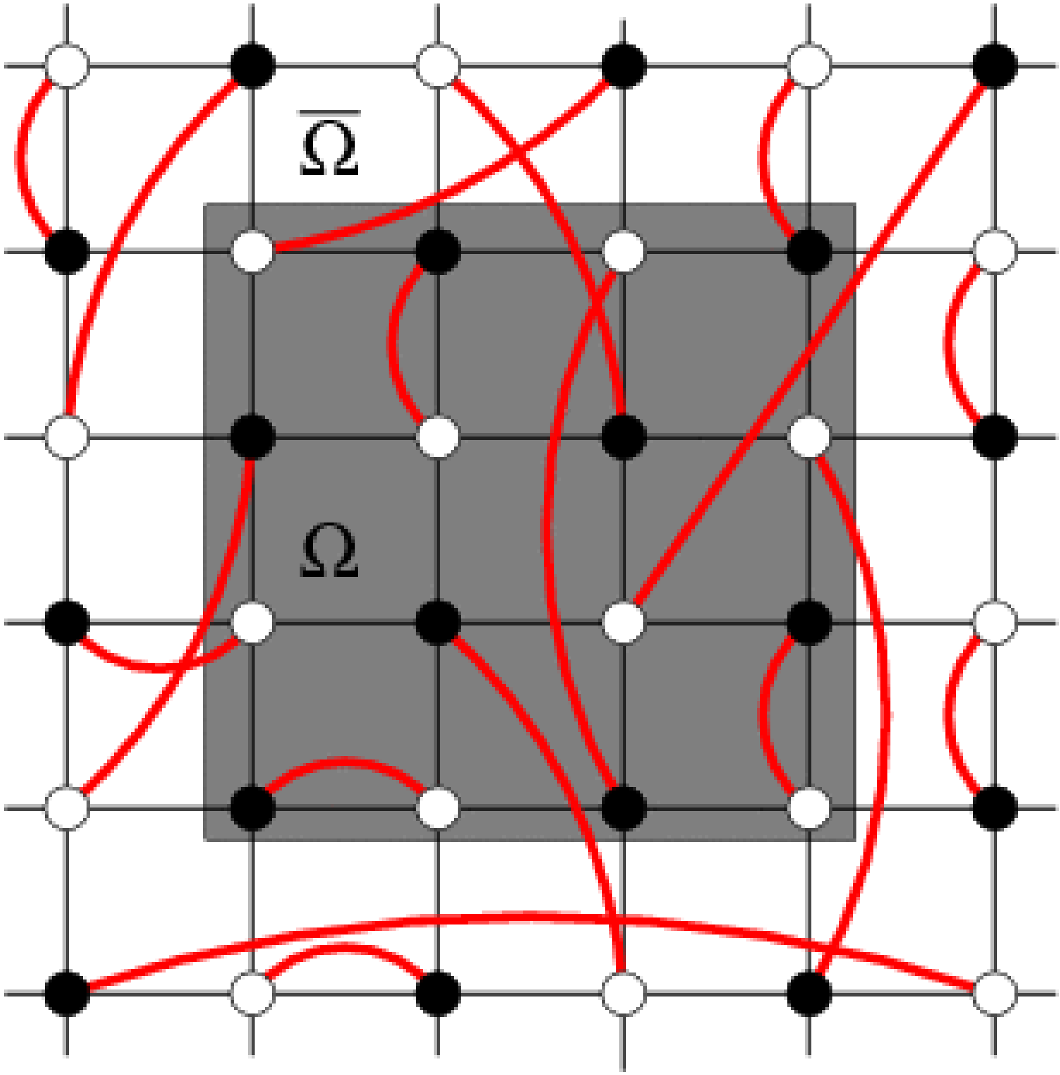







“Quantum entanglement is not just a property of QM, it is THE character of QM. It fundamentally breaks QM from classical physics.” (E. Schrodedinger)

# Monogamy of quantum entanglement

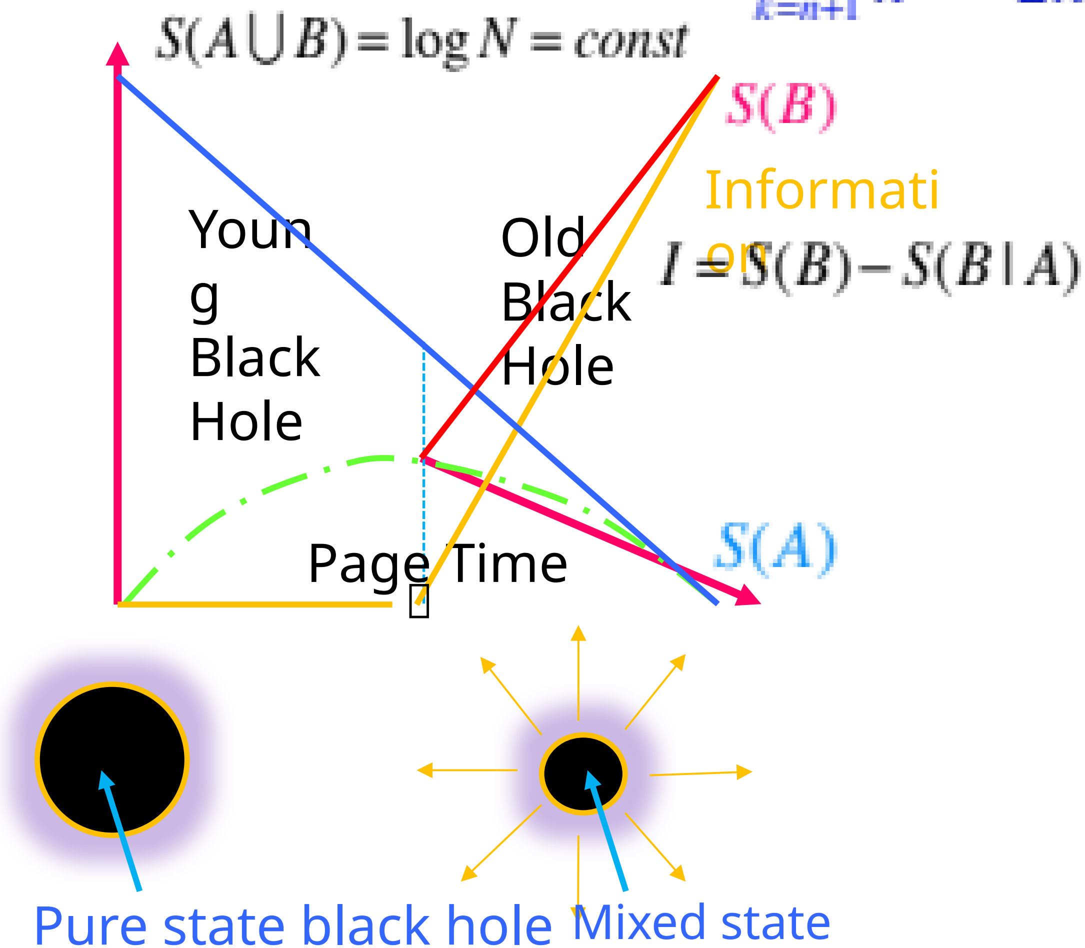


# When would BH information come out?

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

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

(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 th

# Resolution with Euclidean path integral

(P. Chen, M. Sasaki, D.-h. Yeom, J. Yoon, arXiv:2111.01005, 2021)

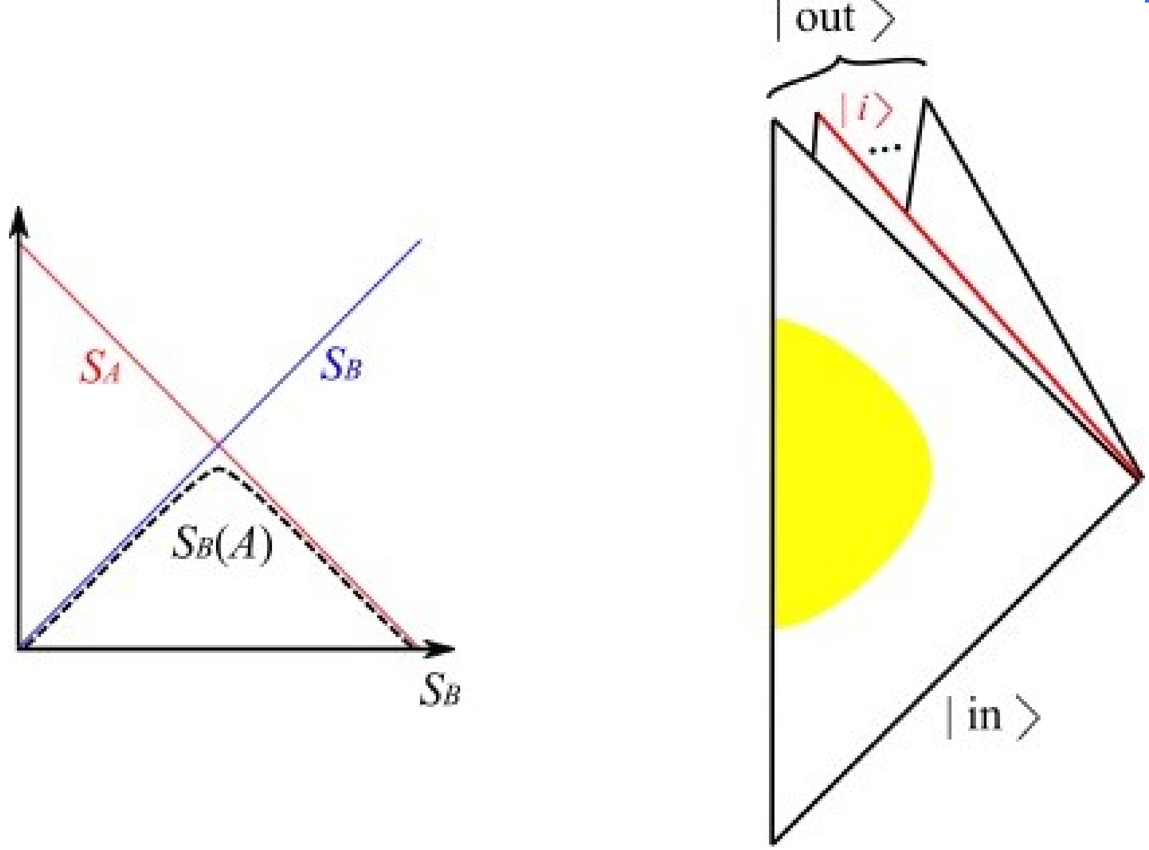



FIG. 1: Left: The Page curve, where $S_A$ and $S_B$ are Boltzmann entropies of $A$ and $B$, respectively, and $S_B(A)$ denotes the entanglement entropy. Right: The path integral from the in-state $|\text{in}\rangle$ to the out-state $|\text{out}\rangle$, where the out-state is a superposition of classical boundaries $\{|i\rangle\}$.

# *Multi-histories* and *late-time dominance* conditions of BH evolution

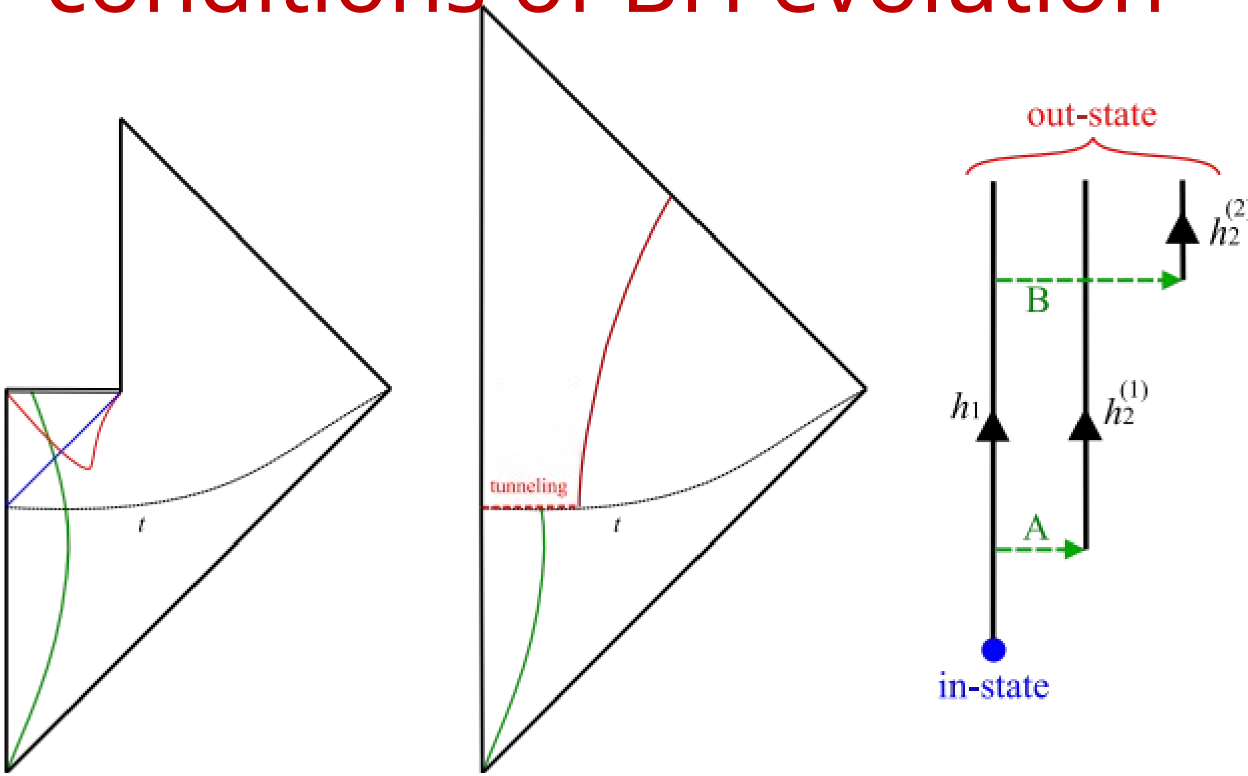



FIG. 2: Left: the causal structure of the usual semi-classical black hole, where the green curve is the trajectory of the collapsing matter, the red curve is the apparent horizon, and the blue line is the event horizon. Middle: the causal structure after a quantum tunneling at the time slice $t$. After the tunneling, matter or information (red curve) is emitted and the black hole structure disappears. Right: $h_1$ is the information-losing history, while $h_2^{(1,2)}$ are the information-preserving histories. Tunneling may happen either early time (A) or late time (B); the tunneling probability must be dominated at the late time.

# Page curve modified

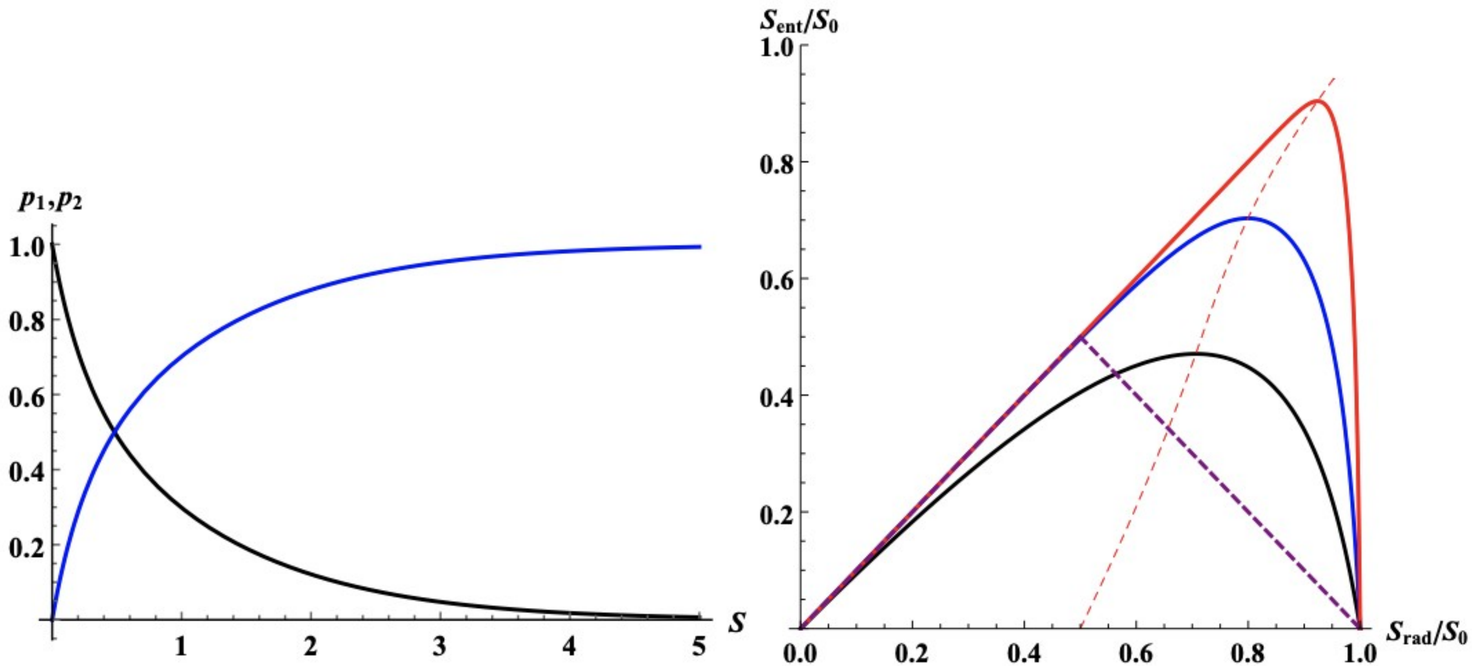



FIG. 3: Left: Probabilities of the information-losing history ($p_1$, blue curve) and the information-preserving history ($p_2$, black curve). Right: Entropy of emitted radiation $S_{\rm rad}/S_0$ vs. entanglement entropy $S_{\rm ent}/S_0$, where $S_0 = 3$ (black), 10 (blue), 50 (red), respectively. The thin red dashed curve is the location of the Page time, i.e., $dS_{\rm ent}/dS_{\rm rad} = 0$.

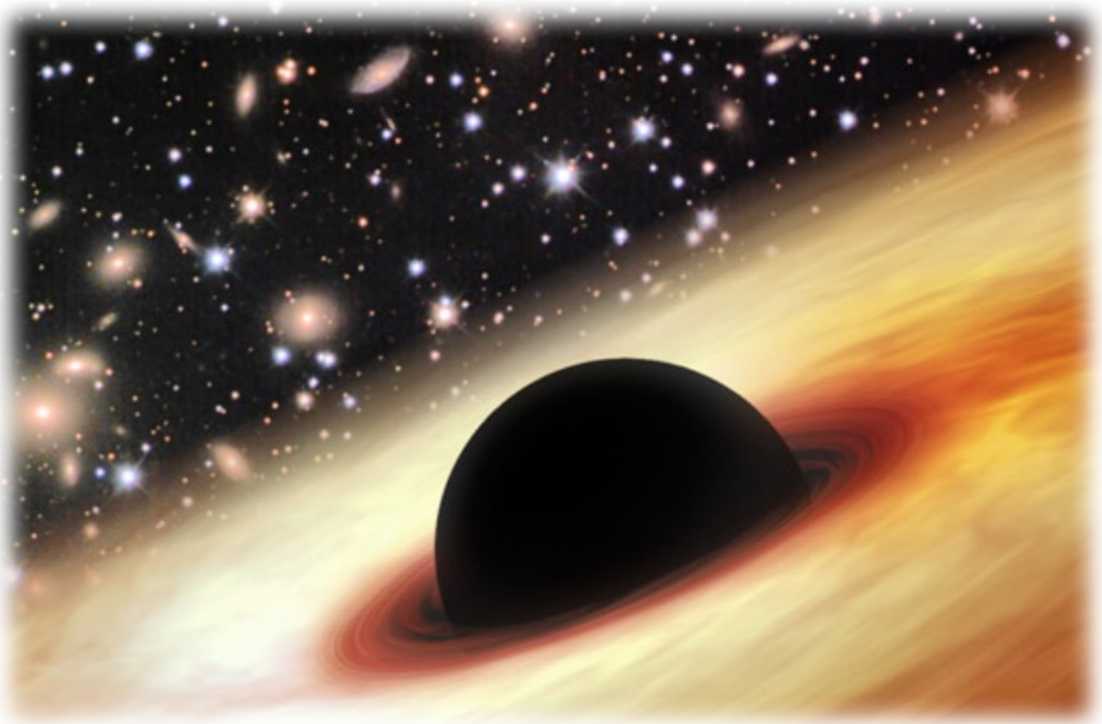
# Comparison with recent developments based on string theory

- The string-based islands approach and ours share two essential features.
  1. There exist more than two contributions to the evolution of the entanglement entropy, where one is dominant at early-time and the other at late-time.
  2. The final entanglement entropy is dominated by the late-time condition.

  Analogous in spirit to the Quantum Extremal Surface (QES) computations for BHs.
- However, the entanglement entropy computed in QES is based on the density matrix instead of the quantum states, which is the standard quantum field theory approach and what we have followed.

# 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: $1.38 \times 10^{10}$ years



# Analog Black Holes

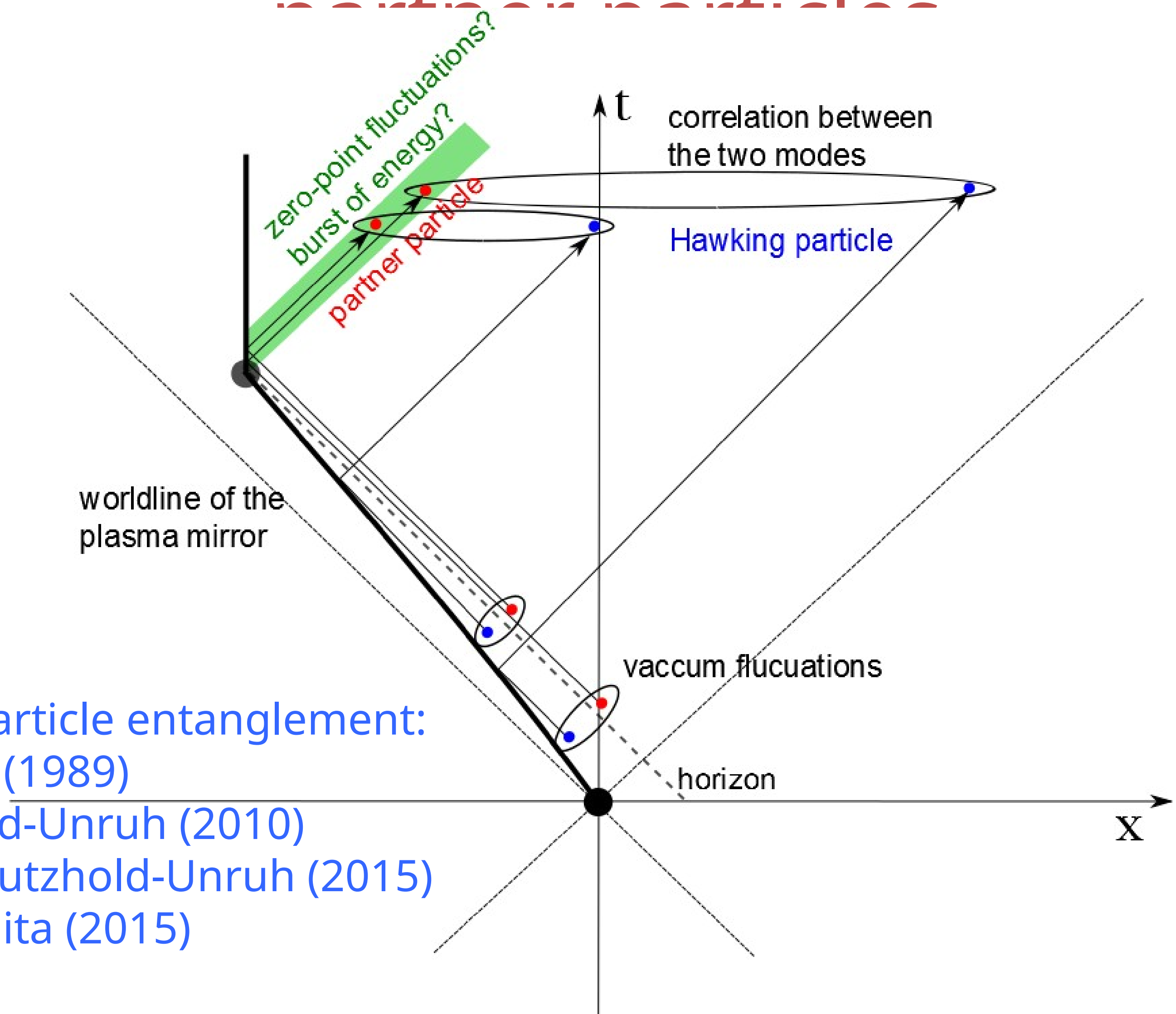
- Sound waves in moving fluids – "dumb holes"
  Unruh (1981, 1995)
- Traveling index of refraction in media
  Yablonovitch (1989)
- Violent acceleration of electron by lasers
  Chen-Tajima (1999)
- Electromagnetic waveguides
  Schutzhold-Unruh (2005)
- Bose-Einstein condensate
  Steinhauer (2014)

Testing thermal nature of Hawking radiation

- Accelerating mirror
  Fulling-Davies (1976), Davies-Fulling-Unruh (1977), Wilczek (1989), Carlitz-Willey (1987), Hotta-Schutzhold-Unruh (2015), Chen-Mourou (2017), Chen-Yeom (2017)

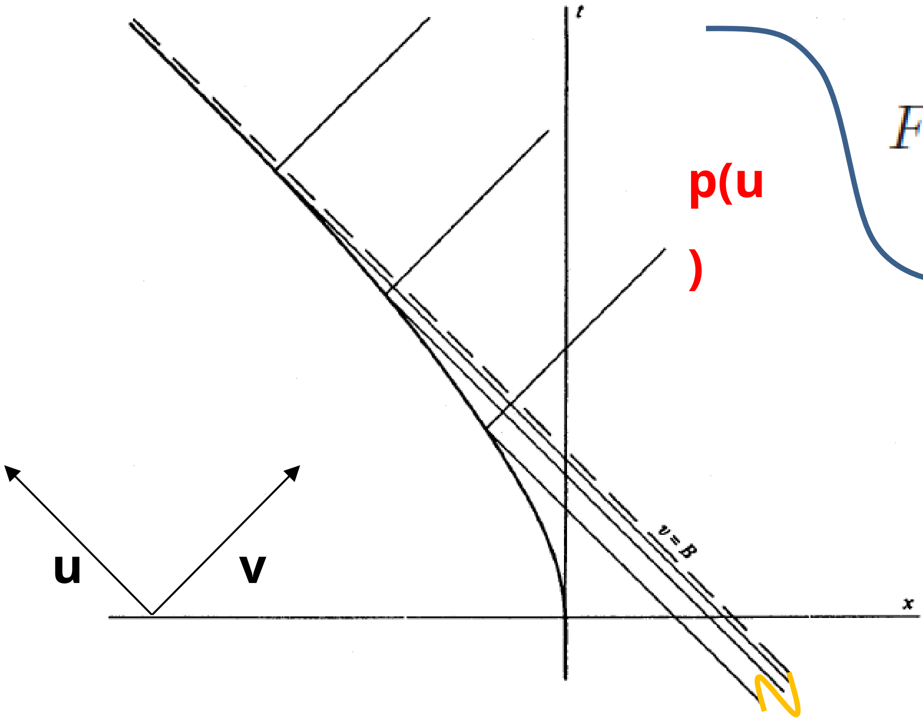
Can also Test ILP

# Flying Mirror:
## Entanglement between Hawking & partner particles




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

# 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

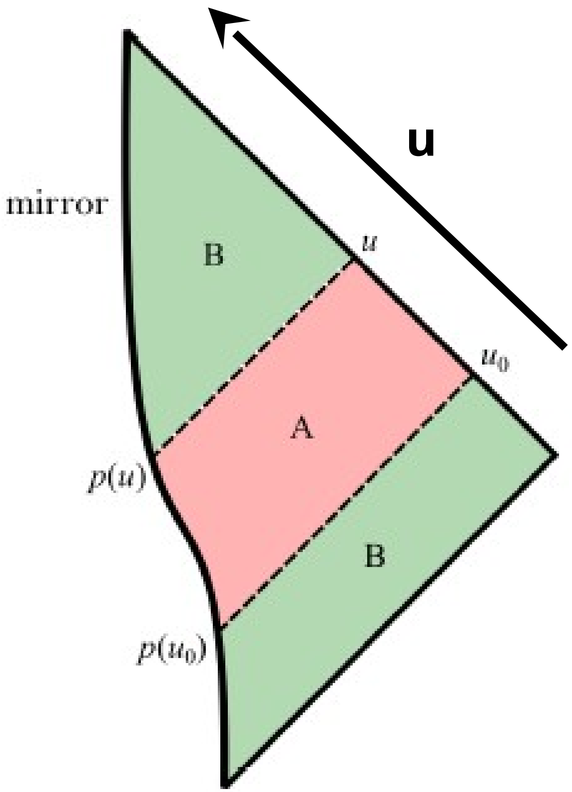
- One can calculate the **out-going energy flux** as a function of the mirror trajectory (for 2D spacetime).
- Definitely, there should be no information loss in the mirror dynamics.
- Then what can we learn about the **entanglement entropy**?

# Mirror trajectories

Chen, D-h Yeom, “Entropy evolution of moving mirrors and the information loss probl
RD 96, 025016 (2017) [arXiv:1704.08613]

- Using this formula, we can test several candidate traject

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




$$\begin{aligned} \frac{dS(t)}{dt} &= A \sin^2 \pi \frac{t}{t_{\rm P}} & 0 \le t < t_{\rm P}, \\ &= -A \frac{t_{\rm P}}{t_{\rm f} - t_{\rm P}} \sin^2 \pi \frac{t - t_{\rm P}}{t_{\rm f} - t_{\rm P}} & t_{\rm P} \le t < t_{\rm f}, \end{aligned}$$

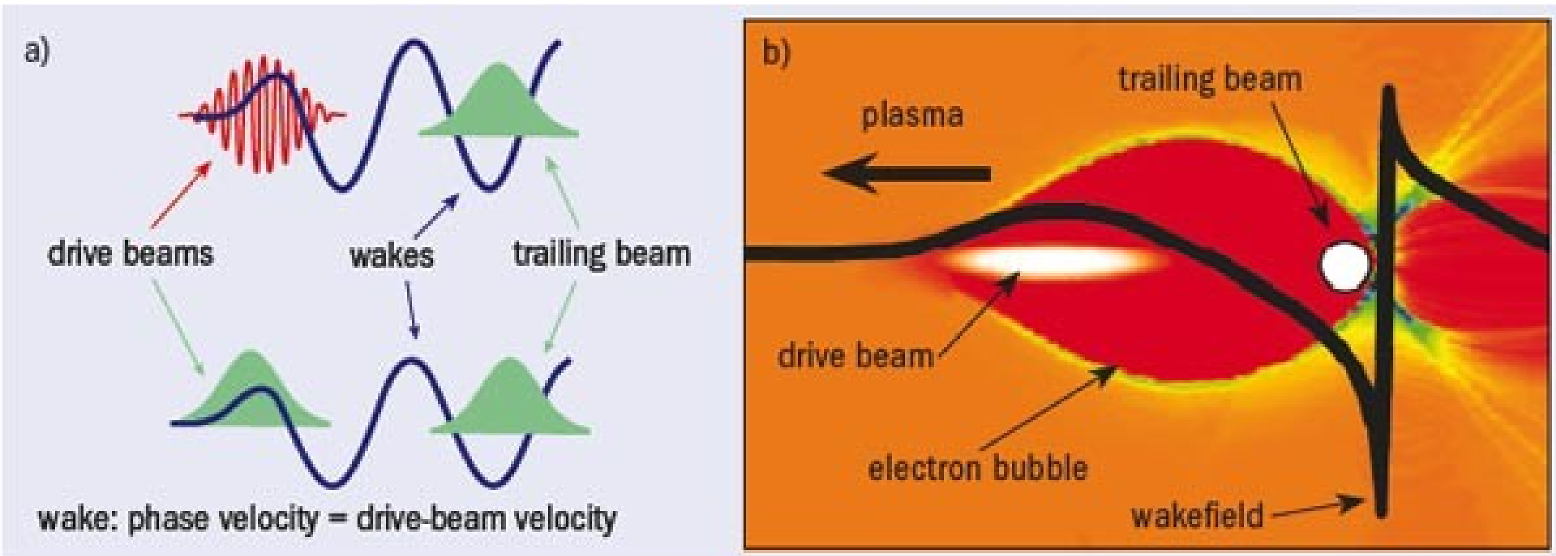
– Suddenly stopping mirror: $t_{\rm f} = 15$,

– Slowly stopping mirror: $t_{\rm f} = 20$,

– Long propagating mirror: $t_{\rm f} = 50$.

# Q: How to physically realize it?
# A: Plasma Wakefield Acceleration

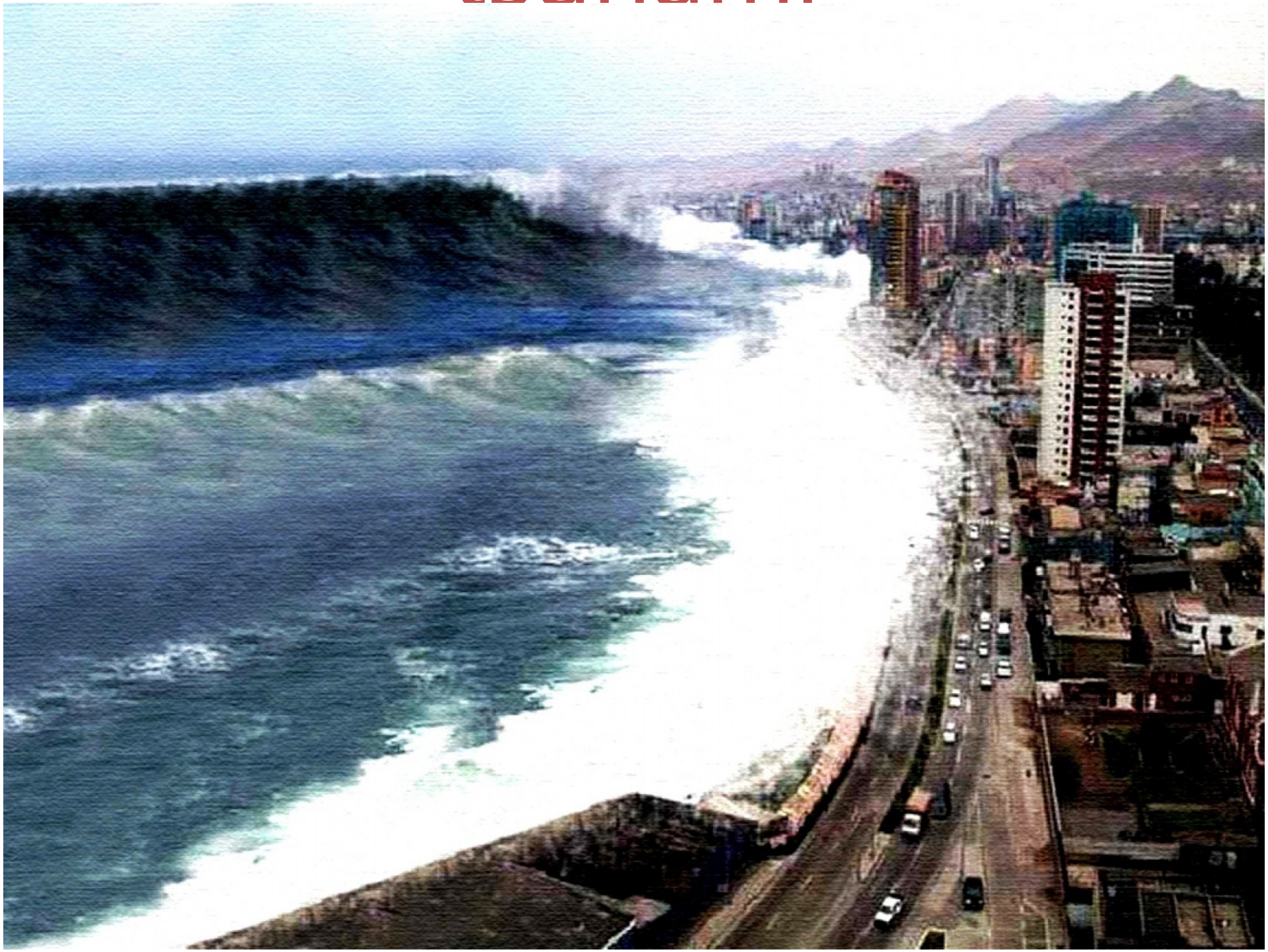
Tajima-Dawson (1979)- Laser driven (LWFA)
Chen-Dawson-Huff-Katsouleas (1985)- Particle beam driven (PWFA)




- SLAC & LBL- Acceleration of O(100) GeV/m observed!
- AWAKE- A new PWFA experiment at CERN

By now plasma wakefield acceleration has become a very active field of research worldwide.

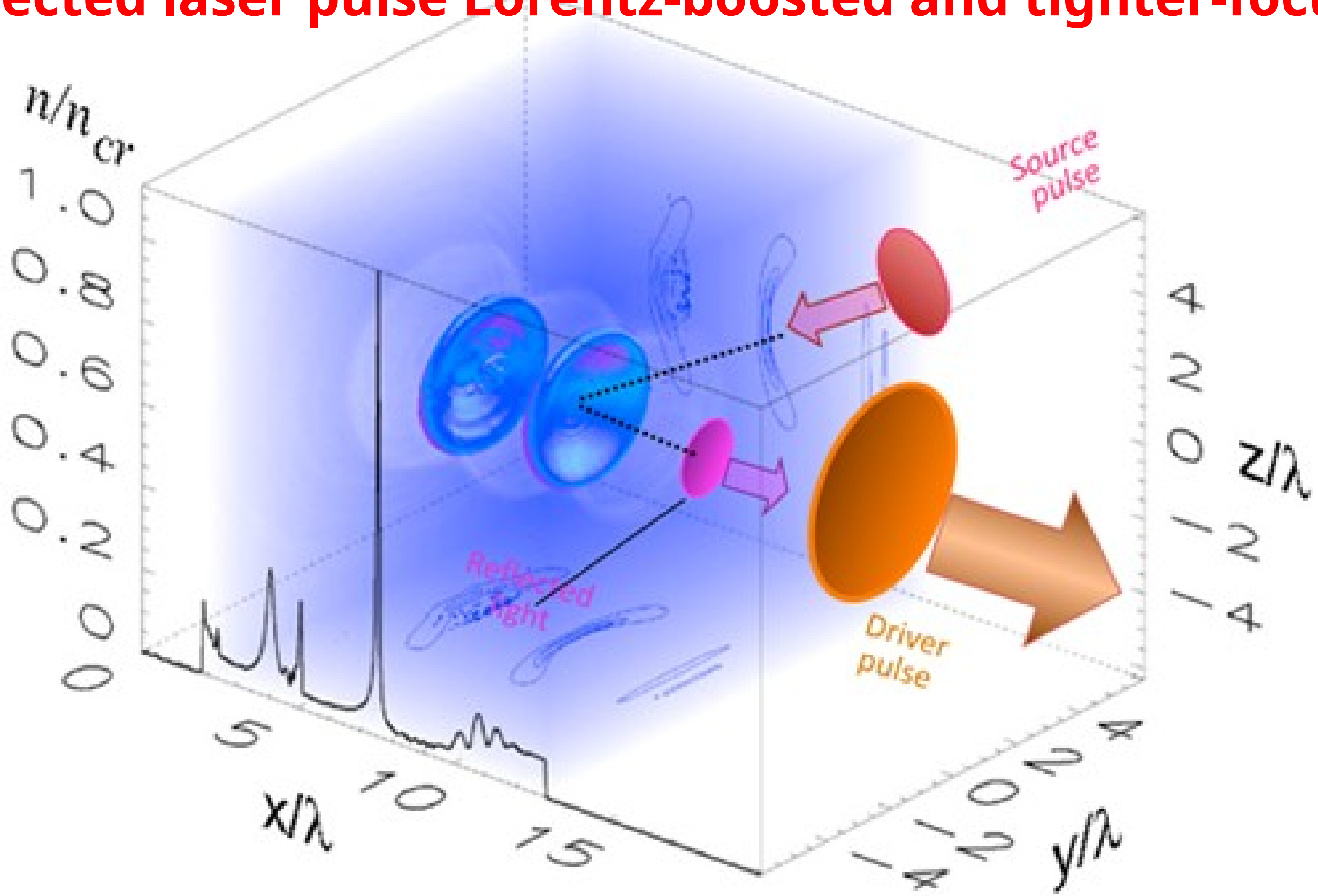
# Plasma wakefield is like a tsunami



# Relativistic Flying Plasma Mirror

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

**Reflected laser pulse Lorentz-boosted and tighter-focused.**

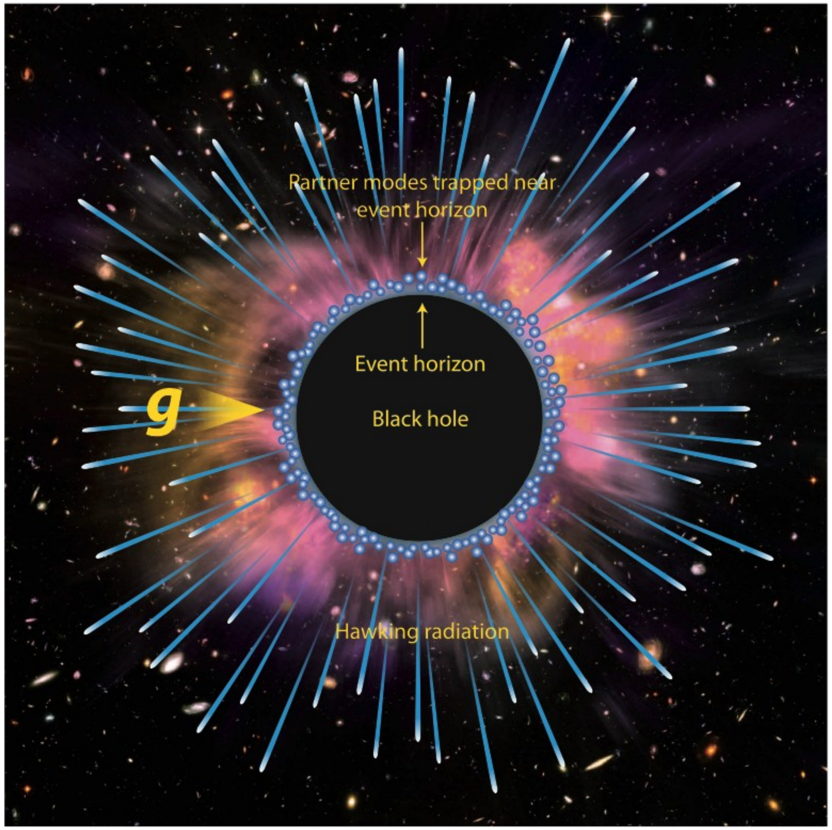


# Accelerating plasma mirror as an analog black hole

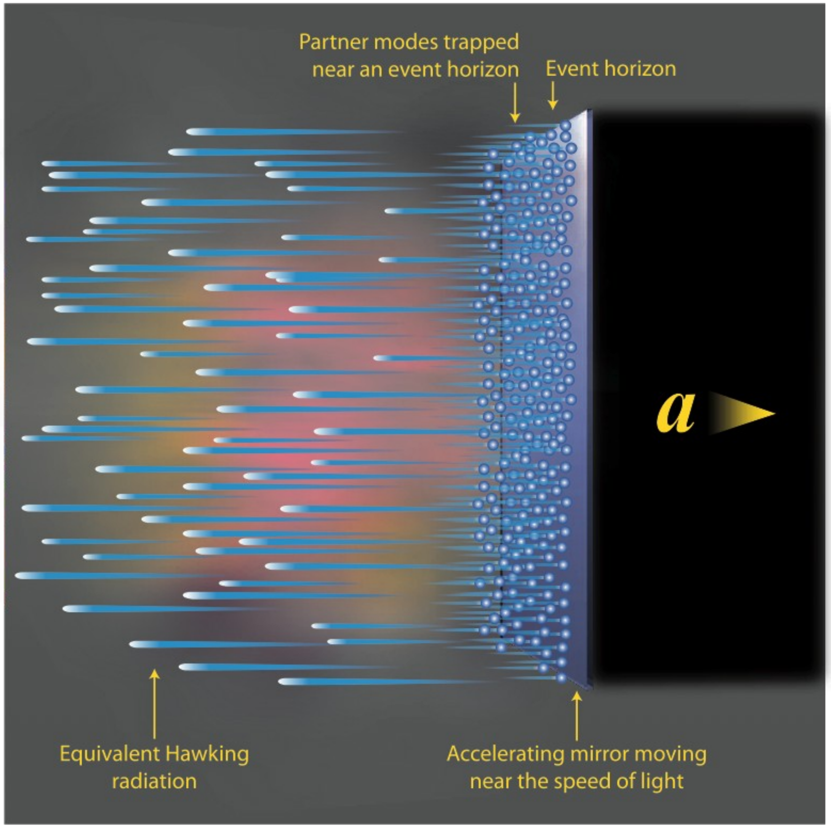
P. Chen and G. Mourou, Phys. Rev. Lett. (2017).

**SIMULATING A BLACK HOLE ON A TABLE**

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

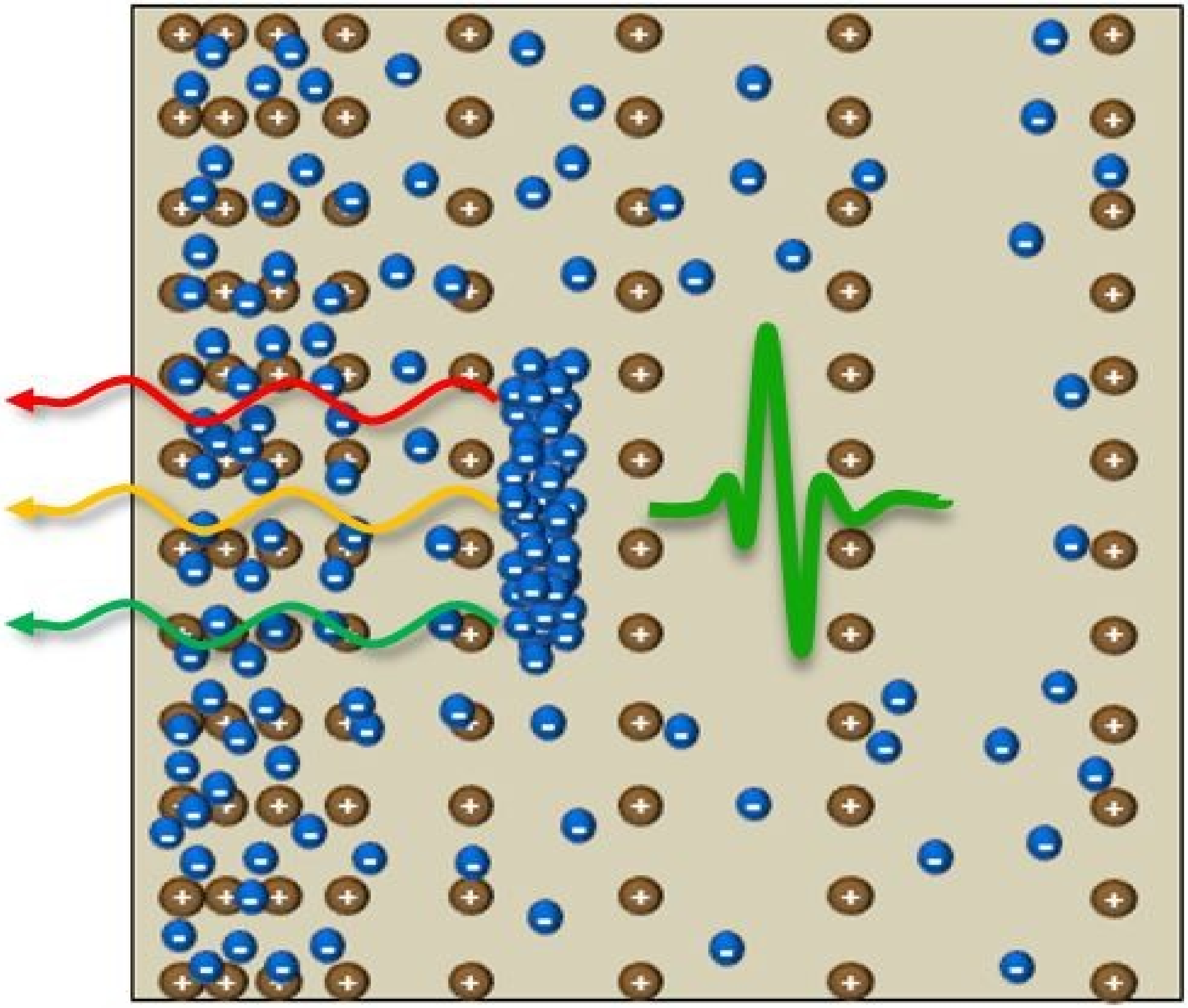



*Black hole Hawking evaporation*




*Accelerating mirror as an analog black hole*

# Plasma wakefield speeds up as plasma density gradually decreases



# Plasma density-Mirror trajectory Correspondence

P. Chen and G. Mourou. Phys. Plasmas (2020)

- Constant-plus-Gaussian density profile

$$n_p(x) = n_{p0}(a + be^{-x^2/2D^2})^2, \quad 0 \le x \le L,$$

asymptotically gives rise to the Davies-Fulling trajectory:

$$x_M(t) = -\eta_a ct - Ae^{-\eta_a ct/D} + A, \quad t \to \infty, \qquad \eta_a = 1 - a^2\omega_{p0}^2/2\omega_0^2$$

which in turn give the analog Hawking temperature

$$\boxed{k_B T_H = \frac{\hbar c}{4\pi}\frac{\eta_a}{D}.}$$

- Diff. BH scenarios corresponds to diff. trajectories, which can be tested thru pre-designed density profiles.

# AnaBHEL Collaboration
# (Analog Black Hole Evaporation via Lasers)

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ÉCOLE POLYTECHNIQUE
UNIVERSITÉ PARIS-SACLAY

KPSI
Kansai Photon Science Institute

# AnaBHEL Collaboration
# (Analog Black Hole Evaporation via Lasers)

National Taiwan University + Ecole Polytechnique
+ Kansai Photon Science Inst.

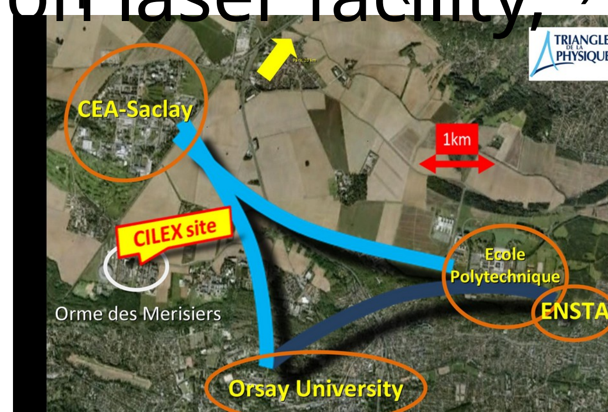
- Three stages:

  1. R&D of key components at NTU, Taiwan. Major progress
  2. KPSI laser facility @PW. Scheduled for summer of 2022
  3. Full scale expt. with 10PW Apollon laser facility, S

NTU LeCosPA (Taiwan)

KPSI Laser (Japan)

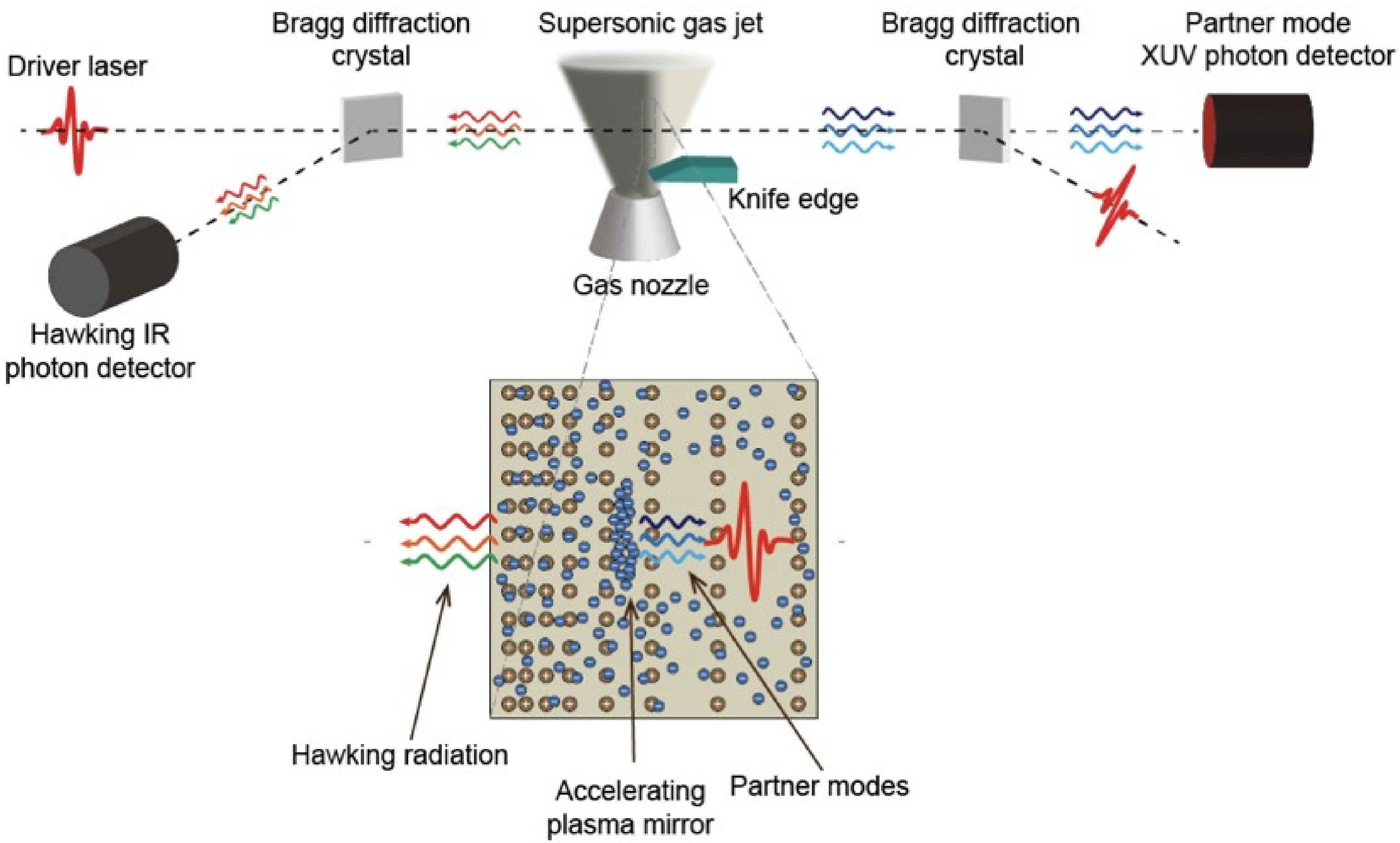
Apollon Laser (France)



# Schematic Layout of AnaBHEL Experiment

## Entanglement between Hawking and partner photons

## A flying Einstein-Podolsky-Rosen experiment

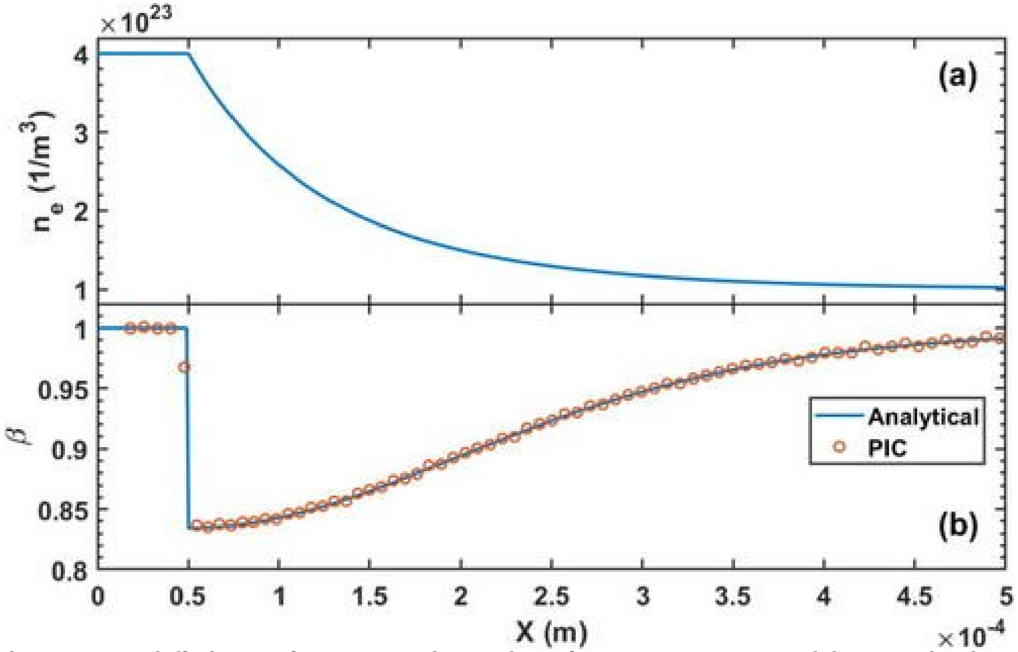


# Status of AnaBHEL R&D

1. Laser-plasma interaction dynamics
2. Deviation  plasma mirrors & estimation of Hawking photon yield
3. Supersonic gas jet with density gradient
4. Superconducting nanowire single-photon Hawking detector

# Trajectory of the flying plasma mirror with graded density

P. Chen and G. Mourou. Phys. Plasmas (2020)



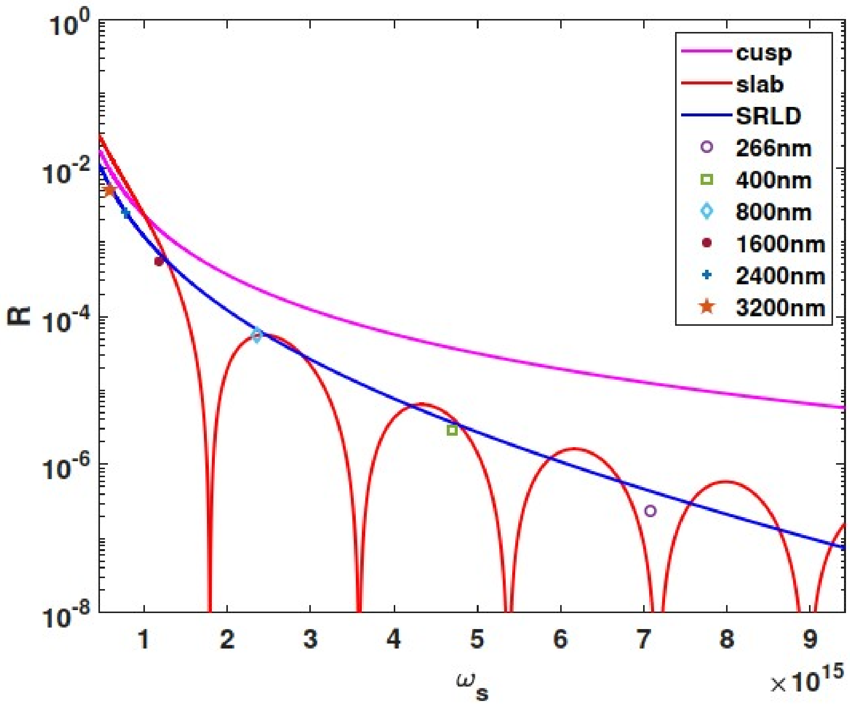

Trajectory of flying plasma mirror in plasma target with graded density.

- Flying plasma mirror is always one “bubble length” behind the driving laser.
- Bubble width can be controlled by tailoring the density of the plasma background, therefore the trajectory of the mirror can be designed.

# Reflectivity of flying plasma mirror

Y.K. Liu, P. Chen and P. Fang. Phys. Plasmas (2021)

- Reflectivity *highly* depends on the density distribution of electrons that compose the flying plasma mirror.
- Square Root Lorentzian Distribution (SRLD) provides a better estimation of reflectivity.




Reflectivity of the relativistic flying mirror as a function of the source pulse frequency .

# Semitransparency and finite-size effect of flying plasma mirror

Number of particles per mode for a semitransparent mirror in (1+3)D with any prescribed trajectory:

$$\frac{dN}{d^3k} \approx \int d^3p \left| \frac{\langle \mathbf{k}, \mathbf{p}; out \,|\, 0; in \rangle}{\langle 0; out \,|\, 0; in \rangle} \right|^2, \quad \beta_{\mathbf{kp}} = (u_{\mathbf{p}}^{in*}, u_{\mathbf{k}}^{out})_{KG} \approx \frac{\langle \mathbf{k}, \mathbf{p}; out \,|\, 0; in \rangle}{\langle 0; out \,|\, 0; in \rangle}.$$

Mimic the mirror by: $V(x) = \gamma^{-1}(t) H(\mathbf{x}_\perp) f(z - Z(t))$

- Mirror's transversal distribution: $H(\mathbf{x}_\perp)$
- Mirror's longitudinal distribution: $f(z - Z(t))$

The result for a Dirac delta mirror of infinite transverse area.

K.-N. Lin, C.-E. Chou, and P. Chen, Phys. Rev. D **103**, 025014, arXiv: 2008.12251 **[gr-qc]**.

We then have: $\beta_{\mathbf{kp}} \approx F(\mathbf{k}, \mathbf{p}) \times \left( \frac{-i\alpha}{16\pi^3 \sqrt{\omega_k \omega_p}} \int dt \gamma^{-1}(t) e^{i(\omega_k + \omega_p)t - i(k_3 - p_3)Z(t)} \right),$

where $F(\mathbf{k}, \mathbf{p}) = \int d^2x_\perp H(\mathbf{x}_\perp) e^{-i(k_\perp + p_\perp)\cdot x_\perp} \int d\zeta f(\zeta) e^{-i(k_3 - p_3)\zeta}, \quad \zeta = z - Z(t).$

Transverse distribution leads to diffraction, whereas longitudinal distribution may lead to enhancement of

# Estimation of Hawking Photon Yield

- The analog Hawking particles emitted by this semitransparent mirror has the particle spectrum:

K.-N. Lin and P. Chen, arXiv:2107.09033 [gr-qc].

$$\frac{dN_{ref}}{d\omega_k d\Omega} \approx \frac{\alpha^2 \mathscr{F}_L(\mathbf{k}_\perp)\mathscr{F}_D(k_3)}{8\pi\kappa}\left[\frac{\omega_k}{e^{\omega_k/T_{eff}(\theta_k)}+1}\right], \quad T_{eff}(\theta_k) = \frac{\kappa}{(1+\cos\theta_k)\pi}.$$

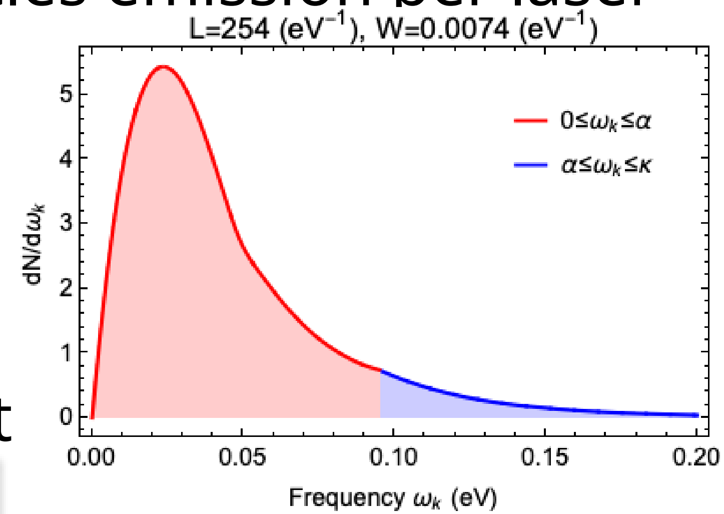
where $F$'s are form factors due to the mirror's finite area & thickness, which are independent of reflectivity and mirror's motion.

- Number of analog Hawking particles emission per laser (

$$N \approx \int_0^\kappa d\omega_k \int d\Omega \, \frac{dN}{d\omega_k d\Omega} = (0.27 + 0.02),$$

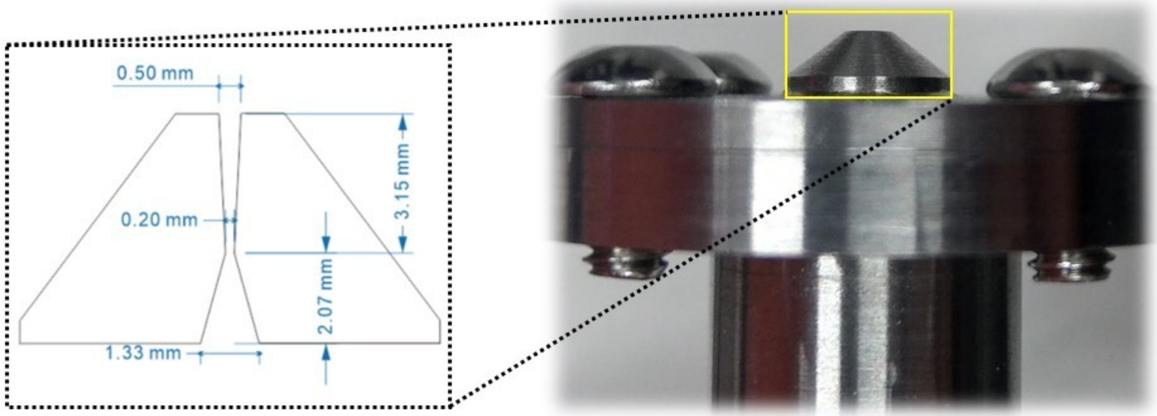
Assuming 1 laser shot/min and 8-hr running time/day, a 20-day experiment with an ideal detector efficiency gives the detected event yield:

$$N_{\text{detect}} = (1 \times 60 \times 8 \times 20) \times 1 \times N \approx 3000.$$

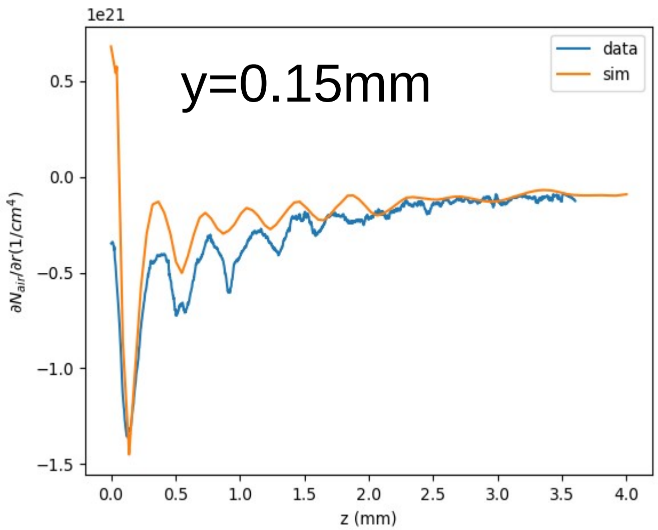


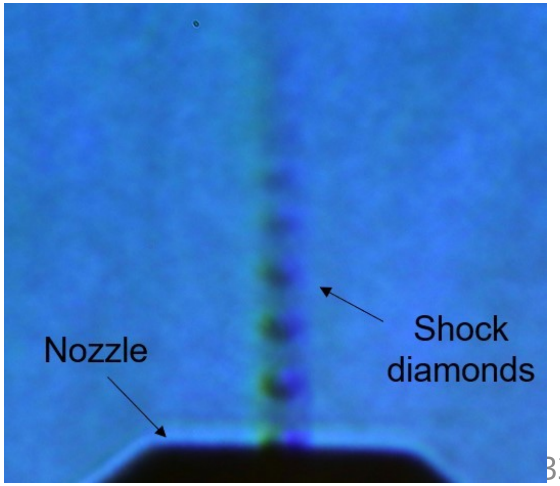
# Significant Progress in R&D at NTU

- Supersonic gas jet



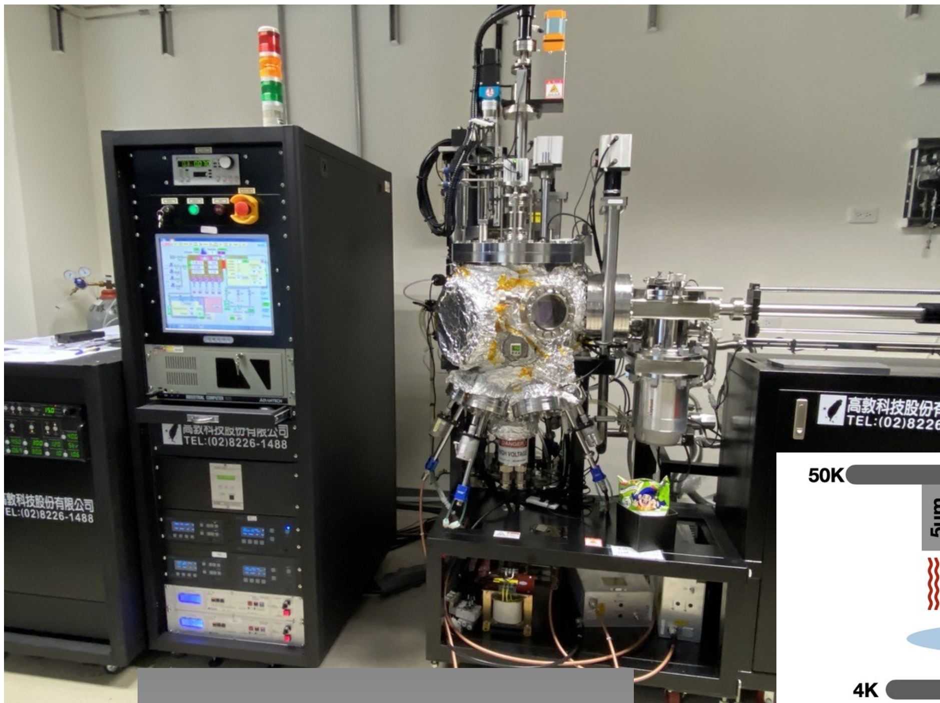

- Delivers expected density gradient

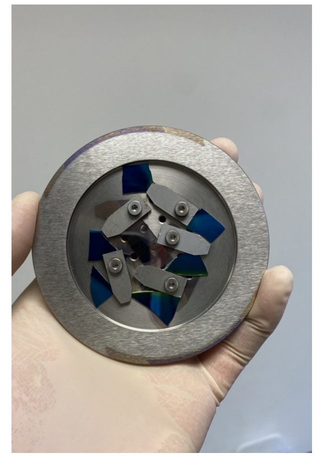


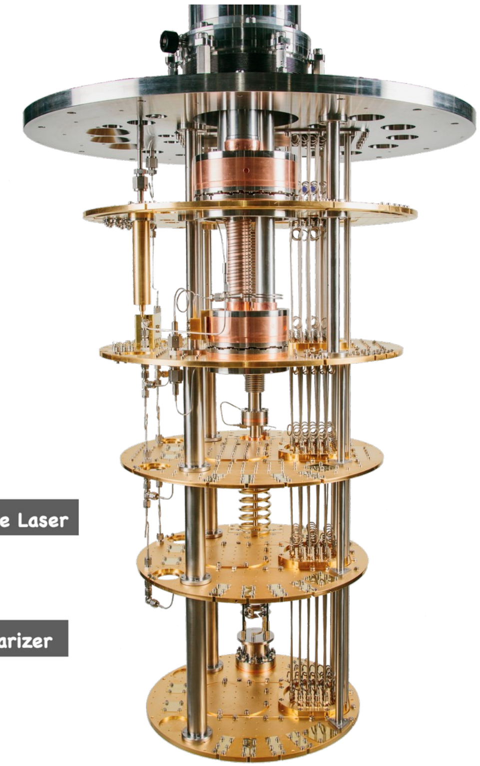



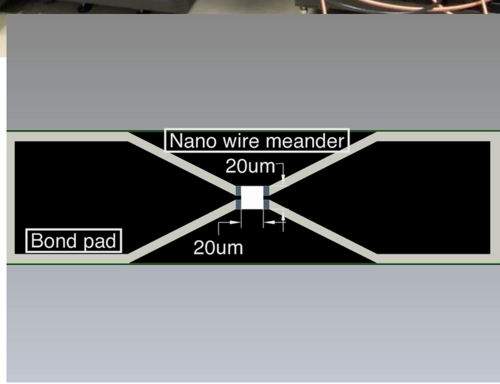
# Superconducting nanowire single-photon Hawking detector

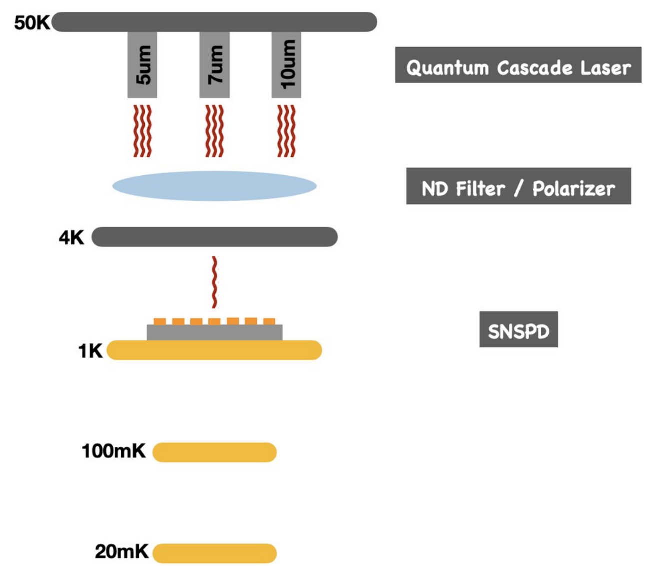
## Near 100% quantum efficiency attainable!









# 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.
- AnaBHEL experiment is in good progress.