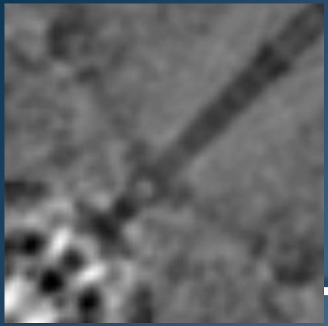
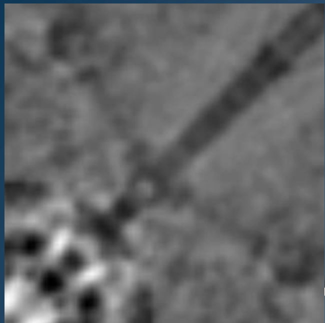


Observation of spontaneous thermal Hawking radiation and its temperature in an analogue black hole

Jeff Steinhauer
Juan Ramón Muñoz de Nova
Katrine Golubkov
Victor I. Kolobov

Technion -- Israel
Institute of Technology



Theoretical background

Black hole thermodynamics (entropy, temperature)

Bekenstein, J. D. Black holes and entropy. *Phys. Rev. D* **7**, 2333 (1973).

Hawking radiation

Hawking, S. W. Black hole explosions? *Nature* **248**, 30 (1974).

Hawking, S. W. Particle creation by black holes. *Commun. Math. Phys.* **43**, 199 (1975).

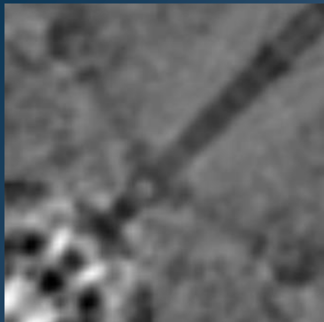
Hawking combined general relativity with quantum field theory.

$$k_{\mathrm{B}}T_{\mathrm{H}} = \hbar g/2\pi c$$

Information paradox

Hawking, S. W. Breakdown of predictability in gravitational collapse. *Phys. Rev. D* **14**, 2460 (1976).

Wald, R. M. On particle creation by black holes. *Commun. Math. Phys.* **45**, 9 (1975).



Theoretical background

Graybody factors

Page, D. N. Particle emission rates from a black hole: Massless particles from an uncharged, nonrotating hole. *Phys. Rev. D* **13**, 198 (1976).

Visser, M. Thermality of the Hawking Flux. *J. High Energ. Phys.* **9** (2015).

Hawking radiation from very small black holes

Page, D. N. Particle emission rates from a black hole: Massless particles from an uncharged, nonrotating hole. *Phys. Rev. D* **13**, 198 (1976).

Dimopoulos, S. & Landsberg, G. Black holes at the large hadron collider. *Phys. Rev. Lett.* **87**, 161602 (2001).

Giddings, S. B. & Thomas, S. High energy colliders as black hole factories: The end of short distance physics. *Phys. Rev. D* **65**, 056010 (2002).

Hawking radiation in an analogue black hole

Unruh, W. G. Experimental black-hole evaporation? *Phys. Rev. Lett.* **46**, 1351 (1981).

"Black-hole evaporation is one of the most surprising discoveries of the past ten years."

$$k_{\mathrm{B}}T_{\mathrm{H}} = \hbar g/2\pi c$$

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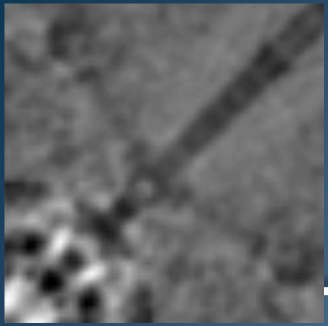


Theoretical background

Bose-Einstein condensates

Garay, L. J., Anglin, J. R., Cirac, J. I. & Zoller, P., Sonic analog of gravitational black holes in Bose-Einstein condensates. *Phys. Rev. Lett.* **85**, 4643 (2000).

Barceló, C., Liberati, S. & Visser, M. Analogue gravity from Bose-Einstein condensates. *Class. Quant. Grav.* **18**, 1137 (2001).

Recati, A., Pavloff, N. & Carusotto, I. Bogoliubov theory of acoustic Hawking radiation in Bose-Einstein condensates. *Phys. Rev. A* **80**, 043603 (2009).

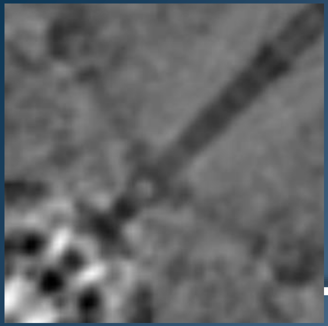
Zapata, I., Albert, M., Parentani, R. & Sols, F. Resonant Hawking radiation in Bose–Einstein Condensates. *New J. Phys.* **13**, 063048 (2011).

Balbinot, R., Fabbri, A., Fagnocchi, S., Recati, A. & Carusotto, I. Nonlocal density correlations as a signature of Hawking radiation from acoustic black holes. *Phys. Rev. A* **78**, 021603(R) (2008).

Macher, J. & Parentani, R. Black-hole radiation in Bose-Einstein condensates. *Phys. Rev. A* **80**, 043601 (2009).

Carusotto, I., Fagnocchi, S., Recati, A., Balbinot, R. & Fabbri, A. Numerical observation of Hawking radiation from acoustic black holes in atomic Bose–Einstein condensates. New J. Phys. 10, 103001 (2008).

Larré, P.-É., Recati, A., Carusotto, I. & Pavloff, N. Quantum fluctuations around black hole horizons in Bose-Einstein condensates. *Phys. Rev. A* **85**, 013621 (2012).



Theoretical background

Bose-Einstein condensates (continued)

Busch, X. & Parentani, R. Quantum entanglement in analogue Hawking radiation: When is the final state nonseparable? *Phys. Rev. D* **89**, 105024 (2014).

Finazzi, S. & Carusotto, I. Entangled phonons in atomic Bose-Einstein condensates. *Phys. Rev. A* **90**, 033607 (2014).

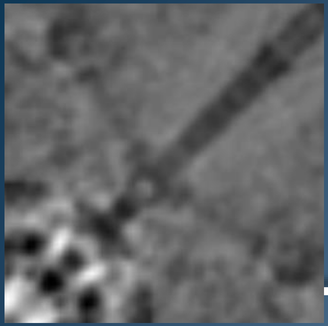
Steinhauer, J. Measuring the entanglement of analogue Hawking radiation by the density-density correlation function. *Phys. Rev. D* **92**, 024043 (2015).

de Nova, J. R. M., Sols, F. & Zapata, I. Violation of Cauchy-Schwarz inequalities by spontaneous Hawking radiation in resonant boson structures. *Phys. Rev. A* **89**, 043808 (2014).

Doukas, J. Adesso, G. & Fuentes, I. Ruling out stray thermal radiation in analogue black holes. arXiv 1404.4324.

Boiron, D., Fabbri, A., Larré, P.-É., Pavloff, N., Westbrook, C. I. & Ziń, P. Quantum signature of analog Hawking radiation in momentum space. *Phys. Rev. Lett.* **115**, 025301 (2015).

de Nova, J. R. M., Sols, F. & Zapata, I. Entanglement and violation of classical inequalities in the Hawking radiation of flowing atom condensates. *New J. Phys.* **17**, 105003 (2015).



Theoretical background

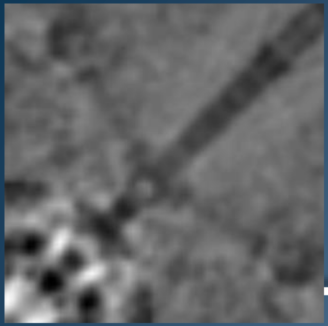
Bose-Einstein condensates (continued)

Michel, F., Coupechoux, J.-F. & Parentani, R. Phonon spectrum and correlations in a transonic flow of an atomic Bose gas. *Phys. Rev. D* **94**, 084027 (2016).

Coutant A. & Weinfurtner, S. Low-frequency analogue Hawking radiation: The Bogoliubov-de Gennes model. *Phys. Rev. D* **97**, 025006 (2018).

Fabbri, A. & Pavloff, N. Momentum correlations as signature of sonic Hawking radiation in Bose-Einstein condensates. *SciPost Phys.* **4**, 019 (2018).

Robertson, S., Michel, F. & Parentani, R. Assessing degrees of entanglement of phonon states in atomic Bose gases through the measurement of commuting observables. *Phys. Rev. D* **96**, 045012 (2017).



Theoretical background

Superfluid ^{3}He

Jacobson T. A. & Volovik, G. E. Event horizons and ergoregions in ^{3}He. *Phys. Rev. D* **58**, 064021 (1998).

Electromagnetic waveguide

Schützhold, R. & Unruh, W. G. Hawking radiation in an electromagnetic waveguide? *Phys. Rev. Lett.* **95**, 031301 (2005).

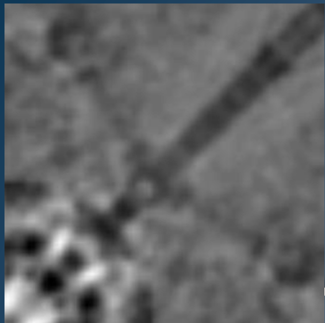
Ultracold Fermions

Giovanazzi, S. Hawking radiation in sonic black holes. *Phys. Rev. Lett.* **94**, 061302 (2005).

Giovanazzi, S. Entanglement entropy and mutual information production rates in acoustic black holes. *Phys. Rev. Lett.* **106**, 011302 (2011).

Ring of trapped ions

Horstmann, B., Reznik, B., Fagnocchi, S. & Cirac, J. I. Hawking radiation from an acoustic black hole on an ion ring. *Phys. Rev. Lett.* **104**, 250403 (2010).



Theoretical background

Light in a nonlinear liquid

Elazar, M. Fleurov, V. & Bar-Ad, S. All-optical event horizon in an optical analog of a Laval nozzle. *Phys. Rev. A* **86**, 063821 (2012).

Exciton-polariton condensates

Solnyshkov, D. D., Flayac, H. & Malpuech, G. Black holes and wormholes in spinor polariton condensates. *Phys. Rev. B* **84**, 233405 (2011).

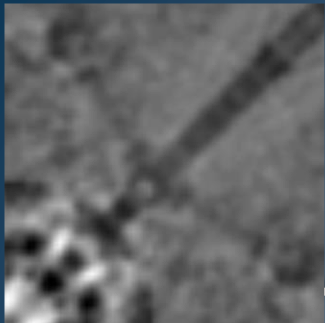
Magnons in a magnetic wire

Roldan-Molina, A., Nunez, A. S. & Duine R. A. Magnonic Black Holes. *Phys. Rev. Lett.* **118**, 061301 (2017).

Jannes, G, Maïssa, P., Philbin, T. G. & Rousseaux, G. Hawking radiation and the boomerang behavior of massive modes near a horizon. *Phys. Rev. D* **83**, 104028 (2011).

Weyl semimetals

Volovik, G. E. Black Hole and Hawking Radiation by Type-II Weyl Fermions. *JETP Letters* **104**, 645 (2016).



Experimental background

Bose-Einstein condensates

Lahav, O., Itah, A., Blumkin, A., Gordon, C., Rinott, S., Zayats, A. & Steinhauer, J. Realization of a sonic black hole analog in a Bose-Einstein condensate. *Phys. Rev. Lett.* **105**, 240401 (2010).

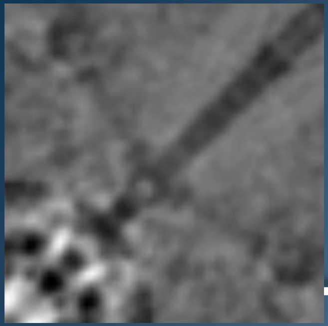
Shammass, I., Rinott, S., Berkovitz, A., Schley, R. & Steinhauer, J. Phonon dispersion relation of an atomic Bose-Einstein condensate. *Phys. Rev. Lett.* **109**, 195301 (2012).

Schley, R., Berkovitz, A., Rinott, S., Shammass, I., Blumkin, A. & Steinhauer, J. Planck Distribution of Phonons in a Bose-Einstein Condensate. *Phys. Rev. Lett.* **111**, 055301 (2013).

Steinhauer, J. Observation of self-amplifying Hawking radiation in an analog black hole laser. *Nature Phys.* 10, 864 (2014).

Steinhauer, J. Observation of quantum Hawking radiation and its entanglement in an analogue black hole. *Nature Phys.* **12**, 959 (2016).

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. Observation of thermal Hawking radiation and its temperature in an analogue black hole. *Nature* 569, 688 (2019).



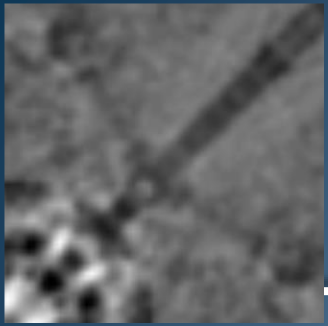
Experimental background

Surface waves in water

Rousseaux, G., Mathis, C., Maïssa, P., Philbin, T. G. & Leonhardt, U. Observation of negative-frequency waves in a water tank: a classical analogue to the Hawking effect? *New J. Phys.* **10**, 053015 (2008).

Weinfurtner, S., Tedford, E. W., Penrice, M. C. J., Unruh, W. G. & Lawrence, G. A. Measurement of stimulated Hawking emission in an analogue system. *Phys. Rev. Lett.* **106**, 021302 (2011).

Euvé, L.-P., Michel, F., Parentani, R., Philbin, T. G. & Rousseaux, G. Observation of noise correlated by the Hawking effect in a water tank. PRL **117**, 121301 (2016).



Experimental background

Non-linear optical fibers

Philbin, T. G., Kuklewicz, C., Robertson, S., Hill, S., König, F. & Leonhardt, U. Fiber-optical analog of the event horizon. *Science* **319**, 1367-1370 (2008).

Belgiorno, F., Cacciatori, S. L., Clerici, M., Gorini, V., Ortenzi, G., Rizzi, L., Rubino, E., Sala, V. G. & Faccio, D. Hawking Radiation from Ultrashort Laser Pulse Filaments. *Phys. Rev. Lett.* **105**, 203901 (2010).

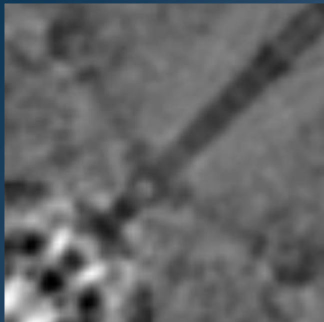
Unruh, W. & Schützhold, R. Hawking radiation from ‘‘phase horizons’’ in laser filaments? *Phys. Rev. D* **86**, 064006 (2012).

Liberati, S., Prain, A. & Visser, M. Quantum vacuum radiation in optical glass. *Phys. Rev. D* **85**, 084014 (2012).

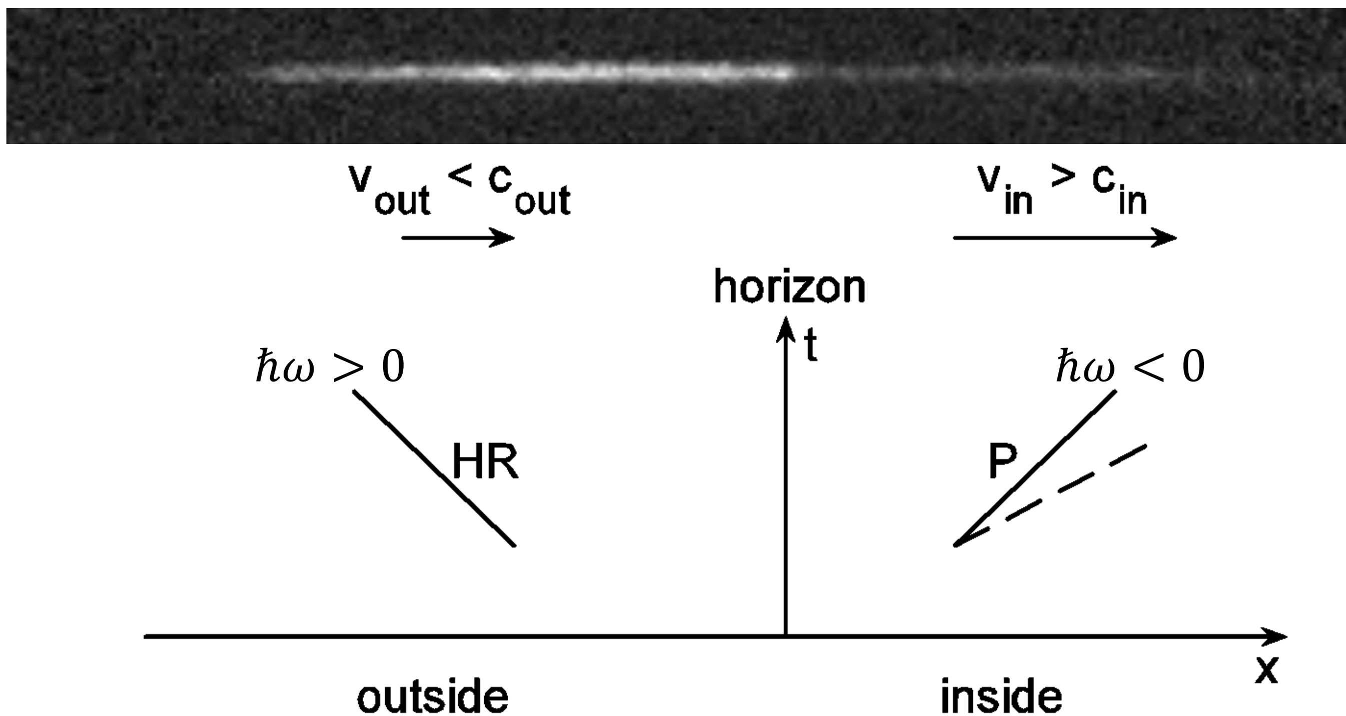
Drori, J., Rosenberg, Y., Bermudez, D., Silberberg, Y. & Leonhardt, U. Observation of stimulated Hawking radiation in an optical analogue. *Phys. Rev. Lett.* **122**, 010404 (2019).

Exciton-polariton condensate

Nguyen, H. S., Gerace, D., Carusotto, I., Sanvitto, D., Galopin, E., Lemaître, A., Sagnes, I., Bloch, J. & Amo, A. Acoustic Black Hole in a Stationary Hydrodynamic Flow of Microcavity Polaritons. *Phys. Rev. Lett.* **114**, 036402 (2015).



Analogue black hole



$E_{\text{pair}} = 0$

Hawking radiation

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. Observation of thermal Hawking radiation and its temperature in an analogue black hole. *Nature* 569, 688 (2019).

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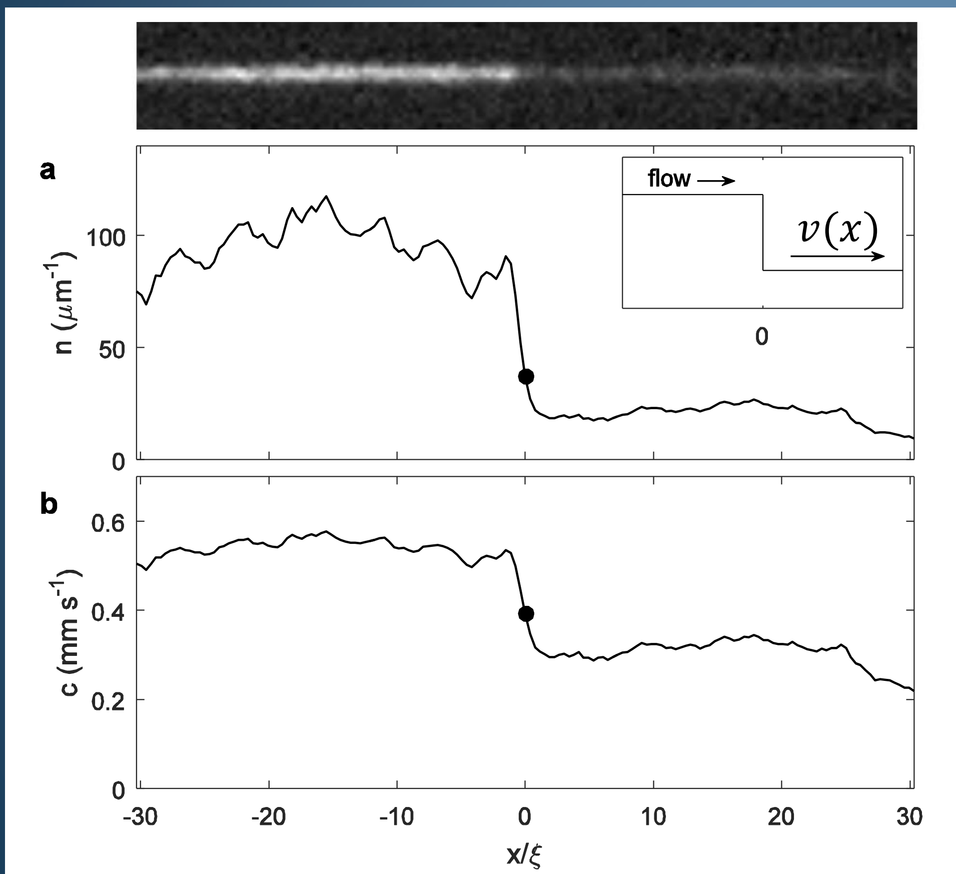
Predicted Hawking temperature



$$k_B T_H = \hbar g / 2\pi c$$

$$g = c(dv/dx - dc/dx)\Big|_{x=0}$$

Visser, M. *Class. Quantum Grav.* **15**, 1767-1791 (1998).

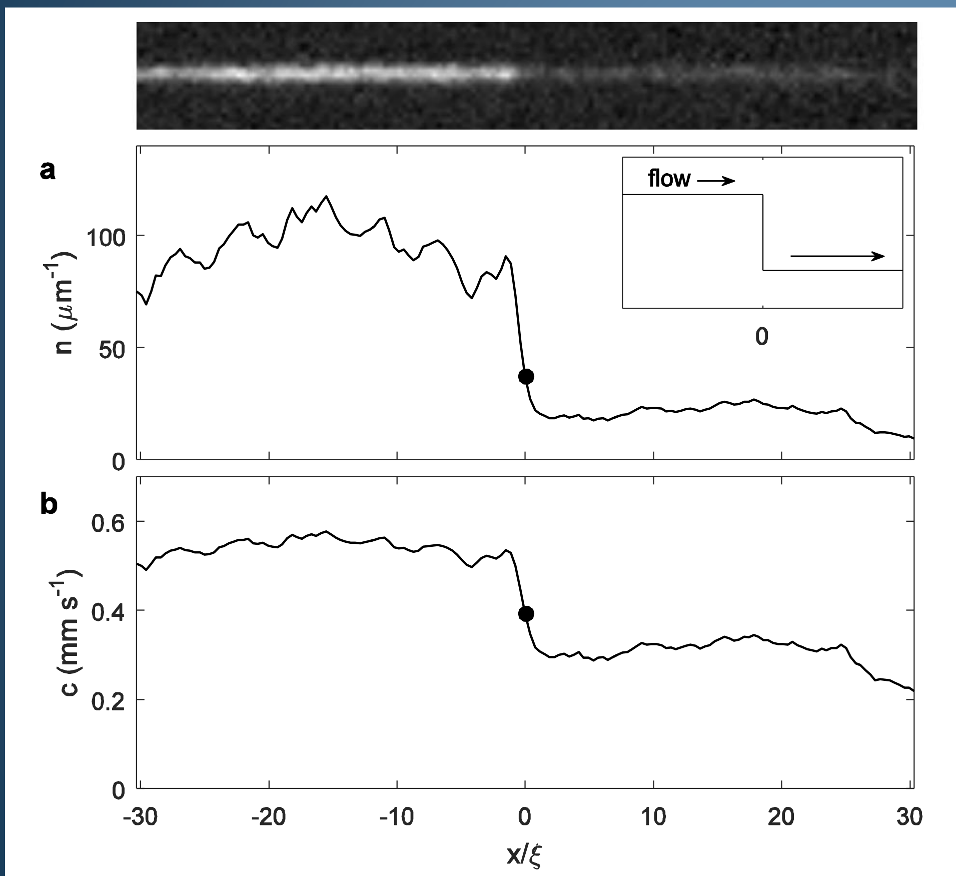
based on linear dispersion

$$J = nv = \text{constant}$$

$$k_B T_H = -\frac{\hbar}{2\pi}\left(\frac{c}{n}\frac{dn}{dx} + \frac{dc}{dx}\right)\Big|_{x=0}$$

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. Observation of thermal Hawking radiation and its temperature in an analogue black hole. *Nature* 569, 688 (2019).

Predicted Hawking temperature



$$g = c(dv/dx - dc/dx)\Big|_{x=0}$$

$$c(x) = \sqrt{\frac{2\hbar a \omega_r(x) n(x)}{m}} \sqrt{\frac{1 + 3n(x)\,a/2}{(1 + 2n(x)a)^{3/2}} - \frac{\hbar \omega_{r_0}}{2U_0}}$$

Salasnich, L., Parola, A. & Reatto, L. Dimensional reduction in Bose-Einstein-condensed alkali-metal vapors. *Phys. Rev. A* **69**, 045601 (2004).

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. Observation of thermal Hawking radiation and its temperature in an analogue black hole. *Nature* 569, 688 (2019).

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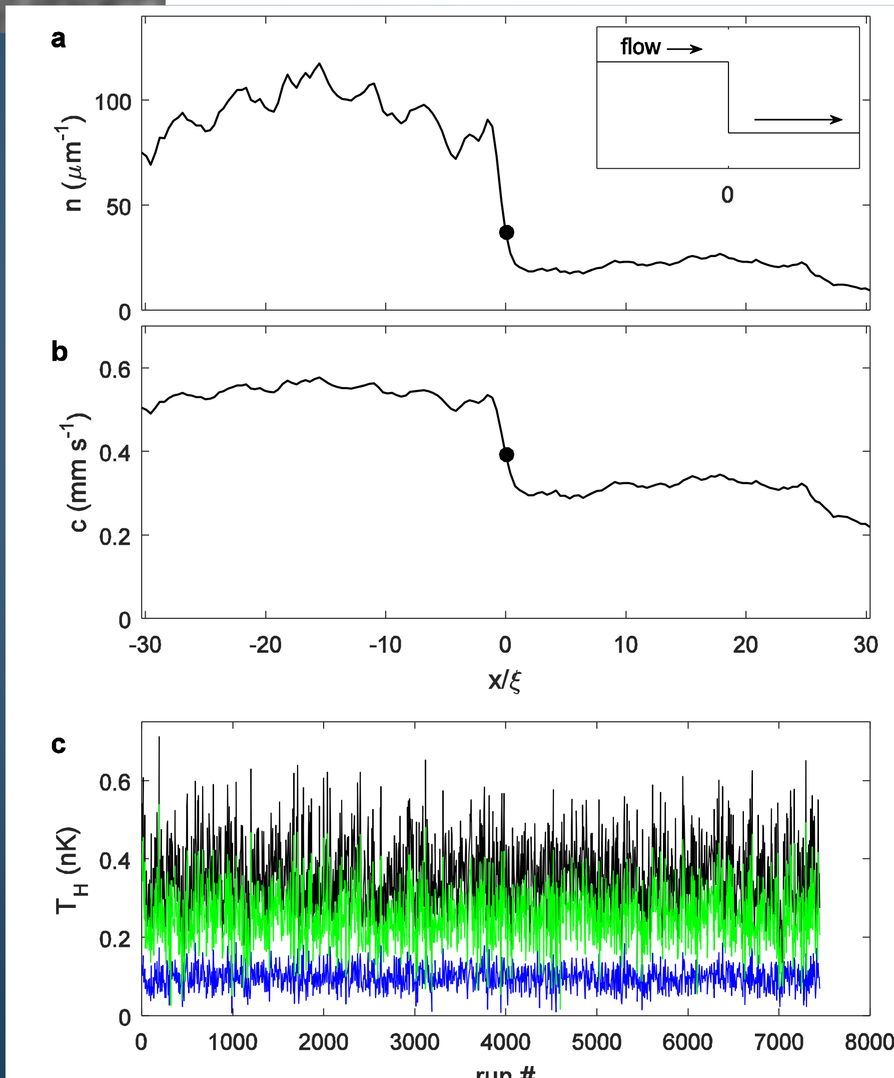
Predicted Hawking temperature



$$k_B T_H = \hbar g / 2\pi c$$

$$g = c(dv/dx - dc/dx)\Big|_{x=0}$$

based on linear dispersion

$$J = nv = \text{constant}$$

$$k_B T_H = -\frac{\hbar}{2\pi}\left(\frac{c}{n}\frac{dn}{dx} + \frac{dc}{dx}\right)\Bigg|_{x=0}$$

$$k_B T_H = 0.351(4)\ \text{nK}$$

$$k_B T_H = 0.125(1)\ mc_{\text{out}}^2$$

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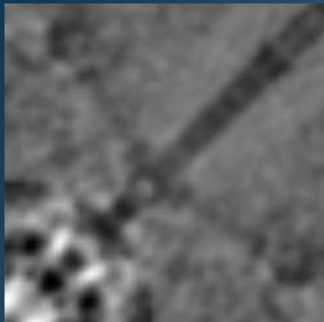


Theoretical predictions

$$k_{\mathrm{B}}T_{\mathrm{H}} = 0.125(1)\, mc_{\mathrm{out}}^2$$

Larré, P.-É., Recati, A., Carusotto, I. & Pavloff, N. Quantum fluctuations around black hole horizons in Bose-Einstein condensates. *Phys. Rev. A* **85**, 013621 (2012).

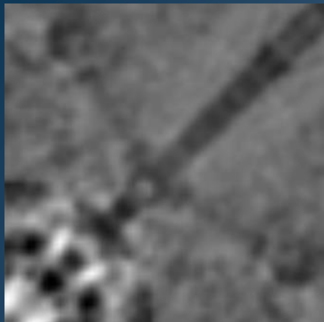
$k_{\mathrm{B}}T_{\mathrm{H}} \lesssim 0.14\, mc_{\mathrm{out}}^2$ for agreement with Hawking's prediction

Michel, F., Coupechoux, J.-F. & Parentani, R. Phonon spectrum and correlations in a transonic flow of an atomic Bose gas. *Phys. Rev. D* **94**, 084027 (2016).

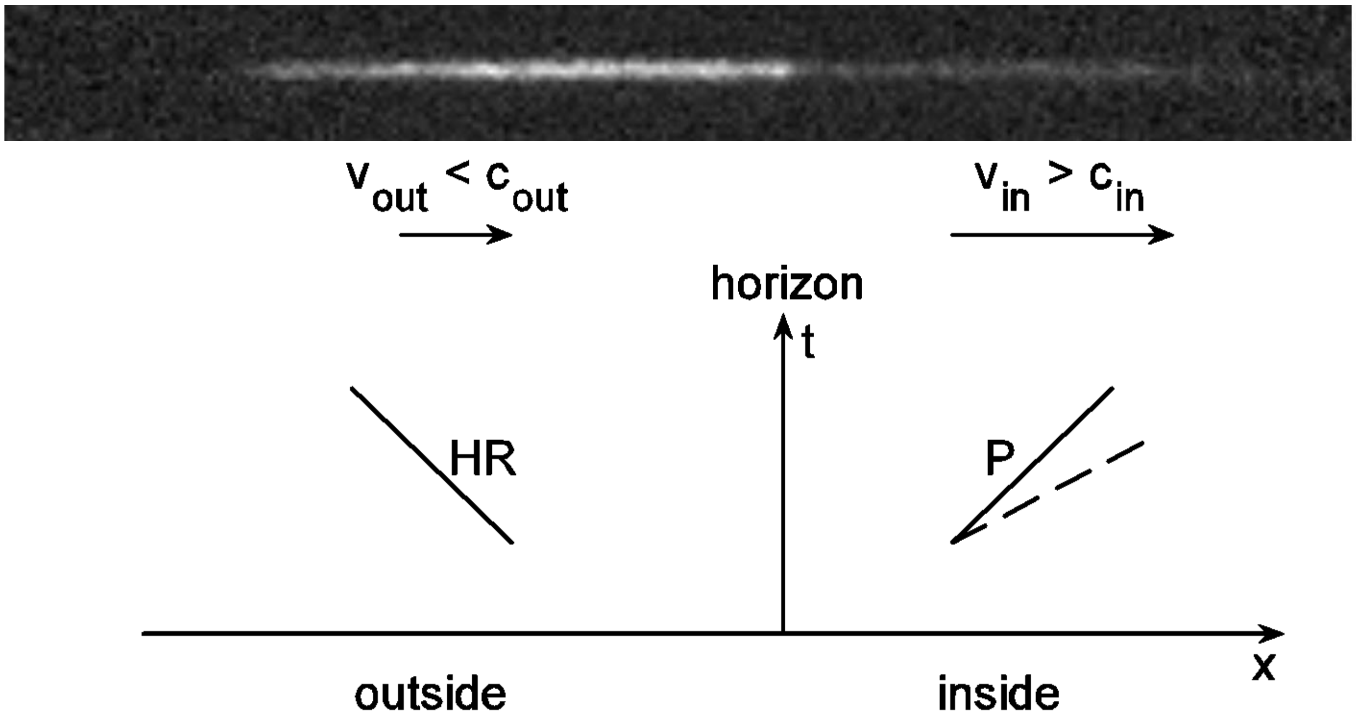
- The spectrum should be accurately Planckian.
- T_{H} should agree with the relativistic prediction within 10%.

Coutant A. & Weinfurtner, S. Low-frequency analogue Hawking radiation: The Bogoliubov-de Gennes model. *Phys. Rev. D* **97**, 025006 (2018).

- T_{H} is expected to be quite close to Hawking's prediction.



Analogue black hole



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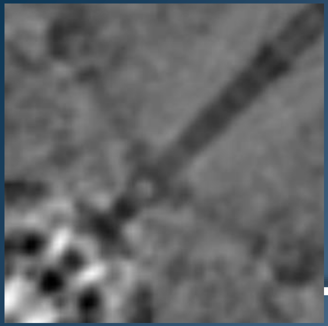
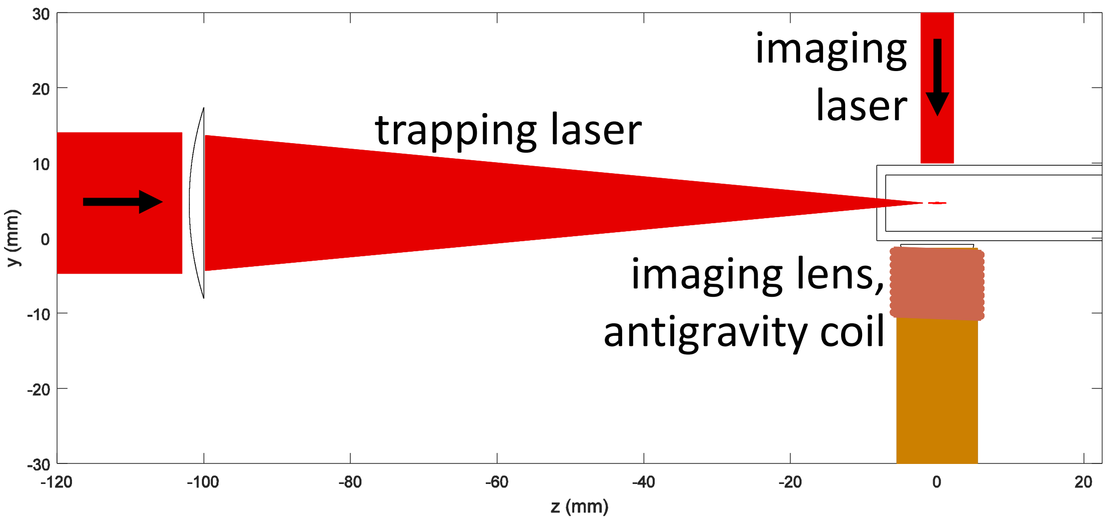


Experimental system



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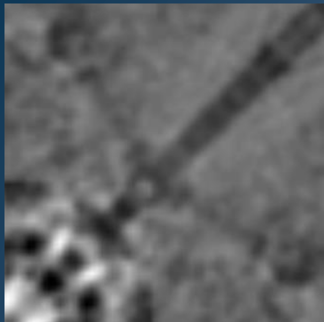
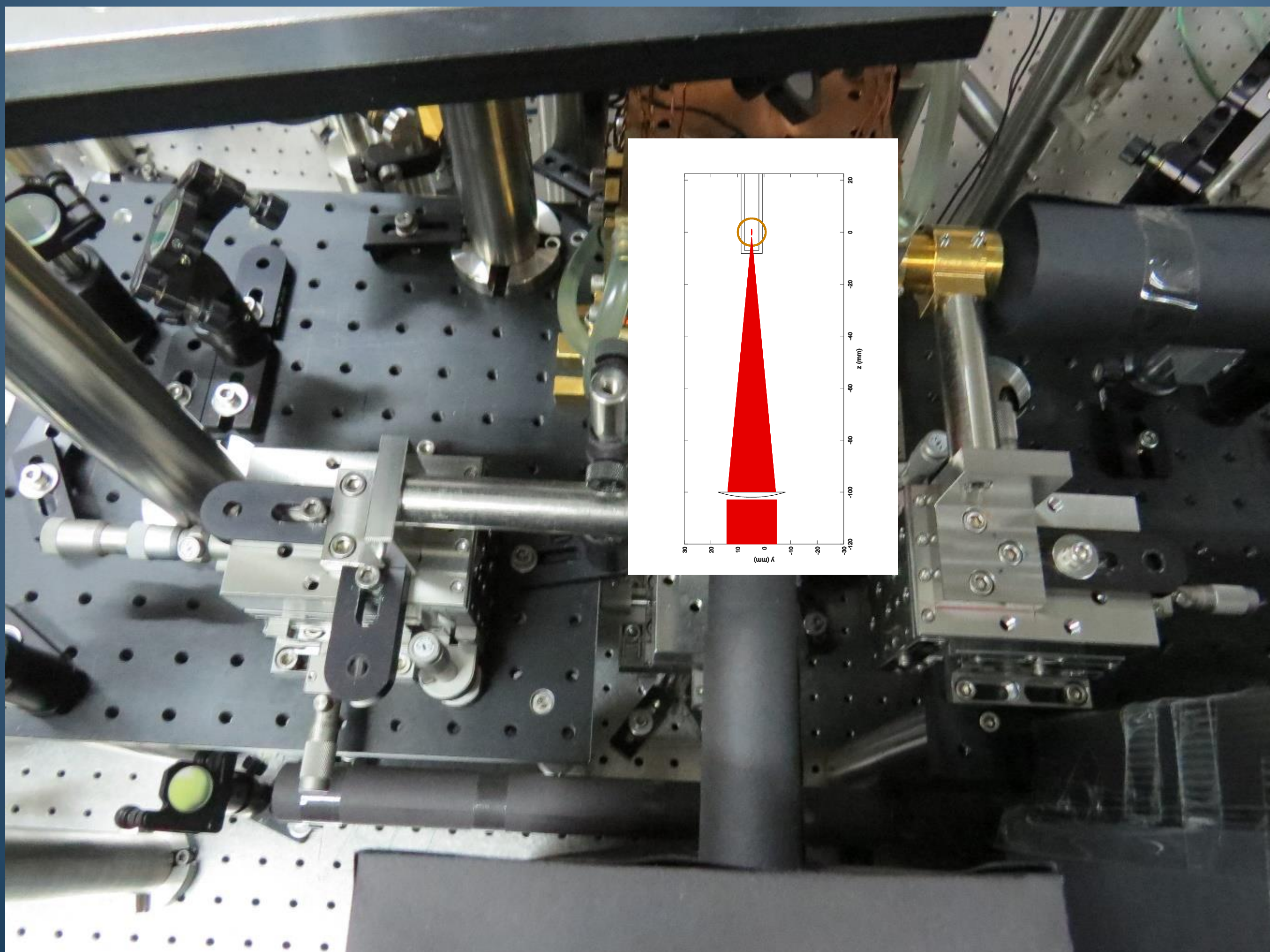
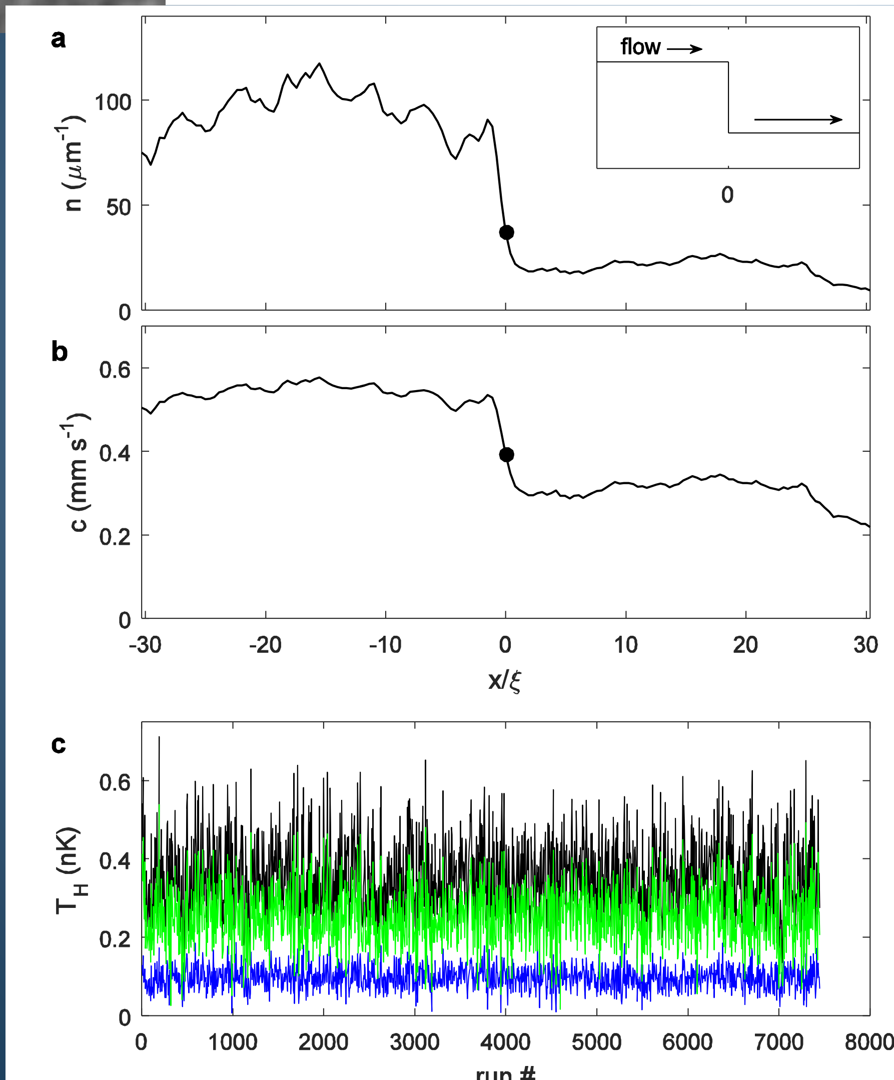


Apparatus (top view)



Predicted Hawking temperature



$$k_B T_H = \hbar g / 2\pi c$$

$$g = c(dv/dx - dc/dx)\Big|_{x=0}$$

$$J = nv = \text{constant}$$

$$k_B T_H = -\frac{\hbar}{2\pi}\left(\frac{c}{n}\frac{dn}{dx} + \frac{dc}{dx}\right)\Bigg|_{x=0}$$

$$k_B T_H = 0.351(4)\ \text{nK}$$

$$k_B T_H = 0.125(1)\ mc_{\text{out}}^2$$

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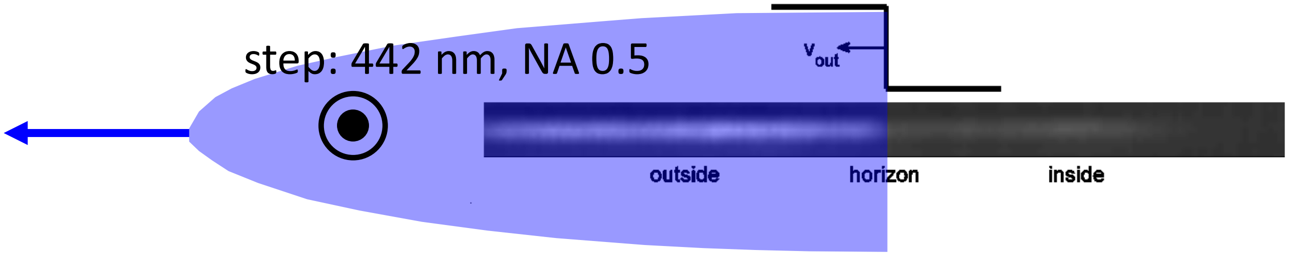
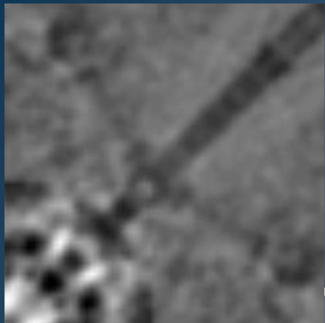
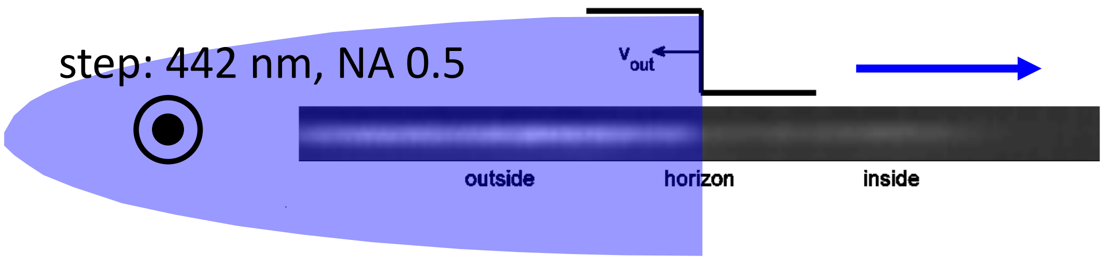
Experimental Technique

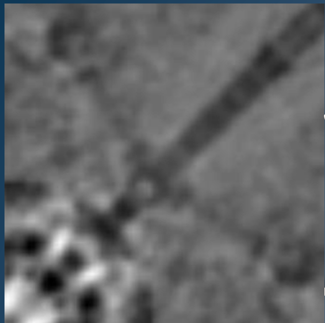


Lahav, O., Itah, A., Blumkin, A., Gordon, C., Rinott, S., Zayats, A. & Steinhauer, J. *Phys. Rev. Lett.* **105**, 240401 (2010).

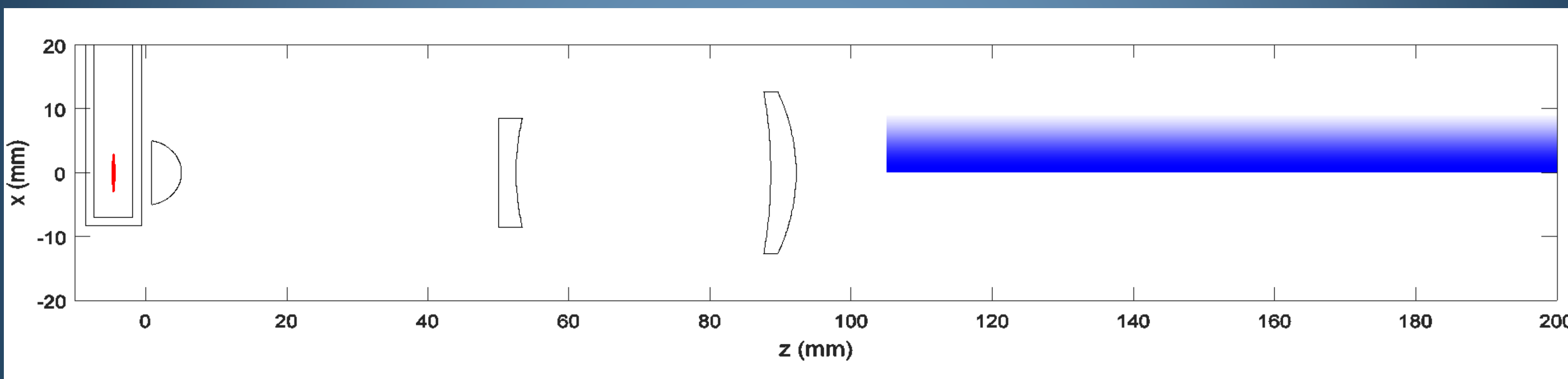


Experimental Technique





Waterfall objective lenses



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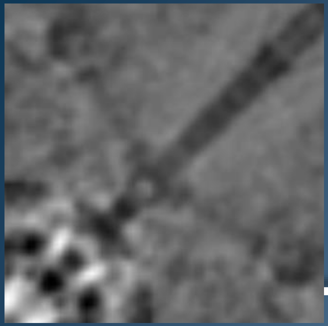
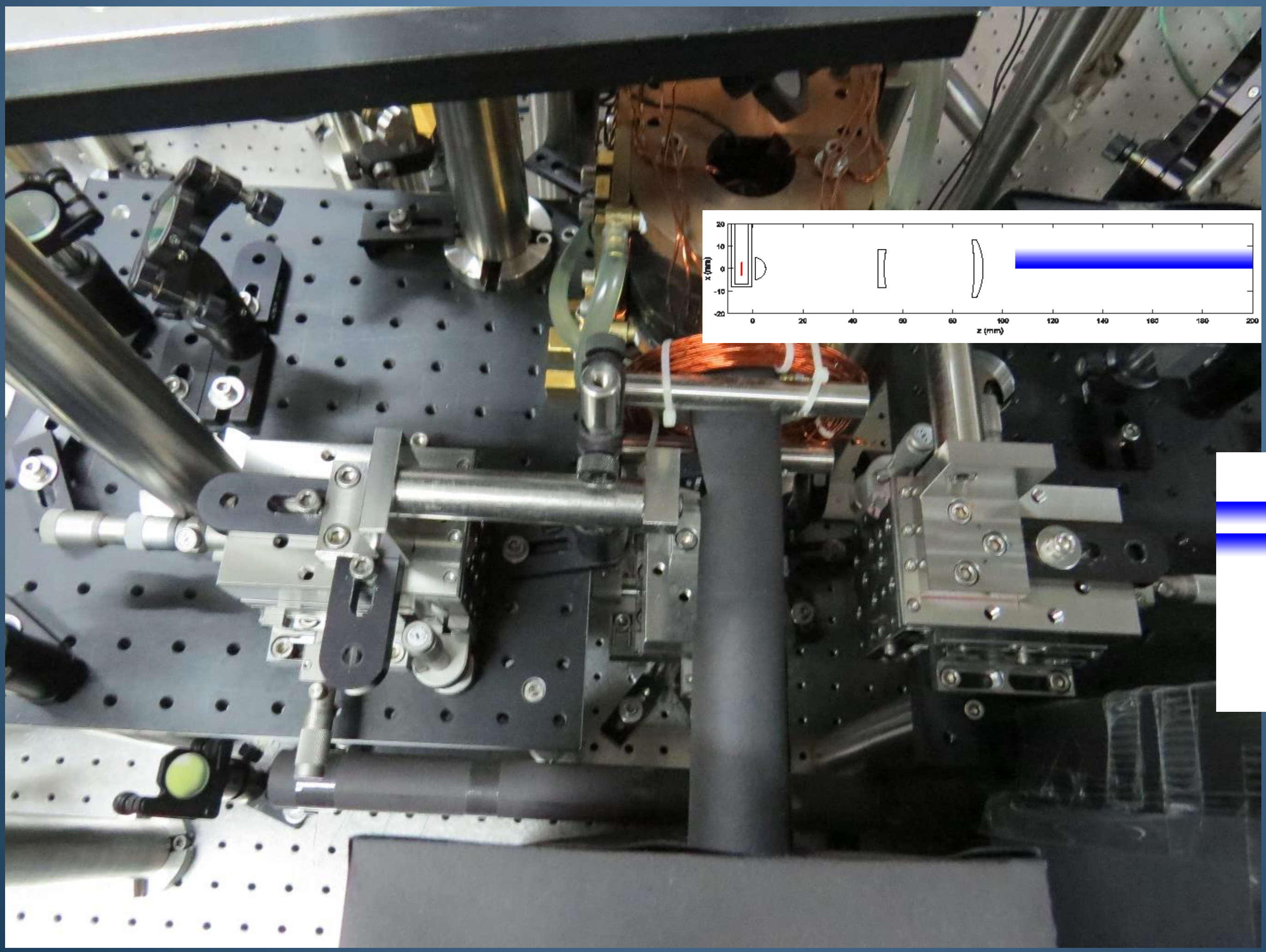
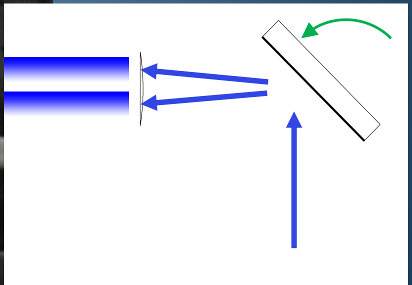
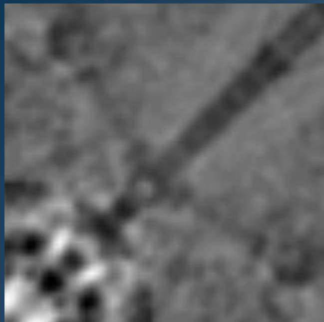


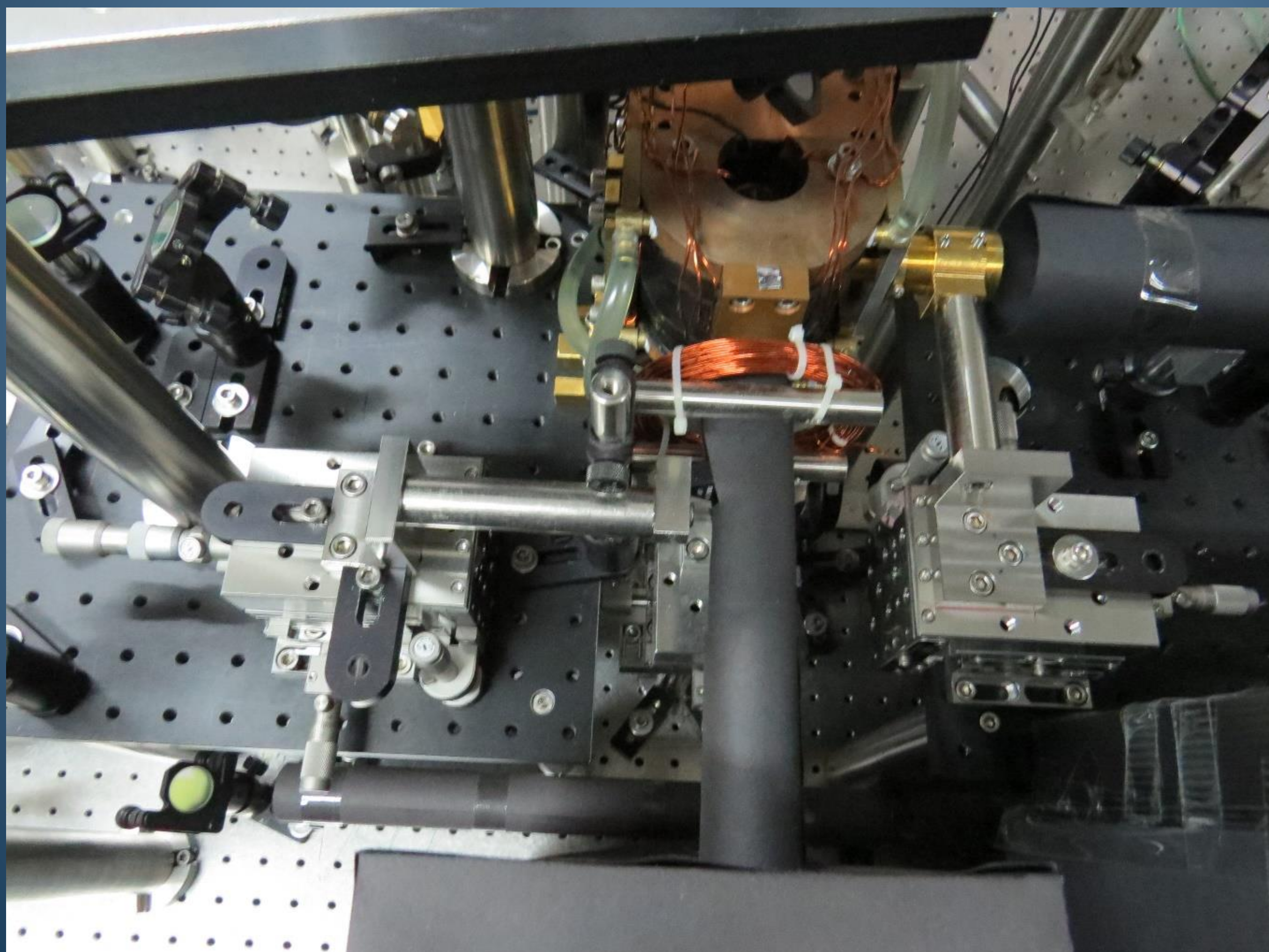
Apparatus

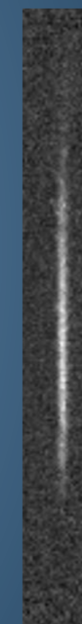


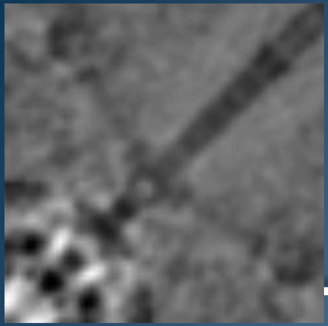




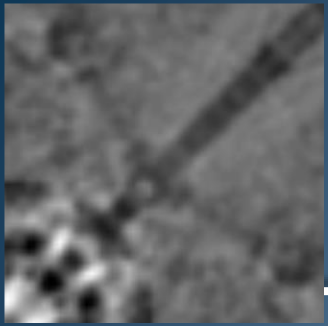
Reference images



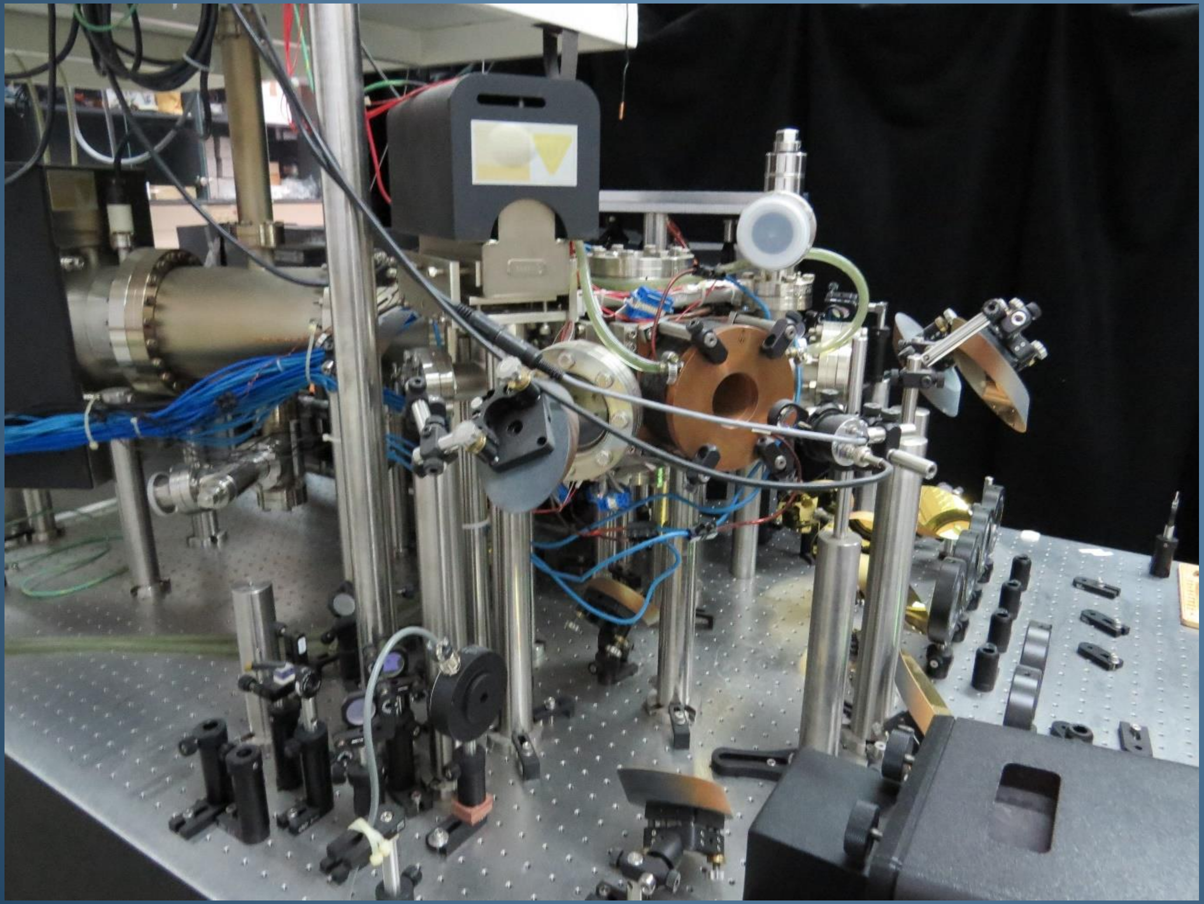




Apparatus



Apparatus



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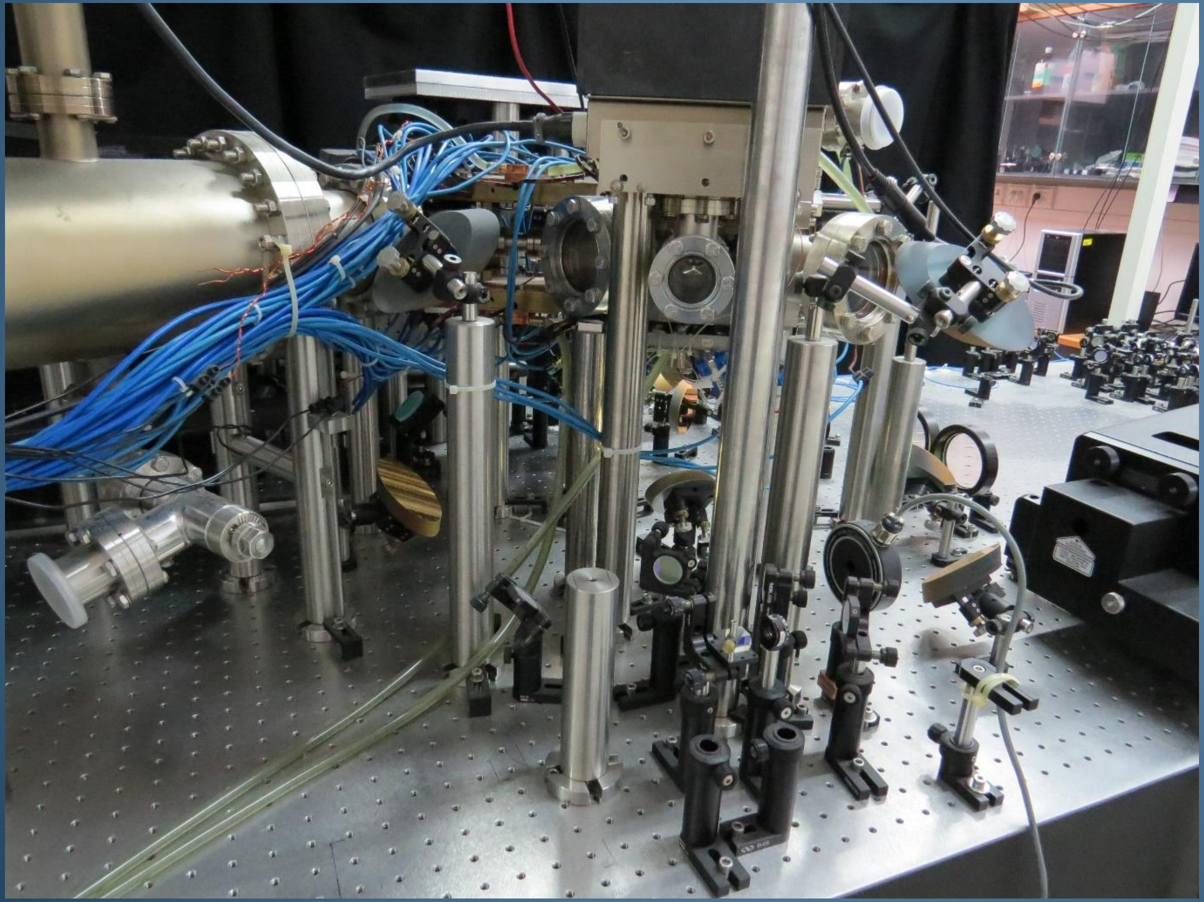

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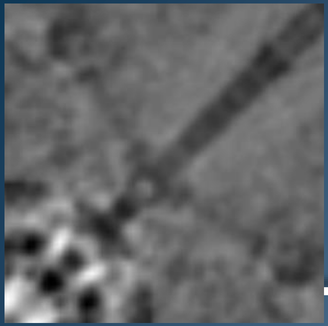

Apparatus

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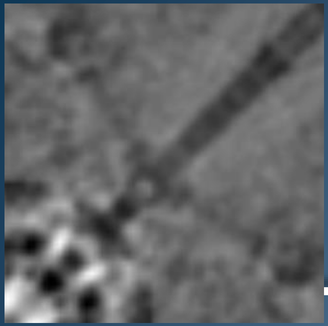
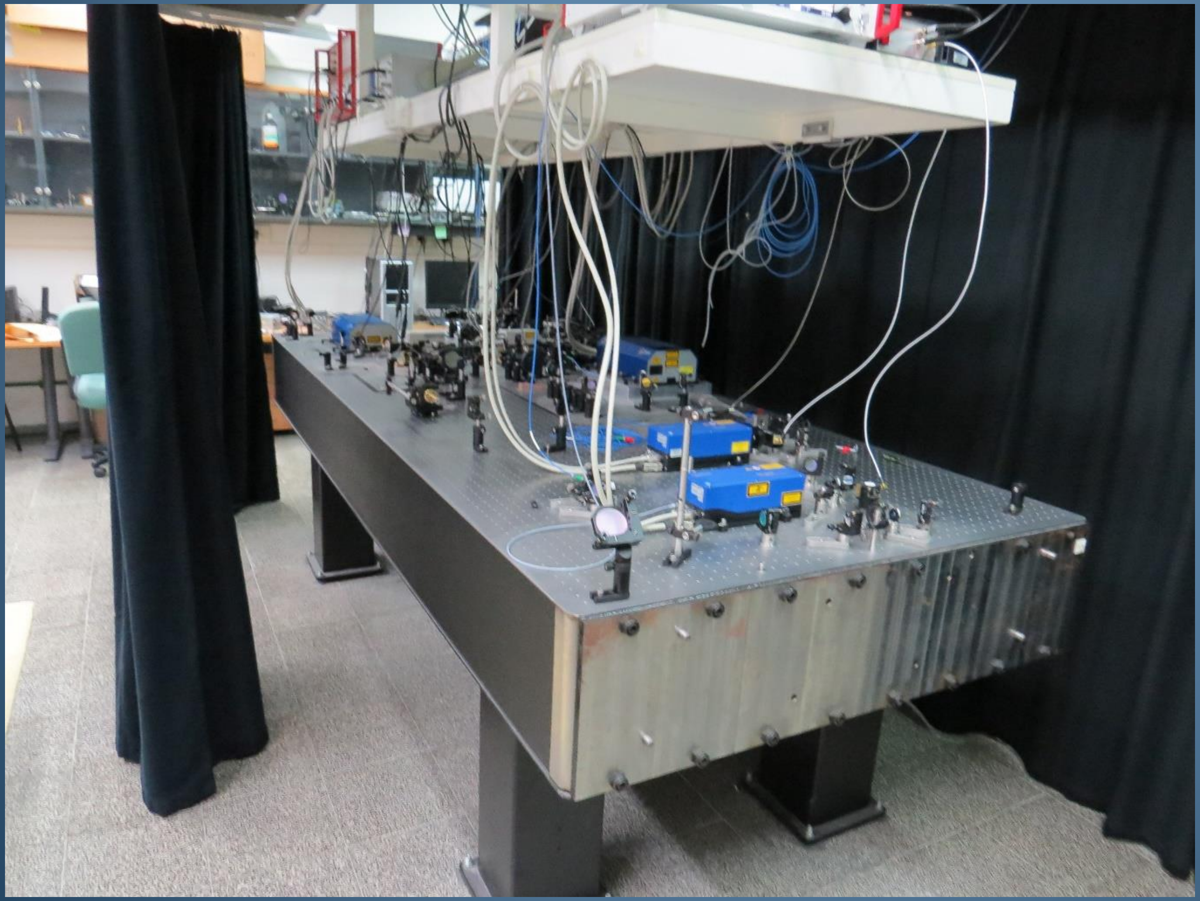


Apparatus



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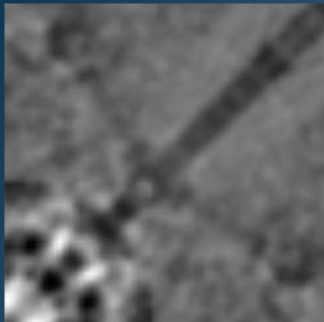
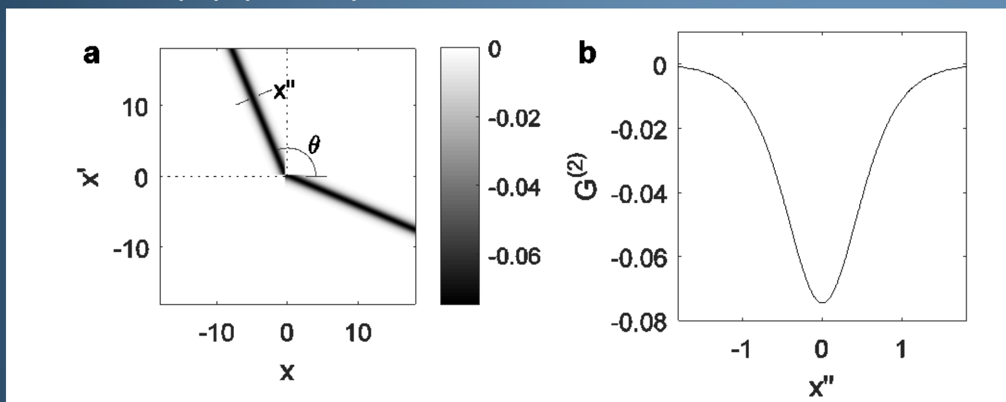


Correlation function

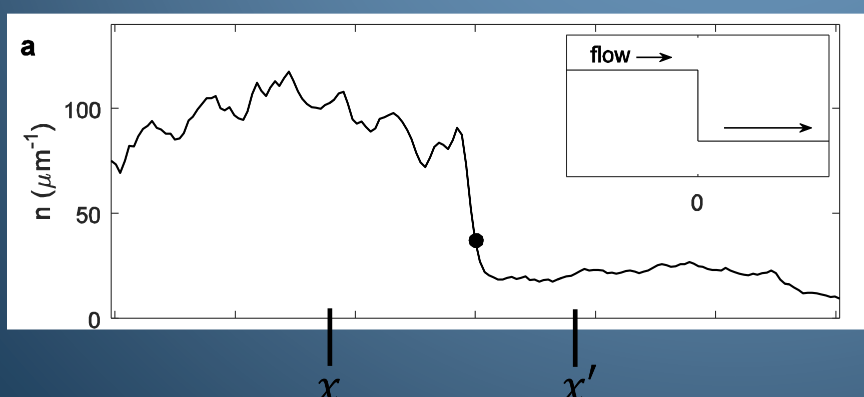
Balbinot, R., Fabbri, A., Fagnocchi, S., Recati, A. & Carusotto, I. *Phys. Rev. A* **78**, 021603(R) (2008).



This is how we observe Hawking radiation

Giovanazzi, S. *Phys. Rev. Lett.* **106**, 011302 (2011).

$$G^{(2)}(x,x') = \sqrt{n_{\text{out}} n_{\text{in}} \xi_{\text{out}} \xi_{\text{in}}} \langle \delta n(x) \delta n(x') \rangle / n_{\text{out}} n_{\text{in}}$$



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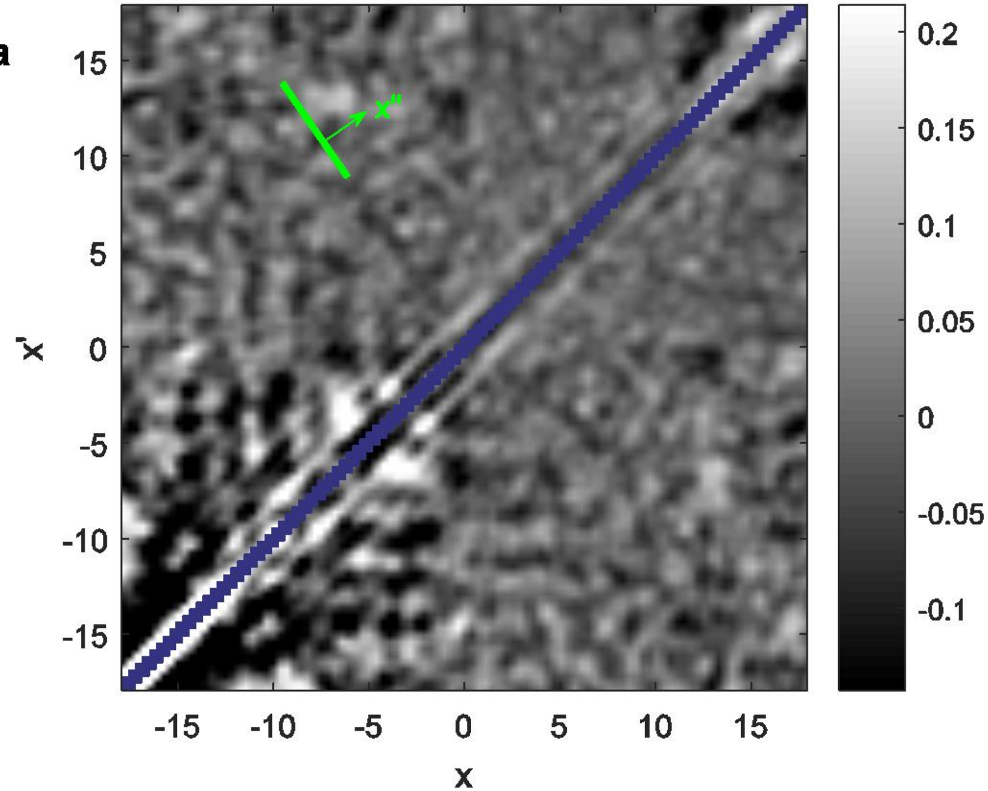
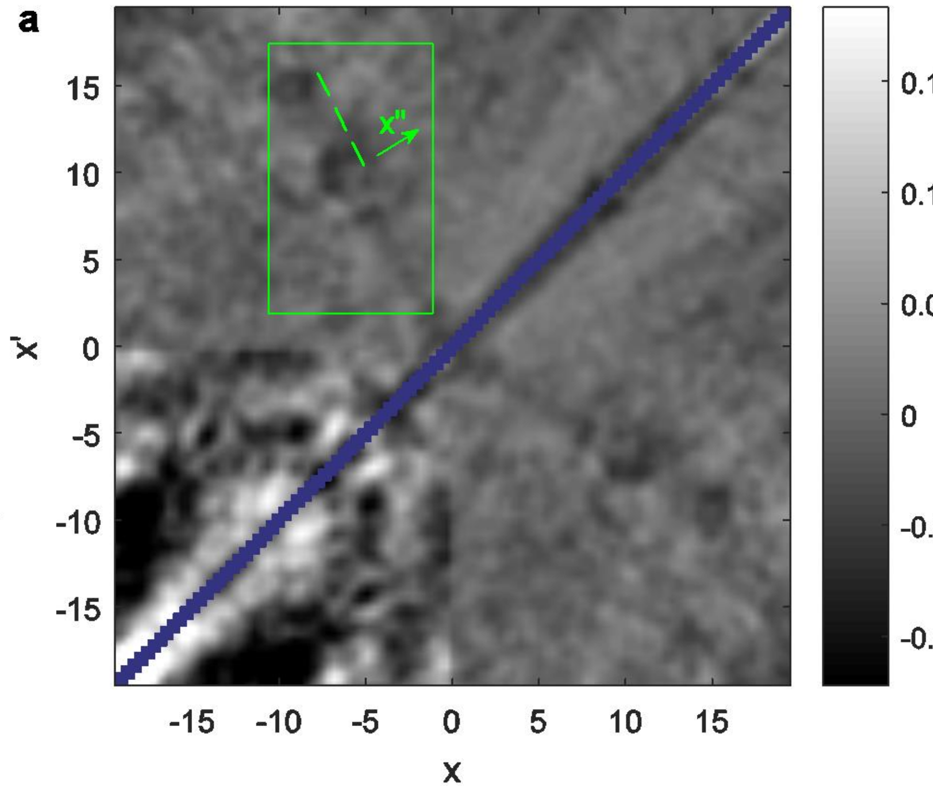
Observation of Hawking radiation

Old



New



Jeff Steinhauer, Nature Physics 12, 959 (2016).
de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. *Nature* 569, 688 (2019).

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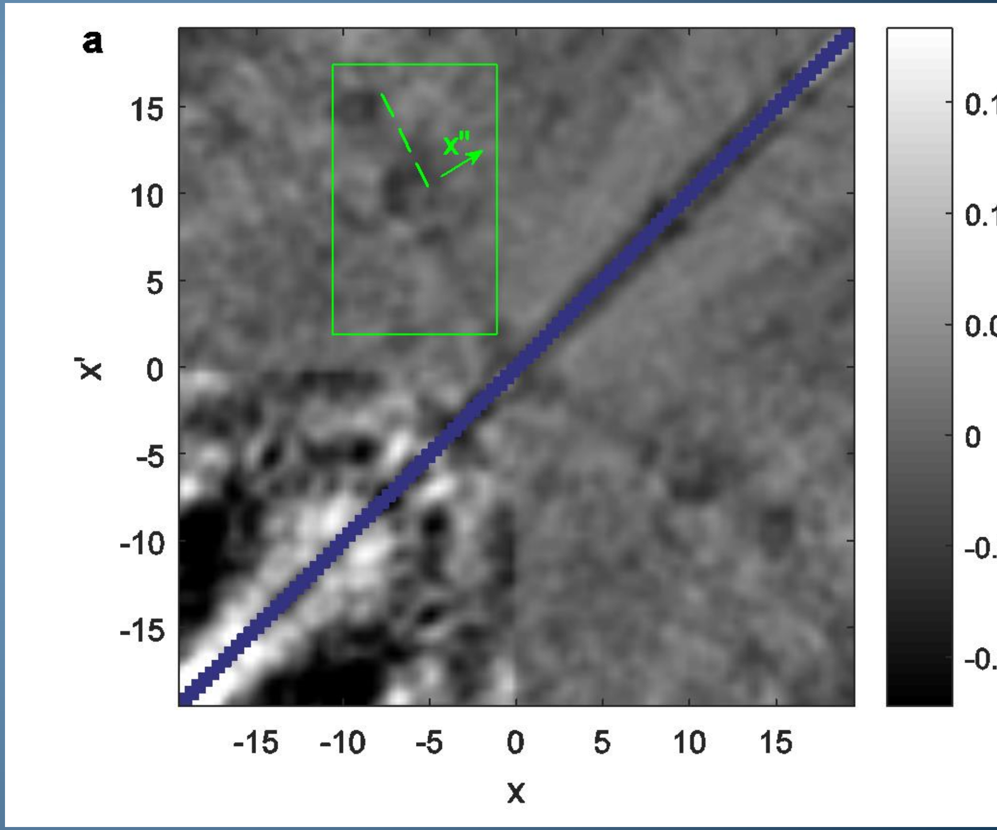
Observation of Hawking radiation

New



Correlations between Hawking and partner particles

Ensemble of 7400 images

Jeff Steinhauer, Nature Physics 12, 959 (2016).
de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. *Nature* 569, 688 (2019).

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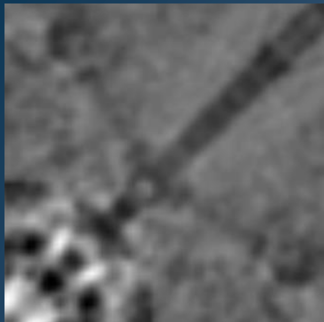
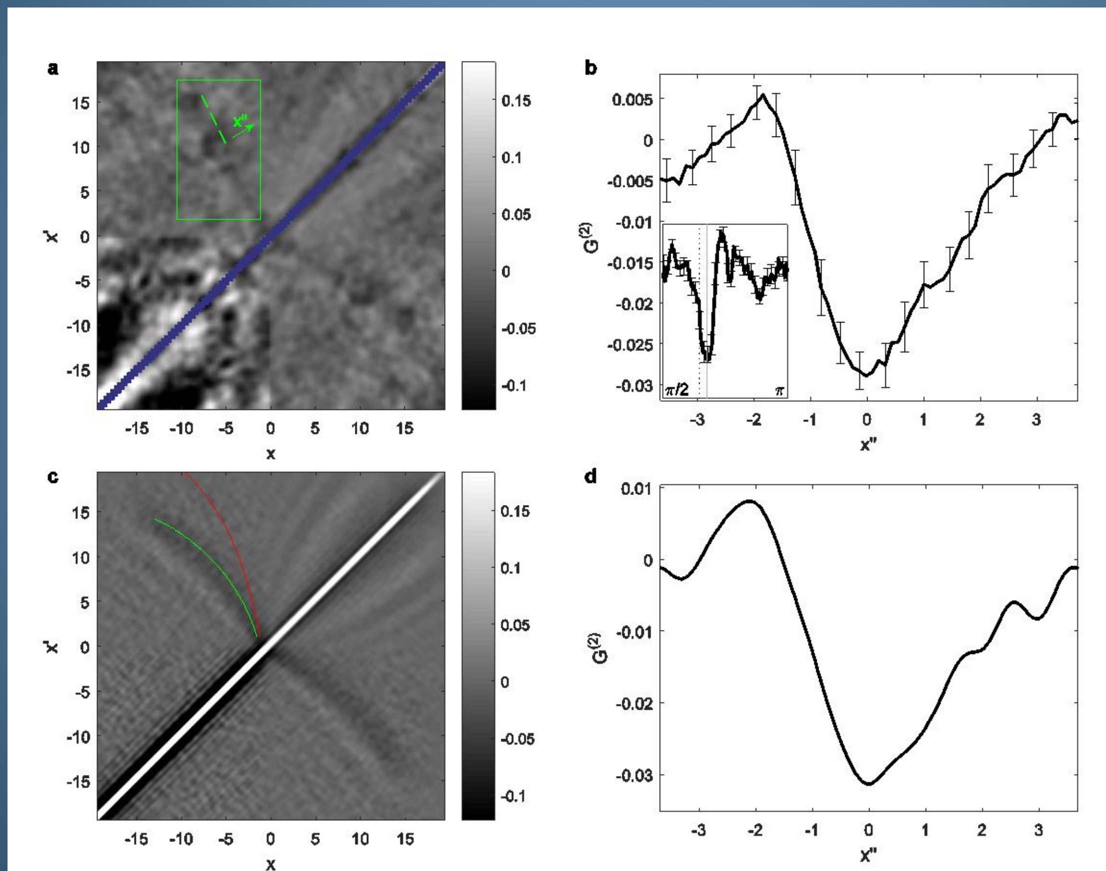


Profile



Recati, A., Pavloff, N. & Carusotto, I. *Phys. Rev. A* **80**, 043603 (2009).

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. *Nature* 569, 688 (2019).

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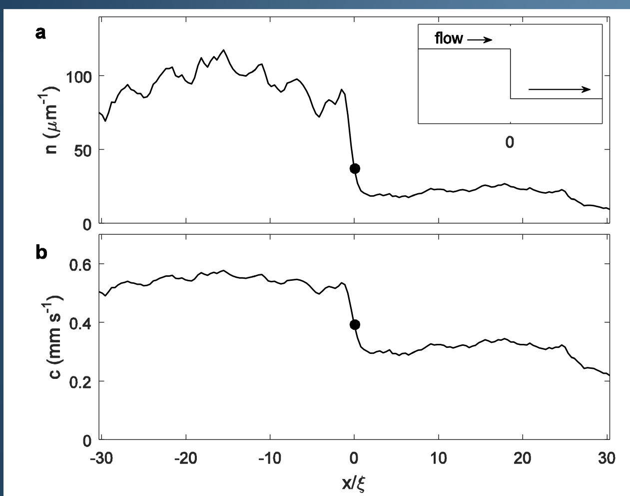
Prediction versus measurement

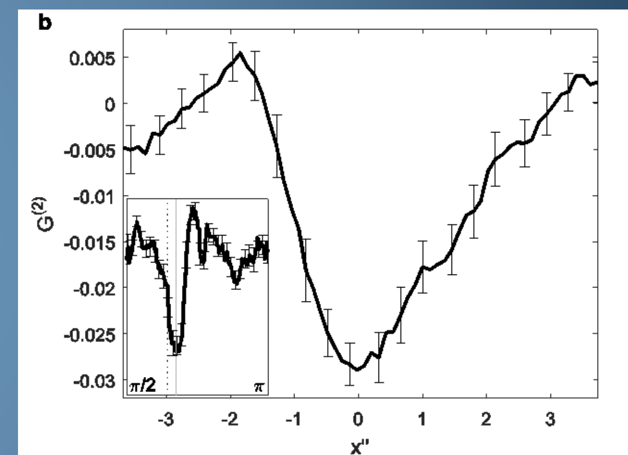
Surface gravity



$$k_B T_H = 0.125(1)\, m c_{out}^2$$

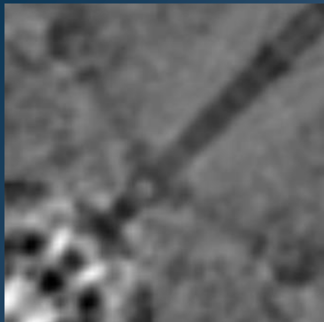
compare

Observed Hawking radiation

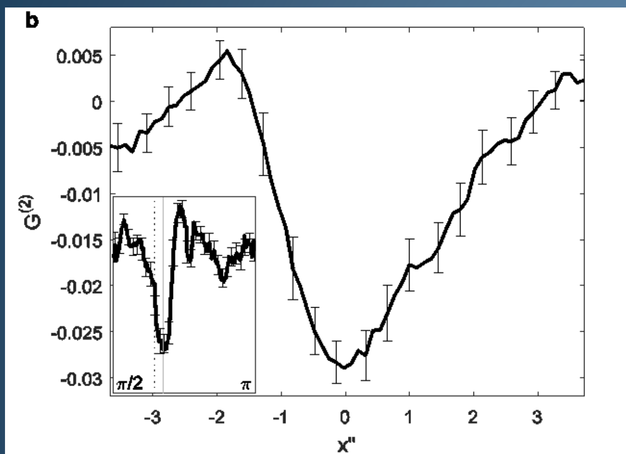


energy → *dispersion relation* → *k-space* ← *Fourier transform* ← *position space*

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. *Nature* 569, 688 (2019).



Fourier transform



$$S_0\langle \hat{b}_{\mathrm{H}} \hat{b}_{\mathrm{P}}\rangle = \sqrt{-\tan\theta - \cot\theta}\int dx'' e^{ikx''} G^{(2)}(x,x')$$

$$S_0 = \left(U_{k_H}+V_{k_H}\right)\left(U_{k_P}+V_{k_P}\right)$$

Assumption: Modes of different frequencies are uncorrelated.

Robertson, S., Michel, F. & Parentani,
R. *Phys. Rev. D* **96**, 045012 (2017).

Steinhauer, J. *Phys. Rev. D* **92**, 024043 (2015).

Steinhauer, J. *Nature Phys.* **12**, 959 (2016).

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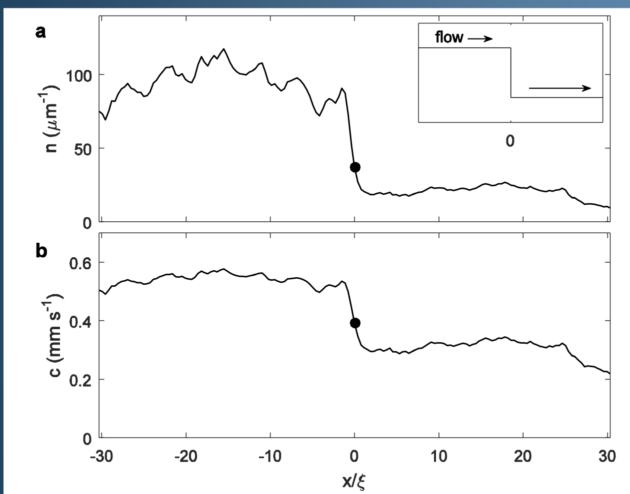
Prediction versus measurement

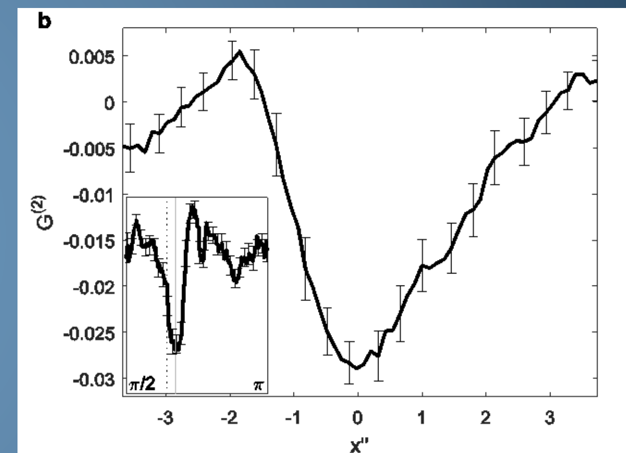
Surface gravity



$k_B T_H = 0.125(1)\, m c_{\mathrm{out}}^2$

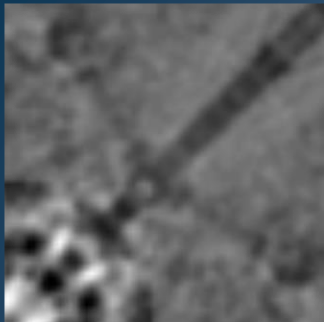
compare

Observed Hawking radiation

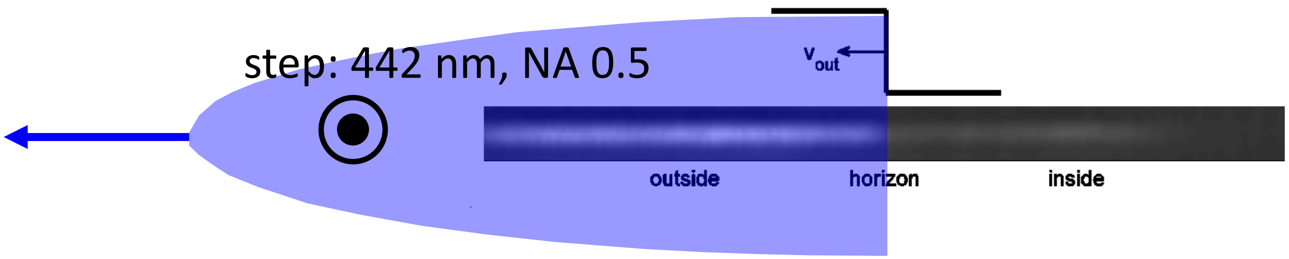


energy → *dispersion relation* → *k-space* ← *Fourier transform* ← *position space*

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. *Nature* 569, 688 (2019).



Experimental Technique



Lahav, O., Itah, A., Blumkin, A., Gordon, C., Rinott, S., Zayats, A. & Steinhauer, J. *Phys. Rev. Lett.* **105**, 240401 (2010).

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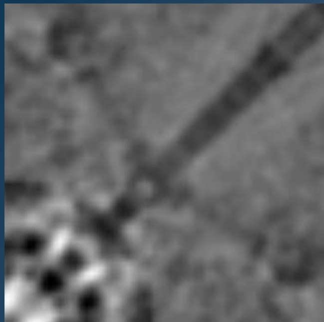
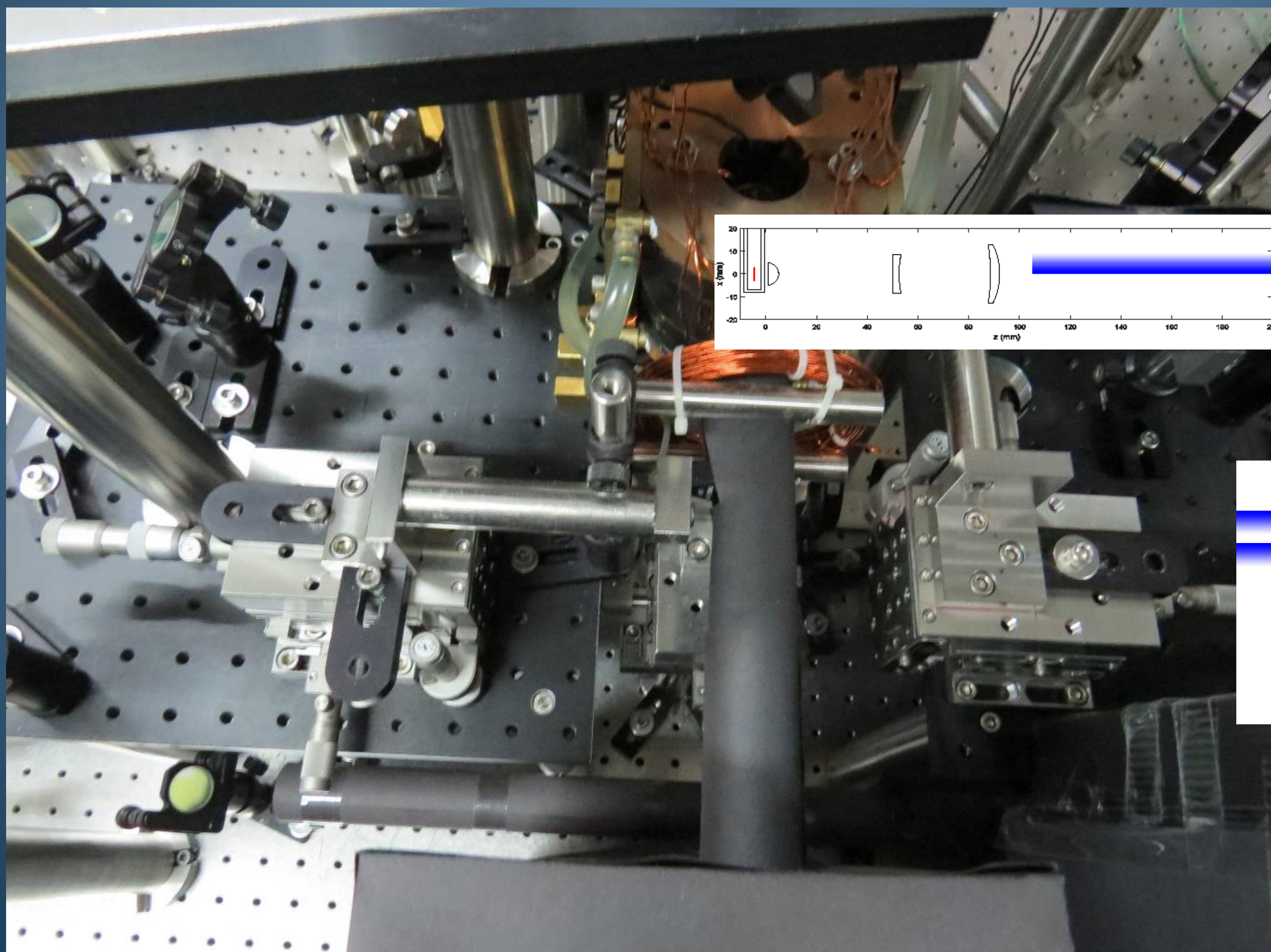
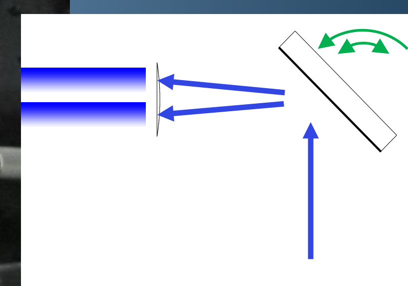
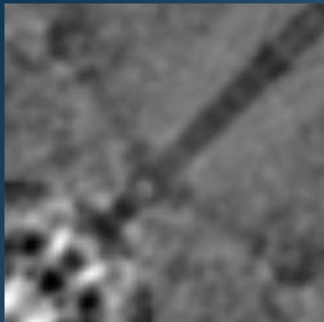


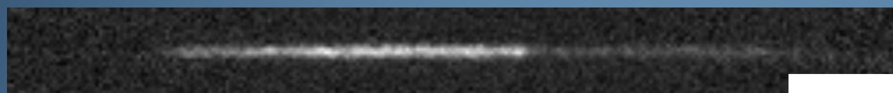
Apparatus

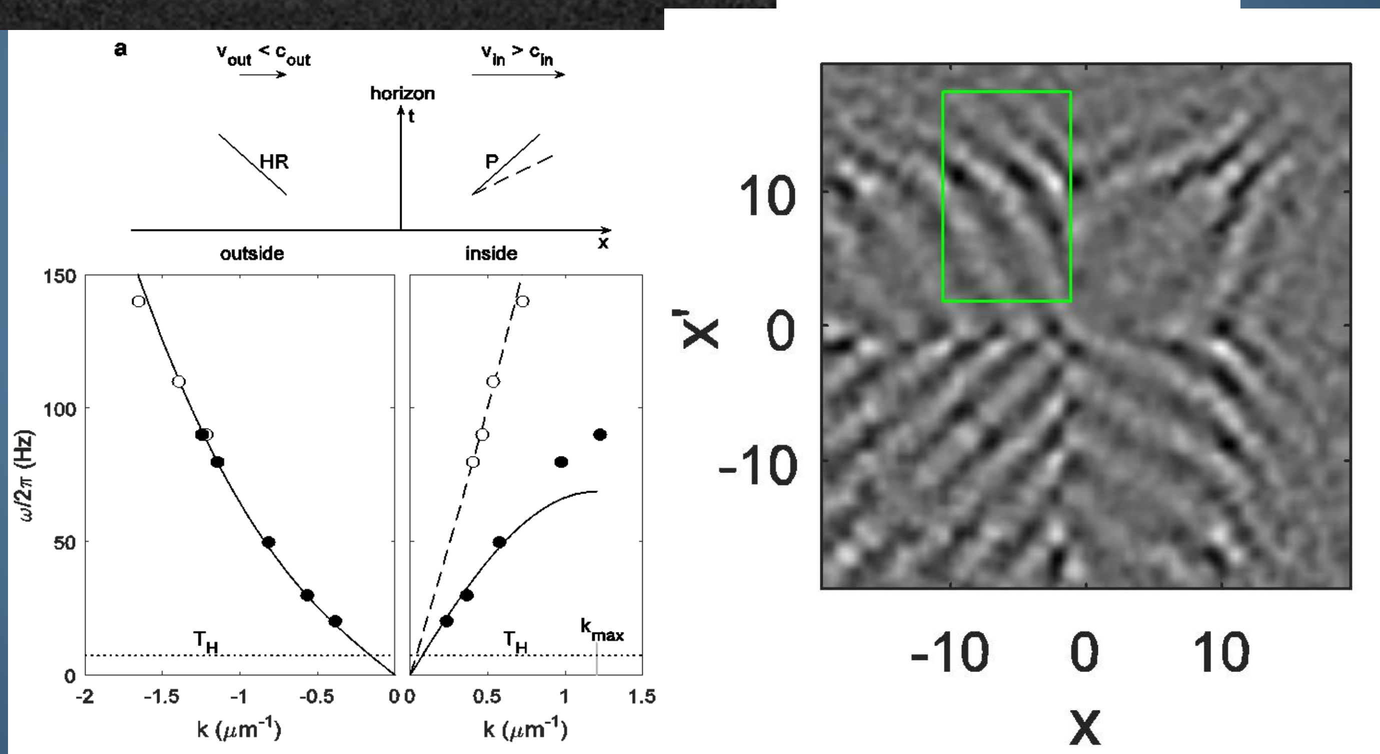






Analogue black hole





Now we can convert energies to wavenumbers.

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. *Nature* 569, 688 (2019).

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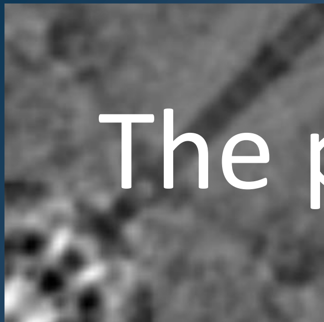


The prediction of Hawking's theory

$$\hat{b}_{\mathrm{H}} = \alpha \hat{b}_{+} + \beta \hat{b}_{-}^{\dagger} \qquad \hat{b}_{\mathrm{P}} = \alpha \hat{b}_{-} + \beta \hat{b}_{+}^{\dagger}$$ *(linear dispersion)*

$$|\beta|^2 = 1/\left(e^{\hbar\omega(k)/k_{\mathrm{B}}T_{\mathrm{H}}} - 1\right) \quad |\alpha|^2 = |\beta|^2 + 1$$

$$\langle \hat{b}_{\mathrm{H}} \hat{b}_{\mathrm{P}} \rangle = \alpha\beta\left(1 + \langle \hat{b}_{+}^{\dagger} \hat{b}_{+} \rangle + \langle \hat{b}_{-}^{\dagger} \hat{b}_{-} \rangle\right)$$

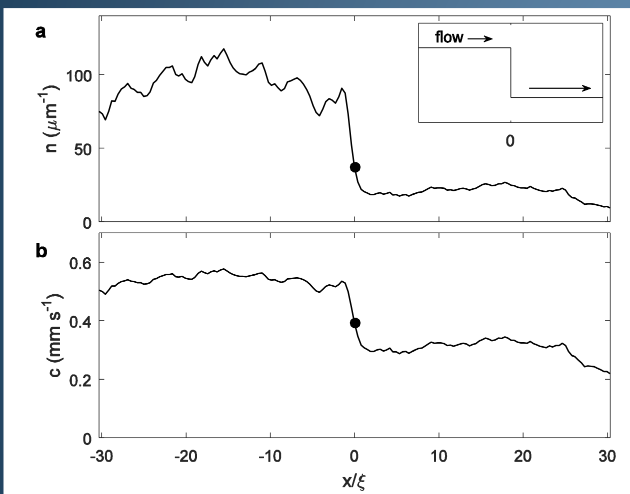
$$\langle \hat{b}_{\mathrm{H}} \hat{b}_{\mathrm{P}} \rangle = \alpha\beta$$ *(spontaneous Hawking radiation)*

$$S_0^2 \left|\langle \hat{b}_{\mathrm{H}} \hat{b}_{\mathrm{P}} \rangle\right|^2 = S_0^2 (|\beta|^2 + 1)|\beta|^2$$

Steinhauer, J. *Nature Phys.* **12**, 959 (2016).

Prediction versus measurement

Surface gravity

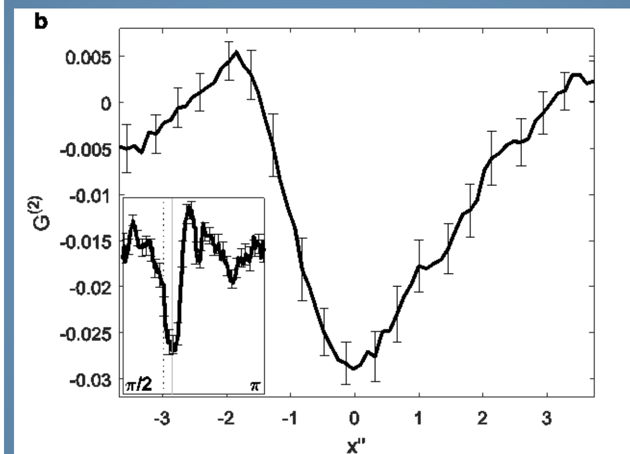


$$k_B T_H = 0.125(1)\, mc_{\text{out}}^2$$

$$|\beta|^2 = 1/\left(e^{\hbar\omega(k)/k_B T_H} - 1\right)$$

$$S_0^2 \left|\langle \hat{b}_H \hat{b}_P \rangle\right|^2 = S_0^2(|\beta|^2 + 1)|\beta|^2$$

Observed Hawking radiation

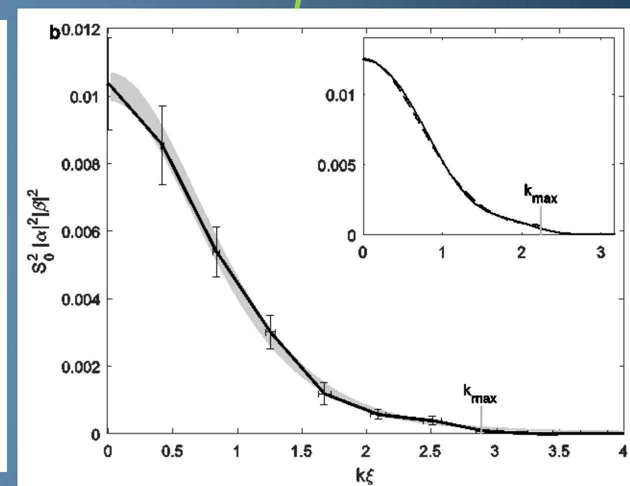


$$S_0 \langle \hat{b}_H \hat{b}_P \rangle$$

$$= \sqrt{-\tan\theta - \cot\theta} \int dx'' e^{ikx''} G^{(2)}(x, x')$$

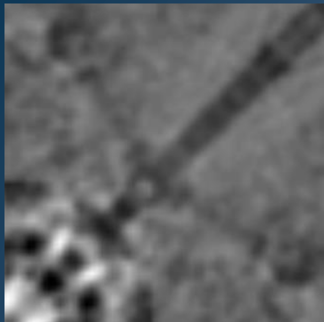
$$k_B T_H = 0.124(6)\, mc_{\text{out}}^2$$

Comparison

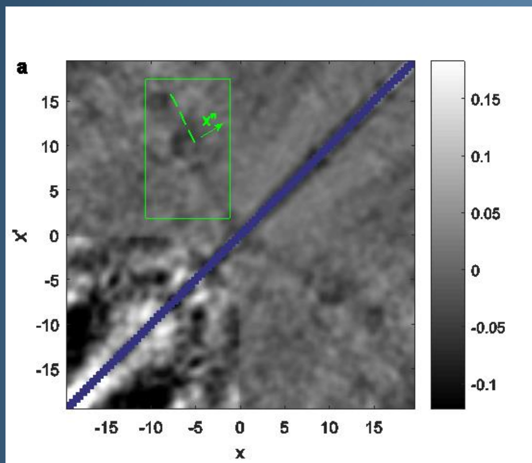


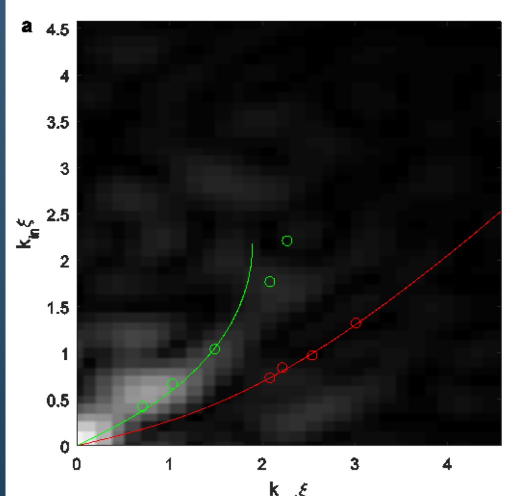
- *Thermal spectrum*
- *Agreement within 6%*
- *Spontaneous*
- *Quantum*

de Nova, J. R. M., Golubkov, K., Kolobov, V. I. & Steinhauer, J. *Nature* 569, 688 (2019).

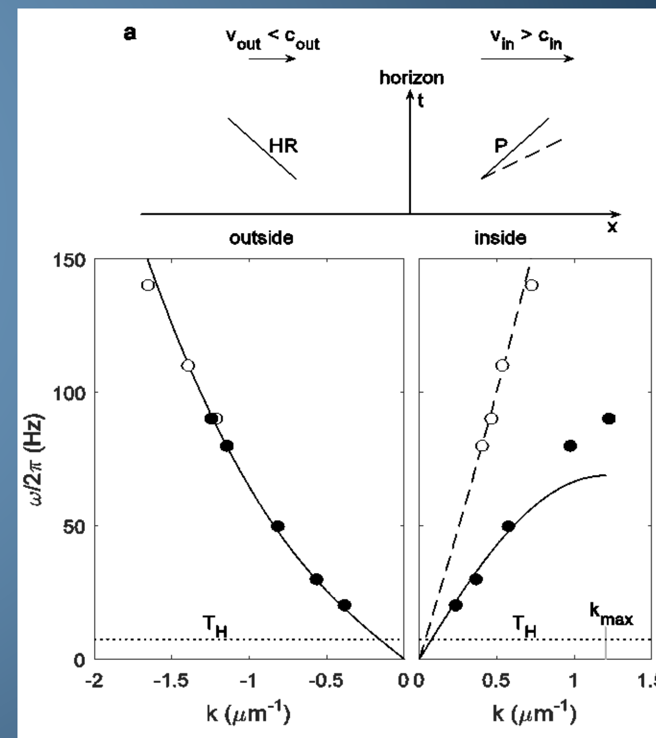


Correlation spectrum





$$S_0\langle \hat{b}_H \hat{b}_P \rangle = \sqrt{\frac{\xi_{out}\xi_{in}}{L_{out}L_{in}}} \int dx\, dx'\, e^{ik_H x} e^{ik_P x'} G^{(2)}(x, x')$$



Negative energy partners only

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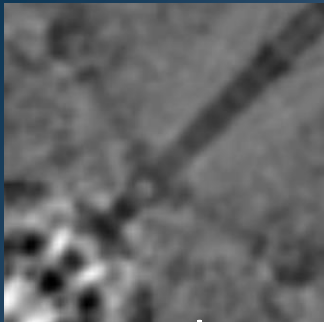

Conclusions

- The correlation spectrum of the Hawking radiation is seen to be thermal.
- The Hawking temperature of the radiation is in agreement with the prediction from the analogue surface gravity.
- The experiment is in the regime of linear dispersion in analogy with a real black hole.
- Only negative-energy partners are seen.
- The results are in agreement with the predictions found in the literature for our system.
- Apparently, dispersion and graybody factors have little effect on the Hawking radiation.
- The results are in agreement with a numerical simulation.

Implications for real gravity

- Hawking's calculation is confirmed quantitatively. This includes:
  - The thermality of the spectrum
  - The Hawking temperature
- The correlations between the Hawking and partner modes are of the predicted magnitude, with no reduction due to the underlying quantum structure.
- The thermality of Hawking radiation is the basis for the information paradox.
- The temperature links Hawking radiation with black hole entropy.