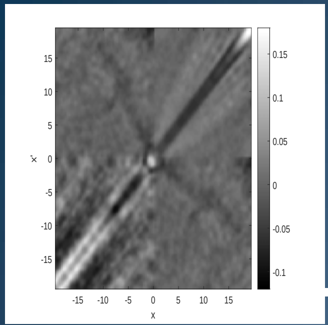

Spontaneous Hawking radiation, black-hole lasing and beyond: Observing the time evolution of an analogue black hole

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

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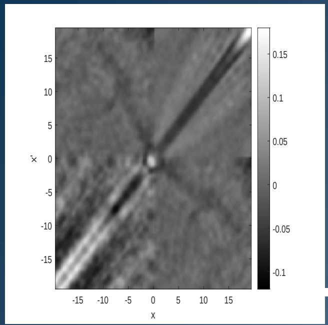

Theoretical background

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

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

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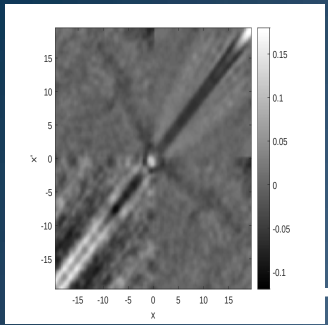

Theoretical background

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."

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

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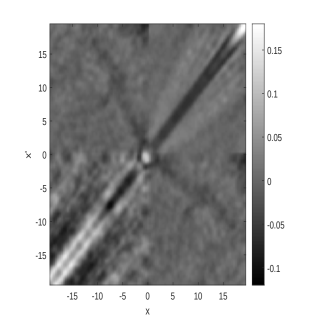


Theoretical background

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).

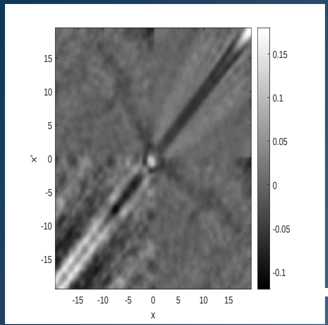
Zapata, I., Albert, M., Parentani, R. & Sols, F. Resonant Hawking radiation in Bose–Einstein Condensates. *New J. Phys.* **13**, 063048 (2011).

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).

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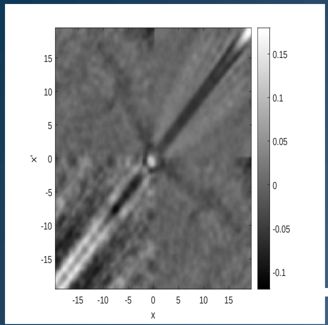
de Nova, J. R. M., Sols, F. & Zapata, I. Violation of Cauchy-Schwarz inequalities by spontaneous Hawking radiation in resonant boson structures. *Phys. Rev. A* **89**, 043808 (2014).

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).

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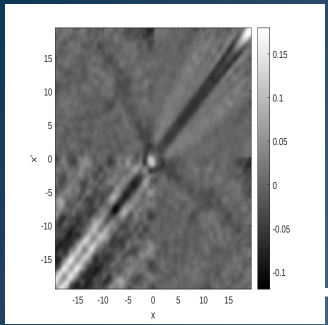


Theoretical background

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).

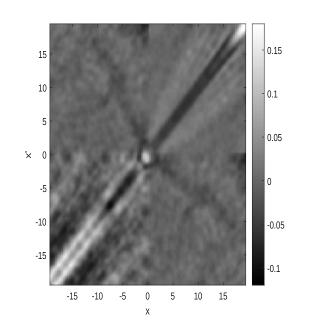
Ultracold Fermions

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).

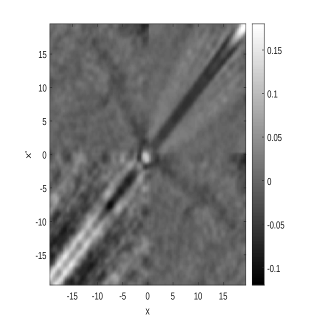
Magnons in a magnetic wire

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).

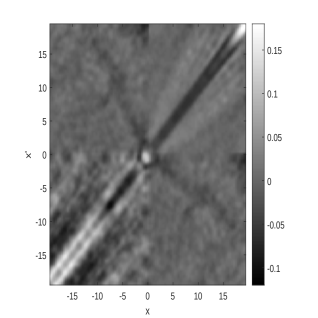
Schley, R., Berkovitz, A., Rinott, S., Shammass, I., Blumkin, A. & Steinhauer, J. Planck Distribution of Phonons in a Bose-Einstein Condensate. *Phys. Rev. Lett.* **111**, 055301 (2013).

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).

Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J. Spontaneous Hawking radiation and beyond: Observing the time evolution of an analogue black hole. arXiv:1910.09363 (2019).



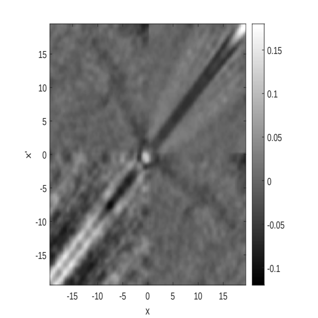
Experimental background

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).

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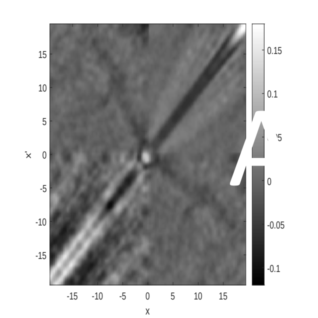
Exciton-polariton condensate

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 expanding universe

Gibbons-Hawking Effect (theory) ***Similar to the Unruh Effect***

Fedichev, Petr O. & Fischer, Uwe R. Gibbons-Hawking Effect in the Sonic de Sitter Space-Time of an Expanding Bose-Einstein-Condensed Gas. *PRL* **91**, 240407 (2003).

Analogue cosmological particle production (theory) ***Similar to the Dynamical Casimir Effect***

Barceló, C., Liberati, S. & Visser, M. Analogue models for FRW cosmologies. *Int. J. Mod. Phys. D* **12**, 1641 (2003).

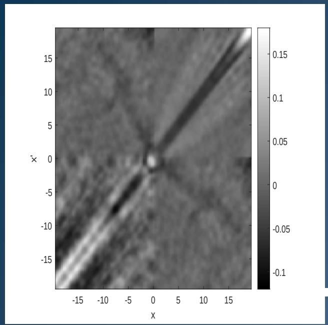
Barceló, C., Liberati, S. & Visser, M. Probing semiclassical analog gravity in Bose-Einstein condensates with widely tunable interactions. *PRA* **68**, 053613 (2003).

Fedichev, Petr O. & Fischer, Uwe R. "Cosmological" quasiparticle production in harmonically trapped superfluid gases. *PRA* **69**, 033602 (2004).

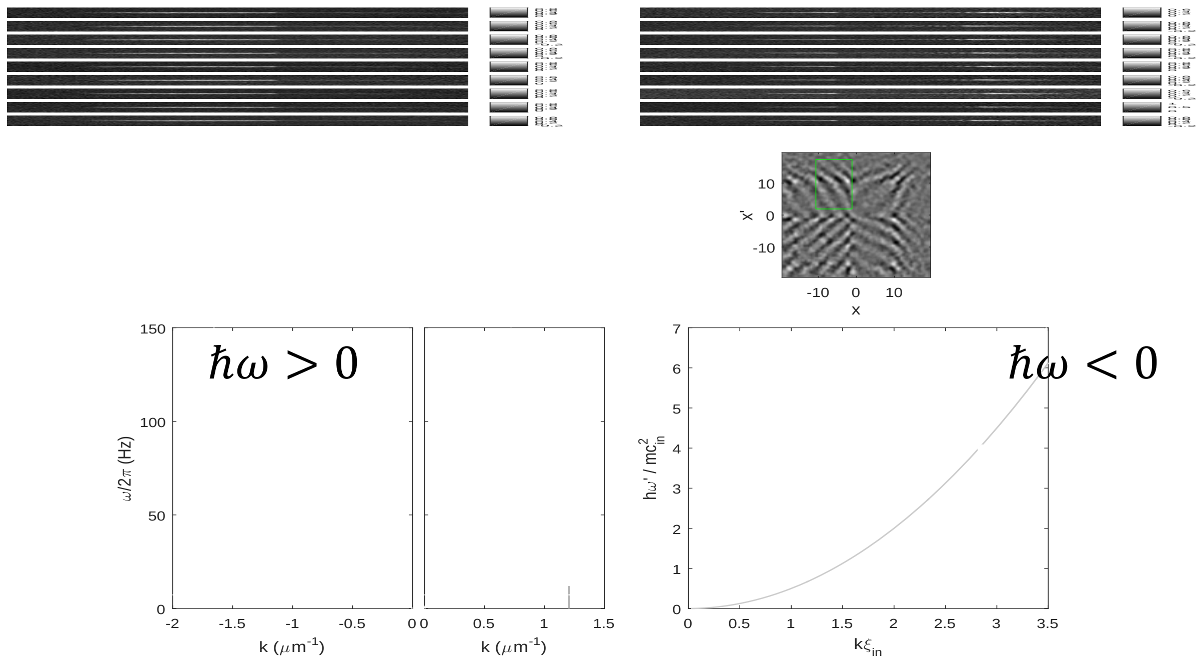
Fischer, Uwe R. & Schützhold, R. Quantum simulation of cosmic inflation in two-component Bose-Einstein condensates. *PRA* **70**, 063615 (2004).

Nonlinear dynamics (experiment)

Eckel, S., Kumar, A., Jacobson, T., Spielman, I. B., & Campbell, G. K. A rapidly expanding Bose-Einstein condensate: An expanding universe in the lab. *PRX* **8**, 021021 (2018).



Analogue black hole



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

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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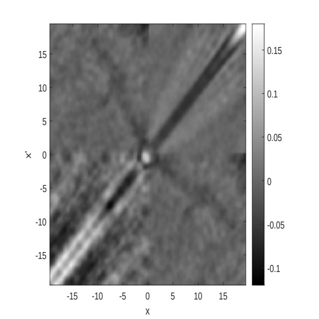
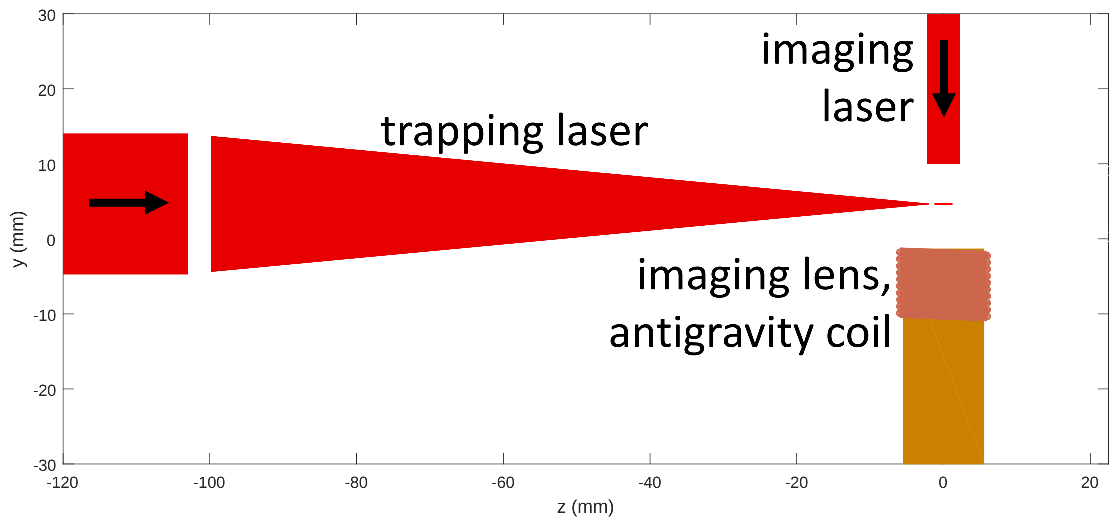
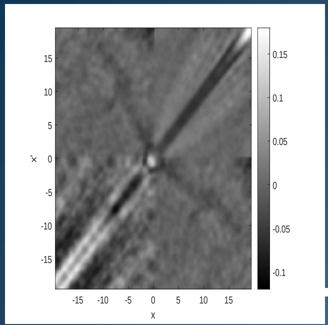
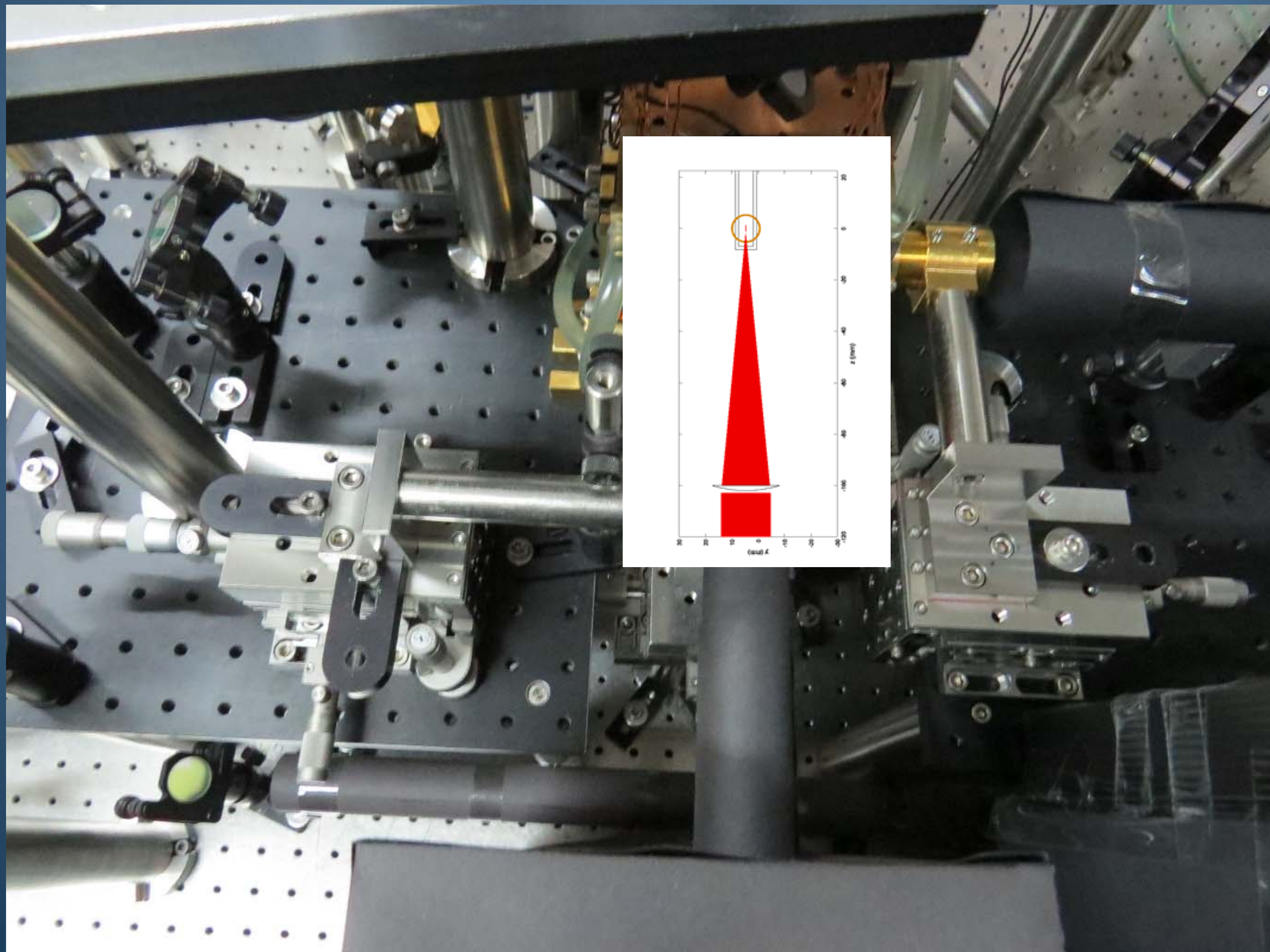


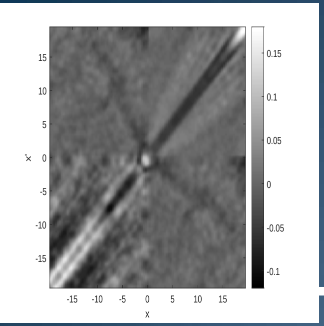
Experimental system



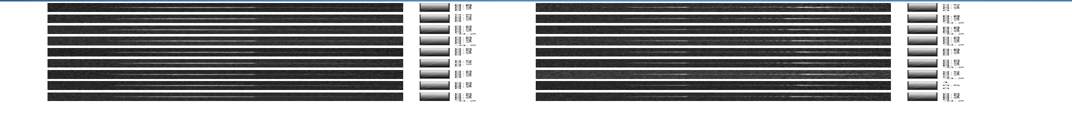


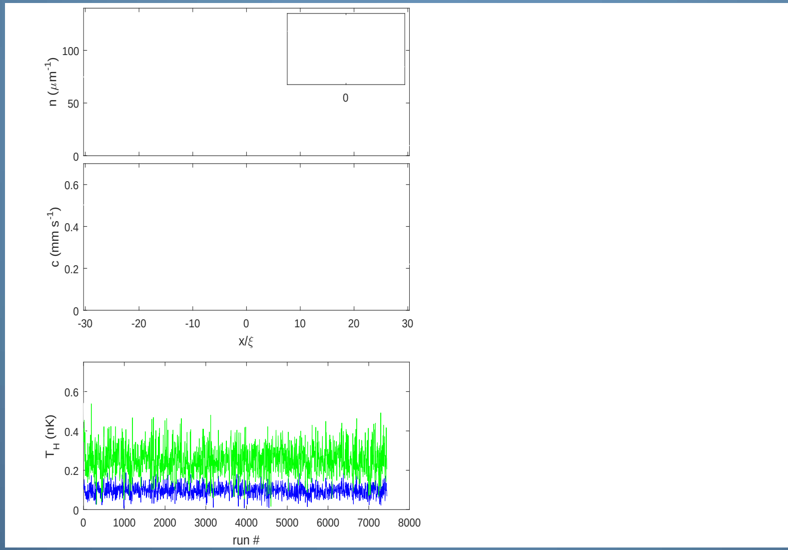
Apparatus (top view)





Waterfall potential





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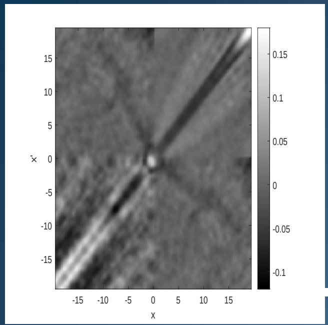
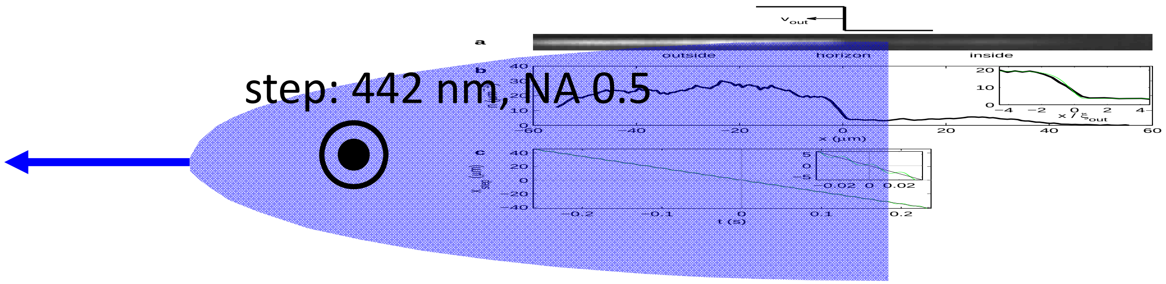
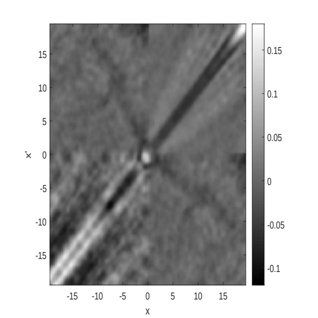


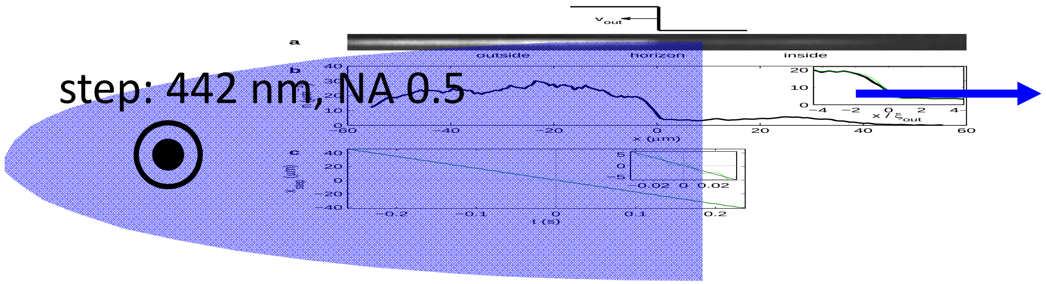
Experimental Technique

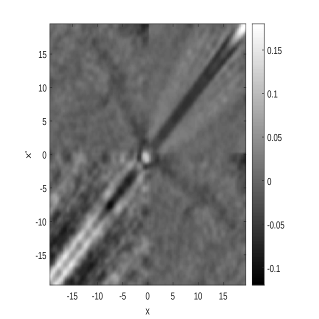


Lahav, O., Itah, A., Blumkin, A., Gordon, C., Rinott, S., Zayats, A. & Steinhauer, J. *Phys. Rev. Lett.* **105**, 240401 (2010).

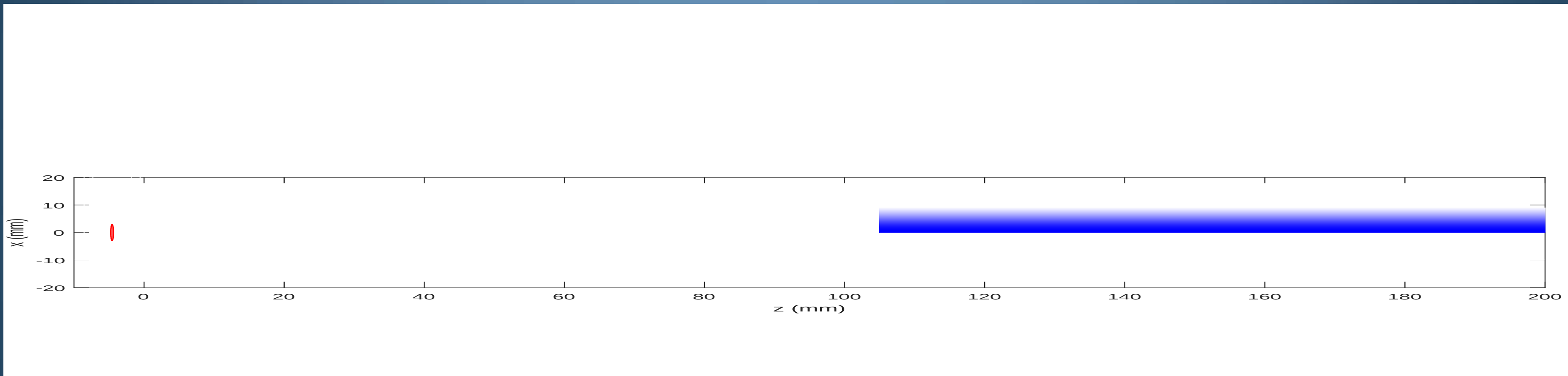


Experimental Technique





Waterfall objective lenses



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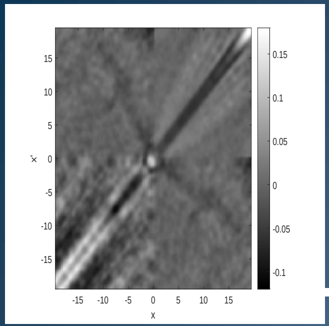
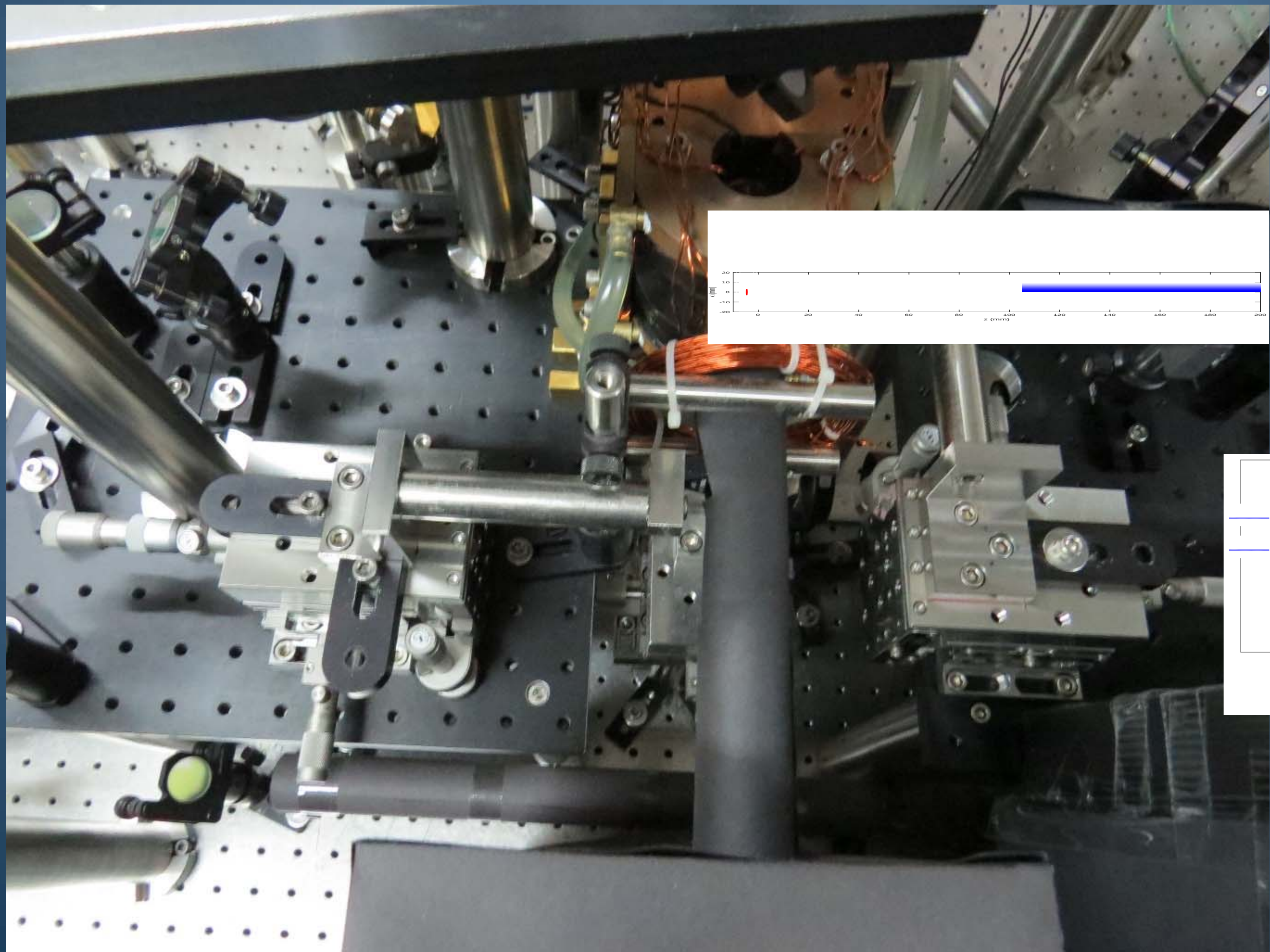
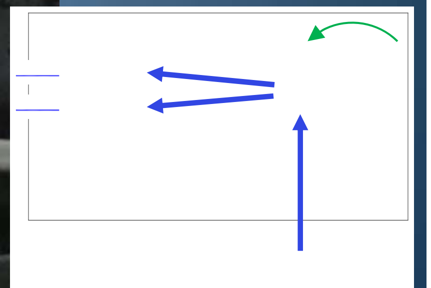
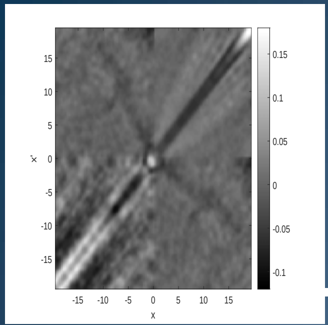


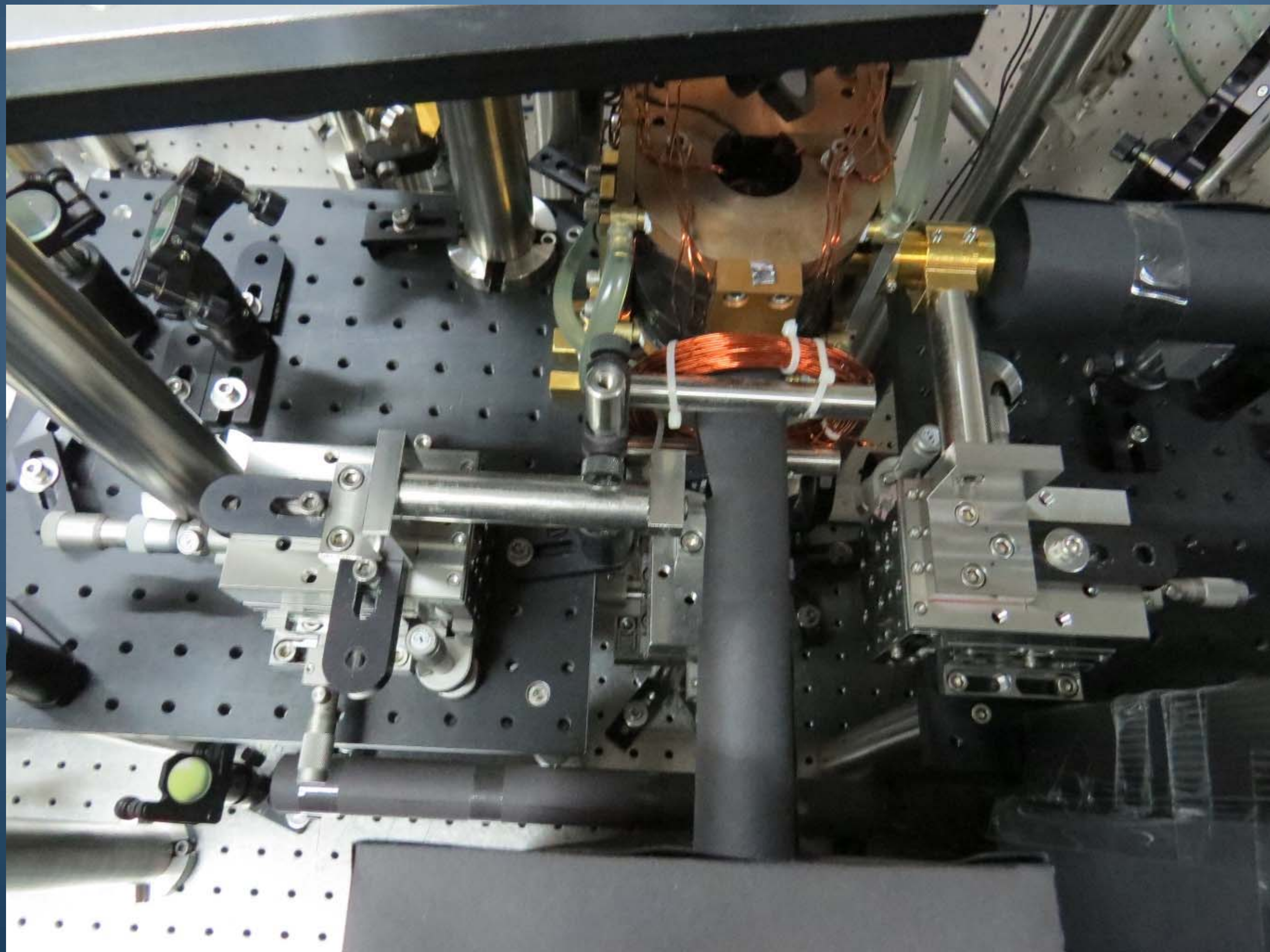
Apparatus

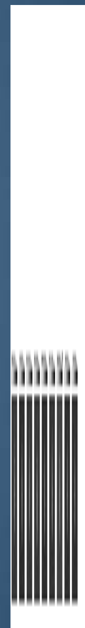


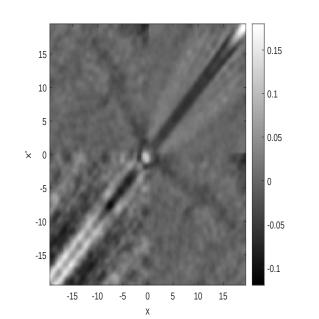




Reference images







Apparatus

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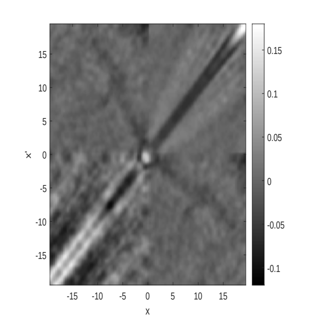

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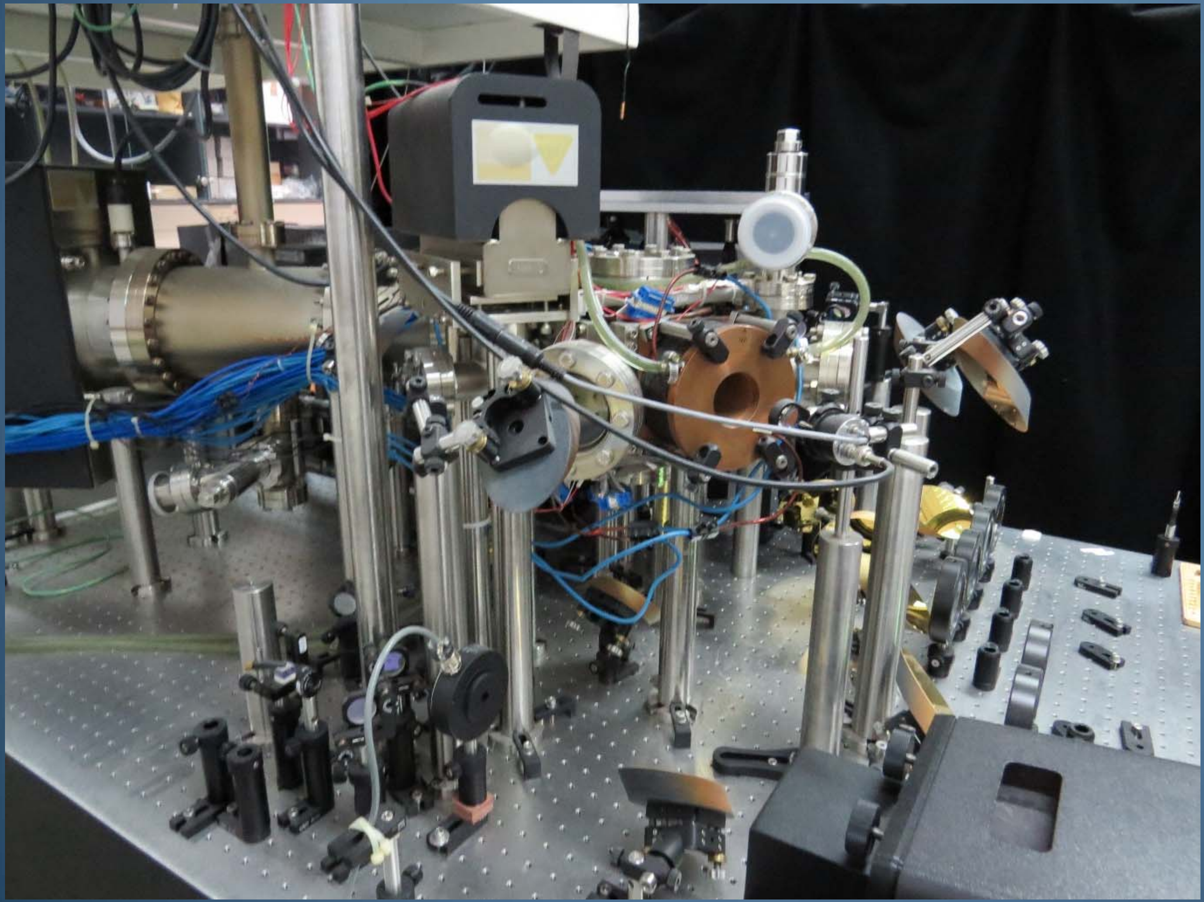

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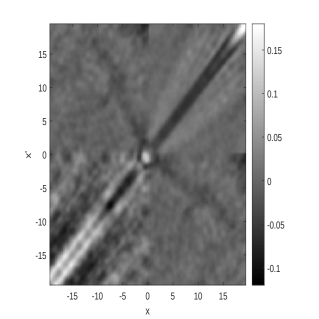

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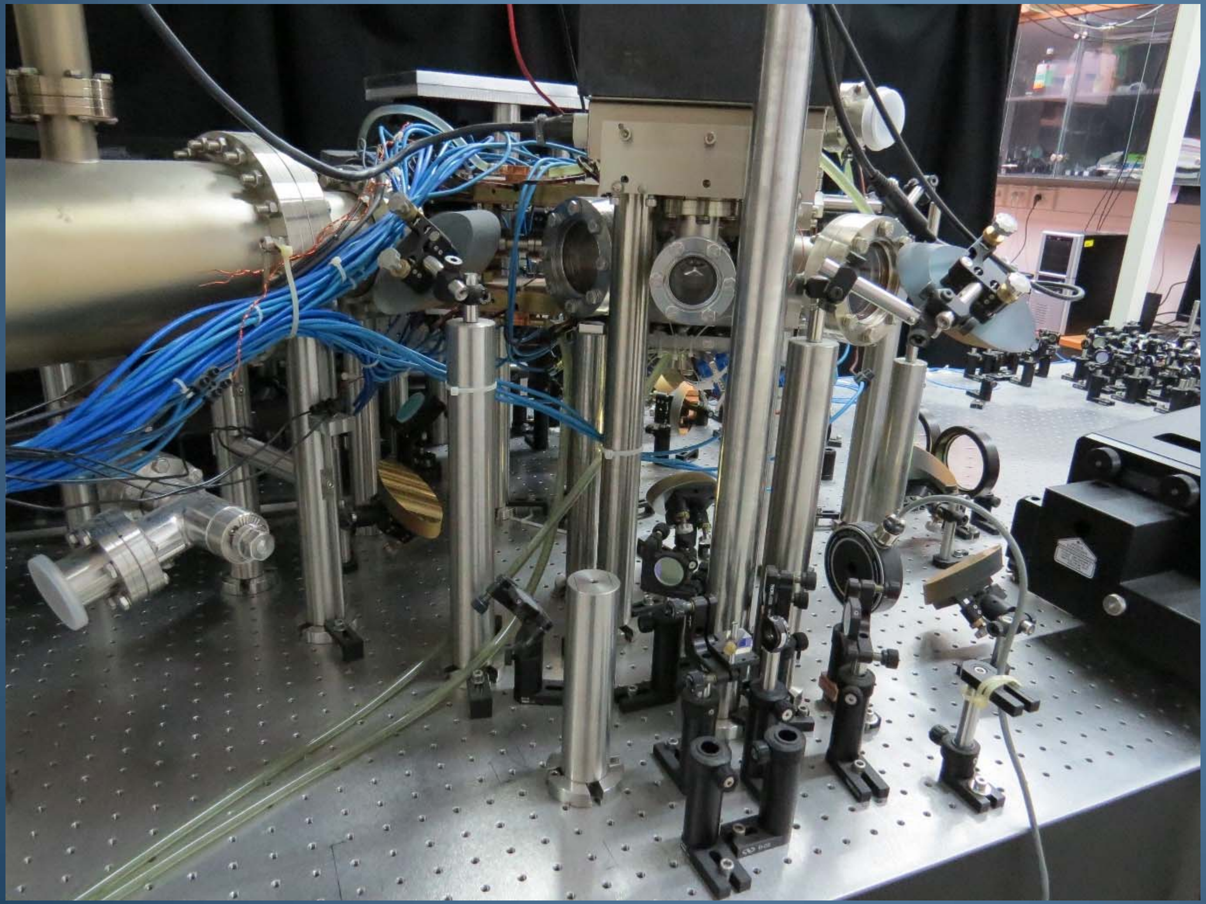

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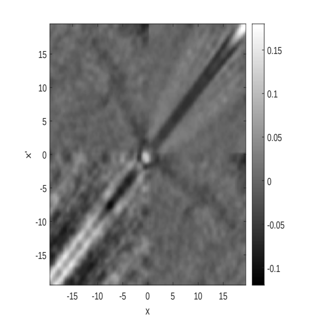

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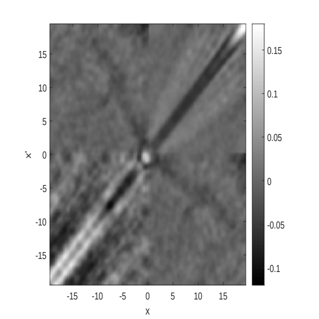
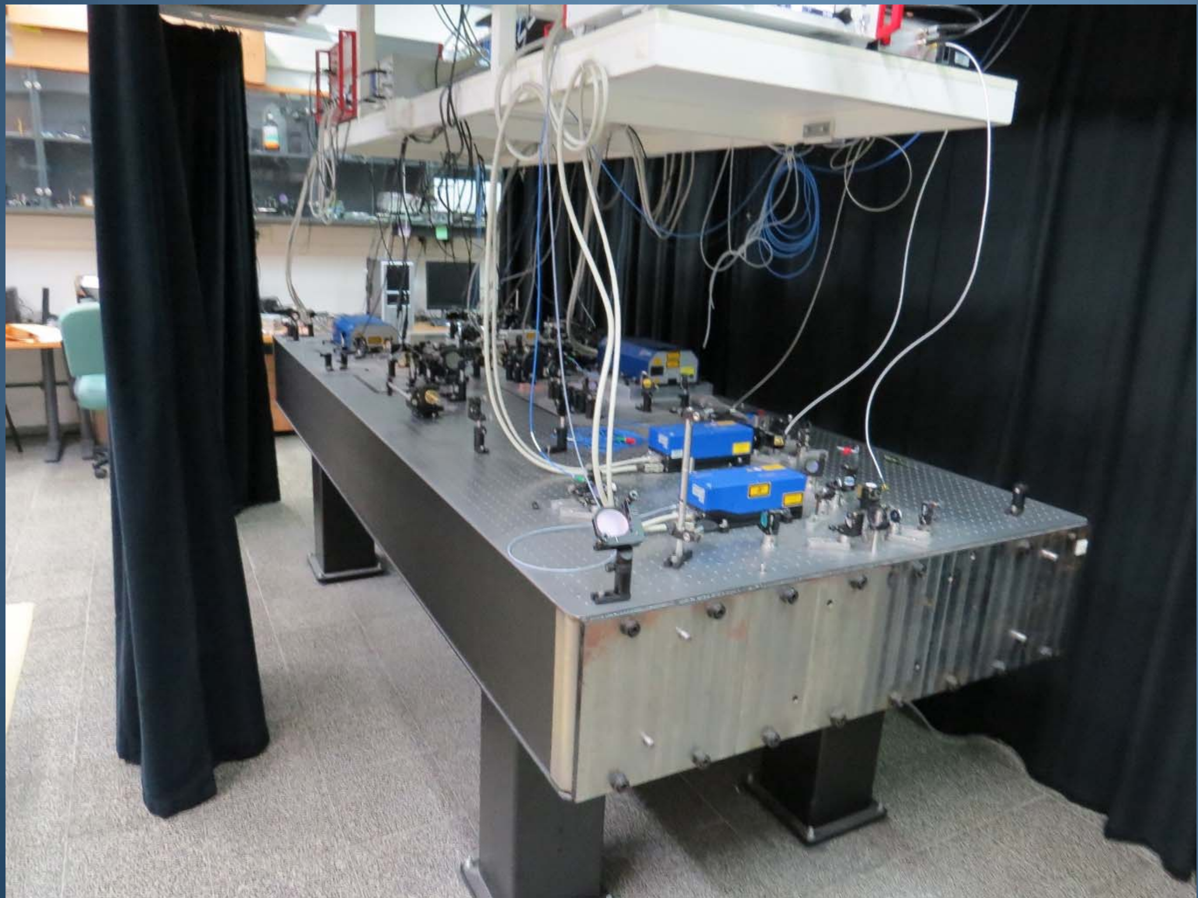


Apparatus



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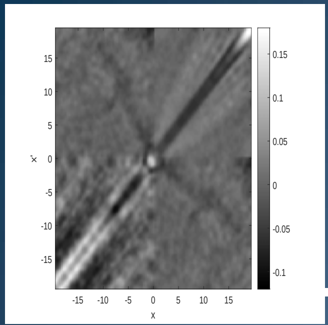
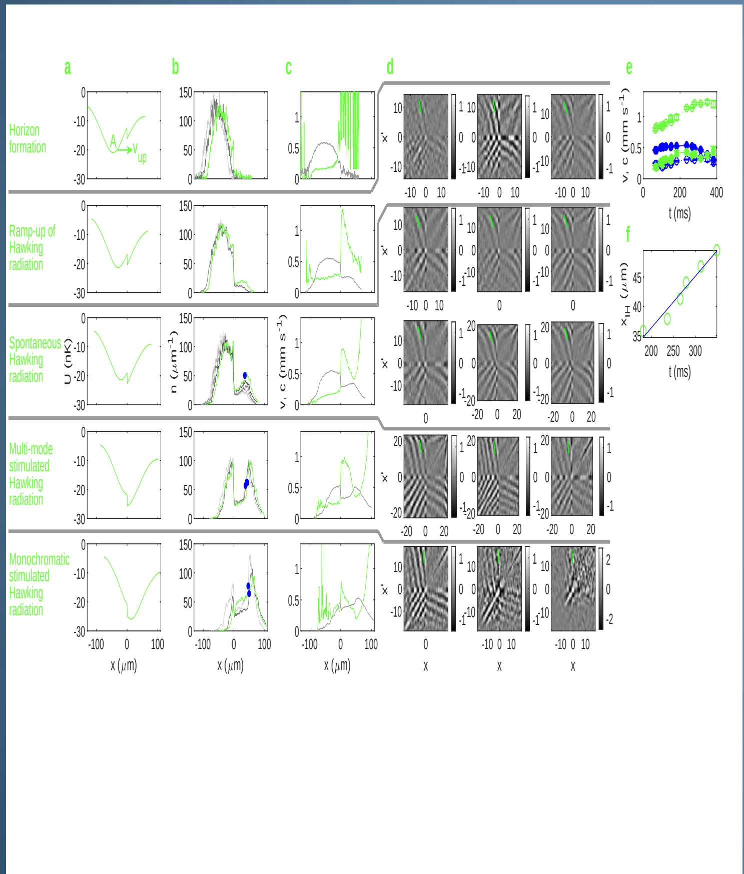


The metric



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

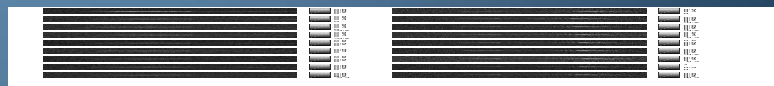
$$g = c(dv/dx - dc/dx)\Big|_{x=0}$$

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

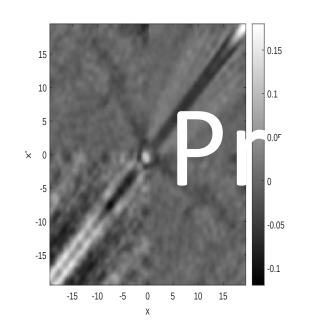
based on linear dispersion

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

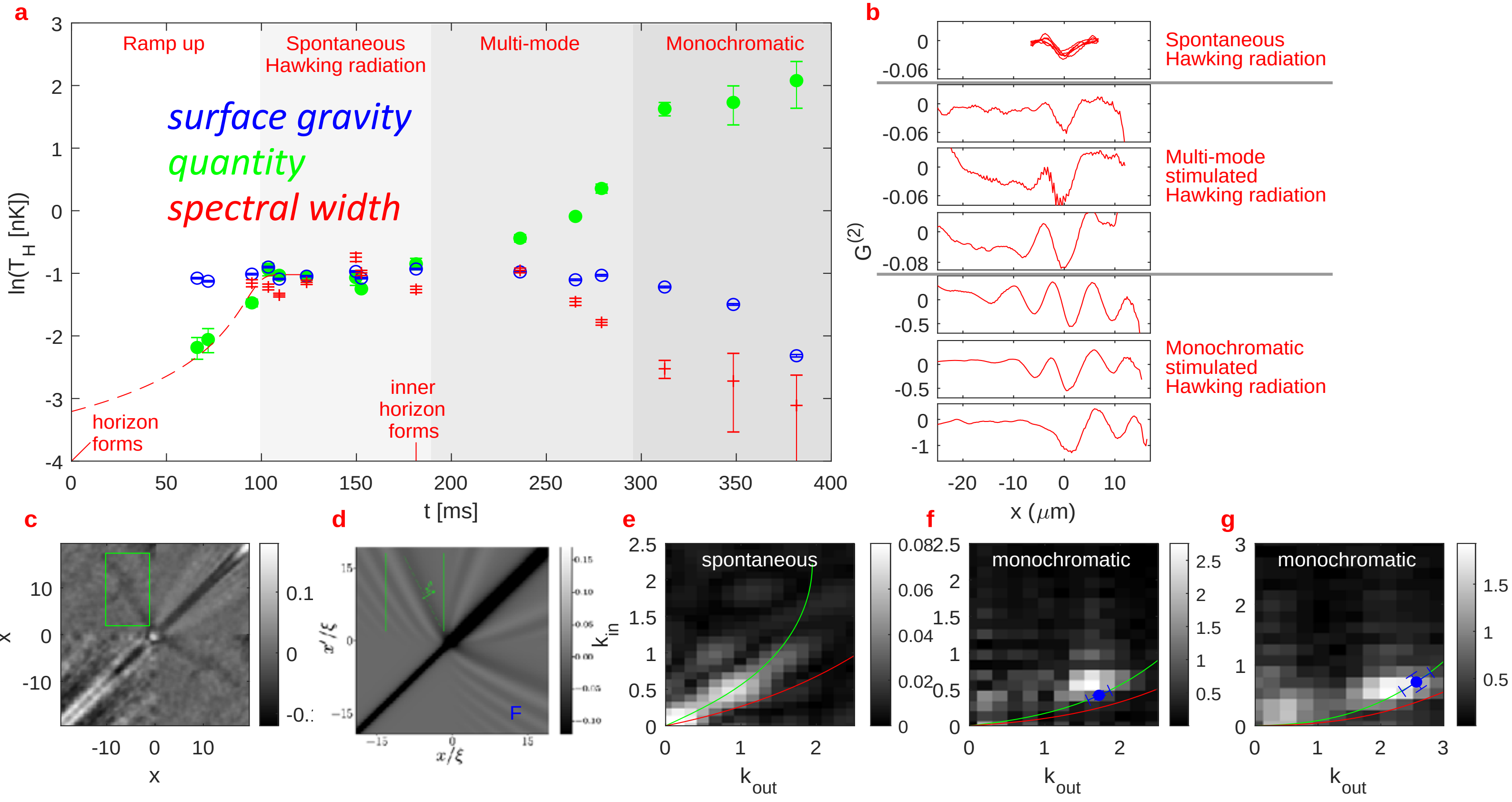
$$k_B T_H = -\frac{\hbar}{2\pi}\left(\frac{c}{n}\frac{dn}{dx} + \frac{dc}{dx}\right)\Bigg|_{x=0}$$



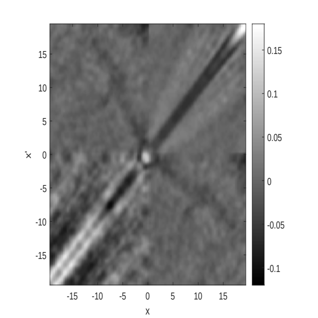
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



Predicted Hawking temperature

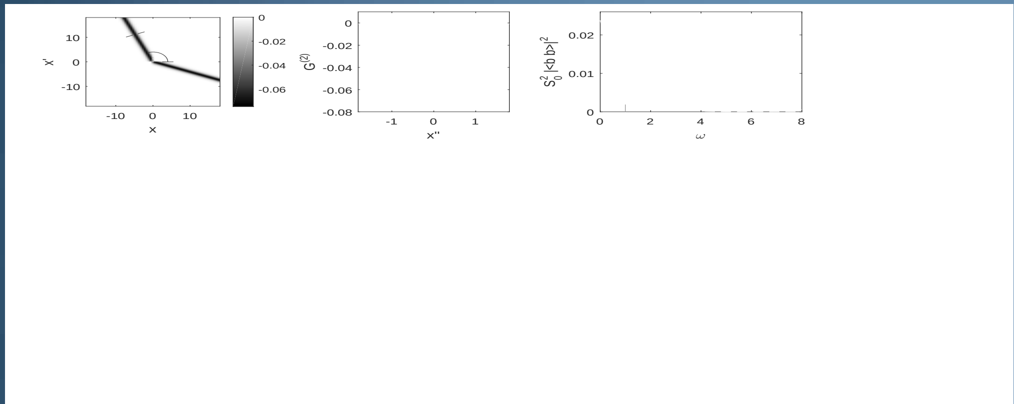


Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



Correlation function

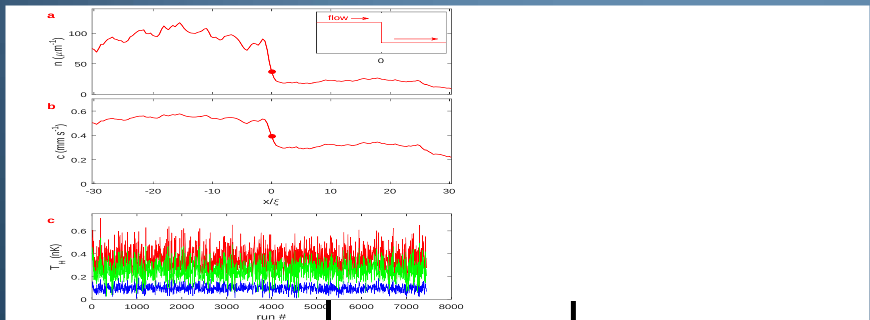
Balbinot, R., Fabbri, A., Fagnocchi, S., Recati, A. & Carusotto, I. *Phys. Rev. A* **78**, 021603(R) (2008).

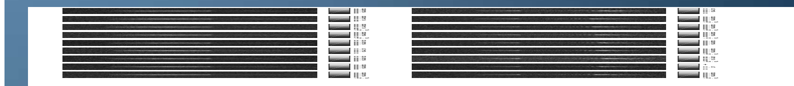


This is how we observe Hawking radiation

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

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





x x'

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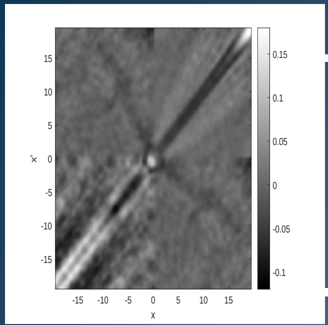


Time dependence of Hawking radiation

Correlations between Hawking and partner particles

Total of 97,000 images

Corresponds to 124 days

t = 66, 72, 95 ms

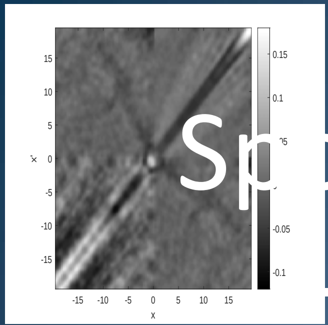
t = 104, 109, 124 ms

t = 150, 153, 181 ms

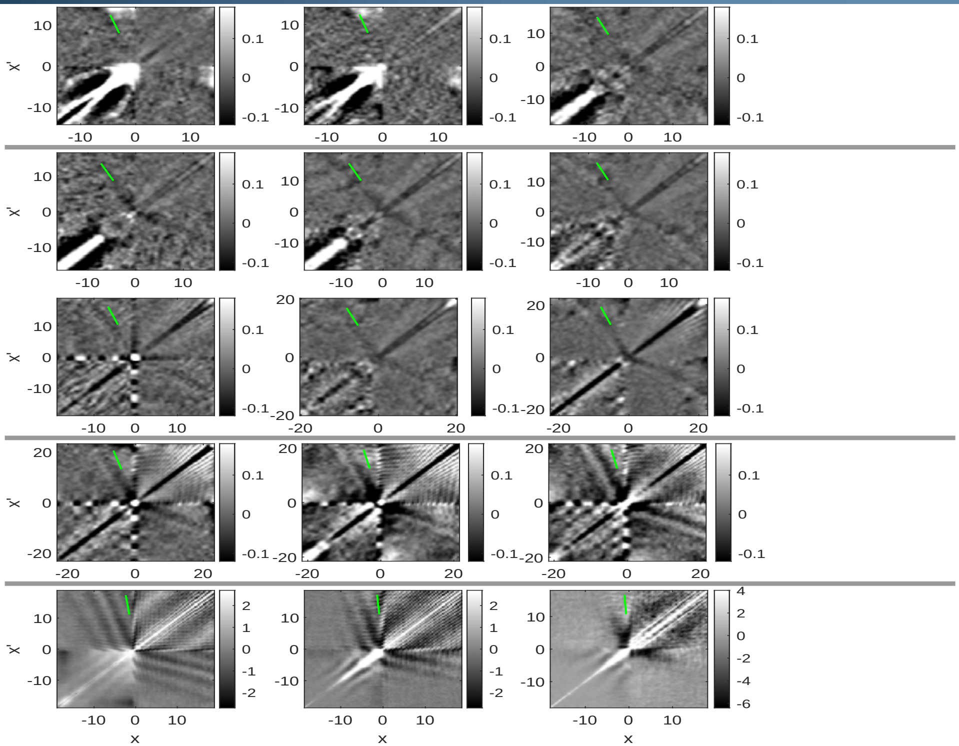
t = 236, 265, 279 ms

t = 312, 348, 382 ms

Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



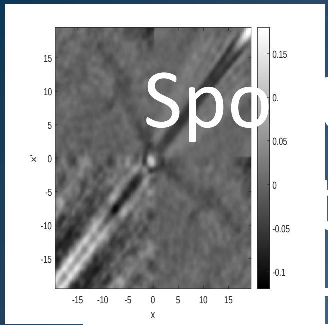
Spontaneous Hawking radiation



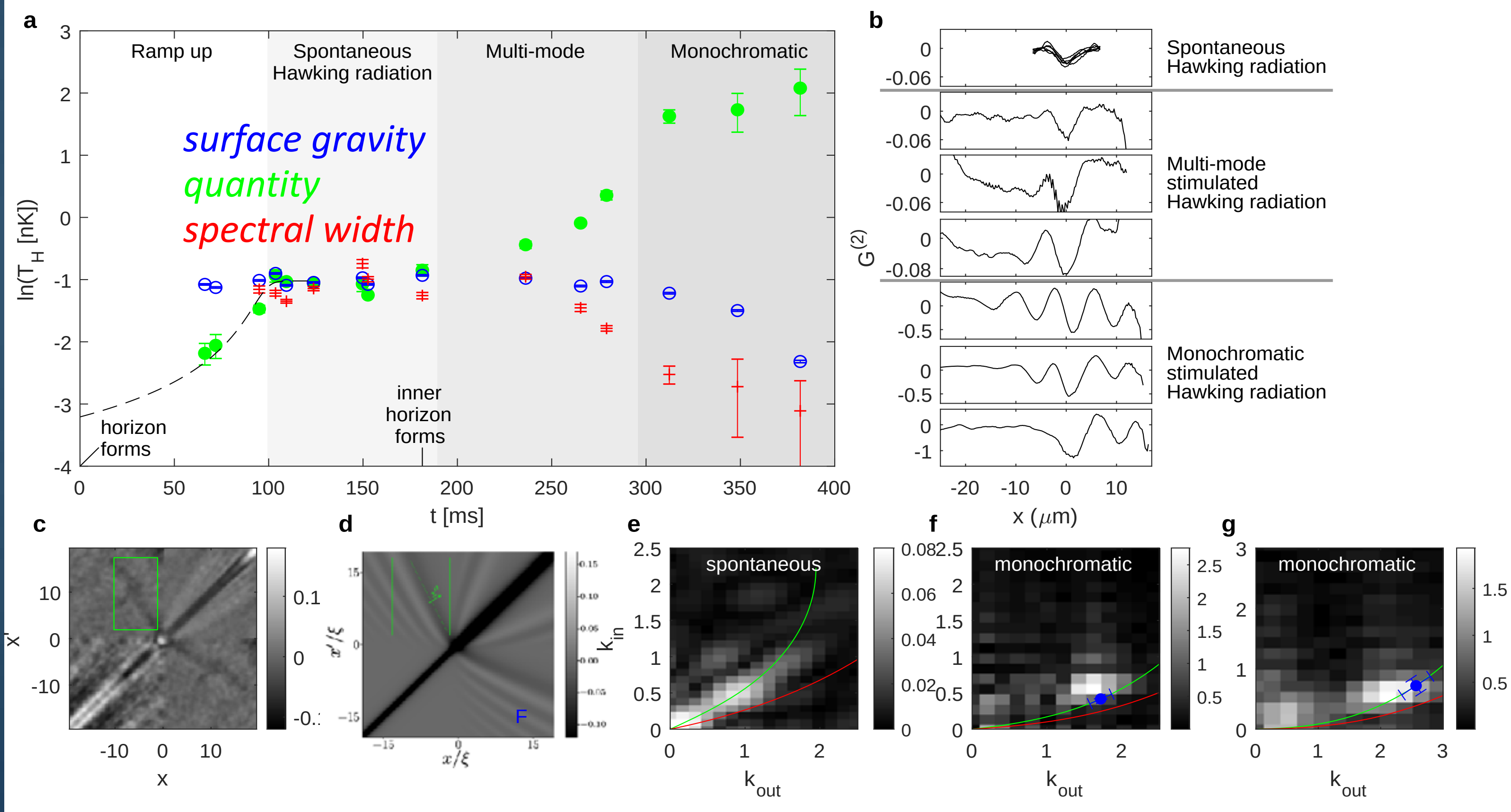
deeper band ⇒
More Hawking
radiation ⇒
high temperature

t = 104, 109, 124, 150, 153, 181 ms

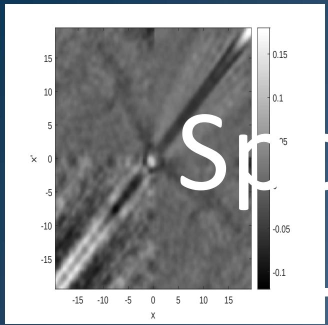
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



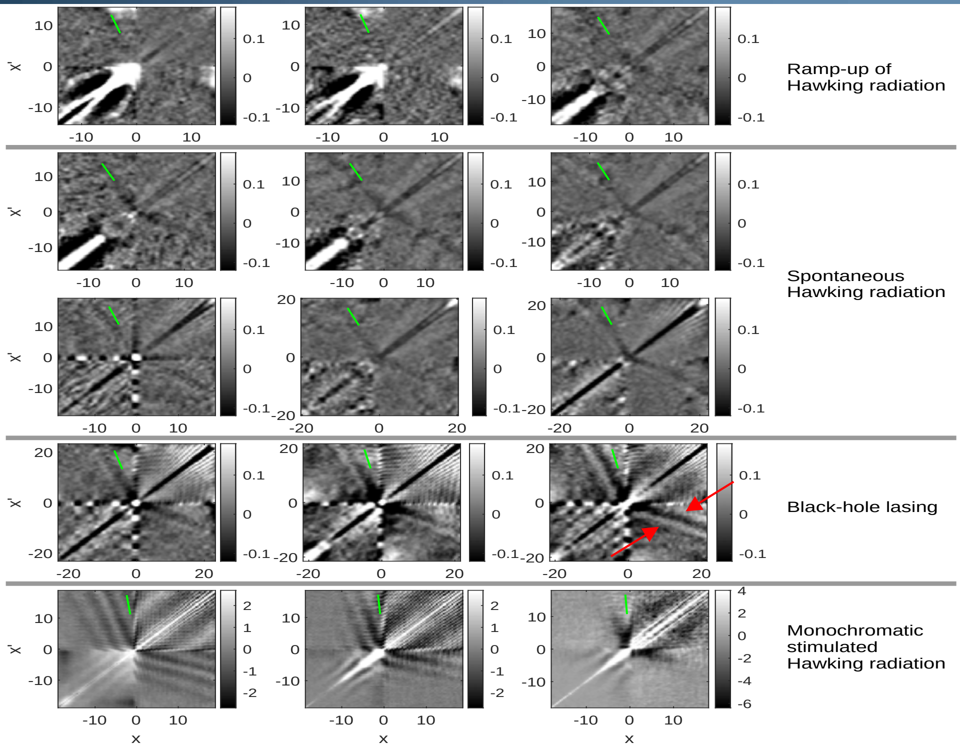
Spontaneous, stationary Hawking radiation at the predicted Hawking temperature



Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



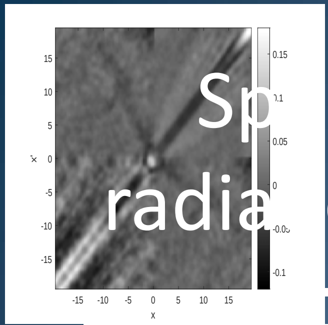
Spontaneous Hawking radiation



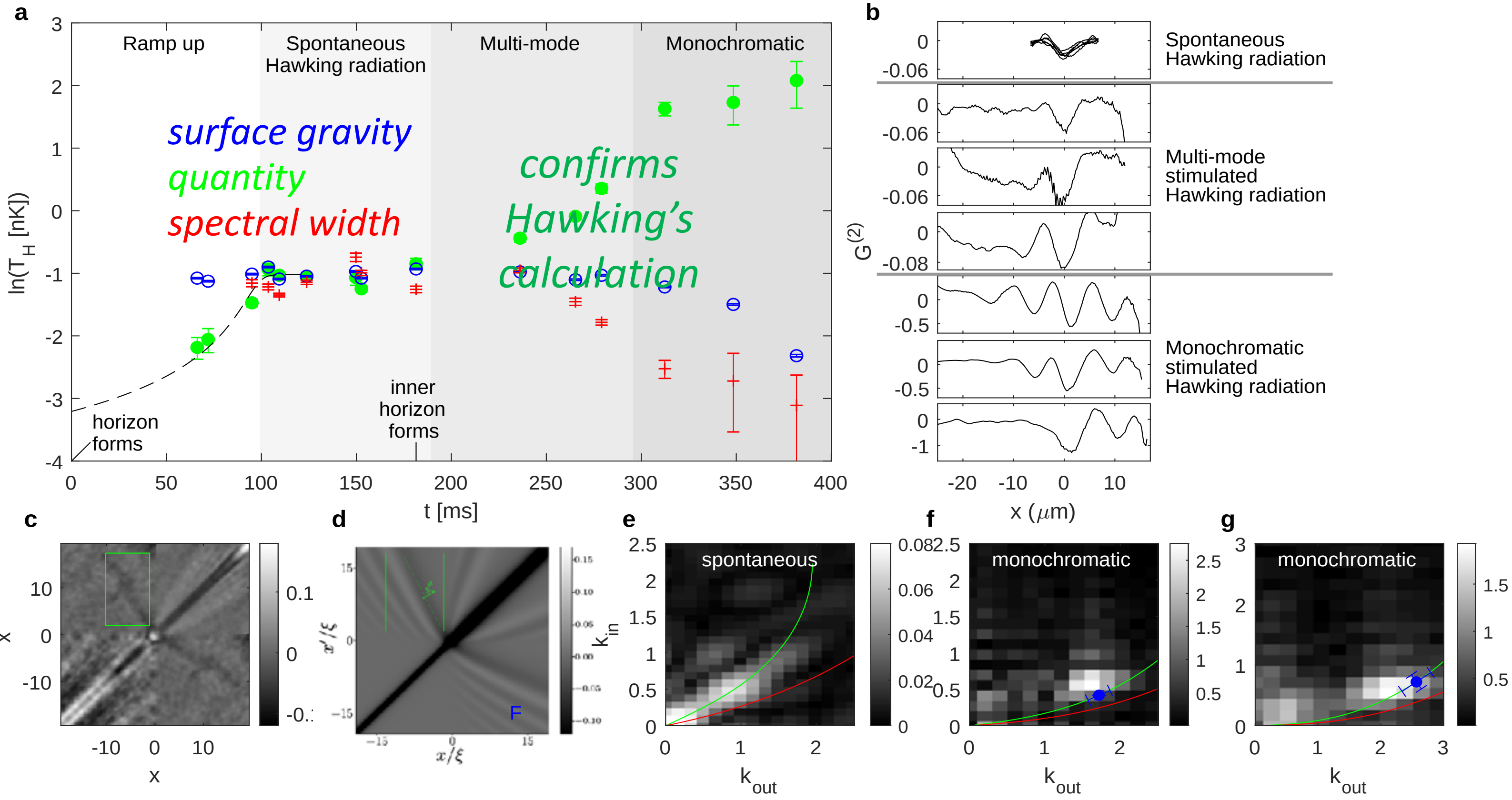
narrow width ⇒
short wavelength ⇒
high temperature

t = 104, 109, 124, 150, 153, 181 ms

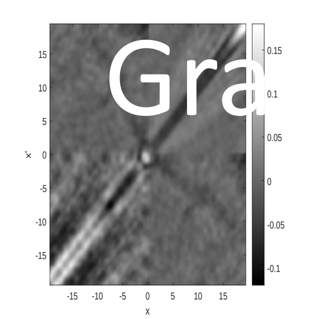
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



Spontaneous, thermal, stationary Hawking radiation at the predicted Hawking temperature

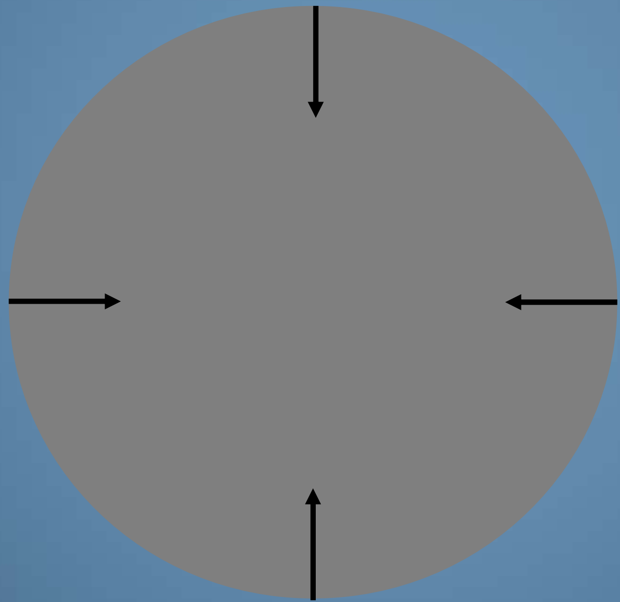


Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



Gravitational collapse of a cloud of dust

170 solar masses



$$\Phi_\infty \propto T_{\rm H}^4$$

$$t_\infty$$

R. Brout, S. Massar, R. Parentani, and Ph. Spindel, A primer for black hole quantum physics. Phys. Rept. **260**, 329-446 (1995).

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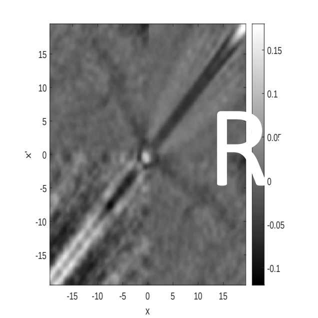
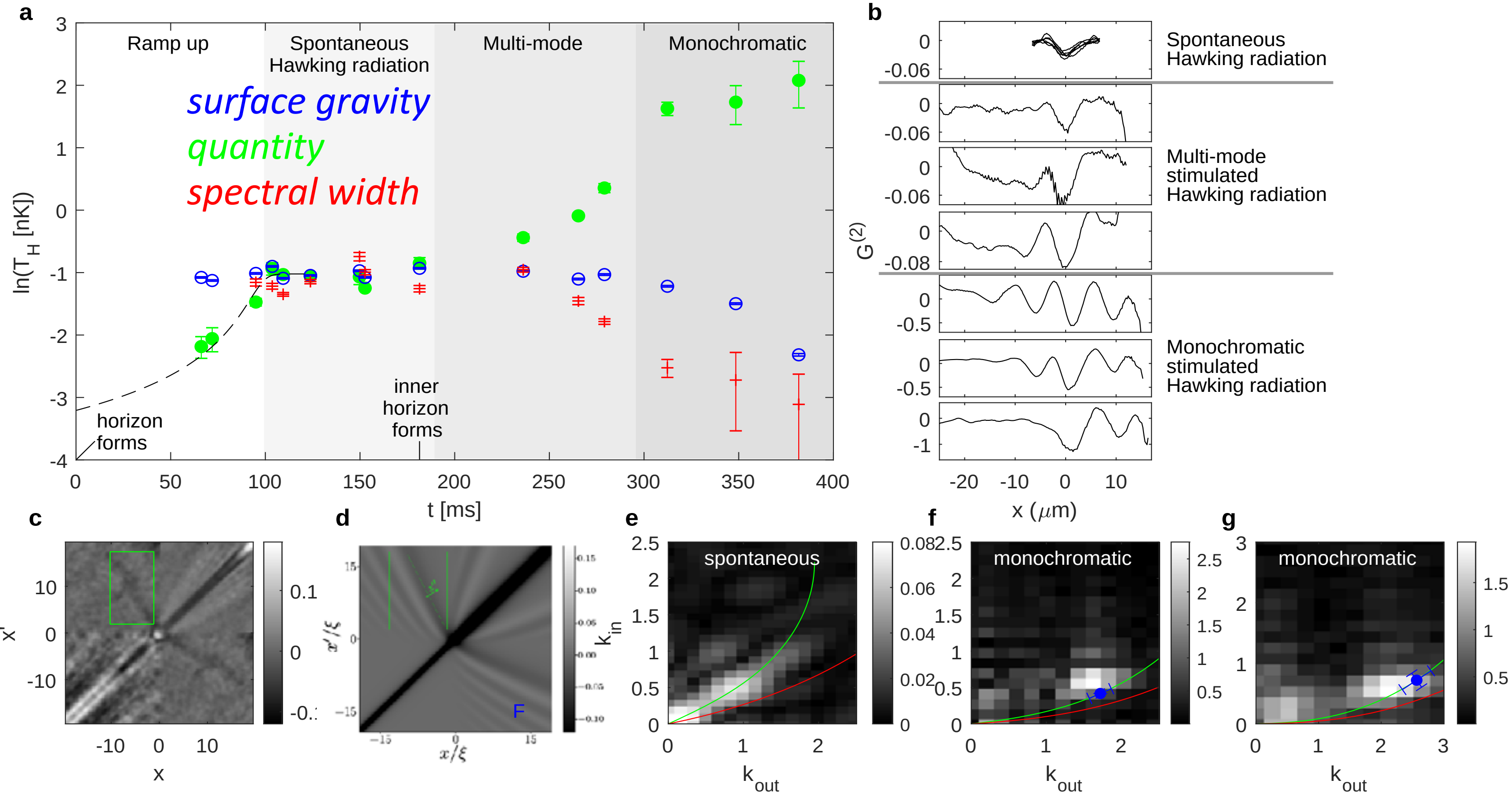
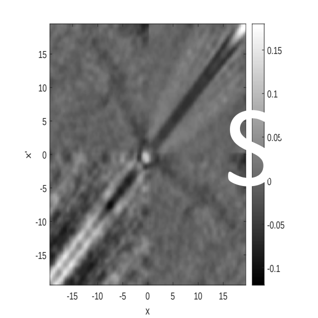


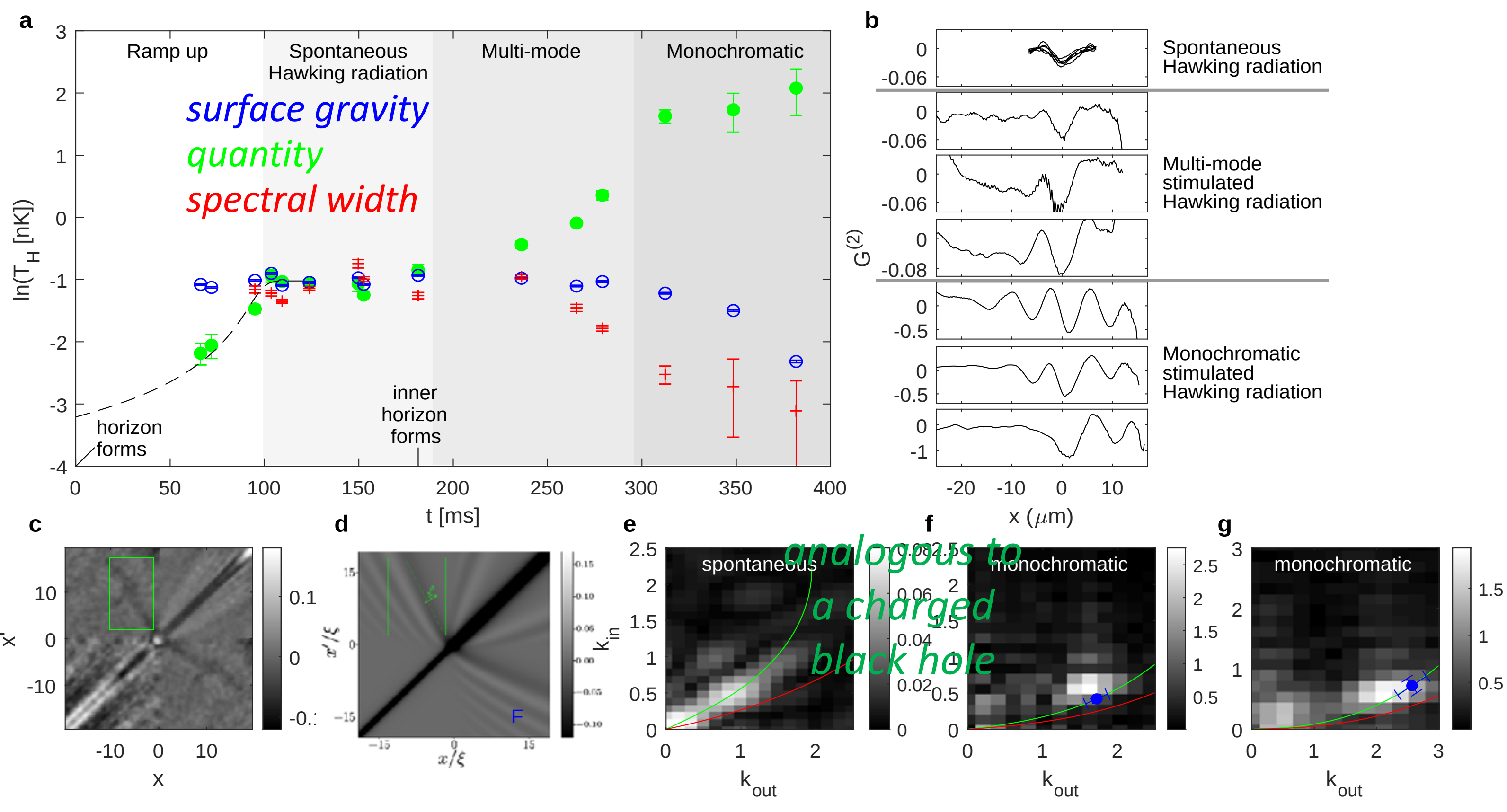
Ramp up of Hawking radiation



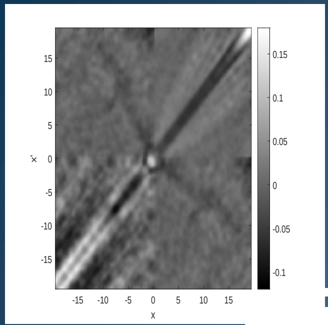
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).

Simulated Hawking radiation

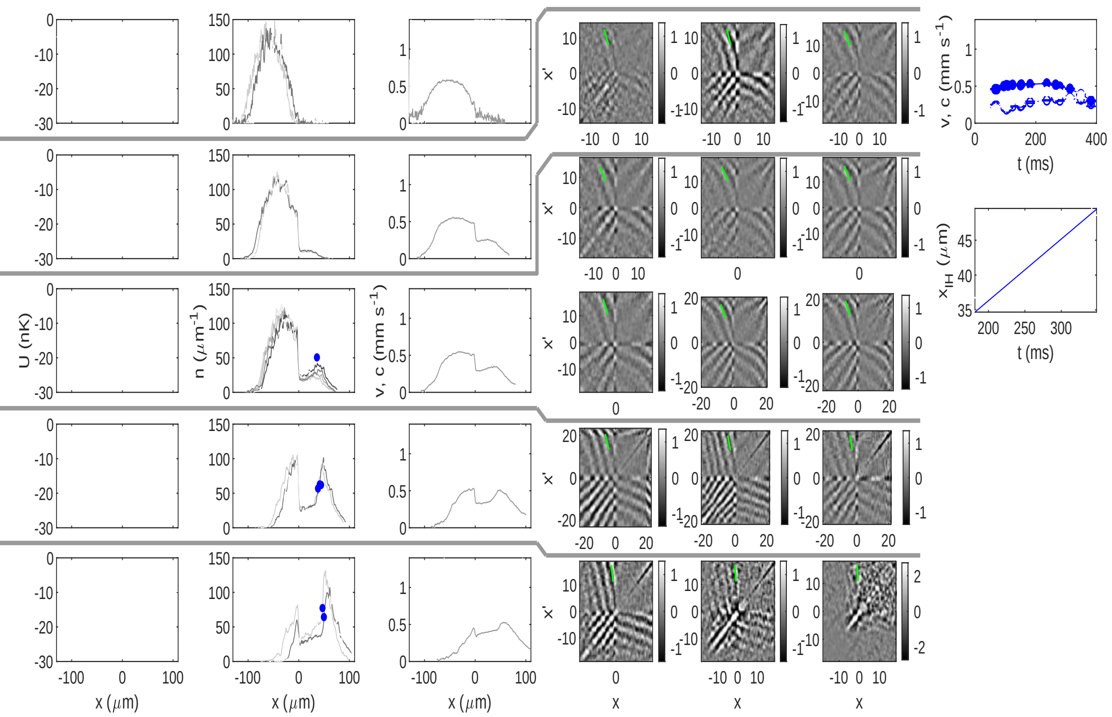




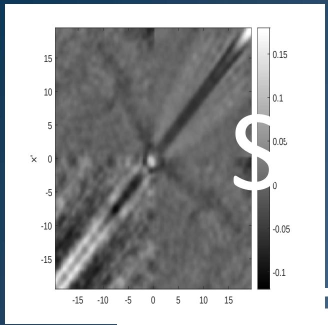
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



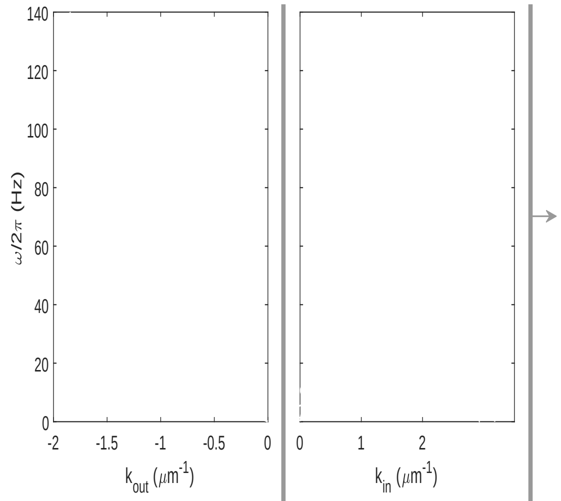
The metric



Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



Stimulated Hawking radiation



Spontaneous Hawking radiation

Black-hole lasing

Monochromatic stimulated Hawking radiation

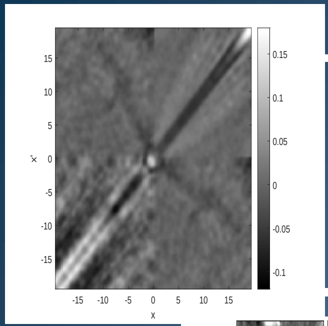
$\omega = k_0 v_{\mathrm{IH}}$

Steven Corley and Ted Jacobson, Black hole lasers. *Phys. Rev. D* 59, 124011 (1999).

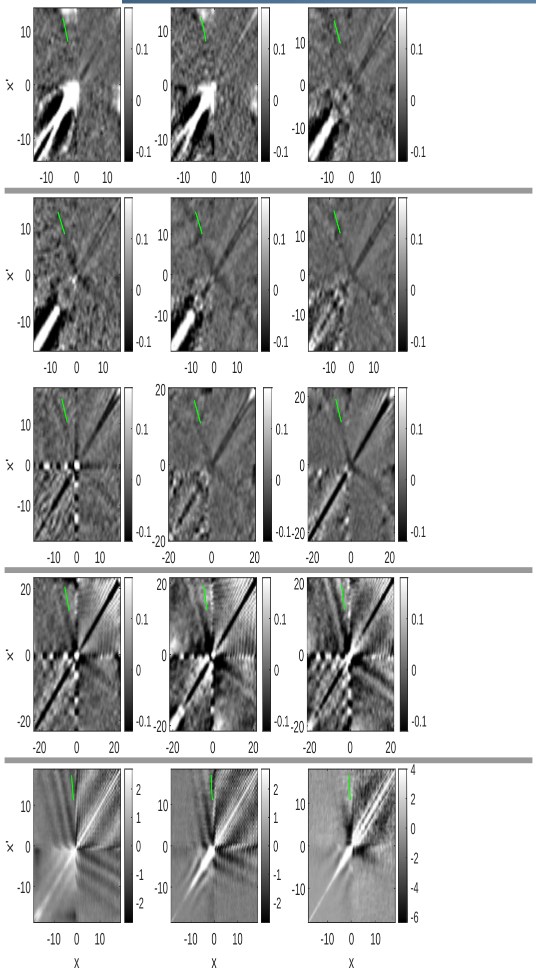
Yi-Hsieh Wang, Ted Jacobson, Mark Edwards, and Charles W. Clark, Mechanism of stimulated Hawking radiation in a laboratory Bose-Einstein condensate. Phys. Rev. A **96**, 023616 (2017).

Lorentz violation might occur well beyond the Planck scale

G. E. Volovik, Black hole and Hawking radiation by Type-II Weyl Fermions. JETP Letters **104**, 645-648 (2016).



Time dependence of Hawking radiation



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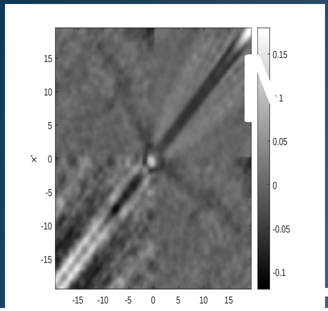
t = 104, 109, 124 ms

t = 150, 153, 181 ms

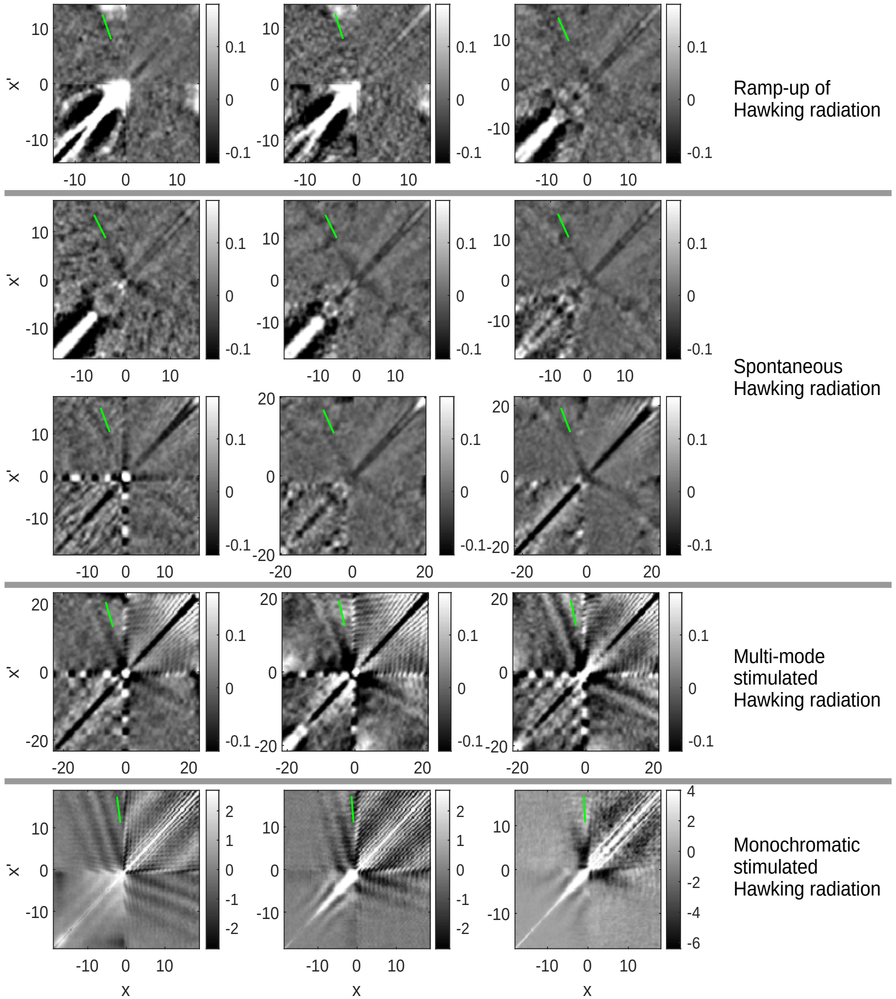
t = 236, 265, 279 ms

t = 312, 348, 382 ms

Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



Multi-mode stimulated Hawking radiation



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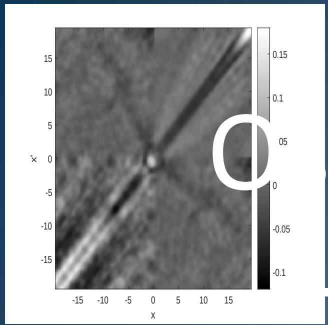
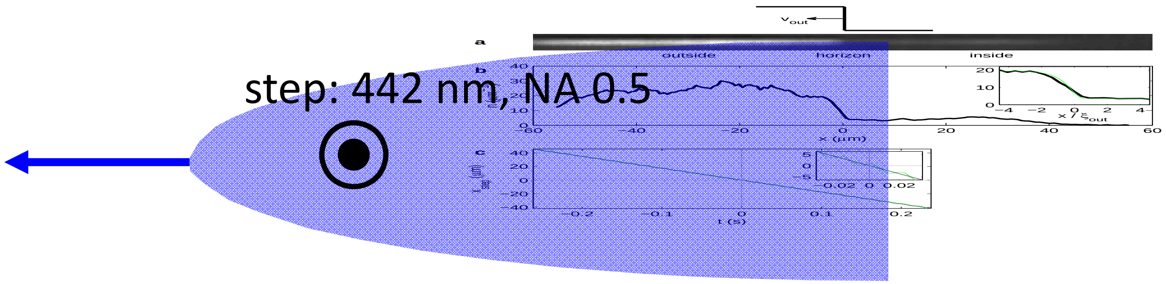
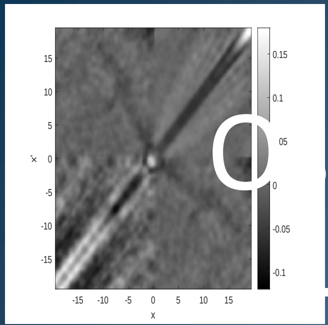
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



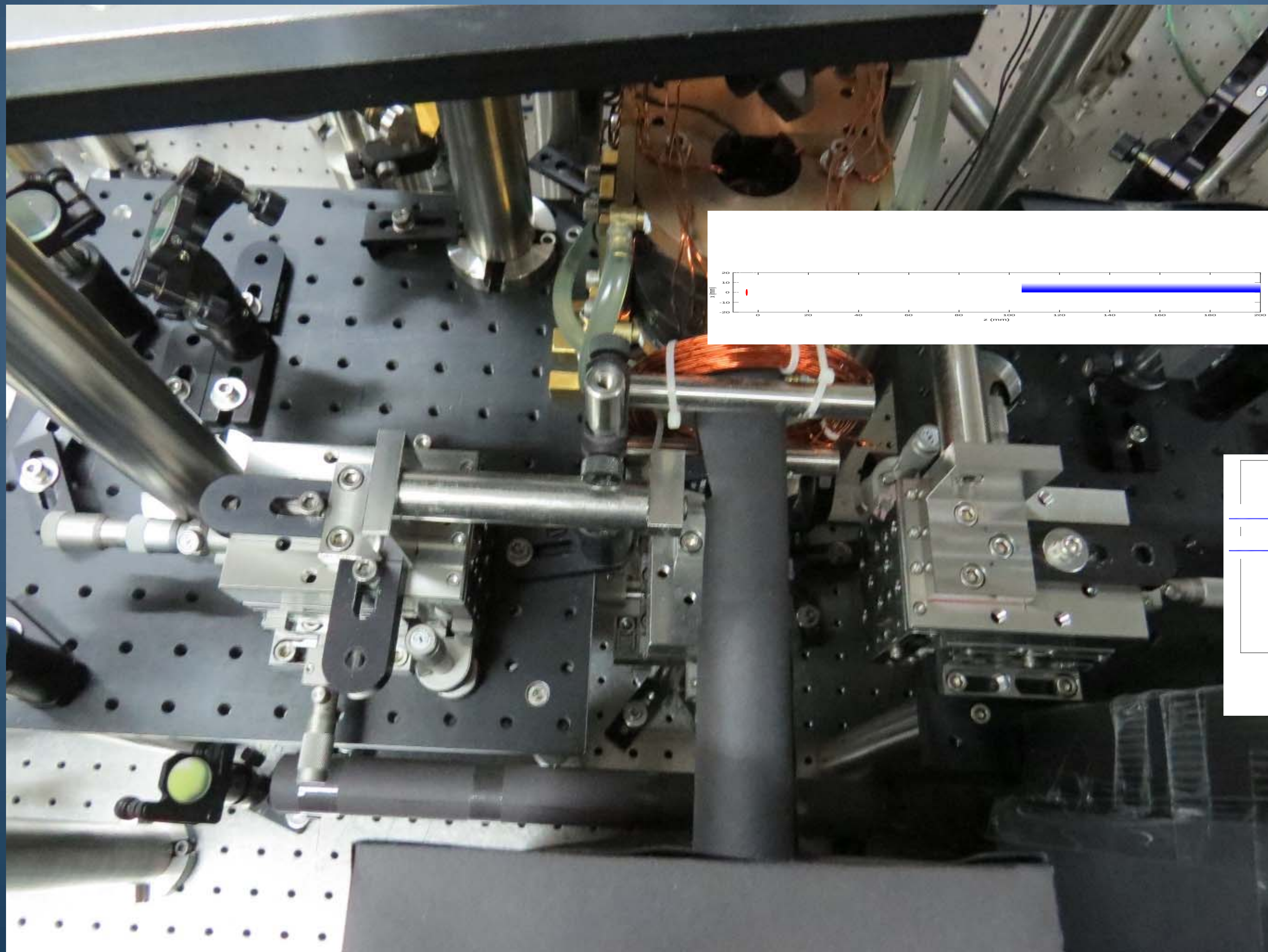
Oscillating horizon experiment

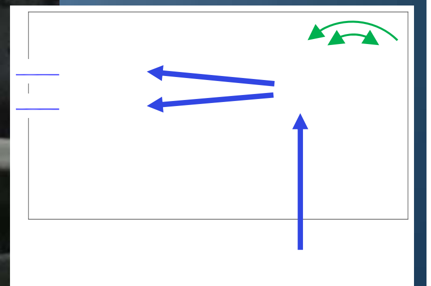


Lahav, O., Itah, A., Blumkin, A., Gordon, C., Rinott, S., Zayats, A. & Steinhauer, J. *Phys. Rev. Lett.* **105**, 240401 (2010).

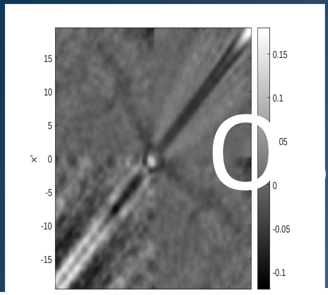


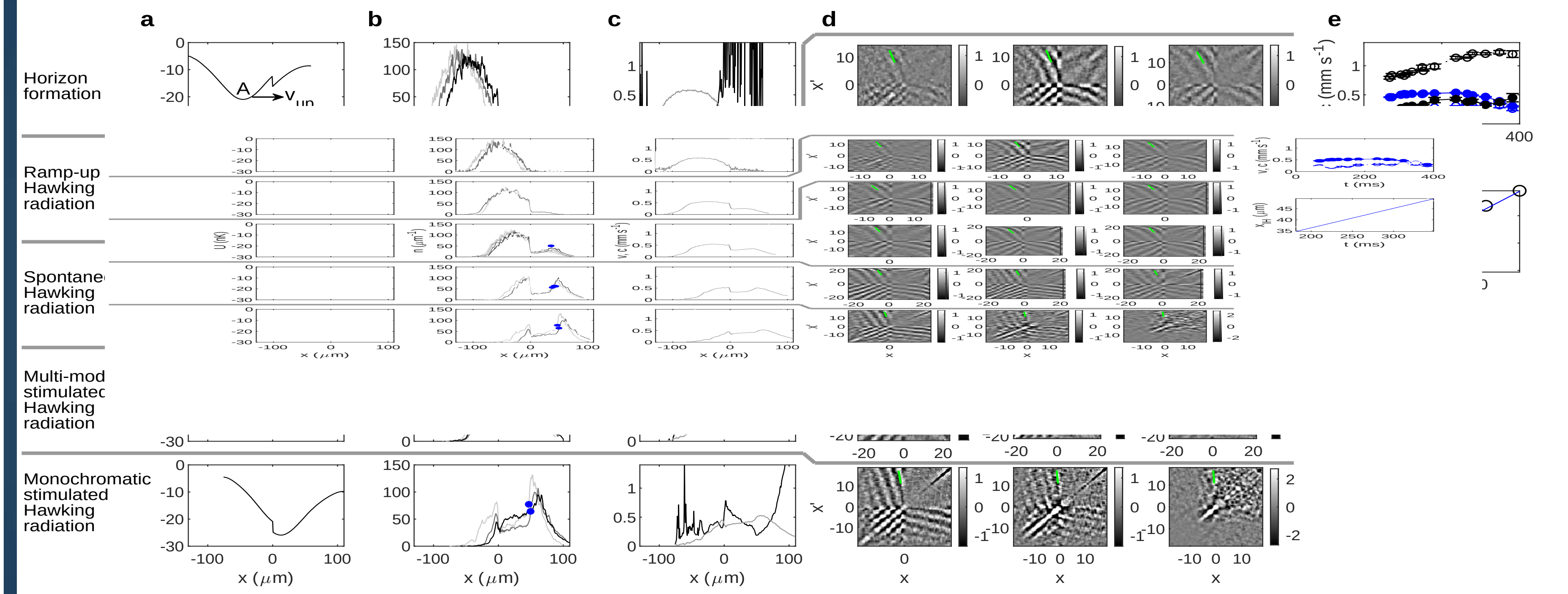
Oscillating horizon experiment





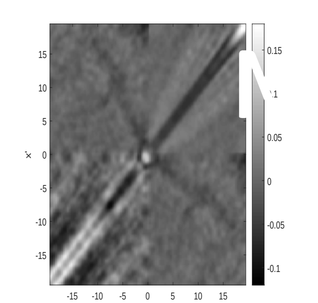
Oscillating horizon experiment

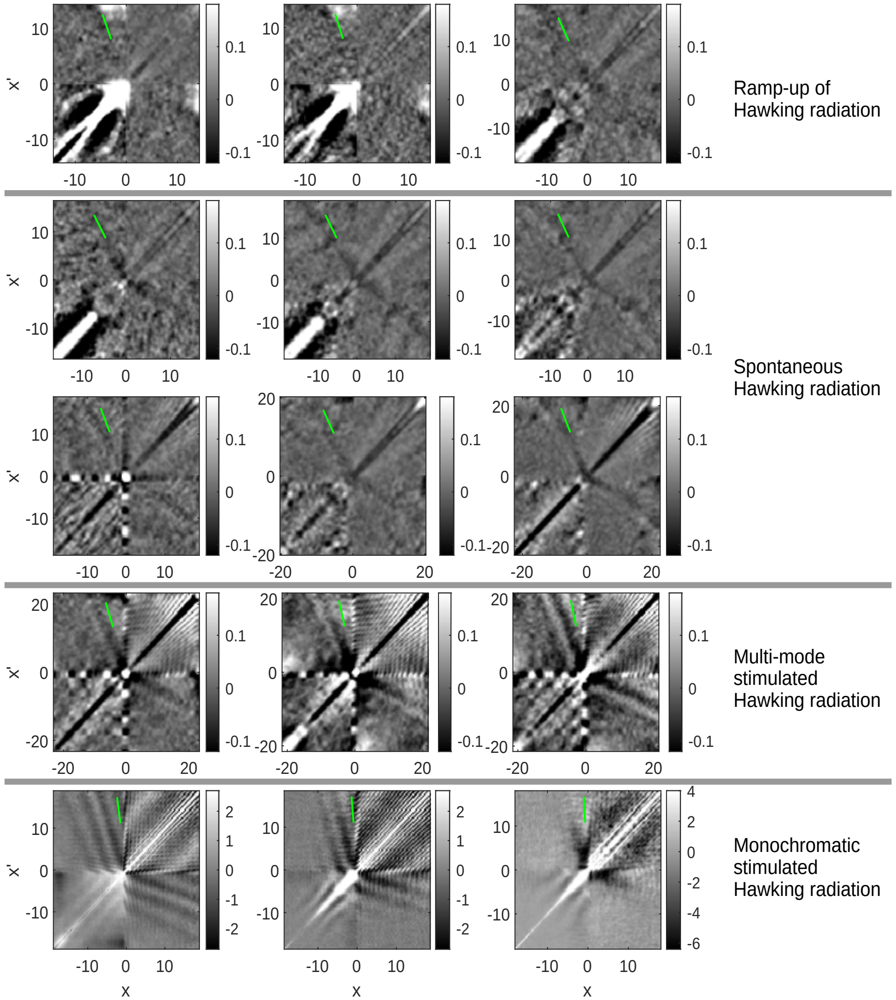




Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).

Multi-mode stimulated Hawking radiation





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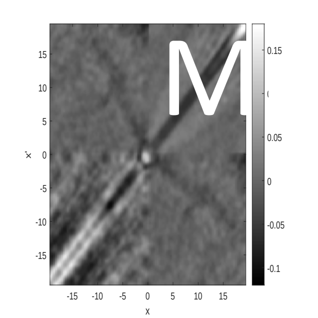
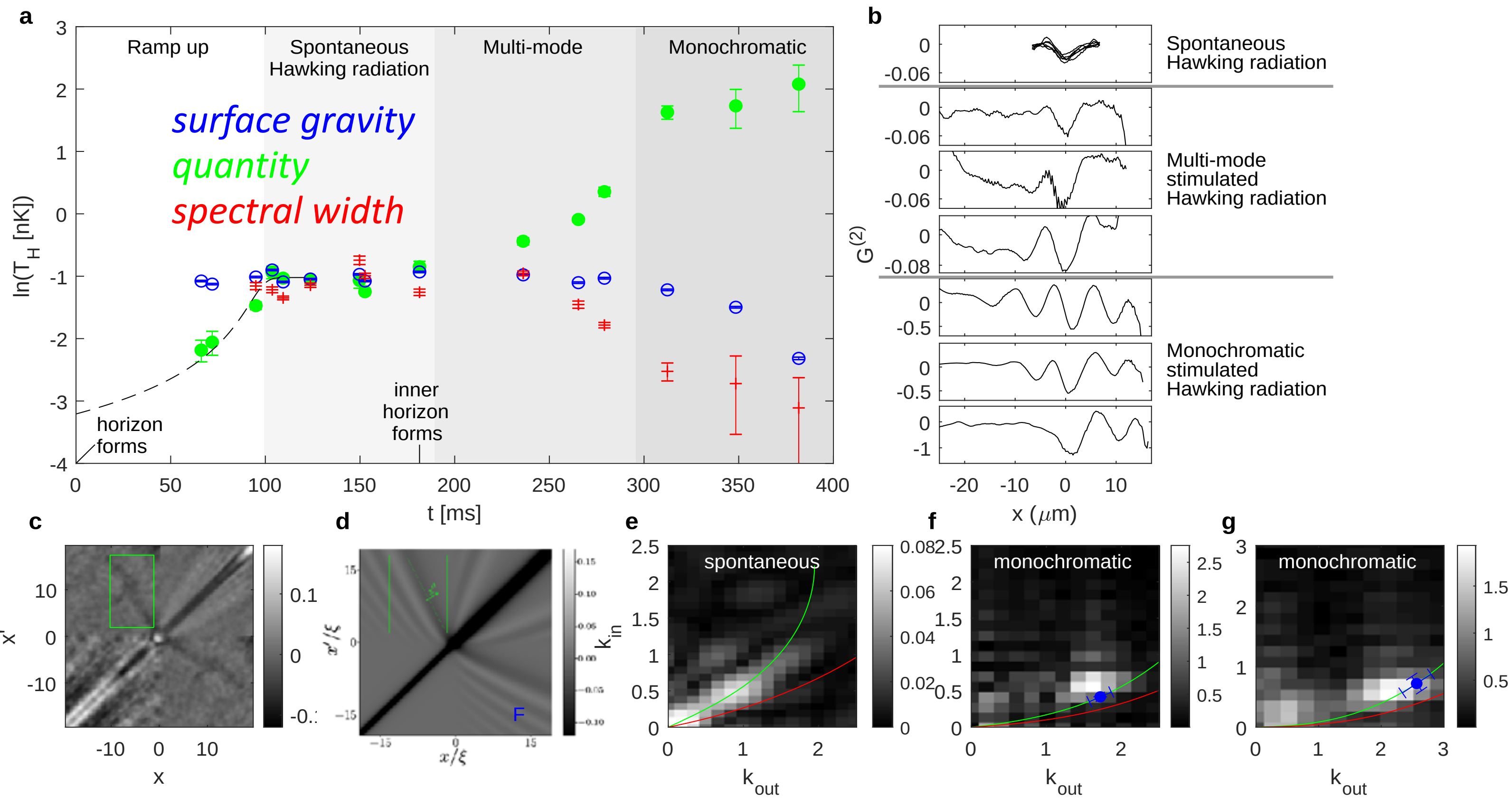
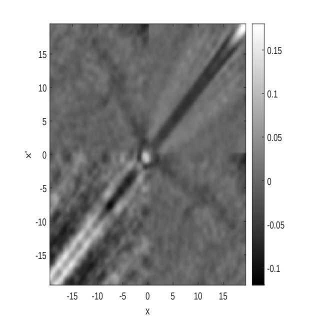


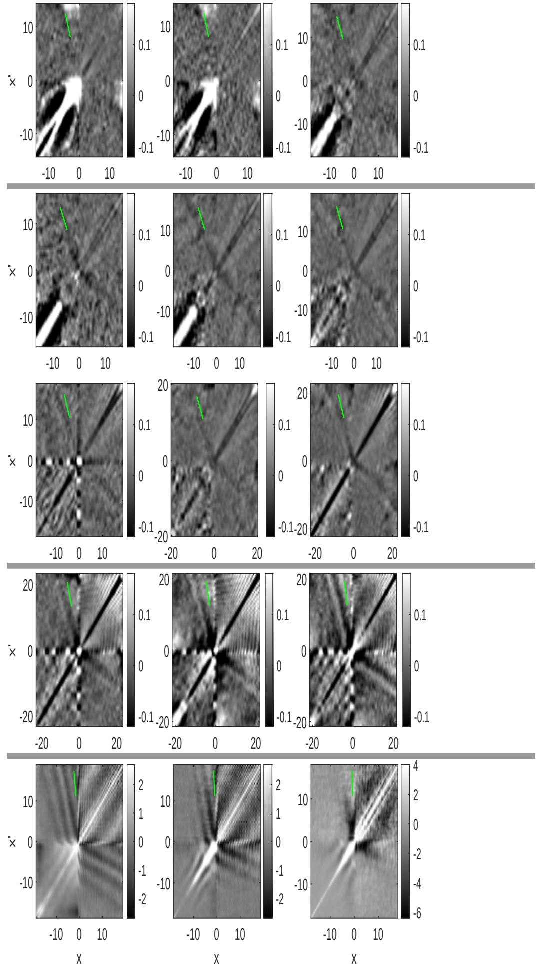
Multi-mode stimulated Hawking radiation



Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



Time dependence of Hawking radiation



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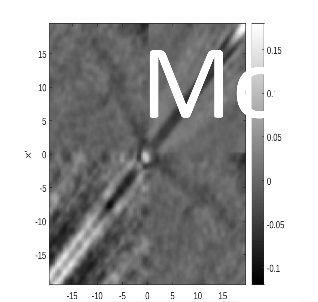
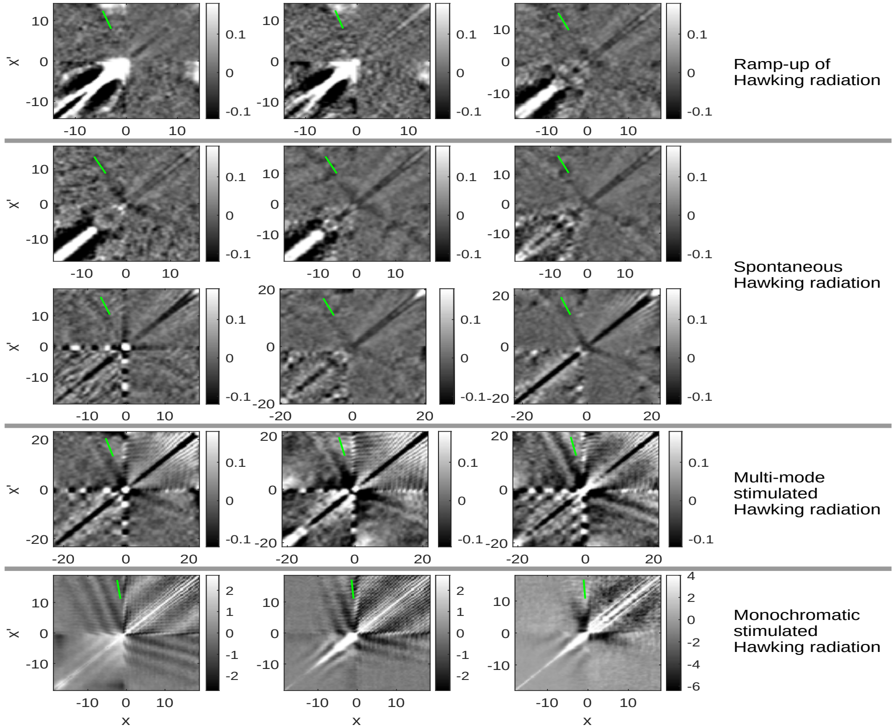
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).

Monochromatic stimulated Hawking radiation





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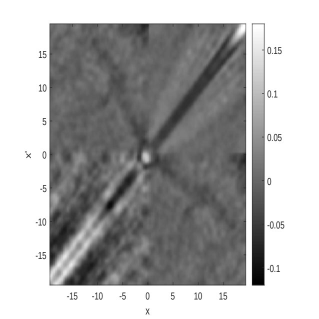
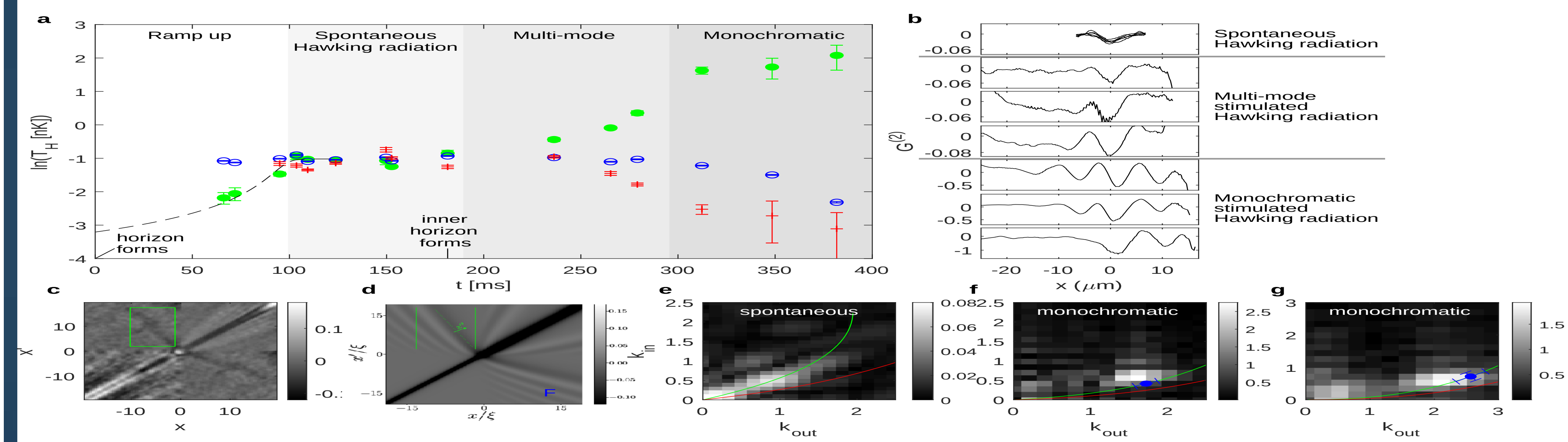
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).

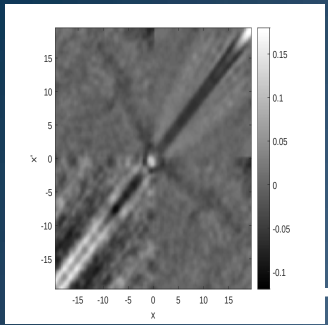


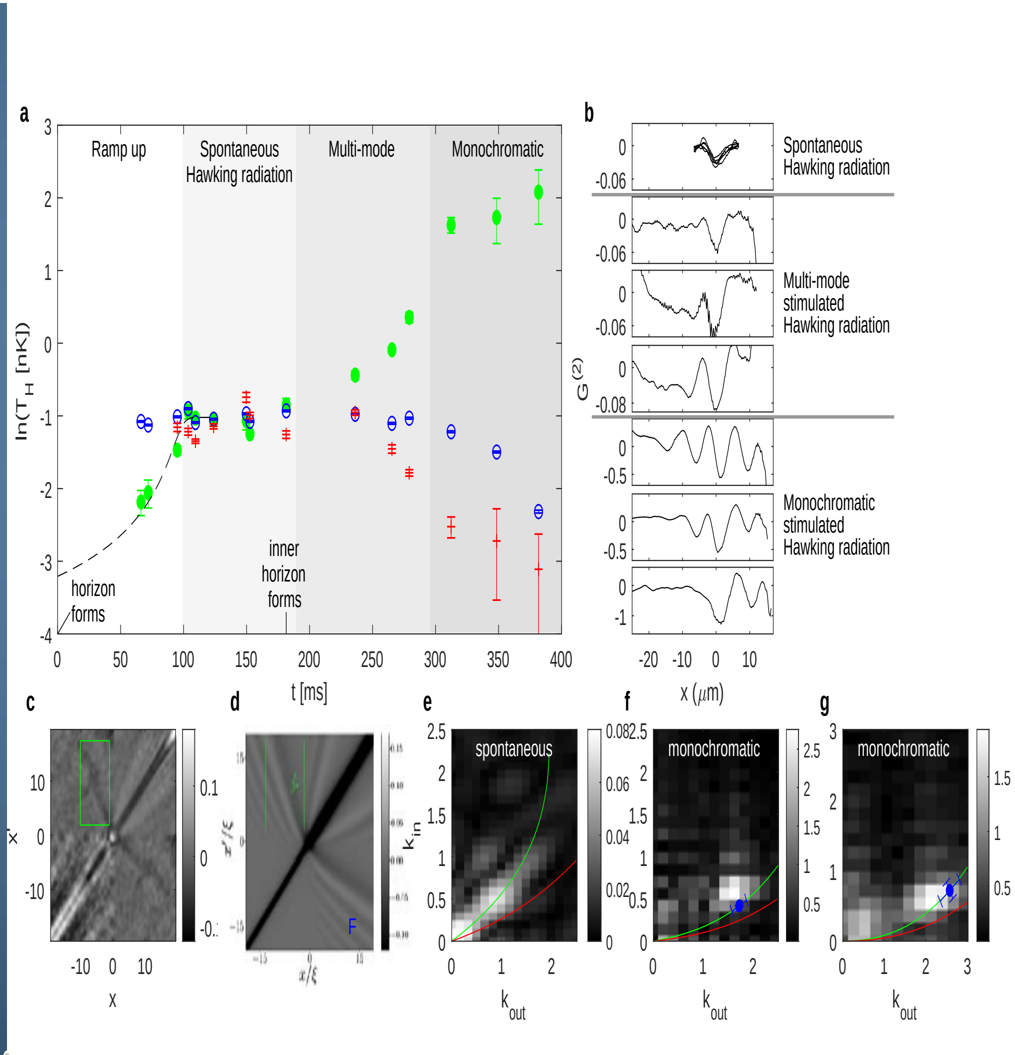
Single modes



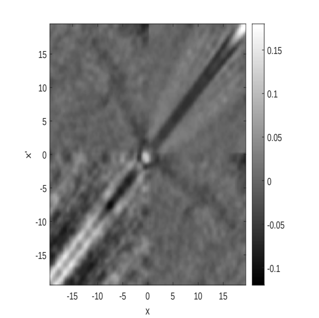
Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).

Profiles



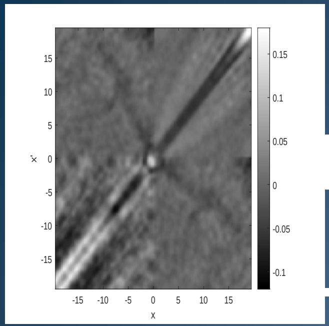


Kolobov, V. I., Golubkov, K., de Nova, J. R. M. & Steinhauer, J., arXiv:1910.09363 (2019).



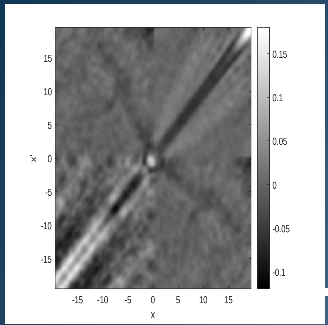
Conclusions

- The Hawking radiation is seen to be spontaneous, thermal, at the correct temperature, and stationary.
- 6 independent measurements of Hawking radiation are made in the spontaneous period.
- Thus, the semiclassical regime has been verified in an analogue black hole.
- This confirms Hawking's calculation.
- Stimulated Hawking radiation is also seen.



mplications for real gravity

- The thermality of Hawking radiation is the basis for the information paradox.
- The temperature links Hawking radiation with black hole entropy.
- The correlations between the Hawking and partner modes are of the predicted magnitude, with no reduction due to the underlying quantum structure.

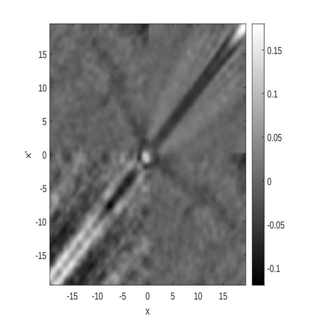


Future

- *Going beyond the semiclassical approximation*
- *Getting information regarding quantum gravity*

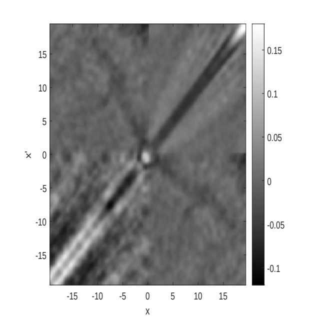
Analogue black holes ← Quantum gravity

Could quantum gravity models be tested in some type of analogue system? Proposals are needed.



Large Hadron Collider

- They are searching for semiclassical and quantum black holes at the LHC.
- They could study the Hawking radiation and see the effect of QG.



Future

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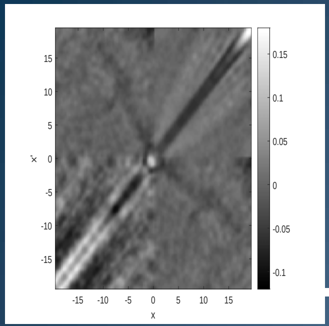
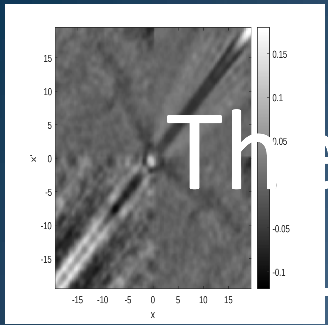
Analogue black holes → Quantum gravity



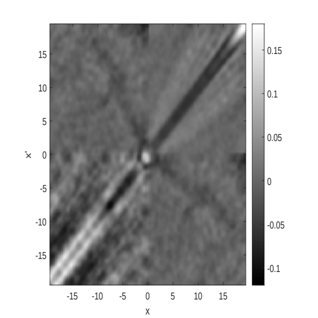
Analogue black holes

- We would like Quantum Gravity to definitively answer the following questions:
  - What is the role of quantum gravity in the information paradox?
  - How does quantum gravity affect Hawking radiation?
- Let's first answer an easier question:
  - How does analogue quantum gravity affect Hawking radiation in an analogue black hole?



The semiclassical approximation

- We partially ignore the underlying quantum (atomic) structure
- Assume that the BEC is smooth (Gross-Pitaevskii equation)
- Compute the spectrum of linear excitations
- Quantum field theory
- Current simulations are only valid when the fluctuations are small.



Analogue quantum gravity

- What is the backreaction of the phonons onto the analogue black hole?
- What is the effect of phonon-phonon interactions on the Hawking radiation?

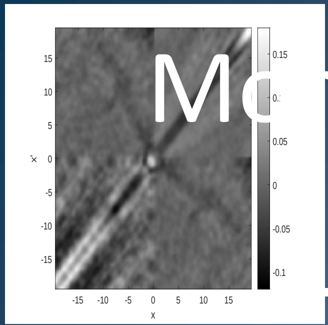
The interactions between particles should be increased to increase the effect of Analogue Quantum Gravity (AQG).

Theory

- Analytical studies are needed.
- New simulation techniques are needed.

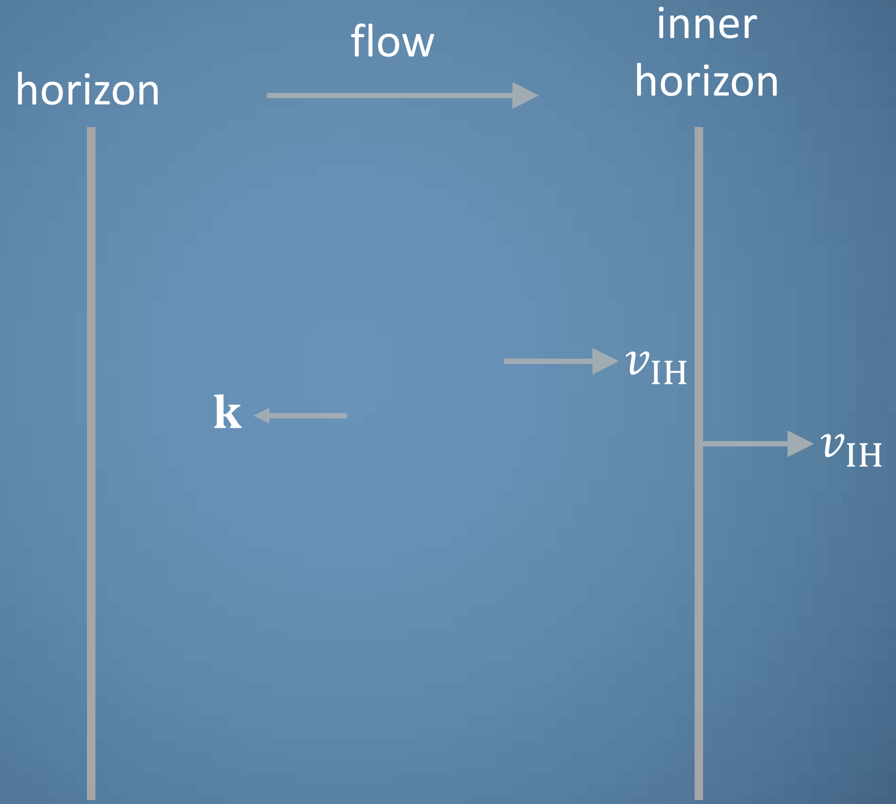
Experiment

- Strongly-interacting condensates could be studied.

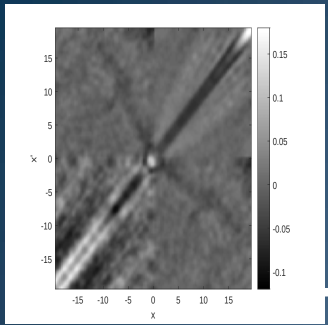


Monochromatic stimulated Hawking radiation

$\omega = -k_0 v_{\mathrm{IH}}$

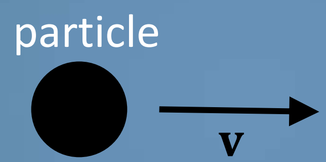


Yi-Hsieh Wang, Ted Jacobson, Mark Edwards, and Charles W. Clark, Mechanism of stimulated Hawking radiation in a laboratory Bose-Einstein condensate. Phys. Rev. A **96**, 023616 (2017).



Landau critical velocity

Superfluid



The particle sees a Doppler-shifted dispersion relation.

$$\omega' = \omega(k) - \mathbf{k}\cdot\mathbf{v}$$

Production of quasiparticles $\omega' = 0$ Bogoliubov-Cherenkov radiation