Synthetic Quantum Systems

SynQS

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

Quantum Field Simulator for a relativistic scalar field in curved space time

Experiment

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Theory

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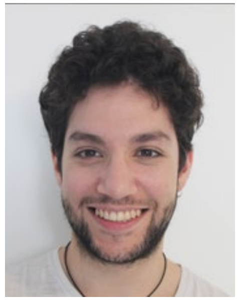

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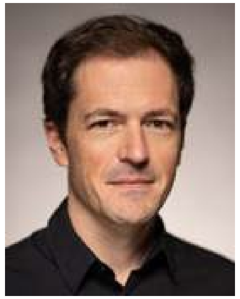
Natalia Sánchez-Kuntz

Tobias Haas

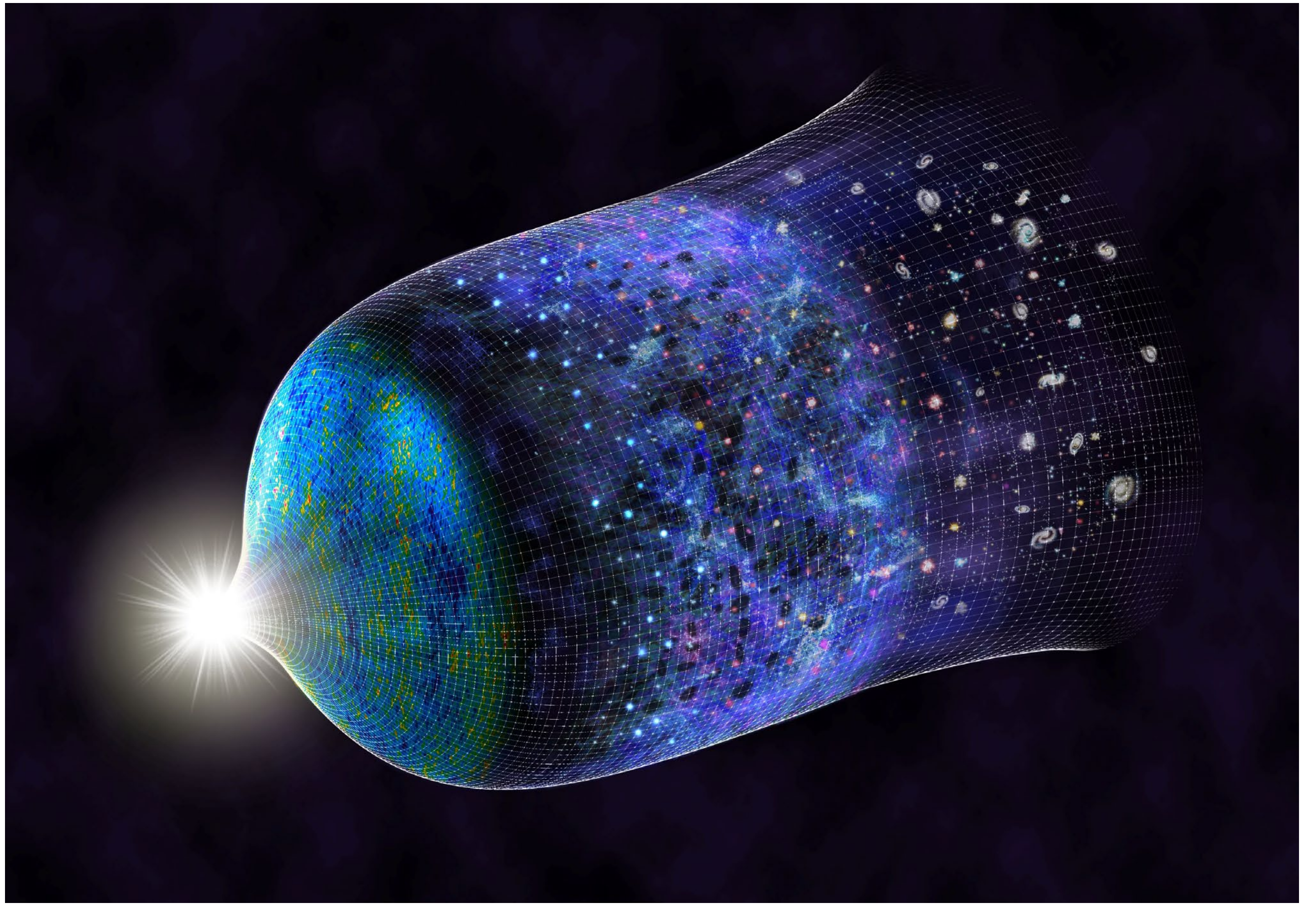


Stefan Floerchinger

STRUCTURES CLUSTER OF EXCELLENCE

IsoQuant SFB1225

Curved Spacetimes



Nicolle R. Fuller, National Science Foundation

- Quantum field with fluctuations in expanding spacetime
- Homogeneous and isotropic universe
  - **Friedmann-Lemaître-Robertson-Walker (FLRW) Metric of 2D – spacetime:**

$$ds^2 = -dt^2 + a^2(t)\left(\frac{du^2}{1-\kappa u^2} + u^2 d\varphi^2\right)$$

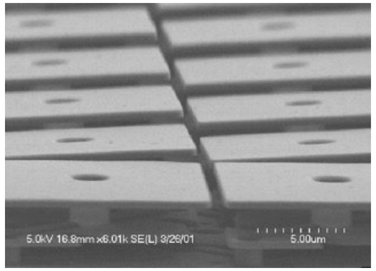
Time-dependent scale factor

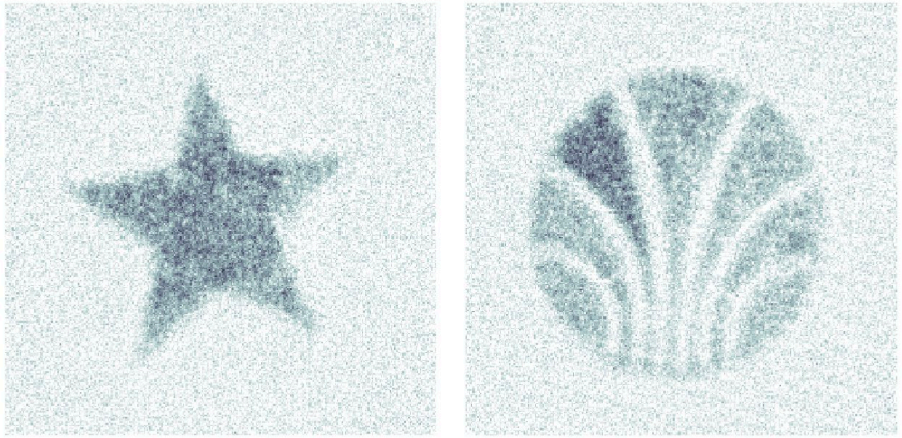
Spatial curvature

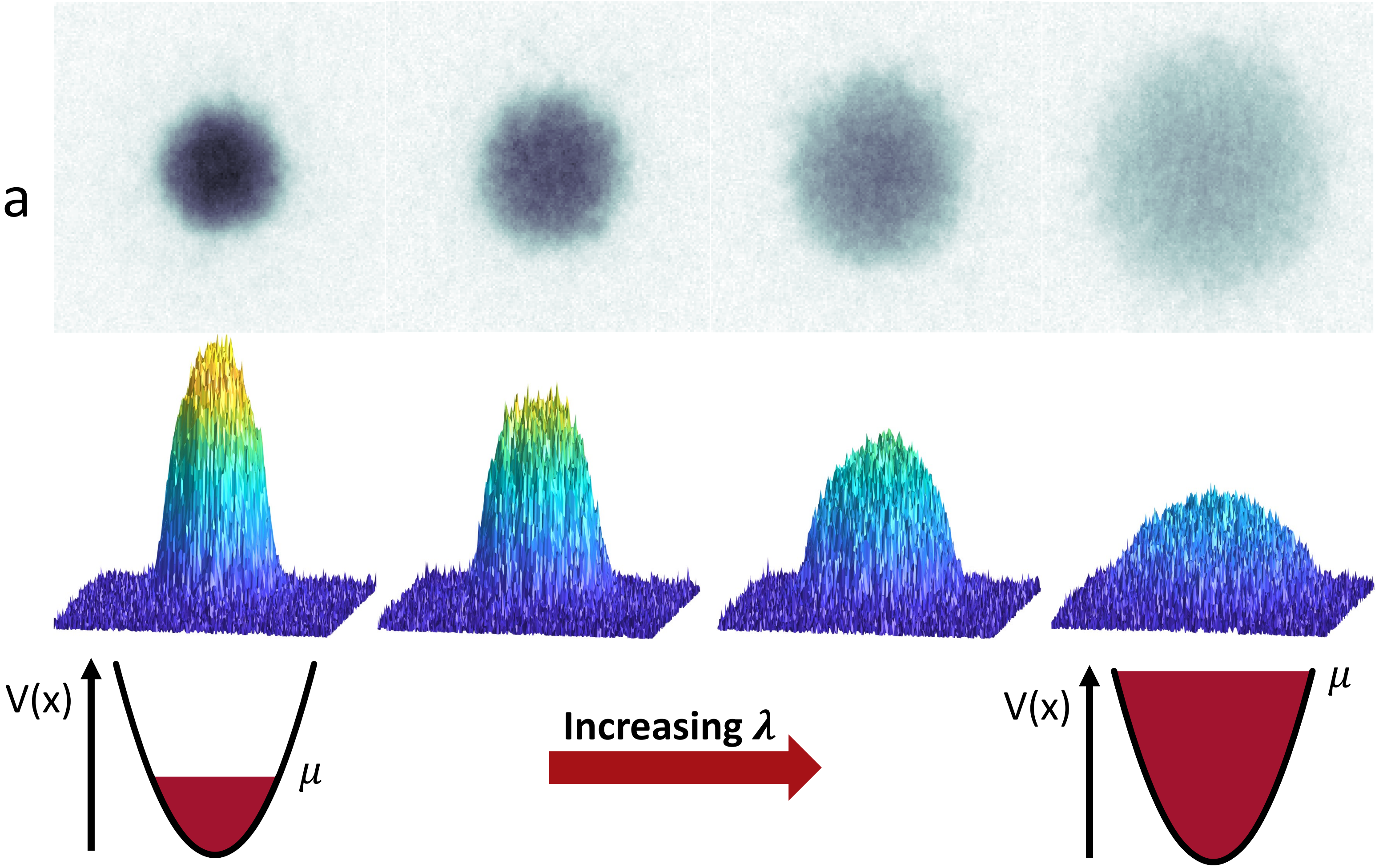
Previous work by: S. Weinfurtner, I. Carusotto, J. Steinhauer, G. K. Campbell, C. Chin…

2D – Bose-Einstein Condensate of 39-K

- Precise control over magnetic field
  - Tunable interactions $\lambda(t) = g_{2D}$
- Adjustable potentials $V(x,t)$ via a Digital Micromirror Device
  - Arbitrary 2D-densities $n(x)$

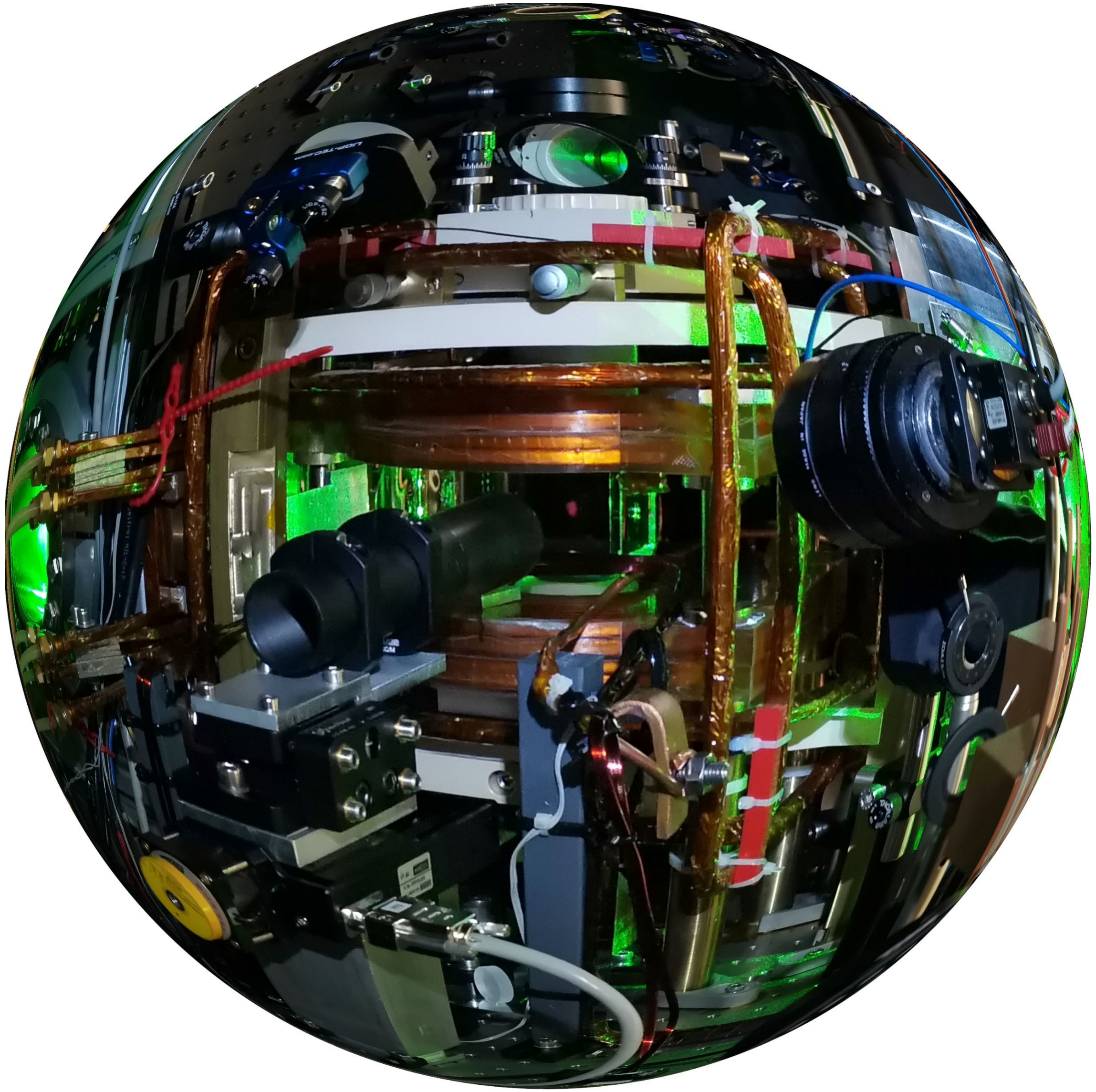

[1]





[1]Andrew B. Sontheimer, IEEE Int. Rel. Phys. Symposium. Proceedings. 40th Annual (Cat. No.02CH37320) (2002): 118-121.

Curved Spacetimes in the Lab



Curved Spacetimes in a BEC

Scalar Quantum Field in 2D - Spacetime:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + a^2(t)\left(\frac{\mathrm{d}u^2}{1-\kappa u^2} + u^2\mathrm{d}\varphi^2\right)$$

- Global curvature κ, and scale factor $a(t)$
- Speed of light
  $$c = const.$$

Phononic Excitations of a 2D – BEC of 39-K:

$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \frac{1}{c^2}\left(\mathrm{d}r^2 + r^2\mathrm{d}\varphi^2\right)$$

- Speed of sound
  $$c = \sqrt{\frac{n(r)\lambda(t)}{m}}$$

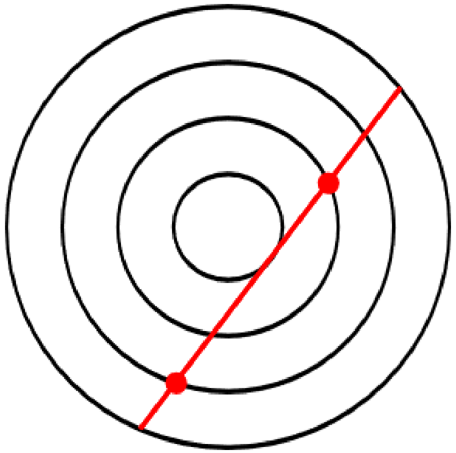
Incorporate κ and $a(t)$ in $c(r,t)$ and coordinate transformation $r \rightarrow u$

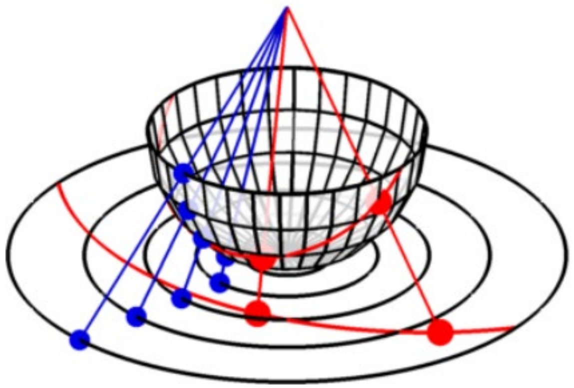
Phys. Rev. A **106, 033313 (2022)**

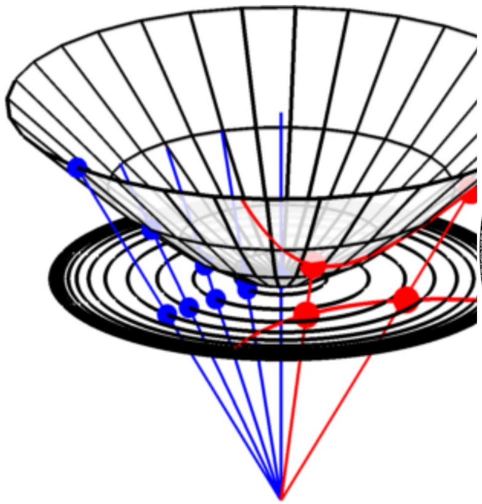
Spatial Curvature – Phonon trajectories

	Flat $\kappa = 0$	Spherical $\kappa > 0$	Hyperbolic $\kappa < 0$

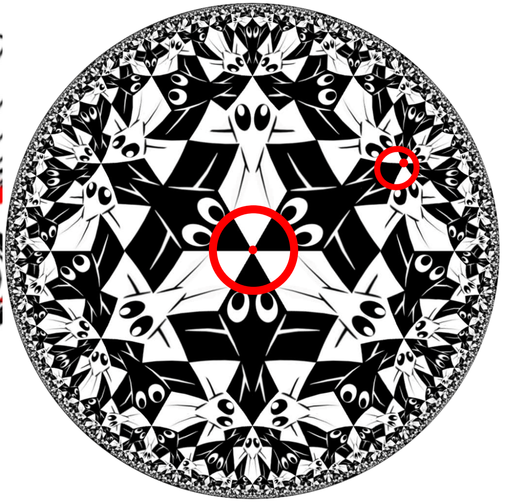
Curved Space:







github.com/looeee/hyperbolic-tiling



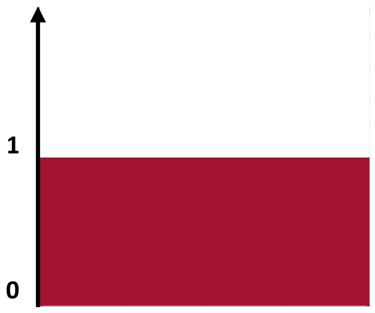
Density:

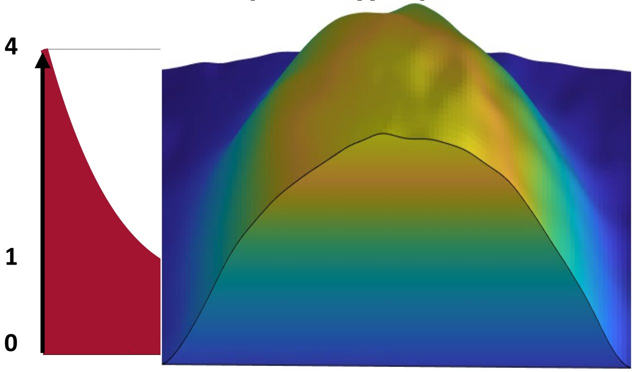
$$n_0(r) = \bar{n}_0$$

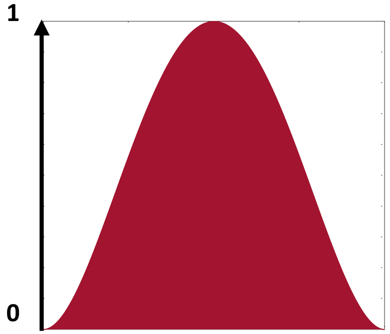
$$n_0(r) = \bar{n}_0 \left(1 + \frac{r^2}{R^2}\right)^2$$

$$n_0(r) = \bar{n}_0 \left(1 - \frac{r^2}{R^2}\right)^2$$

$$\kappa = \mp 4/R^2$$





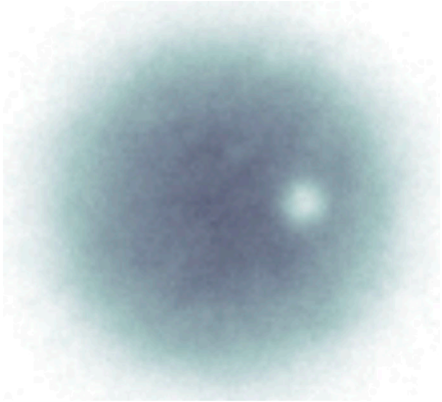


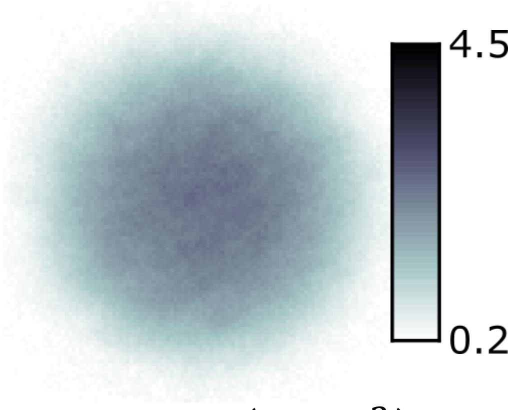
arXiv:2202.10399 (accepted)

Spatial Curvature – Phonon trajectories

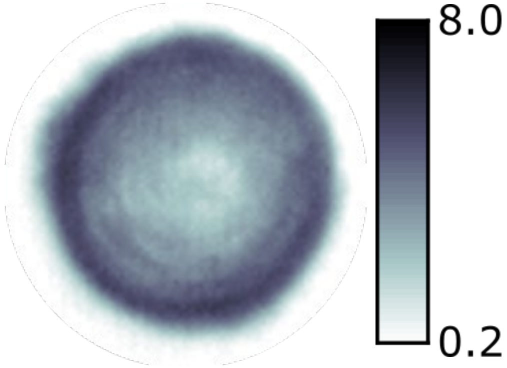
Measuring phonon trajectories:

- Make initial density dip with additional beam
- Turn beam off
- Measure phononic wave packet travelling outwards

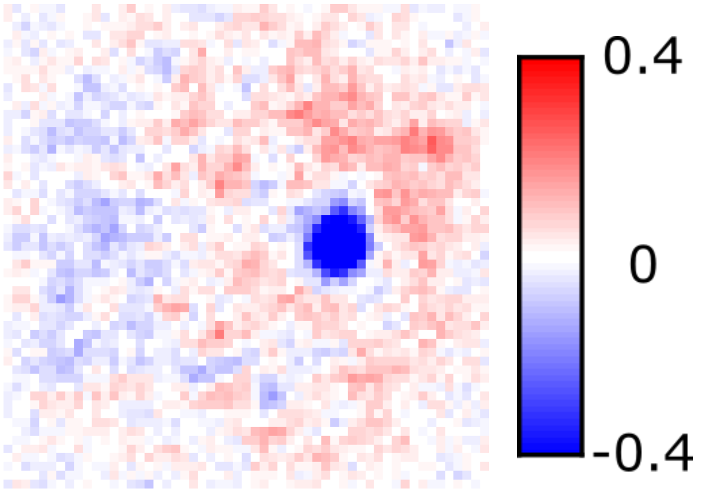


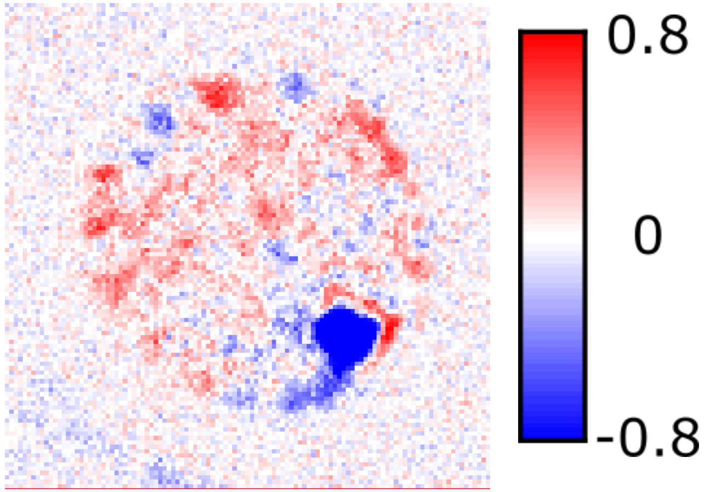


$$n_0(r) = \bar{n}_0 \left(1 - \frac{r^2}{R^2}\right)$$



$$n_0(r) = \bar{n}_0 \left(1 + \frac{r^2}{R^2}\right)^2$$





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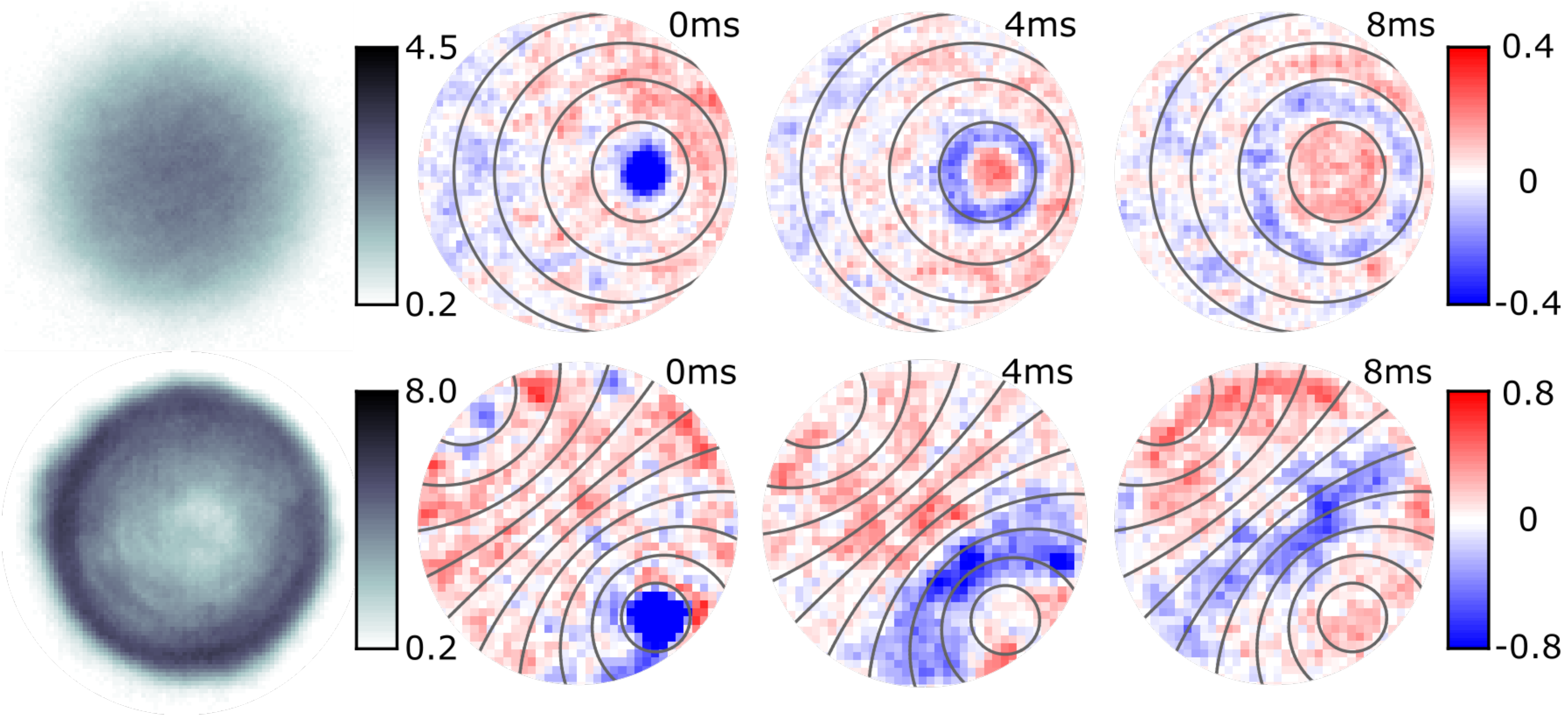
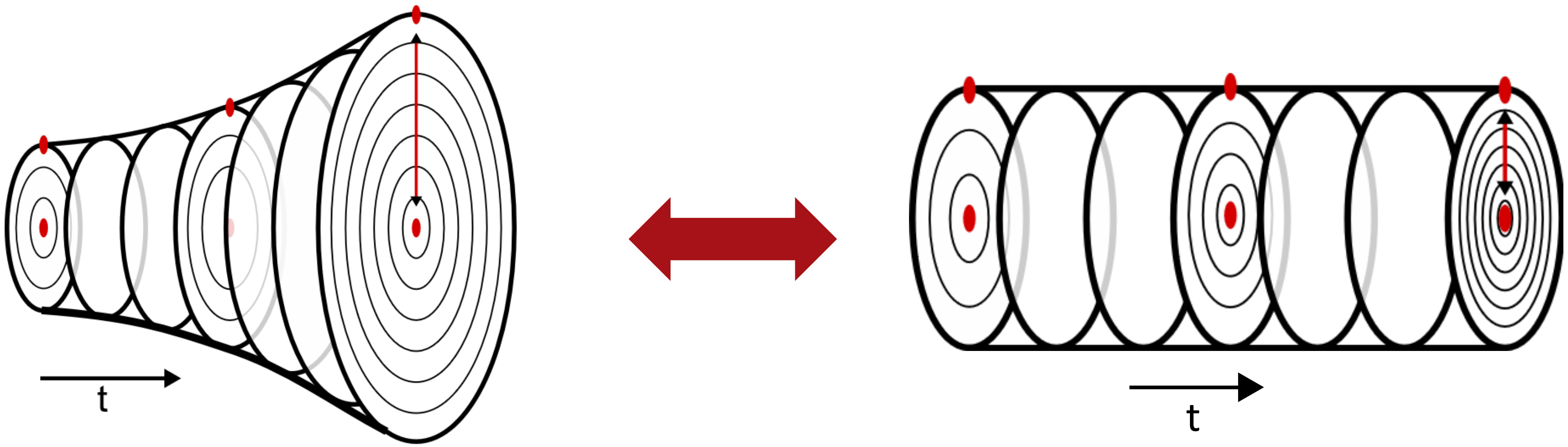
Spatial Curvature – Phonon trajectories

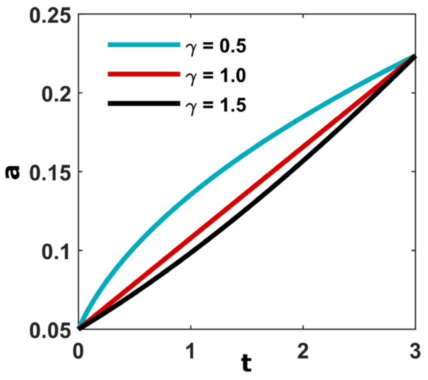


arXiv:2202.10399 (accepted)

Expanding Spacetimes – Particle Production

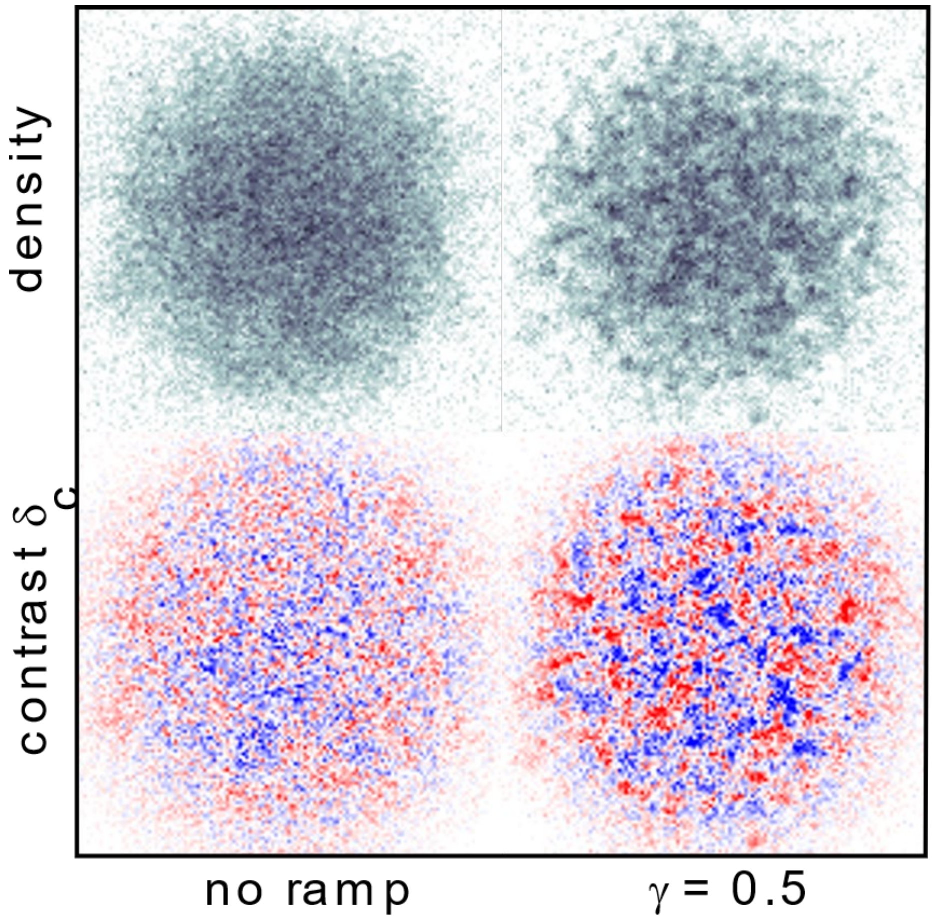
$$\mathrm{d}s^2 = -\mathrm{d}t^2 + \boxed{a^2(t)}\left(\frac{\mathrm{d}u^2}{1-\kappa u^2} + u^2\mathrm{d}\varphi^2\right)$$

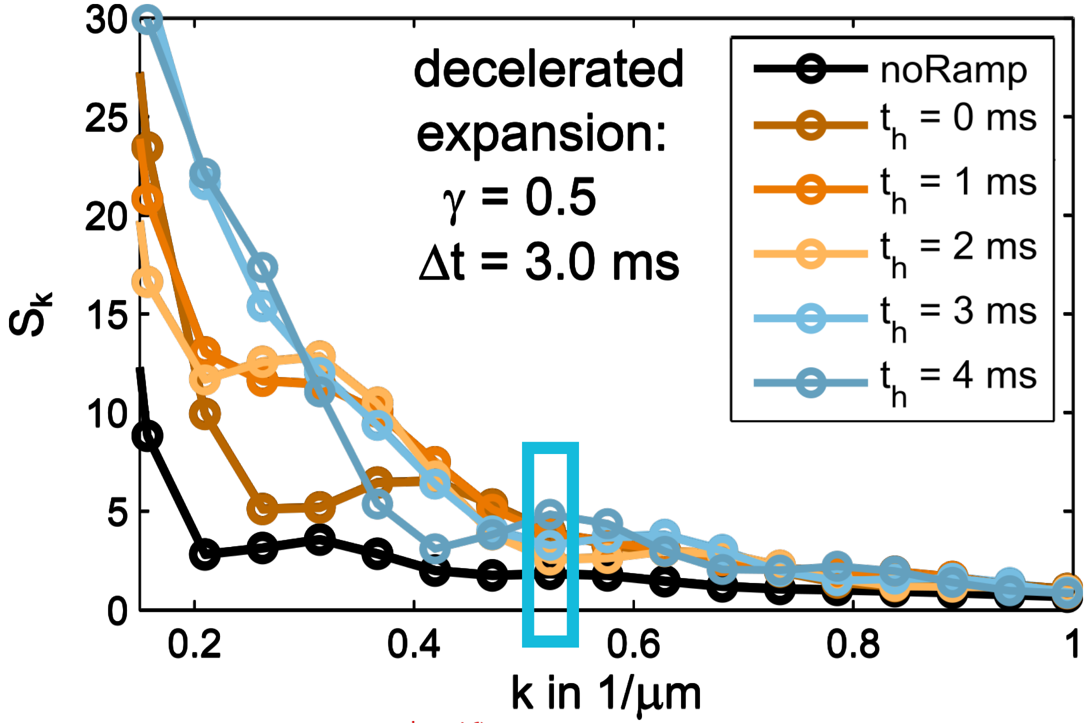


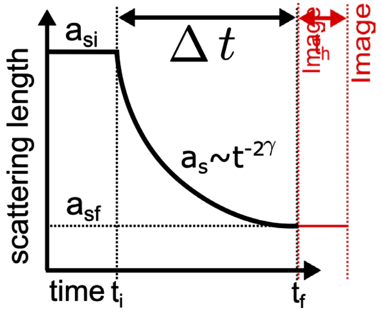


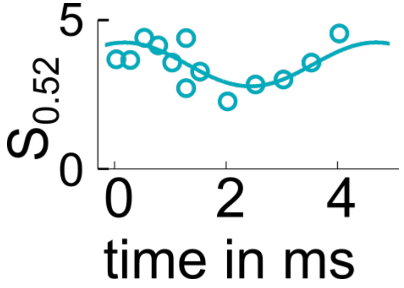
- Ramp scale factor via interaction
- Keep density profile that defines curvature constant
- Non-adiabatic change results in excitations

arXiv:2202.10399 (accepted)



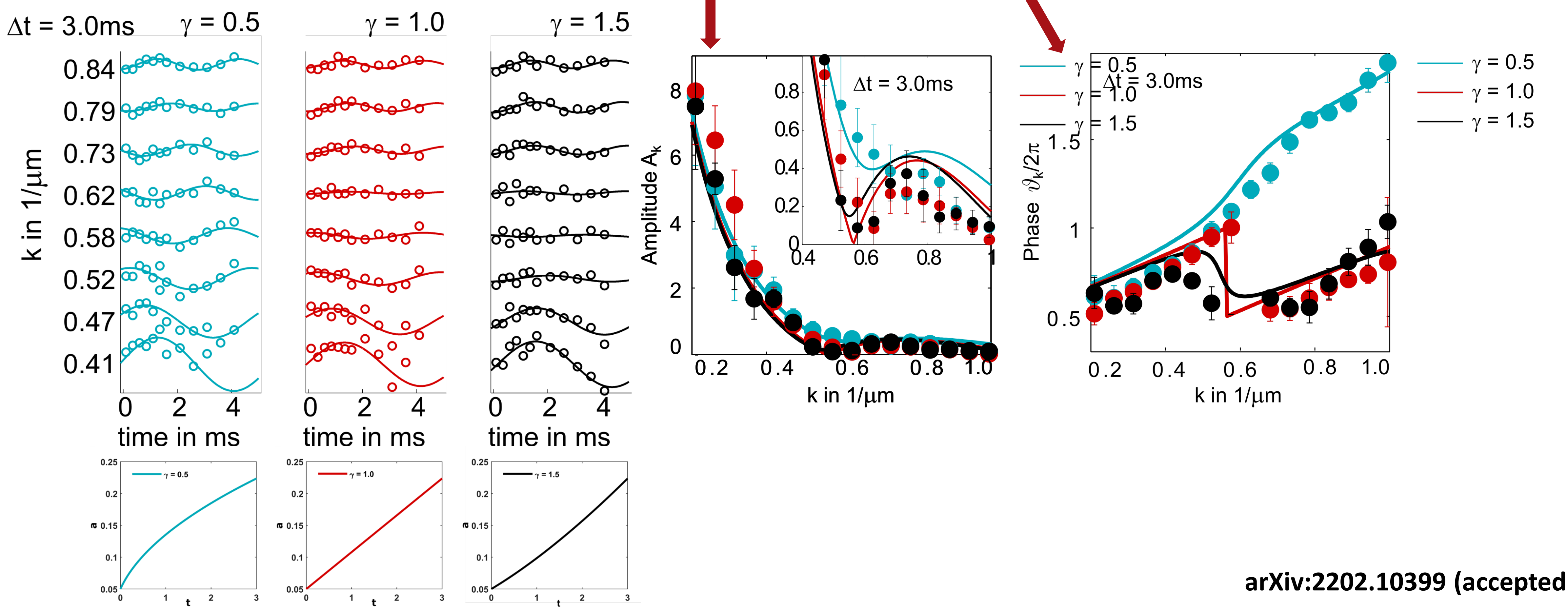






C. Chin et al. *Science* **341, 1213–1215 (2013)**
arXiv:2202.10399 (accepted)

Time Evolution of Spectrum: $S_k(t) = \frac{1}{2} + N_k + A_k \cos(2\omega_k t + \vartheta_k)$



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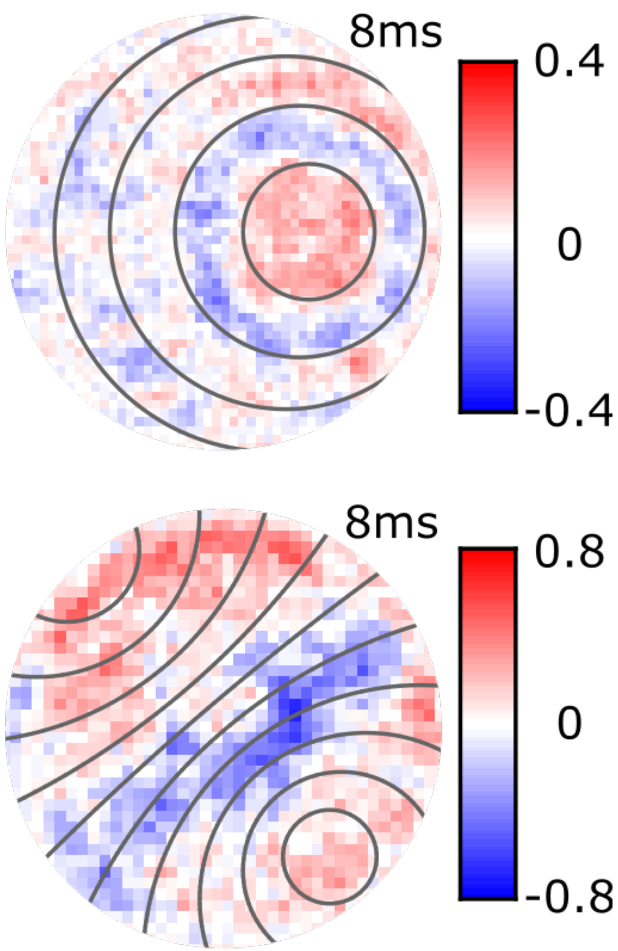

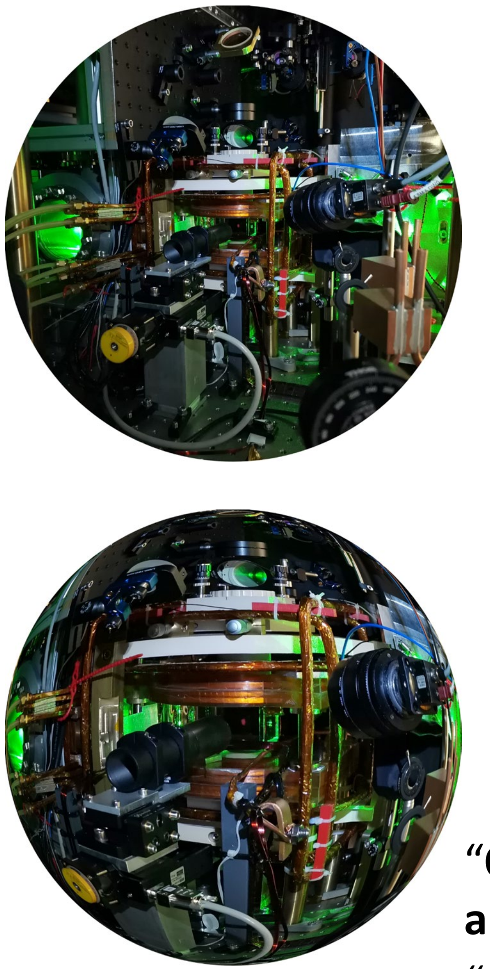

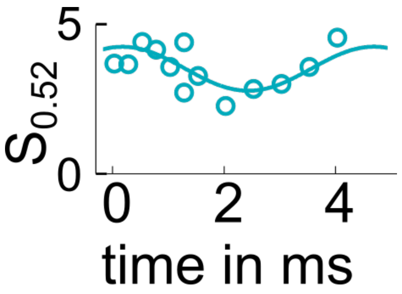

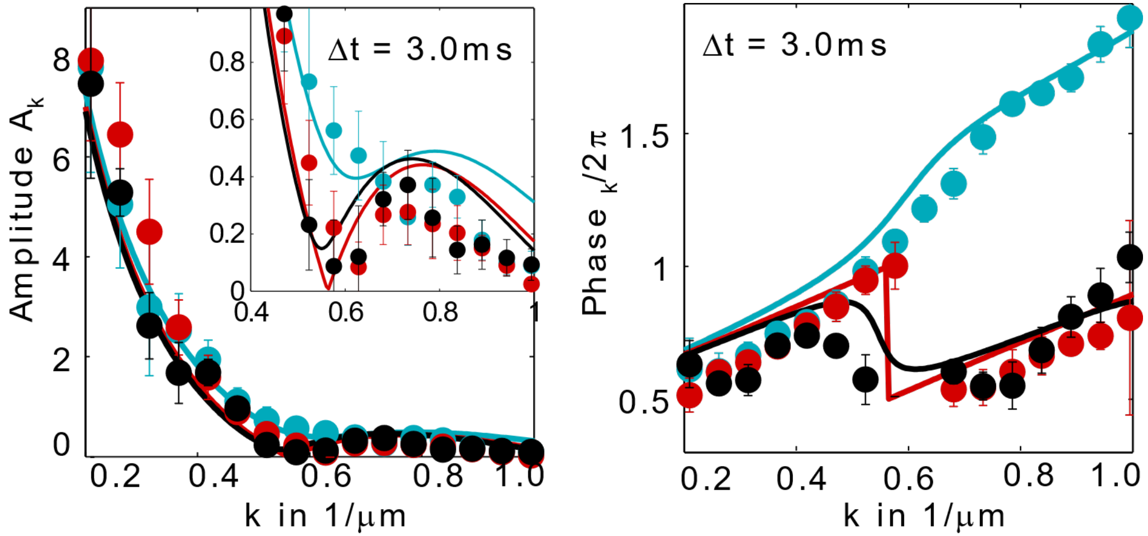

"Quantum field simulator for dynamics in curved spacetime"
arXiv:2202.10399 (accepted)

"Curved and expanding spacetime geometries in Bose-Einstein condensates", *Phys. Rev. A* **106, 033313 (2022)**