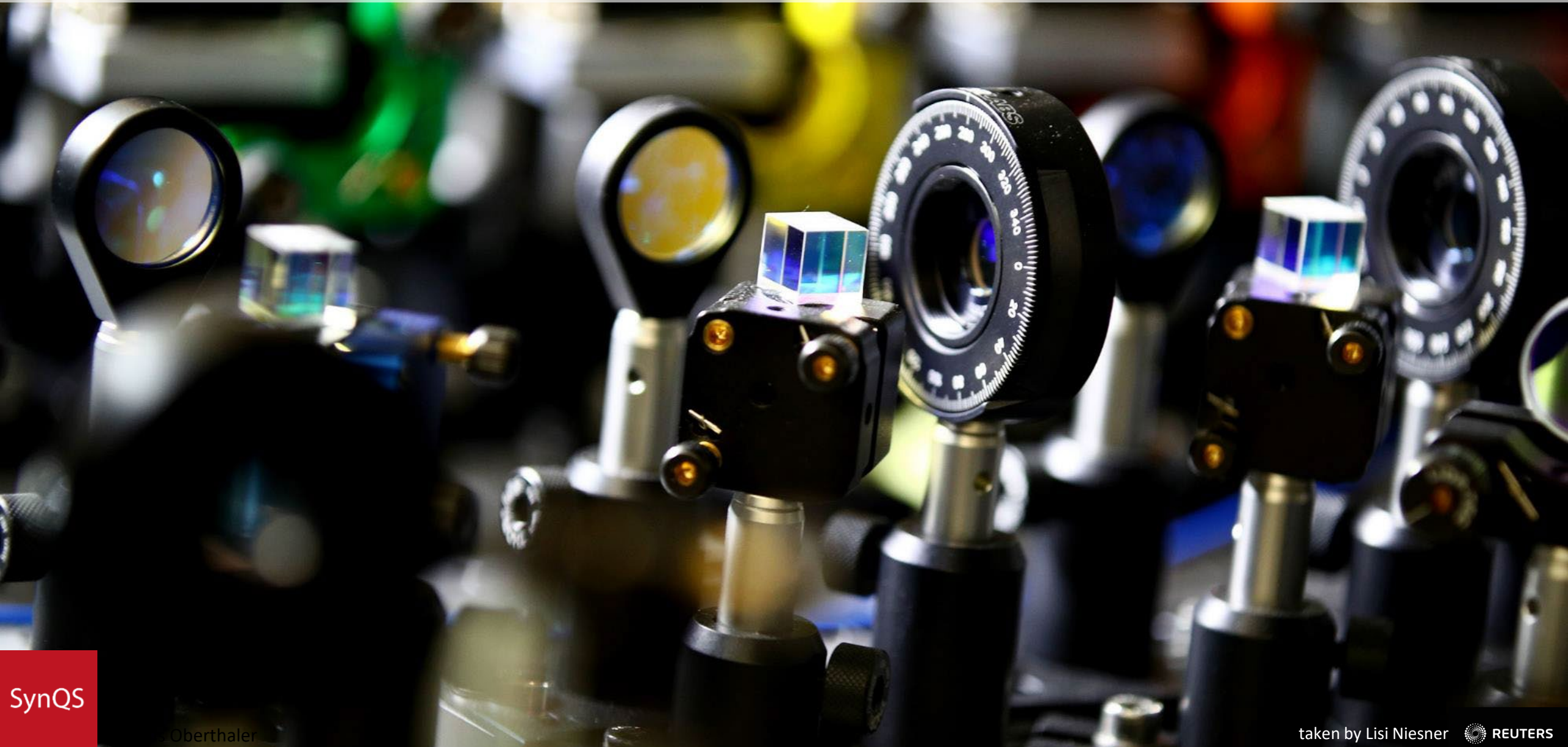


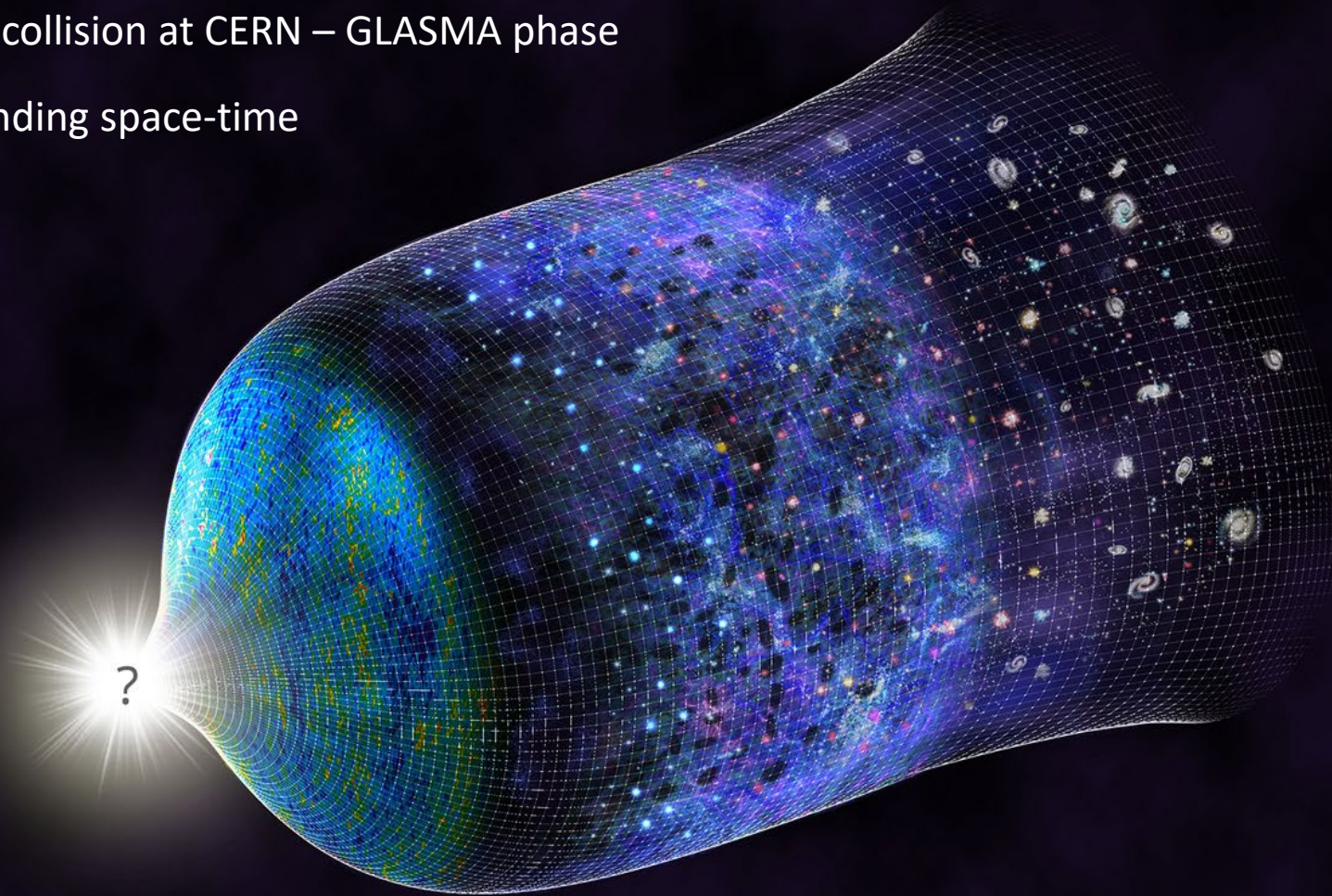
Quantum Field Simulator – Universal Dynamics & Fields in Curved Space



Quantum Field Simulator – Universal Dynamics & Fields in Curved Space-Time

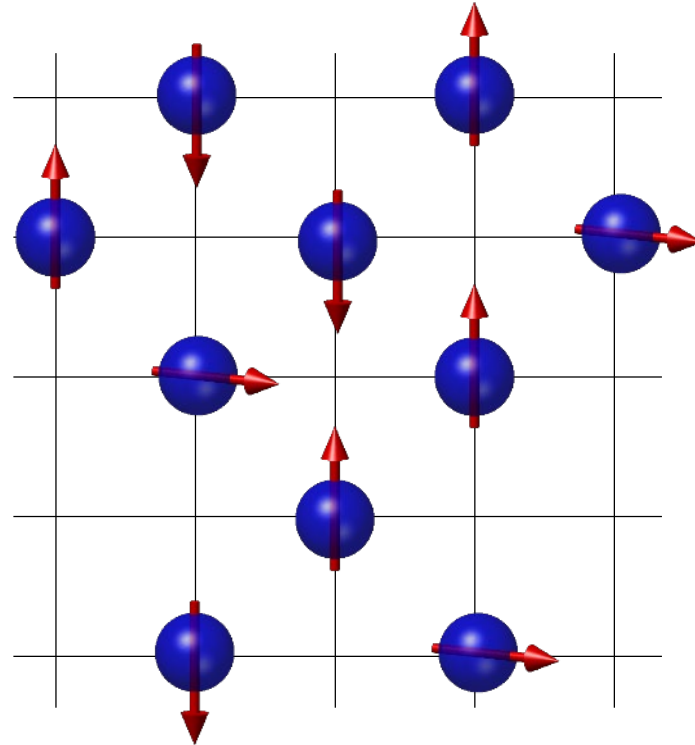
Early phase after heavy ion collision at CERN – GLASMA phase

Particle production in expanding space-time



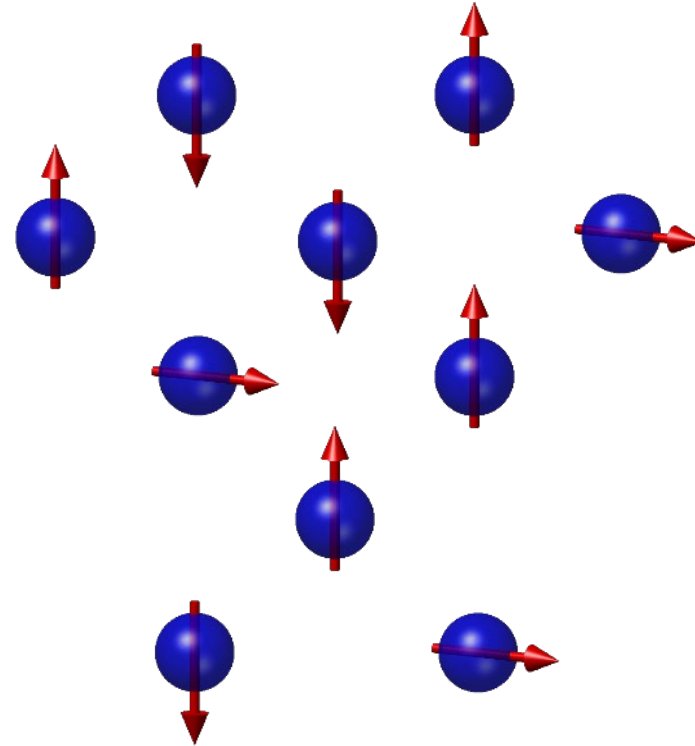
As example Spin-1 bosonic gas

Quantum Field Settings



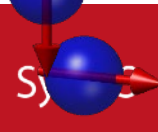
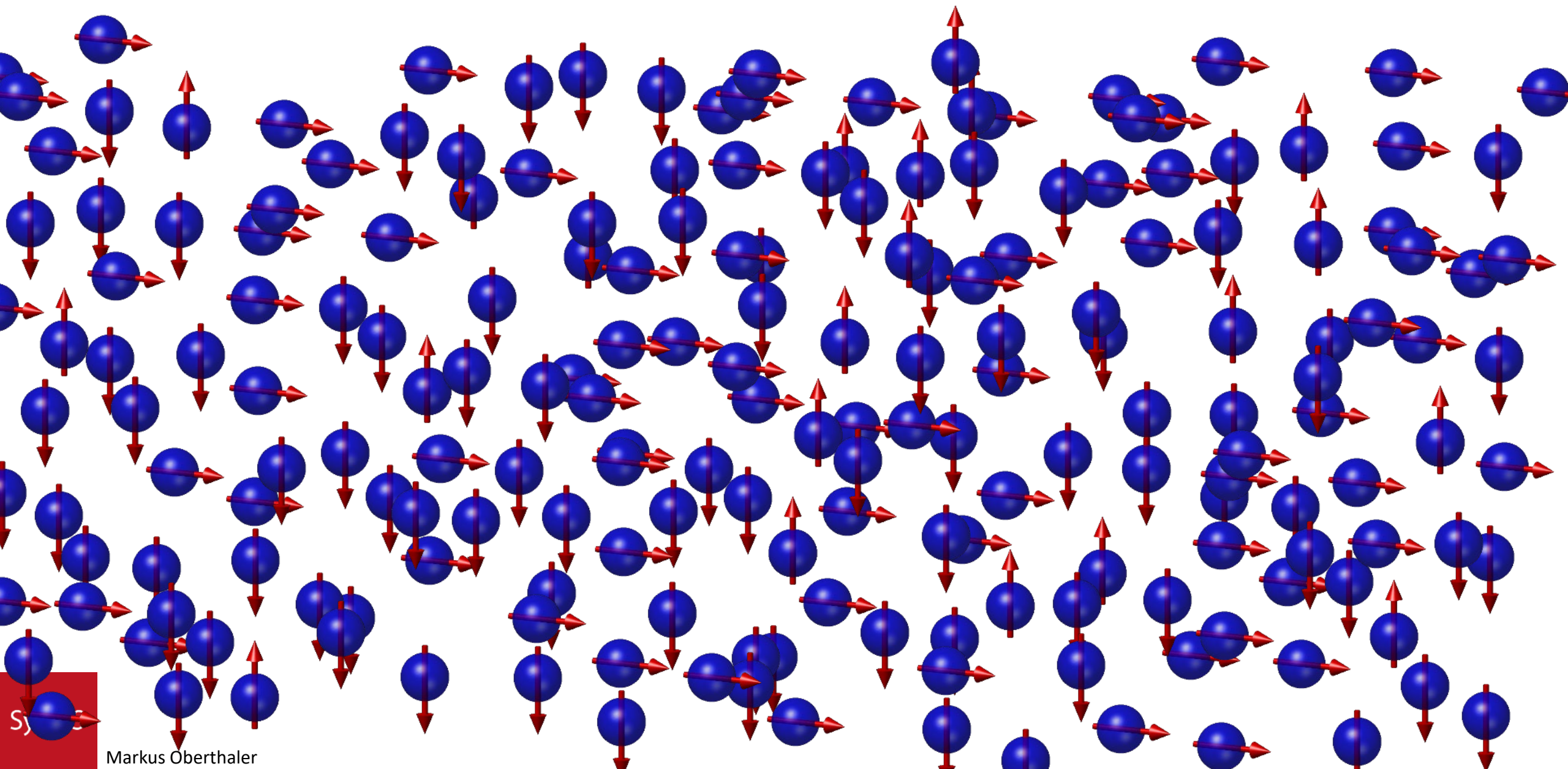
No lattice – free space

Quantum Field Settings



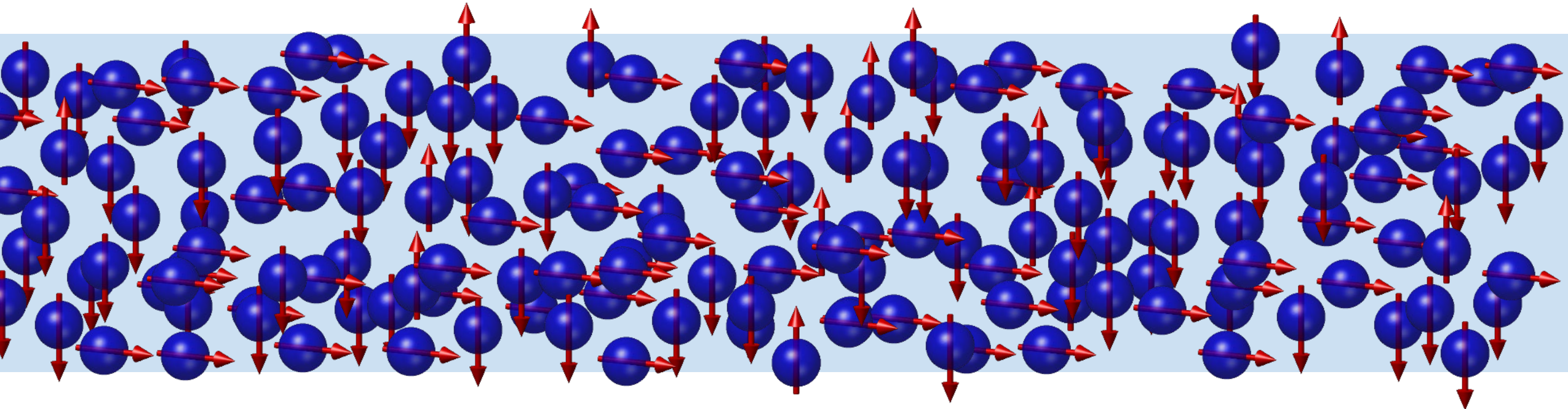
Many atoms

Quantum Field Settings



Quasi-one-dimensional spin-1 bosonic gas

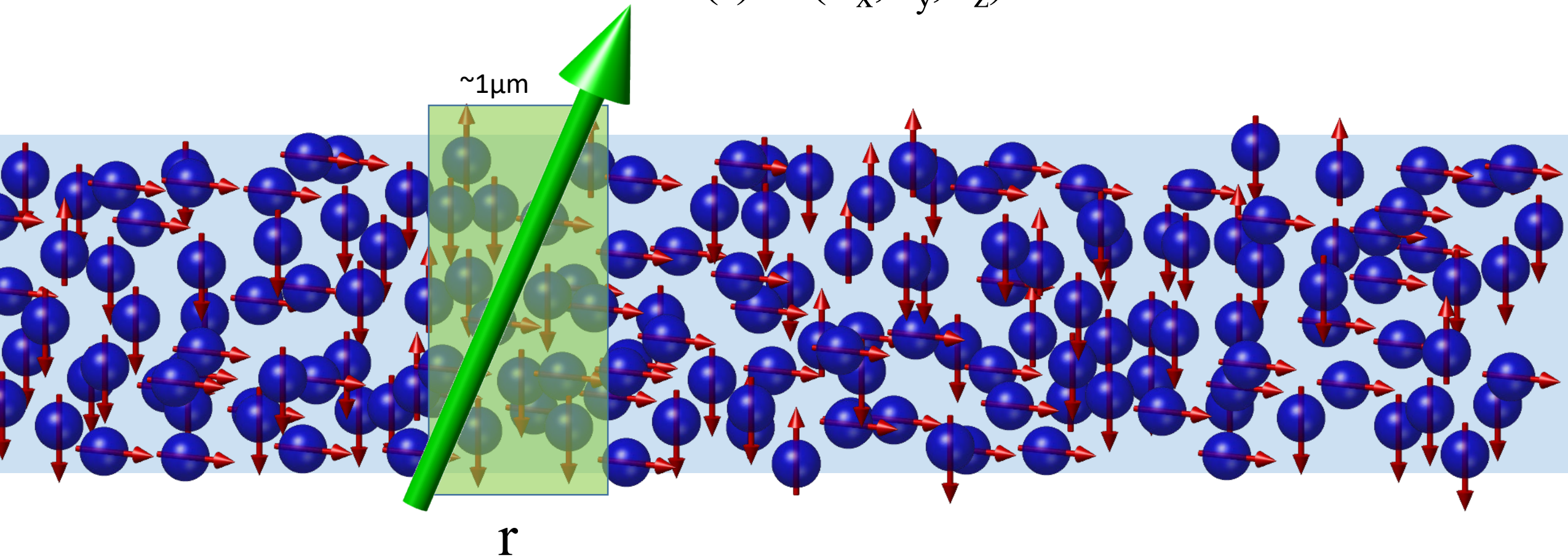
Quantum Field Settings

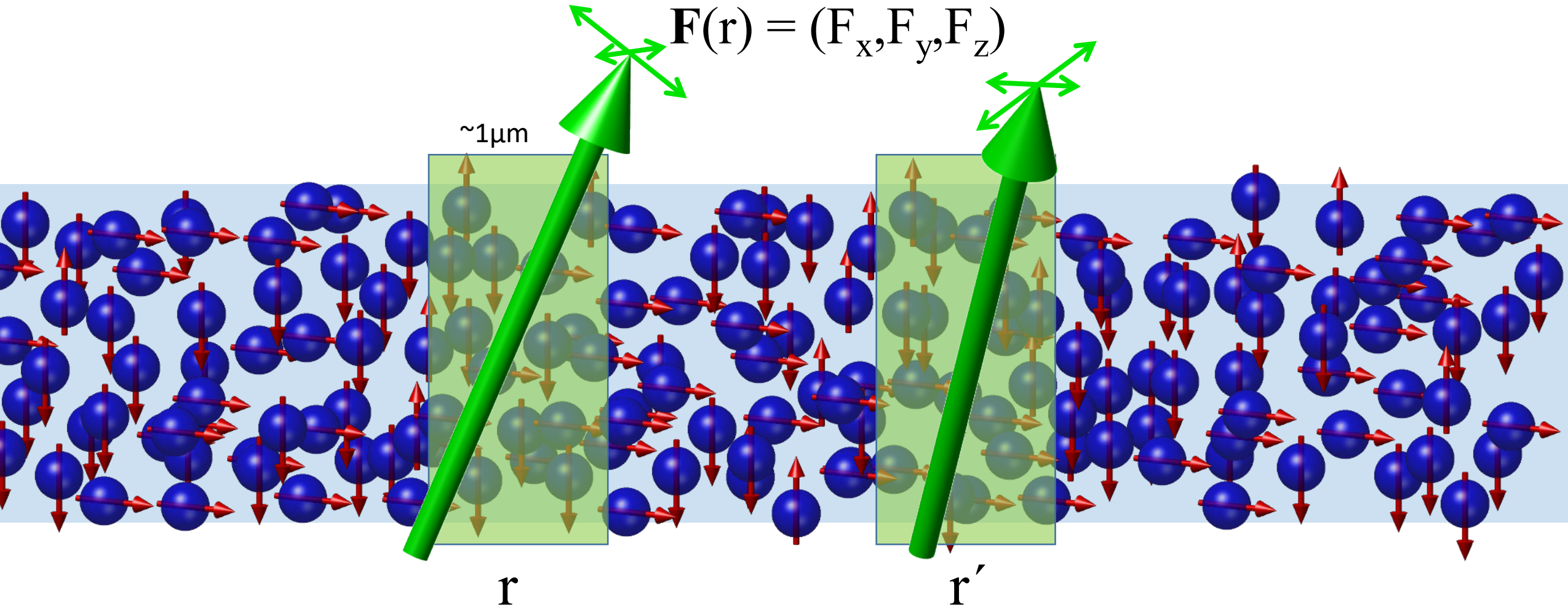


Voxel contains approx. 200 atoms – spin degree is 1d

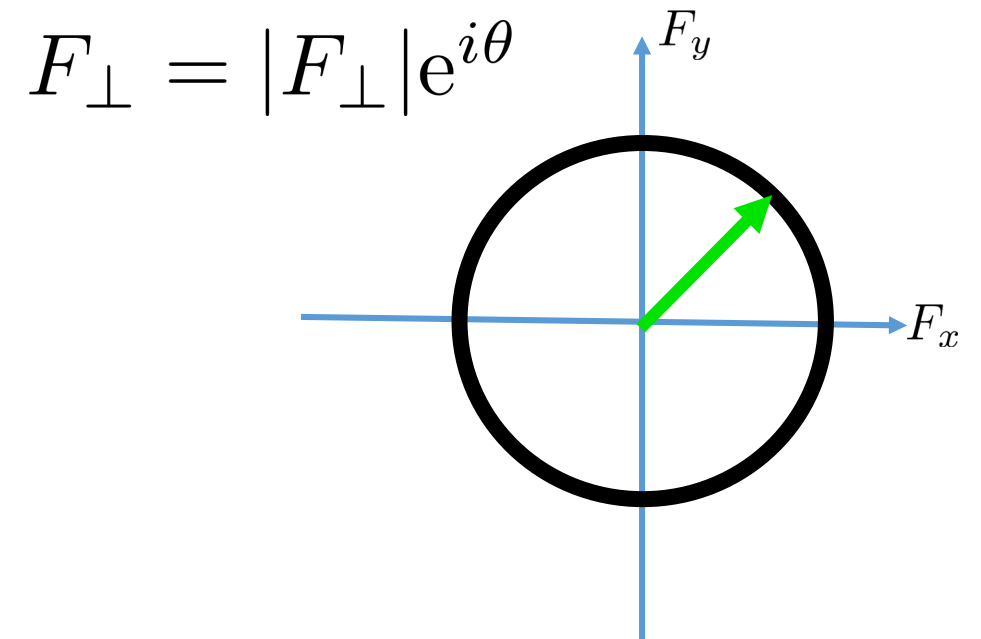
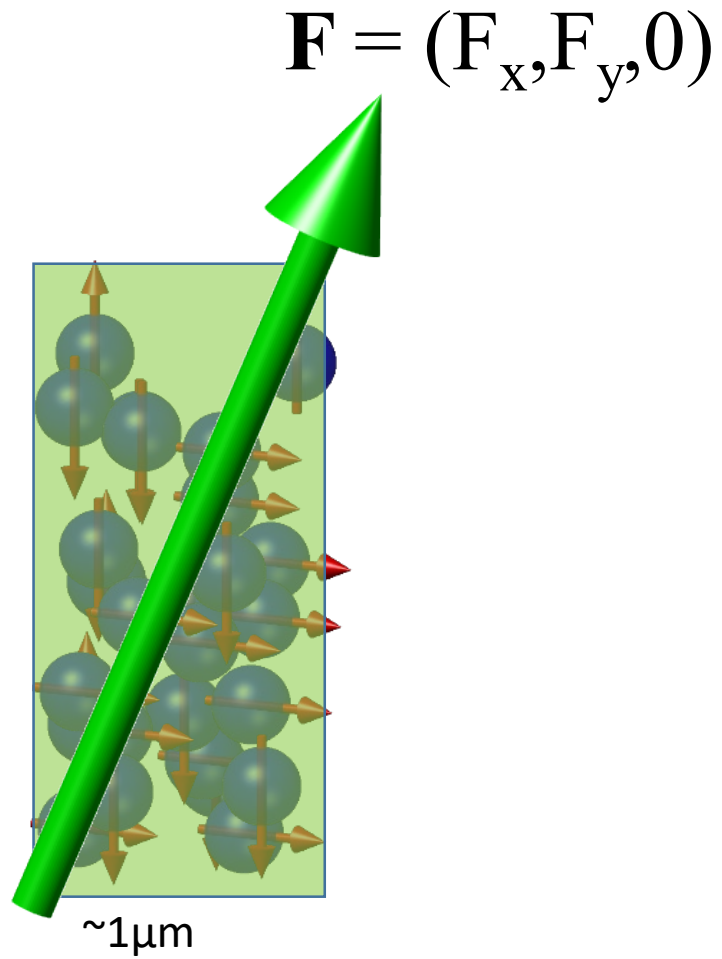
(Quantum) Field Settings

$$\mathbf{F}(\mathbf{r}) = (F_x, F_y, F_z)$$

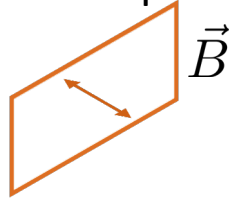




spatial correlation $\langle \mathbf{F}(\mathbf{r})\mathbf{F}(\mathbf{r}') \rangle$, $\langle \mathbf{F}(\mathbf{r})\mathbf{F}(\mathbf{r}')\mathbf{F}(\mathbf{r}'') \rangle$, ...



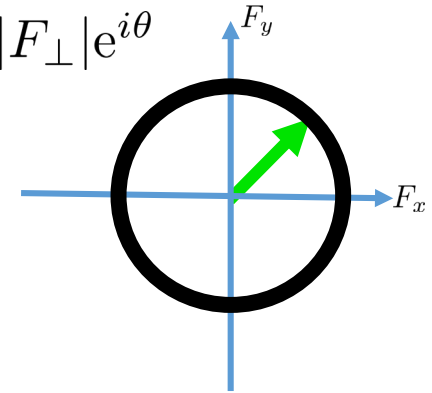
Radio-frequency



readout after expanding Hilbert space

Kunkel et al. Phys. Rev. Lett. 123, 063603 (2019)

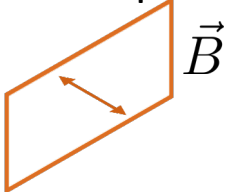
$$F_{\perp} = |F_{\perp}|e^{i\theta}$$



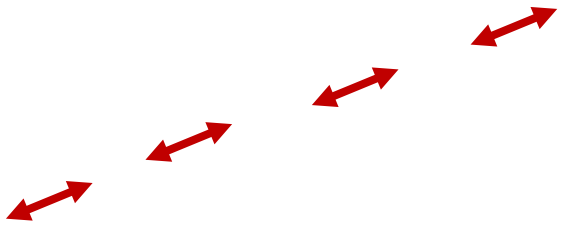
readout after expanding Hilbert space

Kunkel et al. Phys. Rev. Lett. 123, 063603 (2019)

Radio-frequency



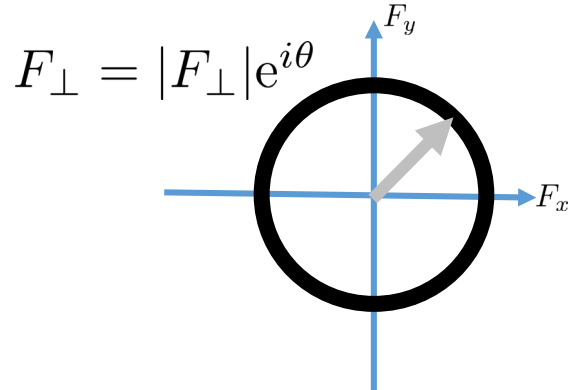
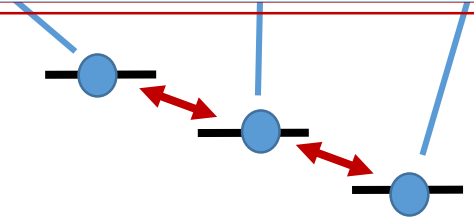
rotation around
y-Axis



rotation around
x-Axis

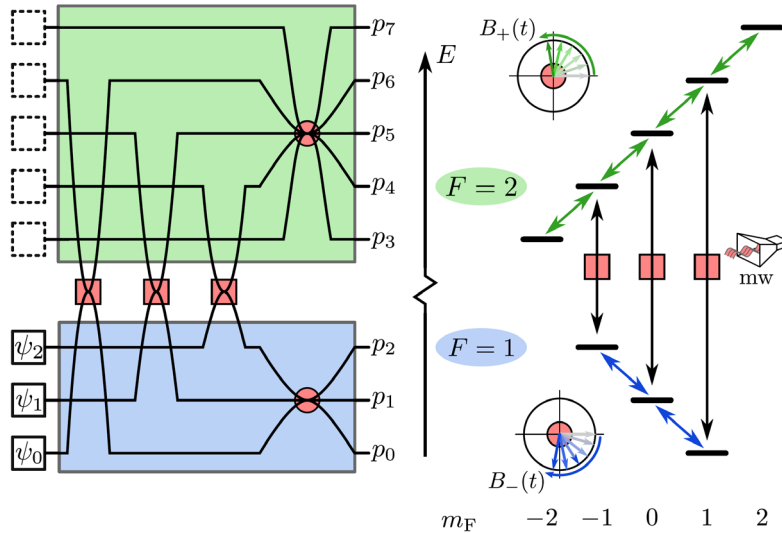
$F=1$

m_F -2 -1 0 +1 +2

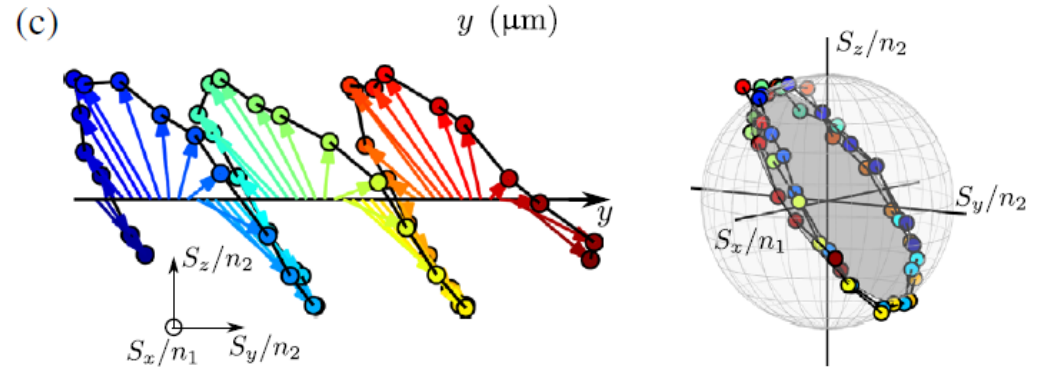
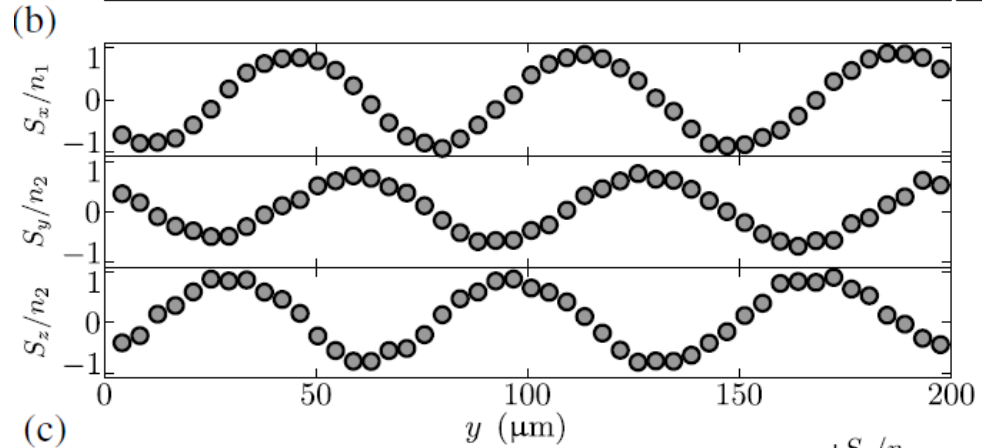
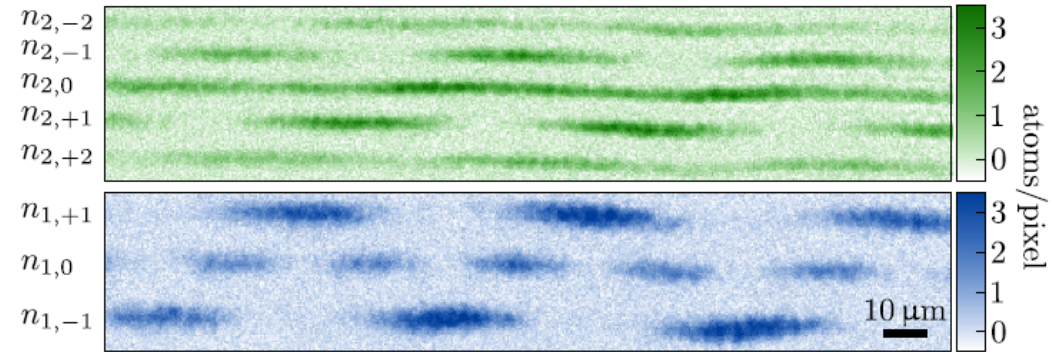


Implementation of POVMs

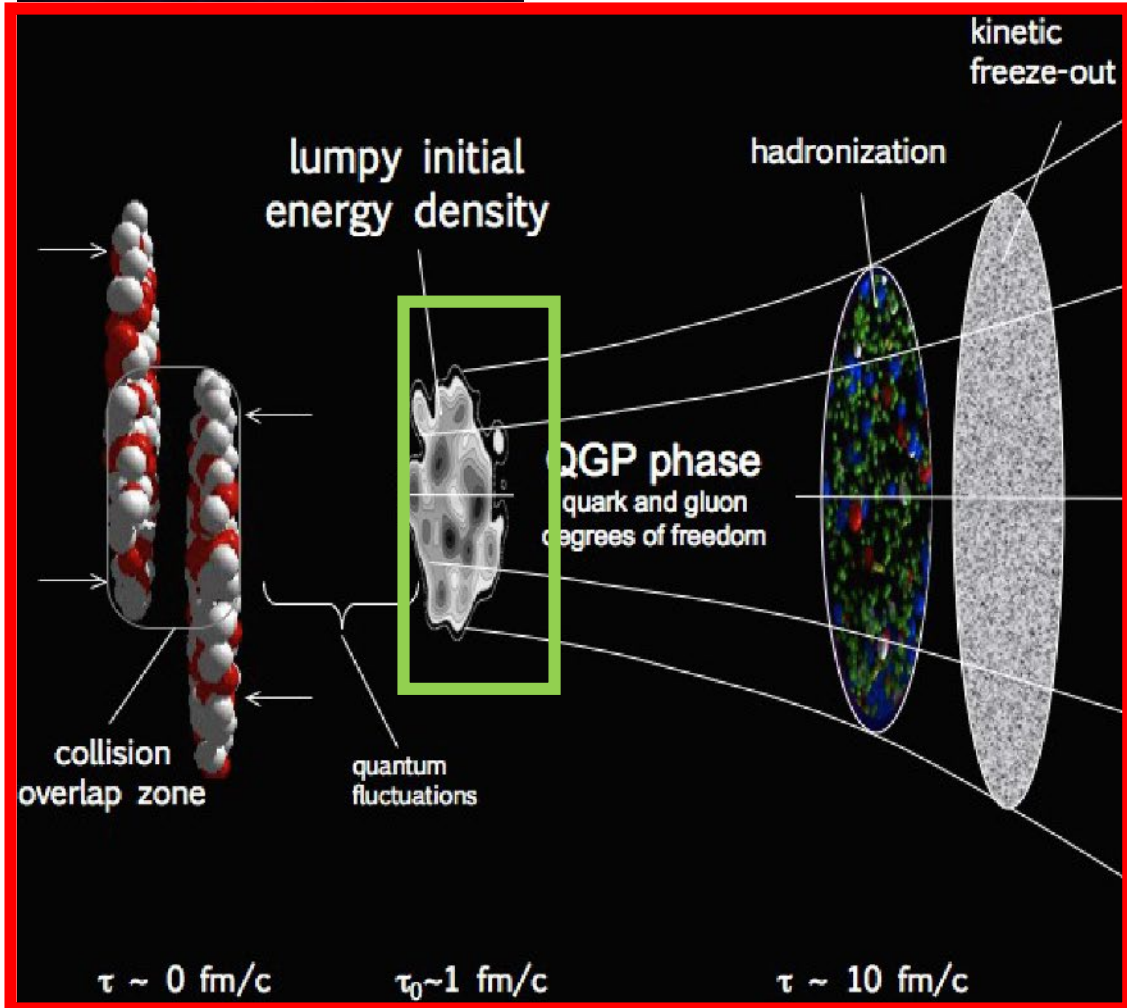
Kunkel et al. Phys. Rev. Lett. 123, 063603 (2019)



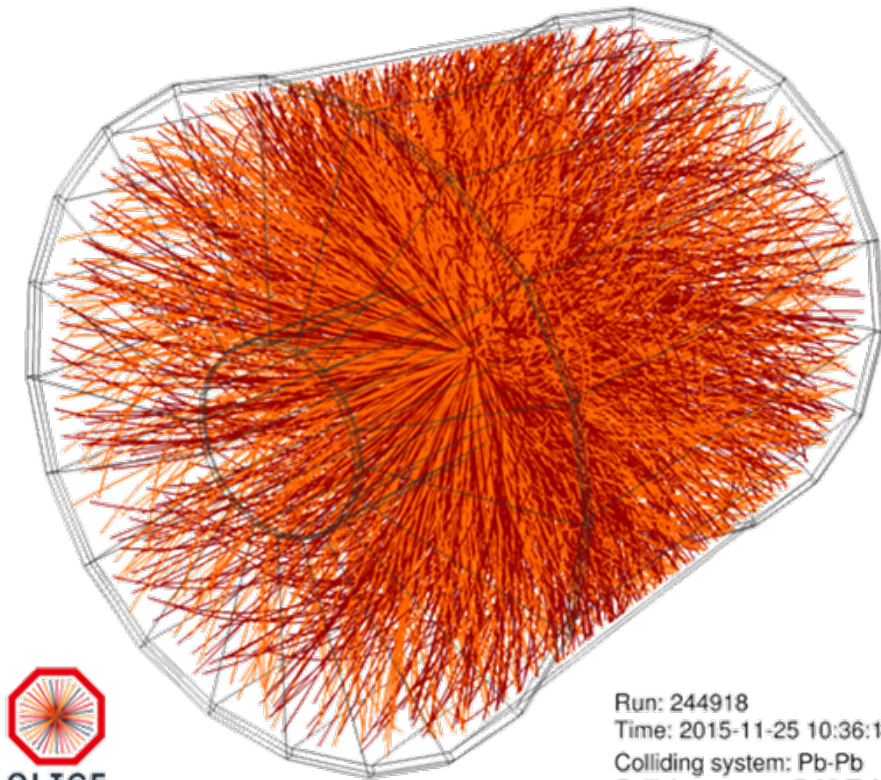
see Jessen group:
PRL 111, 170502 (2013)



Little Bang(s) at CERN



0.000 000 000 000 000 000 000 000 1 sec



Little Bang(s) at CERN



Jürgen Berges



Thomas Gasenzer

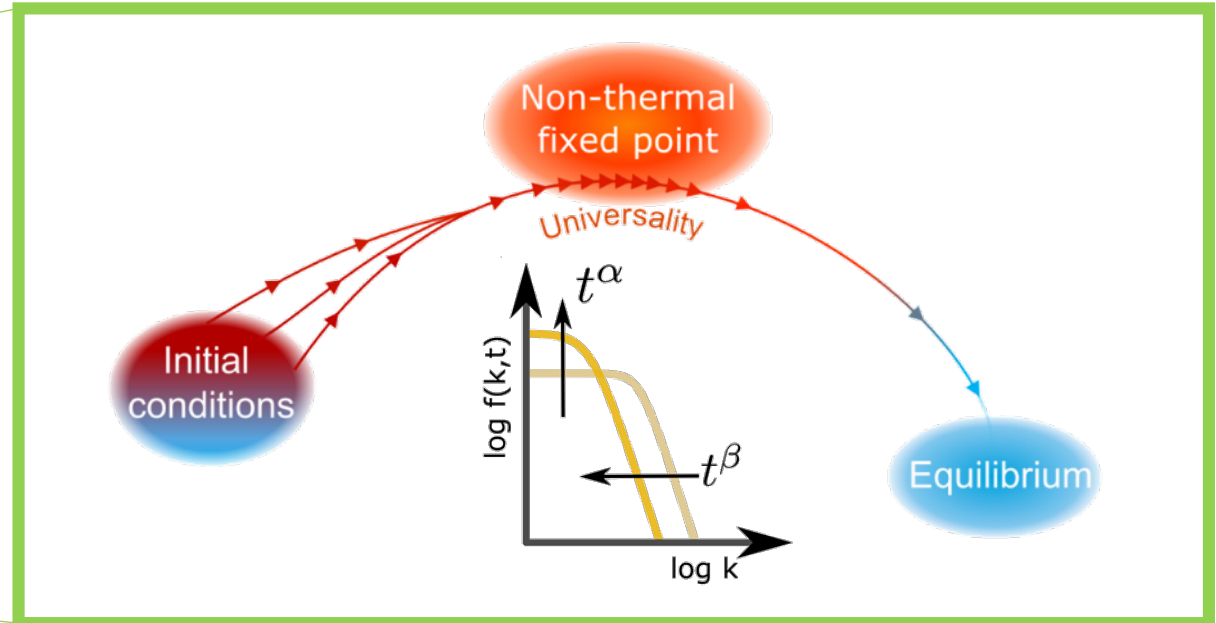
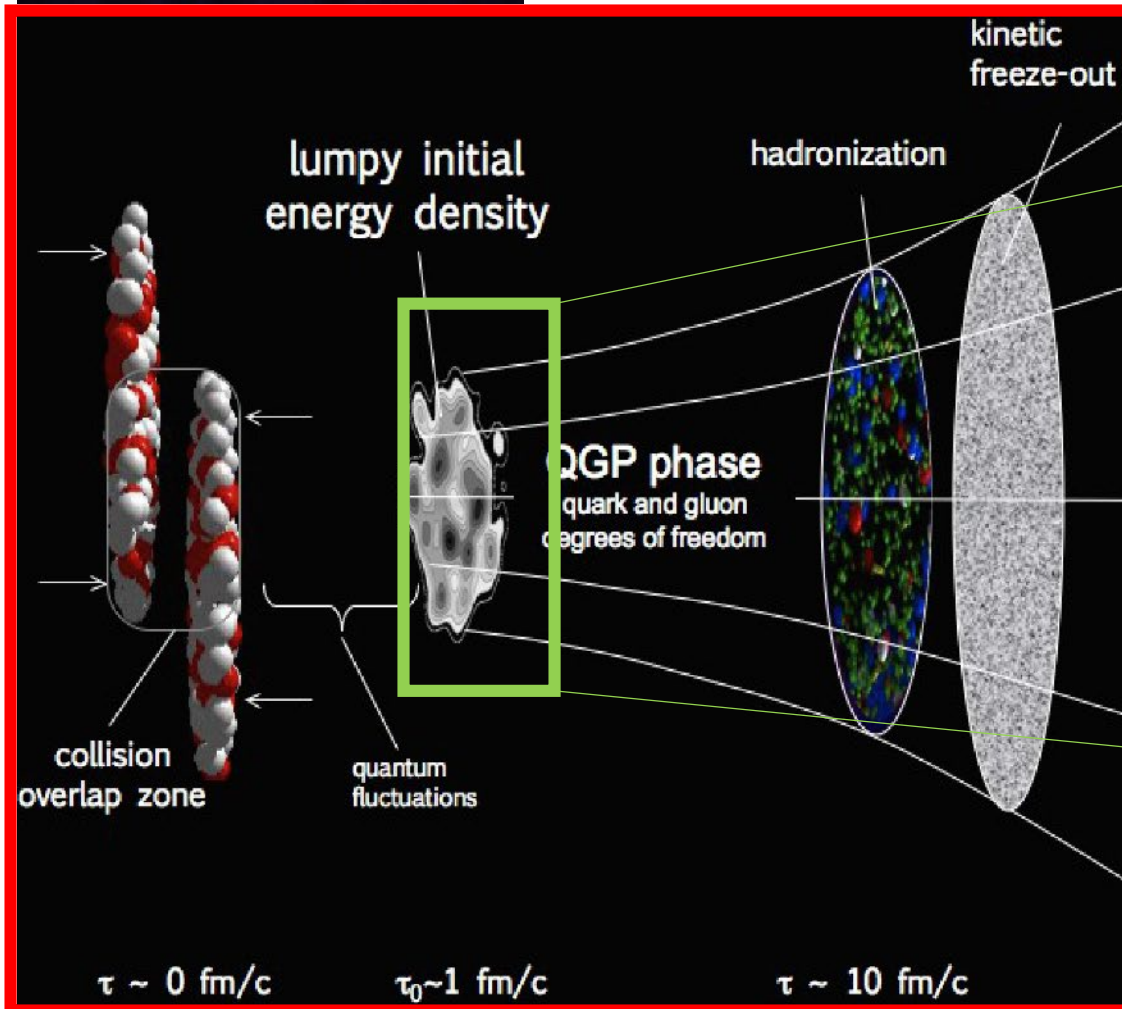
Non-thermal fixed point

J. Berges, A. Rothkopf, J. Schmidt, PRL 101 (2008)

J. Berges, G. Hofmeister, NPB 813 (2009)

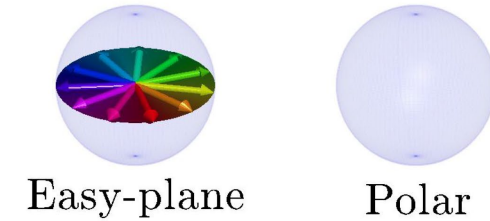
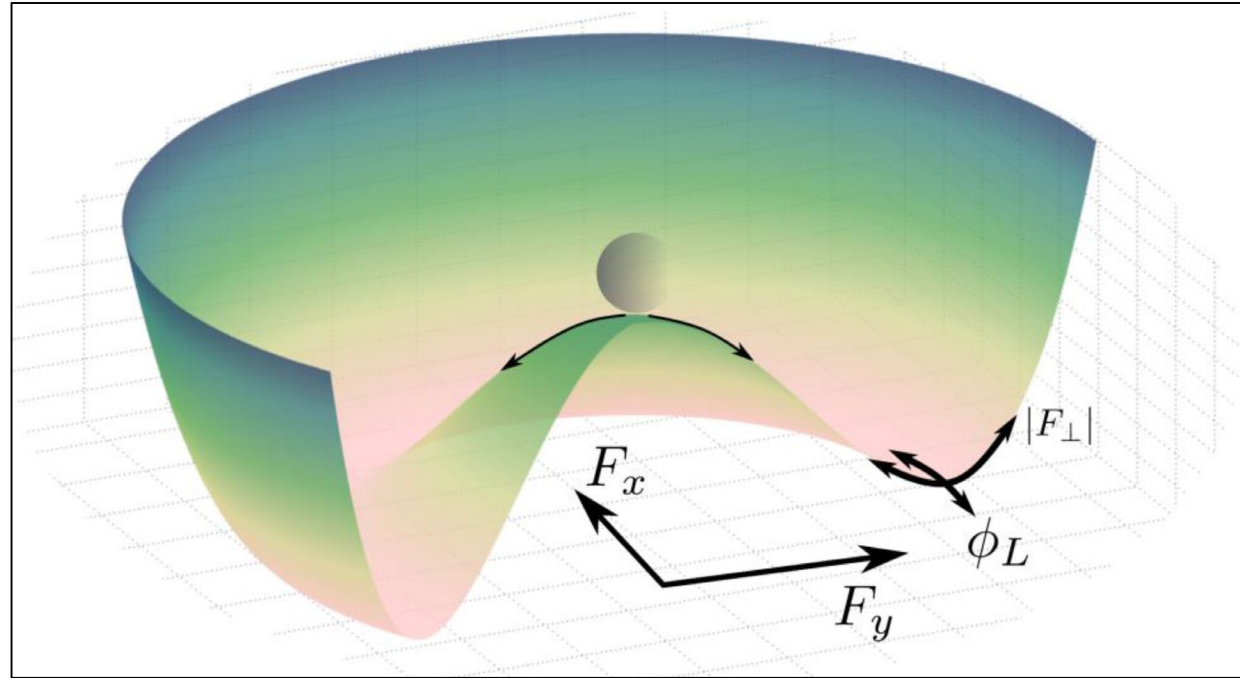
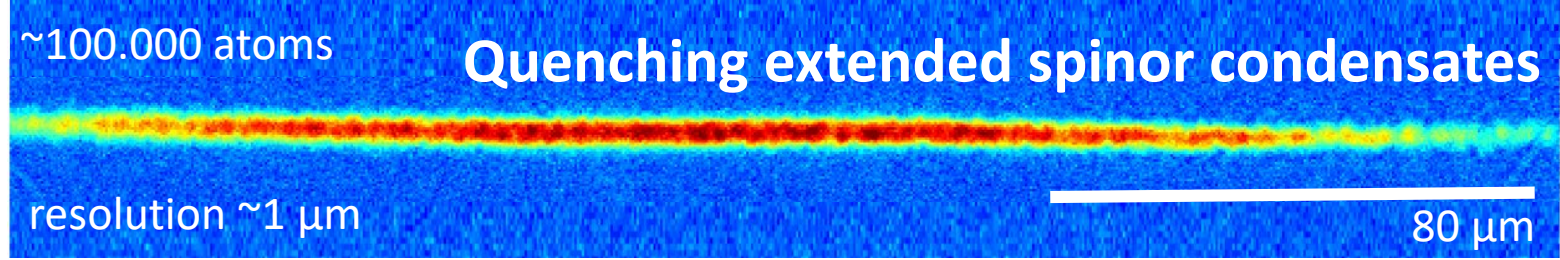
C. Scheppach, J. Berges, T. Gasenzer, PRA 81 (2010)

...



0.000 000 000 000 000 000 000 000 1 sec

Quantum Bang(s)

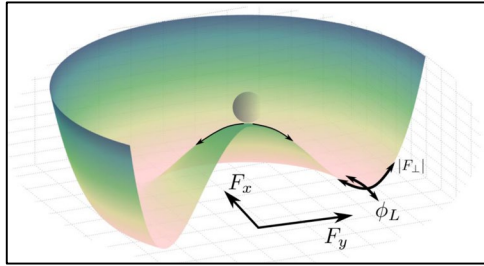


$F=1$

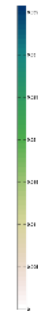


Watching the build-up of transverse spin

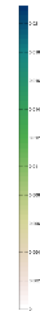
dynamics



0.2s



0.4s



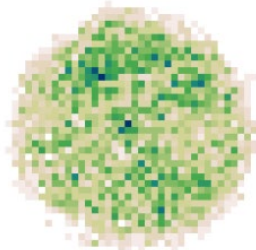
0.6s



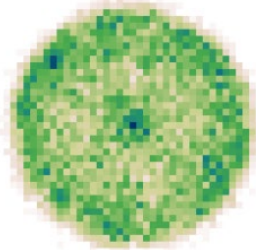
0.8s



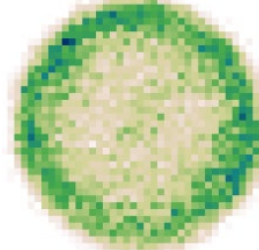
1s



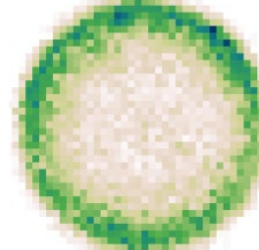
10s



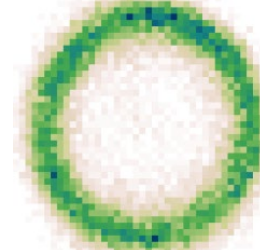
14s



20s

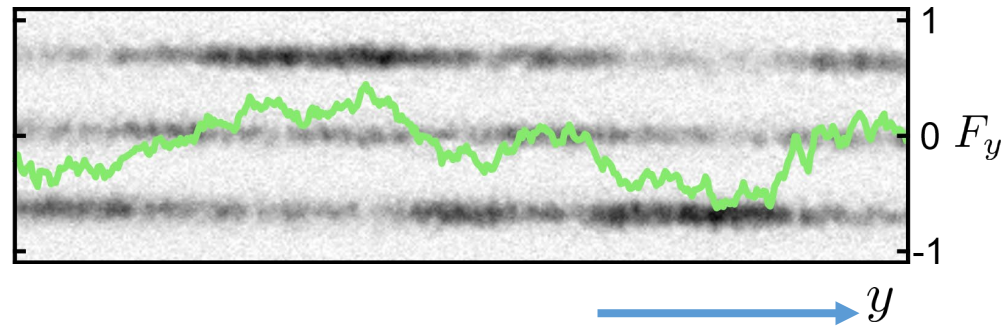


42s



Spatial information in Fourier space

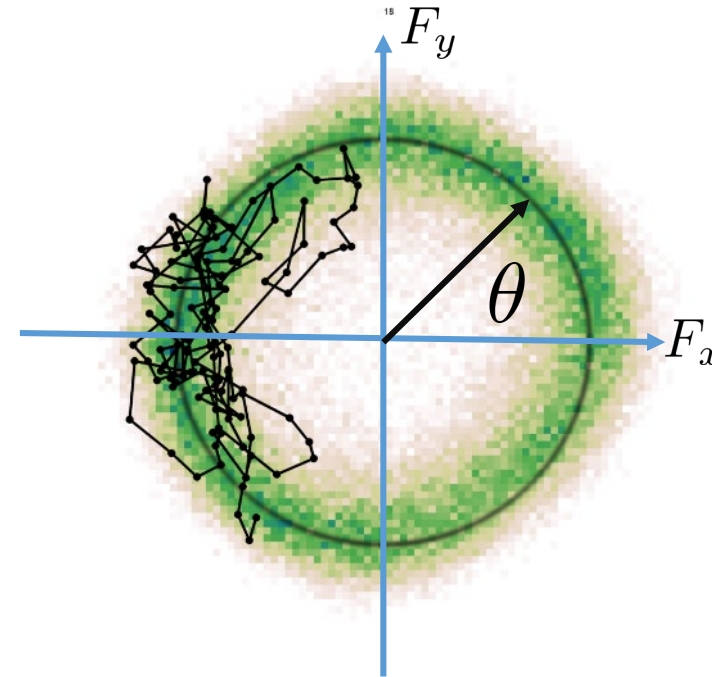
dynamics



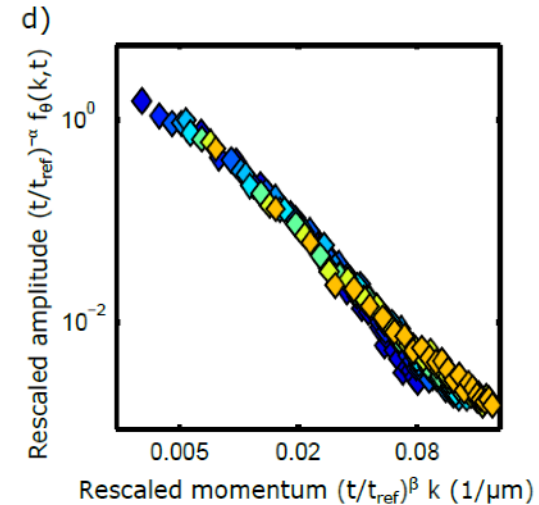
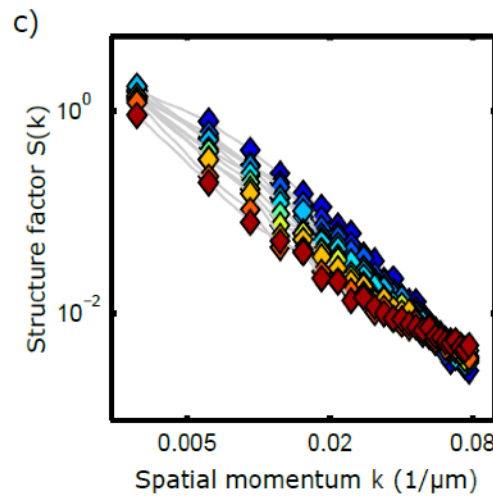
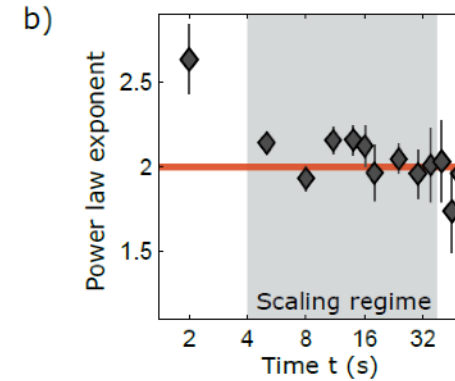
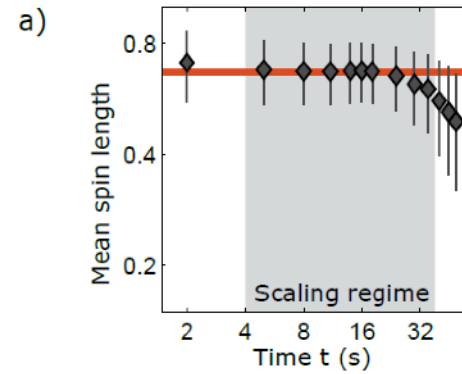
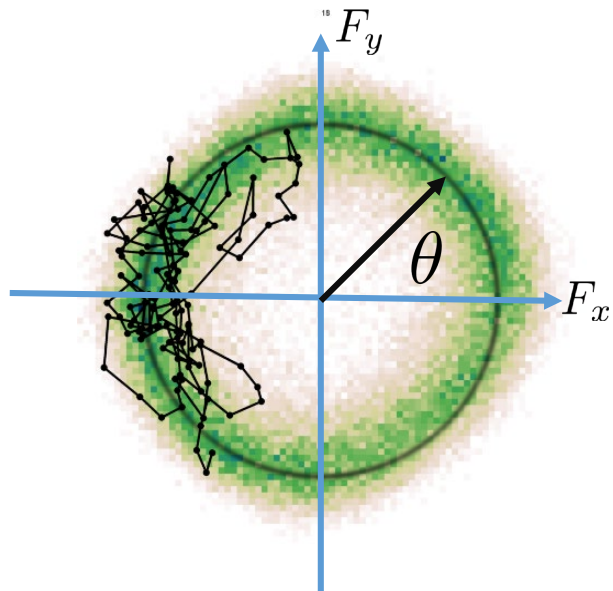
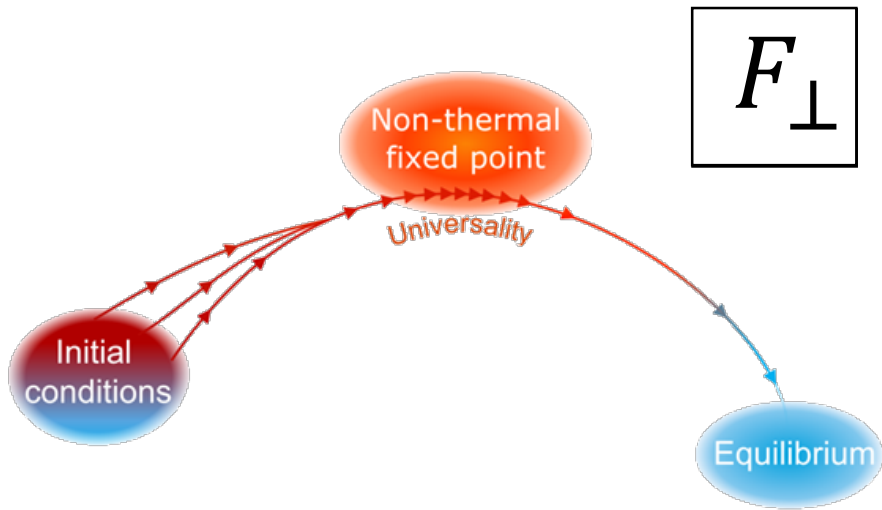
Correlation functions $\langle \theta(y)\theta(y') \rangle$

Structure factor

$$f_{\theta}(k) = \text{FT} \langle \theta(y)\theta(y') \rangle$$



,close to' $O(N)$ expectations



Thesis:
Max Prüfer



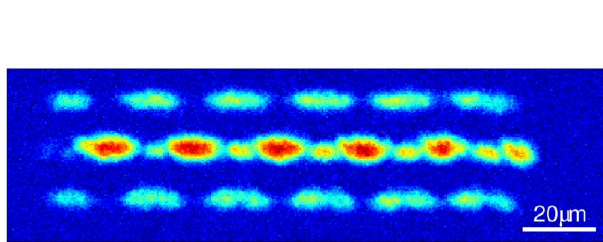
See also:

Extraction of quantum effective action
Nature Physics, **16**,1012 (2020)

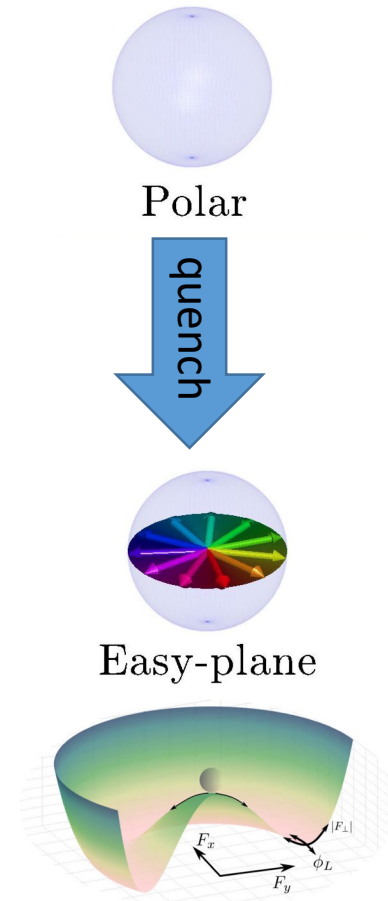
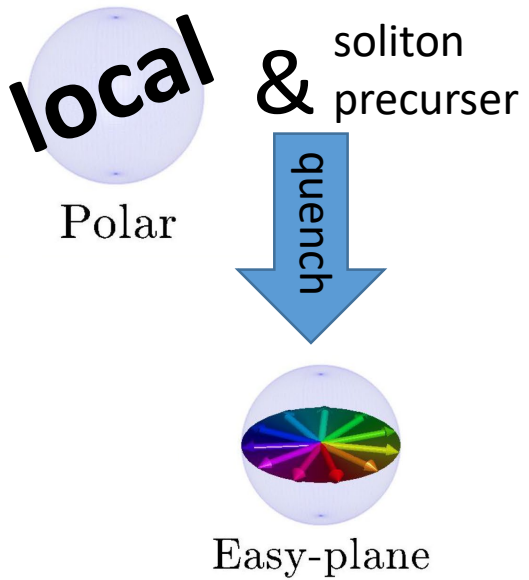
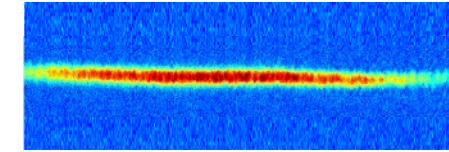
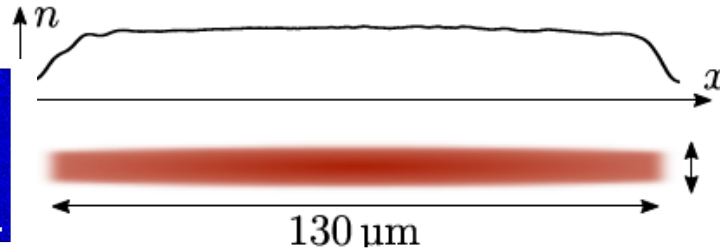


Torsten Zache

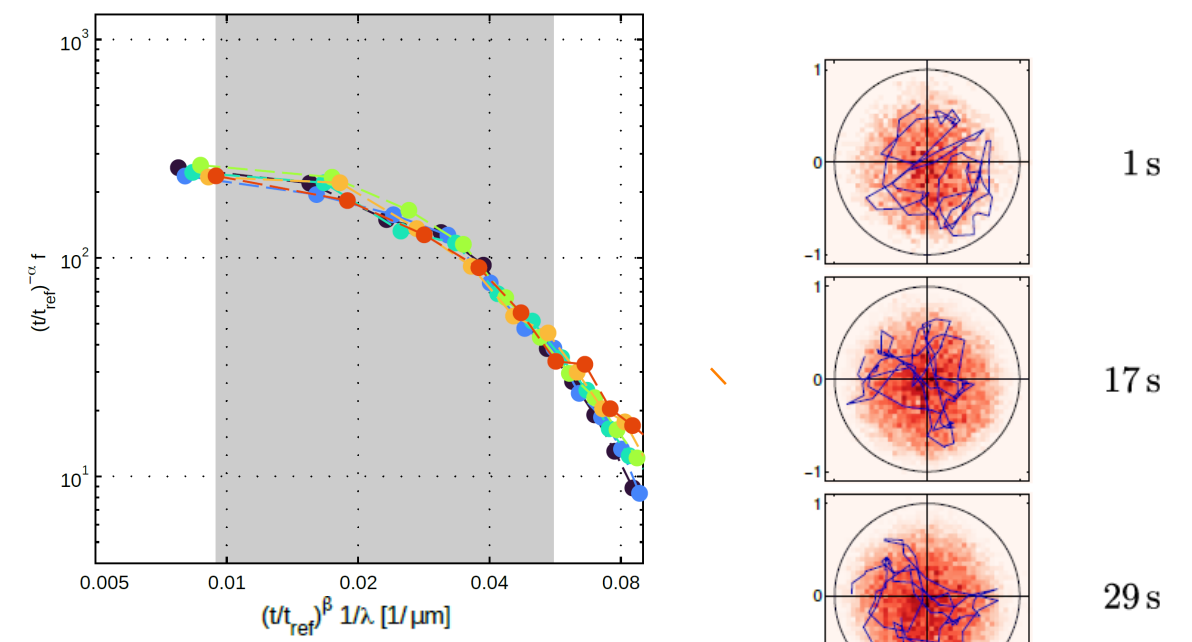
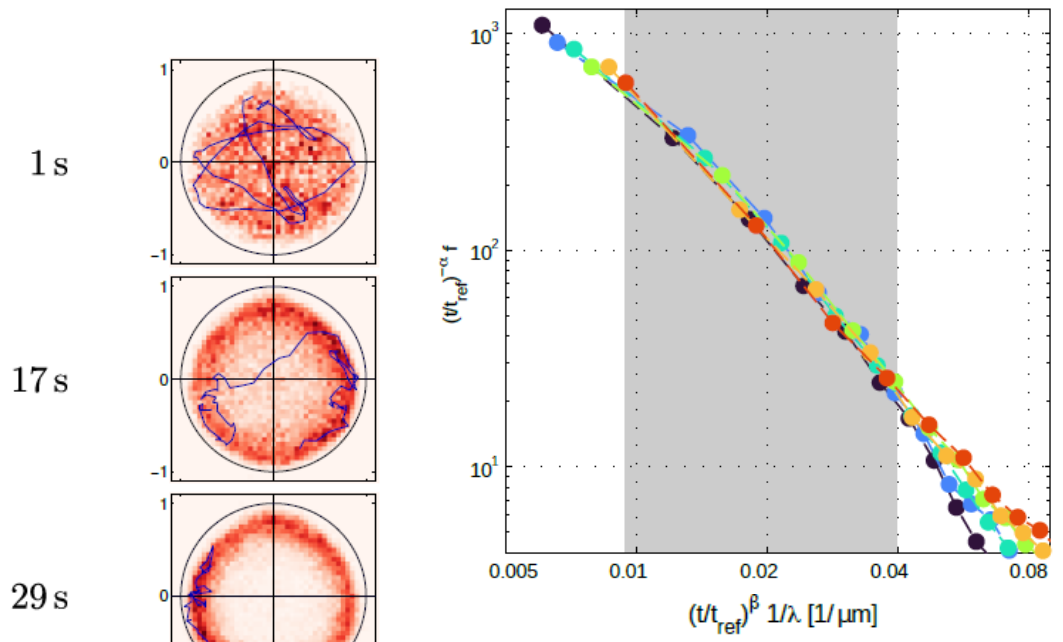
A very ,different' phase far-from-equilibrium



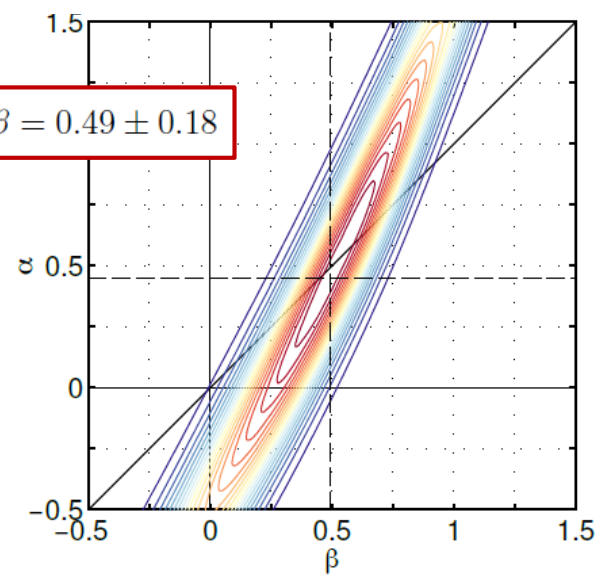
PRL 125, 170401 (2020)



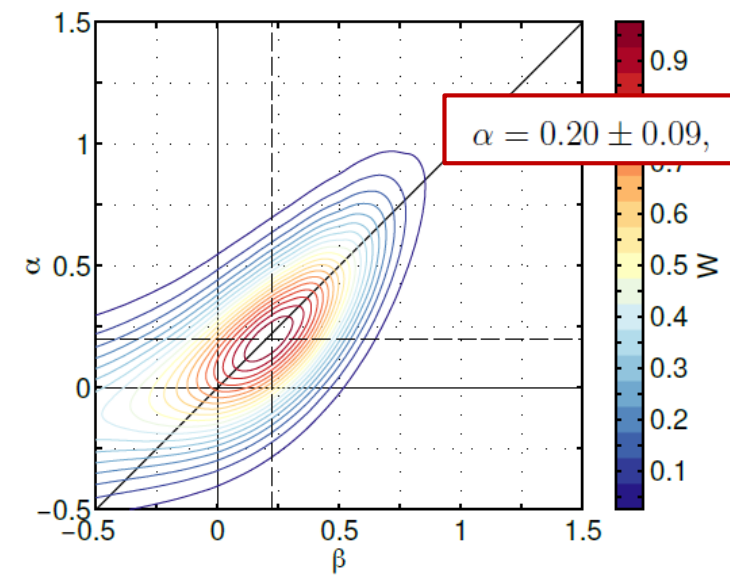
Rescaling and exponents

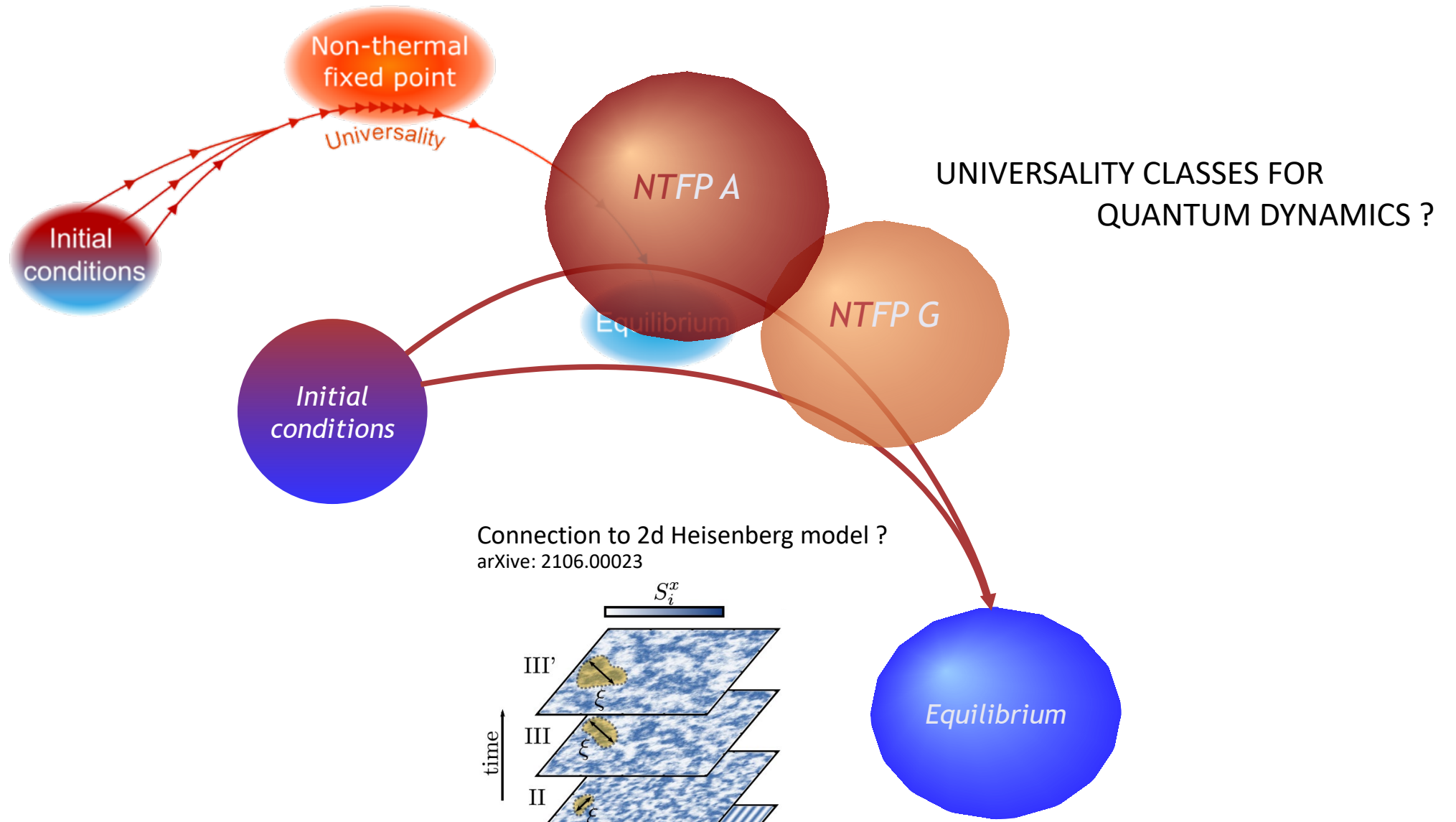


$\alpha = 0.46 \pm 0.38, \beta = 0.49 \pm 0.18$



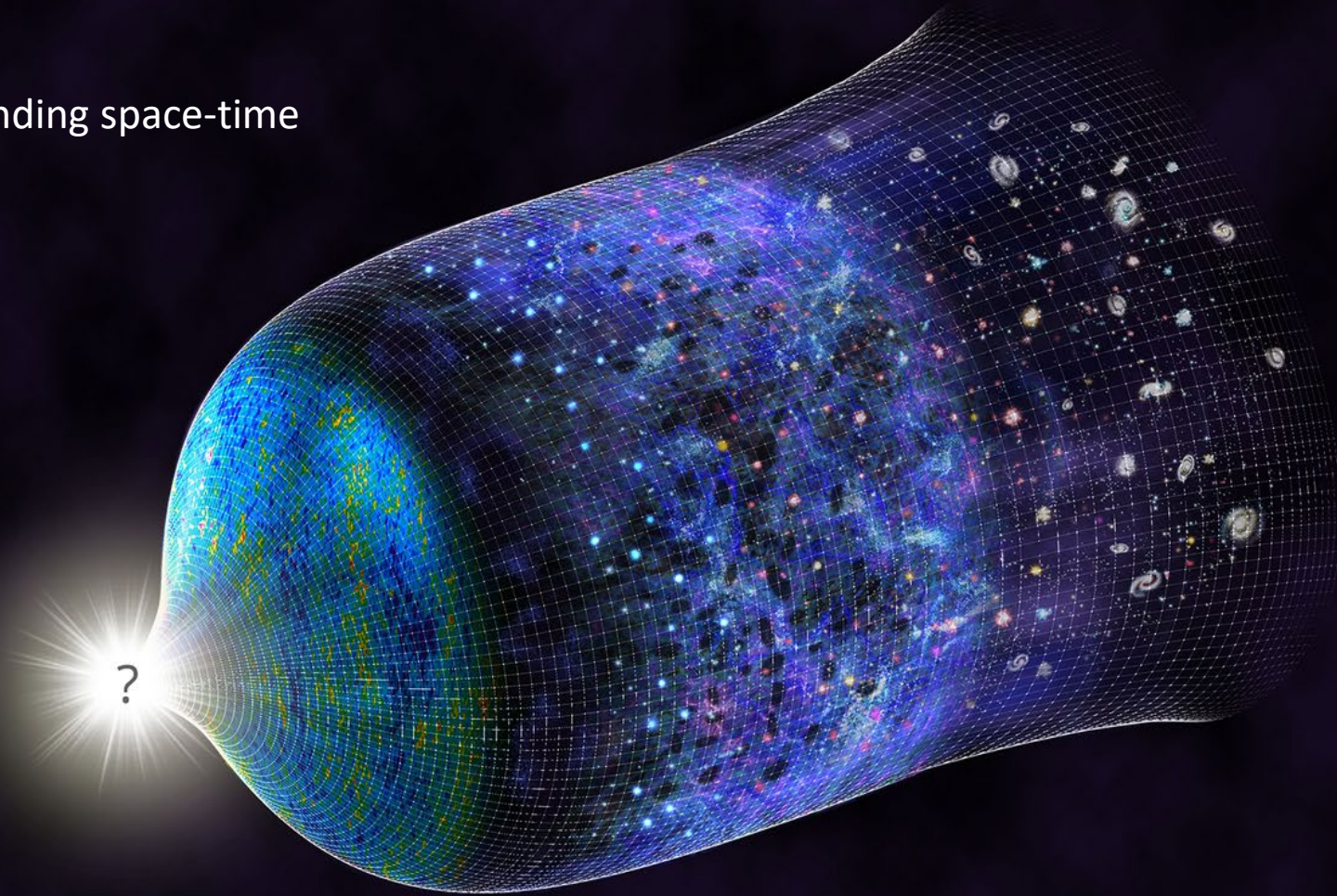
$\alpha = 0.20 \pm 0.09, \beta = 0.22 \pm 0.09$

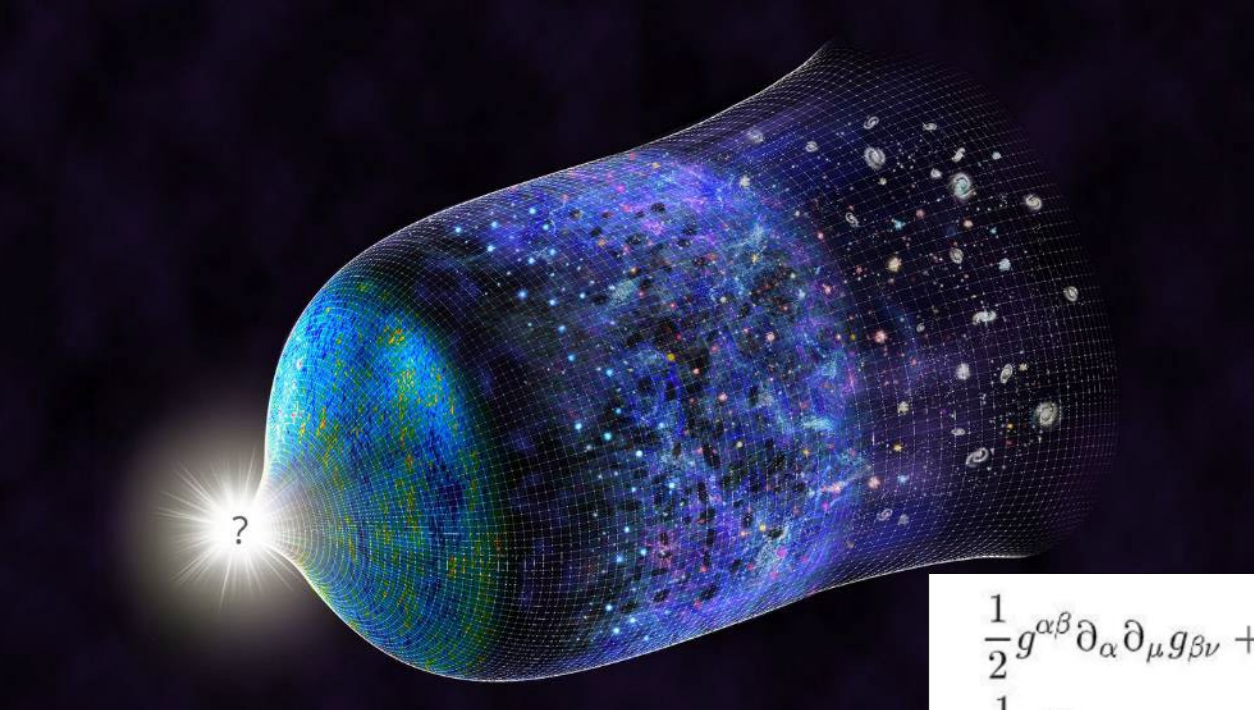




Quantum Field Simulator – Universal Dynamics & Fields in Curved Space

Particle production in expanding space-time





$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

$$\begin{aligned} & \frac{1}{2} g^{\alpha\beta} \partial_\alpha \partial_\mu g_{\beta\nu} + \frac{1}{2} g^{\alpha\beta} \partial_\alpha \partial_\nu g_{\mu\beta} - \frac{1}{2} g^{\alpha\beta} \partial_\alpha \partial_\beta g_{\mu\nu} - \frac{3}{2} g^{\alpha\beta} \partial_\mu \partial_\nu g_{\alpha\beta} - \frac{1}{2} g^{\beta\lambda} g^{\alpha\rho} \partial_\alpha g_{\rho\lambda} \partial_\mu g_{\beta\nu} \\ & - \frac{1}{2} g^{\beta\lambda} g^{\alpha\rho} \partial_\alpha g_{\rho\lambda} \partial_\nu g_{\mu\beta} + \frac{1}{4} g^{\beta\lambda} g^{\alpha\rho} \partial_\nu g_{\alpha\lambda} \partial_\mu g_{\rho\beta} + \frac{1}{4|g|} g^{\alpha\beta} \partial_\beta |g| \partial_\nu g_{\mu\alpha} - \frac{1}{4|g|} g^{\alpha\beta} \partial_\beta |g| \partial_\alpha g_{\mu\nu} \\ & - \frac{1}{4|g|} g^{\alpha\beta} \partial_\beta |g| \partial_\mu g_{\alpha\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \end{aligned}$$

With additional symmetry assumption: **homogeneous** and **isotropic**

$$ds^2 = -dt^2 + a^2(t) \left(\frac{du^2}{1 - \kappa u^2} + u^2 d\varphi^2 \right) \quad \text{Friedmann-Lemaître-Robertson-Walker (FLRW) metric}$$

Simulating free massless scalar field in curved space

$$\Gamma = -\frac{\hbar^2}{2} \int dt \, d\mathbf{u} \, d\varphi \, \sqrt{g} \, g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

adjustable metric
of FLRW form

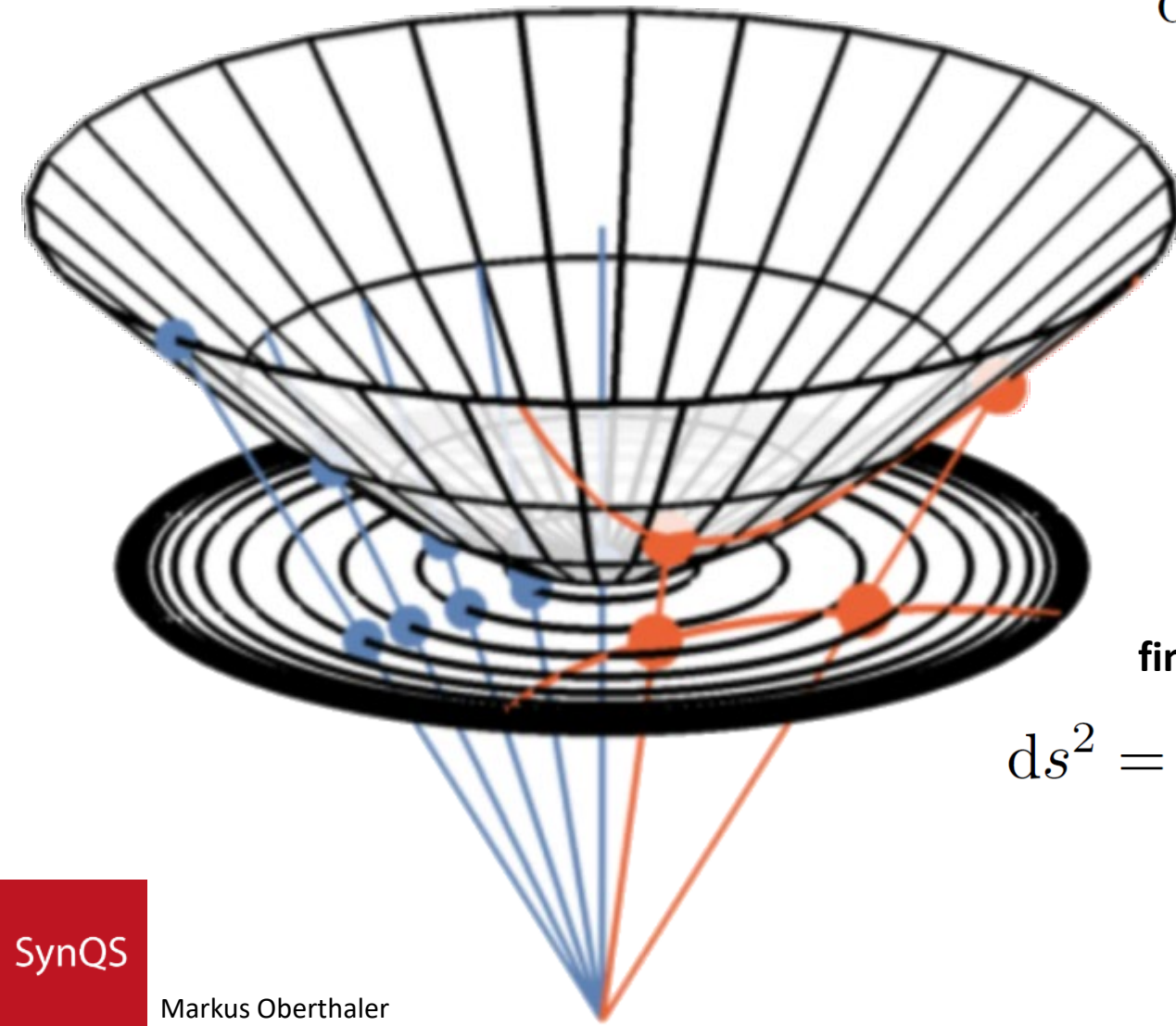
infinite extension

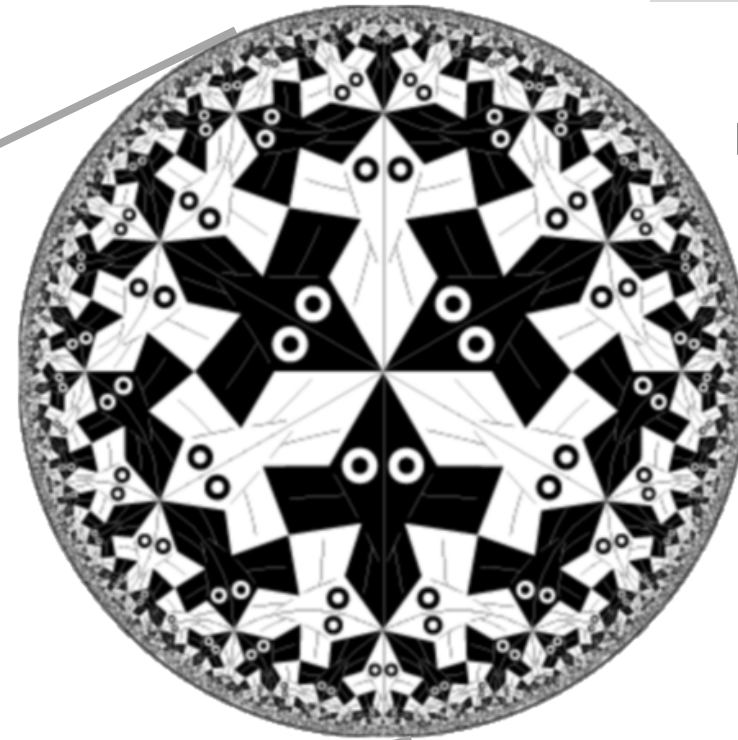
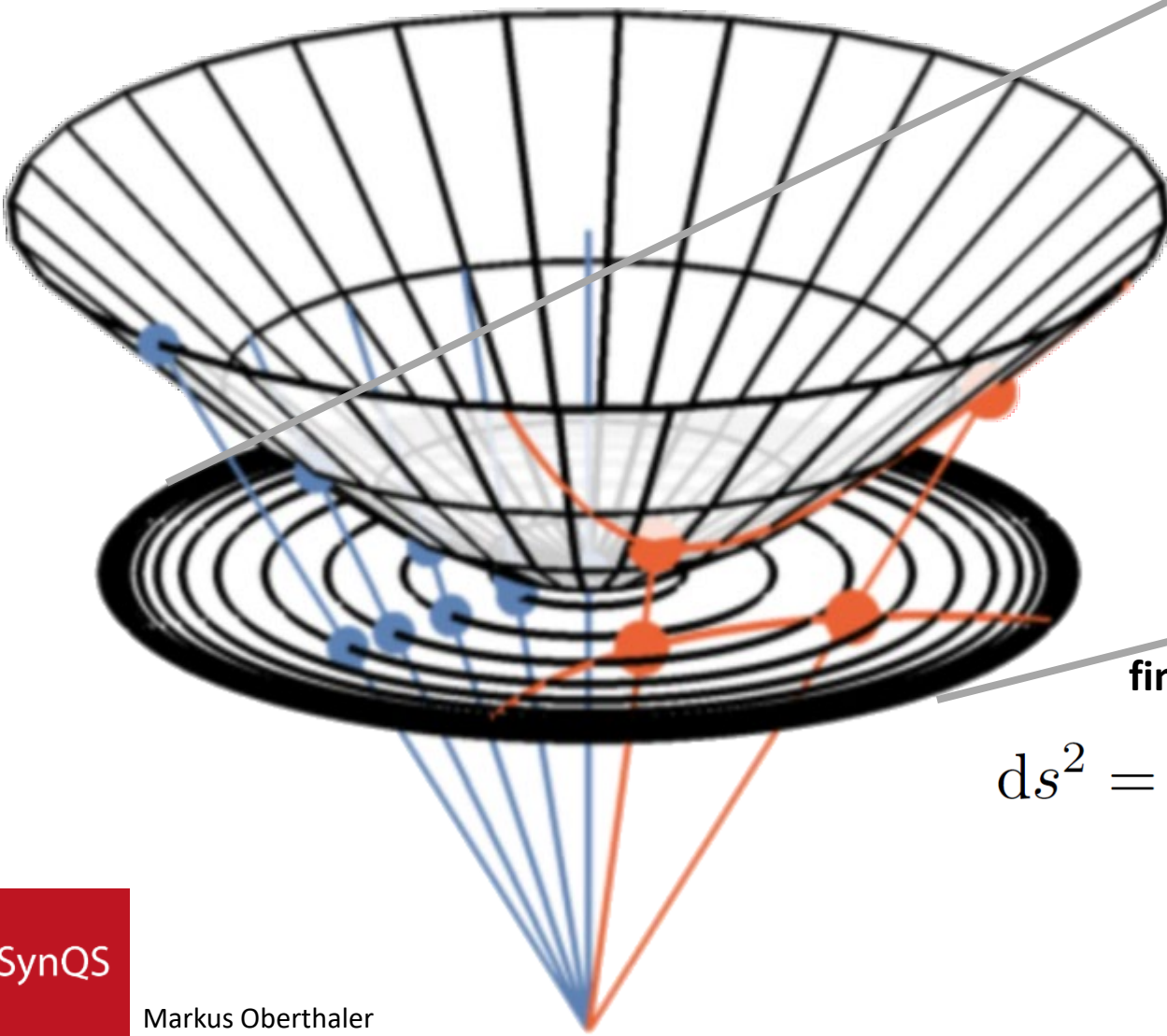
$$ds^2 = -dt^2 + a^2(t) \left(\frac{du^2}{1 - \kappa u^2} + u^2 d\varphi^2 \right)$$

finite extension

$$ds^2 = -dt^2 + a^2(t) \left(1 \mp \frac{r^2}{R^2} \right)^{-1} (dr^2 + r^2 d\varphi^2)$$

$$u(r) = \frac{r}{\left(1 \mp \frac{r^2}{R^2} \right)^{1/2}}$$





hyperbolic geometry

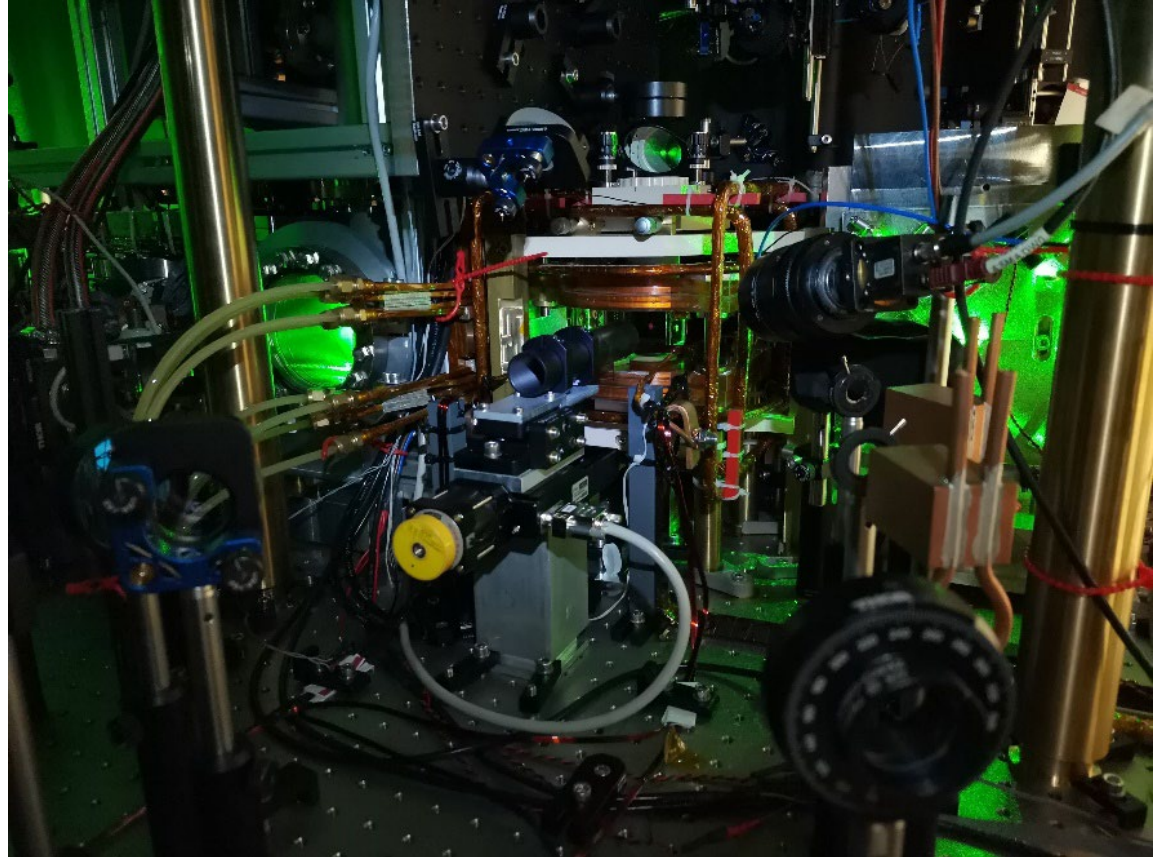
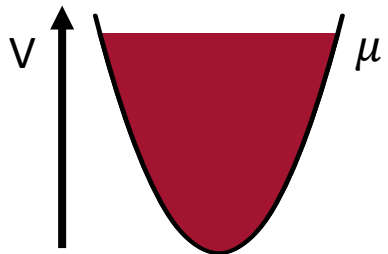
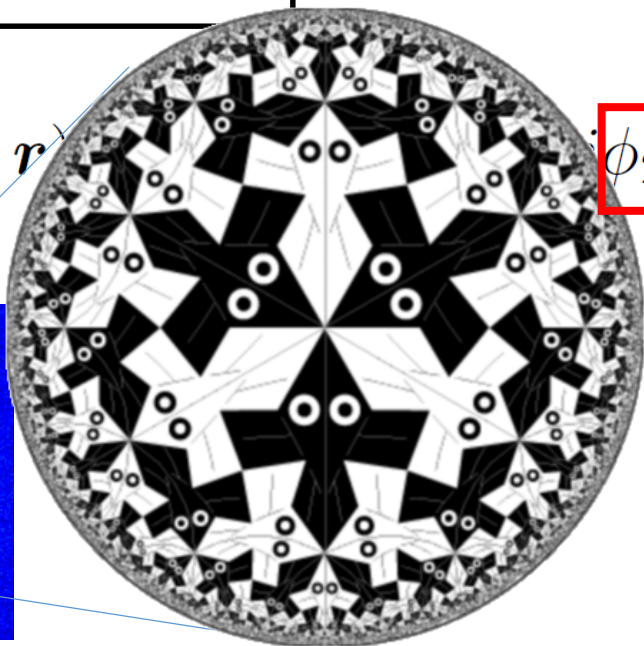
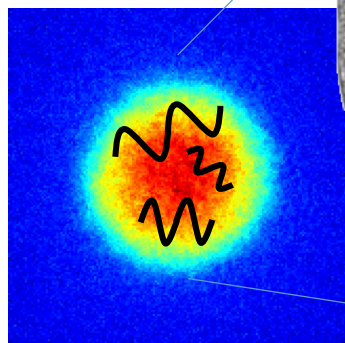
finite extension

$$ds^2 = -dt^2 + a^2(t) \left(1 \mp \frac{r^2}{R^2} \right)^{-1} (dr^2 + r^2 d\varphi^2)$$

$$u(r) = \frac{r}{\left(1 \mp \frac{r^2}{R^2} \right)^{1/2}}$$

2D Bose gas – potassium 39

$$\Phi(t, \mathbf{r}) = \phi_0(t, \mathbf{r}) \left[\phi_2(t, \mathbf{r}) \right]$$



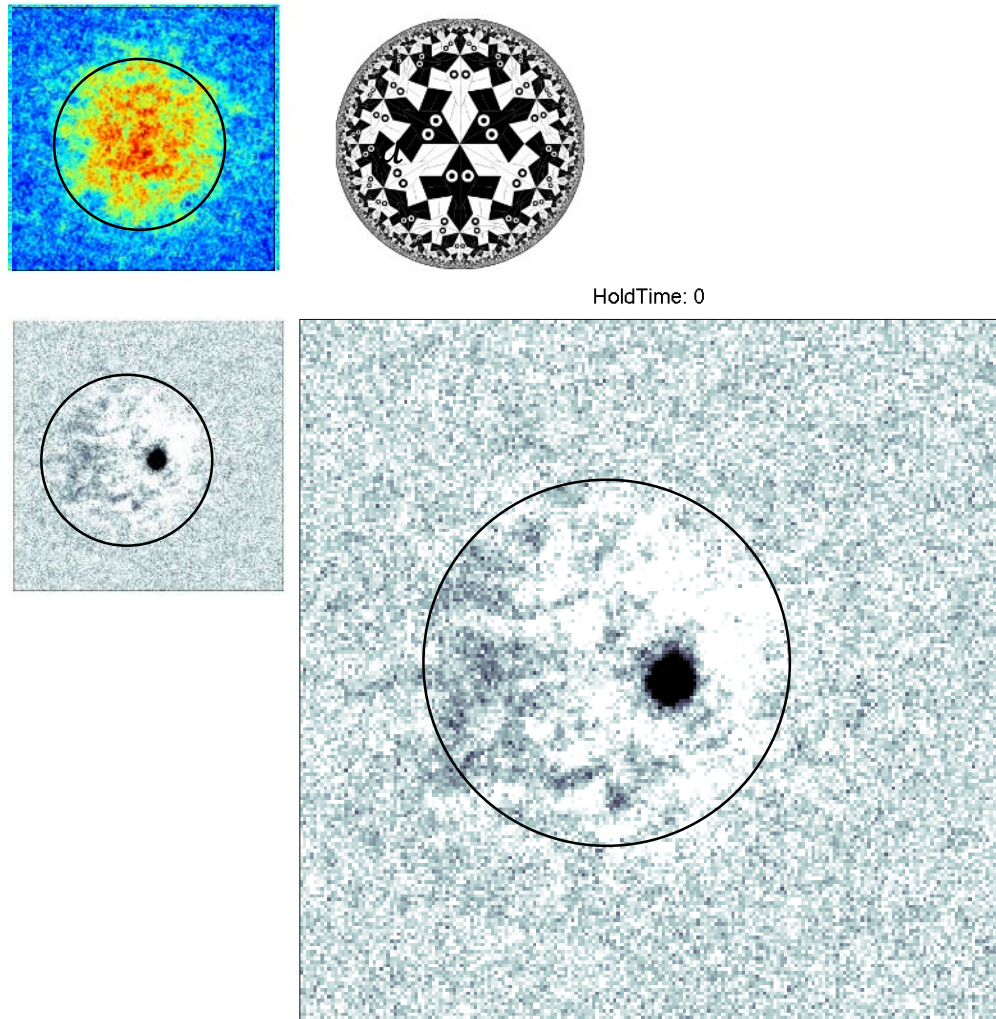
$$\Gamma = -\frac{\hbar^2}{2} \int dt \, d\mathbf{r} \, d\varphi \, \sqrt{g} \, g^{\mu\nu} \partial_\mu \phi \partial_\nu \phi$$

ϕ is the imaginary part of the phononic field
arXiv:2202.10441

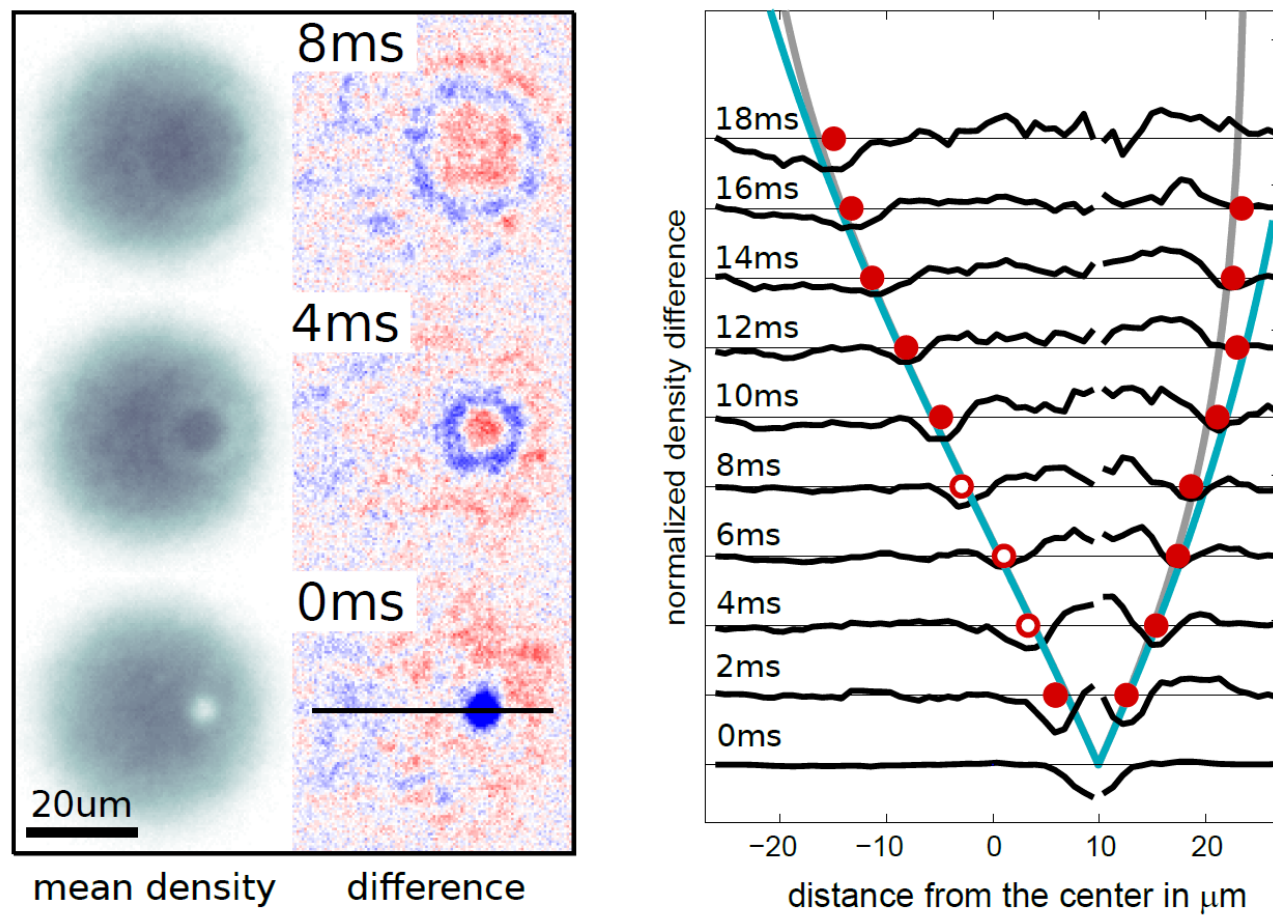


Stefan Flörchinger

Geodesics via free wavepacket dynamics



Realization of 2D space with negative curvature

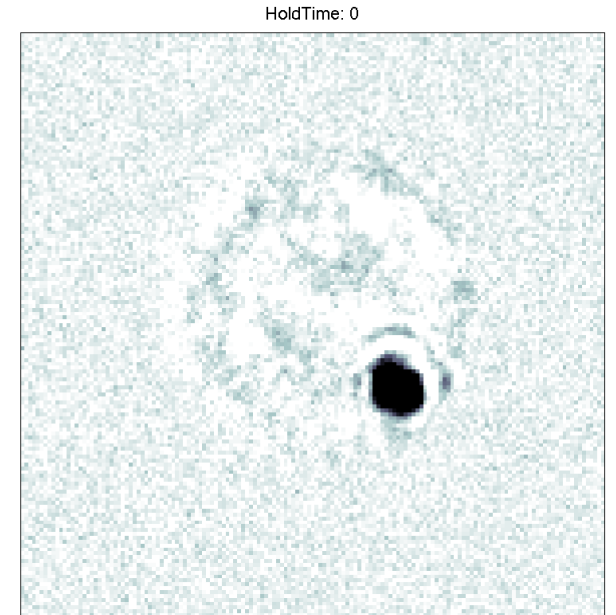
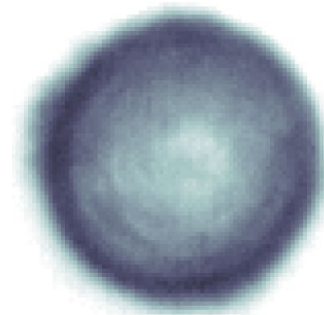
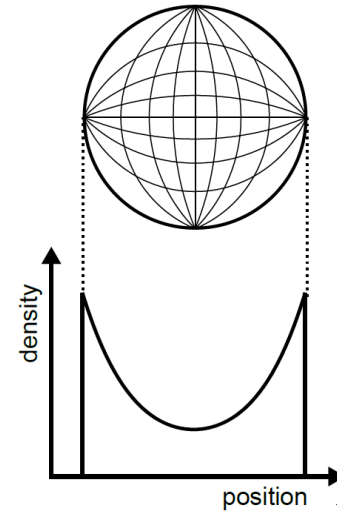
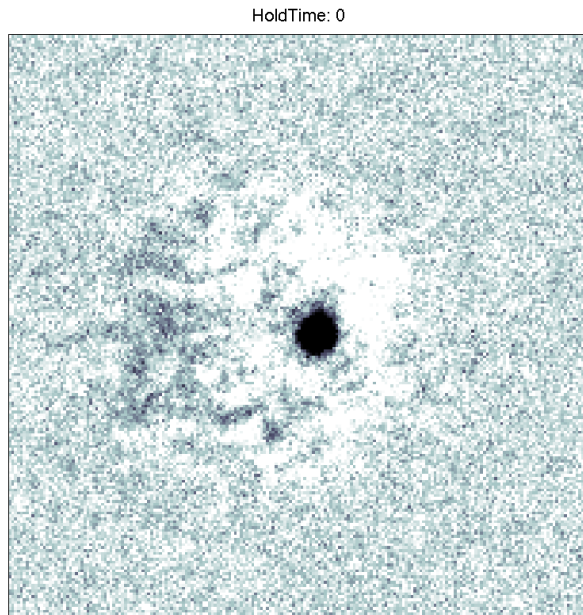
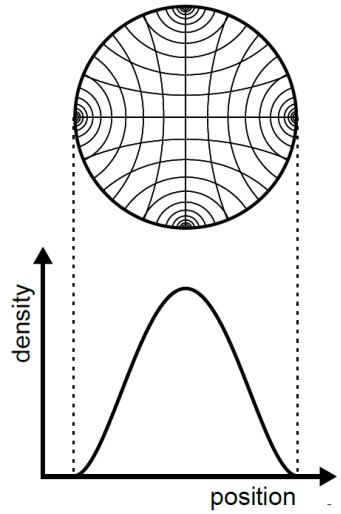


Quantum field simulator for dynamics in curved spacetime

arXiv:2202.10399

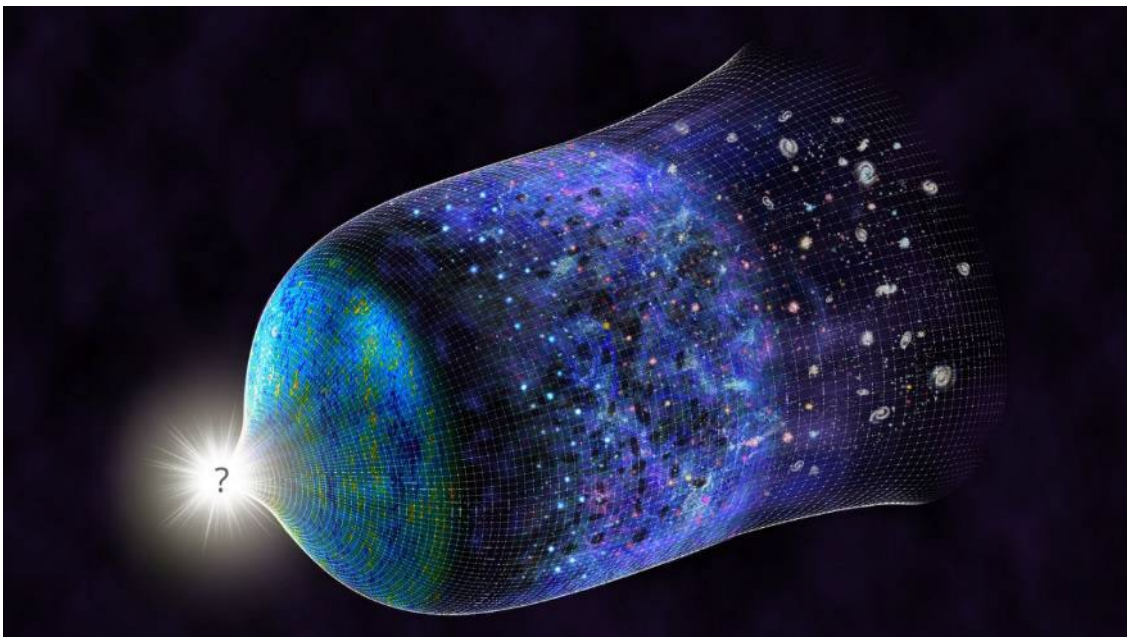
Hyperbolic to spherical

Bizar density distribution leads to positive **curvature**

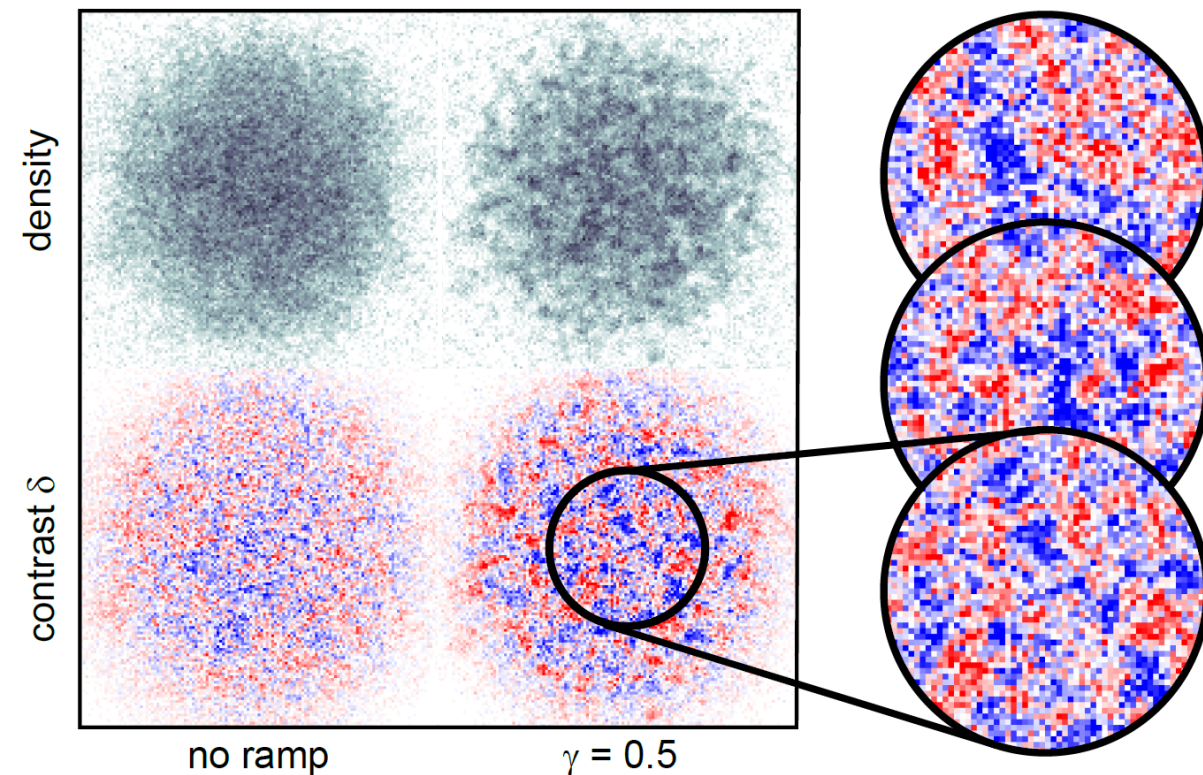
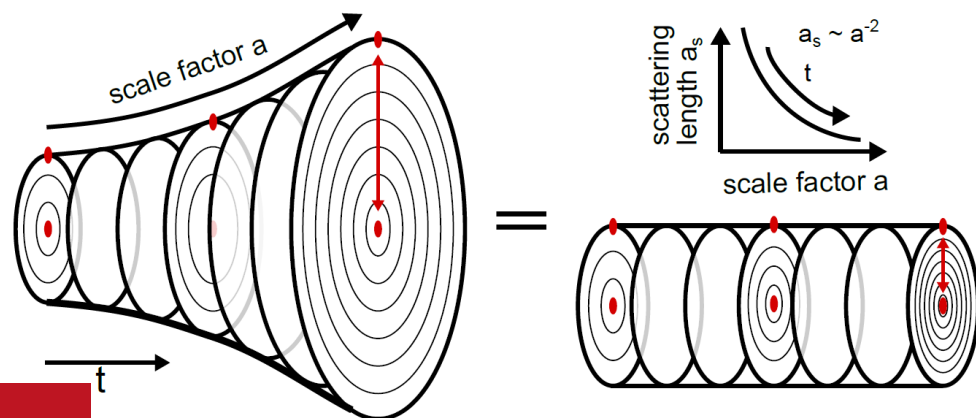


Particle production in accelerated space-time

Curvature in time

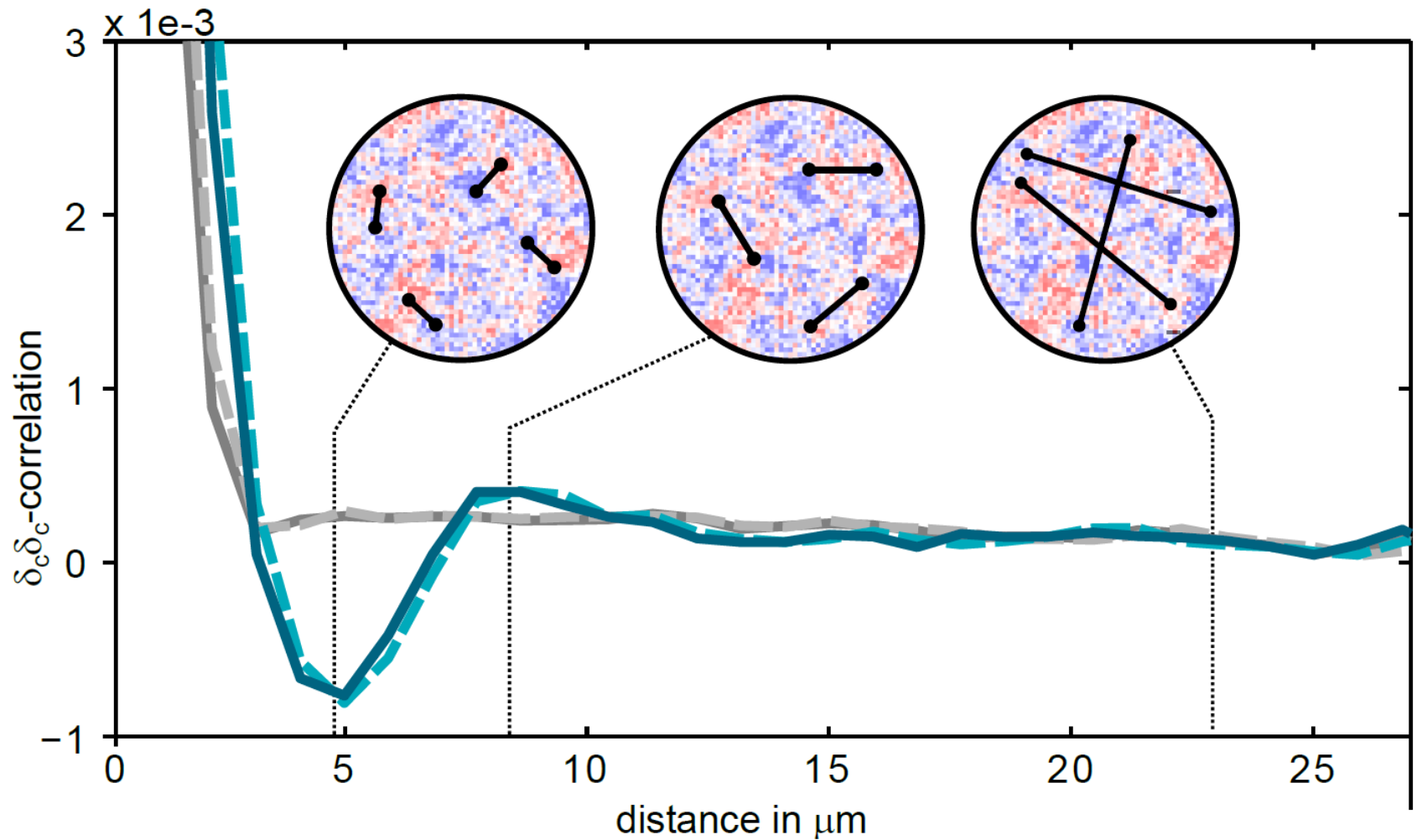
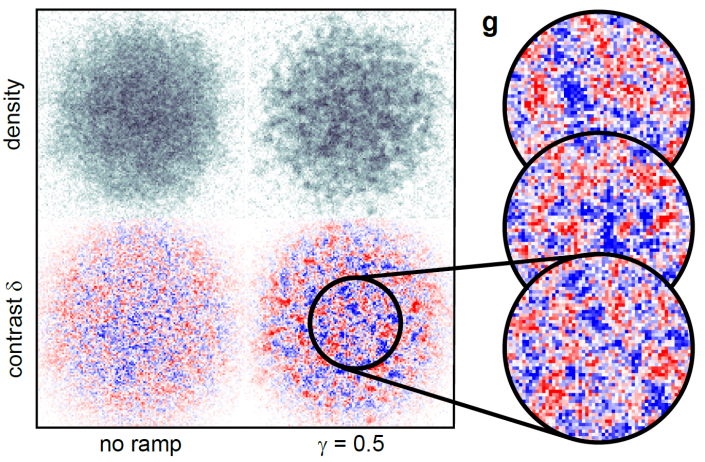


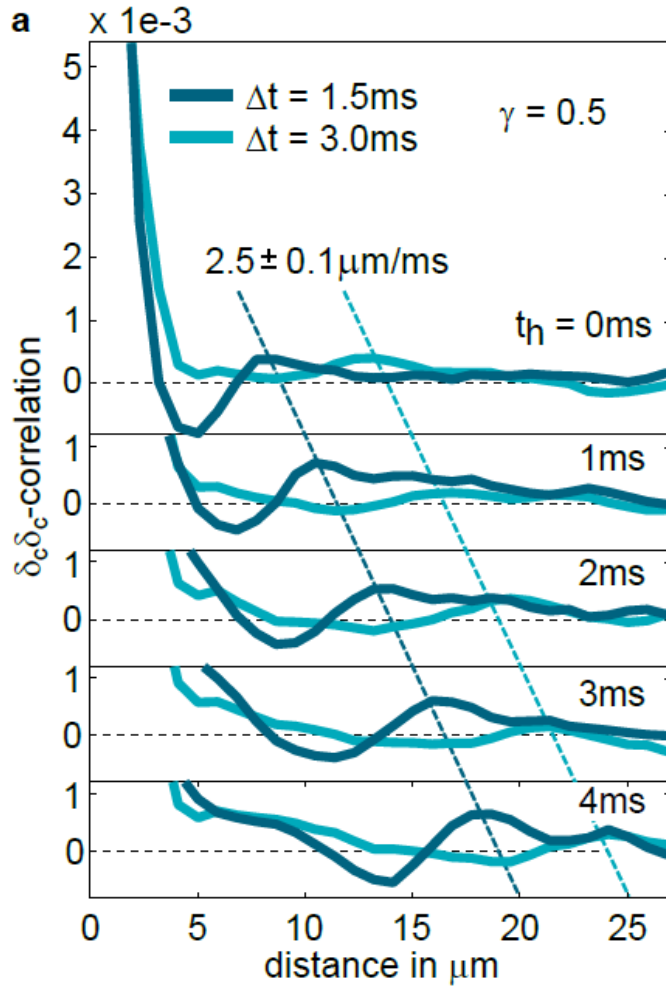
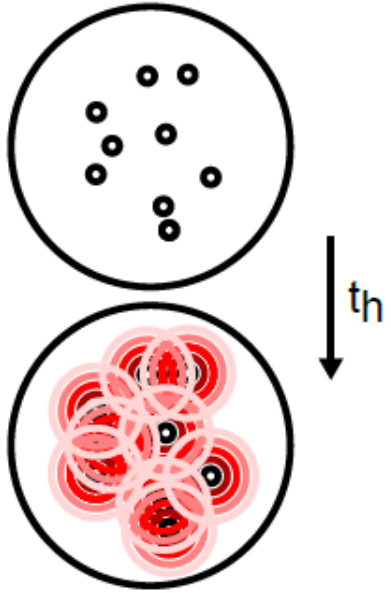
Quantum field simulator for dynamics in curved spacetime
arXiv:2202.10399



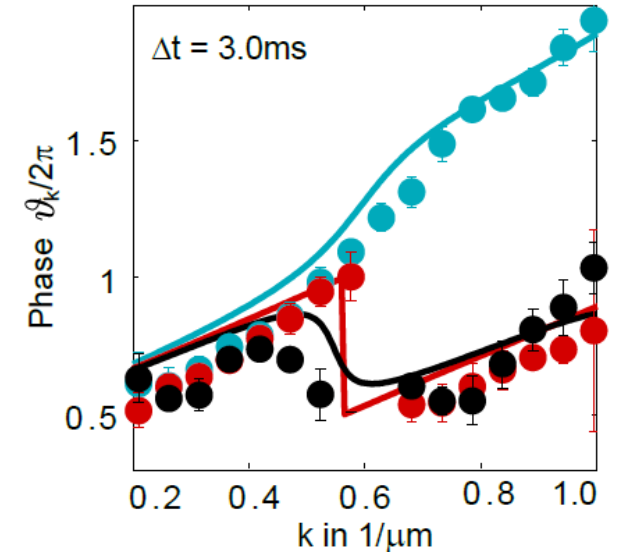
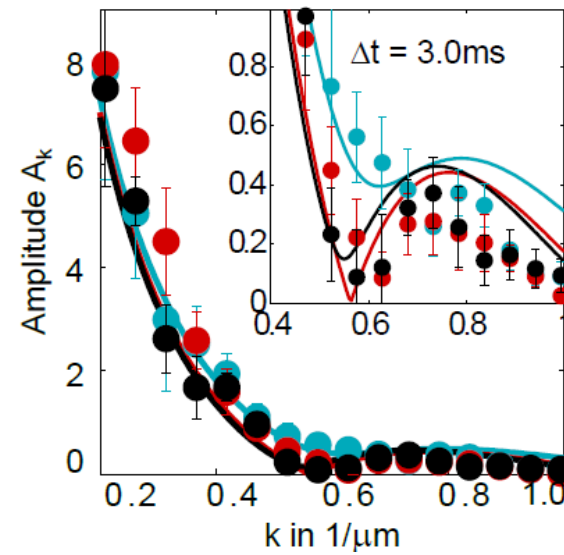
Particle production in accelerated space-time

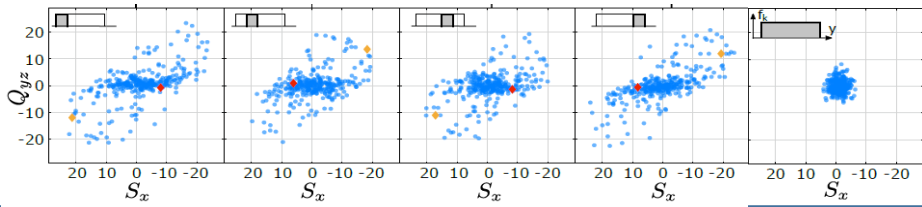
Curvature in time



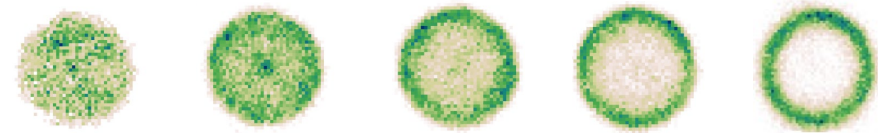


Comparison to analytic theory prediction:



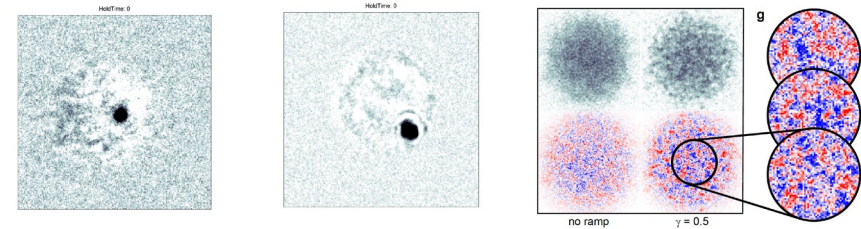


Detecting Entanglement in Quantum Field Setting
PRL 128, 020502 (2022)



Universal dynamics
Nature, 2018, Vol. 563, 217-220

Extracting quantum effective action
Nature Physics, 2020, Vol. 16, 1012-1016



Quantum field simulator for dynamics in curved spacetime
arXiv:2202.10399

Curved and expanding spacetime geometries in BECs
arXiv:2202.10441

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Potassium:

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