Title: How Quantum Field Simulators can address Quark Gluon Plasma and Cosmoloy inspired Questions

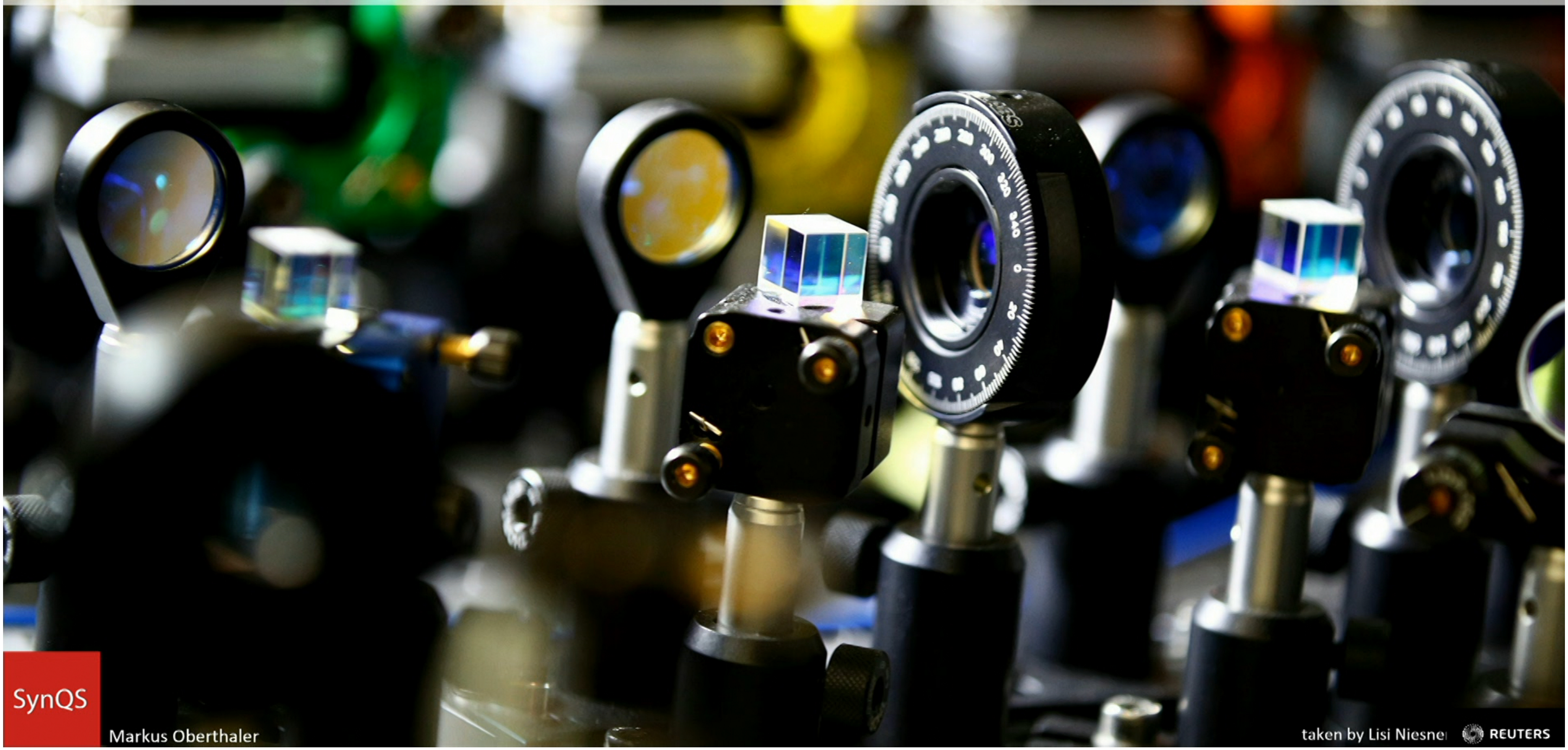
Speakers: Markus Oberthaler

Collection: Quantum Simulators of Fundamental Physics

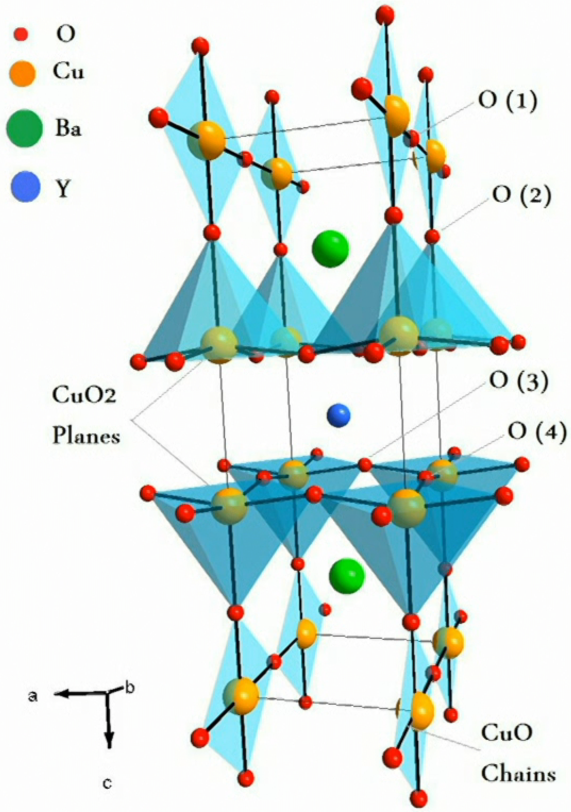
Date: June 08, 2023 - 10:30 AM

URL: https://pirsa.org/23060018

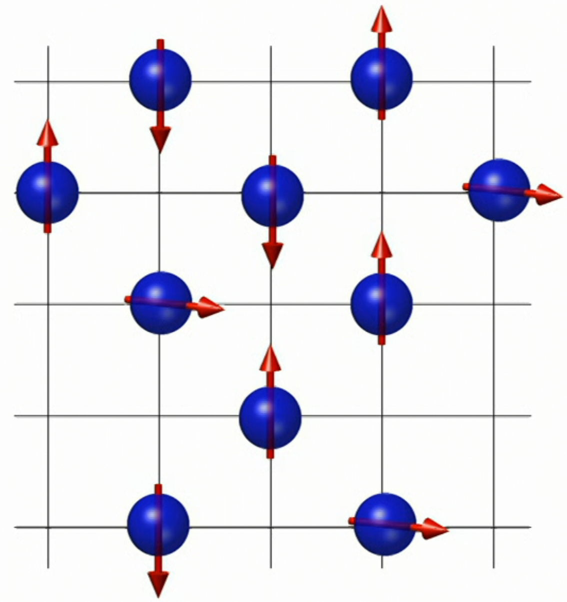
How a Ultracold Gases can address Quark Gluon Plasma and Cosmology inspired Questions



Condensed Matter Application



Discrete Quantum Simulator



e.g. Quantum simulations with ultracold atoms in optical lattices
C. Gross, I. Bloch, *Science* **357** 995 (2017)

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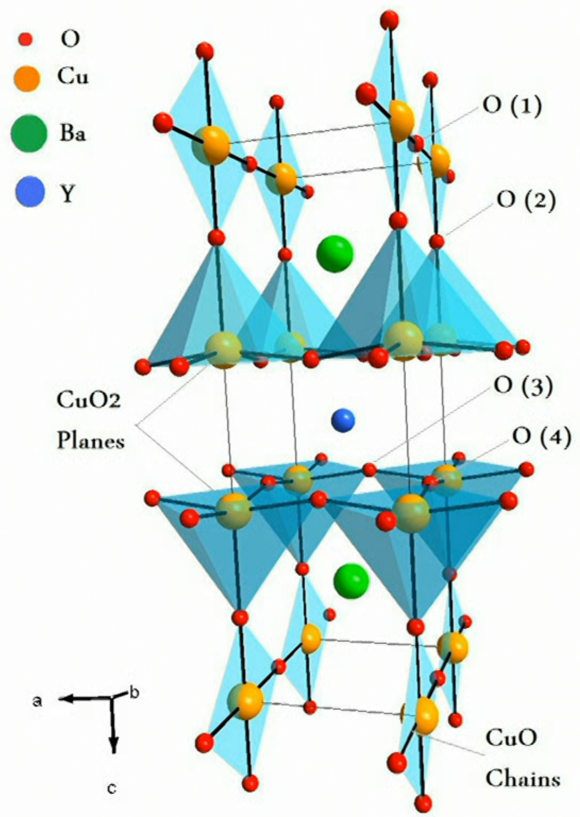
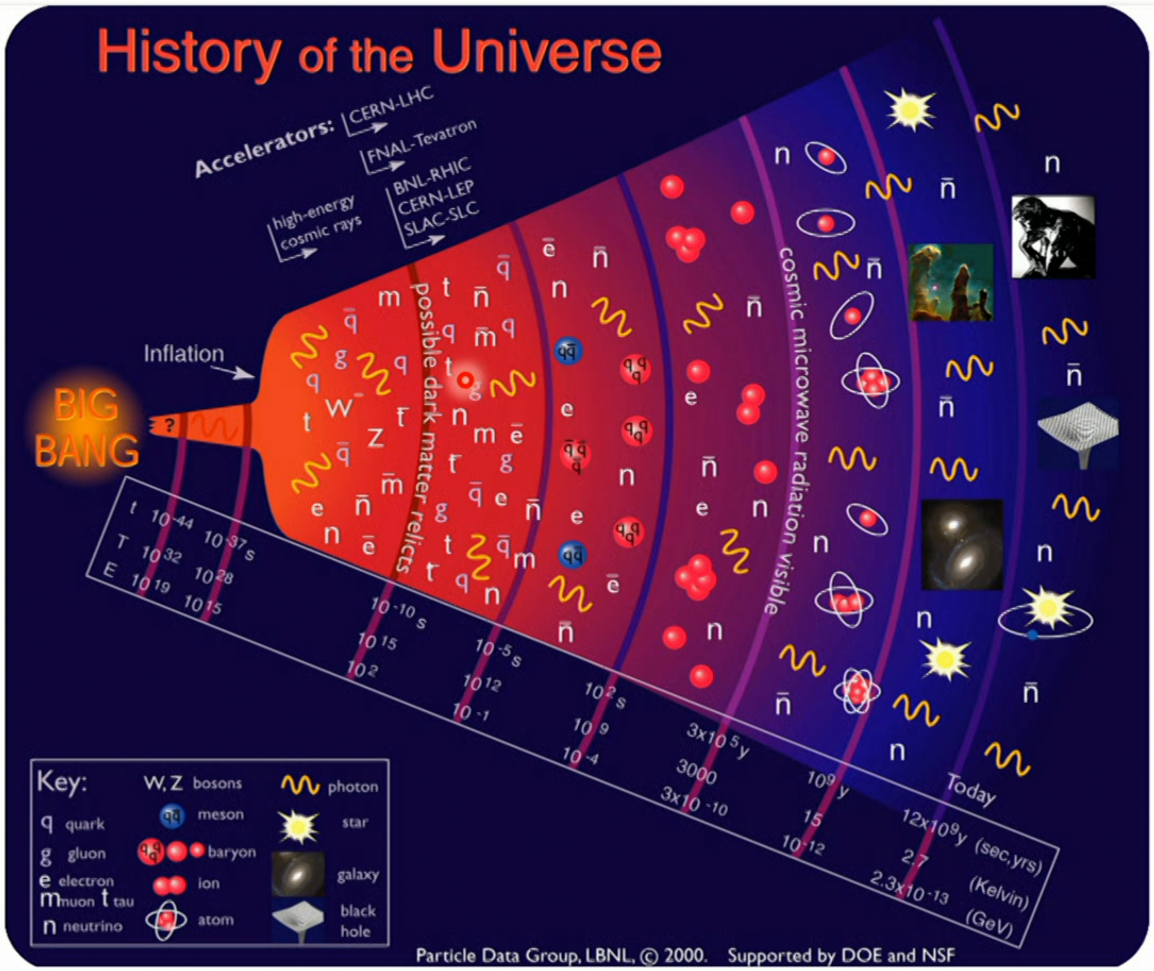
Condensed Matter – Final Stage of a Long Story

Continuous Quantum Field Settings





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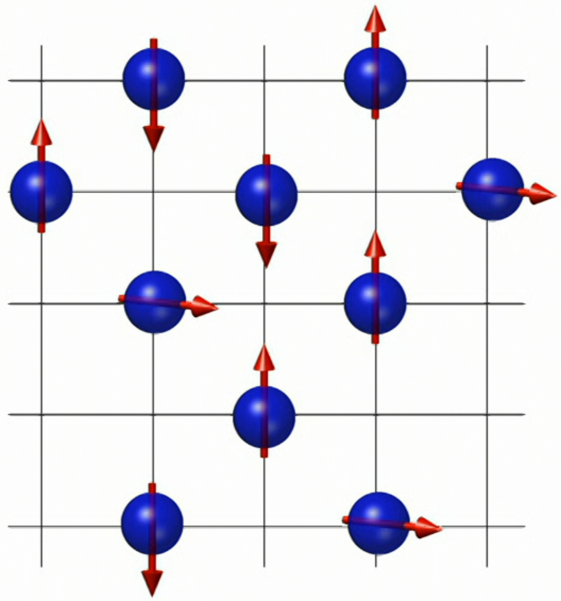

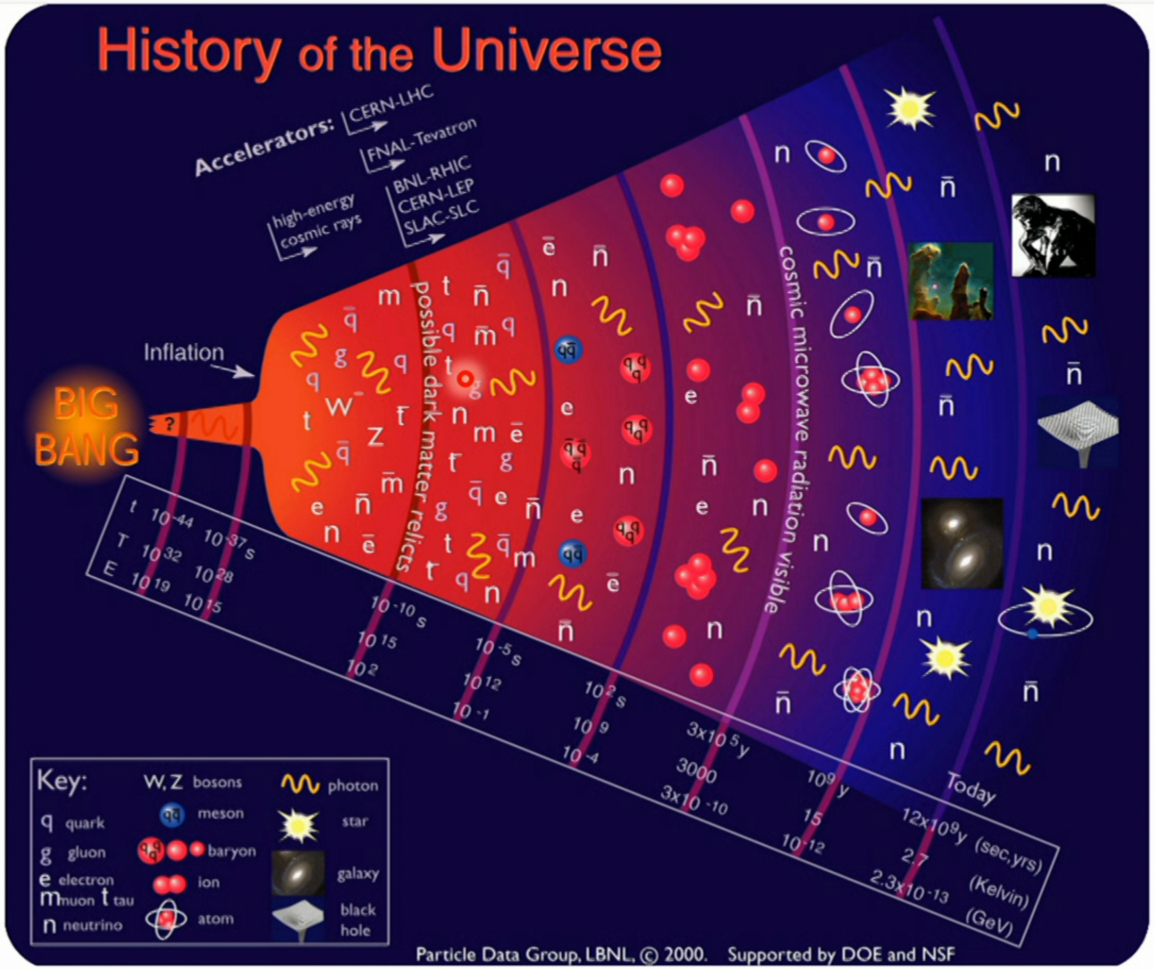

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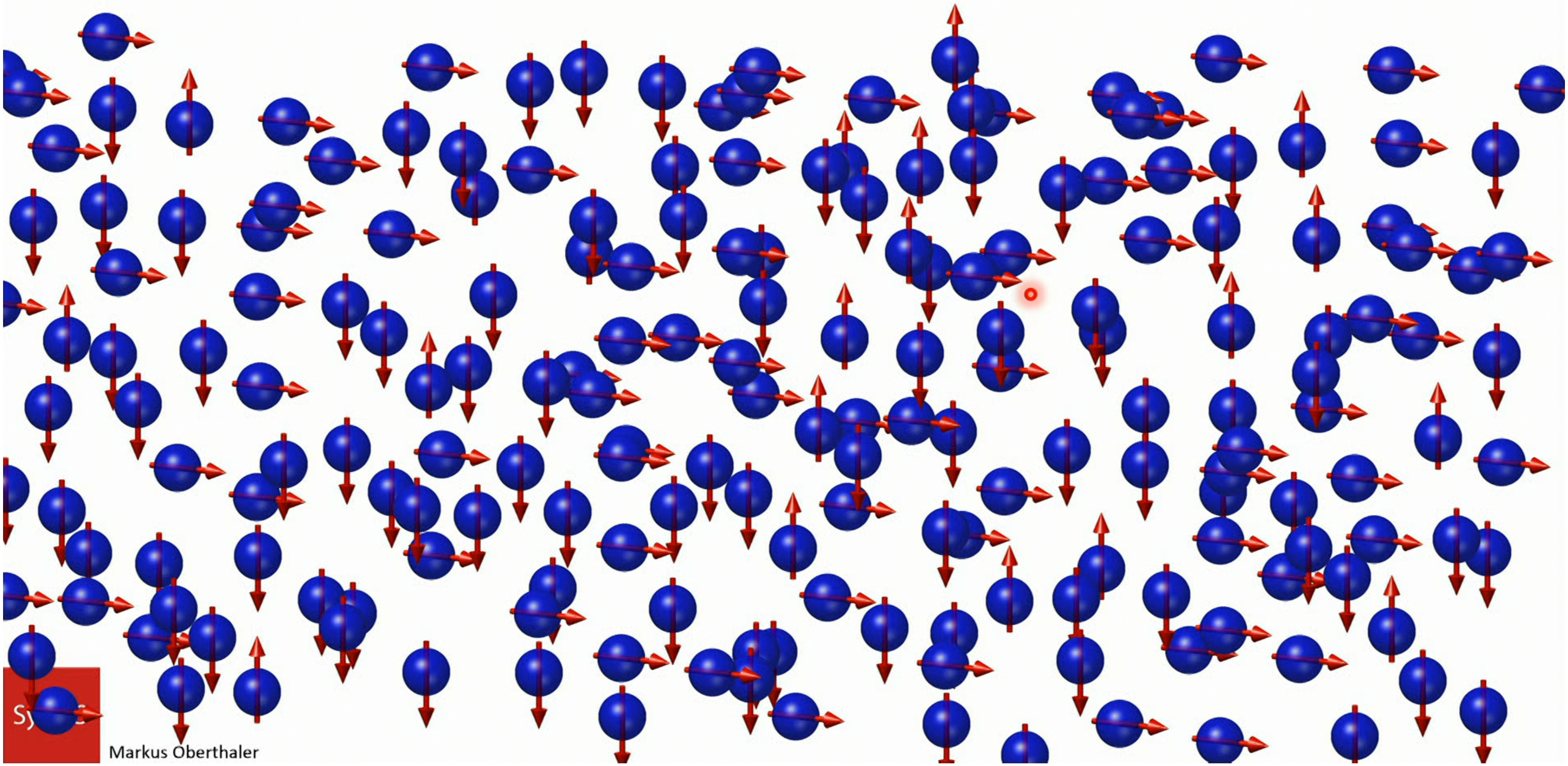
Many atoms

Continuous Quantum Field Settings



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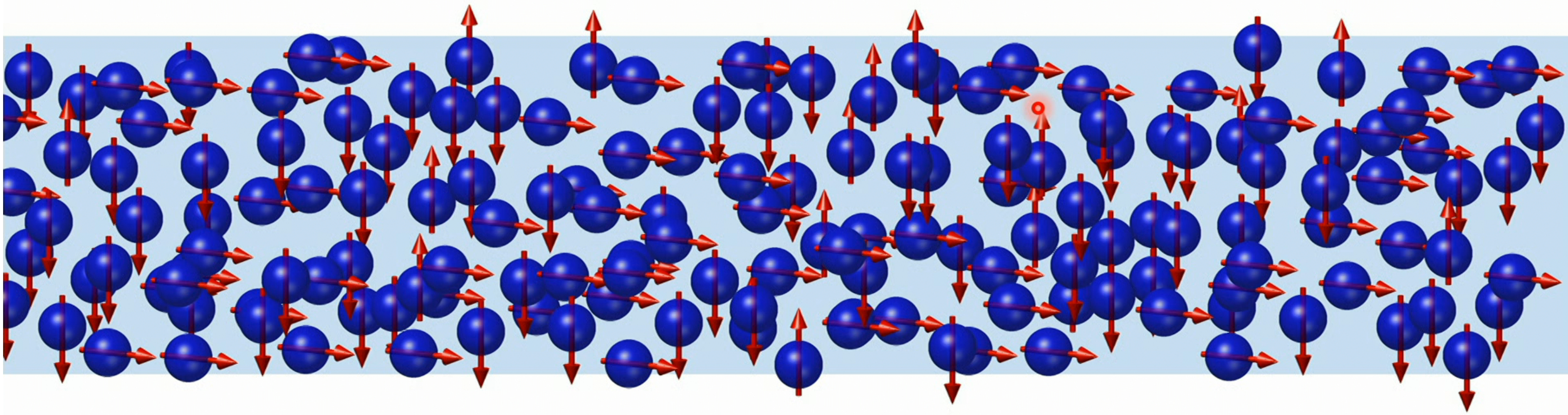
Quasi-one-dimensional spin-1 bosonic gas

Quantum Field Settings



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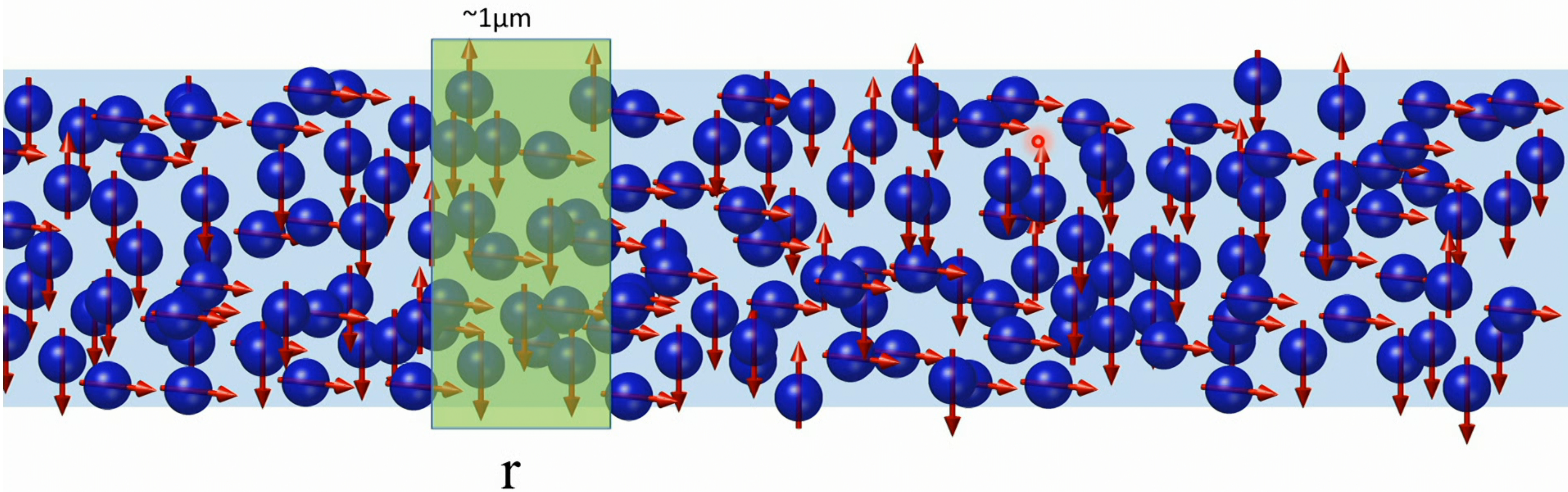
Voxel contains approx. 200 atoms – spin degree is 1d

(Quantum) Field Settings



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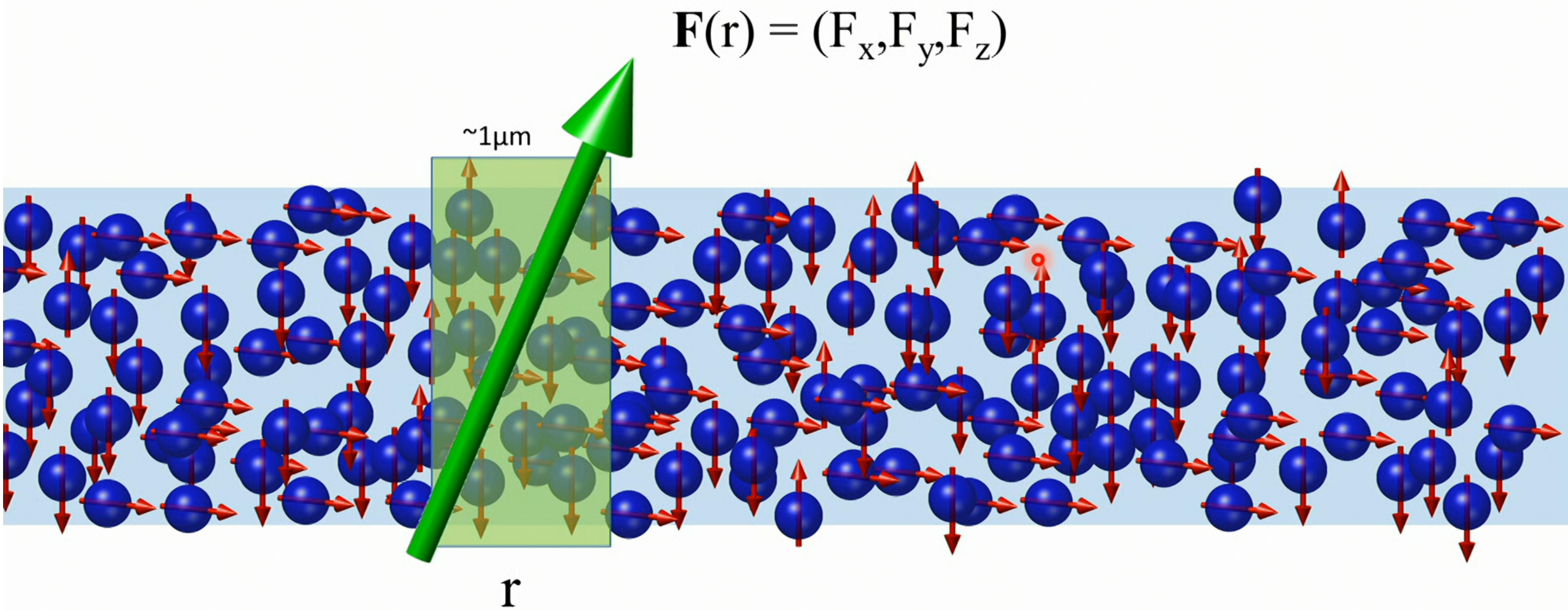

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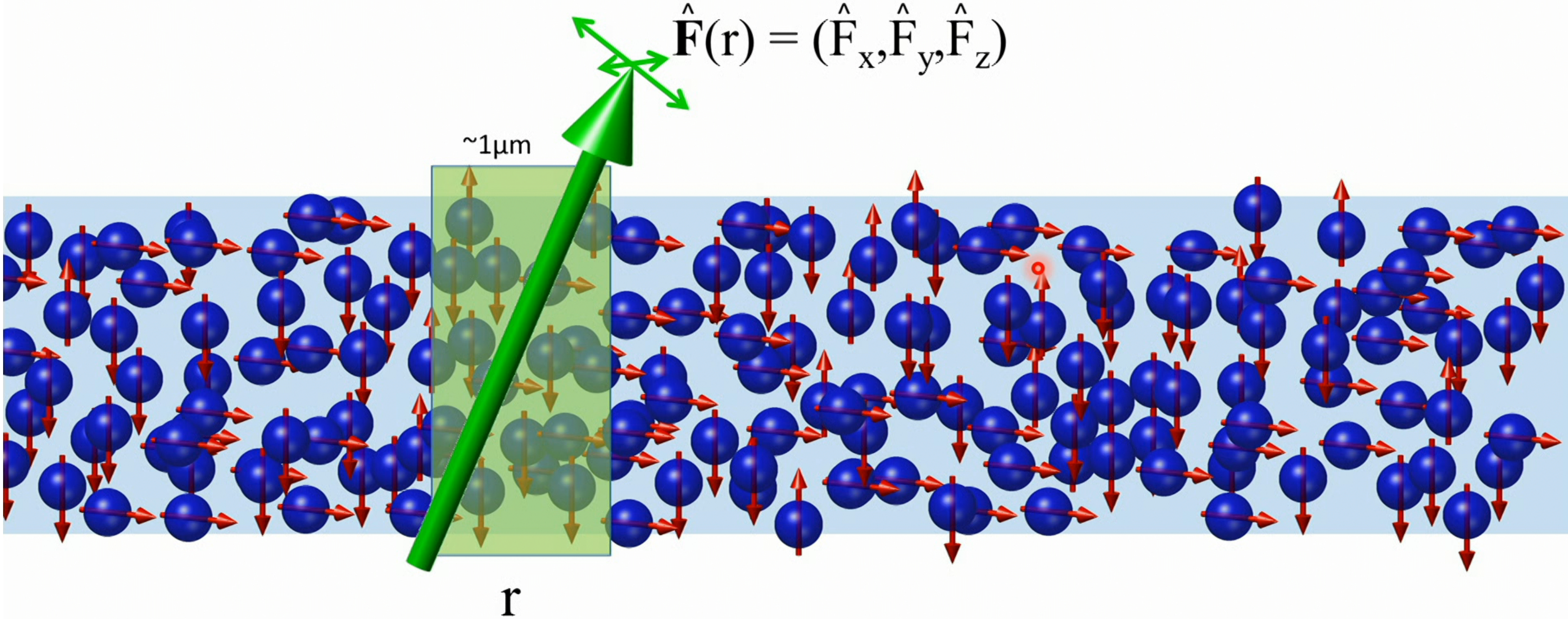
Quantum is in the fluctuations

Quantum Field Settings



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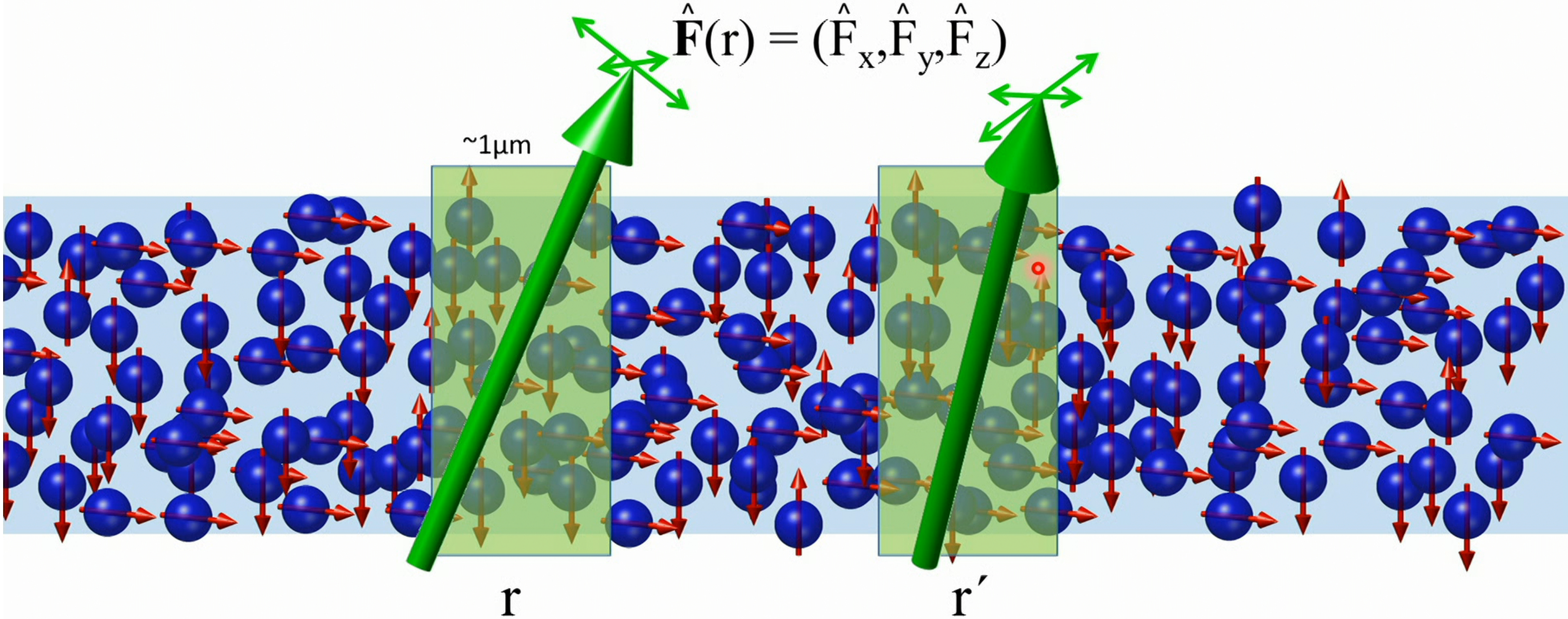
Quantum is in the fluctuations

Quantum Field Settings



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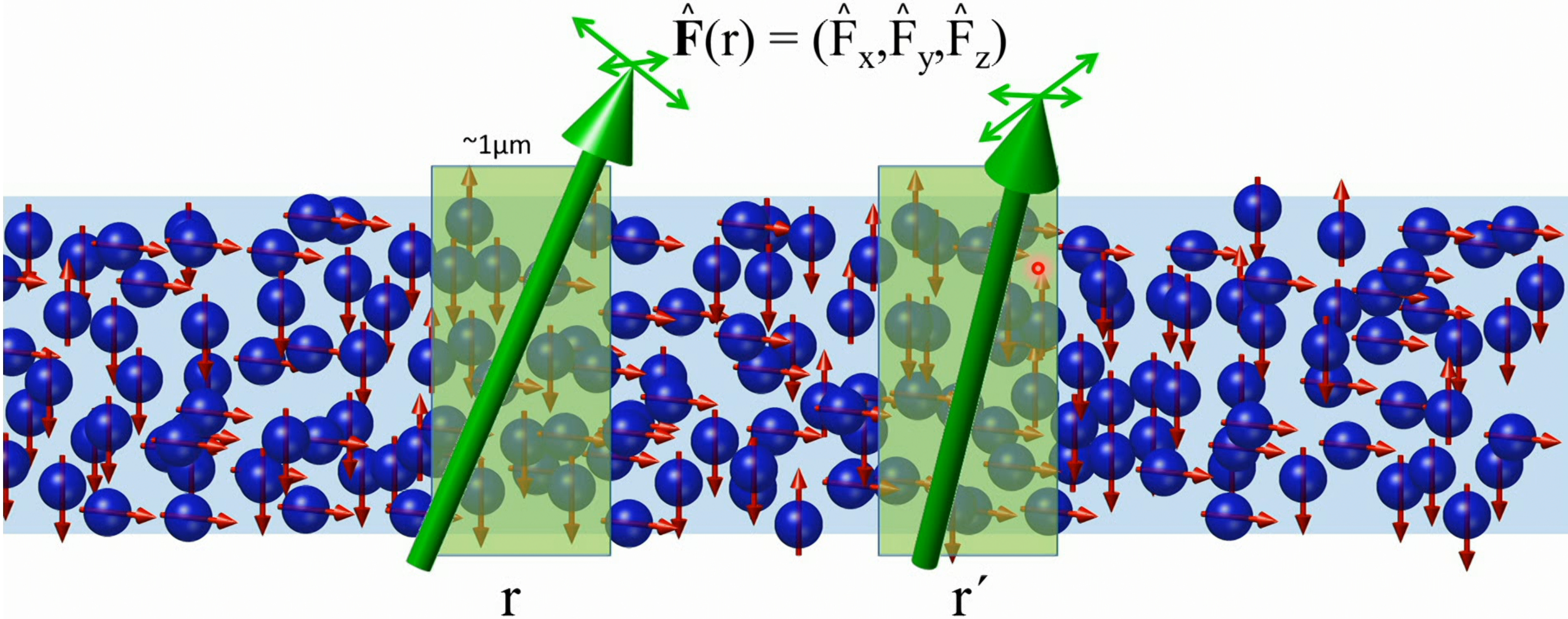
Quantum is in the fluctuations

Quantum Field Settings



spatial correlation $<\hat{\mathbf{F}}(\mathrm{r})\hat{\mathbf{F}}(\mathrm{r}')>, <\hat{\mathbf{F}}(\mathrm{r})\hat{\mathbf{F}}(\mathrm{r}')\hat{\mathbf{F}}(\mathrm{r}'')>, \ldots$

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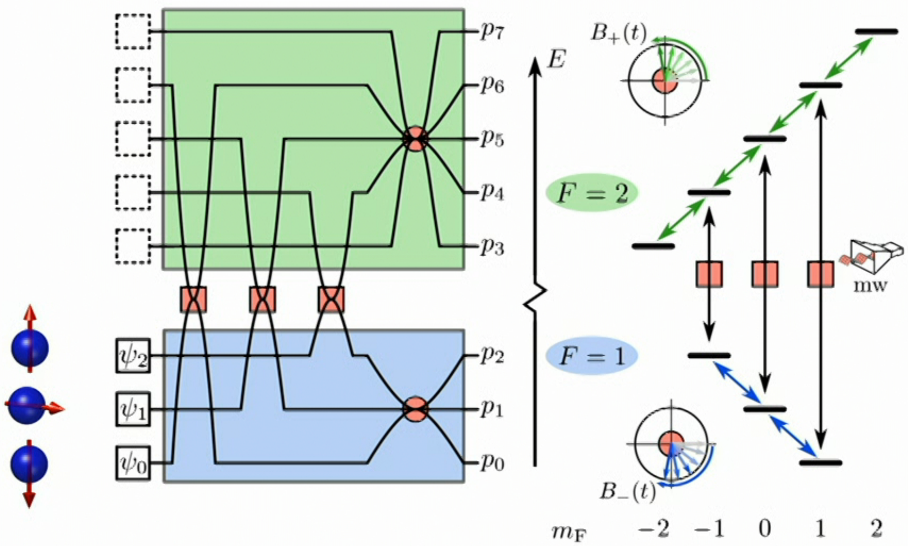
POVM readout

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



Kunkel

see also Jessen group:
PRL 111, 170502 (2013)

Matrix notation:

$$\hat{S}_x = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}$$

$$\hat{S}_y = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & -i & 0 \\ i & 0 & -i \\ 0 & i & 0 \end{pmatrix}$$

$$\hat{S}_z = \begin{pmatrix} 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -1 \end{pmatrix}$$

$$\hat{Q}_{yz} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & -i & 0 \\ i & 0 & i \\ 0 & -i & 0 \end{pmatrix}$$

$$\hat{Q}_{xz} = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & -1 \\ 0 & -1 & 0 \end{pmatrix}$$

$$\hat{Q}_{zz} = \begin{pmatrix} \frac{2}{3} & 0 & 0 \\ 0 & -\frac{4}{3} & 0 \\ 0 & 0 & \frac{2}{3} \end{pmatrix}$$

$$\hat{V}_x = \frac{1}{2}(\hat{Q}_{xx} - \hat{Q}_{yy}) = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}$$

$$\hat{V}_y = \hat{Q}_{xy} = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}$$

Second-quantization:

$$\hat{S}_x = \frac{1}{\sqrt{2}}\hat{a}_0^\dagger\left(\hat{a}_{+1} + \hat{a}_{-1}\right) + \frac{1}{\sqrt{2}}\left(\hat{a}_{+1}^\dagger + \hat{a}_{-1}^\dagger\right)\hat{a}_0$$

$$\hat{S}_y = \frac{i}{\sqrt{2}}\hat{a}_0^\dagger\left(\hat{a}_{+1} - \hat{a}_{-1}\right) - \frac{i}{\sqrt{2}}\left(\hat{a}_{+1}^\dagger - \hat{a}_{-1}^\dagger\right)\hat{a}_0$$

$$\hat{S}_z = \hat{a}_{+1}^\dagger\hat{a}_{+1} - \hat{a}_{-1}^\dagger\hat{a}_{-1}$$

$$\hat{Q}_{yz} = \frac{i}{\sqrt{2}}\hat{a}_0^\dagger\left(\hat{a}_{+1} + \hat{a}_{-1}\right) - \frac{i}{\sqrt{2}}\left(\hat{a}_{+1}^\dagger + \hat{a}_{-1}^\dagger\right)\hat{a}_0$$

$$\hat{Q}_{xz} = \frac{1}{\sqrt{2}}\hat{a}_0^\dagger\left(\hat{a}_{+1} - \hat{a}_{-1}\right) + \frac{1}{\sqrt{2}}\left(\hat{a}_{+1}^\dagger - \hat{a}_{-1}^\dagger\right)\hat{a}_0$$

$$\hat{Q}_{zz} = \frac{2}{3}\left(\hat{a}_{+1}^\dagger\hat{a}_{+1} + \hat{a}_{-1}^\dagger\hat{a}_{-1}\right) - \frac{4}{3}\hat{a}_0^\dagger\hat{a}_0$$

$$\hat{V}_x = \hat{a}_{+1}^\dagger\hat{a}_{-1} + \hat{a}_{-1}^\dagger\hat{a}_{+1}$$

$$\hat{V}_y = i\hat{a}_{+1}^\dagger\hat{a}_{-1} - i\hat{a}_{-1}^\dagger\hat{a}_{+1}$$

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POVM readout

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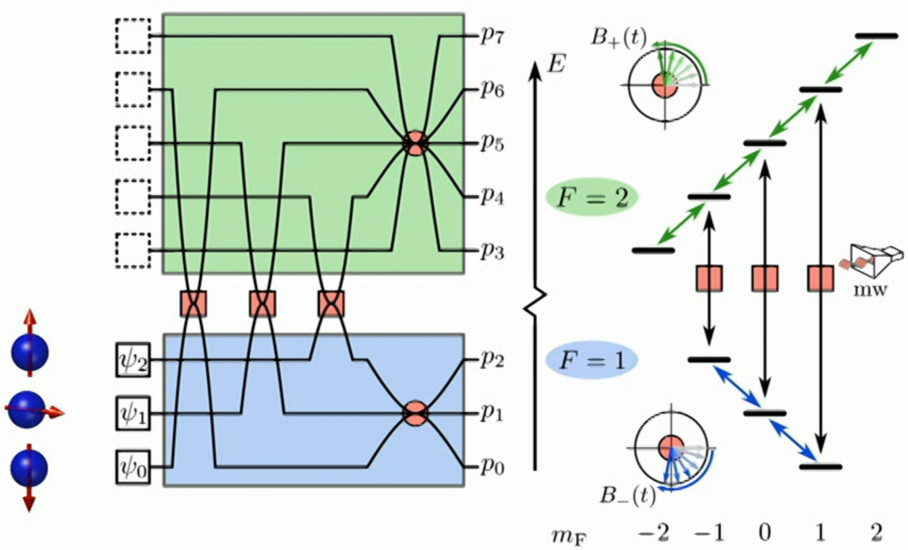

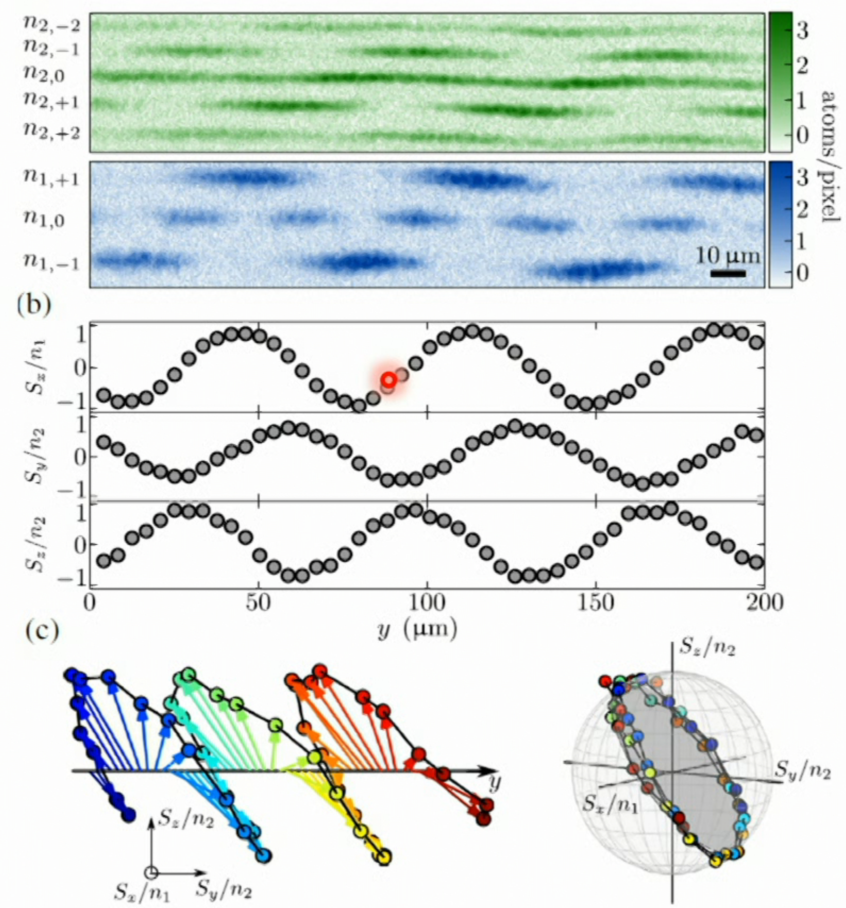

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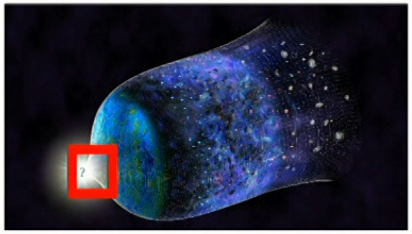
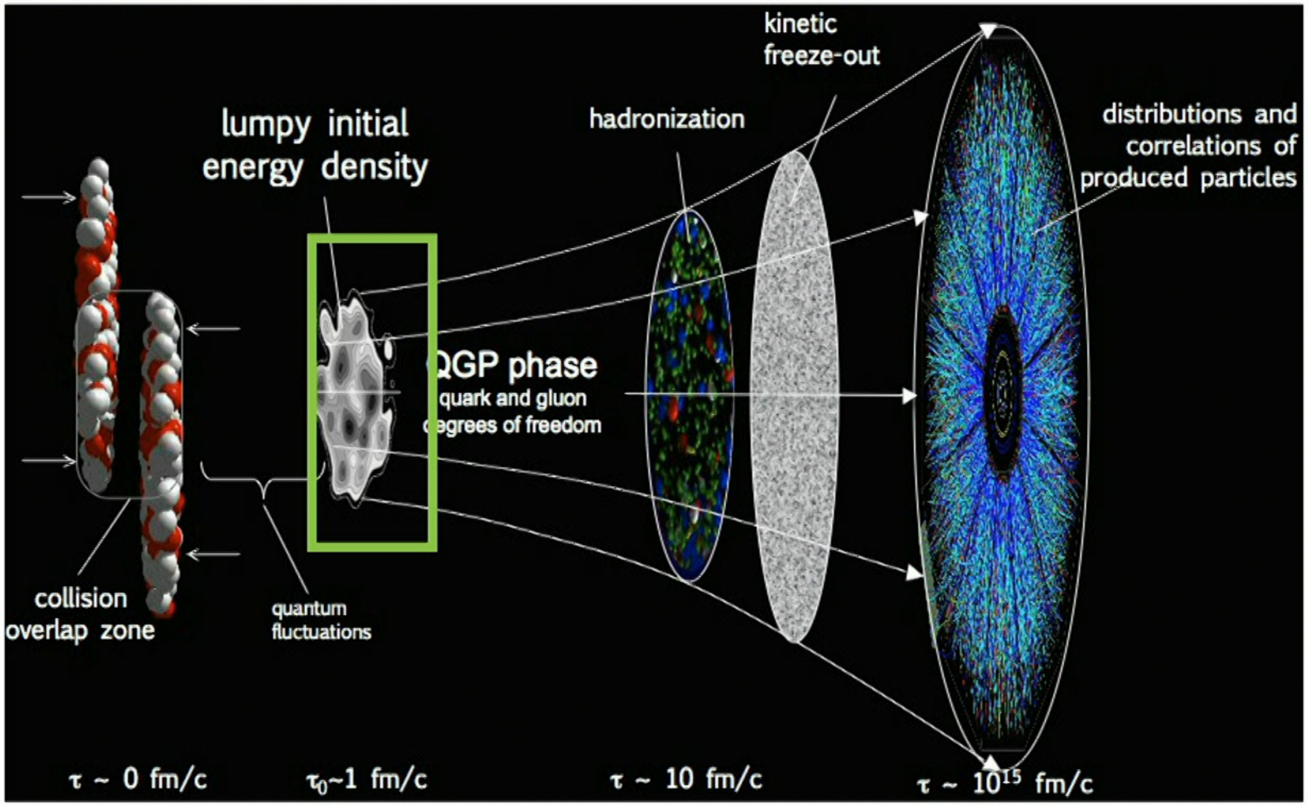
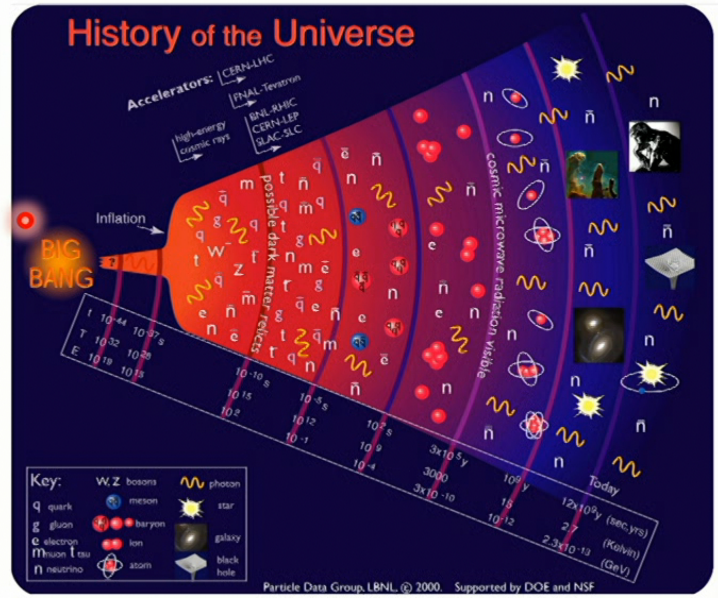


Little Bang(s) at CERN





Jürgen Berges

Non-thermal fixed point

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

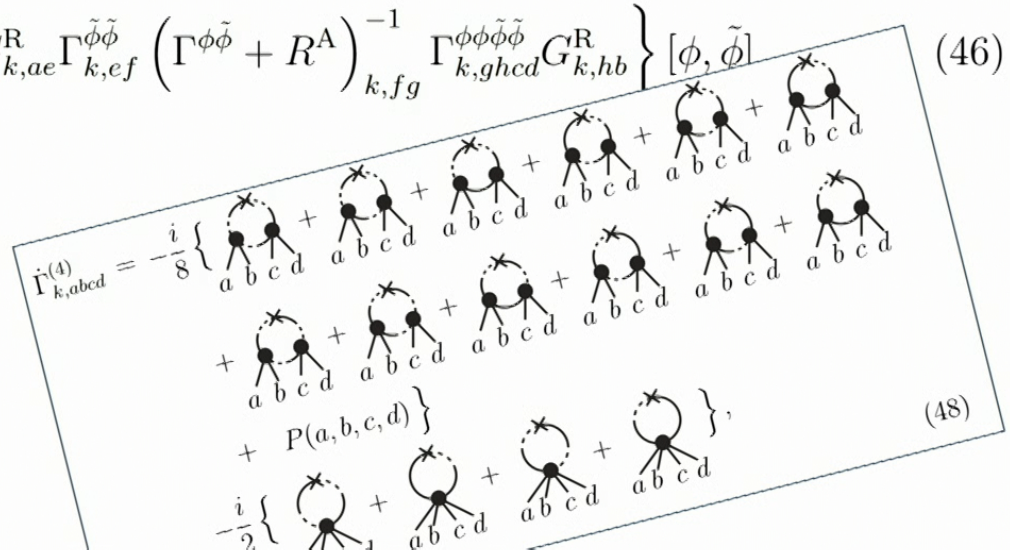
J.Berges, G. Hofmeister, NPB 813 (2009)

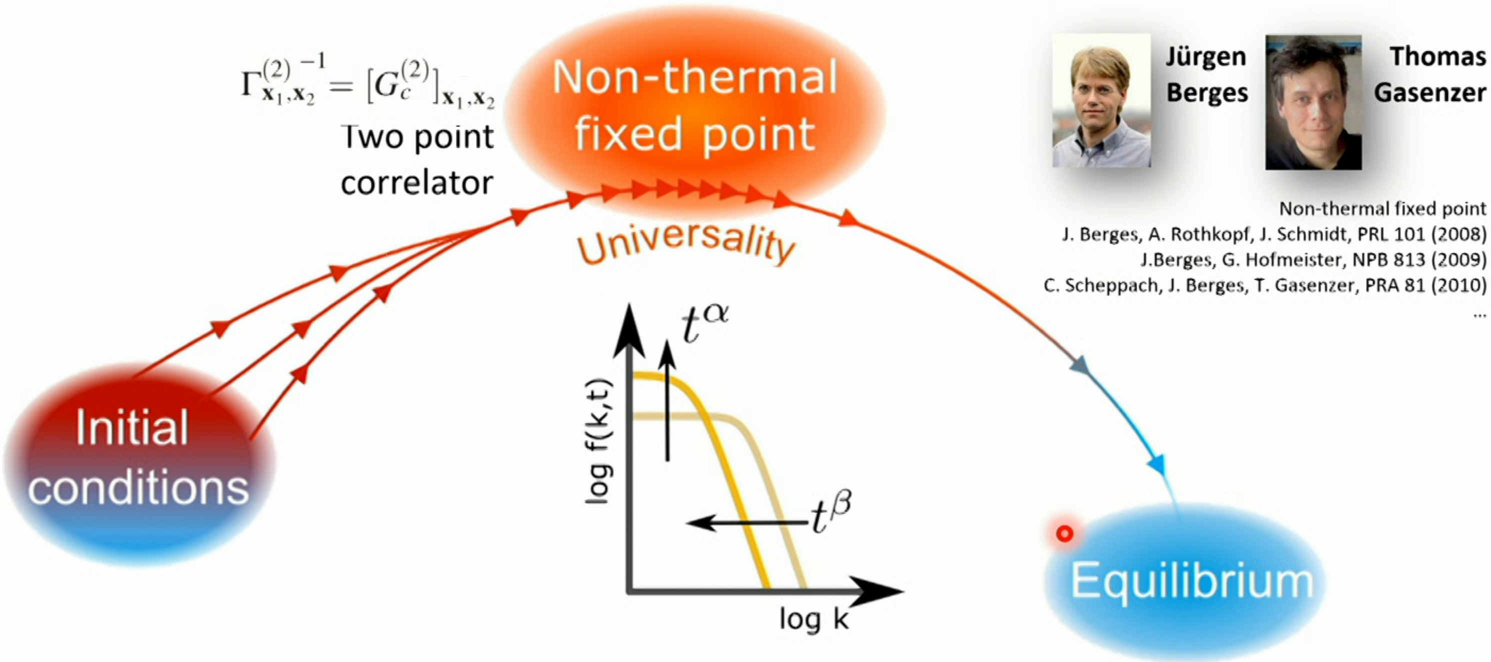
Quantum Field Theory Model

Non-thermal fixed point in O(N) arXiv:0809.5208, NPB 813 (2009)

$$S[\varphi] = \frac{1}{2}\int_{xy,\mathcal{C}} \varphi_a(x) i D^{-1}_{ab}(x,y)\varphi_b(y) - \frac{\lambda}{4!N}\int_{x,\mathcal{C}} \varphi_a(x)\varphi_a(x)\varphi_b(x)\varphi_b(x). \quad (9)$$

$$\begin{aligned}\frac{\delta^2 G^{\mathrm{R}}_{k,ab}[\phi,\tilde\phi]}{\delta\tilde\phi_c\delta\tilde\phi_d} = & \Big\{ G^{\mathrm{R}}_{k,ae}\Gamma^{\tilde\phi\phi\tilde\phi\tilde\phi}_{k,efcd}G^{\mathrm{R}}_{k,fb} - G^{\mathrm{R}}_{k,ae}\Gamma^{\tilde\phi\tilde\phi\tilde\phi\tilde\phi}_{k,efcd}\left(\Gamma^{\phi\tilde\phi}+R^{\mathrm{A}}\right)^{-1}_{k,fg}\Gamma^{\phi\phi}_{k,gh}G^{\mathrm{R}}_{k,hb} \\ & + G^{\mathrm{R}}_{k,ae}\Gamma^{\tilde\phi\tilde\phi}_{k,ef}\left(\Gamma^{\phi\tilde\phi}+R^{\mathrm{A}}\right)^{-1}_{k,fg}\Gamma^{\phi\tilde\phi\tilde\phi\tilde\phi}_{k,ghcd}\left(\Gamma^{\phi\tilde\phi}+R^{\mathrm{A}}\right)^{-1}_{k,hi}\Gamma^{\phi\phi}_{k,ij}G^{\mathrm{R}}_{k,jb} \\ & - G^{\mathrm{R}}_{k,ae}\Gamma^{\tilde\phi\tilde\phi}_{k,ef}\left(\Gamma^{\phi\tilde\phi}+R^{\mathrm{A}}\right)^{-1}_{k,fg}\Gamma^{\phi\phi\tilde\phi\tilde\phi}_{k,ghcd}G^{\mathrm{R}}_{k,hb}\Big\}[\phi,\tilde\phi] \end{aligned} \quad (46)$$





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

$$f(k,t) = \left(\frac{t}{t_{\mathrm{ref}}}\right)^{\alpha} f_s\left(\left(\frac{t}{t_{\mathrm{ref}}}\right)^{\beta} k\right)$$

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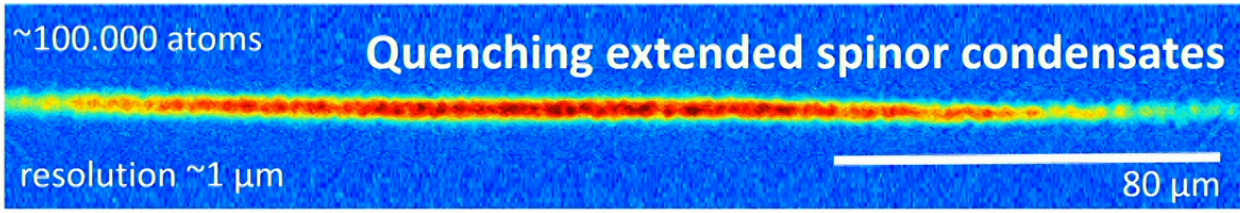
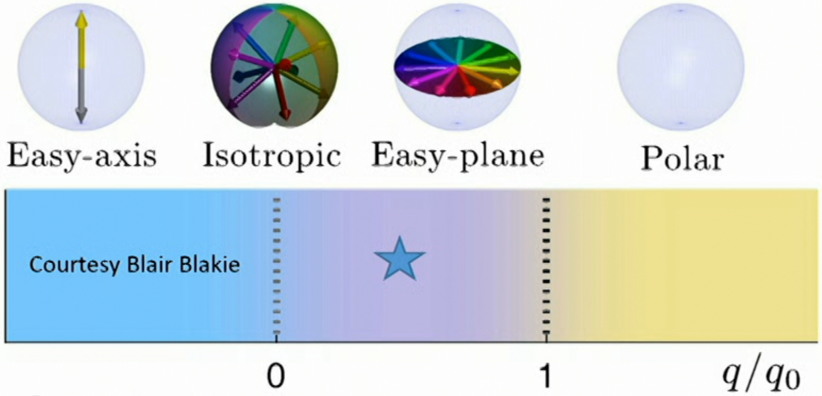
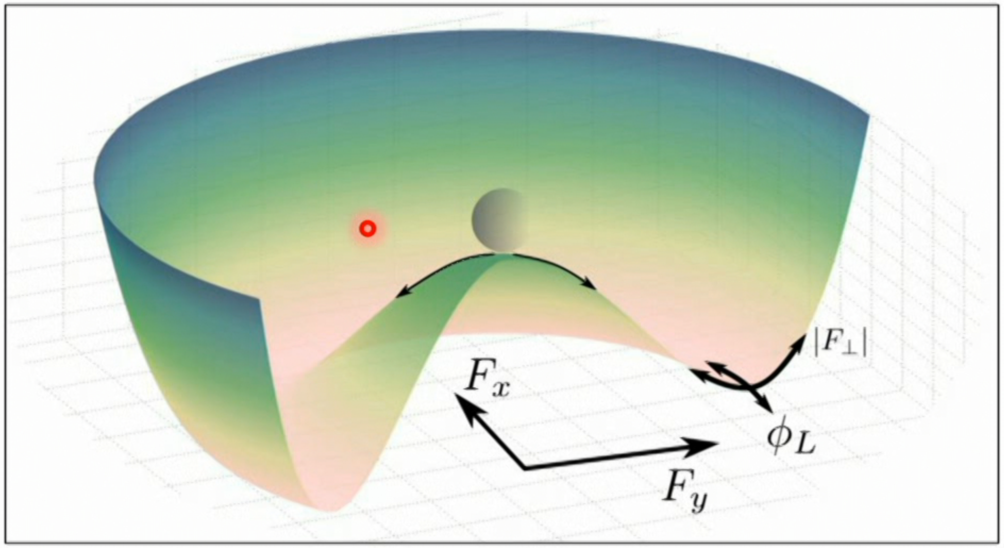
The narrative of universal time dynamics

Quantum Bang(s)





For review see:
D.M. Stamper-Kurn, M. Ueda RMP 85, 1191 (2013)



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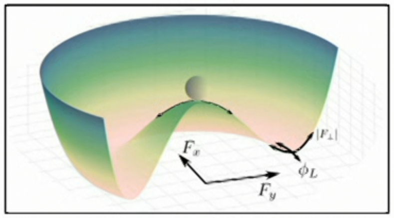
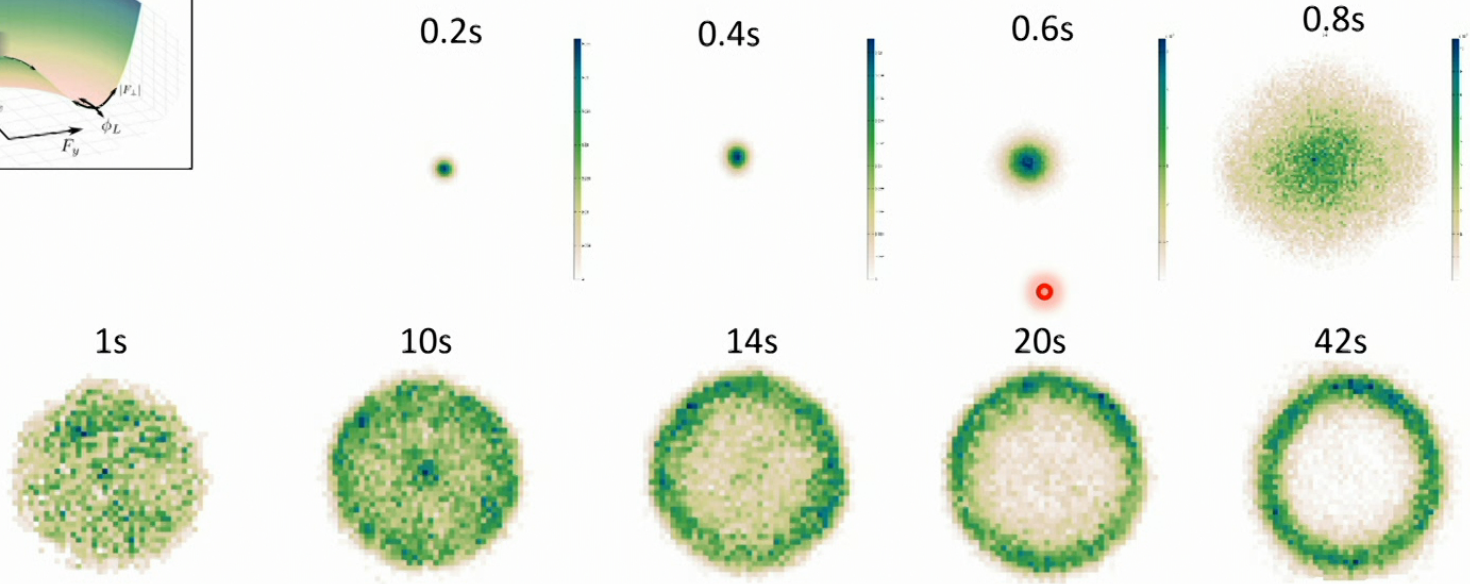
Watching the build-up of transverse spin

dynamics





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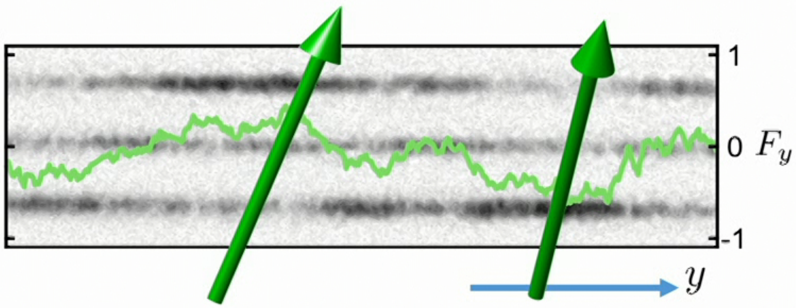
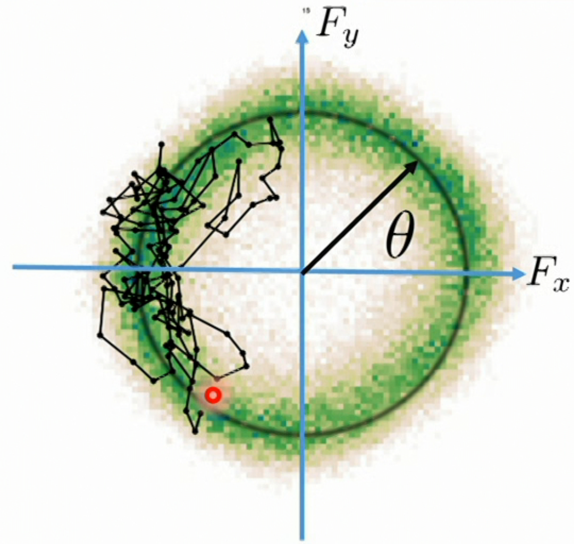
Spatial information in Fourier space

dynamics



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

but experiment (simulator) delivers also
$\langle\theta(y)\theta(y')\theta(y'')\theta(y''')\rangle$



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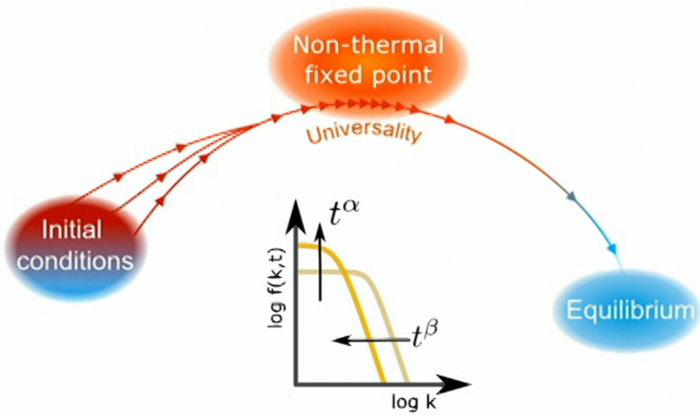
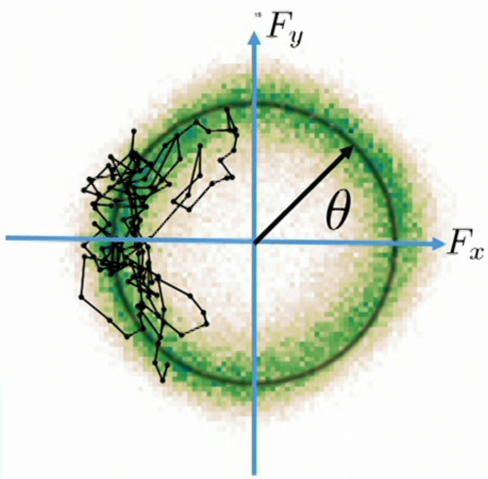
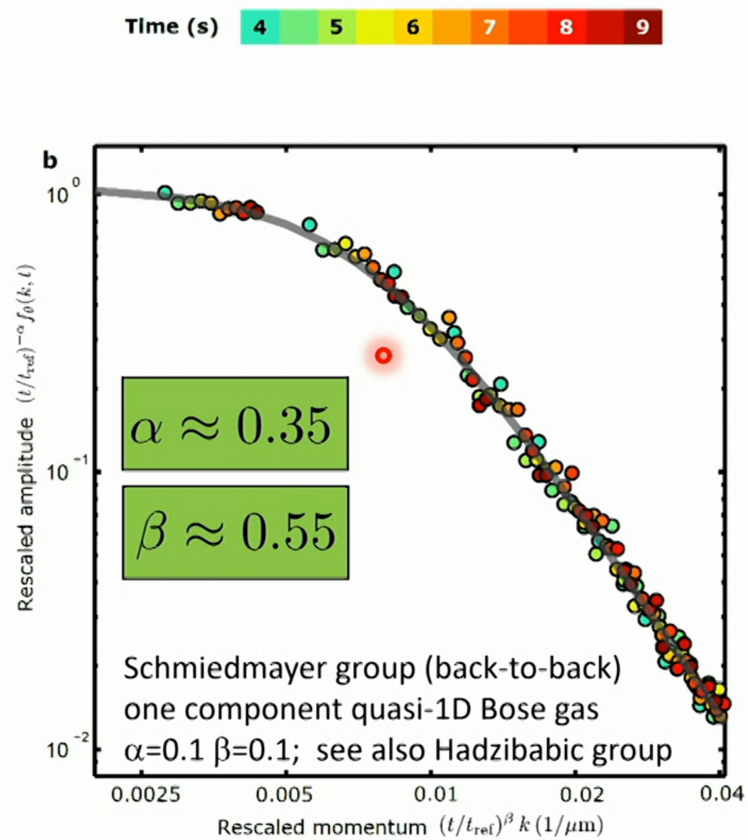
‚close to‘ O(N) expectations

Nature **568**, 217 (2018)







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Non-thermal fixed point

J. Berges, A. Rothkopf, J. Schmidt, PRL 101 (2008)
J.Berges, G. Hofmeister, NPB 813 (2009)

extracting emerging interactions

PRE **56**, 2687194 (1997), PRX **10**, 011020 (2020)
Berges — Berges, Schmiedmayer

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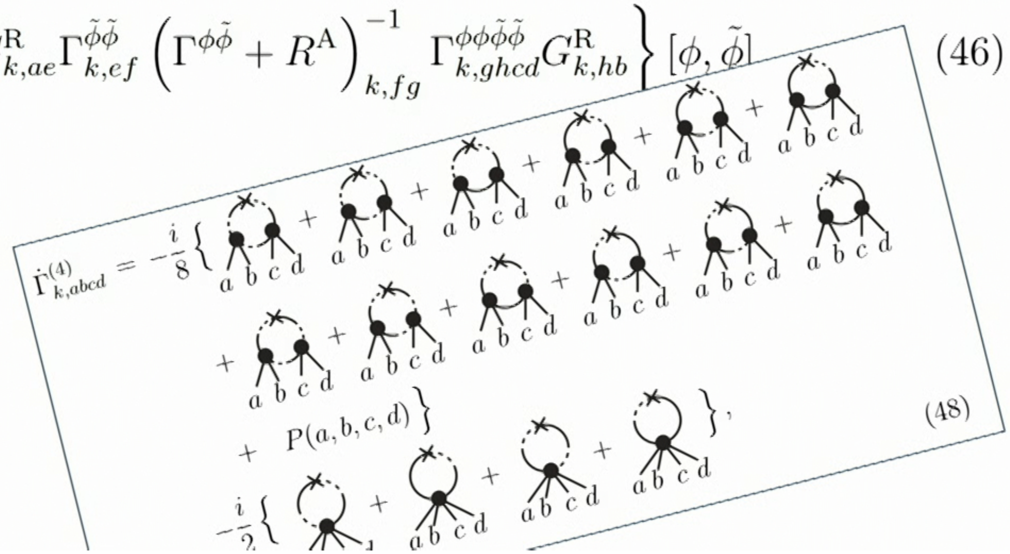

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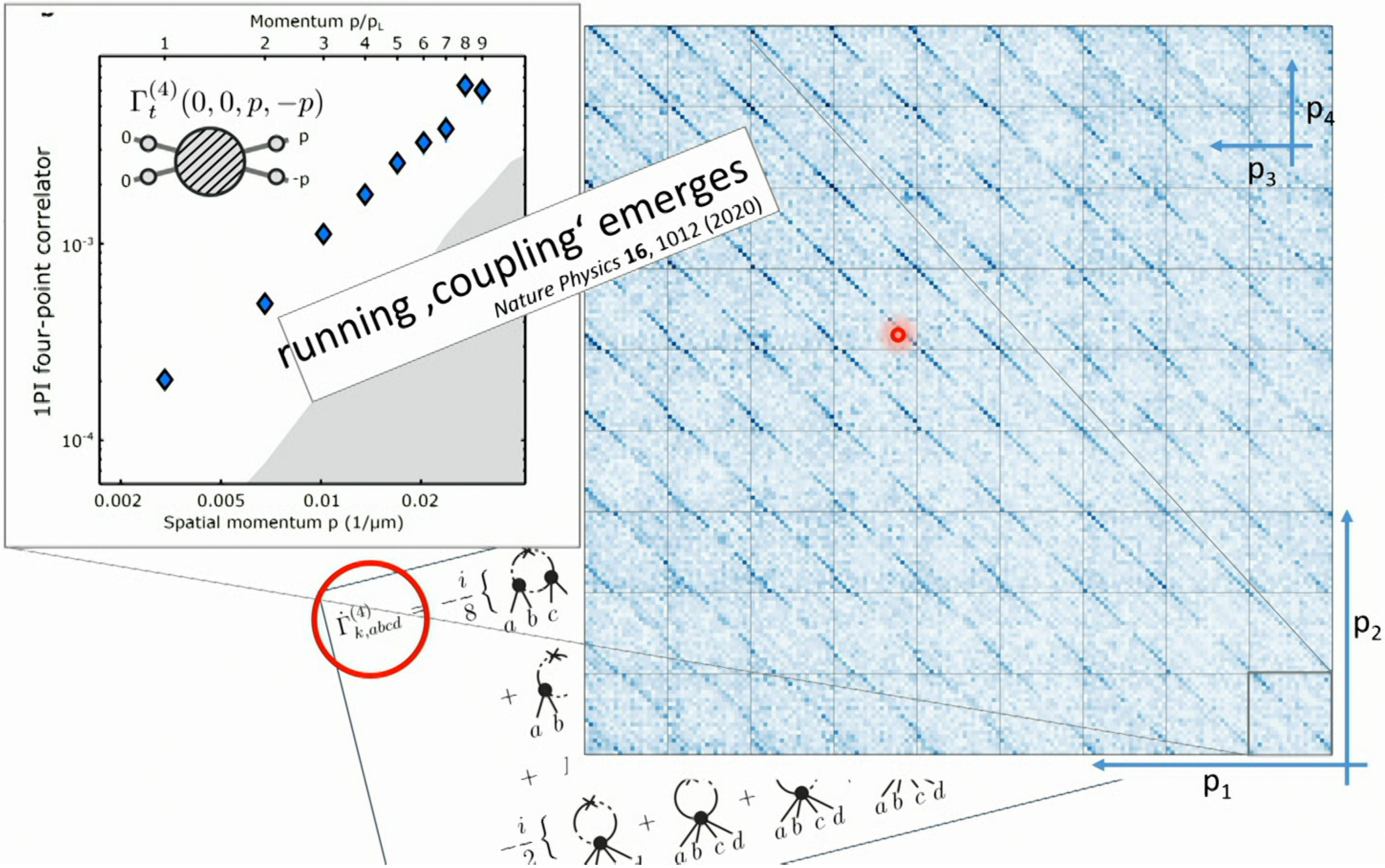

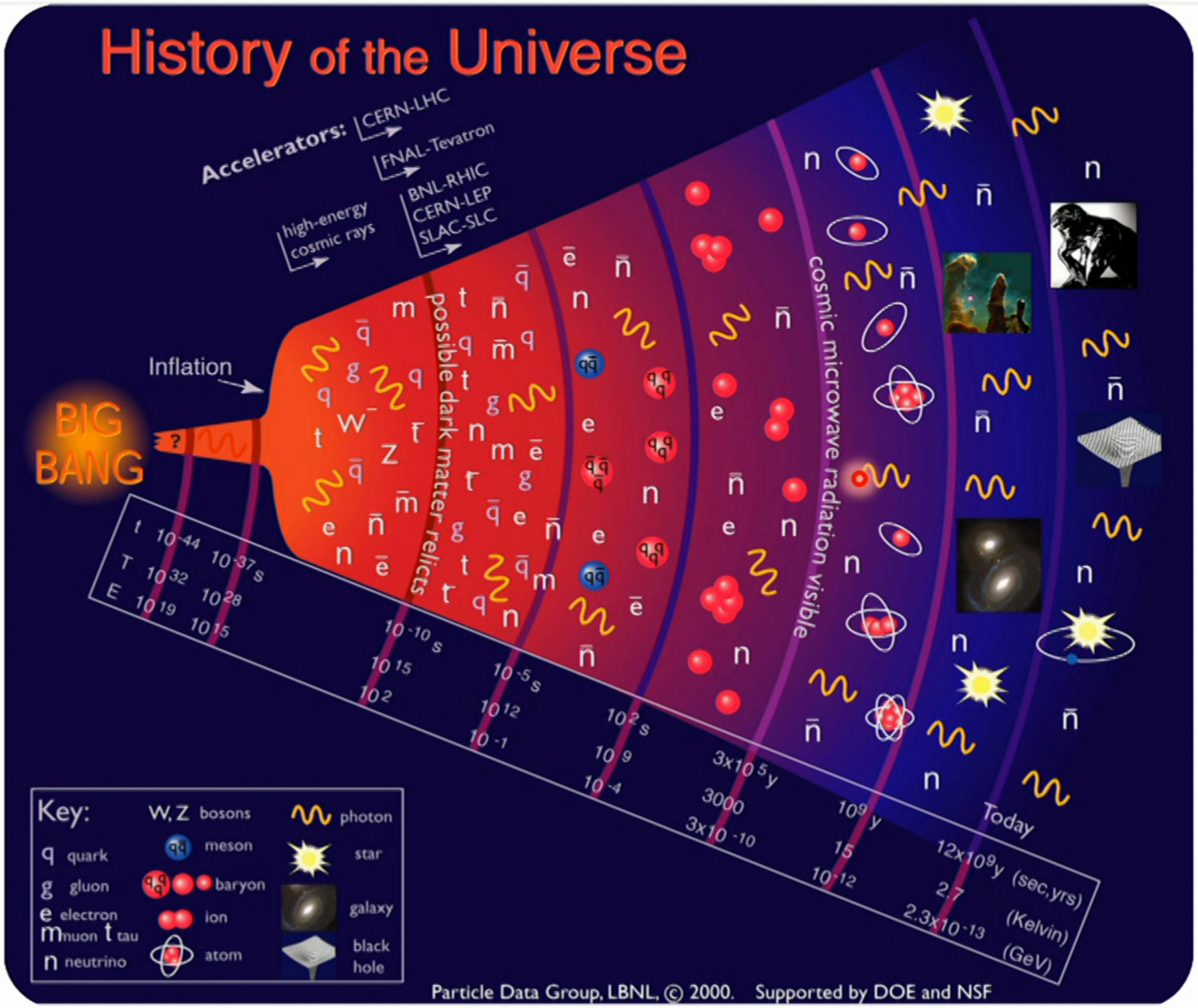

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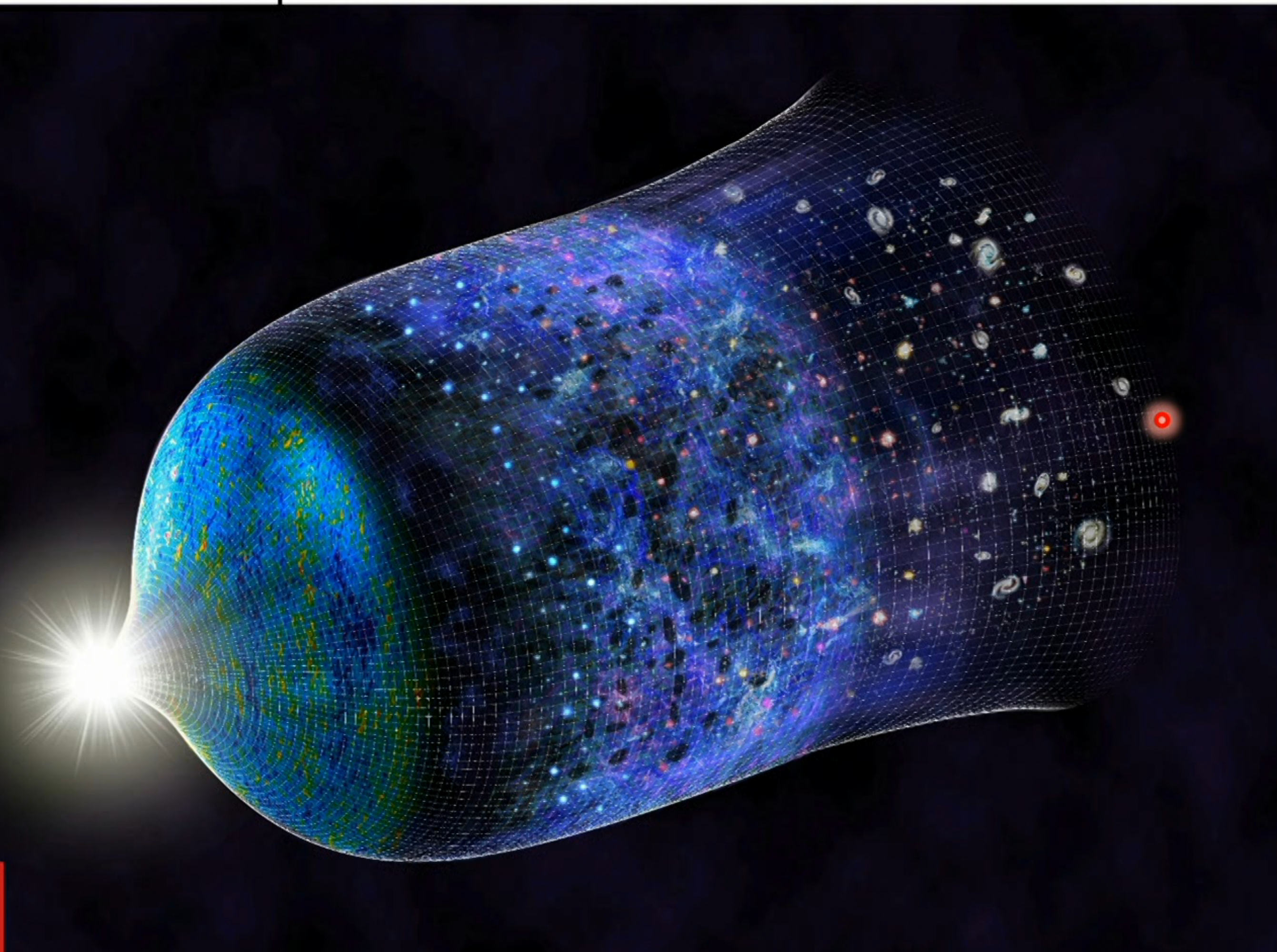
Inspiration by …

Cosmology



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

Various other experiments, including
S. Weinfurtner
J. Steinhauer
C. Chin
G. K. Campbell
J. Schmiedmayer
…

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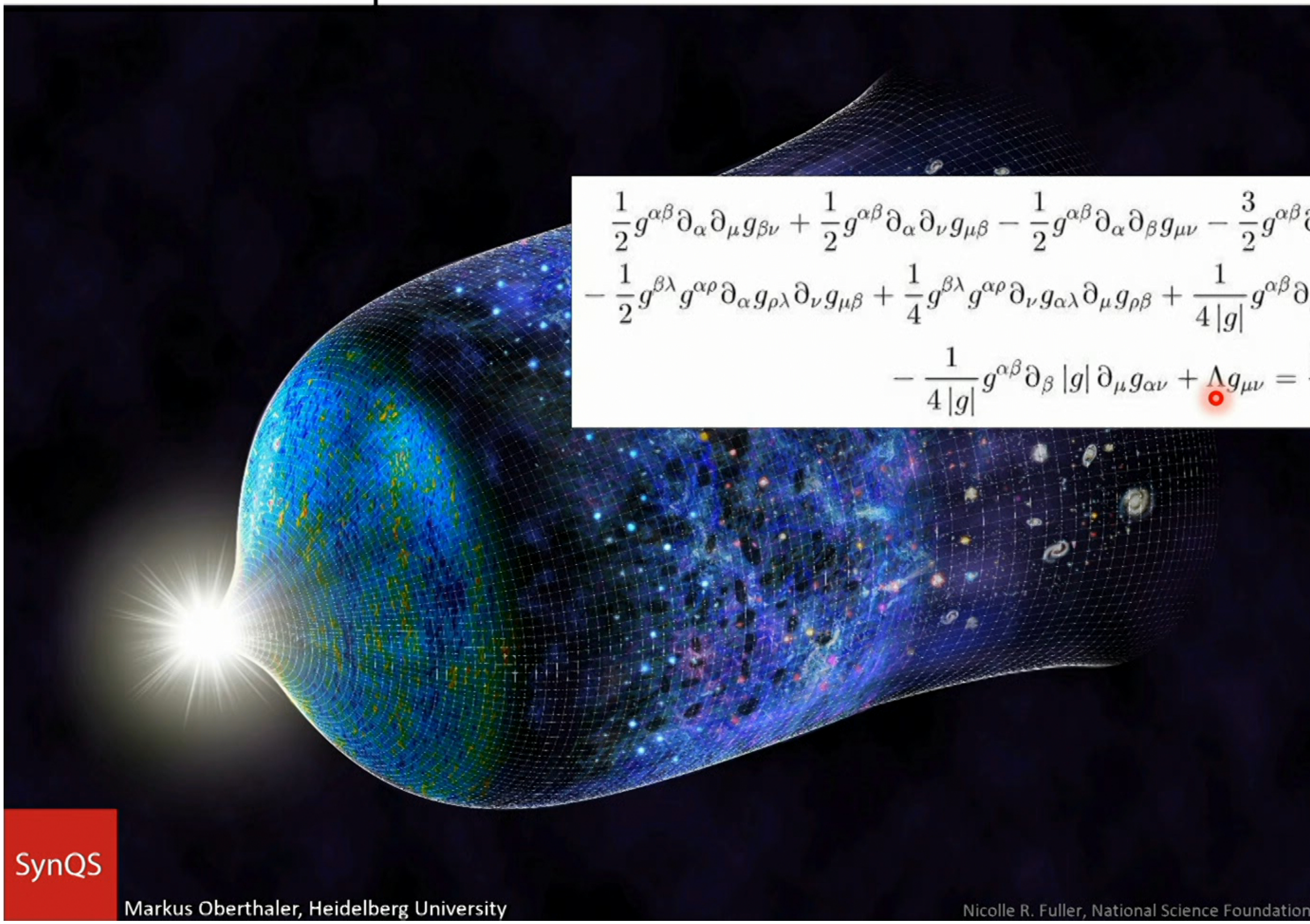
Markus Oberthaler, Heidelberg University

STRUCTURES CLUSTER OF EXCELLENCE

Inspiration by ...

Cosmology



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

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

Various other experiments, including
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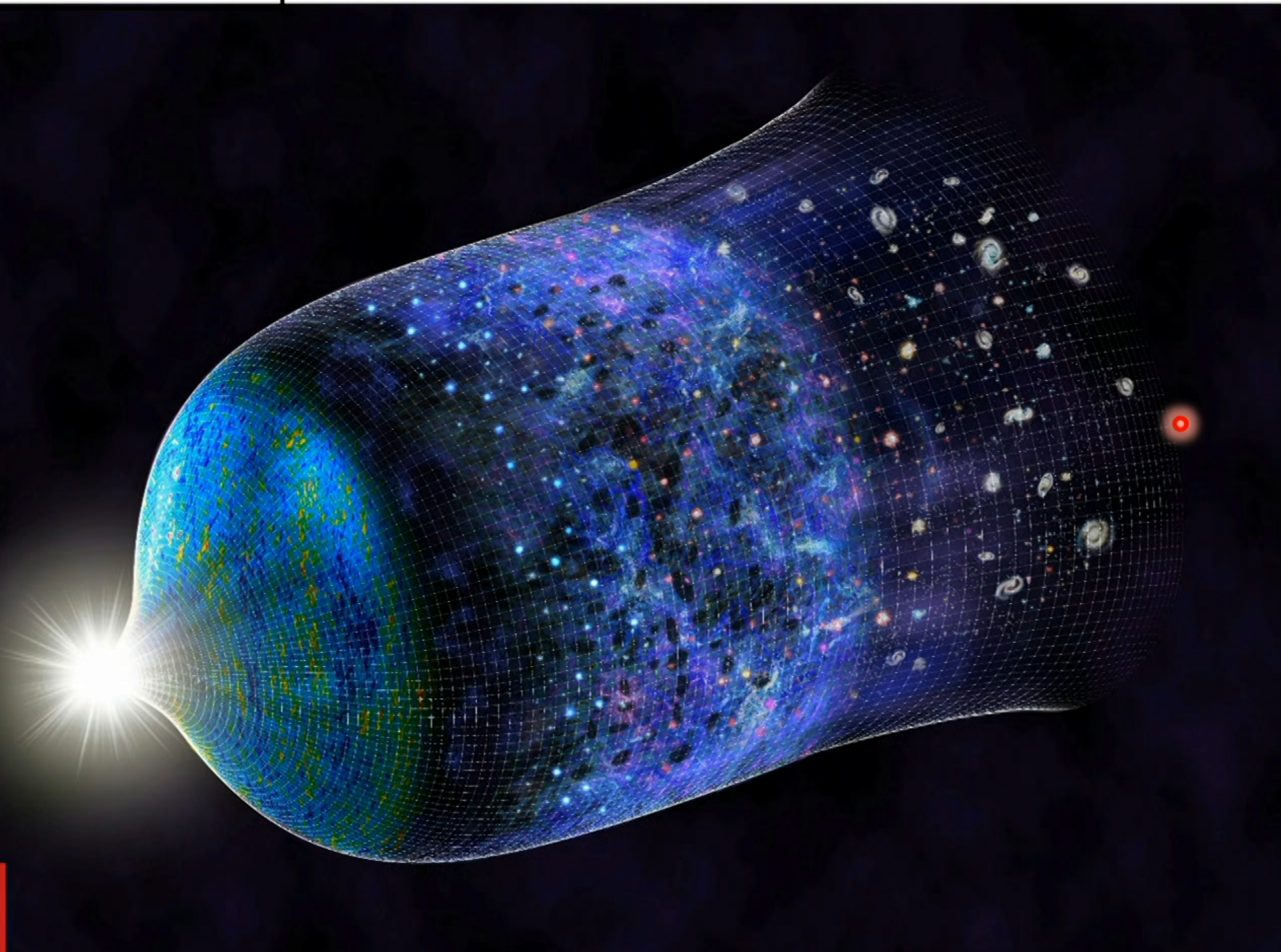
...

STRUCTURES CLUSTER OF EXCELLENCE

Inspiration by ...

Cosmology



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

$$\mathrm{d}s^2 \equiv g_{\mu\nu}\, \mathrm{d}x^\mu \mathrm{d}x^\nu$$

Various other experiments, including
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...

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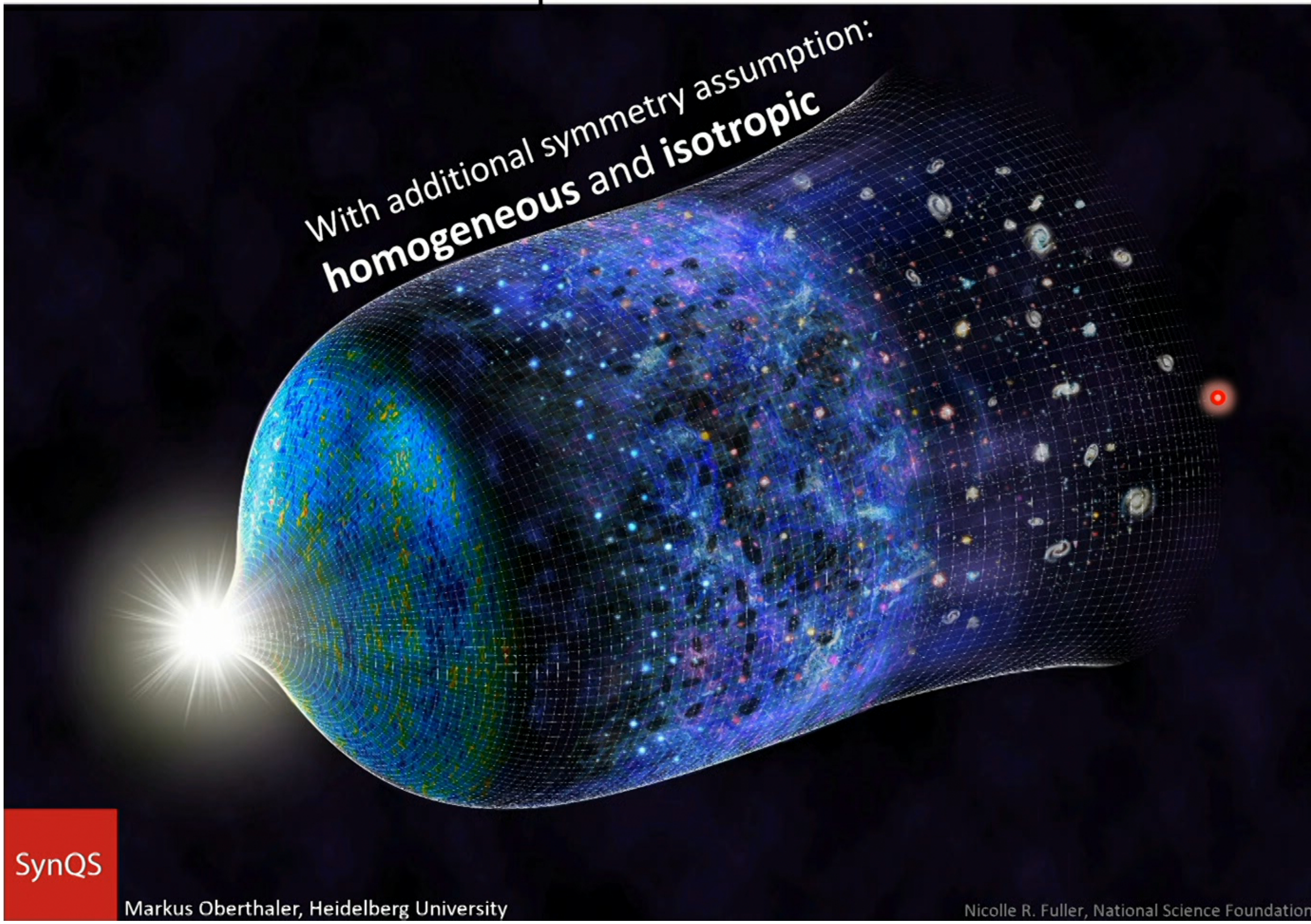
Cosmology



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

$$ds^2 \equiv g_{\mu\nu}\, dx^\mu dx^\nu$$

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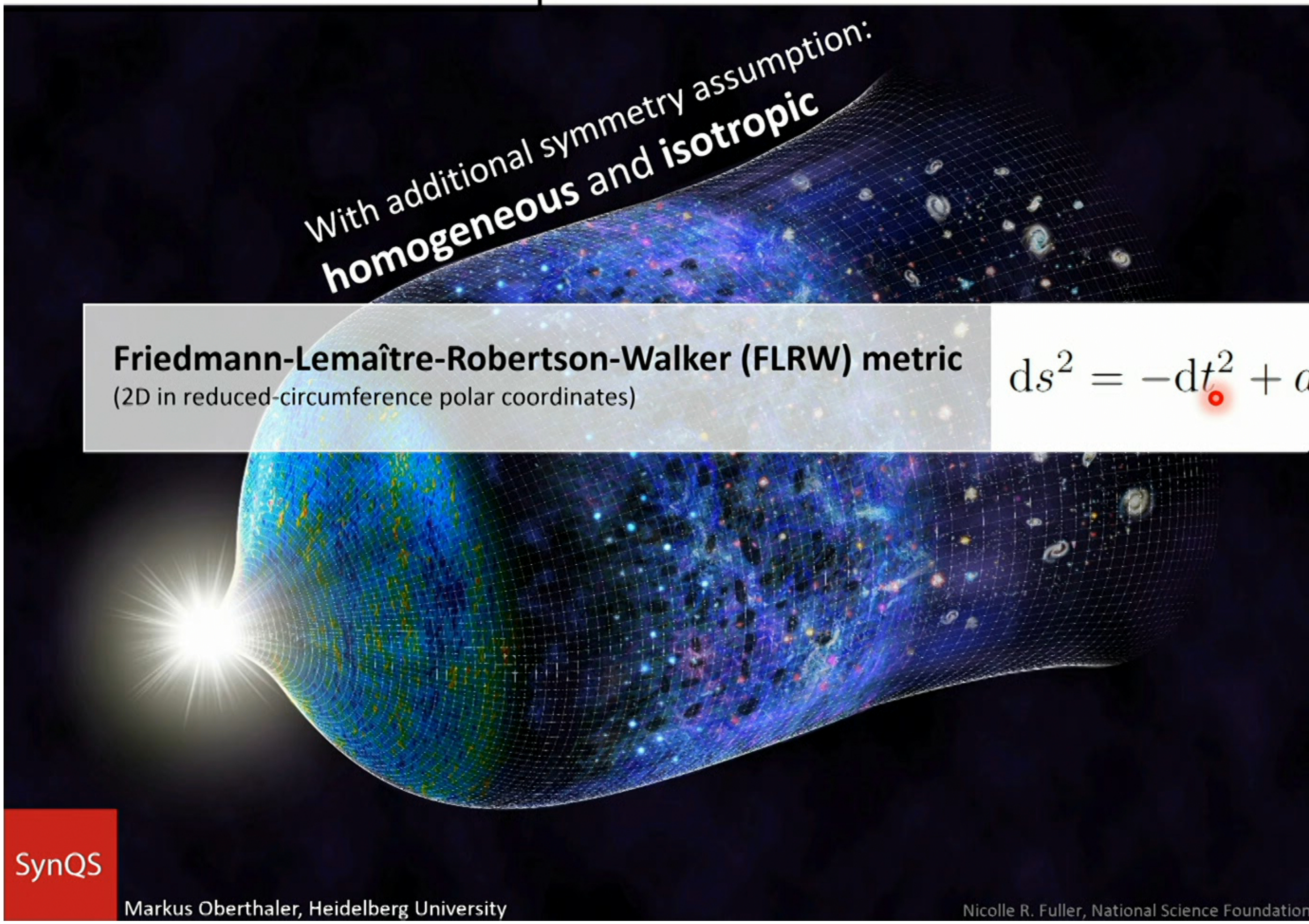
EXCELLENCE

Inspiration by ...

Cosmology

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

$$\mathrm{d}s^2 \equiv g_{\mu\nu}\,\mathrm{d}x^\mu \mathrm{d}x^\nu$$



Nicolle R. Fuller, National Science Foundation

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

Friedmann-Lemaître-Robertson-Walker (FLRW) metric
(2D in reduced-circumference polar coordinates)

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

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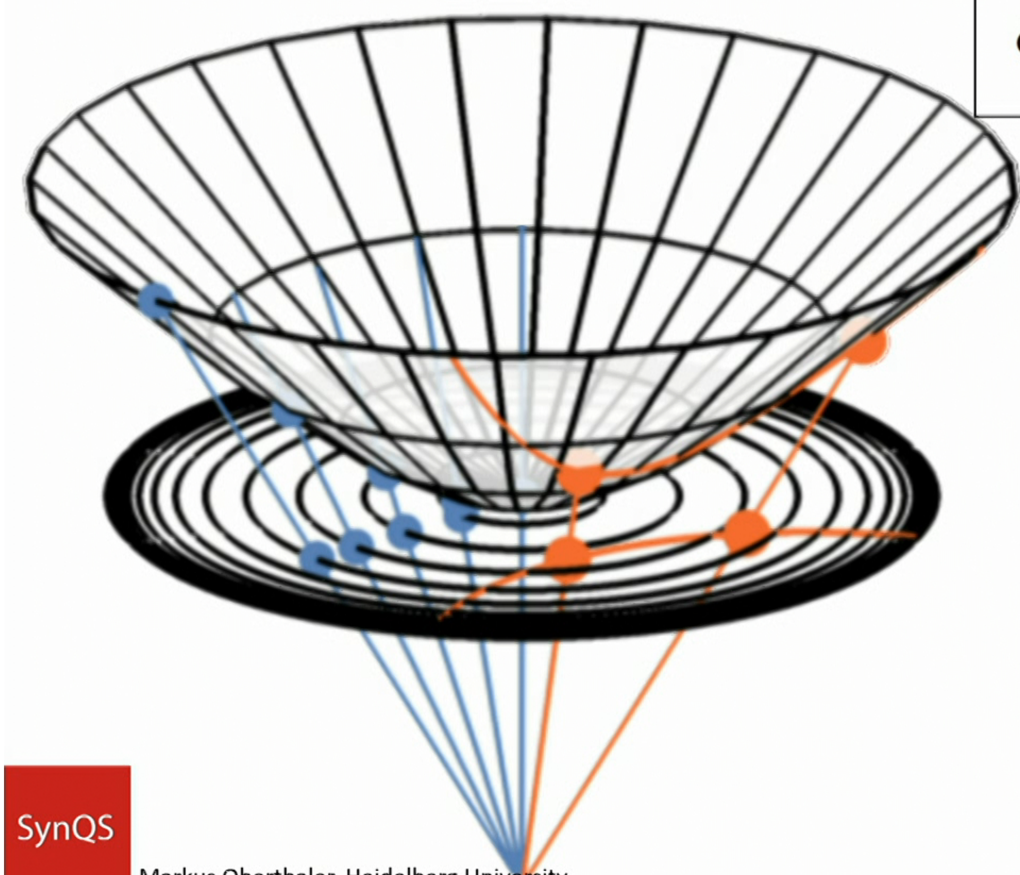
Mapping on experimental reality



how 2D infinite curved space fits on a flat disc

see details in PRA **106**, 033313 (2022)

infinite extension

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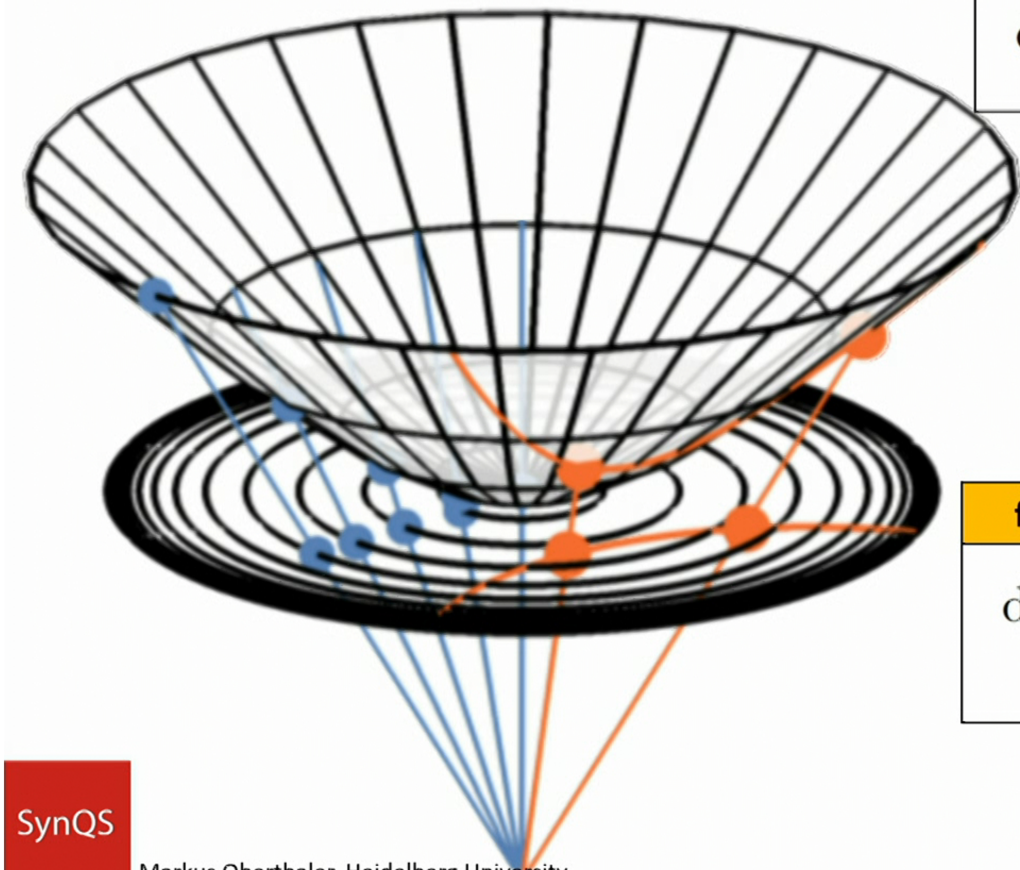

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finite extension

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

$$u(r) = \frac{r}{1-\frac{r^2}{R^2}}$$

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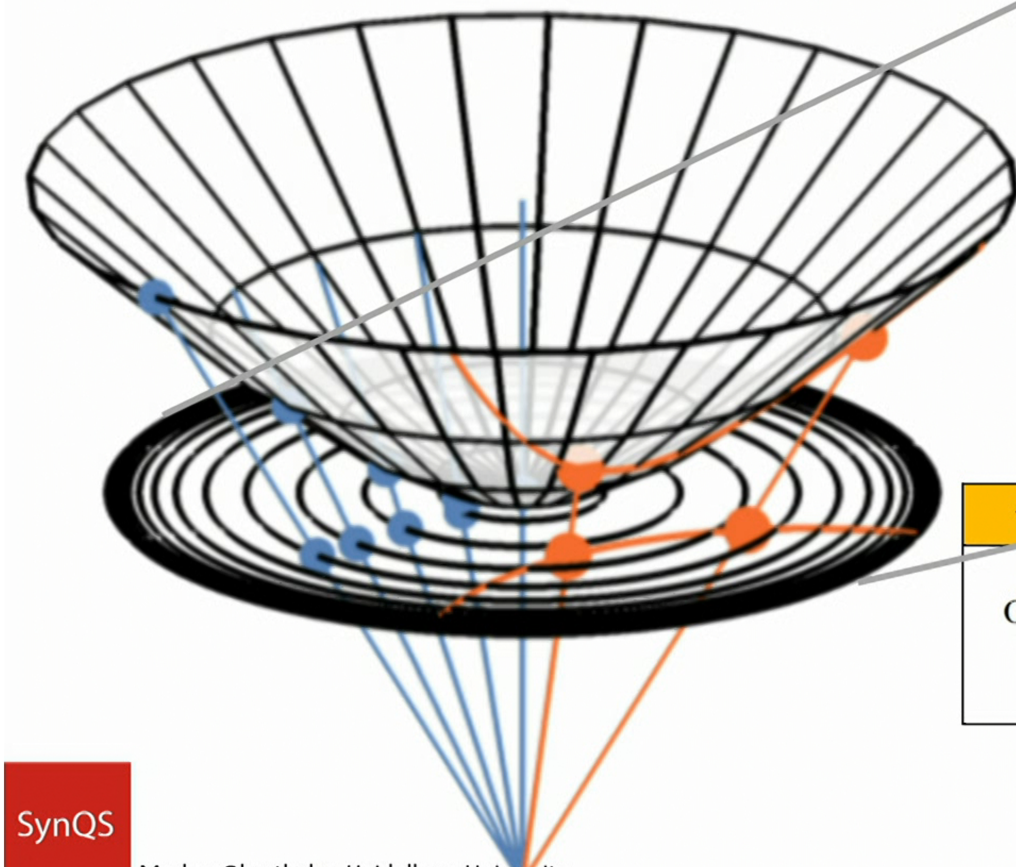
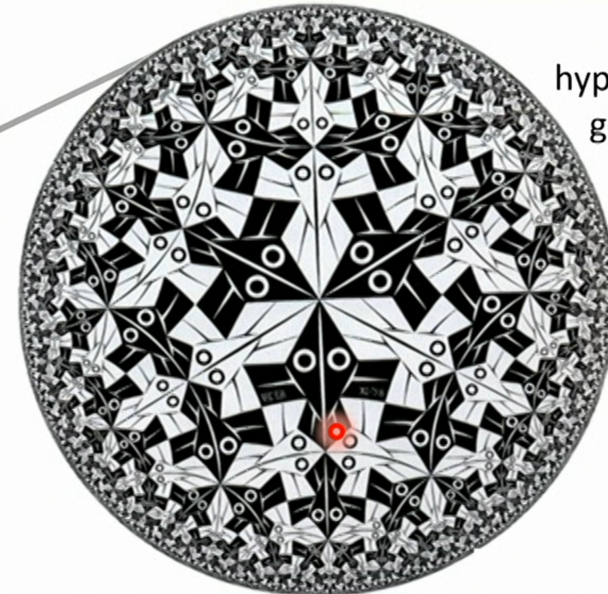
Mapping on experimental reality

M.C. Escher & S.N. Bose, A. Einstein





hyperbolic geometry

finite extension

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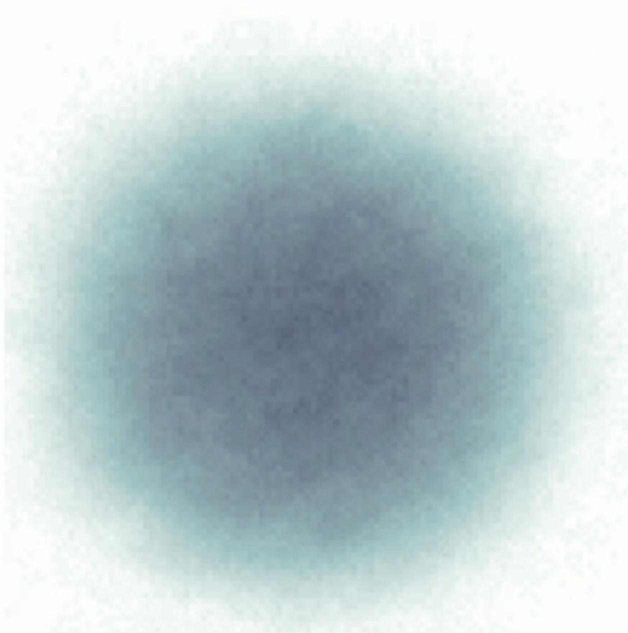
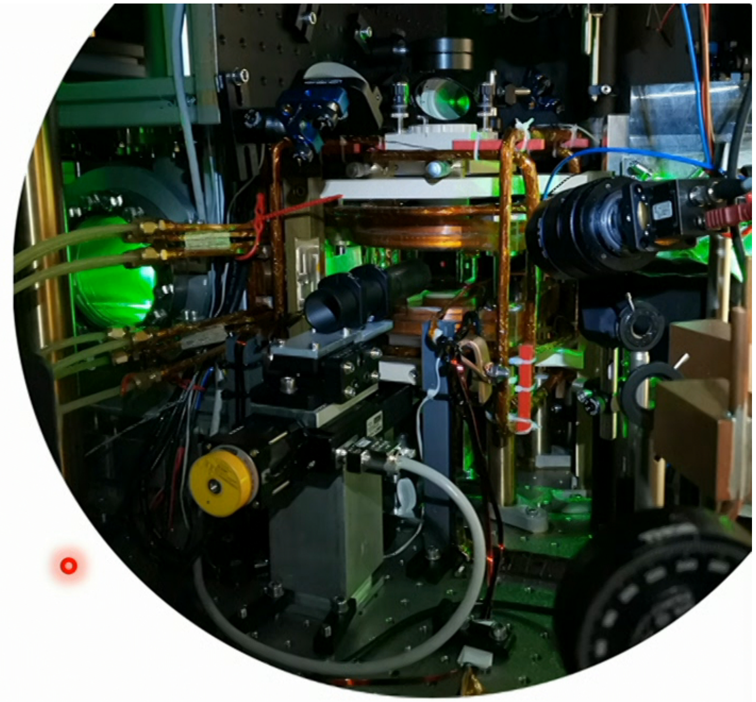
2D Bose gase – potassium 39





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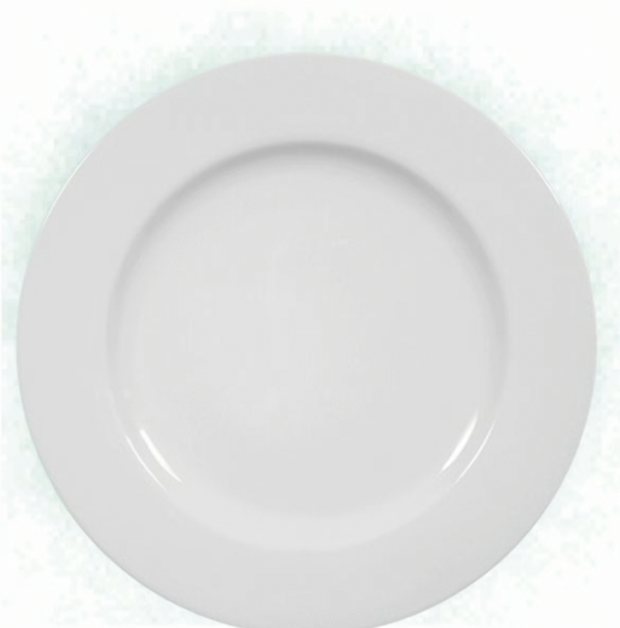

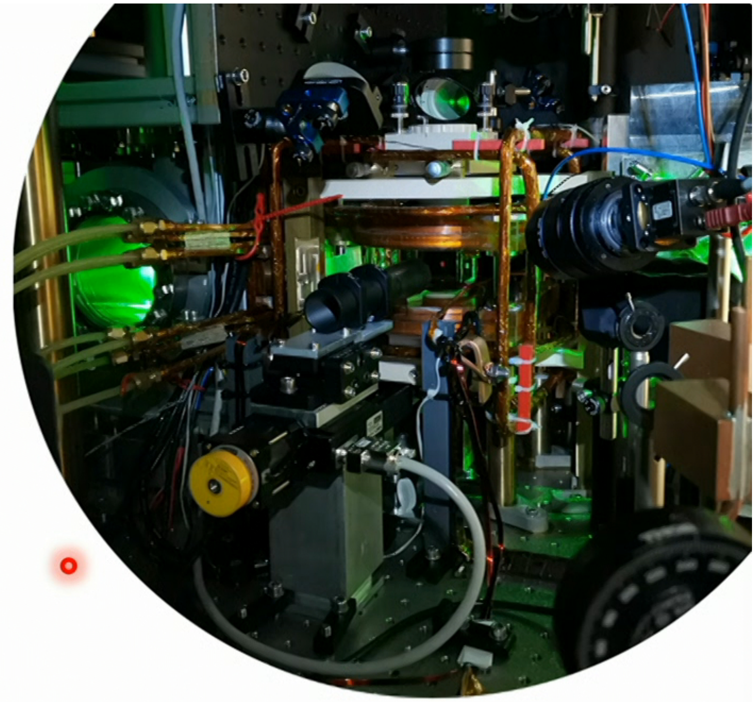

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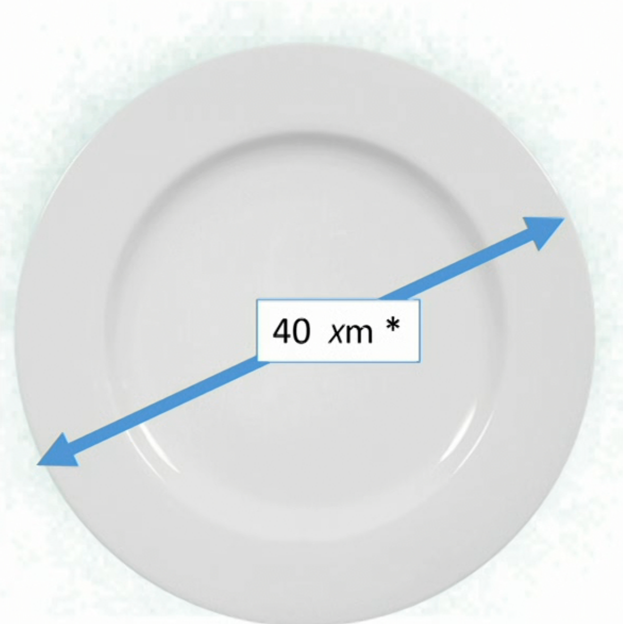
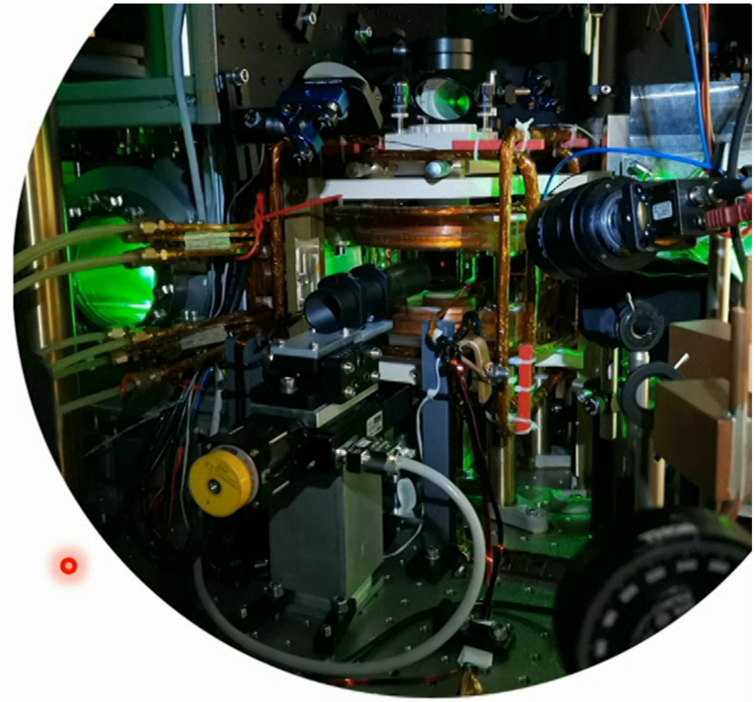
2D Bose gase – potassium 39





* x = μ

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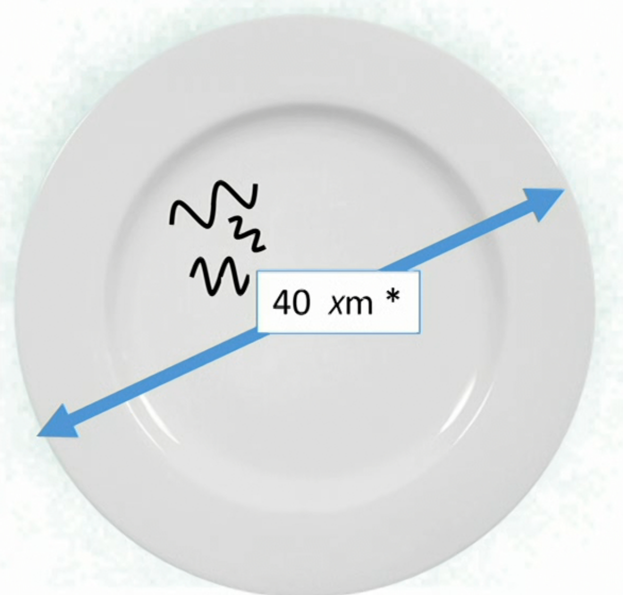
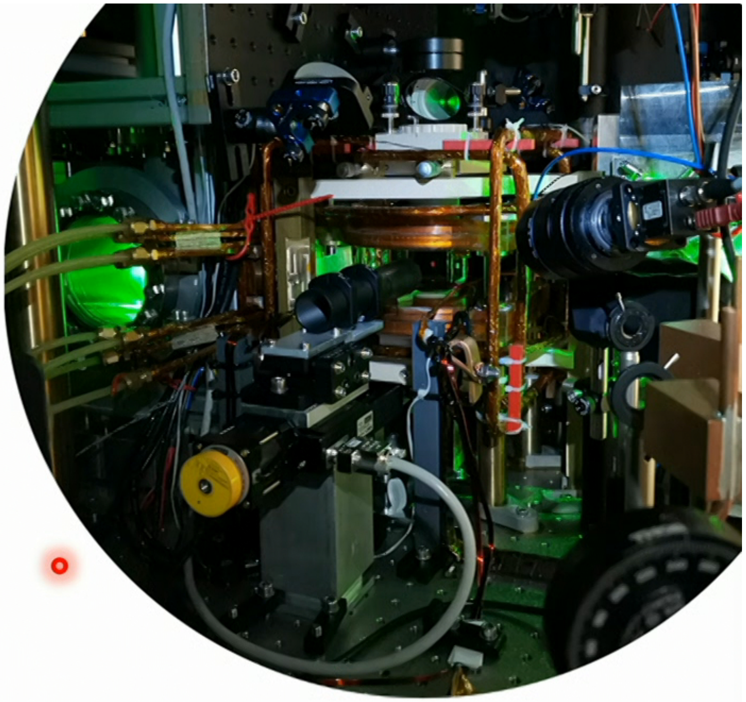
2D Bose gase – potassium 39





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$* \; x = \mu$

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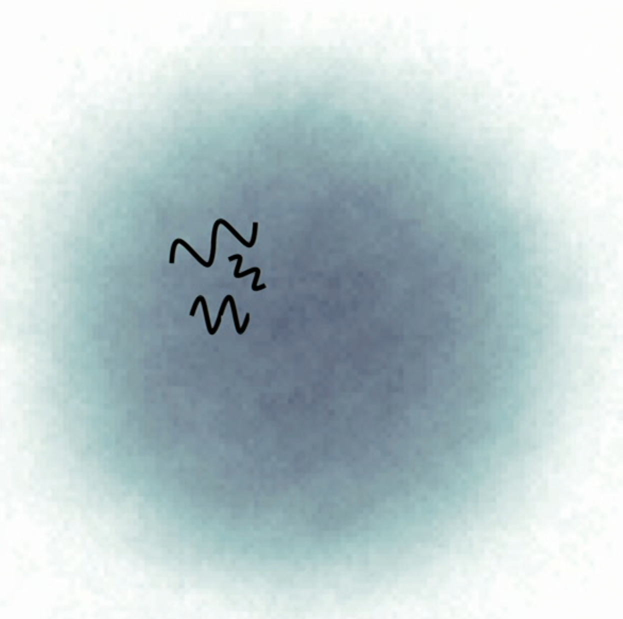
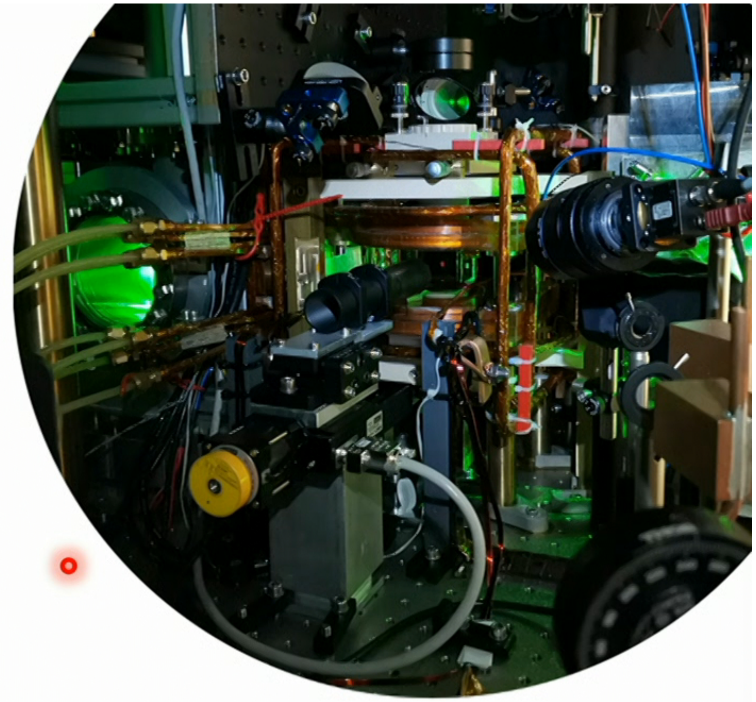
2D Bose gase – potassium 39





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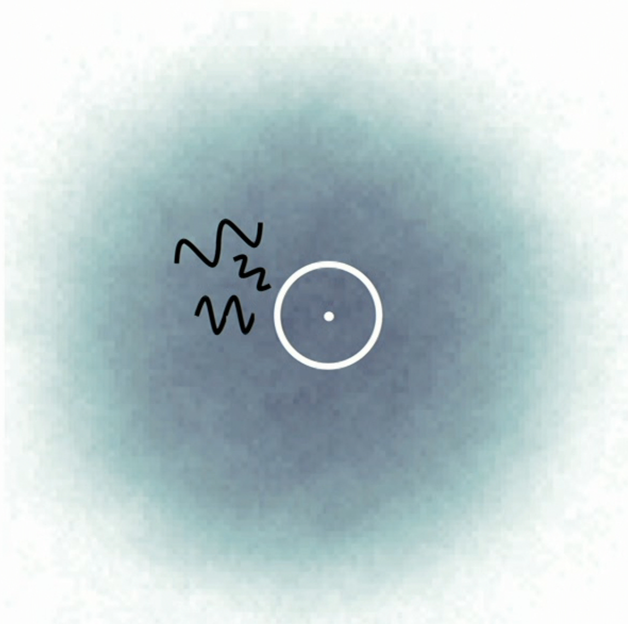
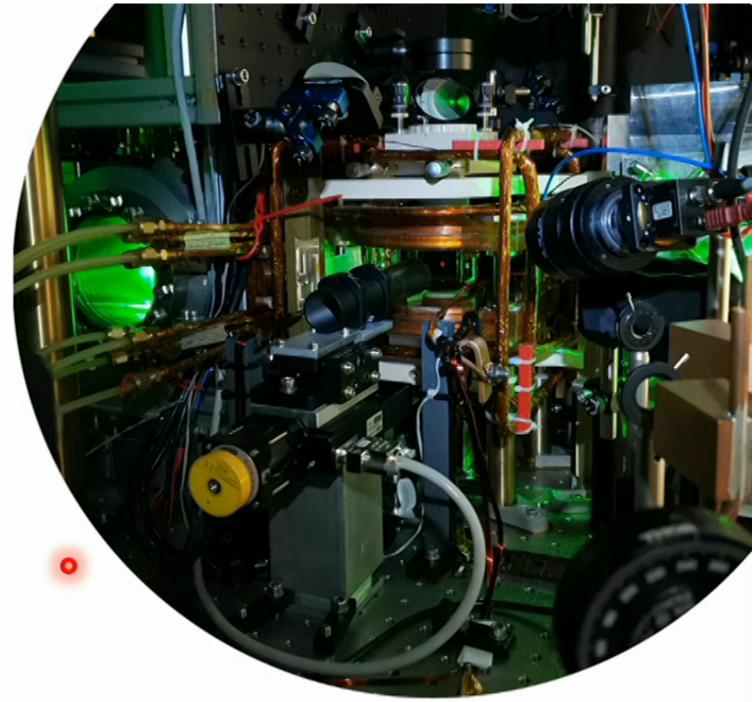
2D Bose gase – potassium 39





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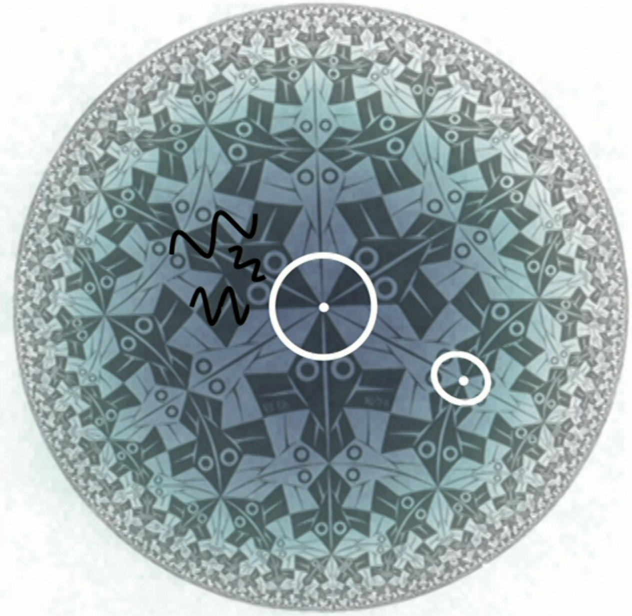
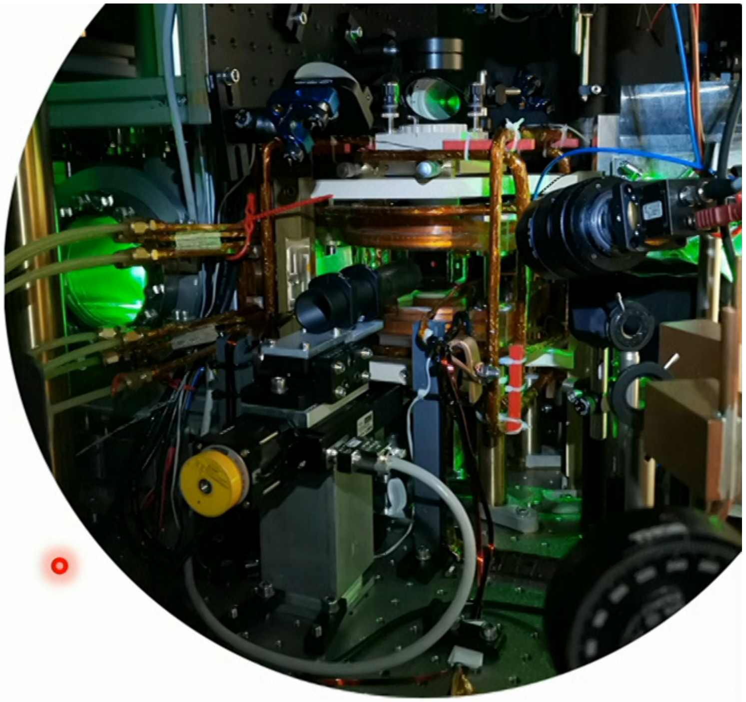
2D Bose gase – potassium 39





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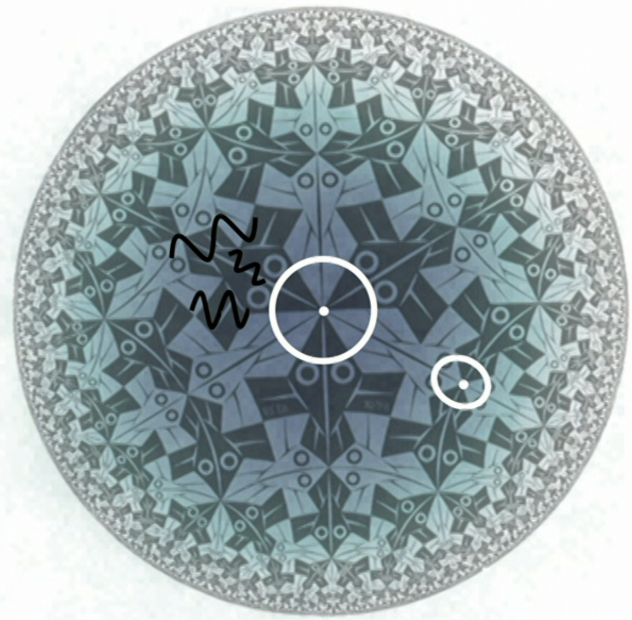
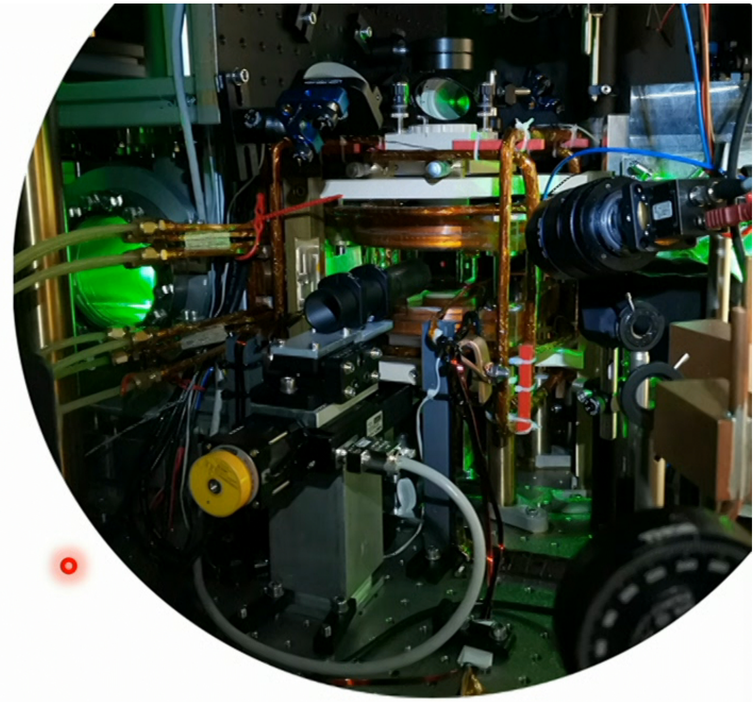
STRUCTURES CLUSTER OF EXCELLENCE

2D Bose gase – potassium 39

$$\Phi(t,\boldsymbol{r}) = \phi_0(t,\boldsymbol{r}) + \frac{1}{\sqrt{2}}\left[\phi_1(t,\boldsymbol{r}) + i\phi_2(t,\boldsymbol{r})\right]$$





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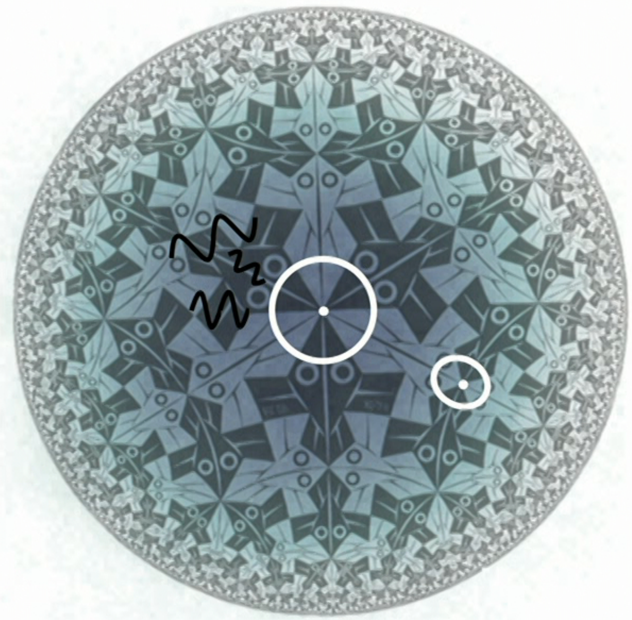
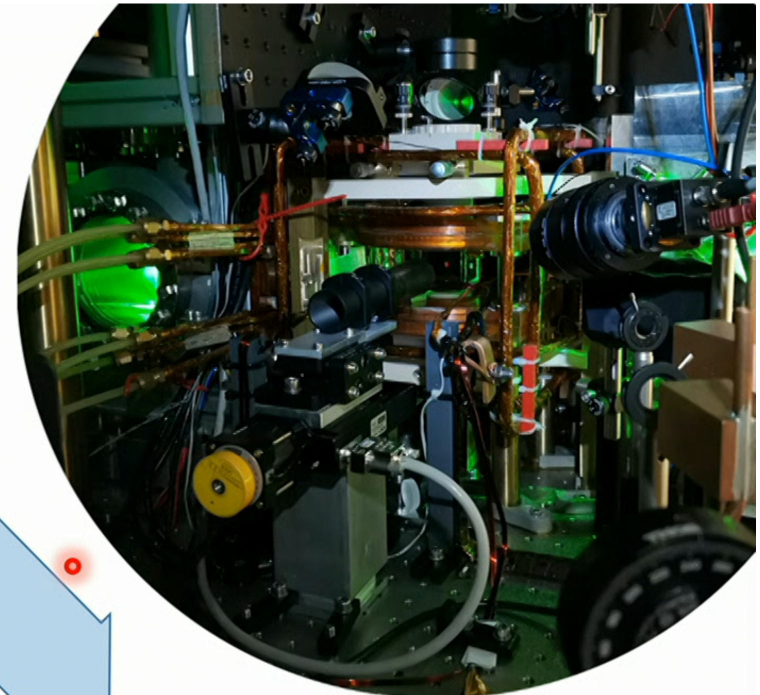


see details in
PRA **106**, 033313 (2022)

Stefan Flörchinger



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

ϕ is the imaginary part of the phononic field

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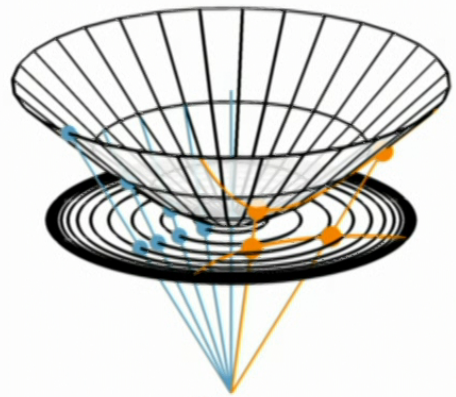
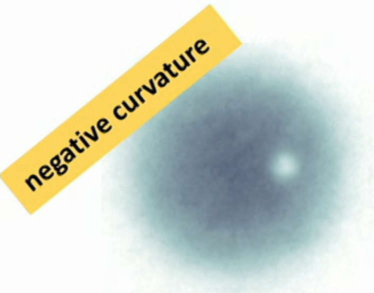
STRUCTURES CLUSTER OF EXCELLENCE

Hyperbolic to spherical

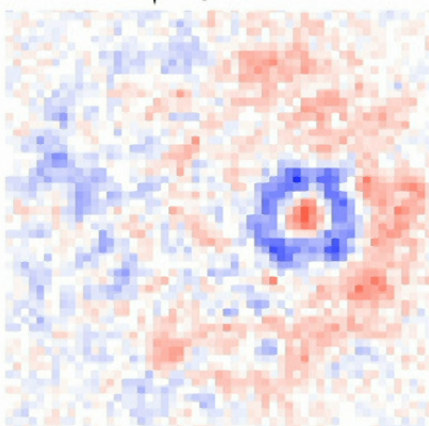
Bizar density distribution leads to positive **curvature**

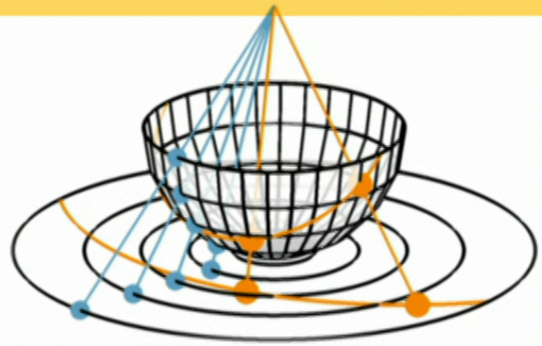


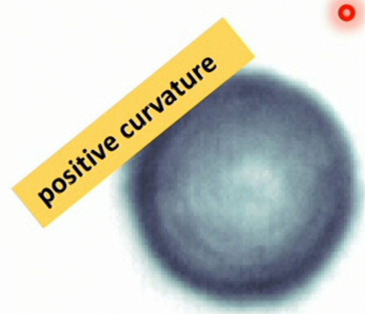


density contrast

$$\delta_c(t,u,\varphi) = \sqrt{\frac{n_0(u)}{\bar{n}_0^3}}\,[n(t,u,\varphi) - n_0(u)]$$







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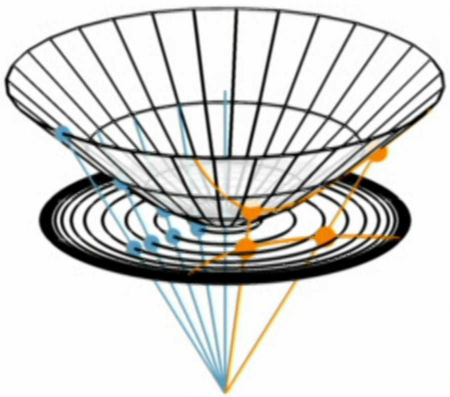
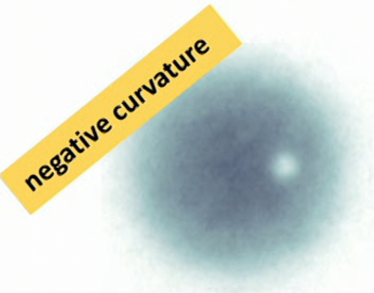
STRUCTURES CLUSTER OF EXCELLENCE

Hyperbolic to spherical





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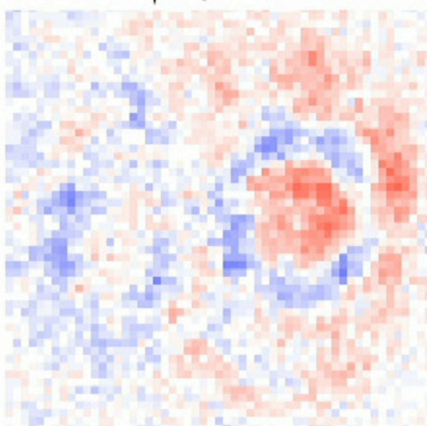

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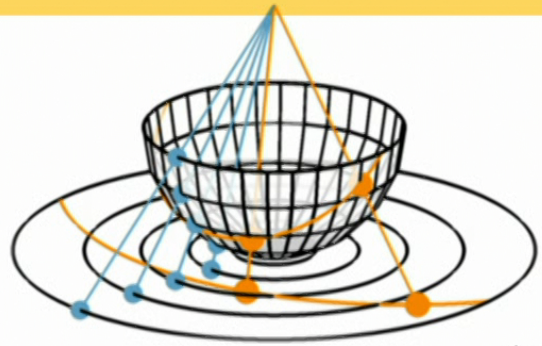

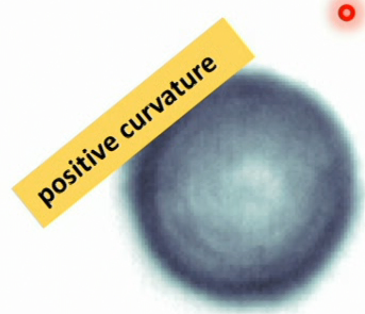

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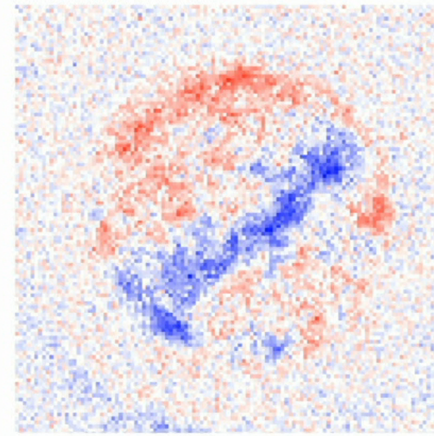

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STRUCTURES CLUSTER OF EXCELLENCE

Mapping on experimental reality

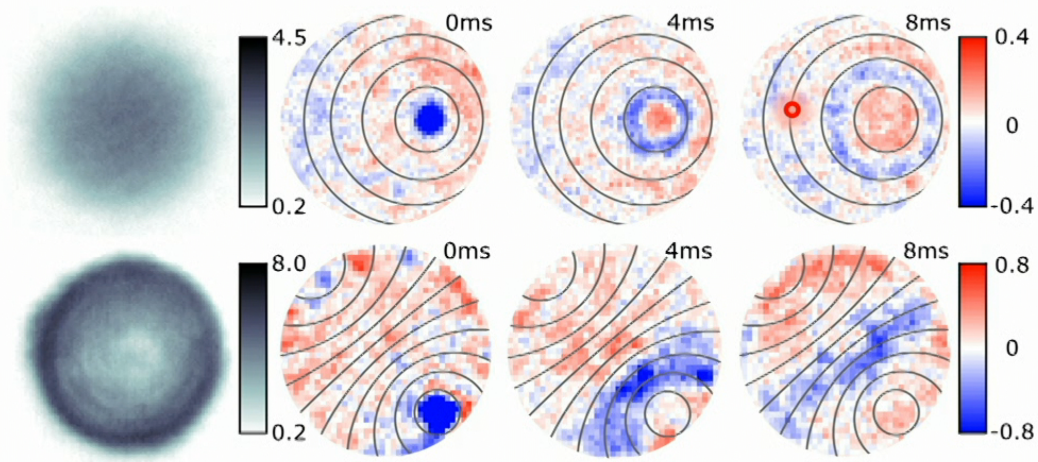
how 2D infinite curved space fits on a flat disc

infinite extension

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

Hyperbolical: $\boldsymbol{\kappa < 0}$

Spherical: $\boldsymbol{\kappa > 0}$



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Viermann et. al, *Nature* **611**, 260-264 (2022)

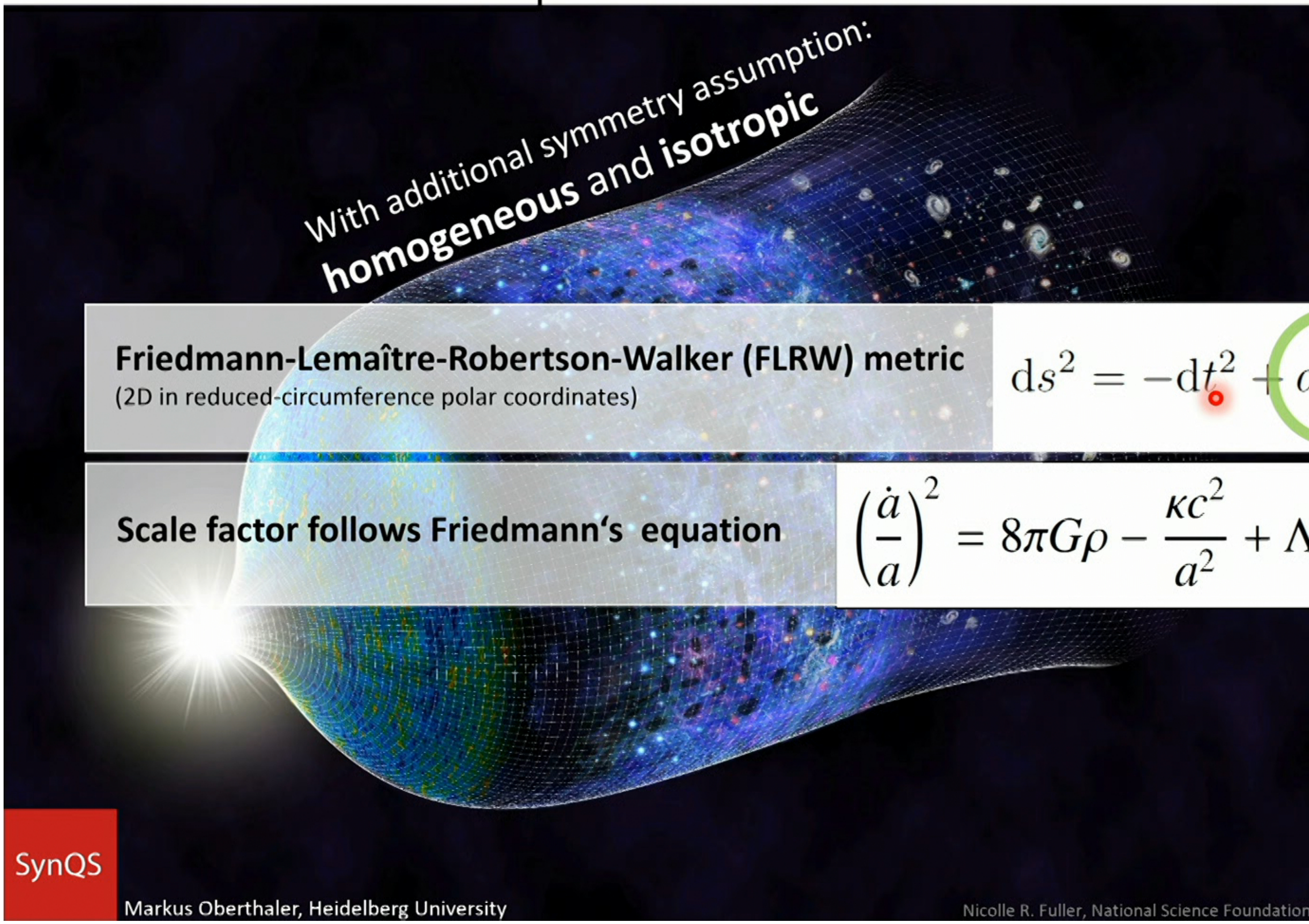
STRUCTURES CLUSTER OF EXCELLENCE

Inspiration for questions

Cosmology

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

$$ds^2 \equiv g_{\mu\nu}\, dx^\mu dx^\nu$$



Friedmann-Lemaître-Robertson-Walker (FLRW) metric
(2D in reduced-circumference polar coordinates)

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

Scale factor follows Friedmann's equation

$$\left(\frac{\dot{a}}{a}\right)^2 = 8\pi G\rho - \frac{\kappa c^2}{a^2} + \Lambda c^2\,, \quad \frac{\ddot{a}}{a} = -\frac{8\pi G}{c^2}P + \Lambda c^2$$

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STRUCTURES CLUSTER OF EXCELLENCE

Inspiration for questions

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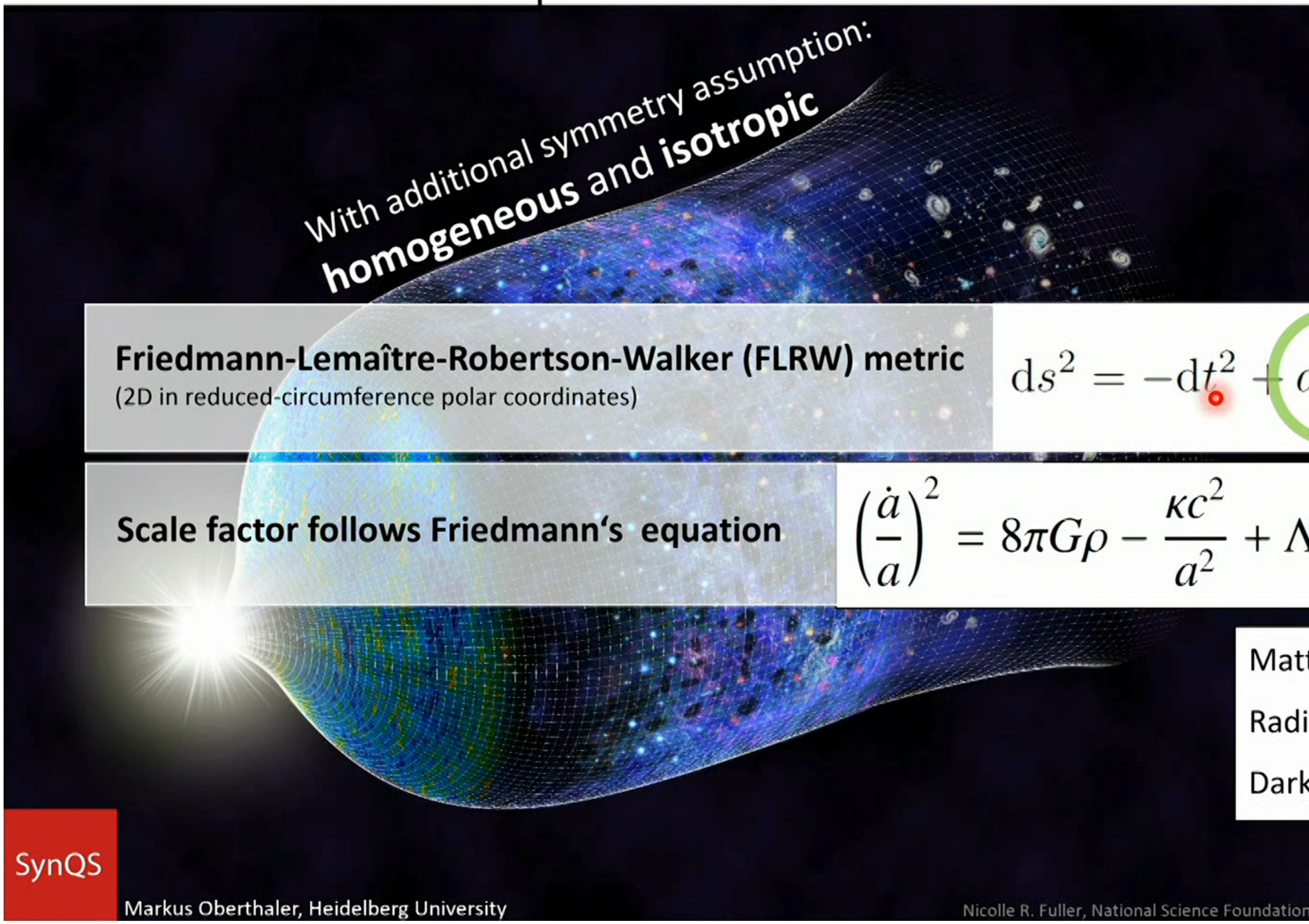

With additional symmetry assumption: **homogeneous** and **isotropic**

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

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Matter dominated	$a(t) \propto t$
Radiation dominated	$a(t) \propto t^{2/3}$
Dark energy dominated	$a(t) \propto t^{\sqrt{\Lambda}c}$

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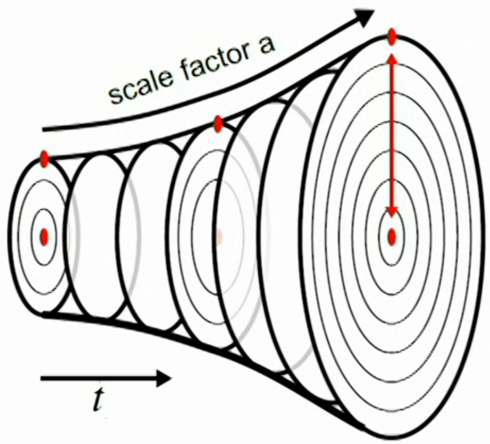
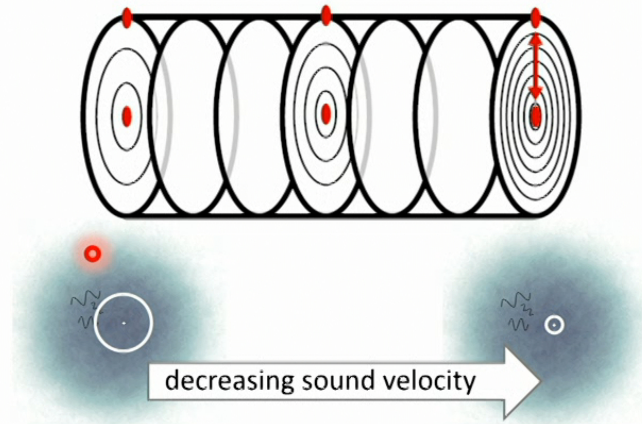
STRUCTURES CLUSTER OF EXCELLENCE

Expansion with motionless BEC



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

Change of metric in time



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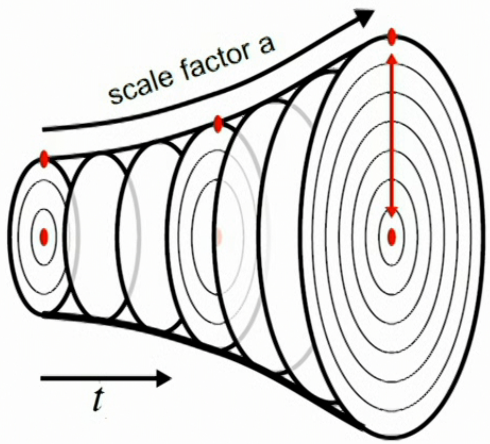
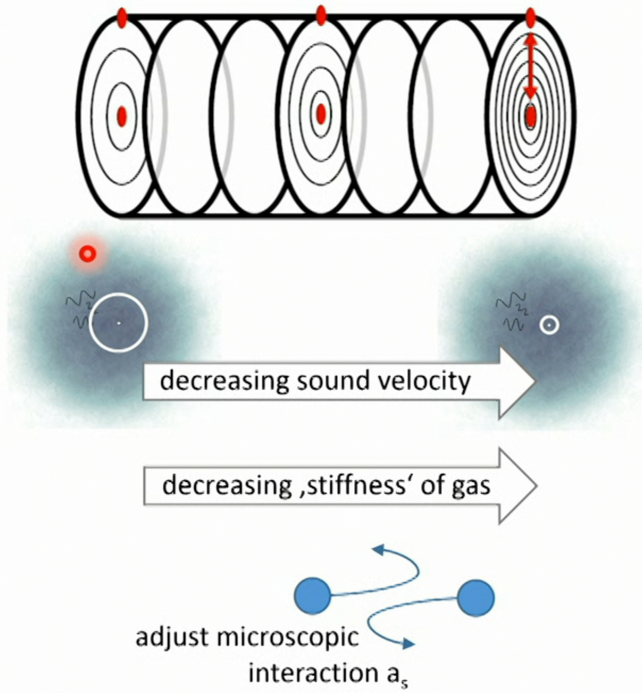


$$ds^2 = -dt^2 + a^2(t)\left(du^2 + u^2 d\varphi^2\right)$$

Change of metric in time



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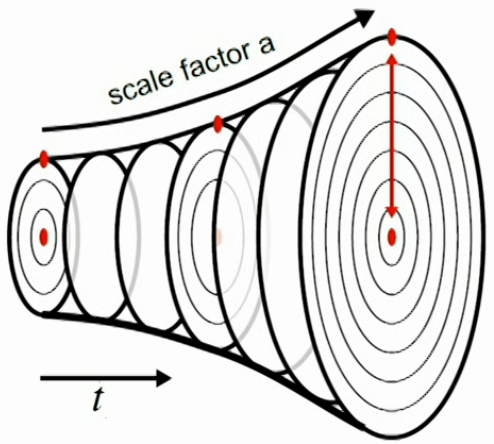
Change of metric in time



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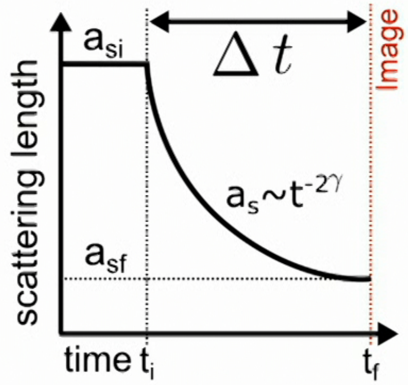
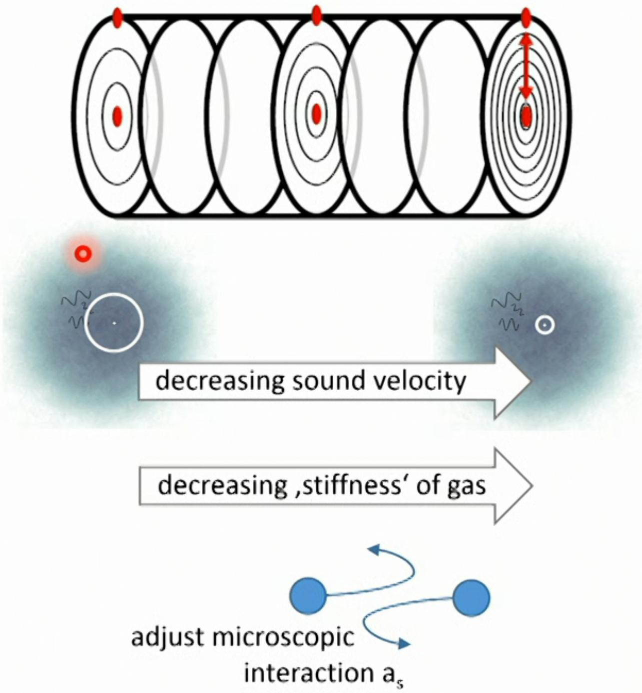


$$a(t) \propto t^{\gamma}$$

solution to Friedmann's equation

$$\gamma = \frac{2}{d(1+w)}$$

$$P = w\rho$$



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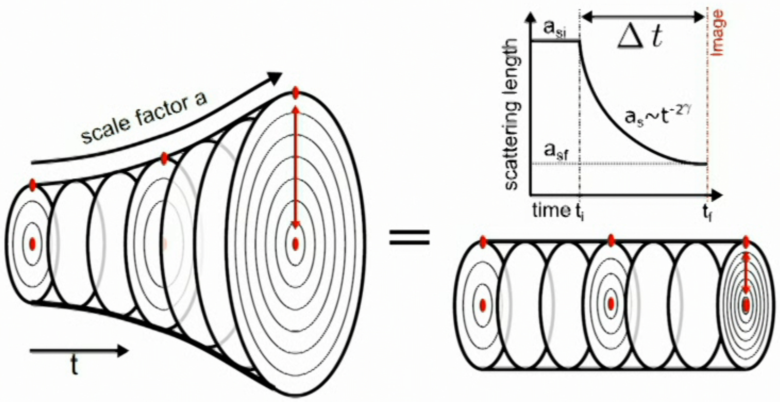
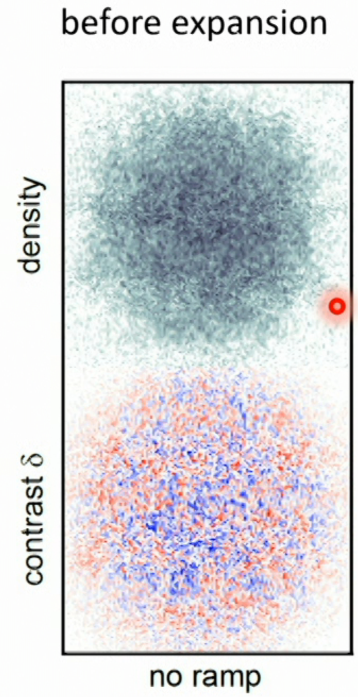
STRUCTURES CLUSTER OF EXCELLENCE

Particle production in accelerated space-time

Experimental data – quantum field simulator result





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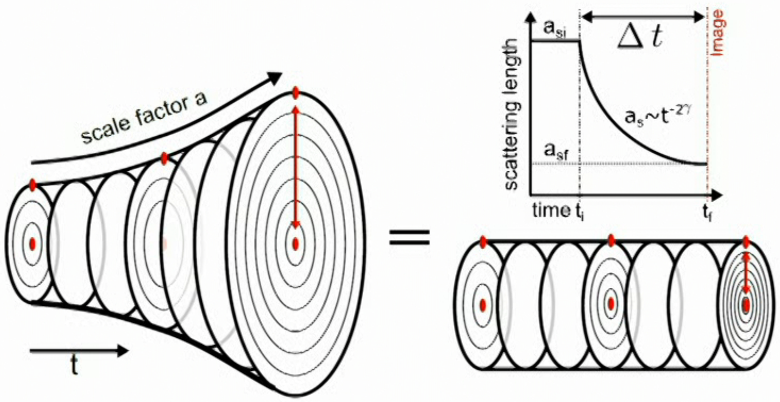

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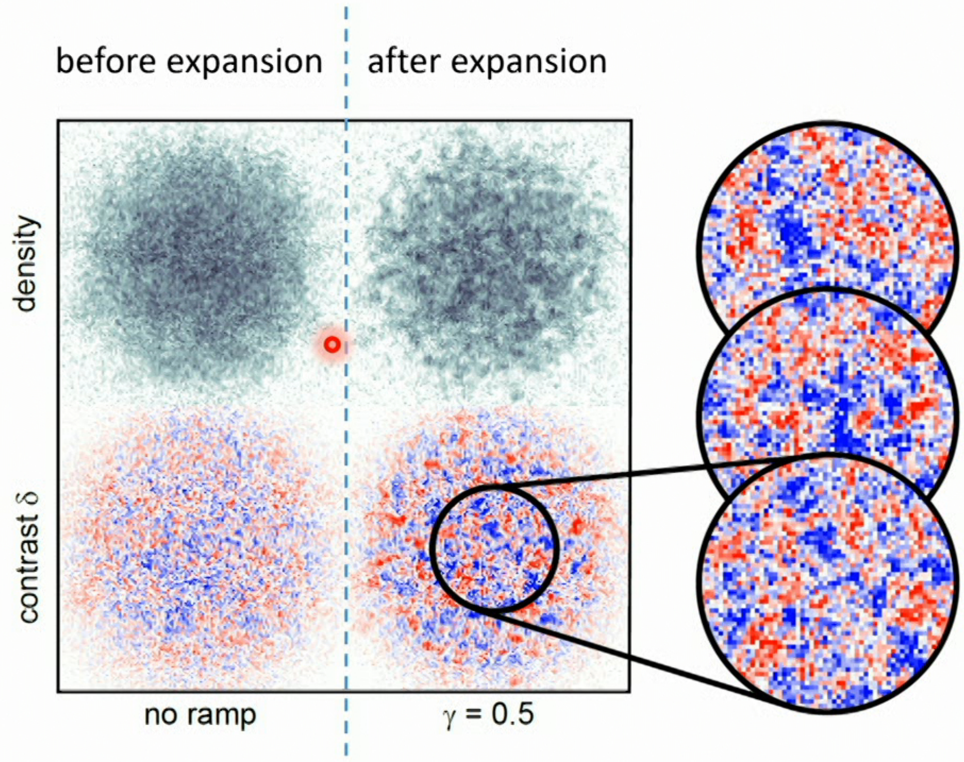

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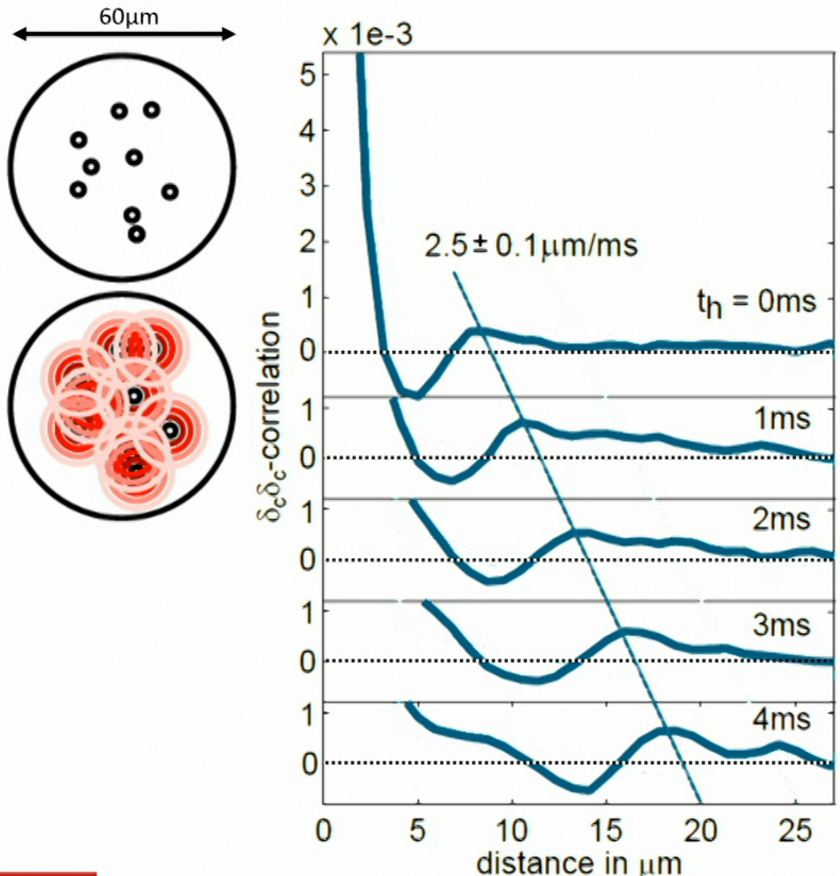
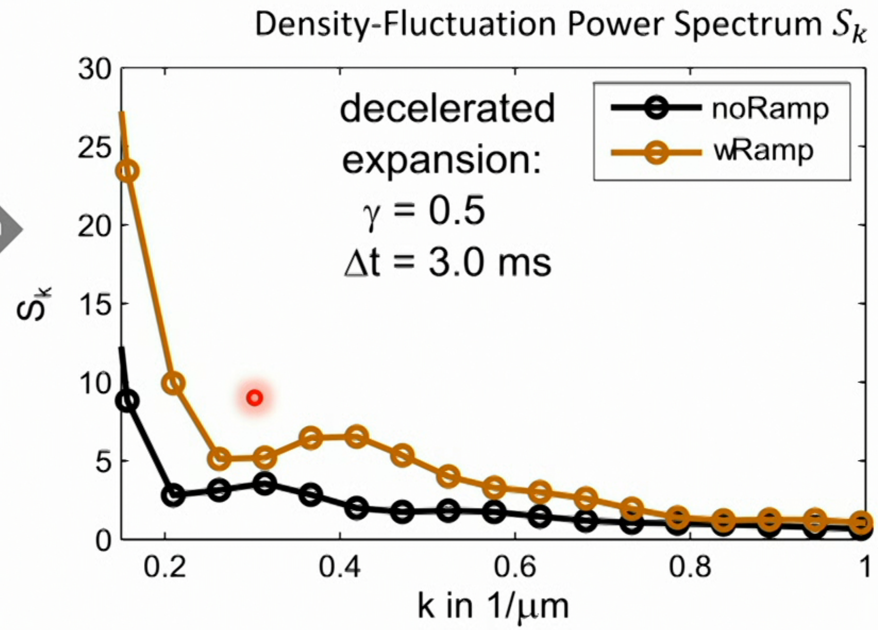
STRUCTURES CLUSTER OF EXCELLENCE

Detection scheme building on Sakharov oscillations

Benchmark with new analytical solutions



Hankel transform



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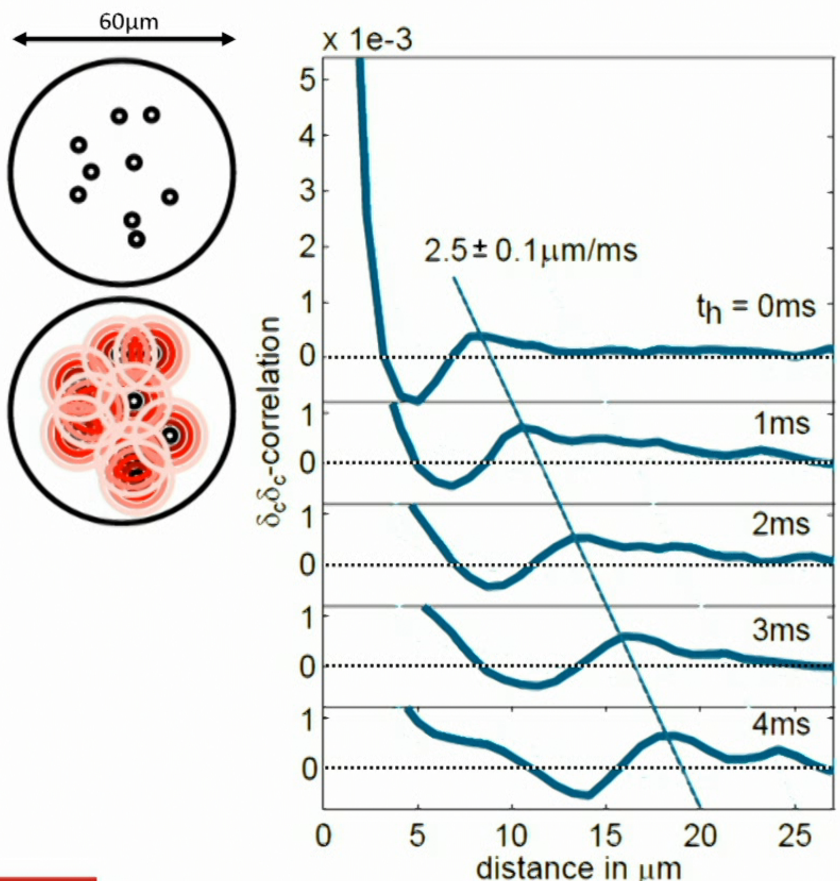
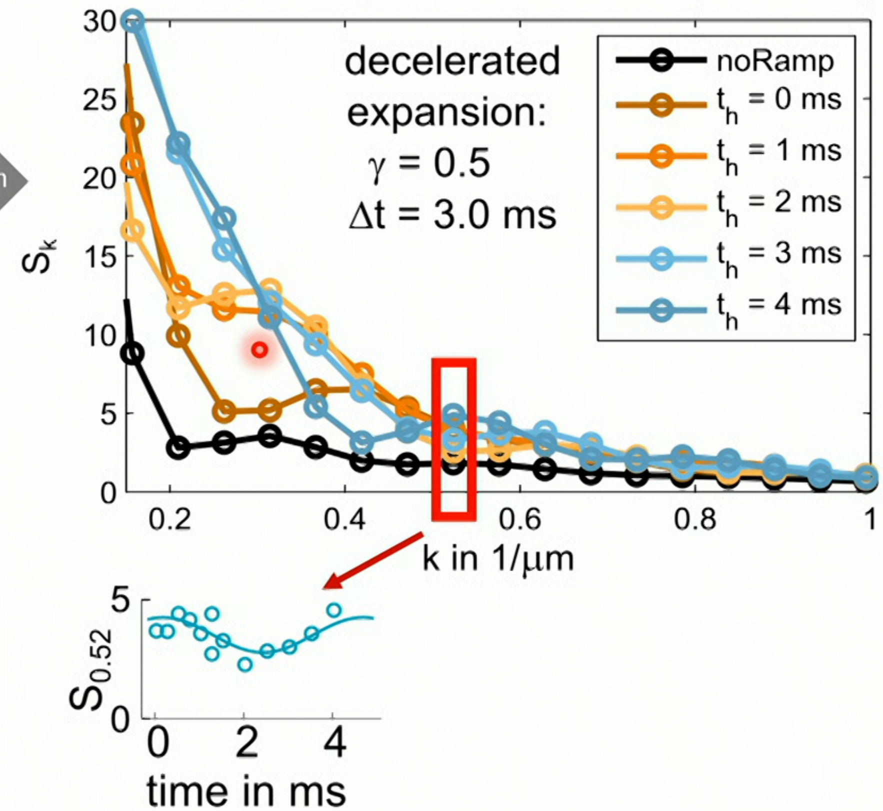


Hankel transform

Benchmark with new analytical solutions

Density-Fluctuation Power Spectrum S_k



Hung et al. *Science* **341**, 1213–1215 (2013)

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STRUCTURES CLUSTER OF EXCELLENCE

$$a(t) \propto t^{\gamma}$$

solution to Friedmann's equation

$$\gamma = \frac{2}{d(1+w)}$$

$$P = w\rho$$

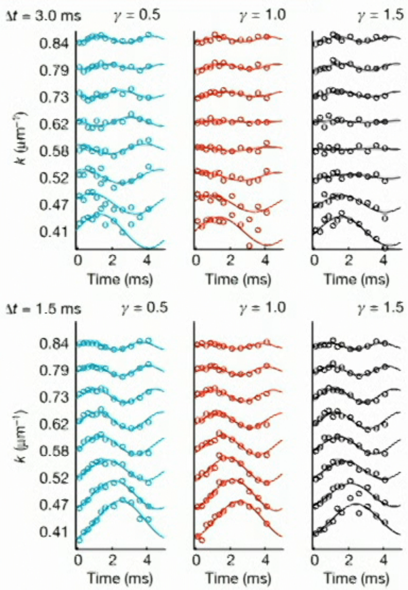
$\gamma = 0.5$ decelerated expansion

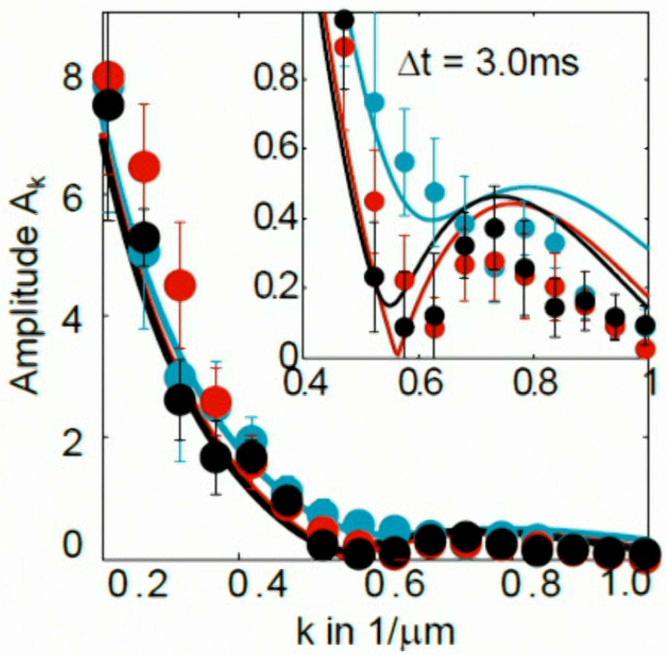
$\gamma = 1.0$ constant expansion

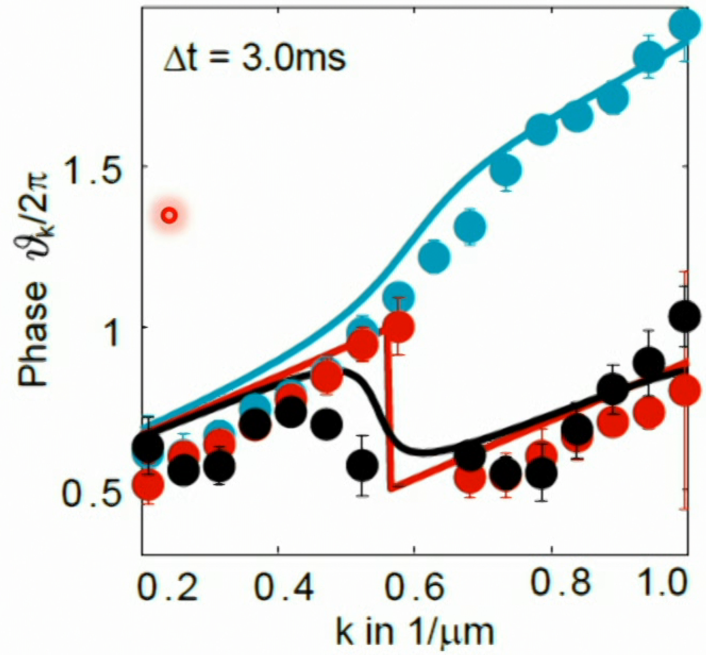
$\gamma = 1.5$ accelerated expansion

Benchmark with new analytical solutions

$$S_k(t) = \frac{1}{2} + N_k + A_k \cos(2\omega_k t + \vartheta_k)$$







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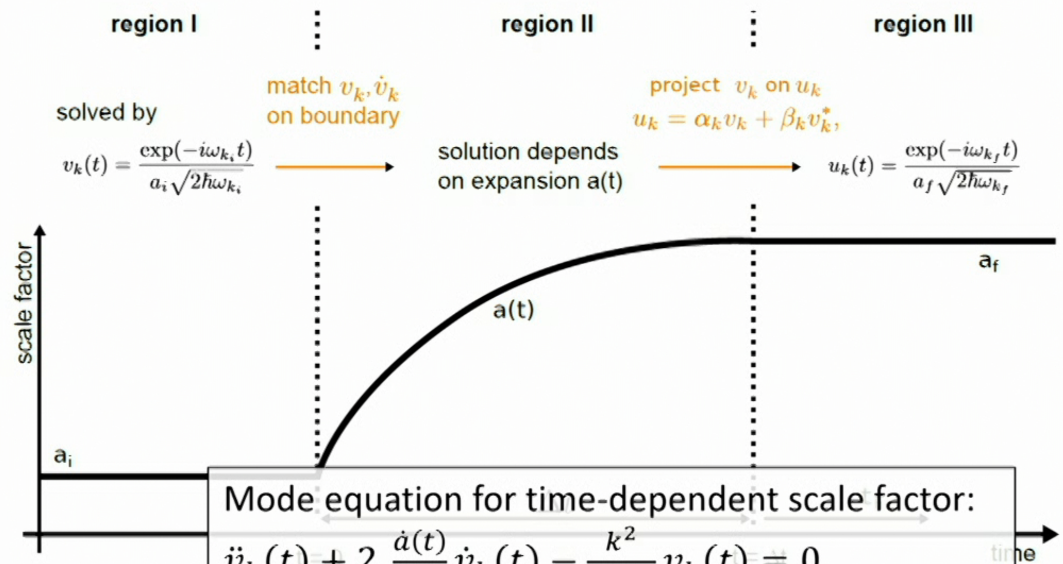
Expansion history

‚New ‚phenomenon – certain modes are not occupied after expansion



Mode equation for time-dependent scale factor:

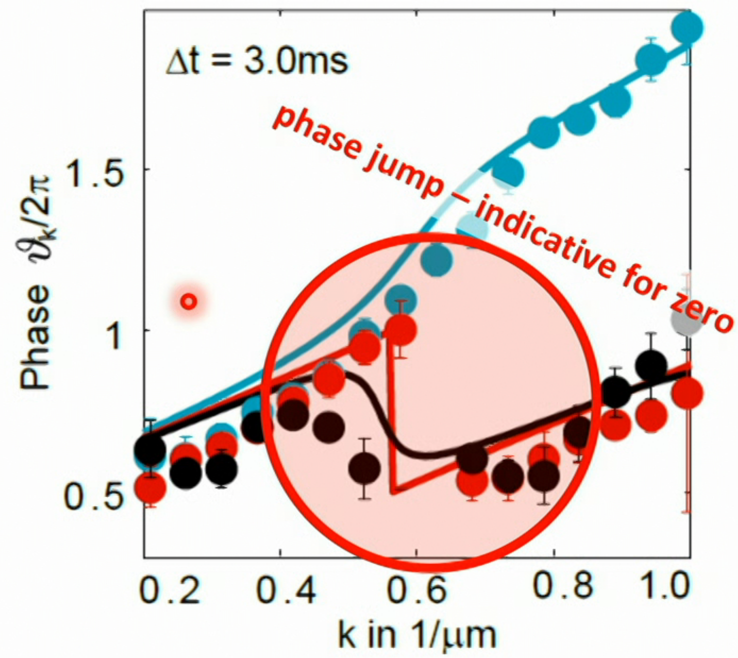
$$\ddot{v}_k(t) + 2\,\frac{\dot{a}(t)}{a(t)}\,\dot{v}_k(t) - \frac{k^2}{a^2(t)}\,v_k(t) = 0$$

rescaled mode function $\psi_k(\eta) = \sqrt{a(t)}\,v_k(t)$
conformal time $dt = a(t)\,d\eta$

$$\frac{d^2}{d\eta^2}\psi_k(\eta) + \left(k^2 - \left(\frac{1}{4}\dot{a}^2 + \frac{1}{2}\ddot{a}a\right)\right)\psi_k(\eta) = 0$$

„stationary Schrödinger equation“

$$S_k(t) = \frac{1}{2} + N_k + A_k\cos(2\omega_k t + \vartheta_k)$$



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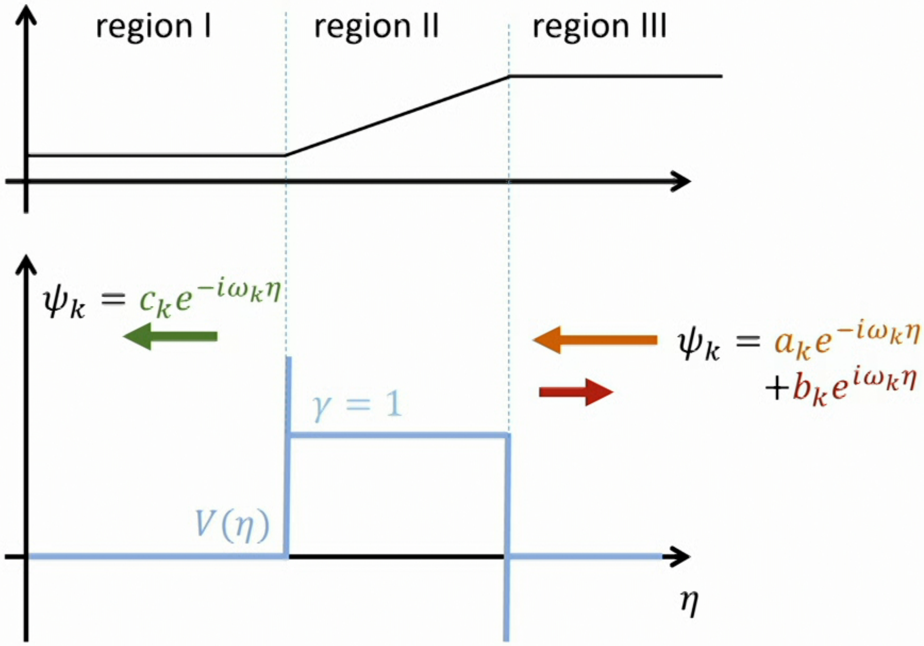
‚Atomic physics‘

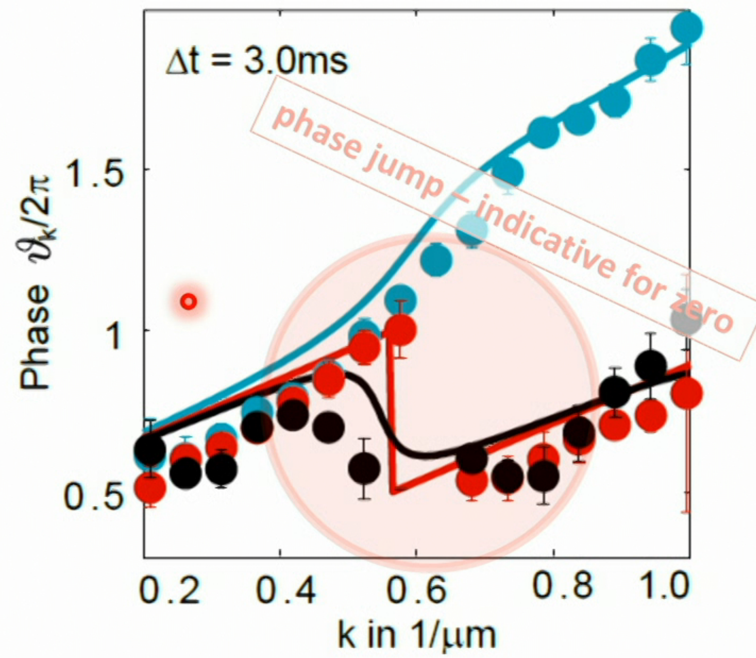
„stationary Schrödinger equation“

$$\boxed{\frac{d^2}{d\eta^2}\psi_k(\eta) + \left(k^2 - \left(\frac{1}{4}\dot{a}^2 + \frac{1}{2}\ddot{a}a\right)\right)\psi_k(\eta) = 0}$$



Ramsauer-Townsend effect in cosmology

$$S_k(t) = \frac{1}{2} + N_k + A_k cos(2\omega_k t + \vartheta_k)$$



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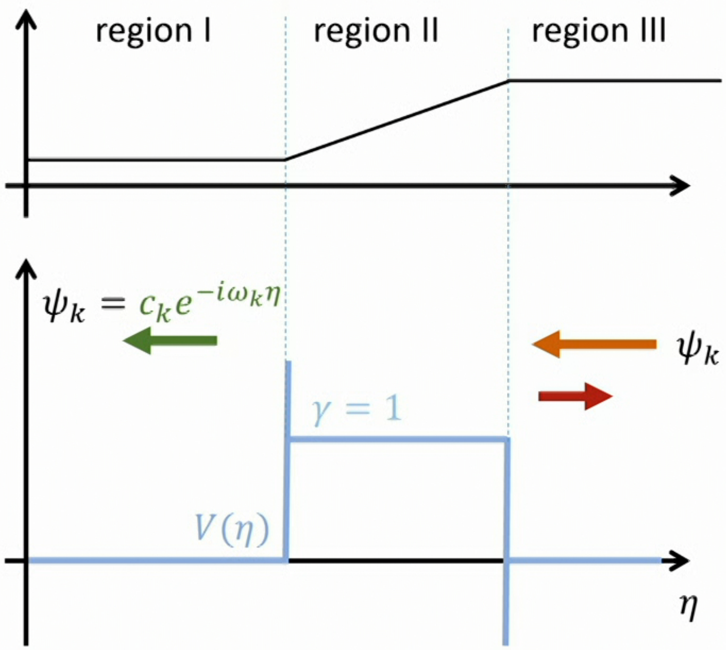
‚Atomic physics‘

„stationary Schrödinger equation“

$$\boxed{\frac{d^2}{d\eta^2}\psi_k(\eta) + \left(k^2 - \left(\frac{1}{4}\dot{a}^2 + \frac{1}{2}\ddot{a}a\right)\right)\psi_k(\eta) = 0}$$

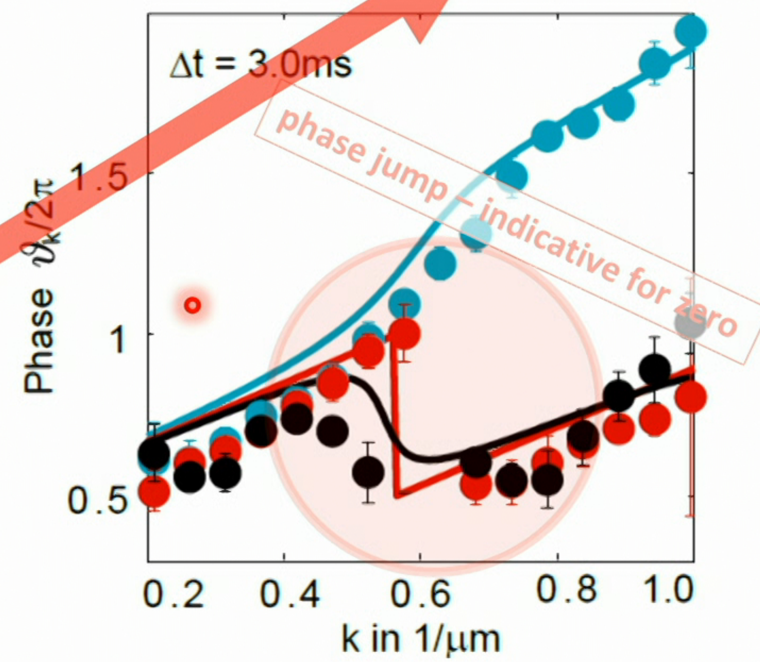


$$\psi_k = a_k e^{-i\omega_k\eta} + b_k e^{i\omega_k\eta}$$

Ramsauer-Townsend effect in cosmology

$$S_k(t) = \frac{1}{2} + N_k + A_k \cos(2\omega_k t + \vartheta_k)$$

$$\boxed{A_k = \frac{|R_k|}{|T_k|^2}}$$



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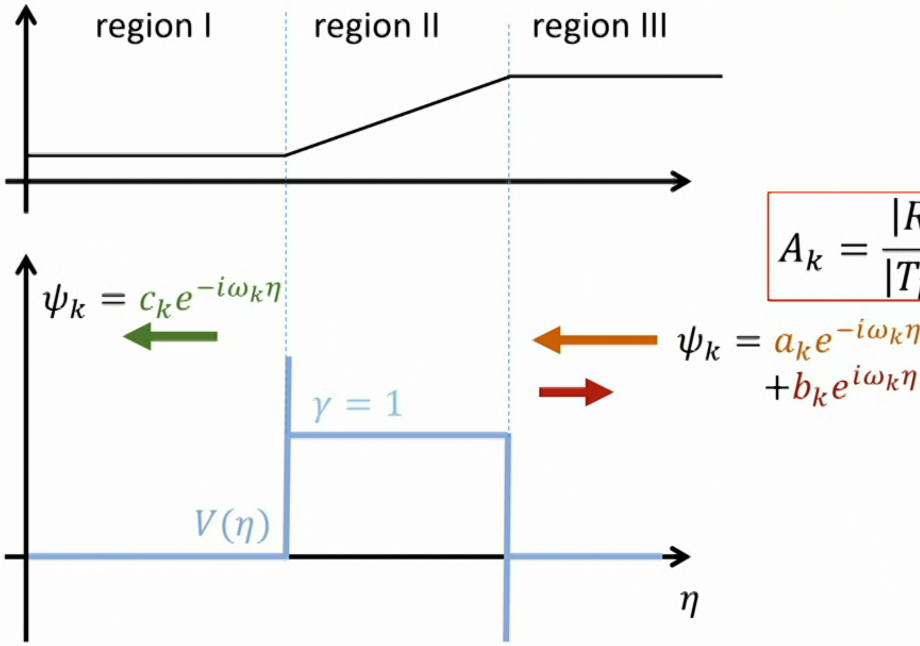

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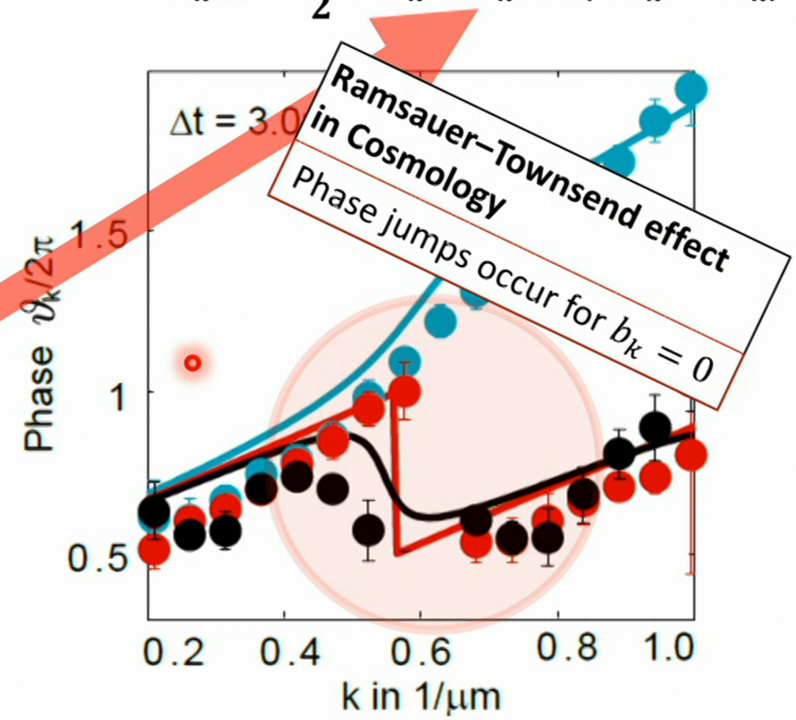

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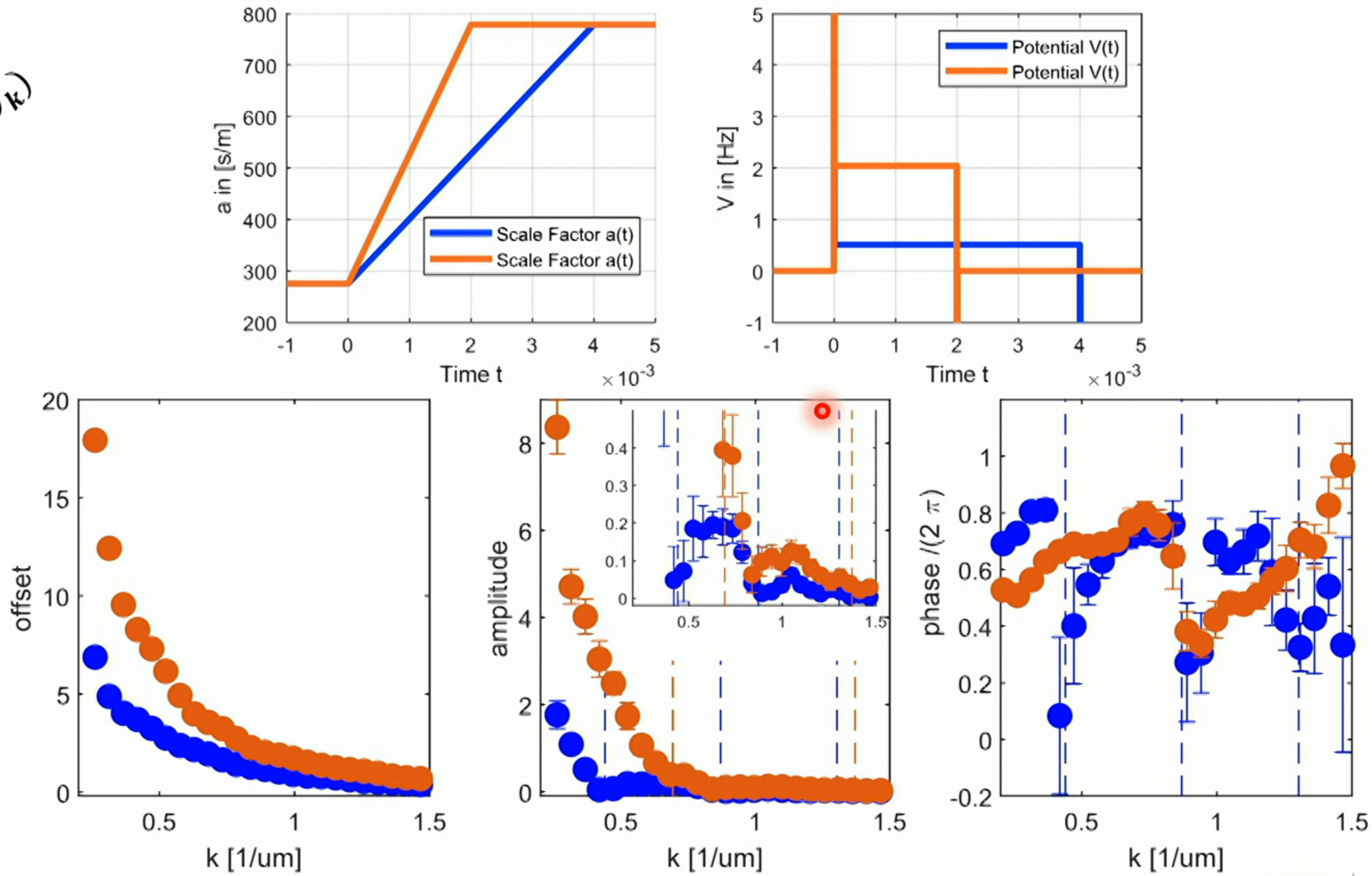

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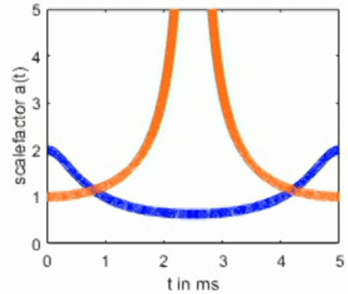
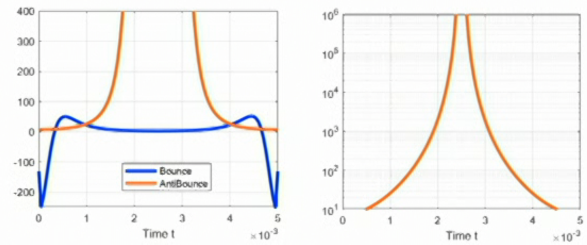
Single bounce and anti-bounce

Question about history – what is forgotten in the bounce

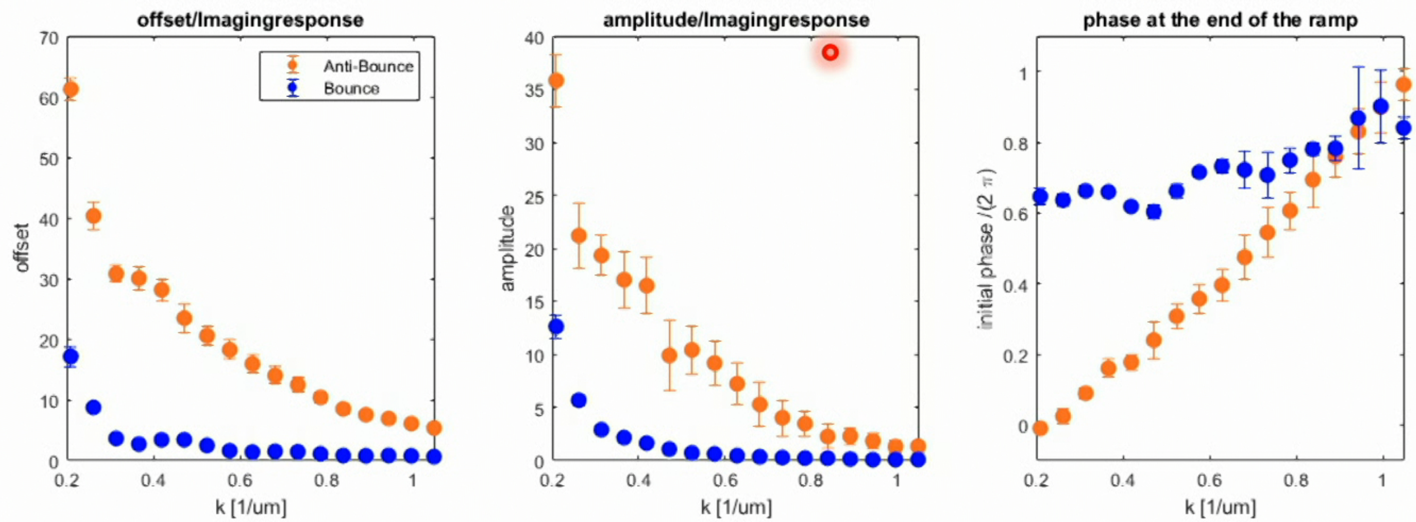
Bounce



Potentials [Hz]



$$S_k(t) = \frac{1}{2} + N_k + A_k cos(2\omega_k t + \vartheta_k)$$



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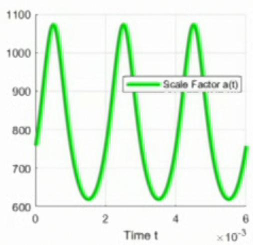
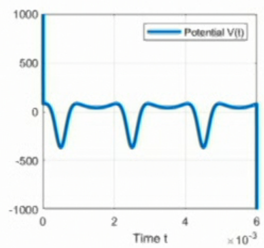
Many bounces

Transition from cosmological picture and parameteric resonance





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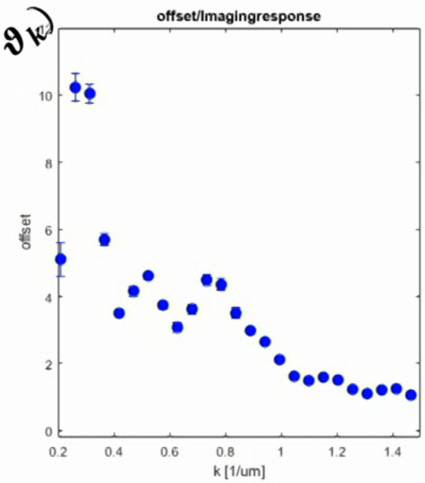

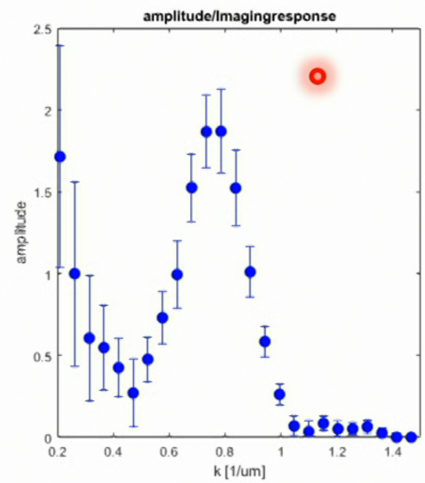

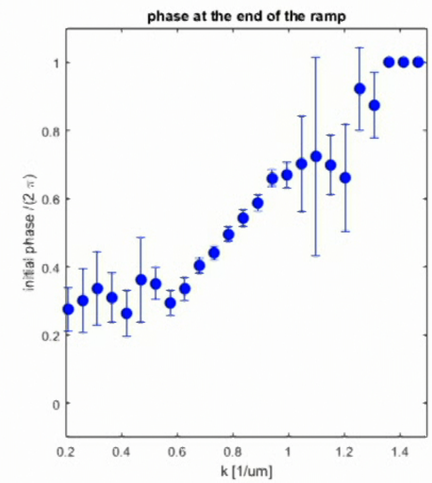

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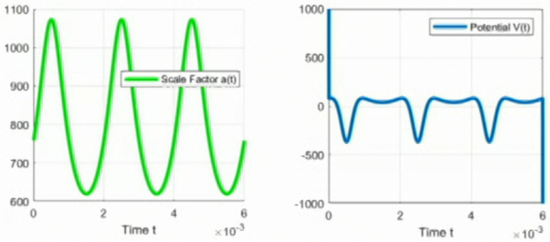

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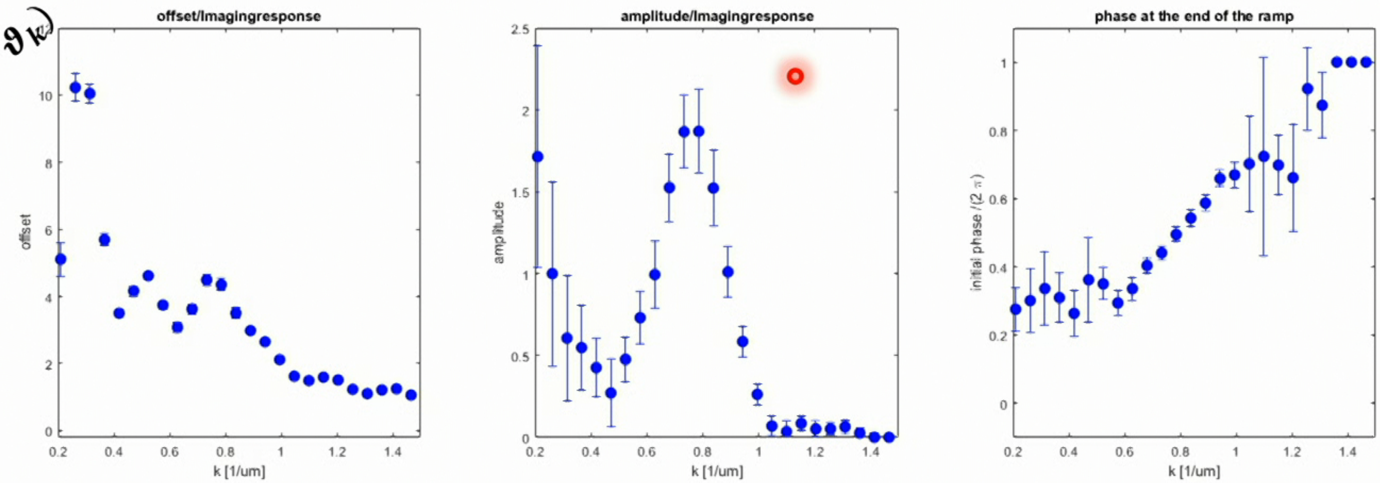

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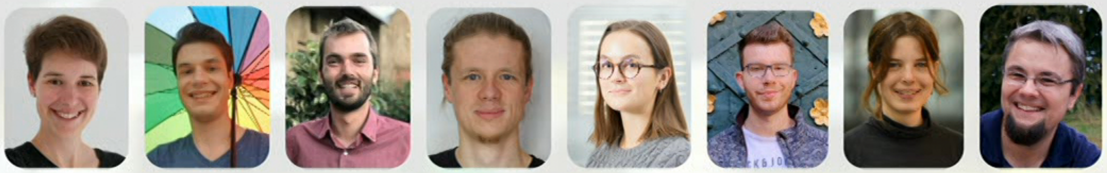

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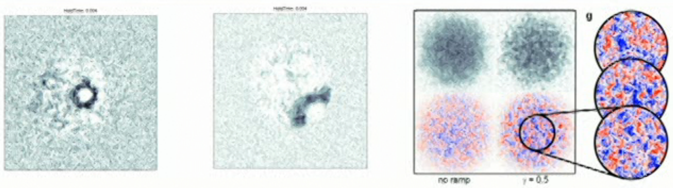
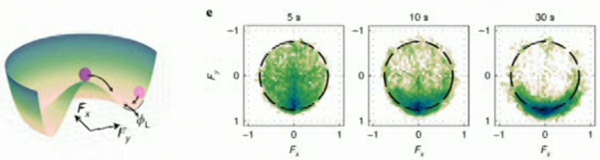
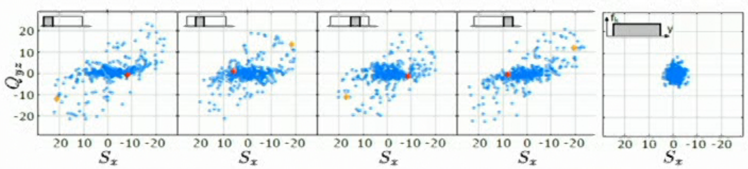


Quantum field simulator for dynamics in curved spacetime
Nature **611**, 260 (2022)

Curved and expanding spacetime geometries in BECs
PRA **106**, 033313 (2022)



Condensation and thermalization of an easy-plane ferromagnet
Nature Physics **18**, 1459 (2022)



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

Experiment: H. Strobel

Rubidium:

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S. Lannig
M. Prüfer (Vienna)

Potassium:

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E. Kath
N. Liebster
M. Sparn
C. Viermann

Theorie:

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M. Gärttner (Jena)
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