The structure of the early cosmos in a Bose-Einstein condensate

Stefan Floerchinger (Uni Jena)

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STRUCTURES CLUSTER OF EXCELLENCE

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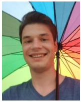
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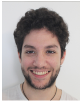
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- Celia Viermann, Marius Sparn, Nikolas Liebster, Maurus Hans, Elinor Kath, Álvaro Parra-López, Mireia Tolosa-Simeón, Natalia Sánchez-Kuntz, Tobias Haas, Helmut Strobel, Stefan Floerchinger, Markus K. Oberthaler, *Quantum field simulator for dynamics in curved spacetime*, arXiv:2202.10441
- Mireia Tolosa-Simeón, Álvaro Parra-López, Natalia Sánchez-Kuntz, Tobias Haas, Celia Viermann, Marius Sparn, Nikolas Liebster, Maurus Hans, Elinor Kath, Helmut Strobel, Markus K. Oberthaler, Stefan Floerchinger, *Curved and expanding spacetime geometries in Bose-Einstein condensates*, arXiv:2202.10399
- Natalia Sánchez-Kuntz, Álvaro Parra-López, Mireia Tolosa-Simeón, Tobias Haas, Stefan Floerchinger, *Scalar quantum fields in cosmologies with 2+1 spacetime dimensions*, arXiv:2202.10440

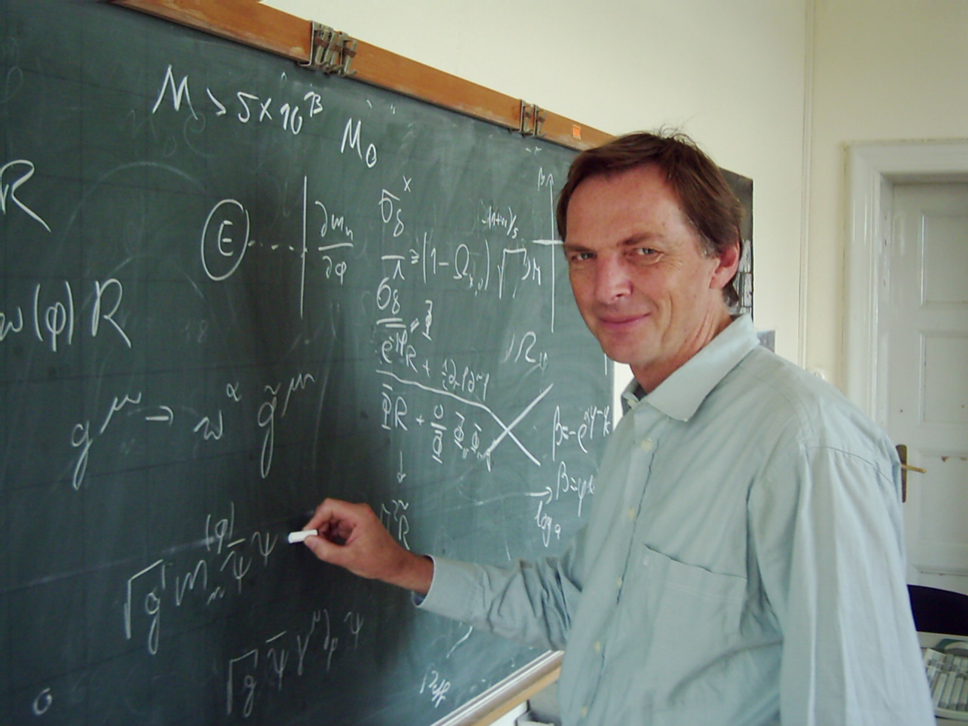
Previous work on analoge gravity and cold atom cosmology

- W. G. Unruh, *Experimental Black-Hole Evaporation?*, PRL 46, 1351 (1981)
- M. Visser, *Acoustic black holes: horizons, ergospheres and Hawking radiation*, Class. Quant. Gravity 15, 1767 (1998)
- L. J. Garay, J. R. Anglin, J. I. Cirac, P. Zoller, *Sonic Analog of Gravitational Black Holes in Bose-Einstein Condensates*, PRL 85, 4643 (2000)
- G. E. Volovik, *Superfluid analogies of cosmological phenomena*, Phys. Rep. 351, 195 (2001); *The Universe in a Helium Droplet* (OUP, 2003)
- M. Visser, C. Barceló, S. Liberati, *Analogue Models of and for Gravity*, Gen. Relativ. Gravit. 34, 1719 (2002)
- C. Barceló, S. Liberati, M. Visser, *Probing semiclassical analog gravity in Bose-Einstein condensates with widely tunable interactions*, PPA 68, 053613 (2003)
- P. O. Fedichev, U. R. Fischer, *Gibbons-Hawking Effect in the Sonic de Sitter Space-Time of an Expanding Bose- Einstein-Condensed Gas*, PRL 91, 240407 (2003)
- U. R. Fischer, R. Schützhold, *Quantum simulation of cosmic inflation in two-component Bose-Einstein condensates*, PRA 70, 063615 (2004)
- M. Uhlmann, Y. Xu, R. Schützhold, *Aspects of cosmic inflation in expanding Bose-Einstein condensates*, New J. Phys. 7, 248 (2005)
- E. A. Calzetta, B. L. Hu, *Early Universe Quantum Processes in BEC Collapse Experiments*, Int. J. Theor. Phys. 44, 1691 (2005)
- P. Jain, S. Weinfurtner, M. Visser, C. W. Gardiner, *Analog model of a Friedmann-Robertson-Walker universe in Bose-Einstein condensates: Application of the classical field method*, PRA 76, 033616 (2007)
- A. Prain, S. Fagnocchi, S. Liberati, *Analogue cosmological particle creation: Quantum correlations in expanding Bose-Einstein condensates*, PRD 82, 105018 (2010).
- C. Barceló, S. Liberati, M. Visser, *Analogue Gravity*, Living Rev. Relativ. 14, 3 (2011)
- N. Bilić, D. Tolić, *FRW universe in the laboratory*, PRD 88, 105002 (2013)
- C.-L. Hung, V. Gurarie, and C. Chin, *From Cosmology to Cold Atoms: Observation of Sakharov Oscillations in a Quenched Atomic Superfluid*, Science 341, 1213 (2013).
- J. Schmiedmayer, J. Berges, *Cold atom cosmology*, Science 341, 1188 (2013)
- J. Rodriguez-Laguna, L. Tarruell, M. Lewenstein, A. Celi, *Synthetic Unruh effect in cold atoms*, PRA 95, 013627 (2017).
- S. Eckel, A. Kumar, T. Jacobson, I. B. Spielman, G. K. Campbell, *A Rapidly Expanding Bose-Einstein Condensate: An Expanding Universe in the Lab*, PRX 8, 021021 (2018)
- M. Wittemer *et al.*, *Phonon Pair Creation by Inflating Quantum Fluctuations in an Ion Trap*, PRL 123, 180502 (2019)
- C. Gooding, S. Biermann, S. Erne, J. Louko, W. G. Unruh, J. Schmiedmayer, S. Weinfurtner, *Interferometric Unruh Detectors for Bose-Einstein Condensates*, PRL 125, 213603 (2020)
- S. Weinfurtner, E. W. Tedford, M. C. J. Penrice, W. G. Unruh, G. A. Lawrence, *Measurement of Stimulated Hawking Emission in an Analogue System*, PRL 106, 021302 (2011)
- Steinhauer, *Observation of quantum Hawking radiation and its entanglement in an analogue black hole*, Nat. Phys. 12, 959 (2016)
- J. R. Muñoz de Nova, K. Golubkov, V. I. Kolobov, J. Steinhauer, *Observation of thermal Hawking radiation and its temperature in an analogue black hole*, Nature 569, 688–691 (2019)
- S. Banik *et al.*, *Hubble Attenuation and Amplification in Expanding and Con- tracting Cold-Atom Universes*, 2107.08097
- J. Steinhauer *et al.*, *Analogue cosmological particle creation in an ultracold quantum fluid of light*, 2102.08279 (2021)
- A. Chatrchyan, K. T. Geier, M. K. Oberthaler, J. Berges, P. Hauke, *Analog cosmological reheating in an ultracold Bose gas*, PRA 104, 023302 (2021)
- S. Butera, I. Carusotto, *Particle creation in the spin modes of a dynamically oscillating two-component Bose-Einstein condensate*, PRD 104, 083503 (2021)

The night sky

- many bright stars and galaxies
- but overall dark
- Heinrich Wilhelm Olbers (1823):

  "Sind wirklich im ganzen unendlichen Raum Sonnen vorhanden, sie mögen nun in ungefähr gleichen Abständen von einander, oder in Milchstrassen-Systeme vertheilt sein, so wird ihre Menge unendlich, und da müsste der ganze Himmel eben so hell sein wie die Sonne. Denn jede Linie, die ich mir von unserem Auge gezogen denken kann, wird nothwendig auf irgend einen Fixstern treffen, und also müsste uns jeder Punkt am Himmel Fixsternlicht, also Sonnenlicht zusenden."
- out-of-equilibrium state needed
- the Universe expands !



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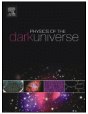

Universe without expansion

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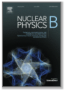
Big bang singularity
Inflation

ABSTRACT

We discuss a cosmological model where the universe shrinks rather than expands during the radiation and matter dominated periods. Instead, the Planck mass and all particle masses grow exponentially, with the size of atoms shrinking correspondingly. Only dimensionless ratios as the distance between galaxies divided by the atom radius are observable. Then the cosmological increase of this ratio can also be attributed to shrinking atoms. We present a simple model where the masses of particles arise from a scalar "cosmon" field, similar to the Higgs scalar. The potential of the cosmon is responsible for inflation and the present dark energy. Our model is compatible with all present observations. While the value of the cosmon field increases, the curvature scalar is almost constant during all cosmological epochs. Cosmology has no big bang singularity. There exist other, equivalent choices of field variables for which the universe shows the usual expansion or is static during the radiation or matter dominated epochs. For those "field coordinates" the big bang is singular. Thus the big bang singularity turns out to be related to a singular choice of field coordinates.

Nuclear Physics B
Volume 302, Issue 4, 13 June 1988, Pages 668-696



Cosmology and the fate of dilatation symmetry

C. Wetterich

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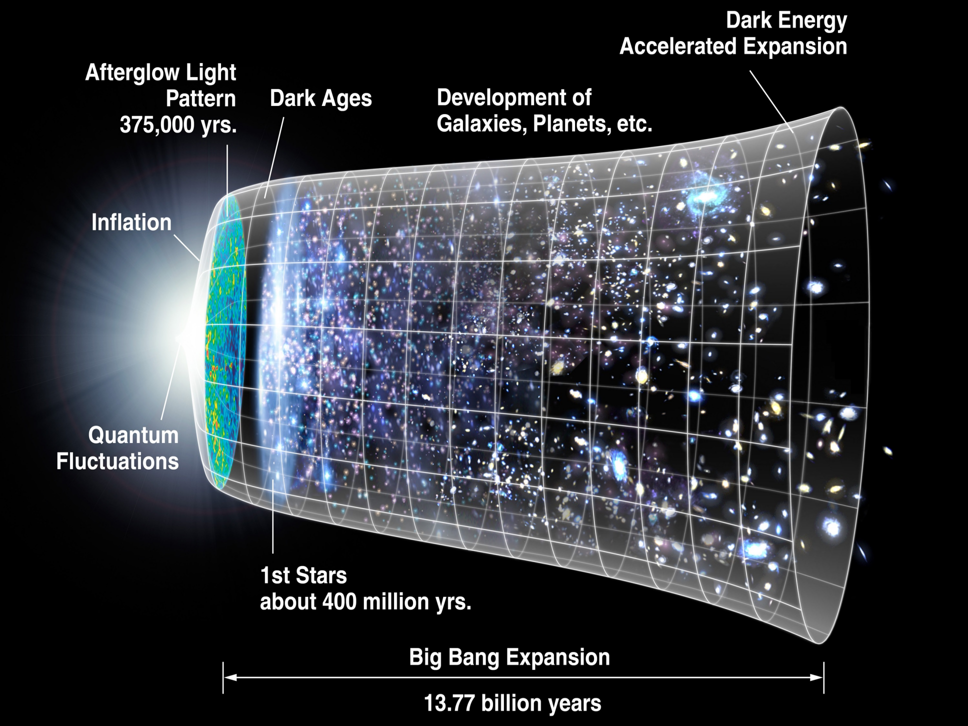
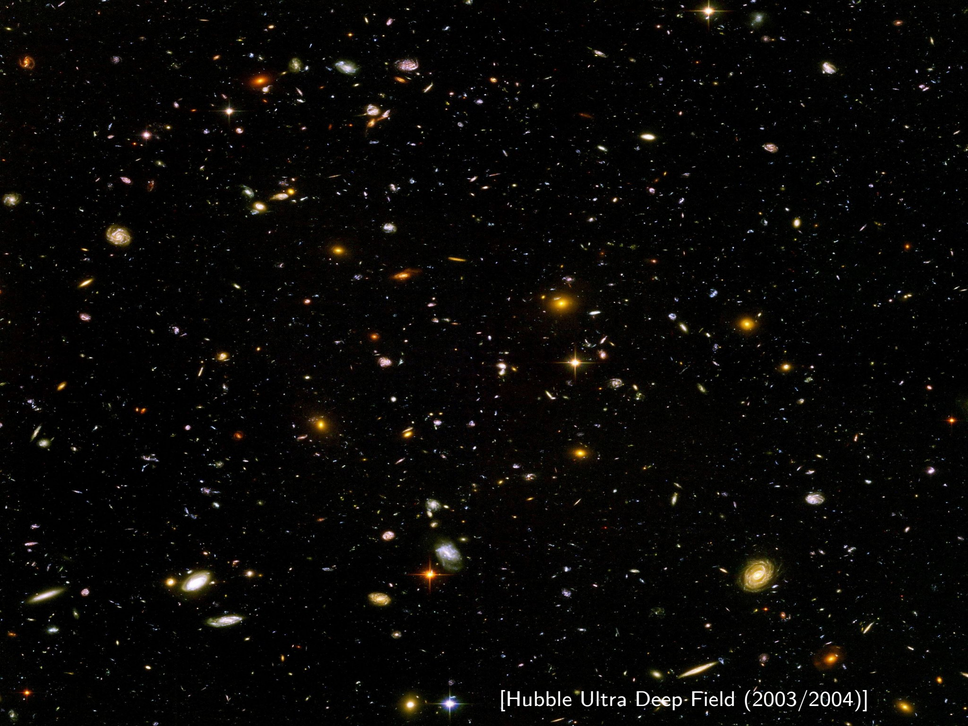
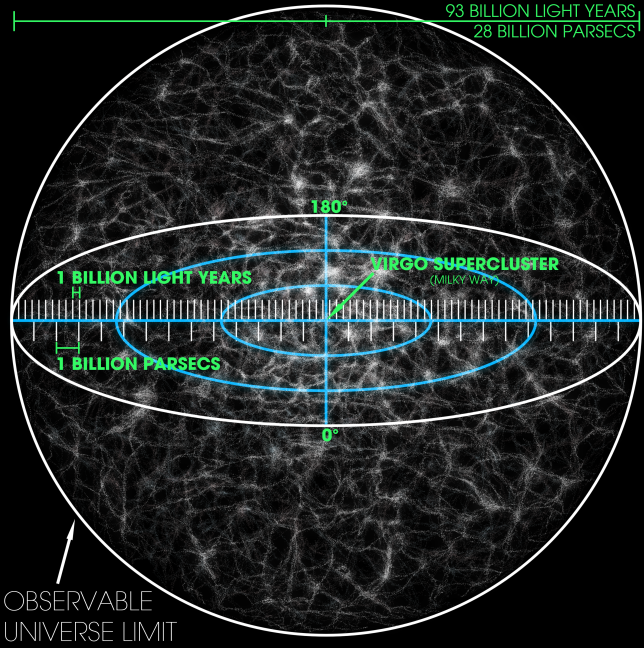
Abstract

We discuss the cosmological constant problem in the light of dilatation symmetry and its possible anomaly. For dilatation symmetric quantum theories realistic asymptotic cosmology is obtained provided the effective potential has a nontrivial minimum. For theories with dilatation anomaly one needs as a nontrivial "cosmon condition" that the energy-momentum tensor in the vacuum is purely anomalous. Such a condition is related to the short distance renormalization group behaviour of the fundamental theory. Observable deviations from the standard hot big bang cosmology are possible.


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

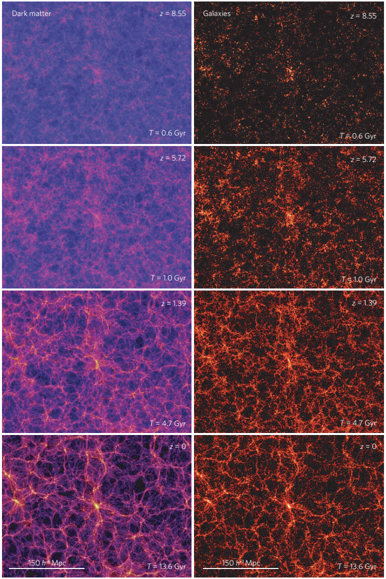


[Hubble Ultra Deep Field (2003/2004)]



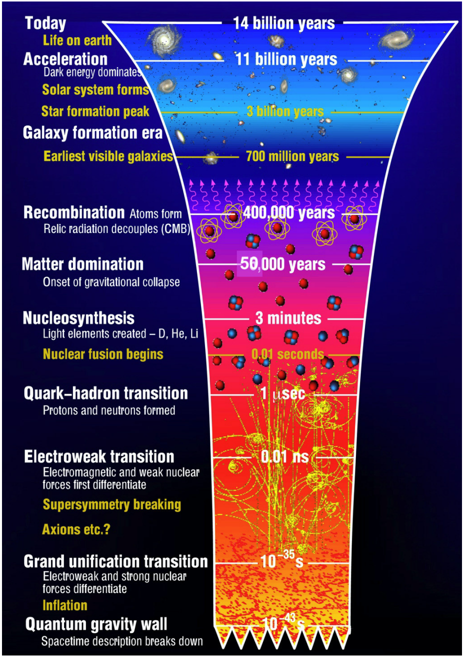
93 BILLION LIGHT YEARS
28 BILLION PARSECS
180°
VIRGO SUPERCLUSTER
(MILKY WAY)
1 BILLION LIGHT YEARS
1 BILLION PARSECS
0°
OBSERVABLE
UNIVERSE LIMIT

Evolution of cosmic large-scale structure



[Springel, Frenk & White, Nature 440, 1137 (2006)]

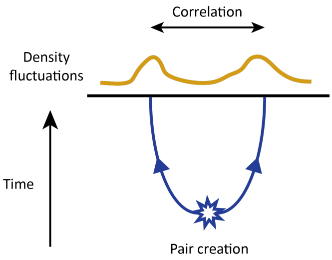
Time history



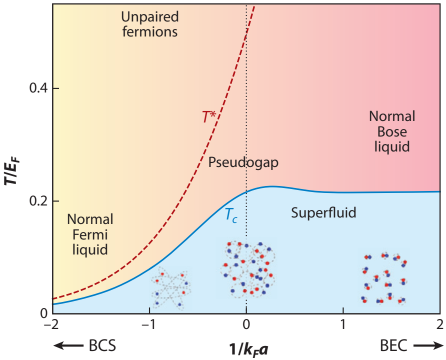
Quantum origin of fluctuations

- Universe was almost homogeneous at early times
- small fluctuations magnified by gravitational attraction
- primordial fluctuations most likely quantum fluctuations maginfied by inflation

  [Mukhanov & Chibisov (1981), Hawking (1982), Starobinsky (1982), Guth & Pi (1982), Bardeen, Steinhardt & Turner (1983), Fischler, Ratra & Susskind (1985)]



Ultracold quantum gases



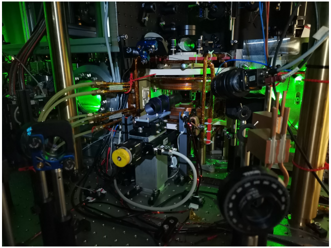
- why study ultracold quantum gases?
- develop and test understanding of quantum fields
- functional renormalization group developed for cold atoms in Heidelberg [Wetterich, Diehl, Gies, Pawlowski, Floerchinger, Scherer, Krahl, Schmidt, Moroz, Boettcher, Faigle-Cedzich, ... Salmhofer, Honerkamp, Metzner, Gubbels, Stoof, Dupuis, Strack, Bartosch, Kopietz, ...]

Non-relativistic quantum fields

- Bose-Einstein condensate in two dimensions
  [Gross (1961), Pitaevskii (1961)]

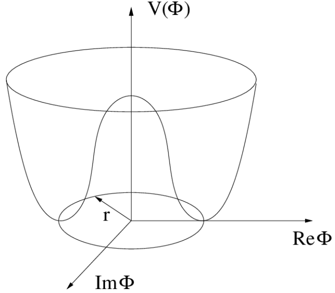
$$\Gamma[\Phi] = \int \mathrm{d}t\, \mathrm{d}^2x \Big\{ \hbar\Phi^*(t,\mathbf{x}) \left[i\frac{\partial}{\partial t} - V(t,\mathbf{x}) \right] \Phi(t,\mathbf{x}) - \frac{\hbar^2}{2m} \boldsymbol{\nabla}\Phi^*(t,\mathbf{x}) \boldsymbol{\nabla}\Phi(t,\mathbf{x}) - \frac{\lambda(t)}{2} \Phi^*(t,\mathbf{x})^2 \Phi(t,\mathbf{x})^2 \Big\}$$

- traping potential $V(t,\mathbf{x})$ and coupling strength $\lambda(t)$
- can be realized and controlled experimentally



[Oberthaler group, KIP Heidelberg]

Superfluid and small excitations



- Complex non-relativistic field can be decomposed

$$\Phi = e^{iS_0}\left(\sqrt{n_0} + \frac{1}{\sqrt{2}}\left[\phi_1 + i\phi_2\right]\right)$$

- real fields ϕ_1 and ϕ_2 describe excitations on top of the superfluid
- stationary superfluid density $n_0(\mathbf{x})$ and vanishing superfluid velocity

$$\mathbf{v} = \frac{\hbar}{m}\boldsymbol{\nabla} S_0 = 0$$

Sound waves / phonons

- small energy excitations are sound waves or phonons
- propagate with finite velocity, similar to light
- local speed of sound

$$c_S(t, \mathbf{x}) = \sqrt{\frac{\lambda(t)\, n_0(\mathbf{x})}{m}}$$

- sound waves propagate along

$$ds^2 = -dt^2 + \frac{1}{c_S(t, \mathbf{x})^2}(d\mathbf{x} - \mathbf{v}\, dt)^2 = 0$$

- acoustic metric for $\mathbf{v} = 0$

$$g_{\mu\nu} = \begin{pmatrix} -1 & 0 & 0 \\ 0 & \frac{1}{c_S(t,\mathbf{x})^2} & 0 \\ 0 & 0 & \frac{1}{c_S(t,\mathbf{x})^2} \end{pmatrix}$$

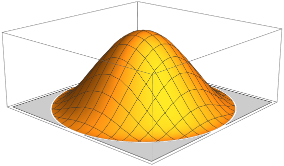
Relativistic scalar field

- Low energy theory for phonons (with $\phi = \phi_2/\sqrt{2m}$)

$$\Gamma[\phi] = \int \mathrm{d}t\,\mathrm{d}^2x\,\sqrt{g}\left\{-\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi\right\}$$

- metric determinant $\sqrt{g} = \sqrt{-\det(g_{\mu\nu})}$
- acoustic metric depends on space and time like the space-time metric in Einsteins theory of general relativity !
- phonons behave like real, massless, relativistic scalar field in a curved spacetime !

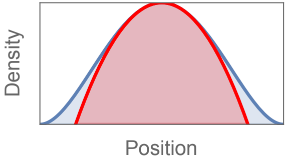
Density profiles



- assume specifically for $r = |\mathbf{x}| < R$

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

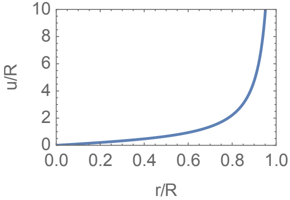
- experimental realization with optical trap and digital micromirror device
- approximate realization in harmonic trap



Acoustic spacetime geometry

- variable transform to $0 \leq u < \infty$

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



- leads to Friedmann-Lemaitre-Robertson-Walker metric

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

- negative spatial curvature

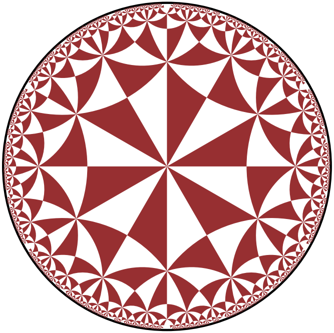
$$\kappa = -4/R^2$$

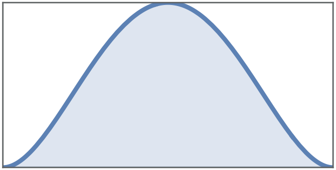
- scale factor

$$a(t) = \sqrt{\frac{m}{\bar{n}_0}\frac{1}{\lambda(t)}}$$

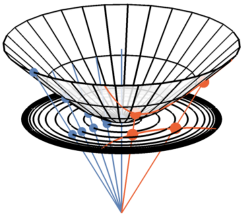
Hyperbolic geometry

Lewis Carroll (1888): "Too fanciful !"





Hyperbolic geometry in Minkowski space



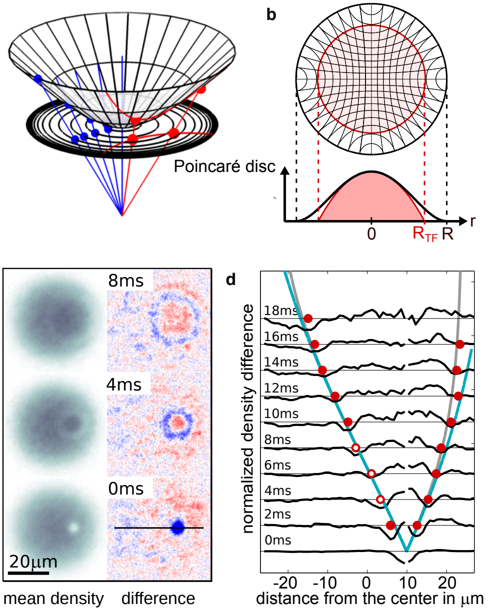
- start with Minkowski space $ds^2 = dX^2 + dY^2 - dZ^2$
- consider hyperbloid $X^2 + Y^2 - Z^2 = -R^2/4$
- stereographic projection to Poincaré disc

Poincaré disc and M. C. Eschers circle limit series

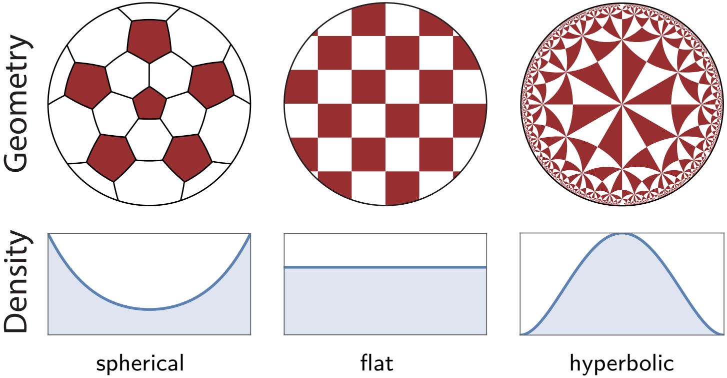
Circle limit III, M. C. Escher, 1959.

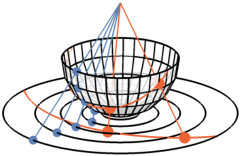
Hyperbolic geometry in biology

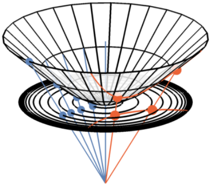
Experimental realization in a Bose-Einstein condensate



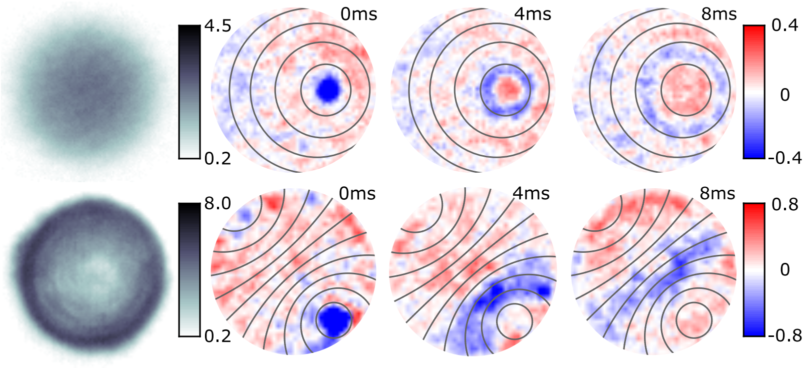
Geometries with constant spatial curvature





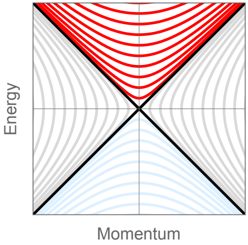


Propagating sound waves



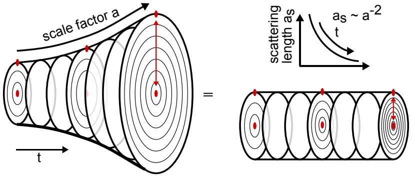
Symmetries and physics

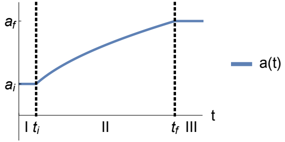
- Emmy Noether (1918): *Symmetries imply conservation laws*
- Eugene P. Wigner (1939): *Classification of particles through representations of symmetries*



- translations in space and time $\leftrightarrow$ momentum, energy, mass
- rotations and Lorentz boosts $\leftrightarrow$ spin / helicity
- further internal symmetries $\leftrightarrow$ charge, isospin, etc.
- symmetries are needed for particle concept to work properly
- what happens if they get broken?

Particle production





- time-dependent scattering length induces time-dependent metric

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

- particle concept works well in regions I and III but not in region II
- vacuum state in region I leads to state with particles in region III
- expanding space produces particles !
- analytic calculations possible for power law scale factors

$$a(t) = \text{const} \times t^\gamma$$

Mode functions and Bogoliubov transforms

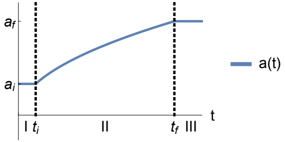
- field gets expanded in modes

$$\phi(t,u,\varphi) = \int_{k,m} \left[\hat{a}_{km}\mathcal{H}_{km}(u,\varphi)v_k(t) + \hat{a}^\dagger_{km}\mathcal{H}^*_{km}(u,\varphi)v^*_k(t) \right]$$

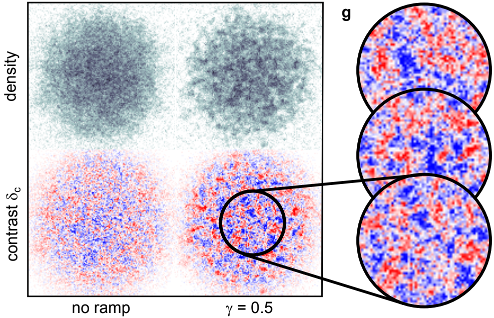
- spatial part $\mathcal{H}_{km}(u,\varphi)$ can be expressed in terms of spherical harmonics at complex angular momenta
- mode functions satisfy

$$\ddot{v}_k(t) + 2\frac{\dot{a}(t)}{a(t)}\dot{v}_k(t) + \frac{k^2 + |\kappa|/4}{a^2(t)}v_k(t) = 0$$

- vacuum state only unique for $\dot{a}(t) = 0$ where $v_k(t) \sim e^{-i\omega_k t}$
- Bogoliubov transforms between different choices of $\hat{a}_{km}$ and vacuum states



Observation of particle production

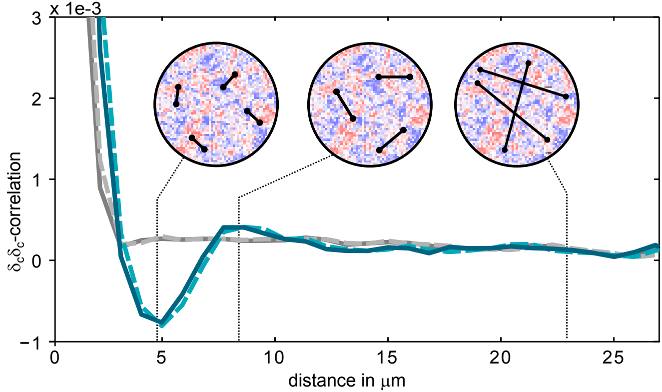


- rescaled density contrast

$$\delta_c(t,\mathbf{x}) = \sqrt{\frac{n_0(\mathbf{x})}{\bar{n}_0^3}}\,[n(t,\mathbf{x}) - n_0(\mathbf{x})] \sim \partial_t \phi(t,\mathbf{x})$$

- allows to test relativistic scalar field

Density contrast correlation function

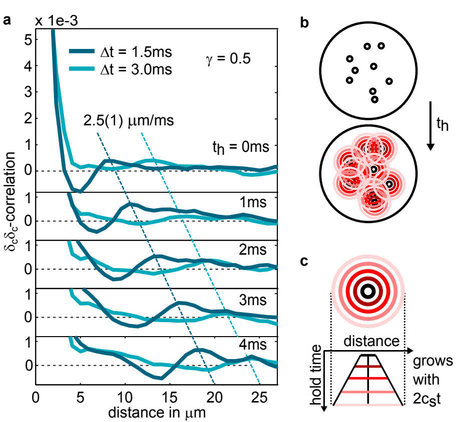


- correlation function

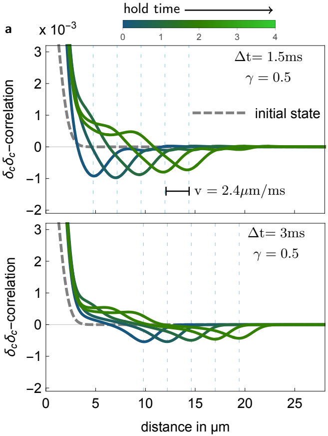
$$\langle \delta_c(\mathbf{x})\delta_c(\mathbf{y}) \rangle$$

- before and after expansion

Time dependent correlation functions after expansion



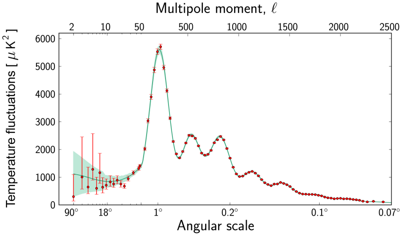
Experiment

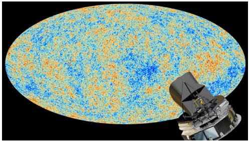


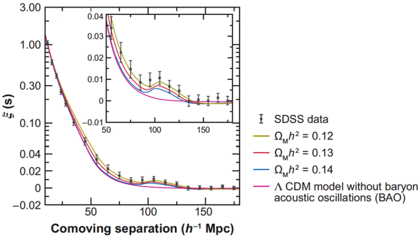
Theory

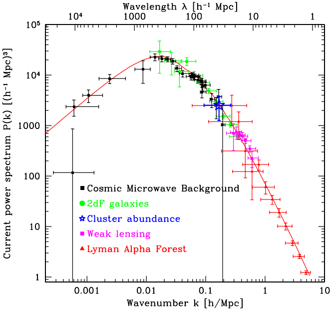
- analgous to baryon accoustic or Sakharov oscillations in cosmology
- optical resolution important for detailed shape

Baryon acoustic oscillations

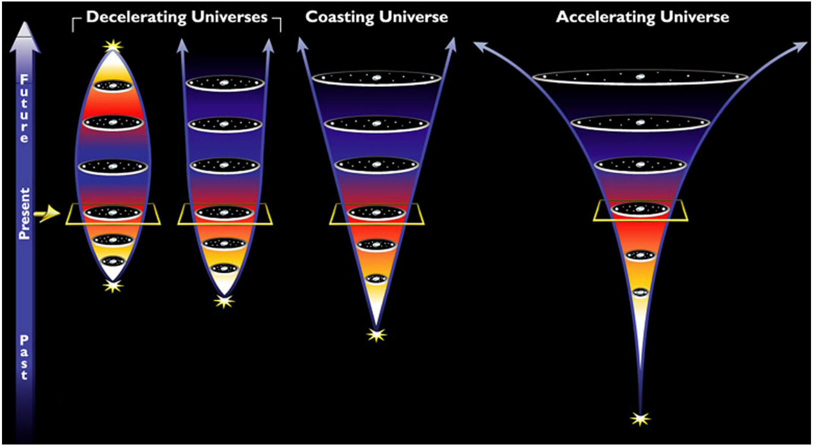




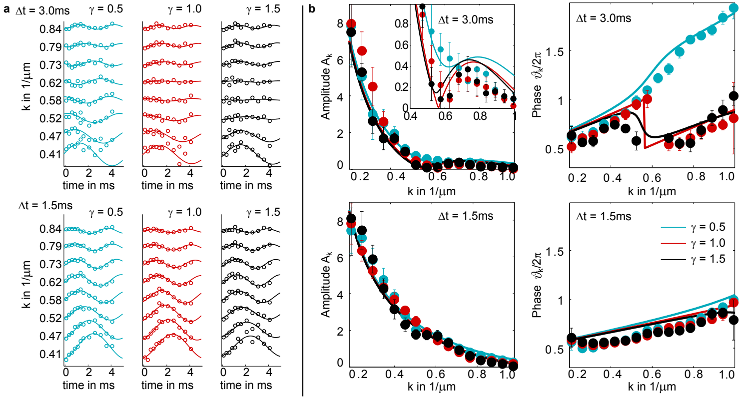




Expansion history



Oscillations in Fourier space



- Fourier spectrum of excitations

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

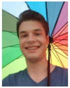
- decelerated, coasting and accelerated expansion
- good agreement with analytic theory (solid lines)

Conclusion

- Bose-Einstein condensates can be quantum simulators for quantum fields in curved spacetime
- Symmetric spaces with constant curvature can be realized with specific radial density profiles
- Experimental realization in two spatial dimensions
- Time-dependent coupling allows to simulate expansion
- Particle production by time-dependent scale factor
- Oscillations after expansion allow detailed investigations
- Quantum information theoretic aspects also accessible
- Extensions to three dimensions, other geometries, other field content, and more, are possible

Many thanks to the team...


Celia Viermann


Marius Sparn


Nikolas Liebster

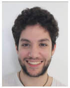

Maurus Hans


Elinor Kath


Helmut Strobel


Markus Oberthaler


Mireia Tolosa-Simeón


Álvaro Parra-López


Natalia Sánchez-Kuntz

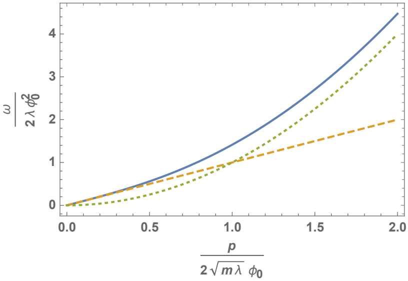

Tobias Haas


Stefan Floerchinger

... and Happy Birthday Christof Wetterich !

Backup

Bogoliubov dispersion relation



- Quadratic part of action for excitations

$$S_2 = \int dt\ d^3x \left\{ -\frac{1}{2}(\phi_1, \phi_2) \begin{pmatrix} -\frac{\nabla^2}{2m} + 2\lambda n_0 & \partial_t \\ -\partial_t & -\frac{\nabla^2}{2m} \end{pmatrix} \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} \right\}$$

- Dispersion relation

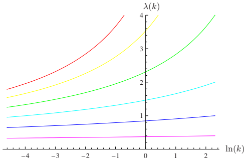
$$\omega = \sqrt{\left(\frac{\mathbf{p}^2}{2m} + 2\lambda\phi_0^2\right)\frac{\mathbf{p}^2}{2m}}$$

becomes linear for

$$\mathbf{p}^2 \ll 4\lambda m n_0 = \frac{2}{\xi^2}$$

Renormalization in two dimensions

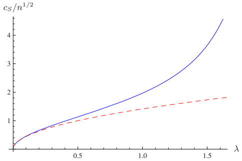
[S. Floerchinger, C. Wetterich, *Superfluid Bose gas in two dimensions*, PRA 79, 013601 (2009)]

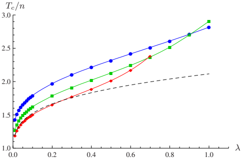


- scale-dependent coupling in two dimensions

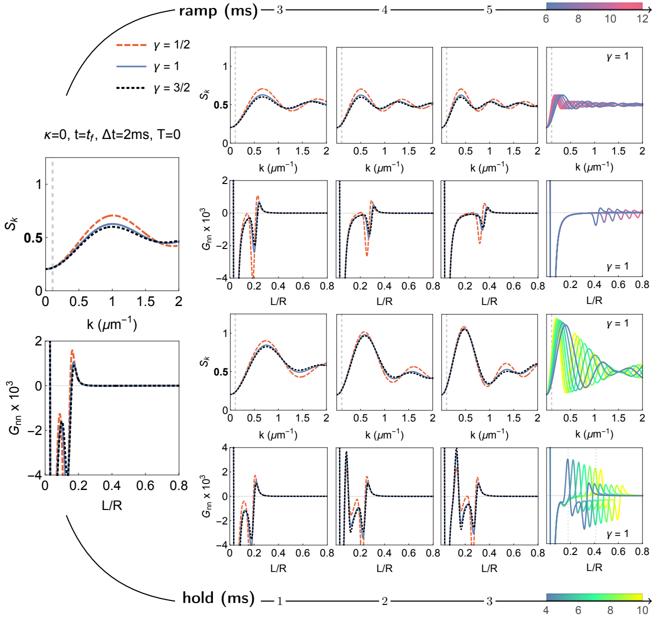
$$k\frac{\partial}{\partial k}\lambda = \frac{\lambda^2}{4\pi}$$

- sound velocity and critical temperature

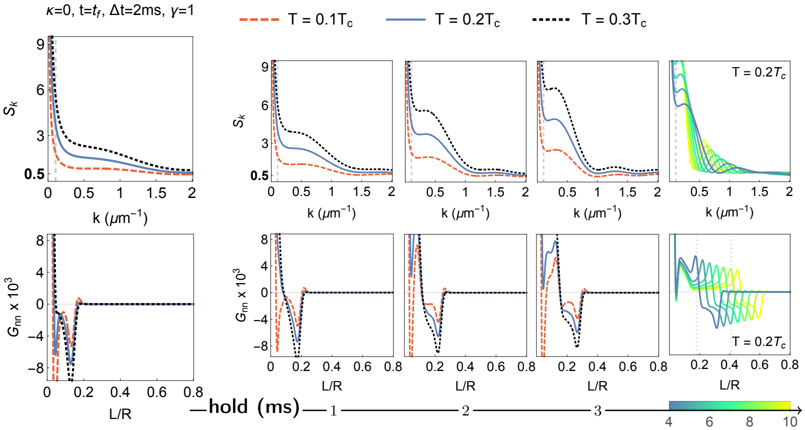




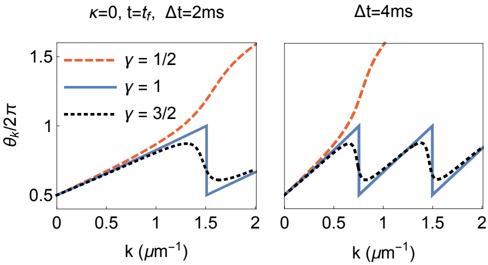
Expansion and hold time dependence



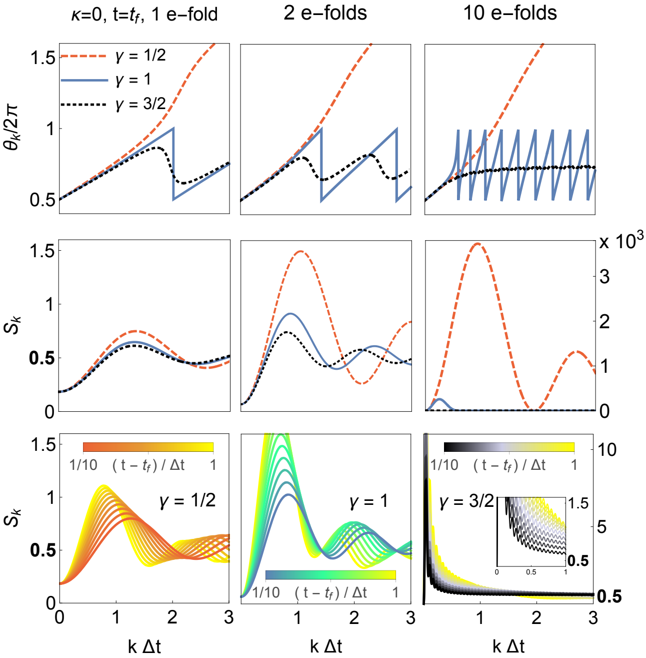
Temperature dependence



Phases

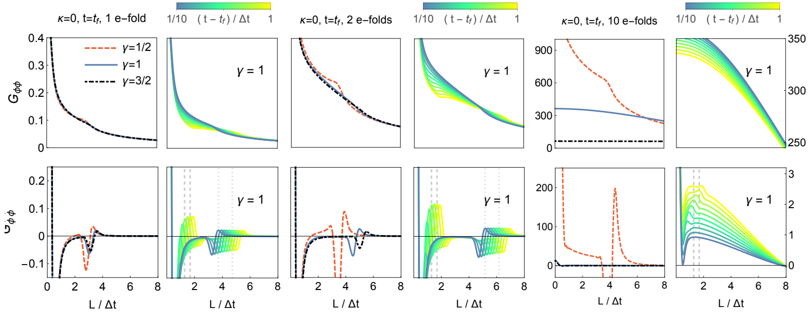


More e-folds

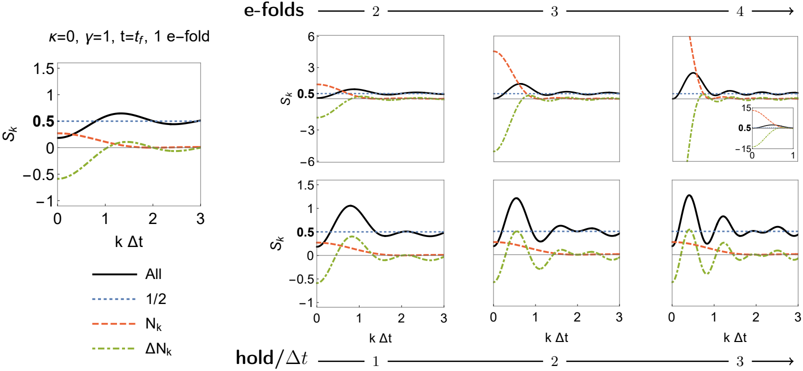


κ=0, t=t_f, 1 e−fold
2 e−folds
10 e−folds
γ = 1/2
γ = 1
γ = 3/2
θ_k/2π
S_k
x 10^3
1/10 (t − t_f) / Δt 1
γ = 1/2
γ = 1
γ = 3/2
k Δt

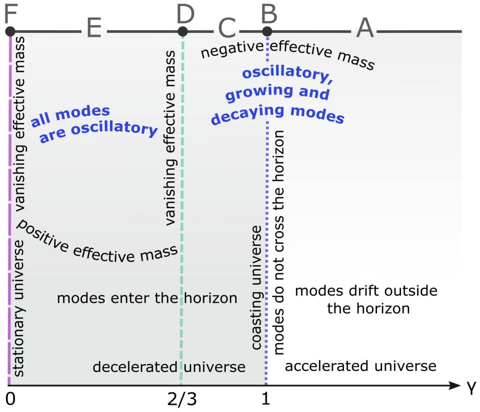
Correlation functions



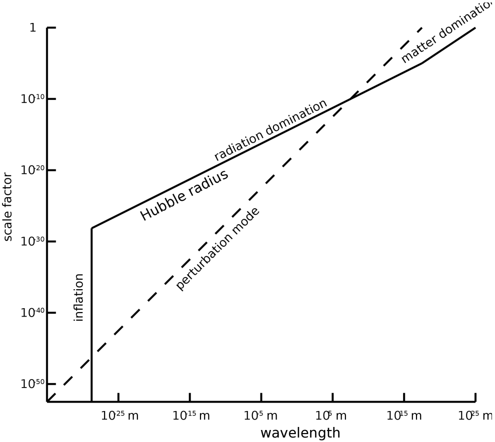
Power spectra



Horizon crossing



Horizons and inflation



Bogoliubov transforms

- in region I one has positive frequency modes v_k and corresponding operators. Define vacuum

$$\hat{a}_{km}|\Omega\rangle = 0$$

- similar in region III positive frequency modes u_k with

$$\hat{b}_{km}|\Psi\rangle = 0$$

- Bogoliubov transform mediates between them

$$u_k = \alpha_k v_k + \beta_k v_k^*, \qquad v_k = \alpha_k^* u_k - \beta_k u_k^*$$

- operators are related by

$$\hat{b}_{km} = \alpha_k^* \hat{a}_{km} - \beta_k^* (-1)^m \hat{a}_{k,-m}^\dagger$$

- condition $|\alpha_k|^2 - |\beta_k|^2 = 1$
- constant term in spectrum $N_k = |\beta_k|^2$
- oscilating term $\Delta N_k = \mathrm{Re}[\alpha_k \beta_k e^{2i\omega_k t}]$