Title: Five short talks - see description for talk titles

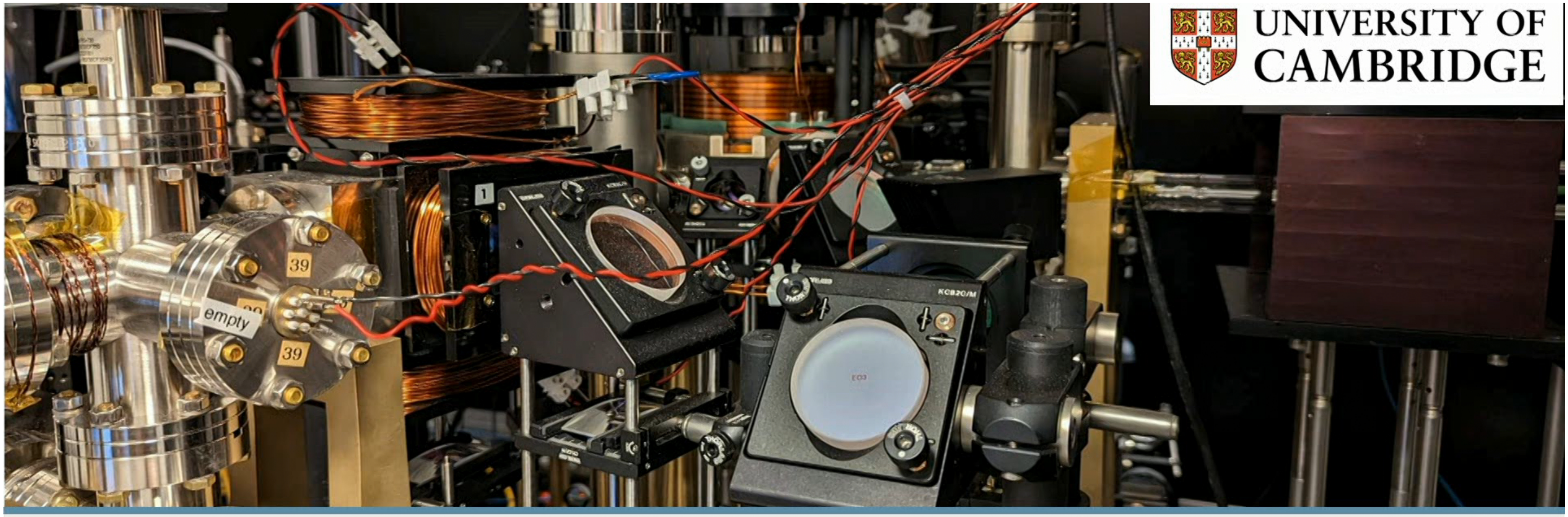
Speakers: ShiQian Hu

Collection: Quantum Simulators of Fundamental Physics

Date: June 07, 2023 - 2:00 PM

URL: https://pirsa.org/23060015

Abstract: Towards an ultracold atom quantum simulator of the false vacuum decay (Konstantinos Konstantinou); Regge pole description of scattering by dirty black holes (Shiqian Hu); Quantum catastrophes and Hawking corrections (Liam Farrell); Numerical simulation of Kibble-Zurek mechanism with Landau-Ginzburg dynamics (Fumika Suzuki)



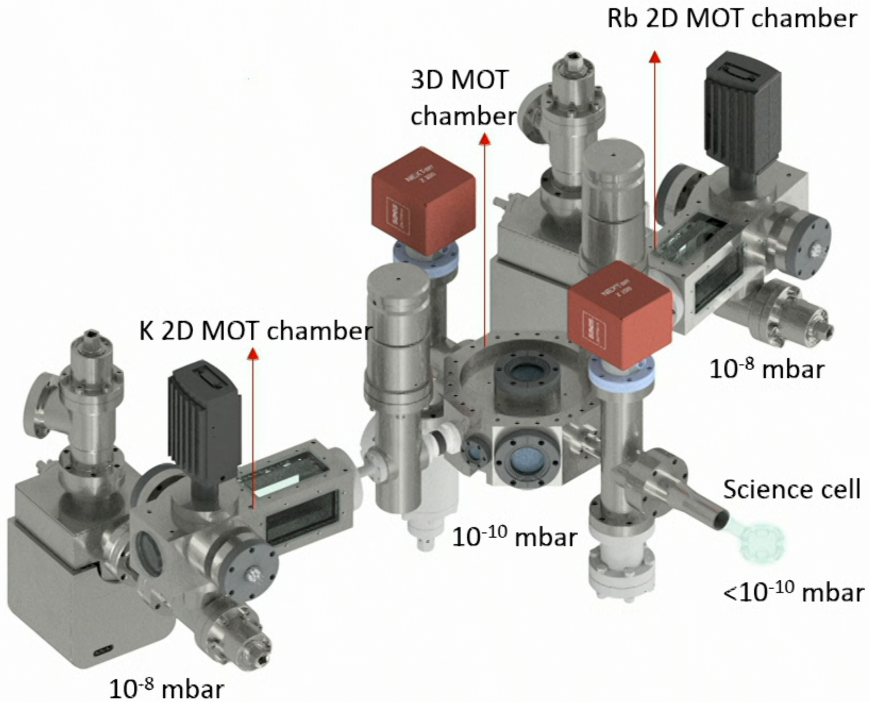
UNIVERSITY OF CAMBRIDGE

Towards an ultracold atom quantum simulator of false vacuum decay

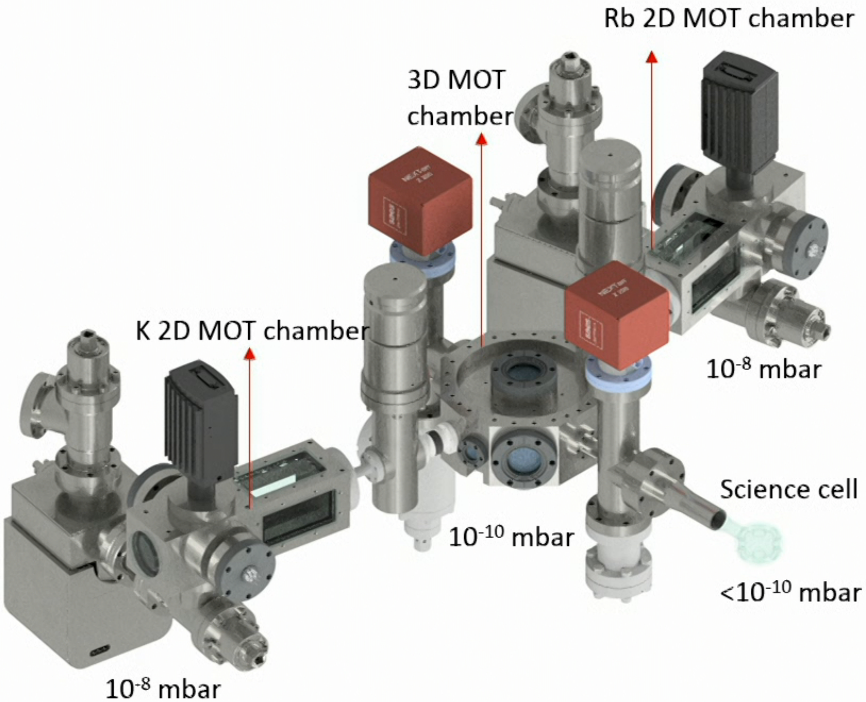
Konstantinos Konstantinou

QSimFP erc EPSRC Engineering and Physical Sciences Research Council DesOEQ THE ROYAL SOCIETY

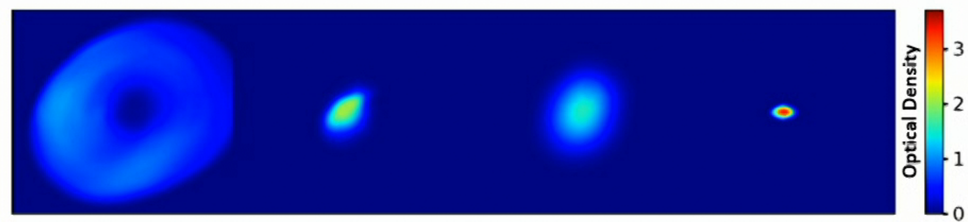
The machine


Rb 2D MOT chamber
3D MOT
chamber
K 2D MOT chamber
10^{-8} mbar
Science cell
10^{-10} mbar
<10^{-10} mbar
10^{-8} mbar

The machine



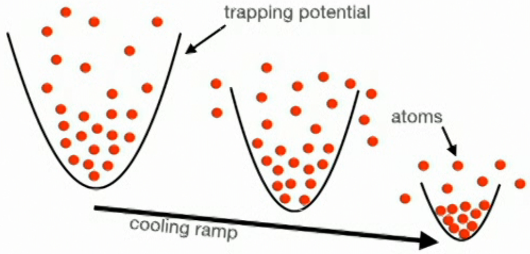
Cooling down from room temperature:



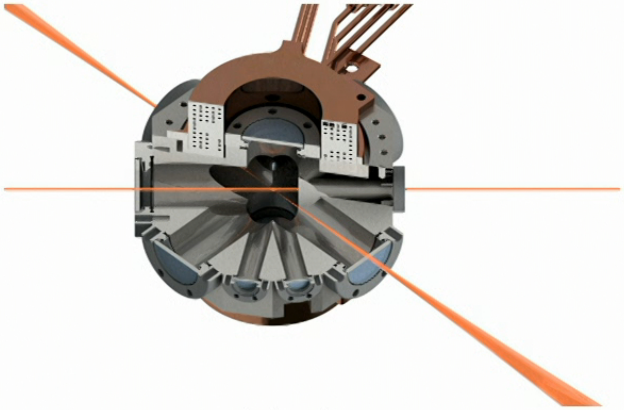
MOT	**Compressed MOT**	**Gray molasses**	**Magnetic trap**
10^9 atoms 10 mK	10^9 atoms 1 mK	0.8×10^9 atoms 15 μK	0.6×10^9 atoms 150 μK Spin-polarized to $\vert F=1,m_F=-1\rangle$

Evolution of the cloud during evaporation

Optical evaporation in a crossed-dipole trap in the |1,-1⟩, spin state close to the 33.582G feshbach resonance



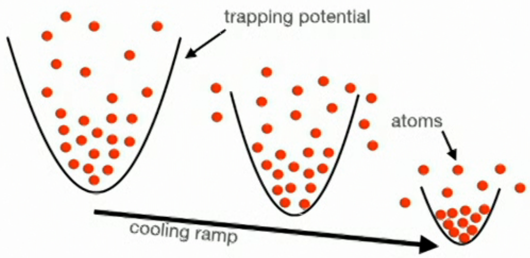
Evaporative cooling



Crossed dipole trap geometry

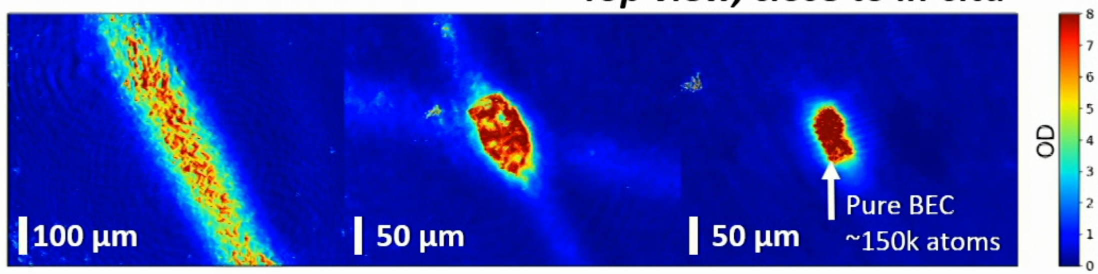
Evolution of the cloud during evaporation

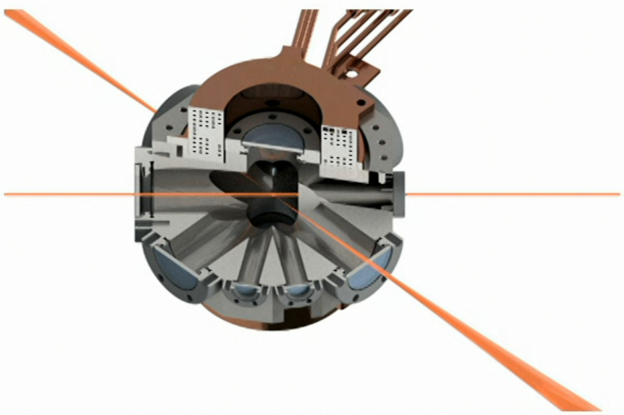
Optical evaporation in a crossed-dipole trap in the |1,-1⟩, spin state close to the 33.582G feshbach resonance



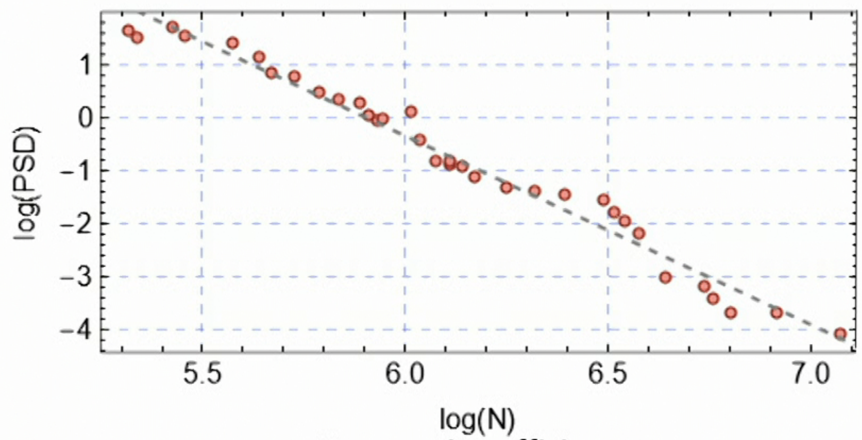
Evaporative cooling

Top view, close to in-situ



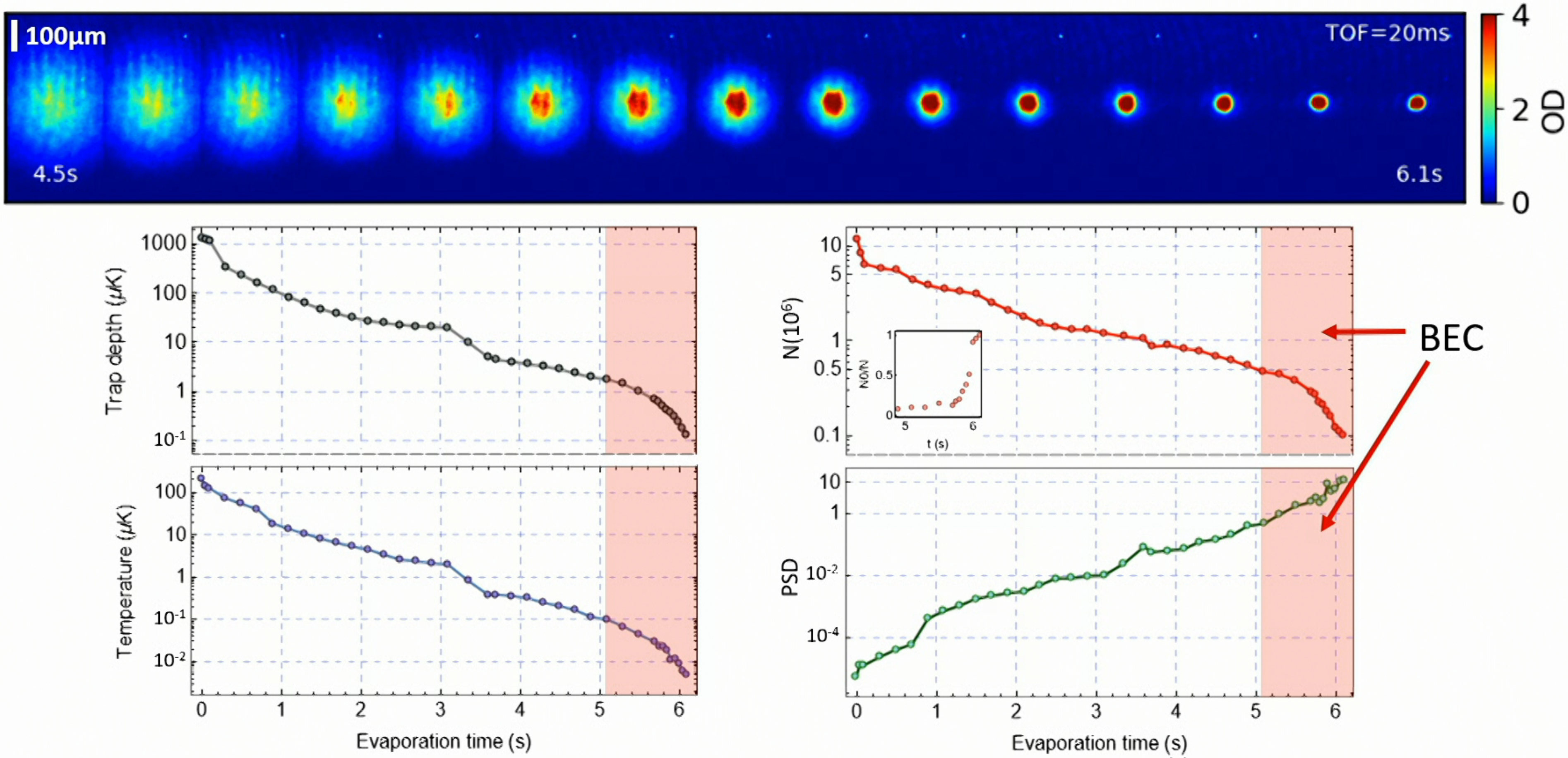


Crossed dipole trap geometry

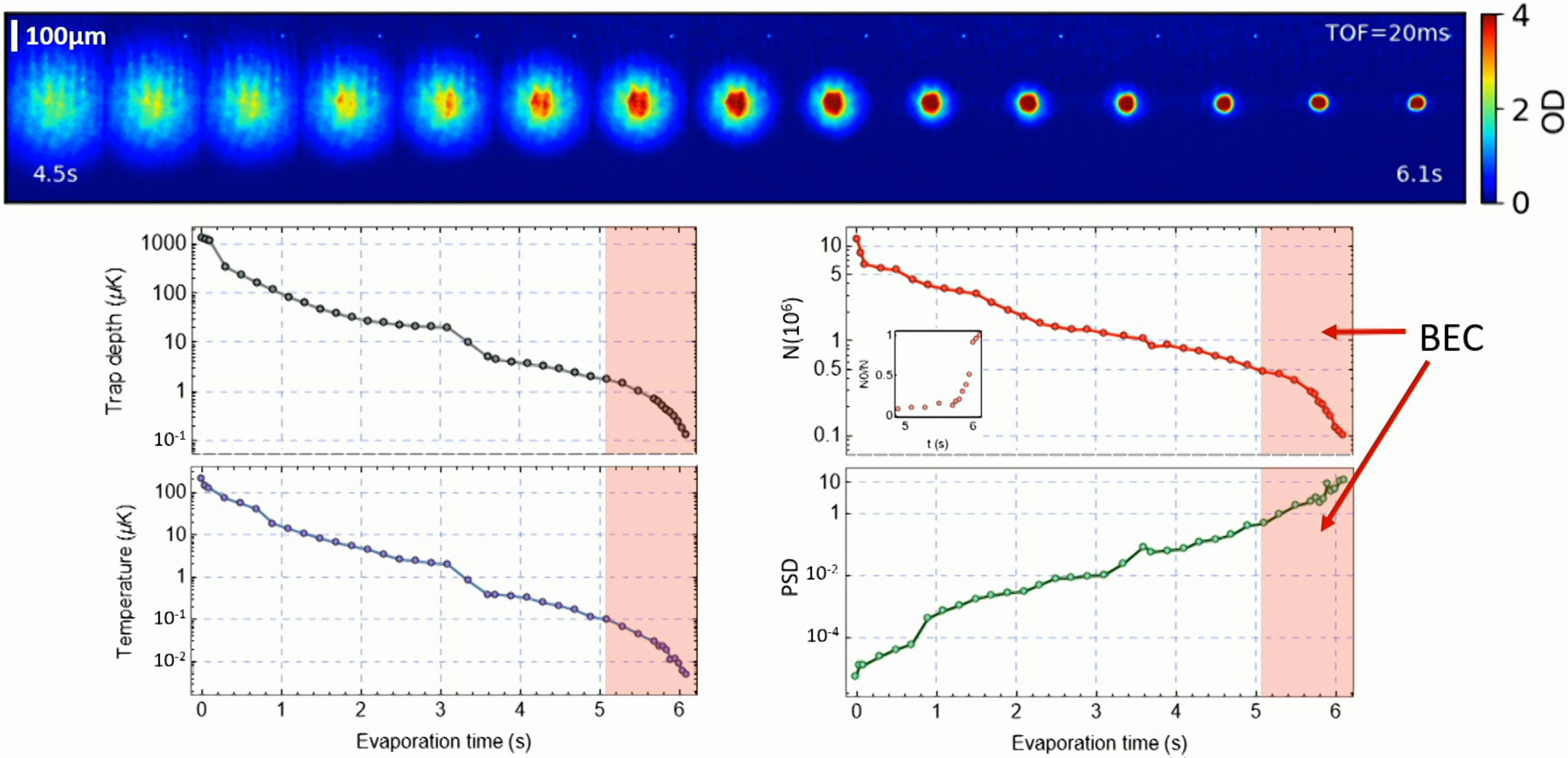


Evaporation efficiency=
-d(log(PSD))/d(log(N))=3.6

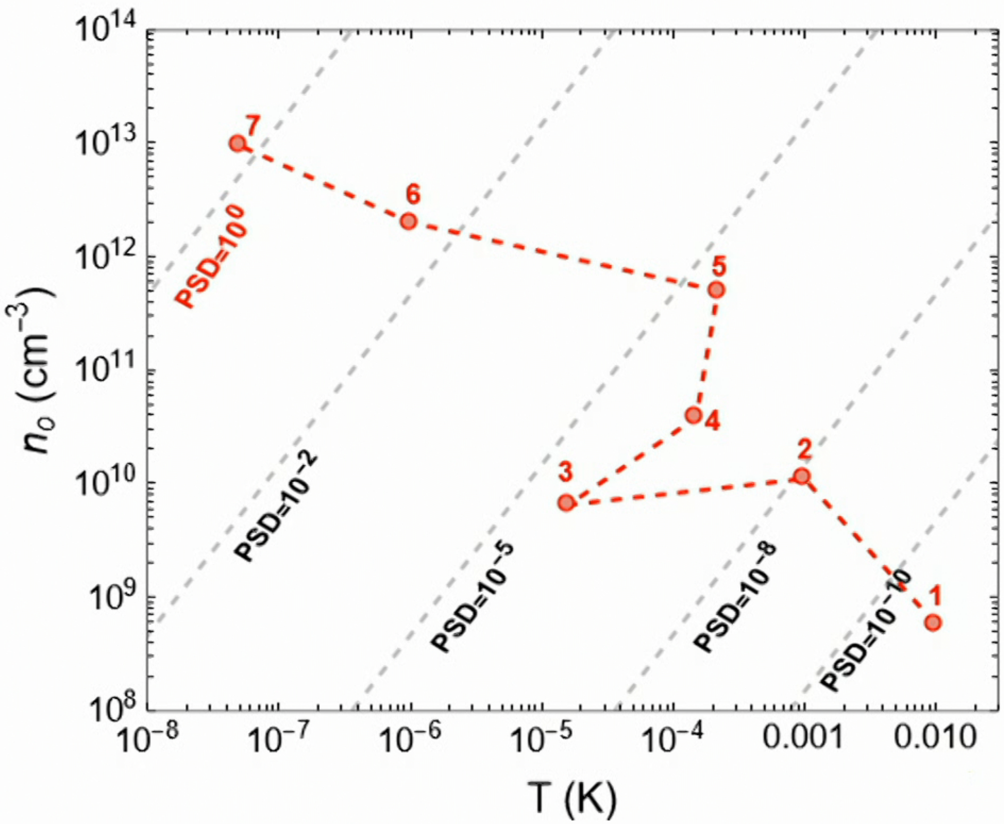
Reaching quantum degeneracy



Reaching quantum degeneracy



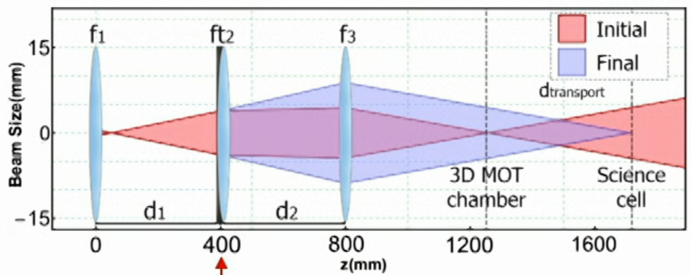
Summary of steps



Sequence step	Atom number	Temperature
(1) MOT	10^9	10mK
(2) cMOT	10^9	1mK
(3) Gray molasses	0.8×10^9	15μK
(4) Magnetic trap	0.6×10^9	150μK
(5) Dipole trap	10^7	200μK
(6) Mid-evaporation	10^6	1μK
(7) BEC	1.5×10^5	~50nK

Optical transport

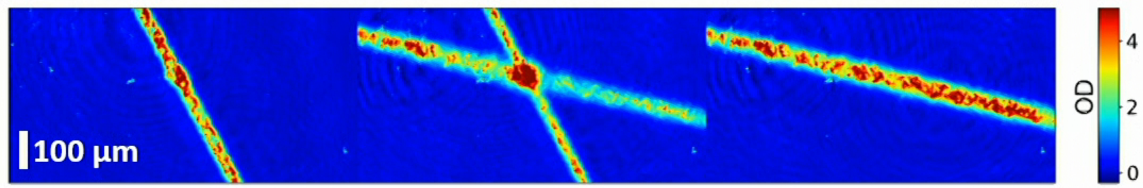
-Polymer lens whose focal length can be changed with current
-Transport carried out with a thermal cloud



Focus-tunable lens

Loading process of the transport trap

TOF=2ms



Evaporated cloud

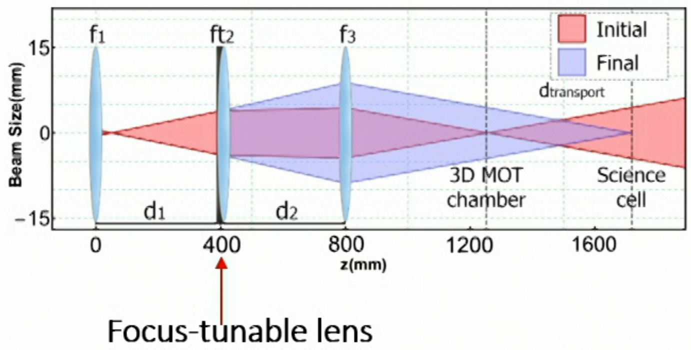
Loading into dipole trap

Loaded transport trap

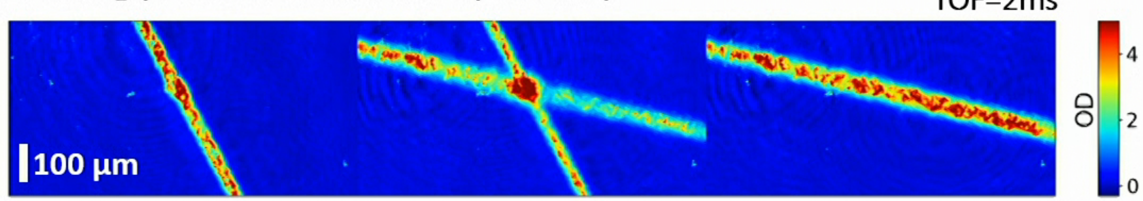
PSD before ≈ PSD after ≈ 10^{-2}

Optical transport

- -Polymer lens whose focal length can be changed with current
- -Transport carried out with a thermal cloud



Loading process of the transport trap



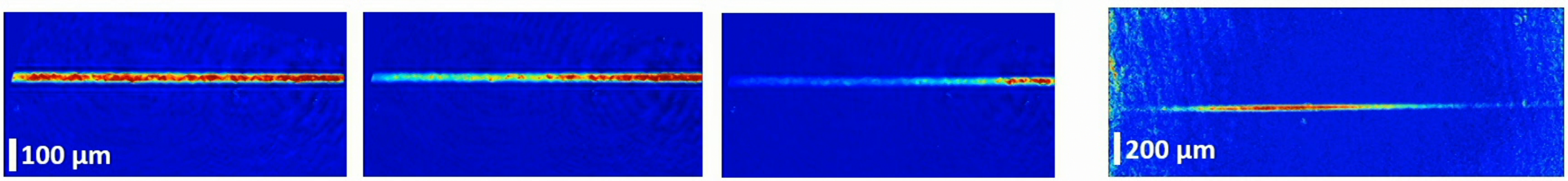
Evaporated cloud

Loading into dipole trap

Loaded transport trap

PSD before ≈ PSD after ≈ 10^{-2}

Demonstration of the transport principle

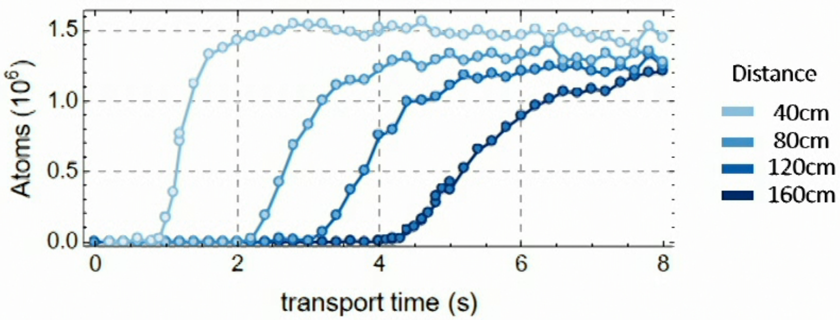


3D MOT chamber

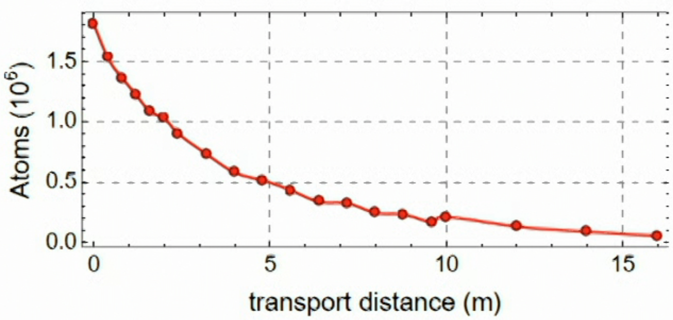
Science chamber

Transport characterisation

Transport efficiency



Transport distance:



Transport characterisation

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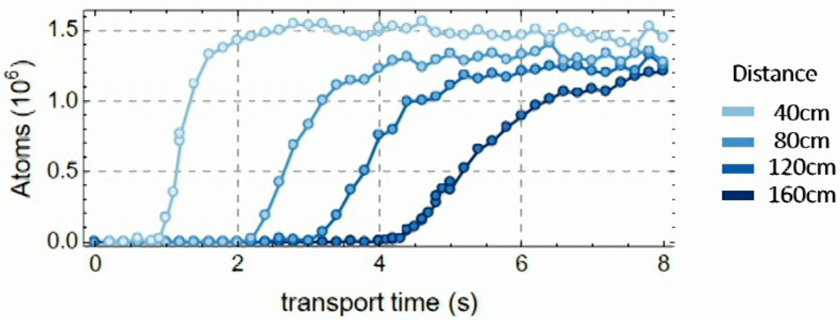
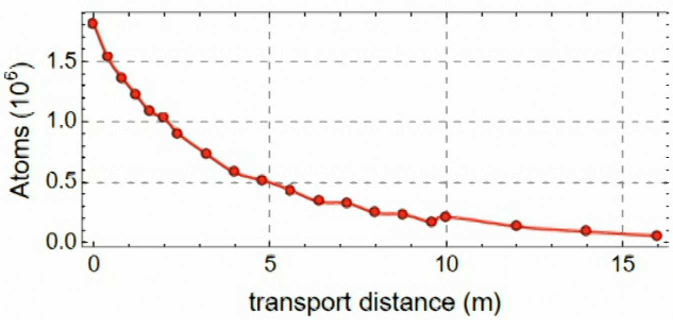
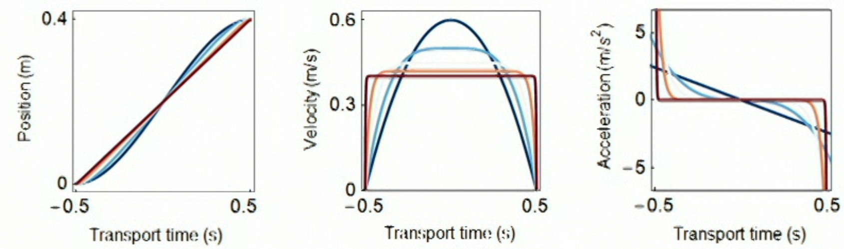


Transport distance:

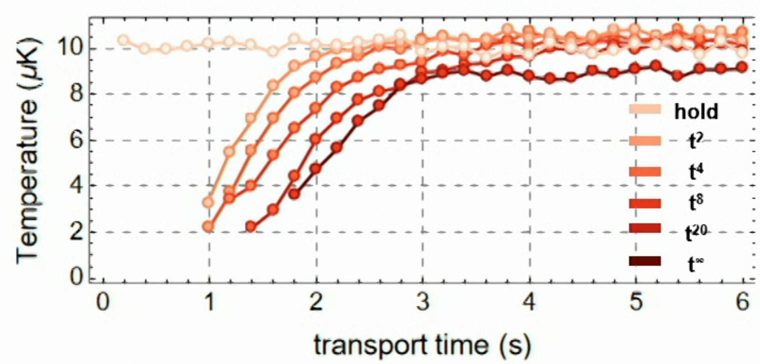


Heating:



Profiles: $$s(t) = \frac{n+1}{n} \times D \times \frac{2^n}{{t_f}^{n+1}} \times \left(\left(\frac{t_f}{2} \right)^n \times t - \frac{t^{n+1}}{n+1} \right)$$

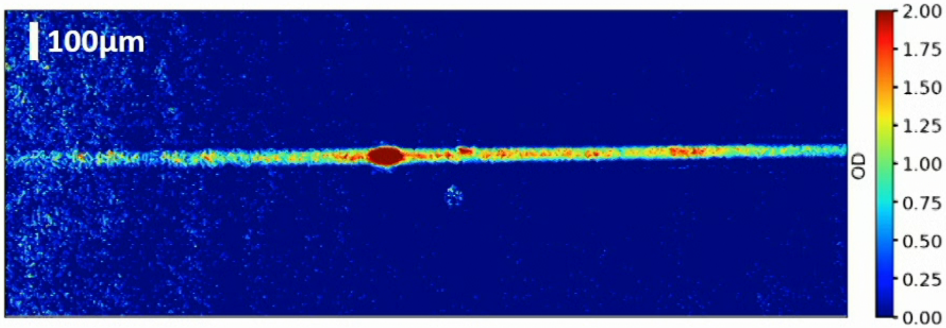
D: distance, t_f: transport time, n: index



Outlook:

The group: Konstantinos Konstantinou, Paul Wong, Tanish Satoor, Chris Eigen, Nishant Dogra , Zoran Hadzibabic

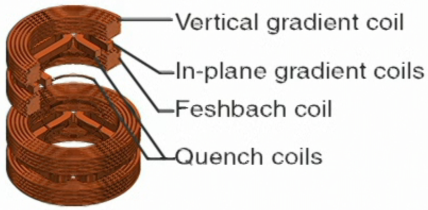
Current state:



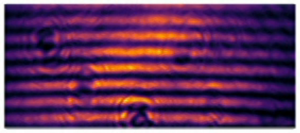
Crossed dipole trap in the science cell

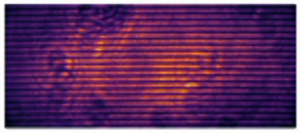
Future milestones:

Coil installation:



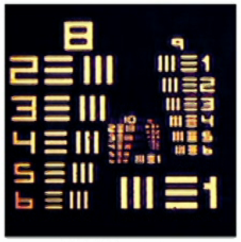
2D confinement:

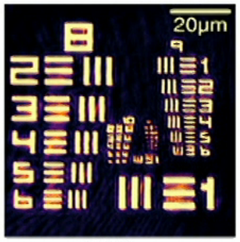




Spacing: 6μm 1 μm

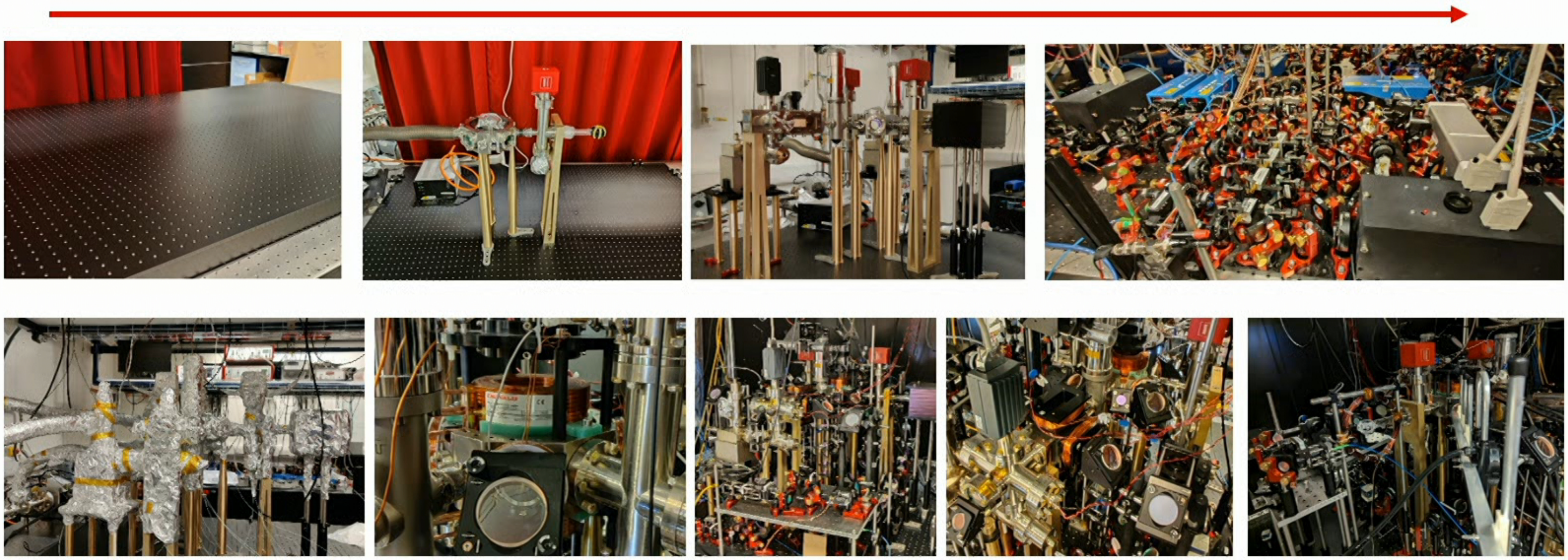
High resolution microscope: NA:0.7, DOF:1μm, FOV:200μm





λ:	532nm	780nm
Resolution:	690nm	976nm

Progress so far:



Quantum catastrophes and Near Horizon Physics in a Bose-Einstein Condensate

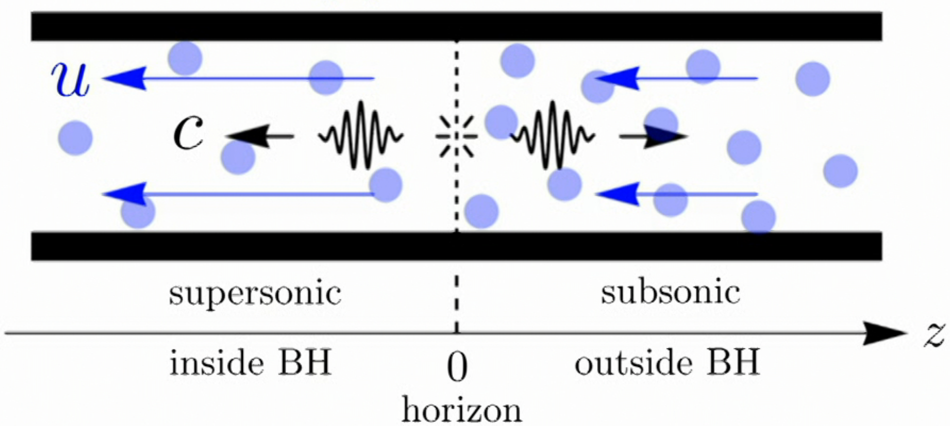
McMaster University

Liam Farrell, Christopher Howls & Duncan O'Dell. 2023 *J. Phys. A: Math. Theor.* 56 044001

- Quasi-1D acoustic black hole and HR

Unruh, *Phys. Rev. Lett.* 46: 1351-1353 (1981)
Kolobov, ..., Steinhauer et al, *Nat. Phys.* 17, 362–367 (2021)

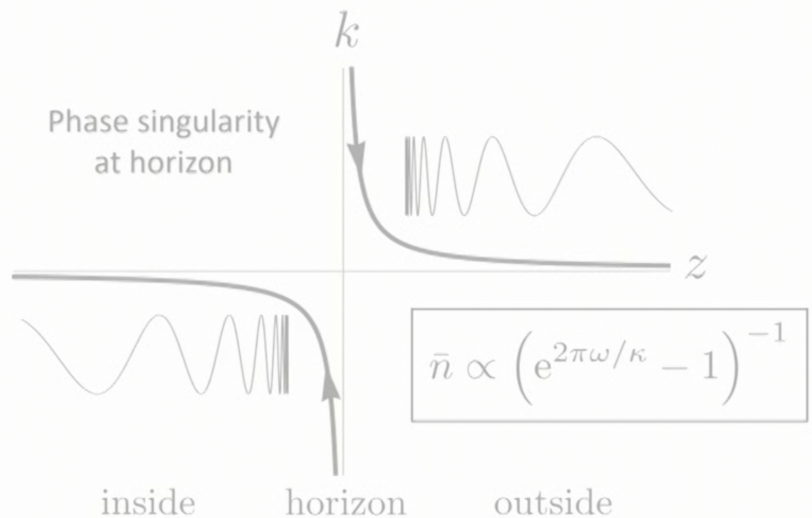
$$u(z) = -c + \kappa z$$



- Bogoliubov dispersion

$$\omega \approx (c+u)k + \frac{c}{8k_c^2}k^3, \qquad k_c = \frac{mc}{\hbar} = \frac{1}{\sqrt{2}\xi}$$

Leonhardt et al, J. *Opt. B: Quant. Semiclass. Opt.* 5 S42–S49 (2003)



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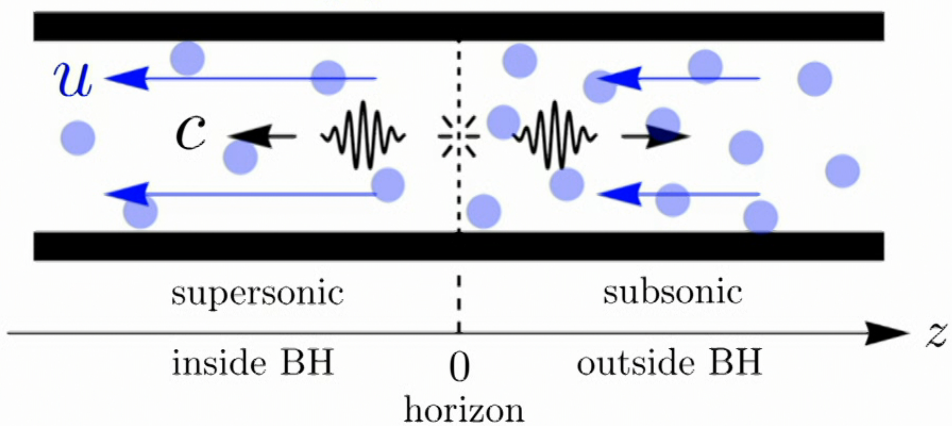
$$u(z) = -c + \kappa z$$



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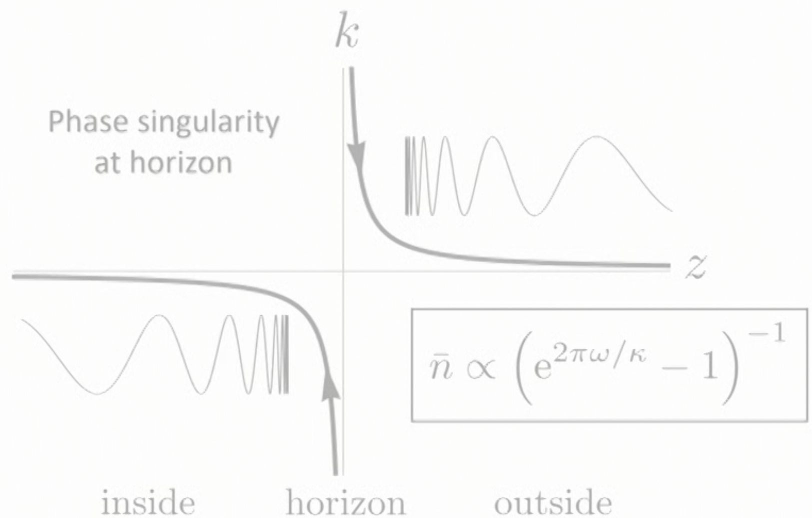


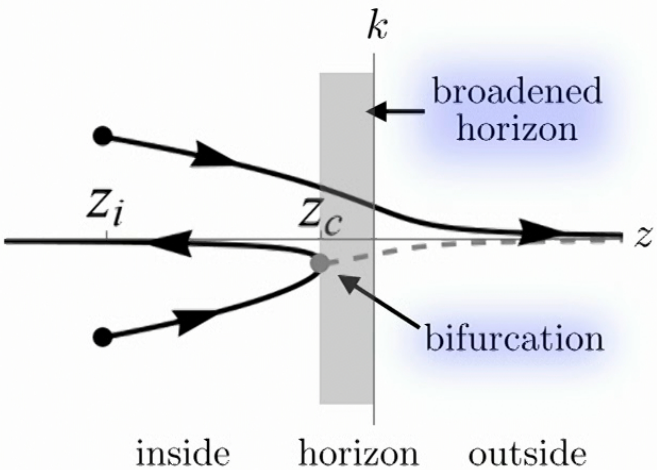
1

- Non-linearity: Compton scale regularizes

$$\omega \approx (c+u)k + \frac{c}{8k_c^2}k^3$$

Jacobson, *Phys. Rev. D* 44 1731 (1991)

- Broken pitchfork bifurcation

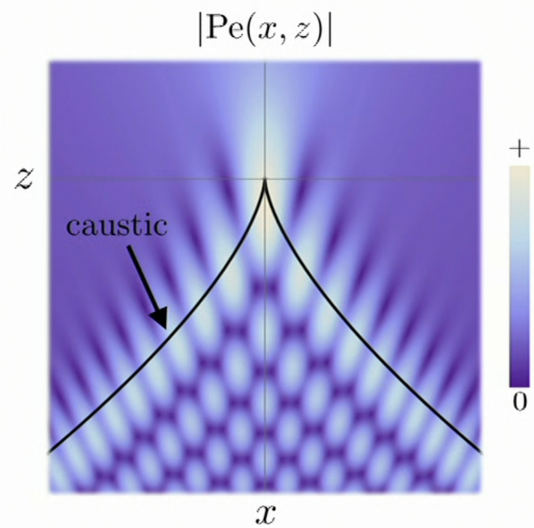


$$\bar{n} \propto \left(e^{2\pi\omega/\kappa} - 1\right)^{-1} + \text{small corrections}$$

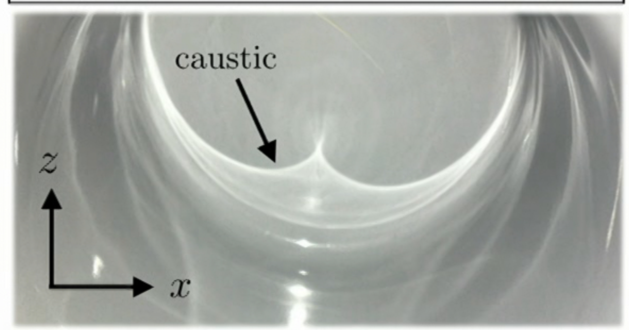
- Catastrophe theory ➔ regulates singularities, can only have certain shapes, universal

Poston & Stewart, Catastrophe Theory and its Applications (1978)

Berry et al, *Progress in Optics XVIII*, 257-346 (1980)



$$\text{Pe}(x,z) = \int_{-\infty}^{\infty} e^{i(s^4/4 + zs^2/2 + xs)}\,ds$$



- Expect HR wave theory to be given by Pearcey, yet...

- Wave theory yields new class of ***quantum catastrophe***: log-Airy function, accounts for particle production

Leonhardt, Phys. Rev. A 65, 043818 (2002)

$$\omega \approx (c+u)k + \frac{c}{8k_c^2}k^3$$

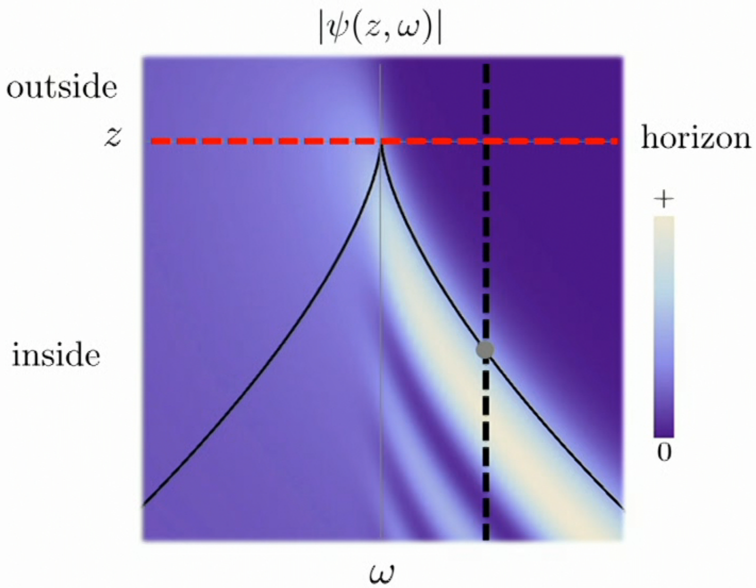
$$\psi(z,\omega) \approx \int_{-\infty}^{\infty} \frac{1}{k} e^{i\Lambda\left(k^3/3 + kz - \omega \ln(k)\right)} dk, \quad \Lambda \propto \hbar^{-1}$$

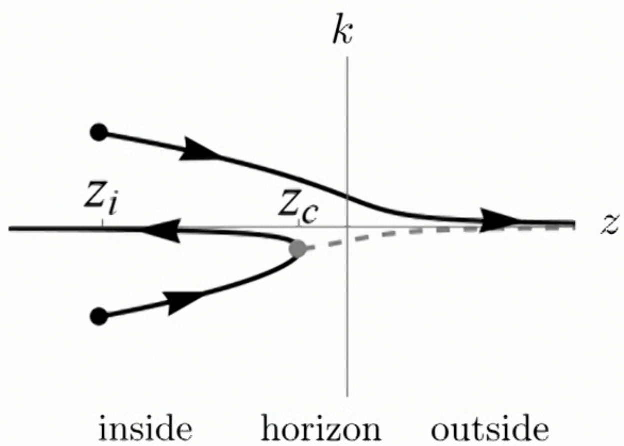
Coutant, Parentani, & Finazzi, *Phys. Rev. D* 85, 024021 (2012)

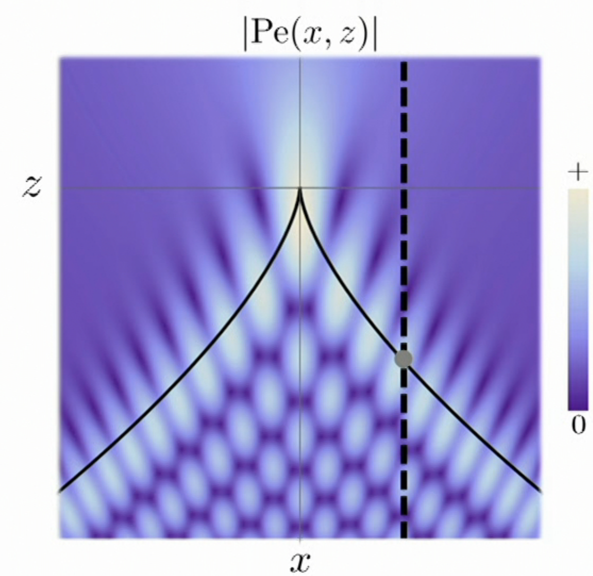
Ray theories equivalent

Wave theories differ

$$\mathrm{Pe}(x,z) = \int_{-\infty}^{\infty} e^{i(s^4/4 + zs^2/2 + xs)} ds$$





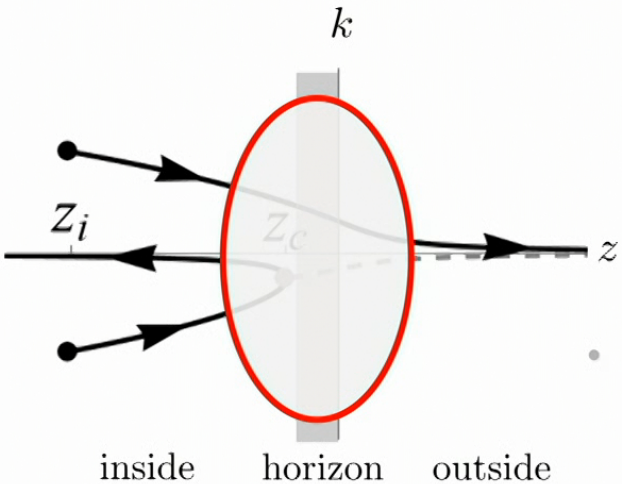


*Compressed leftmost plot vertical scale when compared to rightmost plot for aesthetics

- Construct S-matrix via asymptotics ➔ Hawking spectrum + corrections

$$\bar{n} \propto \left(e^{2\pi\omega/\kappa} - 1\right)^{-1} + \begin{array}{c}\text{small}\\ \text{corrections}\end{array}$$

Coutant, Parentani, & Finazzi, *Phys. Rev. D* 85, 024021 (2012)



- Previous literature makes some approximations, neglects near horizon physics

- Developed an asymptotic approach which accounts for near horizon physics:
  Liam Farrell, Christopher Howls & Duncan O'Dell. 2023 *J. Phys. A: Math. Theor.* 56 044001

➔ 1) No longer neglects near horizon physics
   2) Can apply catastrophe theory

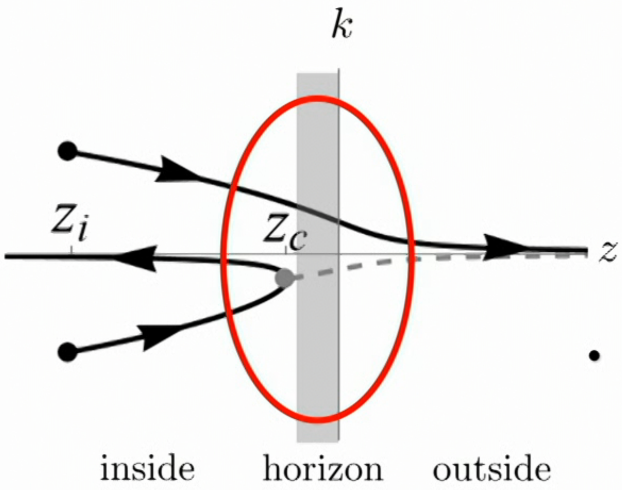
- Although studied HR in flowing BEC, universality may provide quantum gravity insight: are HR corrections universal?

Questions!

- Construct S-matrix via asymptotics ➔ Hawking spectrum + corrections

$$\bar{n} \propto \left(e^{2\pi\omega/\kappa} - 1\right)^{-1} + \begin{array}{c}\text{small}\\\text{corrections}\end{array}$$

Coutant, Parentani, & Finazzi, *Phys. Rev. D* 85, 024021 (2012)



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Questions!

Regge pole description of scattering by dirty black holes

Shiqian Hu

Theoretical Particle Physics and Cosmology

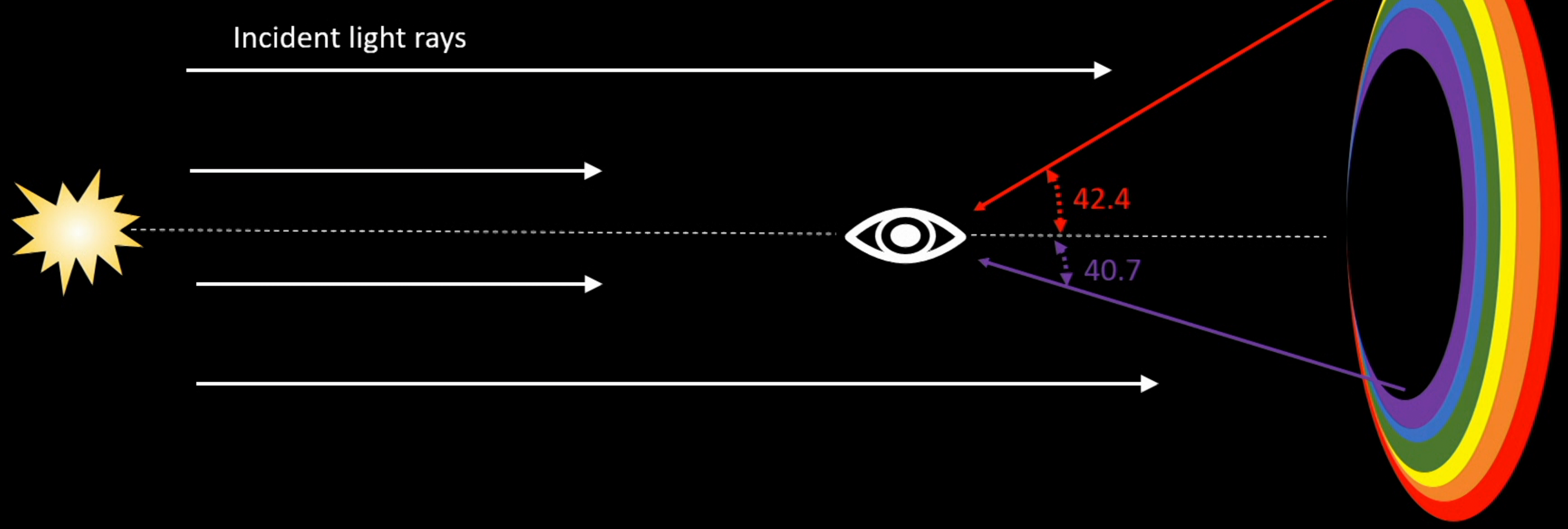
King's College London

Quantum Simulator for Fundamental Physics, PI, 07/06/2023

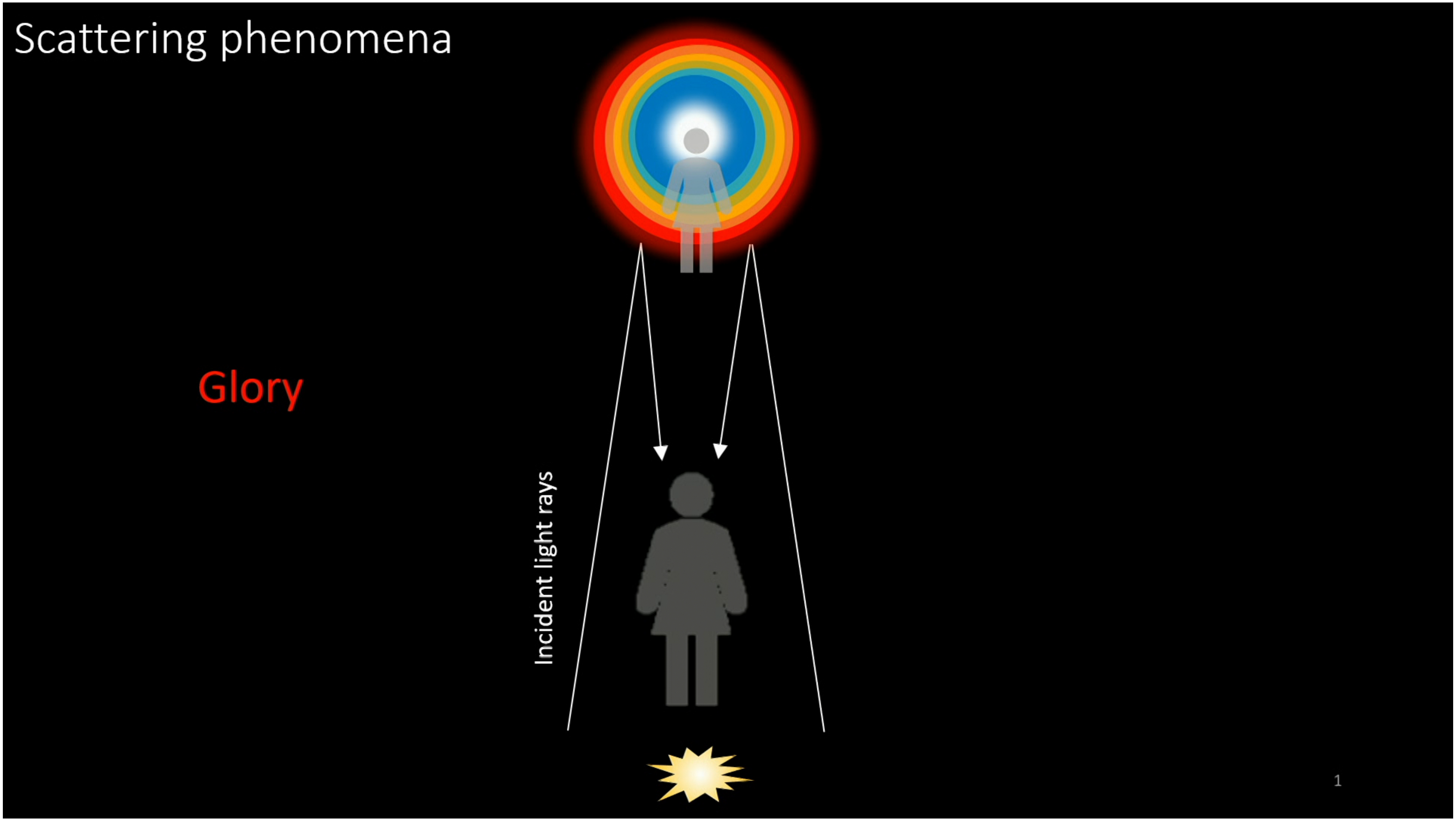
Phys. Rev. D 107, 064028 (2023)
with Theo Torres, Mohamed Ould El Hadj and Ruth Gregory

Scattering phenomena

Rainbow

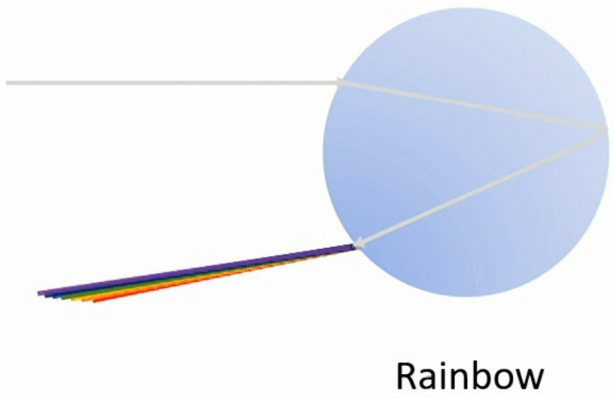


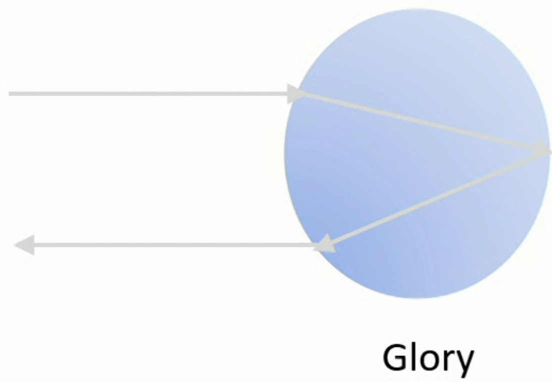
1


Scattering phenomena
Glory
Incident light rays
1

Scattering phenomena in black hole

Water droplet [1]

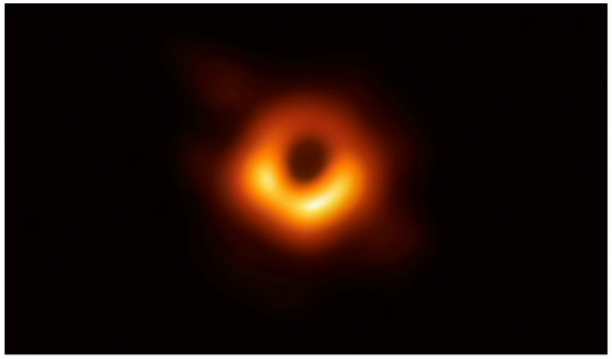




Dirty Black holes [2]

Black hole with surroundings:

The presence of matter and fields around black holes



[1] John A. Adam, Physics Reports 356 (2002) 229–365

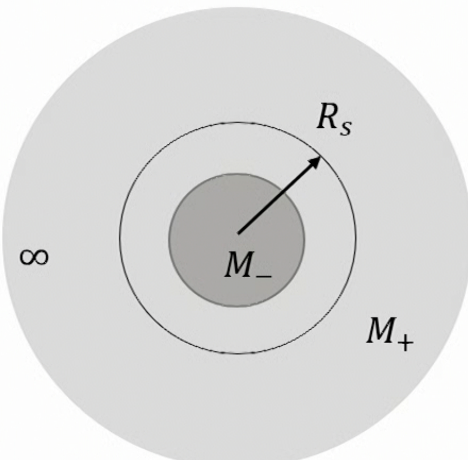
[2] M. Visser, Phys. Rev. D 46, 2445-2451 (1992)

Dirty black hole

The spacetime is given by two distinct Schwarzschild geometries:

$$ds^2 = f_\pm(r)dt_\pm^2 - \frac{dr^2}{f_\pm(r)} - r^2 d\Omega^2$$

$$f_\pm(r) = 1 - 2M_\pm/r$$



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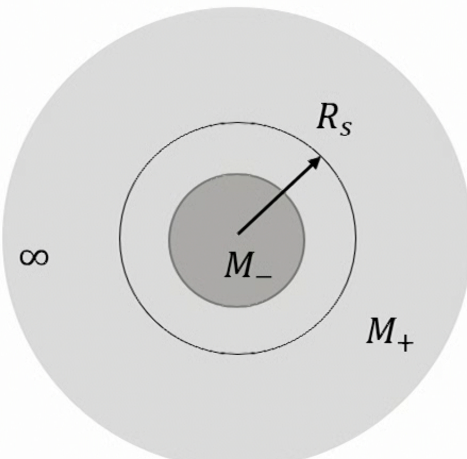

$$\Delta K_{ab} - \Delta K h_{ab} = 8\pi S_{ab} = E u_a u_b - P\left(h_{ab} - u_a u_b\right)$$

$$\dot{R}_s^2 + 1 = (4\pi E)^2 R_s^2 + \frac{(M_+ + M_-)}{R_s} + \frac{(M_+ - M_-)^2}{(8\pi E)^2 R_s^4},$$

$$\dot{E} + 2\frac{\dot{R}_s}{R_s}(E+P) = 0.$$

Locations of shell

The minimum value of R_s, $(M_+ = M_-)$

$$R_{s,min} = \frac{1 + 4\omega}{2\omega} M_\pm$$

Different locations of the shell:

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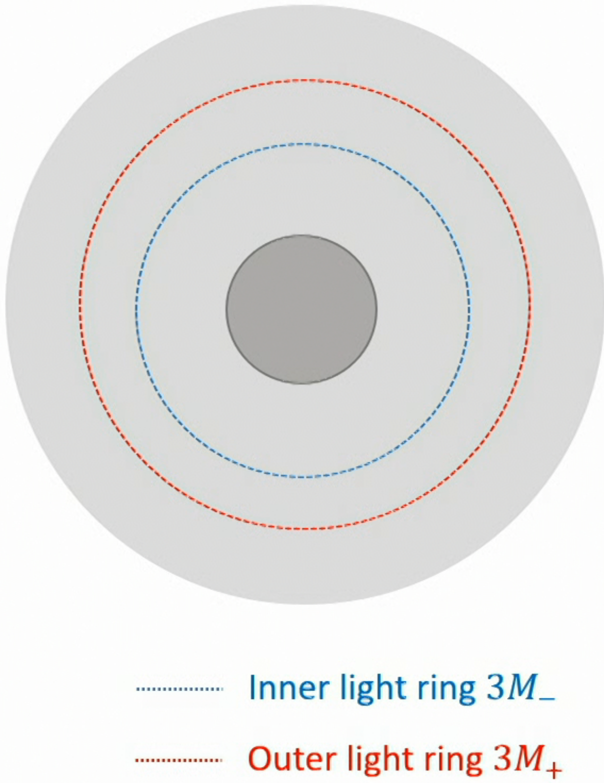

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Different locations of the shell:

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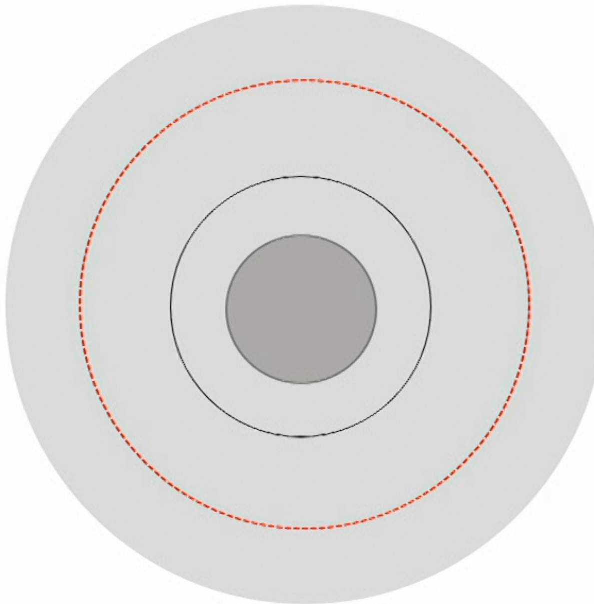

4

Locations of shell

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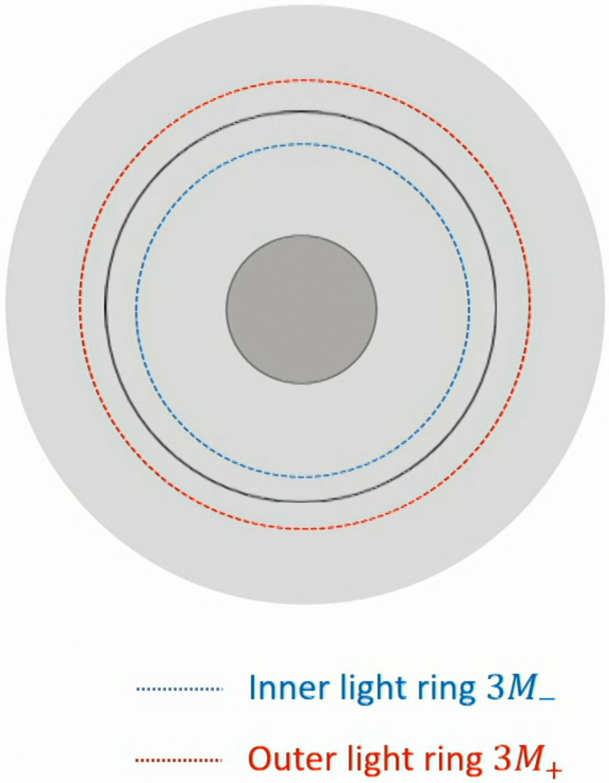
- $3M_- \leq R_s \leq 3M_+, (\frac{\sqrt{3}-1}{4} < \omega \leq 1)$ Config. 1

  The shell lies between the light-rings



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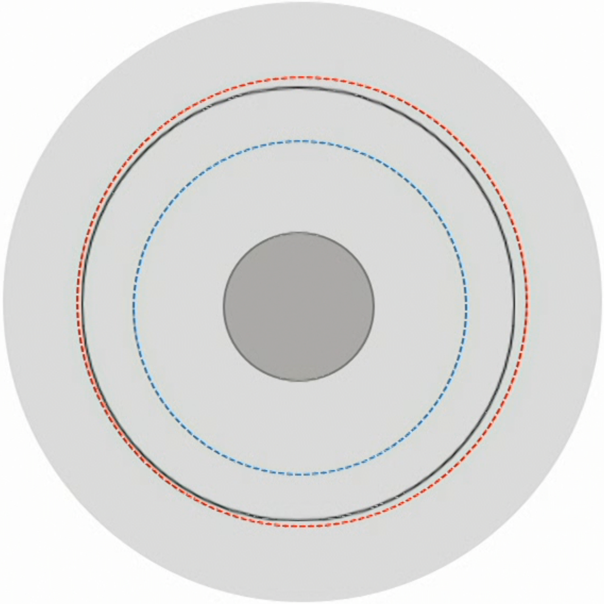
- $R_s > 3M_+, (\omega < \frac{1}{2})$ Config. 2
  The shell lies out the outer light ring



Inner light ring $3M_-$

Outer light ring $3M_+$

4

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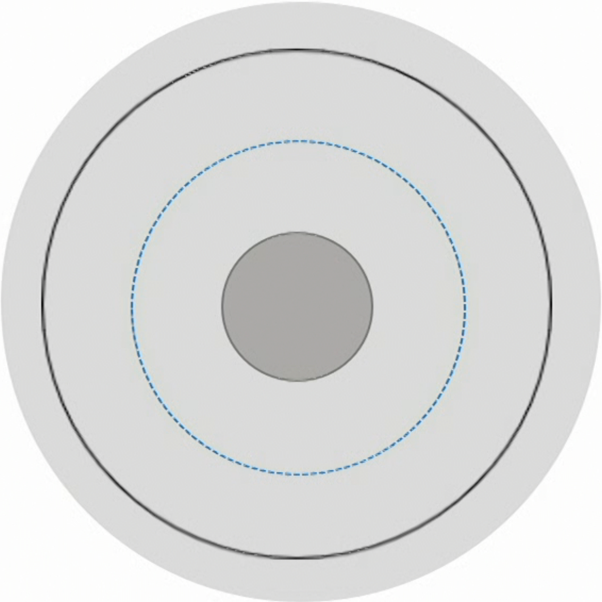


Inner light ring $3M_-$

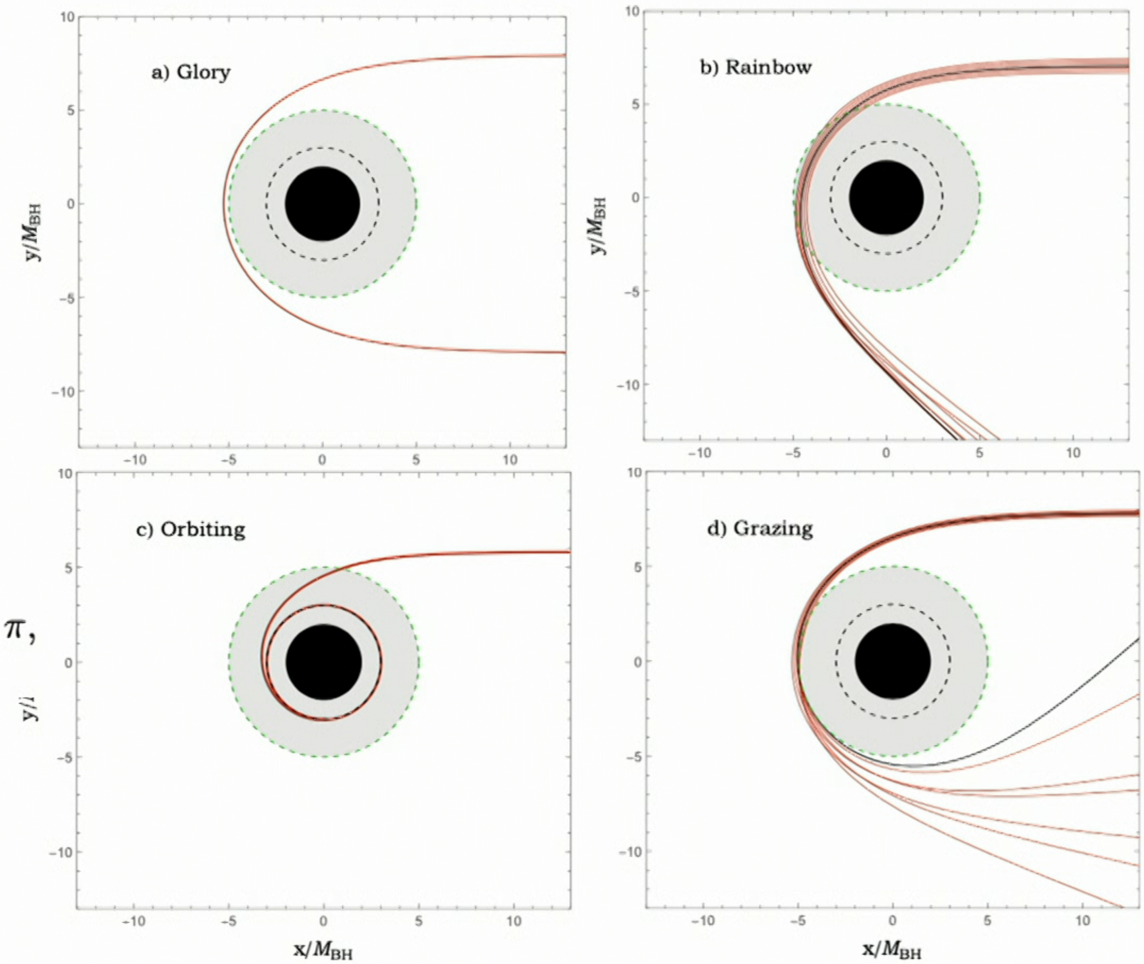
Outer light ring $3M_+$

Critical effects in DBH spacetimes

Classical scattering cross section and geodesic deflection angle

$$\frac{d\sigma}{d\Omega} = \frac{b}{\sin(\theta)} \frac{1}{\left|\frac{d\Theta_{\text{geo}}(b)}{db}\right|}$$

$$\Theta_{\text{geo}}(b) = 2\int_0^{u_0} du \left[B(u)\frac{1 - A(u)b^2u^2}{A(u)b^2}\right]^{-1/2} - \pi,$$



Waves on a dirty black hole spacetime

We consider a scalar field, $\phi(x)$, propagating on the DBH spacetime

$$\Box\Phi \equiv \frac{1}{\sqrt{-g}}\partial_\mu\left(\sqrt{-g}g^{\mu\nu}\partial_\nu\Phi\right) = 0 \qquad \Phi = \frac{1}{r}\sum_{\omega\ell m}\phi_{\omega\ell}(r)Y_{\ell m}(\theta,\phi)e^{-i\omega t},$$

Radial equation and effective potential

Tortoise coordinate

$$\frac{dr_*}{dr} = \frac{1}{\sqrt{A(r)B(r)}},$$

$$\left[\frac{d^2}{dr_*^2} + \omega^2 - V_\ell(r)\right]\phi_{\omega\ell} = 0,$$

$$V_\ell(r) = A(r)\Big[\frac{\ell(\ell+1)}{r^2} + \frac{2}{r^3}\left(M_{\rm BH}\Theta(R_s - r) + M_\infty\Theta(r - R_s)\right)\Big]$$

The solutions defined by their behavior at the horizon $r = 2M_{BH}$, and at spatial infinity $r \to +\infty$

$$\phi^{\rm in}_{\omega\ell}(r_*) \sim \begin{cases} e^{-i\omega r_*} & (r_* \to -\infty), \\ A^{(-)}_\ell(\omega)e^{-i\omega r_*} + A^{(+)}_\ell(\omega)e^{+i\omega r_*} & (r_* \to +\infty). \end{cases}$$

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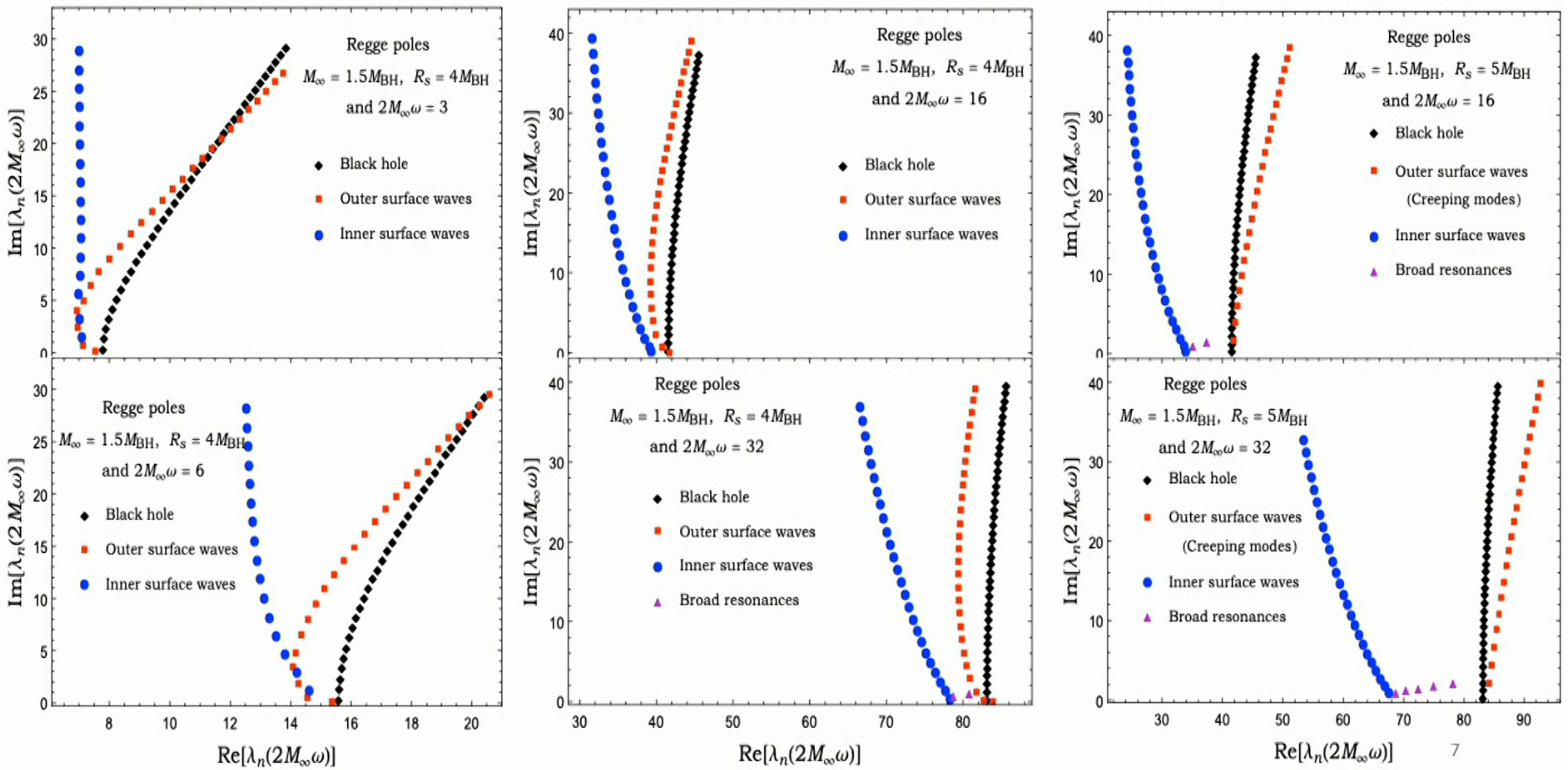
Boundary condition on the eigenfunctions $\phi_{\omega l}$ at the shell

$$\left[\sqrt{B(R_s)}\left(R_s\phi'_{\omega\ell}(R_s) - \phi_{\omega\ell}(R_s)\right)\right]_+ = \left[\sqrt{B(R_s)}\left(R_s\phi'_{\omega\ell}(R_s) - \phi_{\omega\ell}(R_s)\right)\right]_-$$

Resonances of the dirty black holes



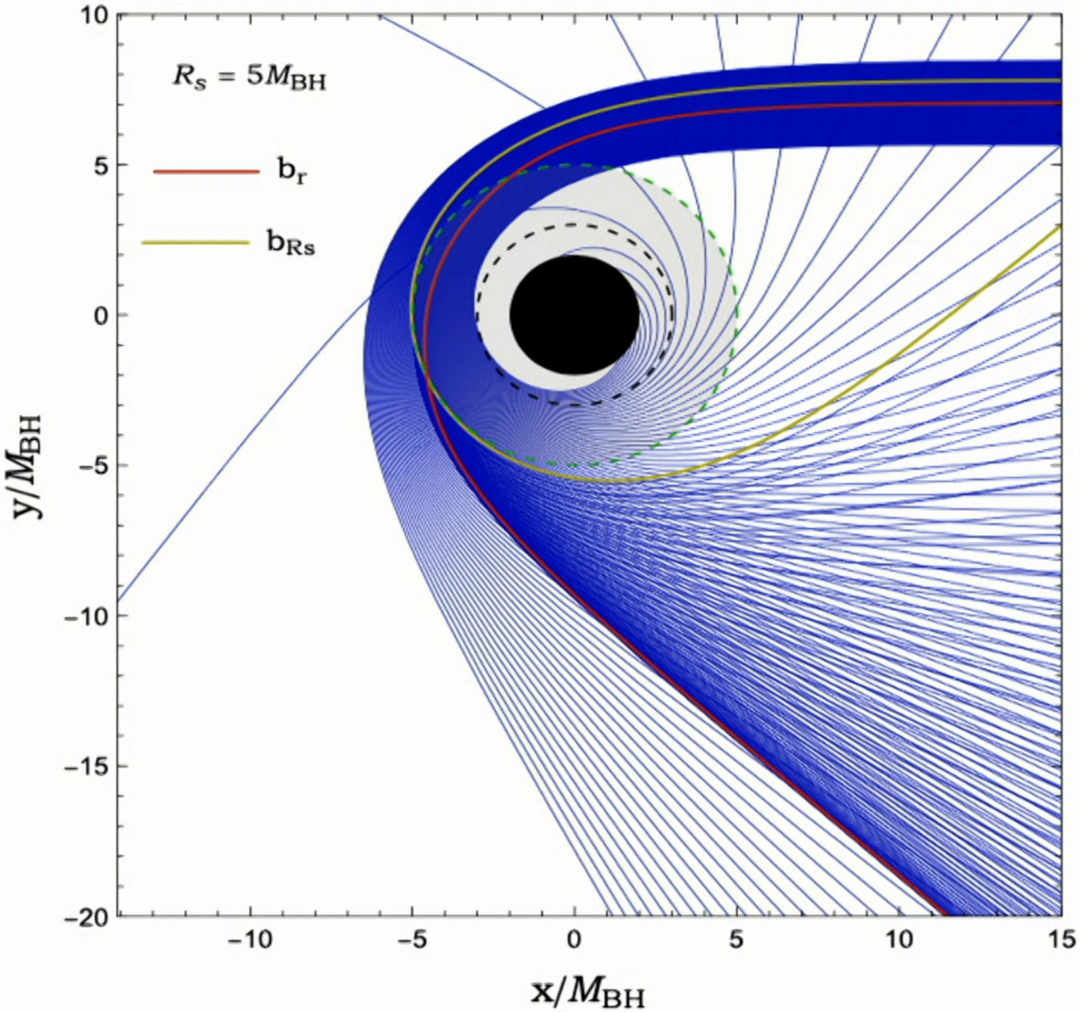
7

Conclusions

- The critical effects of scattering in a dirty black hole spacetime by showing the scattered null geodesics

- The Regge pole spectrum of different DBH configurations
  - The existence of two branches are associated with the inner light-ring and with either the outer light-ring or the shell depending on the DBH configuration.
  - The possible existence of a third branch with a nearly constant imaginary part.

Critical effects in DBH spacetimes



Null geodesics scattered by a DBH

- Rainbow Ray: Impact parameter b_r leads a divergence for $\theta \neq 0 \; or \; \pi$
- Graze Ray: b_{R_s} leads to a singular point where the scatter has a discontinuity

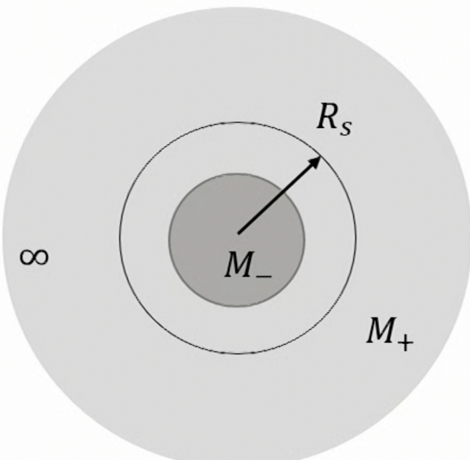
10

Dirty black hole

The spacetime is given by two distinct Schwarzschild geometries:

$$ds^2 = f_\pm(r)dt_\pm^2 - \frac{dr^2}{f_\pm(r)} - r^2 d\Omega^2$$

$$f_\pm(r) = 1 - 2M_\pm/r$$



$$\Delta K_{ab} - \Delta K h_{ab} = 8\pi S_{ab} = E u_a u_b - P\left(h_{ab} - u_a u_b\right)$$

$$\dot{R}_s^2 + 1 = (4\pi E)^2 R_s^2 + \frac{(M_+ + M_-)}{R_s} + \frac{(M_+ - M_-)^2}{(8\pi E)^2 R_s^4},$$

$$\dot{E} + 2\frac{\dot{R}_s}{R_s}(E+P) = 0.$$

Numerical simulation of Kibble-Zurek mechanism with Landau-Ginzburg dynamics

Fumika Suzuki, Los Alamos National Lab

Los Alamos NATIONAL LABORATORY

Center for Nonlinear Studies

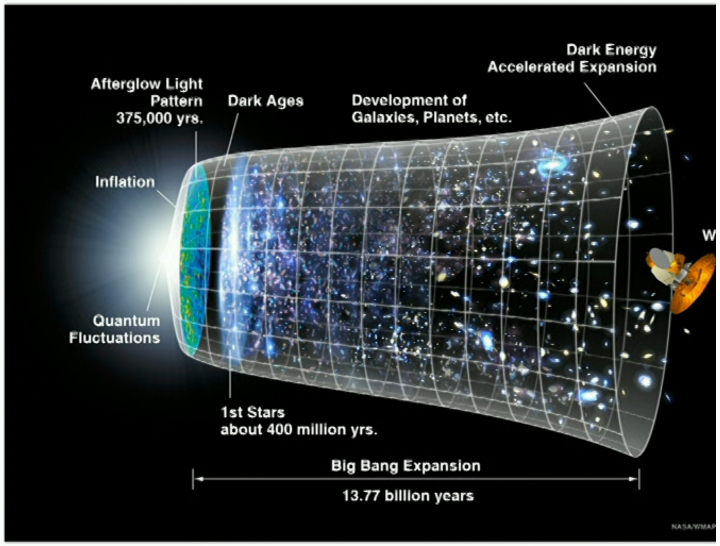
Introduction

Kibble-Zurek mechanism:
non-equilibrium dynamics and defect formulation in systems that cross second-order phase transitions.

Applications:

- cosmology
  domain structure formulation in early universe e.g., cosmic strings

- condensed matter physics
  e.g., liquid crystals, superfluid helium, superconductors, Bose-Einstein condensation



Phase transitions in early universe

Kibble-Zurek mechanism (KZM)

Equilibrium correlation length & relaxation time

$$\xi(\varepsilon) = \frac{\xi_0}{|\varepsilon|^{\nu}} \qquad \tau(\varepsilon) = \frac{\tau_0}{|\varepsilon|^{z\nu}}$$

Relative distance to the critical point $\varepsilon = \dfrac{\lambda_c - \lambda}{\lambda_c}$

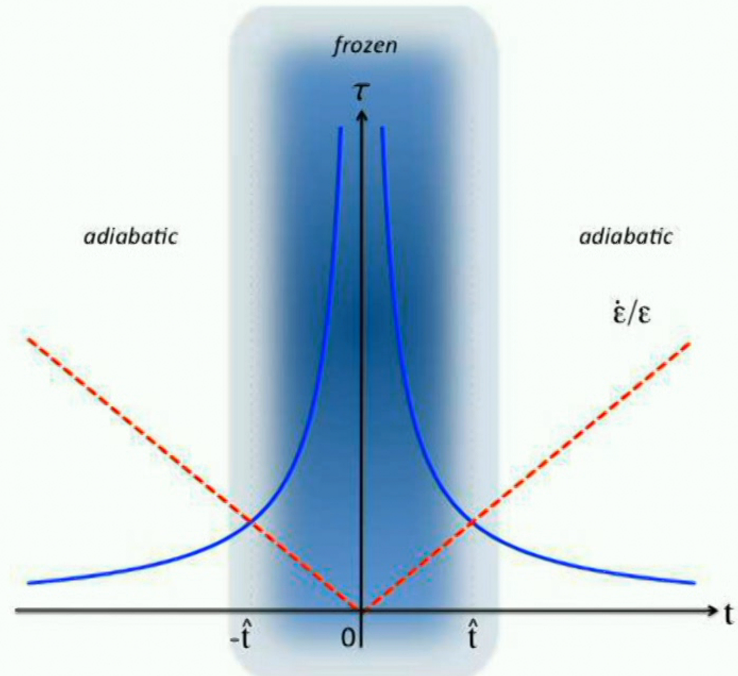
Linear quench $\varepsilon(t) = \dfrac{t}{\tau_Q}$ ⟵ quench time

Domain size $\hat{\xi} \equiv \xi[\hat{\varepsilon}] = \xi_0 \left(\dfrac{\tau_Q}{\tau_0}\right)^{\frac{\nu}{1+z\nu}}$

Density of topological defects

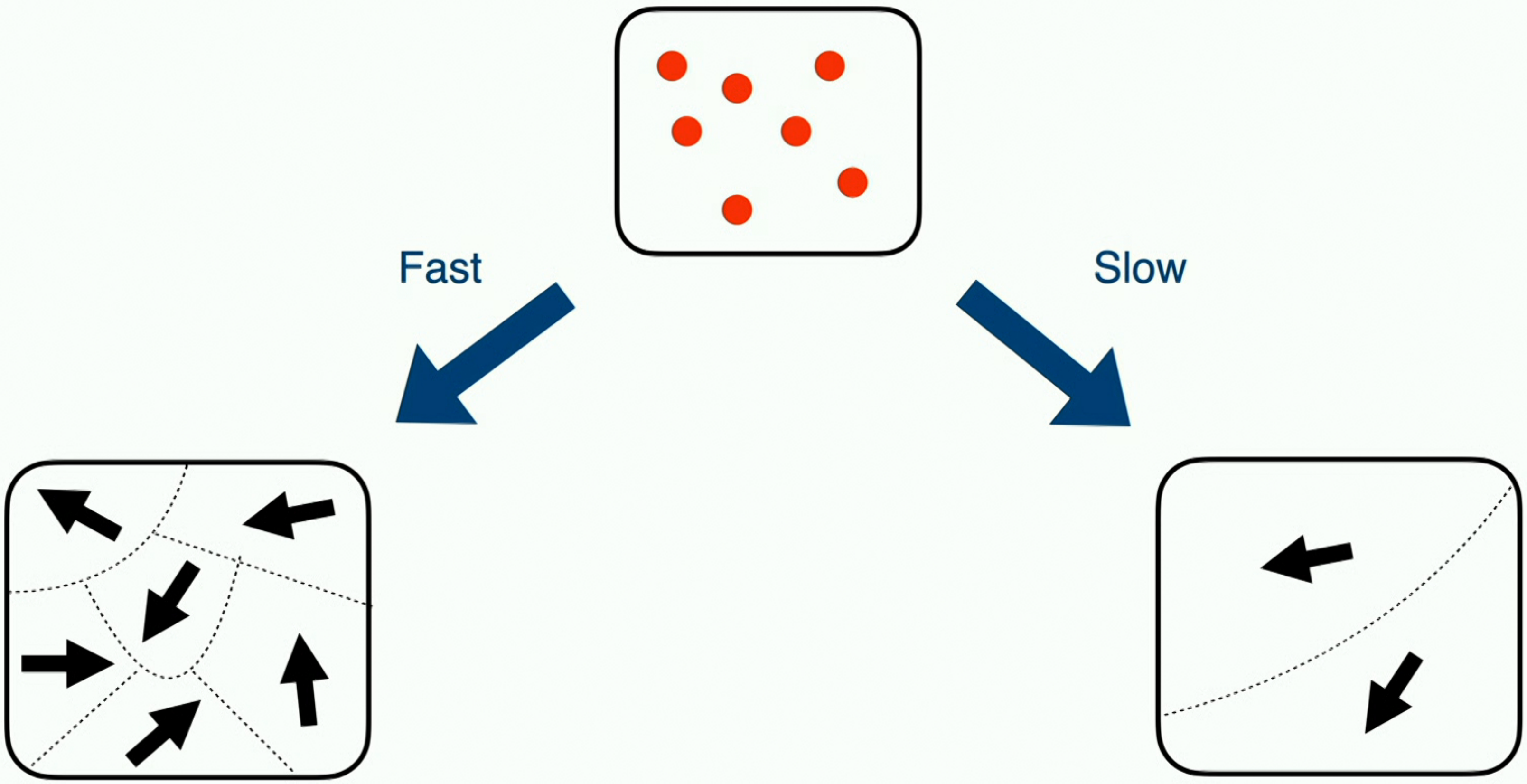
$$n \sim \frac{\hat{\xi}^d}{\hat{\xi}^D} = \frac{1}{{\xi_0}^{D-d}} \left(\frac{\tau_0}{\tau_Q}\right)^{(D-d)\frac{\nu}{1+z\nu}}$$

D: dimensions of space *d*: dimensions of defects



A. Del Campo & W. H. Zurek, Int. J. Mod. Phys. A **29,** 1430018 (2014)

Fast vs slow quench



A large number of defects

A few number of defects

Numerical test of second-order phase transition

Langevin equation

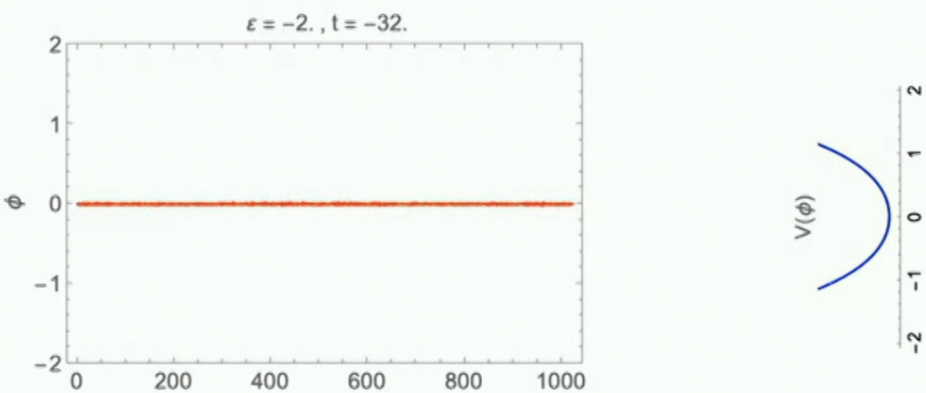
$$\ddot{\phi} + \eta\dot{\phi} - \partial_{xx}\phi + \partial_{\phi}V(\phi) = \theta \longleftarrow \text{noise}$$

order parameter

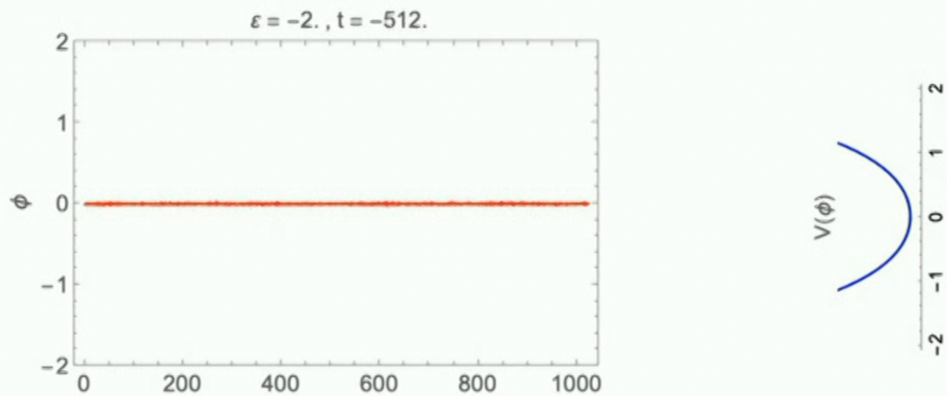
damping constant

$$V(\phi) = (\phi^4 - 2\epsilon\phi^2 + 1)/8$$

$$\epsilon = t/\tau_Q$$

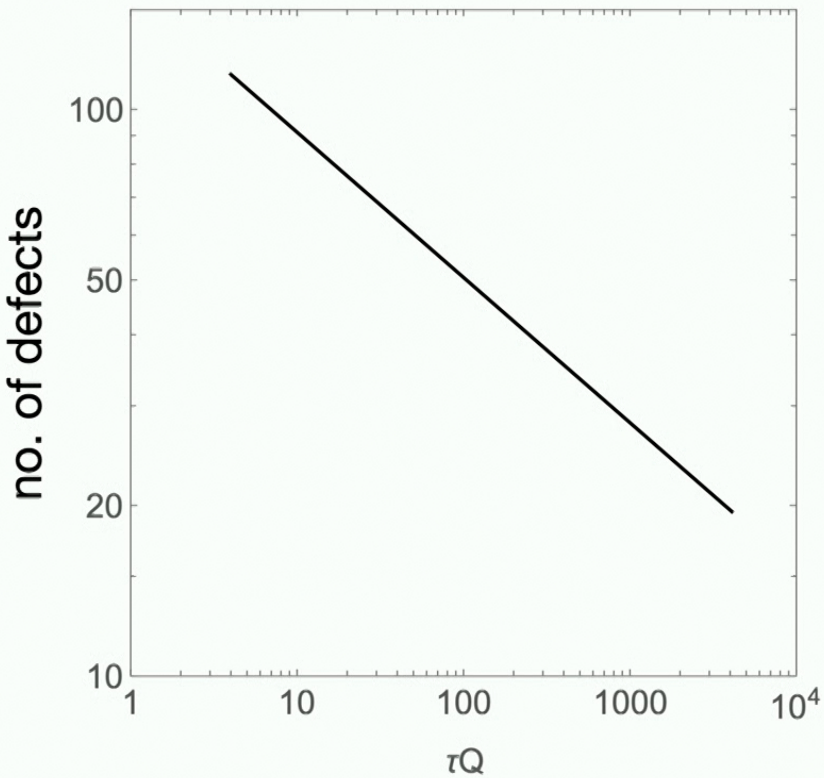


Fast quench



Slow quench

Number of defects vs τQ



Larger τQ → slower quench → fewer defects

$$N = N_0 \tau_Q^{-a}$$

$a = 0.26$ $N_0 = 164$

Agrees well with theoretical prediction 1/4

(Power-law decreases of no. of defects as predicted by KZM)

Weakly first-order phase transitions

KZM is generally not applicable to 1st order phase transition

superconducting phase transition
smectic-*A* to nematic liquid crystal

→ Weakly first-order
due to the effects of the intrinsic fluctuating magnetic field

Free-energy functional

$$F\{\psi, \vec{A}\} = \int d^3r\left[a|\psi|^2 + \tfrac{1}{2}b|\psi|^4 + \gamma|(\nabla - iq_0\vec{A})\psi|^2 + (8\pi\mu_0)^{-1}\sum_{i>j}(\nabla_j A_i - \nabla_i A_j)^2\right].$$

First-order phase transition

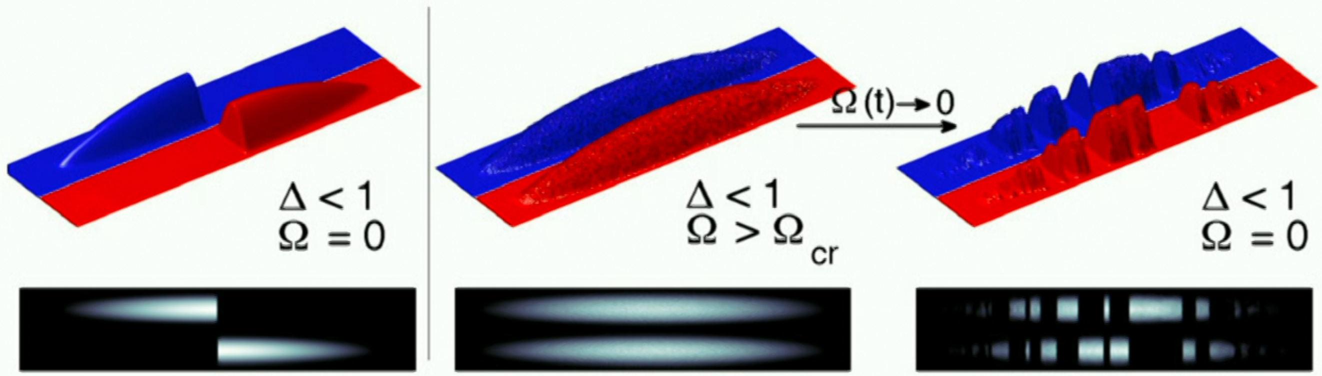
KZM in weakly first-order phase transition?

B. I. Halperin, T. C. Lubensky and Shang-keng Ma, PRL **32,** 292 (1973)

Bose-Einstein condensate

Miscible-immiscible phase transition
of binary BEC (composed of two hyperfine states)

Phase transition by controlling coupling



Immiscible　　　　Miscible → immiscible

J. Sabbatini, W. H. Zurek, and M. J. Davis, New J. Phys. **14,** 095030 (2012)

Thanks: W. H. Zurek
Malcolm Boshier

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Center for Nonlinear Studies