Note Title 7/19/2014

# SCALING IN QUANTUM QUENCH
## HOLOGRAPHY & BEYOND

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IN EQUILIBRIUM CRITICAL PHENOMENA, UNDERSTANDING THE ORIGIN OF SCALING AND UNIVERSALITY CONSTITUTES PERHAPS ONE OF THE MOST PROFOUND DEVELOPMENTS IN PHYSICS. — THE RENORMALIZATION GROUP

RG EXPLAINS WHY WE CAN DO PHYSICS AT USUAL ENERGY SCALES WITHOUT BOTHERING TOO MUCH ABOUT PHYSICS AT THE MICROSCOPIC SCALES

e.g LATTICE EFFECTS IN COND-MAT SYSTEMS
OR PLANCK SCALE IN PARTICLE PHYSICS

IS THERE A SIMILAR UNIVERSALITY FOR FAR FROM EQUILIBRIUM PROCESSES ?

THERE IS VERY LITTLE UNDERSTANDING OF THIS IMPORTANT QUESTION

HOWEVER, MODERN EXPERIMENTS WITH COLD ATOM SYSTEMS CAN PROBE THIS KIND OF NONEQUILIBRIUM PHYSICS IN DETAIL – THIS HAS PROMPTED A VIGOROUS THEORETICAL ACTIVITY IN THIS FIELD

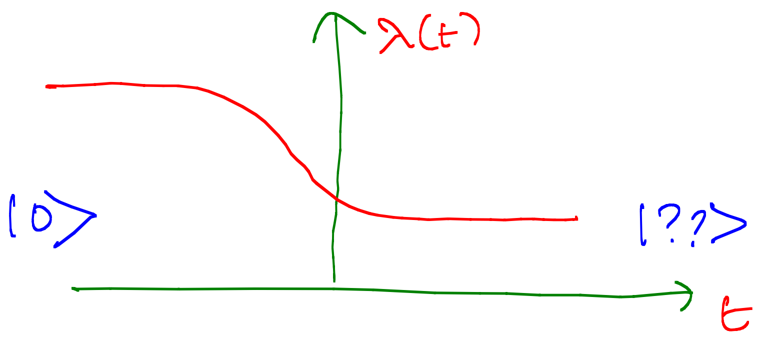
## QUANTUM QUENCH

ONE WAY TO TAKE A SYSTEM OUT OF EQUILIBRIUM IS TO MAKE EXTERNAL PARAMETERS TIME DEPENDENT – CORRESPONDING TO A HAMILTONIAN $H[\lambda(t)]$ WITH TIME DEPENDENT PARAMETERS

WE WILL CALL SUCH PARAMETERS COUPLINGS

AND THE PROCESS QUANTUM QUENCH

THE COUPLING WILL ASYMPTOTE TO CONSTANT VALUES AT EARLY AND LATE TIMES





STARTING FROM A NICE INTIAL STATE (e.g GROUND STATE)

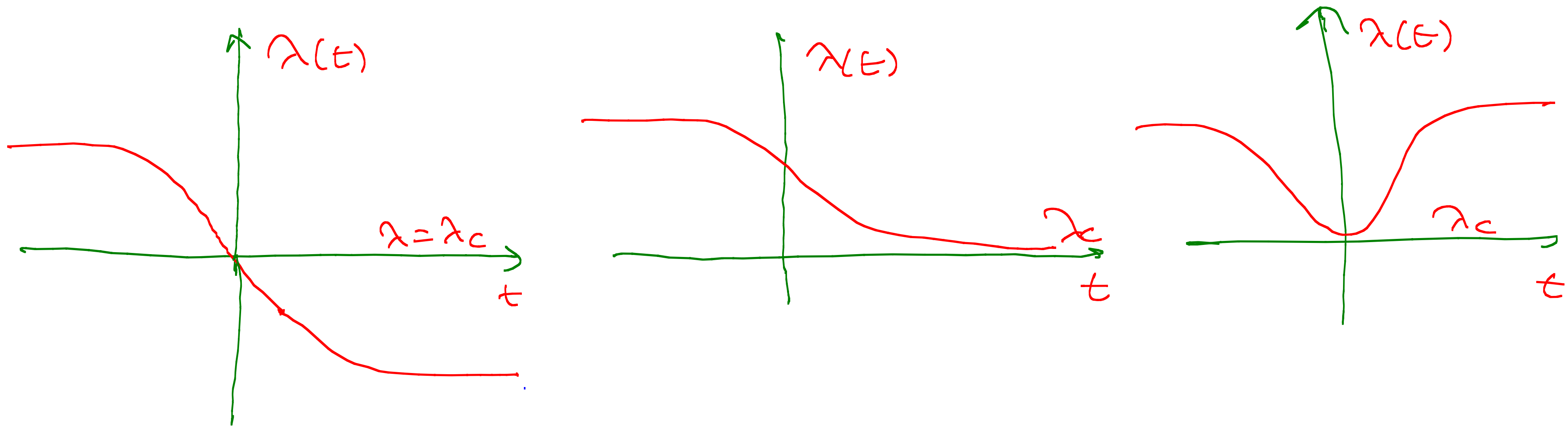
- WHAT IS THE NATURE OF THE STATE AT INTERMEDIATE AND LATE TIMES

ONE OF THE REASONS WHY THIS IS INTERESTING IS THE QUESTION OF THERMALIZATION

- DOES THE SYSTEM SETTLE DOWN TO A STEADY STATE ?
- DOES THE STEADY STATE RESEMBLE A THERMAL STATE
  - IF SO : IN WHAT SENSE ?

THIS QUESTION LIES AT THE FOUNDATIONS OF STATISTICAL MECHANICS

A DIFFERENT QUESTION RELATES TO TIME DEPENDENT COUPLINGS WHICH CROSS OR APPROACH OR TOUCH A QUANTUM CRITICAL POINT

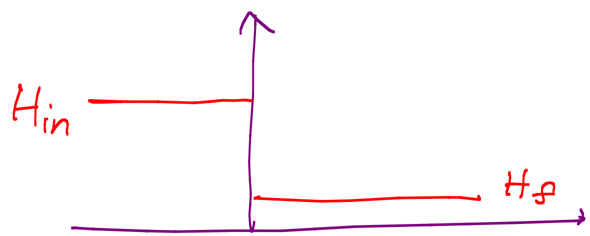



DOES THE SUBSEQUENT TIME EVOLUTION CARRY UNIVERSAL SIGNATURES OF THE CRITICAL POINT ?

THIS PROBLEM IS USUALLY STUDIED IN TWO EXTREME REGIMES

(1) SLOW QUENCH : STARTING IN A GAPPED PHASE THE RATE OF CHANGE IS SLOW COMPARED TO THE GAP.

(2) ABRUPT QUENCH : HERE THE RATE OF CHANGE IS FAST COMPARED TO ALL SCALES



# KIBBLE-ZUREK SCALING

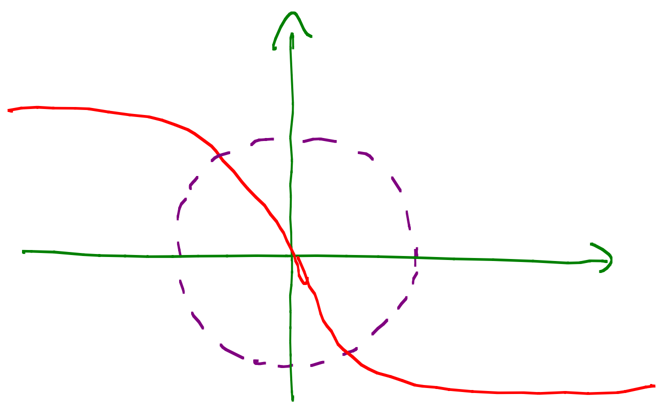
FOR SLOW QUENCH THERE IS A WELL-KNOWN CONJECTURE FOR A UNIVERSAL BEHAVIOR WHEN THE QUENCH CROSSES A CRITICAL POINT

ORIGINALLY PROPOSED BY KIBBLE IN THE CONTEXT OF THERMAL TRANSITIONS AND DEFECT FORMATION IN COSMOLOGY

EXTENDED TO CONDENSED MATTER ZUREK

EXTENDED TO QUANTUM TRANSITIONS RECENTLY

(Dziarmaga; Polkovnikov; Zurek et.al.)



FOR A GENERIC PASSAGE THROUGH THE CRITICAL POINT

$$\lambda(t) - \lambda_c \sim \vartheta t$$

$$\vartheta \ll E_{gap}(t=-\infty).$$

$$\boxed{\langle \mathcal{O}_\Delta \rangle \sim (\vartheta)^{\frac{\Delta\nu}{z\nu+1}} F\left(t\,\vartheta^{\frac{z\nu}{z\nu+1}}\right)}$$

$\Delta$ : OPERATOR DIMENSION

$\nu$ : CORRELATION LENGTH EXPONENT

$z$ : DYNAMICAL CRITICAL EXPONENT

THERE ARE SIMILAR SCALING RELATIONS FOR CORRELATORS

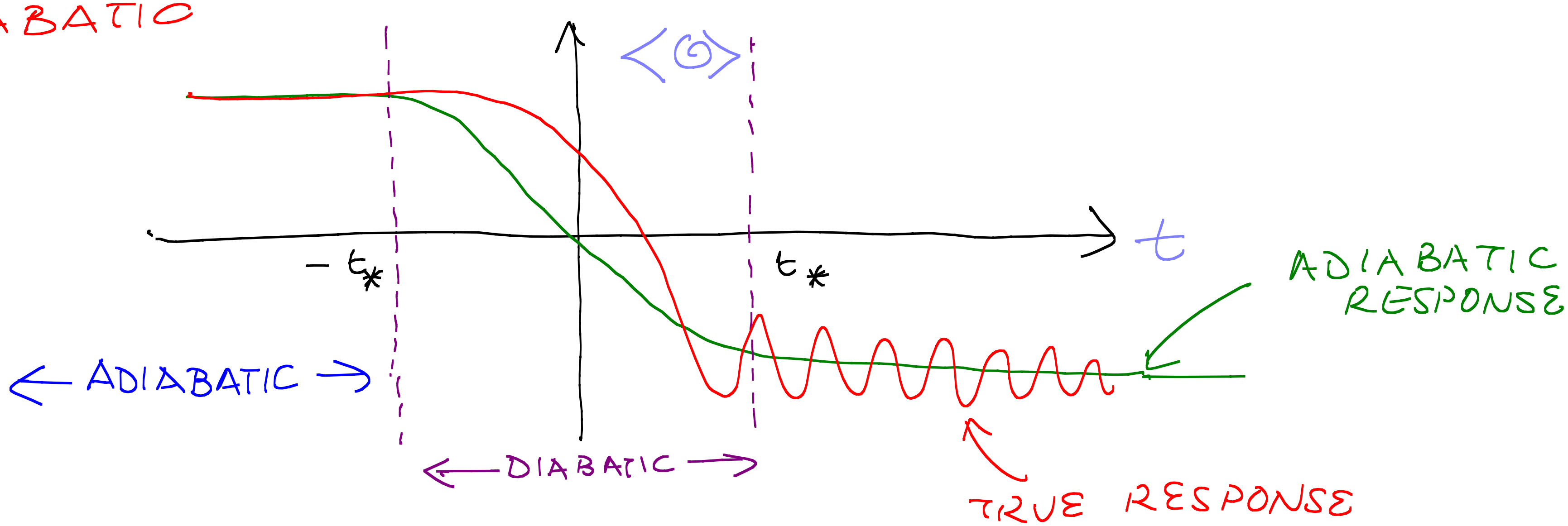
$$\left\langle \mathcal{O}_\Delta(x,t)\,\mathcal{O}_\Delta(x',t)\right\rangle \sim (\vartheta)^{\frac{2\Delta\nu}{2\nu+1}} F\left(\vartheta^{\frac{\nu}{2\nu+1}}|\vec{x}-\vec{x}'|\,;\,\vartheta^{\frac{2\nu}{2\nu+1}}t\right)$$

THE ARGUMENTS LEADING TO THESE SCALING BEHAVIOR ARE QUITE PRIMITIVE

– HOWEVER THESE RELATIONS APPEAR TO BE CONSISTENT WITH MODEL HAMILTONIANS AS WELL AS EXPERIMENTS

AT EARLY TIMES THE DYNAMICS IS ADIABATIC SINCE $\upsilon \ll E_{gap}$. HOWEVER NEAR CRITICALITY GAP VANISHES — ADIABATICITY IS BROKEN.

KIBBLE ZUREK ASSUMED THAT EVOLUTION IS THEN DIABATIC



THE SECOND KEY ASSUMPTION IS : THERE IS ONLY ONE LENGTH SCALE IN THE CRITICAL REGION – THE INSTANTANEOUS CORRELATION LENGTH $\xi(t)$.

$$\xi(t) \sim |\lambda(t) - \lambda_c|^{-\nu} \sim (v t)^{-\nu}$$

$$E_{gap}(t) \sim (v t)^{z\nu}$$

ADIABATICITY BREAKS AT $t = -t_*$ $\quad \left.\frac{1}{E_g^2} \frac{dE_g}{dt}\right|_{t_*} \sim 1$

$$\Rightarrow \quad t_* \sim v^{-\frac{z\nu}{z\nu+1}}$$

SINCE STATE IS FROZEN $(-t_*, t_*)$

$$\mathcal{O}(t_*) \sim \xi(t_*)^{-\Delta} \sim v^{\frac{\Delta\nu}{z\nu+1}}$$

KIBBLE & ZUREK WERE ACTUALLY INTERESTED IN DEFECT FORMATION IN SYMMETRY BREAKING TRANSITIONS IN e.g. COSMOLOGICAL BACKGROUNDS.

AS IS USUAL – SYMMETRY BREAKING LEADS TO DOMAINS – AND DEFECTS – SINCE CORRELATIONS ARE EXPECTED TO HAPPEN ONLY OVER THE SCALE OF INSTANTANEOUS CORRELATION LENGTH

DEFECT DENSITY → OPERATOR OF DIMENSION $d$

SUCH DEFECT FORMATION & RESULTING KIBBLE ZUREK SCALING HAS BEEN OBSERVED IN MANY SYSTEMS EXPERIMENTALLY

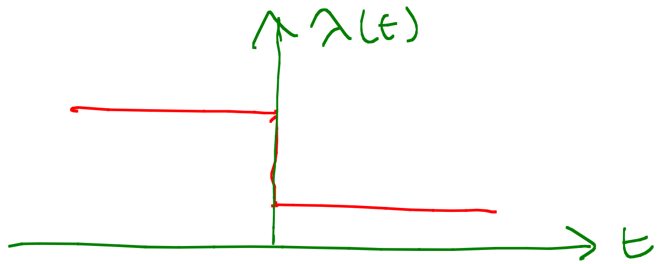
HOWEVER THERE ARE VERY FEW THEORETICAL TOOLS — ESPECIALLY FOR STRONGLY COUPLED SYSTEMS TO STUDY SUCH FAR-FROM-EQUILIBRIUM PHENOMENA

IN THIS TALK WE WILL USE HOLOGRAPHIC METHODS TO UNDERSTAND THE ORIGINS OF SUCH SCALING BEHAVIOR

WE WILL ALSO DISCUSS SOME OTHER ASPECTS OF QUENCH ACROSS CRITICAL POINTS — AND THE DISCOVERY OF NEW DYNAMICAL REGIMES.

# ABRUPT QUENCH

THE OTHER REGIME CONCERNS AN ABRUPT QUENCH




STATE AT $t=0$ OBTAINED BY TIME EVOLUTION OF INTIAL HAMILTONIAN SERVES AT INITIAL CONDITION FOR EVOLUTION FOR $t>0$ WITH NEW CONSTANT HAMILTONIAN

WHEN THE FINAL HAMILTONIAN IS CRITICAL AND THE THEORY IS 1+1 DIMENSIONAL, CALABRESE & CARDY USED POWERFUL TECHNIQUES OF BOUNDARY CONFORMAL FIELD THEORY TO SHOW

$$\langle \mathcal{O}_\Delta(t) \rangle \sim \exp\left[ - \frac{t\Delta}{\tau_0} \right]$$

WHERE $\tau_0 \sim 1/E_{gap}$ OF THE INITIAL HAMILTONIAN

THUS, RATIOS OF RELAXATION TIMES ARE UNIVERSAL

$$\frac{\tau_{\Delta_1}}{\tau_{\Delta_2}} = \frac{\Delta_2}{\Delta_1}$$

ABRUPT QUENCH INVOLVES A RATE OF CHANGE WHICH IS FAST COMPARED TO ALL SCALES IN THE THEORY

IN REALISTIC SITUATIONS IT IS INTERESTING TO CONSIDER SMOOTH QUENCHES WHICH ARE FAST COMPARED TO THE GAP BUT SLOW COMPARED TO UV SCALE

FOR SUCH QUENCHES HOLOGRAPHIC STUDIES HAVE DISCOVERED NEW SCALING LAWS

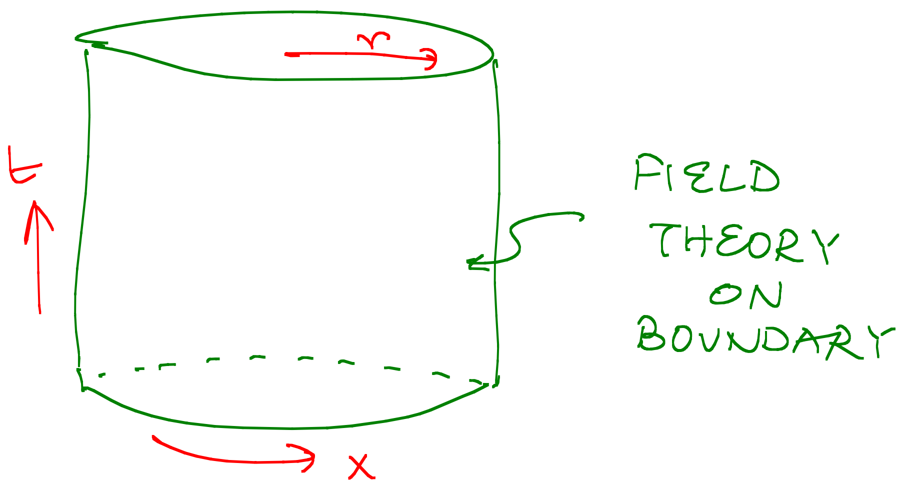
WE WILL SHOW THAT THIS NEW SCALING LAW IS GENERAL – INDEPENDENT OF HOLOGRAPHY

HOLOGRAPHIC KIBBLE ZUREK

CONSIDER A FIELD THEORY ACTION OF THE FORM

$$S = S_{CFT} + \int dt\, d^{d-1}x\ \lambda(t)\, \mathcal{O}_\Delta(t,x)$$

ASSUME THIS HAS A AdS/CFT GRAVITY DUAL.




IN THE BULK THERE IS A FIELD $\phi(t,x,r)$ DUAL TO THE OPERATOR $\mathcal{O}_\Delta$

NEAR THE BOUNDARY $r \to \infty$

$$\phi(r,x,t) \longrightarrow r^{\Delta-d}\left[J(t,x) + O(1/r^2)\right] + r^{-\Delta}\left[A(t,x) + O(1/r^2)\right]$$

WHEN $\mathcal{O}$ IS A SINGLE TRACE OPERATOR

$$\lambda(t,x) = J(t,x)$$

$$\langle \mathcal{O}_\Delta(t,x)\rangle = A(t,x).$$

TIME DEPENDENT COUPLING $\equiv$ TIME DEPENDENT BOUNDARY CONDITION

THE QUANTUM PROBLEM OF FAR-FROM-EQUILIBRIUM EVOLUTION BECOMES A CLASSICAL PROBLEM WITH A TIME DEPENDENT BOUNDARY CONDITION.

THIS SETUP HAS BEEN USED IN AdS/CFT TO UNDERSTAND LINEAR RESPONSE IN A WIDE VARIETY OF SITUATIONS – e.g VISCOSITY
CONDUCTIVITY

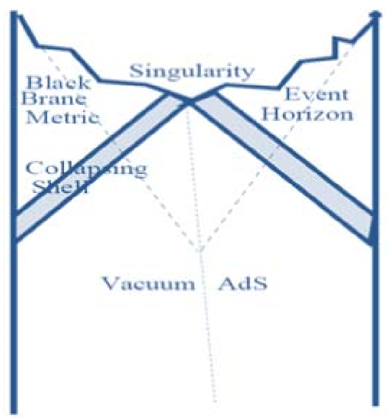
IN FAR-FROM-EQUILIBRIUM THIS SETUP HAS BEEN USED TO CONSTRUCT MODELS OF AdS COSMOLOGY

( S.R.D, J. Michelson, K. Narayan, A. Awad, A. Ghosh, J-H Oh - 2006-2009.
C.S. Chu & P.M. Ho - 2006
SOURCE

Hertog & Horowitz - 2004
Craps, Hertog & Turok - 2007
Englehardt, Hertog & Horowitz - 2014
STATE

THE SETUP – IN VARIOUS FORMS – HAS ALSO BEEN USED TO UNDERSTAND THERMALIZATION OF STRONGLY COUPLED FIELD THEORIES

THE DUAL DESCRIPTION IS THE FORMATION OF EVENT HORIZONS OR APPARENT HORIZONS




CHESLER & YAFFE

BHATTACHARYA & MINWALLA

BALASUBRAMANIAN ET. AL.

. . . . . . .

S.R.D, T. NISHIOKA & T. TAKAYANAGI

HASHIMOTO, IIZUKA & OKA

ALI-AKBARI, GURSOY . . . . . . . . . .

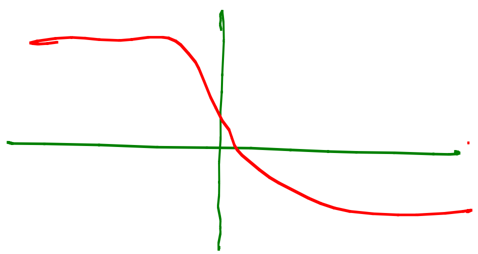
TO APPLY THIS SETUP WE NEED TO FIND A HOLOGRAPHIC MODEL FOR ISOLATED CRITICAL POINT

$S_{CFT} \rightarrow$ THEORY EXACTLY AT CRITICAL POINT

e.g. MAGNET AT $T = T_c$ AND $H = 0$

WE THEN NEED TO APPLY A TIME DEPENDENT EXTERNAL SOURCE FOR THE ORDER PARAMETER $\mathcal{O}_\Delta$

e.g. MAGNET AT $T = T_c$ AND $H(t)$



AIM : CALCULATE $\langle \mathcal{O}_\Delta \rangle (t)$.

IMPLEMENTED IN A VARIETY OF SITUATIONS

P. BASU & S.R.D JHEP 1201(2012) 103

P. BASU, D. DAS, S.R.D & T. NISHIOKA JHEP 1303(2013) 146

P. BASU, D. DAS, S.R.D & K. SENGUPTA JHEP 1312(2013) 070

S.R.D. & T. MORITA — TO APPEAR

$$\boxed{\text{EXAMPLE : QUENCH IN A } T=0 \text{ SUPERFLUID}}$$

(P. BASU, D. DAS, SRD, T. NISHIOKA)

BULK ACTION:

$$S = \int d^{d+2}x \sqrt{g} \left\{ \frac{1}{2\kappa^2}\left(R + d(d+1)\right) - \frac{1}{4q^2} F_{\mu\nu}F^{\mu\nu} - \frac{1}{\lambda}\left(|D\Phi|^2 - m^2|\Phi|^2 - U(|\Phi|^2)\right) \right\}$$

$\Phi$ : COMPLEX SCALAR FIELD

ONE OF THE SPATIAL DIMENSIONS COMPACT

$$A_t \xrightarrow[r\to\infty]{} \mu$$

BOUNDARY FIELD THEORY HAS A CHEMICAL POTENTIAL.

WE WILL WORK IN A PROBE APPROXIMATION

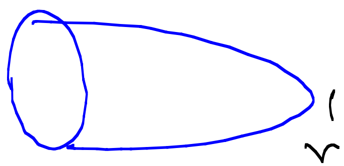
$\lambda \gg q^2 \qquad \lambda \gg k^2$

THEN TO LEADING ORDER THE DYNAMICS OF THE SCALAR DOES NOT BACK-REACT ON GEOMETRY OR MAXWELL FIELD. — ONLY SCALAR EQUATION

(e.g. Iqbal, Liu, Mezei, Si)

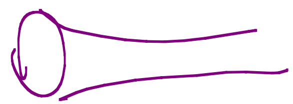
$\mu_0$ $\quad$ $\mu$

AdS SOLITON $\quad$ EXTREMAL BLACK BRANE



$r = r_0$

$$\Theta \sim \Theta + \frac{4\pi}{(d+1)\, r_0} \qquad A_t = \mu$$



WE WILL CONSIDER THE AdS SOLITON PHASE

AFTER A CHANGE OF VARIABLES $r \to \rho$
AND A REDEFINITON OF FIELD $\Phi \to \Psi$
EQUATION OF MOTION FOR SCALAR

$$\left[-\partial_t^2 + 2i\mu\partial_t\right]\Psi = \mathcal{D}\Psi + \frac{r^{2-d}}{\sqrt{1-(r_0/r)^{d+1}}}\,U'(\Psi,\Psi^*)$$

$$\mathcal{D} = -\partial_\rho^2 + V_0(\rho) - \mu^2.$$

ASYMPTOTIC SOLUTION AS $r \to \infty$ $(\rho \to 0)$.

$$\Psi(\rho,t) \to \rho^{\frac{d}{2}+1-\Delta}\left[J(t) + \cdots\right] + \rho^{\Delta-d/2}\left[A(t) + \cdots\right]$$

## STATIC SOLUTION WITH $J = 0$

THERE EXISTS A CRITICAL VALUE OF $\mu = \mu_c$

$\mu < \mu_c$ : PREFERRED SOLUTION IS $\Psi = 0$

$\mu > \mu_c$ : PREFERRED SOLUTION HAS NONTRIVIAL $\Psi(\rho)$ ie $\Phi(r)$

$\Rightarrow$ FOR $\mu > \mu_c$ $\langle \mathcal{O} \rangle \neq 0$ $\Rightarrow$ GLOBAL $U(1)$ SYMMETRY IS SPONTANEOUSLY BROKEN

THIS IS A MODEL OF SUPERFLUID

THIS KIND OF MODEL FIRST CONSIDERED BY RYU, NISHIOKA & TAKAYANAGI

- THEY CONSIDERED $U(\Phi) = 0$ - SO $\lambda$ HAS NO MEANING.

  PROBE APPROX $q^2 \gg k^2$ THEN MEANS GRAVITY BACKGROUND UNCHANGED - BUT GAUGE FIELD BACKREACTION NONTRIVIAL

HOROWITZ & WAY : RESULTS NOT SIGNIFICANTLY MODIFIED BY GRAVITY BACKREACTION

OUR WORK SHOWS THAT THE SAME EQUILIBRIUM PHYSICS FOR NONTRIVIAL $U(\Phi)$ AND $\lambda \gg q^2, k^2$

THE POINT $\mu = \mu_c$ IS A QUANTUM CRITICAL POINT.

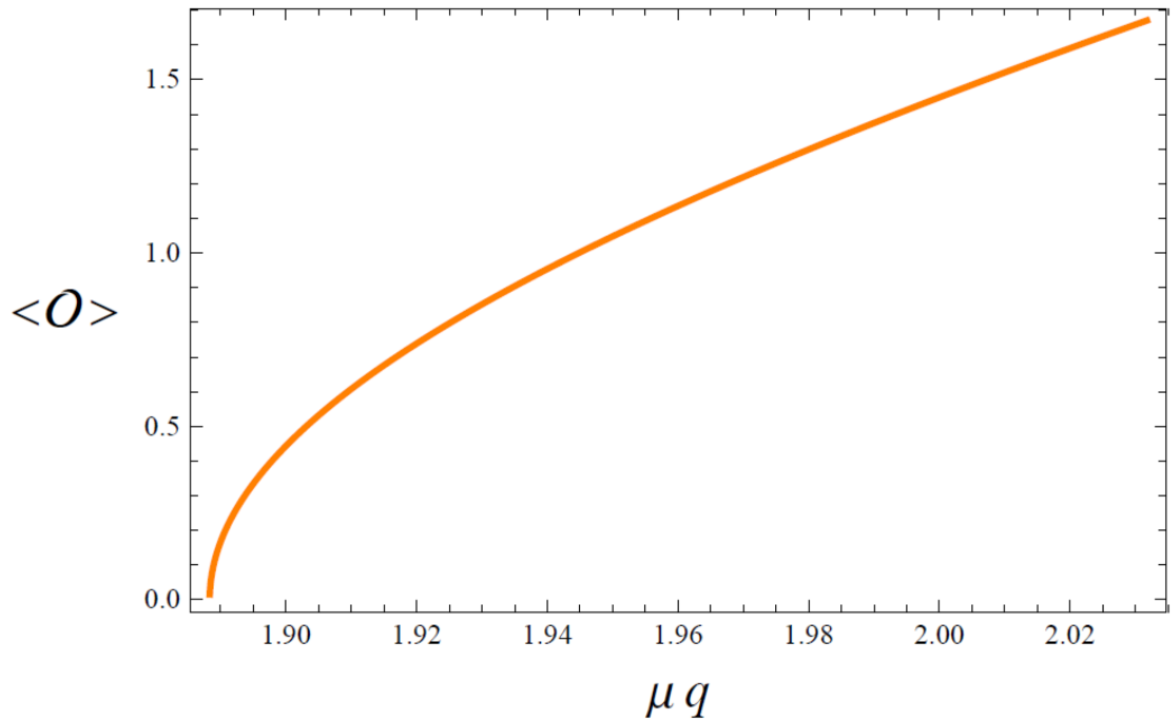
$$\boxed{\text{AT } \mu = \mu_c \text{ THE SCHRÖDINGER OPERATOR HAS A ZERO MODE.}}$$

FOR $U(\Phi) = |\Phi|^{n+1}$

$$\langle \mathcal{O} \rangle_{J=0} \sim |\mu - \mu_c|^{\frac{1}{n-1}}$$

$$\langle \mathcal{O} \rangle_{J \neq 0} \sim |J| \qquad \mu \neq \mu_c$$

$$\langle \mathcal{O} \rangle_{J \neq 0} \sim |J|^{1/n} \qquad \mu = \mu_c$$




EQUILIBRIUM ORDER PARAMETER

NOW TURN ON A TIME-DEPENDENT SOURCE

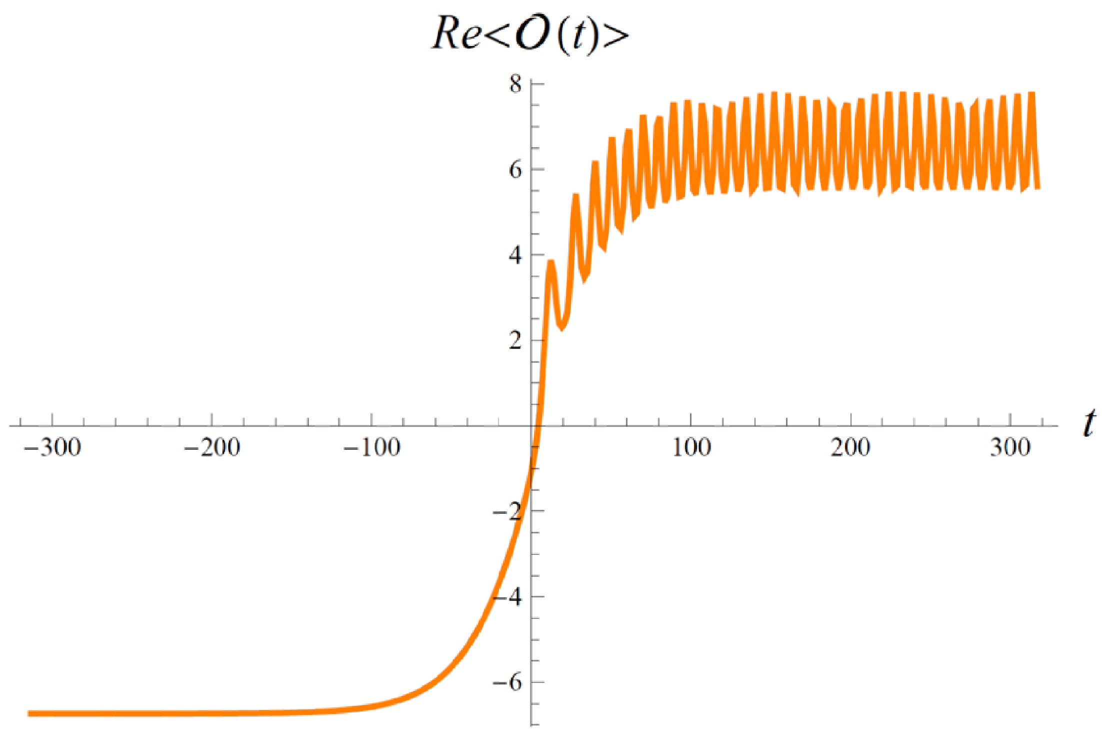
$$\Psi \sim \rho^{\frac{d}{2}+1-\Delta}\left[ J(t) + \dots \right] + \rho^{\Delta - d/2}\left[ A(t) + \dots \right]$$

AND WE CHOOSE e.g.

$$J(t) = J_0 \tanh(\vartheta t)$$

$$\vartheta \ll E_{gap}(t=-\infty)$$

AS EXPECTED, AT EARLY TIMES THE SOLUTION IS ADIABATIC




TIME EVOLUTION OF ORDER PARAMETER

IF $\Psi_{static}(J,\rho)$ IS THE SOLUTION FOR A CONSTANT SOURCE THE ADIABATIC EXPANSION

$$\Psi[\rho,t] = \Psi_{static}(J(t),\rho) + \Psi_1(\rho,t) + \cdots$$

$$\left[\mathcal{D} + \frac{r^{d-2}}{\sqrt{1-(r_0/r)^{d+1}}}\, U''(\Psi_{st})\right] \mathrm{Im}\,\Psi_1 = 2\mu\, \partial_t \Psi_{st}$$

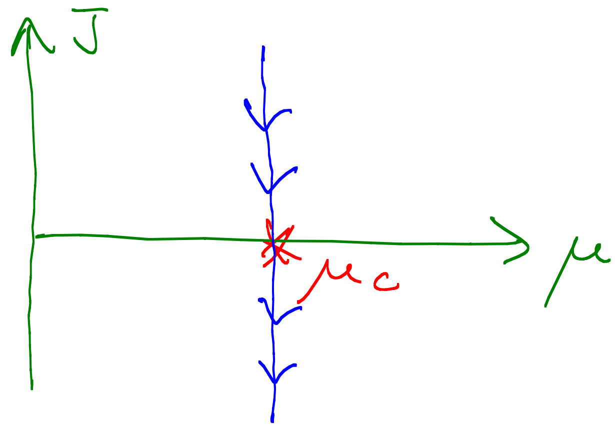
THE CRITICAL POINT IS APPROACHED WHEN

$$\mu = \mu_c \qquad J = 0$$

SINCE $\mathcal{D}$ HAS A ZERO MODE $\mathrm{Im}\,\Psi$ BECOMES LARGE — ADIABATICITY FAILS

IN THE $J-\mu$ PLANE OUR DYNAMICAL PROTOCOL IS

$$J(t) = J_0 \tanh(\vartheta t)$$
$$\mu = \mu_c$$




FOR $U(\Phi) = |\Phi|^4$ ADIABATICITY FAILS WHEN

$$t_{ad} \sim \vartheta^{-2/5} \qquad \Theta(t_{ad}) \sim \vartheta^{1/5}$$

ONCE ADIABATICITY FAILS THERE IS NO TAYLOR EXPANSION IN POWERS OF $\vartheta$ – WE NEED TO LOOK AT THE EQUATION IN GENERALITY

HOWEVER SOMETHING VERY SPECIAL HAPPENS IN THE CRITICAL REGION WHERE –

$$J(t) \sim J_0 \vartheta t$$

TAKING THE CLUE FROM OUR ADIABATICITY ANALYSIS RESCALE

$$t = \vartheta^{-2/5} \eta \qquad \Psi = \rho^{\alpha} \vartheta t + \vartheta^{1/5} \chi$$

THE EQUATION NOW BECOMES

$$\mathcal{L}\chi = \vartheta^{2/5}\left[2i\mu\partial_\eta \chi - G(\varrho)|\chi|^2\chi - \eta\,\mathcal{L}\rho^\alpha\right] + O(\vartheta^{4/5})$$

THE SOLUTION HAS AN EXPANSION IN $\vartheta^{2/5}$

PERFORM A SPECTRAL DECOMPOSITION

$$\chi(\varrho,\eta) = \sum_n \chi_n(\eta)\,\varphi_n(\varrho)$$

$$\mathcal{L}\varphi_n = \lambda_n\varphi_n$$

$$\boxed{\lambda_n \chi_n = \vartheta^{2/5}\left[2i\mu\,\partial_\eta \chi_n - C^{n}_{n_1 n_2 n_3}\chi^*_{n_3}\chi_{n_2}\chi_{n_1} + \eta J_n\right] + O(\vartheta^{4/5})}$$

RECALL THAT THERE IS A ZERO MODE $\chi_0$ WITH $\lambda_0 = 0$

CLEARLY THE ZERO MODE DOMINATES DYNAMICS

$$\chi_0 \sim O(1) + O(\vartheta^{2/5})$$

$$\chi_n \sim O(\vartheta^{2/5}) + O(\vartheta^{4/5})$$

IN TERMS OF THE ORIGINAL $\Phi$, $t$ THIS MEANS

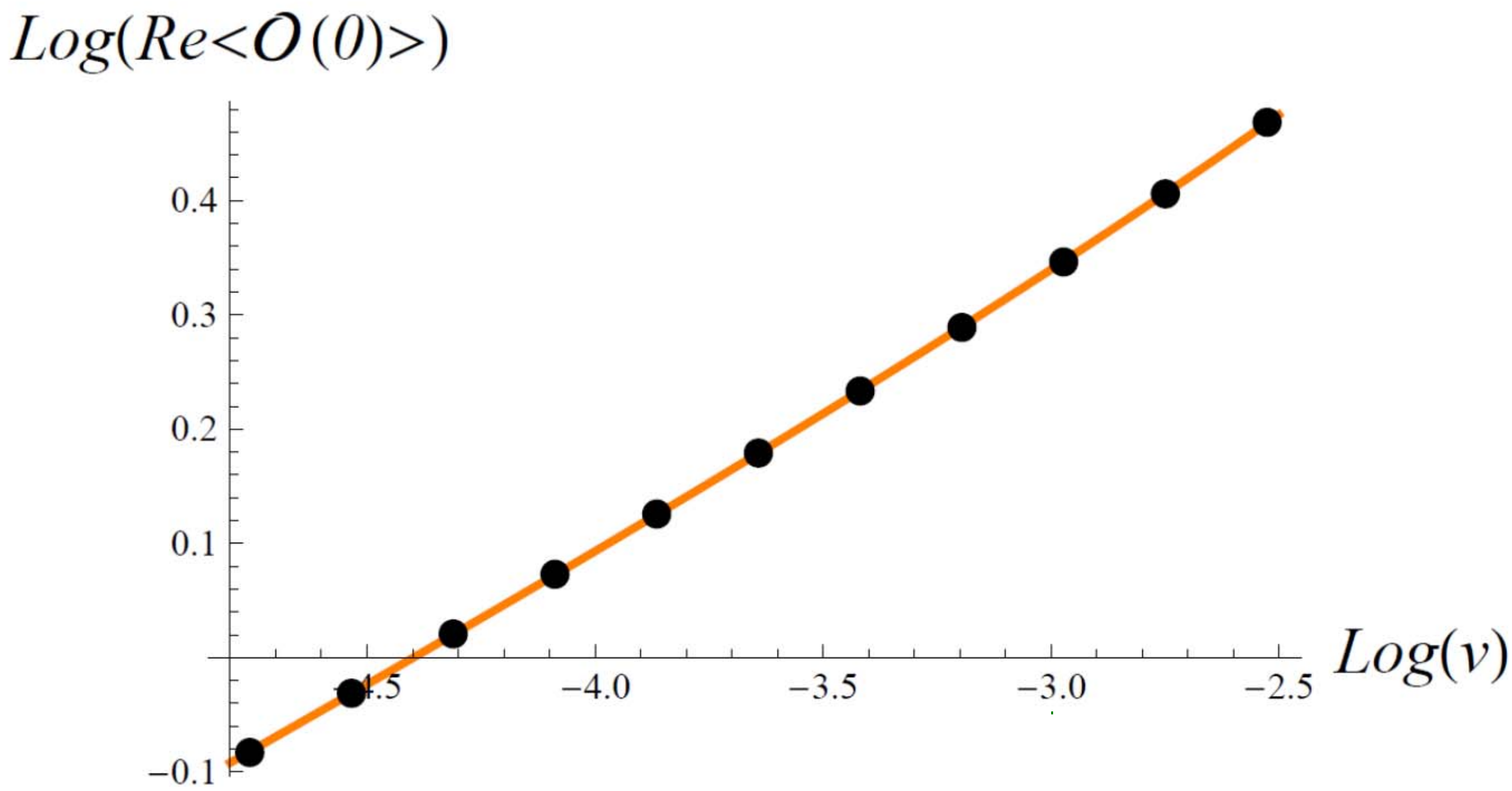
$$\Phi(t,\rho;v) = v^{1/5}\,\Phi(t v^{2/5},\rho;1)$$

THIS MEANS THAT IN THE BOUNDARY THEORY

$$\langle \mathcal{O}(t,v)\rangle = v^{1/5}\,F(t v^{2/5})$$

THIS IS KIBBLE-ZUREK SCALING

HOWEVER WE NOW KNOW THE SYSTEMATIC CORRECTIONS TO KZ SCALING




$\log \mathcal{O}(0) = 0.794 + 0.206 (\log v)$

IN AdS/CFT DEPENDENCE OF BULK FIELDS ON THE RADIAL DIRECTION IS RELATED TO SCALE DEPENDENCE IN DUAL FIELD THEORY

THE FACT THAT DURING A QUENCH A ZERO MODE DOMINATES DYNAMICS IMPLIES THAT IN THE FIELD THEORY THERE IS A DECOUPLING OF SCALES

SUCH DECOUPLING IS AN ASPECT OF CRITICAL DYNAMICS WE SET OUT TO UNDERSTAND

$$\boxed{\text{BACK-REACTION}}$$

(w/ T. MORITA)

ZERO MODE OF THE SCALAR FEEDS INTO THE EQUATION FOR GAUGE FIELD — LEADS TO LOSS OF ADIABATICITY

$$\langle \mathcal{O}_\Delta \rangle \sim v^{1/5} f(t v^{2/5})$$

CHARGE DENSITY

$$\langle \rho \rangle \sim v^{2/5} f(t v^{2/5})$$

OHTER ASPECTS OF HOLOGRAPHIC QUENCH
ACROSS CRITICAL POINTS

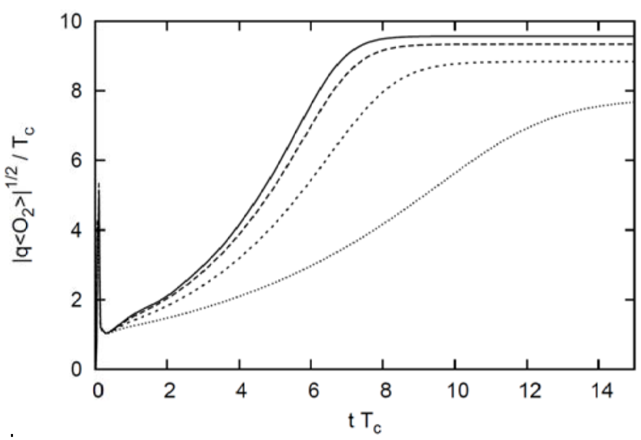
MURATA, KINOSHITA & TANAHASHI : JHEP 1007 (2010)

CONSIDER USUAL HOLOGRAPHIC SUPERCONDUCTOR

START IN SUPERCOOLED STATE

INTRODUCE BULK PERTURBATIONS

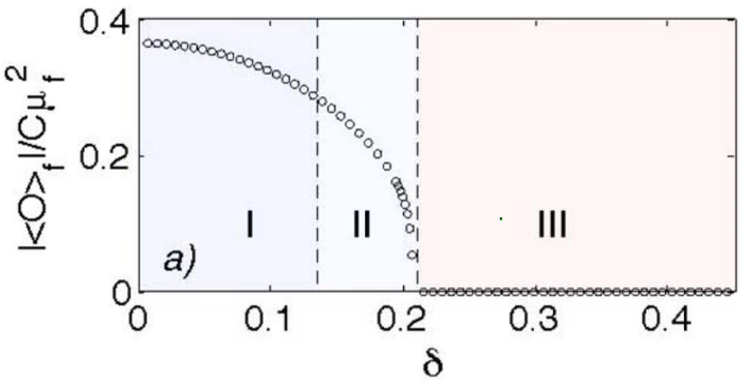
FIND THAT SOLUTION APPROACHES HAIRY BLACK HOLES (CONDENSED PHASE)



BHASEEN, GAUNTLETT, SONNER & WISEMAN : PRL 110 (2013)

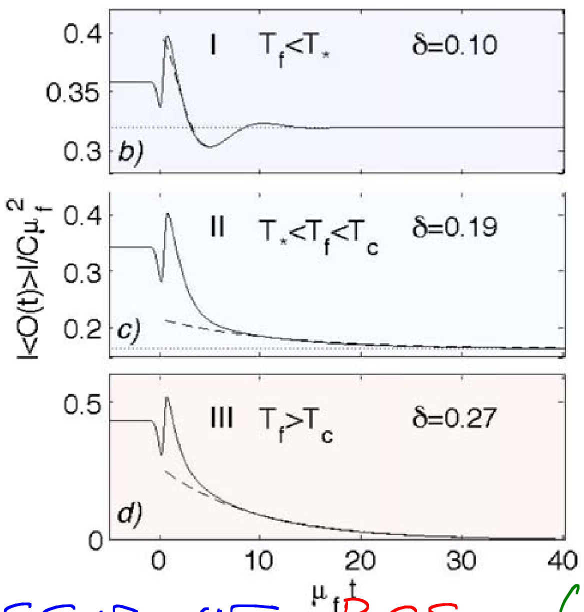
INTRODUE A TIME DEPENDENT BOUNDARY CONDITION FOR A FINITE TIME INTERVAL IN A HOLOGRAPHIC SUPERCONDUCTOR IN THE CONDENSED PHASE. $T<T_c$

SYSTEM HEATS UP & ORDER PARAMETER RELAXES TO ZERO




$\delta$ : AMPLITUDE OF PULSE

HOWEVER THERE ARE THREE DISTINCT REGIMES DISPLAYING DIFFERENT RELAXATIONS




HAVE BEEN SEEN IN BCS (BARANKOV & LEVITOV)

THE HOLOGRAPHIC STUDIES DESCRIBED SO FAR INVOLVED GLOBAL QUENCH – AND THE RESULTING BULK SOLUTION ( HENCE ORDER PARAMETER ) ARE HOMOGENEOUS IN SPACE.
THIS FOLLOWS FROM BULK EQUATIONS OF MOTION

IN A GENERAL QFT, FLUCTUATIONS WILL INDUCE INHOMOGENTIES.

THIS IS INVISIBLE IN BULK EQUATIONS OF MOTION SINCE THESE CAPTURE A $N=\infty$ LIMIT OF THE DUAL THEORY
FLUCTUATIONS ARE SUPPRESSED AT $N=\infty$

$1/N$ CORRECTIONS = QUANTUM EFFECTS IN BULK

— WE DO NOT KNOW HOW TO CALCULATE THESE

SONNER, DEL CAMPO & ZUREK 1406.2329

CHESLER, GARCIA-GARCIA & LIU : 1407.1862

MODEL THIS BY INTRODUCING RANDOMNESS INTO THE BOUNDARY CONDITIONS.

— IN A WAY CONSISTENT WITH FLUCTUATION-DISSIPATION THEOREM

SETUP : THERMAL QUENCH IN HOLOGRAPHIC SUPERFLUID

- CONSIDER BLACK BRANE METRIC WITH A SPECIFIED TIME-DEPENDENT TEMPERATURE $T(t)$
- THIS IS APPROXIMATE SOLUTION OF BULK EQUATIONS WHEN $T(t)$ VARIES SLOWLY
- NOW IMPOSE RANDOM BOUNDARY CONDITION FOR THE BULK COMPLEX SCALAR $\varphi(\vec{x}, t)$.

$$\langle \varphi(\vec{x}, t) \rangle = 0 \qquad \langle \varphi(\vec{x}, t)\, \varphi(\vec{x}', t') \rangle = \zeta\, \delta(\vec{x}-\vec{x}')\, \delta(t-t')$$

- SOLVE EQUATIONS OF MOTION

WHEN SYSTEM IS COOLED BELOW $T_c$ – $\langle \theta \rangle$ SHOWS DOMAINS AND DEFECTS.

- DEFECT DENSITY CONSISTENT WITH KIBBLE-ZUREK
- NEW EFFECT : THERE IS A PERIOD OF NON-ADIABATIC EVOLUTION AFTER $t_{KZ}$ BEFORE A WELL-DEFINED CONDENSATE FORMS
  — MODIFICATION OF ORIGINAL KIBBLE-ZUREK

# CONCLUSIONS I

- HOLOGRAPHIC TECHNIQUES HAVE THROWN VALUABLE LIGHT ON THE ORIGIN OF KIBBLE-ZUREK SCALING
- NEW RESULT : CORRECTIONS TO SCALING
- THEY HAVE ALSO LED TO DISCOVERY OF NEW DYNAMICAL REGIMES

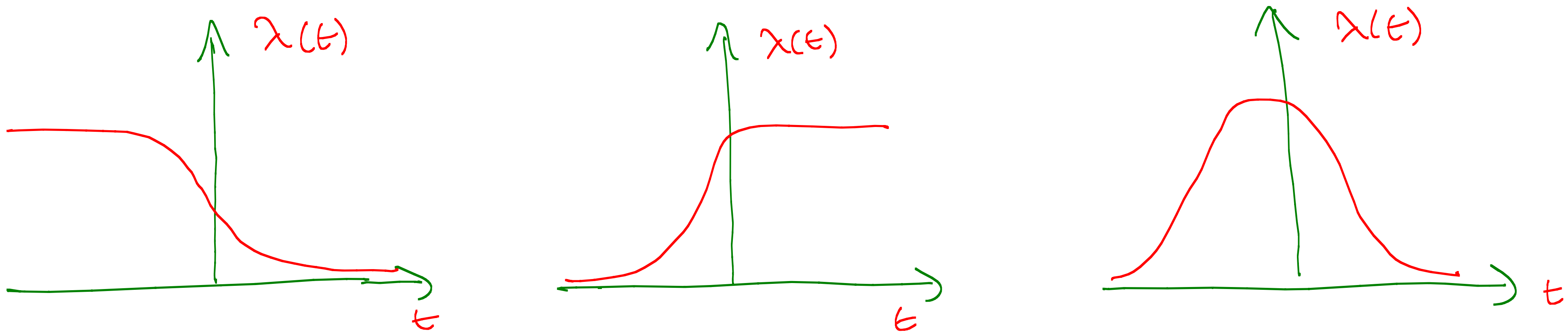
FAST QUENCH, ABRUPT QUENCH

CONSIDER A RELEVANT DEFORMATION OF A CFT

$$S = S_{CFT} + \int dt\, d^{d-1}x\; \lambda(t)\, \mathcal{O}_\Delta(x,t)$$

$\Delta$ : DIMENSION OF OPERATOR $< d$

$$\lambda(t) = \lambda_0 f(\nu t)$$



BUCHEL, LEHNER, MYERS JHEP 1305 (2013) 067

BUCHEL, LEHNER, MYERS, VAN NIEKERK PRL 111 (2013) 201602

STUDIED THIS HOLOGRAPHICALLY

- START WITH PURE AdS
- TURN ON BOUNDARY CONDITION OF SCALAR

IN THE FAST REGIME $\vartheta \gg (\lambda_0)^{\frac{1}{d-\Delta}}$ THEY FOUND

$$\langle \mathcal{O}_\Delta \rangle \sim \lambda_0 \vartheta^{2\Delta-d} \qquad \Delta E \sim \lambda_0^2 \vartheta^{2\Delta-d}$$

FOR $d/2 < \Delta < d$ IT APPEARS THAT $\vartheta \to \infty$ PROBLEMATIC

ON THE OTHER HAND $v \to \infty$ SHOULD REDUCE TO ABRUPT QUENCH — THERE ARE SENSIBLE RESULTS KNOWN IN THIS CASE

COULD THIS BE A FEATURE OF STRANGE STRONGLY COUPLED THEORIES WHICH HAVE GRAVITY DUALS ?

S.R.D, D. GALANTE & R.C. MYERS, PRL 112 (2014) 171601
S.R.D, D. GALANTE & R.C. MYERS arXiv: 1407.xxxx

→ INVESTIGATE THIS IN FIELD THEORY ITSELF

- LOOK AT FREE BOSONIC & FERMIONIC FIELDS WITH TIME DEPENDENT MASS

$$(\partial\phi)^2 - m^2(t)\,\phi^2$$

- CHOOSE $m^2(t)$ SO THAT MODEL SOLUABLE FOR ARBITRARY RATES

- PERFORM $v \gg m$ LIMIT

RESULT : RENORMALIZED QUANTITLES SCALE EXACTLY
LIKE HOLOGRAPHIC MODEL

IN FACT THE RESULT IS VALID FOR ARBITRARY
INTERACTING DEFORMED CFT'S

$$S = S_{CFT} + \lambda_0 \int d^d x \, f(t)\, \mathcal{O}_\Delta(x,t)$$

THE RENORMALIZED $\langle \mathcal{O}_\Delta \rangle$ AT SOME TIME $t=0$ CAN ONLY DEPEND ON $v$ AND $\lambda_0$

THUS BY DIMENSION COUNTING

$$\langle \mathcal{O}_\Delta \rangle \sim v^\Delta \, g\left(\lambda_0 v^{\Delta-d}\right)$$

THE FUNCTION $g(x)$ HAS A POWER SERIES EXPANSION IN THE DIMENSIONLESS COUPLING $\lambda_0 v^{\Delta-d}$

THUS FOR $v \gg \lambda_0^{\frac{1}{\Delta-d}}$

$$\boxed{\langle \mathcal{O}_\Delta \rangle \sim \lambda_0 v^{2\Delta-d}}$$

THIS IS A NEW SCALING RESULT IN QUANTUM QUENCH — VALID FOR ANY THEORY

WHAT ABOUT ABRUPT QUENCH ?

RENORMALIZED QUANTITIES ARE PHYSICAL ONLY WHEN

$$(\lambda_0)^{\frac{1}{d-\Delta}} \ll v \ll \Lambda_{UV}$$

HOWEVER ABRUPT QUENCH REQUIRES $v \gg \Lambda_{UV}$ !

(IN FACT IN OUR CASE THE COUNTERTERMS REQUIRED TO RENORMALIZE ARE EXACTLY HIGH MOMENTUM PARTS OF THE ADIABATIC EXPANSION)

PREDICTION:

IN SYSTEMS WITH FINITE LATTICE SPACING THIS SCALING HOLDS IN THIS INTERMEDIATE REGIME – QUENCH FAST COMPARED TO SCALE OF RELEVANT COUPLING, BUT SLOW COMPARED TO UV SCALE

WHEN THE RATE OF QUENCH APPROACHES THE UV SCALE – $\nu$ DEPENDENCE SATURATES AND RESULTS OF ABRUPT QUECH HOLD

$$\boxed{\text{QUESTIONS}}$$

ONE OF THE ISSUES IN THE FIELD IS TO FIGURE OUT OBSERVABLES – AND EFFICIENT WAYS OF CALCULATING THEM

ONE SUCH QUANTITY IS WORK STATISTICS

$$P(W) = \sum_n \delta\left[W - (E_n^f - E_0^i)\right] \cdot {}_f\langle n | \mathcal{U}(T) | 0 \rangle_i$$

$|n\rangle_f$ : EIGENSTATES OF FINAL HAMILTONIAN AT $t = T$

$|0\rangle_i$ : GROUND STATE OF INITIAL HAMILTONIAN

THIS IS ALSO SOMETHING WHICH IS DIFFICULT TO CALCULATE

AdS/CFT SHOULD PROVIDE SOME INSIGHT

(In progress with DIPTARKA DAS)

# CONCLUSIONS II

HOLOGRAPHIC METHODS PROVIDE A NEW WAY
OF THINKING ABOUT QUANTUM QUENCH

THIS HAS LED TO NEW UNIVERSAL SCALING LAWS

HOWEVER MANY OF THESE SCALING LAWS ARE
COMPLETELY GENERAL – HENCE OF DIRECT
PHYSICAL RELEVANCE

→ HOLOGRAPHY INSPIRED FIELD THEORY