

Title: PSI 2016/2017 Statistical Mechanics - Lecture 7

Date: Oct 19, 2016 10:45 AM

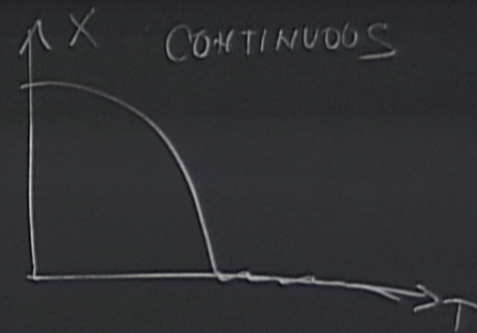
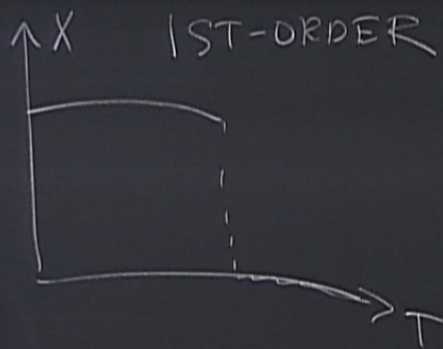
URL: <http://pirsa.org/16100021>

Abstract:

GOAL, UNDERSTAND CONTINUOUS PHASE TRANS. NEAR CRITICAL POINT,

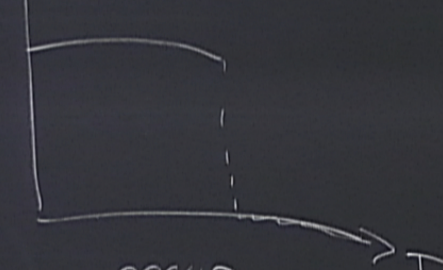
- GOAL. UNDERSTAND CONTINUOUS PHASE TRANS. NEAR CRITICAL POINT,
- PHASE TRANSITIONS: 1ST-ORDER, CONTINUOUS, TOPOLOGICAL PT,
GLASSY, QUANTUM ($T=0$)
 - ORDER PARAMETER X ... SYMMETRY BREAKING
E.G. MAGNETIZATION, $\Delta\rho = \rho_L - \rho_g$

ORDER PARAMETER X ... SYMMETRY BREAKING
E.G. MAGNETIZATION, $\Delta\rho = \rho_l - \rho_g$



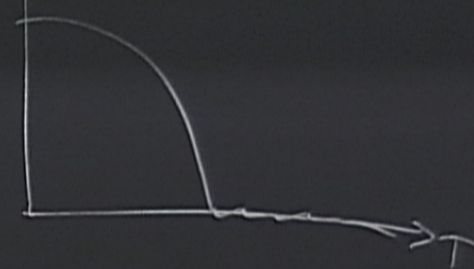
E.G. MAGNETIZATION, $\Delta p = p_l - p_g$

$\uparrow X$ 1ST-ORDER

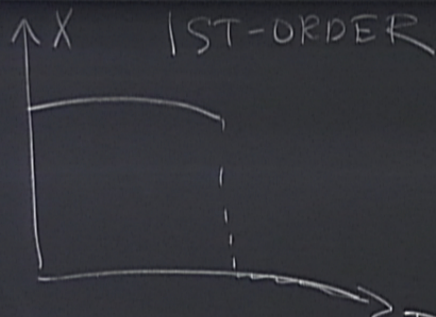


- OCCUR OFTEN IN NATURE
- LATENT HEAT $\Rightarrow$ DISTINCT PHASES

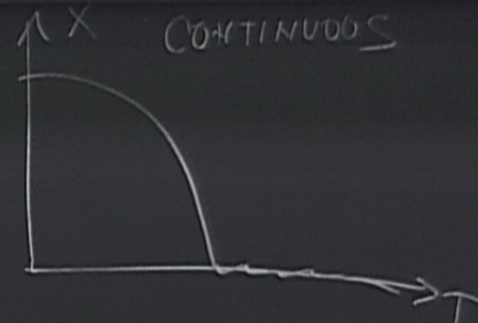
$\uparrow X$ CONTINUOUS



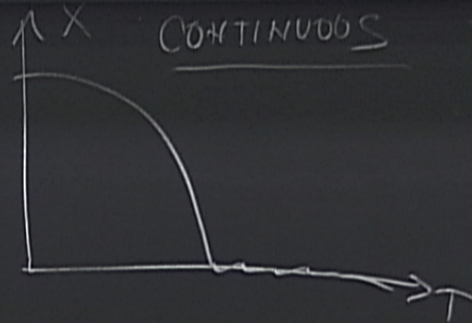
E.G. MAGNETIZATION, $\Delta p = p_l - p_g$



- OCCUR OFTEN IN NATURE
- LATENT HEAT $\Rightarrow$ DISTINCT PHASES
- "DIFFICULT TO DESCRIBE"



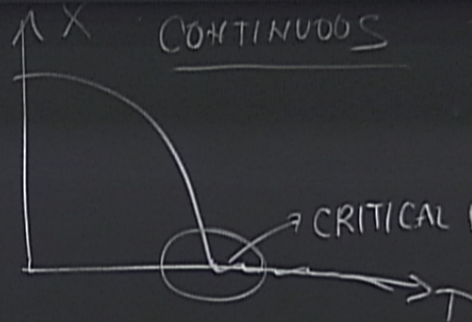
MAGNETIZATION, $\Delta p = p_l - p_g$



- LESS OFTEN (NEED SYMMETRY)
- "NICE"... UNIVERSALITY.

IN NATURE
T $\Rightarrow$ DISTINCT PHASES $\propto$ NO UNIVERSALITY
TO DESCRIBE" DEPEND ON MICROSCOPICS

MAGNETIZATION, $\Delta p = p_l - p_g$

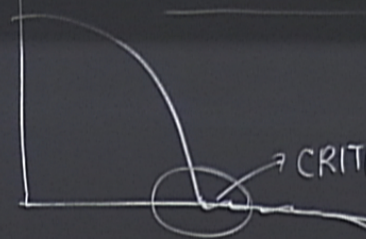


- LESS OFTEN (NEED SYMMETRY)
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$\rightarrow T$
 EN IN NATURE
 AT $\Rightarrow$ DISTINCT PHASES $\propto$ NO UNIVERSALITY
 TO DESCRIBE" ... DEPEND ON MICROSCOPICS

CONTINUOUS



CRITICAL POINT ... CRITICAL EXPONENTS

• LESS OFTEN (NEED SYMMETRY)

• "NICE" ... UNIVERSALITY

$$C = |t|^{-\alpha}, M = |t|^\beta$$

$$\chi = |t|^{-\gamma}, B \propto M^\delta$$

$$G(\eta) \propto \frac{e^{-\eta/3}}{\eta^{d+2+\eta}}$$

$$\xi \sim |t|^{-\nu}$$

- OCCUR OFTEN IN NATURE
- LATENT HEAT $\Rightarrow$ DISTINCT PHASES $\propto$ NO UNIVERSALITY
- "DIFFICULT TO DESCRIBE" ... DEPEND ON MICROSCOPICS

NOT ALL G ARE INDEPENDENT:

RUSHBROOK. $\alpha + 2\beta + \gamma = 2$

- OCCUR OFTEN IN NATURE
- LATENT HEAT $\Rightarrow$ DISTINCT PHASES $\propto$ NO UNIVERSALITY
- "DIFFICULT TO DESCRIBE" ... DEPEND ON MICROSCOPICS

$$\chi = 1 + \dots$$

NOT ALL ζ ARE INDEPENDENT:

RUSHBROOK: $\alpha + 2\beta + \eta = 2$

GRIFFITHS: $\alpha + \beta(\delta + 1) = 2$

FISHER: $\eta = \nu(2 - \gamma)$

JOSEPHSON: $\alpha' = 2 - \nu d$

- OCCUR OFTEN IN NATURE
- LATENT HEAT $\Rightarrow$ DISTINCT PHASES $\propto$ NO UNIVERSALITY
- "DIFFICULT TO DESCRIBE" ... DEPEND ON MICROSCOPICS

CRITICAL POINT ... CRITICAL EXPON

$C = |t|^{-\alpha}$, $M = |t|^{-\beta}$

$\chi = |t|^{-\gamma}$, $B \propto M^{\delta}$

NOT ALL 6 ARE INDEPENDENT:

RUSHBROOK: $\alpha + 2\beta + \gamma = 2$

BRIFFITHS: $\alpha + \beta(\delta + 1) = 2$

FISHER: $\gamma = \nu(2 - \alpha)$

JOSEPHSON: $\alpha = 2 - \nu\delta$

$\Rightarrow$ 2 INDEPENDENT CRIT. EXPS

$G(n) \propto \frac{e^{-n/3}}{n^{\alpha-2+\gamma}}$

$\xi \sim t^{-\nu}$

6 CRITICAL EXPS.

- OCCUR OFTEN IN NATURE
- LATENT HEAT $\Rightarrow$ DISTINCT PHASES $\propto$ NO UNIVERSALITY
- "DIFFICULT TO DESCRIBE" ... DEPEND ON MICROSCOPICS

CRITICAL POINT ... CRITICAL EXPON

$C = |t|^{-\alpha}$, $M = |t|^{-\beta}$

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NOT ALL 6 ARE INDEPENDENT:

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GRIFFITHS: $\alpha + \beta(\delta + 1) = 2$

FISHER: $\gamma = \nu(2 - \alpha)$

JOSEPHSON: $\alpha = 2 - \nu\delta$

$\Rightarrow$ 2 INDEPENDENT CRIT. EXPS.

MFT: $\alpha = 0, \beta = \frac{1}{2}, \gamma = 1, \delta = 3, \nu = 0, \nu = \frac{1}{2}$

$G(t) \propto \frac{e^{-t/\tau}}{\tau^{\alpha-2+\gamma}}$ $\xi \sim t^{\nu}$

6 CRITICAL EXPS.

MFT... "PREDICTS" PHASE TRANSITION. BUT GIVES WRONG CRITICAL EXPONENTS.
TO GET "BETTER AGREEMENT" - RENORMALIZATION PROCEDURE

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TO GET "BETTER AGREEMENT" .. RENORMALIZATION PROCEDURE

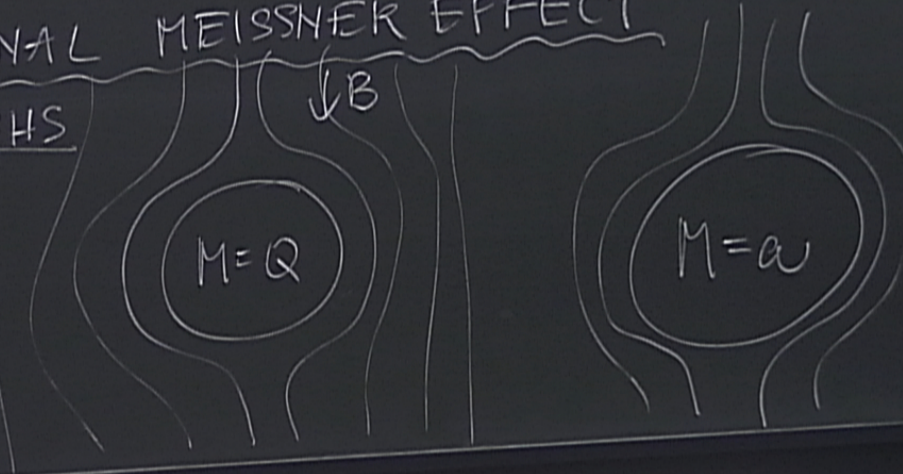
• GRAVITATIONAL MEISSNER EFFECT
EXTREMAL BHS

$$M=Q$$

$$M=a$$

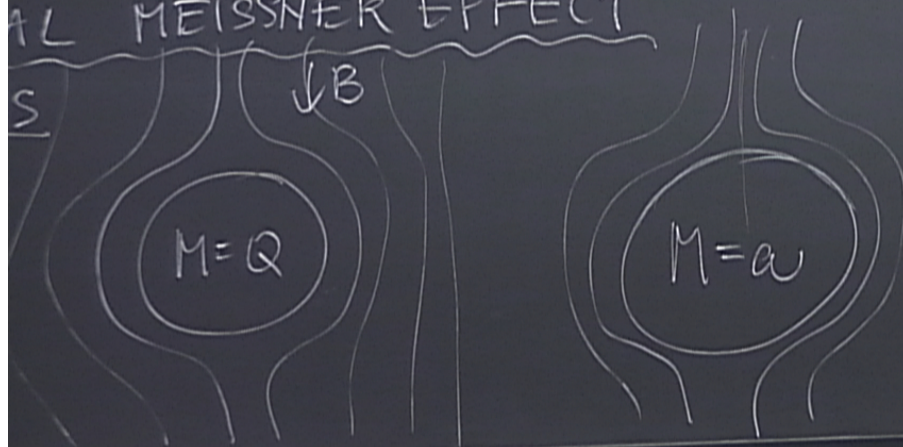
MFT... "PREDICTS" PHASE TRANSITION. BUT GIVES WRONG CRITICAL EXPONENTS.
TO GET "BETTER AGREEMENT" .. RENORMALIZATION PROCEDURE

• GRAVITATIONAL MEISSNER EFFECT
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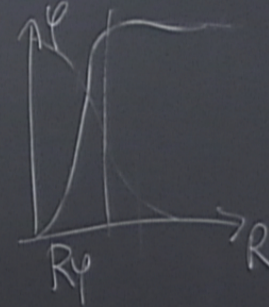
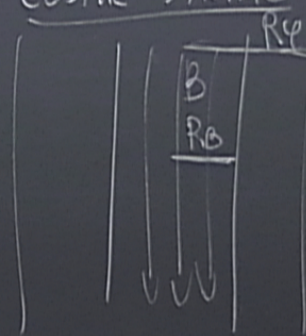


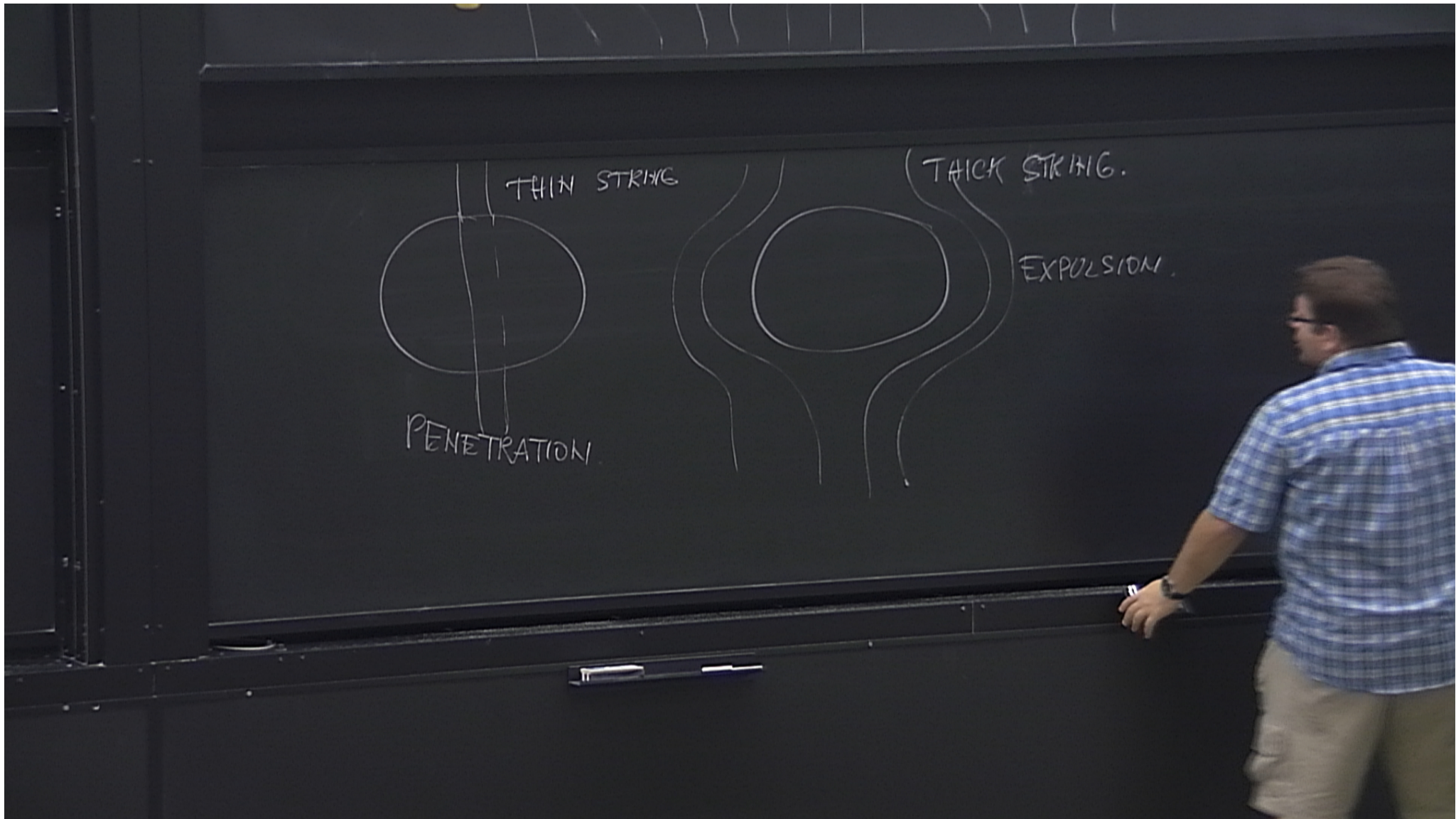
S' PHASE TRANSITION, BUT GIVES WRONG CRITICAL EXPONENTS.
 T "BETTER AGREEMENT" - RENORMALIZATION PROCEDURE

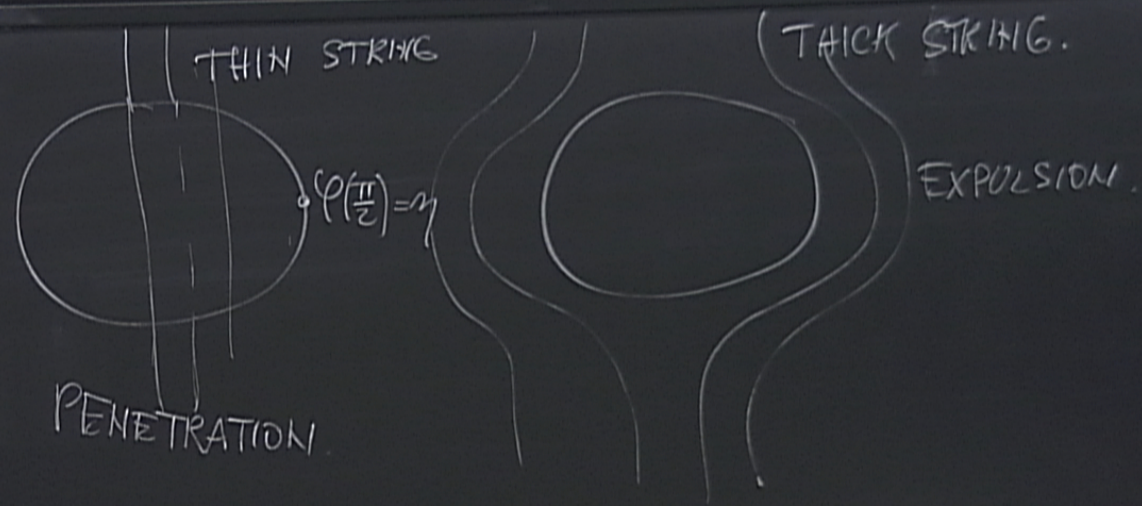
AL MEISSNER EFFECT



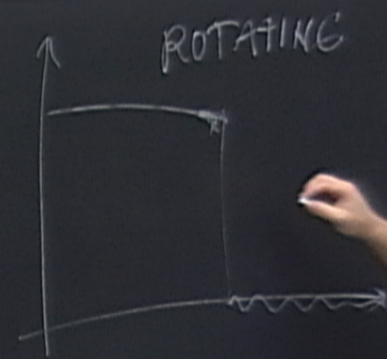
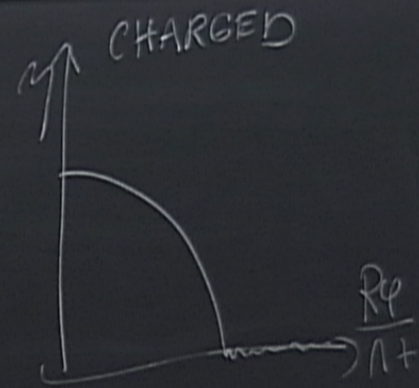
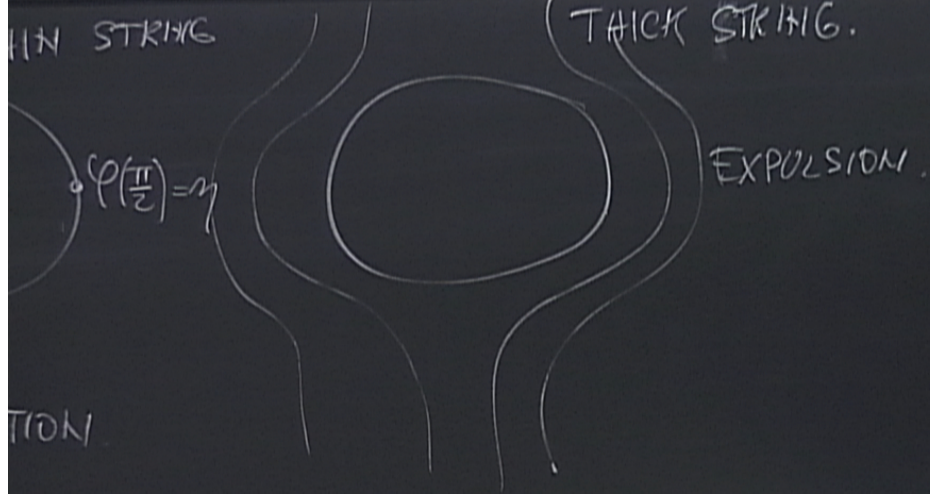
• COSMIC STRING ... TOPOLOGICAL DEFECT.







THIN STRING



IN STRING

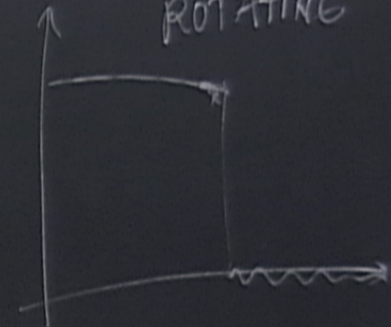
THICK STRING.

EXPULSION.

CHARGED

ROTATING

$$\varphi\left(\frac{\pi}{2}\right) = \eta$$



THICK STRING.

EXPULSION.

CHARGED

MORE SYMMETRY?

$$\frac{R\phi}{\Lambda^+}$$

ROTATING

- OCCUR OFTEN IN NATURE
- LATENT HEAT $\Rightarrow$ DISTINCT PHASES $\propto$ NO UNIVERSALITY
- "DIFFICULT TO DESCRIBE" ... DEPEND ON MICROSCOPICS

$$C = kT^{-\alpha}, \quad M = kT^{-\beta}$$

$$\chi = kT^{-\gamma}, \quad B \propto M^{\delta}$$

1) WILSONIAN RENORMALIZATION

$$Z = \int D\varphi e^{-S[\varphi]}, \quad S[\varphi] = \int d^d x \left[\frac{1}{2} (\nabla \varphi)^2 + \frac{r}{2} \varphi^2 + \frac{u}{4!} \varphi^4 \right]$$

LANDAU-GINSBURG

- OCCUR OFTEN IN NATURE
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$$C = |t|^{-\alpha}, \quad M = |t|^{-\beta}, \quad B \propto M^{\frac{1}{\delta}}$$

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LANDAU-GINSBURG

SPATIAL DIMS. $\rightarrow d$ $\rightarrow S_0$ $\rightarrow S_{INT.}$

- OCCUR OFTEN IN NATURE
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1) WILSONIAN RENORMALIZATION

$$Z = \int D\varphi e^{-S[\varphi]}$$

$$S[\varphi] = \int d^d x \left[\frac{1}{2} (\nabla \varphi)^2 + \frac{r}{2} \varphi^2 + \frac{u}{4!} \varphi^4 \right]$$

$\xrightarrow{\text{SPATIAL DIMS.}} \frac{S_0}{\text{SINT.}}$
LANDAU-GINSBURG $n \sim 4$ $n > 0$

$S[\varphi] = \int d^d x \left[\frac{1}{2} (\nabla \varphi)^2 + \frac{R}{2} \varphi^2 + \dots \right]$

SPATIAL DIMS. $\rightarrow d$

LANDAU-GINSBURG

$[n] = 2, \quad [n] = \varepsilon = 4 - d$

$\uparrow$ UPPER CRITICAL DIMS.

$\boxed{n \sim t}$

RENORMALIZATION = DO THE $\underline{z}$ -INTEGRAL STEP BY STEP,

$$\phi(\vec{x}) = \int_0^\Lambda \frac{d^d k}{(2\pi)^d} \phi(\vec{k}) e^{i\vec{k} \cdot \vec{x}}$$

AL STEP BY STEP,

$$e^{i\vec{k}\cdot\vec{x}}$$

$\Lambda \sim \frac{1}{a} \dots$ NATURAL CUT-OFF.

STEP BY STEP,

$\vec{h} \cdot \vec{x}$

$\Lambda \sim \frac{1}{a} \dots$ NATURAL CUT-OFF,
(MAY EXIST FOR "SPACETIME
AS WELL")

RENORMALIZATION = DO THE $\underline{z}$ -INTEGRAL STEP BY STEP,

$$\langle \rho(\vec{x}) \rangle = \int_0^\Lambda \frac{d^d k}{(2\pi)^d} \langle \rho(\vec{k}) \rangle e^{i\vec{k} \cdot \vec{x}}$$

$\Lambda \sim \frac{1}{a}$
(MA)

DEAL WITH IR DIVERGENCES.

TO AVOID THIS:

$$\int_0^\Lambda = \int_0^{1/b} + \int_{1/b}^\Lambda$$

SLOW MODES FAST MODES.

$b > 1$

FISHER:

$$\gamma = \nu(2 - \gamma)$$

JOSEPHSON:

$$\alpha = 2 - \nu d$$

$\Rightarrow$ 2 INDEPENDENT CRIT.

MFT:

$$\alpha = 0, \beta = \frac{1}{2}, \eta =$$

TO AVOID THIS:

$$\int_0^N = \int_0^{N/6} + \int_{N/6}^N$$

SLOW MODES FAST MODES.

$$\underline{b > 1}$$

$$\psi = \psi_{<} + \psi_{>}$$

$$\psi_{<}(k) = \begin{cases} \psi(k) \\ 0 \end{cases}$$

$$\begin{cases} 0 < k < N/6 \\ k > N/6 \end{cases}$$

SLOW

$$\psi_{>}(k) = \begin{cases} 0 \\ \psi(k) \end{cases}$$

$$\begin{cases} 0 < k < N/6 \\ k > N/6 \end{cases}$$

FAST

IDE

+ $\int$
N/6
FAST MODES.

$b > 1$

IDEA: DO THE INTEGRAL OVER
FAST ONLY.

SLOW

FAST

THIN STRING

THICK STRING.

CHARGED

$$S = S_0 + S_{\text{INT}}$$
$$S_0[\varphi] = \frac{1}{2} \int dx \left(|\nabla \varphi|^2 + n \varphi^2 \right) = \frac{1}{2} \int \frac{d^d k}{(2\pi)^d} |\varphi(k)|^2 (n + k^2)$$

$$S = S_0 + S_{\text{INT}}$$

$$S_0[\varphi] = \frac{1}{2} \int d^2x \left(|\nabla \varphi|^2 + n \varphi^2 \right) = \frac{1}{2} \int \frac{d^2k}{(2\pi)^d} |\varphi(k)|^2 (n + k^2) = \underline{S_0[\varphi_L] + S_0[\varphi_R]}$$

$$S = S_0 + S_{\text{INT}}$$

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$$S_{\text{INT}}[\varphi] = \frac{\mu}{4!} \int d^d x \varphi^4$$

$$S = S_0 + S_{\text{INT}}$$

$$S_0[\varphi] = \frac{1}{2} \int d^d x \left(|\nabla \varphi|^2 + m^2 \varphi^2 \right) = \frac{1}{2} \int \frac{d^d k}{(2\pi)^d} |\varphi(k)|^2 (m^2 + k^2) = \underline{S_0[\varphi_L] + S_0[\varphi_R]}$$

$$S_{\text{INT}}[\varphi] = \frac{\mu}{4!} \int d^d x \varphi^4 = \frac{\mu}{4!} \int \frac{d^d k_1 \dots d^d k_4}{(2\pi)^d \dots (2\pi)^d} \varphi(k_1) \dots \varphi(k_4) (2\pi)^d \delta(k_1 + k_2 + k_3 + k_4)$$

$$S_0[\varphi] = \frac{1}{2} \int d^d x \left(|\nabla \varphi|^2 + m^2 \varphi^2 \right) = \frac{1}{2} \int \frac{d^d k}{(2\pi)^d} |\varphi(k)|^2 (k^2 + m^2) = \text{Sol}$$

$$S_{\text{INT}}[\varphi] = \frac{\mu}{4!} \int d^d x \varphi^4 = \frac{\mu}{4!} \int \frac{d^d k_1 \dots d^d k_4}{(2\pi)^d \dots (2\pi)^d} \varphi(k_1) \dots \varphi(k_4) (2\pi)^d \delta(k_1 + k_2 + k_3 + k_4)$$

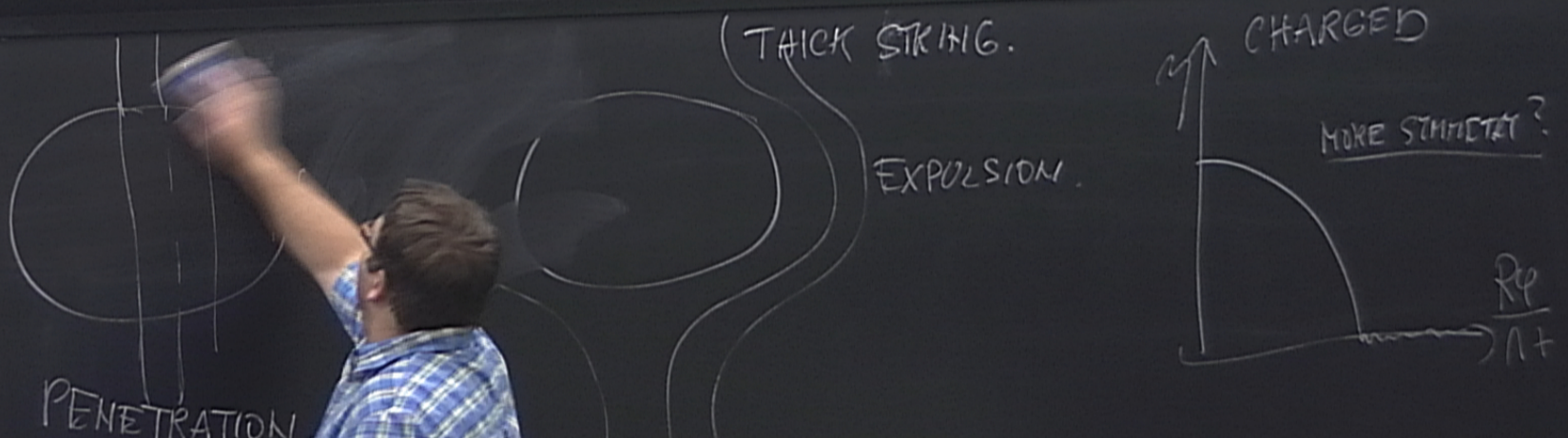
$$Z = \int D\varphi D\bar{\varphi} e^{-S[\varphi, \bar{\varphi}]} = \int D\varphi e^{-\tilde{S}[\varphi]}$$

$$S_0[\varphi] = \frac{1}{2} \int d^d x \left(|\nabla \varphi|^2 + \lambda \varphi^2 \right) = \frac{1}{2} \int \frac{d^d k}{(2\pi)^d} |\varphi(k)|^2 (\lambda + k^2) = S_0$$

$$S_{\text{INT}}[\varphi] = \frac{\mu}{4!} \int d^d x \varphi^4 = \frac{\mu}{4!} \int \frac{d^d k_1 \dots d^d k_4}{(2\pi)^{d_1} \dots (2\pi)^{d_4}} \varphi(k_1) \dots \varphi(k_4) (2\pi)^d \delta(k_1 + k_2 + k_3 + k_4)$$

$$Z = \int D\varphi D\psi e^{-S[\varphi, \psi]} = \int D\varphi e^{-\tilde{S}[\varphi]}$$

AFTER INTEGRATING FAST MODES.



$$Z = \int D\varphi_k D\varphi_{-k} e^{-S[\varphi_k, \varphi_{-k}]} = \int D\varphi_k e^{-\tilde{S}[\varphi_k]}$$

AFTER INTEGRATING FAST MODES.

WE MUST HAVE

$$\tilde{S}[\varphi_k] = \frac{1}{Z} \int_0^{N_b} \frac{d^d k}{(2\pi)^d} |\varphi_k(k)|^2 \left(\tilde{n}_2 k^2 + \tilde{n}_0 \right) + \frac{\tilde{n}_4}{4!} \int_0^{N_b} \frac{d^d k_1 \dots d^d k_4}{(2\pi)^{4d}} \varphi_k(k_1) \dots \varphi_k(k_4) (2\pi)^d \delta(k_1 + \dots + k_4)$$

$S[\psi] = \int_0^{2\pi} (2\pi)^d$
 BRING TO THE EXACTLY "SAME FORM"
 $\tilde{k} = k b, \quad \tilde{\varphi}(\tilde{k}) = \psi(k)/z$

WAVE FUNCTION RENORMALIZATION

BRING TO THE EXACTLY "SAME FORM" WAVE FUNCTION RENORMALIZATION

$$\tilde{k} = k b, \quad \tilde{\varphi}(\tilde{k}) = \varphi(k) / z$$

$$\tilde{S}[\tilde{\varphi}] = \frac{1}{z} \int_0^\Lambda \frac{d^d \tilde{k}}{(2\pi)^d} \left(b^{-d} \tilde{\Lambda}^2 b^{-2} z^2 \tilde{k}^2 + b^{-d} \Lambda_0 z^2 \right) |\tilde{\varphi}(\tilde{k})|^2$$

$$\tilde{S}[\varphi_k] = \frac{1}{Z} \int_0^\Lambda \frac{d^d k}{(2\pi)^d} |\varphi_k(k)|^2 \left(\tilde{\Lambda}_2 k^2 + \tilde{\Lambda}_0 \right) + \frac{1}{4!} \int_0^\Lambda \frac{d^d k}{(2\pi)^d} \varphi_k(k) \varphi_k(k) \varphi_k(k) \varphi_k(k)$$

BRING TO THE EXACTLY "SAME FORM"

WAVE FUNCTION RENORMALIZATION

$$\tilde{k} = k b, \quad \tilde{\varphi}(\tilde{k}) = \varphi(k)/Z$$

$$\tilde{S}(\tilde{\varphi}) = \frac{1}{Z} \int_0^\Lambda \frac{d^d \tilde{k}}{(2\pi)^d} \left(b^{-d} \tilde{\Lambda}_2 b^{-2} Z^2 \tilde{k}^2 + b^{-d} \tilde{\Lambda}_0 Z^2 \right) |\tilde{\varphi}(\tilde{k})|^2 + \frac{1}{4!} \tilde{\Lambda}_4 b^{-4d} Z^4 \int_0^\Lambda \frac{d^d \tilde{k}}{(2\pi)^d} \tilde{\varphi}(\tilde{k}) \tilde{\varphi}(\tilde{k}) \tilde{\varphi}(\tilde{k}) \tilde{\varphi}(\tilde{k})$$

$$|\varphi_k|^2 \left(\tilde{\Lambda}_2 k^2 + \tilde{\Lambda}_0 \right) + \frac{\tilde{\Lambda}_4}{4!} \int_0^{k/b} \frac{d^4 q_1 \dots d^4 q_4}{(2\pi)^{4d}} \varphi_k(q_1) \dots \varphi_k(q_4) (2\pi)^d \delta(q_1 + \dots + q_4)$$

FORM''

WAVE FUNCTION RENORMALIZATION

$$\delta(f(k)) = \frac{\delta(v \cdot x)}{f'(v)}$$

$$= \varphi_k(k) / Z$$

$$\left(\tilde{\Lambda}_2 b^{-2} Z^2 \tilde{k}^2 + b^{-d} \tilde{\Lambda}_0 Z^2 \right) |\tilde{\varphi}(k)|^2 + \frac{1}{4!} \tilde{\Lambda}_4 b^{-4d} Z^4 \int_0^{k/b} \frac{d^4 q_1 \dots d^4 q_4}{(2\pi)^{4d}} \dots$$



$$\boxed{\tilde{A}_2 = b^\gamma}$$

γ ... ANOMALOUS DIMENSION

$$\boxed{\tilde{A}_2 = b^\gamma} \quad \gamma \dots \text{ANOMALOUS DIMENSION}$$

$$1 = b^{-d} b^\gamma b^{-2} z^2$$

$$\Rightarrow \boxed{z = b^{\frac{d+2-\gamma}{2}}}$$

$$b, \quad \tilde{\varphi}(\tilde{k}) = \psi(k)/z$$

$$\frac{d^d \tilde{k}}{(2\pi)^d} \left(\underbrace{b^{-d} \tilde{\Lambda}^2 b^{-2} z^2 \tilde{k}^2}_{1} + \underbrace{b^{-d} \tilde{\Lambda}^2 z^2}_{\tilde{\Lambda}^2} \right) |\tilde{\varphi}(\tilde{k})|^2 + \frac{1}{4!} \tilde{\Lambda}^4 b^{-4d} z^{4d} \tilde{k}^4$$

$$b^{\gamma} b^{-2} z^2$$

$$b^{\frac{d+2-\gamma}{2}}$$

$$b, \quad \tilde{\varphi}(\tilde{k}) = \varphi(k)/z'$$

$$\frac{d^d \tilde{k}}{(2\pi)^d} \left(\underbrace{b^{-d} \tilde{\Lambda}^2 b^{-2} z^2 \tilde{k}^2}_{\tilde{\Lambda}^2} + \underbrace{b^{-d} \tilde{\Lambda}^0 z^2}_{\tilde{\Lambda}^0} \right) |\tilde{\varphi}(\tilde{k})|^2 + \frac{1}{4!} \underbrace{\tilde{\Lambda}^4 b^{-4d} z^{4d}}_{\tilde{\Lambda}^4} \int \frac{d^d \tilde{k}}{b^d}$$

$$b^{\gamma} b^{-2} z^2$$

$$b^{\frac{d+2-\gamma}{2}}$$



γ ... ANOMALOUS DIMENSION

$$\gamma b^{-2} z^2$$

$$b^{\frac{d+2-\gamma}{2}}$$

$$\tilde{\mu} = b^{-d} \tilde{\mu} z^2 = b^{2-\gamma} \tilde{\mu}$$

$$\tilde{\mu} = \tilde{\mu}_4 b^{-4d+d} z^4 = b^{4-2\gamma-d} \tilde{\mu}_4$$

η ... ANOMALOUS DIMENSION

$$\eta b^{-2} z^2$$

$$b^{\frac{d+2-\eta}{2}}$$

$$\tilde{\Lambda} = b^{-d} \Lambda_0 z^2 = b^{2-\eta} \tilde{\Lambda} = \tilde{\Lambda}$$

$$\tilde{\mu} = \tilde{\Lambda}_4 b^{-4d+d} z^4 = b^{4-2\eta-d} \tilde{\mu} = \tilde{\mu}$$



DO THIS REPEATEDLY UNTIL
 WE FIND A FIXED POINT, (λ^*, μ^*)
 SO THAT $(\lambda^*, \mu^*) \rightarrow (\lambda^*, \mu^*)$
WHY FIXED POINT? IN EACH STEP
 $\xi = \xi(\lambda, \mu) \rightarrow \xi(\tilde{\lambda}, \tilde{\mu}) = \underline{3/6}$

SLOW MODES

FAST MODES.

EFFECTIVELY. $(n, m) \rightarrow (\tilde{n}, \tilde{m})$

AT

DO THIS REPEATEDLY UNTIL

WE FIND A FIXED POINT, (n^*, m^*) SO THAT $(n^*, m^*) \rightarrow (n^*, m^*)$ WHY FIXED POINT?

IN EACH STEP

$$\xi = \xi(n, m) \rightarrow \xi(\tilde{n}, \tilde{m}) = \xi/l$$

FAST MODES.

AT FIXED POINT:

$$\boxed{\zeta = \underline{3/6}}$$

$$(\lambda^*, \mu^*)$$

$$(\lambda^*, \mu^*)$$

$$\rightarrow \zeta(\tilde{\lambda}, \tilde{\mu}) = \underline{3/6}$$

FAST MODES.

AT FIXED POINT:

$$\boxed{\zeta = \frac{3}{6}} \begin{cases} 0 \\ \infty \end{cases}$$

$$(\lambda^*, \mu^*)$$

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FAST MODES.

AT FIXED POINT:

$$\xi = \underline{3/6}$$

0 ... PHASE ($T \neq T_c$)

∞ ... CRITICAL POINT
($T = T_c$)

$$(\lambda^*, \mu^*)$$

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FAST MODES.

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PHASE I

PHASE ?

$$(\lambda^*, \mu^*)$$

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