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Non-Commutative Geometry in Condensed Matter Physics and Field Theory
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# *Emergent gravity as the nematic dual of Lorentz-invariant Elasticity*

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***These are preliminary lecture notes, intended only for distribution to participants.***

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# Emergent gravity as the nematic dual of Lorentz-invariant Elasticity


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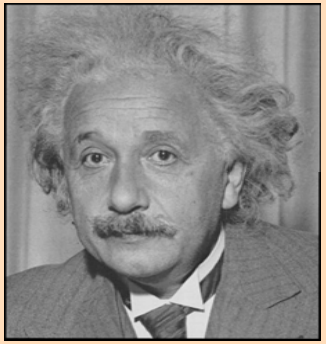
FOM

STANFORD UNIVERSITY

# Emergent Einstein Gravity



$$S = -\frac{c^3}{16\pi G}\int dV \sqrt{-g}\, R + S_{matter}$$

Einstein's space time = the Lorentz invariant topological nematic superfluid (at least in 2+1D)

A medium characterized by:

- emergent general covariance
- absence of torsion- and compressional rigidity
- presence of curvature rigidity (topological order)

# Plan of talk

1. Plasticity (defected elasticity) and differential geometry

2. Fluctuating order and high Tc superconductivity

3. Dualizing non-relativistic quantum elasticity

    3.a Quantum nematic orders

    3.b Superconductivity: dual Higgs is Higgs

4. The quantum nematic world crystal and Einstein's space time

# Quantum-elasticity: basics

Quantum elastic action, isotropic medium

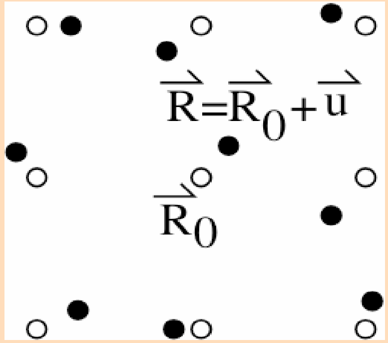
$$S = \mu \left[ u_{xx}^2 + 2u_{xy}^2 + u_{yy}^2 + \frac{\nu}{1-\nu}\left(u_{xx} + u_{yy}\right)^2 + \left(\partial_\tau u_x\right)^2 + \left(\partial_\tau u_y\right)^2 \right]$$

Shear modulus $\mu$, Poisson ratio $\nu$, compression modulus $\kappa = \mu(1+\nu)/(1-\nu)$

$$c_{ph}^2 = 2\mu/\rho = 1, \hbar = 1, u_{ab} = \left(\partial_a u_b + \partial_b u_a\right)/2$$

Describes transversal- (T) and longitudinal (L) phonon,

$$S = \mu \left[ \left( \frac{q^2}{2} + \omega^2 \right) | u^T |^2 + \left( \frac{q^2}{1-\nu} + \omega^2 \right) | u^L |^2 \right]$$



# Elasticity and topology: the dislocation

J.M. Burgers (Delft):

Discovery of the topological excitation

War time needs (Peierls, Mott, Friedel, …)

# The Singularities

**Dislocation:**

Restores translational invariance

Destroys shear rigidity

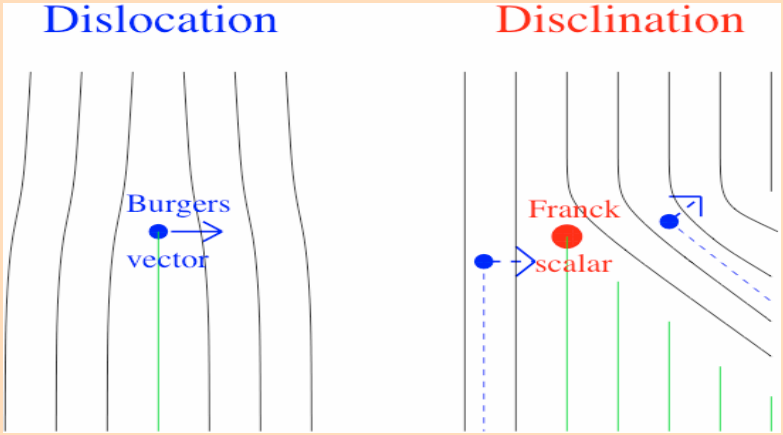
Topological charge: Burgers vector

**Disclination:**

Restores rotational invariance

Destroys ***curvature*** rigidity, like mass source in gravity (!)

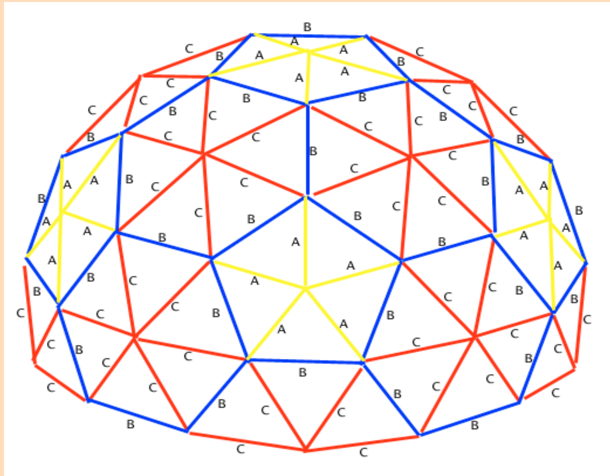
Topological charge: Franck 'scalar'

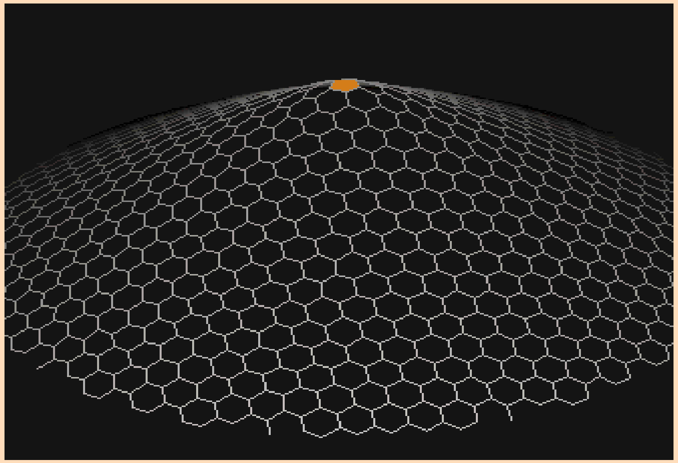



**Disclinations are 'bad' (difficult)**

Disclinations 'liberate' **non-abelian** nature of the euclidean group (diffeomorphism)

# Engineering curvature

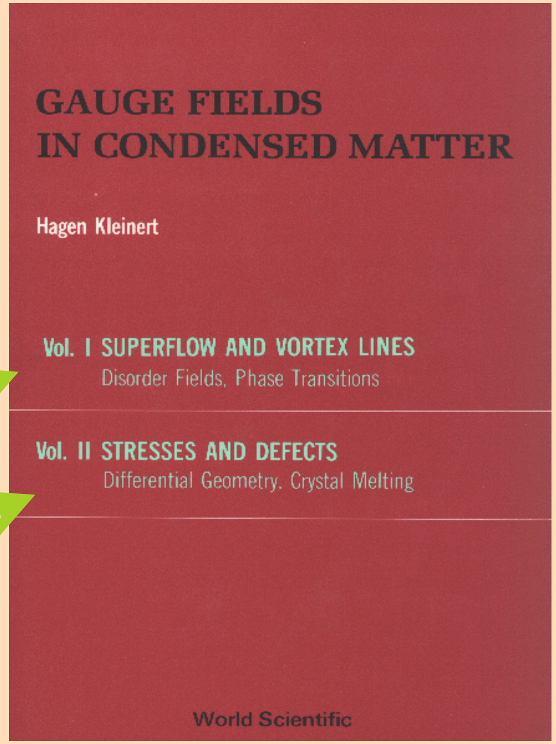




Disclination in ‘buckystuff’: like conical singularity in 2+1 D gravity
Fluctuating geometry = simplexes with fluctuating edge-lengths “Regge Calculus”

# The mathematical machine

Hagen Kleinert
(FU Berlin)




Abelian Higgs duality

Theory of plasticity in 3D (classical):
similarity with **euclidean gravity!**

# Elasticity and general covariance

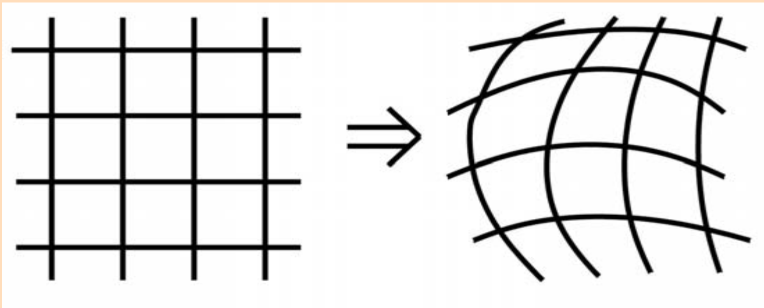
General covariance: infinitisimal coordinate transformation

$$e_a{}^{\mu} = \delta_a{}^{\mu} \to \delta_a{}^{\mu} - \partial_a \xi^{\mu}$$

$$g_{\mu\nu} = e_{\mu}{}^{a} e_{a\nu} = \delta_{\mu\nu} \to \delta_{\mu\nu} + \left(\partial_\mu \xi_\nu + \partial_\nu \xi_\mu\right)$$

General covariance = gauge invariance under elastic deformations

$$g_{ij} = \delta_{ij} \to \delta_{ij} + \left(\partial_i u_j + \partial_j u_i\right)$$



# Plasticity and differential geometry

Covariant derivative:

$$D_\nu v^\mu = \partial_\nu v^\mu + \Gamma_{\nu\lambda}{}^{\mu} v^\lambda$$

Connection, linearized:

$$\Gamma_{\mu\nu}{}^{\lambda} = \partial_\mu \partial_\nu \xi^\lambda$$

Curvature tensor: $R_{\mu\nu\lambda\kappa} = \left(\partial_\mu \, \partial_\nu - \partial_\nu \partial_\mu\right) \partial_\lambda \xi_\kappa$

Associate: $\xi^\lambda \to u^\lambda$

==> Einstein tensor corresponds with disclination current!

$$\Theta_{\mu\nu} \equiv G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R_\kappa{}^{\kappa}$$

'Bad' news: torsion = dislocation currents

$$S_{\mu\nu\lambda} = \frac{1}{2}\left(\partial_\mu \partial_\nu - \partial_\nu \partial_\mu\right)\xi_\lambda \qquad J_{\mu a} = \varepsilon_{\mu\nu\lambda} S_{\nu\lambda a}$$

Crystal = geometry with curvature and torsion.

# Non-linear plasticity

Use gravity techniques to solve problems associated with large defect densities/plastic deformations ( K. Kondo, 1952 ….)

Substitute covariant derivatives for derivatives

$$\partial_\nu v^\mu \rightarrow D_\nu v^\mu = \partial_\nu v^\mu + \Gamma_{\nu\lambda}{}^{\mu} v^\lambda$$

Use full curvature, torsion tensors instead of linearized tensors

Program not greatly successful when it matters (e.g. glasses).

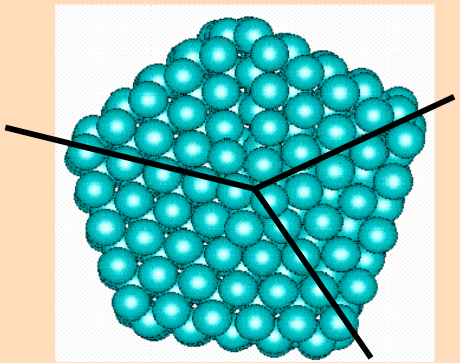
# The universe as a strange crystal …

Special ‘crystal’: isotropic elastic medium in space and time directions (Euclidean signature)

(a) Lorentz-invariance

(b) Curvature is not quantized, Franck vectors are …

$\frac{2\pi}{3}$ disclination in a triangular lattice



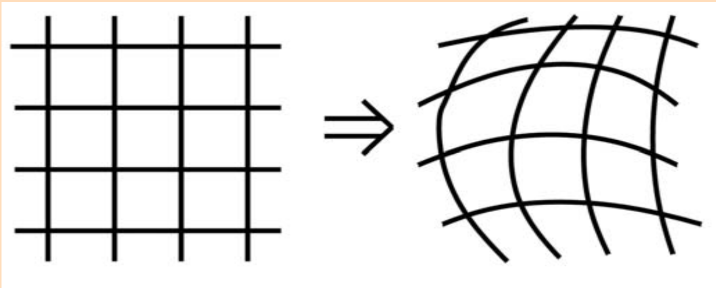
Deep geometrical/topological similarity with space-time (also: Bais et al, ‘quantum doubles’: crystal ==> Witten’s 2+1 D gravity)

# Why the universe is not a 'Lorentz' crystal

(a) Crystal 'geometry' is characterized by torsion, the universe is not …

(b) Disclinations are (quadratically) confined: curvature costs infinite energy!

(c) Deadly: crystals have no general covariance, the flat metric is preferred !!!



Elastic deformation costs energy: action is not gauge invariant …

These problems seem to be cured in the quantum NEMATIC world crystal … (at least in 2+1D)

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# Correlated superconductors

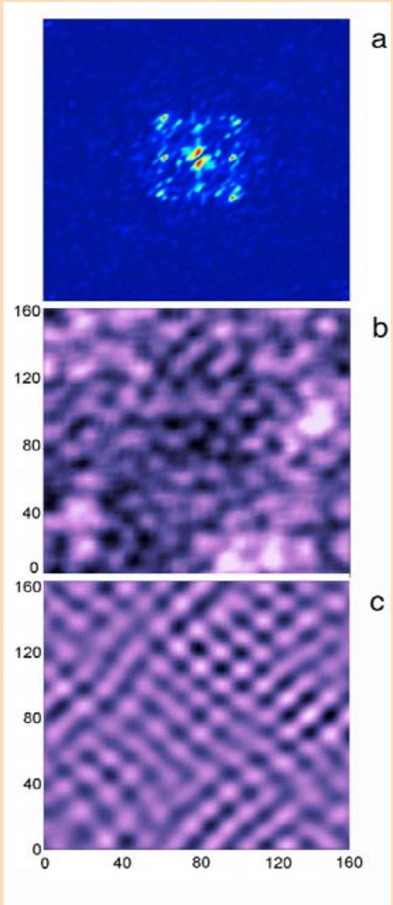
**Ideal Bose-Einstein gas**

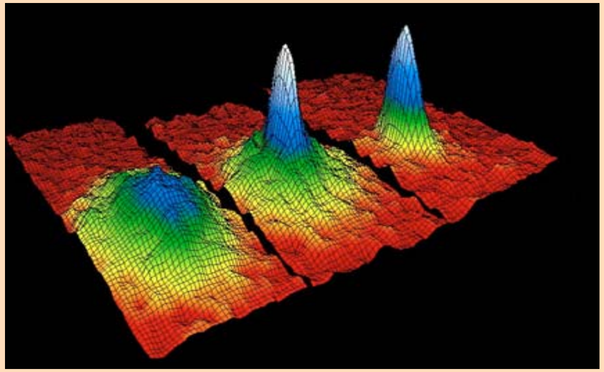
BEC cold atomic gas, BCS metallic superconductor

Helium 4 superfluid

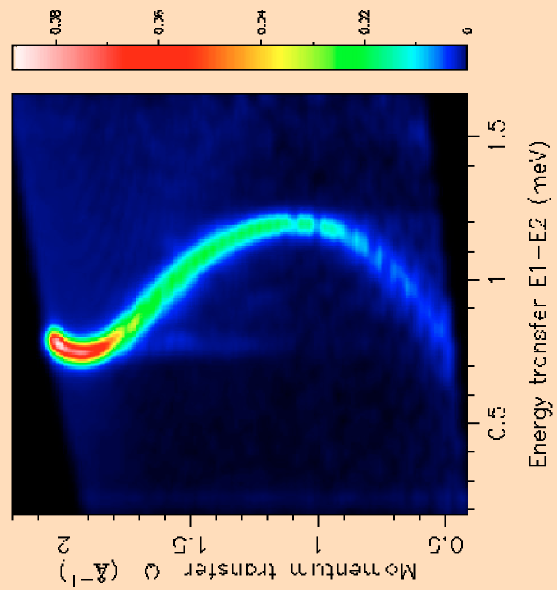
**High Tc superconductors**

**Strongly correlated fluid: locally like a solid.**

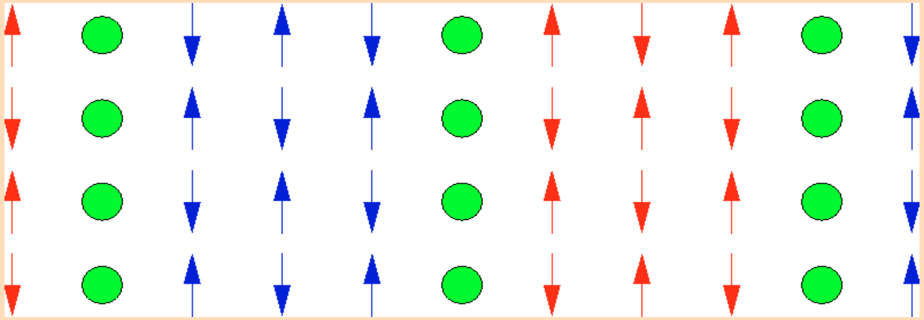


Roton



# Stripe order: charge, spin, domain walls

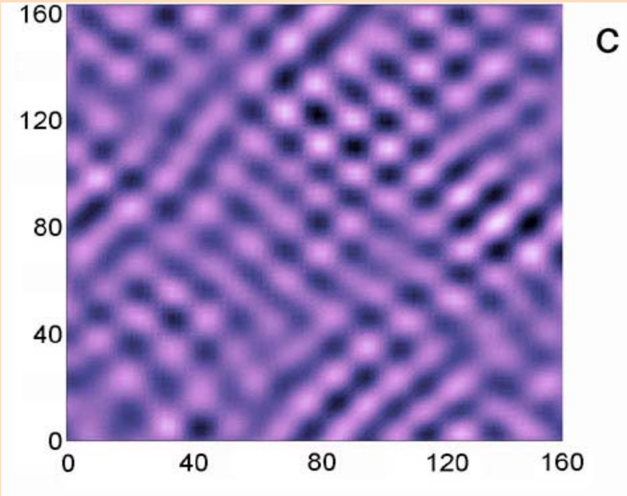


-- Charge order (e.g. STM)

-- Spin order (neutrons,NMR)

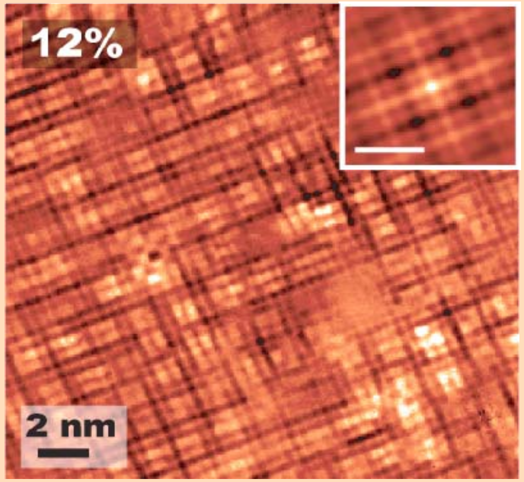
-- ‘Topological order’, ‘domainwall-ness’, ‘antiphaseboundariness’

# Electrons coming to a standstill




Kapitulnik et al (Stanford)

STM



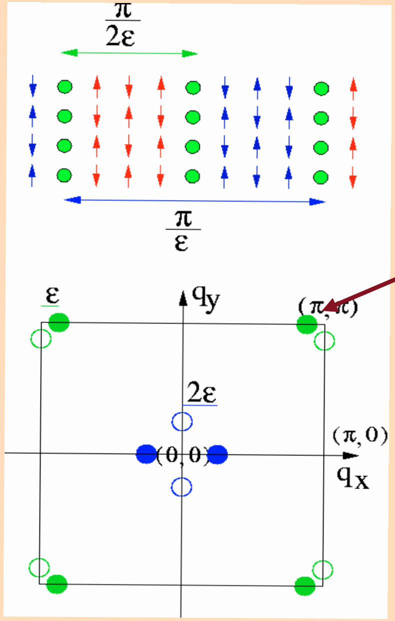

Davis et al (Cornell)

These ‘stripes’ are ubiquitous in doped Mott insulator (nickelates, manganites, …)

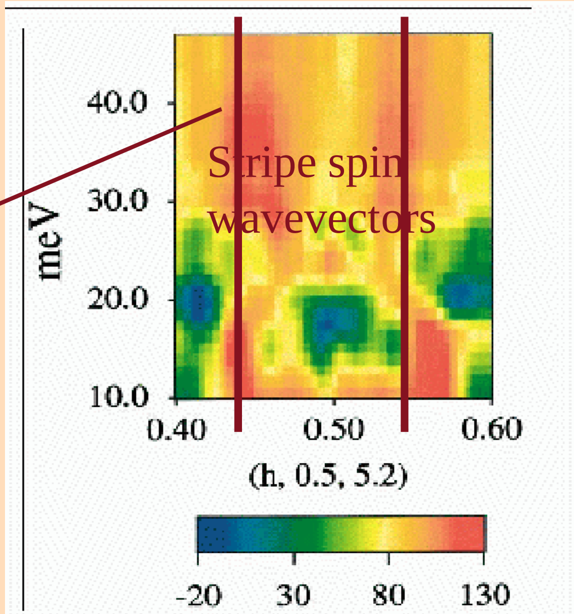
Cuprates: stripes are extremely quantum mechanical …

# Quantum Fluctuating stripe order

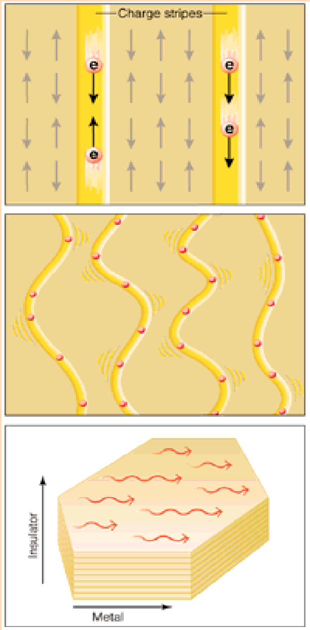
Fourier transform




Neutron scattering: spin fluctuations, subpicosecond!




YBCO Tc=60K: Mook et al, Oak Ridge



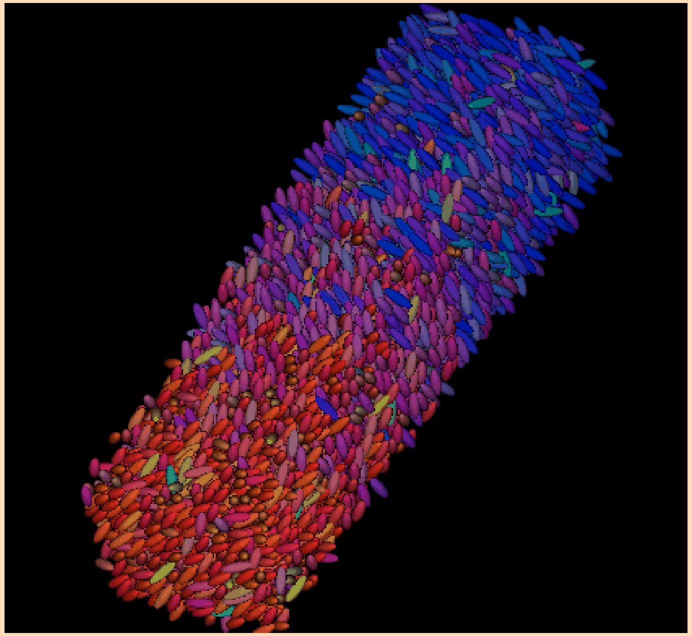

JZ, Science 286, 251 (1999)

# Nematic superfluids

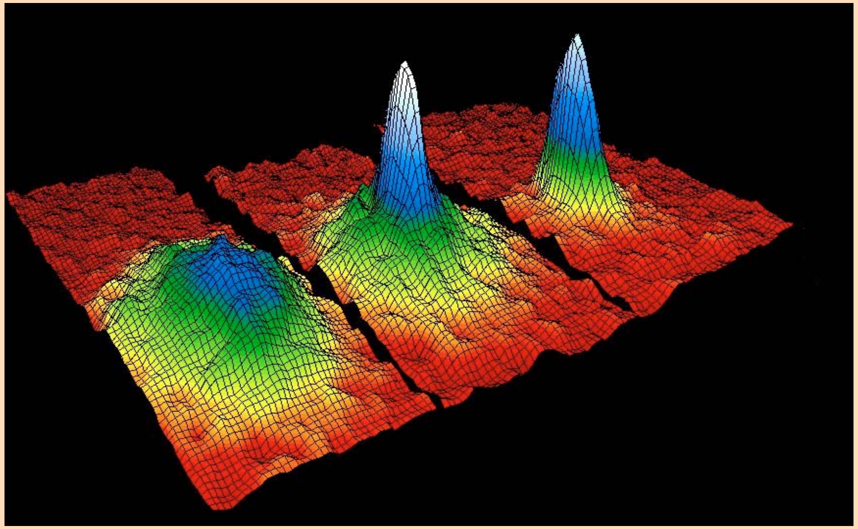
Kivelson,Fradkin, Emery, Nature 393, 550,1998



**Nematic order**



**Bose condensation**



# The Singularities

**Dislocation:**

Restores translational invariance

Destroys shear rigidity

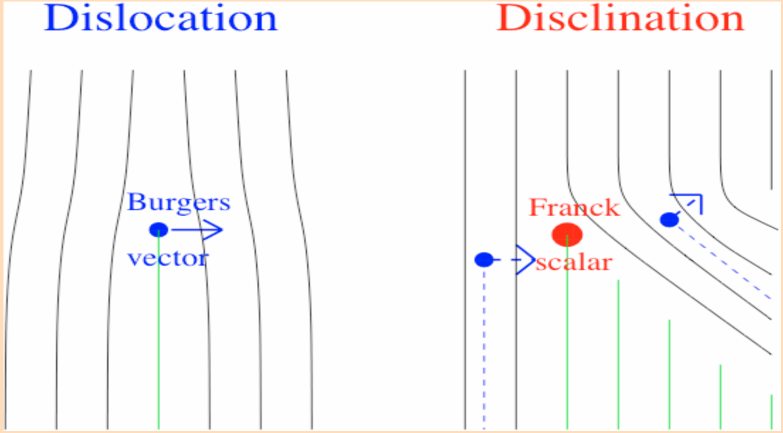
Topological charge: Burgers vector

**Disclination:**

Restores rotational invariance

Destroys ***curvature*** rigidity, like mass source in gravity (!)

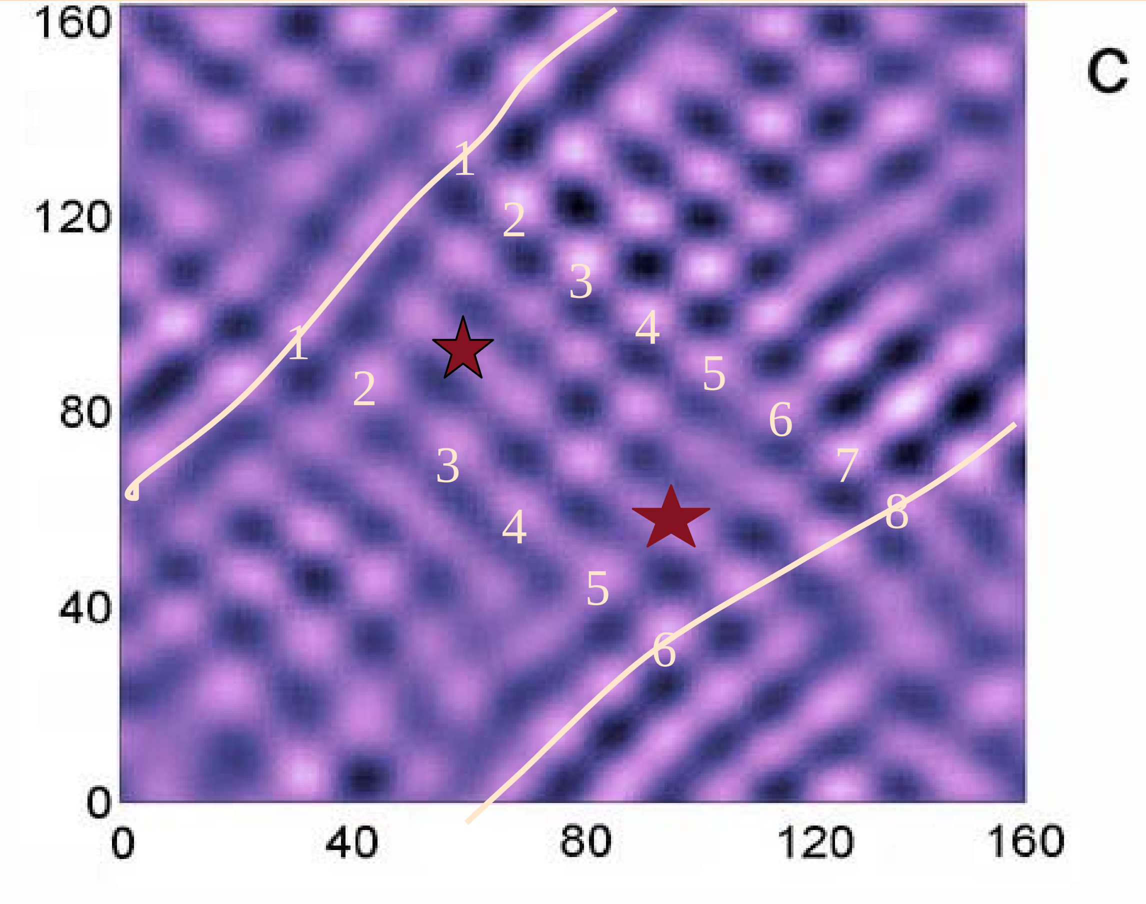
Topological charge: Franck ‘scalar’




**Disclinations are ‘bad’ (difficult)**

Disclinations ‘liberate’ **non-abelian** nature of the euclidean group (diffeomorphism)

# Dislocations: example



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# XY-electromagnetism duality in 2+1D

Relativistic short hand (magnon),

Consider quantum phase dynamics (XY in 2+1D),

$$S = \frac{1}{g}(\partial_\mu \varphi)^2 \quad \mathrm{mod}(2\pi) \qquad \boxed{H = \sum_i (n_i)^2 - J \sum_{<ij>} \cos(\varphi_i - \varphi_j)}$$

Hubbard-Stratanovich auxiliary field $\xi_\mu$

$$S = g\xi_\mu \xi_\mu + i\xi_\mu \partial_\mu \varphi$$

Divide in smooth and multivalued field configurations, $\varphi = \varphi_{sm} + \varphi_{MV}$

$$S = \quad g\xi_\mu\xi_\mu + i\xi_\mu\partial_\mu\varphi_{MV} + i\xi_\mu\partial_\mu\varphi_{sm} \qquad g\xi_\mu\xi_\mu + i\xi_\mu\partial_\mu\varphi_{MV} - i\varphi_{sm}(\partial_\mu\xi_\mu)$$

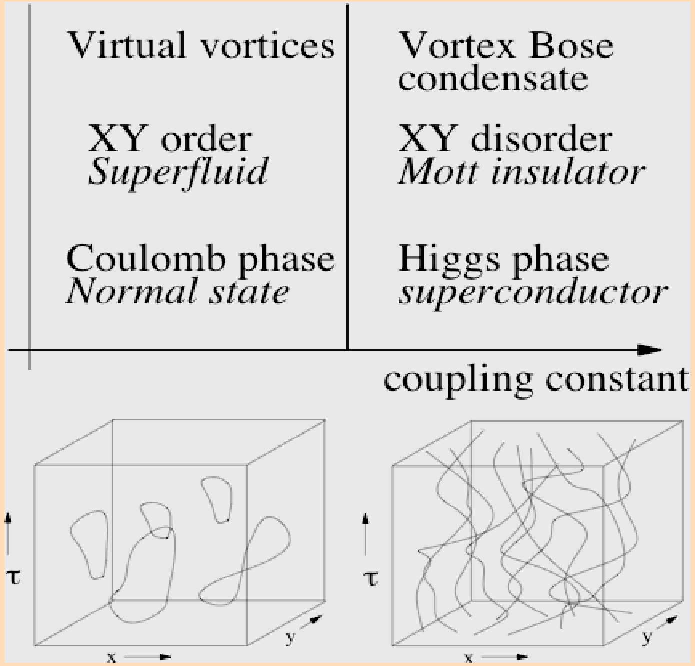
$\varphi_{sm}$ acts like Lagrange multiplier ==> $\xi_\mu$ conserved==>imposed by gauge field $A_\mu$

$$\partial_\mu \xi_\mu = 0 \qquad \Rightarrow \xi_\mu = \varepsilon_{\mu\nu\lambda}\partial_\nu A_\lambda$$

**Dual action:** $S = gF_{\mu\nu}F^{\mu\nu} + iA_\mu J^\mu_V,$

**Vortex current:** $J^\mu_V = \varepsilon_{\mu\nu\lambda}\partial_\nu\partial_\lambda\varphi \quad \Leftrightarrow \quad \oint d\varphi = 2\pi n$

# Disorder field theory




Theory describing vortex **tangle**:

Long range interaction — Core vs kinetic energy — Hard cores

$$S = \int dx^d d\tau \left[ |(\partial_\mu - iA_\mu)\Psi|^2 + m^2 |\Psi|^2 + w |\Psi|^4 + F_{\mu\nu}F^{\mu\nu} \right]$$

# Dualize elasticity: stress **gauge** fields (Kleinert)

Quantum elasticity: $S = C_{\mu\nu ab}\partial_\mu u^a \partial_\nu u^b$

Hubbard-Stratanovich = stress ($\sigma_\mu^a$ ) - strain ( $\partial_\mu u^a$) duality,

$$S = \sigma_\mu^a C_{\mu\nu ab}^{-1} \sigma_\nu^b + i\sigma_\mu^a \partial_\mu u_{sm}^a + i\sigma_\mu^a \, \partial_\mu u_{MV}^a$$

Integrate over smooth displacement fields $u_{sm}^a$

$$\partial_\mu \sigma_\mu^a = 0 \quad \Rightarrow \quad \sigma_\mu^a = \varepsilon_{\mu\nu\lambda}\partial_\nu B_\lambda^a$$

Conservation of stress imposed by ‘stress photons’ $B_\mu^a$ (pseudo tensors)

**Dual action:** $$S = \left[(\varepsilon\partial B)\; C^{-1}\,(\varepsilon\partial B)\right] + iB_\mu^a J_\mu^a$$

$$J_\mu^a = \varepsilon_{\mu\nu\lambda}\partial_\nu \partial_\lambda u_{MV}^a \quad \Leftrightarrow \quad \oint du^a = b^a$$

$J_\mu^a$ are **dislocation** currents, $\vec{b} = \left(b_x, b_y\right)$ **Burgers vector**.

# Phonons as stress photons

'Phonon' action (elastic medium) in stress photons:

$$S = \frac{\hbar c_{ph}}{4\mu} \int dq^2 d\omega \left[ 2(\omega^2 + q^2/2)\,|B^T_{-1}|^2 + \frac{1}{1+\nu}\big((1-\nu)\omega^2 + q^2\big)\,|B^T_{+1}|^2 + \big(\omega^2 + q^2\big)\,|B^L_{-1}|^2 \right]$$

Transversal phonon

Longitudinal phonon

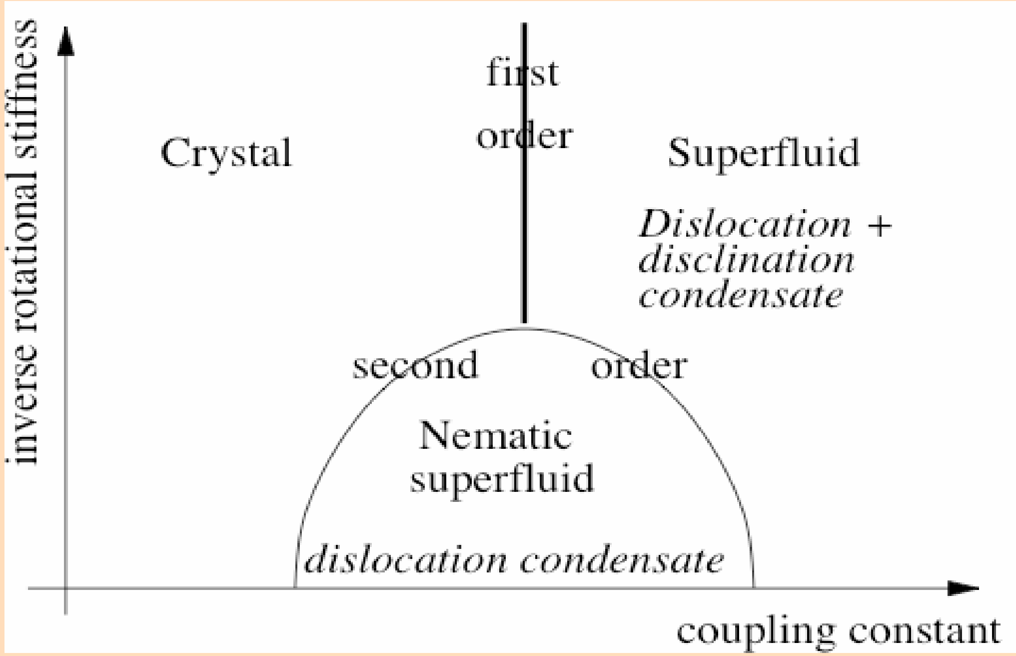
Instanteneous stress

Strain (phonon) propagator recovered through dual relation:

$$\langle \langle \partial_\mu u^a | \partial_\nu u^b \rangle \rangle_{\vec{p}} = C^{-1}_{\mu\mu aa}\delta_{\mu\nu}\delta_{ab} - C^{-1}_{\mu\lambda ac} C^{-1}_{\nu\kappa bd} \langle \langle \sigma^c_\lambda | \sigma^d_\kappa \rangle \rangle_{\vec{p}}$$

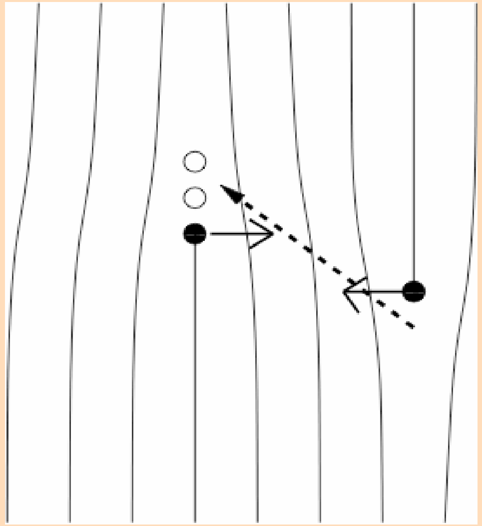
$$\sigma^a_\mu = \varepsilon_{\mu\nu\lambda}\partial_\nu B^a_\lambda$$

# Nelson-Halperin-Young + hbar




**Nematic** (‘hexatic’) **quantum order**:

Dislocations bose condense
Disclinations stay massive
Idealization: interstitials non-existent.



Particle transport at dislocation collsions

# The dual (dislocation) condensate

Dislocation Meissner Phase: $\Psi = |\Psi| e^{i\psi}, \langle |\Psi|^2 \rangle \neq 0 \Rightarrow L_{eff} = L_{Meissner} + L_{Maxwell} + L_{Director}$

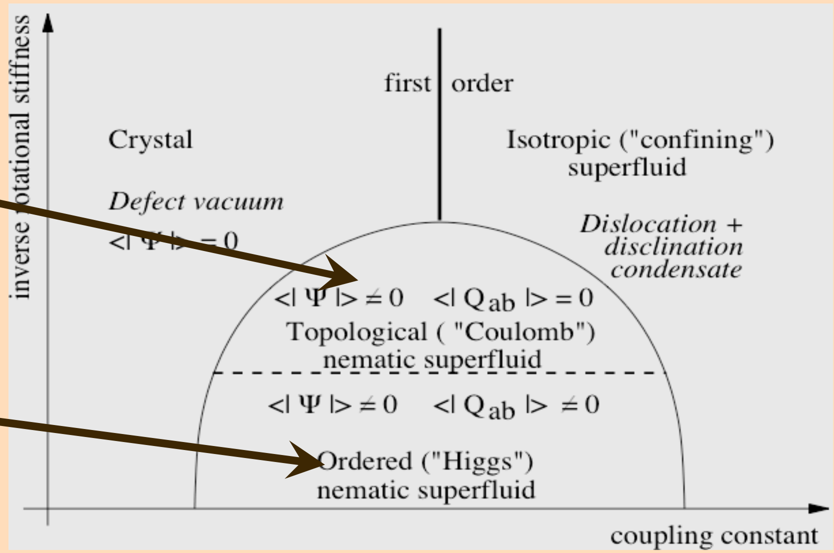
$$L_{Meissner} = \frac{q_0^2 \, |n_T(Q_{ab})|^2}{2\mu} \left[ |B^T_{-1}|^2 + 4\frac{\hat{\omega}^2}{1+\hat{\omega}^2} \, |B^L_{-1}|^2 - 2\frac{\hat{\omega}\,(1-\hat{\omega}^2)}{1+\hat{\omega}^2} \left( B^{T*}_{+1} B^L_{-1} + h.c. \right) \right]$$

$$L_{Maxwell} = \text{"}\, (\varepsilon\partial B)\, C^{-1}\, (\varepsilon\partial B) \,\text{"} \qquad L_{Director} = \text{"}\, (\partial Q)^2 + m_Q^2 Q^2 + w_Q Q^4 \,\text{"}$$

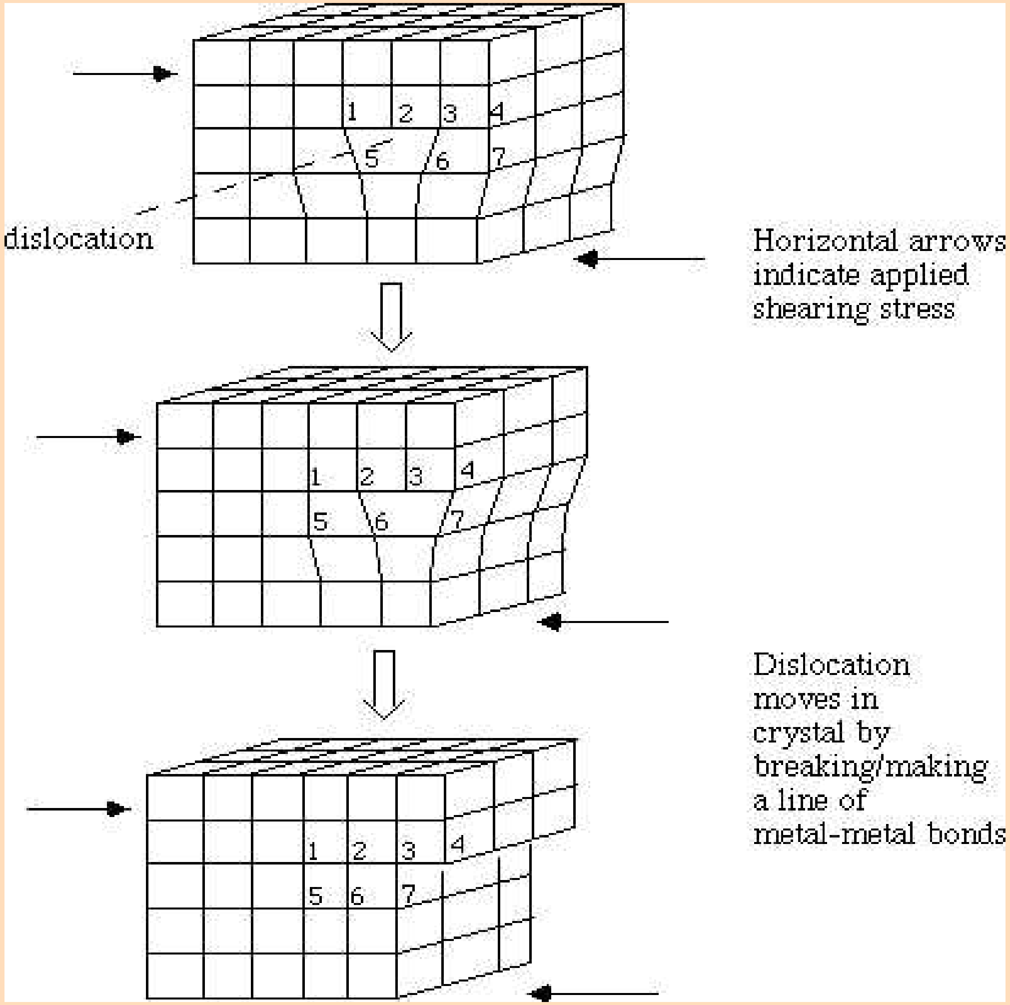
$\lambda_{shear} = 1/q_0$ : **shear penetration depth**

**"Topological Nematic"** (Toner-Lammert-Rokshar) Burgers vectors disordered **Isotropic, but massive disclinations**

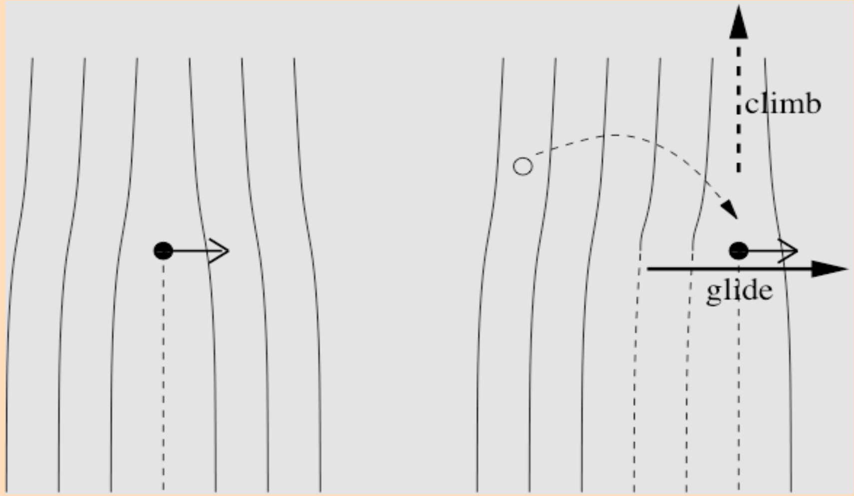
**"Glide nematic"** Burgers vectors disordered Broken rotational symmetry **Anisotropic** $\lambda_{shear}$



# Dislocations and shear



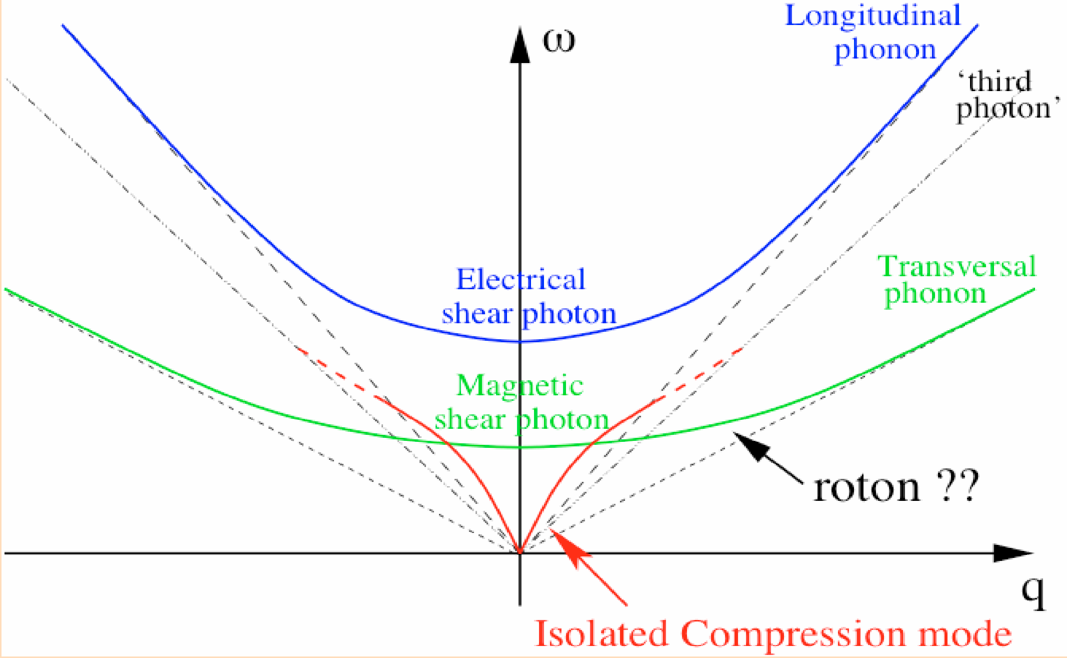
# Dynamics: glide principle




‘**topological dynamics’**: propagation only possible along Burgers vector

Field theory: requirement for **finite compression** modulus in liquid

# Topological nematic superfluid: excitations




Superfluid hydrodynamics:

Isolated massless compression, massive shear: Euler fluid

Periodicity (vortex quantization): inherited from dislocation condensate

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# Superconductivity: photons vs. stress-photons

**Charged** elastic medium (bosonic Wigner crystal): couple in **EM** gauge fields

$$S = \int dx^2 d\tau \left[ n_e e \vec{u} \bullet \vec{E} + F_{\mu\nu} F^{\mu\nu} \right] \quad E_{x,y} = \pm \left( \partial_{x,y} A_\tau - \frac{1}{c} \partial_\tau A_{x,y} \right) \quad F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$$

**Dualize** in stress photons, focus on **magnetic** sector:

$$L_{tot} = L_{AA} + L_{AB} + L_{BB}$$

$$L_{AA} = \left( \frac{1}{\lambda_L^2} + \frac{\omega^2}{c^2} + q^2 \right) | A_{-1} |^2 + \dots | A_{+1} |^2$$

$$\frac{1}{\lambda_L^2} = \frac{n_e^2 e^2}{\rho c^2}$$

bare London penetration depth, **superconductor**??

**Effective EM action**: integrate out stress photons

$$L_{AB} = -\frac{n_e e}{\rho c^2} B_{-1}^T A_{-1} + f\left( A_{+1}, B_{-1}^L, B_{+1}^T \right)$$

$$L_{BB} = \frac{1}{4\mu} \left[ \left( 2\omega^2 + q^2 + \frac{2}{\lambda_{shear}^2} \right) | B_{-1}^T |^2 + g\left( B_{-1}^L, B_{+1}^T \right) \right]$$

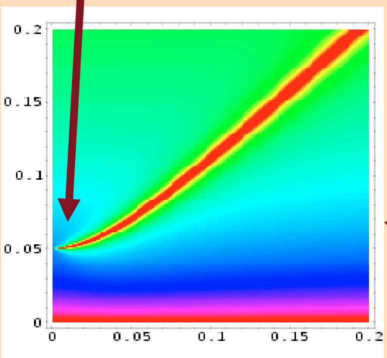
**Shear length finite** (fluid):
Crystal: Meissner term **eaten**
compensation incomplete,
**electromagnetic Meissner ‘liberated’!!**

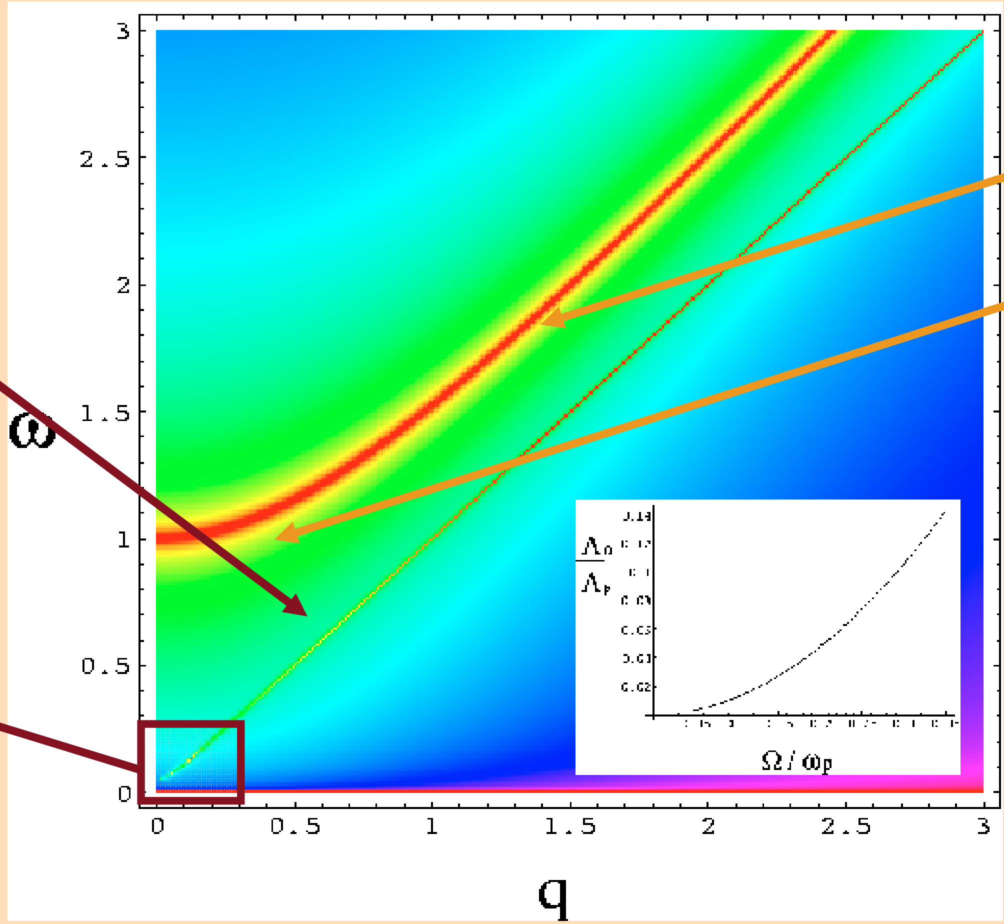
# The dual Higgs boson and electron loss

Dual (shear) Higgs photon

Dual Higgs mass

$\Omega \approx 50\, meV$ !?




Plasmon

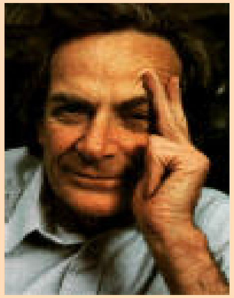
$\omega_p \approx 1eV$

# Superfluid hydrodynamics

Landau

Superfluid: quantized Euler fluid

$$\partial_t \vec{u} + (\vec{u} \bullet \vec{\nabla})\vec{u} = \vec{\nabla} p, \text{"mod}(2\pi)\text{"}$$



Feynman

Footnote (this talk): this is the zero temperature hydrodynamics of a solid which has lost its rigidity against long range shear forces.

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    3.a Quantum nematic orders

    3.b Superconductivity: dual Higgs is Higgs

4. The quantum nematic world crystal and Einstein's space time

# Emergent gravity: general covariance

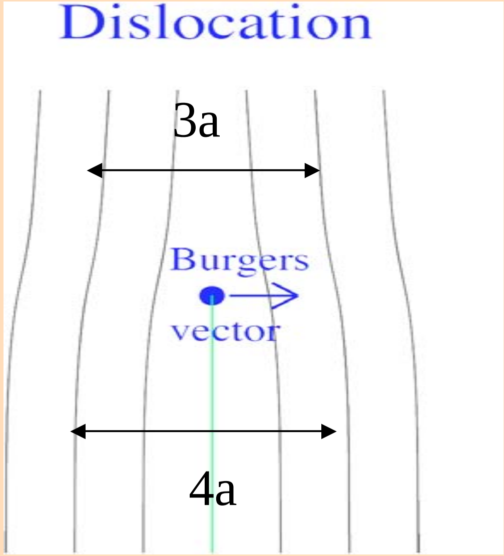
Distances measured by hopping from lattice site to lattice site, metric:

$$g_{\mu\nu} = \delta_{\mu\nu} + (\partial_\mu u_\nu + \partial_\nu u_\mu)$$

**General covariance**: metric is defined modulo local translations

**Dislocation condensate:**

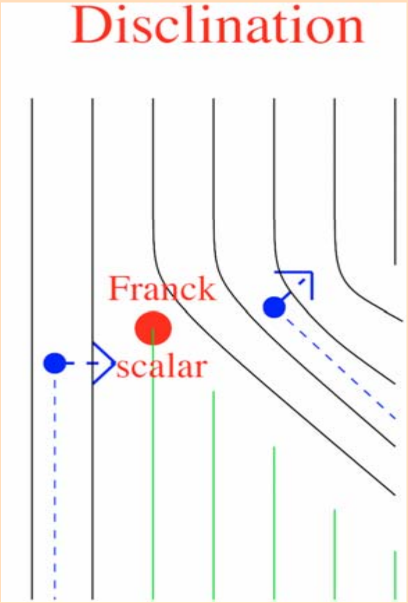
Coherently delocalized dislocations ==>
distances defined modulo local translations!




**Bonus:**

Dislocations represent torsion, dislocation condensate = Riemann space without torsion (like general relativity)!

# Emergent gravity: curvature




Represent curvature (e.g., in 2+1D literally like conical defects)

Disclination current (2+1D):

$$\Theta_{\mu\nu} = \varepsilon_{\mu\kappa\lambda}\partial_\kappa\partial_\lambda\omega_\nu, \;\; \omega_\mu = \frac{1}{4}\varepsilon_{\mu\nu\lambda}(\partial_\nu u_\lambda - \partial_\lambda u_\nu)$$

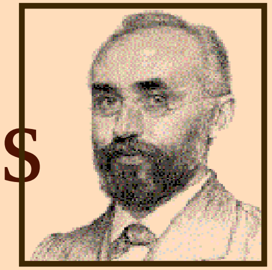
corresponds with the (linearized) Einstein tensor:

$$\Theta_{\mu\nu} \cong G_{\mu\nu} = R_{\nu\mu} - \frac{1}{2} g_{\nu\mu} R$$

In “solid”: disclinations are confined (infinite energy)

In nematic superfluid: deconfined but massive …

# Dynamics: double curl gauge fields



Recall: ‘conventional’ stress photons ==> only sources are disclinations

$$\sigma^{\mu\nu} = \epsilon^{\mu\kappa\gamma}\partial^{\kappa} B^{\gamma\nu} \rightarrow \partial B^{\mu\nu}\eta^{\mu\nu}, \quad \eta^{\mu\nu} = \epsilon^{\mu\kappa\gamma}\partial^{\kappa}\partial^{\gamma}\omega^{\nu}_{p}$$

Disclination currents: one ‘order’ higher in duality

$$\Theta_{\mu\nu} = \varepsilon_{\mu\kappa\lambda}\partial_\kappa\partial_\lambda\omega_\nu, \;\; \omega_\mu = \frac{1}{4}\varepsilon_{\mu\nu\lambda}(\partial_\nu u_\lambda - \partial_\lambda u_\nu)$$

Kleinert: double curl stress gauge fields (two forms)

$$\sigma_{\mu\nu} = \varepsilon_{\mu\kappa\lambda}\varepsilon_{\nu\alpha\beta}\partial_\kappa\partial_\alpha h_{\lambda\beta}$$

==> $$S_{WC} = \int d^2x\, d\tau \left[ \frac{1}{4\mu}\left( \sigma_{\mu\nu}^2 - \frac{\nu}{1+\nu}\sigma_{\mu\mu}^2 \right) + i h_{\mu\nu}\eta_{\mu\nu} \right]$$

Sources are truely conserved $\left(\partial_\mu \eta_{\mu\nu} = 0\right)$ ‘defect currents’

$$\eta_{\mu\nu} = \theta_{\mu\nu} + \varepsilon_{\lambda\mu\kappa}\partial_\lambda J_{\nu\kappa}$$

# The nematic 'Lorentz' crystal

Dislocation melting of the 2+1D 'Lorentz' (space-time isotropic) crystal:

(a) Consider topological nematic ==> space-time isotropy.

(b) No preferred time direction ==> glide constraint is impossible ==>

Dislocations turn into sources of compressional 'photons' ==> sound acquires a Higgs mass!

Symmetric = simple version of non-relativistic nematics

# The nematic 'Lorentz' crystal

Input: $S_{WC} = \int d^2x\, d\tau \left[ \frac{1}{4\mu}\left( \sigma^2_{\mu\nu} - \frac{\nu}{1+\nu}\sigma^2_{\mu\mu} \right) + ih_{\mu\nu}\eta_{\mu\nu} \right]$

$$\sigma_{\mu\nu} = \varepsilon_{\mu\kappa\lambda}\varepsilon_{\nu\alpha\beta}\partial_\kappa\partial_\alpha h_{\lambda\beta}$$

$$\eta_{\mu\nu} = \theta_{\mu\nu} + \varepsilon_{\lambda\mu\kappa}\partial_\lambda J_{\nu\kappa}$$

Condense dislocations 'isotropically', $S_{dislo} = \int d^2xd\tau \left[ \frac{m_d^2}{2} J^2_{\mu\nu} + iJ_{\mu\nu}\varepsilon_{\mu\kappa\lambda}\partial_\kappa h_{\lambda\nu} \right]$

$$S_{eff,space} = \int d^2xd\tau \left[ \frac{1}{4\mu}\left( \sigma^2_{\mu\nu} - \frac{\nu}{1+\nu}\sigma^2_{\mu\mu} \right) + \frac{1}{2m_d^2}\sigma_{\mu\nu}\frac{1}{\partial^2}\sigma_{\mu\nu} \right]$$

$$S_{discl} = \int d^2xd\tau \left[ \frac{m_\theta^2}{2}\theta^2_{\mu\nu} + ih_{\mu\nu}\theta_{\mu\nu} \right]$$

# Geometrical meaning

Consider dual 'stress' geometry: $h_{\mu\nu} = g_{\mu\nu} - \delta_{\mu\nu}$

Stress tensor turns into Einstein tensor: $\sigma_{\mu\nu} \equiv G_{\mu\nu}$

$$S_{eff,space} = \int d^2 x d\tau \left[ \frac{1}{4\mu} \left( G_{\mu\nu}^2 - \frac{\nu}{1+\nu} G_{\mu\mu}^2 \right) + \frac{1}{2m_d^2} G_{\mu\nu} \frac{1}{\partial^2} G_{\mu\nu} \right]$$

Non-linear generalization $\partial_\mu \to D_\mu$, etc; identify $m_d^2 = 8\pi G$

$$\to \int d^2 x dt \sqrt{-g} \frac{1}{2m_d^2} G_{\mu\nu} \frac{1}{-D^2} G_{\mu\nu} \to -\frac{c^3}{16\pi G} \int d^2 x dt \sqrt{-g} R$$

At long distances this becomes exactly the Einstein action

Incompressible (2+1 D): shear and compression massive, curvature rigidity is still present.

# Gravitating matter

Normal matter: gravity is uniformly attractive

$$S_{matter} = \int d^2 x d\tau \left[ h_{\mu\nu} T_{\mu\nu} \right]$$

T - symmetric Belinfante energy-momentum tensor

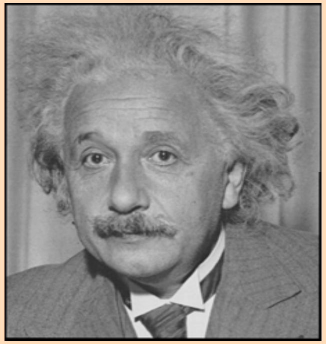
No condensed matter analogy !

Disclinations: massive excitations ‘guarding’ the curvature rigidity of space

$$S_{discl} = \int d^2 x d\tau \left[ \frac{m_\theta^2}{2} \theta_{\mu\nu}^2 + i h_{\mu\nu} \theta_{\mu\nu} \right]$$

Anti-dislocations do antigravity … Startrek!

# Emergent Einstein Gravity



$$S = -\frac{c^3}{16\pi G}\int dV\sqrt{-g}\,R + S_{matter}$$

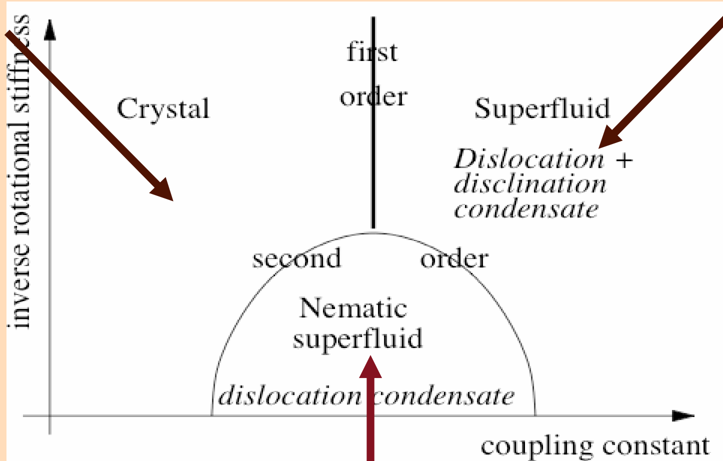
Einstein's space time = the Lorentz invariant topological nematic superfluid (at least in 2+1D)

A medium characterized by:

- emergent general covariance
- absence of torsion- and compressional rigidity
- presence of curvature rigidity (topological order)

# Plastic Cosmology: the competing phases

The Lorentz-crystal: non-gravitating torsion and vacuum pressure dominated universe (curvature confined)




Space-time does not resist curvature: matter causes catastrophic deflation

Our place

Fortunately!

# Conclusions

- Condensed matter physics: strongly correlated superconductors
  - The quantum nematic orders
  - The Meissner phase as the dual dislocation condensate
- Waiting for experiments

- Relativistic generalization: emergent gravity.
  - Makes sense in 2+1D, 3+1D generalization?
- Allegory or the holy truth? Subject for the Theology Department!

**J. Zaanen, Z. Nussinov and S.I. Mukhin, Ann. Phys. (NY) 310, 181 (2004) (cond-mat/0309397) ; H. Kleinert and J. Zaanen, Phys. Lett. A 324, 361 (2004) (cond-mat/0309379); V. Cvetkovic, S.I. Mukhin, J. Zaanen, in preparation.**