Title: Condensed Matter - Yi Zhang

Date: Dec 02, 2011 12:40 PM

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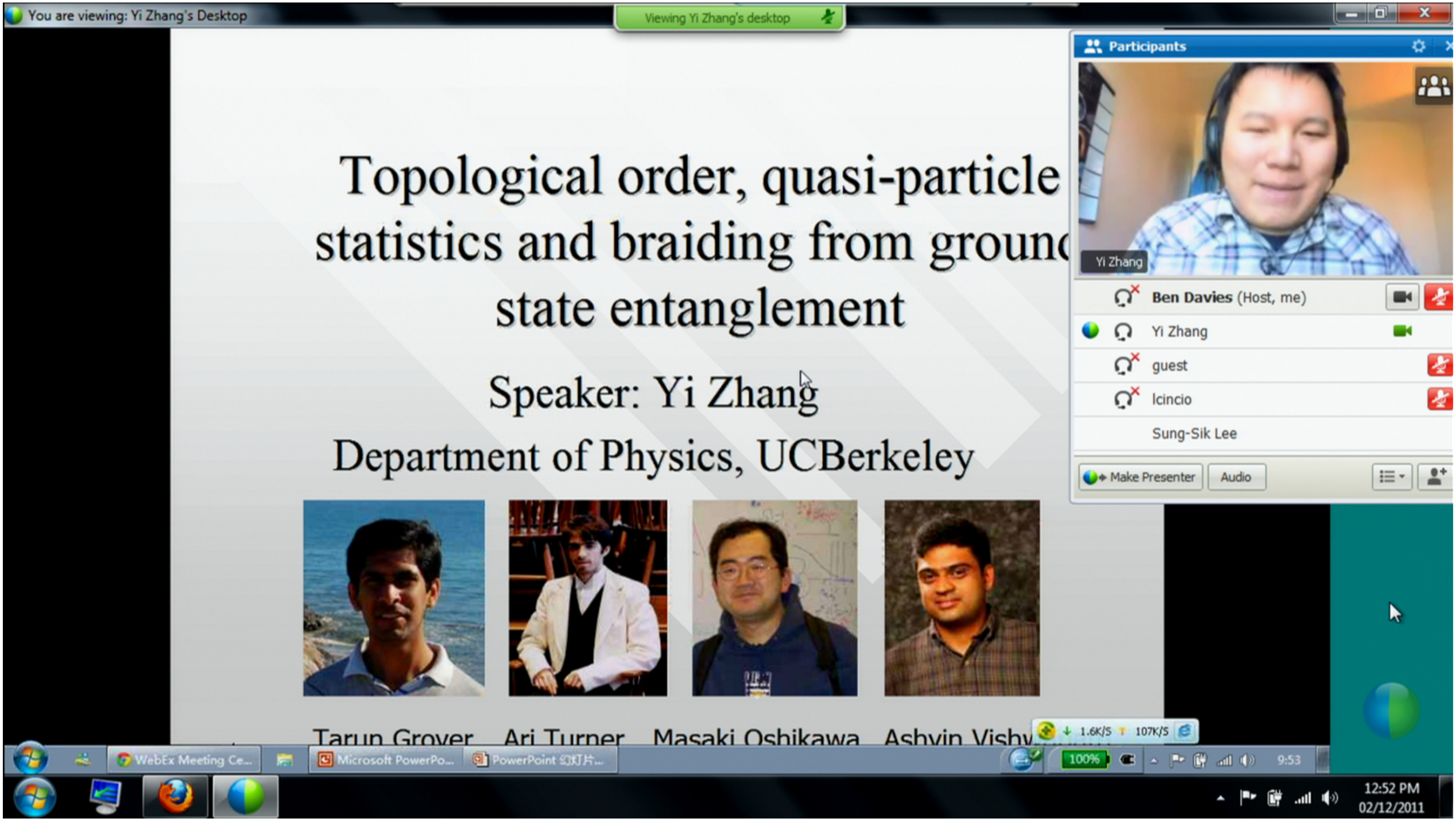
Abstract: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Topological order, quasi-particle statistics and braiding from ground state entanglement
Speaker: Yi Zhang
Department of Physics, UCBerkeley
Tarun Grover
Ari Turner
Masaki Oshikawa
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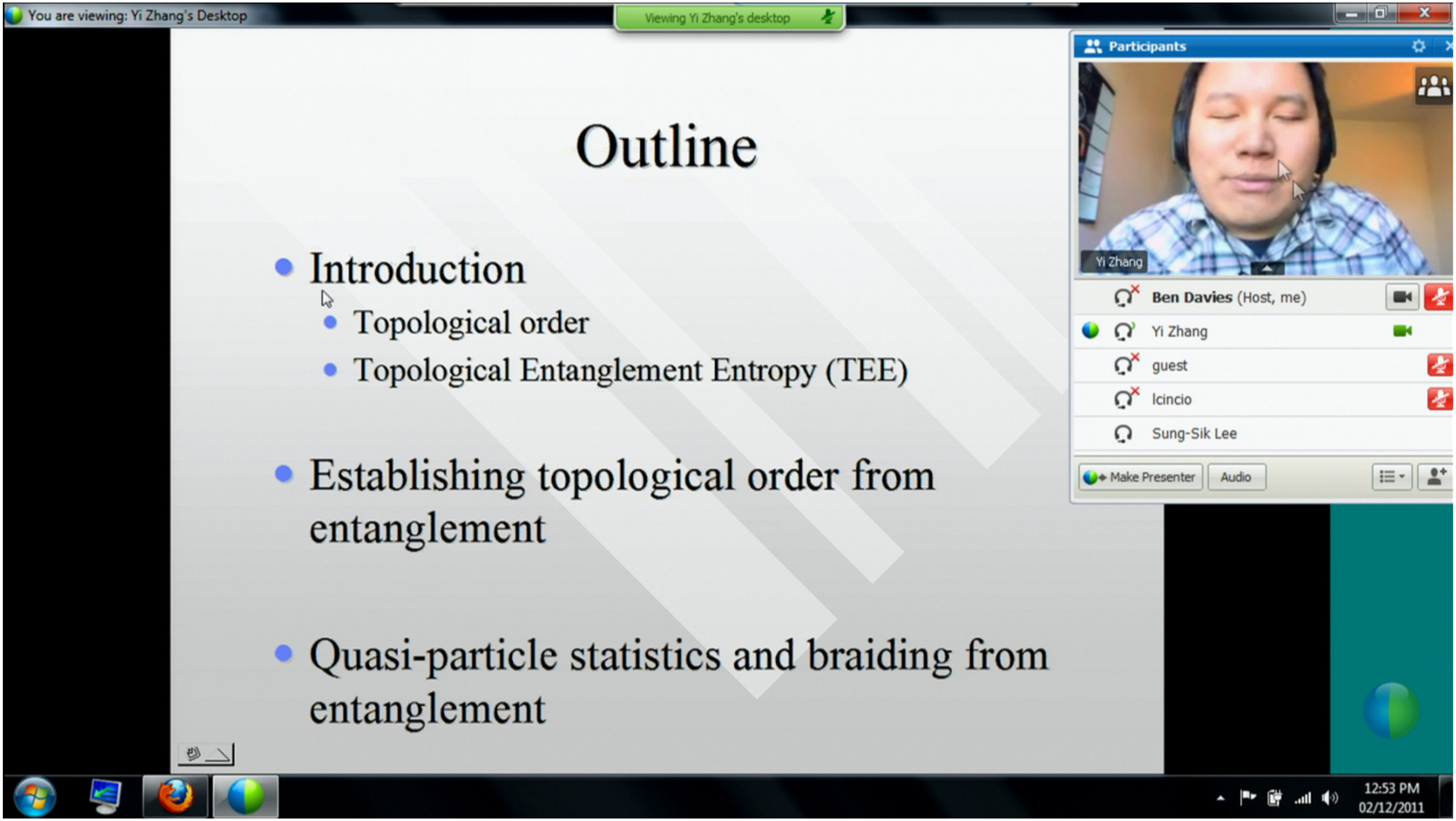
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Outline
Introduction
Topological order
Topological Entanglement Entropy (TEE)
Establishing topological order from entanglement
Quasi-particle statistics and braiding from entanglement
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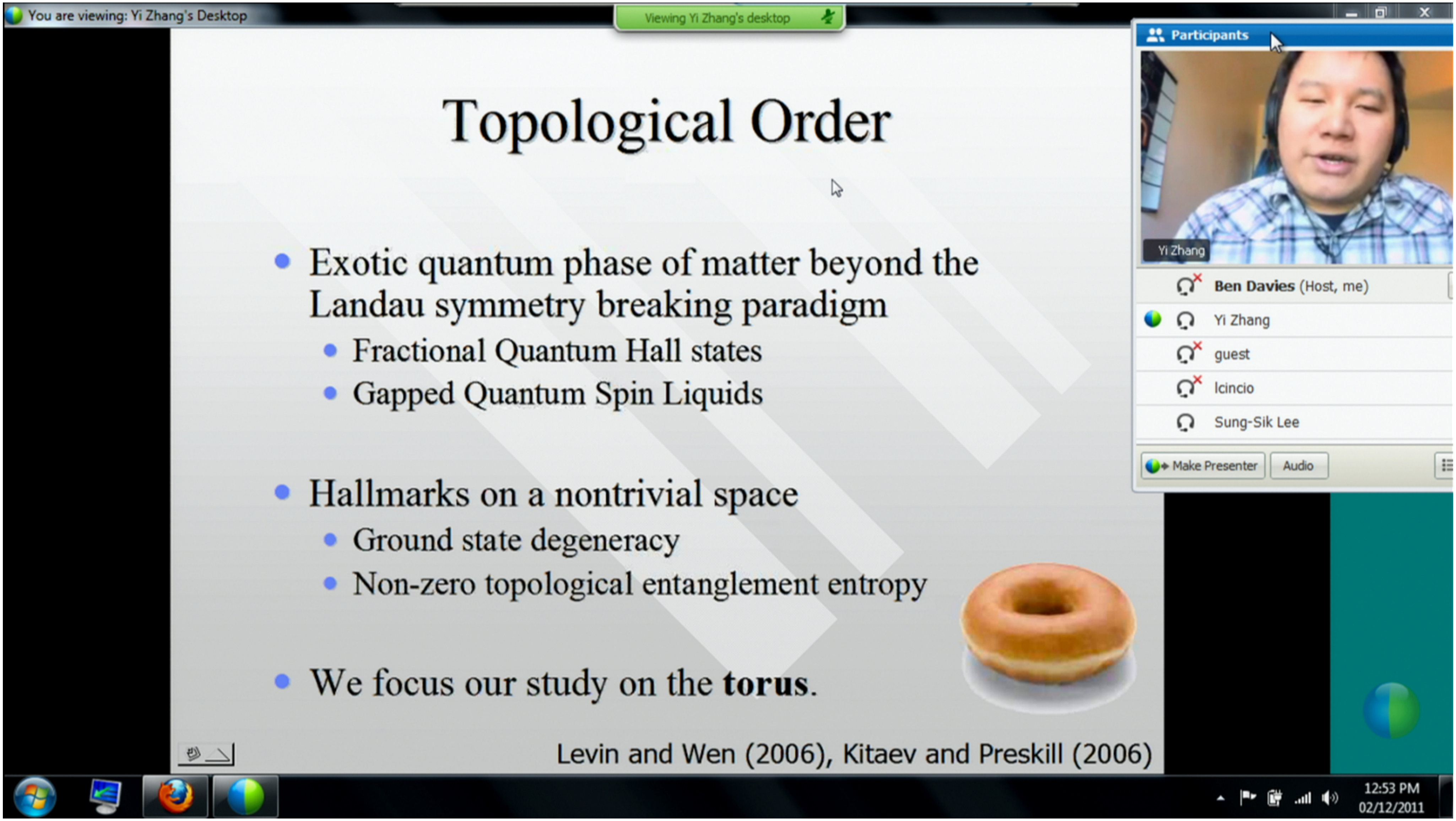
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Topological Order
Exotic quantum phase of matter beyond the Landau symmetry breaking paradigm
Fractional Quantum Hall states
Gapped Quantum Spin Liquids
Hallmarks on a nontrivial space
Ground state degeneracy
Non-zero topological entanglement entropy
We focus our study on the **torus**.
Levin and Wen (2006), Kitaev and Preskill (2006)
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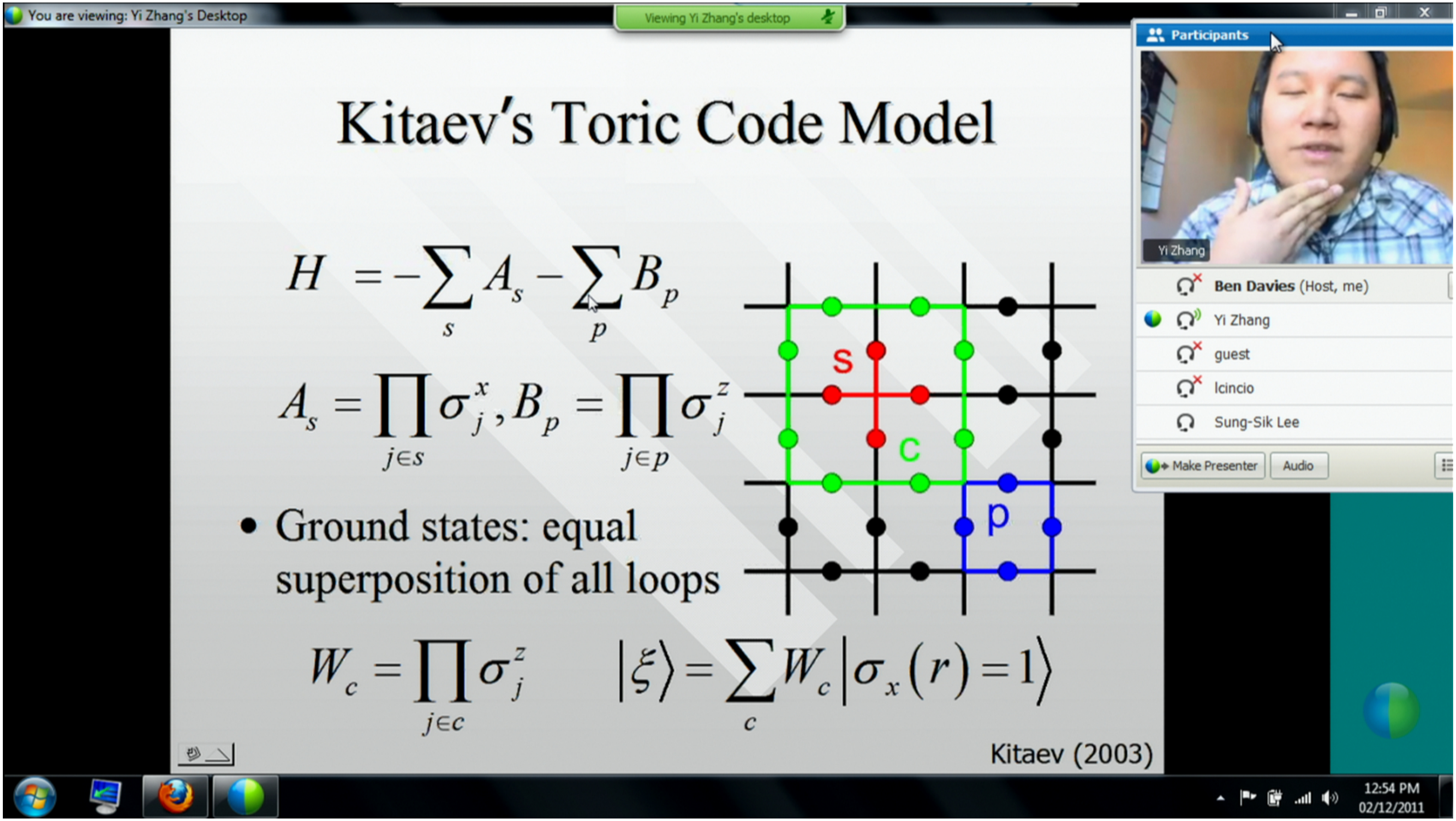
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Kitaev's Toric Code Model
$H = -\sum_s A_s - \sum_p B_p$
$A_s = \prod_{j\in s} \sigma_j^x, B_p = \prod_{j\in p} \sigma_j^z$
s
c
p
• Ground states: equal superposition of all loops
$W_c = \prod_{j\in c} \sigma_j^z$
$|\xi\rangle = \sum_c W_c |\sigma_x(r) = 1\rangle$
Kitaev (2003)
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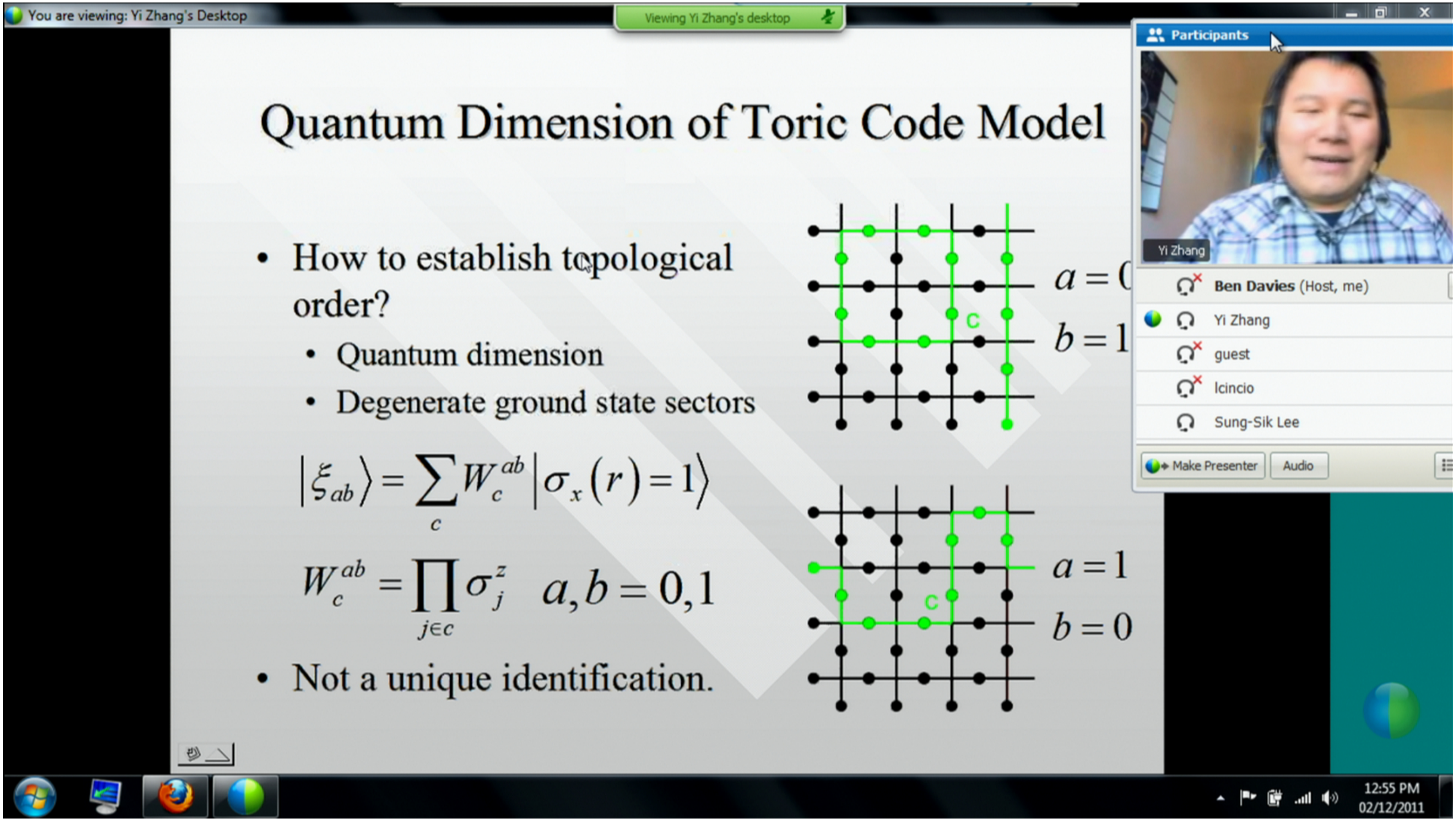

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Quantum Dimension of Toric Code Model
• How to establish topological order?
• Quantum dimension
• Degenerate ground state sectors
$|\xi_{ab}\rangle = \sum_c W_c^{ab} |\sigma_x(r)=1\rangle$
$W_c^{ab} = \prod_{j \in c} \sigma_j^z \quad a,b=0,1$
• Not a unique identification.
c
$a=0$
$b=1$
c
$a=1$
$b=0$
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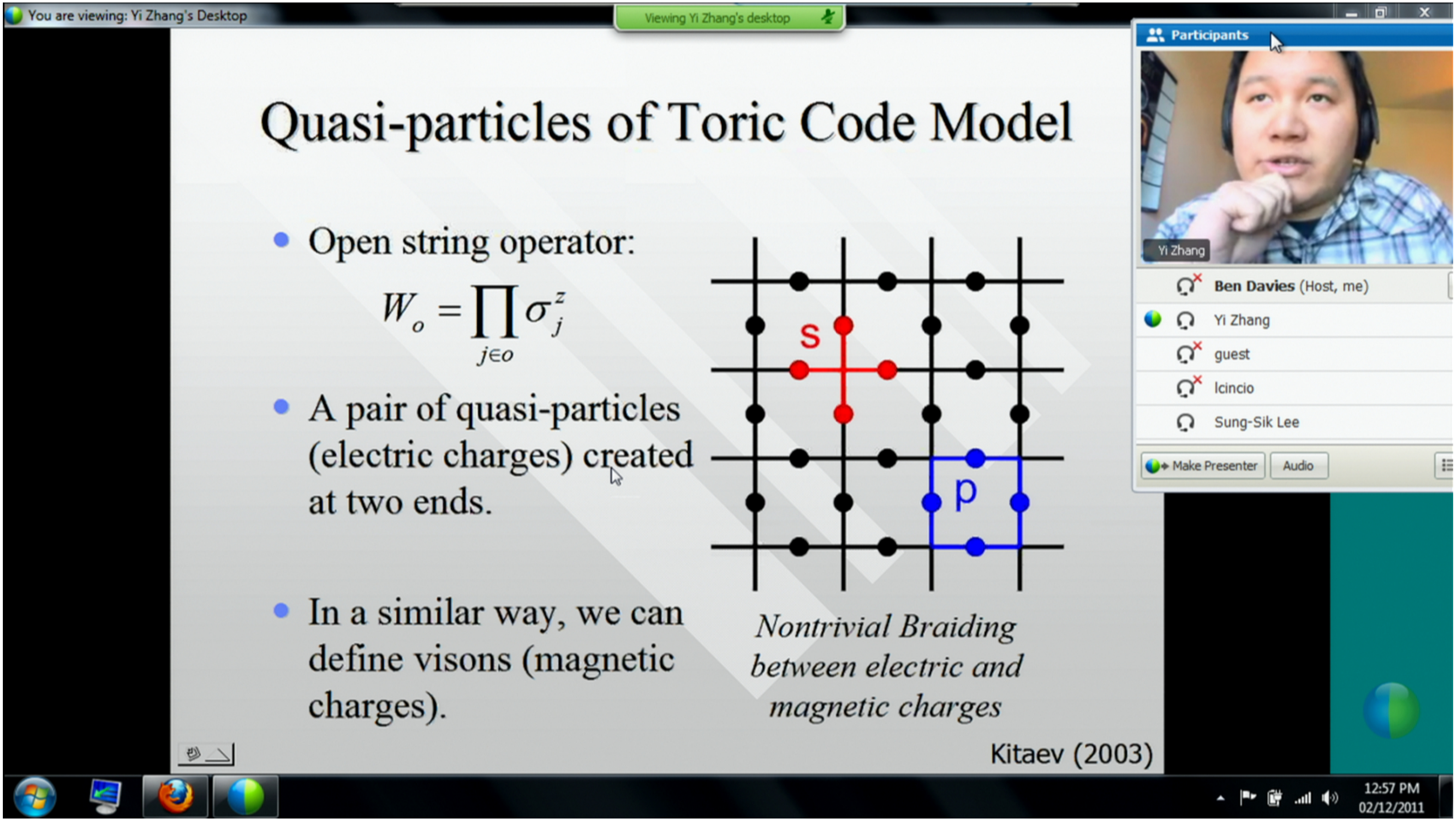
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Quasi-particles of Toric Code Model
Open string operator:
$W_o = \prod_{j \in o} \sigma_j^z$
A pair of quasi-particles (electric charges) created at two ends.
In a similar way, we can define visons (magnetic charges).
s
p
Nontrivial Braiding between electric and magnetic charges
Kitaev (2003)
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Modular Matrices of Toric Code Model

- More definitive information on the topological order:
- **Modular S matrix**:
  - phase when one quasi-particle encircles another one
- **Modular U matrix**:
  - phase when one quasi-particle exchanges with an identical one

$$\mathcal{S} = \frac{1}{2}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix}$$

$$\mathcal{U} = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -1 \end{pmatrix} \begin{matrix} \leftarrow 1 \\ \leftarrow m \\ \leftarrow e \\ \leftarrow em \end{matrix}$$

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Modular Matrices of Toric Code Model

- More definitive information on the topological order:
- **Modular S matrix**:
  - phase when one quasi-particle encircles another one

$$\mathcal{S} = \frac{1}{2}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix}$$

- **Modular U matrix**:
  - phase when one quasi-particle exchanges with an identical one

$$\mathcal{U} = \begin{pmatrix} 1 & & & \\ & 1 & & \\ & & 1 & \\ & & & -1 \end{pmatrix} \begin{matrix} \leftarrow 1 \\ \leftarrow m \\ \leftarrow e \\ \leftarrow em \end{matrix}$$

Modular Matrices of Toric Code Model

- More definitive information on the topological order:
- **Modular S matrix**:
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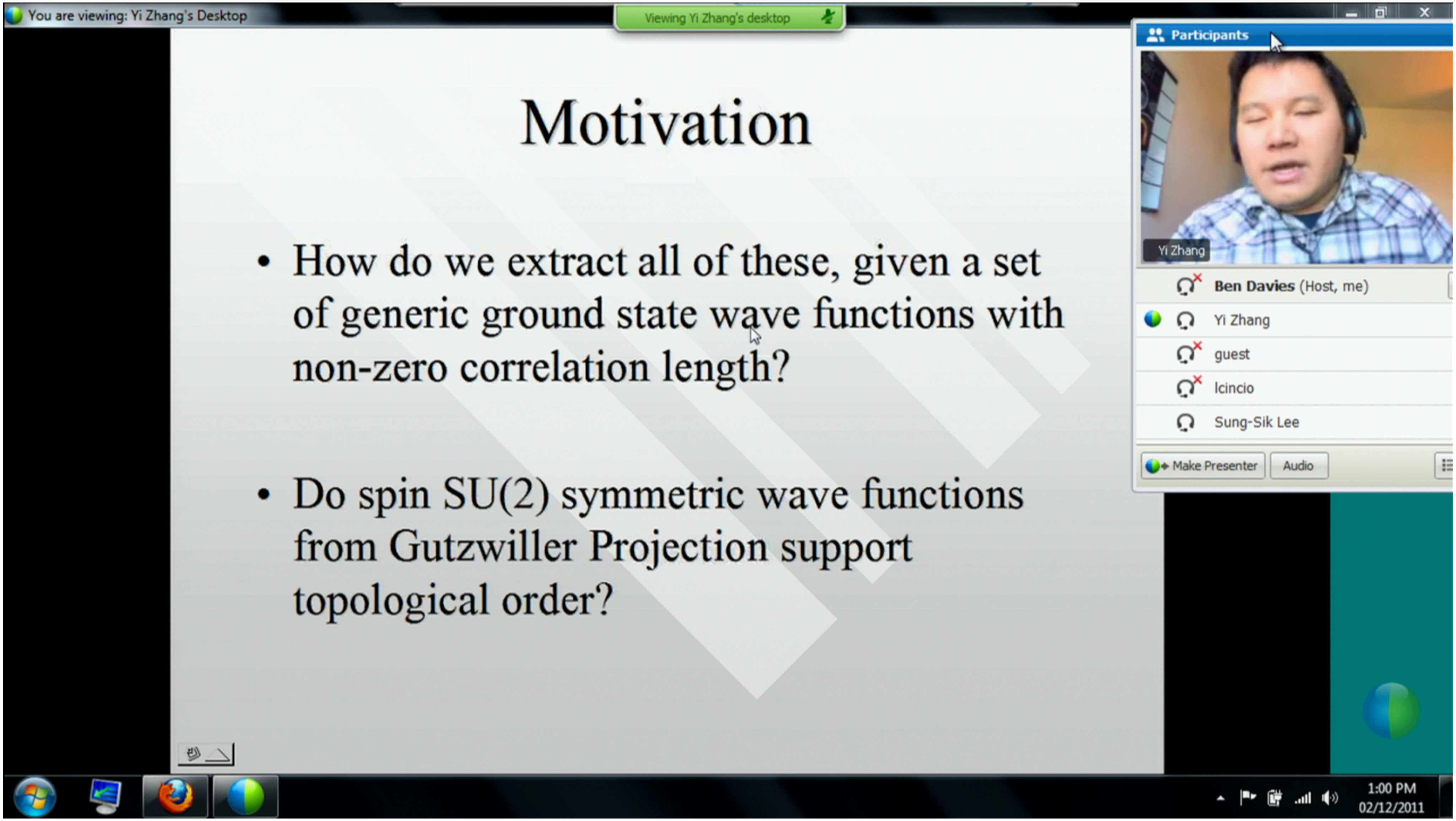
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Motivation
• How do we extract all of these, given a set of generic ground state wave functions with non-zero correlation length?
• Do spin SU(2) symmetric wave functions from Gutzwiller Projection support topological order?
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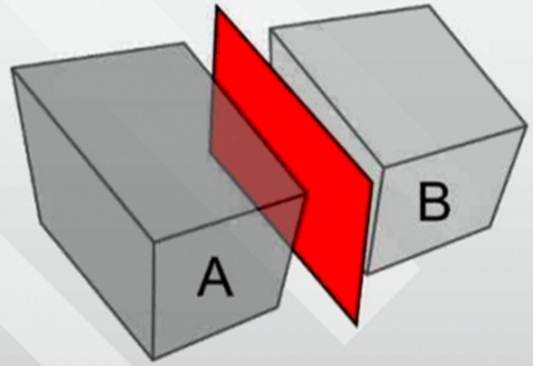
Renyi Entanglement Entropy

- Given a partition of the system into subsystems A and B, trace out B for the reduced density matrix on A: $$\rho_A = Tr_B |\Phi\rangle\langle\Phi|$$



- Renyi Entropy: $$S_n = \frac{1}{1-n}\log\left(Tr\rho_A^n\right)$$
- We focus on index **n = 2**: $$S_2 = -\log\left(Tr\rho_A^2\right)$$

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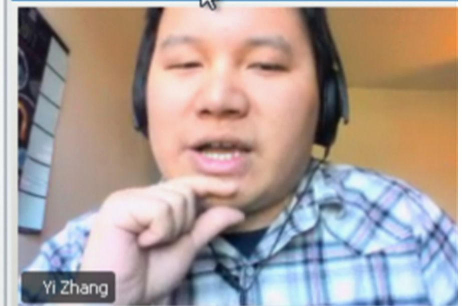

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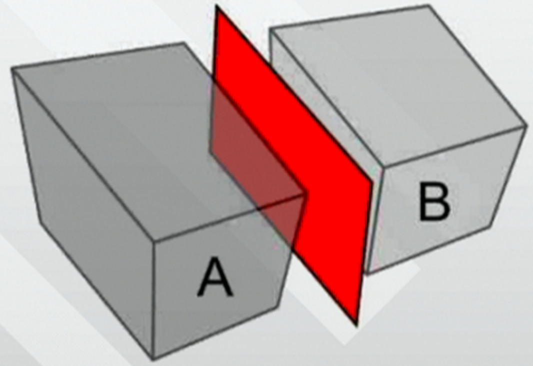
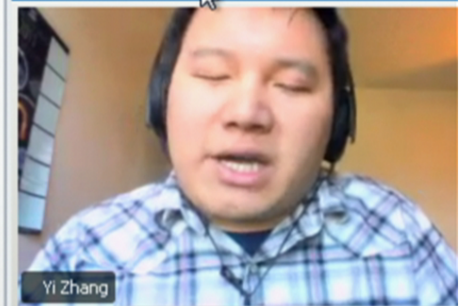
Renyi Entanglement Entropy

- Given a partition of the system into subsystems A and B, trace out B for the reduced density matrix on A: $\rho_A = Tr_B |\Phi\rangle\langle\Phi|$



- Renyi Entropy: $S_n = \frac{1}{1-n}\log\left(Tr\,\rho_A^n\right)$
- We focus on index **n = 2**: $S_2 = -\log\left(Tr\,\rho_A^2\right)$



Topological Entanglement Entropy

- For 2D gapped topological order with
  - contractible region A **(disc geometry)**
  - smooth boundary of length l_A
- Area Law :

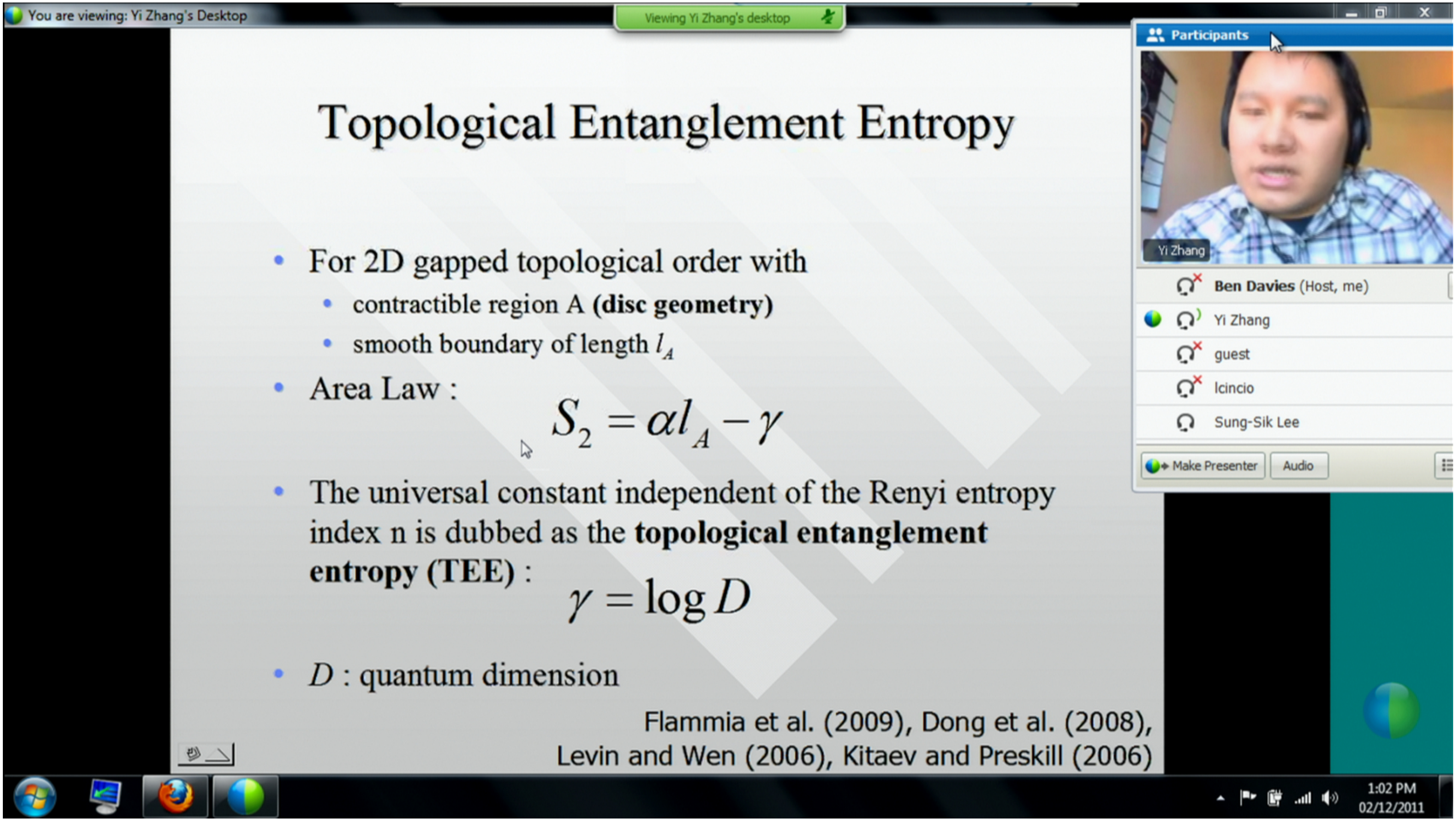
$$S_2 = \alpha l_A - \gamma$$

- The universal constant independent of the Renyi entropy index n is dubbed as the **topological entanglement entropy (TEE)** :

$$\gamma = \log D$$

- D : quantum dimension

Flammia et al. (2009), Dong et al. (2008), Levin and Wen (2006), Kitaev and Preskill (2006)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Topological Entanglement Entropy
For 2D gapped topological order with
contractible region A (disc geometry)
smooth boundary of length l_A
Area Law :
$S_2 = \alpha l_A - \gamma$
The universal constant independent of the Renyi entropy index n is dubbed as the topological entanglement entropy (TEE) :
$\gamma = \log D$
D : quantum dimension
Flammia et al. (2009), Dong et al. (2008),
Levin and Wen (2006), Kitaev and Preskill (2006)
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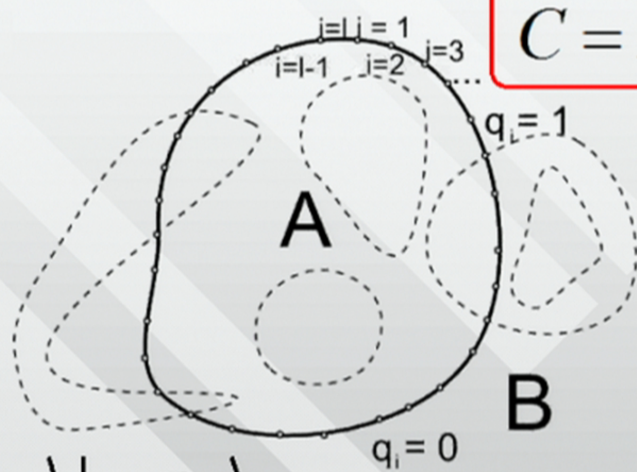
Area Law of Toric Code Model

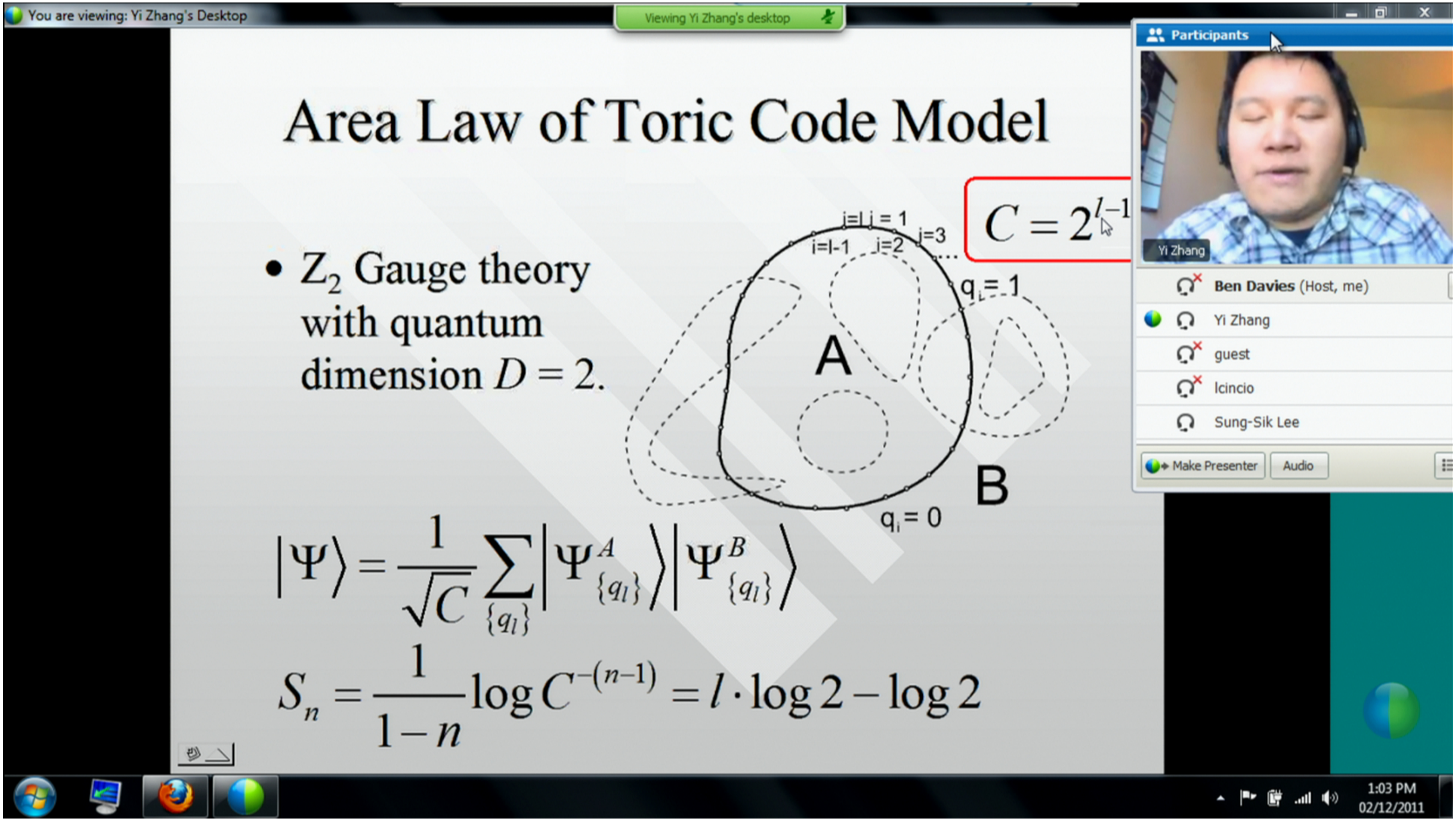
- Z_2 Gauge theory with quantum dimension $D = 2$.

$$C = 2^{l-1}$$



$$|\Psi\rangle = \frac{1}{\sqrt{C}} \sum_{\{q_l\}} \left|\Psi^A_{\{q_l\}}\right\rangle \left|\Psi^B_{\{q_l\}}\right\rangle$$

$$S_n = \frac{1}{1-n} \log C^{-(n-1)} = l \cdot \log 2 - \log 2$$



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Area Law of Toric Code Model
• Z_2 Gauge theory with quantum dimension $D = 2$.
$C = 2^{l-1}$
i=l i = 1
i=l-1 i=2 i=3
$q_i = 1$
A
B
$q_i = 0$
$|\Psi\rangle = \frac{1}{\sqrt{C}} \sum_{\{q_l\}} |\Psi^A_{\{q_l\}}\rangle |\Psi^B_{\{q_l\}}\rangle$
$S_n = \frac{1}{1-n} \log C^{-(n-1)} = l \cdot \log 2 - \log 2$
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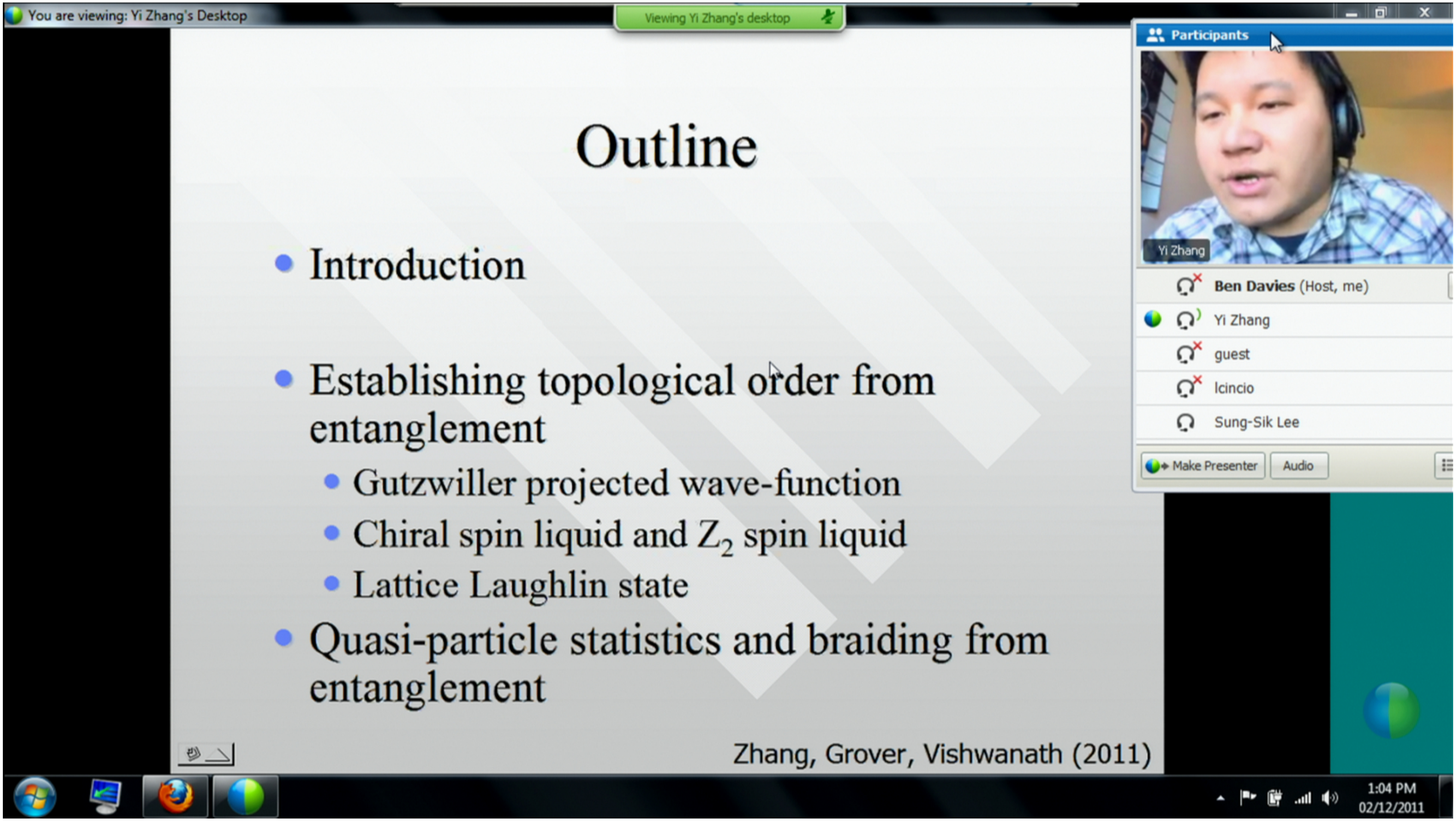
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Outline
Introduction
Establishing topological order from entanglement
Gutzwiller projected wave-function
Chiral spin liquid and Z_2 spin liquid
Lattice Laughlin state
Quasi-particle statistics and braiding from entanglement
Zhang, Grover, Vishwanath (2011)
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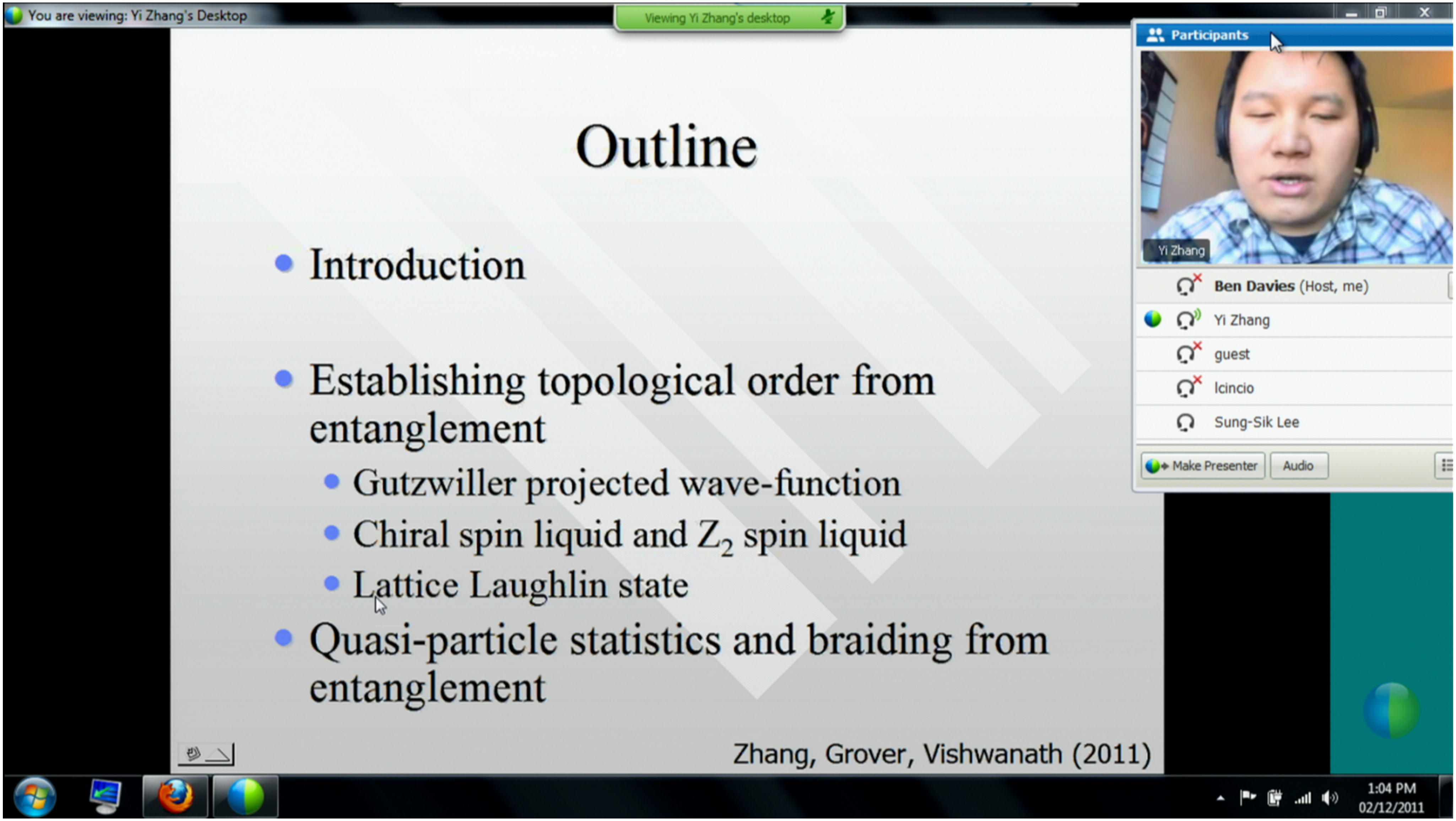
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Outline
Introduction
Establishing topological order from entanglement
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Chiral spin liquid and Z2 spin liquid
Lattice Laughlin state
Quasi-particle statistics and braiding from entanglement
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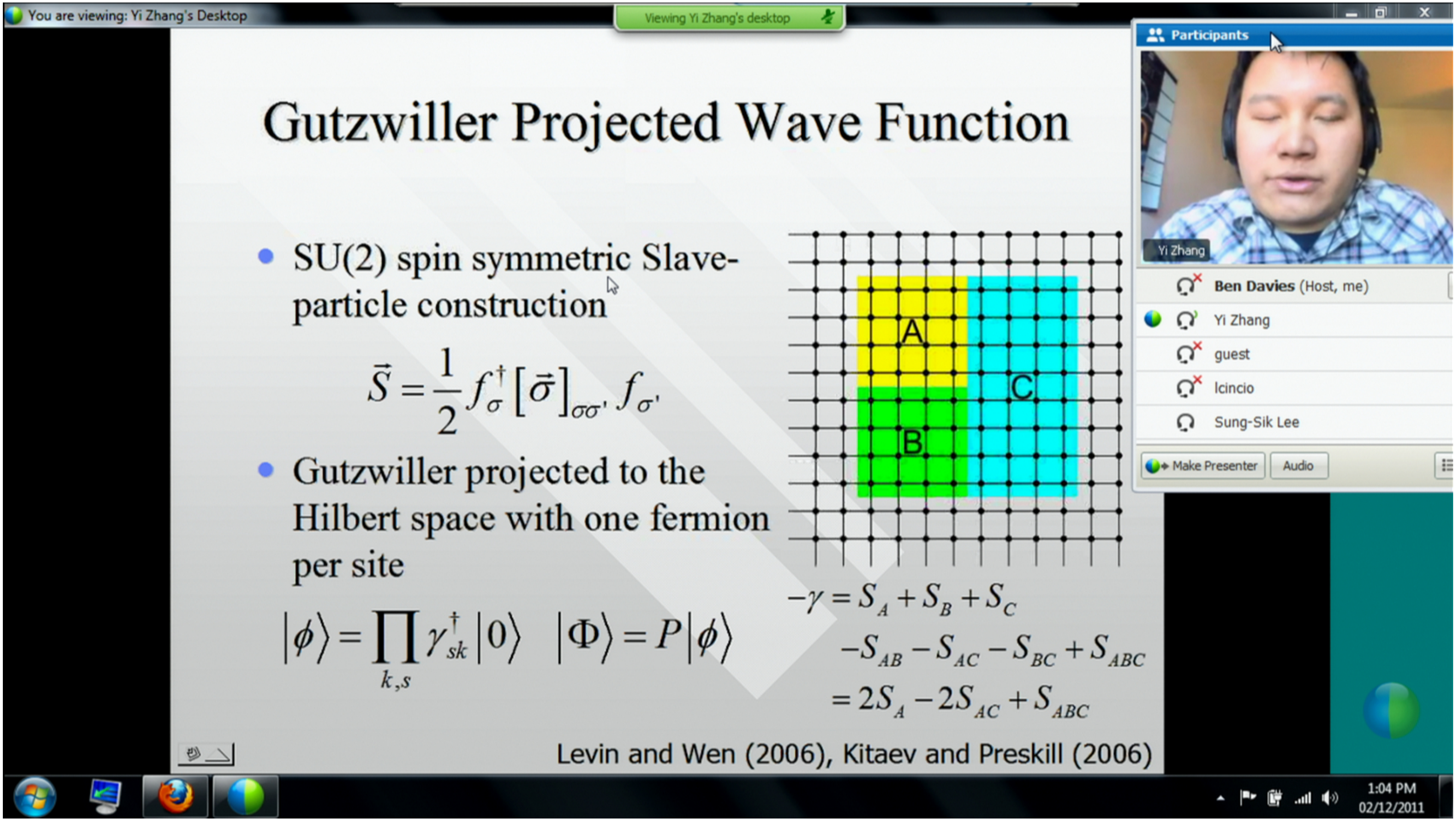
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Gutzwiller Projected Wave Function
SU(2) spin symmetric Slave-particle construction
$\vec{S} = \frac{1}{2} f_\sigma^\dagger [\vec{\sigma}]_{\sigma\sigma'} f_{\sigma'}$
Gutzwiller projected to the Hilbert space with one fermion per site
$|\phi\rangle = \prod_{k,s} \gamma_{sk}^\dagger |0\rangle \quad |\Phi\rangle = P|\phi\rangle$
A
B
C
$-\gamma = S_A + S_B + S_C - S_{AB} - S_{AC} - S_{BC} + S_{ABC} = 2S_A - 2S_{AC} + S_{ABC}$
Levin and Wen (2006), Kitaev and Preskill (2006)
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Gutzwiller Projected Wave Function

- SU(2) spin symmetric Slave-particle construction

$$\vec{S} = \frac{1}{2} f_{\sigma}^{\dagger} [\vec{\sigma}]_{\sigma\sigma'} f_{\sigma'}$$

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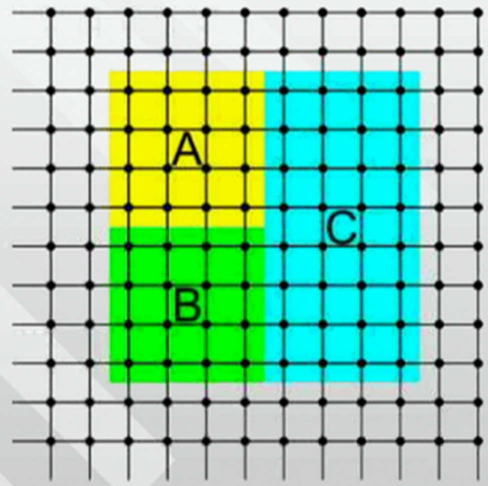

$$-\gamma = S_A + S_B + S_C - S_{AB} - S_{AC} - S_{BC} + S_{ABC} = 2S_A - 2S_{AC} + S_{ABC}$$

Levin and Wen (2006), Kitaev and Preskill (2006)

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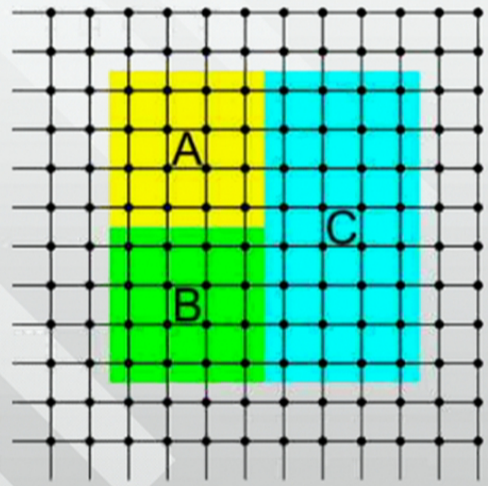
Gutzwiller Projected Wave Function

- SU(2) spin symmetric Slave-particle construction

$$\vec{S} = \frac{1}{2} f_{\sigma}^{\dagger} [\vec{\sigma}]_{\sigma\sigma'} f_{\sigma'}$$

- Gutzwiller projected to the Hilbert space with one fermion per site

$$|\phi\rangle = \prod_{k,s} \gamma_{sk}^{\dagger} |0\rangle \quad |\Phi\rangle = P|\phi\rangle$$



$$-\gamma = S_A + S_B + S_C - S_{AB} - S_{AC} - S_{BC} + S_{ABC} = 2S_A - 2S_{AC} + S_{ABC}$$

Levin and Wen (2006), Kitaev and Preskill (2006)

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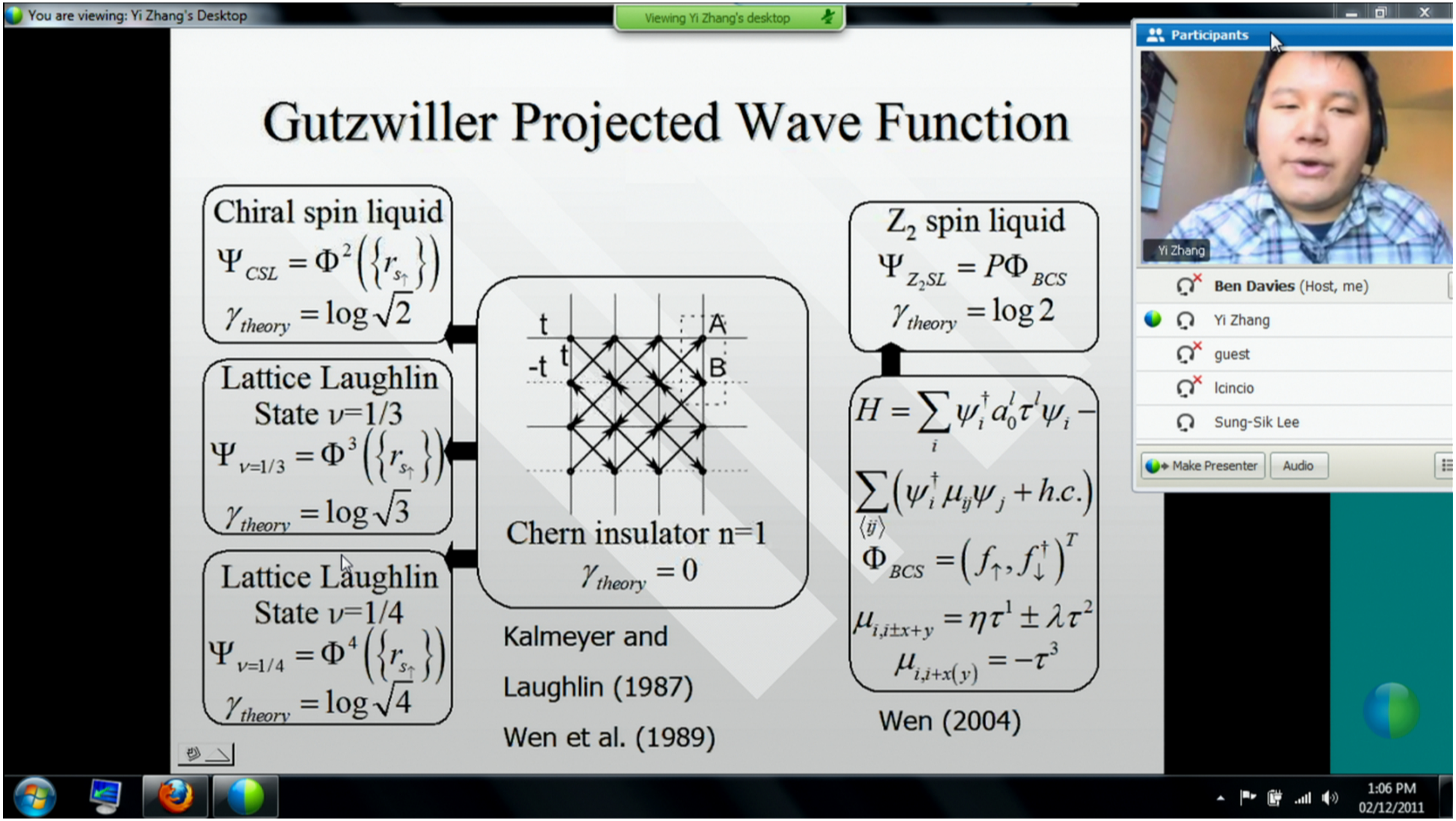
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Gutzwiller Projected Wave Function
Chiral spin liquid
$\Psi_{CSL} = \Phi^2\left(\left\{r_{s_\uparrow}\right\}\right)$
$\gamma_{theory} = \log\sqrt{2}$
Lattice Laughlin State ν=1/3
$\Psi_{\nu=1/3} = \Phi^3\left(\left\{r_{s_\uparrow}\right\}\right)$
$\gamma_{theory} = \log\sqrt{3}$
Lattice Laughlin State ν=1/4
$\Psi_{\nu=1/4} = \Phi^4\left(\left\{r_{s_\uparrow}\right\}\right)$
$\gamma_{theory} = \log\sqrt{4}$
t
-t
t
A
B
Chern insulator n=1
$\gamma_{theory} = 0$
Kalmeyer and Laughlin (1987)
Wen et al. (1989)
Z_2 spin liquid
$\Psi_{Z_2SL} = P\Phi_{BCS}$
$\gamma_{theory} = \log 2$
$H = \sum_i \psi_i^\dagger a_0^l \tau^l \psi_i -$
$\sum_{\langle ij \rangle}\left(\psi_i^\dagger \mu_{ij} \psi_j + h.c.\right)$
$\Phi_{BCS} = \left(f_\uparrow, f_\downarrow^\dagger\right)^T$
$\mu_{i,i\pm x+y} = \eta\tau^1 \pm \lambda\tau^2$
$\mu_{i,i+x(y)} = -\tau^3$
Wen (2004)
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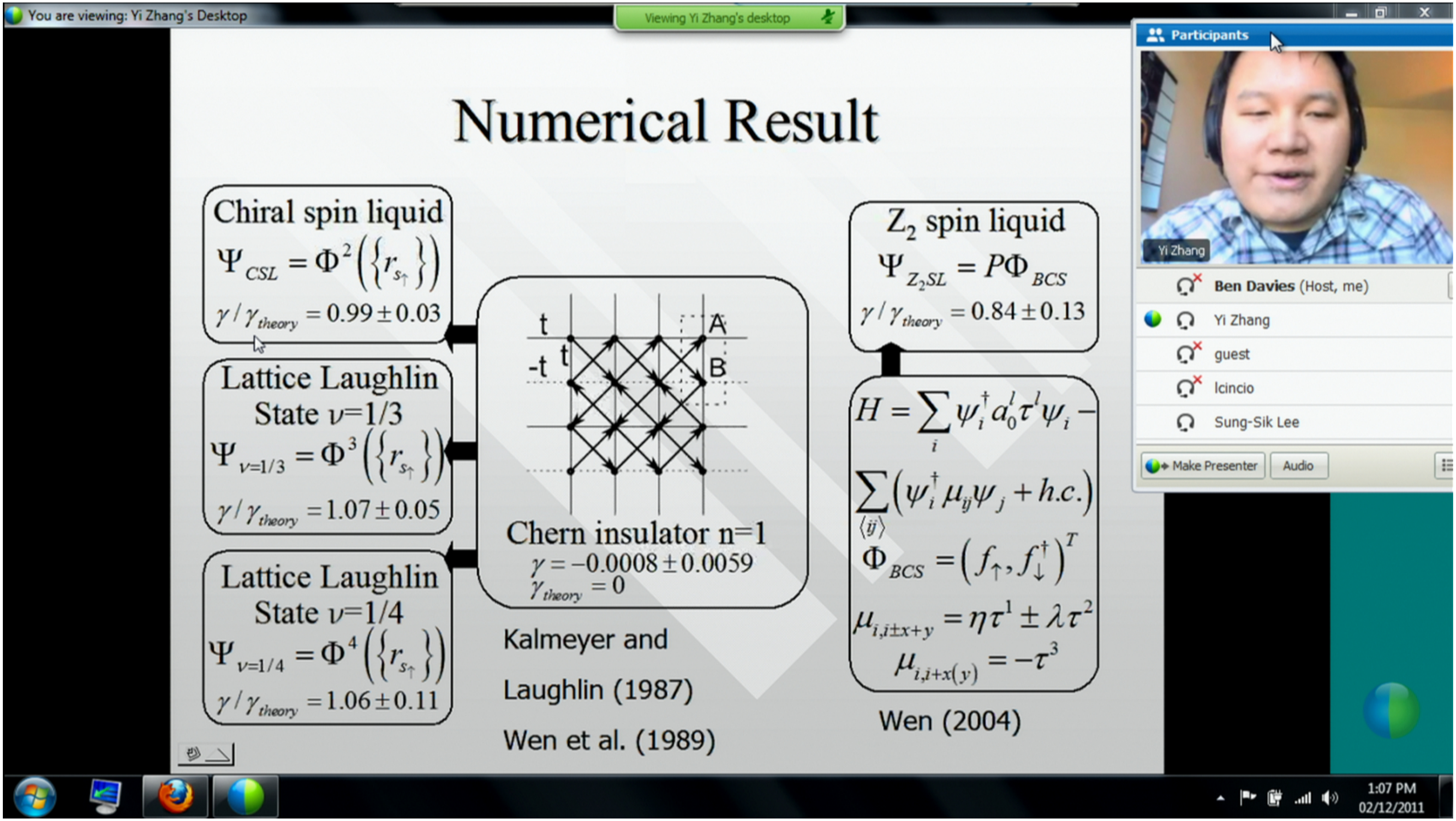
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Numerical Result
Chiral spin liquid
$\Psi_{CSL} = \Phi^2\left(\left\{r_{s_\uparrow}\right\}\right)$
$\gamma/\gamma_{theory} = 0.99 \pm 0.03$
Lattice Laughlin State ν=1/3
$\Psi_{\nu=1/3} = \Phi^3\left(\left\{r_{s_\uparrow}\right\}\right)$
$\gamma/\gamma_{theory} = 1.07 \pm 0.05$
Lattice Laughlin State ν=1/4
$\Psi_{\nu=1/4} = \Phi^4\left(\left\{r_{s_\uparrow}\right\}\right)$
$\gamma/\gamma_{theory} = 1.06 \pm 0.11$
t
-t
t
A
B
Chern insulator n=1
$\gamma = -0.0008 \pm 0.0059$
$\gamma_{theory} = 0$
Kalmeyer and Laughlin (1987)
Wen et al. (1989)
Z_2 spin liquid
$\Psi_{Z_2SL} = P\Phi_{BCS}$
$\gamma/\gamma_{theory} = 0.84 \pm 0.13$
$H = \sum_i \psi_i^\dagger a_0^l \tau^l \psi_i -$
$\sum_{\langle ij \rangle}\left(\psi_i^\dagger \mu_{ij} \psi_j + h.c.\right)$
$\Phi_{BCS} = \left(f_\uparrow, f_\downarrow^\dagger\right)^T$
$\mu_{i,i\pm x+y} = \eta\tau^1 \pm \lambda\tau^2$
$\mu_{i,i+x(y)} = -\tau^3$
Wen (2004)
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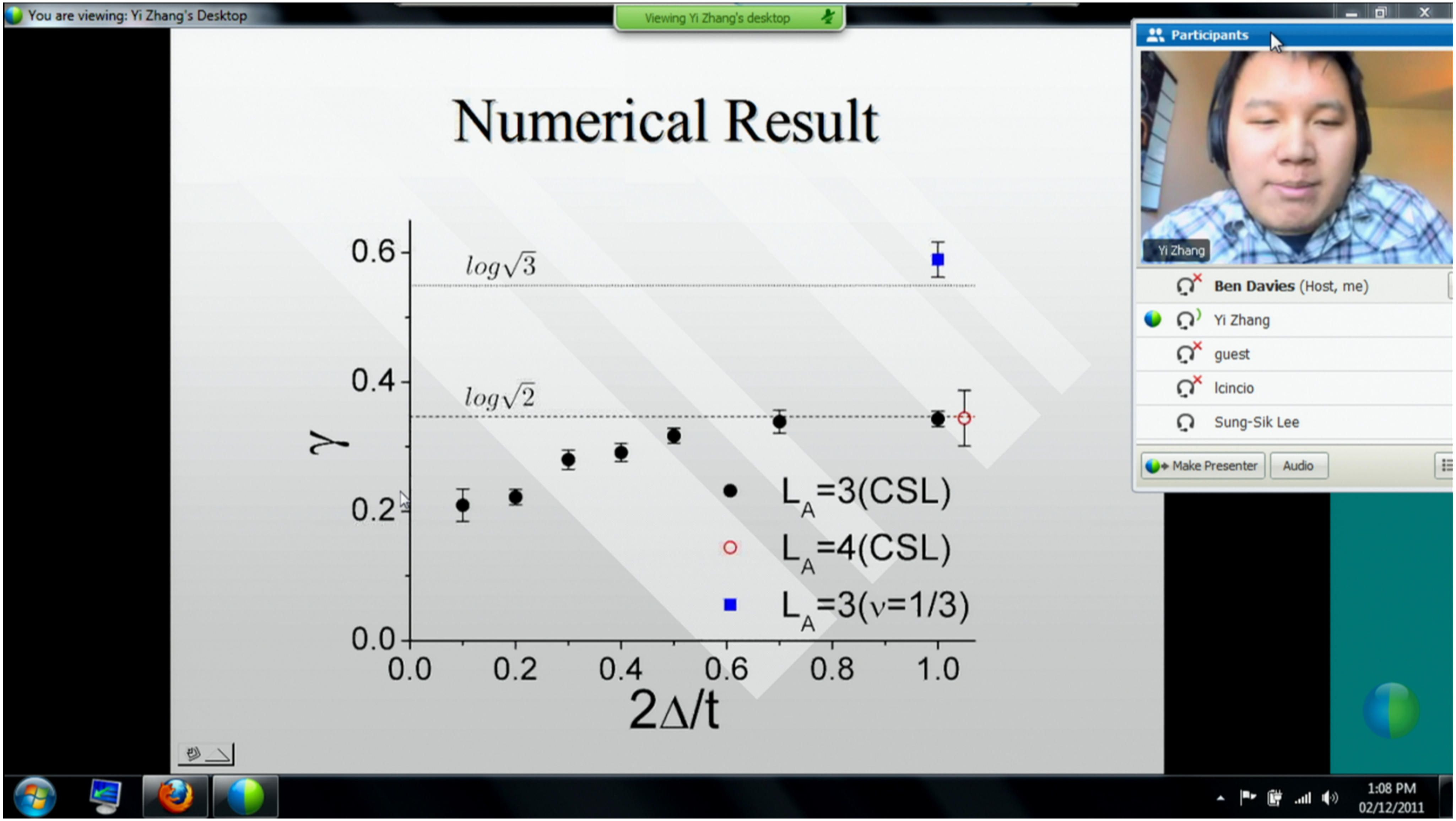
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Numerical Result
0.6
0.4
0.2
0.0
$log\sqrt{3}$
$log\sqrt{2}$
γ
L_A=3(CSL)
L_A=4(CSL)
L_A=3(ν=1/3)
0.0
0.2
0.4
0.6
0.8
1.0
2Δ/t
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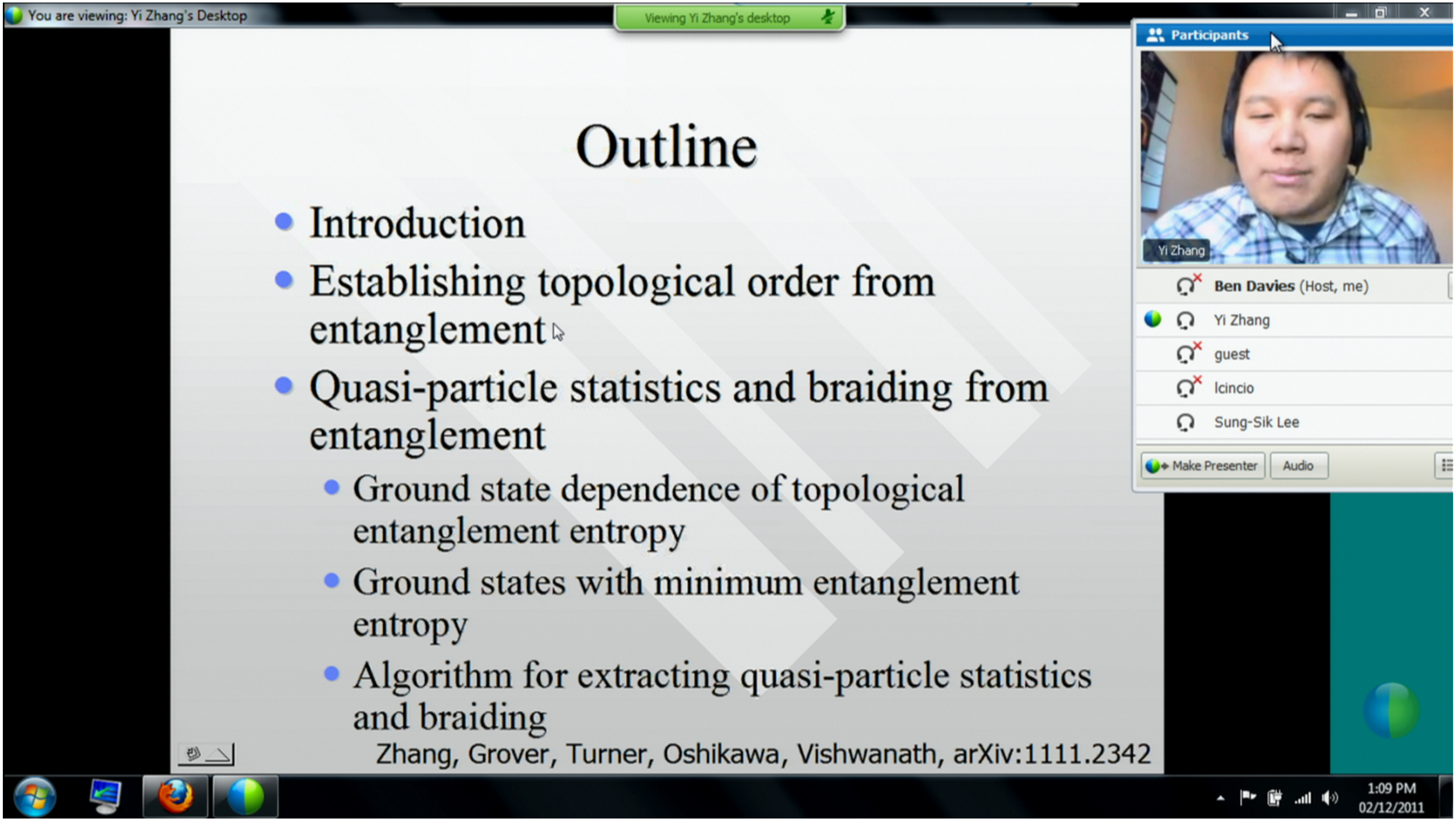
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Introduction
Establishing topological order from entanglement
Quasi-particle statistics and braiding from entanglement
Ground state dependence of topological entanglement entropy
Ground states with minimum entanglement entropy
Algorithm for extracting quasi-particle statistics and braiding
Zhang, Grover, Turner, Oshikawa, Vishwanath, arXiv:1111.2342
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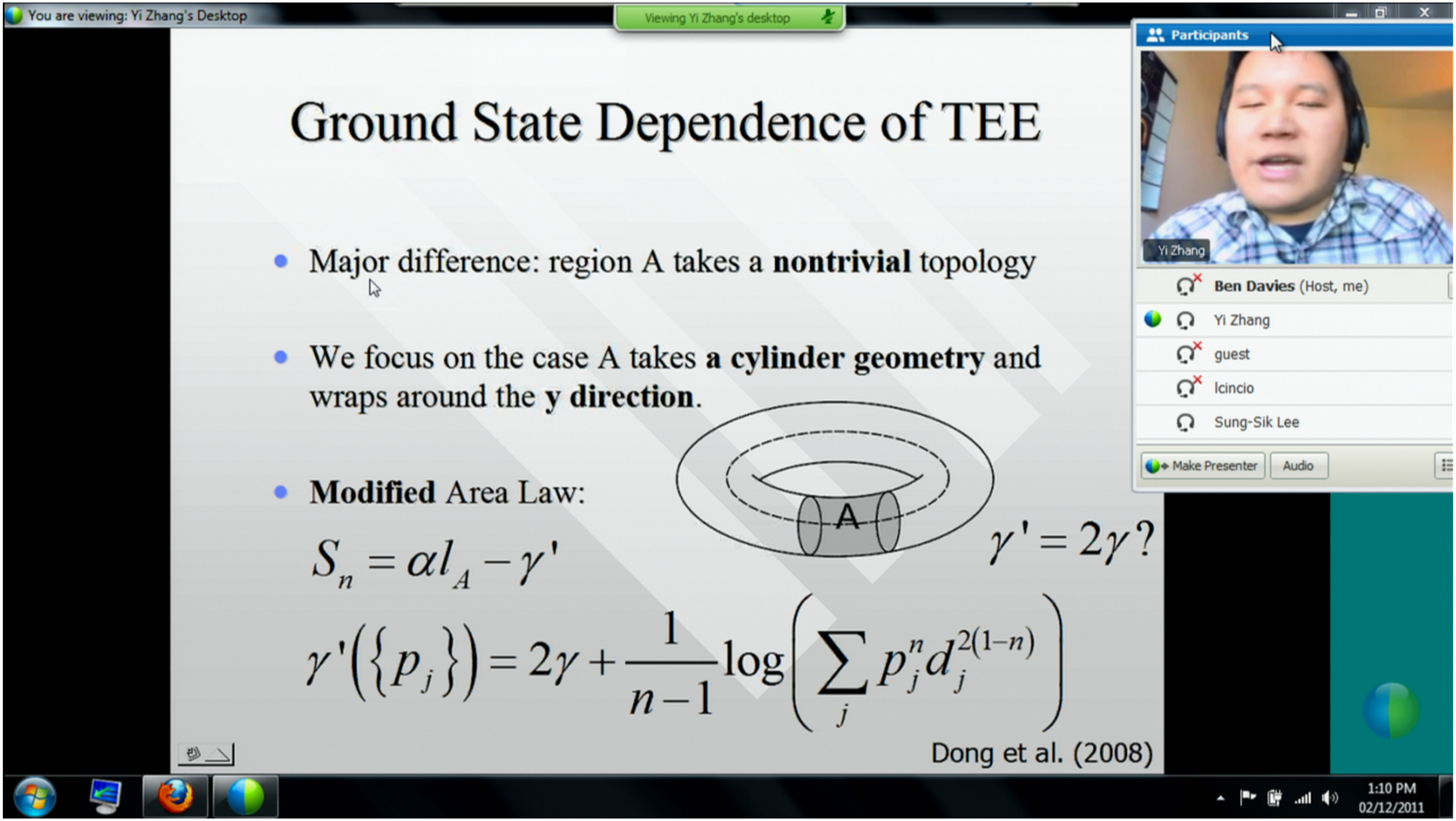
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Ground State Dependence of TEE
Major difference: region A takes a **nontrivial** topology
We focus on the case A takes **a cylinder geometry** and wraps around the **y direction**.
Modified Area Law:
A
$S_n = \alpha l_A - \gamma'$
$\gamma' = 2\gamma?$
$\gamma'(\{p_j\}) = 2\gamma + \frac{1}{n-1}\log\left(\sum_j p_j^n d_j^{2(1-n)}\right)$
Dong et al. (2008)
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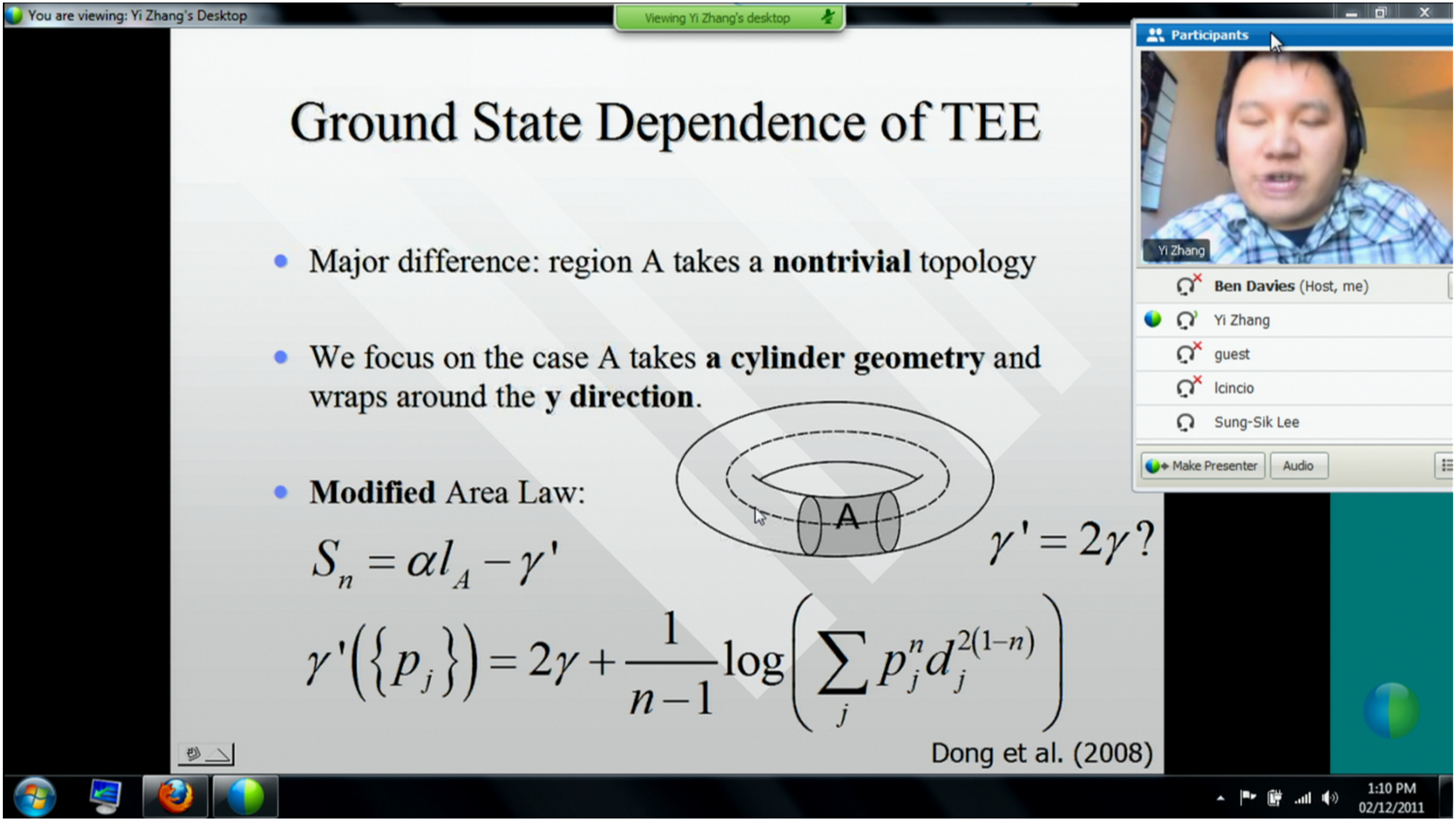

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Ground State Dependence of TEE
Major difference: region A takes a **nontrivial** topology
We focus on the case A takes **a cylinder geometry** and wraps around the **y direction**.
Modified Area Law:
A
$S_n = \alpha l_A - \gamma'$
$\gamma' = 2\gamma ?$
$\gamma'(\{p_j\}) = 2\gamma + \frac{1}{n-1}\log\left(\sum_j p_j^n d_j^{2(1-n)}\right)$
Dong et al. (2008)
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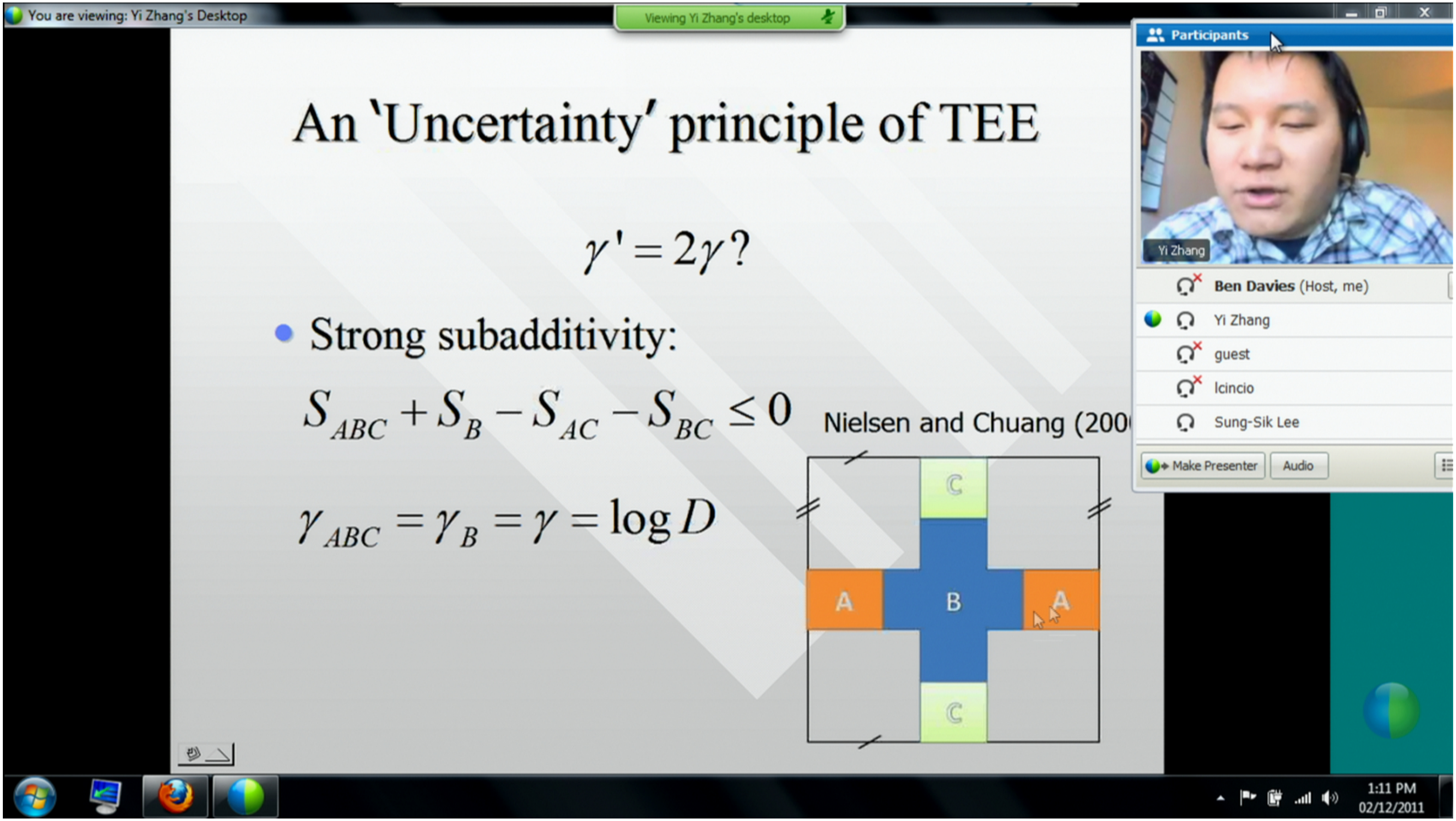
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An 'Uncertainty' principle of TEE
$\gamma' = 2\gamma$?
Strong subadditivity:
$S_{ABC} + S_B - S_{AC} - S_{BC} \leq 0$
$\gamma_{ABC} = \gamma_B = \gamma = \log D$
Nielsen and Chuang (200
C
A
B
A
C
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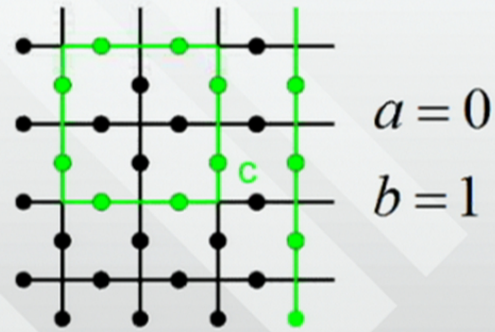
Area Law of Toric Code Model

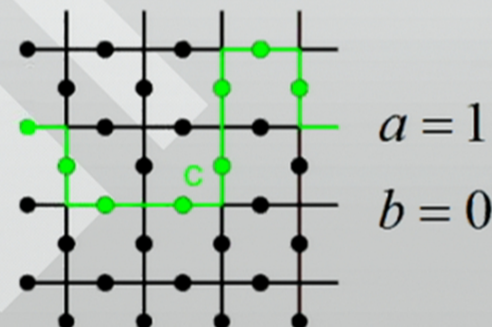
$$W_c^{ab} = \prod_{j \in c} \sigma_j^z$$

$$|\xi_{ab}\rangle = \sum_c W_c^{ab} |\sigma_x(r) = 1\rangle$$

$$|\Phi\rangle = \sum_{a,b=0,1} c_{ab} |\xi_{ab}\rangle$$

$$S_n = l \cdot \log 2 - \gamma'_n$$





Area Law of Toric Code Model

$$\gamma'_n = 2\log 2 + \frac{1}{n-1}\log\sum_{j=1}^{4} p_j^n$$

$$p_1 = \left|c_{00} + c_{01}\right|^2/2 \qquad \left|\Xi_1\right\rangle = \left(\left|\xi_{00}\right\rangle + \left|\xi_{01}\right\rangle\right)/\sqrt{2}$$

$$p_2 = \left|c_{00} - c_{01}\right|^2/2 \qquad \left|\Xi_2\right\rangle = \left(\left|\xi_{00}\right\rangle - \left|\xi_{01}\right\rangle\right)/\sqrt{2}$$

$$p_3 = \left|c_{10} + c_{11}\right|^2/2 \qquad \left|\Xi_3\right\rangle = \left(\left|\xi_{10}\right\rangle + \left|\xi_{11}\right\rangle\right)/\sqrt{2}$$

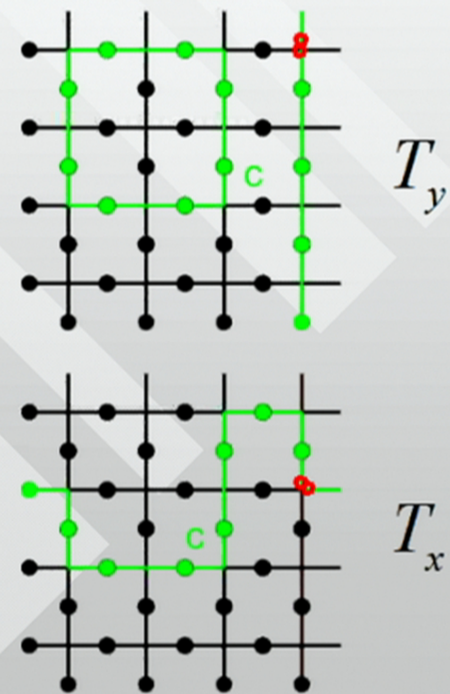
$$p_4 = \left|c_{10} - c_{11}\right|^2/2 \qquad \left|\Xi_4\right\rangle = \left(\left|\xi_{10}\right\rangle - \left|\xi_{11}\right\rangle\right)/\sqrt{2}$$

Minimum Entropy States

- To be a ground state, quasi-particles must be annihilated in pairs. But certain paths may change the parity of electric field.
- Electric field insertion operator:

$$T_x\left|\xi_{1b(0b)}\right\rangle = \left|\xi_{0b(1b)}\right\rangle$$

$$T_y\left|\xi_{a0(a1)}\right\rangle = \left|\xi_{a1(a0)}\right\rangle$$



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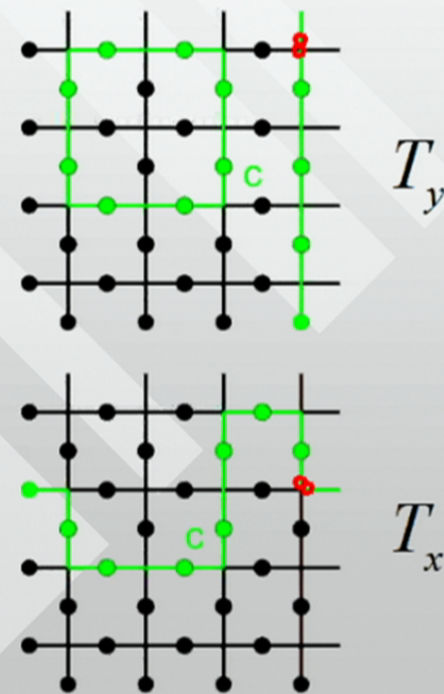

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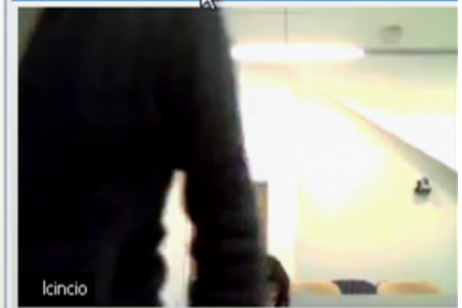

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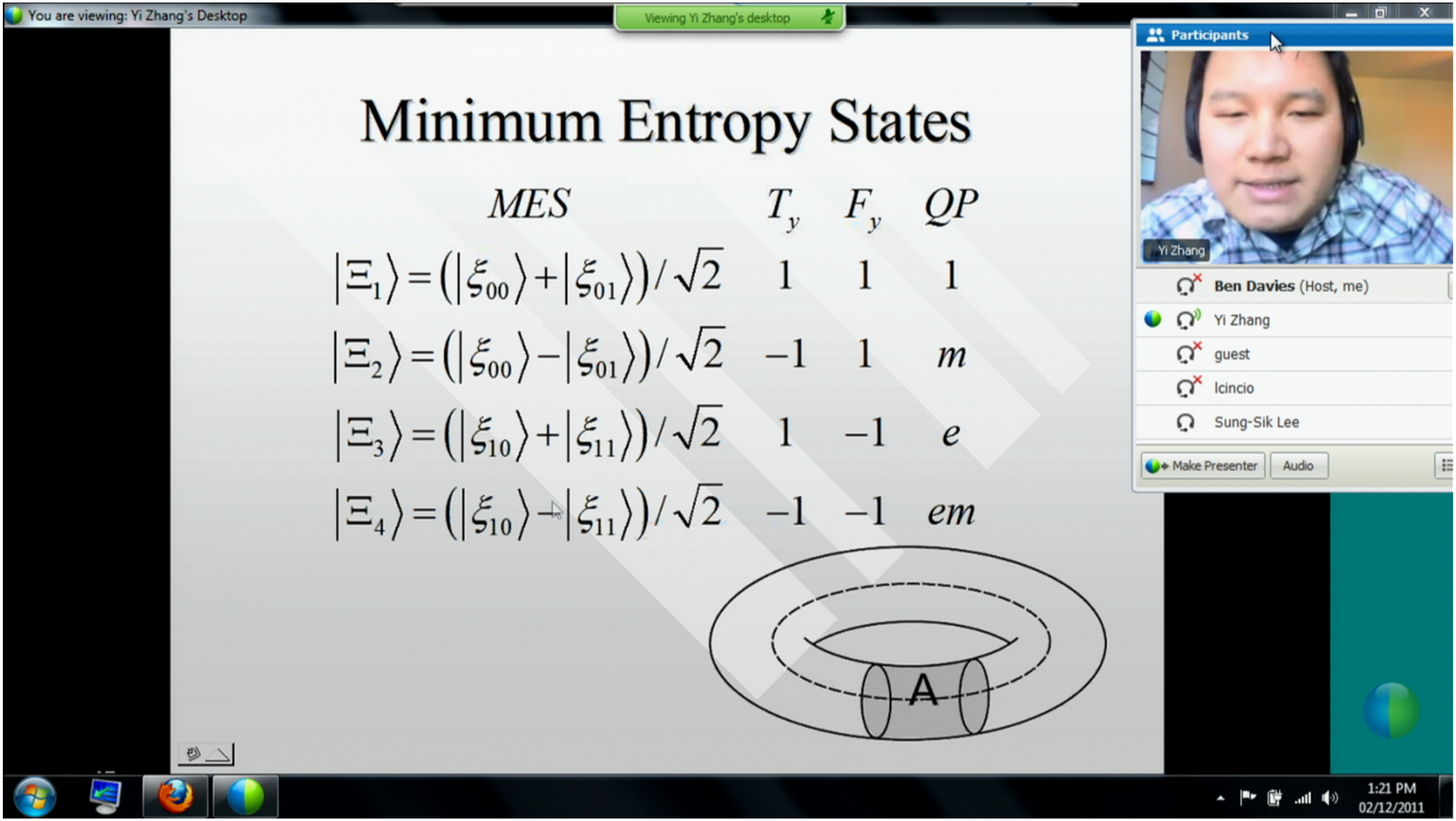
Minimum Entropy States

- Magnetic flux (vison loop) insertion operator:

$$T_x F_y = -F_y T_x \qquad F_y \left| \xi_{ab} \right\rangle = (-1)^a \left| \xi_{ab} \right\rangle$$

$$T_y F_x = -F_y T_x \qquad F_x \left| \xi_{ab} \right\rangle = (-1)^b \left| \xi_{ab} \right\rangle$$

- Note that T_y and F_y are the Wilson loop operators well-defined in region A. They are also the magnetic and electric flux measuring operators through the cylinder.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Minimum Entropy States
MES T_y F_y QP
$|\Xi_1\rangle = (|\xi_{00}\rangle + |\xi_{01}\rangle)/\sqrt{2}$ 1 1 1
$|\Xi_2\rangle = (|\xi_{00}\rangle - |\xi_{01}\rangle)/\sqrt{2}$ −1 1 m
$|\Xi_3\rangle = (|\xi_{10}\rangle + |\xi_{11}\rangle)/\sqrt{2}$ 1 −1 e
$|\Xi_4\rangle = (|\xi_{10}\rangle - |\xi_{11}\rangle)/\sqrt{2}$ −1 −1 em
A
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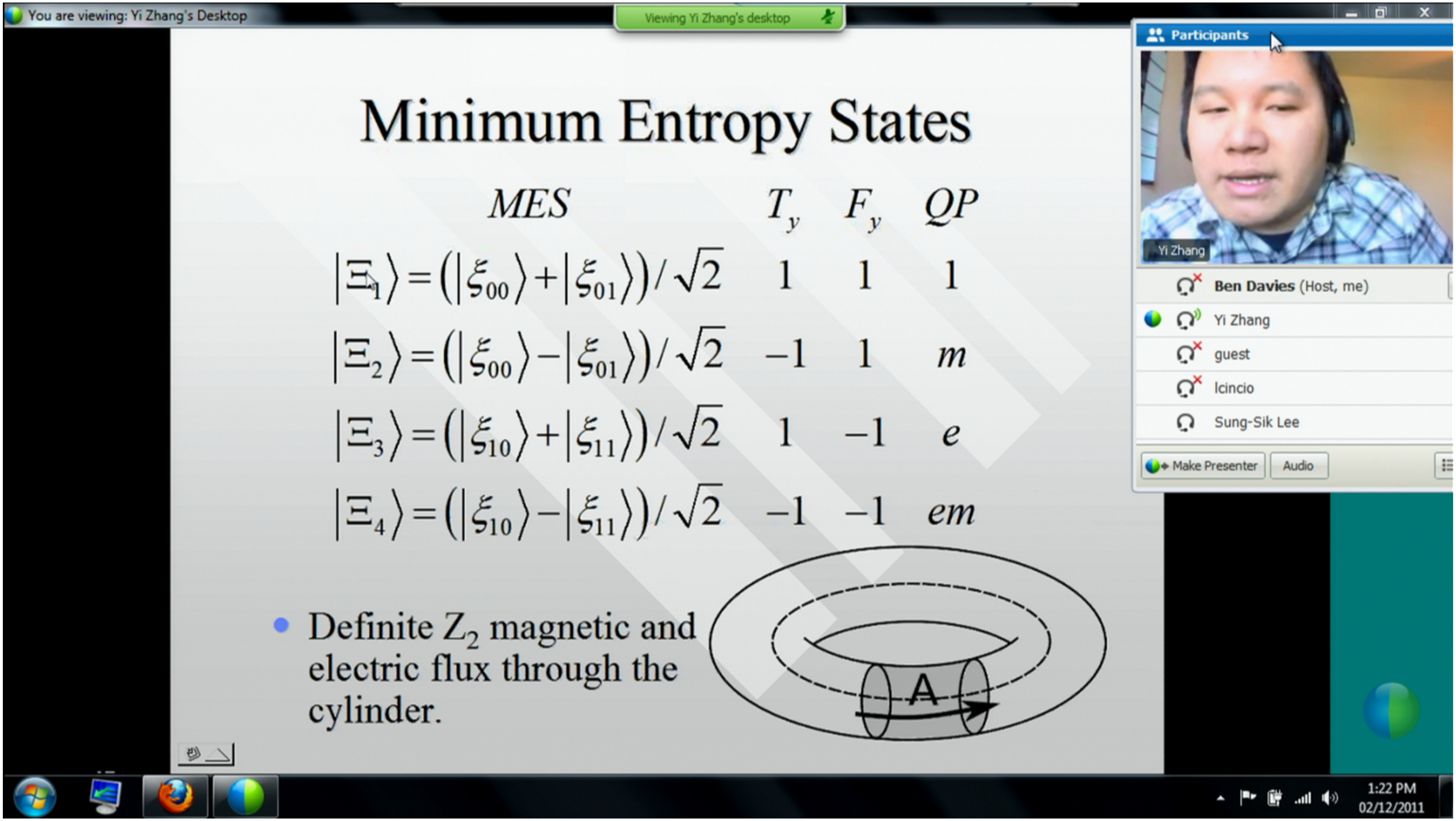
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Minimum Entropy States
MES T_y F_y QP
$|\Xi_1\rangle = (|\xi_{00}\rangle + |\xi_{01}\rangle)/\sqrt{2}$ 1 1 1
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$|\Xi_4\rangle = (|\xi_{10}\rangle - |\xi_{11}\rangle)/\sqrt{2}$ −1 −1 em
Definite Z_2 magnetic and electric flux through the cylinder.
A
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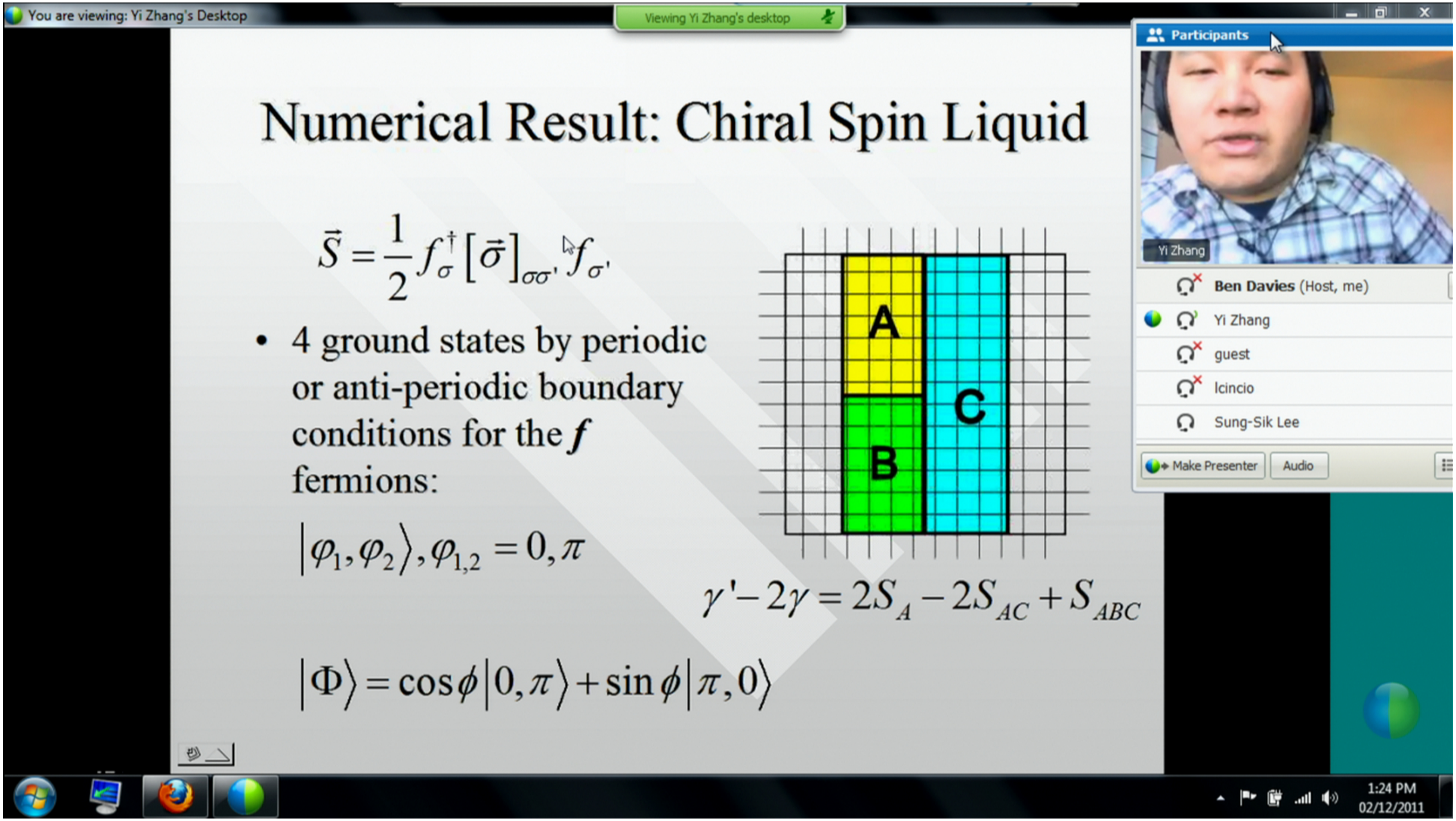
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Numerical Result: Chiral Spin Liquid
$\vec{S} = \frac{1}{2} f_{\sigma}^{\dagger} [\vec{\sigma}]_{\sigma\sigma'} f_{\sigma'}$
• 4 ground states by periodic or anti-periodic boundary conditions for the f fermions:
$|\varphi_1, \varphi_2\rangle, \varphi_{1,2} = 0, \pi$
$|\Phi\rangle = \cos\phi |0, \pi\rangle + \sin\phi |\pi, 0\rangle$
A
B
C
$\gamma' - 2\gamma = 2S_A - 2S_{AC} + S_{ABC}$
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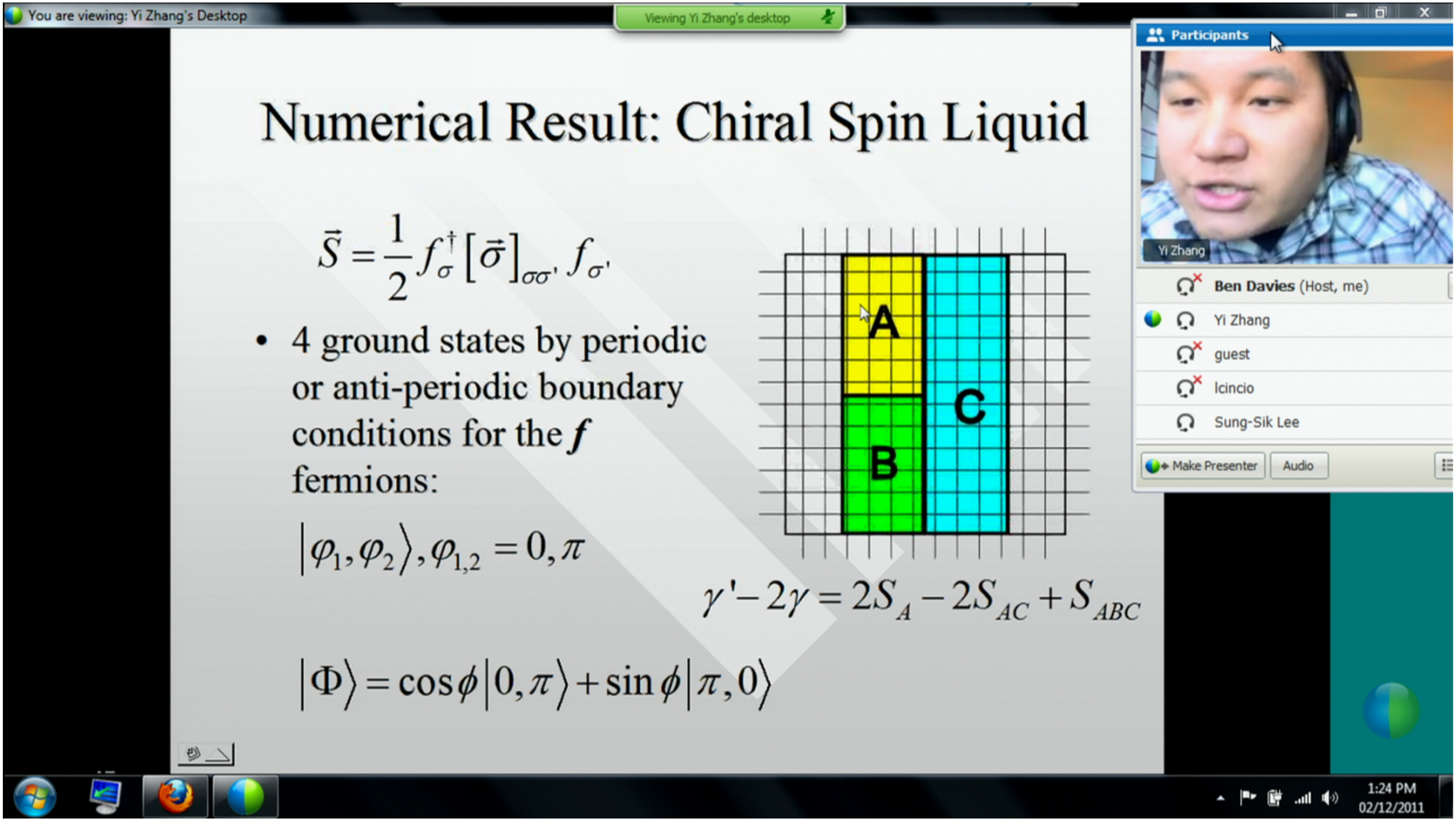
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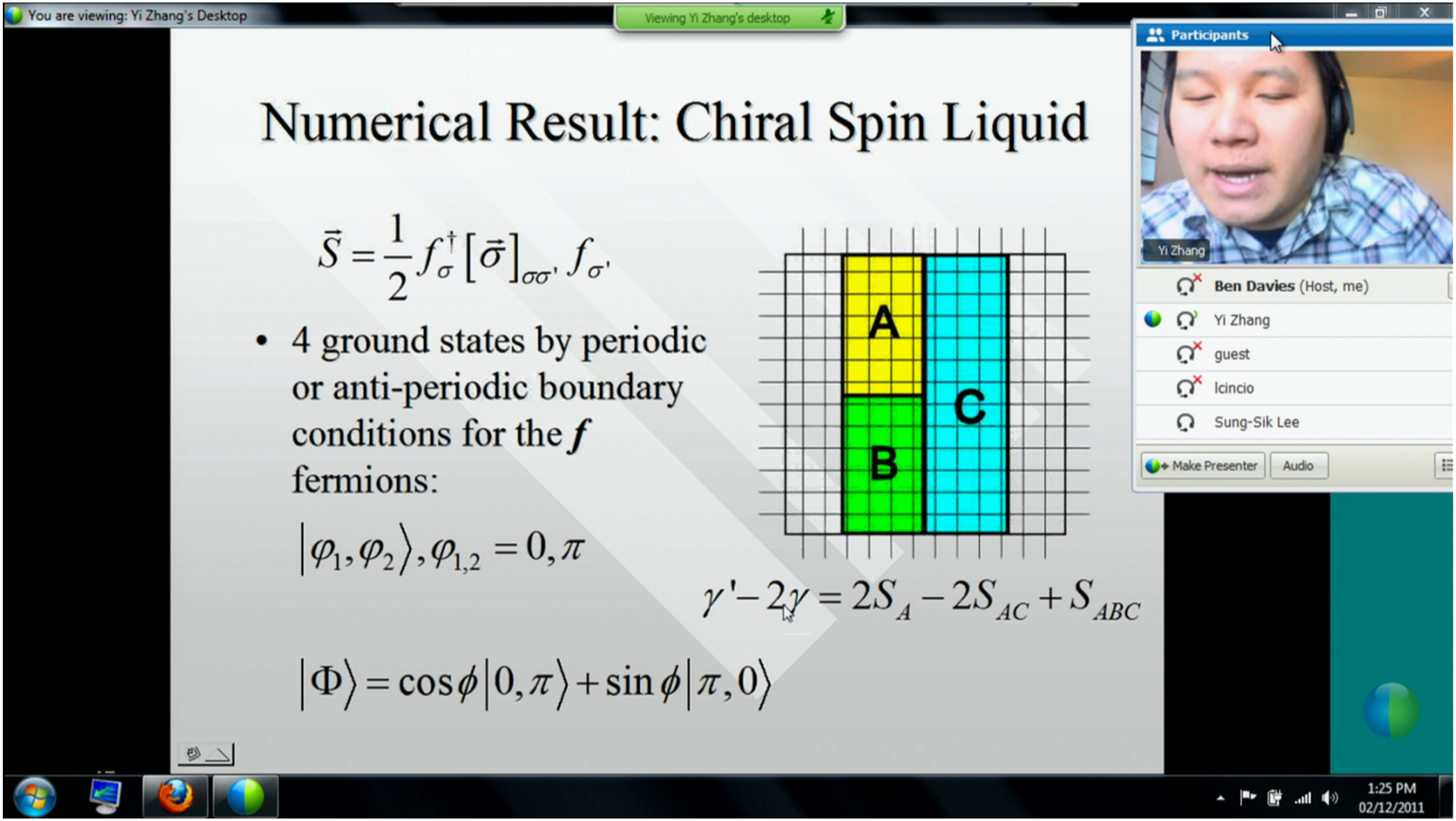
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A
B
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Numerical Result: Chiral Spin Liquid

$$\vec{S} = \frac{1}{2} f_{\sigma}^{\dagger} [\vec{\sigma}]_{\sigma\sigma'} f_{\sigma'}$$

- 4 ground states by periodic or anti-periodic boundary conditions for the ***f*** fermions:

$$|\varphi_1, \varphi_2\rangle, \varphi_{1,2} = 0, \pi$$

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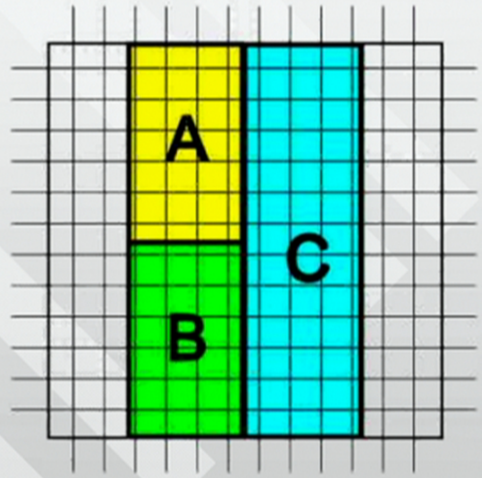
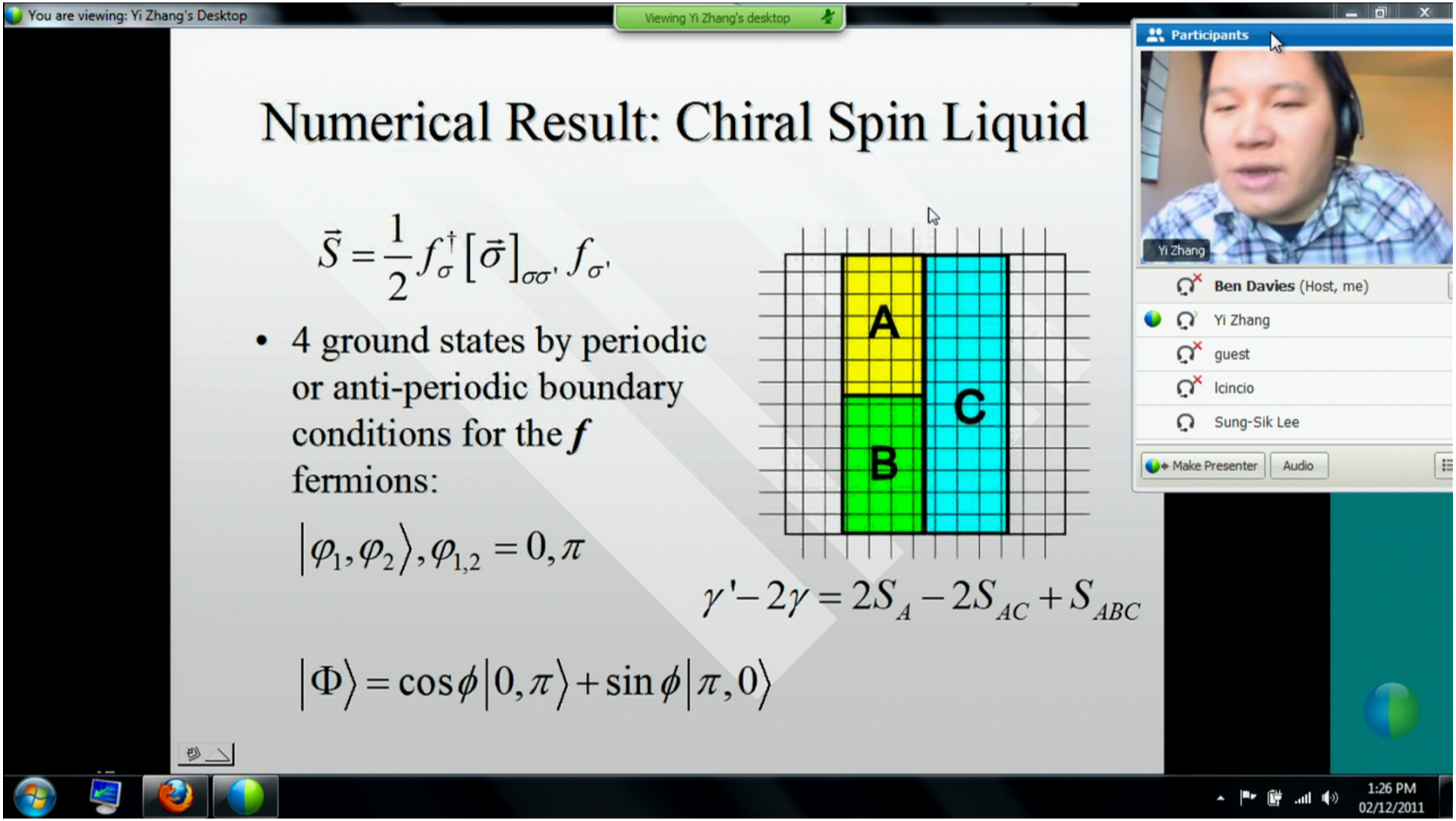


$$\gamma' - 2\gamma = 2S_A - 2S_{AC} + S_{ABC}$$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A
B
C
$\gamma' - 2\gamma = 2S_A - 2S_{AC} + S_{ABC}$
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Numerical Result: Chiral Spin Liquid

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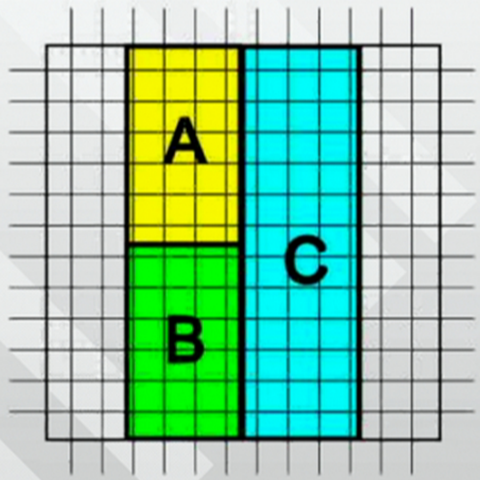

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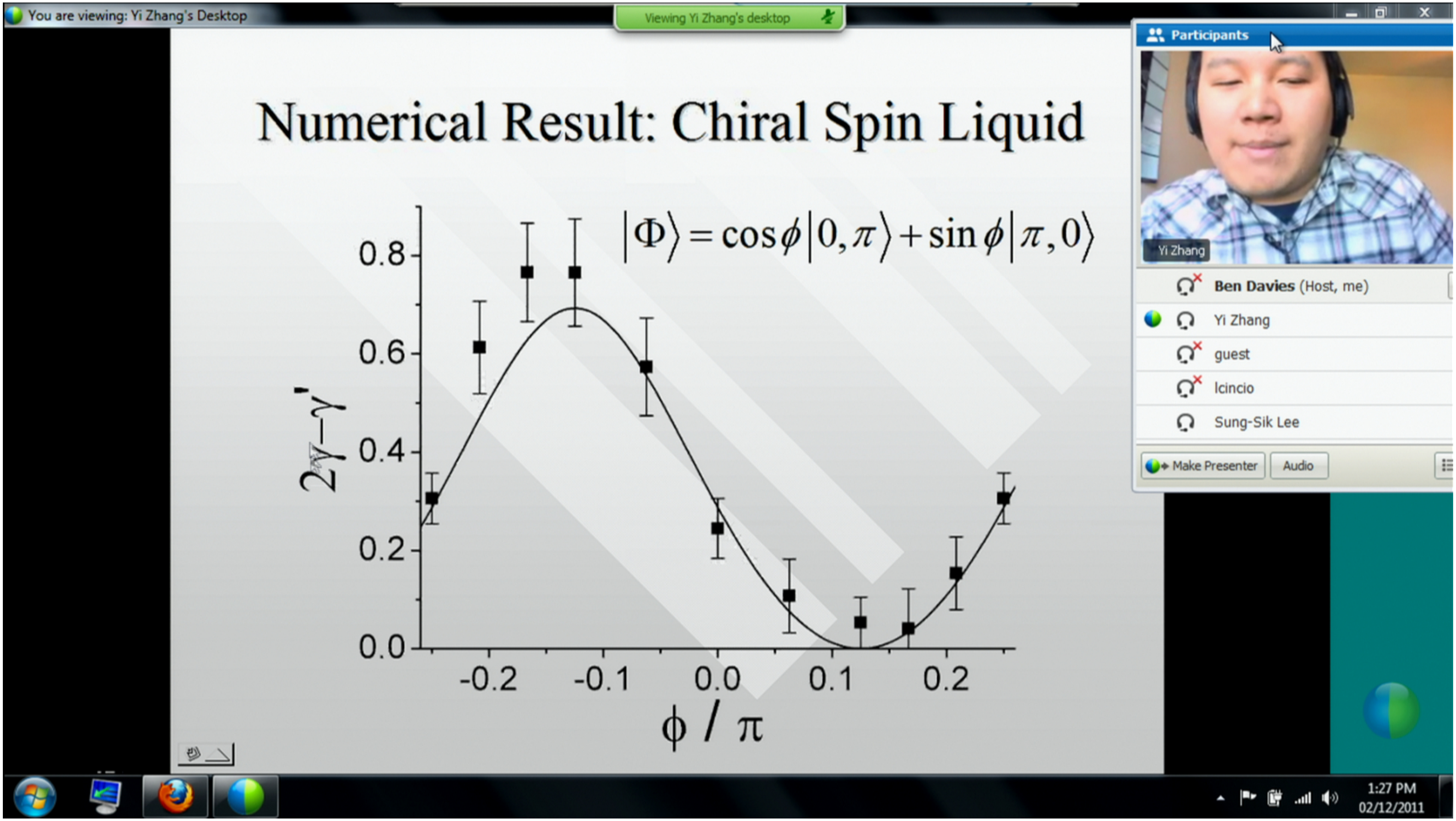
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Numerical Result: Chiral Spin Liquid
$|\Phi\rangle = \cos\phi|0,\pi\rangle + \sin\phi|\pi,0\rangle$
$2\gamma-\gamma'$
0.8
0.6
0.4
0.2
0.0
-0.2
-0.1
0.0
0.1
0.2
ϕ / π
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Theory: Chiral Spin Liquid

- In **basis of minimum entropy states - Wilson loop operator along y direction**:
  - π/2 rotation operator:

$$\mathcal{S} = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} \end{pmatrix}$$

  - π/2 rotation eigenstates:

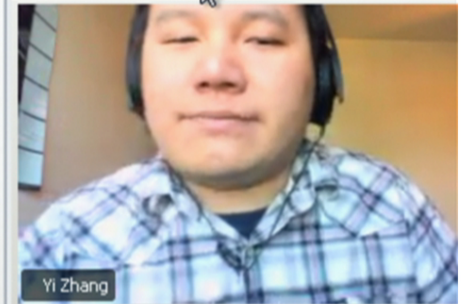
$$|0,0\rangle = \left(\sin(\pi/8), -\cos(\pi/8)\right)^T \quad |0,\pi\rangle = \left(\sin(\pi/8), \cos(\pi/8)\right)^T$$

$$|\pi,\pi\rangle = \left(\cos(\pi/8), \sin(\pi/8)\right)^T \quad |\pi,0\rangle = \left(\cos(\pi/8), -\sin(\pi/8)\right)^T$$

$$|\Phi\rangle = \cos\phi\,|0,\pi\rangle + \sin\phi\,|\pi,0\rangle$$

$$= \left(\cos(\phi-\pi/8), \sin(\phi-\pi/8)\right)^T$$

Participants



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Theory: Chiral Spin Liquid

- In **basis of minimum entropy states - Wilson loop operator along y direction**:
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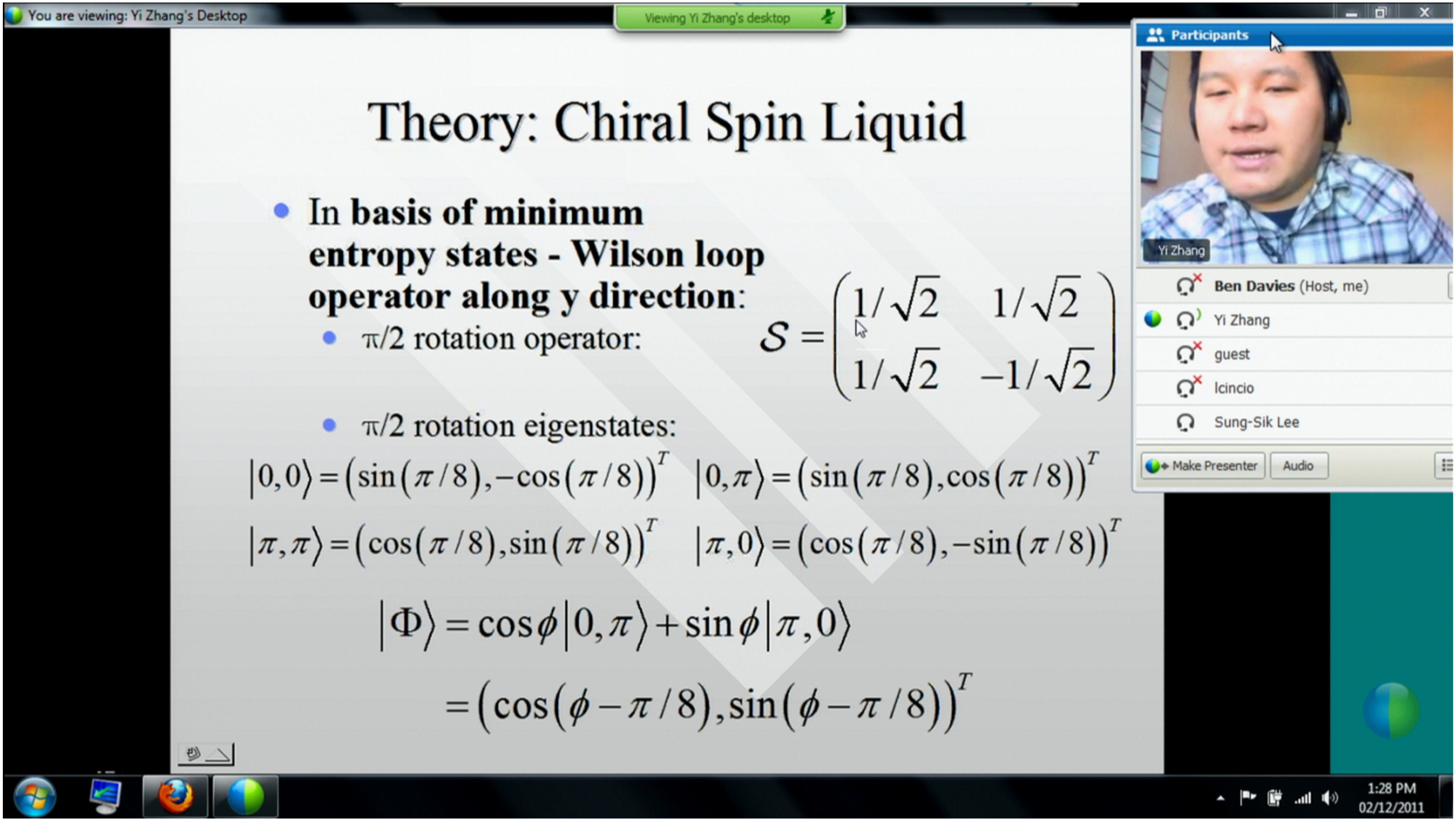
You are viewing: Yi Zhang's Desktop
Viewing Yi Zhang's desktop
Theory: Chiral Spin Liquid
In basis of minimum entropy states - Wilson loop operator along y direction:
π/2 rotation operator:
$\mathcal{S} = \begin{pmatrix} 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & -1/\sqrt{2} \end{pmatrix}$
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Theory: Chiral Spin Liquid

- In **basis of minimum entropy states - Wilson loop operator along y direction**:
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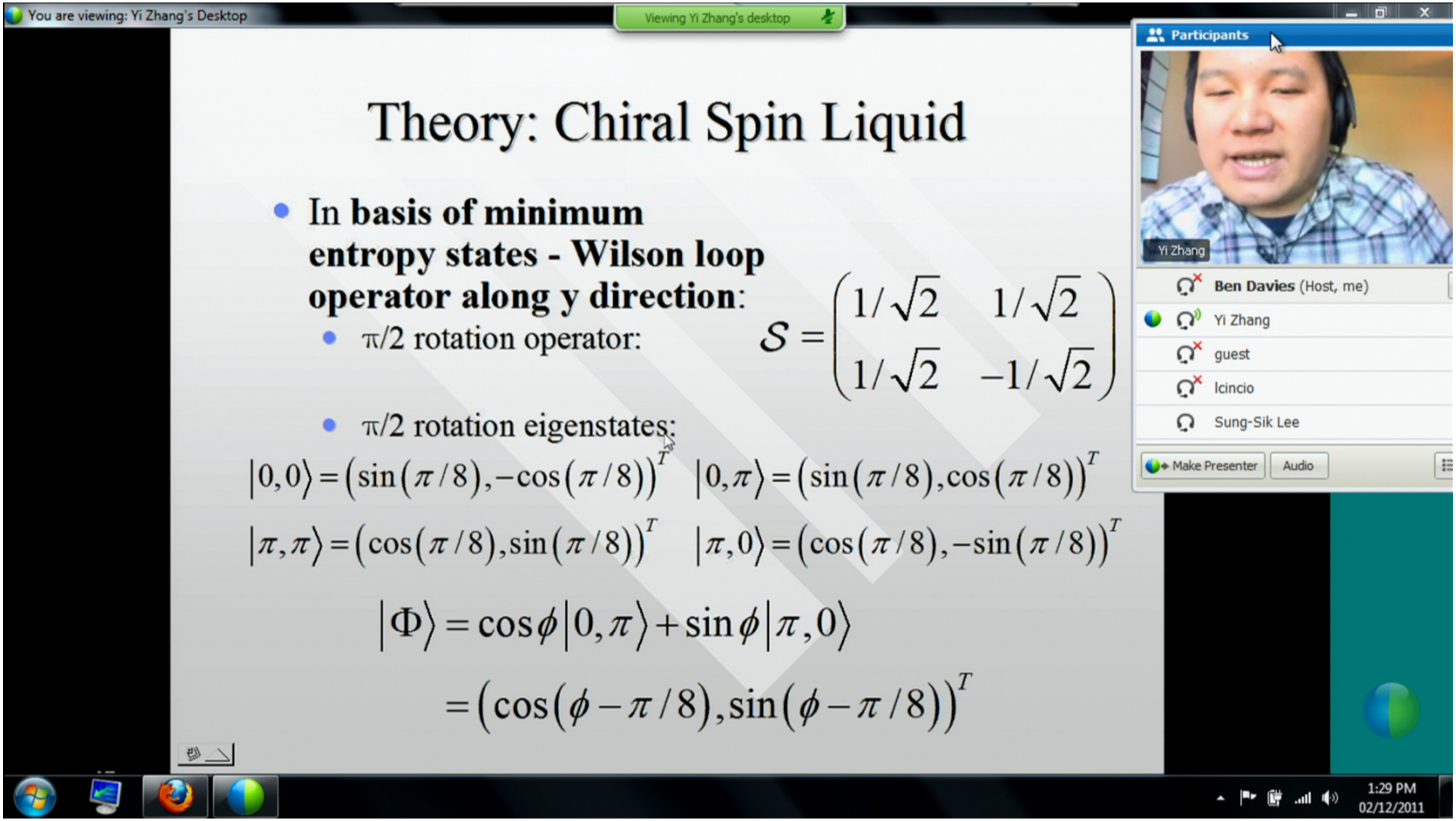
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Theory: Chiral Spin Liquid
In **basis of minimum entropy states - Wilson loop operator along y direction**:
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Extracting Statistics from TEE

- The S matrix implements a $\pi/2$ rotation on minimum entropy states:

$$|\xi_{ab}\rangle \to |\xi_{ba}\rangle$$

$$|\Xi_1\rangle \to (|\Xi_1\rangle + |\Xi_2\rangle + |\Xi_3\rangle + |\Xi_4\rangle)/2$$

$$|\Xi_2\rangle \to (|\Xi_1\rangle + |\Xi_2\rangle - |\Xi_3\rangle - |\Xi_4\rangle)/2$$

$$|\Xi_3\rangle \to (|\Xi_1\rangle - |\Xi_2\rangle + |\Xi_3\rangle - |\Xi_4\rangle)/2$$

$$|\Xi_4\rangle \to (|\Xi_1\rangle - |\Xi_2\rangle - |\Xi_3\rangle + |\Xi_4\rangle)/2$$

$$\mathcal{S} = \frac{1}{2}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix}$$

Extracting Statistics from TEE

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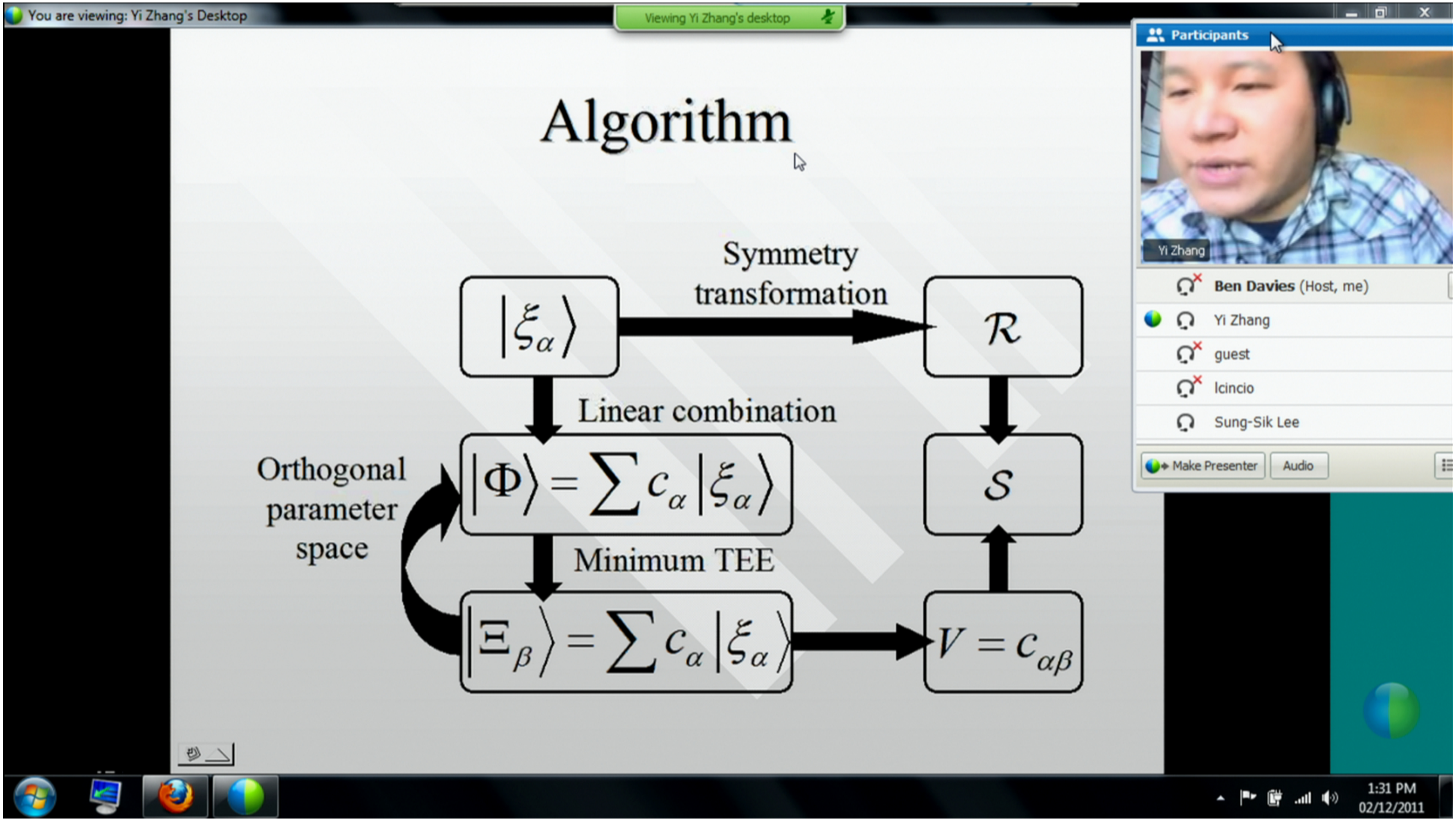
$$|\Xi_4\rangle \rightarrow (|\Xi_1\rangle - |\Xi_2\rangle - |\Xi_3\rangle + |\Xi_4\rangle)/2$$

$$\mathcal{S} = \frac{1}{2}\begin{pmatrix} 1 & 1 & 1 & 1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & 1 & -1 \\ 1 & -1 & -1 & 1 \end{pmatrix}$$


You are viewing: Yi Zhang's Desktop
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Algorithm
Symmetry transformation
$|\xi_\alpha\rangle$
$\mathcal{R}$
Linear combination
Orthogonal parameter space
$|\Phi\rangle = \sum c_\alpha |\xi_\alpha\rangle$
$\mathcal{S}$
Minimum TEE
$|\Xi_\beta\rangle = \sum c_\alpha |\xi_\alpha\rangle$
$V = c_{\alpha\beta}$
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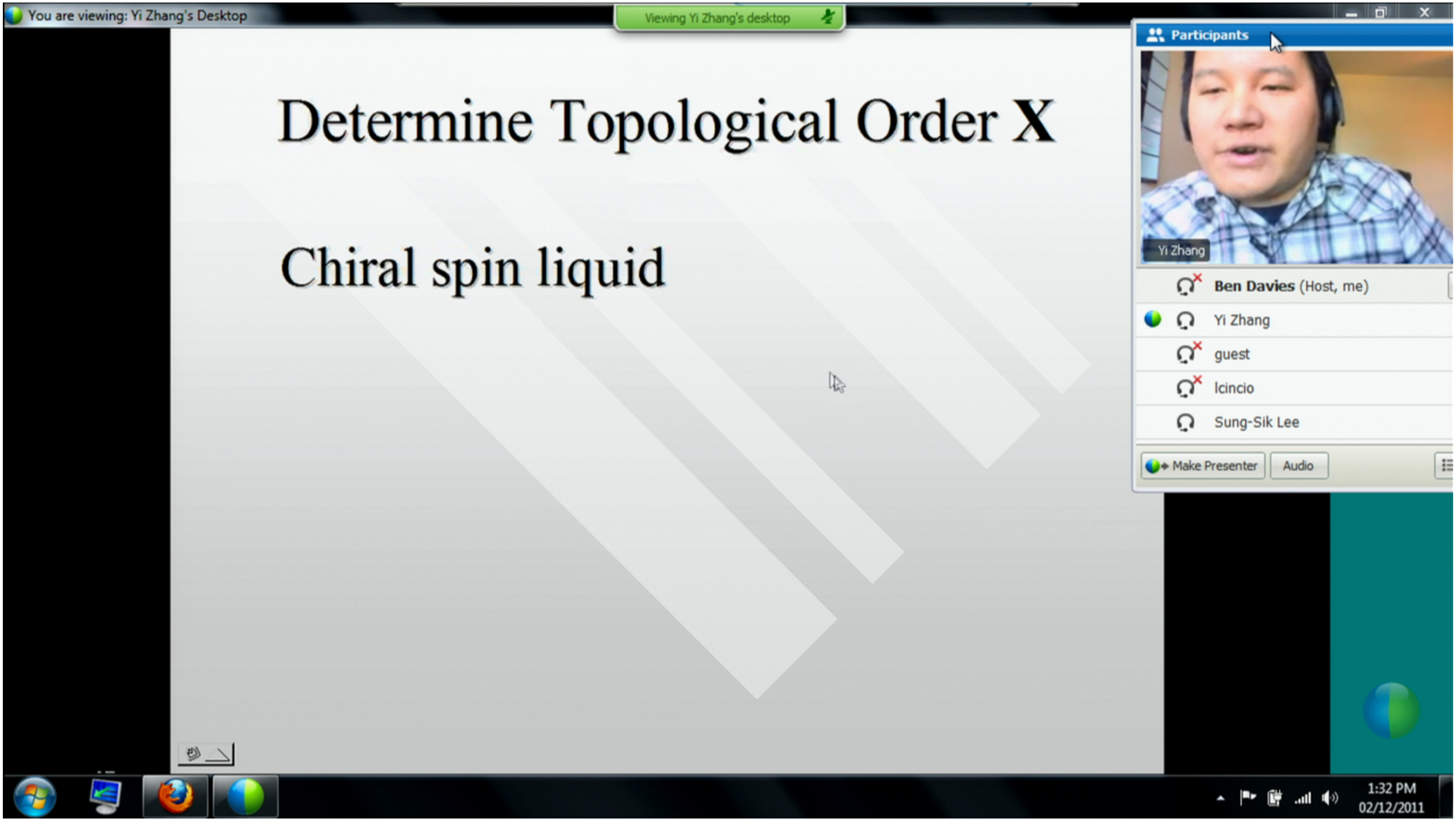
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Determine Topological Order X
Chiral spin liquid
Participants
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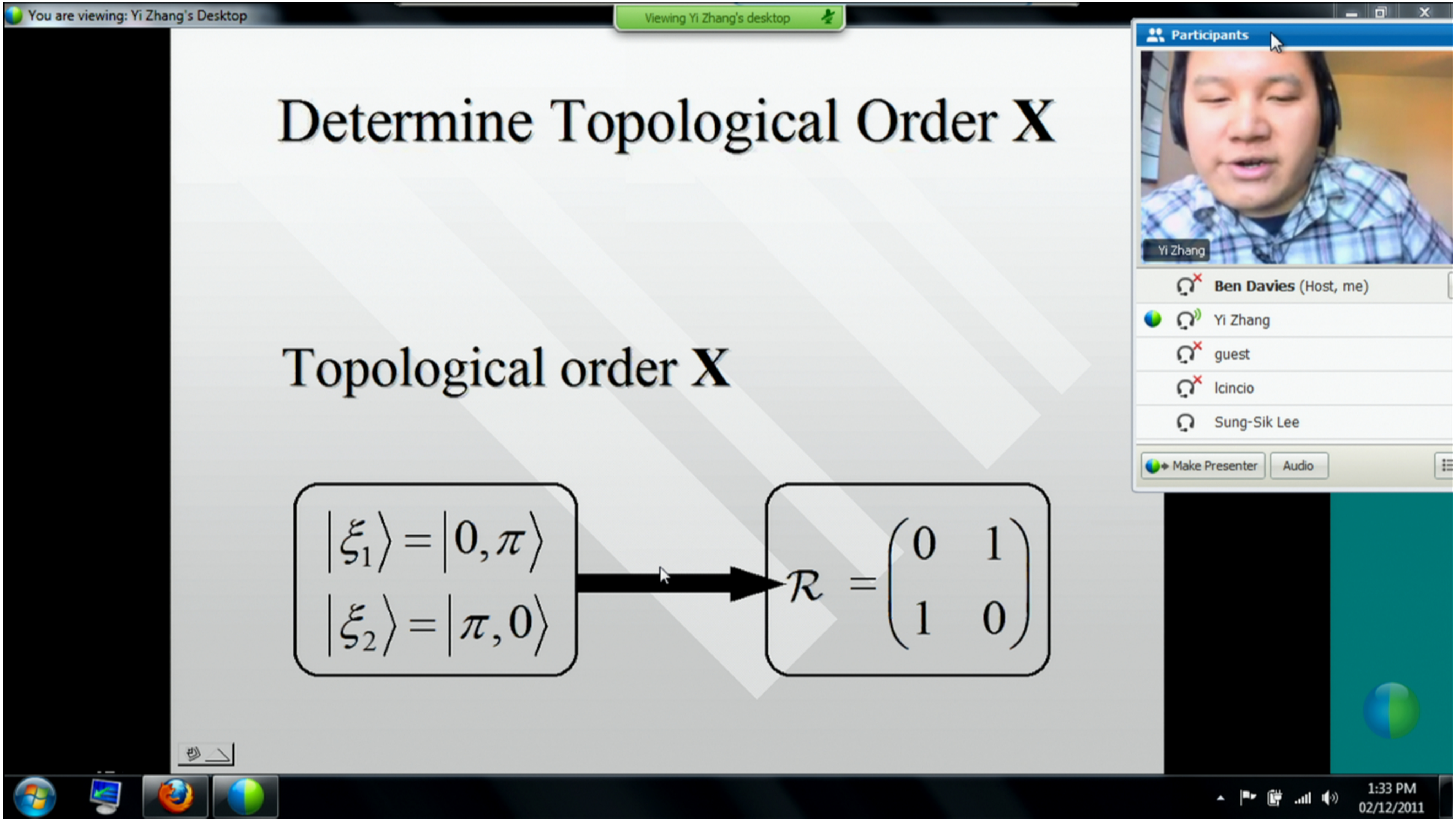
You are viewing: Yi Zhang's Desktop
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Determine Topological Order X
Topological order X
$|\xi_1\rangle = |0,\pi\rangle$
$|\xi_2\rangle = |\pi,0\rangle$
$\mathcal{R} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$
Participants
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Ben Davies (Host, me)
Yi Zhang
guest
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Sung-Sik Lee
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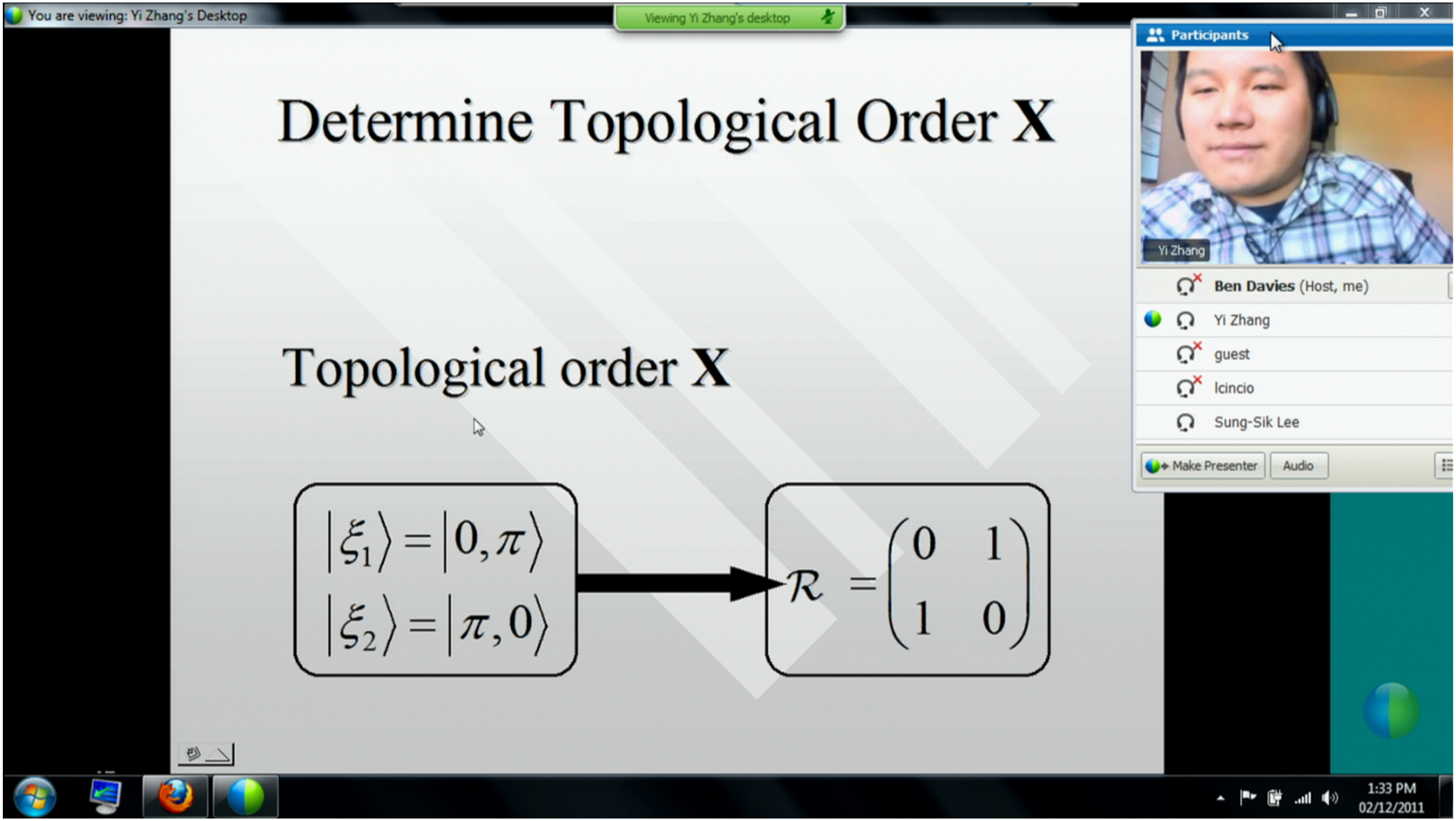
You are viewing: Yi Zhang's Desktop
Viewing Yi Zhang's desktop
Determine Topological Order X
Topological order X
$|\xi_1\rangle = |0,\pi\rangle$
$|\xi_2\rangle = |\pi,0\rangle$
$\mathcal{R} = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$
Participants
Yi Zhang
Ben Davies (Host, me)
Yi Zhang
guest
lcincio
Sung-Sik Lee
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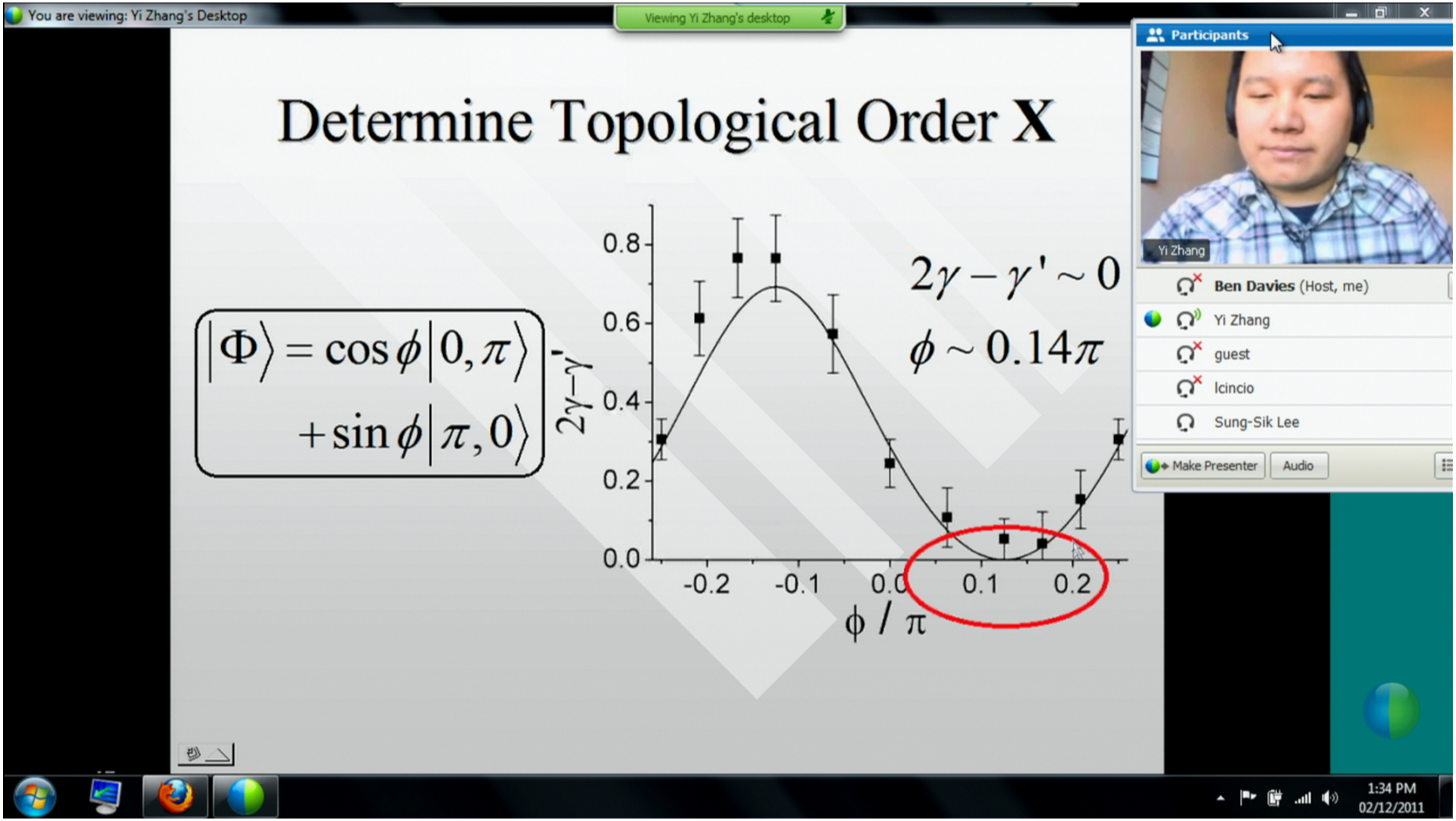

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Determine Topological Order X
$|\Phi\rangle = \cos\phi|0,\pi\rangle + \sin\phi|\pi,0\rangle$
$2\gamma - \gamma' \sim 0$
$\phi \sim 0.14\pi$
2γ−γ'
0.8
0.6
0.4
0.2
0.0
-0.2
-0.1
0.0
0.1
0.2
φ / π
Participants
Yi Zhang
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Yi Zhang
guest
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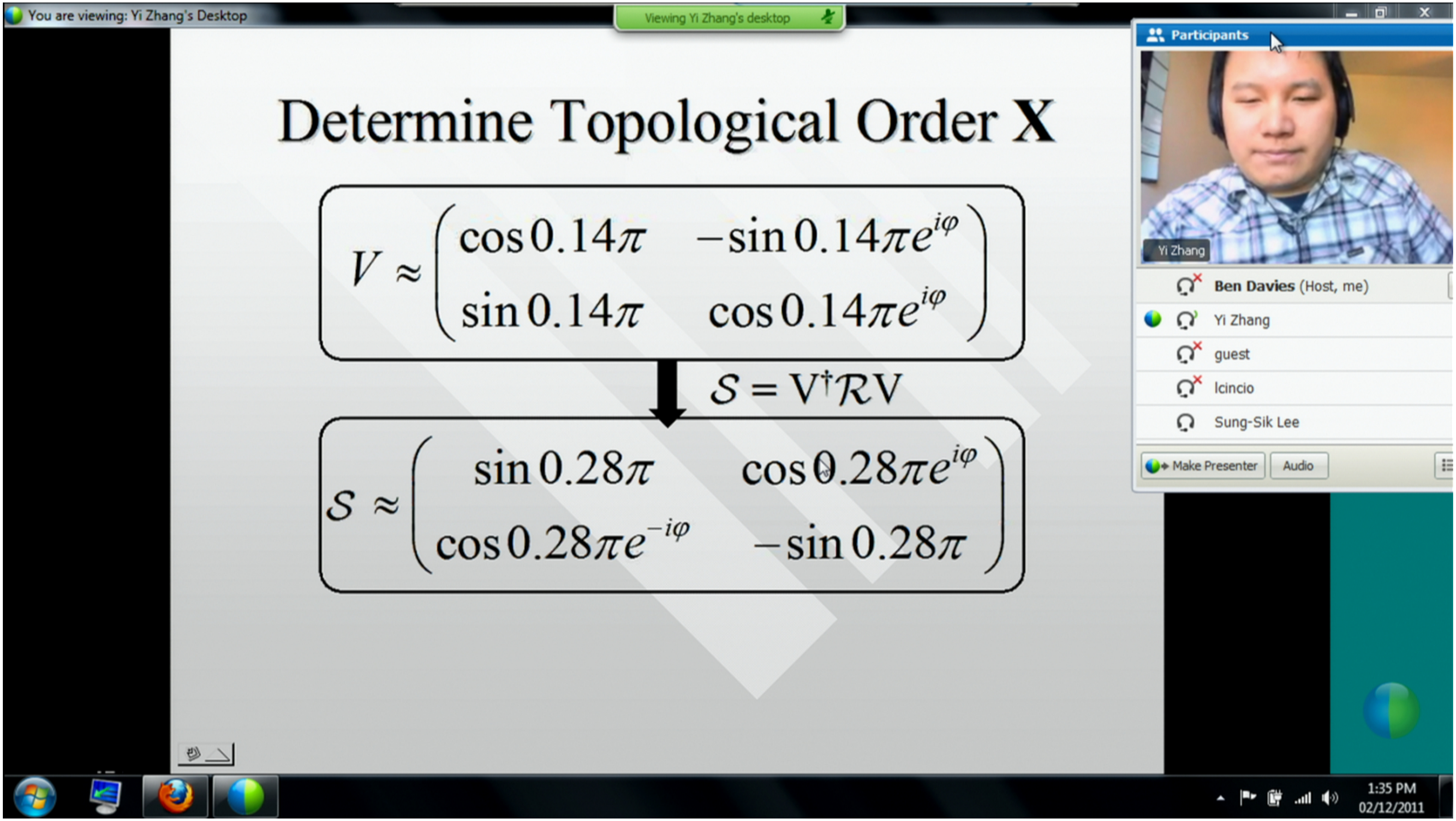
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Determine Topological Order X
$V \approx \begin{pmatrix} \cos 0.14\pi & -\sin 0.14\pi e^{i\varphi} \\ \sin 0.14\pi & \cos 0.14\pi e^{i\varphi} \end{pmatrix}$
$\mathcal{S} = V^\dagger \mathcal{R} V$
$\mathcal{S} \approx \begin{pmatrix} \sin 0.28\pi & \cos 0.28\pi e^{i\varphi} \\ \cos 0.28\pi e^{-i\varphi} & -\sin 0.28\pi \end{pmatrix}$
Participants
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Determine Topological Order X

$$V \approx \begin{pmatrix} \cos 0.14\pi & -\sin 0.14\pi e^{i\varphi} \\ \sin 0.14\pi & \cos 0.14\pi e^{i\varphi} \end{pmatrix}$$

$$\mathcal{S} = V^{\dagger}\mathcal{R}V$$

$$\mathcal{S} \approx \begin{pmatrix} \sin 0.28\pi & \cos 0.28\pi e^{i\varphi} \\ \cos 0.28\pi e^{-i\varphi} & -\sin 0.28\pi \end{pmatrix}$$

$$\mathcal{S} \approx \begin{pmatrix} 0.77 & 0.63 \\ 0.63 & -0.77 \end{pmatrix}$$

Semion Statistics!

Participants

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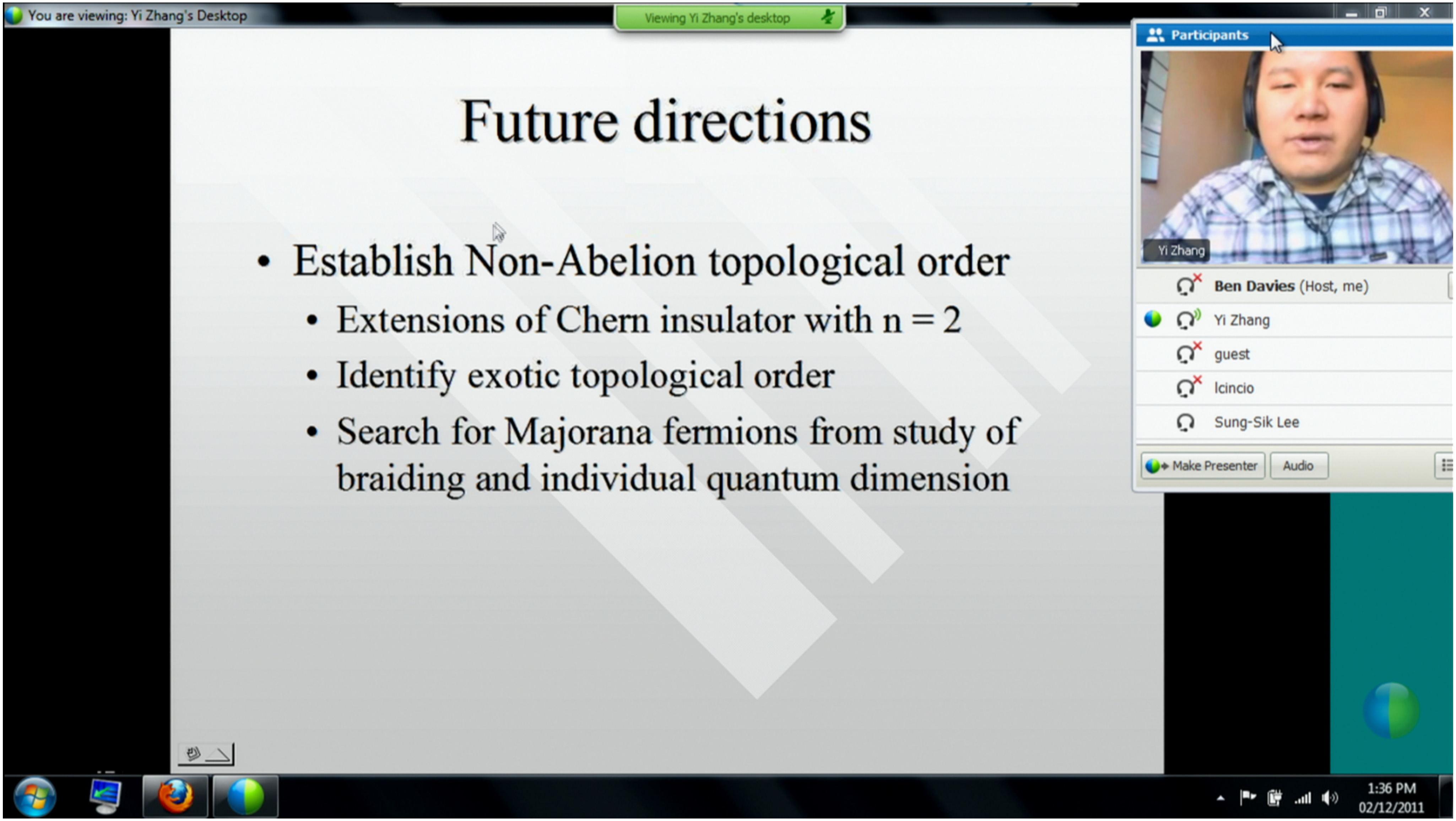
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Future directions
• Establish Non-Abelion topological order
• Extensions of Chern insulator with n = 2
• Identify exotic topological order
• Search for Majorana fermions from study of braiding and individual quantum dimension
Participants
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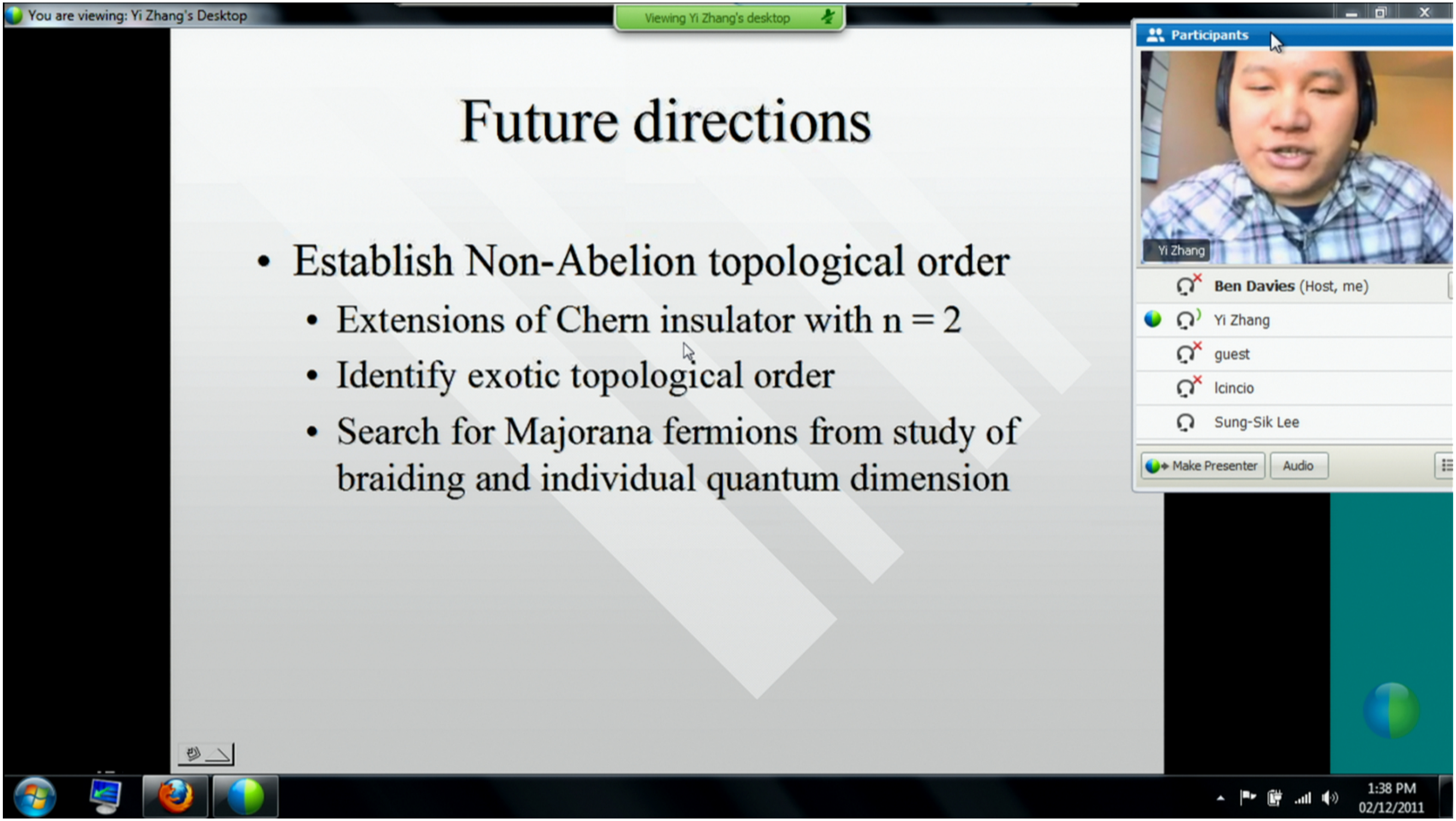
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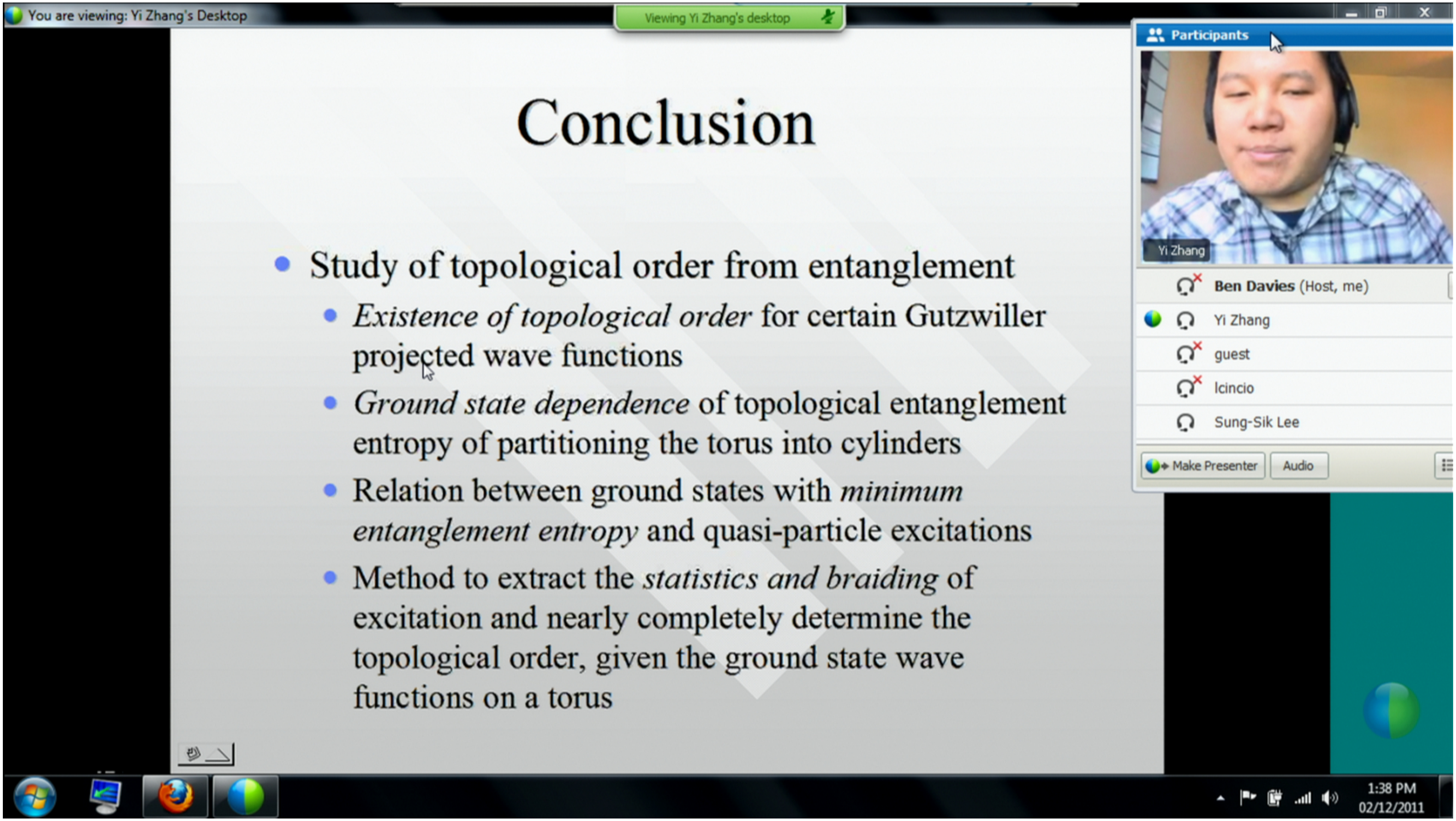
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Conclusion
Study of topological order from entanglement
Existence of topological order for certain Gutzwiller projected wave functions
Ground state dependence of topological entanglement entropy of partitioning the torus into cylinders
Relation between ground states with minimum entanglement entropy and quasi-particle excitations
Method to extract the statistics and braiding of excitation and nearly completely determine the topological order, given the ground state wave functions on a torus
Participants
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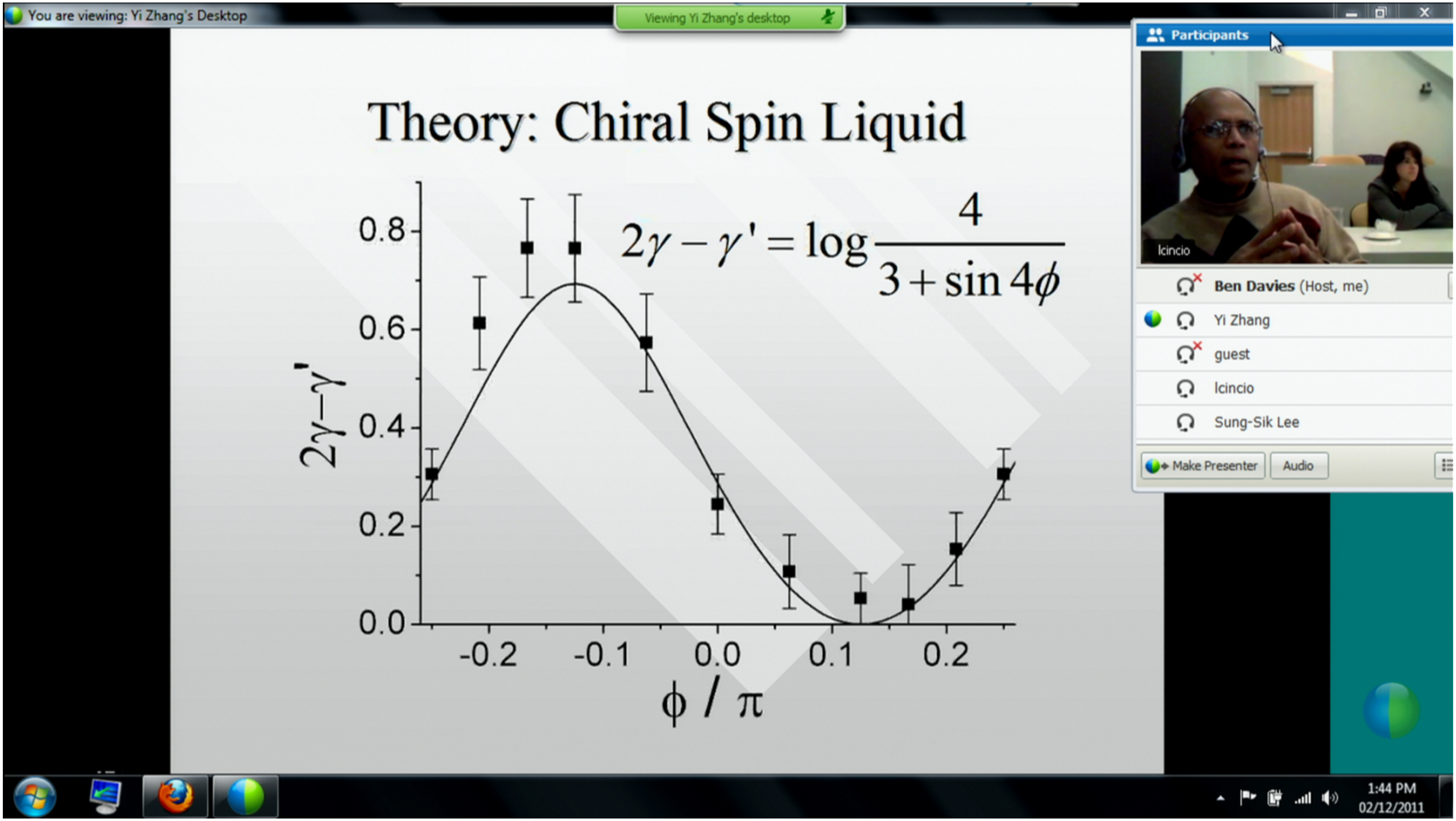
Conclusion

- Study of topological order from entanglement
  - *Existence of topological order* for certain Gutzwiller projected wave functions
  - *Ground state dependence* of topological entanglement entropy of partitioning the torus into cylinders
  - Relation between ground states with *minimum entanglement entropy* and quasi-particle excitations
  - Method to extract the *statistics and braiding* of excitation and nearly completely determine the topological order, given the ground state wave functions on a torus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Theory: Chiral Spin Liquid
$2\gamma - \gamma' = \log \frac{4}{3 + \sin 4\phi}$
0.8
0.6
0.4
0.2
0.0
$2\gamma - \gamma'$
-0.2
-0.1
0.0
0.1
0.2
ϕ / π
Participants
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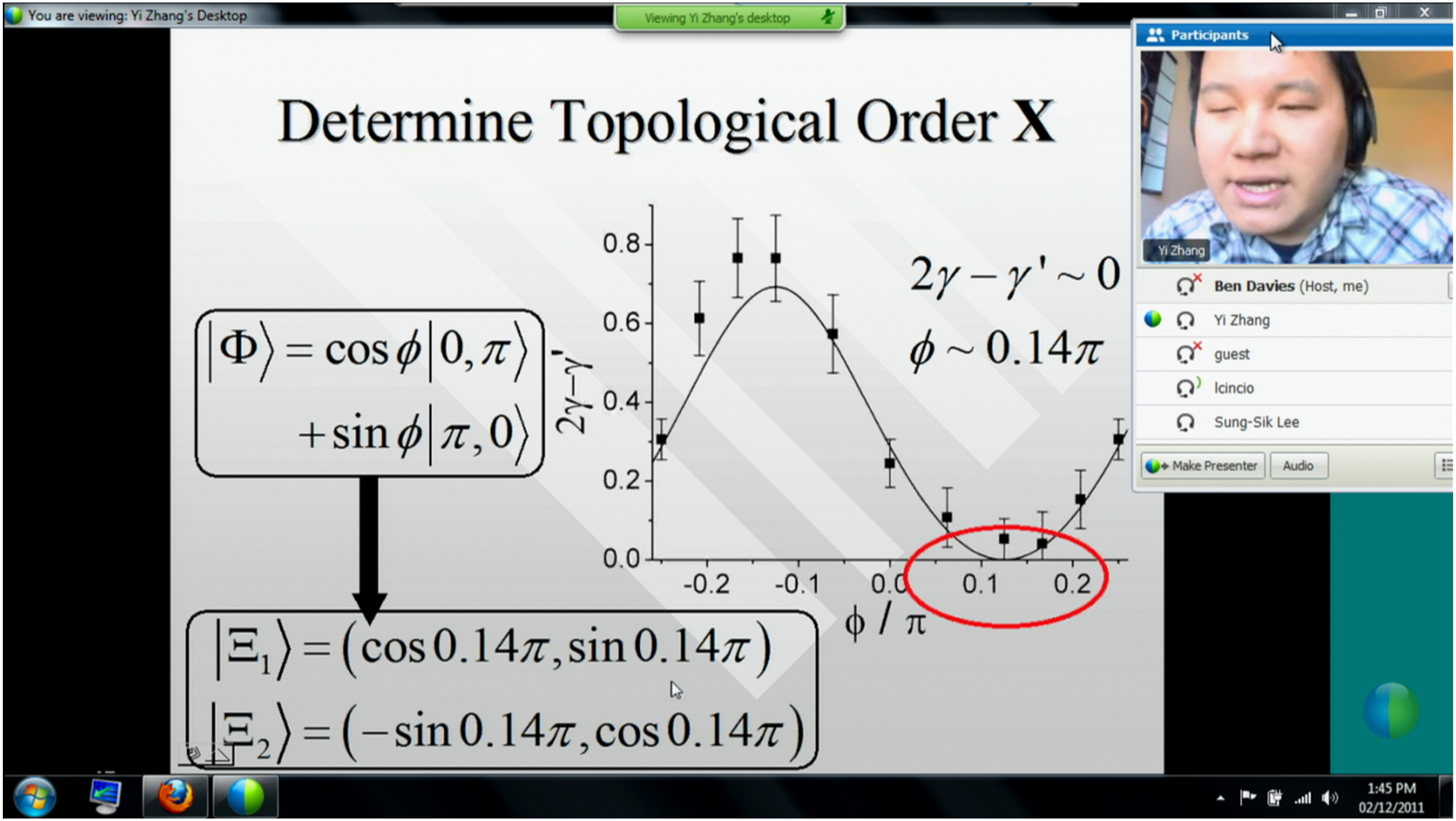

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Determine Topological Order X
$|\Phi\rangle = \cos\phi|0,\pi\rangle + \sin\phi|\pi,0\rangle$
$|\Xi_1\rangle = (\cos 0.14\pi, \sin 0.14\pi)$
$|\Xi_2\rangle = (-\sin 0.14\pi, \cos 0.14\pi)$
$2\gamma - \gamma' \sim 0$
$\phi \sim 0.14\pi$
2γ−γ'
φ / π
0.0
0.2
0.4
0.6
0.8
-0.2
-0.1
0.0
0.1
0.2
Participants
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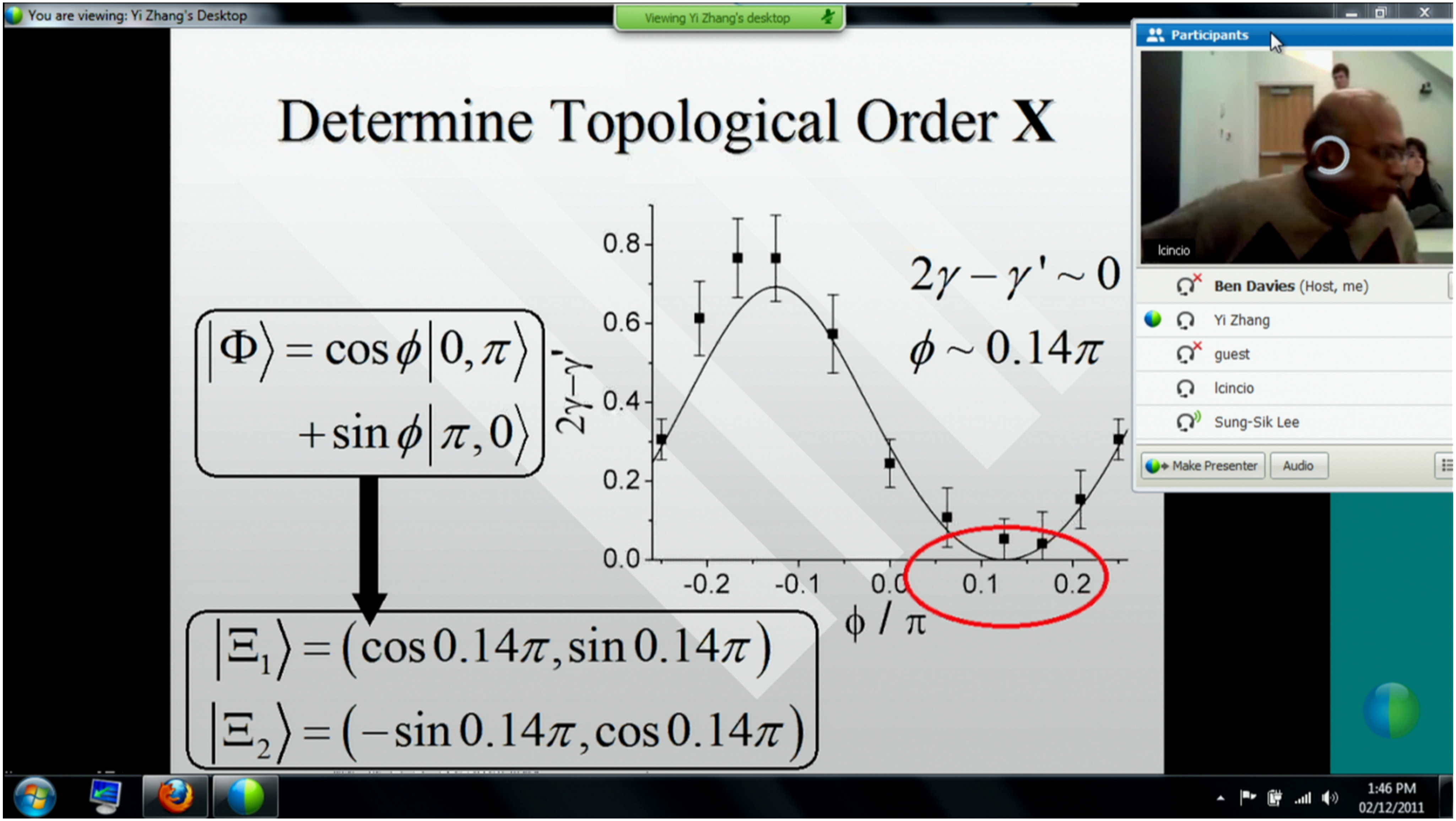
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φ / π
Participants
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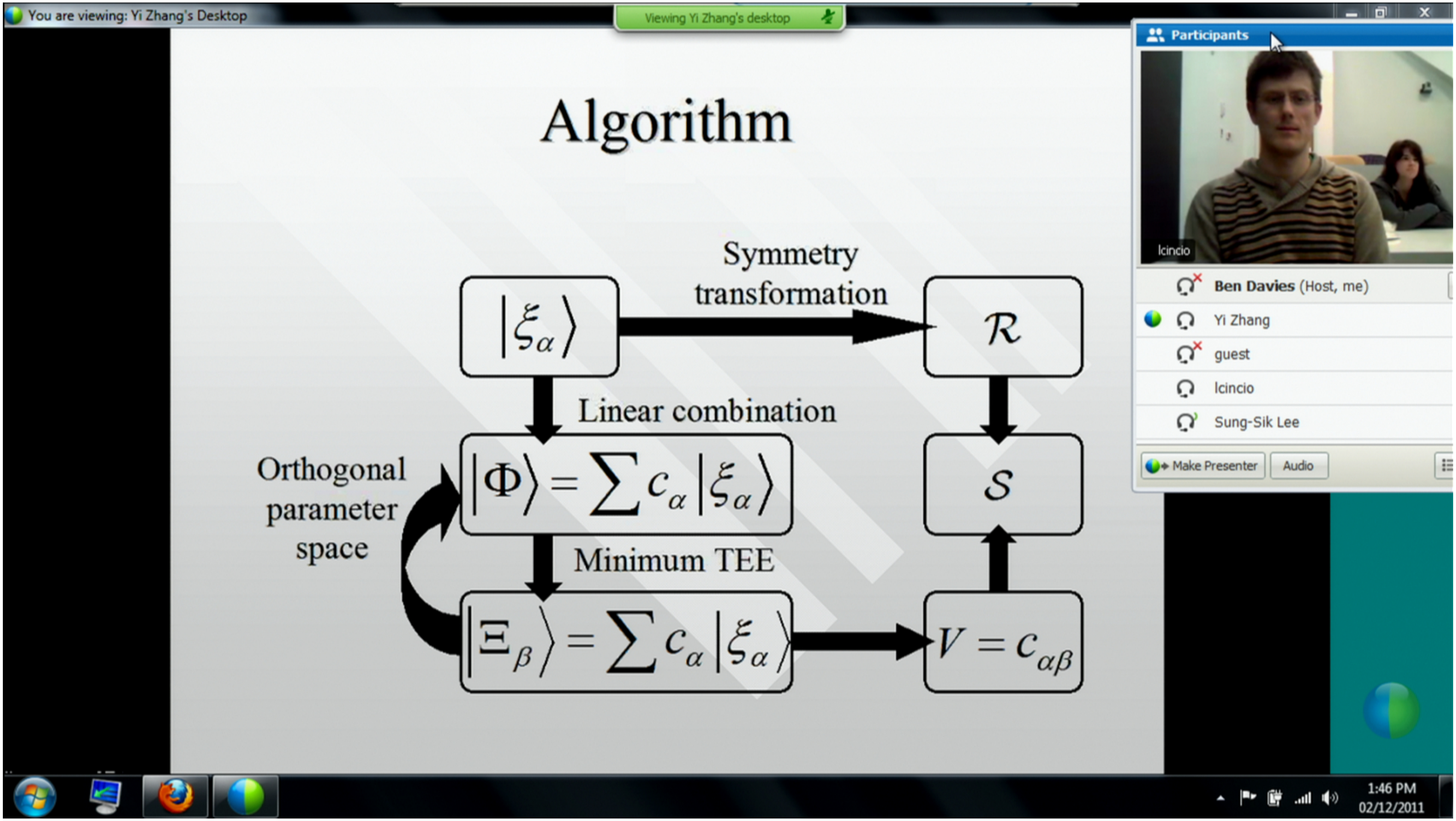
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Algorithm
Symmetry transformation
$|\xi_\alpha\rangle$
$\mathcal{R}$
Linear combination
Orthogonal parameter space
$|\Phi\rangle = \sum c_\alpha |\xi_\alpha\rangle$
$\mathcal{S}$
Minimum TEE
$|\Xi_\beta\rangle = \sum c_\alpha |\xi_\alpha\rangle$
$V = c_{\alpha\beta}$
Participants
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guest
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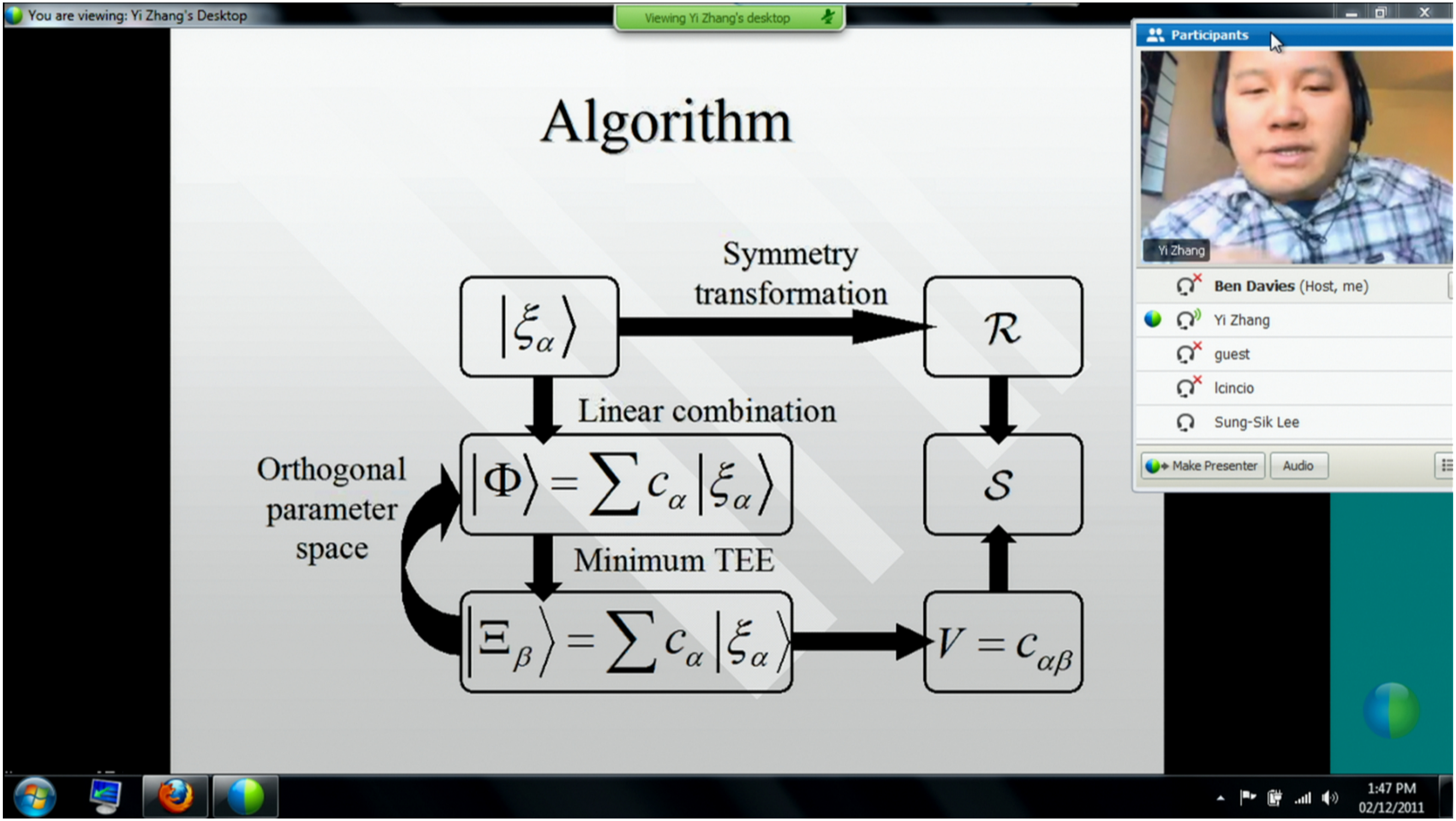
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Algorithm
Symmetry transformation
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Minimum TEE
$|\Xi_\beta\rangle = \sum c_\alpha |\xi_\alpha\rangle$
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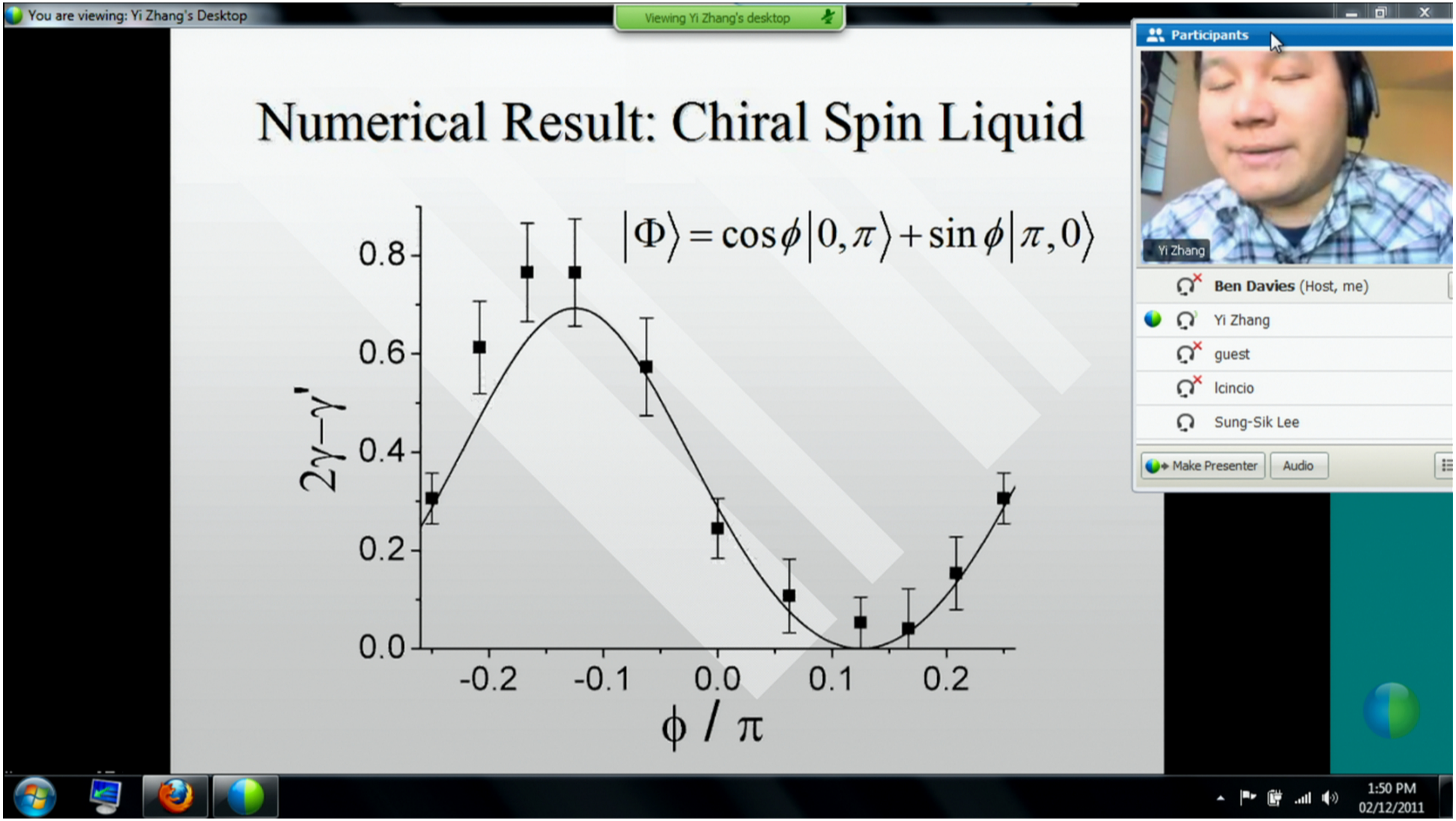
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Numerical Result: Chiral Spin Liquid
$|\Phi\rangle = \cos\phi|0,\pi\rangle + \sin\phi|\pi,0\rangle$
$2\gamma-\gamma'$
0.8
0.6
0.4
0.2
0.0
-0.2
-0.1
0.0
0.1
0.2
ϕ / π
Participants
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