Parity Violation and Topological Currents
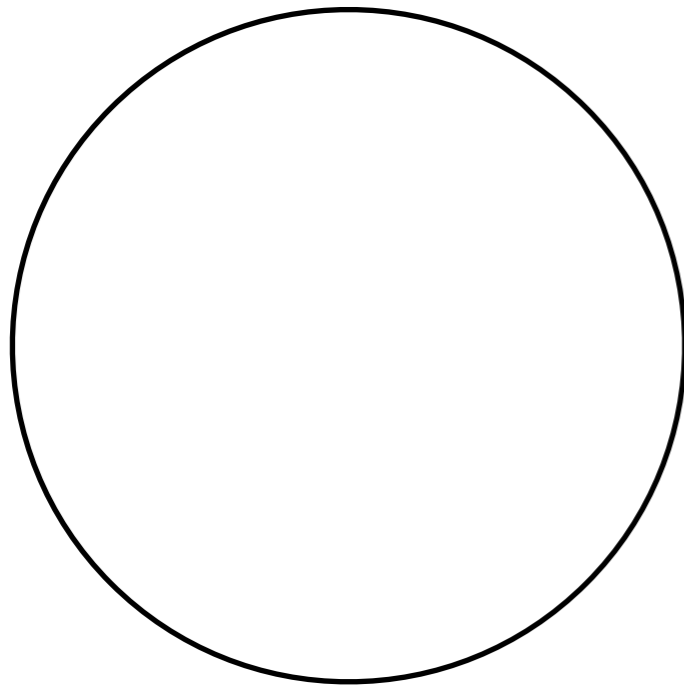
James Charbonneau

UBC

TRU Science Seminar Series

Nov 17th 2011
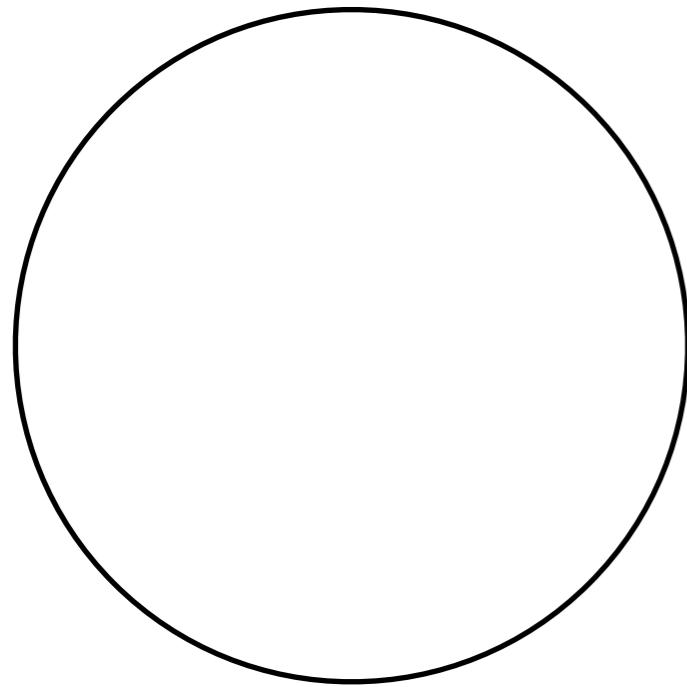
Quantum Field Theory

Quantum Field Theory

Photons
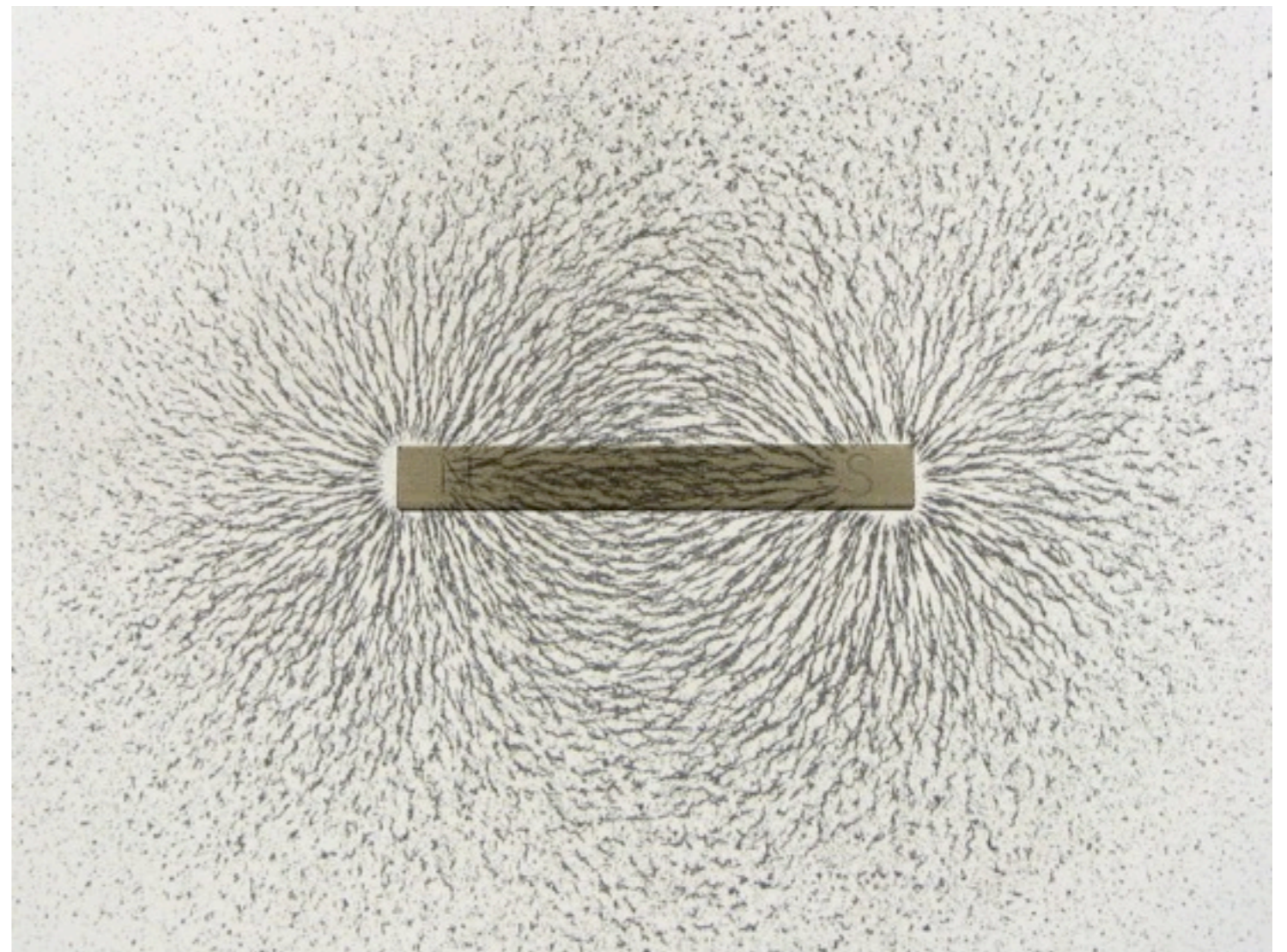(very tiny particles,
see inside circle)

Quantum Field Theory

Photons
(very tiny particles,
see inside circle)
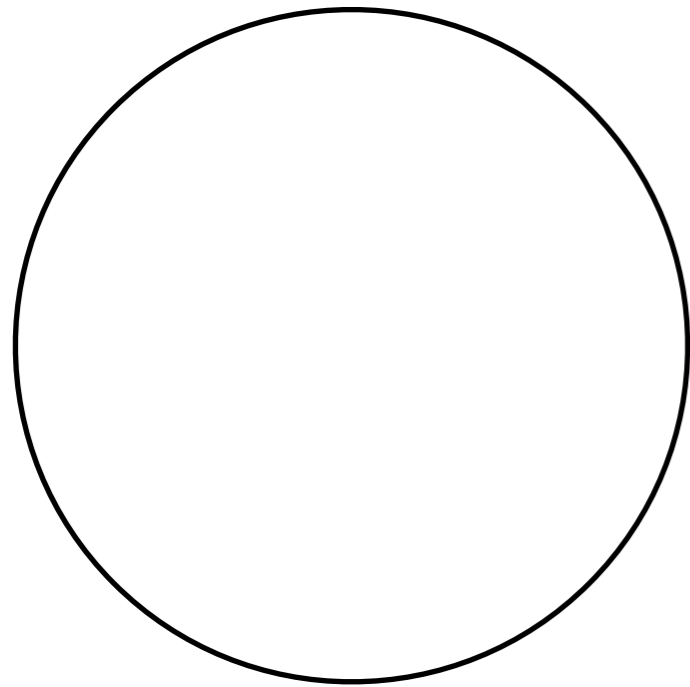
Magnetic Field

Quantum Field Theory

Photons
(very tiny particles,
see inside circle)

Magnetic Field
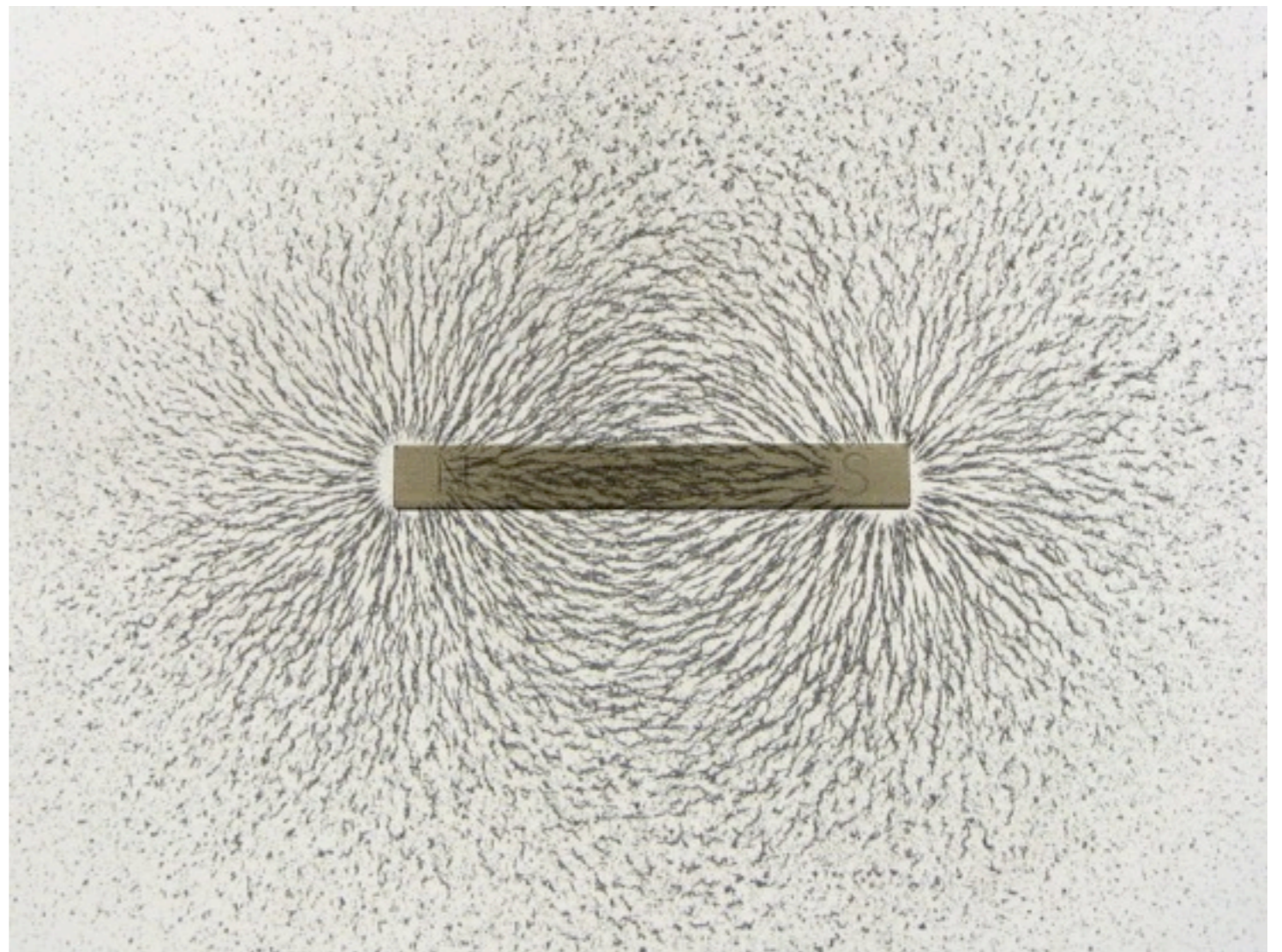
Particles are quantum excitations of fields.

Quantum Field Theory

Particle physics has many particles (fields) and many interactions.

The Standard Model

Three Generations of Matter (Fermions)

The Standard Model

The Standard Model

We understand this part fairly well.

The Standard Model

This part is harder to understand.

The Standard Model

So hard we only usually talk about these.

Mathematically (the Lagrangian) looks like this:
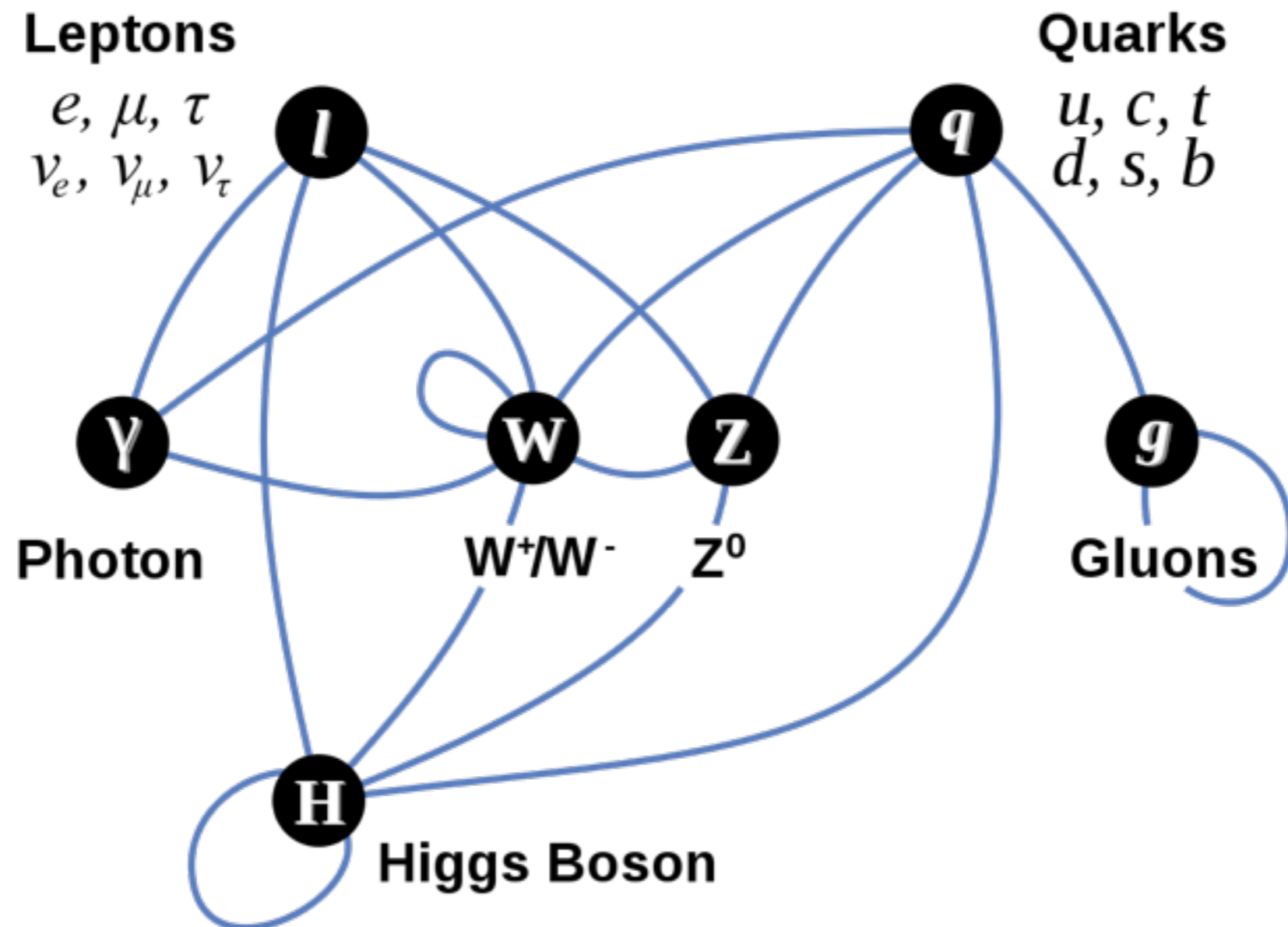
$$-\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g^2_s f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu +$$
$$\frac{1}{2}ig^2_s(\bar{q}^\sigma_i \gamma^\mu q^\sigma_j)g^a_\mu + \bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu -$$
$$M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c^2_w}M^2 Z^0_\mu Z^0_\mu - \frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\frac{1}{2}m^2_h H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \frac{1}{2c^2_w}M\phi^0 \phi^0 - \beta_h[\frac{2M^2}{g^2}+$$
$$\frac{2M}{g}H + \frac{1}{2}(H^2 + \phi^0 \phi^0 + 2\phi^+ \phi^-)] + \frac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu \partial_\nu W^-_\mu -$$
$$W^-_\nu \partial_\nu W^+_\mu)] - igs_w[\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu \partial_\nu W^-_\mu -$$
$$W^-_\mu \partial_\nu W^+_\mu) + A_\mu(W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2}g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2}g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c^2_w(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) +$$
$$g^2 s^2_w(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w[A_\mu Z^0_\nu(W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha[H^3 + H\phi^0 \phi^0 + 2H\phi^+ \phi^-] -$$
$$\frac{1}{8}g^2 \alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+ \phi^-)^2 + 4(\phi^0)^2 \phi^+ \phi^- + 4H^2 \phi^+ \phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW^+_\mu W^-_\mu H - \frac{1}{2}g\frac{M}{c_w}Z^0_\mu Z^0_\mu H - \frac{1}{2}ig[W^+_\mu(\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) -$$
$$W^-_\mu(\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2}g[W^+_\mu(H\partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu(H\partial_\mu \phi^+ -$$
$$\phi^+ \partial_\mu H)] + \frac{1}{2}g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu \phi^0 - \phi^0 \partial_\mu H) - ig\frac{s^2_w}{c_w}MZ^0_\mu(W^+_\mu \phi^- - W^-_\mu \phi^+) +$$
$$igs_w MA_\mu(W^+_\mu \phi^- - W^-_\mu \phi^+) - ig\frac{1-2c^2_w}{2c_w}Z^0_\mu(\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) +$$
$$igs_w A_\mu(\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) - \frac{1}{4}g^2 W^+_\mu W^-_\mu[H^2 + (\phi^0)^2 + 2\phi^+ \phi^-] -$$
$$\frac{1}{4}g^2 \frac{1}{c^2_w}Z^0_\mu Z^0_\mu[H^2 + (\phi^0)^2 + 2(2s^2_w - 1)^2 \phi^+ \phi^-] - \frac{1}{2}g^2 \frac{s^2_w}{c_w}Z^0_\mu \phi^0(W^+_\mu \phi^- +$$
$$W^-_\mu \phi^+) - \frac{1}{2}ig^2 \frac{s^2_w}{c_w}Z^0_\mu H(W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2}g^2 s_w A_\mu \phi^0(W^+_\mu \phi^- +$$
$$W^-_\mu \phi^+) + \frac{1}{2}ig^2 s_w A_\mu H(W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w}(2c^2_w - 1)Z^0_\mu A_\mu \phi^+ \phi^- -$$
$$g^1 s^2_w A_\mu A_\mu \phi^+ \phi^- - \bar{e}^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}^\lambda_j(\gamma\partial + m^\lambda_u)u^\lambda_j - \bar{d}^\lambda_j(\gamma\partial +$$
$$m^\lambda_d)d^\lambda_j + igs_w A_\mu[-(\bar{e}^\lambda \gamma e^\lambda) + \frac{2}{3}(\bar{u}^\lambda_j \gamma u^\lambda_j) - \frac{1}{3}(\bar{d}^\lambda_j \gamma d^\lambda_j)] + \frac{ig}{4c_w}Z^0_\mu[(\bar{\nu}^\lambda \gamma^\mu(1 +$$
$$\gamma^5)\nu^\lambda) + (\bar{e}^\lambda \gamma^\mu(4s^2_w - 1 - \gamma^5)e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu(\frac{4}{3}s^2_w - 1 - \gamma^5)u^\lambda_j) +$$
$$(\bar{d}^\lambda_j \gamma^\mu(1 - \frac{8}{3}s^2_w - \gamma^5)d^\lambda_j)] + \frac{ig}{2\sqrt{2}}W^+_\mu[(\bar{\nu}^\lambda \gamma^\mu(1 + \gamma^5)e^\lambda) + (\bar{u}^\lambda_j \gamma^\mu(1 +$$
$$\gamma^5)C_{\lambda\kappa}d^\kappa_j)] + \frac{ig}{2\sqrt{2}}W^-_\mu[(\bar{e}^\lambda \gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}^\kappa_j C^\dagger_{\lambda\kappa}\gamma^\mu(1 + \gamma^5)u^\lambda_j)] +$$
$$\frac{ig}{2\sqrt{2}}\frac{m^\lambda_e}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \frac{g}{2}\frac{m^\lambda_e}{M}[H(\bar{e}^\lambda e^\lambda) +$$
$$i\phi^0(\bar{e}^\lambda \gamma^5 e^\lambda)] + \frac{ig}{2M\sqrt{2}}\phi^+[-m^\kappa_d(\bar{u}^\lambda_j C_{\lambda\kappa}(1 - \gamma^5)d^\kappa_j) + m^\lambda_u(\bar{u}^\lambda_j C_{\lambda\kappa}(1 +$$
$$\gamma^5)d^\kappa_j] + \frac{ig}{2M\sqrt{2}}\phi^-[m^\lambda_d(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 + \gamma^5)u^\kappa_j) - m^\kappa_u(\bar{d}^\lambda_j C^\dagger_{\lambda\kappa}(1 - \gamma^5)u^\kappa_j] -$$
$$\frac{g}{2}\frac{m^\lambda_u}{M}H(\bar{u}^\lambda_j u^\lambda_j) - \frac{g}{2}\frac{m^\lambda_d}{M}H(\bar{d}^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar{u}^\lambda_j \gamma^5 u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar{d}^\lambda_j \gamma^5 d^\lambda_j) +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \frac{M^2}{c^2_w})X^0 + \bar{Y}\partial^2 Y +$$
$$igc_w W^+_\mu(\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + igs_w W^+_\mu(\partial_\mu \bar{Y}X^- - \partial_\mu \bar{X}^+ Y) +$$
$$igc_w W^-_\mu(\partial_\mu \bar{X}^- X^0 - \partial_\mu \bar{X}^0 X^+) + igs_w W^-_\mu(\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y}X^+) +$$
$$igc_w Z^0_\mu(\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) + igs_w A_\mu(\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) -$$
$$\frac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \frac{1}{c^2_w}\bar{X}^0 X^0 H] + \frac{1-2c^2_w}{2c_w}igM[\bar{X}^+ X^0 \phi^+ -$$
$$\bar{X}^- X^0 \phi^-] + \frac{1}{2c_w}igM[\bar{X}^0 X^- \phi^+ - \bar{X}^0 X^+ \phi^-] + igMs_w[\bar{X}^0 X^- \phi^+ -$$
$$\bar{X}^0 X^+ \phi^-] + \frac{1}{2}igM[\bar{X}^+ X^+ \phi^0 - \bar{X}^- X^- \phi^0]$$

Mathematically (the Lagrangian) looks like this:

How do we build these kinds of models?

$$-\tfrac{1}{2}\partial_\nu g_\mu^a \partial_\nu g_\mu^a - g_s f^{abc}\partial_\mu g_\nu^a g_\mu^b g_\nu^c - \tfrac{1}{4}g_s^2 f^{abc}f^{adc} g_\mu^b g_\nu^c g_\mu^d g_\nu^e +$$
$$\tfrac{1}{2}ig_s^2(\bar{q}_i^\sigma \gamma^\mu q_j^\sigma)g_\mu^a + \bar{G}^a\partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g_\mu^c - \partial_\nu W_\mu^+ \partial_\nu W_\mu^- -$$
$$M^2 W_\mu^+ W_\mu^- - \tfrac{1}{2}\partial_\nu Z_\mu^0 \partial_\nu Z_\mu^0 - \tfrac{1}{2c_w^2}M^2 Z_\mu^0 Z_\mu^0 - \tfrac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \tfrac{1}{2}\partial_\mu H \partial_\mu H -$$
$$\tfrac{1}{2}m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2\phi^+\phi^- - \tfrac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 - \tfrac{1}{2c_w^2}M\phi^0\phi^0 - \beta_h[\tfrac{2M^2}{g^2} +$$
$$\tfrac{2M}{g}H + \tfrac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)] + \tfrac{2M^4}{g^2}\alpha_h - igc_w[\partial_\nu Z_\mu^0(W_\mu^+ W_\nu^- -$$
$$W_\nu^+ W_\mu^-) - Z_\nu^0(W_\mu^+\partial_\nu W_\mu^- - W_\mu^-\partial_\nu W_\mu^+) + Z_\mu^0(W_\nu^+\partial_\nu W_\mu^- -$$
$$W_\nu^-\partial_\nu W_\mu^+)] - igs_w[\partial_\nu A_\mu(W_\mu^+ W_\nu^- - W_\nu^+ W_\mu^-) - A_\nu(W_\mu^+\partial_\nu W_\mu^- -$$
$$W_\mu^-\partial_\nu W_\mu^+) + A_\mu(W_\nu^+\partial_\nu W_\mu^- - W_\nu^-\partial_\nu W_\mu^+)] - \tfrac{1}{2}g^2 W_\mu^+ W_\mu^- W_\nu^+ W_\nu^- +$$
$$\tfrac{1}{2}g^2 W_\mu^+ W_\nu^- W_\mu^+ W_\nu^- + g^2 c_w^2(Z_\mu^0 W_\mu^+ Z_\nu^0 W_\nu^- - Z_\mu^0 Z_\mu^0 W_\nu^+ W_\nu^-) +$$
$$g^2 s_w^2(A_\mu W_\mu^+ A_\nu W_\nu^- - A_\mu A_\mu W_\nu^+ W_\nu^-) + g^2 s_w c_w[A_\mu Z_\nu^0(W_\mu^+ W_\nu^- -$$
$$W_\nu^+ W_\mu^-) - 2A_\mu Z_\mu^0 W_\nu^+ W_\nu^-] - g\alpha[H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-] -$$
$$\tfrac{1}{8}g^2\alpha_h[H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2 H^2] -$$
$$gMW_\mu^+ W_\mu^- H - \tfrac{1}{2}g\tfrac{M}{c_w}Z_\mu^0 Z_\mu^0 H - \tfrac{1}{2}ig[W_\mu^+(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) -$$
$$W_\mu^-(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)] + \tfrac{1}{2}g[W_\mu^+(H\partial_\mu\phi^- - \phi^-\partial_\mu H) - W_\mu^-(H\partial_\mu\phi^+ -$$
$$\phi^+\partial_\mu H)] + \tfrac{1}{2}g\tfrac{1}{c_w}(Z_\mu^0(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) - ig\tfrac{s_w^2}{c_w}MZ_\mu^0(W_\mu^+\phi^- - W_\mu^-\phi^+) +$$
$$igs_w MA_\mu(W_\mu^+\phi^- - W_\mu^-\phi^+) - ig\tfrac{1-2c_w^2}{2c_w}Z_\mu^0(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) +$$
$$igs_w A_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \tfrac{1}{4}g^2 W_\mu^+ W_\mu^-[H^2 + (\phi^0)^2 + 2\phi^+\phi^-] -$$
$$\tfrac{1}{4}g^2\tfrac{1}{c_w^2}Z_\mu^0 Z_\mu^0[H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2\phi^+\phi^-] - \tfrac{1}{2}g^2\tfrac{s_w^2}{c_w}Z_\mu^0\phi^0(W_\mu^+\phi^- +$$
$$W_\mu^-\phi^+) - \tfrac{1}{2}ig^2\tfrac{s_w^2}{c_w}Z_\mu^0 H(W_\mu^+\phi^- - W_\mu^-\phi^+) + \tfrac{1}{2}g^2 s_w A_\mu\phi^0(W_\mu^+\phi^- +$$
$$W_\mu^-\phi^+) + \tfrac{1}{2}ig^2 s_w A_\mu H(W_\mu^+\phi^- - W_\mu^-\phi^+) - g^2\tfrac{s_w}{c_w}(2c_w^2 - 1)Z_\mu^0 A_\mu\phi^+\phi^- -$$
$$g^1 s_w^2 A_\mu A_\mu\phi^+\phi^- - \bar{e}^\lambda(\gamma\partial + m_e^\lambda)e^\lambda - \bar{\nu}^\lambda\gamma\partial\nu^\lambda - \bar{u}_j^\lambda(\gamma\partial + m_u^\lambda)u_j^\lambda - \bar{d}_j^\lambda(\gamma\partial +$$
$$m_d^\lambda)d_j^\lambda + igs_w A_\mu[-(\bar{e}^\lambda\gamma e^\lambda) + \tfrac{2}{3}(\bar{u}_j^\lambda\gamma u_j^\lambda) - \tfrac{1}{3}(\bar{d}_j^\lambda\gamma d_j^\lambda)] + \tfrac{ig}{4c_w}Z_\mu^0[(\bar{\nu}^\lambda\gamma^\mu(1 +$$
$$\gamma^5)\nu^\lambda) + (\bar{e}^\lambda\gamma^\mu(4s_w^2 - 1 - \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(\tfrac{4}{3}s_w^2 - 1 - \gamma^5)u_j^\lambda) +$$
$$(\bar{d}_j^\lambda\gamma^\mu(1 - \tfrac{8}{3}s_w^2 - \gamma^5)d_j^\lambda)] + \tfrac{ig}{2\sqrt{2}}W_\mu^+[(\bar{\nu}^\lambda\gamma^\mu(1 + \gamma^5)e^\lambda) + (\bar{u}_j^\lambda\gamma^\mu(1 +$$
$$\gamma^5)C_{\lambda\kappa}d_j^\kappa)] + \tfrac{ig}{2\sqrt{2}}W_\mu^-[(\bar{e}^\lambda\gamma^\mu(1 + \gamma^5)\nu^\lambda) + (\bar{d}_j^\kappa C_{\lambda\kappa}^\dagger\gamma^\mu(1 + \gamma^5)u_j^\lambda)] +$$
$$\tfrac{ig}{2\sqrt{2}}\tfrac{m_e^\lambda}{M}[-\phi^+(\bar{\nu}^\lambda(1 - \gamma^5)e^\lambda) + \phi^-(\bar{e}^\lambda(1 + \gamma^5)\nu^\lambda)] - \tfrac{g}{2}\tfrac{m_e^\lambda}{M}[H(\bar{e}^\lambda e^\lambda) +$$
$$i\phi^0(\bar{e}^\lambda\gamma^5 e^\lambda)] + \tfrac{ig}{2M\sqrt{2}}\phi^+[-m_d^\kappa(\bar{u}_j^\lambda C_{\lambda\kappa}(1 - \gamma^5)d_j^\kappa) + m_u^\lambda(\bar{u}_j^\lambda C_{\lambda\kappa}(1 +$$
$$\gamma^5)d_j^\kappa] + \tfrac{ig}{2M\sqrt{2}}\phi^-[m_d^\lambda(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1 + \gamma^5)u_j^\kappa) - m_u^\kappa(\bar{d}_j^\lambda C_{\lambda\kappa}^\dagger(1 - \gamma^5)u_j^\kappa] -$$
$$\tfrac{g}{2}\tfrac{m_h^\lambda}{M}H(\bar{u}_j^\lambda u_j^\lambda) - \tfrac{g}{2}\tfrac{m_d^\lambda}{M}H(\bar{d}_j^\lambda d_j^\lambda) + \tfrac{ig}{2}\tfrac{m_u^\lambda}{M}\phi^0(\bar{u}_j^\lambda\gamma^5 u_j^\lambda) - \tfrac{ig}{2}\tfrac{m_d^\lambda}{M}\phi^0(\bar{d}_j^\lambda\gamma^5 d_j^\lambda) +$$
$$\bar{X}^+(\partial^2 - M^2)X^+ + \bar{X}^-(\partial^2 - M^2)X^- + \bar{X}^0(\partial^2 - \tfrac{M^2}{c_w^2})X^0 + \bar{Y}\partial^2 Y +$$
$$igc_w W_\mu^+(\partial_\mu\bar{X}^0 X^- - \partial_\mu\bar{X}^+ X^0) + igs_w W_\mu^+(\partial_\mu\bar{Y}X^- - \partial_\mu\bar{X}^+ Y) +$$
$$igc_w W_\mu^-(\partial_\mu\bar{X}^- X^0 - \partial_\mu\bar{X}^0 X^+) + igs_w W_\mu^-(\partial_\mu\bar{X}^- Y - \partial_\mu\bar{Y}X^+) +$$
$$igc_w Z_\mu^0(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) + igs_w A_\mu(\partial_\mu\bar{X}^+ X^+ - \partial_\mu\bar{X}^- X^-) -$$
$$\tfrac{1}{2}gM[\bar{X}^+ X^+ H + \bar{X}^- X^- H + \tfrac{1}{c_w^2}\bar{X}^0 X^0 H] + \tfrac{1-2c_w^2}{2c_w}igM[\bar{X}^+ X^0\phi^+ -$$
$$\bar{X}^- X^0\phi^-] + \tfrac{1}{2c_w}igM[\bar{X}^0 X^-\phi^+ - \bar{X}^0 X^+\phi^-] + igM s_w[\bar{X}^0 X^-\phi^+ -$$
$$\bar{X}^0 X^+\phi^-] + \tfrac{1}{2}igM[\bar{X}^+ X^+\phi^0 - \bar{X}^- X^-\phi^0]$$

Symmetries!

Cliché Henri Manuel

Henri Poincaré

Symmetries!

- A symmetry is a transformation that doesn't change the physics.

Henri Poincaré

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- What are some examples of symmetries?

Cliché Henri Manuel

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- What are some examples of symmetries?

- We build our models such that they obey the observed symmetries of nature.

- Collection of spacetime symmetries is called the Poincaré Group.

Cliché Henri Manuel

Henri Poincaré

Conserved Charges!

Emmy Noether

- The symmetries of nature imply a quantity is conserved.

Conserved Charges!

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- What are some conserved quantities?

Conserved Charges!

Emmy Noether

- The symmetries of nature imply a quantity is conserved.

- What are some conserved quantities?

- What symmetry are they associated with?

| Class	Invariance	Conserved quantity
Proper orthochronous Lorentz symmetry	translation in time (homogeneity)	energy
	translation in space (homogeneity)	linear momentum
	rotation in space (isotropy)	angular momentum
Discrete symmetry	P, coordinate inversion	spatial parity
	C, charge conjugation	charge parity
	T, time reversal	time parity
	CPT	product of parities
Internal symmetry (independent of spacetime coordinates)	U(1) gauge transformation	electric charge
	U(1) gauge transformation	lepton generation number
	U(1) gauge transformation	hypercharge
	U(1)$_Y$ gauge transformation	weak hypercharge
	U(2) [U(1) × SU(2)]	electroweak force
	SU(2) gauge transformation	isospin
	SU(2)$_L$ gauge transformation	weak isospin
	P × SU(2)	G-parity
	SU(3) "winding number"	baryon number
	SU(3) gauge transformation	quark color
	SU(3) (approximate)	quark flavor
	S(U(2) × U(3)) [U(1) × SU(2) × SU(3)]	Standard Model

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These three
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Poincare Group

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	SU(2) gauge transformation	isospin
	$SU(2)_L$ gauge transformation	weak isospin
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	SU(3) (approximate)	quark flavor
	S(U(2) × U(3)) [U(1) × SU(2) × SU(3)]	Standard Model

These three are the Poincare Group

These three gauge symmetries make the Standard Model

Symmetries are not always symmetries!
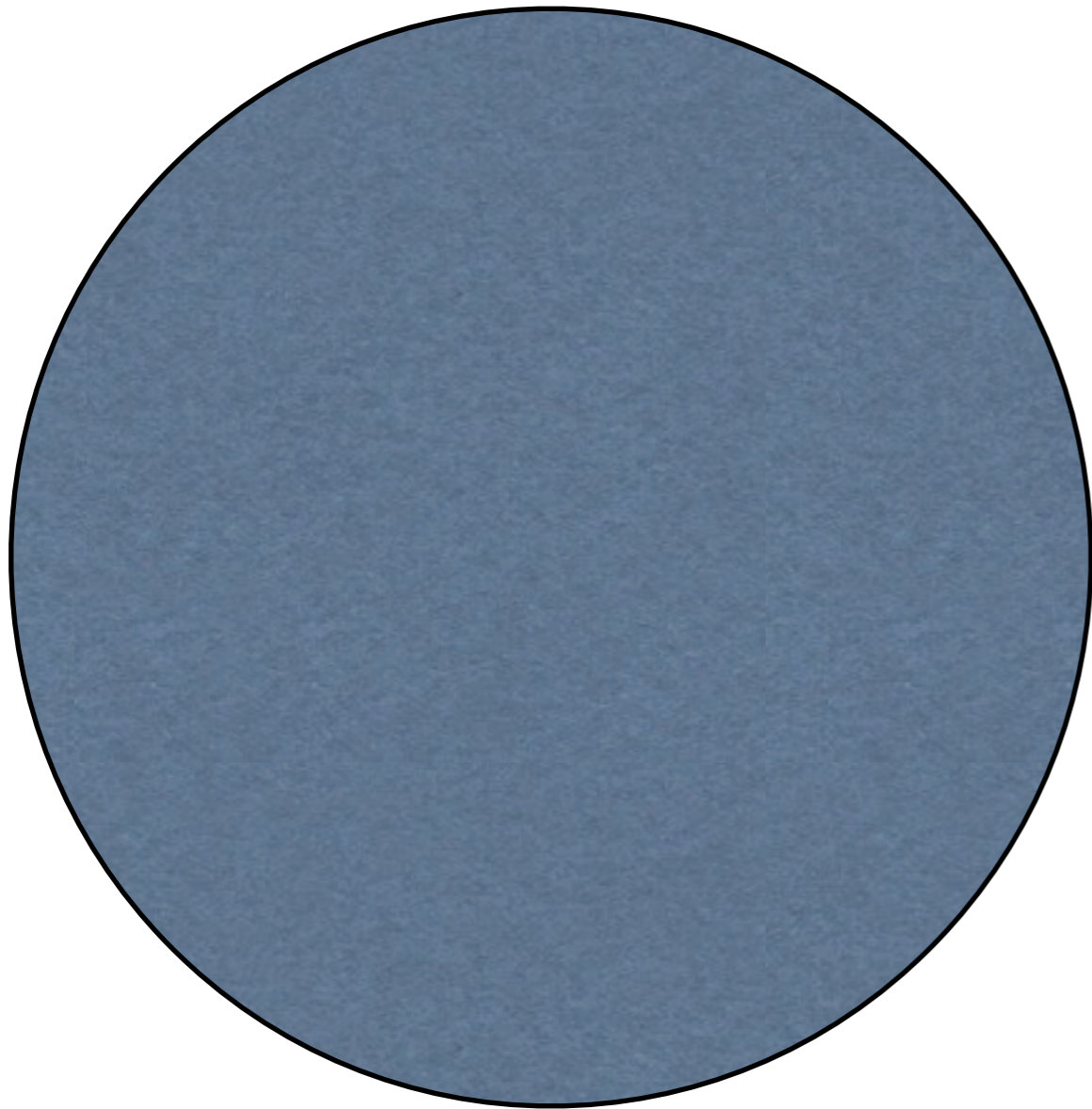
Symmetries are not always symmetries!
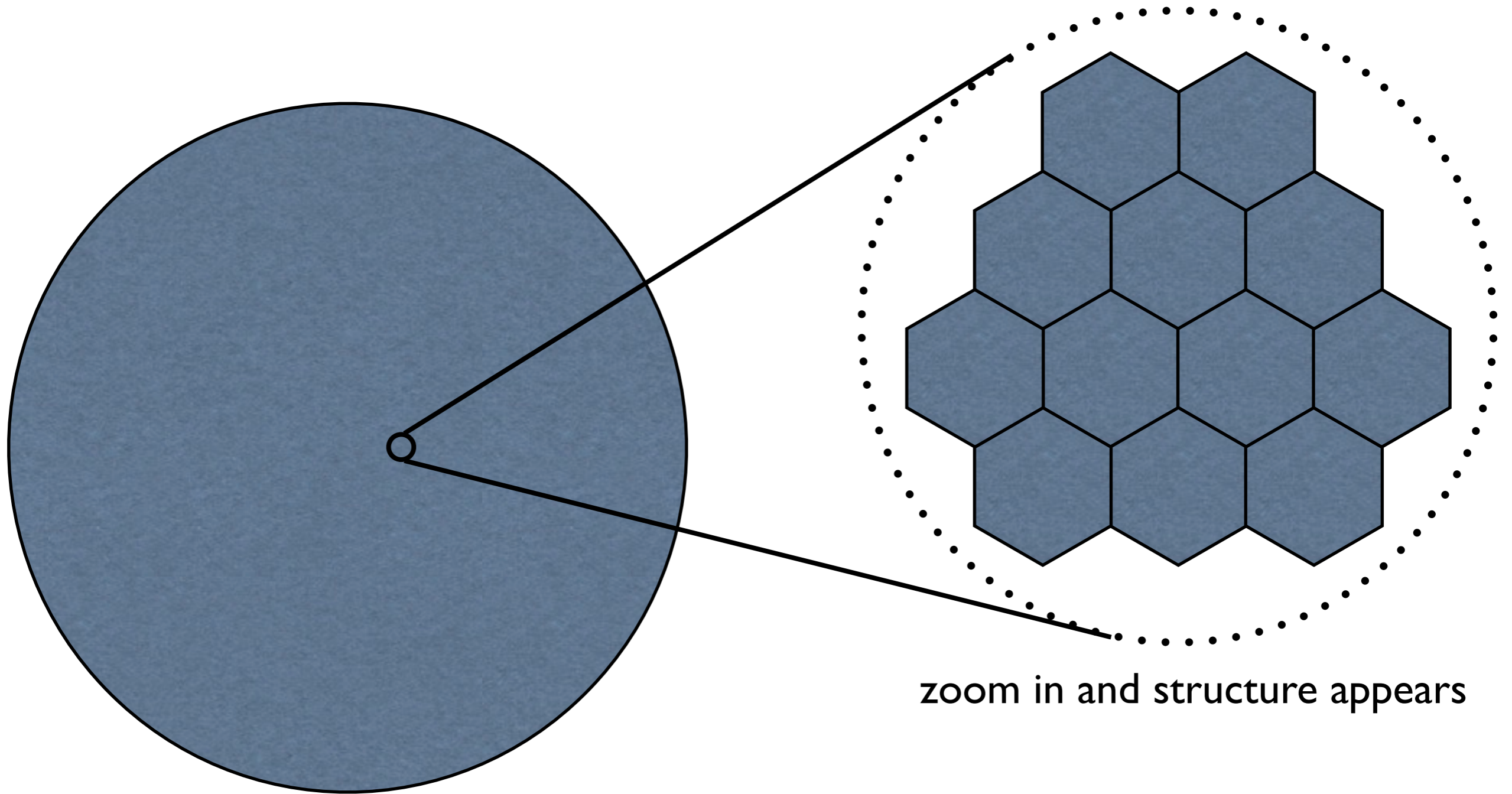
zoom in and structure appears

Symmetries are not always symmetries!
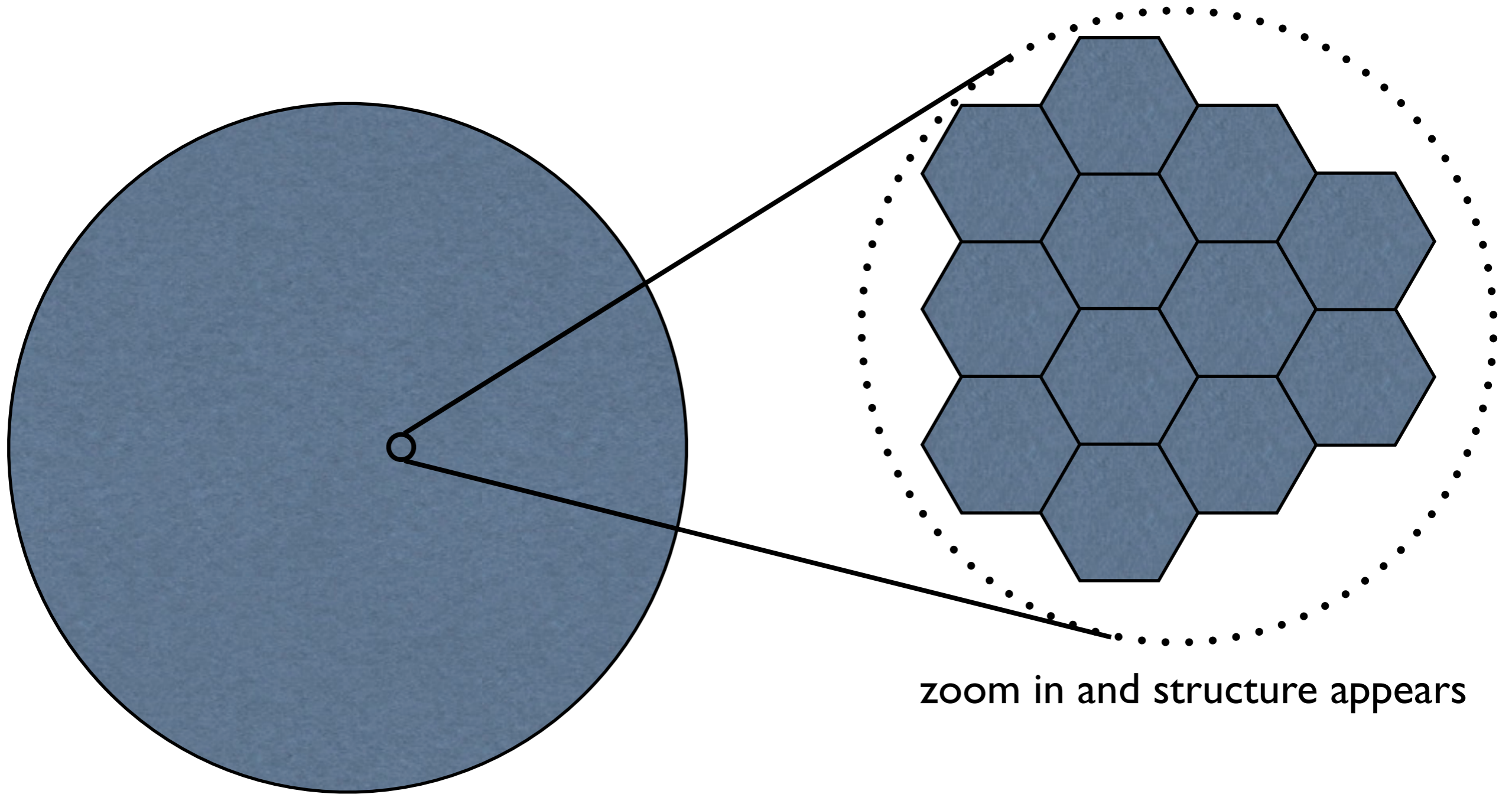
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Symmetries are not always symmetries!
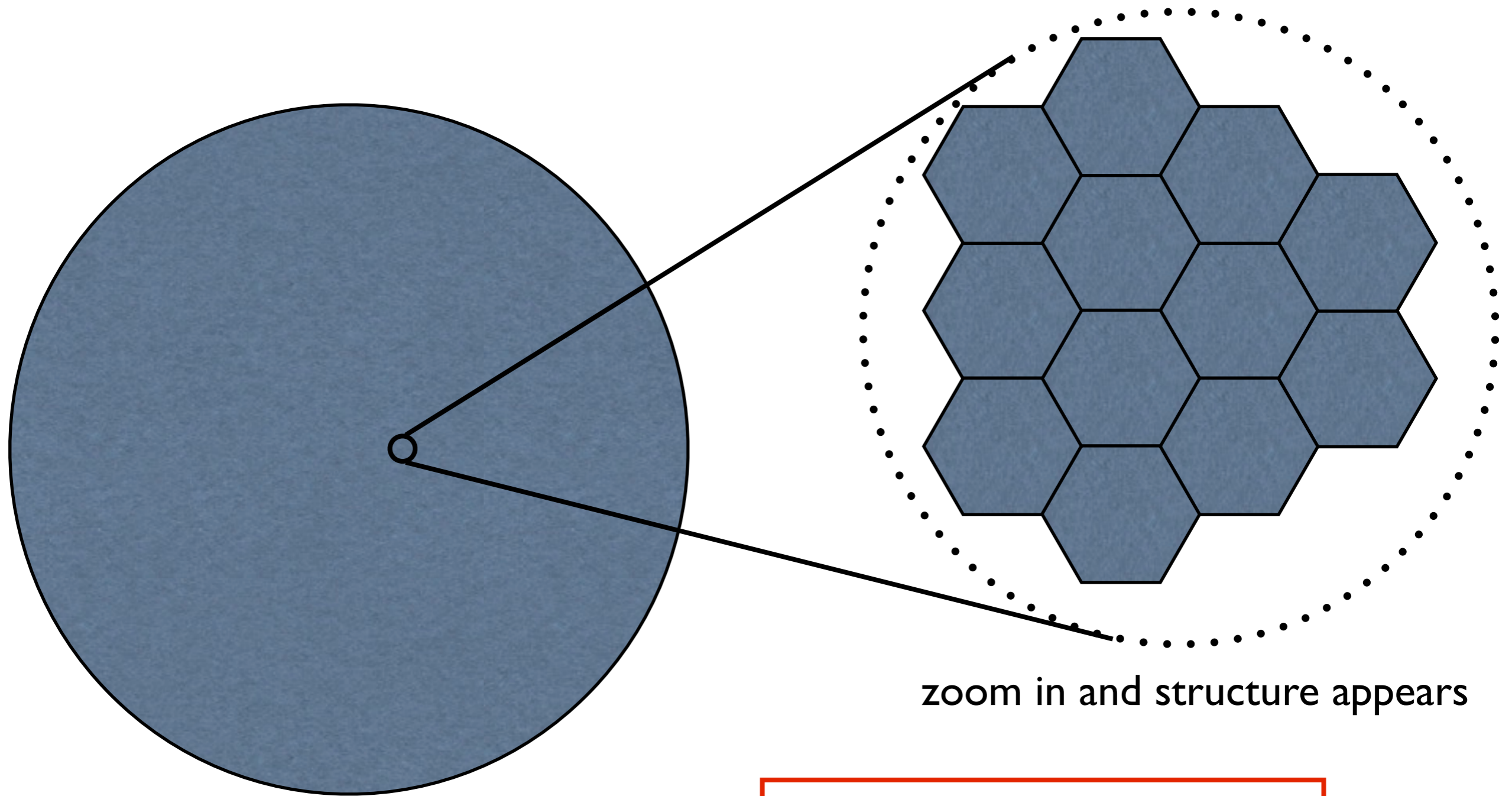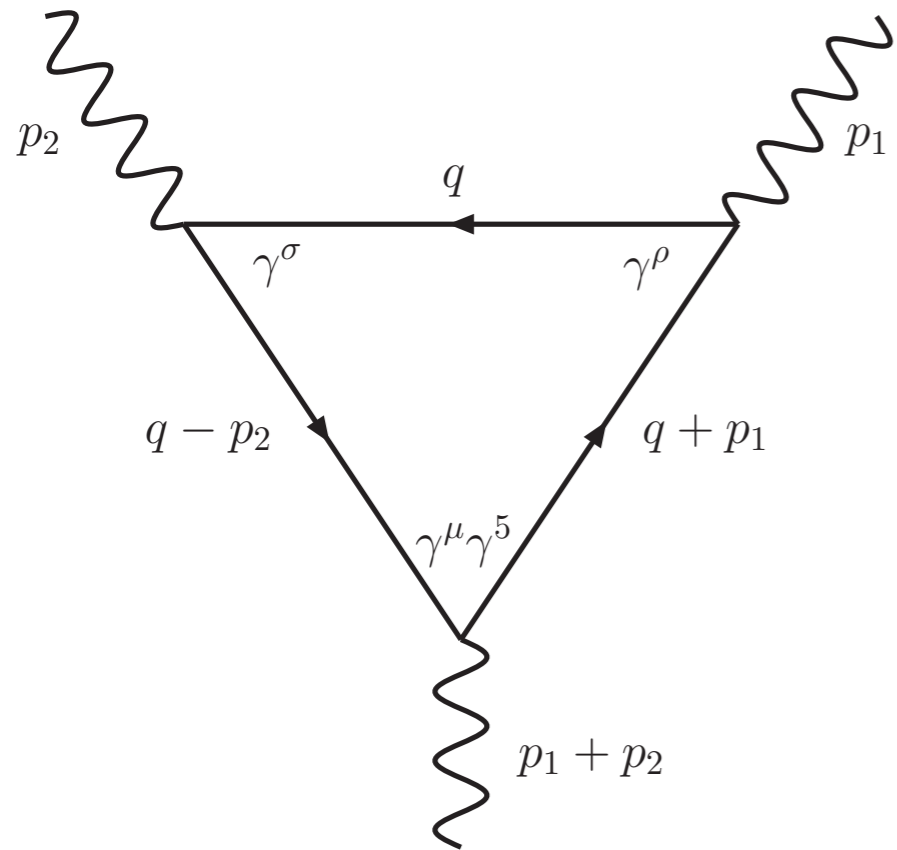
zoom in and structure appears

Quantum effects break the
classical symmetry!

Anomalies:
Symmetries Broken by Quantum Effects

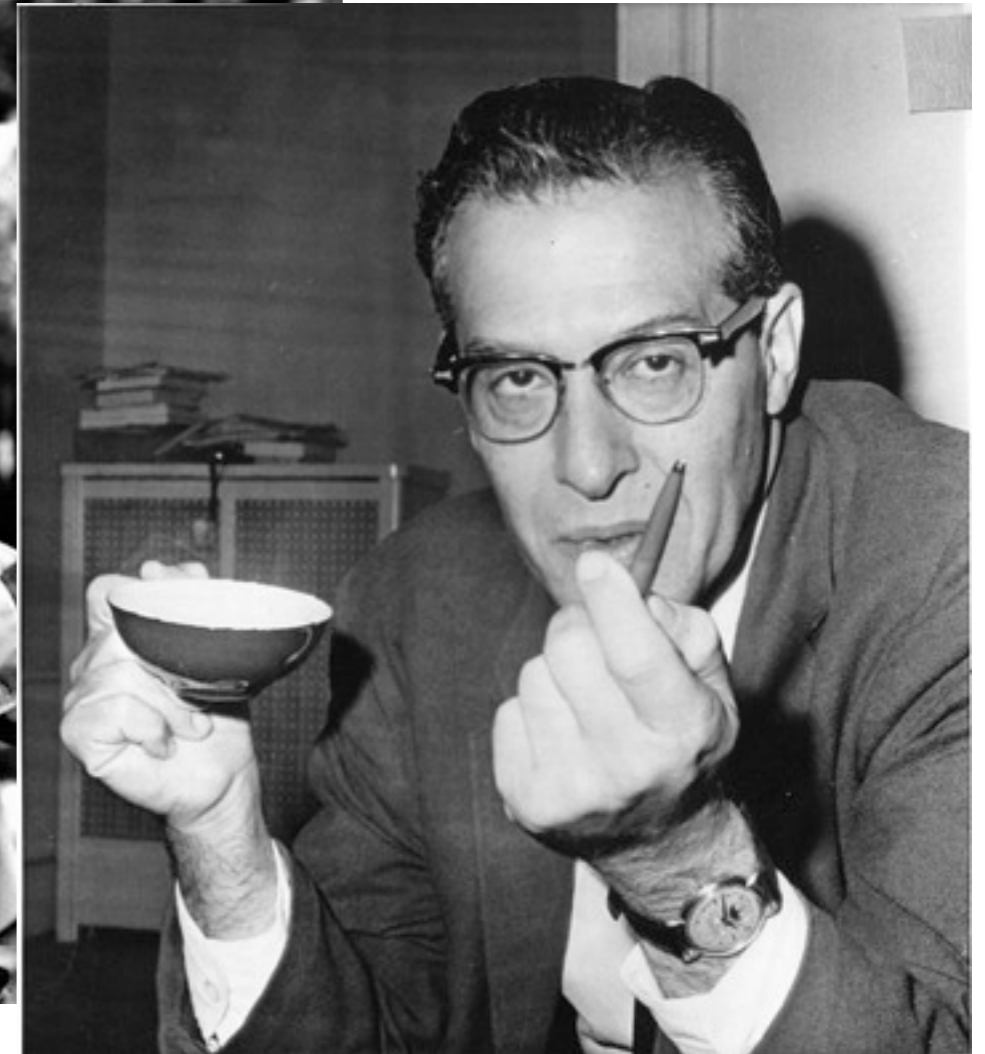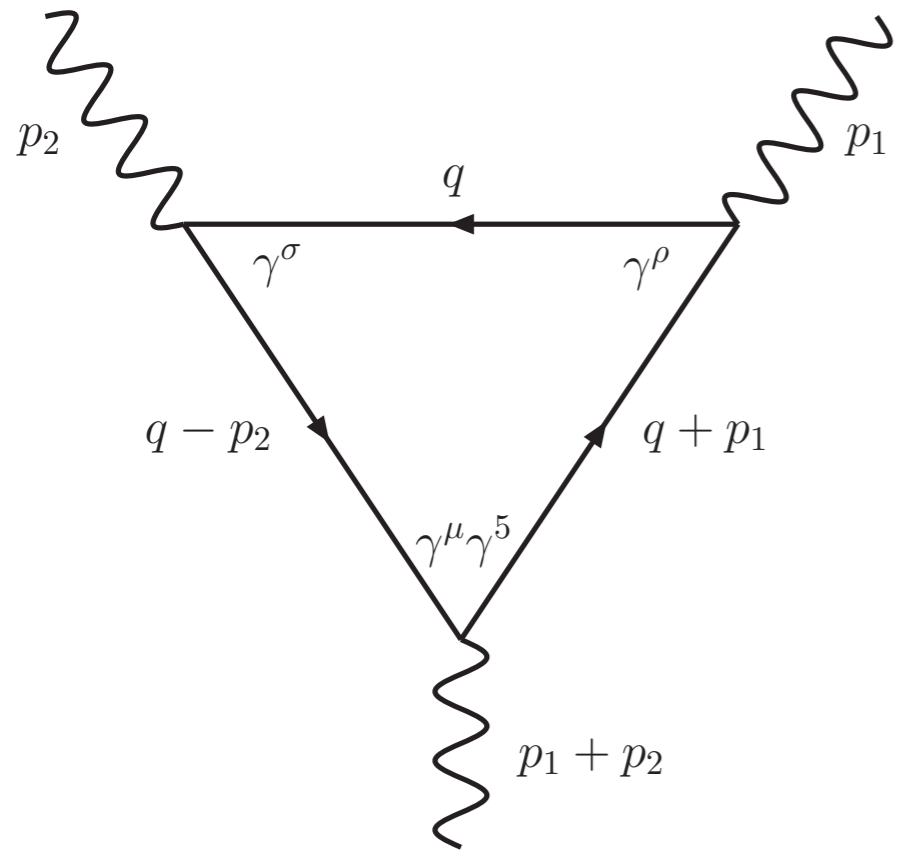# Anomalies:
Symmetries Broken by Quantum Effects
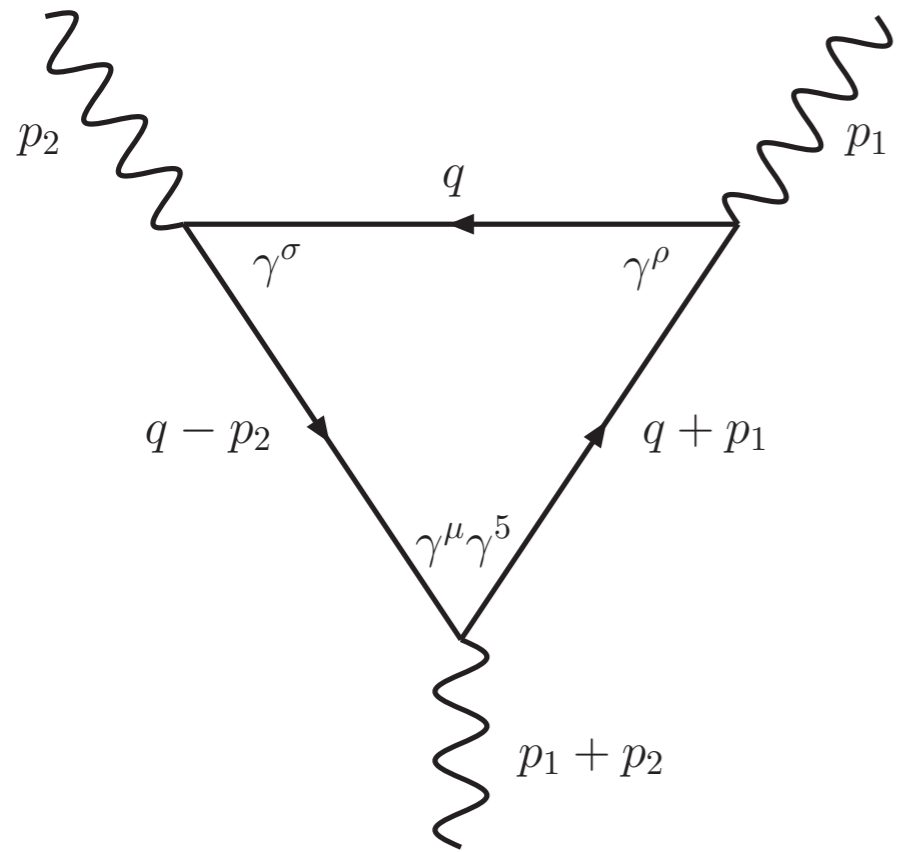
Anomalies:
Symmetries Broken by Quantum Effects
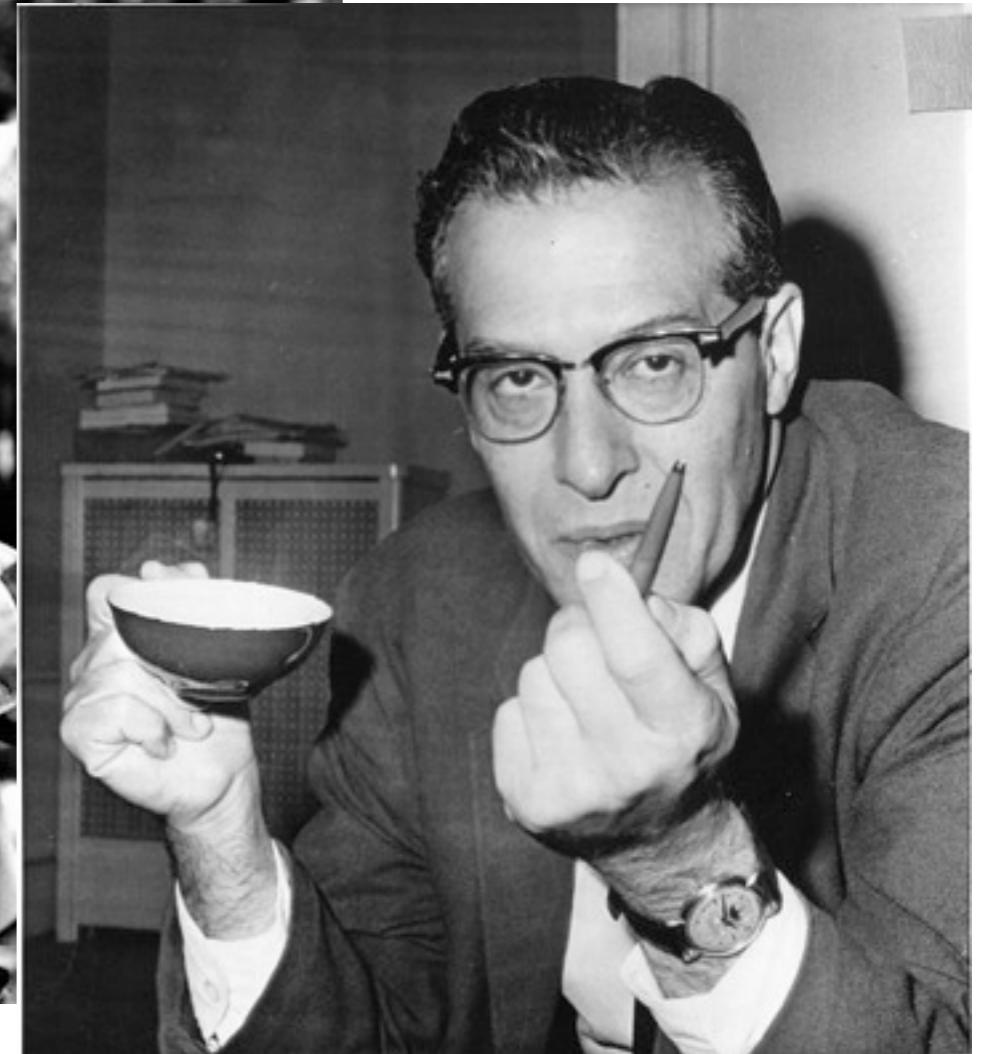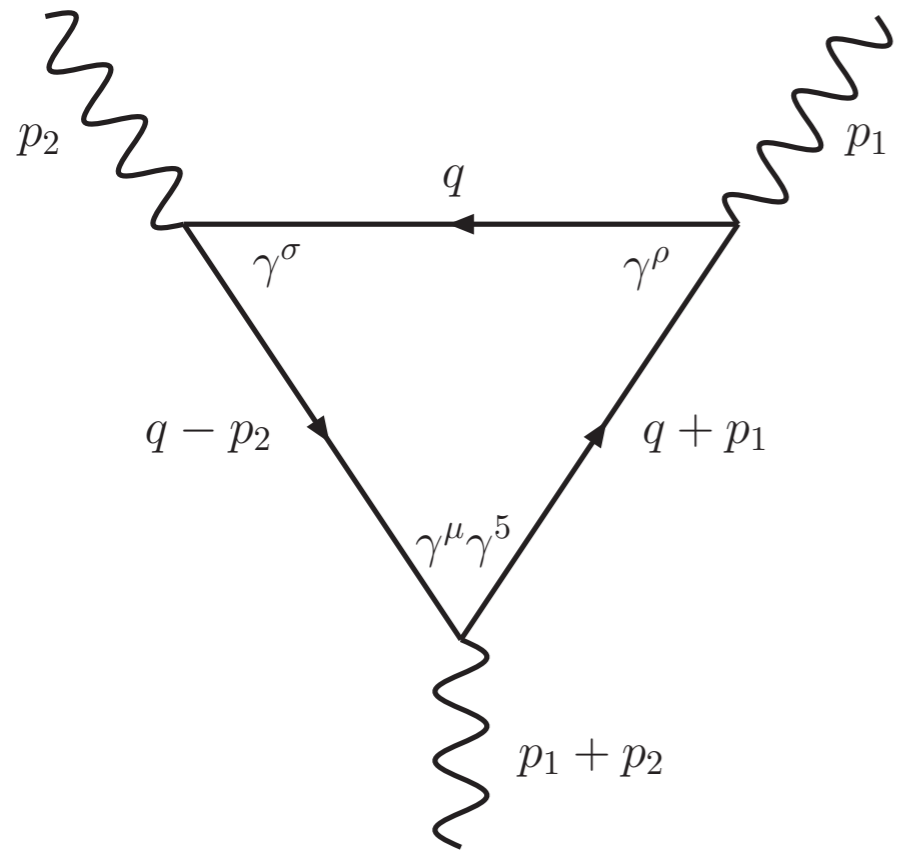
Anomalies:
Symmetries Broken by Quantum Effects

$$S^{\mu\rho\sigma}(p_1, p_2) = -(-ie)^2 \int \frac{d^4q}{(2\pi)^4} \text{Tr}\left[\gamma^\mu \gamma^5 \frac{i}{\slashed{q}+\slashed{p}_2} \gamma^\sigma \frac{i}{\slashed{q}} \gamma^\rho \frac{i}{\slashed{q}-\slashed{p}_1}\right]$$

Anomalies:
Symmetries Broken by Quantum Effects

p_2

q

γ^σ

γ^ρ

p_1

$q - p_2$

$q + p_1$

$\gamma^\mu \gamma^5$

$p_1 + p_2$

For example, gauge symmetries are broken.

Internal symmetry (independent of spacetime coordinates)	U(1) gauge transformation	electric charge

Anomalies:
Symmetries Broken by Quantum Effects
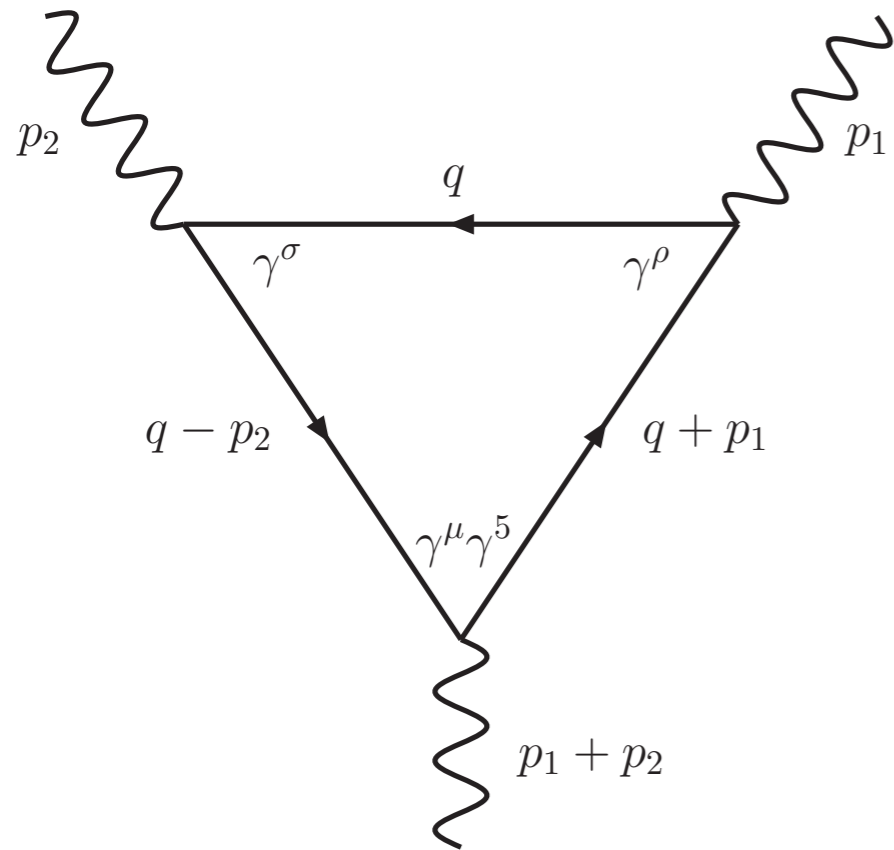
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Classically we have the continuity equation,

$$\partial_\mu J^\mu = \frac{\partial \rho}{\partial t} + \nabla \cdot \vec{J} = 0,$$

Anomalies:
Symmetries Broken by Quantum Effects
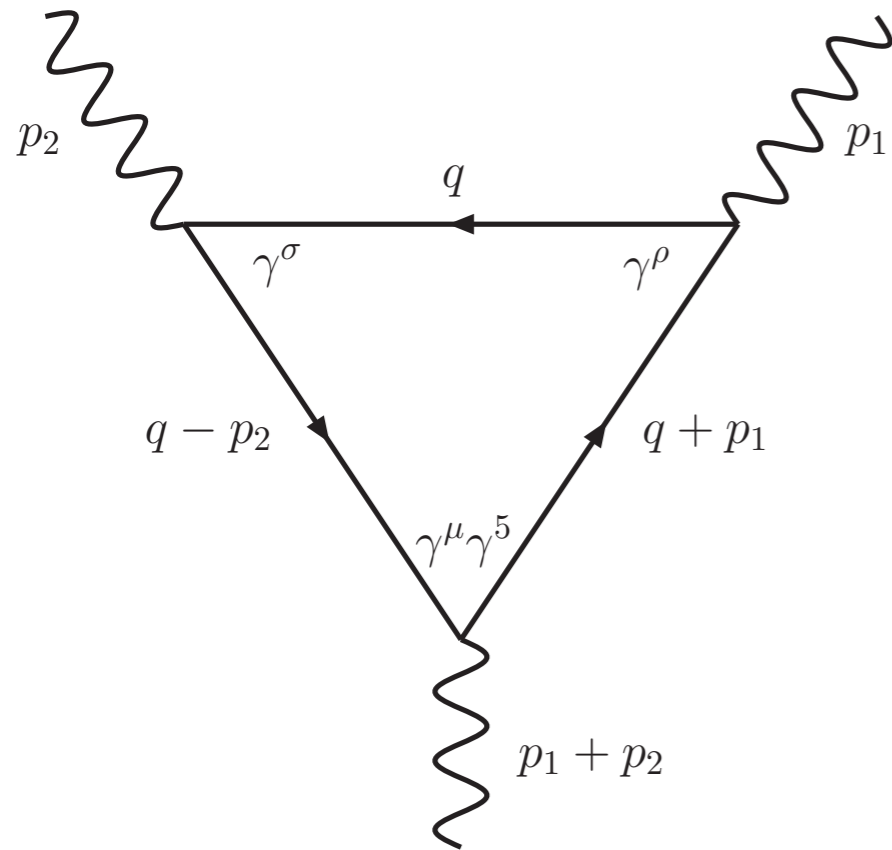
For example, gauge symmetries are broken.

Internal symmetry (independent of spacetime coordinates)	U(1) gauge transformation	electric charge

Classically we have the continuity equation,

$$\partial_\mu J^\mu = \frac{\partial \rho}{\partial t} + \nabla \cdot \vec{J} = 0,$$

but with quantum corrections,

$$\partial_\mu J^\mu = -\frac{1}{8\pi^2} \epsilon^{\mu\nu\rho\sigma} A_{\mu\nu} V_{\rho\sigma}.$$

But they're not always bad!

Chirality
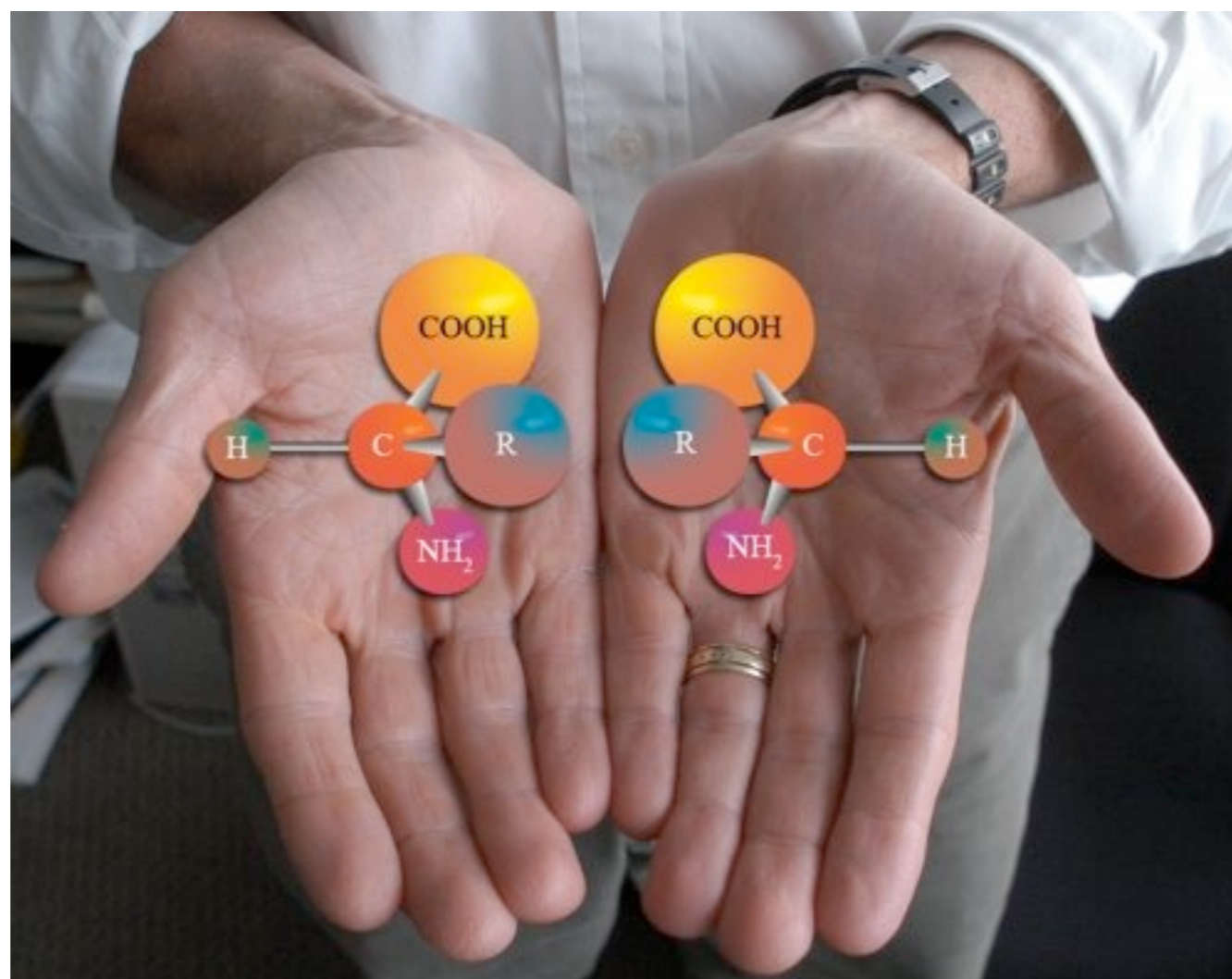
The "handedness" of an object.

Chirality

The "handedness" of an object.
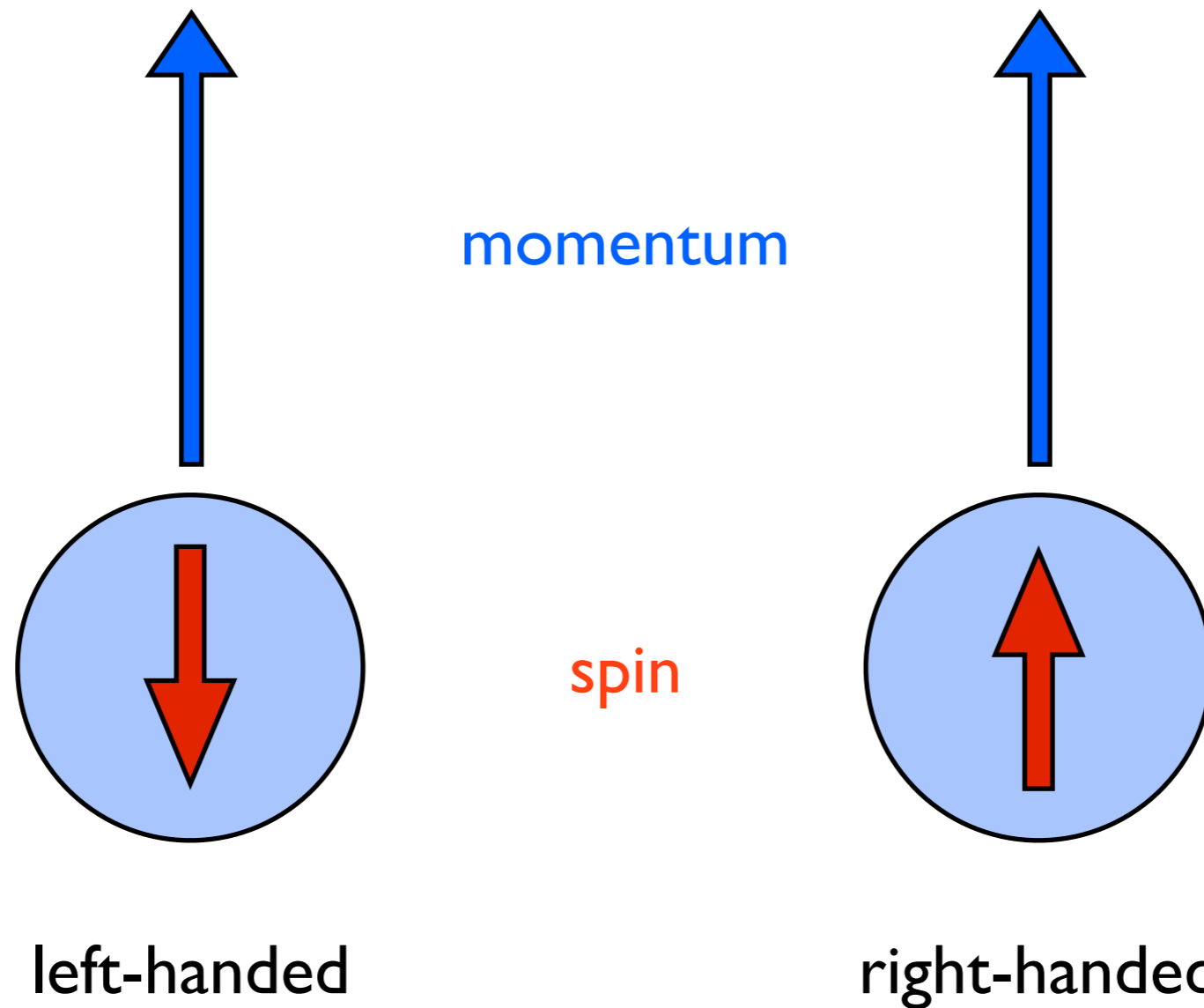
momentum

spin

left-handed   right-handed

Chirality

The "handedness" of an object.

momentum

spin

left-handed   right-handed
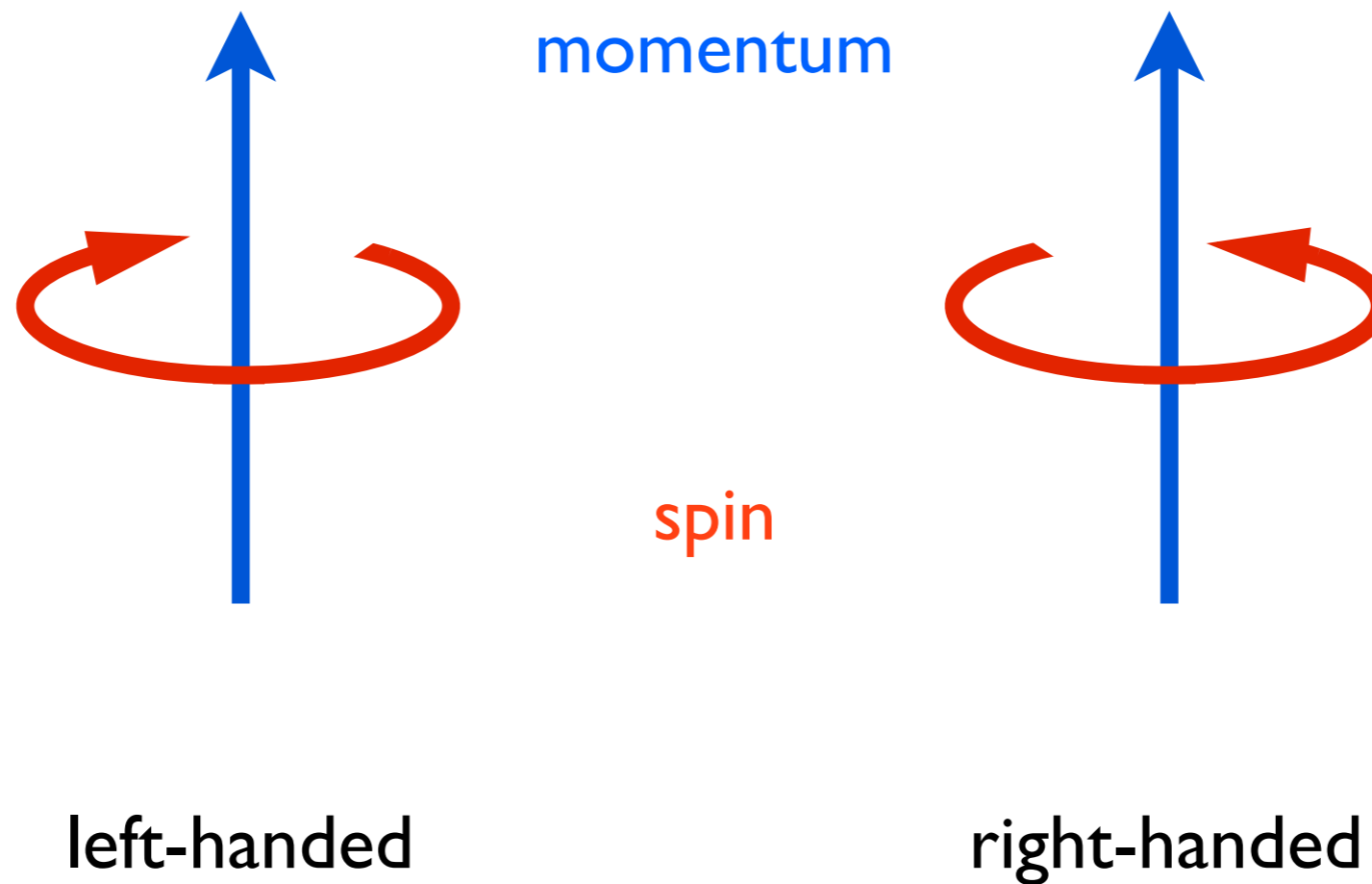
Parity Symmetry

Parity transformation is like looking in a mirror.
(flips chirality)
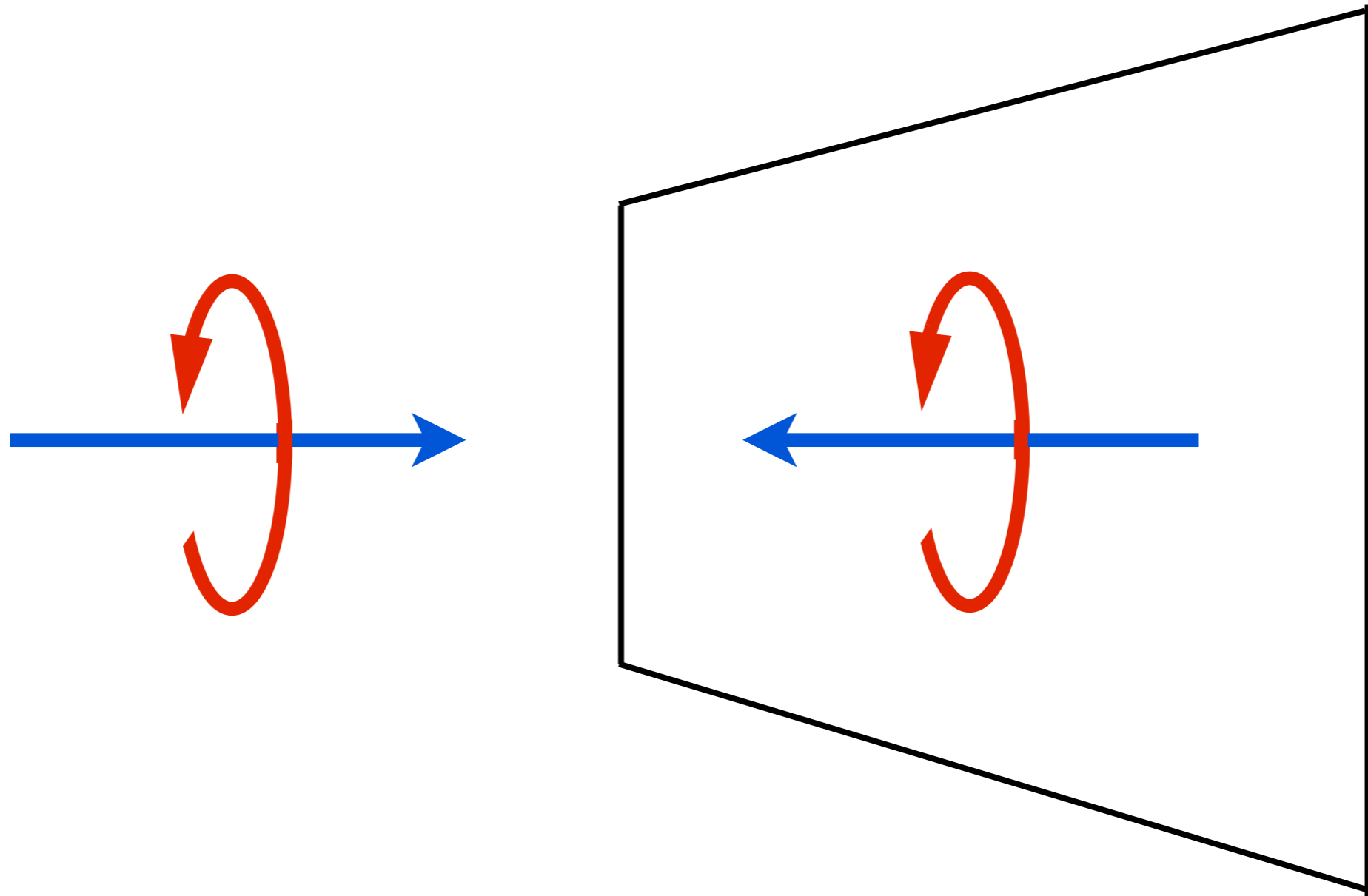
Parity Symmetry

Parity transformation is like looking in a mirror.
(flips chirality)
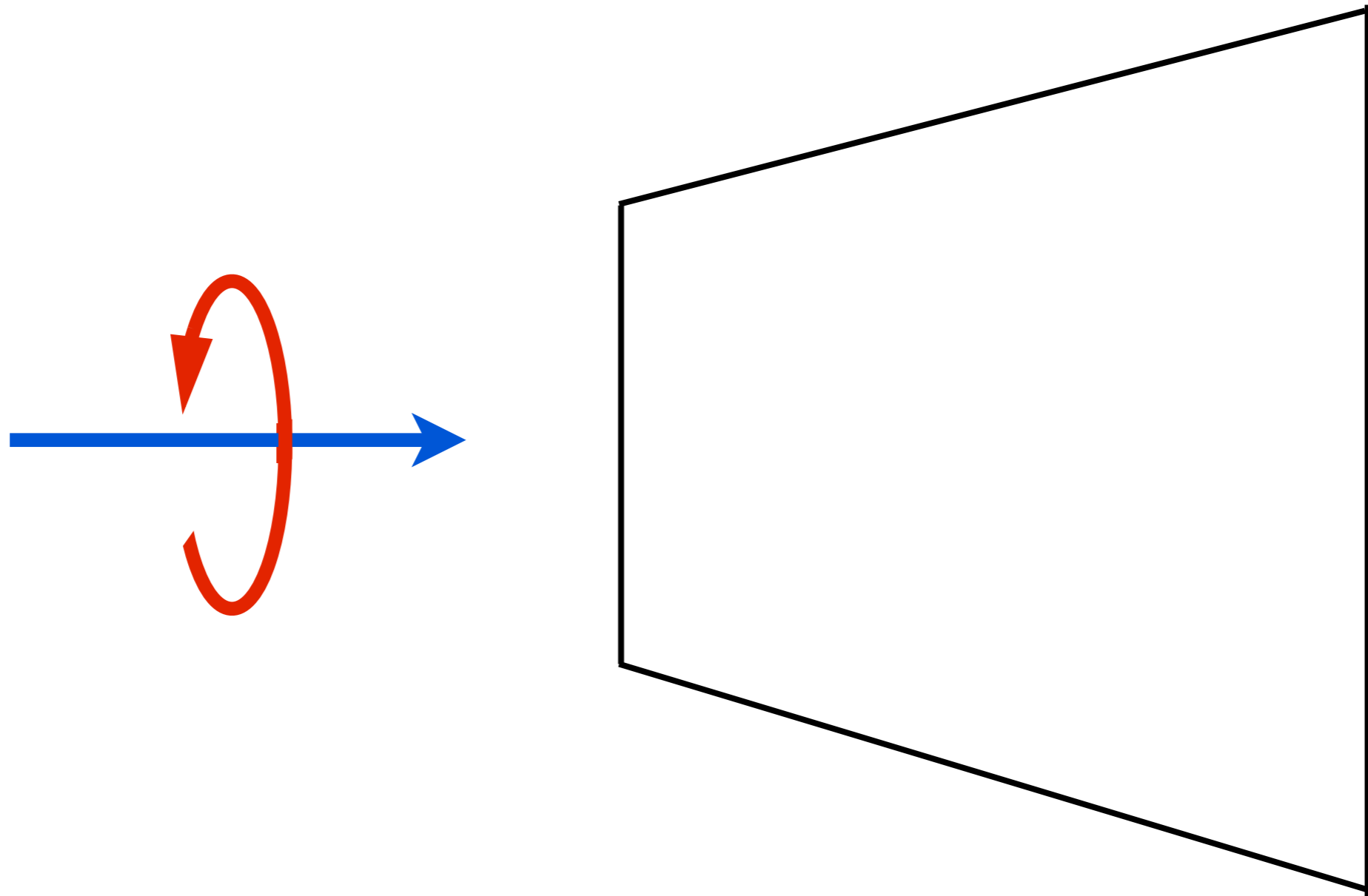
A theory **violates parity symmetry** when
the reflection (other chirality) doesn't exist.

What side do you drive down?

Left?

Right?
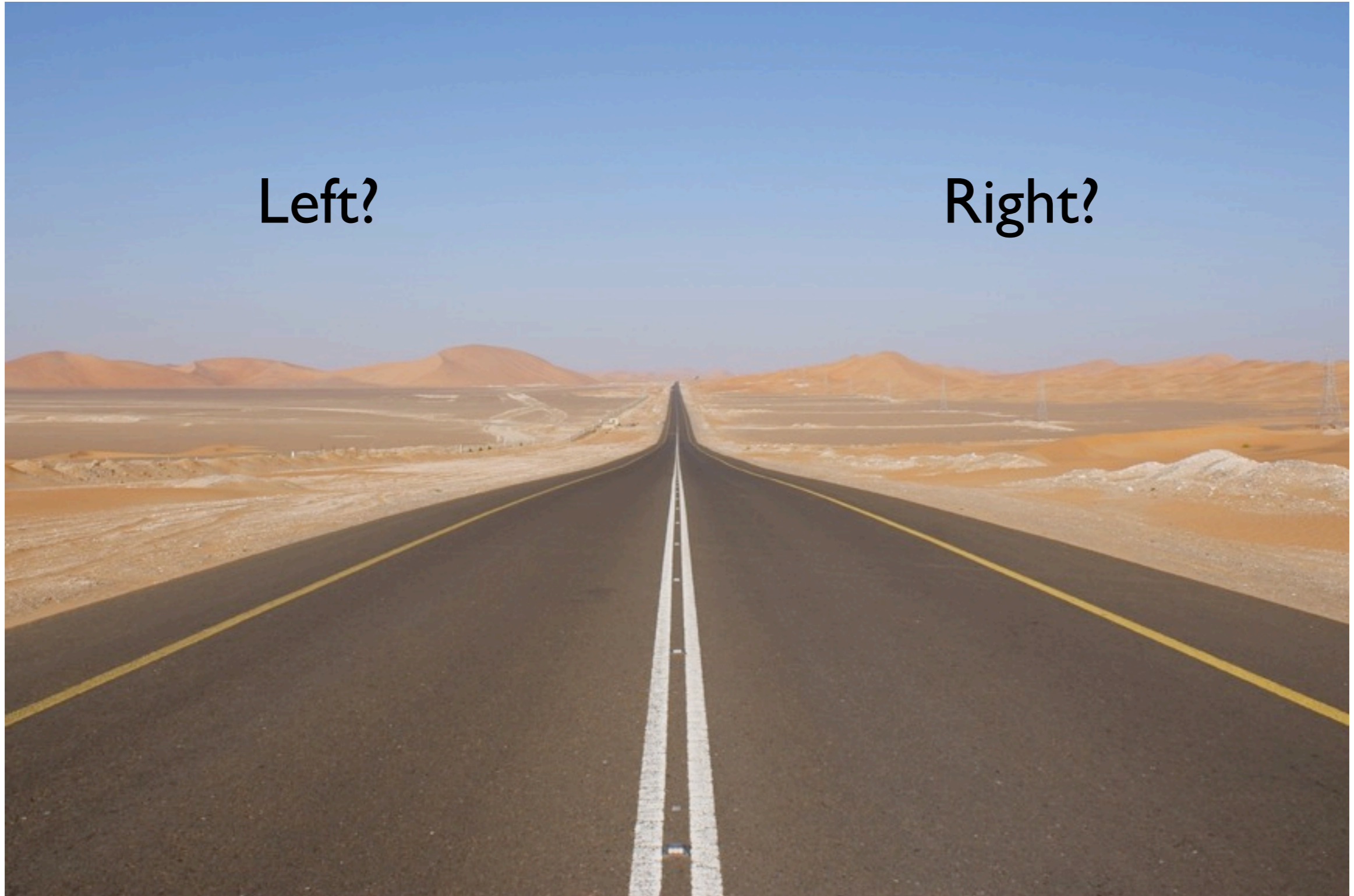
What side do you drive down?
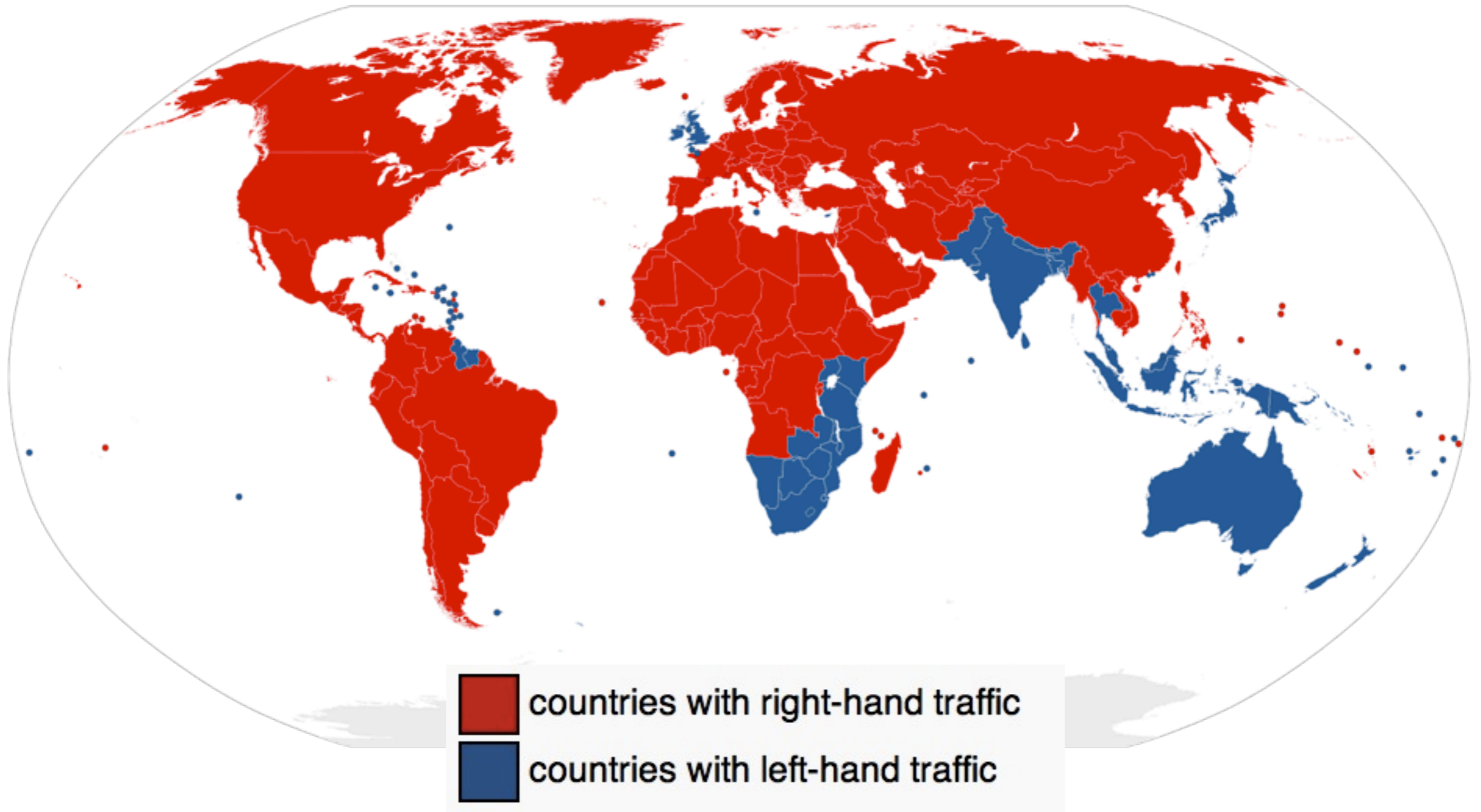
countries with right-hand traffic

countries with left-hand traffic

What side do you drive down?

countries with right-hand traffic
countries with left-hand traffic
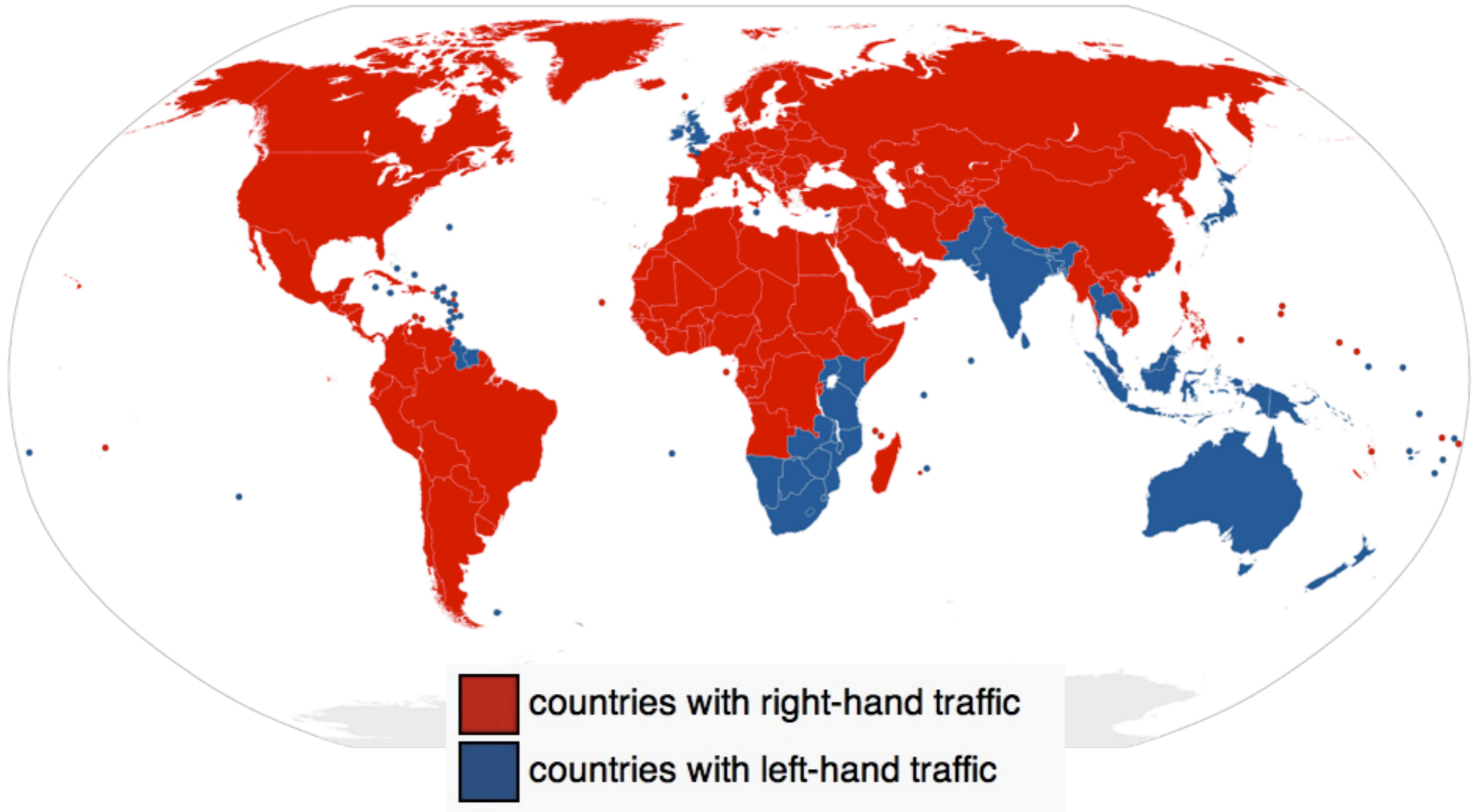
$$N_{\text{left}} - N_{\text{right}} \neq 0$$

Parity Symmetry in this Room

1. Left ears vs. Right ears?
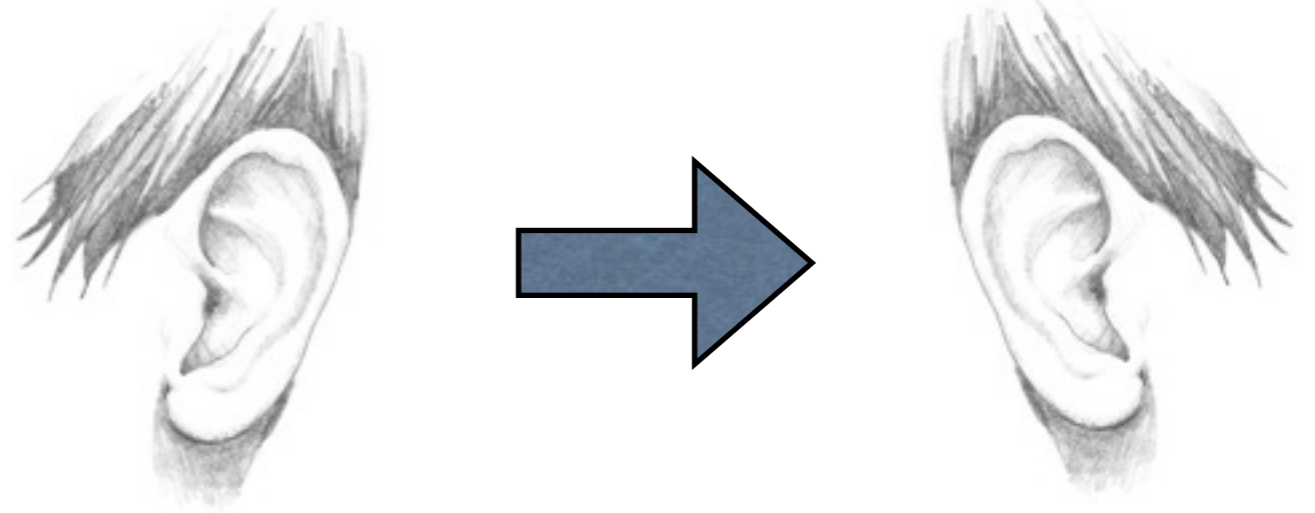
Parity Symmetry in this Room
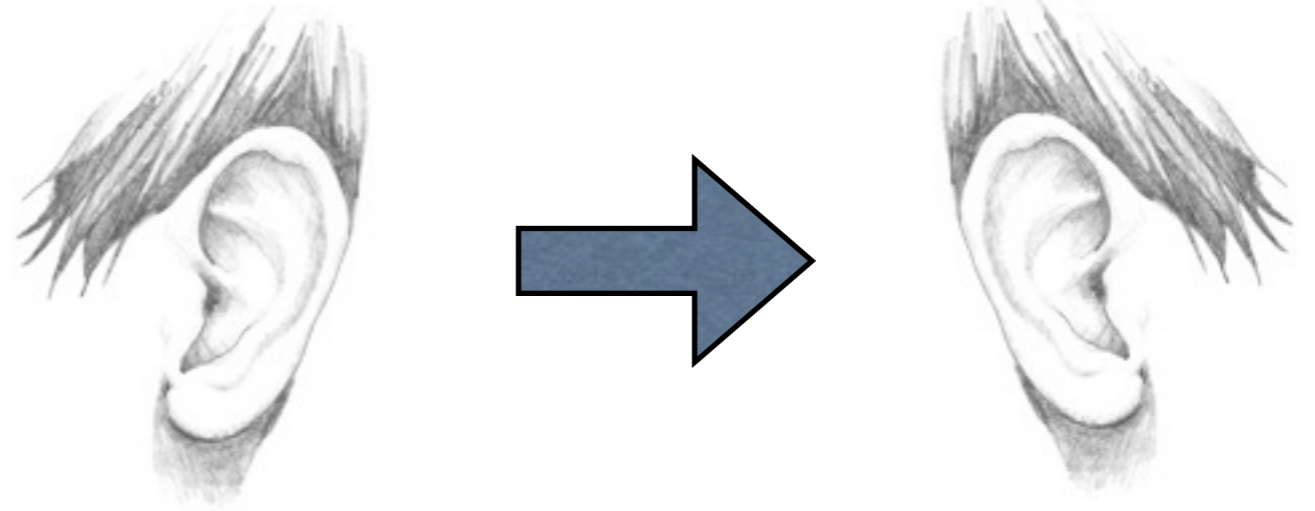
1. Left ears vs. Right ears?

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Parity Symmetry in this Room

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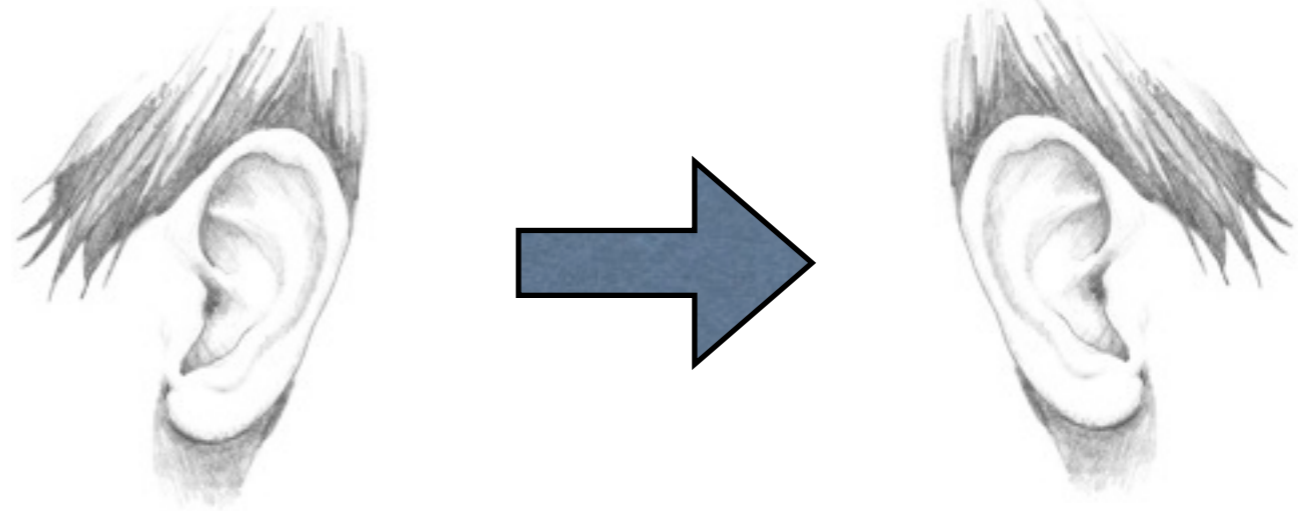
$$N_{\text{left}} - N_{\text{right}} = 0$$

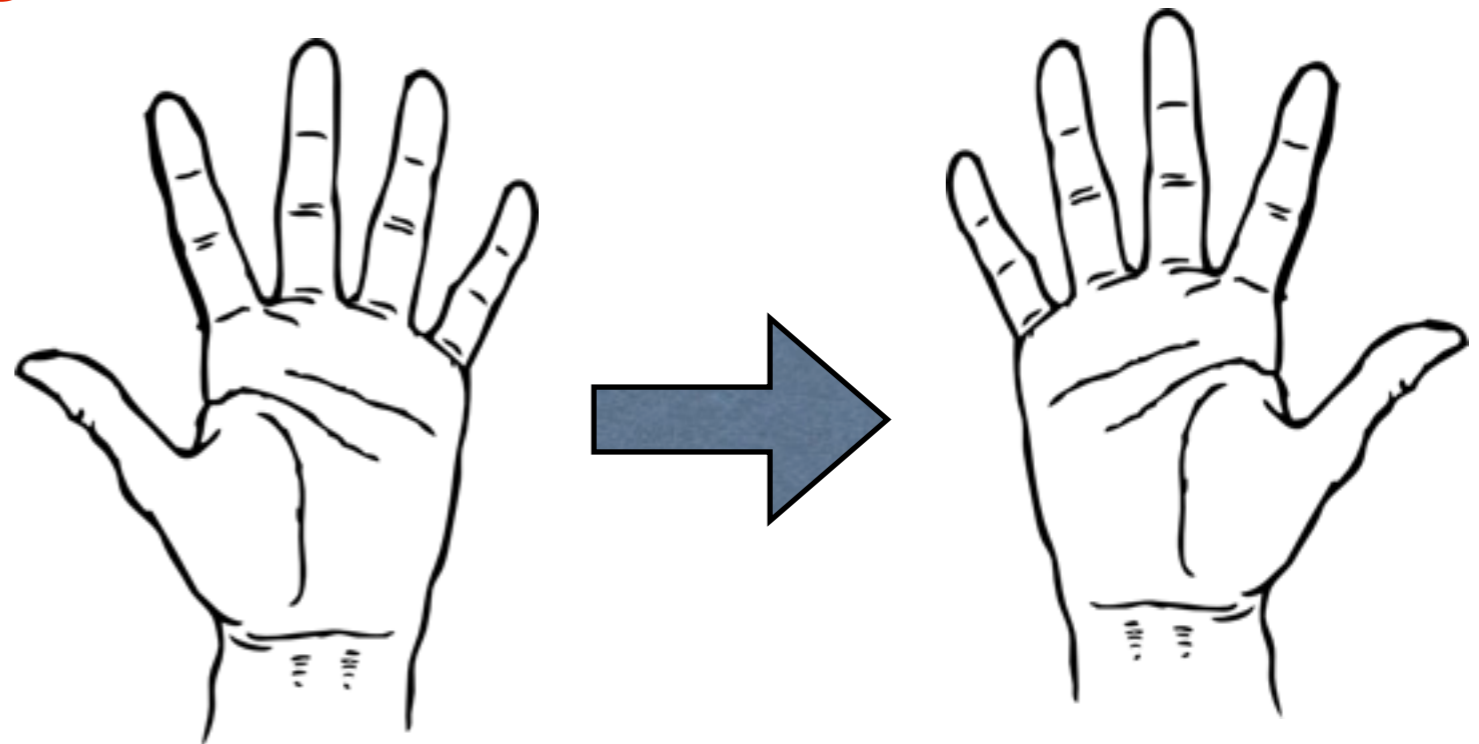2. Dominant hand: left or right?
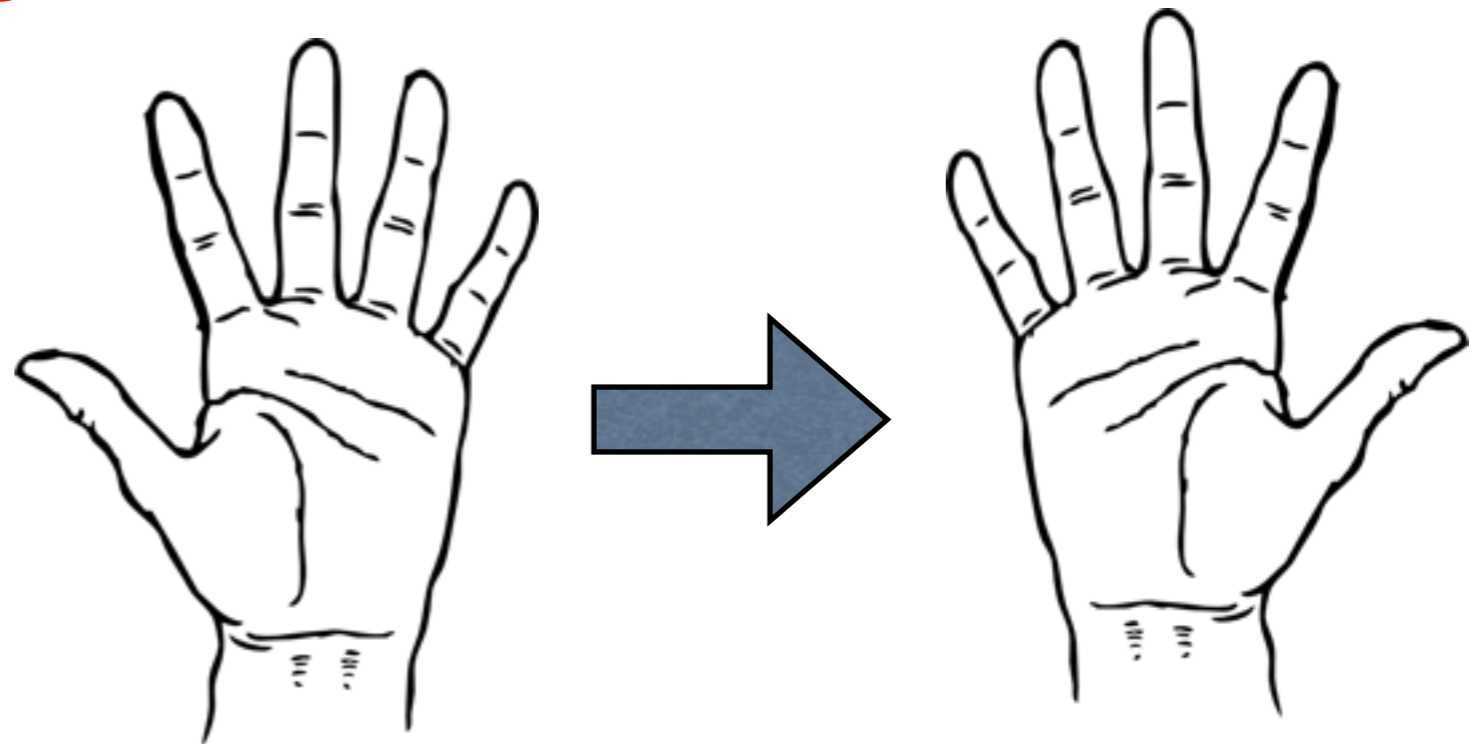
Parity Symmetry in this Room

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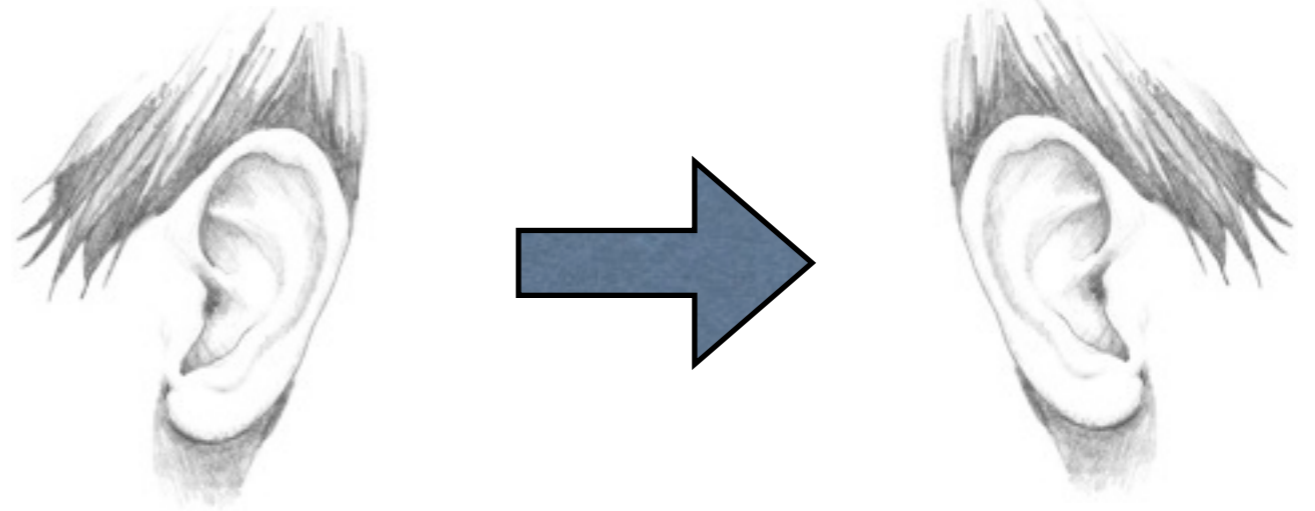
$$N_{\text{left}} - N_{\text{right}} = 0$$

2. Dominant hand: left or right?

$$N_{\text{left}} - N_{\text{right}} \neq 0$$

Topological Currents

$$\vec{j} = -\frac{1}{8\pi^2}\epsilon^{\mu\nu\rho\sigma}A_{\mu\nu}V_{\rho\sigma}$$

Topological Currents

$$\vec{j} = [n_l - n_r]\,\frac{e}{2\pi}\vec{B}$$

$\vec{B}$ = magnetic field

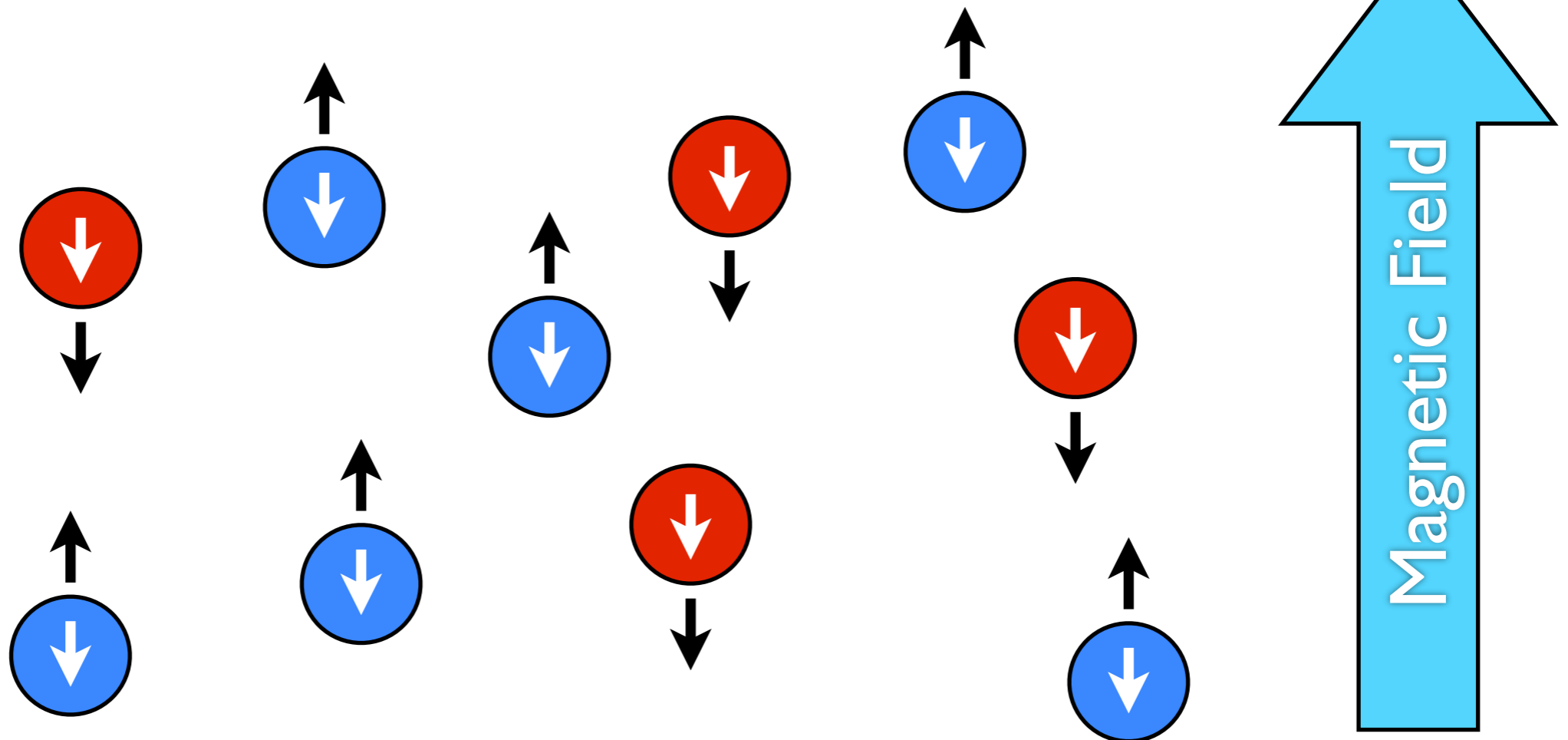$n_l - n_r$ = difference in number of left-handed and right-handed electrons

Topological Currents

$$\vec{j} = [n_l - n_r] \frac{e}{2\pi} \vec{B}$$

$\vec{B}$ = magnetic field

$n_l - n_r$ = difference in number of left-handed and right-handed electrons

Current Needs Parity Violation!

Topological Currents

$$\vec{j} = [n_l - n_r] \frac{e}{2\pi} \vec{B}$$
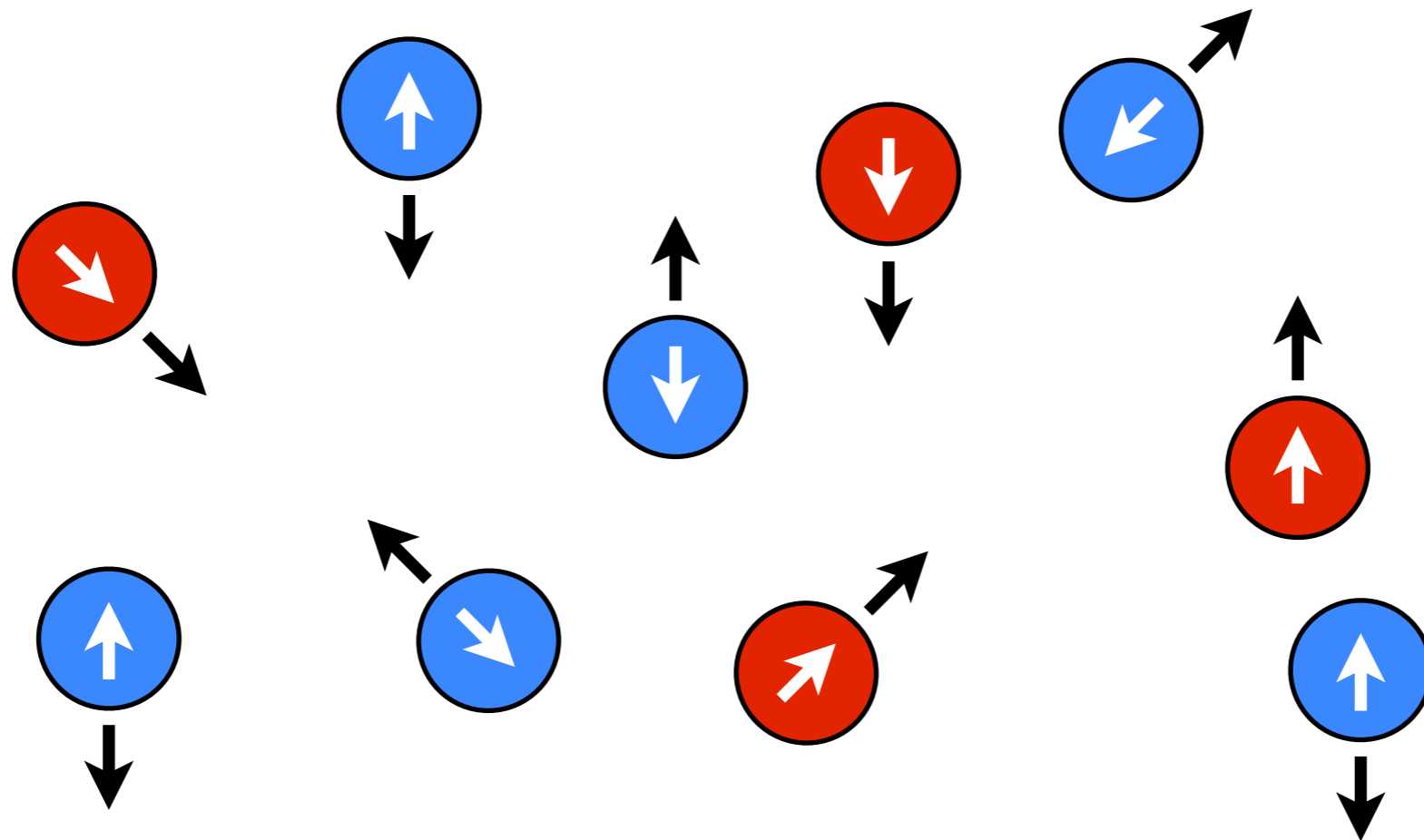
Topological Currents

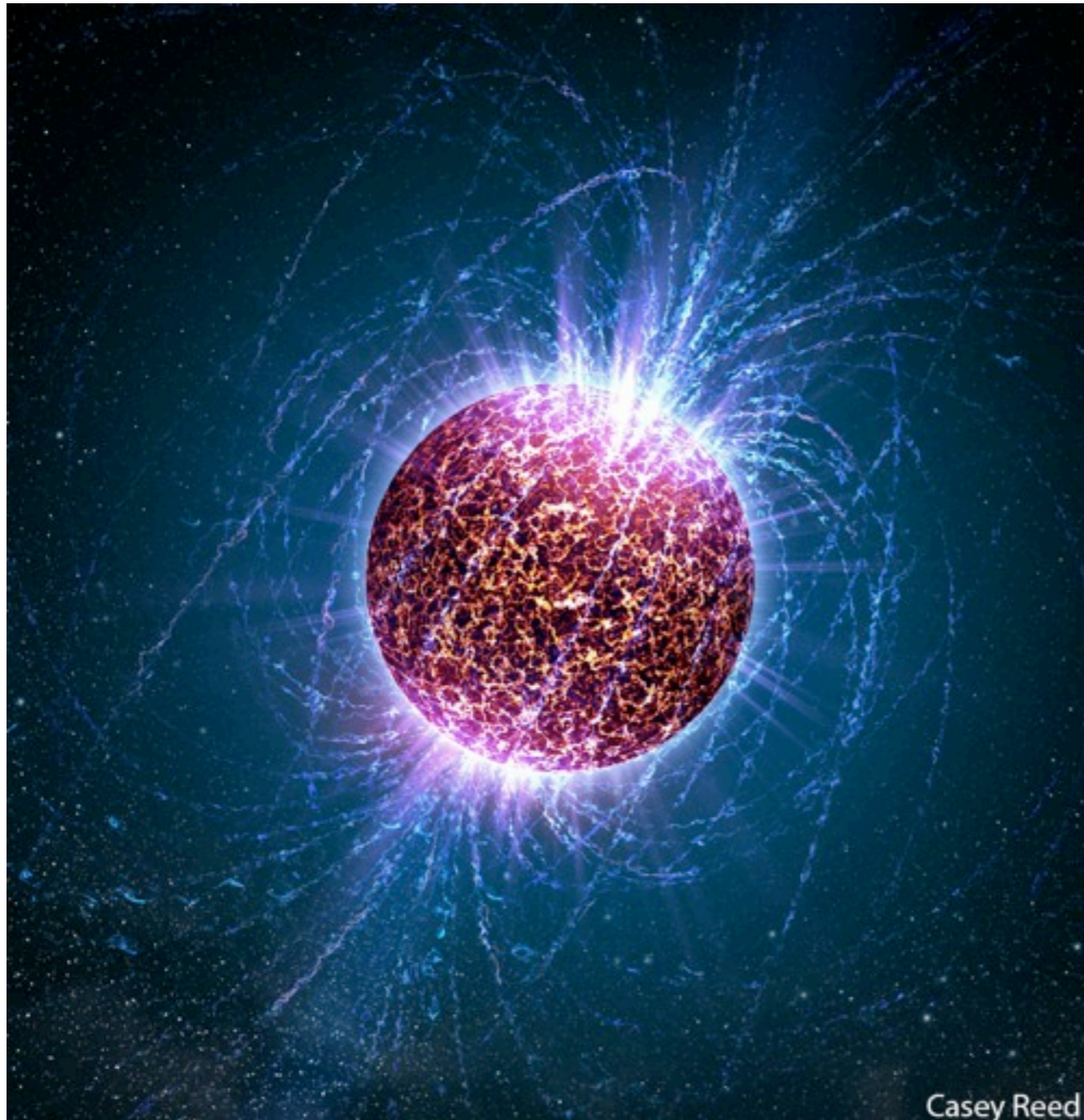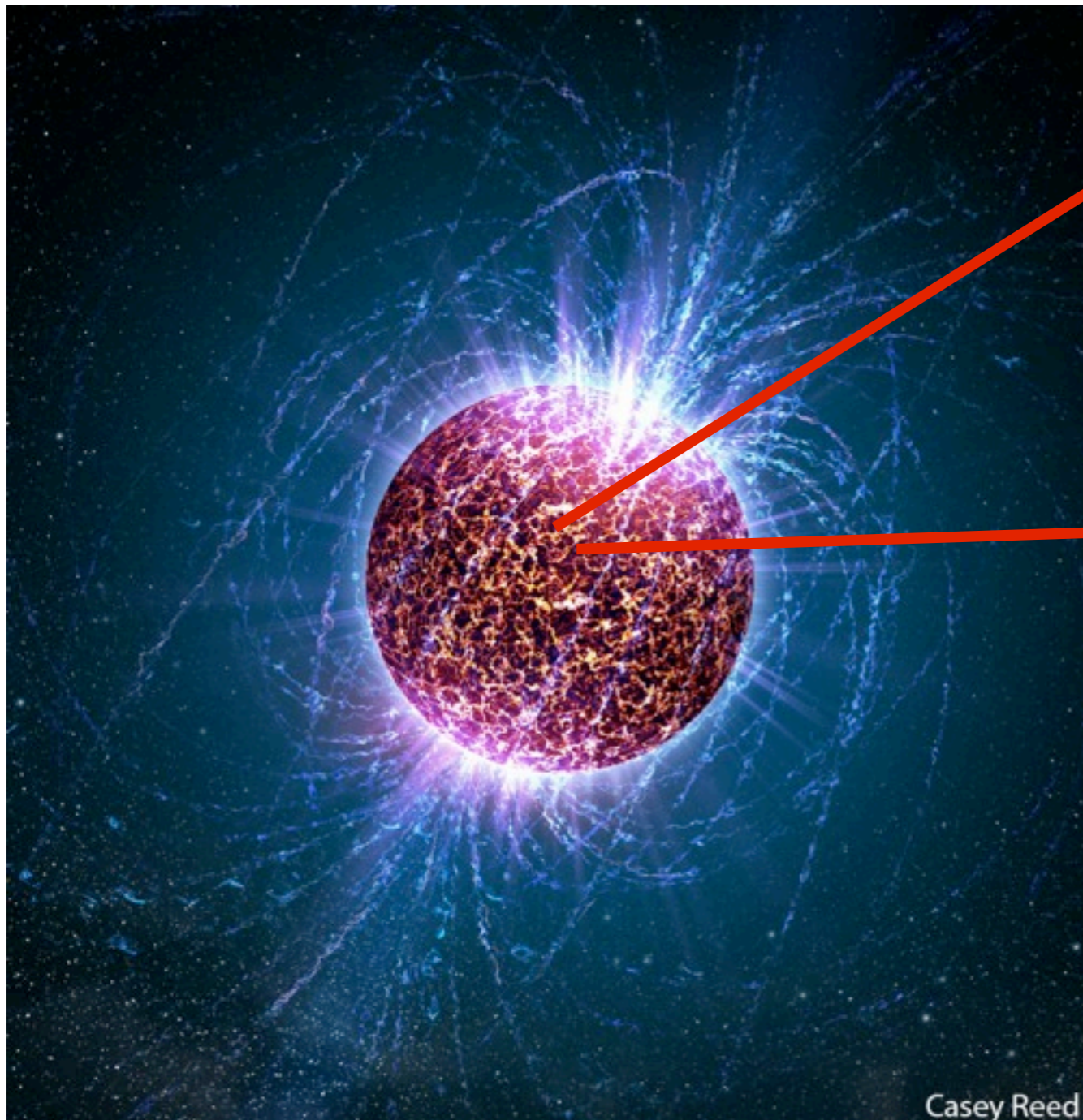$$\vec{j} = [n_l - n_r] \frac{e}{2\pi} \vec{B}$$

Magnetic Field

Neutron Stars

Neutron Stars

Casey Reed

- 10 km radius

- 1.4 solar masses

- 10^12 G magnetic field
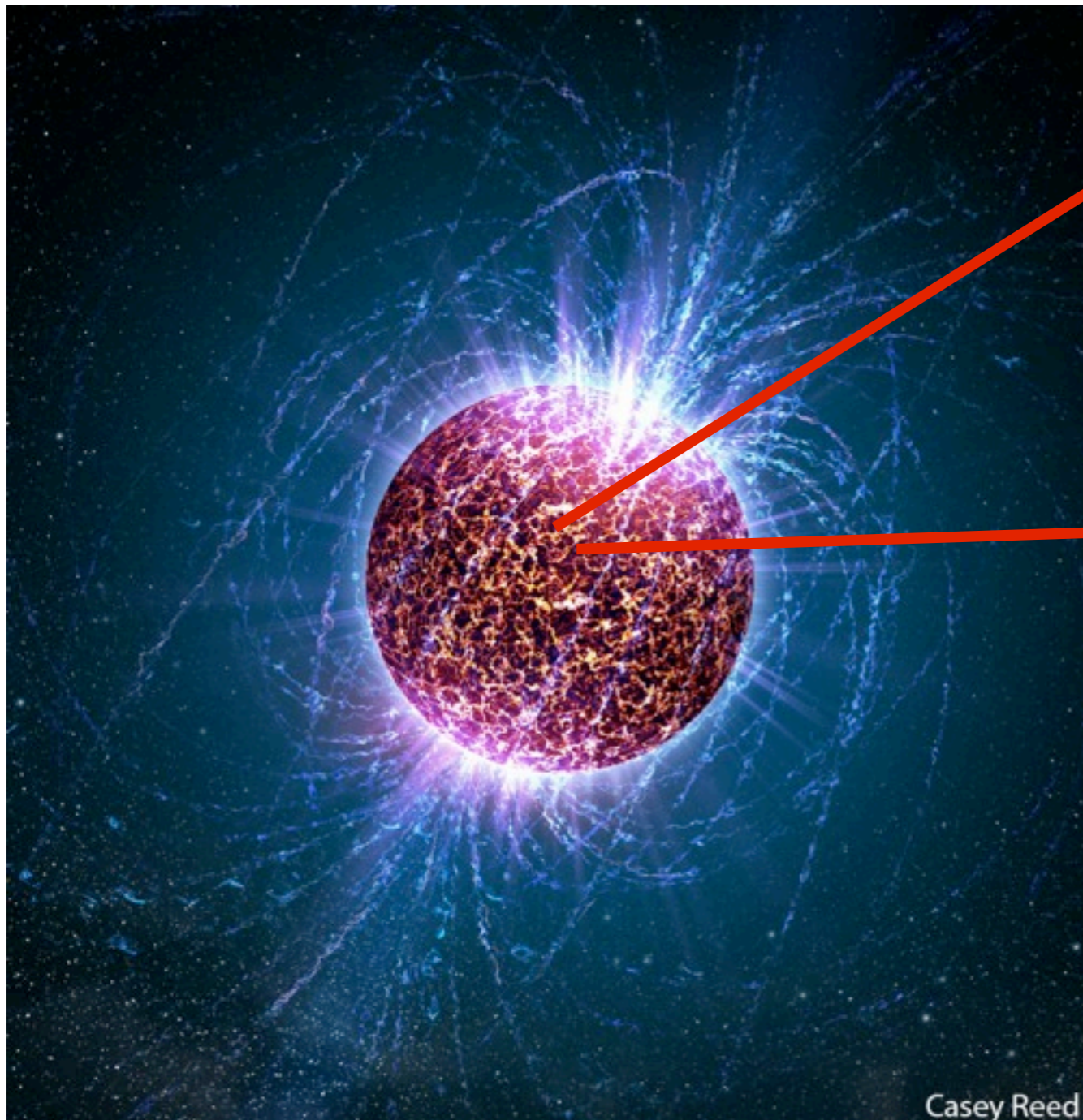
- 1 second spin period

Neutron Stars

Three Generations
of Matter (Fermions)

	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin→	$\frac{1}{2}$ **u**	$\frac{1}{2}$ **c**	$\frac{1}{2}$ **t**	1 **γ**
name→	up	charm	top	photon

Quarks

4.8 MeV	104 MeV	4.2 GeV	0
$-\frac{1}{3}$	$-\frac{1}{3}$	$-\frac{1}{3}$	0
$\frac{1}{2}$ **d**	$\frac{1}{2}$ **s**	$\frac{1}{2}$ **b**	1 **g**
down	strange	bottom	gluon

<2.2 eV	<0.17 MeV	<15.5 MeV	91.2 GeV
0	0	0	0
$\frac{1}{2}$ ν_e	$\frac{1}{2}$ ν_μ	$\frac{1}{2}$ ν_τ	1 Z^0
electron neutrino	muon neutrino	tau neutrino	weak force

Leptons

0.511 MeV	105.7 MeV	1.777 GeV	80.4 GeV
-1	-1	-1	±1
$\frac{1}{2}$ **e**	$\frac{1}{2}$ **μ**	$\frac{1}{2}$ **τ**	1 $W^\pm$
electron	muon	tau	weak force

Bosons (Forces)

Casey Reed

- A new laboratory for the standard model!

Neutron Stars

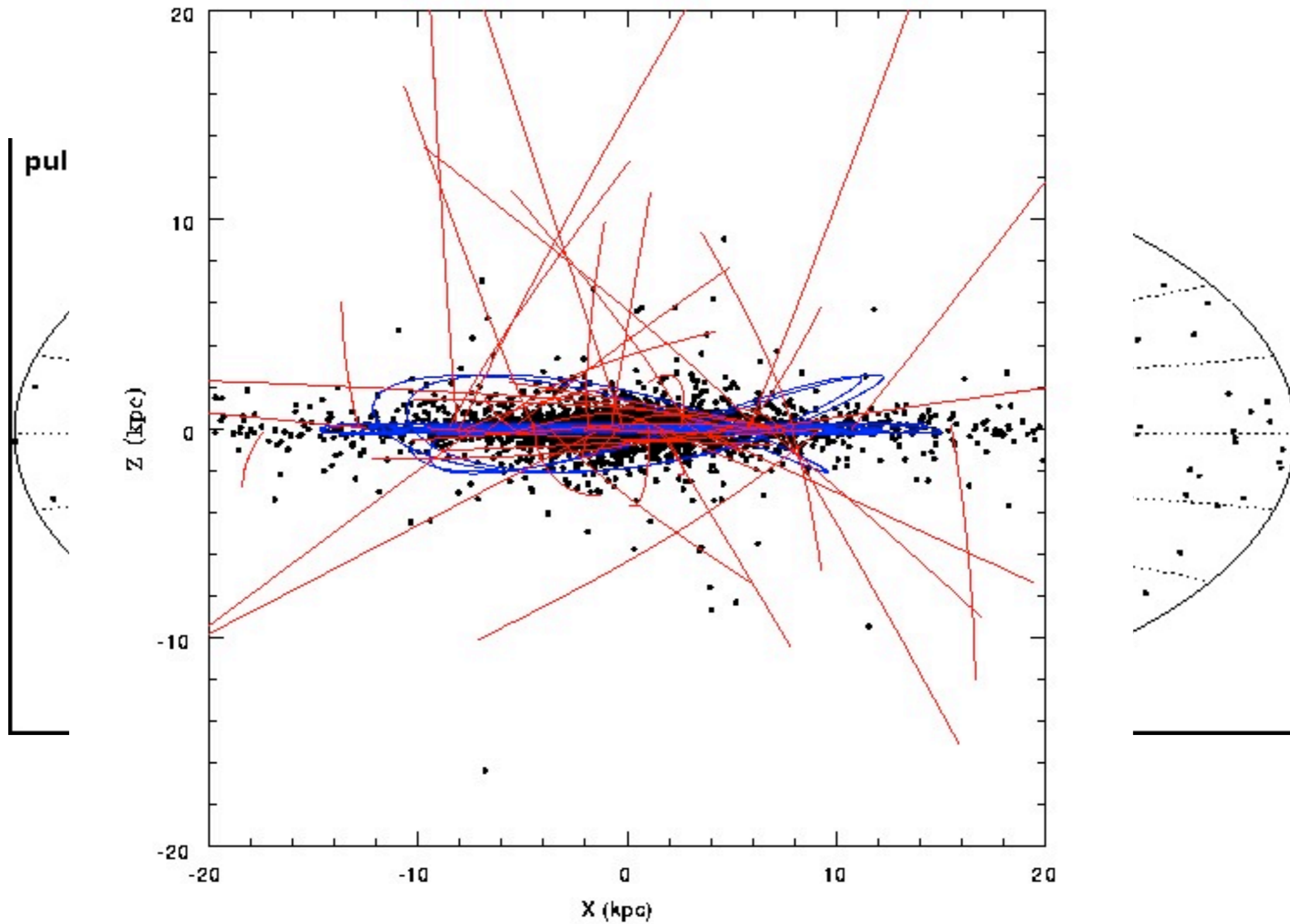

Casey Reed

Three Generations
of Matter (Fermions)

- A new laboratory for the standard model!
- But they're a little far away.

Pulsar (neutron star) Kicks

pulsar distribution
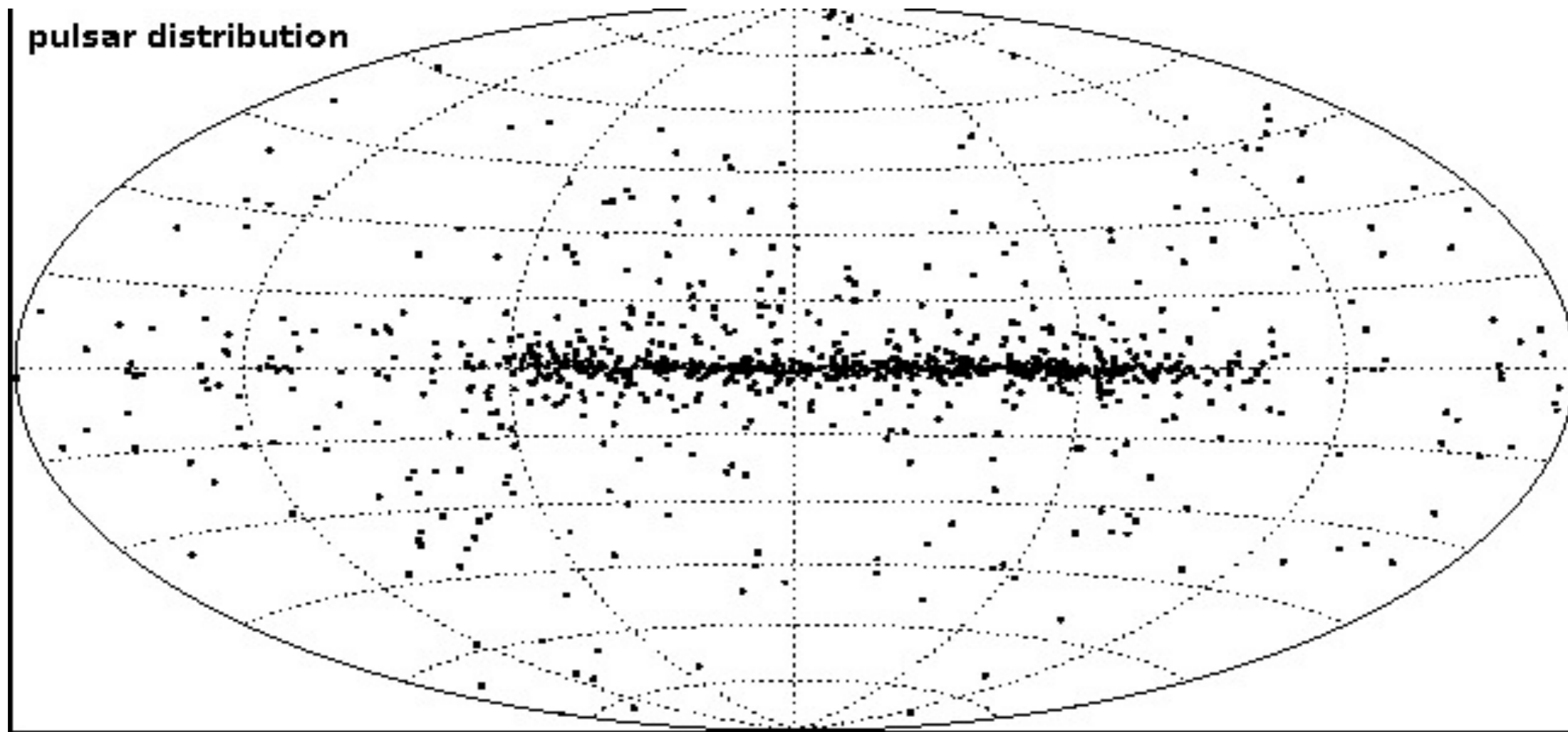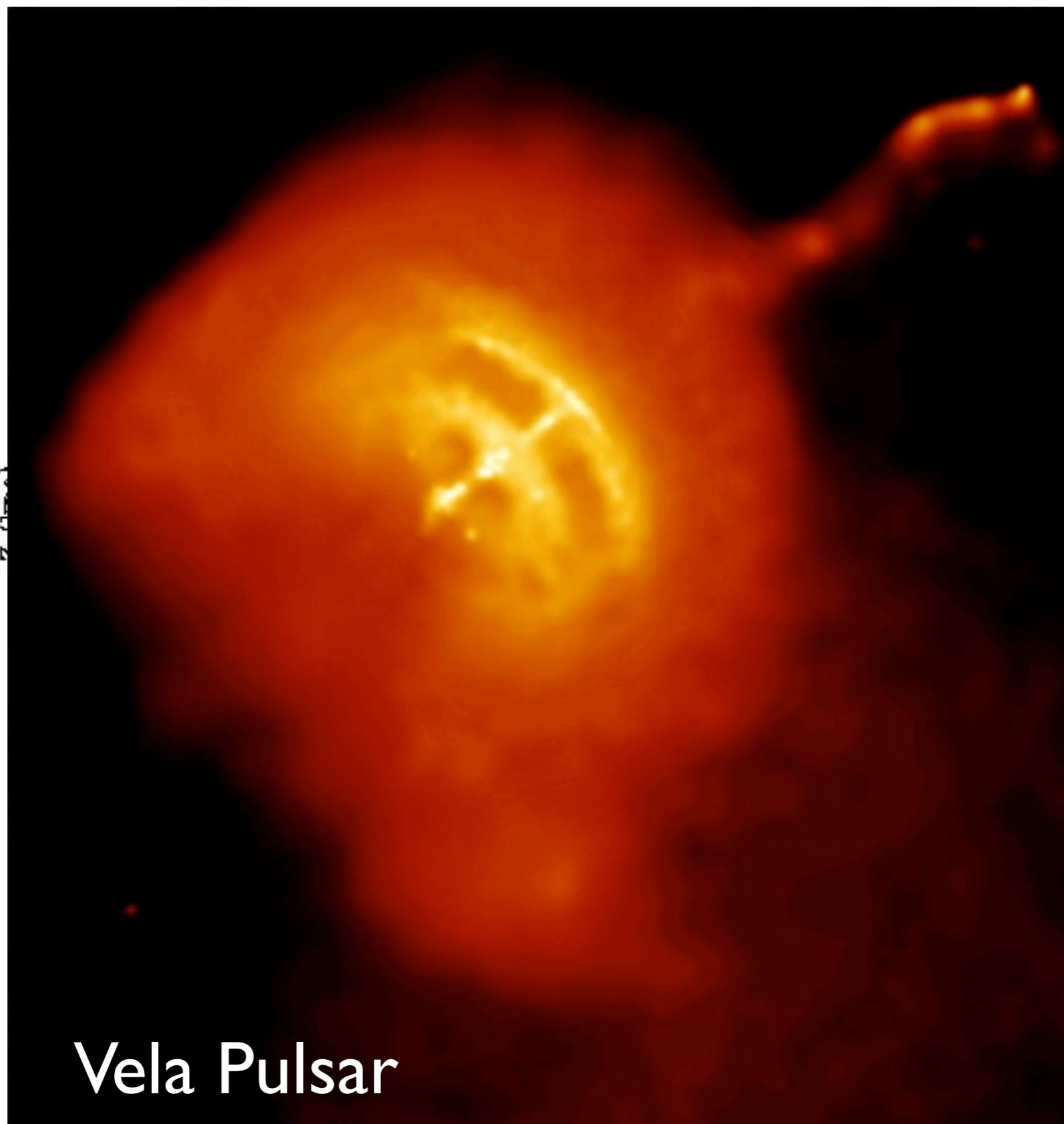
Pulsar (neutron star) Kicks

Pulsar (neutron star) Kicks
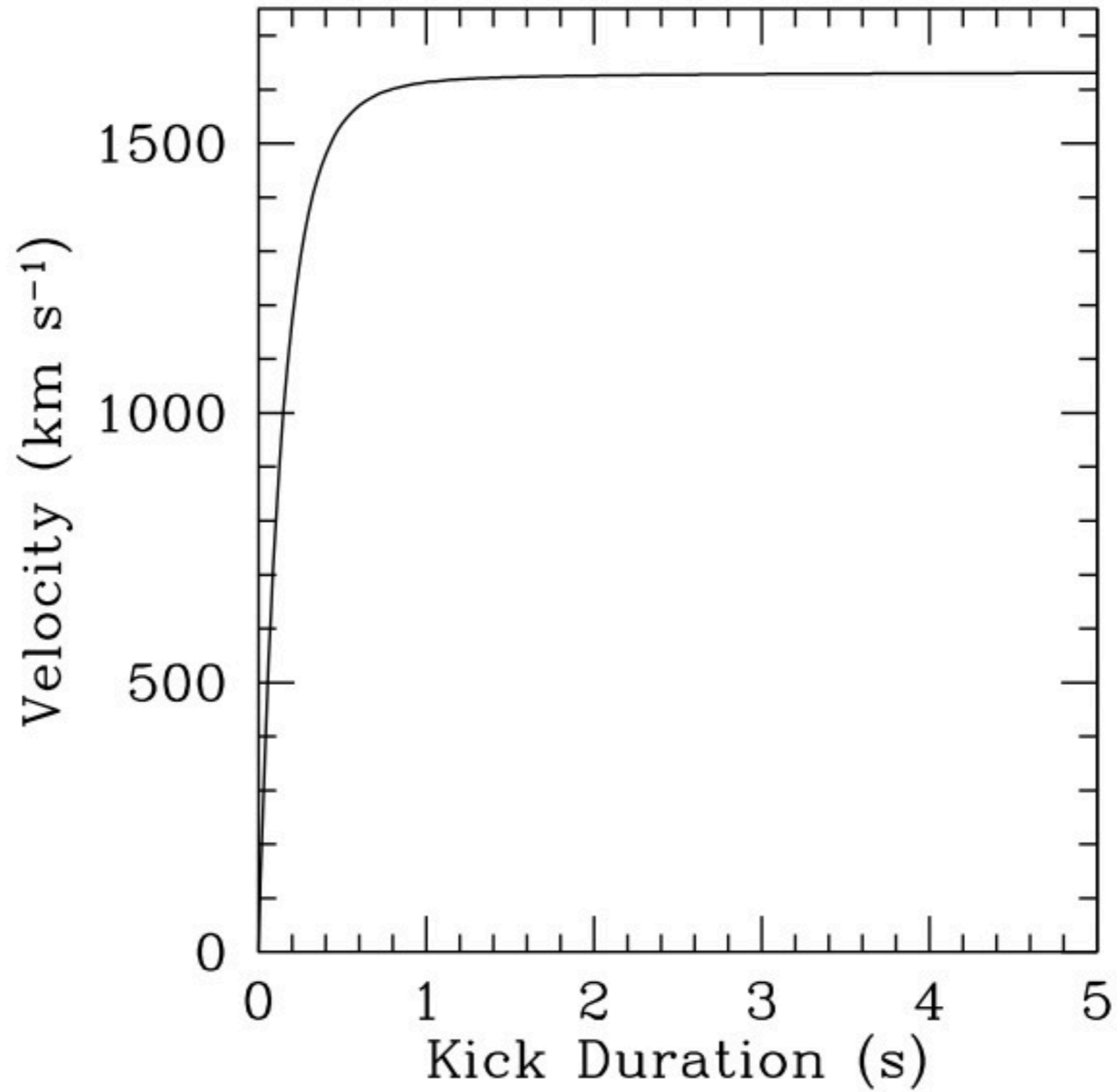

Vela Pulsar

Parity Violation in Pulsars

Urca Processes,

$$e^- + P\,(+\,\overline{\nu}_e) \quad \leftrightarrow \quad N\,(+\,\nu_e),$$
$$e^- + P + N'\,(+\,\overline{\nu}_e) \quad \leftrightarrow \quad N' + N\,(+\,\nu_e),$$

are weak interactions.

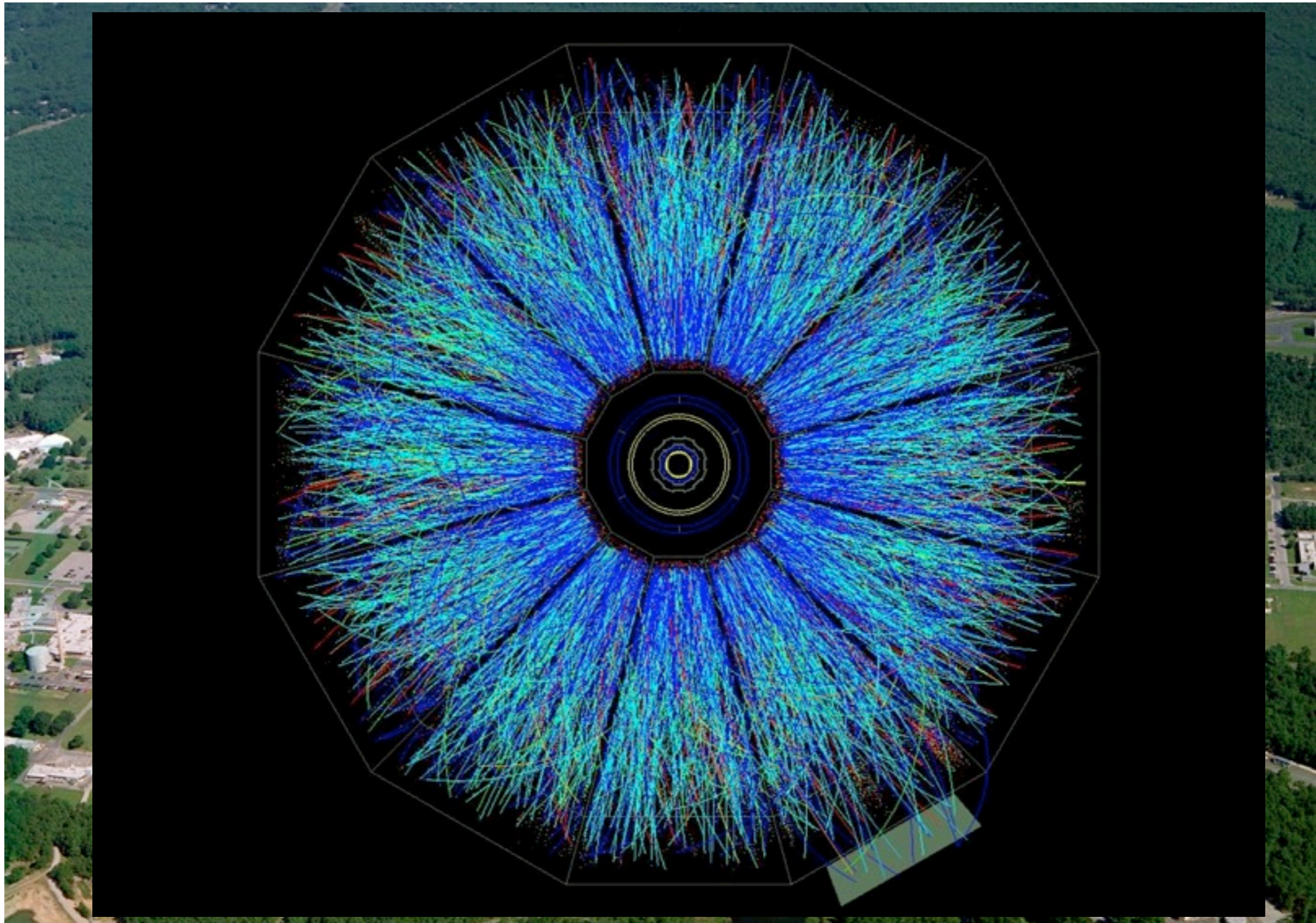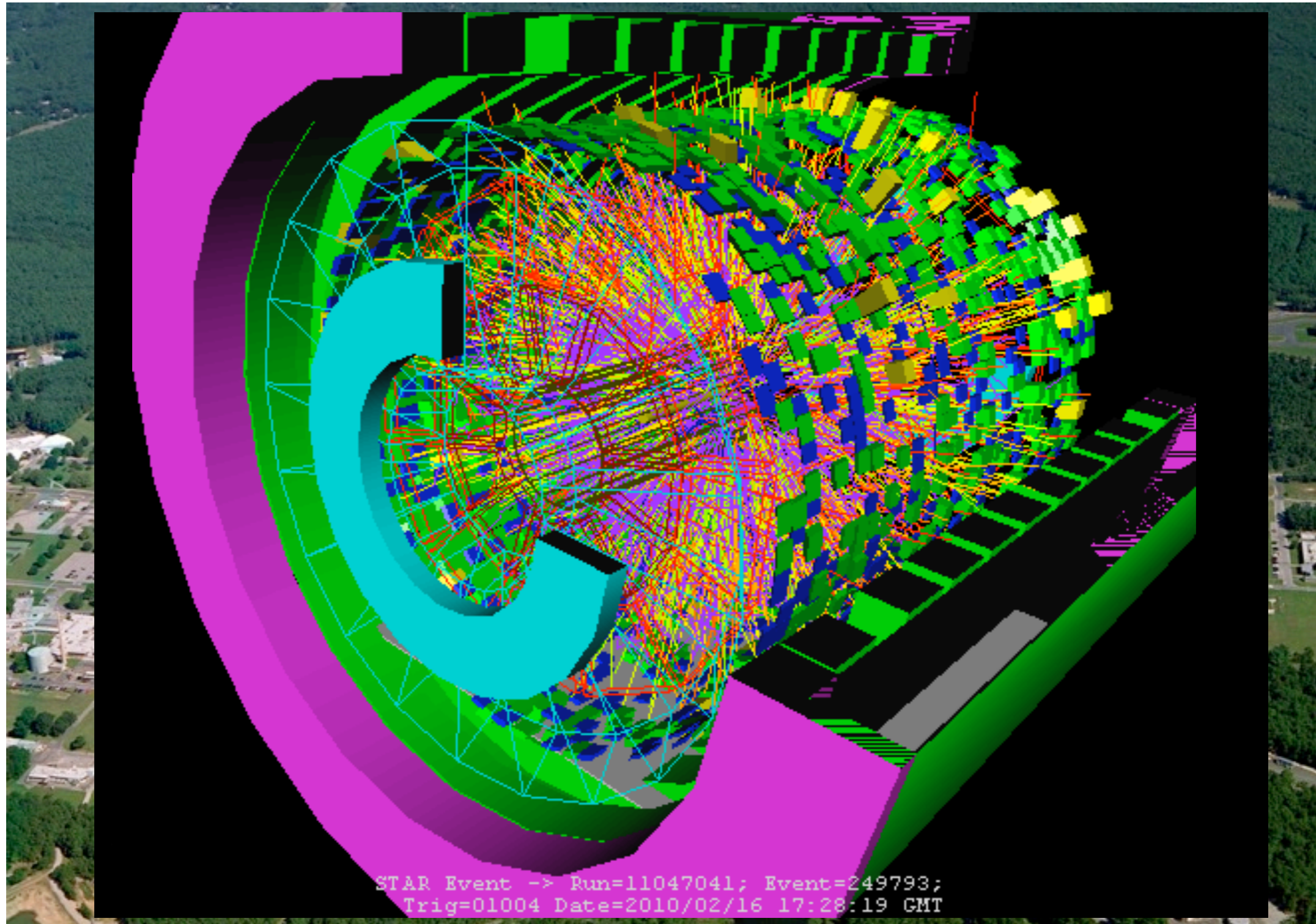> Only left-handed electrons are created.

Parity Violation in Pulsars

Relativistic Heavy Ion Collider (RHIC)

Relativistic Heavy Ion Collider (RHIC)

Relativistic Heavy Ion Collider (RHIC)

STAR Event -> Run=11047041; Event=249793;
Trig=01004 Date=2010/02/16 17:28:19 GMT

Relativistic Heavy Ion Collider (RHIC)