Detecting Magnetic Dark Matter

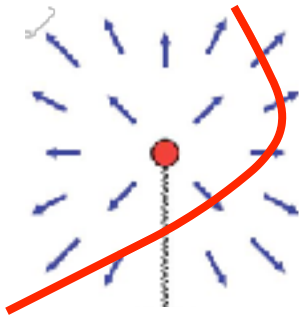
John Terning
with Chris Verhaaren

hep-th/1808.09459
hep-th/1809.05102
hep-ph/190?.?????

Outline

Dark Matter

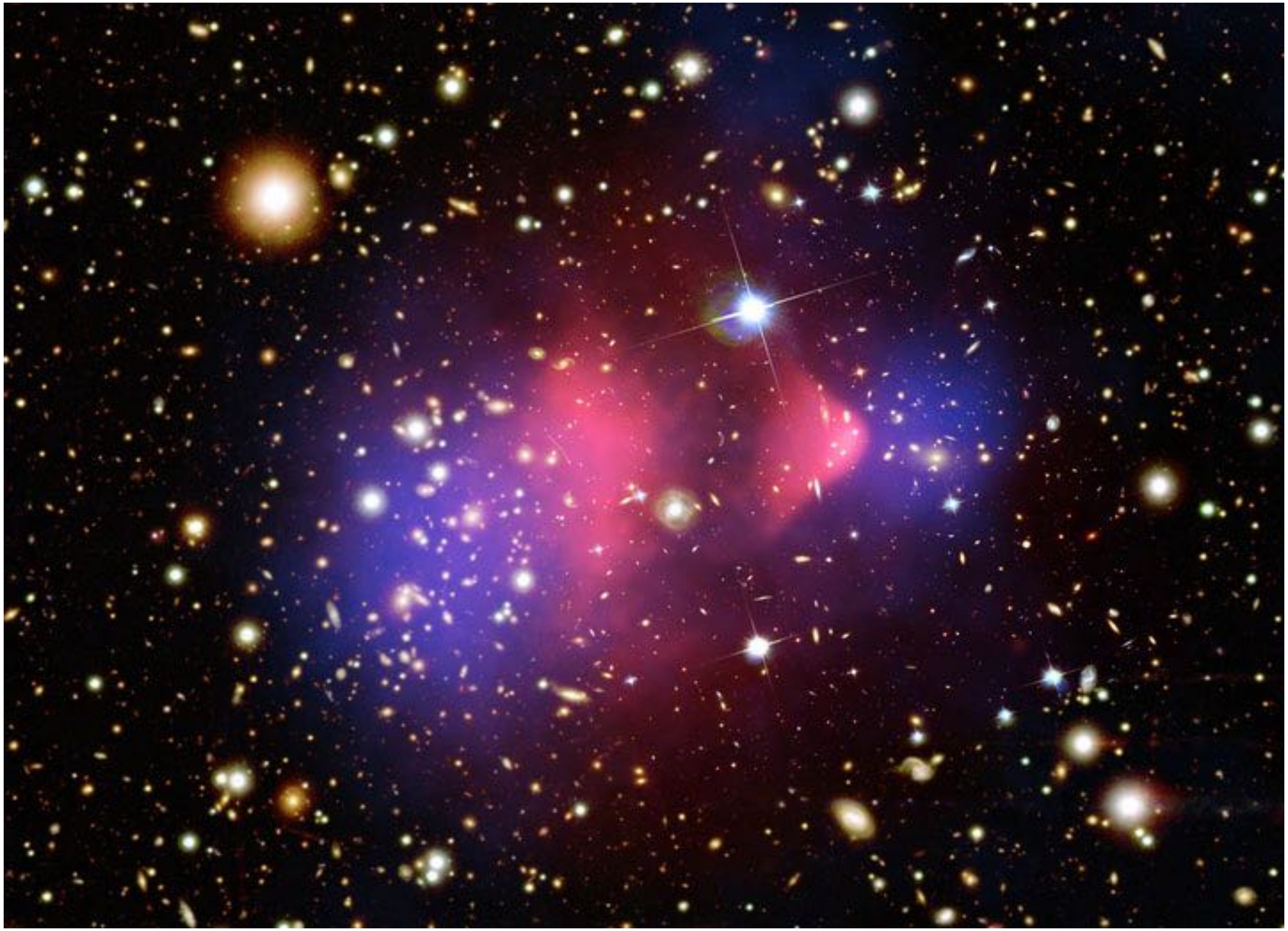
Monopole ABZ's



Magnetic Dark Matter

Conclusions

Dark Matter



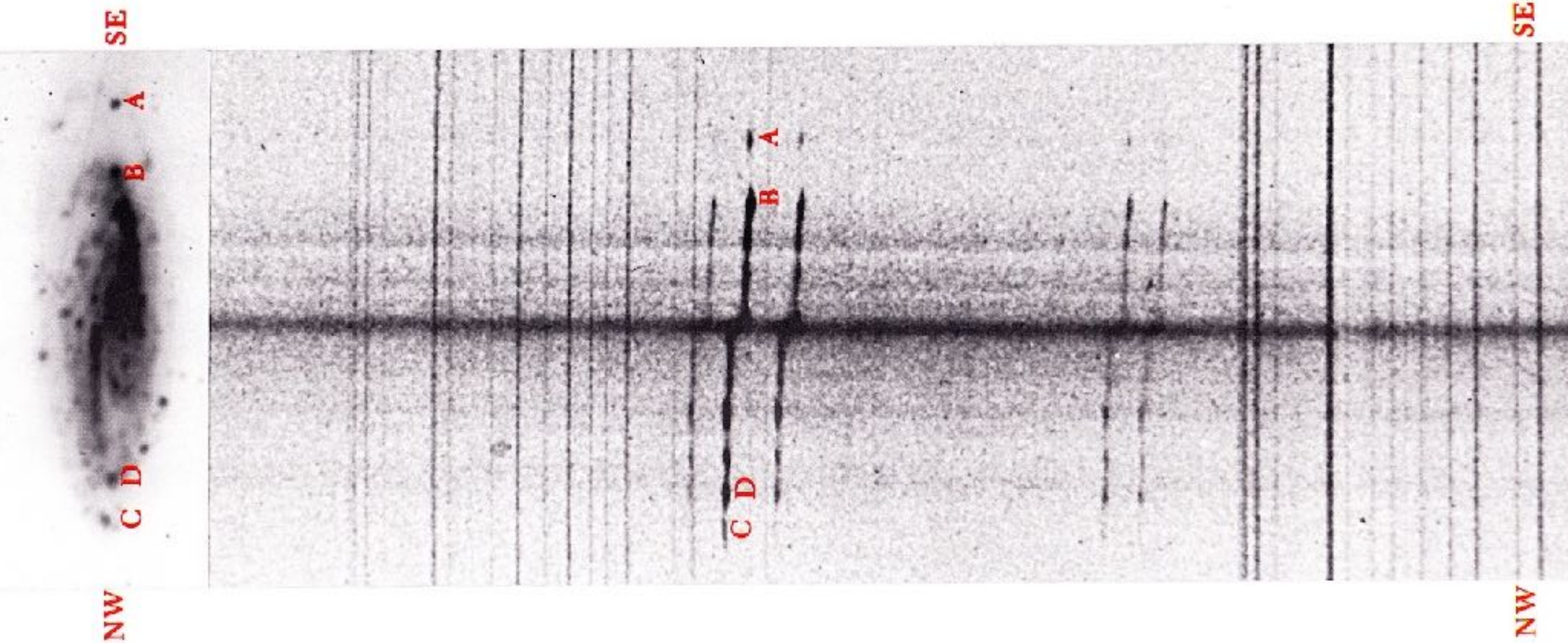
Clowe, Bradac, et. al. astro-ph/060840

Vera Rubin

(1928-2016)

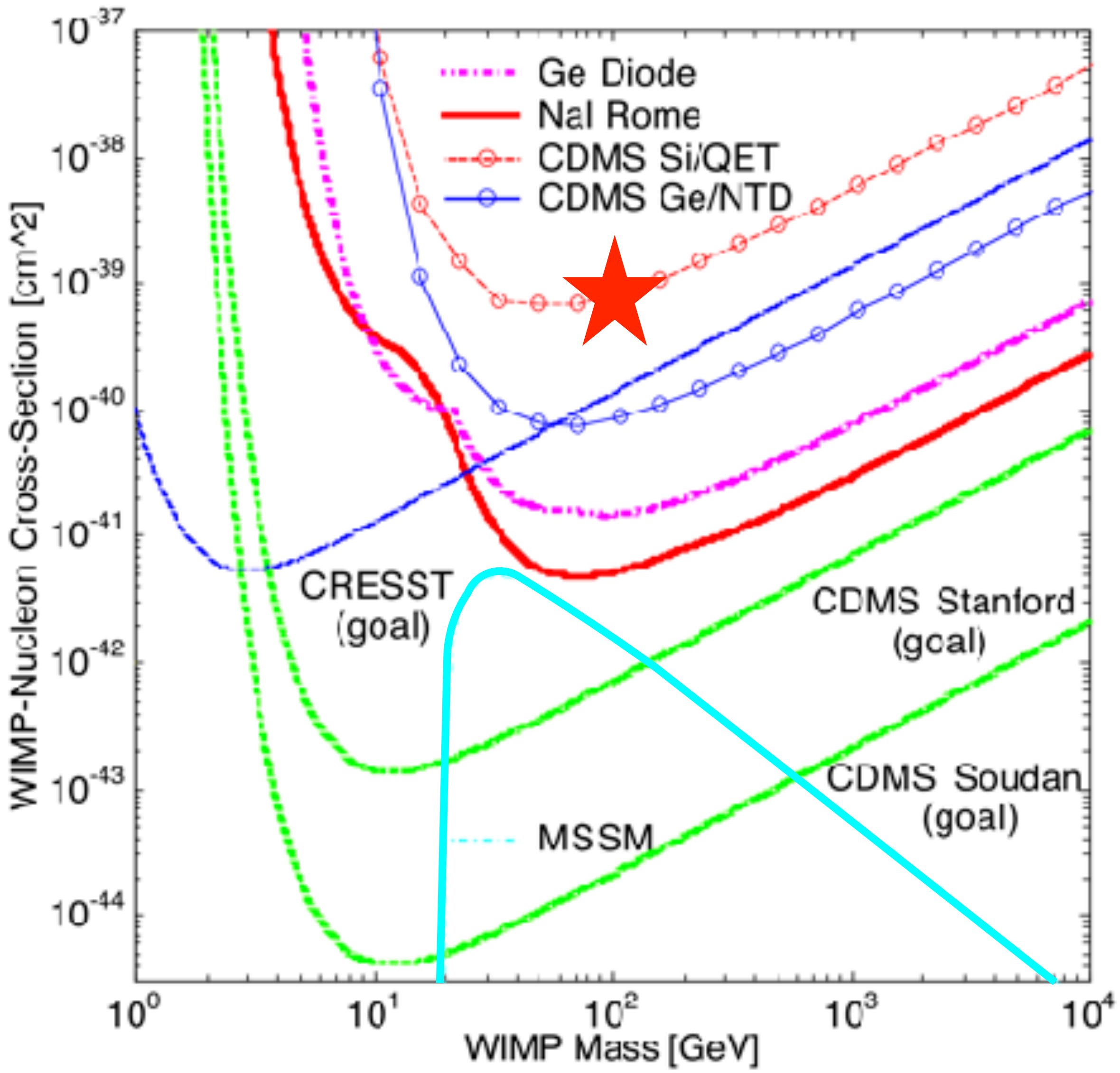
Dark Matter

NGC 7541



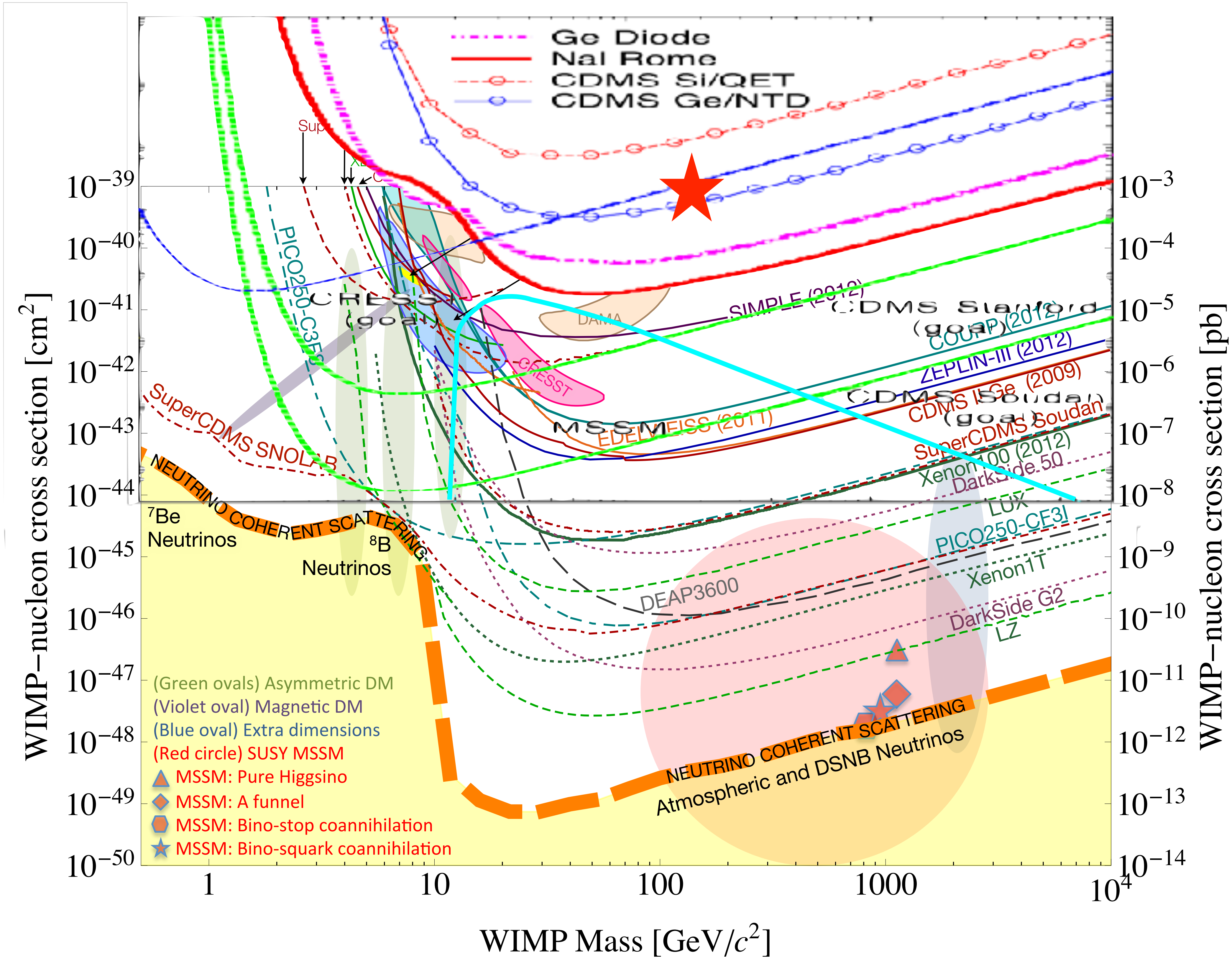
Rubin, Ford, Thonnard ApJ, **225** (1978) L107

Dark Matter Searches



astro-ph/9712343

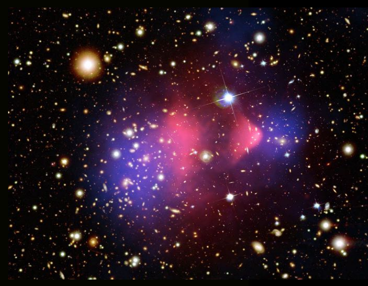
Dark Matter Searches



hep-ex/1310.8327

Strategy

Strategy



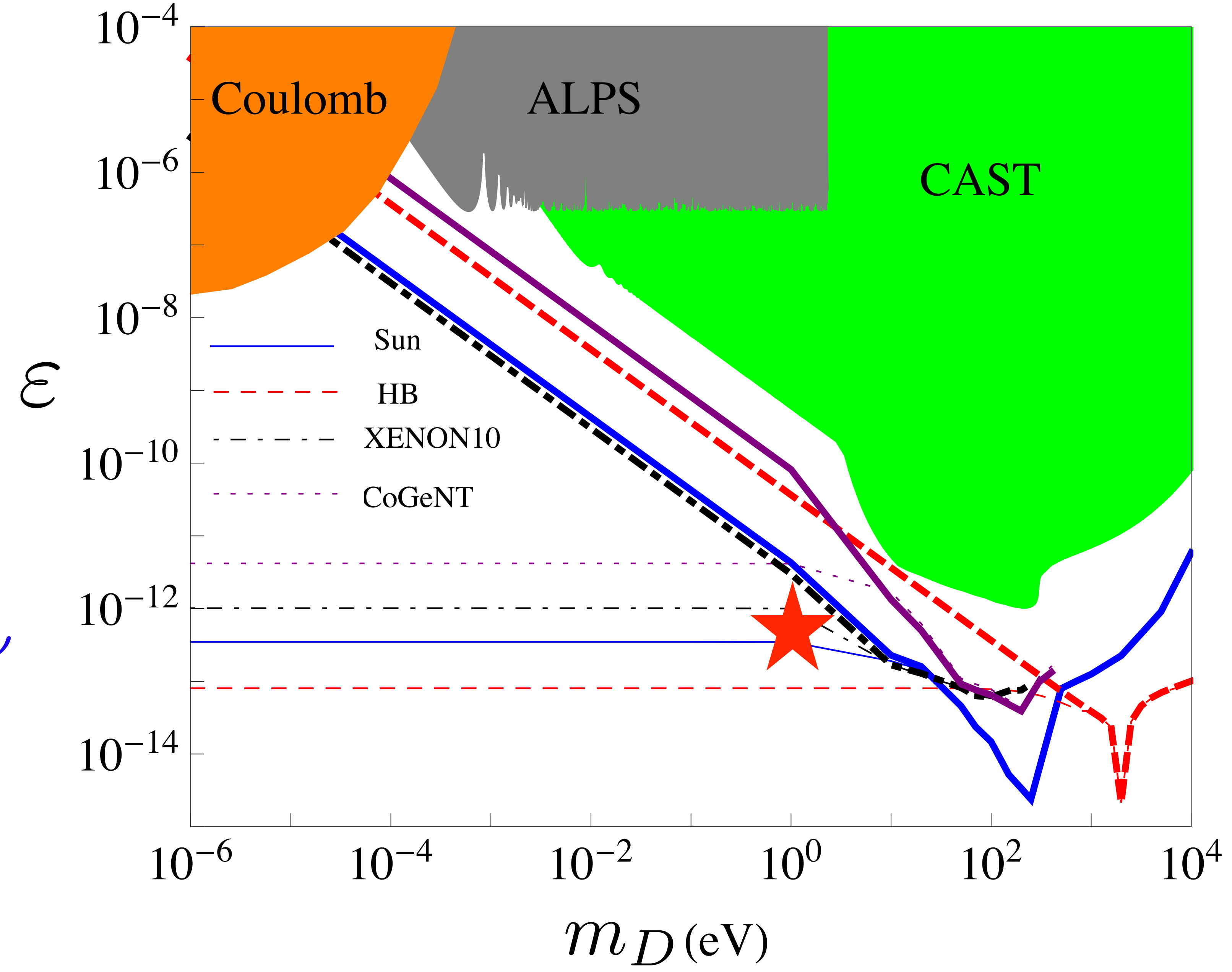
Strategy

Dark Photons

$$\mathcal{L}_{\text{mix}} = \frac{\varepsilon}{2} F_{\mu\nu} F_D^{\mu\nu}$$

Holdom Phys. Lett. 166B (1986) 196

Dark Photons

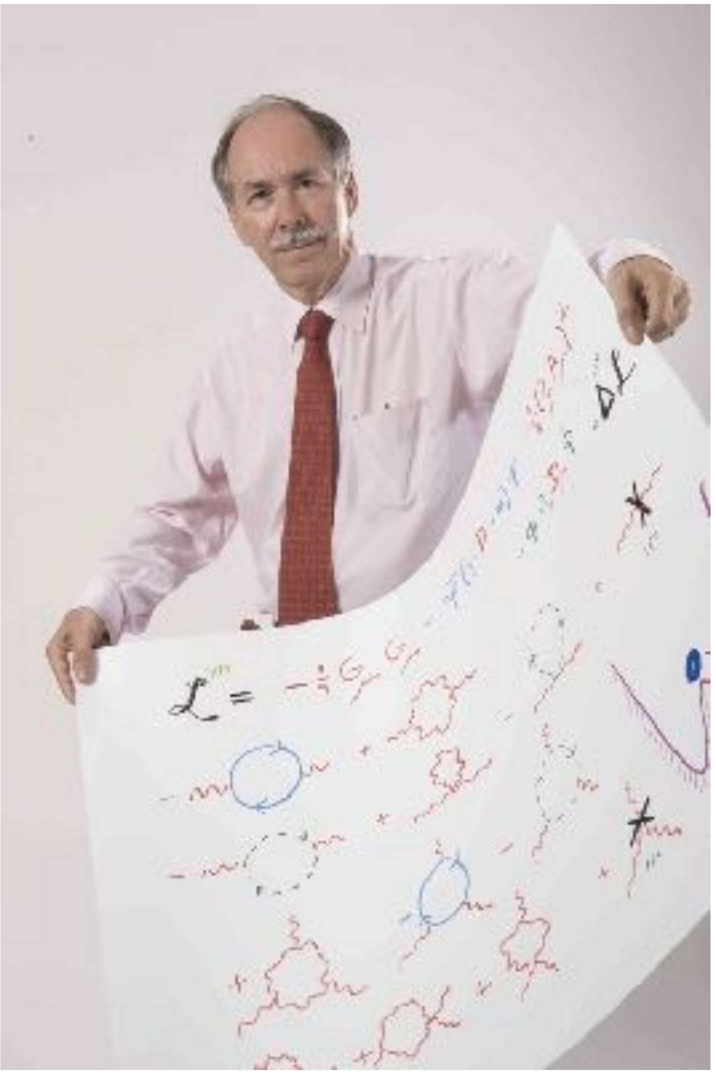


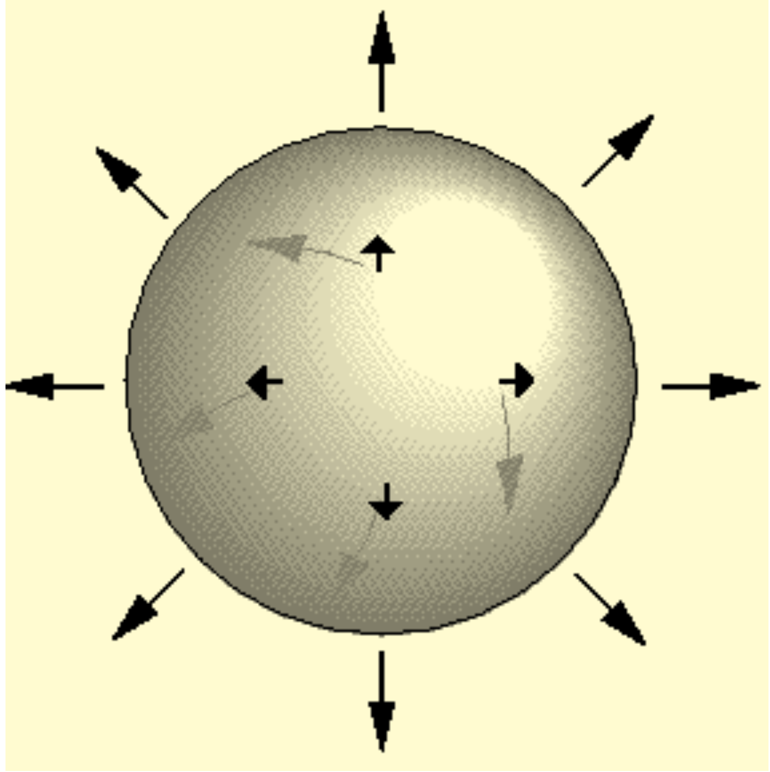
$$\mathcal{L}_{\rm mix} = \frac{\varepsilon}{2} F_{\mu\nu} F_D^{\mu\nu}$$

Holdom Phys. Lett. 166B (1986) 196

An, Pospelov, Pradler hep-ph/1304.3461

Dark Monopoles

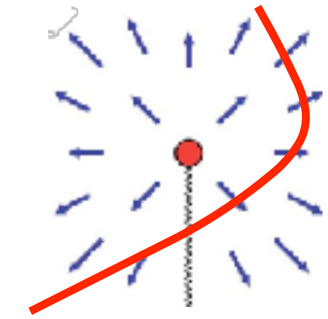


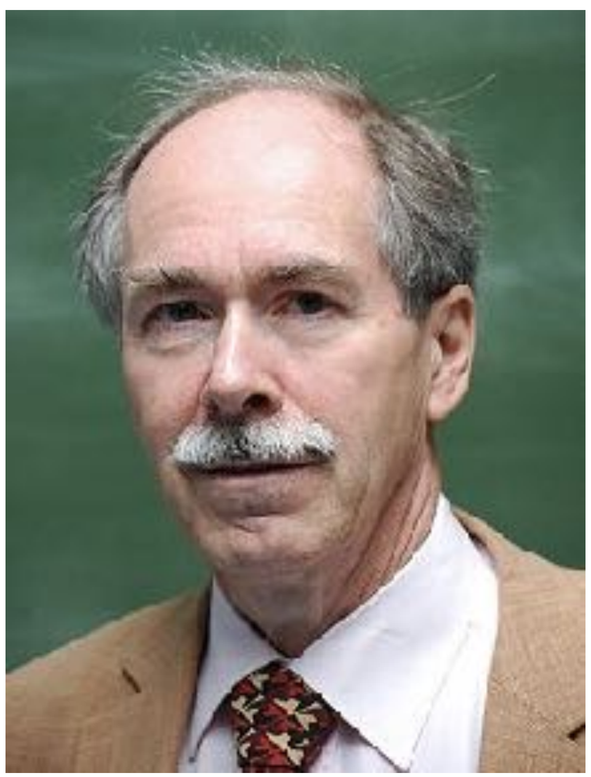


topological monopoles?

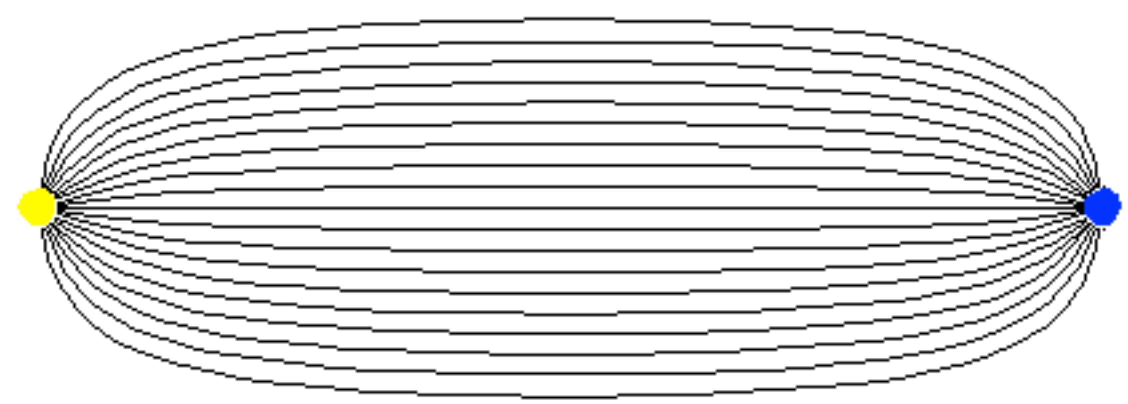
\`t Hooft Nucl. Phys., B79 1974, 276
Polyakov JETP Lett., 20 1974, 194

't Hooft-Mandelstam

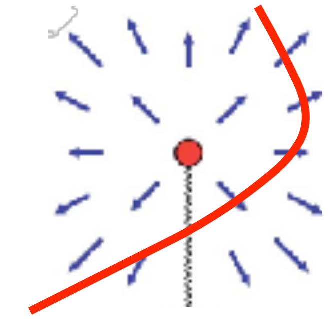


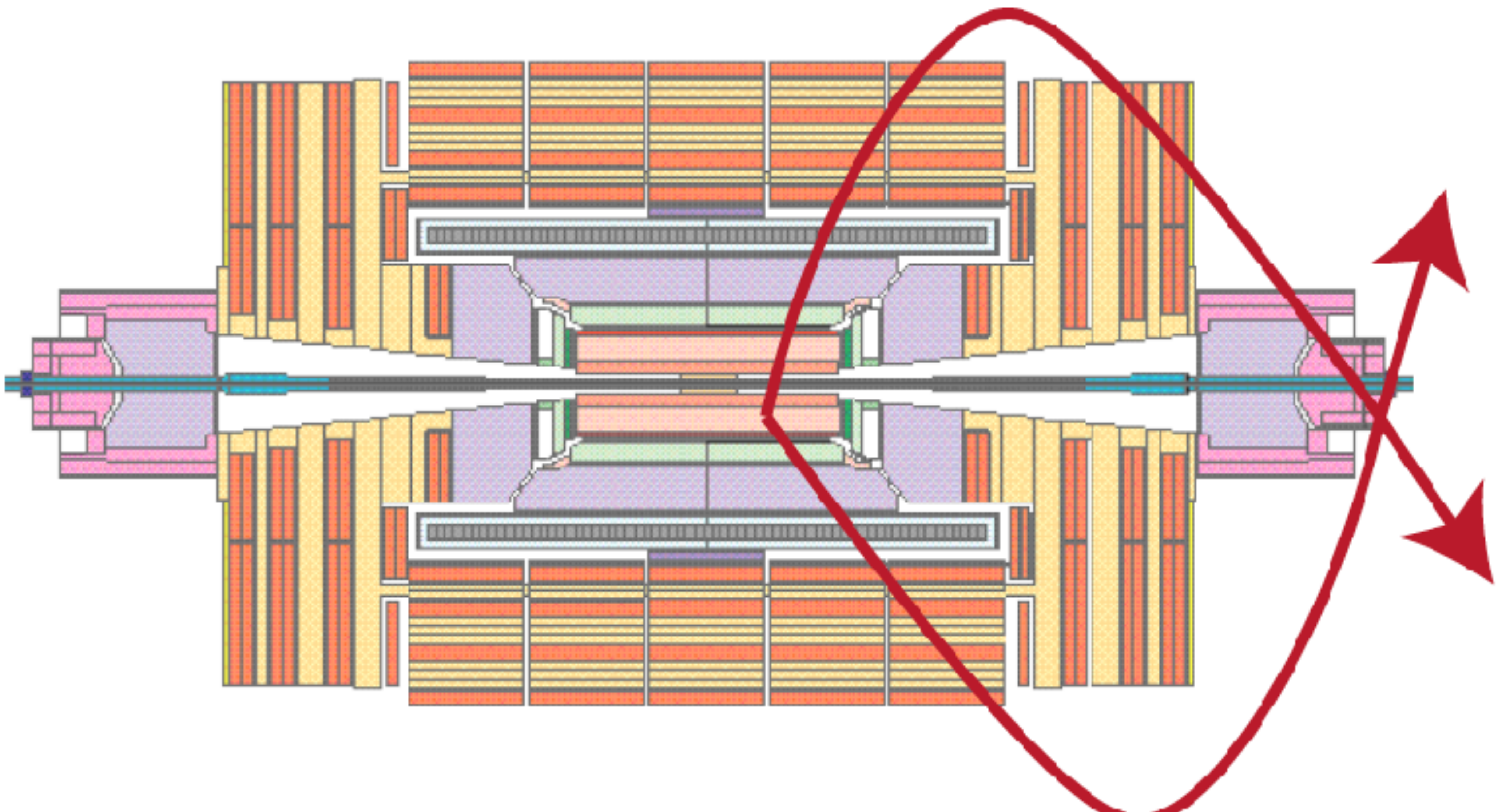


magnetic condensate
confines electric charge
and vice versa



High Energy Physics Ed. Zichichi, (1976) 1225
Phys. Rept. 23 (1976) 245



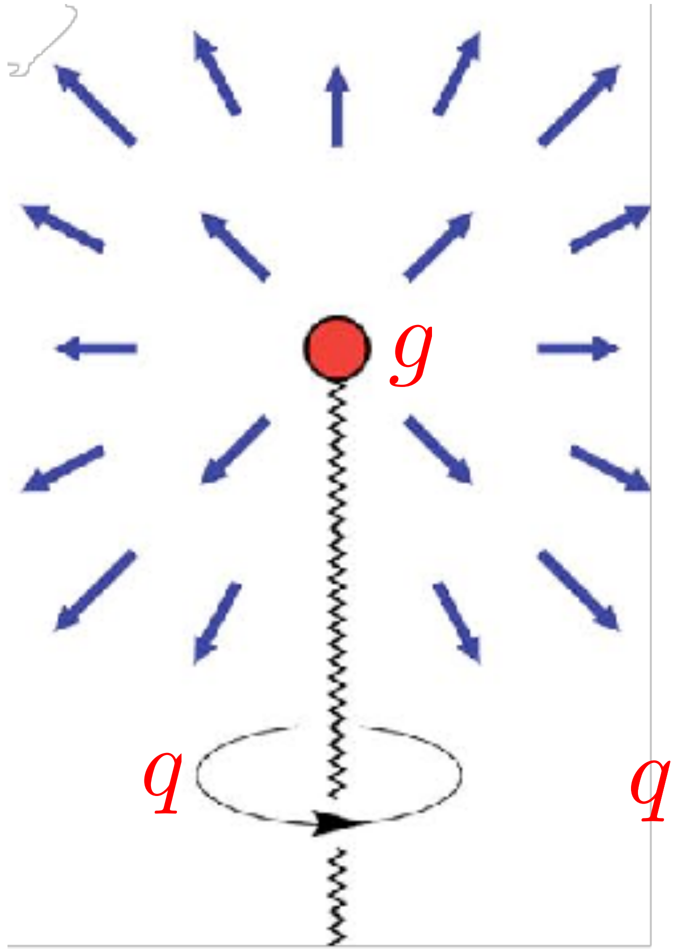


Kang & Luty hep-ph/0805.4642

Cai, Cheng, JT hep-ph/0812.0843

Dirac String

$$\vec{A}(\vec{r}) = \frac{g}{e\,r}\,\frac{\vec{r}\times\vec{n}}{r - \vec{r}\cdot\vec{n}}$$

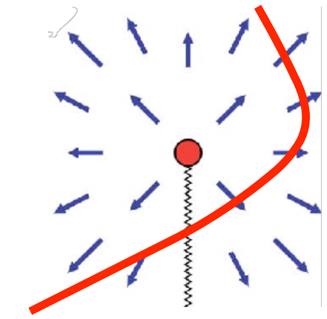


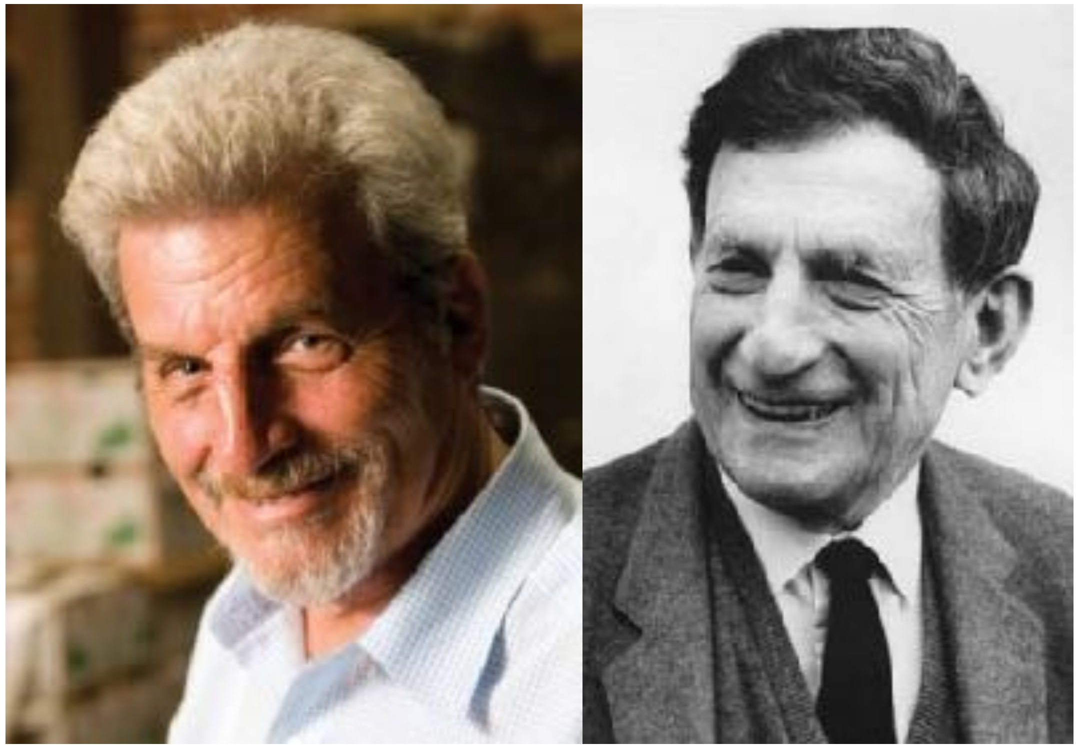
$$q\,g = \frac{N}{2}$$

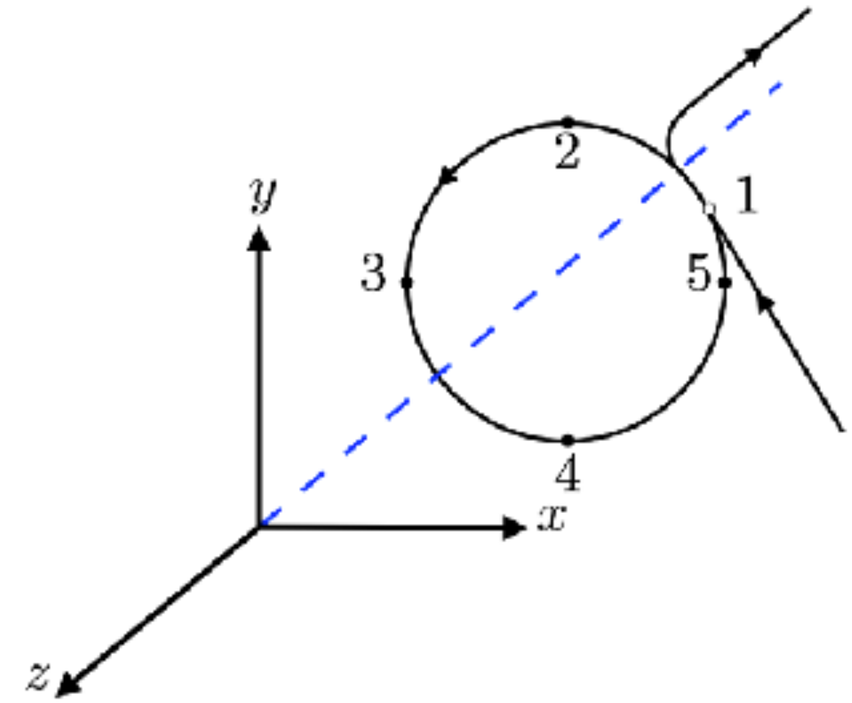
charge quantization

Proc. Roy. Soc. Lond. A133 (1931) 60

Aharonov-Bohm







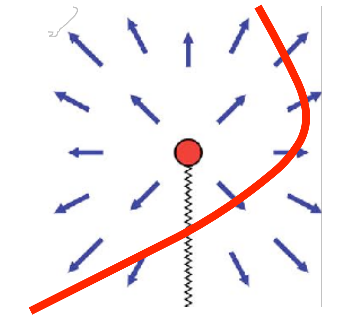
$$A_\phi = \frac{g}{e}(1 - \cos\theta)$$

$$\Phi = eq \int_0^{2\pi} d\phi A_\phi = 2\pi\, qg(1 - \cos\theta_0)$$

$$\Phi_{\text{string}} = \lim_{\theta_0 \to 0} eq \int_0^{2\pi} d\phi A_\phi = 4\pi qg$$

Phys. Rev. 115 (1959) 485

SL(2,Z) Duality



$$\tau \equiv \frac{\theta}{2\pi} + \frac{4\pi i}{e^2} \qquad S : \tau \to -\frac{1}{\tau} \qquad T : \tau \to \tau + 1$$

$$\tau' = \frac{a\tau + b}{c\tau + d}$$

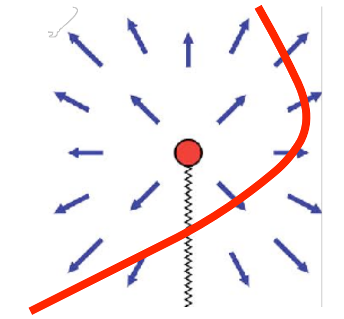
$$K^\mu \to aK'^\mu + cJ'^\mu \ , \quad J^\mu \to bK'^\mu + dJ'^\mu$$

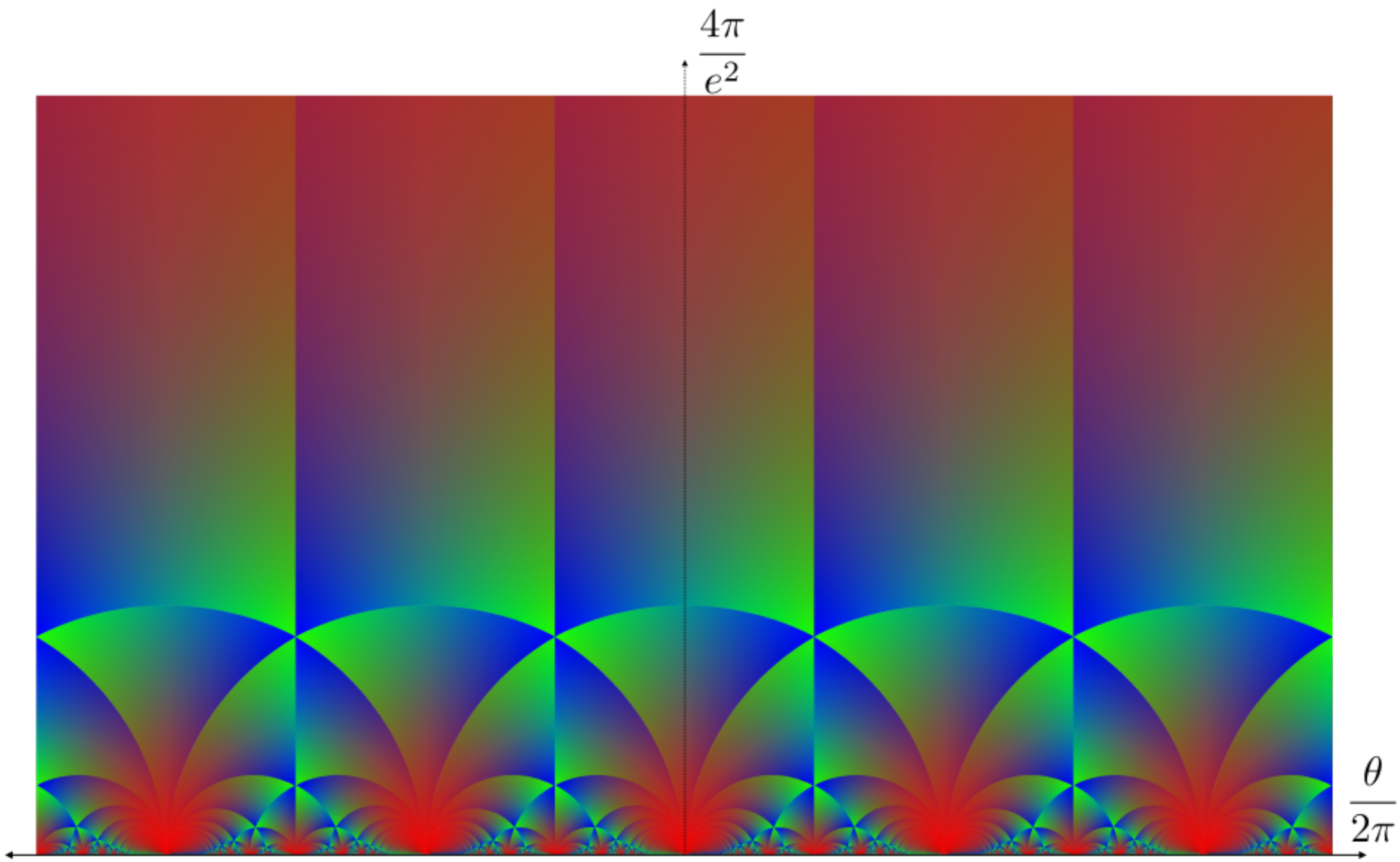
$$ad - bc = 1$$

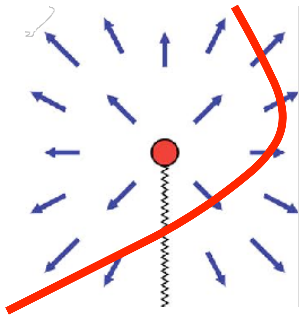
duality, not a symmetry

Cardy and Rabinovici Nucl. Phys. B**205** (1982) 1

Tiling the coupling plane

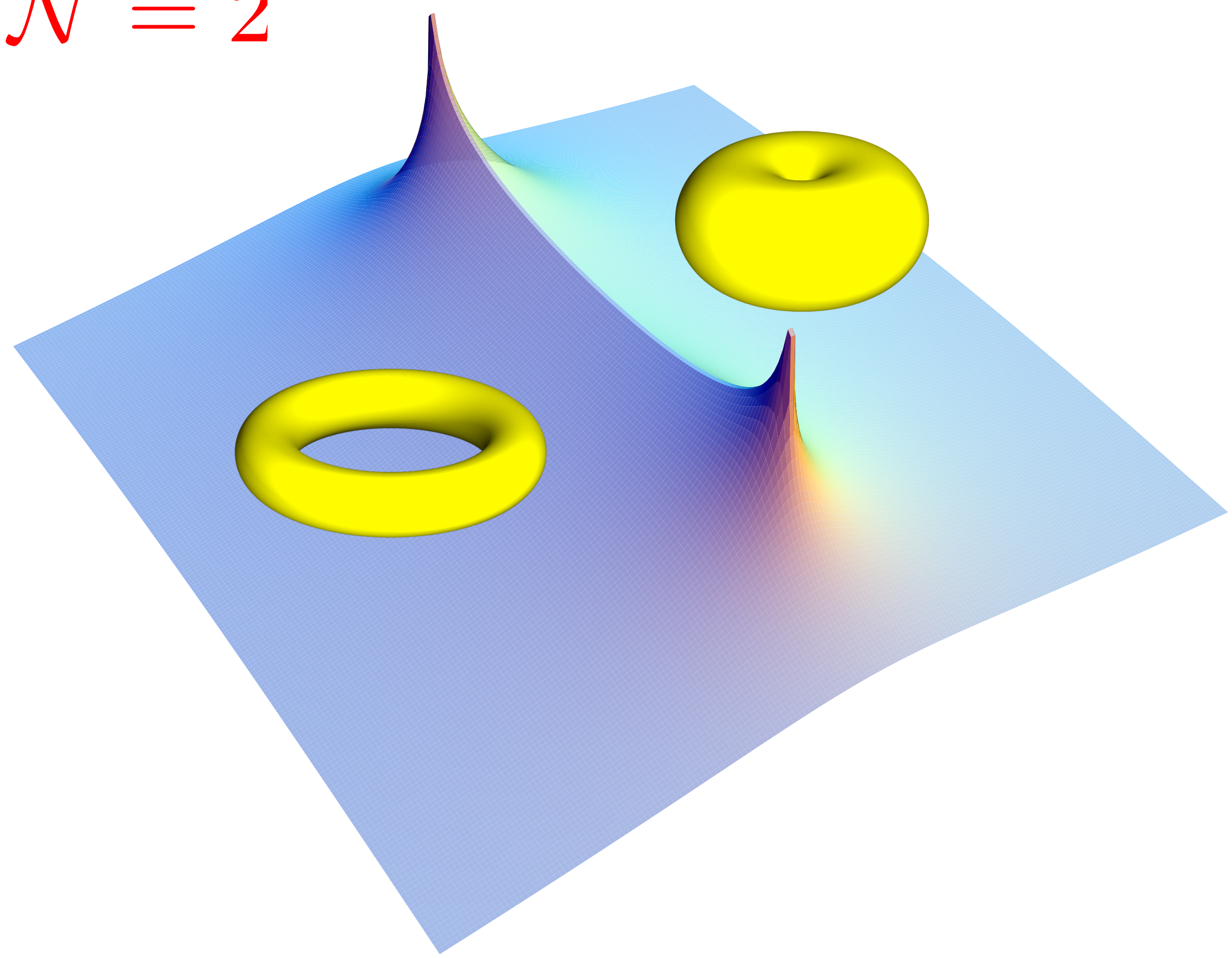






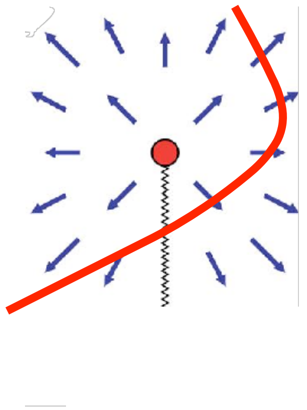
Seiberg-Witten

$\mathcal{N} = 2$

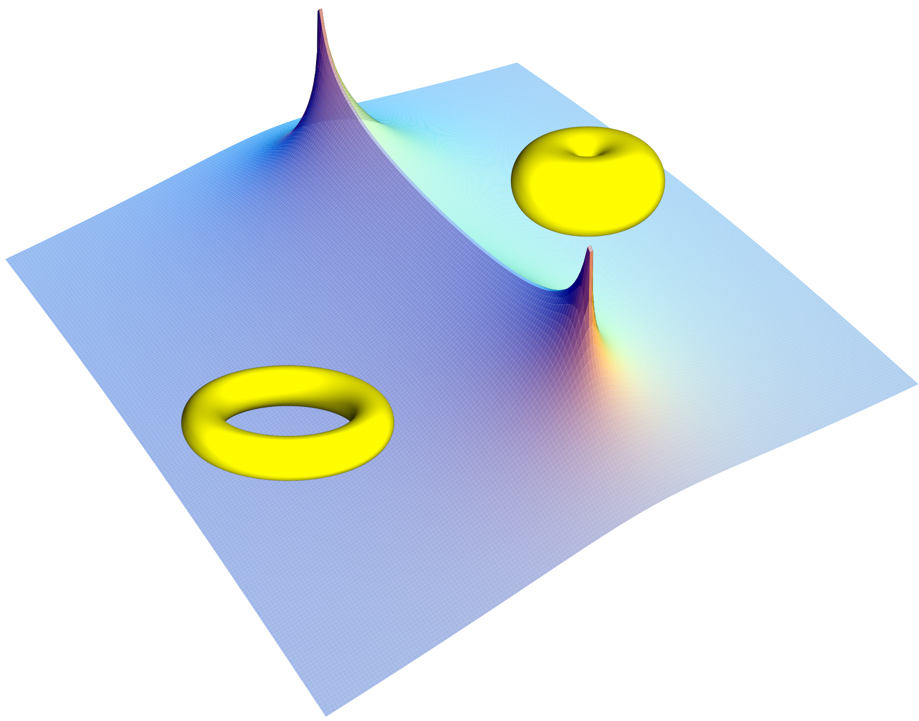


hep-th/9407087

Seiberg-Witten



low-energy effective theory



$$m(q,g;u) = \sqrt{2}\,|q\,a(u) + g\,a_D(u)|$$

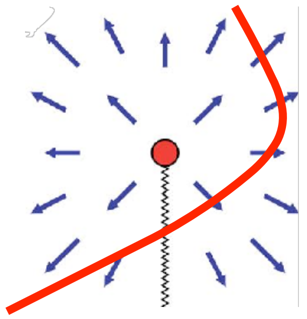
$$\tau = \frac{\partial a_D/\partial u}{\partial a/\partial u}$$

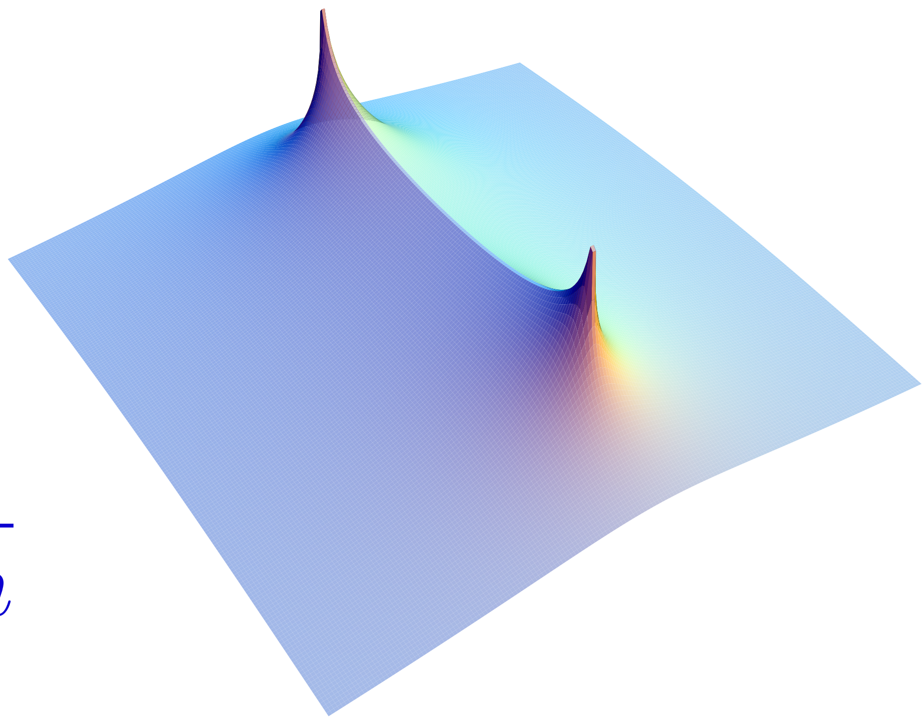
$$a(u) = -\sqrt{2(\Lambda^2+u)}\,F\left(-\frac{1}{2},\frac{1}{2},1;\frac{2}{1+\frac{u}{\Lambda^2}}\right)$$

$$a_D(u) = -i\frac{1}{2}\left(\frac{u}{\Lambda}-\Lambda\right)F\left(\frac{1}{2},\frac{1}{2},2;\frac{1}{2}\left(1-\frac{u}{\Lambda^2}\right)\right)$$

hep-th/9407087

Seiberg-Witten





near the singularity

$$m \approx \frac{u - \Lambda^2}{\sqrt{2}\Lambda}$$

$$\tau = \frac{\theta}{2\pi} + \frac{4\pi i}{e^2} \approx i\,\frac{\pi}{\log \Lambda/m}$$

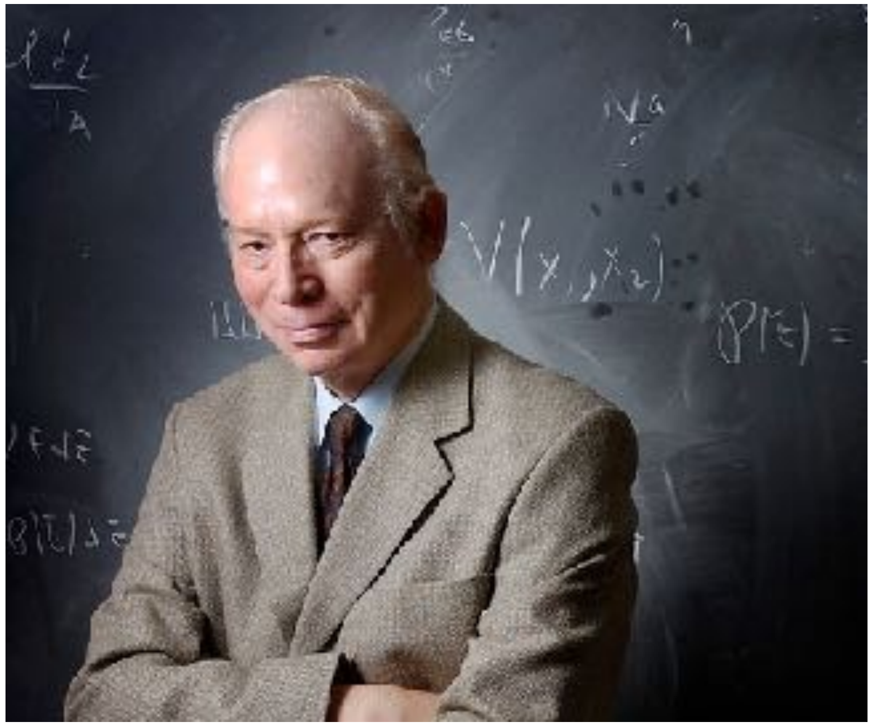
monopole is weakly coupled

dual "electron" $\alpha_d = i/\tau_d = -i\tau$

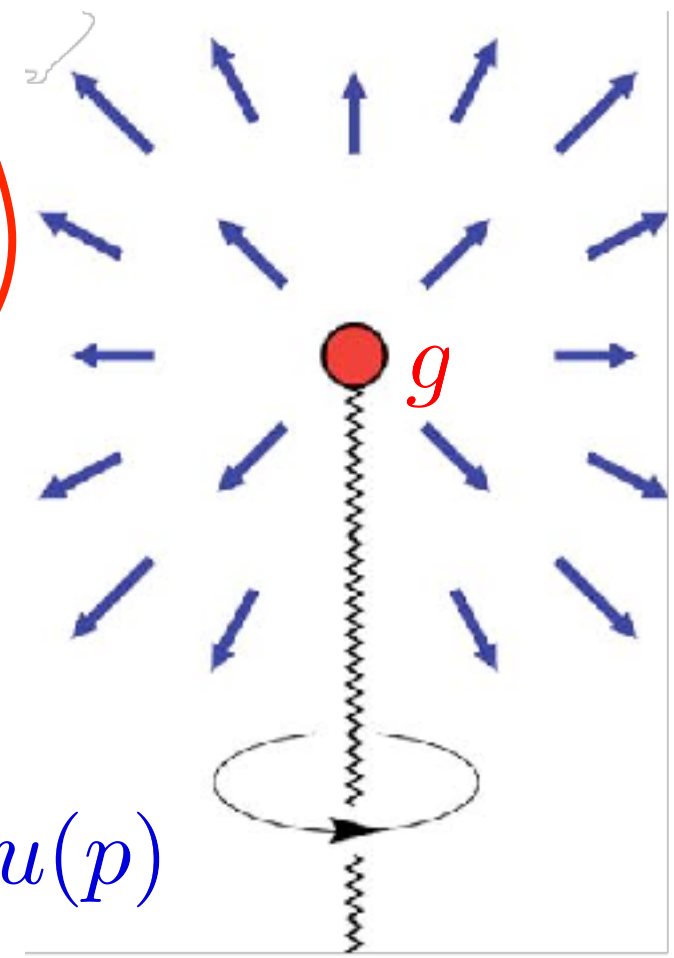
$$\alpha_d \to 0 \text{ as } m \to 0$$

β function flips sign

Weinberg's Paradox



$$\vec{A}(\vec{r}) = \frac{g}{e\,r}\,\frac{\vec{r}\times\vec{n}}{r-\vec{r}\cdot\vec{n}}$$



q

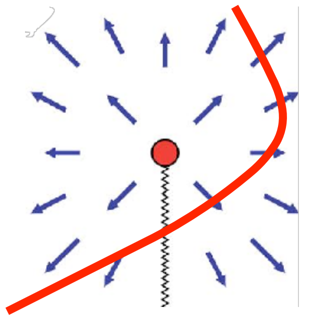
$$\mathcal{M} = e\,q\,\overline{u}(p')\not{A}(\vec{k})u(p)$$

$$A^i_\perp = \frac{4\pi g}{e\,k^2}\,\frac{(k\cdot n)}{(n\cdot k)^2 - n^2k^2}\,\epsilon^{0ij\ell}n_j k_\ell$$

Neither Lorentz nor gauge invariant!

Phys. Rev. **138** (1965) B988

Zwanziger: Two Potentials



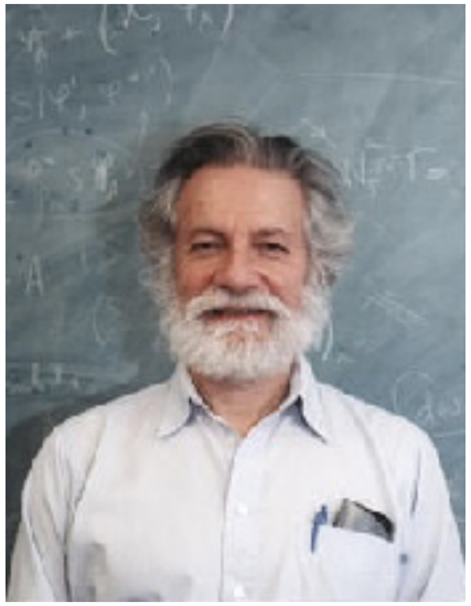
$$\mathcal{L} = -\frac{n^\alpha}{2n^2}\left[n^\mu g^{\beta\nu}\left(F^A_{\alpha\beta}F^A_{\mu\nu} + F^B_{\alpha\beta}F^B_{\mu\nu}\right) - \frac{n_\mu}{2}\varepsilon^{\mu\nu\gamma\delta}\left(F^B_{\alpha\nu}F^A_{\gamma\delta} - F^A_{\alpha\nu}F^B_{\gamma\delta}\right)\right]$$

$$- eJ_\mu A^\mu - \frac{4\pi}{e}K_\mu B^\mu$$

electric magnetic

$$F_{\mu\nu} = \frac{n^\alpha}{n^2}\left(n_\mu F^A_{\alpha\nu} - n_\nu F^A_{\alpha\mu} - \varepsilon_{\mu\nu\alpha}{}^\beta n^\gamma F^B_{\gamma\beta}\right) ,$$

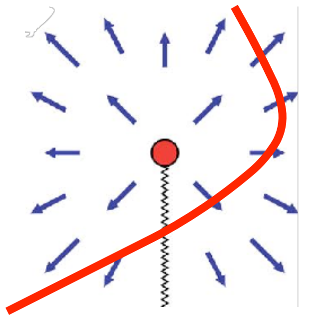
$$^*F_{\mu\nu} = \frac{n^\alpha}{n^2}\left(n_\mu F^B_{\alpha\nu} - n_\nu F^B_{\alpha\mu} + \varepsilon_{\mu\nu\alpha}{}^\beta n^\gamma F^A_{\gamma\beta}\right)$$



$$\partial_\mu F^{\mu\nu} = e\,J^\nu\ , \quad \partial_\mu {}^*F^{\mu\nu} = \frac{4\pi}{e}\,K^\nu$$

Phys. Rev. D3 (1971) 880

Zwanziger: Two Potentials



$$\mathcal{L} = -\frac{n^\alpha}{2n^2}\left[n^\mu g^{\beta\nu}\left(F^A_{\alpha\beta}F^A_{\mu\nu} + F^B_{\alpha\beta}F^B_{\mu\nu}\right) - \frac{n_\mu}{2}\varepsilon^{\mu\nu\gamma\delta}\left(F^B_{\alpha\nu}F^A_{\gamma\delta} - F^A_{\alpha\nu}F^B_{\gamma\delta}\right)\right]$$

$$- eJ_\mu A^\mu - \frac{4\pi}{e}K_\mu B^\mu$$

electric magnetic

S-Duality is already baked in!

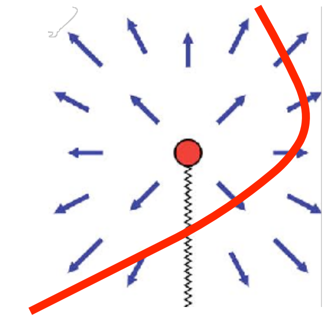
$$K^\mu \rightarrow aK'^\mu + cJ'^\mu\,,\;\; J^\mu \rightarrow bK'^\mu + dJ'^\mu$$

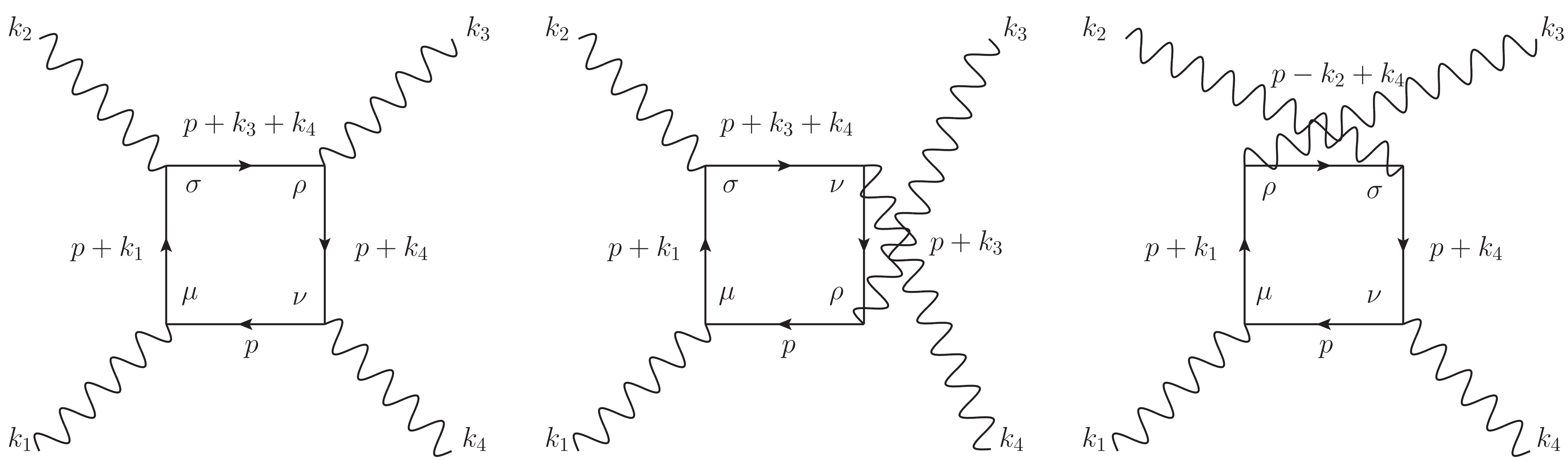
$$\left(F^{\mu\nu} + i\,{}^*F^{\mu\nu}\right) \rightarrow \frac{1}{c\tau^* + d}\left(F'^{\mu\nu} + i\,{}^*F'^{\mu\nu}\right)$$

$$\tau' = \frac{a\tau + b}{c\tau + d}$$

Csaki, Shirman, JT hep-th/1003.0448

S Duality holds at loop level

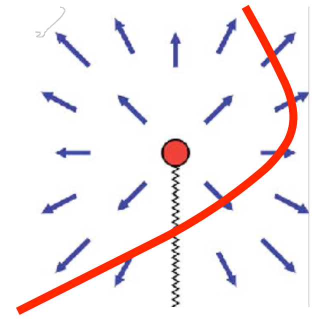


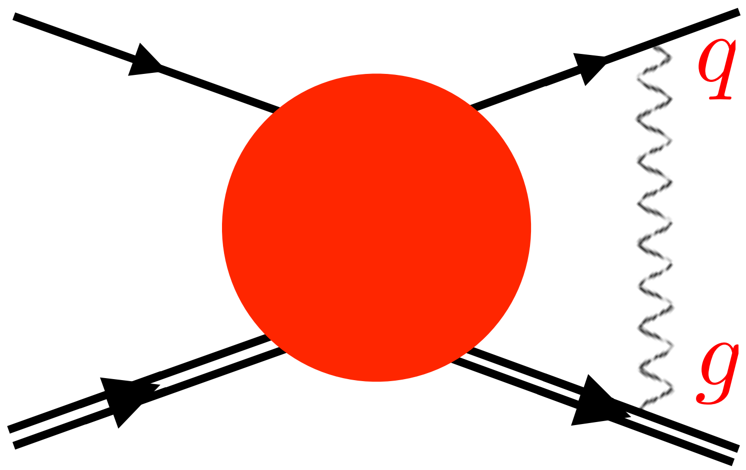


$$|\mathcal{M}|^2 = |\mathcal{M}_d|^2$$

JT, Colwell hep-th/1510.07627

Linking Number





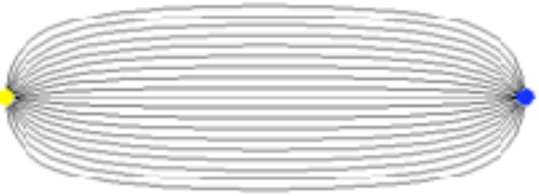
$$\mathcal{M}^{\Lambda_{\rm IR}} = \mathcal{M}^{\Lambda} \exp\left[2\pi \sum_{\ell m} \eta_\ell \eta_m \left(\widehat{S}^{eg}_{\ell m} + 2i q_\ell g_m L_{\ell m}\right)\right]$$

$$2i\, q_\ell g_m\, L_{\ell m} = 2i\, q_\ell g_m \int_{S_\ell} dz^2 e^1_{[\beta} e^2_{\alpha]} \oint dz^\alpha_m n^\beta \int_0^\infty d\tau\, \delta(z_\ell - z_m - n\tau)$$

Lorentz invariant for Dirac charge quantization!

JT, Verhaaren hep-th/1809.05102

Dark Monopoles



$$\mathcal{L}_{\mathrm{SM}}(A_\mu, B_\mu)$$

$$J^\mu, \;\; K^\mu$$

$$q\,g = \frac{N}{2}$$

$$SL(2,\mathbb{Z})$$

$$\mathcal{L}_{\mathrm{D}}(A_{D\mu}, B_{D\mu})$$

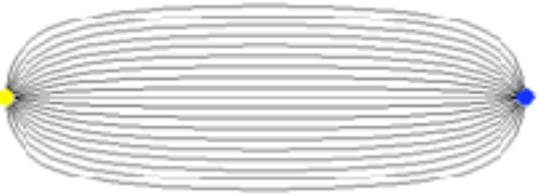
$$J^\mu_D, \;\; K^\mu_D$$

$$q_D\,g_D = \frac{N_D}{2}$$

$$SL(2,\mathbb{Z})$$

JT, Chris Verhaaren hep-th/1808.09459

Dark Monopoles



$$\mathcal{L}_{\rm SM}(A_\mu, B_\mu) \qquad\qquad \mathcal{L}_{\rm D}(A_{D\mu}, B_{D\mu})$$

$$J^\mu,\;\; K^\mu \qquad\qquad J^\mu_D,\;\; K^\mu_D$$

$$q\, g = \frac{N}{2} \qquad\qquad q_D\, g_D = \frac{N_D}{2}$$

$$SL(2,\mathbb{Z}) \qquad\qquad SL(2,\mathbb{Z})$$

$$\mathcal{L}_{\rm mix} = \frac{\varepsilon}{2} F_{\mu\nu} F^{\mu\nu}_D$$

diagonal $SL(2,\mathbb{Z})$

$$\overline{q}\,\overline{g} + \overline{q}_D\,\overline{g}_D = q\,g + q_D\,g_D = \frac{N + N_D}{2}$$

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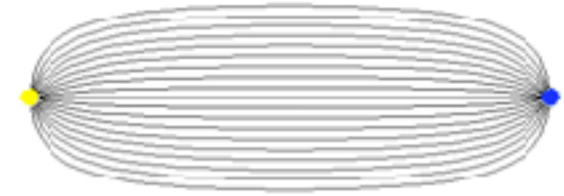
Dark Monopoles



$$\mathcal{L}_{\rm SM}(A_\mu, B_\mu) \qquad \mathcal{L}_{\rm D}(A_{D\mu}, B_{D\mu})$$

$$J^\mu,\ K^\mu \qquad J^\mu_D,\ K^\mu_D$$

$$q\,g = \frac{N}{2} \qquad q_D\,g_D = \frac{N_D}{2}$$

$$SL(2,\mathbb{Z}) \qquad SL(2,\mathbb{Z})$$

$$\delta\mathcal{L} = \frac{\varepsilon}{2} F_{\mu\nu}F^{\mu\nu}_D + \frac{m_D^2}{2} A_{D\mu}A^\mu_D$$

$$\overline{J}_\mu = J_\mu \qquad \overline{J}_{D\mu} = J_{D\mu} + \frac{\varepsilon e}{e_D} J_\mu$$

$$\overline{K}_\mu = K_\mu - \frac{\varepsilon e}{e_D} K_{D\mu} \qquad \overline{K}_{D\mu} = K_{D\mu}$$

$$L \gg \frac{1}{m_D} \ : \quad \overline{q}\,\overline{g} = q\,g - \frac{\varepsilon e}{e_D} q\,g_D$$

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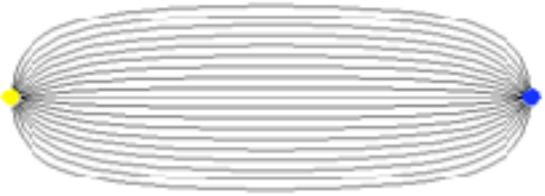
Confined Quirk Spectrum



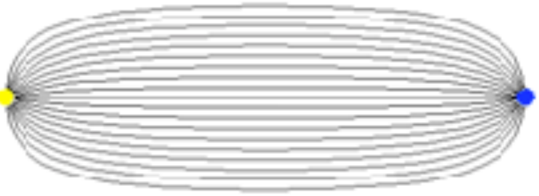
$$mH = \frac{p^2}{2} + b\,v^2 m\,r$$

$$mE \propto \left(v^2 m\right)^{2/3}$$

$$E \propto \frac{v^{4/3}}{m^{1/3}}$$

$$\langle r \rangle \propto \frac{1}{v^{2/3} m^{1/3}}$$

Confined Quirk Spectrum



$$m_D \sim 1\,\mathrm{eV} \qquad e_D = 0.3$$

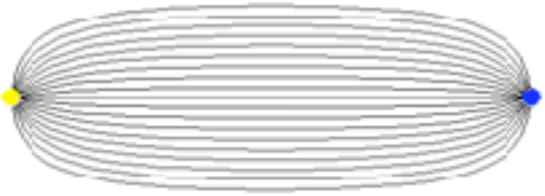
$$m \sim 1\,\mathrm{keV}$$

flux: $\dfrac{10^{11}}{\mathrm{m}^2\,\mathrm{s}}$

$$E \propto \frac{m_D^{4/3}}{e_D^{4/3}\, m^{1/3}} \sim 1\,\mathrm{eV}$$

$$\langle r \rangle \propto \frac{e_D^{2/3}}{m_D^{2/3}\, m^{1/3}} \sim 7\,\mathrm{nm}$$

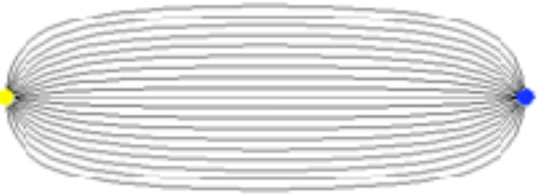
2p <-> 1s Transitions



$$E \propto \frac{m_D^{4/3}}{e_D^{4/3}\, m^{1/3}} \sim 1\,\mathrm{eV}$$

$$\Gamma \sim |\varepsilon \langle r \rangle|^2 E^3 \sim 10^{-11} 1/\mathrm{s}$$

2p <-> 1s Transitions



$$E \propto \frac{m_D^{4/3}}{e_D^{4/3}\, m^{1/3}} \sim 1\,\mathrm{eV}$$

$$\Gamma \sim |\varepsilon\langle r\rangle|^2 E^3 \sim 10^{-11} 1/\mathrm{s}$$

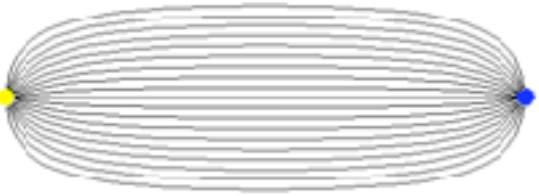
photon absorption cross section

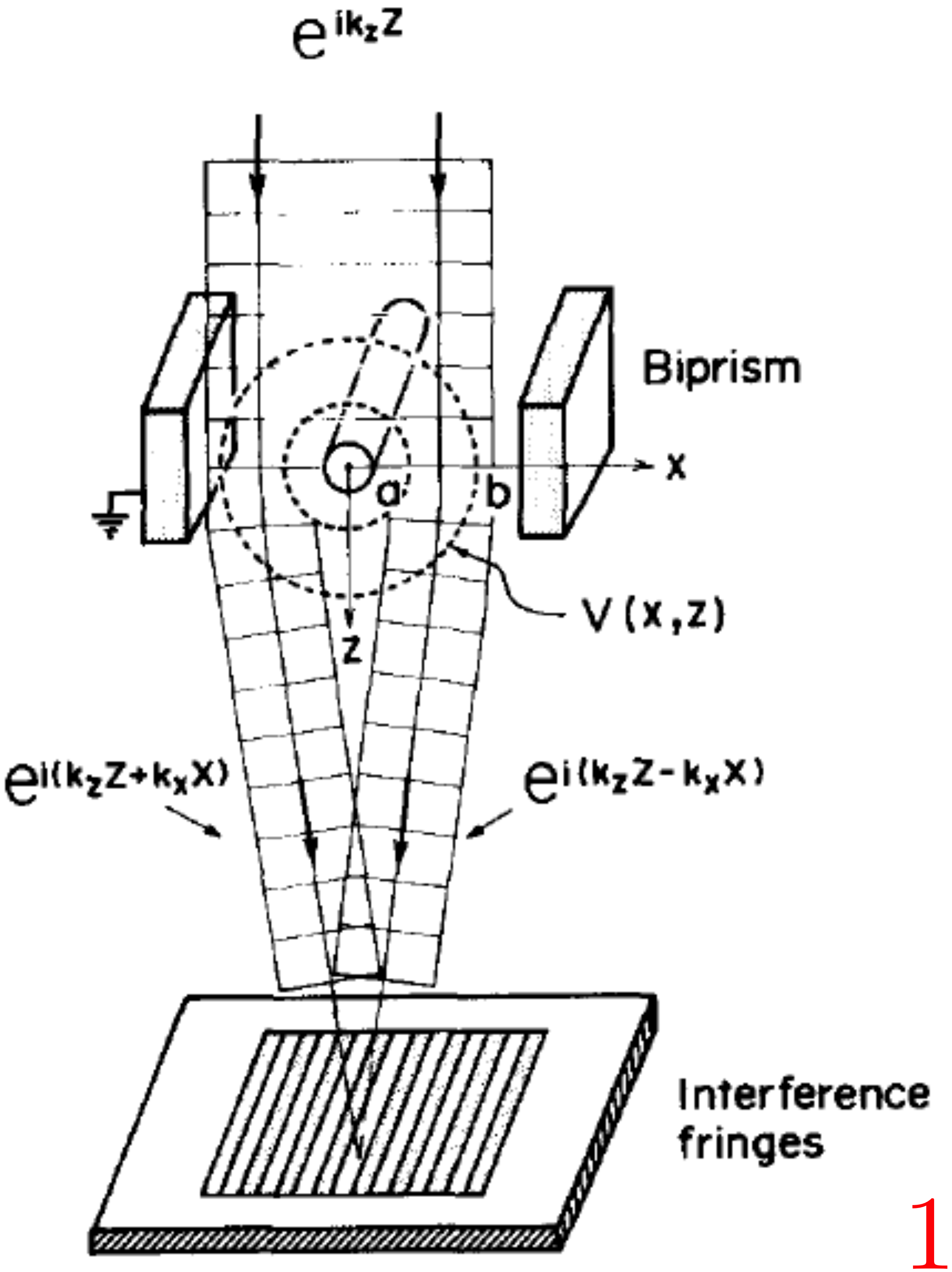
$$\sigma \sim \lambda^2 \Gamma \delta(\omega - \Delta E)$$

1 in 10^8 get excited near Sun

flux: $\dfrac{10 \text{ excited DM}}{\mu\mathrm{m}^2 \text{ day}}$

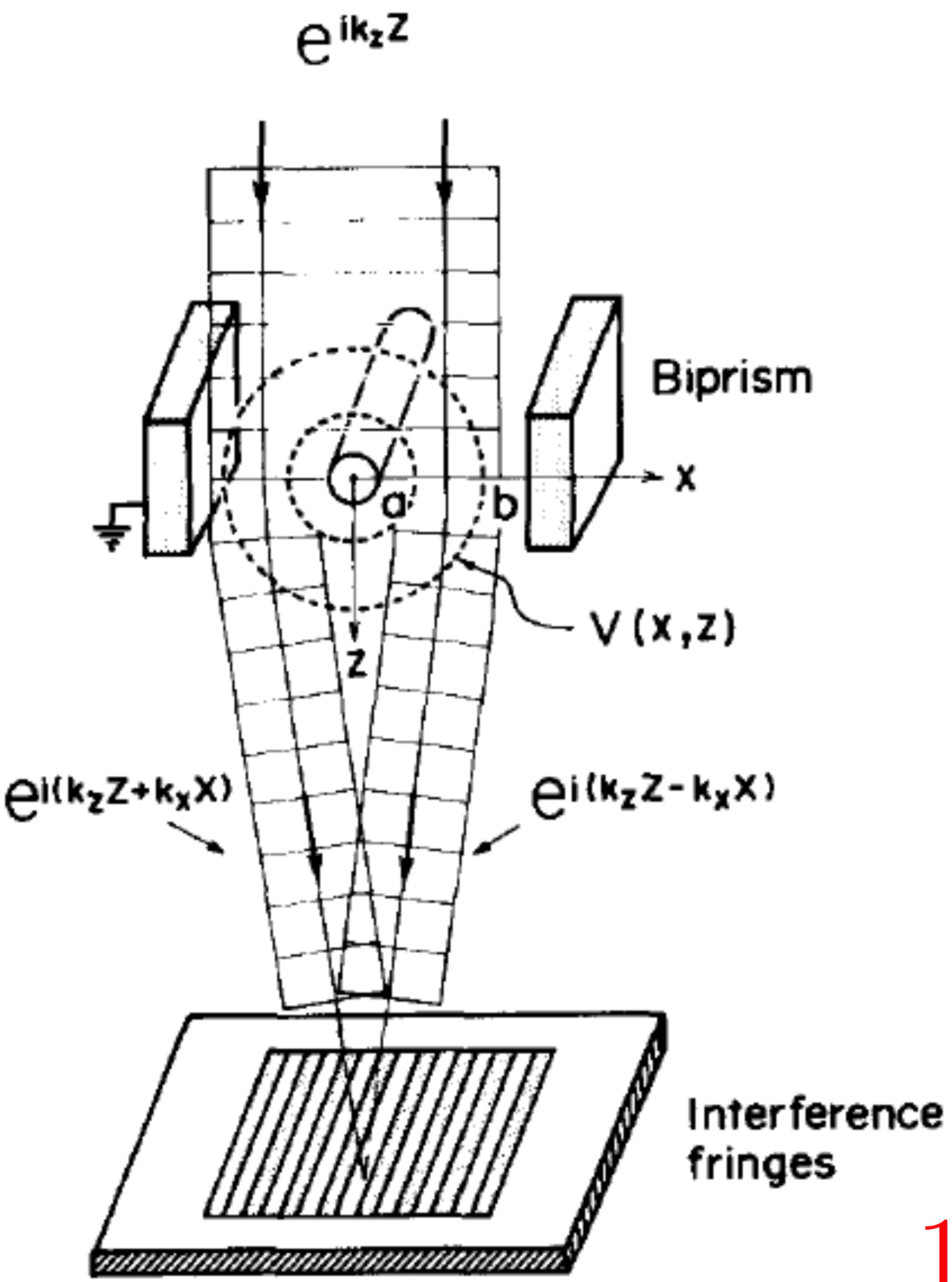
Aharonov-Bohm Experiment





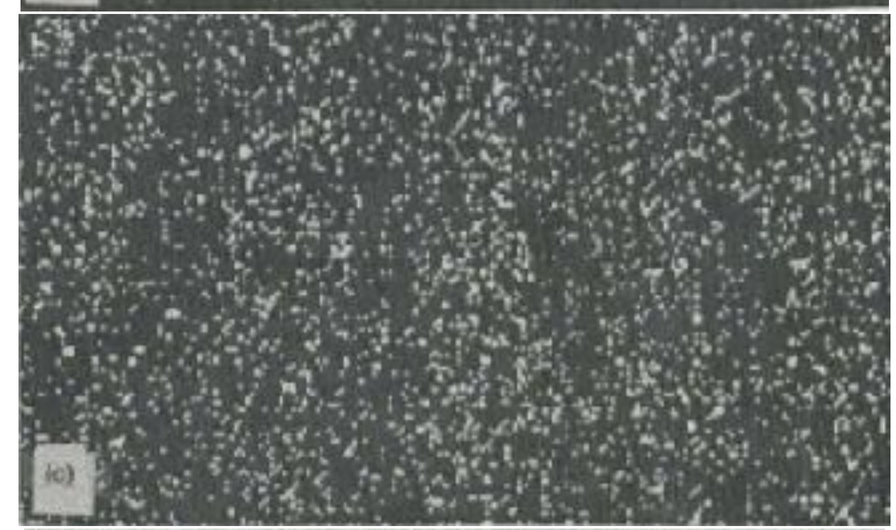
$$a \gg \frac{1}{m_D}$$

Aharonov-Bohm Experiment

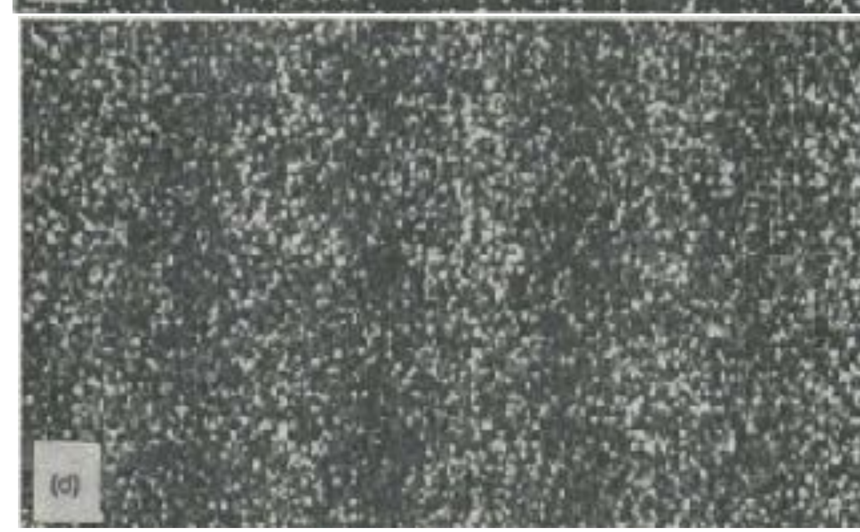


10

3000



20000



$$a \gg \frac{1}{m_D}$$

Aharonov-Bohm Detection

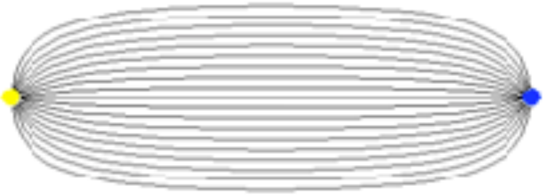


figure of merit: $\Phi = 5 \cdot 10^{-9}$

current best AB: $\Phi = 10^{-3}$

LIGO: $\Phi = 10^{-11}$

Aharonov-Bohm Detection

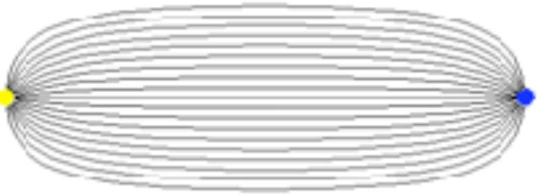


figure of merit: $\Phi = 5 \cdot 10^{-9}$

current best AB: $\Phi = 10^{-3}$

LIGO: $\Phi = 10^{-11}$

new electron microscopes:

20 ns pulses, pm resolution with 10^8 e's

100 fs pulses, Å resolution with 1-2 e's

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Conclusions

Quirky Dark Monopoles:

can have perturbative couplings, violating Dirac charge quantization

are a Dark Matter candidate

can be searched for using the Aharonov-Bohm effect