Fun with axions and axion strings

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Axions

- Solves the strong CP problem
  - Explains why the neutron eDM is small
- Natural dark matter candidate
  - Unique experimental signatures
- Measurement of the fundamental value of electric charge

Anomalies

$$\frac{\alpha_{\rm em}}{4\pi}\left(\mathcal{A}\frac{a}{f}+\theta\right)F\tilde{F}$$

$\boldsymbol{A}$ is the 't Hooft anomaly of the axion

Axion is periodic but coupling is not

$$\frac{a}{f}=\frac{a}{f}+2\pi \qquad \longrightarrow \qquad \theta=\theta+2\pi\mathcal{A}$$

Periodicity of theta

What does this periodicity teach us?

$$\theta = \theta + 2\pi\mathcal{A}$$

Witten effect

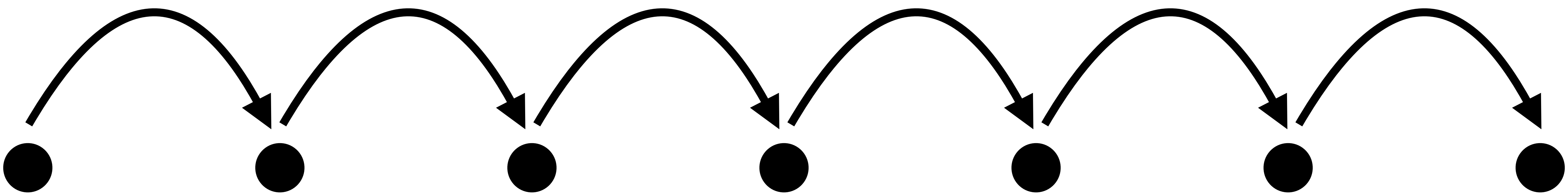
$$q_e = \left(\frac{eg}{2\pi}\right)\frac{\theta e}{2\pi} = \frac{e}{e_{\rm min}}\frac{\theta e}{2\pi}$$

Not periodic!

Need many monopoles that are exchanged

Periodicity of theta

$$\theta \to \theta + 2\pi\mathcal{A}$$



$$q_{-2}(\theta) \quad q_{-1}(\theta) \quad q_0(\theta) \quad q_1(\theta) \quad q_2(\theta)$$

$$q_n(\theta + 2\pi\mathcal{A}) = q_{n+1}(\theta)$$

Periodicity of theta

$$q_n(\theta + 2\pi\mathcal{A}) = q_{n+1}(\theta)$$

Periodicity gives difference in charge between various monopoles

$$\Delta q_e = \frac{e}{e_{\min}}\mathcal{A}\, e$$

Fundamental electric charge of monopoles

$$\Delta q_e = e_{\min} = \sqrt{\mathcal{A}}\, e$$

Periodicity of theta

Without any assumptions

$$\mathcal{A} = \mathbb{Z}\, e_{\rm min}^2 = \sum_f N_f\, N_a\, Q_f^2$$

Fractional anomaly necessarily implies fractional electric charge is the minimal charge

How to use the Axionic coupling

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

Anomaly gives us information about the quantization of electric charge

Can we measure it?

How to use the Axionic coupling

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

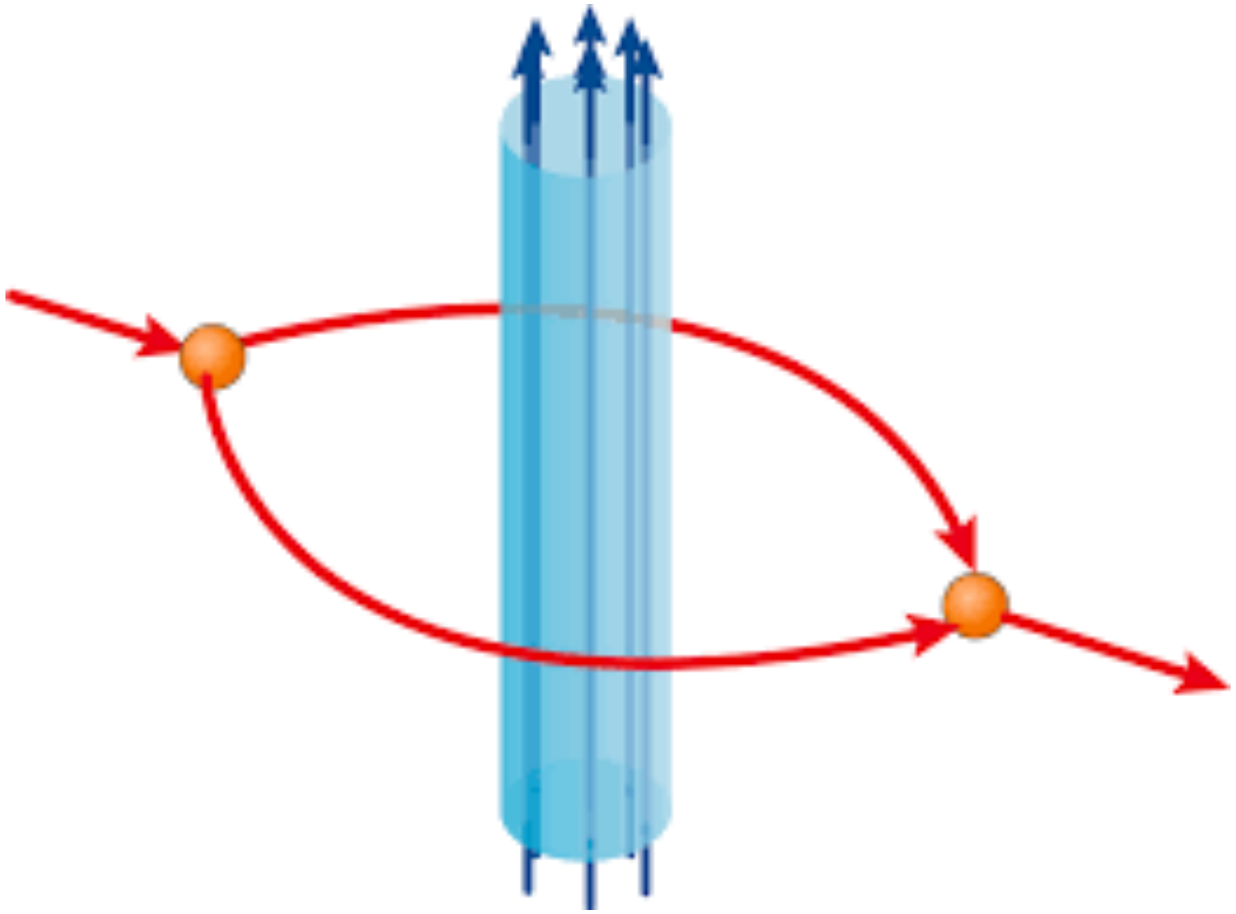
Particle approach **HARD**

Anomaly - decay constant ambiguity and
ambiguity coming from mixing effects

Decay constant RG runs : Wavefunction renormalization

Need something independent of f

How to use the Axionic coupling

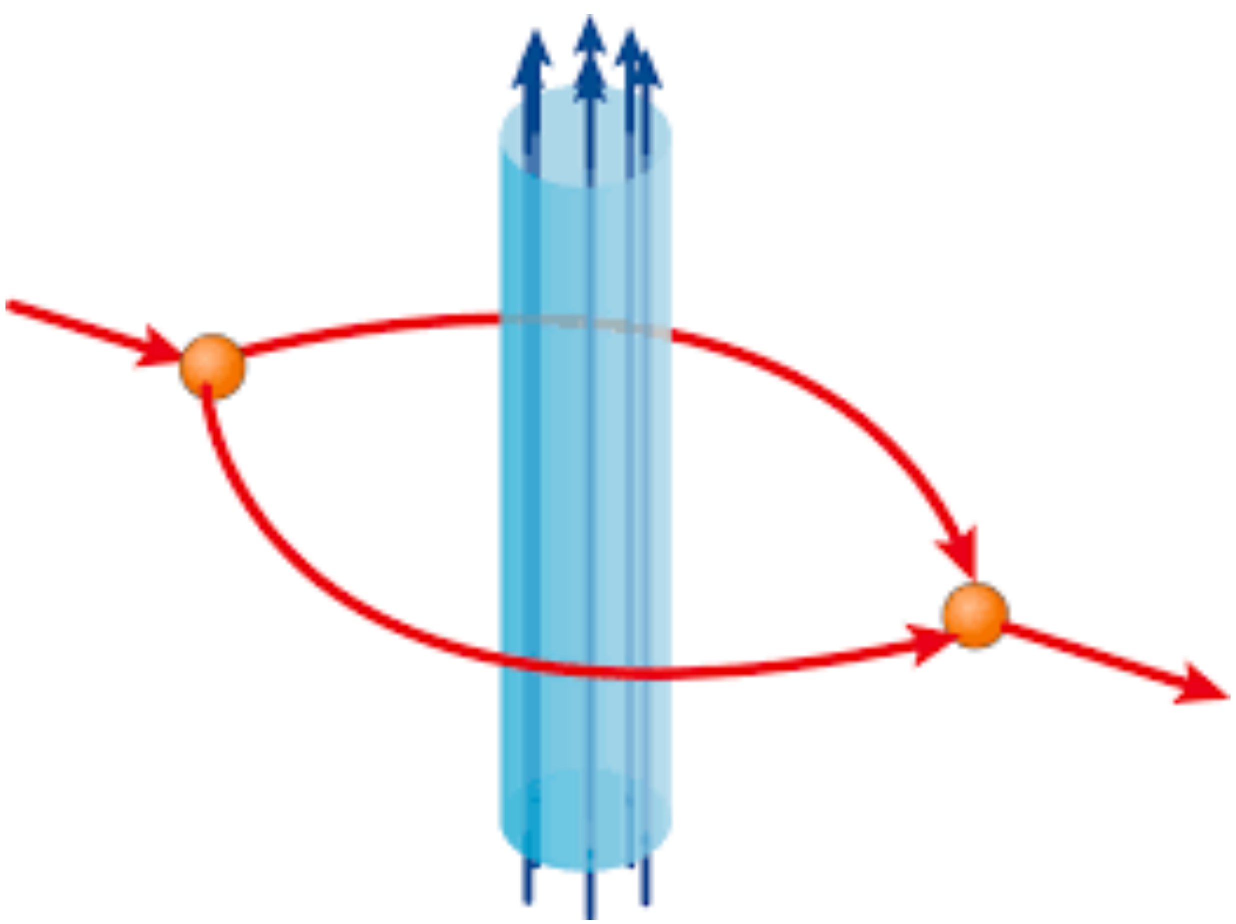


Strings!

$$\frac{a}{f} \rightarrow \frac{a}{f} + 2\pi\,(\mathbb{Z})$$

How to use the Axionic coupling

Many string properties are topological

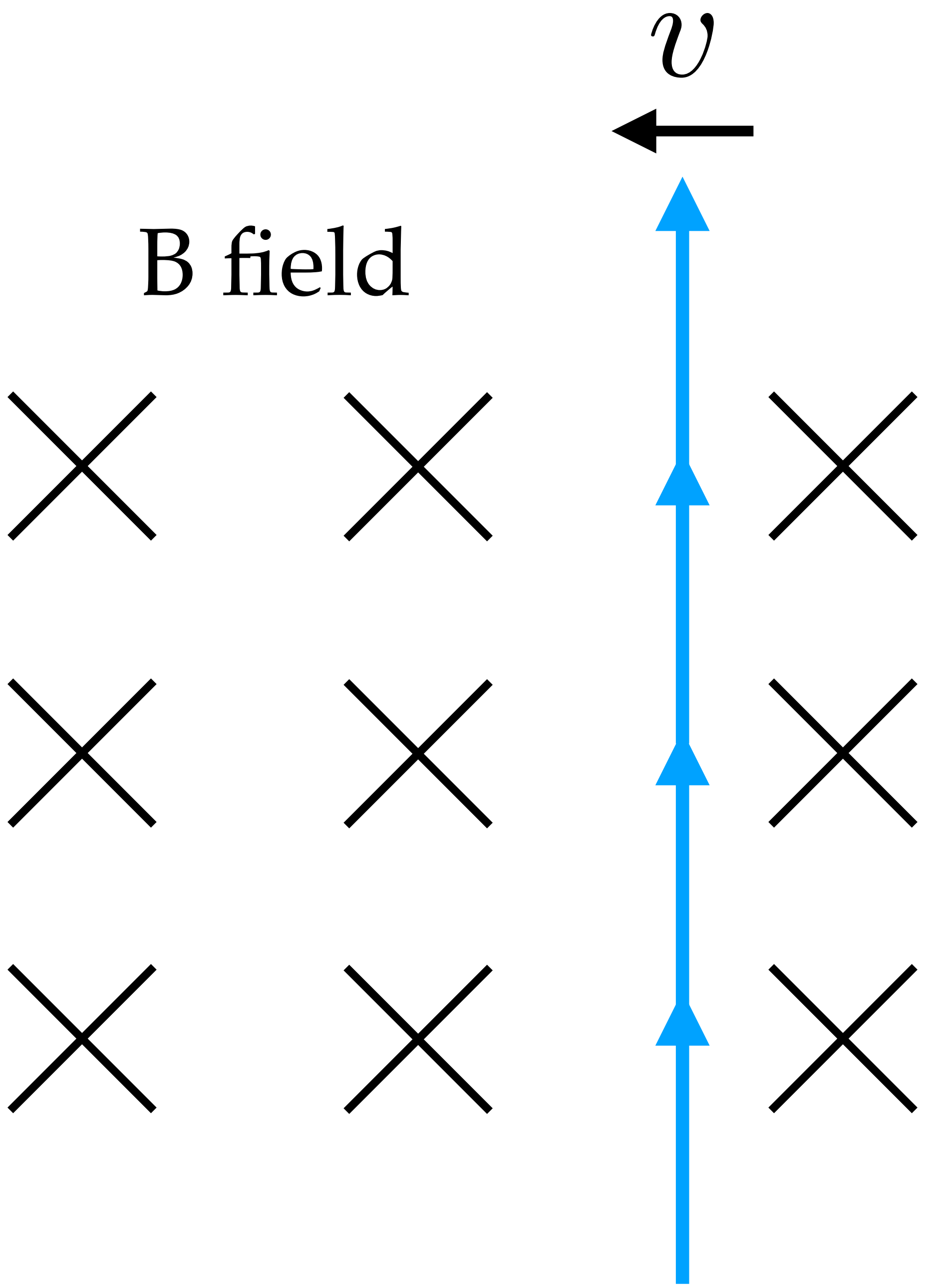


Aharonov-Bohm Effect

Photons acquire phase as it moves around an axion string

How to use the Axionic coupling

Many string properties are topological



Faraday's Law

Strings are (super)-conductors

Large currents

Outline

- How strings affect photons
  - Arahanov-Bohm effects
  - CMB ways of looking for strings
- How photons affect strings
  - Superconducting strings
  - Colliding currents

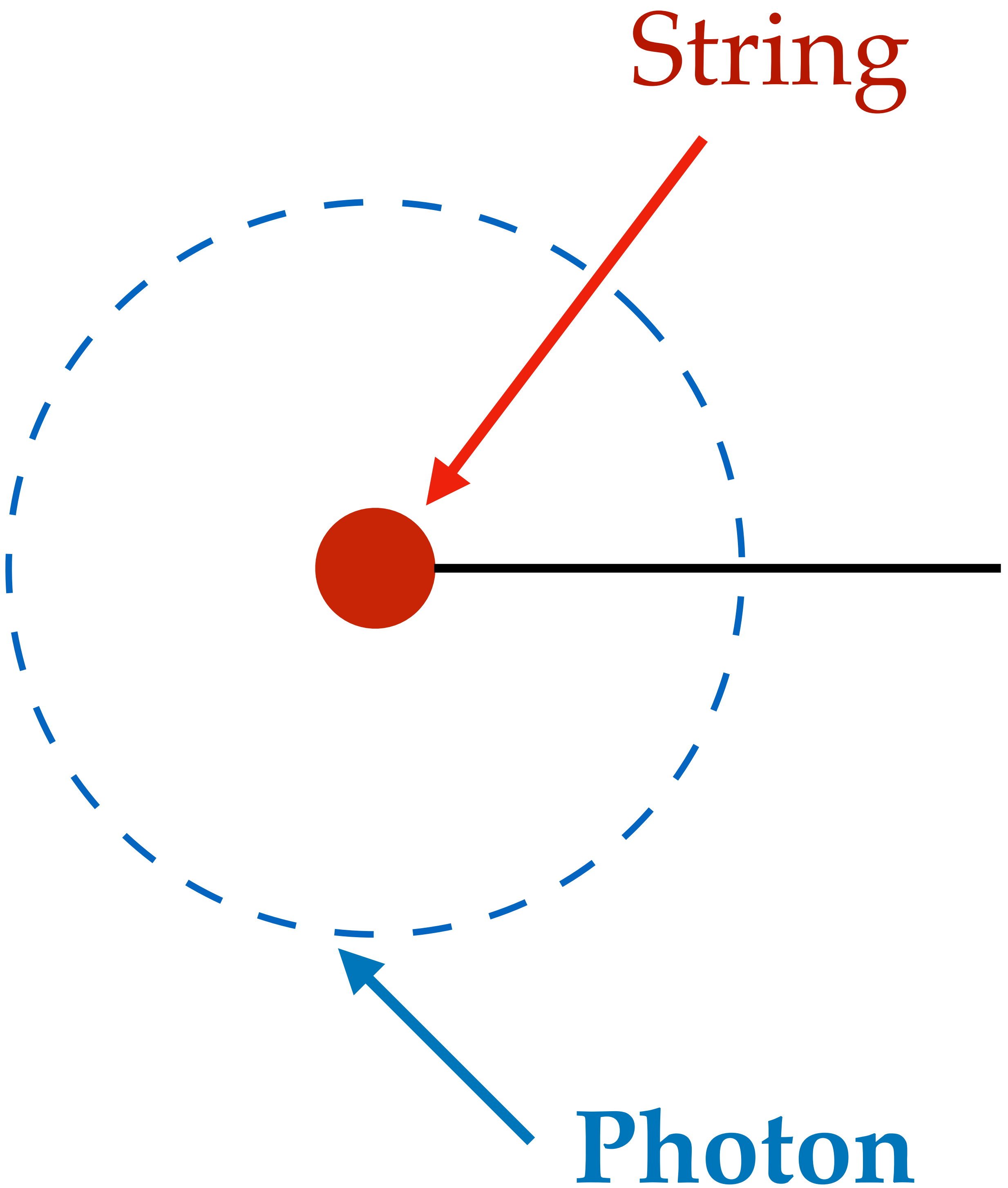
Polarization Rotation

$$\Phi = \int v dt = \mathcal{A} \alpha_{\mathrm{em}} \frac{\Delta a}{2\pi f}$$

Phase rotation of circularly polarized light is a polarization rotation of linearly polarized light

Topological - depends only on initial and final value of the axion

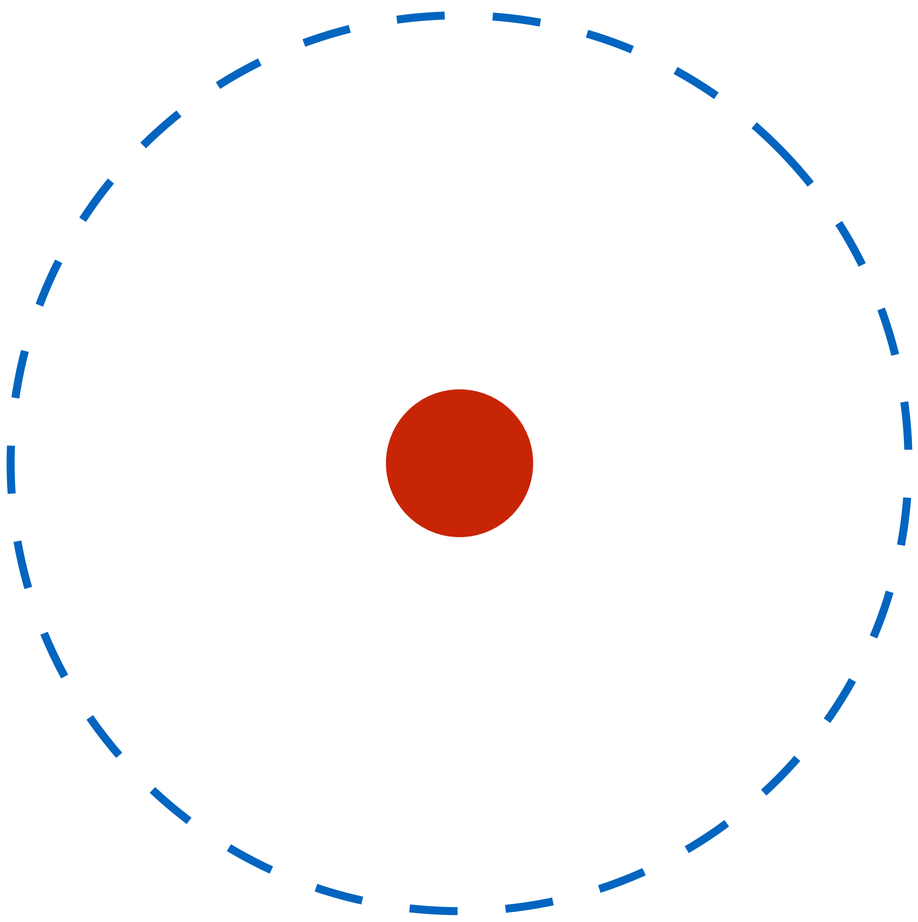
Strings and photons - a love story



$$\theta = \frac{a}{f}$$

Strings and photons - a love story

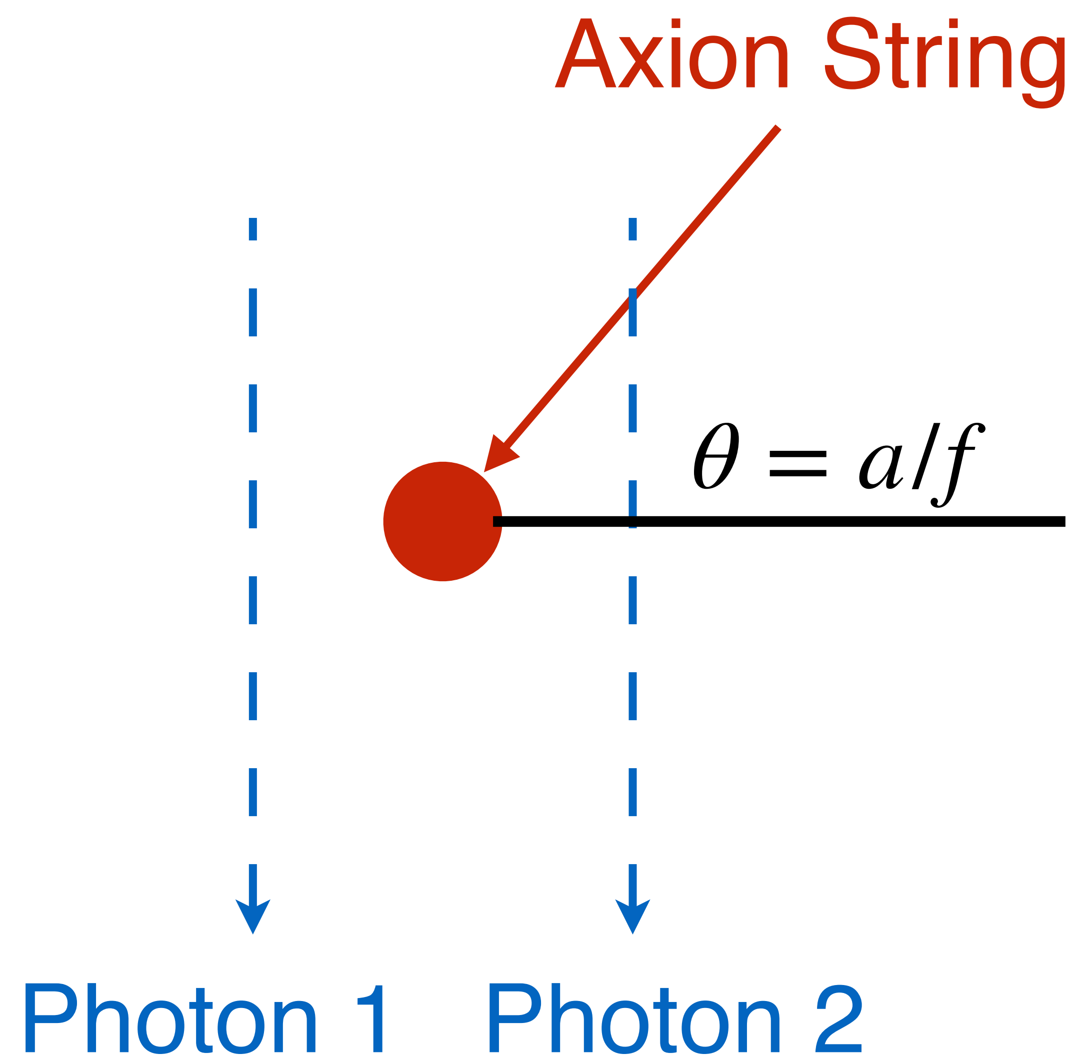
Topological effect



Large polarization rotation from traveling around a string!

$$\Phi = \frac{\mathcal{A}\alpha_{\mathrm{em}}}{2\pi}\frac{\Delta a}{f} = \mathcal{A}\alpha_{\mathrm{em}}$$

Strings and photons - a love story

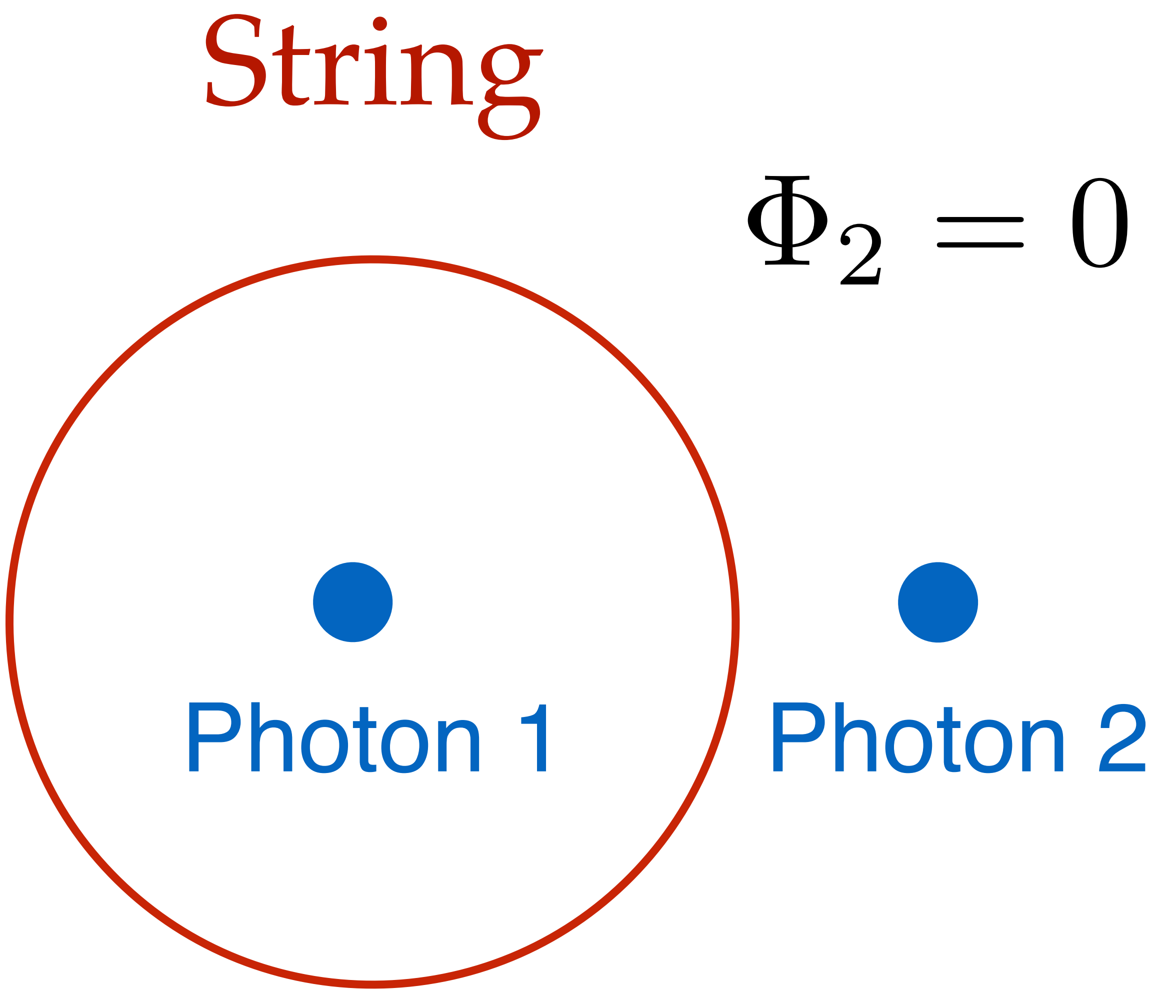


$$\Phi_1 = \frac{\mathcal{A}\alpha_{\rm em}}{2\pi}\frac{\Delta a}{f} = \frac{\mathcal{A}\alpha_{\rm em}}{2}$$

$$\Phi_2 = -\frac{\mathcal{A}\alpha_{\rm em}}{2}$$

$$\Delta\Phi = \mathcal{A}\alpha_{\rm em}$$

Strings and photons - a love story



$$\Phi_2 = 0$$

$$\Phi_1 = \pm \mathcal{A} \alpha_{\rm em}$$

Photons that go through a string loop acquire a rotation

Photons that do not go through a string loop do not acquire a rotation

Outline

- How strings affect photons
  - ~~Arahanov-Bohm effects~~
  - CMB ways of looking for strings
- How photons affect strings
  - Superconducting strings
  - Colliding currents

String evolution

String density $\rho_{\rm string} = \xi(t)\, H^2 f^2 \log\left(f/H\right)$

- Scaling solution : $\xi = \text{constant}$

- Scaling violation : $1 \lesssim \xi \lesssim 1000$

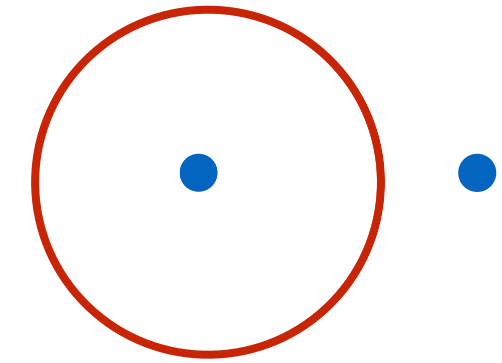
CMB

CMB acts as a backlight which is rotated by strings

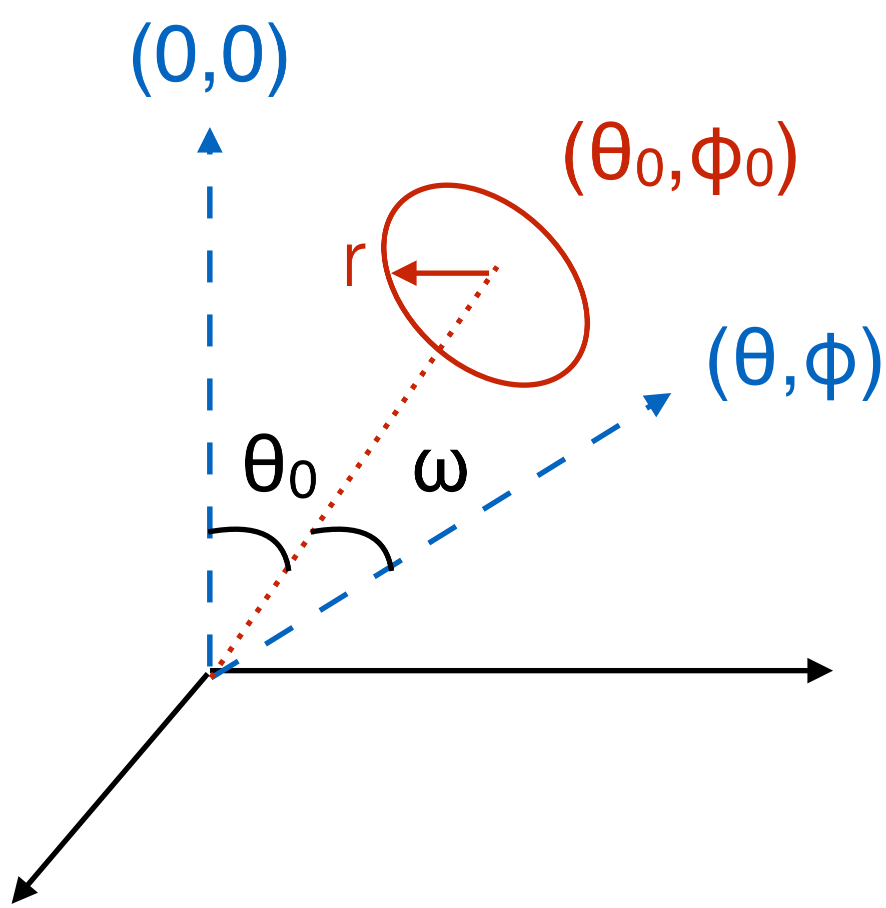
Power spectrum analysis

Look for discontinuous jumps
in the rotation angle

Toy analytics

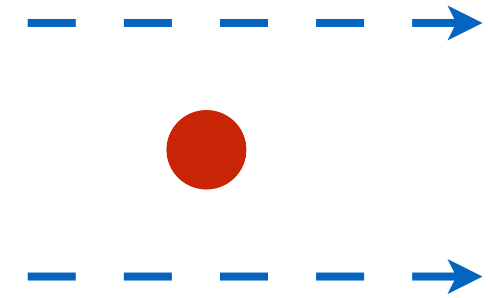


$$\langle \Phi(\hat{\gamma})\Phi(\hat{\gamma}')\rangle = (\mathcal{A}\alpha_{\rm em})^2 \int d\eta \int d^2\hat{s} \int d^2\hat{k}\,(\eta_0-\eta)^2 f(\eta) \times \Theta\left(\frac{\eta}{2} - d(\hat{s},\hat{\gamma},\hat{k},\eta)\right)\Theta\left(\frac{\eta}{2} - d(\hat{s},\hat{\gamma}',\hat{k},\eta)\right)$$

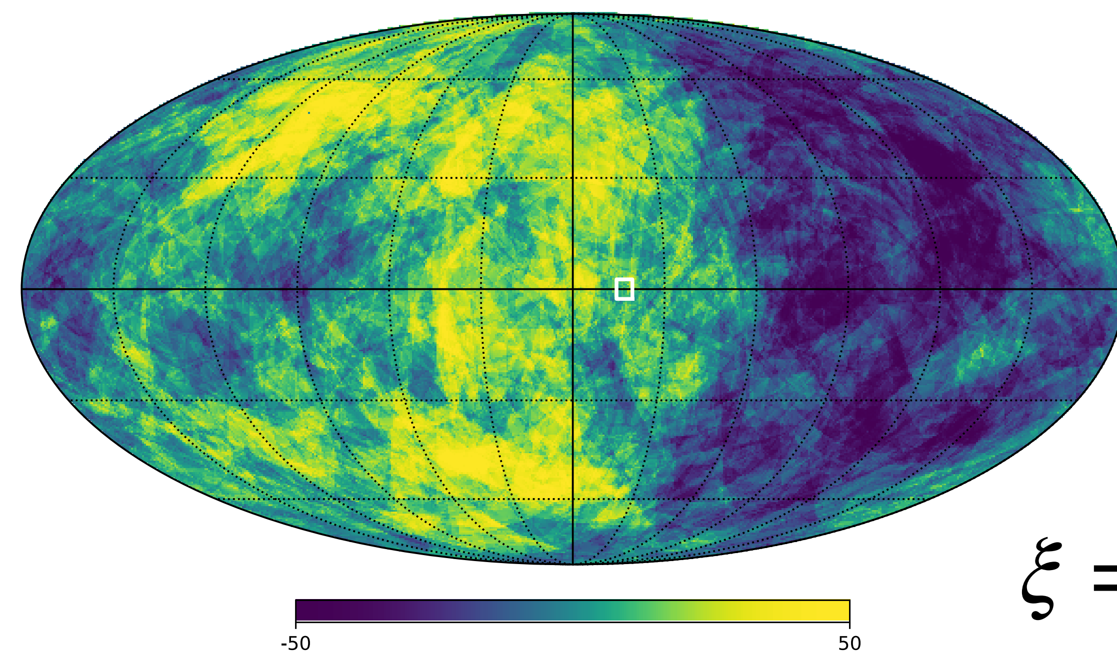


- Take strings to be Hubble sized loops
- Pass through loop acquire a phase $\Phi = \pm\mathcal{A}\alpha_{\rm em}$
- Integrate over all orientations and directions

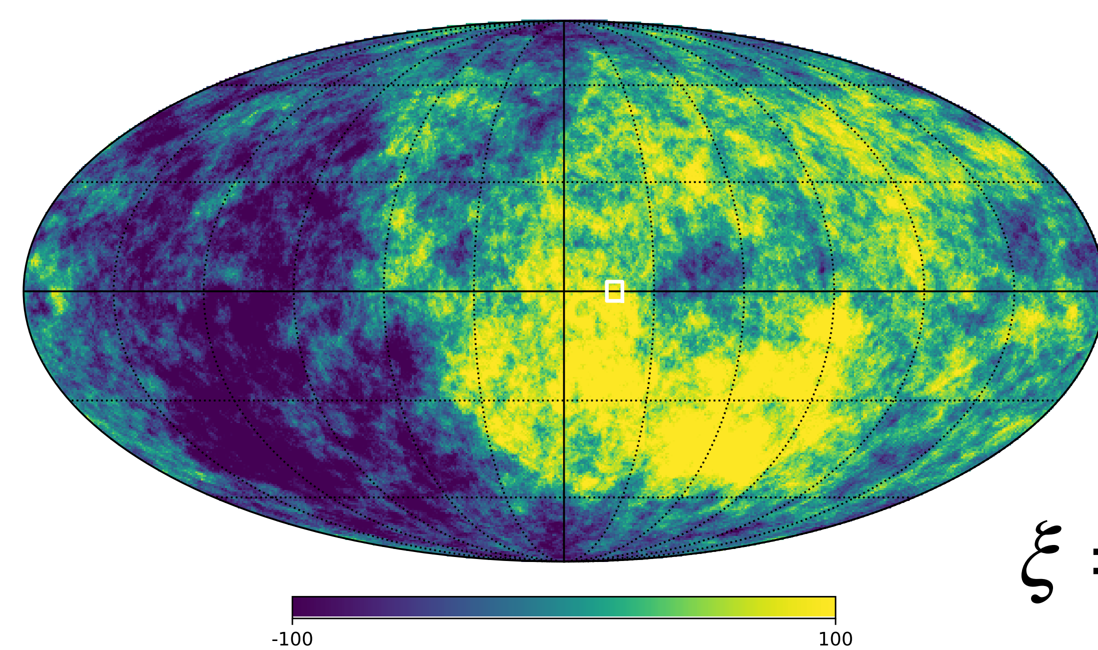
Toy simulation



- Randomly throw down infinitely long straight strings
- Remove strings as time goes on to maintain correct number density
- Trace CMB photon paths

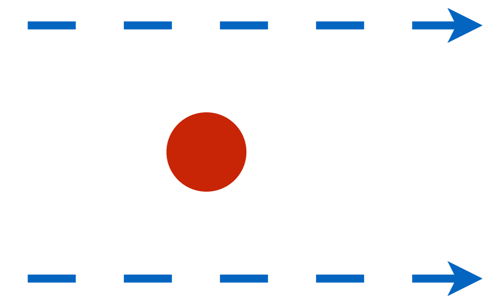


$\xi = 10$

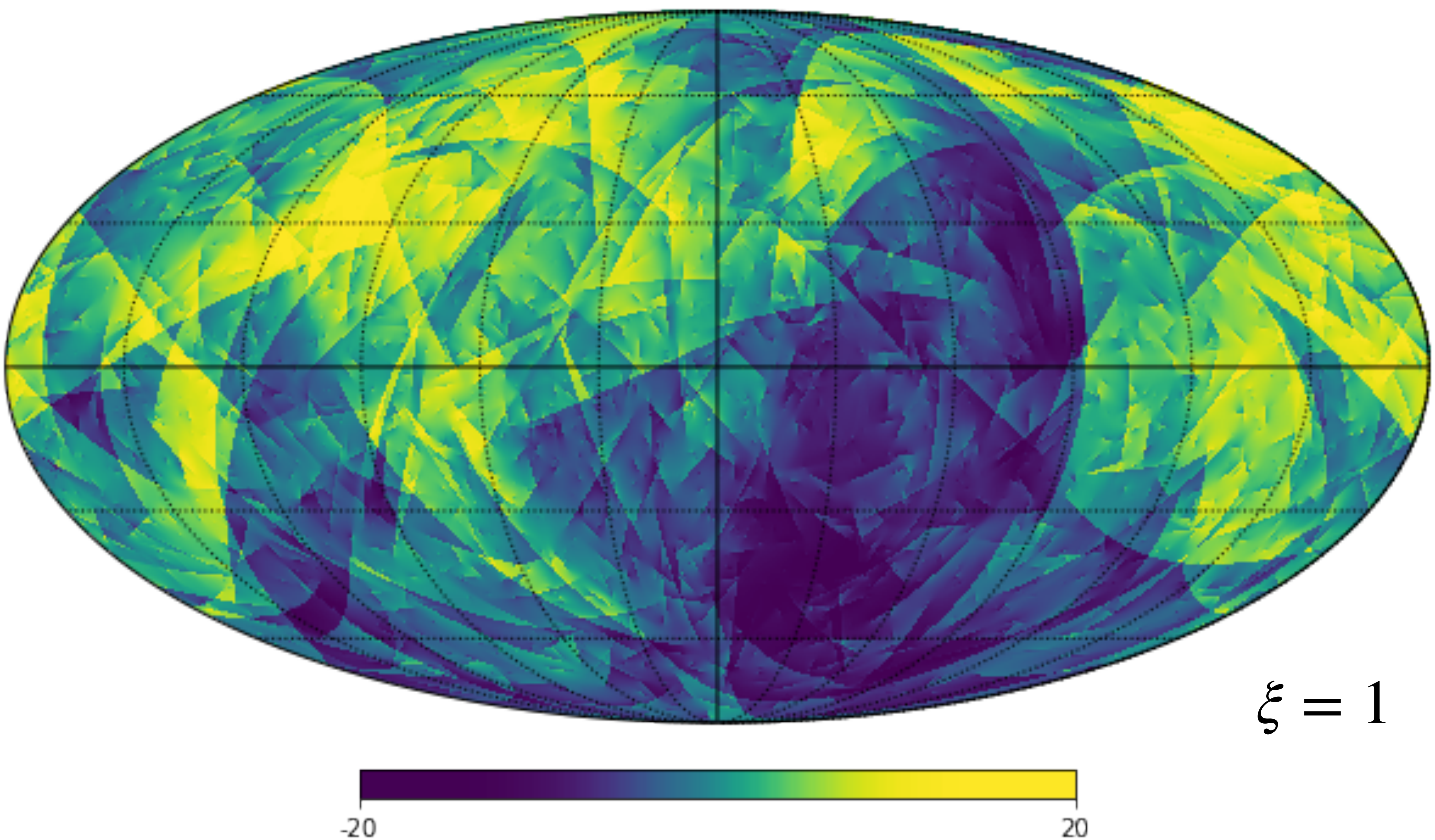


$\xi = 100$

Toy simulation

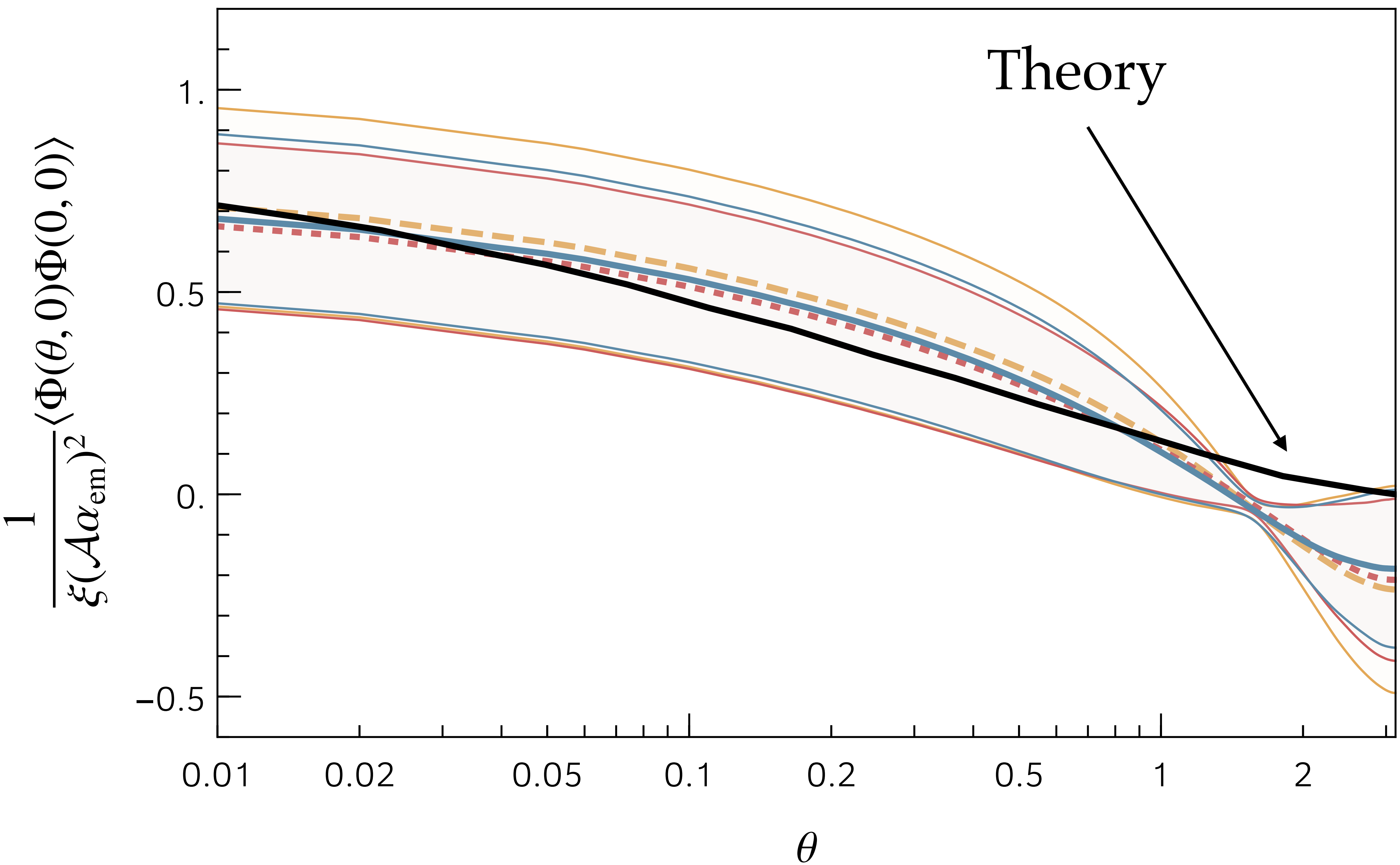


Can see both long and short strings

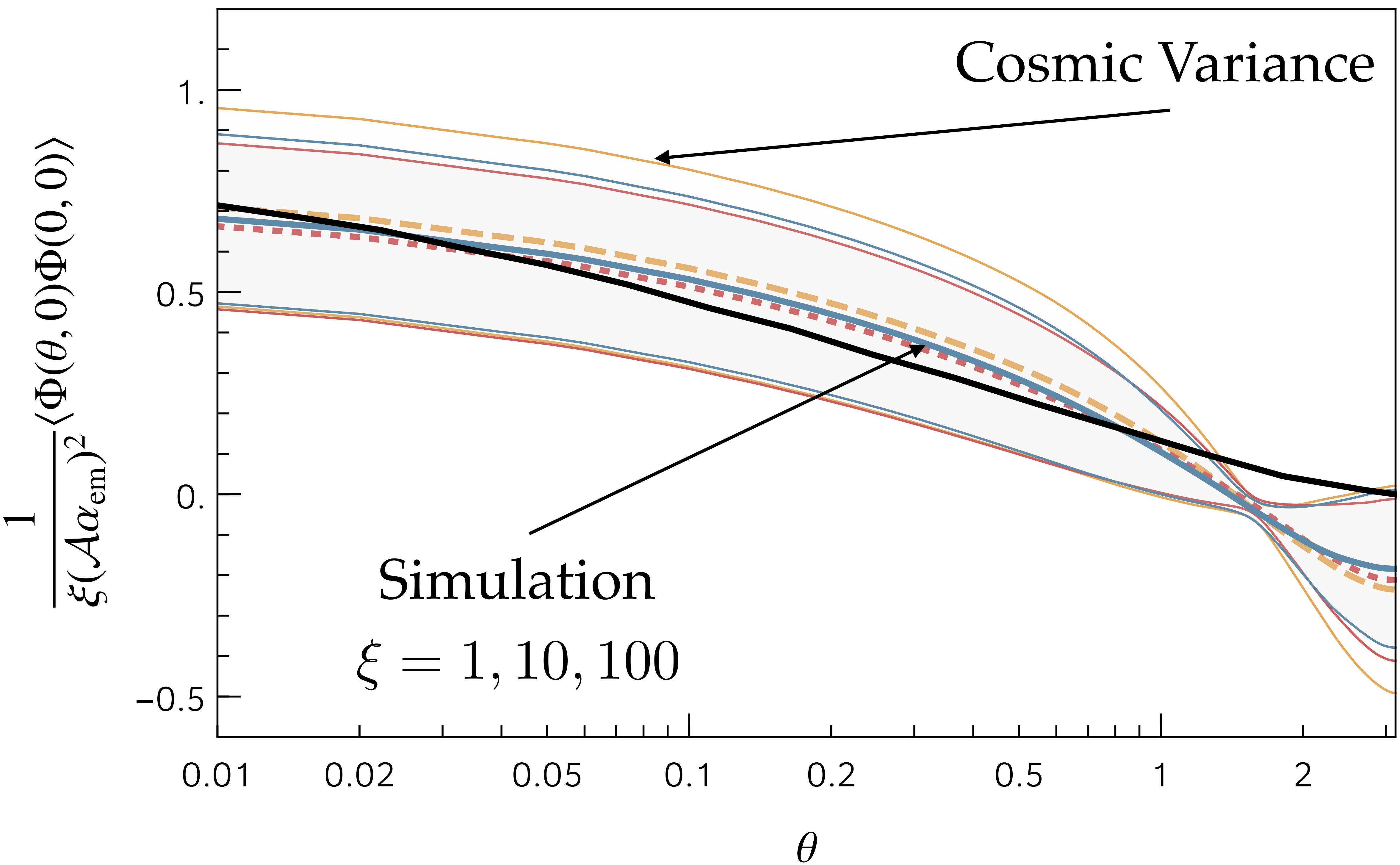


$\xi = 1$

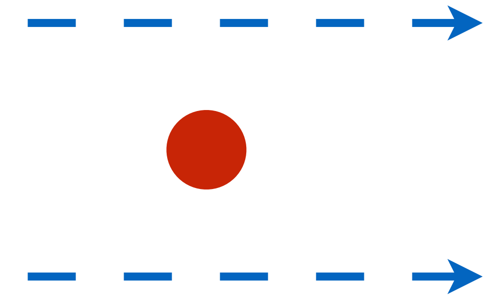
Simulation Comparison



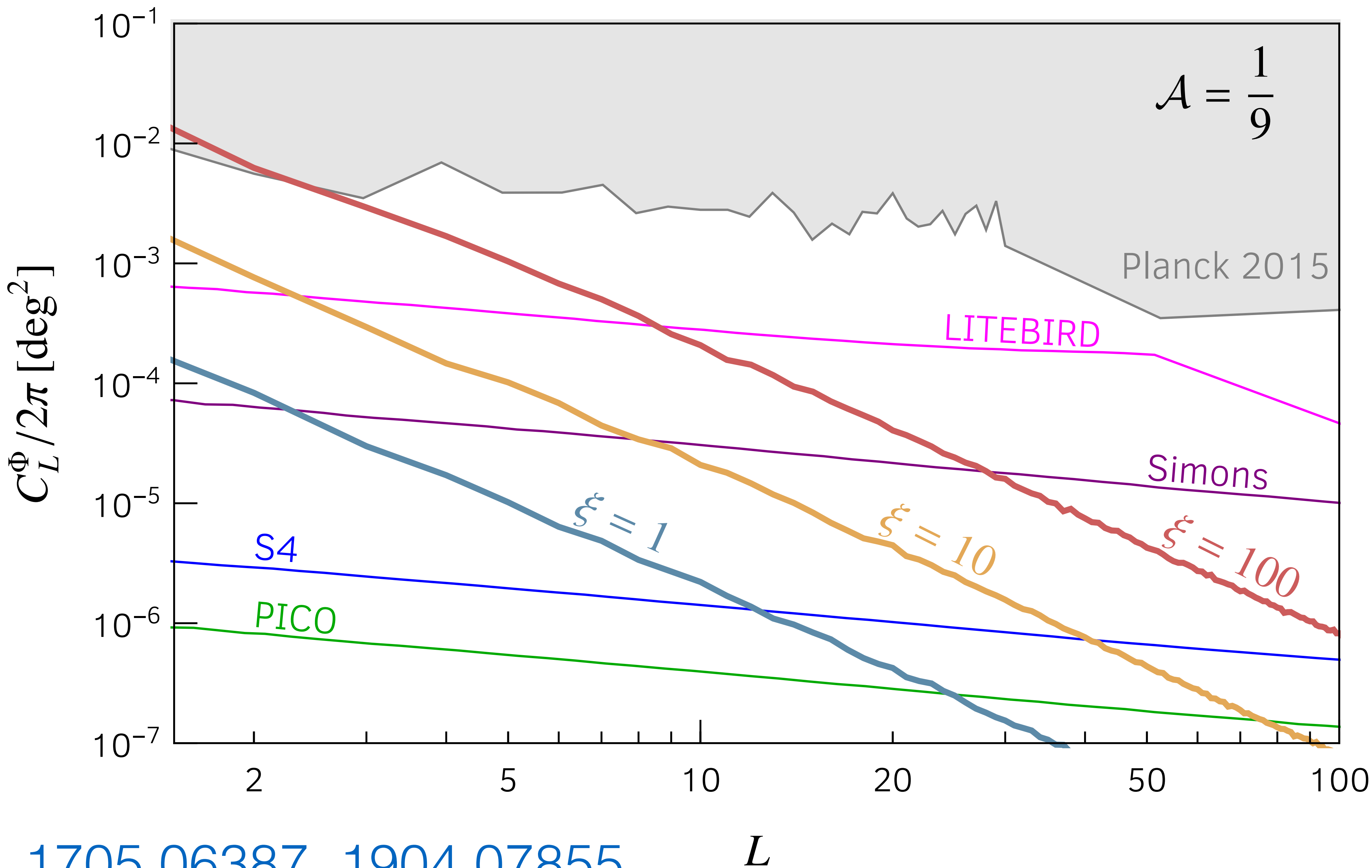
Simulation Comparison



CMB Constraints(ish)

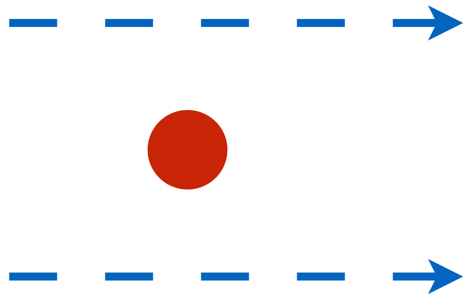


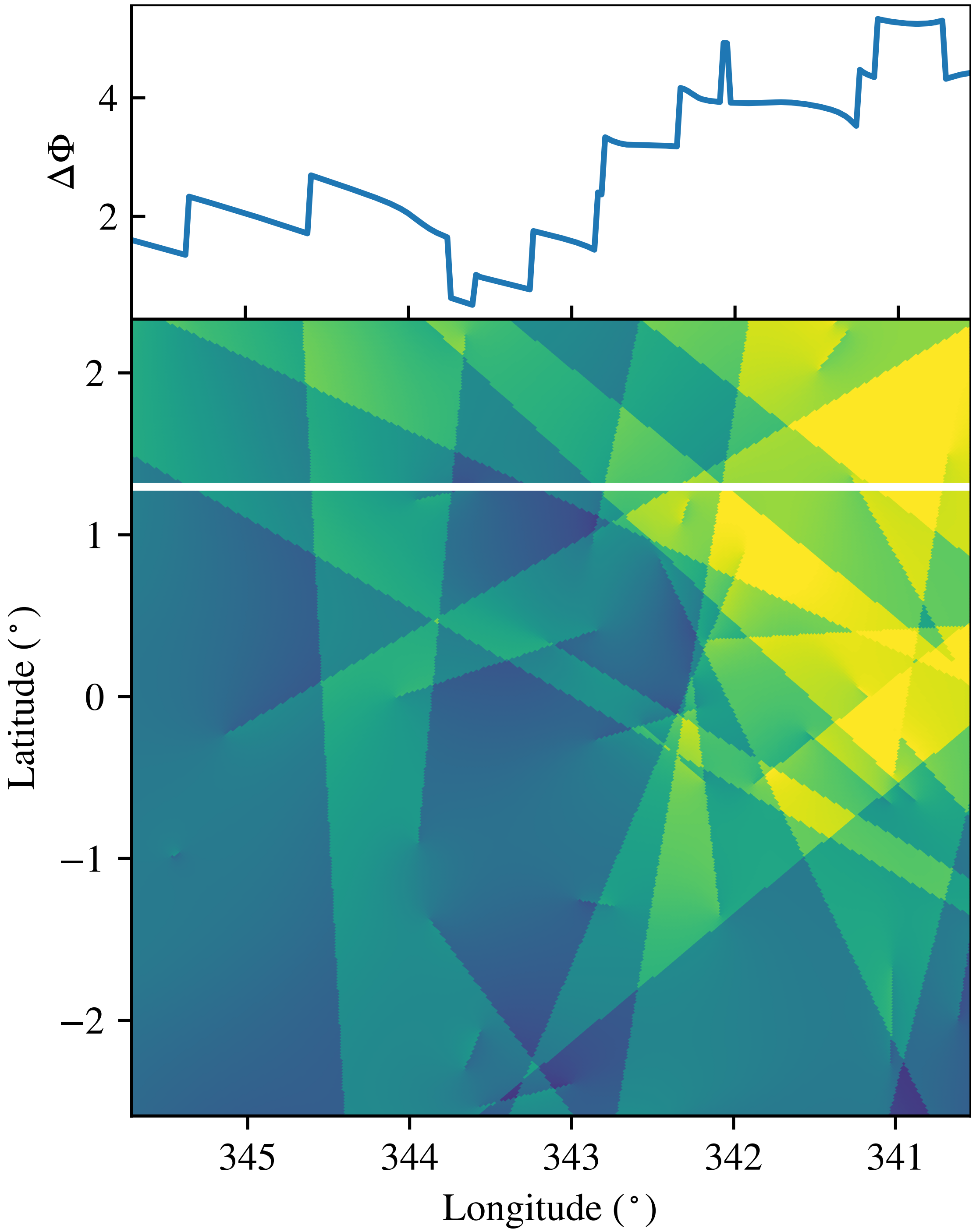
Constraints scale as $\xi \mathcal{A}^2$



9812088, 1705.06387, 1904.07855

Edge Detection

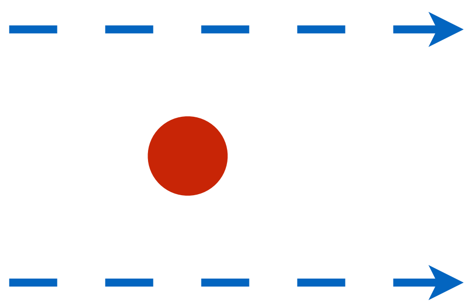


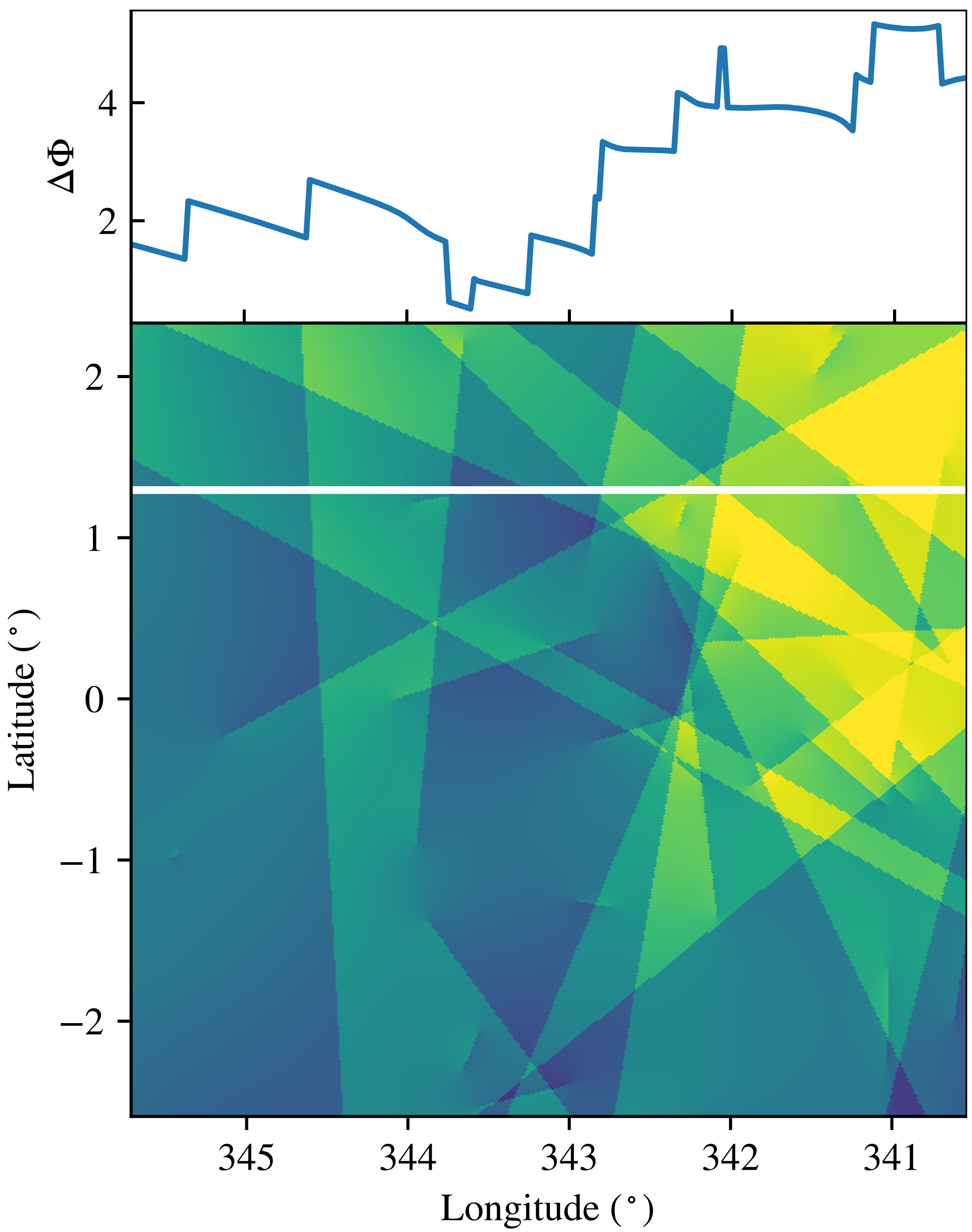


Coolest feature are the edges

- Position space search
- Important elements
  - Angular resolution $\xi \gg 1$
  - Accuracy $\mathcal{A} \ll 1$
- BICEP / KEK / SPT / Polarbear
  - Angular resolution ~ arcmin
  - Accuracy ~ percent

Edge Detection





Coolest feature are the edges

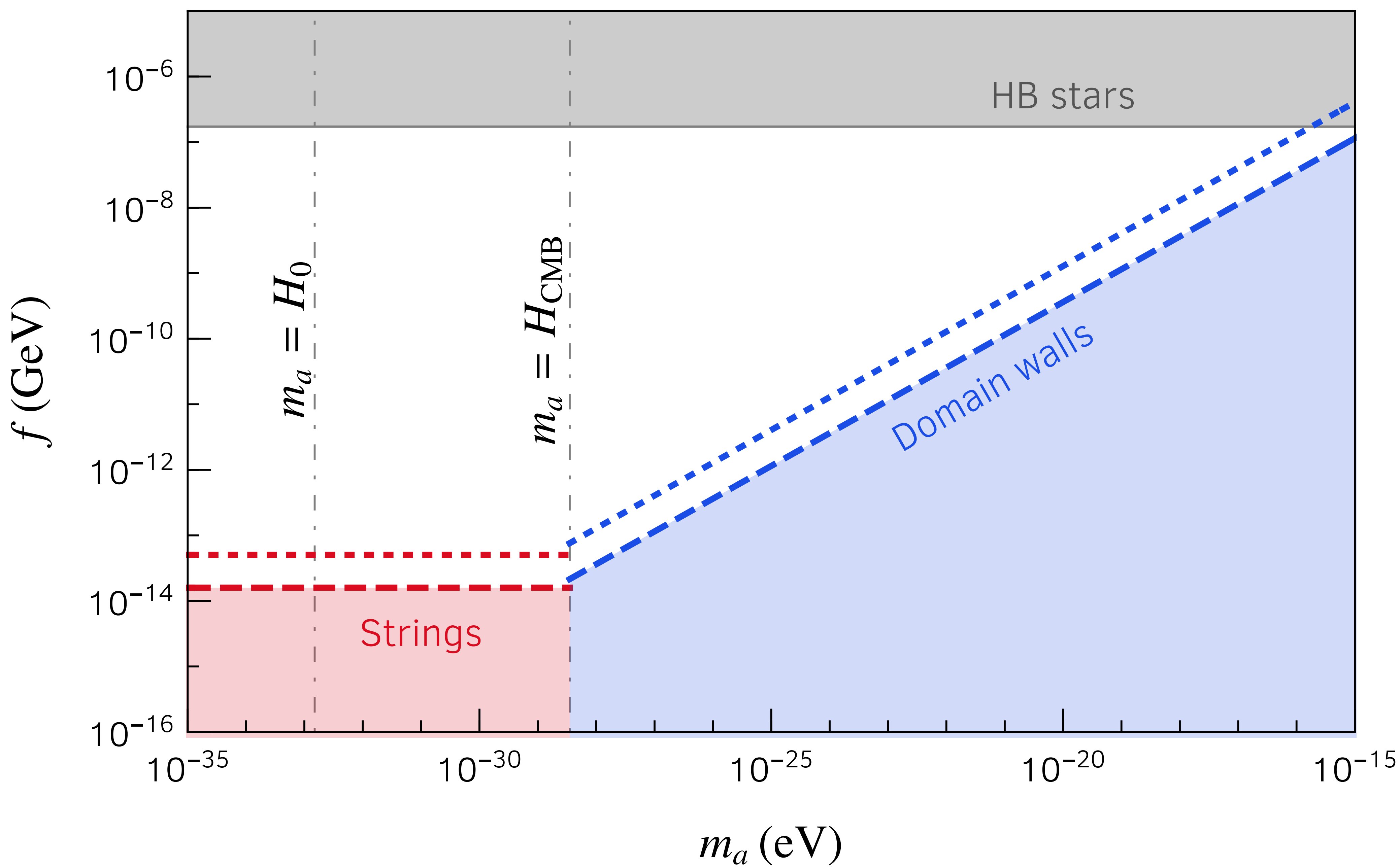
Likely edges are most useful when there are only a few strings

Few strings => production before/during inflation

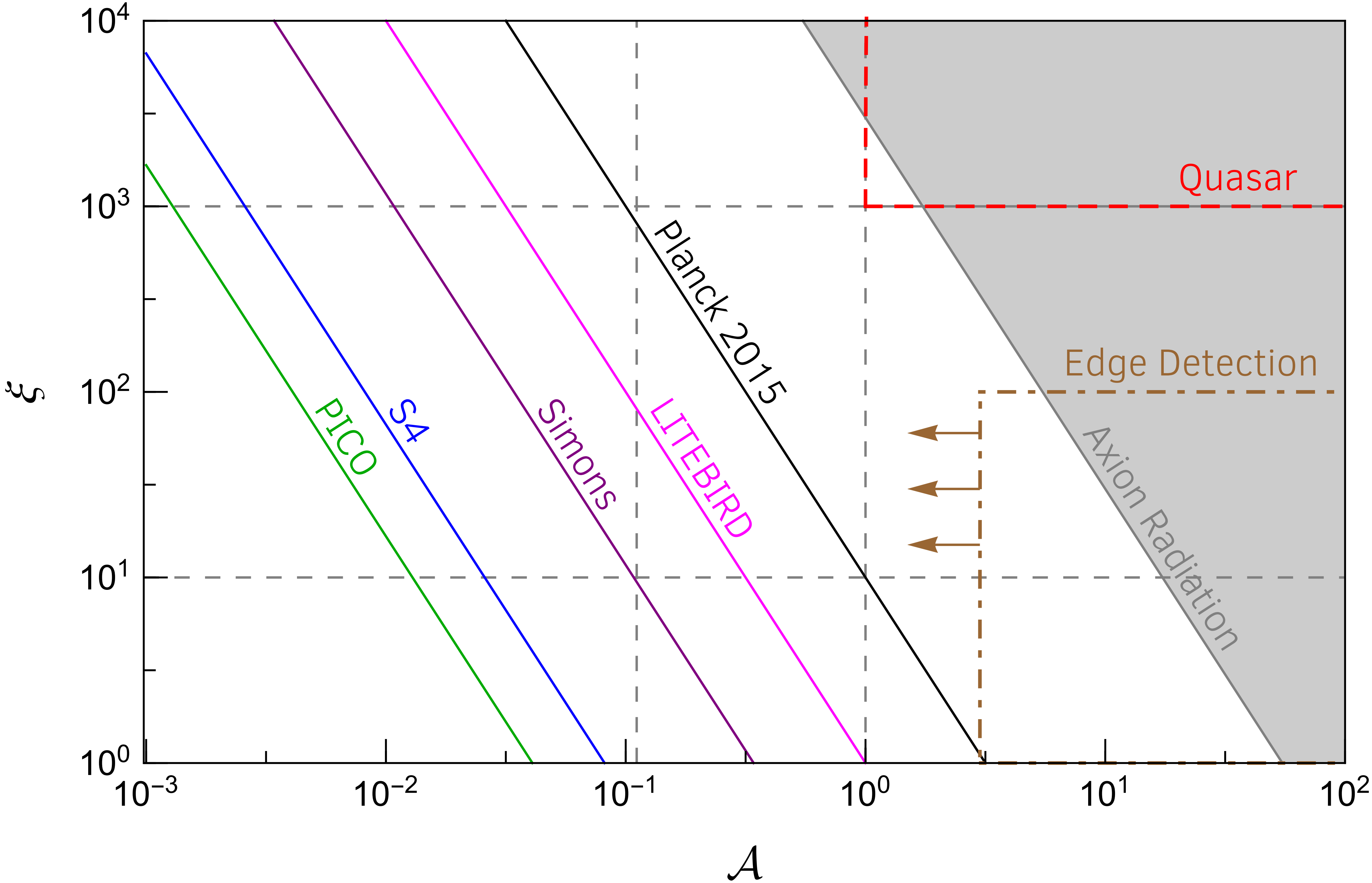
Rare chance at testing pre-inflationary physics

Usual Constraints

Our results are completely independent of decay constant



Constraint(ish)



Outline

- ~~How strings affect photons~~
  - ~~Arahanov-Bohm effects~~
  - ~~CMB ways of looking for strings~~
- How photons affect strings
  - Superconducting strings
  - Colliding currents
- Millikan (What do we learn from anomalies)

Superconducting Strings

Anomaly inflow - anomaly on the string to restore gauge invariance

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

In the presence of strings, this is not gauge invariant

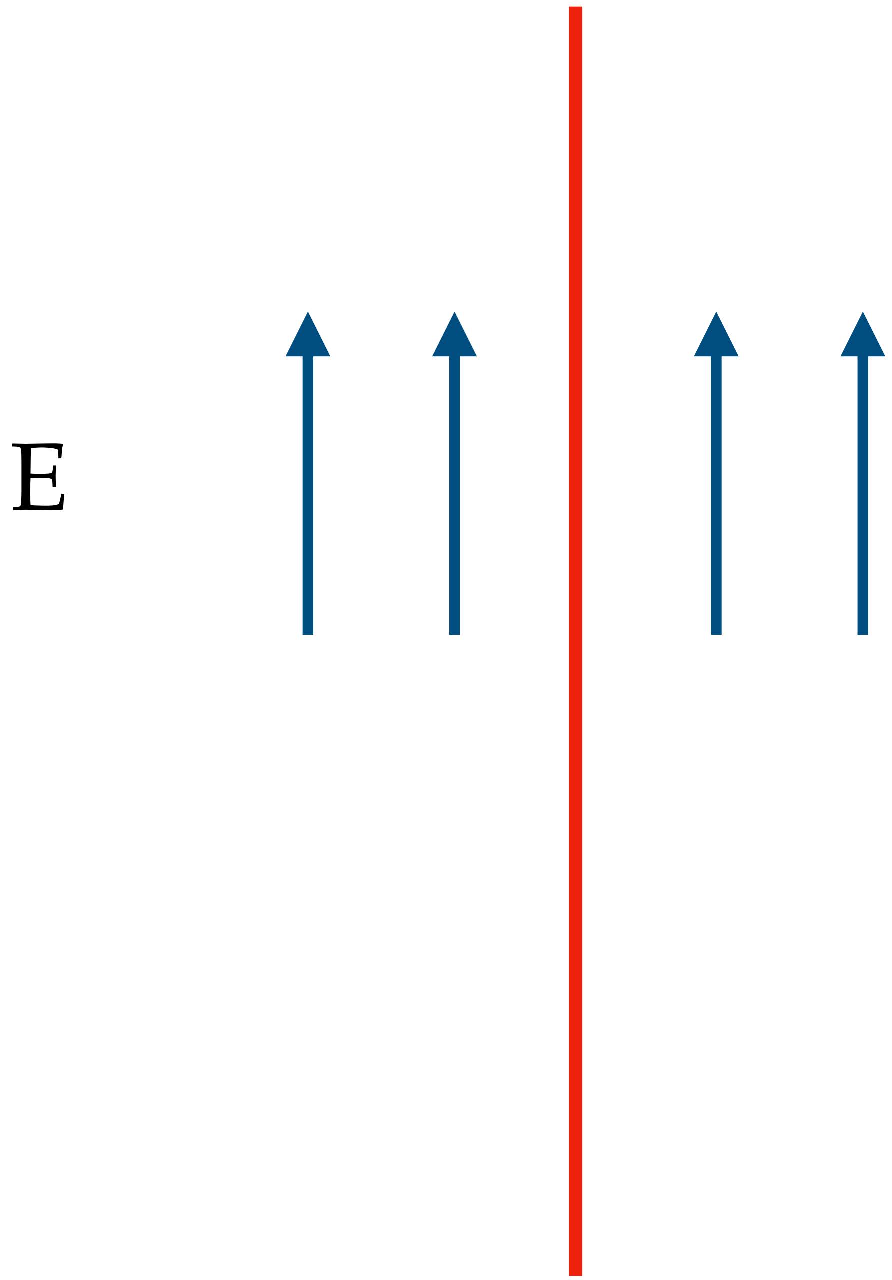
Conservation of charge

$$J_a^\mu = \frac{e^2}{8\pi^2}\epsilon^{\mu\nu\rho\sigma}\partial_\nu\left(\frac{a}{f}\right)F_{\rho\sigma}$$

In a background axion field, electric and magnetic fields generate additional charge and current

Conservation of charge

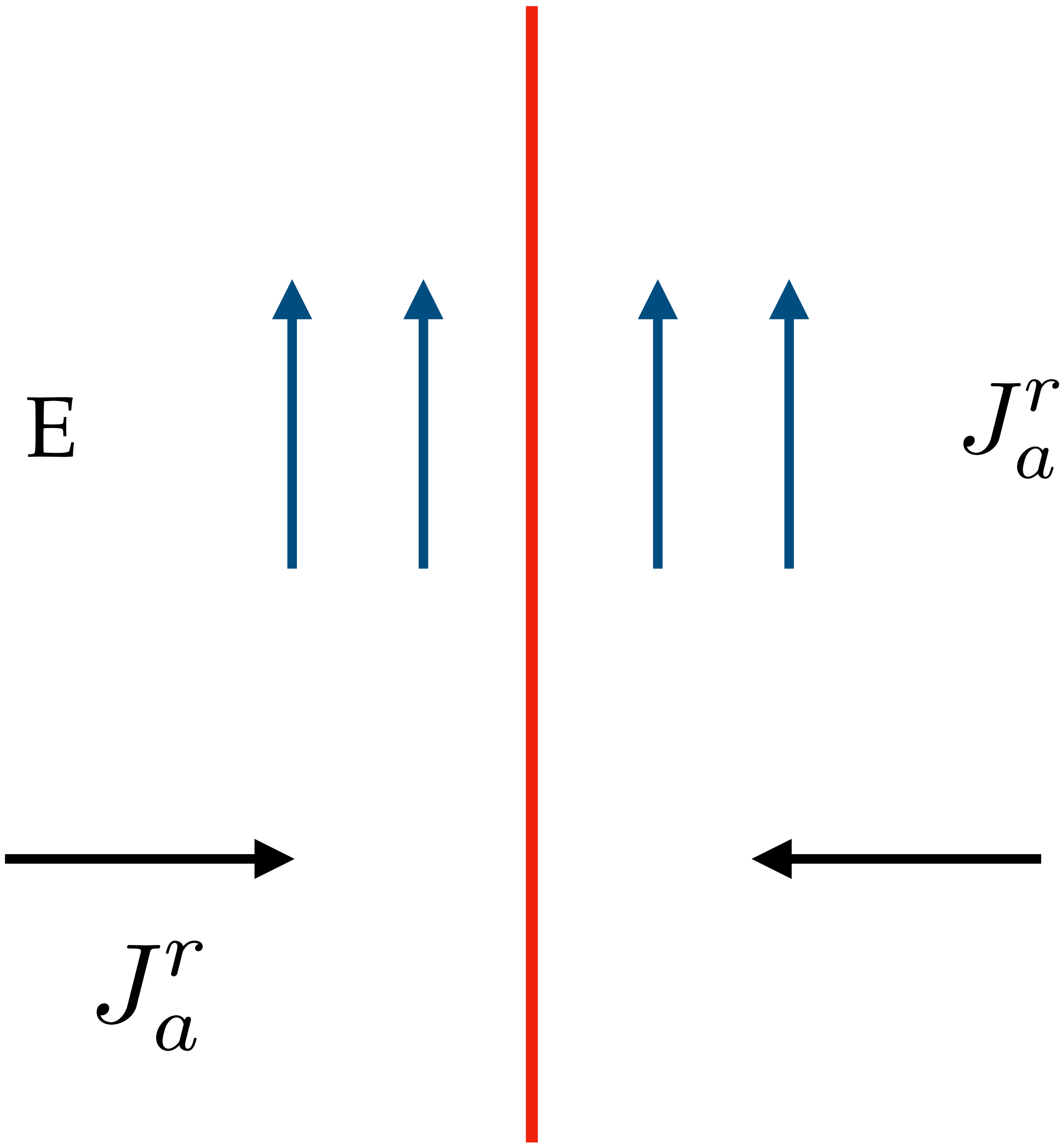
String in a background electric field



$$J_a^\mu = \frac{e^2}{8\pi^2}\epsilon^{\mu\nu\rho\sigma}\partial_\nu\left(\frac{a}{f}\right)F_{\rho\sigma}$$

Conservation of charge

Charge is flowing onto the string!



$$J_a^r = \frac{e^2}{8\pi^2}\epsilon^{r\theta 0 z}\partial_\theta\left(\frac{a}{f}\right)F_{0z} \neq 0$$

Conservation of charge

Arbitrarily small electric field must cause charge to appear on the string

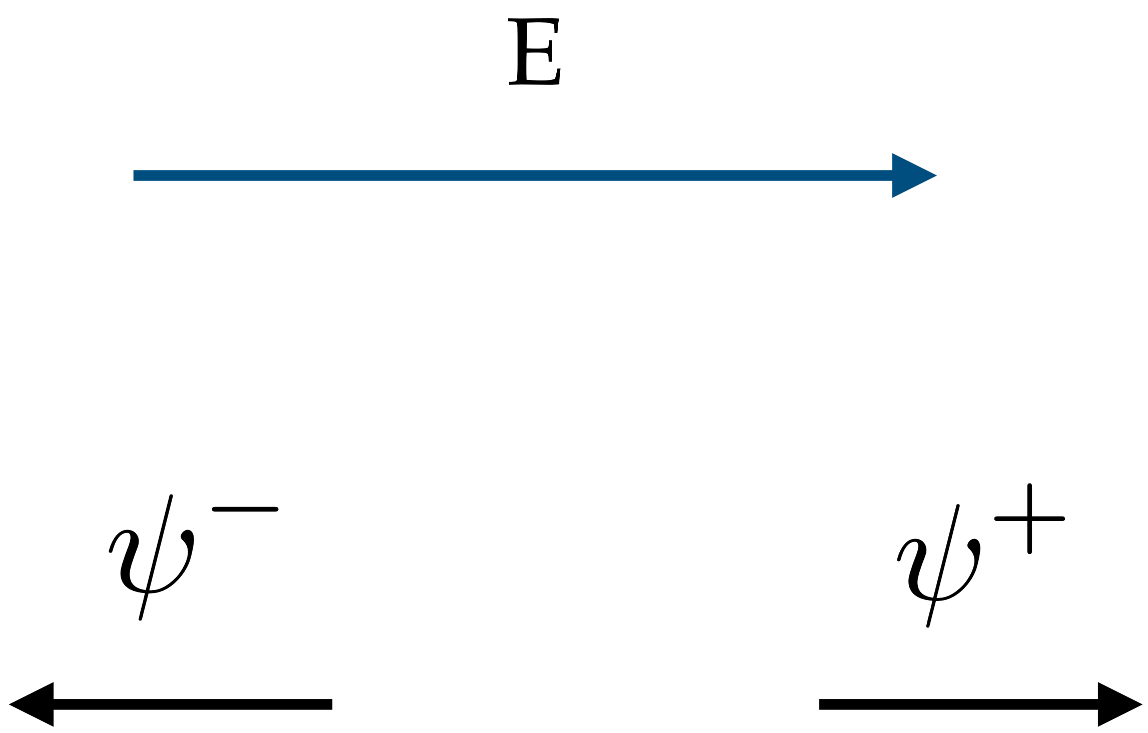
Schwinger pair production : Electric field produces particles

$$\frac{dQ}{dt} \propto e^{-\pi \frac{m^2}{eE}}$$

No exponential in production : must be massless charged particles!

Pair production

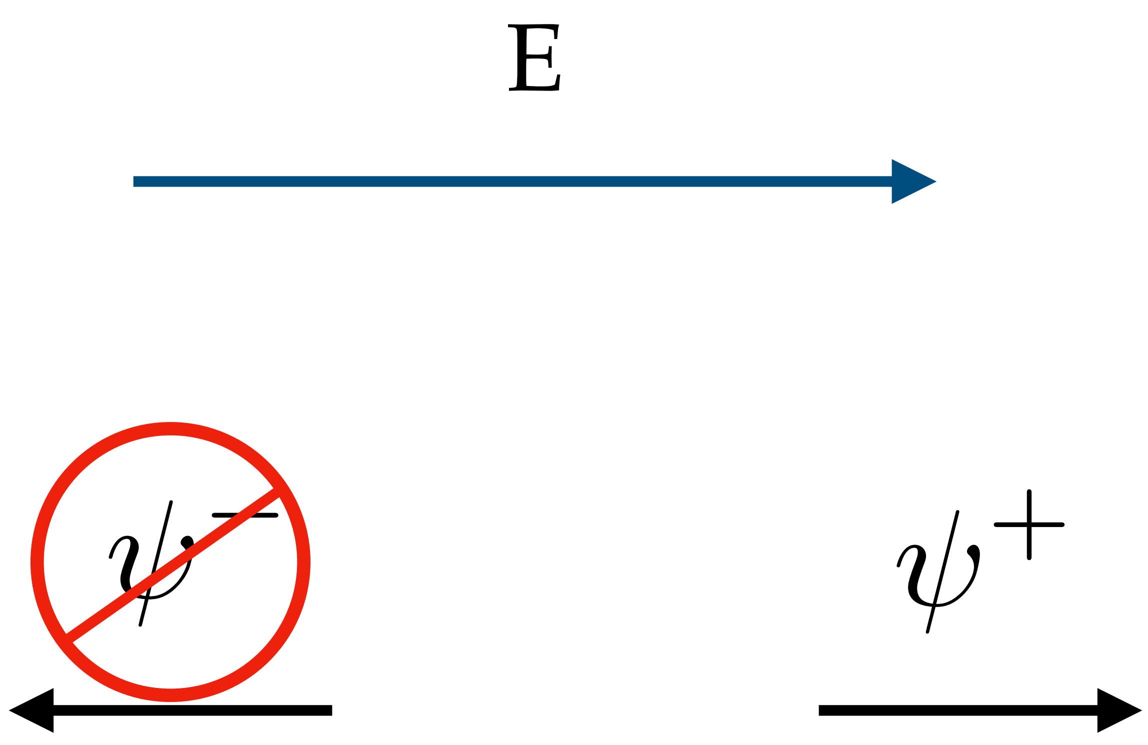
Schwinger pair production



Conserves charge

~~Pair~~ production

Schwinger ~~pair~~ production



Violates charge

Conservation of charge

$$\partial_\mu J^\mu_{\rm string} = -\frac{\mathcal{A}e^2}{4\pi}\epsilon_{ab}F^{ab}$$

Conservation of total charge

Violation of string charge

Mismatch between left movers than right movers

Minimal situation : (anti-)particles move in
only one directions

Superconducting strings

$$\partial_\mu J^\mu_{\rm string} = -\frac{\mathcal{A}e^2}{4\pi}\epsilon_{ab}F^{ab}$$

Consider a uniform string with no electric field

$$\frac{d\lambda}{dt} \propto \frac{dI}{dt} = 0$$

No resistance = superconductor!

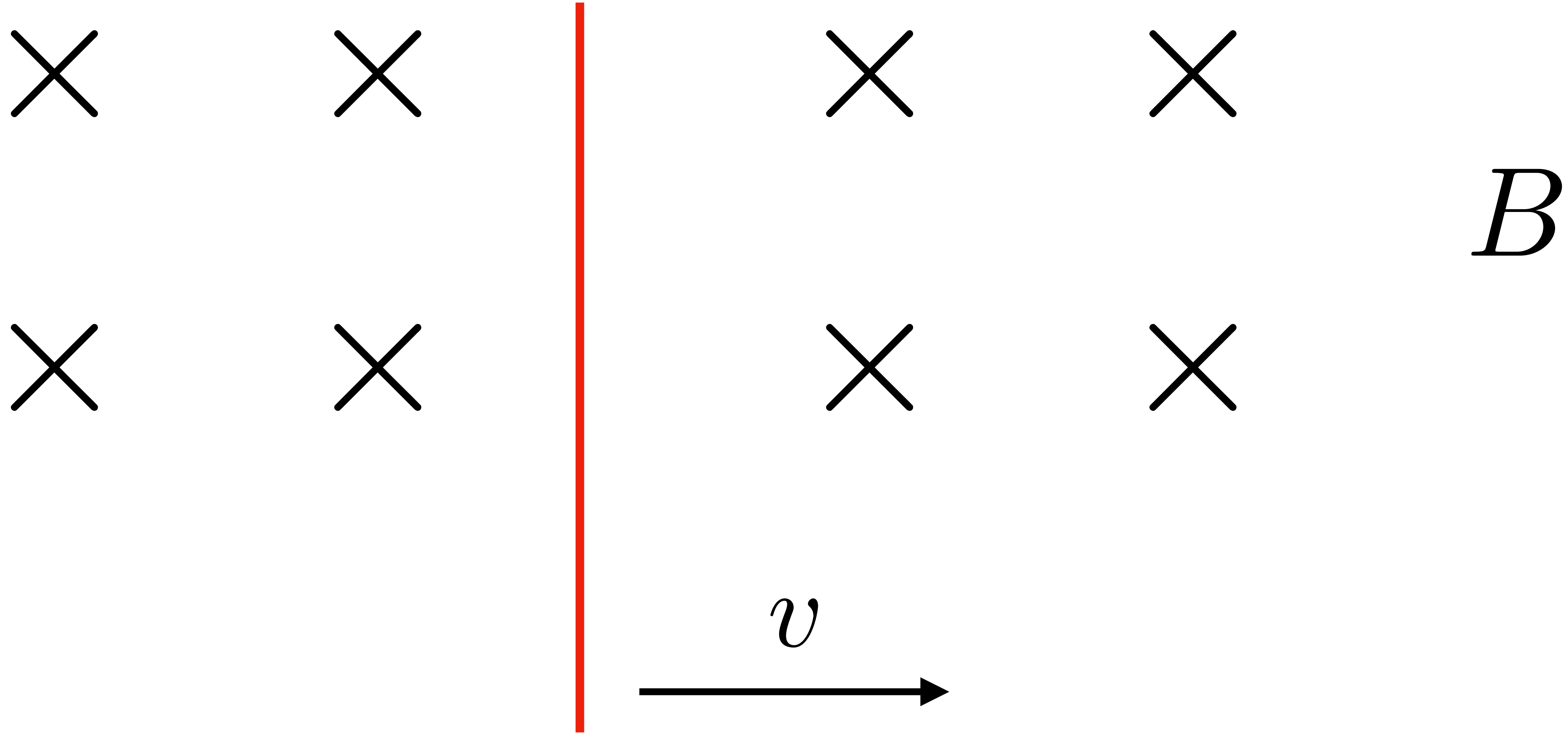
Penetration length comparable with string size

Outline

- ~~How strings affect photons~~
  - ~~Arahanov-Bohm effects~~
  - ~~CMB ways of looking for strings~~
- How photons affect strings
  - ~~Superconducting strings~~
  - Colliding currents

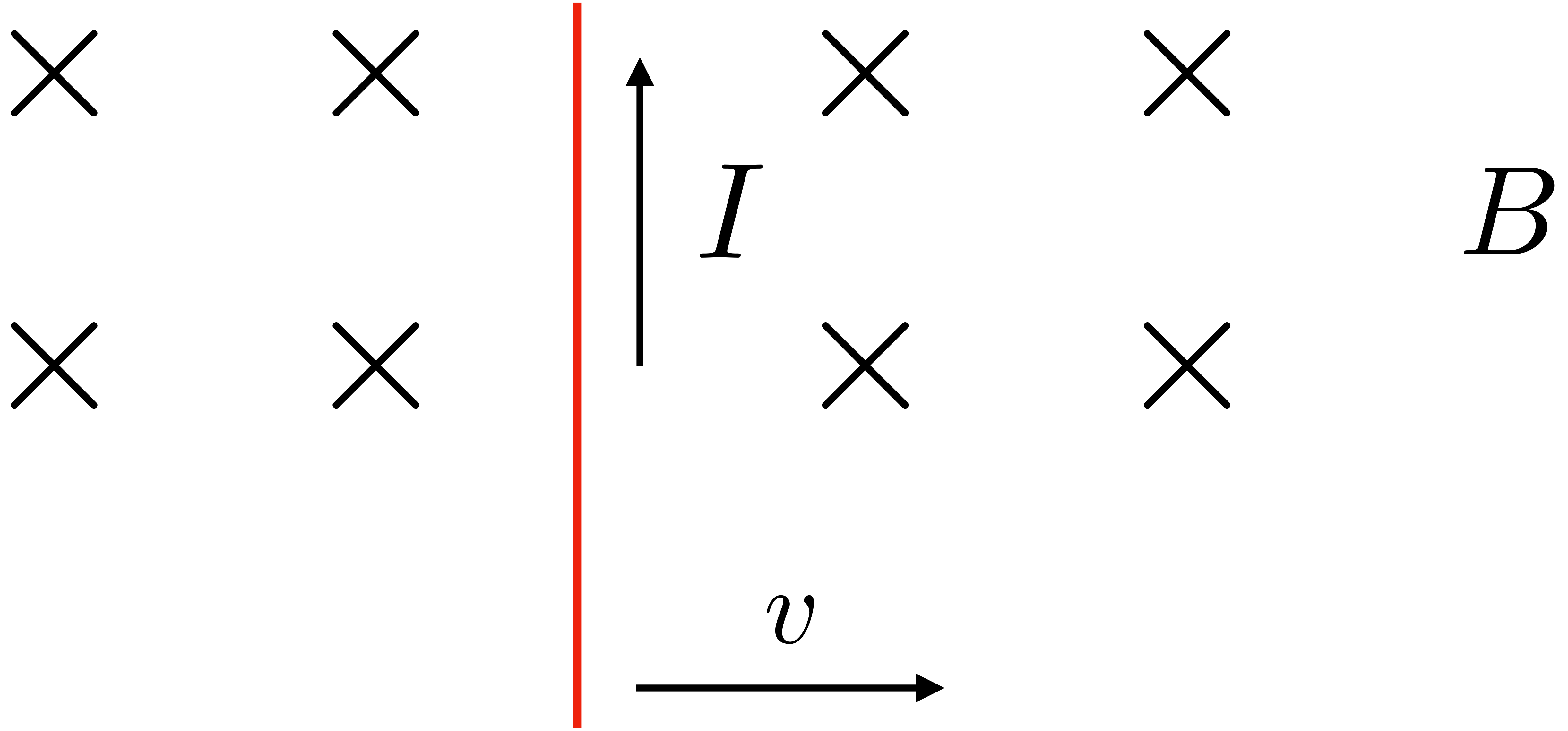
Screening of Flux

String moving through a B field of a galaxy



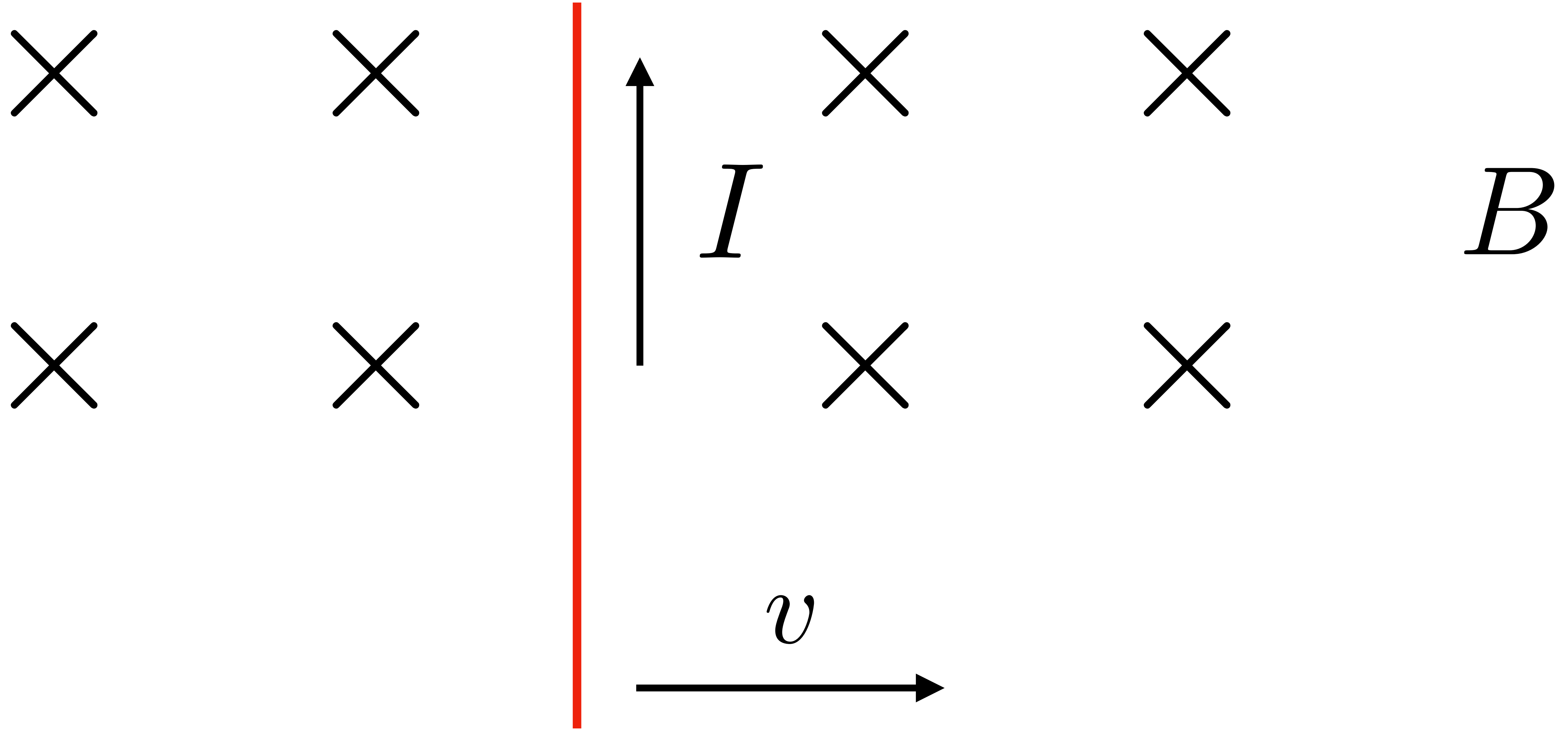
Screening of Flux

Lenz law current



Screening of Flux

Superconductor screens all flux



Screening of Flux

$$\Delta Q = \int dt\dot{Q} = \int d^2x \frac{d\lambda_Q}{dt} = \int d^2x \partial_a j^a_{\text{string}} = -\frac{e^2}{4\pi}\int d^2x \epsilon^{ab} F_{ab}$$

$$= -\frac{e^2}{2\pi}\int d^2x E = \frac{e^2}{2\pi}\int dt \frac{d\Phi}{dt} = \frac{e^2 \Delta\Phi}{2\pi}$$

Take d / dz of above and assuming only left movers

$$I = \frac{\mathcal{A}e^2}{2\pi}\frac{d\Phi}{dz}$$

Screening of Flux

$$I = \frac{\mathcal{A}e^2}{2\pi}\frac{d\Phi}{dz}$$

Flux gives current

$$\frac{d\Phi_I}{dz} = \frac{I}{2\pi}\log\left(\Lambda R\right)$$

Current gives flux

$$\Phi = \Phi_0 - \Phi_I$$

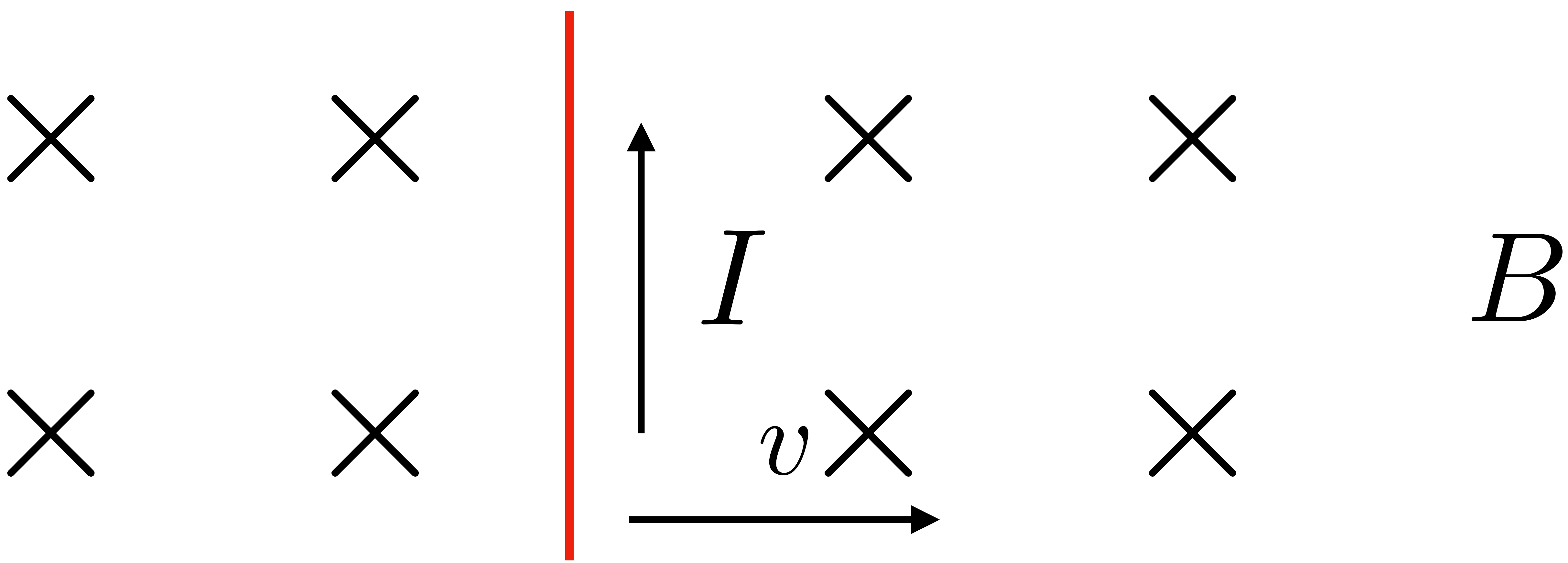
$$\Phi = \frac{\Phi_0}{1 + \frac{\mathcal{A}e^2}{4\pi}\log\left(\Lambda R\right)}$$

Flux is not perfectly screened

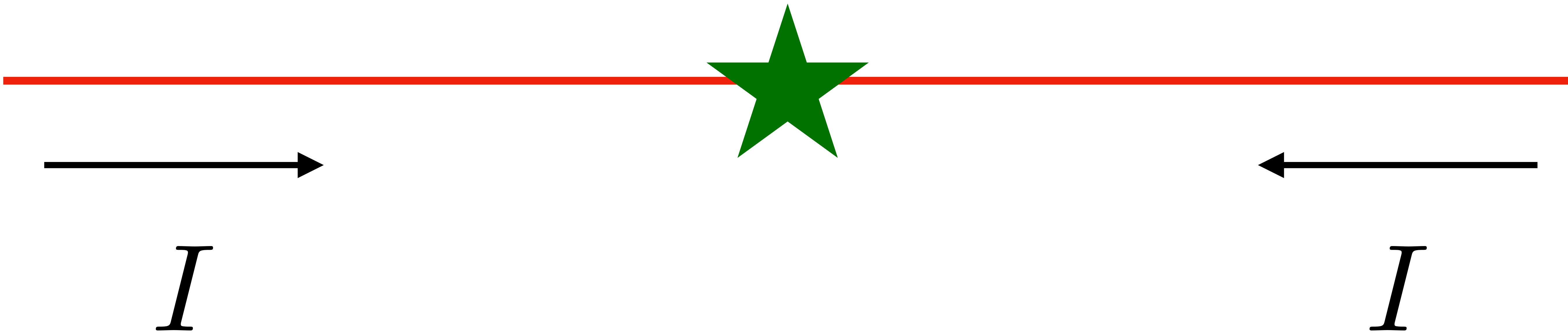
Currents coming from Galaxies

$$I = \frac{e^2}{2\pi} \frac{1}{1 + \frac{e^2}{4\pi} \log\left(\Lambda R\right)} B\, d\, v_s \approx 10^{8-9} \text{GeV}$$

Axion string moving through a magnetic field



Collisions

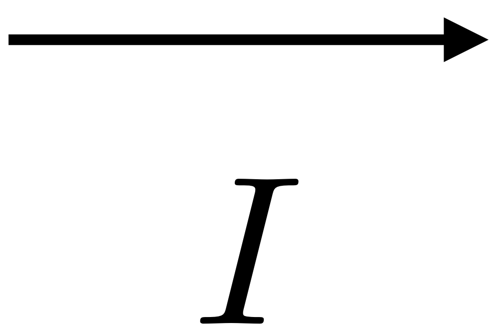


$$P \sim 10^{40} \mathrm{erg/s} \sim 10^{7} \mathcal{L}_{\mathrm{Sun}}$$

Collisions are very bright!

How often to they occur?

Collisions

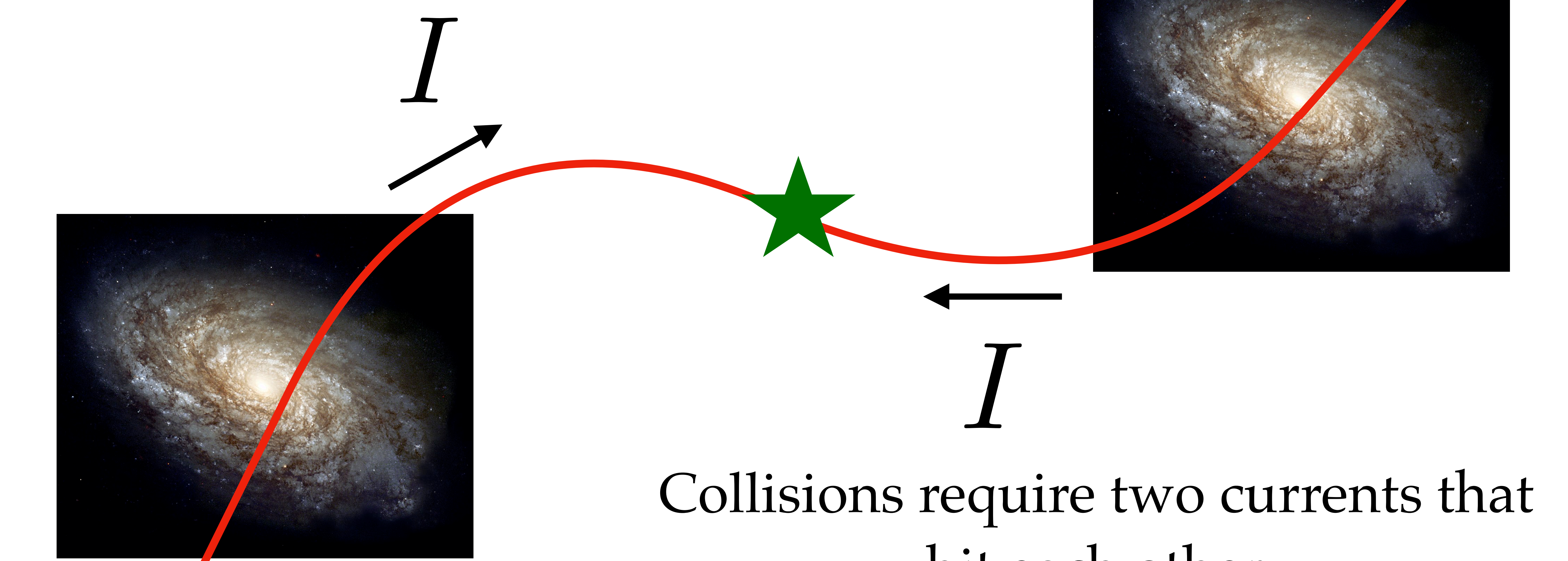


Currents are not generated very often

$$N_K \simeq \xi H^3 L_{\rm string} N_{\rm galaxy} A_{\rm galaxy}$$
$$\approx 100 \left(\frac{\xi}{10}\right)\left(\frac{N_{\rm galaxy}}{10^{12}}\right)\left(\frac{A_{\rm galaxy}}{(10\,{\rm kpc})^2}\right)$$

O(100) String - Galaxy crossings

Collisions

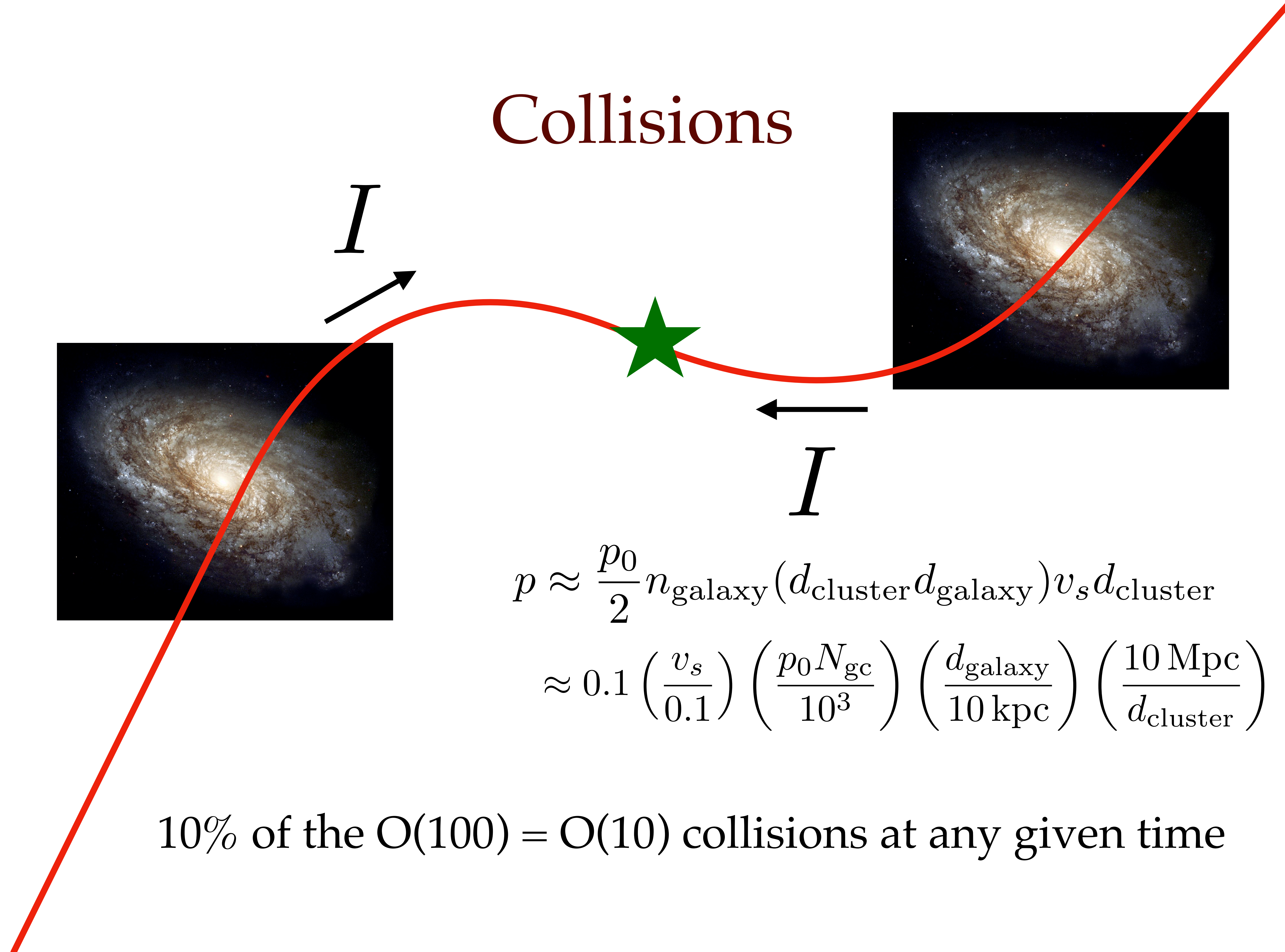


Collisions require two currents that hit each other

Happens if string passes through multiple galaxies in a galaxy cluster

Galaxy cluster ~ 10^2 - 10^3 galaxies in 10 Mpc distances

Collisions

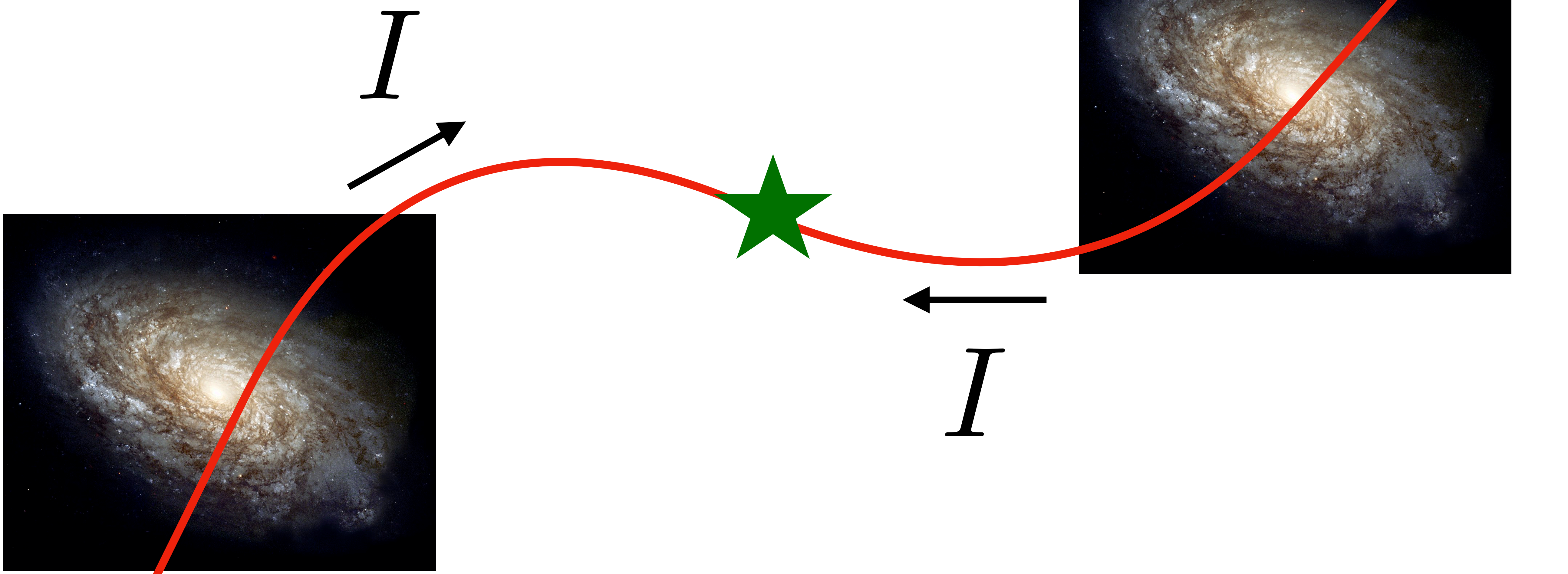


$$p \approx \frac{p_0}{2} n_{\text{galaxy}} (d_{\text{cluster}} d_{\text{galaxy}}) v_s d_{\text{cluster}}$$

$$\approx 0.1 \left(\frac{v_s}{0.1}\right) \left(\frac{p_0 N_{\text{gc}}}{10^3}\right) \left(\frac{d_{\text{galaxy}}}{10\,\text{kpc}}\right) \left(\frac{10\,\text{Mpc}}{d_{\text{cluster}}}\right)$$

10% of the O(100) = O(10) collisions at any given time

Collisions

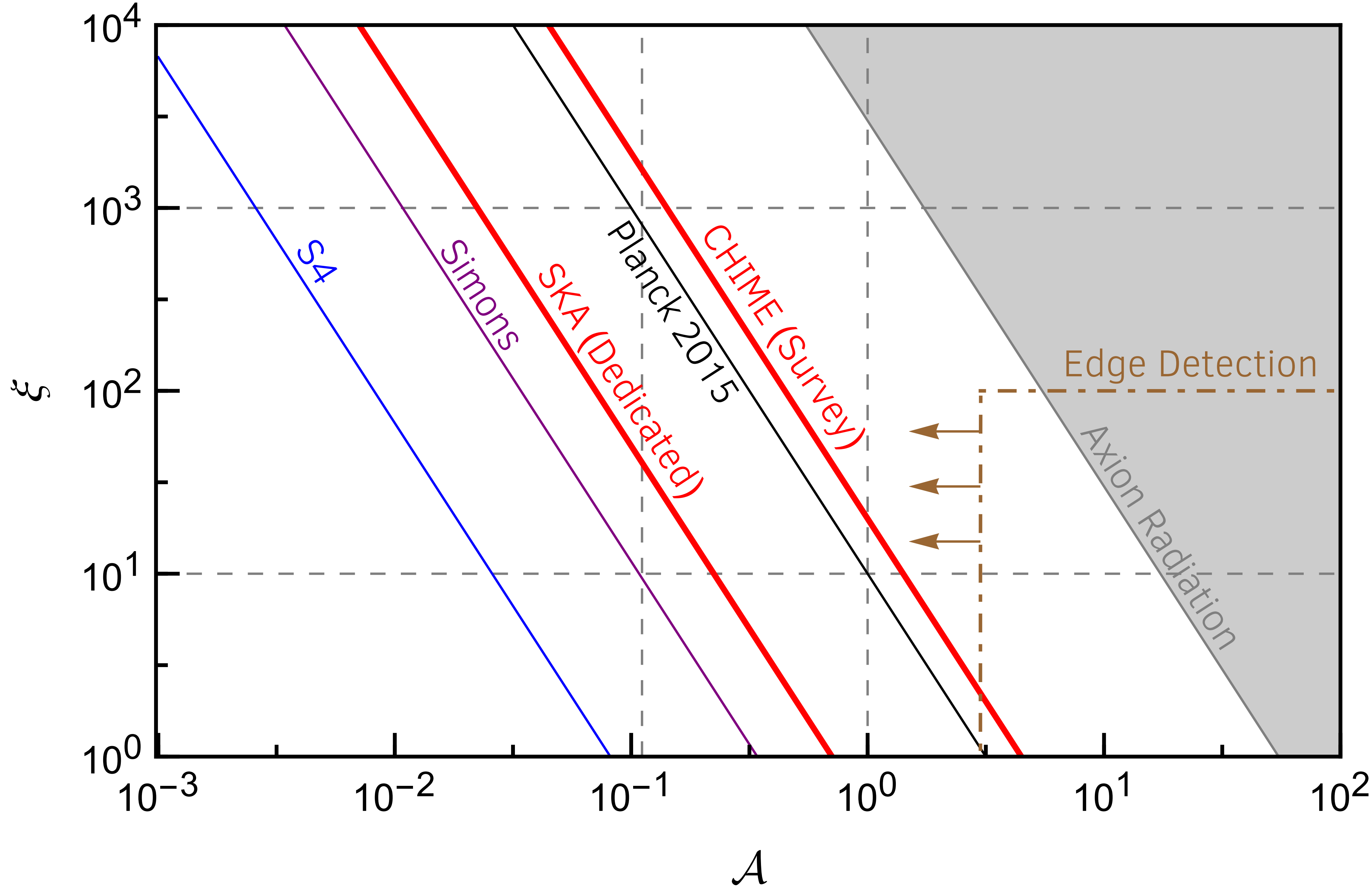


$$P \sim 10^{40} \mathrm{erg/s} \sim 10^{7} \mathcal{L}_{\mathrm{Sun}}$$

But order cosmological distances away

Sensitivity

If these collisions emit 10^{-3} of their energy into radio



Conclusion

Strings

$$\frac{\mathcal{A}\alpha_{\rm em}}{4\pi}\frac{a}{f}F\widetilde{F}$$

Arahanov-Bohm features in the CMB

Power spectrum at the edge of sensitivity

Edges in the CMB

Strings are superconductors
Faraday's Law : currents

Very bright signal coming from collisions