Cosmic Strings in Multi-Step Symmetry Breaking

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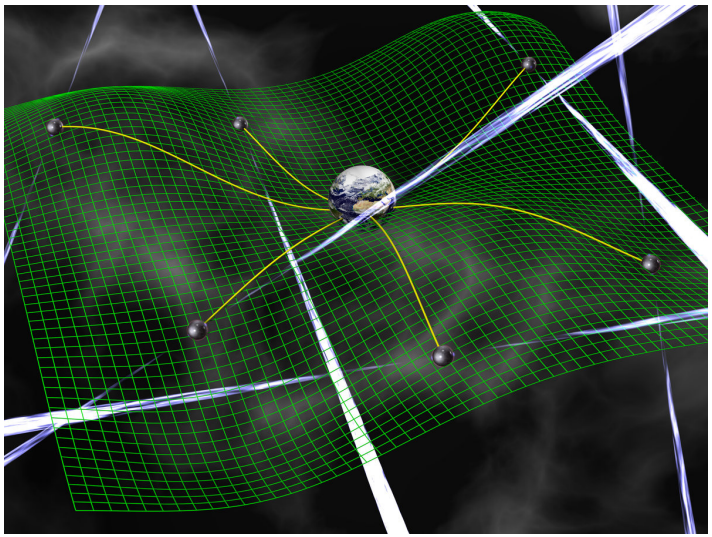
Stochastic Gravitational Wave Background

Evidenced by Pulsar Timing Array (PTA) observations.

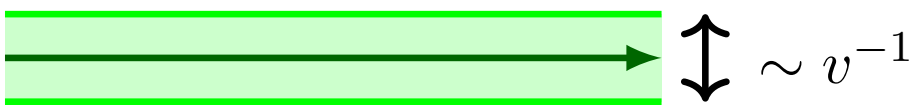
- Regularly observing many pulsars.
- Searching for low-frequency gravitational waves.



- Many possible sources.
  - Black holes
  - Phase transitions
  - **Cosmic string**
  - ...

Cosmic String

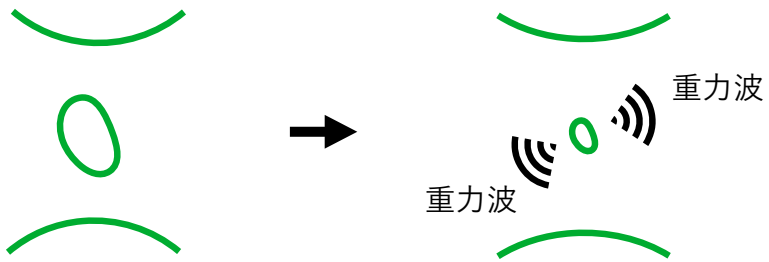
- Line-like topological defect arising from spontaneous $\mathrm{U}(1)$ gauge symmetry breaking.
- Magnetic flux runs along the string, confined within (breaking scale)$^{-1}$.



Cosmic String

- After production strings form network in early universe.
- Strings can reconnect. $\rightarrow$ Loop formation.

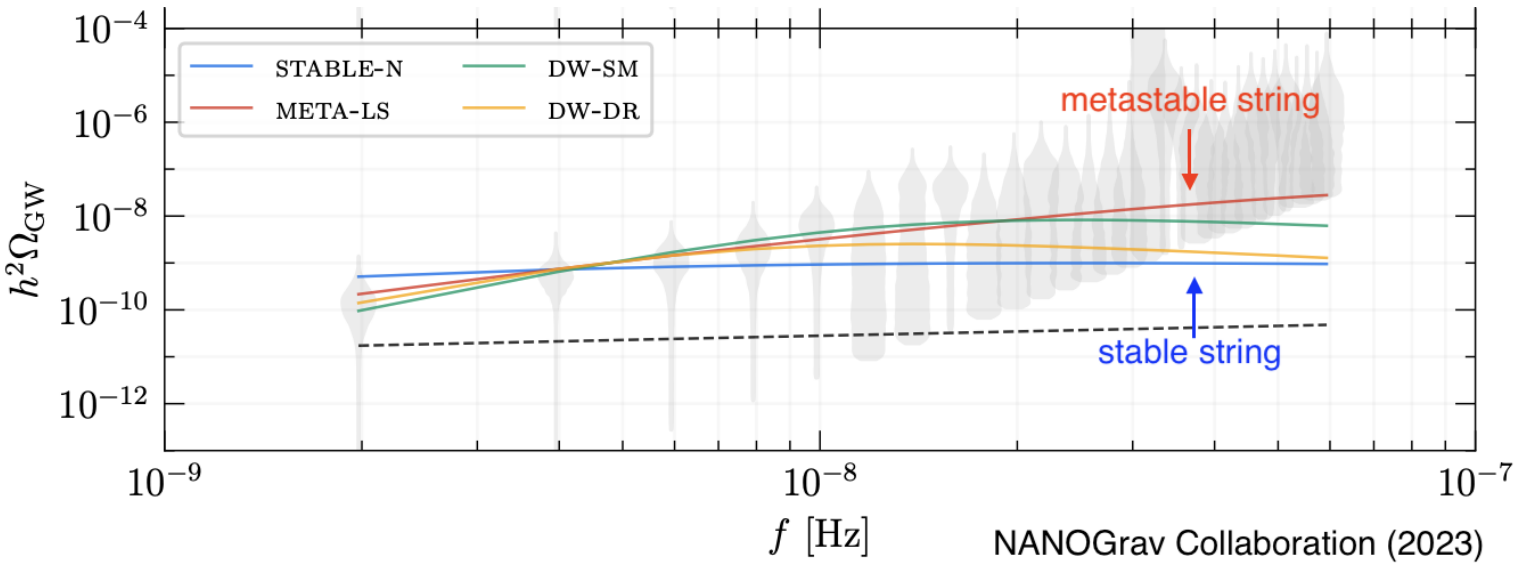
- Loops oscillate and shrink emitting gravitational waves.
  $\rightarrow$ Appear as stochastic gravitational wave background.



Stable VS Metastable String

There are two types of cosmic strings: stable ones and metastable ones.

- Most recent PTA observation **favors metastable string**.



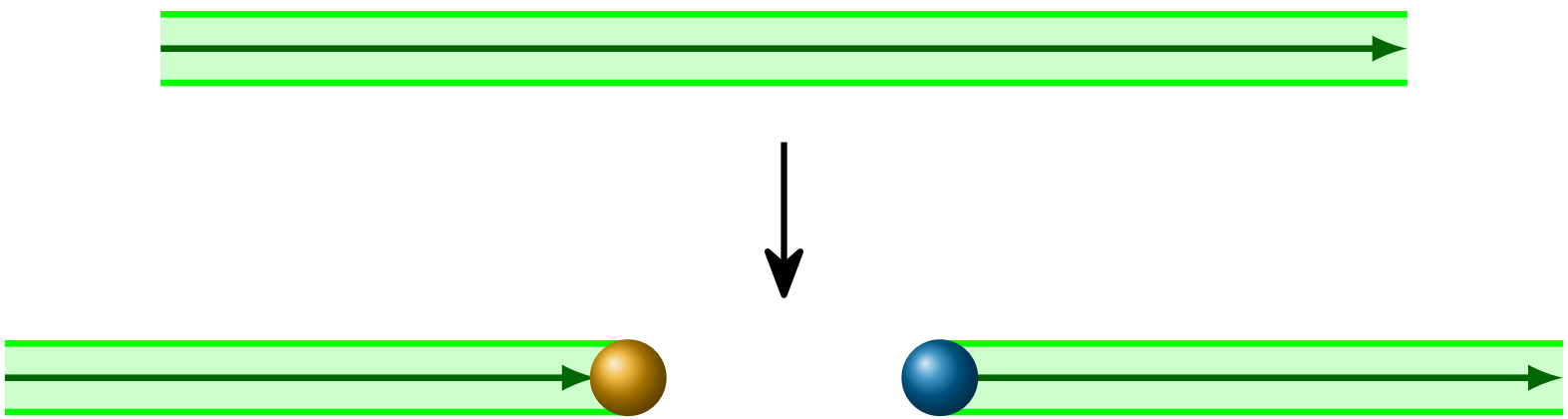
- Stable string (blue) cannot explain the signal.
- Metastable string (red) work nicely!

Metastable Cosmic String

- Two steps of symmetry breaking:

$$\mathrm{SU}(2) \to \mathrm{U}(1) \to \times$$

- Point-like topological defect monopole arise from $\mathrm{SU}(2) \to \mathrm{U}(1)$.
- String can decay via monopole and anti-monopole pair creation.

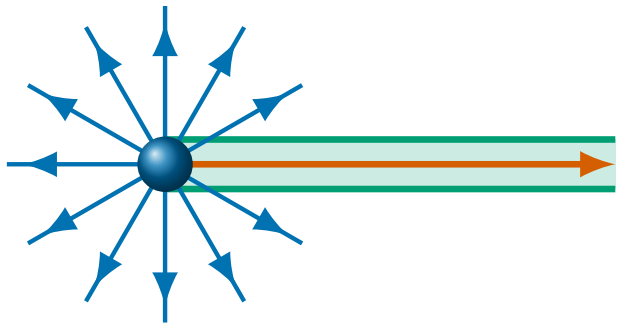


Flux Confinedness

Monopoles carry magnetic flux, which can

- either all confined within the string
- or partially unconfined

confined flux
(contribute more to GW)



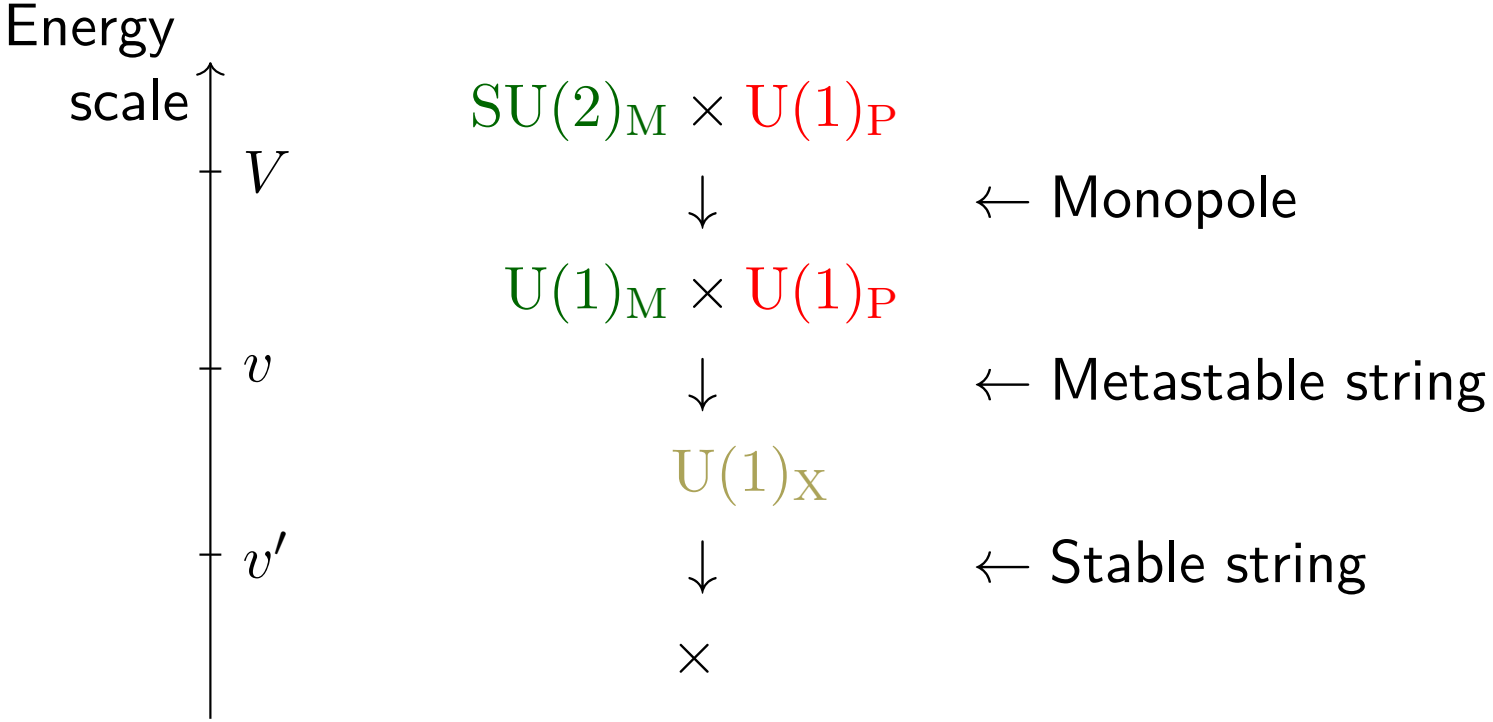
unconfined flux
(contribute less to GW)

In the simplest $\mathrm{SU}(2)$ model, monopoles carry only confined flux.

- Many beyond standard model physics break larger gauge group than $\mathrm{SU}(2)$.
  - GUT
  - Inflation model
  - ...
- How flux confinedness behave in models including gauge group larger than $\mathrm{SU}(2)$?

Extension of the $\mathrm{SU}(2)$ Model

- Three steps of symmetry breaking



Two possible scenarios:

$$\mathrm{SU}(2)_{\mathrm{M}} \times \mathrm{U}(1)_{\mathrm{P}} \to \mathrm{U}(1)_{\mathrm{M}} \times \mathrm{U}(1)_{\mathrm{P}} \to \mathrm{U}(1)_{\mathrm{X}}$$

$$\to \begin{cases} \text{Case.A: string decay} \to \cancel{\mathrm{U}(1)_{\mathrm{X}}} \\ \text{Case.B: } \cancel{\mathrm{U}(1)_{\mathrm{X}}} \to \text{string decay} \end{cases}$$

We will find later that

- In Case.A, monopoles carry unconfined flux.
- In Case.B, fluxes are all confined.

Mass Eigenstates

- In $\mathrm{U}(1)_\mathrm{M} \times \mathrm{U}(1)_\mathrm{P} \to \mathrm{U}(1)_\mathrm{X}$,
  $\mathrm{U}(1)_\mathrm{M}$ and $\mathrm{U}(1)_\mathrm{P}$ gauge fields W_μ^3 and A_μ **mix**
  to form mass eigenstates,
  the massive Z boson and the massless X boson.

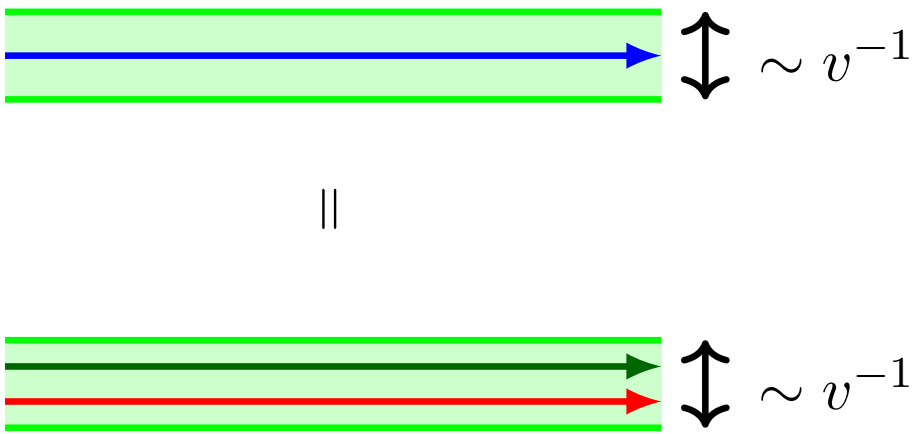
$$\begin{pmatrix} Z_\mu \\ X_\mu \end{pmatrix} := \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ A_\mu \end{pmatrix} , \quad \alpha : \text{mixing angle}$$

- X boson acquires mass later in $\mathrm{U}(1) \to \times$.

Metastable String from $\mathrm{U}(1)_\mathrm{M} \times \mathrm{U}(1)_\mathrm{P} \to \mathrm{U}(1)_\mathrm{X}$

- Z-flux, which corresponds to the broken symmetry, is running.

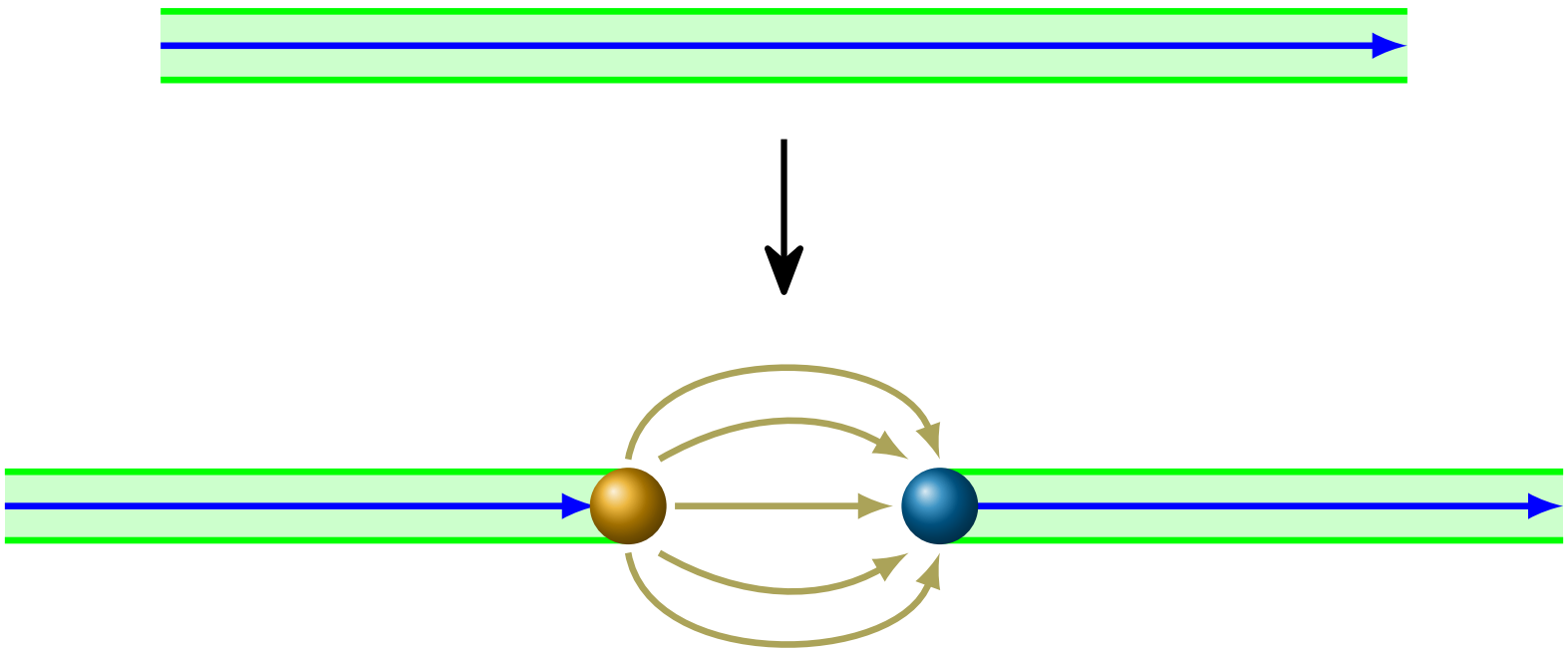
$$Z_\mu = W^3_\mu \cos\alpha + A_\mu \sin\alpha$$



- Flux running along the string $\neq$ Monopole charge !

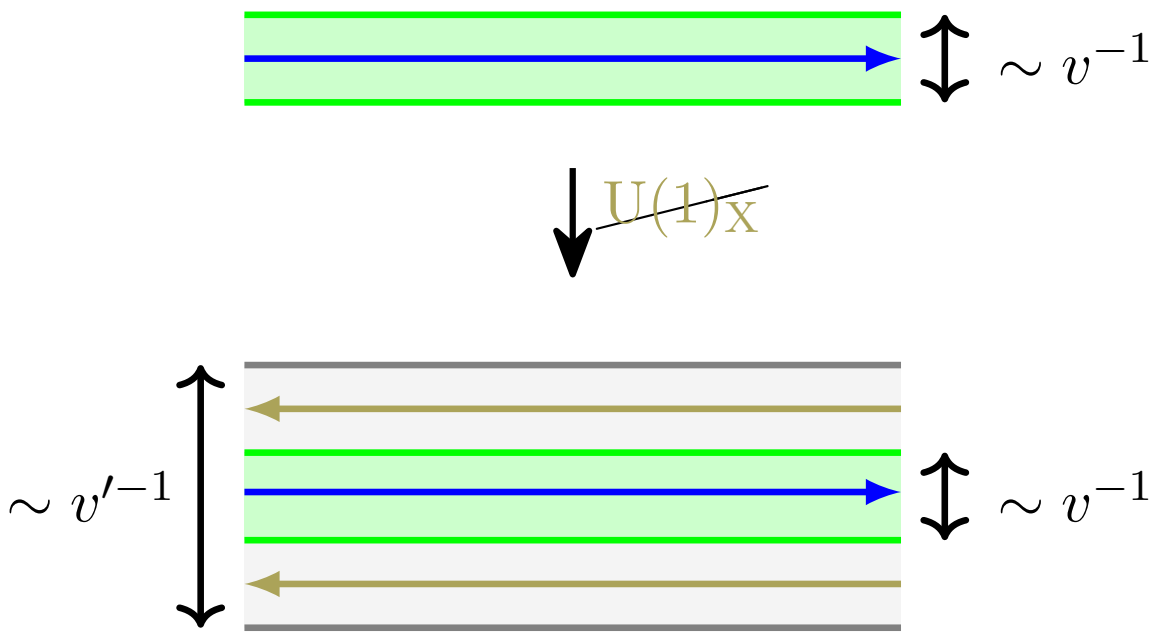
Case A. Metastable String Decay before $\cancel{\mathrm{U}(1)_{\mathrm{X}}}$

- Total flux does not match the monopole charge.
  $\rightarrow$ When the string decays, magnetic flux is partially not confined.
- The unconfined flux is identical to X-flux.



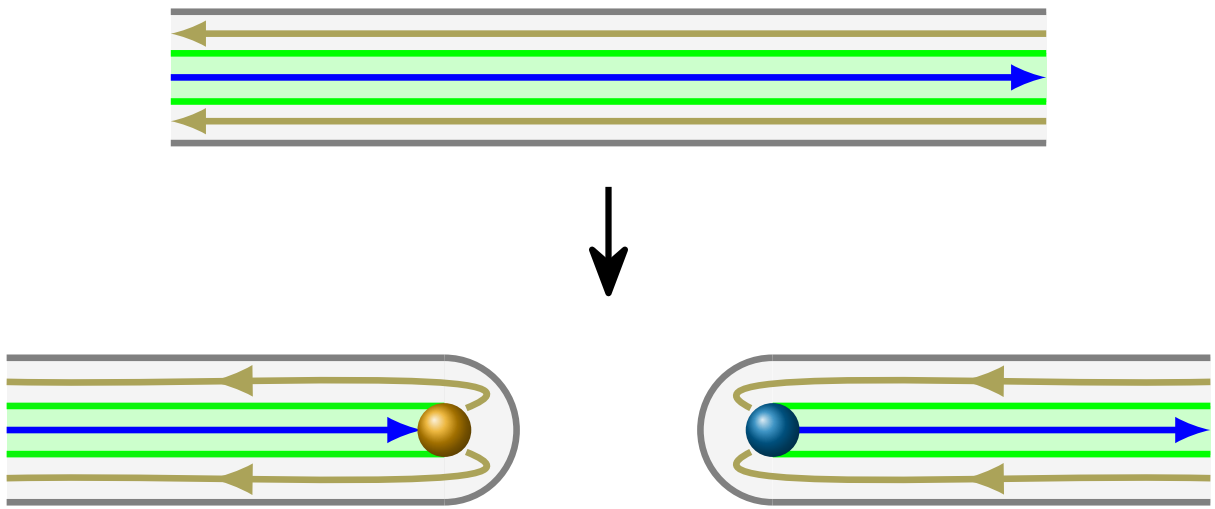
Case B. Impact of $\cancel{\mathrm{U}(1)_{\mathrm{X}}}$ on Metastable String

- X-flux arises when $\mathrm{U}(1)_{\mathrm{X}}$ is broken, even when the scalar field is **not** winding.



Case B. Metastable String Decay after $\cancel{\mathrm{U}(1)_{\mathrm{X}}}$

- The total flux **does match** the monopole charge.
  $\rightarrow$ The fluxes is **all confined**.



Summary

- Metastable string, arising from $\mathrm{SU}(2) \to \mathrm{U}(1) \to 1$, is a strong candidate for explaining PTA signals.
- We studied metastable cosmic strings arising from $\mathrm{SU}(2) \times \mathrm{U}(1) \to \mathrm{U}(1) \times \mathrm{U}(1) \to \mathrm{U}(1)' \to 1$, focusing on two possible scenarios.
  - In **Case.A (string decay $\to \mathrm{U}(1)'$ breaking)** monopoles carry **unconfined flux**,
  - whereas in **Case.B ($\mathrm{U}(1)'$ breaking $\to$ string decay)** they carry only **confined flux**.