Cosmic strings, Dark Matter, and Gravitational Wave Signatures from Pure Yang-Mills Theory

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in collaboration with

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Based on

Phys.Lett.B 838 (2023) 137724 (hep-th/2204.13125),

Phys.Rev.D 106 (2022) 12, 123515 (hep-th/2204.13123),

JHEP 09 (2023) 197 (hep-ph/2307.06586)

Nov. 9th, 2023

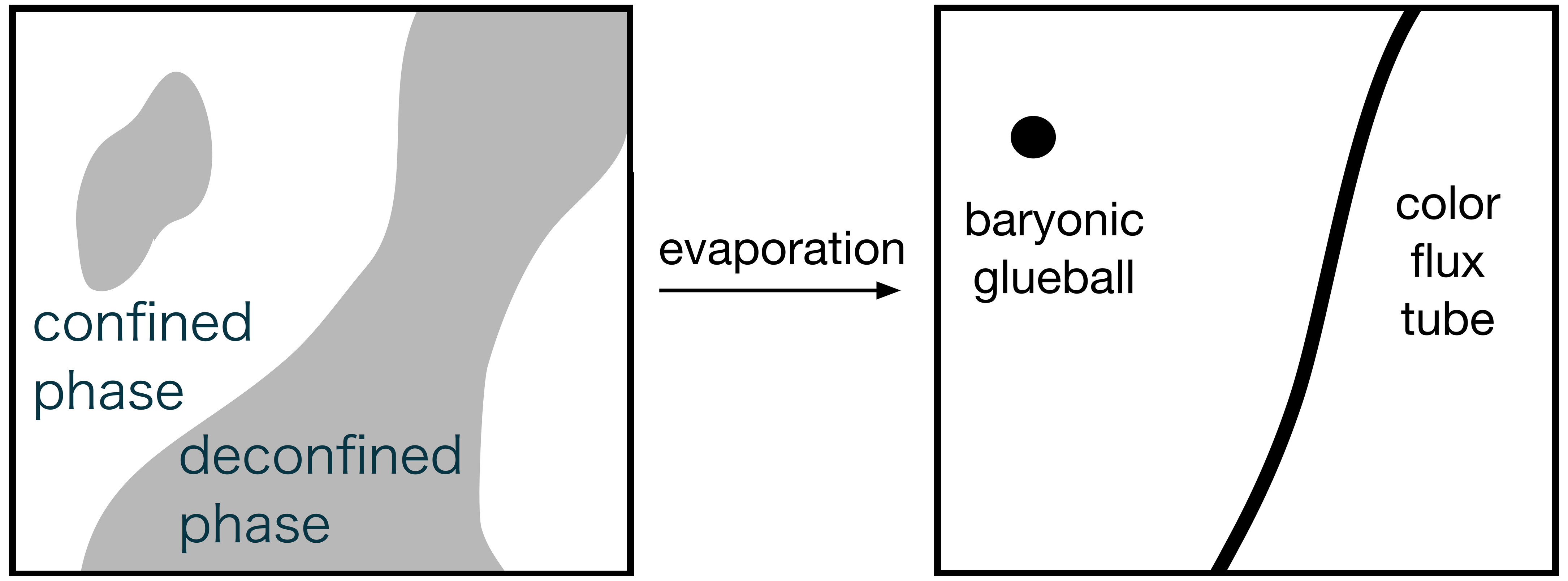
Ellis et.al. '23

Key Takeaways

- **Cosmic Superstrings Formation:** Cosmic strings with a low reconnection probability emerge following the confinement phase transition in pure YM theory.

- **Dark Matter Candidate in SO(2N):** In scenarios with SO(2N), dark matter can be explained by a "baryonic glueball."

GW and DM from $\mathscr{L} = \frac{1}{4g^2}\mathrm{Tr}\left[F_{\mu\nu}F^{\mu\nu}\right]$



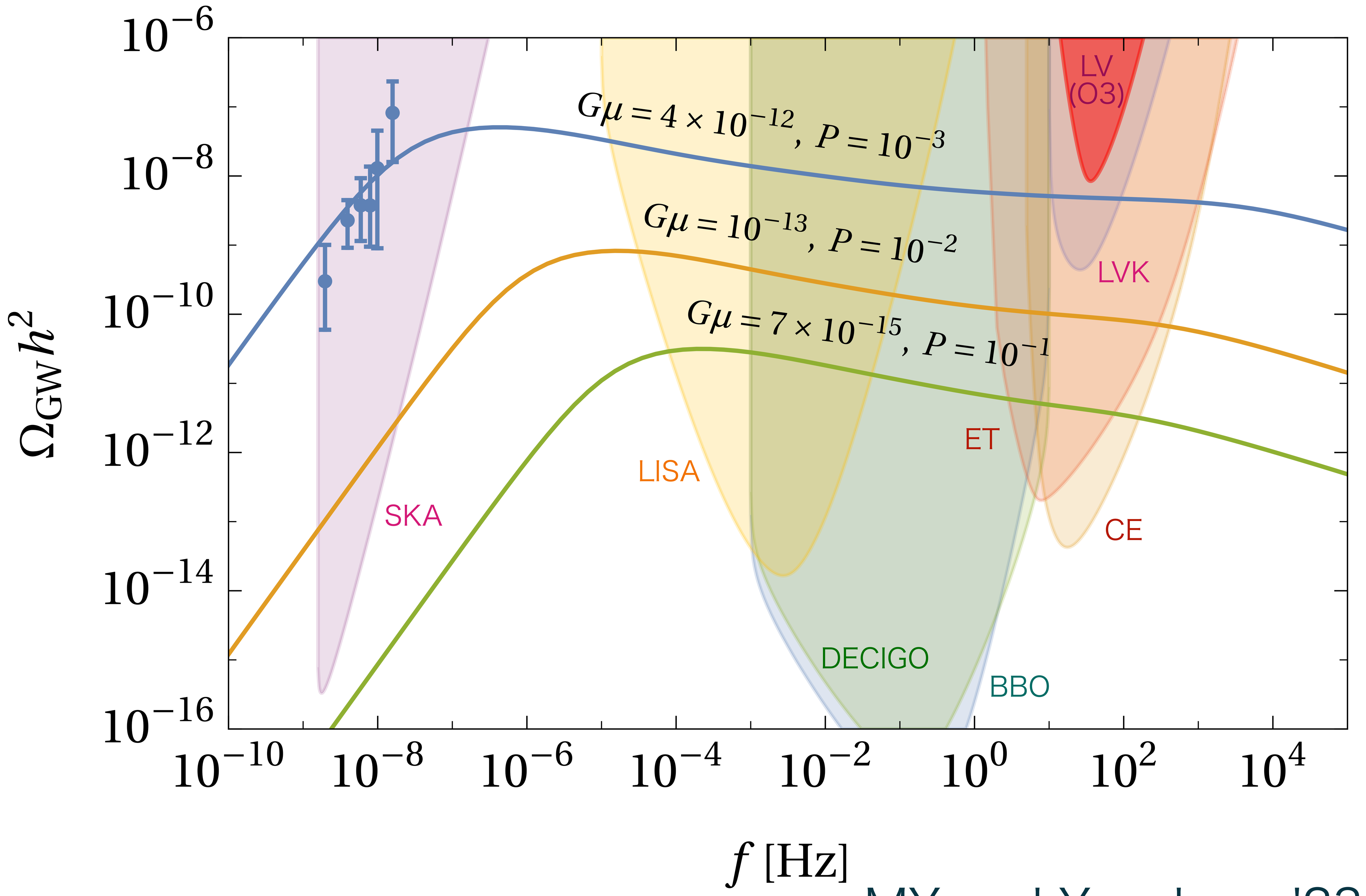


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Table of contents

Cosmic Strings: U(1) Symmetry Breaking

- **Formation of cosmic strings:** Cosmic strings arise through the spontaneous breaking of U(1) symmetry.

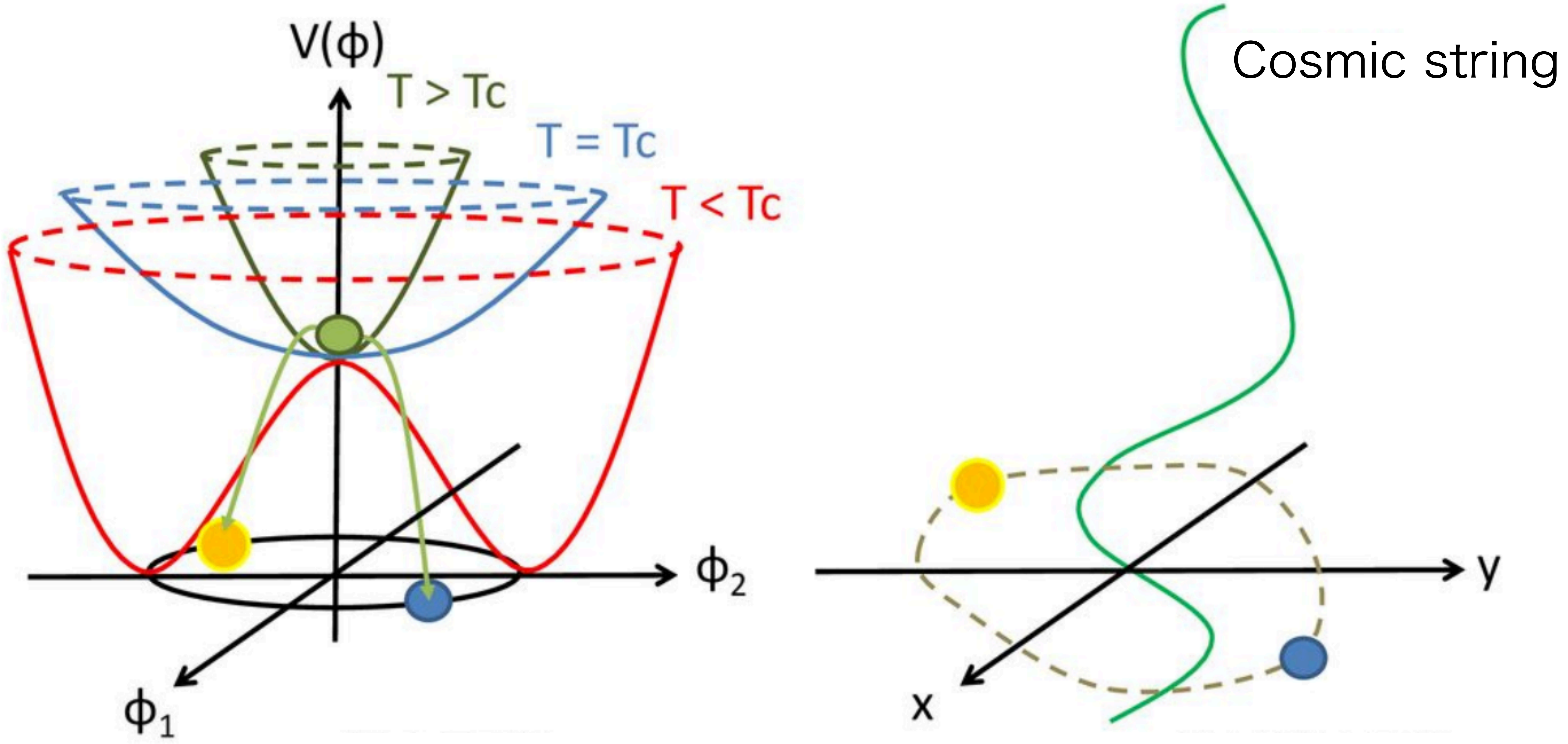


Figure from Daisuke Yamauchi's slide

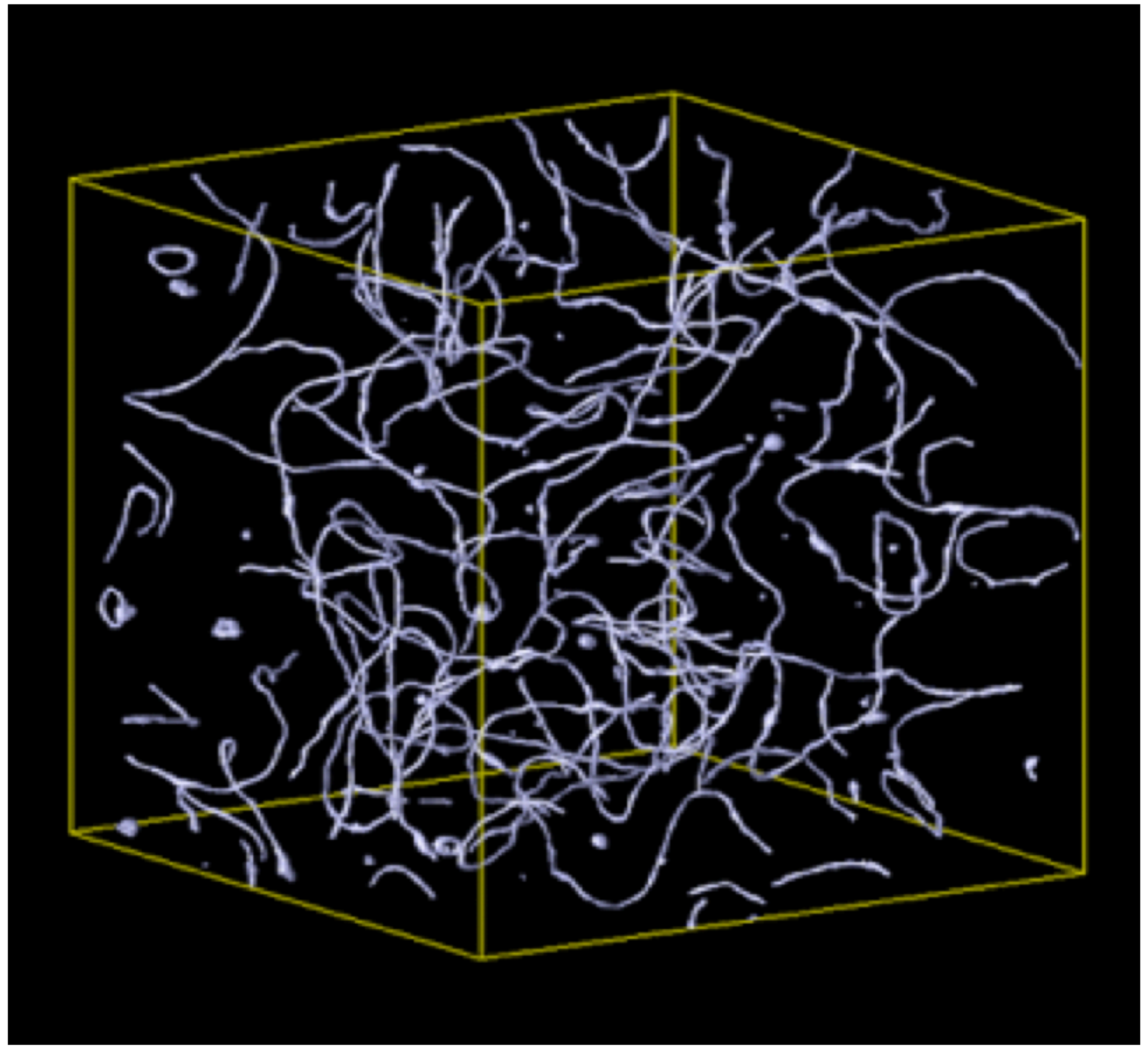
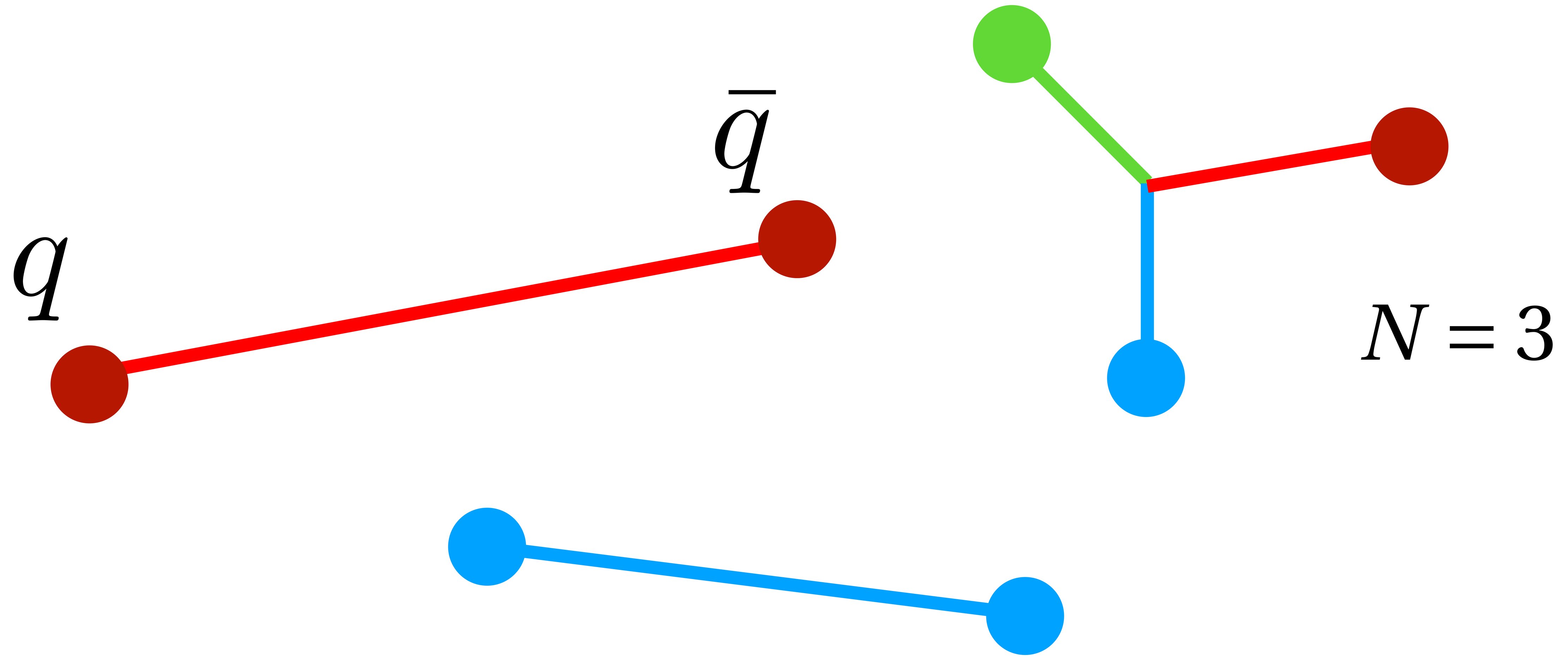
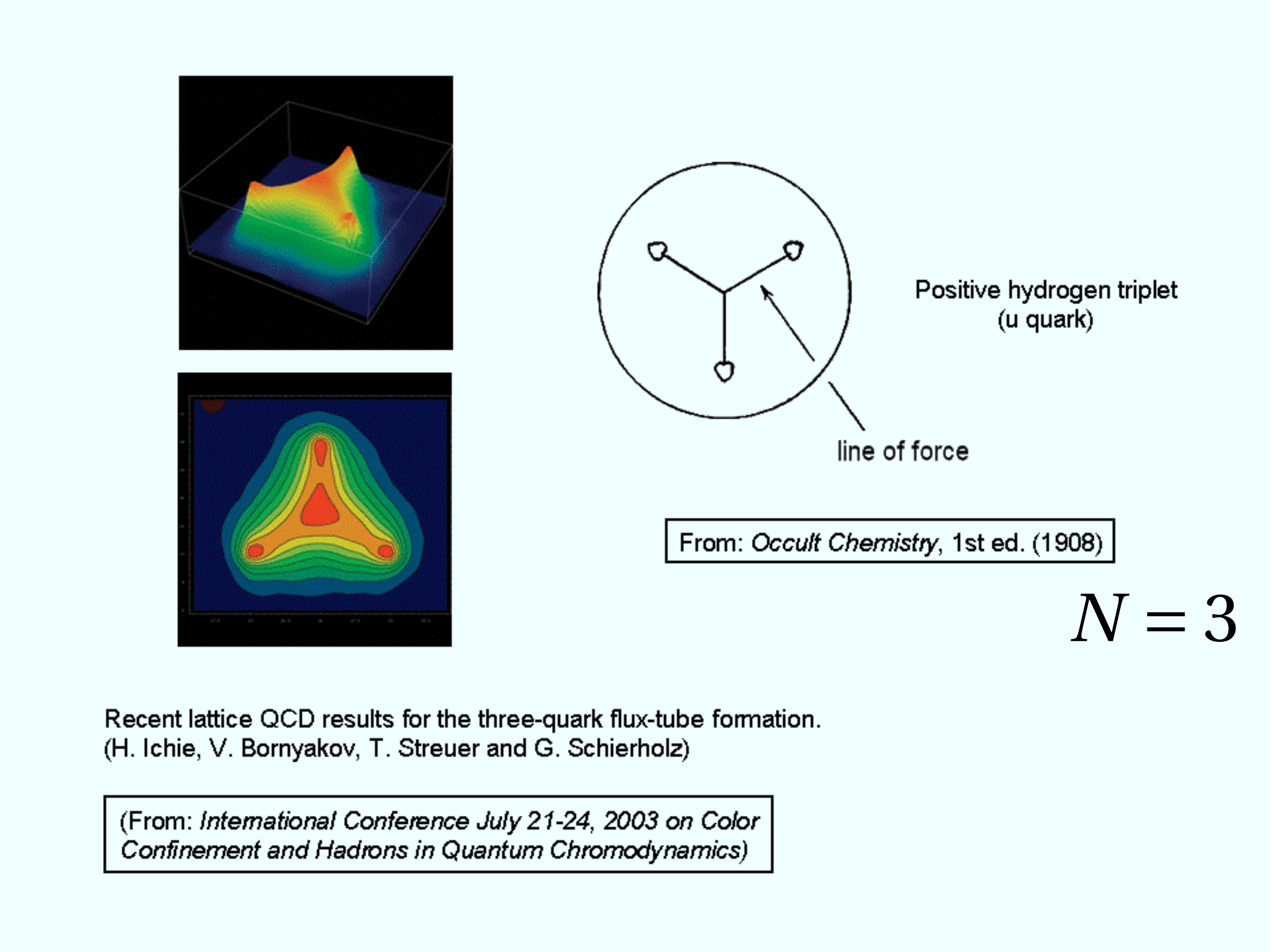


Figure from Hiramatsu et.al. '13

Cosmic Strings: SU(N) Confinement

- **SU(N) gauge theory:** The confinement phase transition leads to the connection of quarks and anti-quarks by a color flux tube.





Cosmic Strings: SU(N) Confinement

- **Duality between strong and weak coupling:** Based on the duality between strong and weak coupling theories, the color flux tube is recognized as a cosmic string.

Seiberg, Witten '94,

- This duality further suggests that color flux tubes can form even in the absence of quarks.

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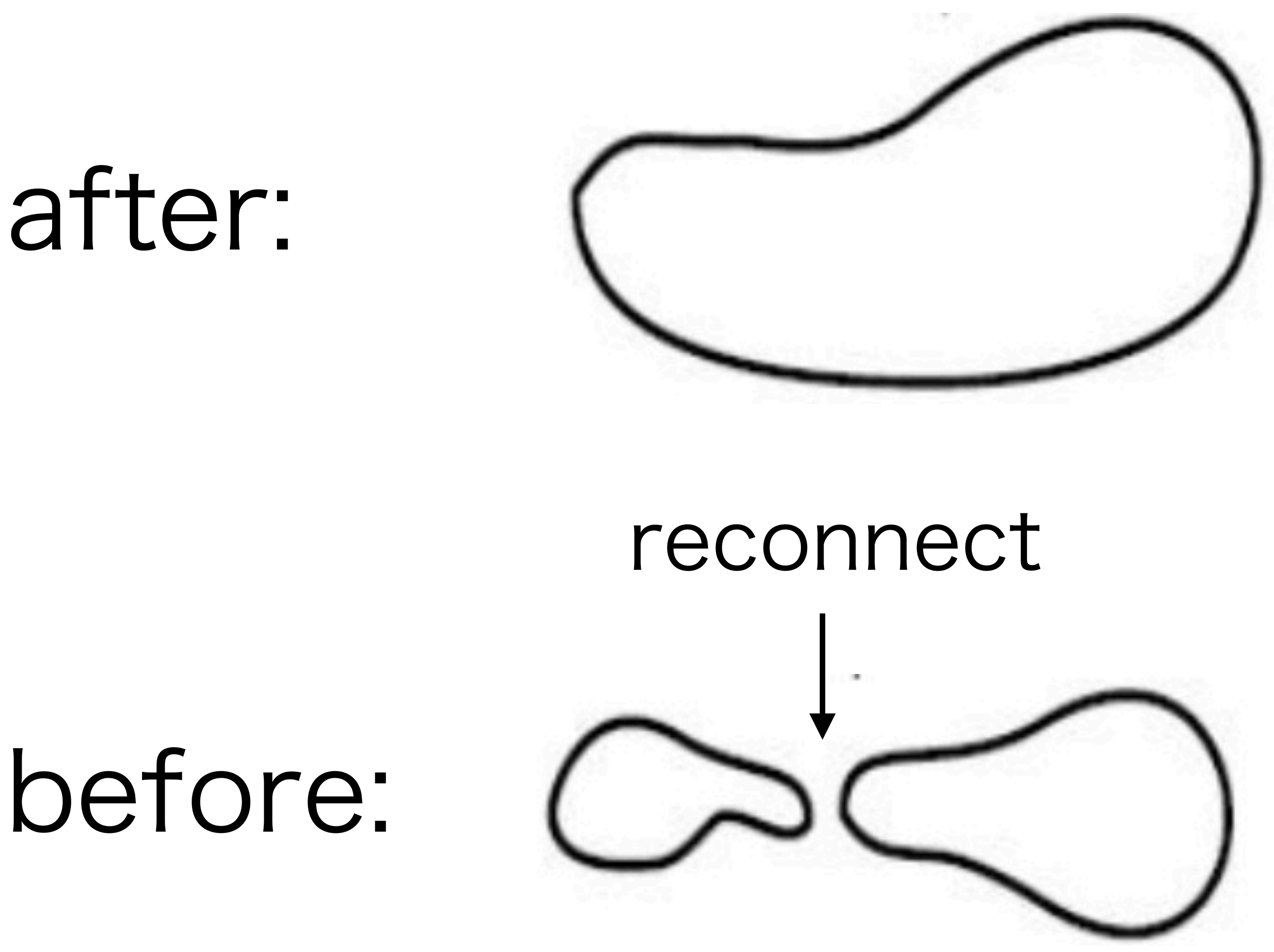
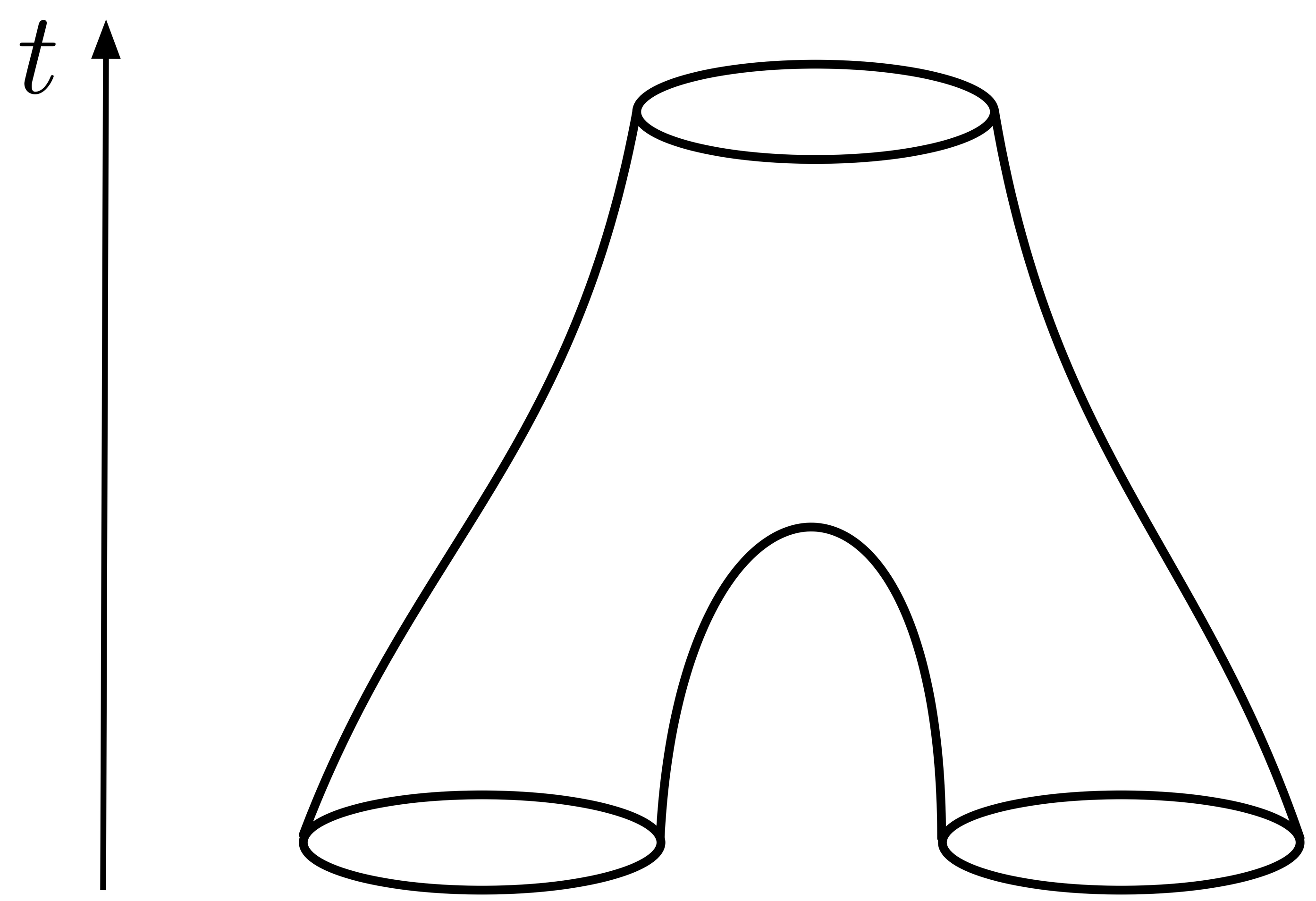
Cosmic Strings: SU(N) Confinement

- **Large N limit argument:** The reconnection probability of color flux tubes can be estimated by the Euler number of a diagram $\chi\,(= 2 - g - h)$, leading to the relationship $P \sim N^{2\chi}$.

# of genus

# of holes





't Hooft '74

See also Jackson, Jones, Polchinski '04, Polchinski '88, Hanany Hashimoto '05

Cosmic Strings: SU(N) Confinement

- **Electric-Magnetic Duality**: Based on the duality, cosmic strings, which are macroscopic color flux tubes, emerge during the confinement phase transition.

Witten '85, MY and Yonekura '22

- **String Tension**: The string tension μ is on the order of the dynamical scale squared, $\mu \sim \Lambda^2$

- **Large N Limit Argument**: Considering the large N limit, the probability of reconnection between two cosmic strings is notably suppressed, with $P \sim N^{-2}$.

- **Holographic Dual Descriptions**: In the context of holographic dual descriptions, these cosmic strings correspond to fundamental (F-) strings or superstrings in the realm of gravity theory.

See, e.g., Witten '98, Polchinski, Strassler '00, Klebanov, Strassler '00, Maldacena, Nunez '00, Vafa '00

Cosmic Strings in Diverse Gauge Groups

- **Exploring Different Gauge Groups**: While we've primarily focused on SU(N) and cosmic F-strings, SO(2N) gauge theory introduces a distinct variety of cosmic strings known as D-strings.
- **One-Form Symmetry Classification**: We can classify the properties of these cosmic strings using one-form symmetry, which imposes restrictions, particularly on composite states of cosmic strings.

$$SU(N) \supset Z_N$$

$$SO(N) \supset \begin{cases} Z_2 \times Z_2 & (N = 4K) \\ Z_4 & (N = 4K+2) \\ Z_2 & (N = 2K+1) \end{cases}$$

	F-string	D-string
μ	Λ^2	$N\Lambda^2$
P	N^{-2}	$\exp(-cN)$

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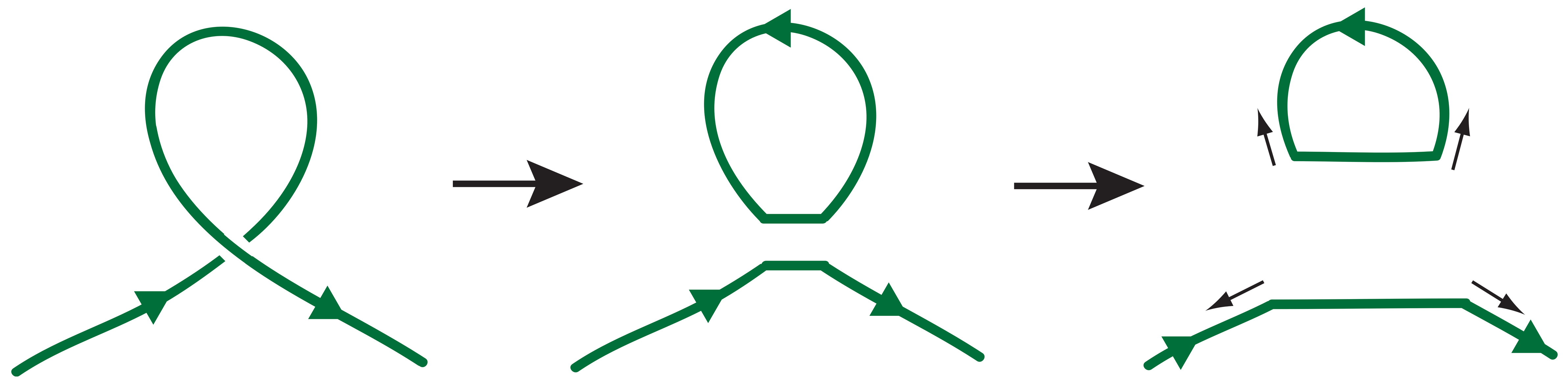
Dynamics of cosmic strings and GW signatures

Dynamics of Cosmic Strings

- **Evolution of Long Strings:** Over time, long strings evolve by shortening themselves through self-reconnection processes.



This results in a roughly constant number of long strings per unit horizon volume, typically of the order O(1) for the case of P = 1.

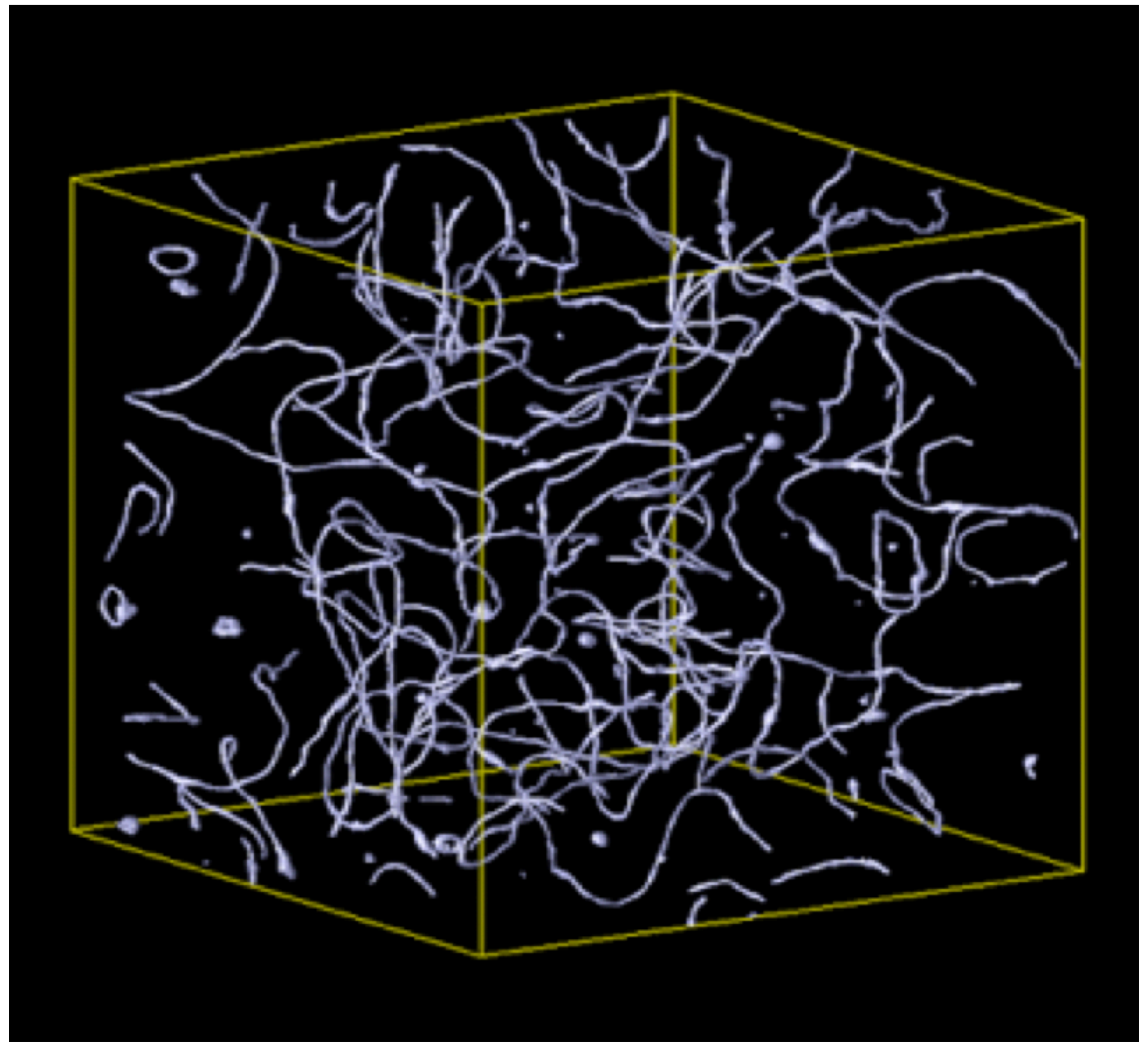


Figure from Hiramatsu et.al. '13

Dynamics of Cosmic Strings

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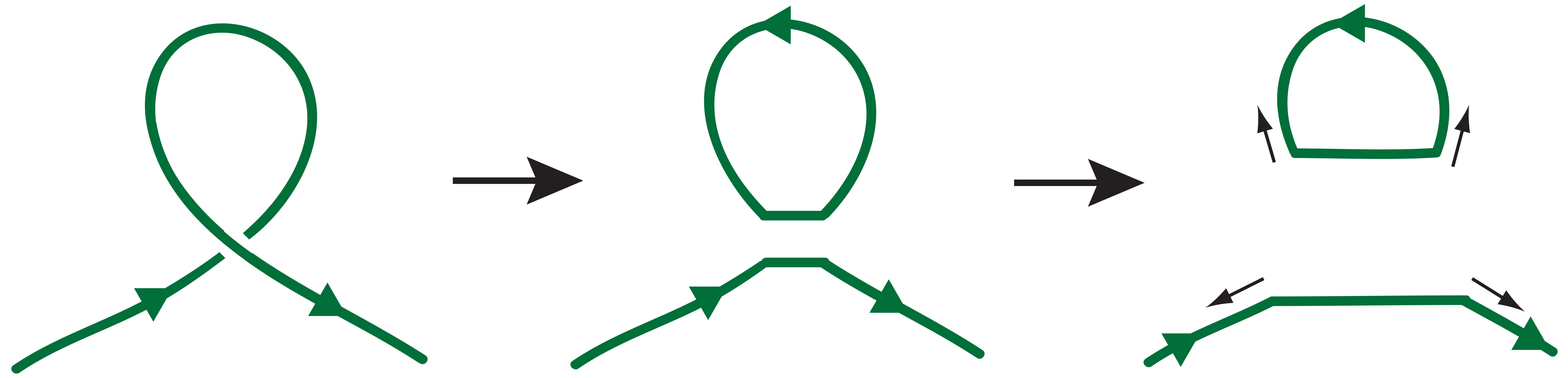

- (energy loss rate) = (reconnection probability) × (density of strings)
  ×(# of colliding strings per unit time)
  ×(energy loss per reconnection event)

$$\left(\frac{d\rho_\infty}{dt}\right)_{\mathrm{loop}} = -P\, n_\infty (\tilde{c}\mu\xi)\frac{n_\infty \xi^3 \bar{v}}{\xi}$$

$\xi = c_\xi t$: correlation length

Avgoustidis, Shellard '05

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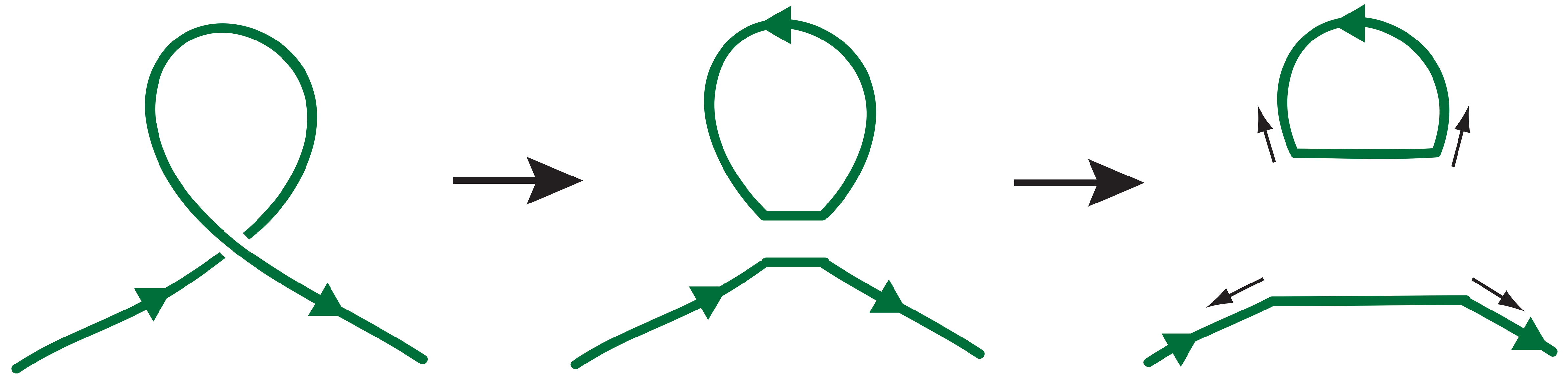


- **Statistical Modeling**: The statistical characteristics of the cosmic string network can be effectively described by a set of equations, often referred to as the VOS model.

Energy density: $$\frac{d\rho_\infty}{dt} = -\left(2H(1+\bar{v}^2)\right)\rho_\infty + \left(\frac{d\rho_\infty}{dt}\right)_{\rm loop},$$ → $\rho_\infty \propto P^{-1}$

$$\left(\frac{d\rho_\infty}{dt}\right)_{\rm loop} = -P\, n_\infty(\tilde{c}\mu\xi)\frac{n_\infty \xi^3 \bar{v}}{\xi}$$

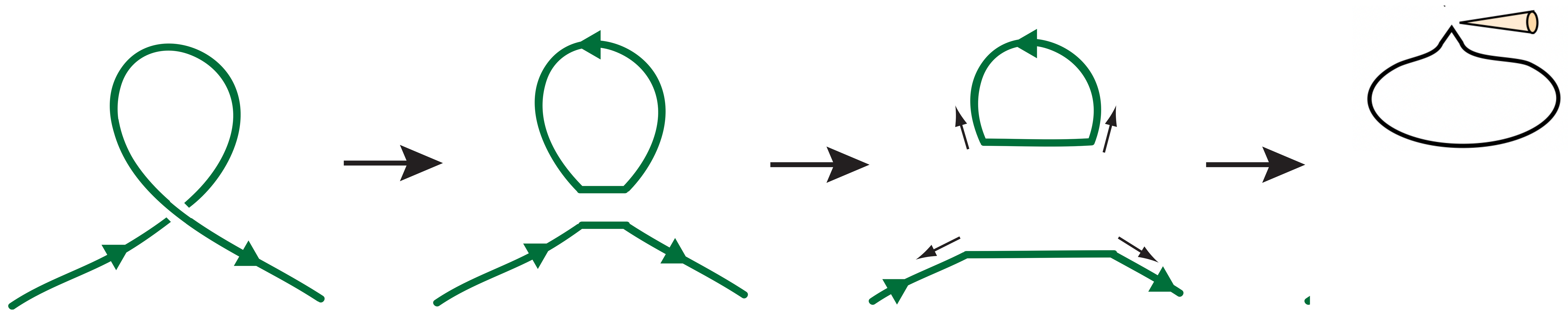
Velocity dispersion: $$\frac{d\bar{v}}{dt} = (1-\bar{v}^2)\left(\frac{k(\bar{v})}{R} - 2H\bar{v}\right),$$

R: curvature ~ H^{-1}

Kibble '85, Martins, Shellard '95, '96, '00
MY and Yonekura '22

Gravitational Waves: Signatures of Cosmic Strings

- **Gravitational Wave Production**: The dynamics of string loops give rise to the generation of gravitational waves.



$$\frac{d\rho_{\rm GW}}{df}(t) = \int_{t_i}^{t} dt' \left(\frac{a(t')}{a(t)}\right)^3 \int_0^l dl\, n_{\rm loop}(l,t')\, h\left(f\frac{a(t)}{a(t')}, l\right)$$

Vilenkin '81, Vachaspati, Vilenkin '85

$$\begin{cases} (\Omega_{\rm GW}h^2)^{(\rm peak)} \simeq 2.5\times 10^{-10} \times P_{\rm eff}^{-1}\left(\dfrac{G\mu}{10^{-12}}\right)^{1/2} \\ f^{(\rm peak)} \simeq 1.9\times 10^{-6}\,{\rm Hz}\times\left(\dfrac{G\mu}{10^{-12}}\right)^{-1} \end{cases}$$

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Gravitational Waves: Signatures of Cosmic Strings

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Peak amplitude of GW:

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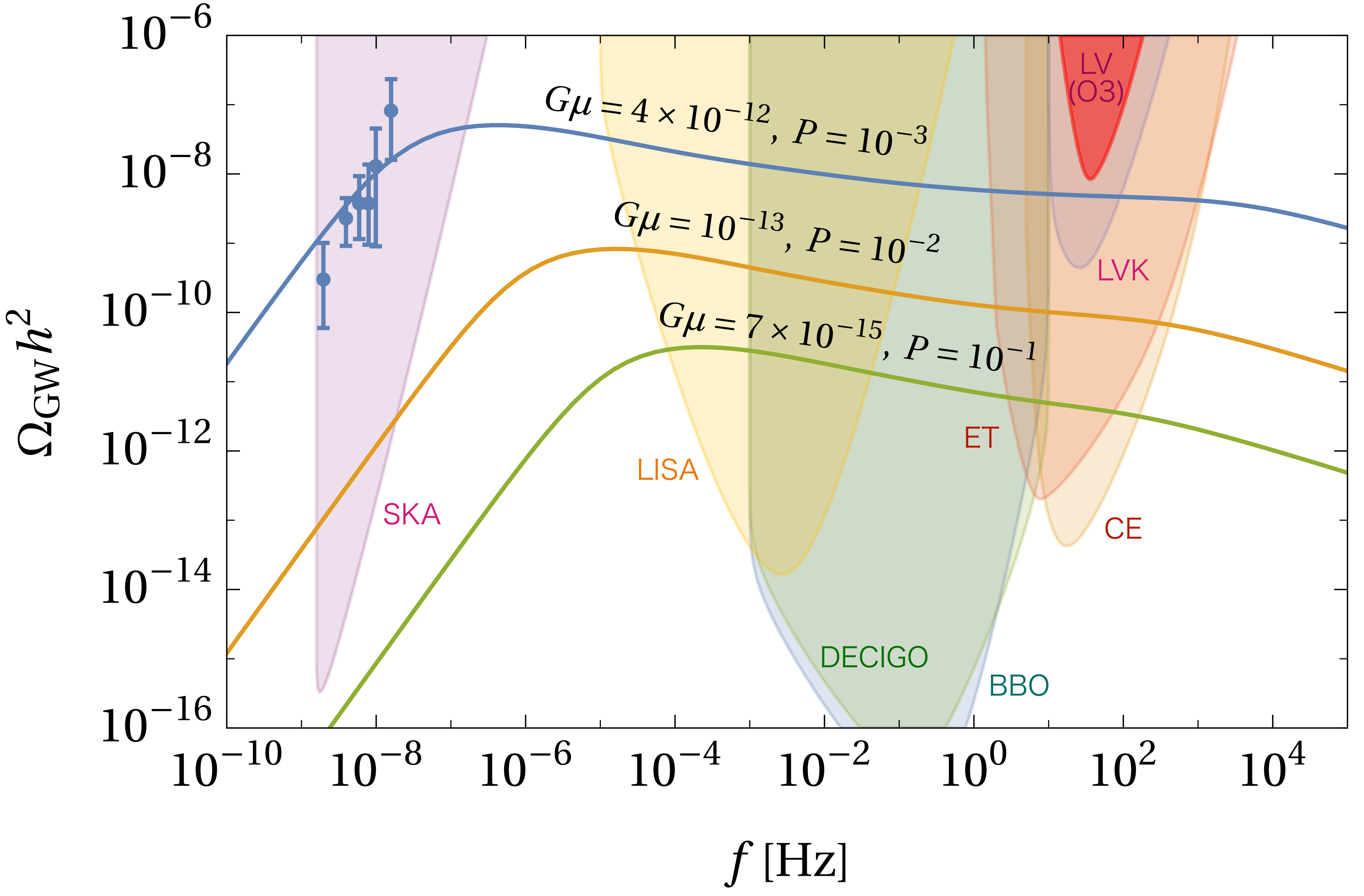
Peak frequency:

$$f^{(\rm peak)} \simeq 1.9\times 10^{-6}\,{\rm Hz}\times\left(\frac{G\mu}{10^{-12}}\right)^{-1}$$

Physical parameters in the theory:

$$\begin{cases} \mu \sim \Lambda^2 \\ P \sim N^{-2} \end{cases}$$



MY and Yonekura '22, '23, (see also Ellis et.al. '23)

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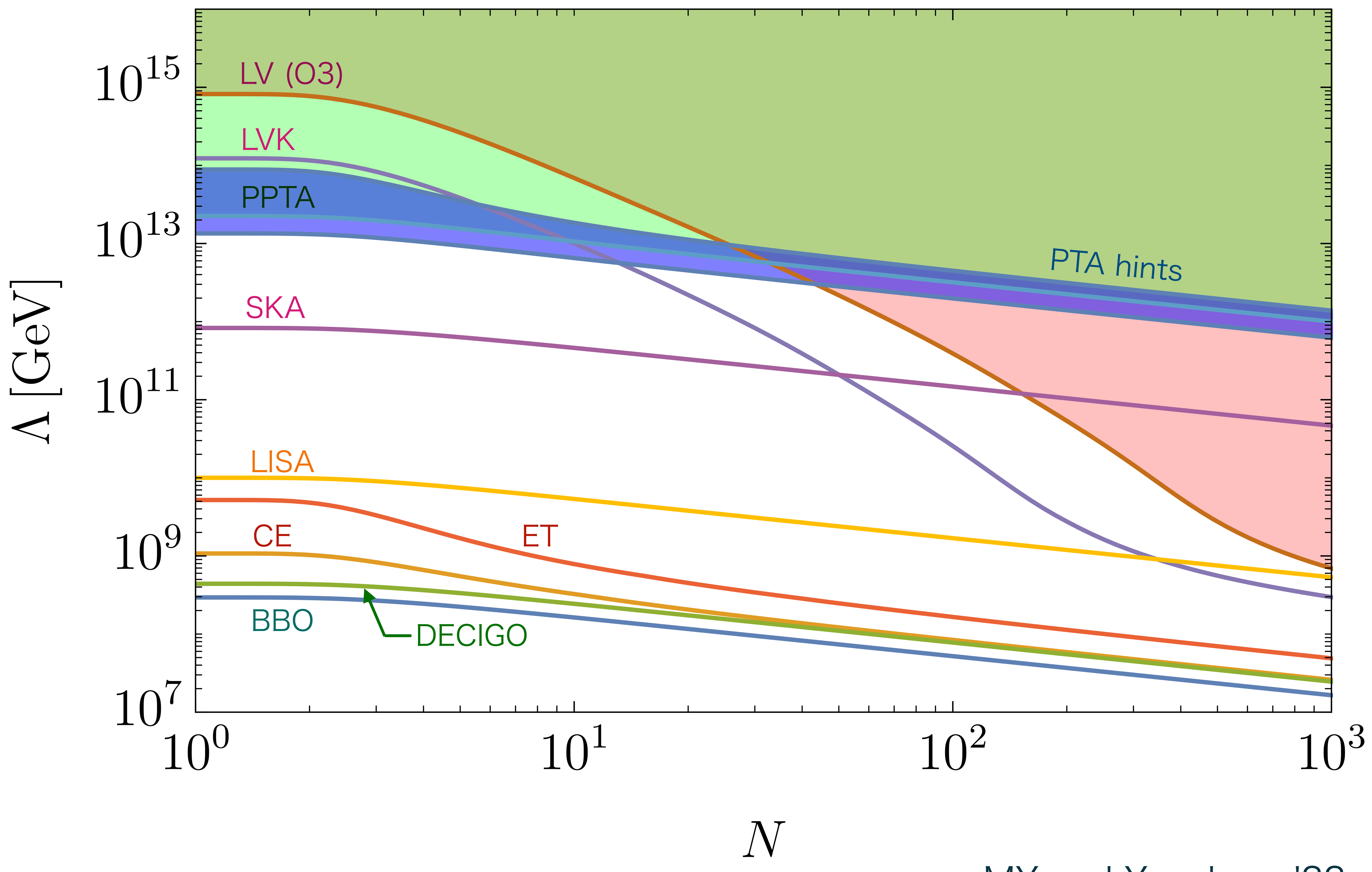

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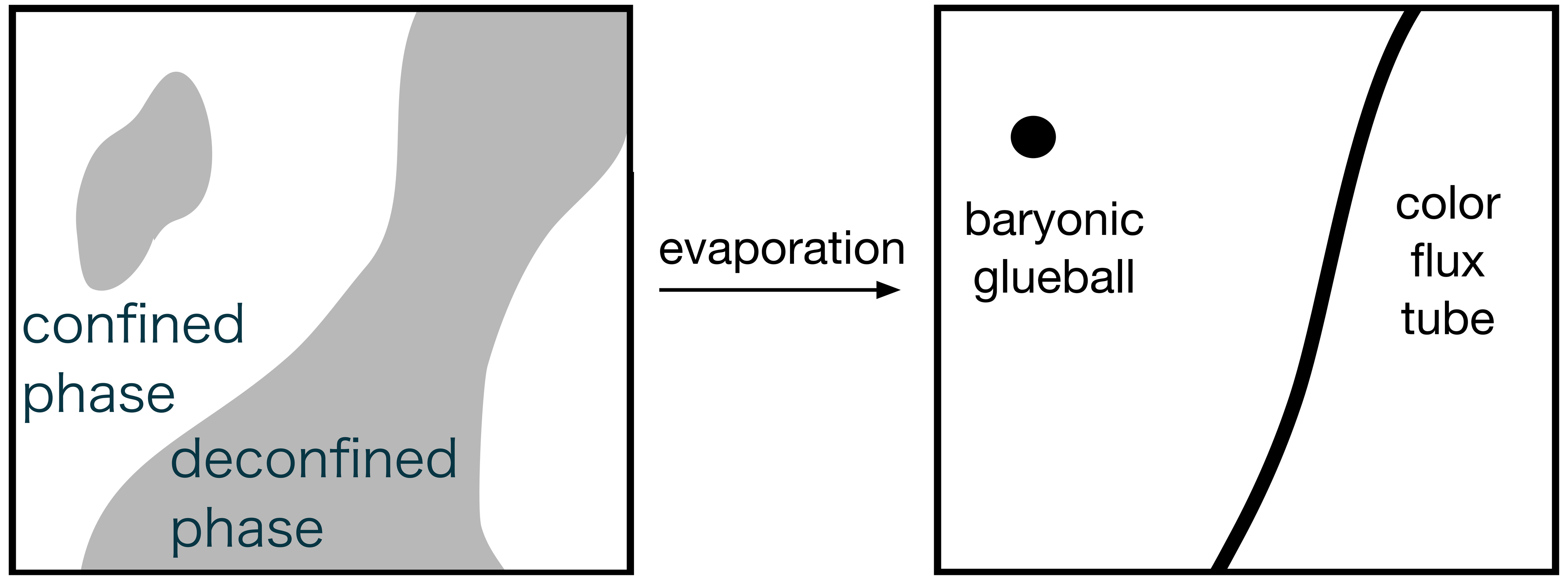
Baryonic glueball as a dark matter candidate

DM Candidate: Baryonic Glueball in SO(2N)

- **Post-Confinement Entities**: Confinement gives rise to both glueballs and cosmic strings.
- **"Baryonic Glueball" in SO(2N)**: In SO(2N) gauge theory, the "baryonic glueball" is a standout candidate for DM, thanks to its long lifetime driven by an accidental symmetry in the large N limit.



$\mathrm{O}(2N)/\mathrm{SO}(2N) = Z_2$

$$B_{\mu_1\cdots\mu_{2N}} = \epsilon_{i_1\cdots i_{2N}} (F_{\mu_1\mu_2})_{i_1 i_2} \cdots (F_{\mu_{2N-1}\mu_{2N}})_{i_{2N-1} i_{2N}}$$

Gross et.al. '20, MY and Yonekura '23

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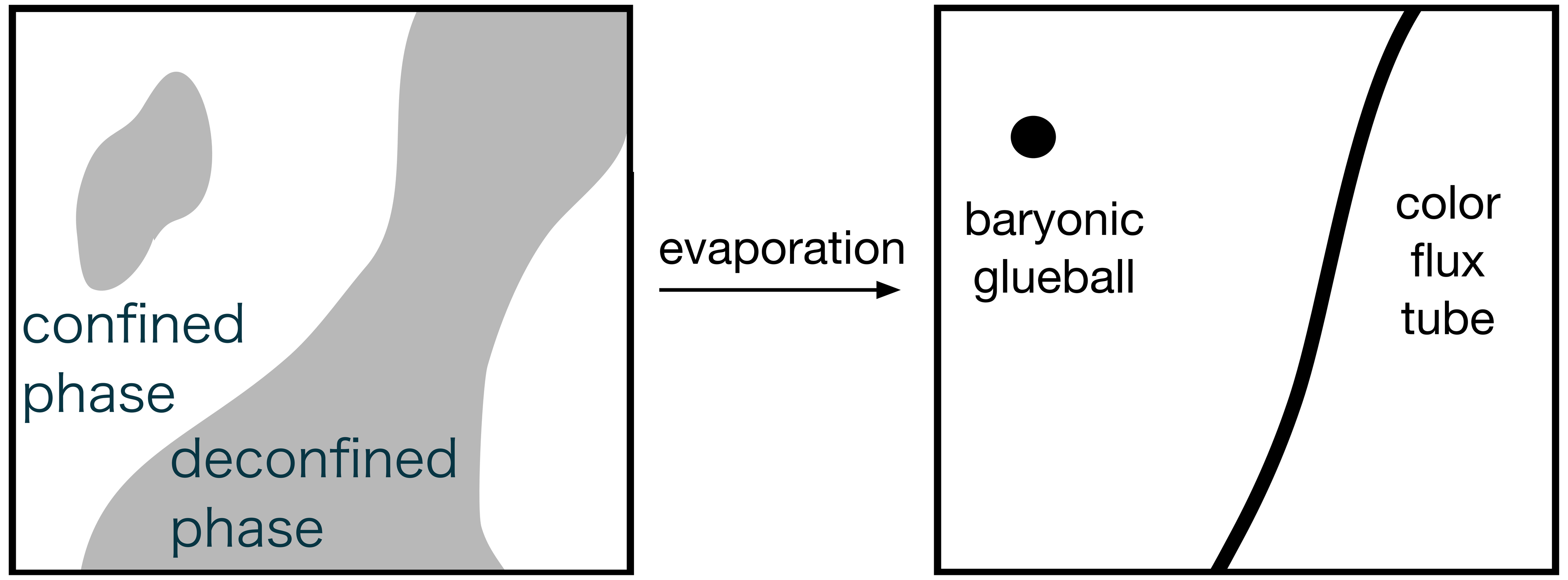
- **"Baryonic Glueball" in SO(2N)**: In SO(2N) gauge theory, the "baryonic glueball" is a standout candidate for DM, thanks to its long lifetime driven by an accidental symmetry in the large N limit.
- **Abundance Estimation**: We estimate the abundance of "baryonic glueball" using the Kibble-Zurek mechanism.



$$\frac{\rho_b}{s} \sim 0.4\,\mathrm{eV} \times N^2 \left(\frac{\beta}{10^2 H_{\mathrm{PT}}}\right)^3 \left(\frac{\Lambda}{10^{13}\,\mathrm{GeV}}\right)^{11/2}$$

MY and Yonekura '23

DM Candidate: Baryonic Glueball in SO(2N)

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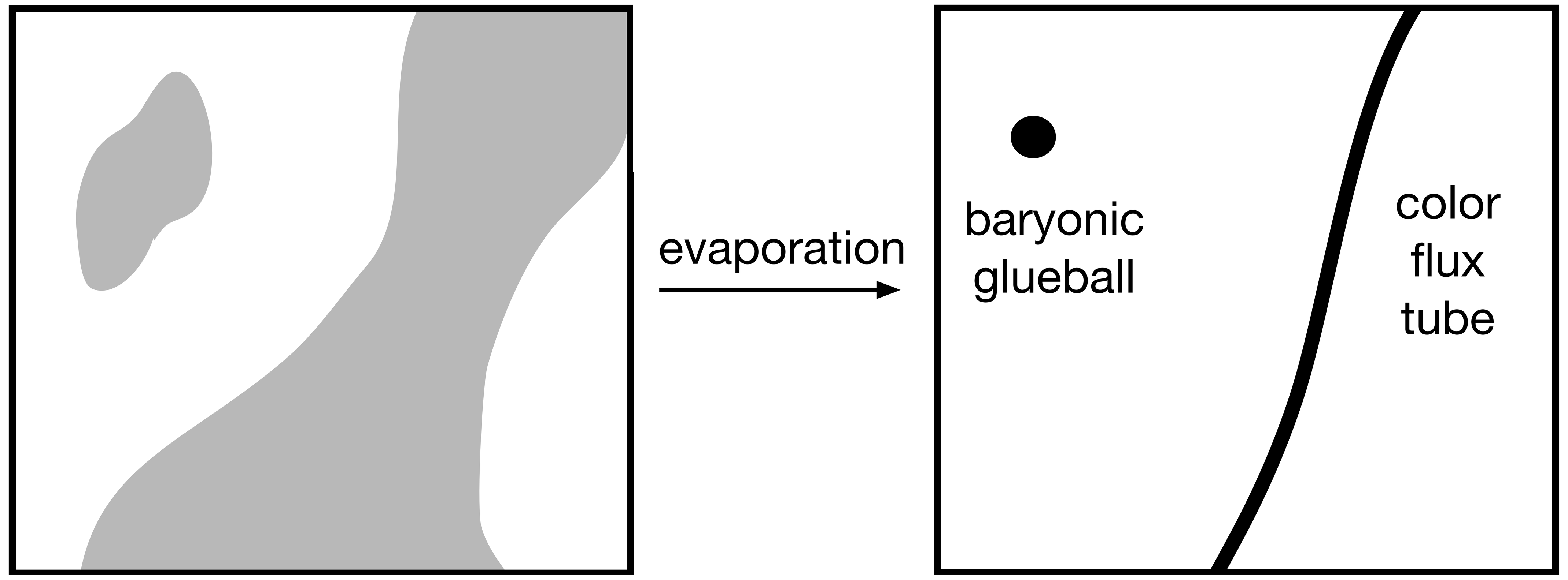
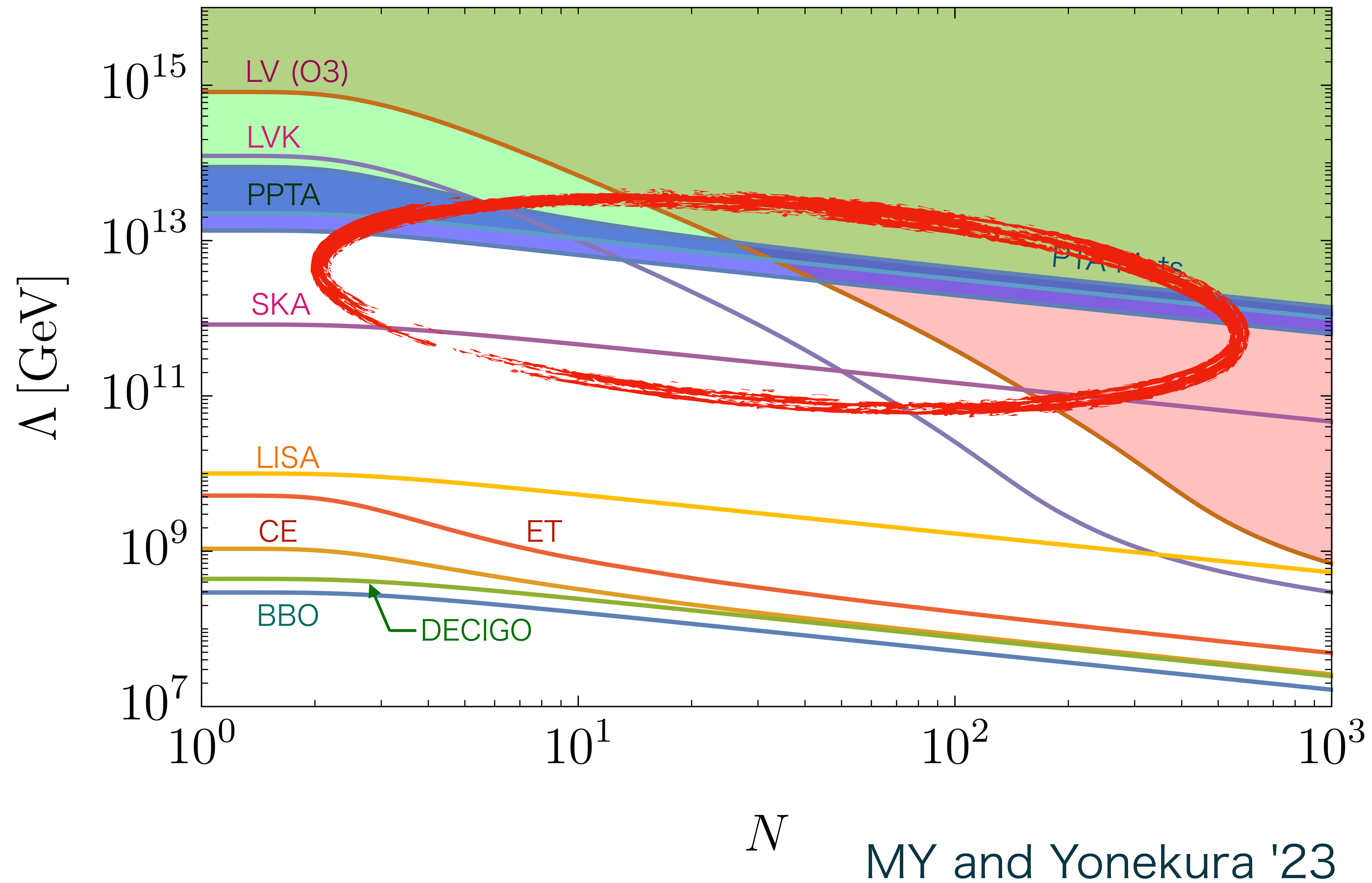
- **"Baryonic Glueball" in SO(2N)**: In SO(2N) gauge theory, the "baryonic glueball" is a standout candidate for DM, thanks to its long lifetime driven by an accidental symmetry in the large N limit.
- **Explaining Dark Matter Abundance:** This model offers a potential explanation for both the observed DM abundance and the signals detected in PTA simultaneously!





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In Conclusion: Key Insights

- **Formation of cosmic strings**: Cosmic (super)strings emerge post-confinement in pure Yang-Mills theory.
- **String characteristics**: The string tension ($\mu \sim \Lambda^2$), reconnection probability $P \sim N^{-2}$; and the dynamics of cosmic strings have been explored, extending the VOS model to calculate the gravitational wave spectrum.
- **Baryonic glueballs for DM**: In SO(2N) gauge theory, baryonic glueballs have been highlighted as a potential explanation for dark matter.

GW and DM from $\mathscr{L} = \frac{1}{4g^2} \mathrm{Tr}\left[F_{\mu\nu}F^{\mu\nu}\right]$