Discrete Symmetries, Proton Stability, and Cosmological Lithium

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Omitted details explained in 2204.01741 2204.01750

Big-Bang Nucleosynthesis after Planck

Brian D. Fields,[a] **Keith A. Olive,**[b] **Tsung-Han Yeh**[c]
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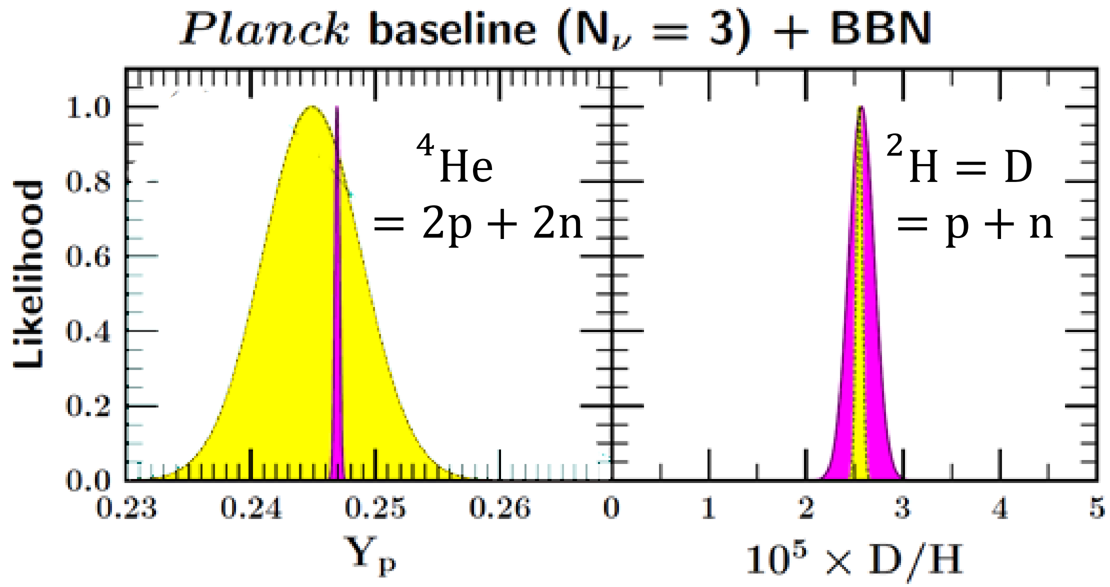
Theory

Observed Abundances



Big-Bang Nucleosynthesis after Planck

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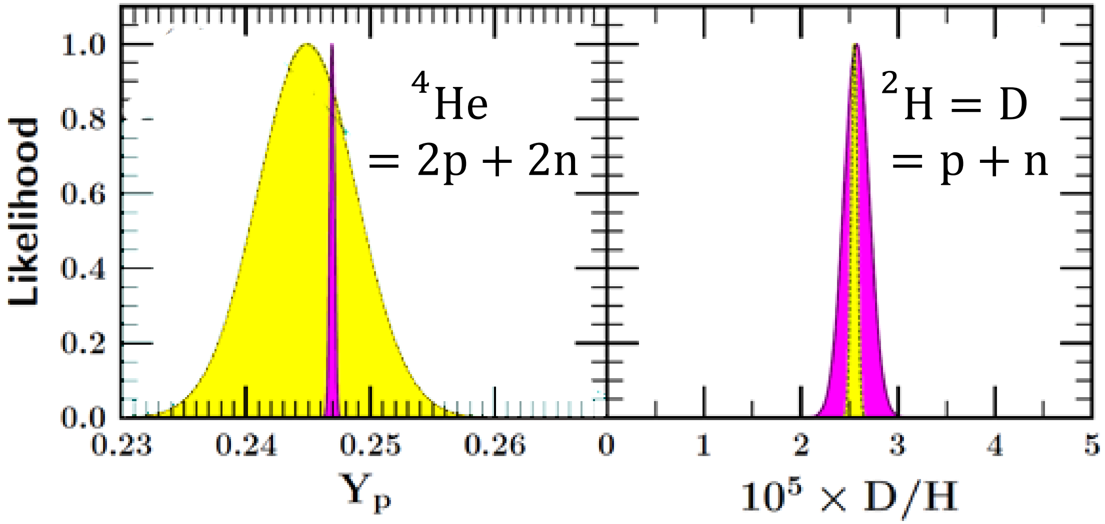
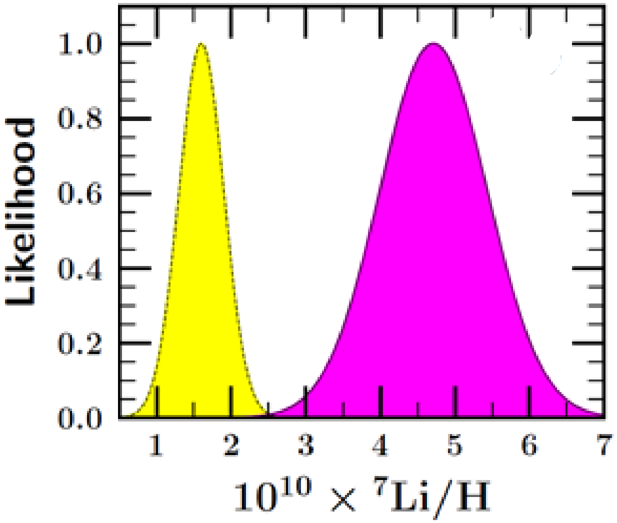
Observed Abundances

Planck baseline ($N_\nu = 3$) + BBN



The Lithium Problem



^{7}Li
= 3p + 4n

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What in the world could uniquely pick out lithium?

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Look to the Standard Model!

a) Discrete global symmetry of the SM fermions $\mathbb{Z}_6^{B+L}$

b) Discrete gauge symmetry of the SM fermions? $\mathbb{Z}_6^{B-L}$

c) Write simplest UV completion $U(1)_{B-L} \to \mathbb{Z}_6^{B-L}$

… …

g) Cosmic strings destroy lithium nuclei

$$\sigma\left(3p^+ + \text{ string loop} \to 3e^+ + \text{ string loop}\right) \sim \Lambda_{\rm QCD}^{-2}$$

Is the proton stable?

- Theory bias from simple GUTs: no
- Empirically: $\tau_p \gtrsim 10^{35}$ years
- In the Standard Model: yes!

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Dynamically you can compute divergences of global currents

$$\partial_\mu J^\mu_{B-L} = 0 \rightarrow \Delta Q_{B-L} = 0$$

$$\partial_\mu J^\mu_{B+L} = 2 \times N_g \times \int \frac{F\,\tilde{F}}{16\,\pi^2} \rightarrow \Delta Q_{B+L} = 2 \times N_g \times \text{integer}$$

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Okay but really why?

There really is an exact discrete subgroup of B+L, $\mathbb{Z}_6^{B+L}$!

Well-motivated to consider BSM extensions which respect this symmetry!

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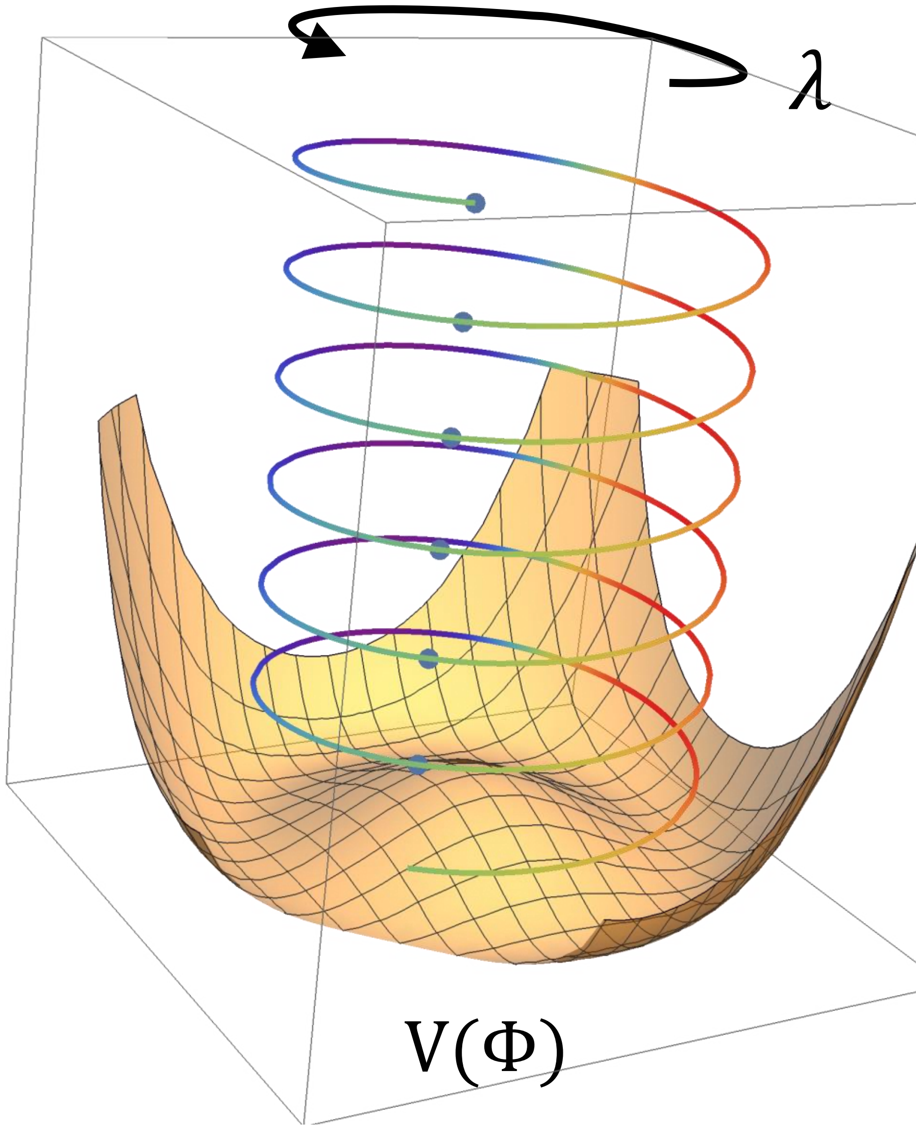
Simple UV completion is just $U(1)_{B-L}$ with a Higgs field Φ with $[\Phi]_{B-L}$=6

$$\Phi \rightarrow \Phi e^{i2N_g\lambda(x)}$$

invariant for $\lambda(x) = \dfrac{2\pi n}{2N_g}$

unbroken $\mathbb{Z}_{2N_g}$ gauged subgroup



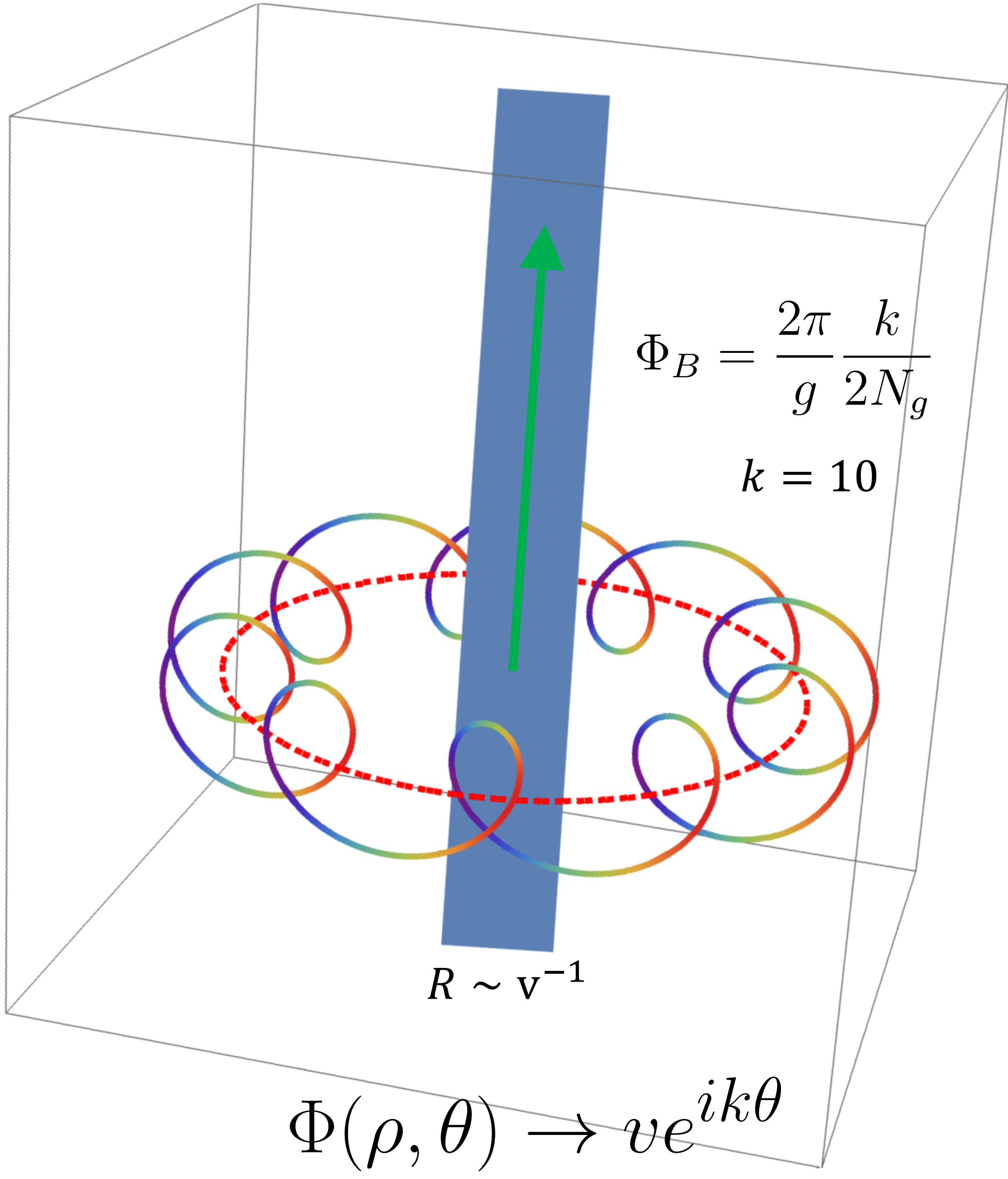
Why might this to be interesting cosmologically?

Unbroken gauge symmetry

$$g_{magnetic} = \frac{2\pi}{g_{electric}}$$

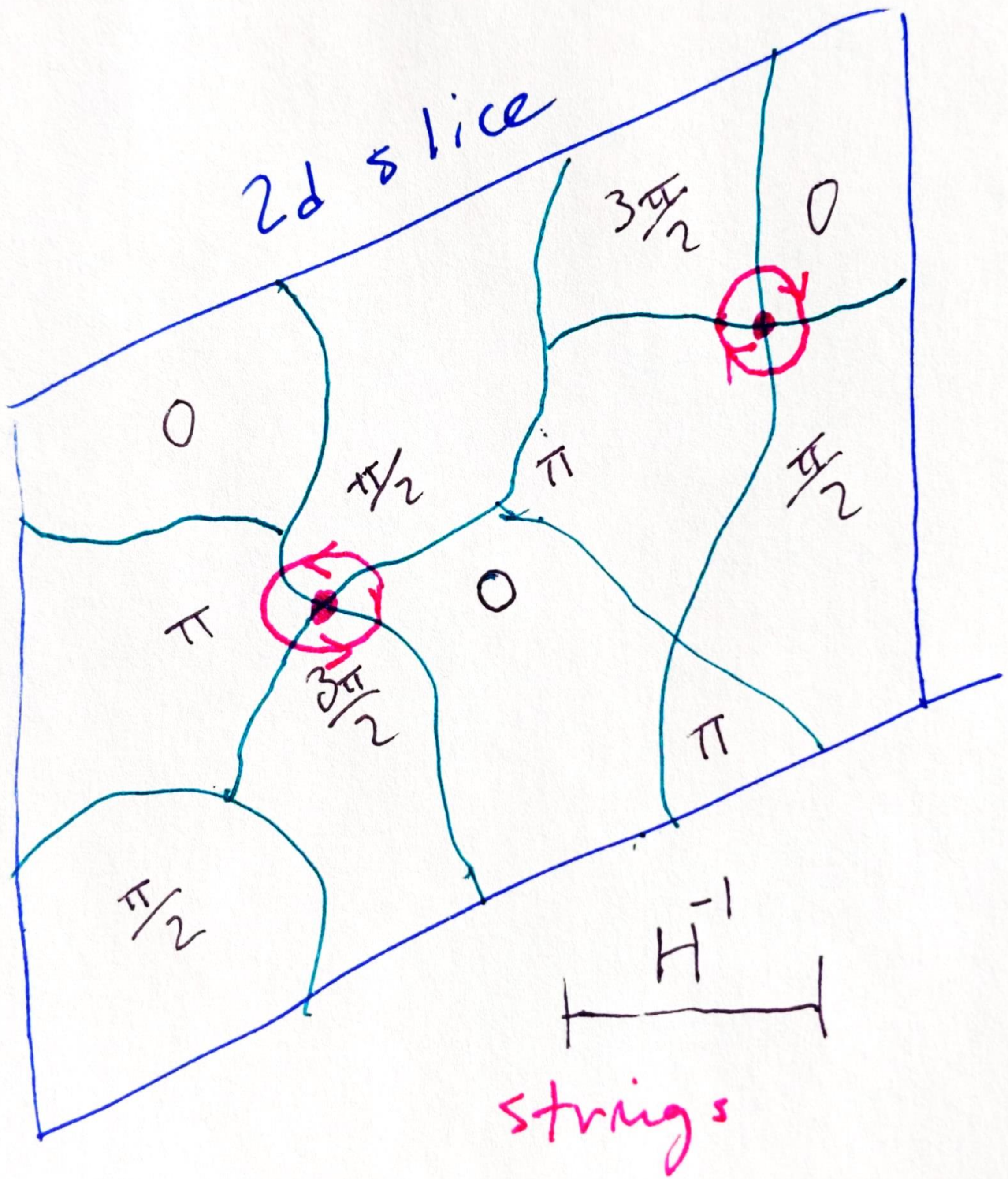
Enormous cross sections!

Here, the magnetic objects are cosmic strings in which fractional $B-L$ flux is confined



Cosmic strings are necessarily formed dynamically during the early universe phase transition

Dynamics very nontrivial, evolve toward fixed point with *tons* of cosmic strings



Topological defects + charged fermions

Callan-Rubakov effect in GUTs:

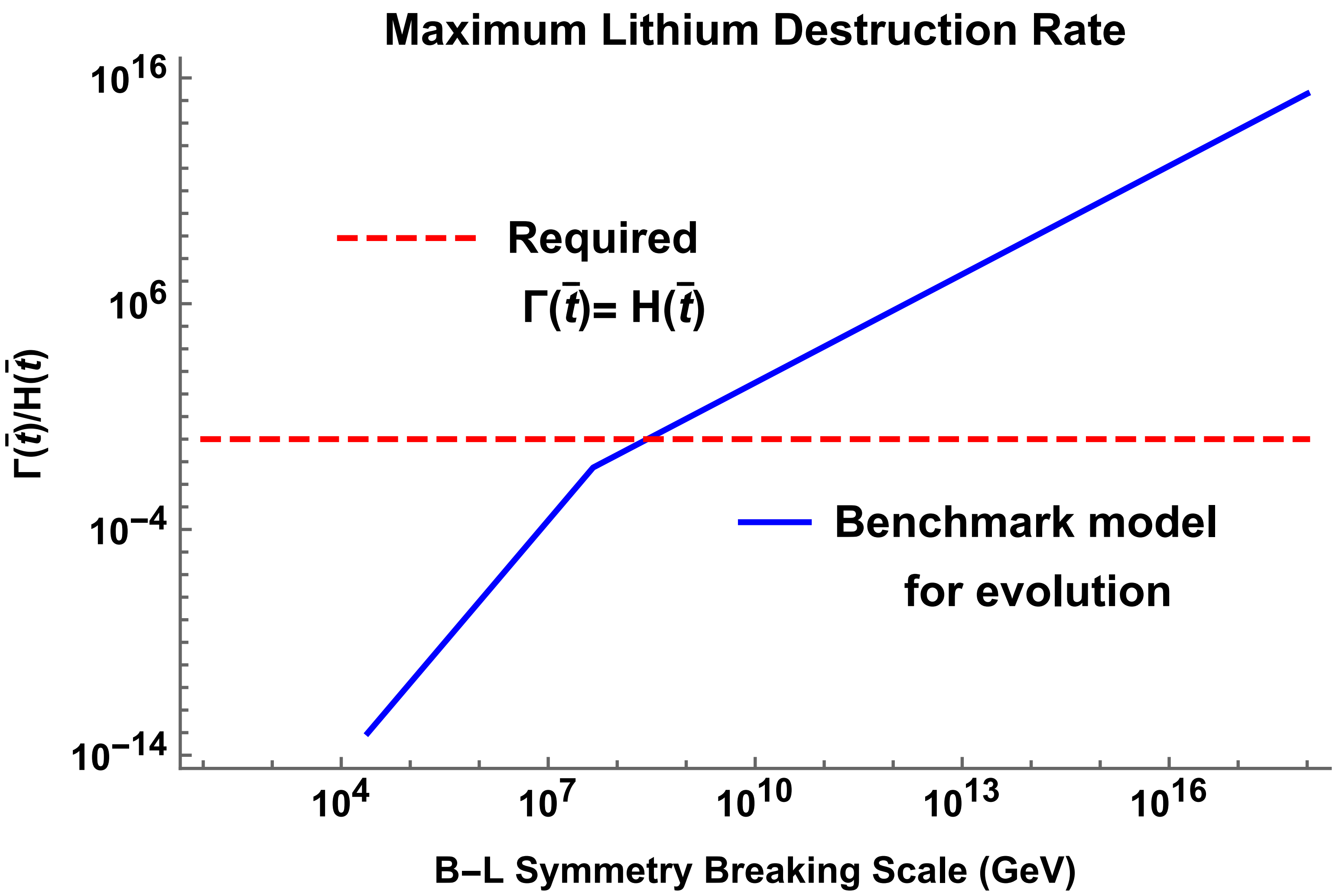
$$\sigma\left(\text{monopole} + p^+ \to \text{monopole} + e^+\right) \sim \Lambda_{QCD}^{-2}$$

Here, we preserve SM $\mathbb{Z}_6^{B+L}$, add correct leptoquarks:

$$\frac{\sigma}{\ell}\left(\text{string} + 3p^+ \to \text{string} + 3e^+\right) \sim \Lambda_{QCD}^{-1}$$

Can the rate be large enough to destroy O(1) of lithium?

TL;DR: Yes!



$$\bar{t}(v) = \max(5 \text{ minutes},\ t(T_f) \sim (G\mu)^{-2} t_{pl})$$

$$n(\bar{t}) \equiv (G\mu)^{1-p} \frac{1}{t_c^3} \left(\frac{t_c}{t_f}\right)^{3\nu_{fric}} \left(\frac{t_f}{\bar{t}}\right)^{3\nu} .$$

$$\sigma \equiv \Lambda_{\mathrm{QCD}}^{-2}$$

Conclusions

- Remarkably close to the SM

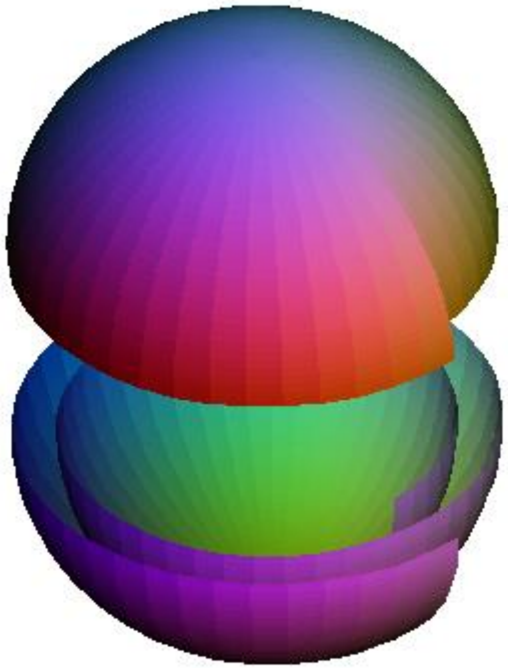
- Lots of well-motivated further study. Precise predictions require better understanding of many topics.

- Pb + string -> Au + string + 3 leptons! Alchemy!

't Hooft-Polyakov
Magnetic Monopoles

$SU(2) \to U(1)$ breaking

$$\Phi^a(x)\colon\ {}^{SU(2)}\!\big/_{U(1)} \simeq S^2 \to S^2_\infty$$

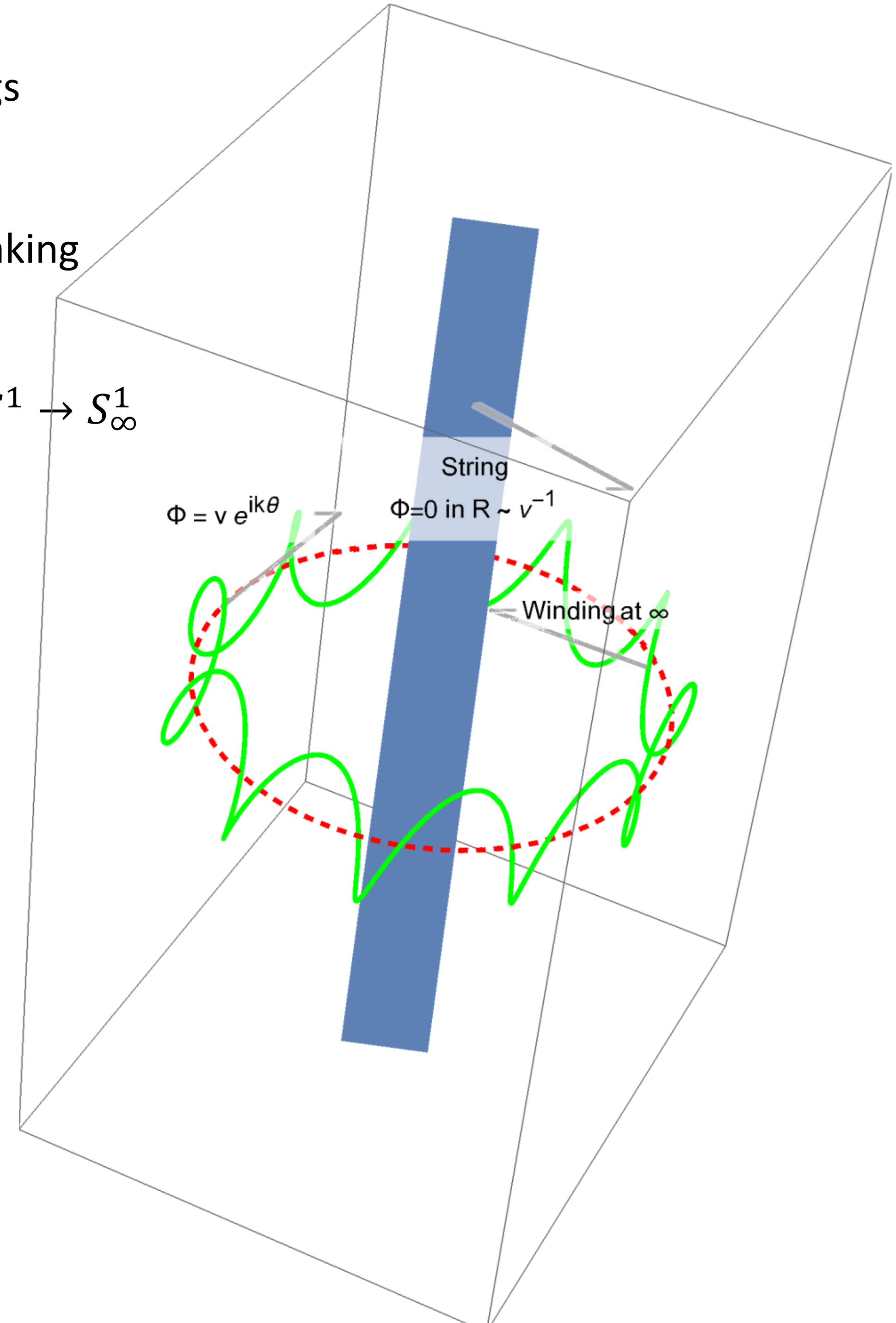


Graphic from Wikipedia by 刻意

Cosmic Strings

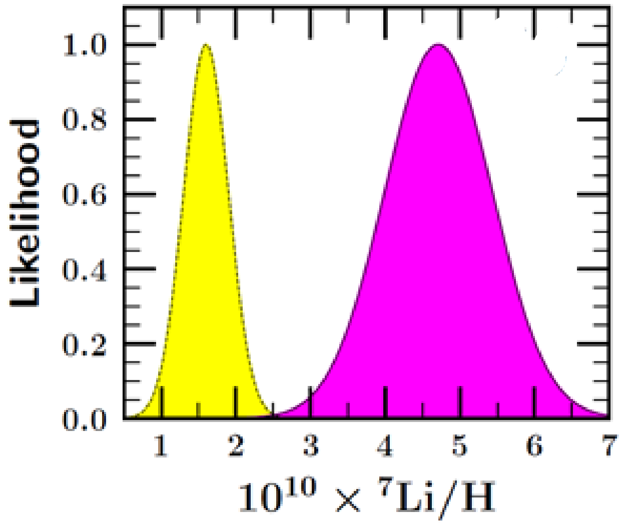
$U(1) \to \mathbb{Z}_6$ breaking

$$\Phi(x)\colon\ {}^{U(1)}\!\big/_{\mathbb{Z}_6} \simeq S^1 \to S^1_\infty$$



The Lithium Problem

	$(^7Li/H)$
Observation	$(1.6 \pm 0.3) \times 10^{-10}$
Theory	$(4.7 \pm 0.7) \times 10^{-10}$



$^7Li = 3p + 4n$

Systematics?

ΛCDM uncertainties? X – not since WMAP at least

Standard model uncertainties? X – long since good enough precision on e.g. neutron lifetime

Nuclear reaction uncertainties? X – by now all relevant rates measured, nuclear theory agrees well

Stellar dynamics uncertainties? ? –Difficult to imagine what subtle effect might be missing, but astrophysicists have been thinking about it for 40 years. No accepted answer yet.

It's at least worth thinking about new physics solutions!

What symmetry is responsible for SM proton stability?

Charged fermions with global chiral U(1) can induce anomaly

$$\psi_i \to \psi_i e^{iq_i\lambda} \quad \Rightarrow \quad \delta S = \lambda \mathcal{A} \int \frac{F\tilde{F}}{16\pi^2}$$

	Q	$\bar{u}$	$\bar{d}$	L	$\bar{e}$
$SU(3)_C$	3	$\bar{3}$	$\bar{3}$	$-$	$-$
$SU(2)_L$	2	$-$	$-$	2	$-$
$U(1)_Y$	$+1$	-4	$+2$	-3	$+6$
$U(1)_B$	$+1$	-1	-1	$-$	$-$
$U(1)_L$	$-$	$-$	$-$	$+1$	-1

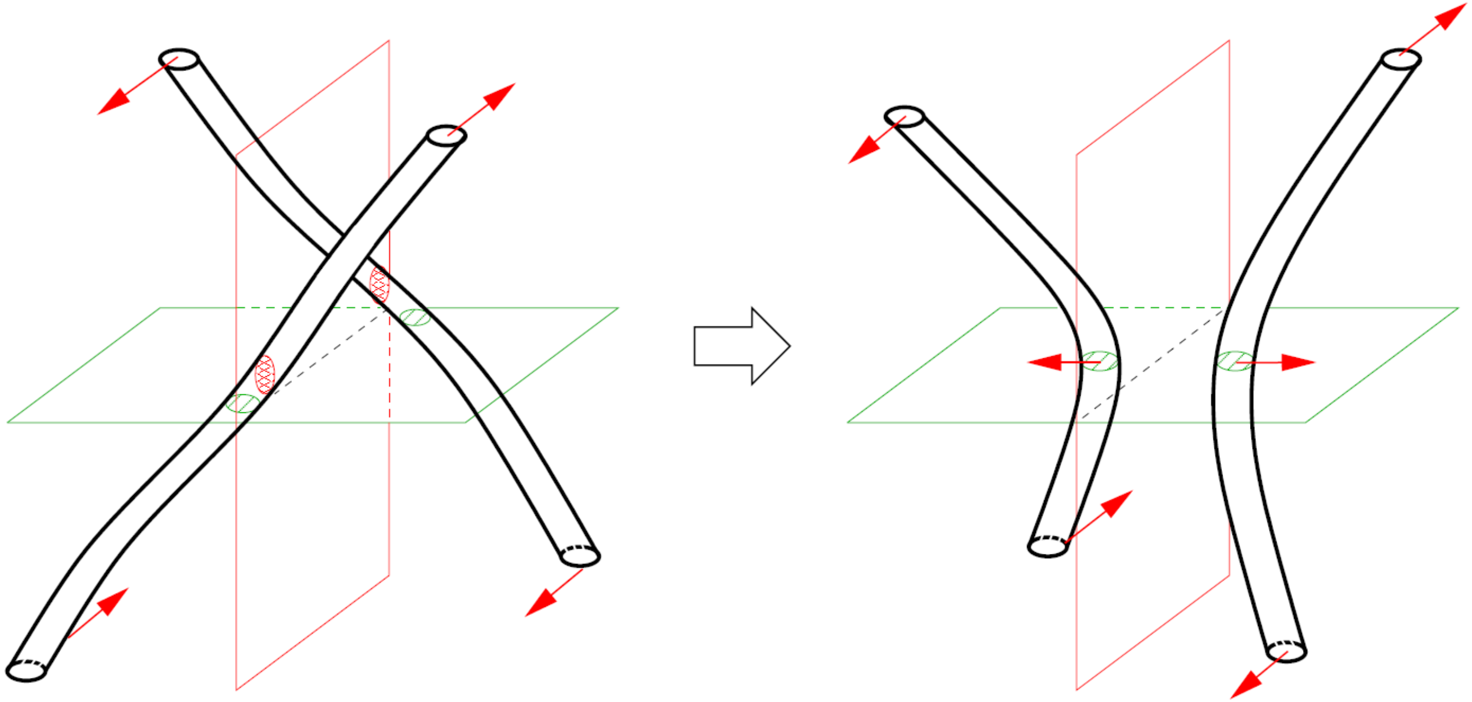
	$U(1)_B$	$U(1)_L$
$SU(2)_L^2$	N_c	1
$U(1)_Y^2$	$-18N_c$	-18

Continuous anomaly-free global symmetry is baryon minus lepton number

N_g generations of SM fermions → $\mathcal{A} = 0$ (mod N_g)

$$U(1)^{B-N_cL} \times \mathbb{Z}_{N_g}^{L}$$

String intercommutation

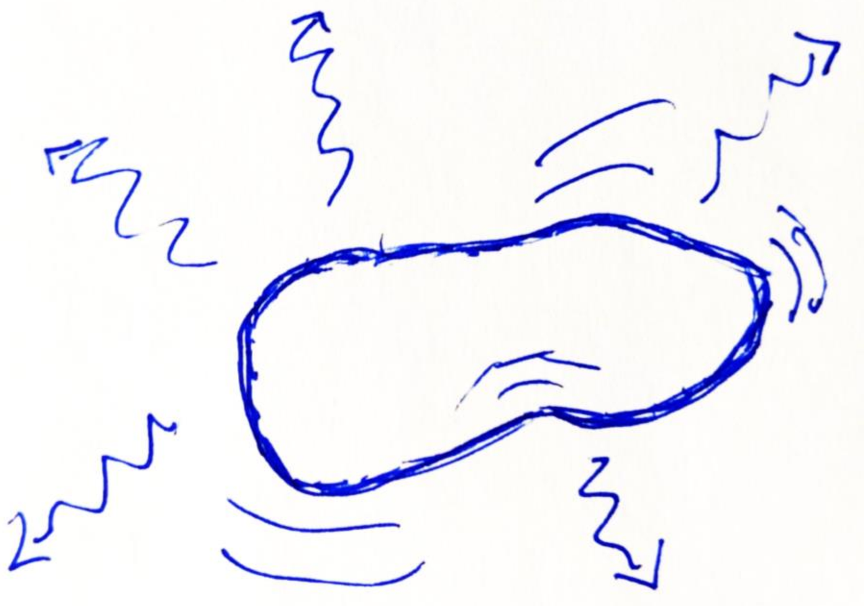


Strings must exchange partners!

Ruback ‘88; Shellard ‘88; Ruback & Shellard ’88; Matzner ‘88; Samols ’92; Moriarty, Myers, Rebbi ’90; Myers, Rebbi Strilka ’92; Hashimoto & Tong ‘05; Hanany & Hashimoto ‘05

Figure from Tong (2005)

Ensmallening



$$-\frac{dM}{dt} \sim G\left(\frac{d^3Q}{dt^3}\right)^2 \sim GM^2\ell^4\omega^6 \sim G\mu^2$$

$$\frac{\text{lifetime}}{\text{Hubble time}} \sim (G\mu)^{-1}\frac{\text{length}}{\text{Hubble length}}$$

Vilenkin '81

Lithium abundance at the formation of the Galaxy

M. Spite & F. Spite 1982

Observatoire de Paris-Meudon, Section d'Astrophysique, 92190 Meudon, France

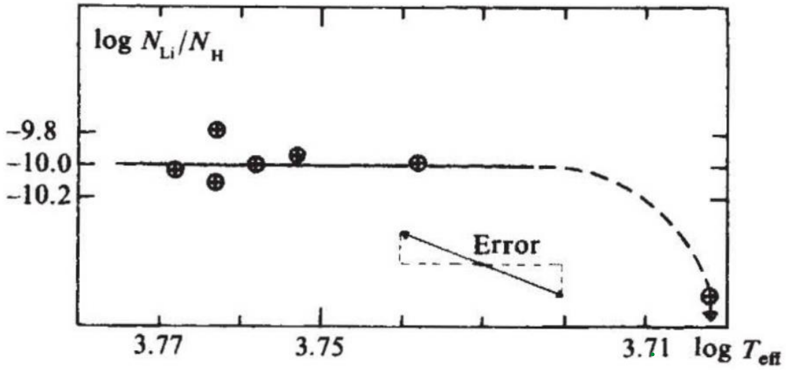
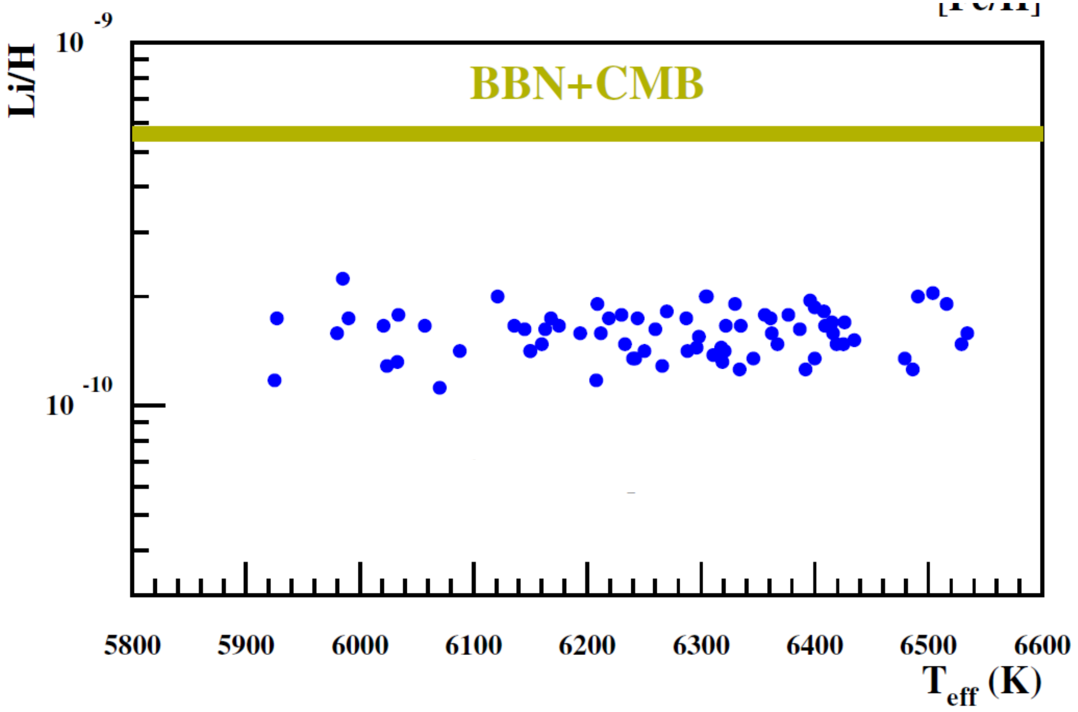


Fig. 1 Lithium abundance plotted against effective temperature (logarithmic scale) for very old metal-poor stars. The lithium abundance is remarkably constant except for the coolest star: here, deep convective movements carry the lithium into very hot layers where it is completely destroyed.

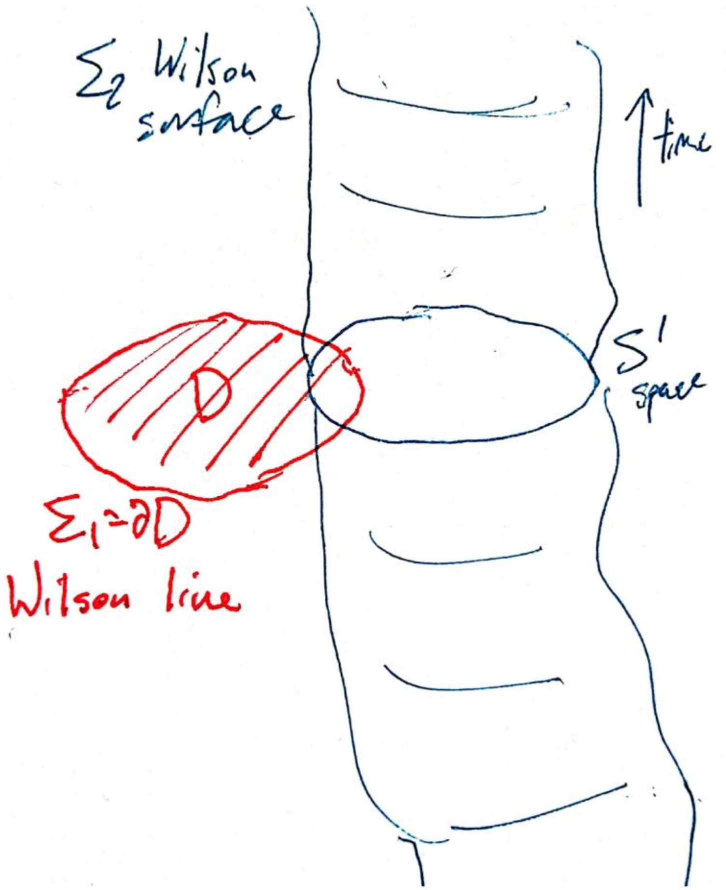


Pitrou et al. (2018)

Dual BF TQFT

$$v d\phi \sim \star dB$$

$$\mathcal{L} = eN A^{\mu} \partial^{\nu} B^{\rho\sigma} \epsilon_{\mu\nu\rho\sigma}$$
$$= -N B \wedge F,$$



$$\left\langle e^{in_A \int_{\Sigma_1} A} \; e^{in_B \int_{\Sigma_2} B} \right\rangle = \exp\left[2\pi i \frac{n_A n_B}{N} \mathrm{link}(\Sigma_1, \Sigma_2)\right]$$