Discrete Symmetries, Proton Stability, and Cosmological Lithium

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Brookhaven National Lab HET Seminar

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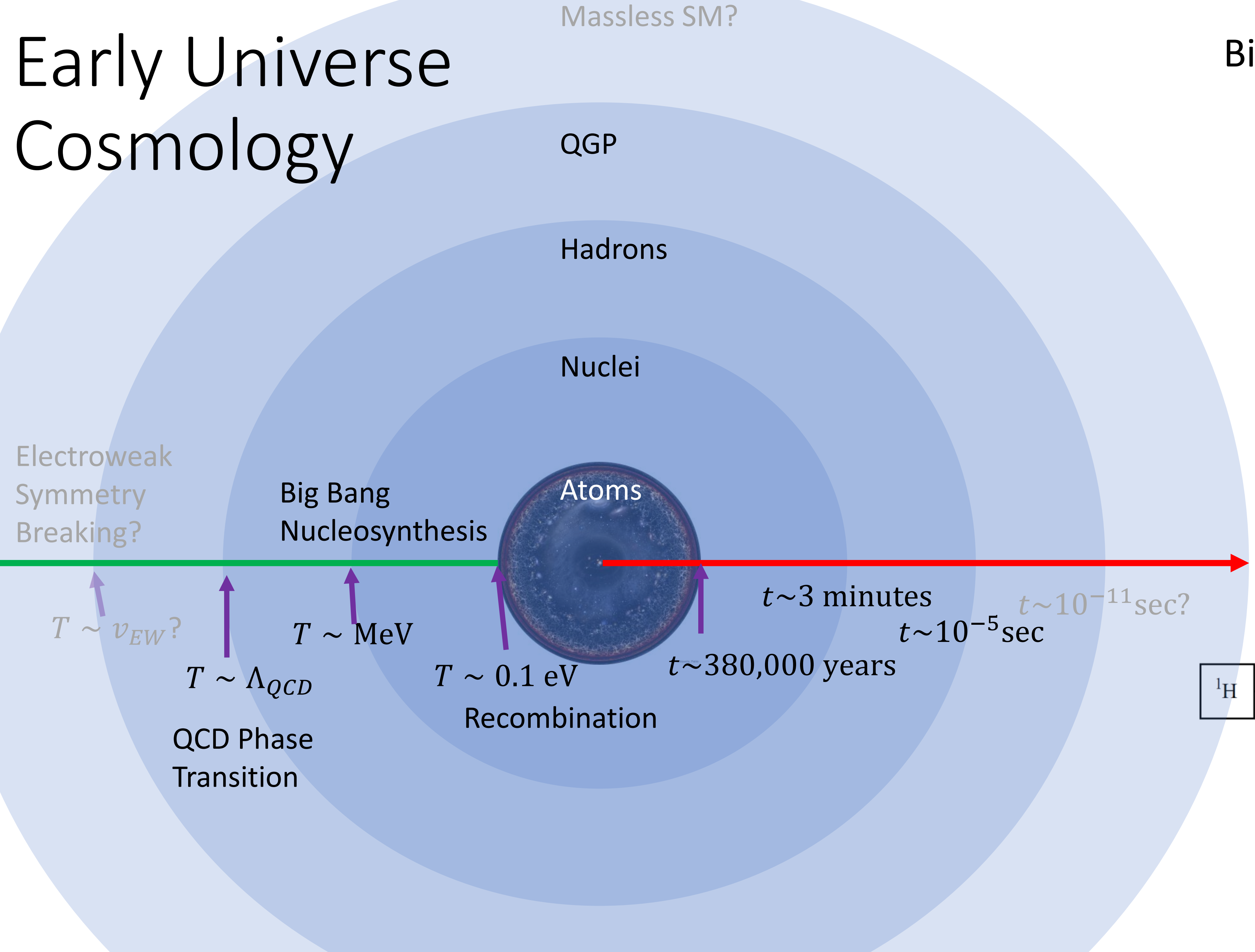
Omitted details explained in
2204.01741
2204.01750

Early Universe Cosmology



Big Bang Nucleosynthesis

Starting with a hot proton-neutron soup, which elements get created before all the neutrons decay?

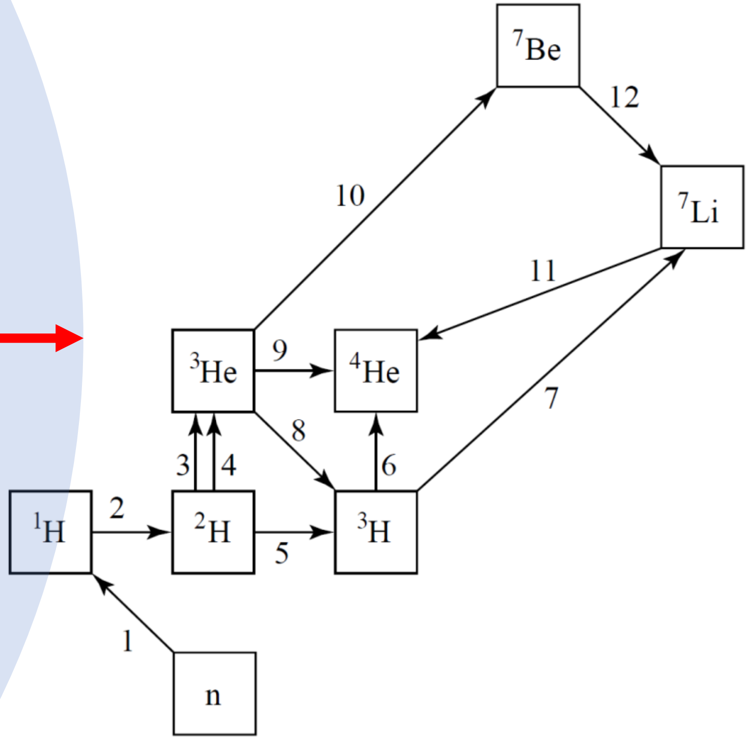


Figure from Carroll & Ostlie

Big-Bang Nucleosynthesis after Planck

Brian D. Fields,[a] **Keith A. Olive,**[b] **Tsung-Han Yeh**[c]
and Charles Young[d] (2020)

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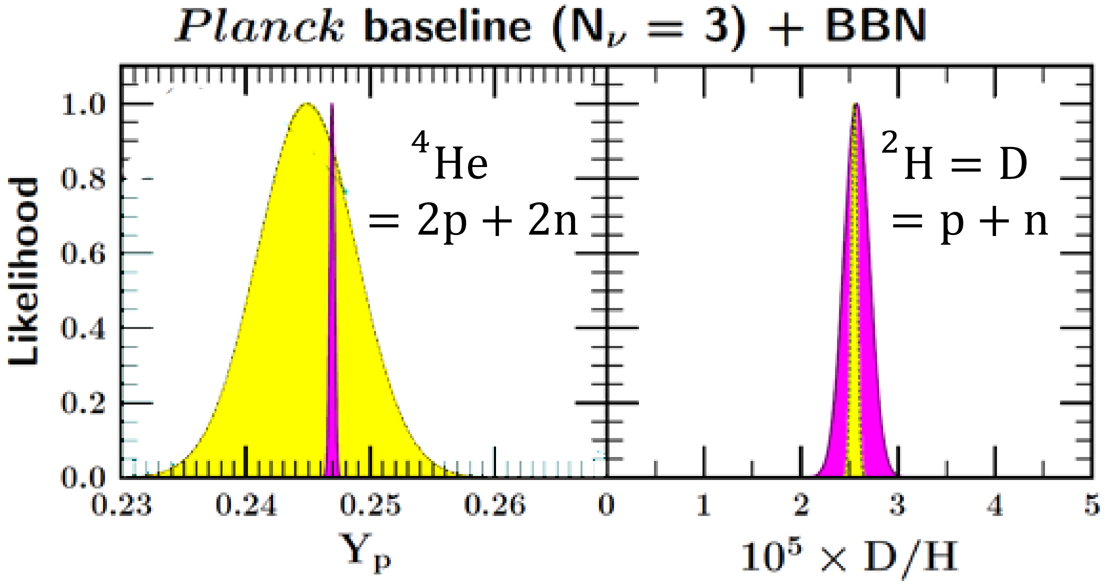
Theory

Observed Abundances



Big-Bang Nucleosynthesis after Planck

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Theory

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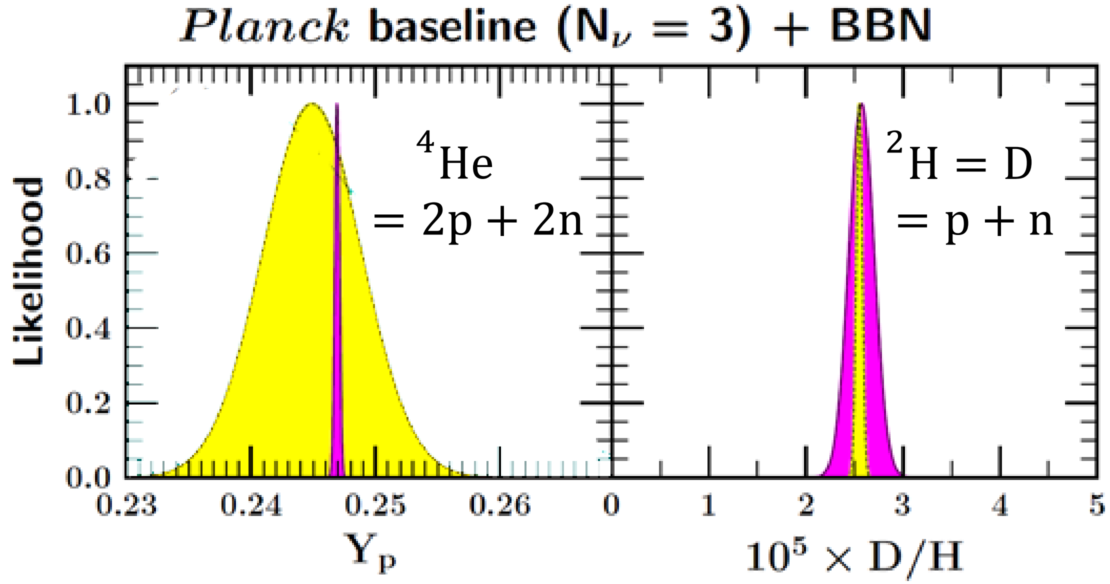
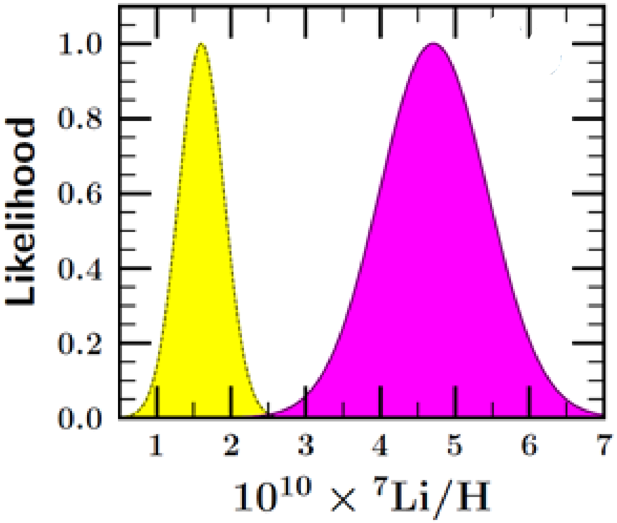


The Lithium Problem



^{7}Li
= 3p + 4n

Way more predicted than observed!

For new physics effects, the big question is

What in the world could uniquely pick out lithium?

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What in the world could uniquely pick out lithium?

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 $U(1)_{B-L} \to \mathbb{Z}_6^{B-L}$

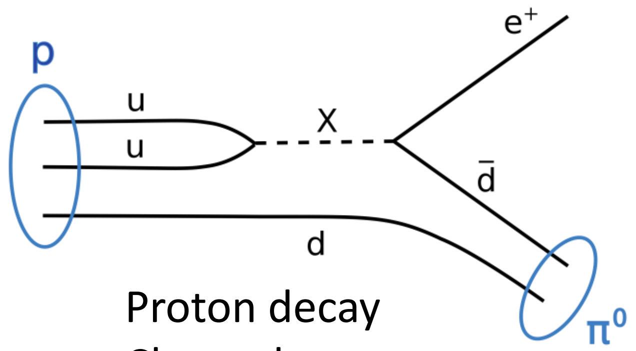
… some neat field theory …

g) Cosmic strings destroy lithium nuclei

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

Is the proton stable?

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



Proton decay
Channel e.g.

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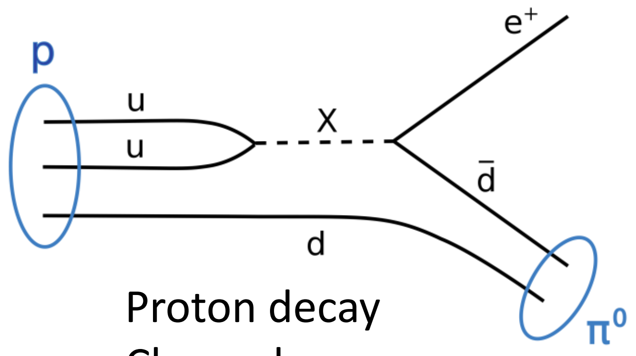

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Why? An exact discrete global symmetry of the SM

Breaking by ABJ anomalies
with $SU(2)_L \times U(1)_Y$

Classical $U(1)_B \times U(1)_L \implies$ Quantum $U(1)_{B-L} \times \mathbb{Z}^L_{N_g} \supset \mathbb{Z}^{B+L}_{2N_g}$

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

What is the IR gauge symmetry of the SM fermions?

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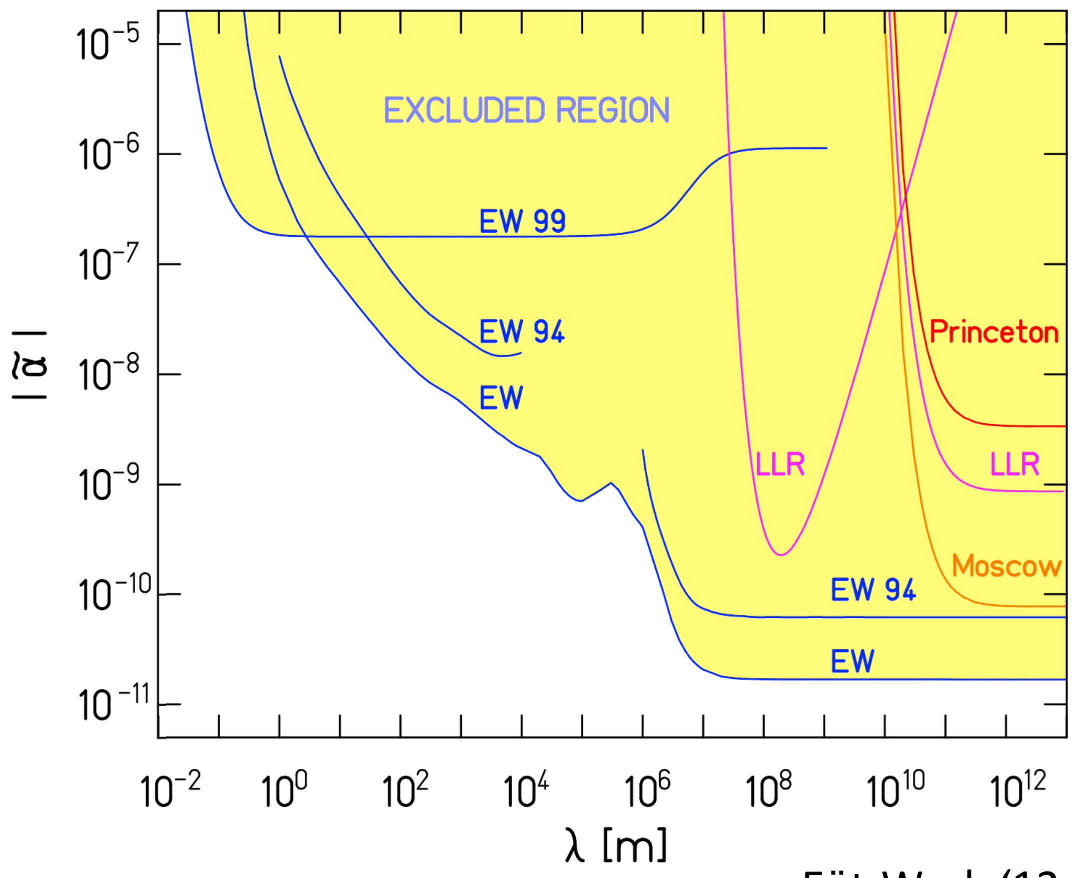
One more available symmetry: $U(1)_{B-L}$ could be gauged without any new matter charged under SM gauge group

But strong fifth force constraints imply if $U(1)_{B-L}$ is gauged it must be broken



Eöt-Wash '12

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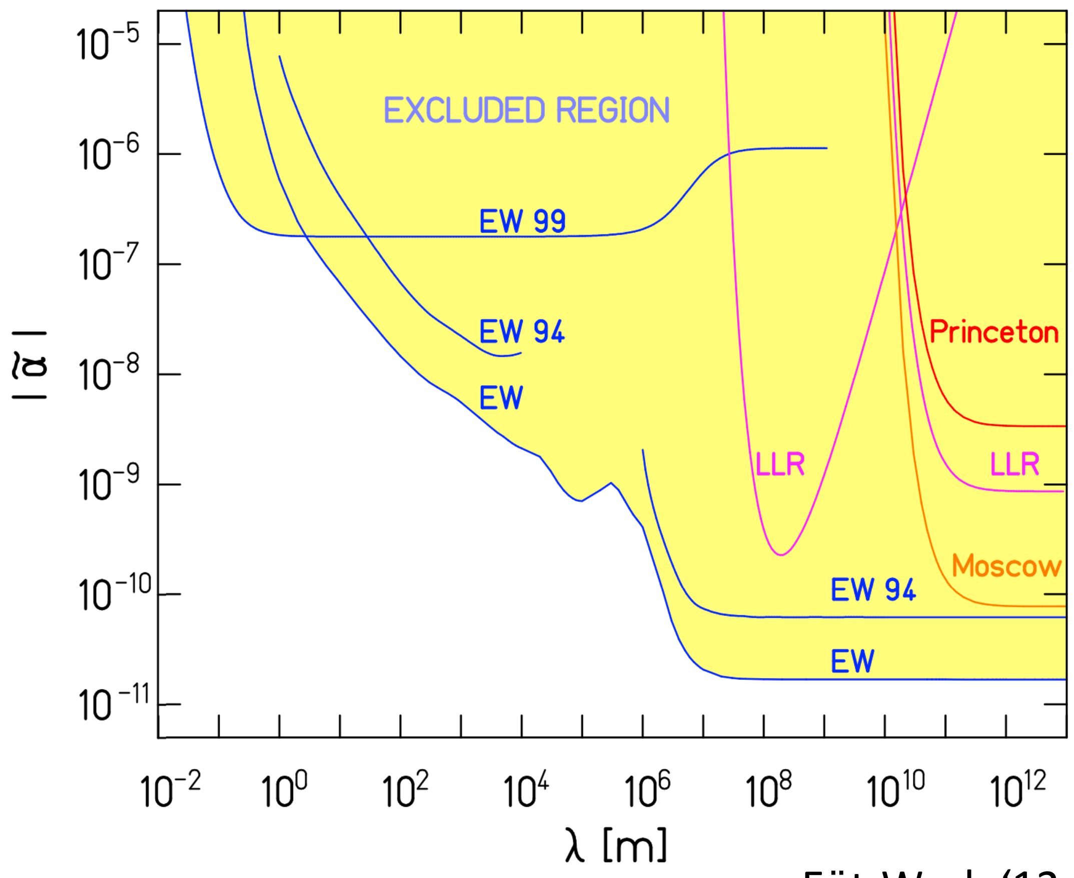
So are we done? Not quite---one last option:

An unbroken *discrete* gauged subgroup $\mathbb{Z}_N^{B-L}$ doesn't come along with massless bosons



Eöt-Wash '12

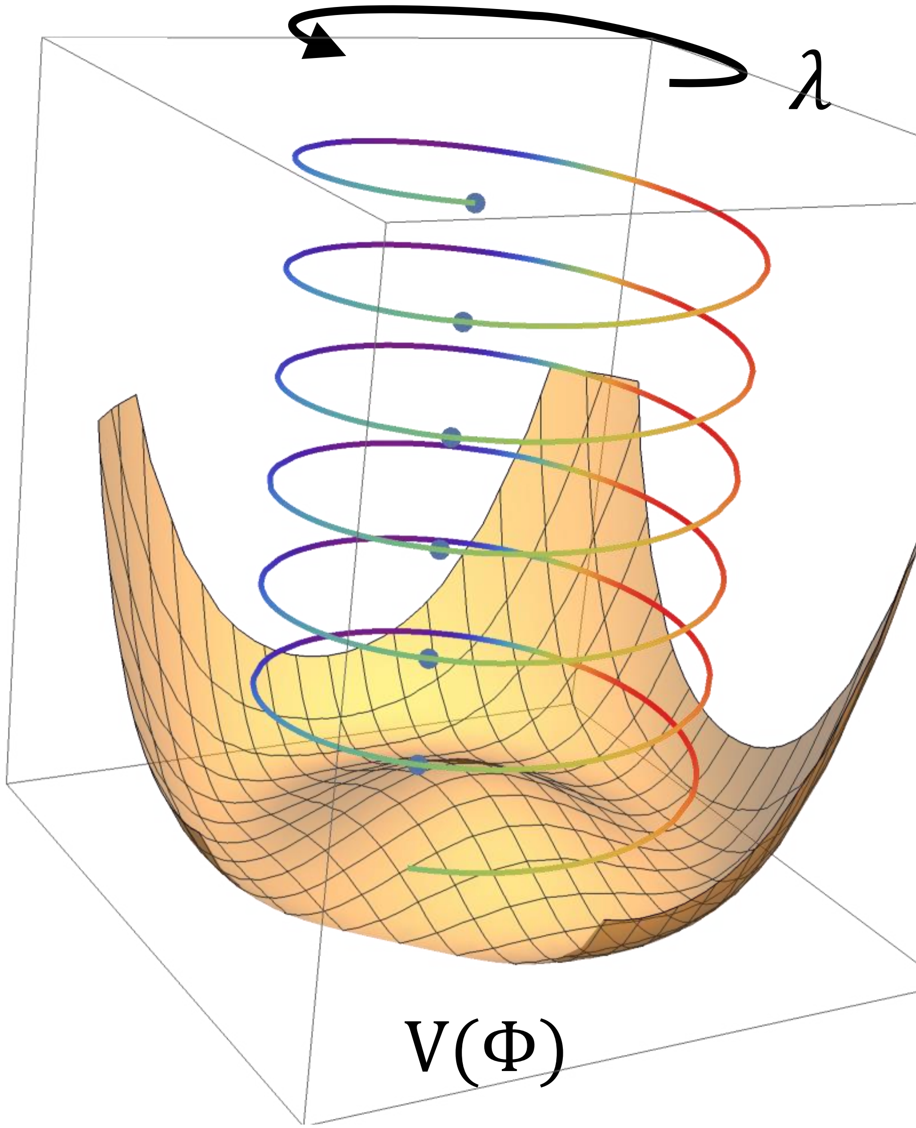
What is the IR gauge symmetry of the SM Fermions?

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

$$gA_\mu \to gA_\mu + \partial_\mu \lambda(x) \;\Rightarrow\; \Phi \to \Phi e^{i2N_g \lambda(x)}$$

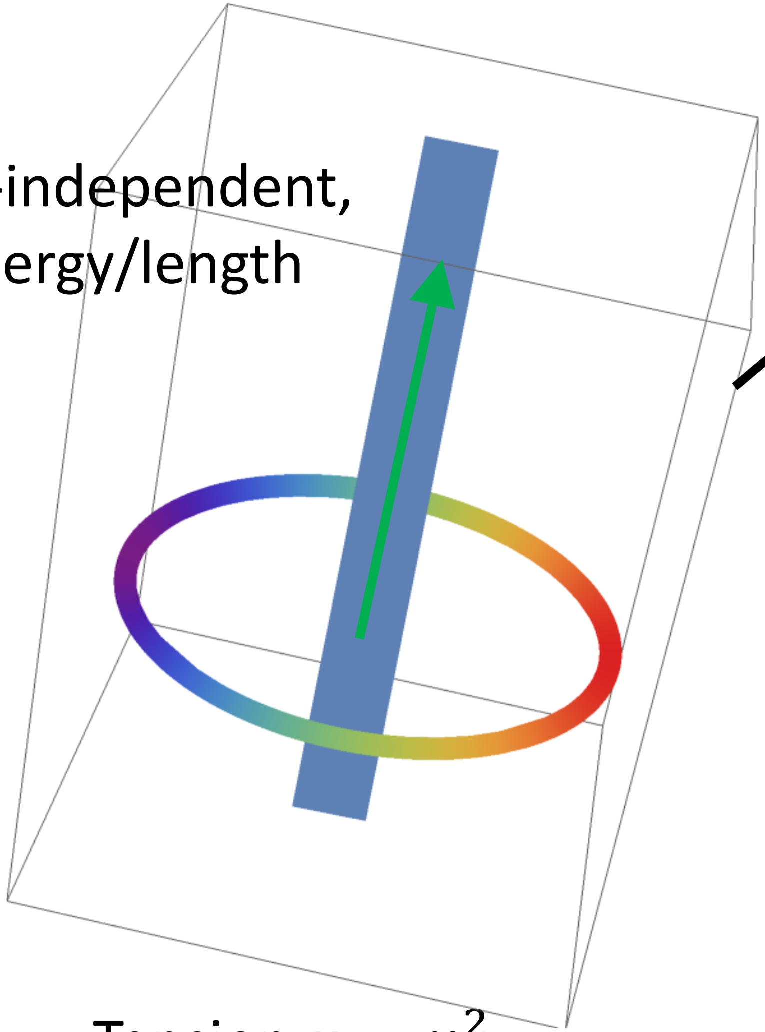
$$\text{invariant for } \lambda(x) = \frac{2\pi n}{2N_g}$$

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

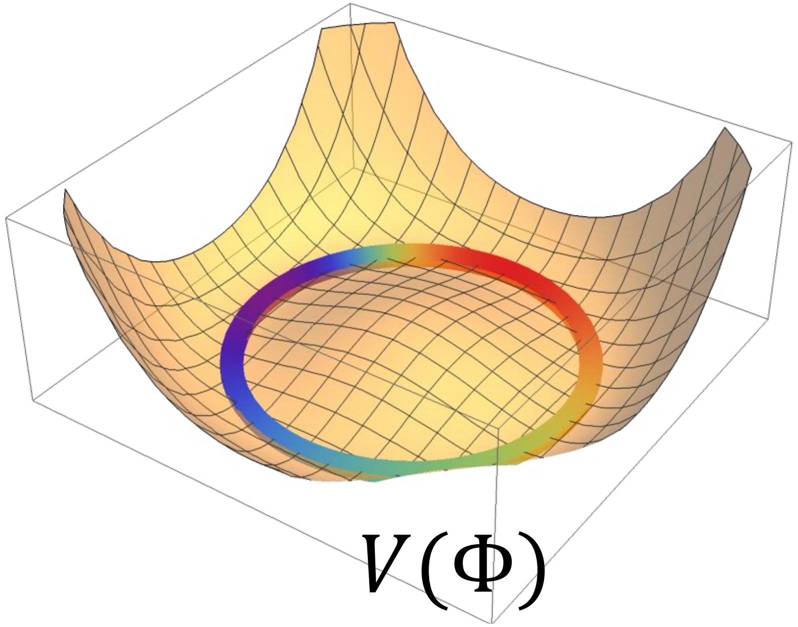


Abelian Higgs Solutions – Cosmic Strings

Static, z-independent,
finite energy/length



$$\Phi(r,\theta) \rightarrow v e^{ik\theta}$$



$V(\Phi)$

Tension $\mu \sim v^2$

$R \sim v^{-1}$

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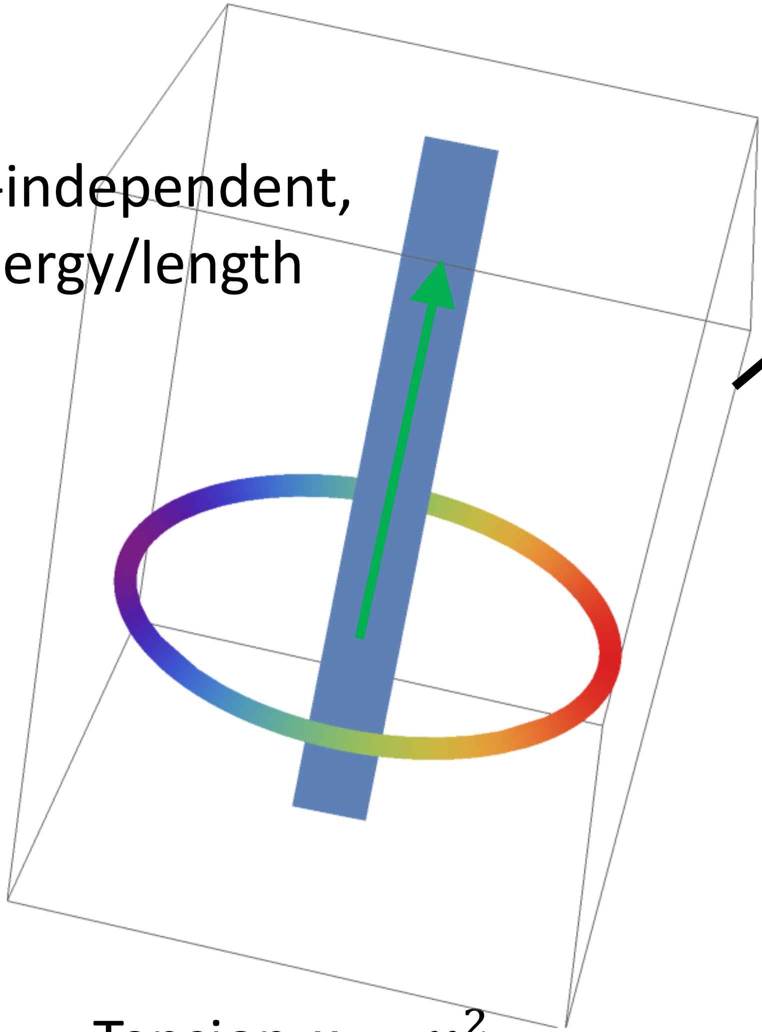

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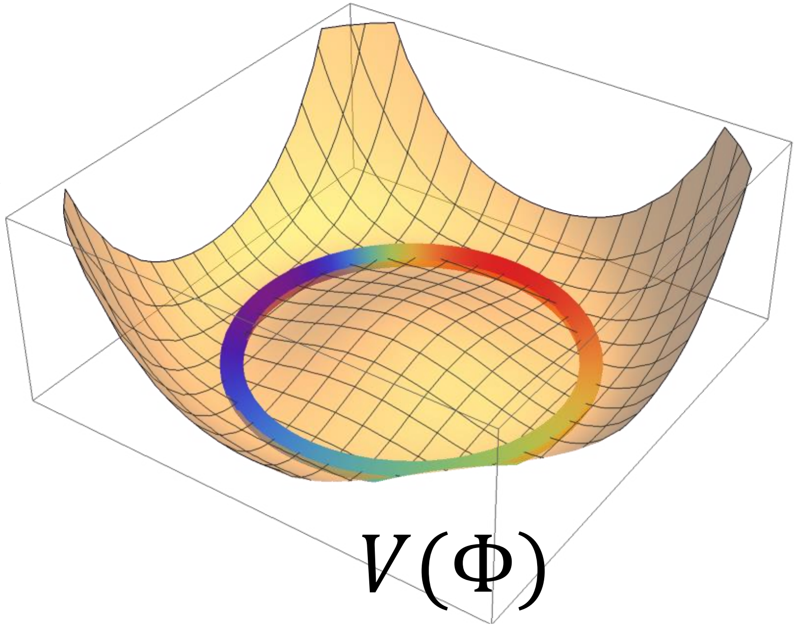


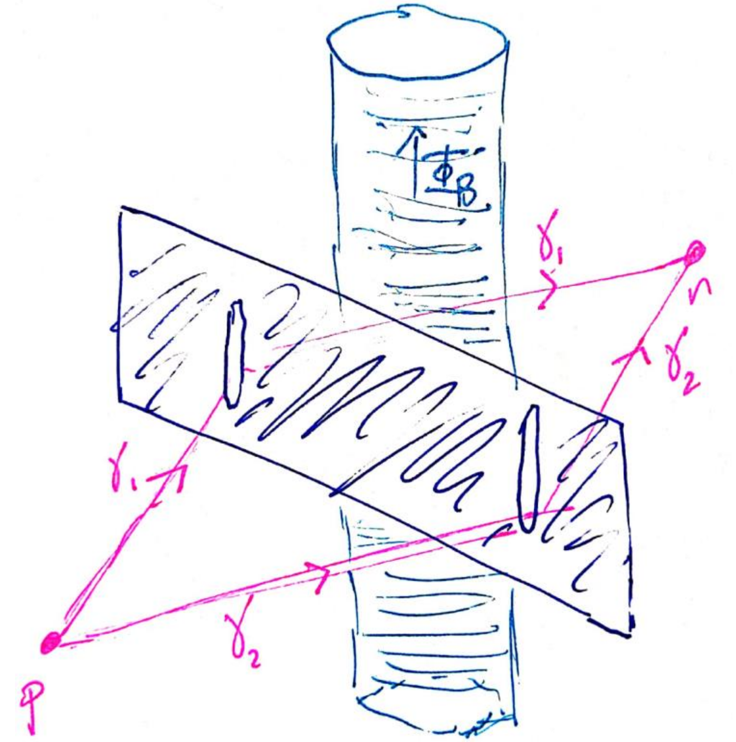
$$\vec{A}(r,\theta) \to \frac{k}{eN}\frac{1}{r}\hat{\theta}$$

Fractional magnetic flux!

$$\Phi_B = \frac{2\pi}{e}\frac{k}{N}$$

Discrete Aharonov-Bohm

$$\psi_r \propto \left(e^{iq\int_{\gamma_1} A} + e^{iq\int_{\gamma_2} A} \right) \psi_p$$



Local cosmic strings are idealized solenoids!

Aharonov & Bohm ’59; Alford & Wilczek ’88; Alford, March-Russell, Wilczek ‘89

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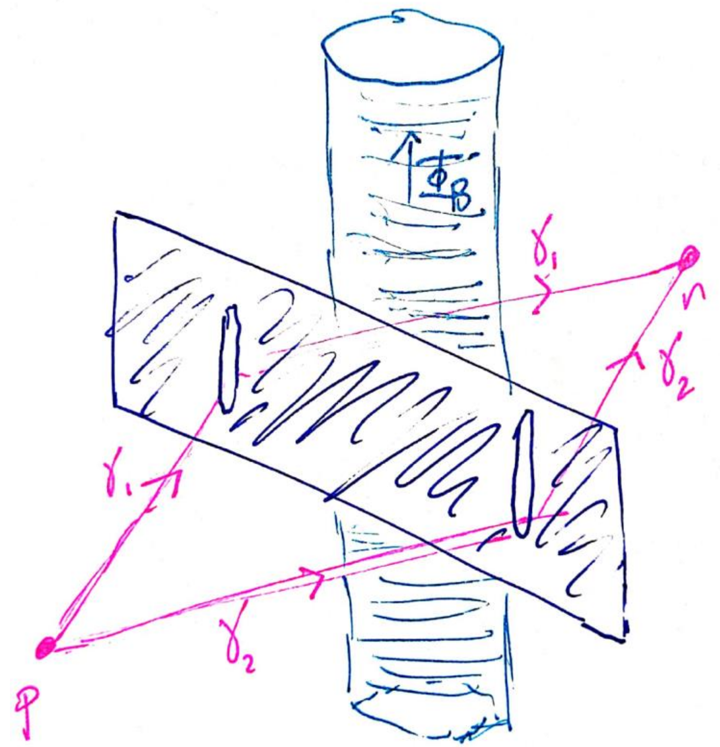


Local cosmic strings are idealized solenoids!

Cross-section per unit length for elastic AB scattering

$$\frac{d\sigma}{d\theta} = \frac{\sin^2\left(\pi \frac{kq}{N}\right)}{2\pi p \sin^2(\theta/2)}$$

Aharonov & Bohm ’59; Alford & Wilczek ’88; Alford, March-Russell, Wilczek ‘89

Cosmic Strings

Unbroken phase

$T_c \sim (G\mu)^{1/2} M_{pl}$

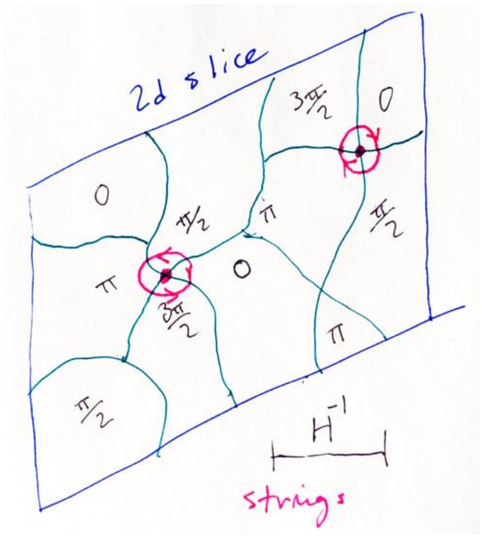
Strings frozen by Aharonov-Bohm friction

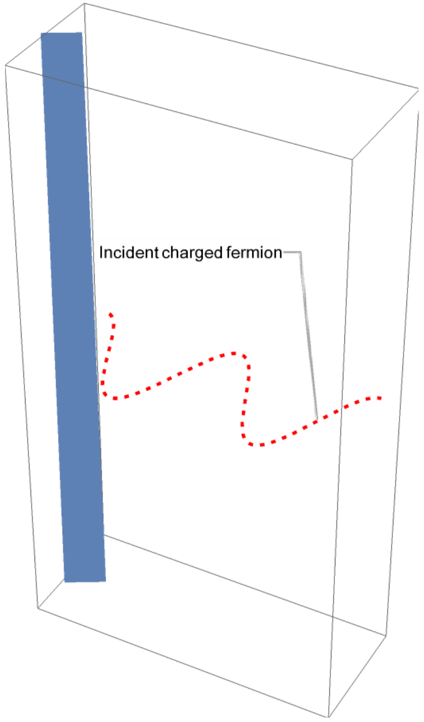
$T_f \ll (G\mu)^1 M_{pl}$

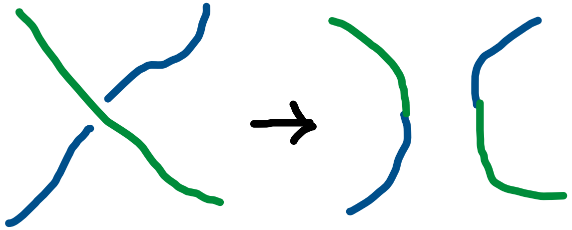
Strings whip around and cut each other up ("intercommute")

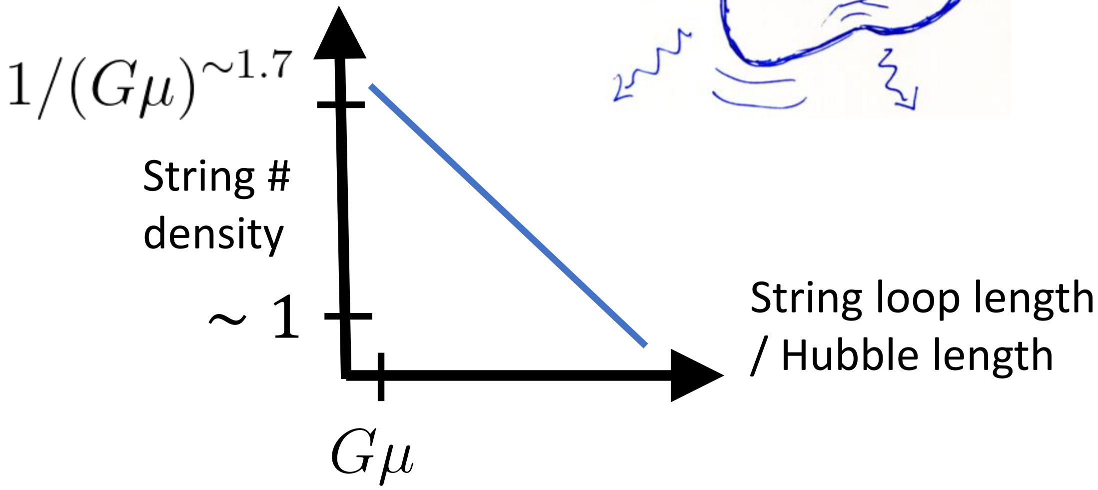
Loops shrink

Scaling solution



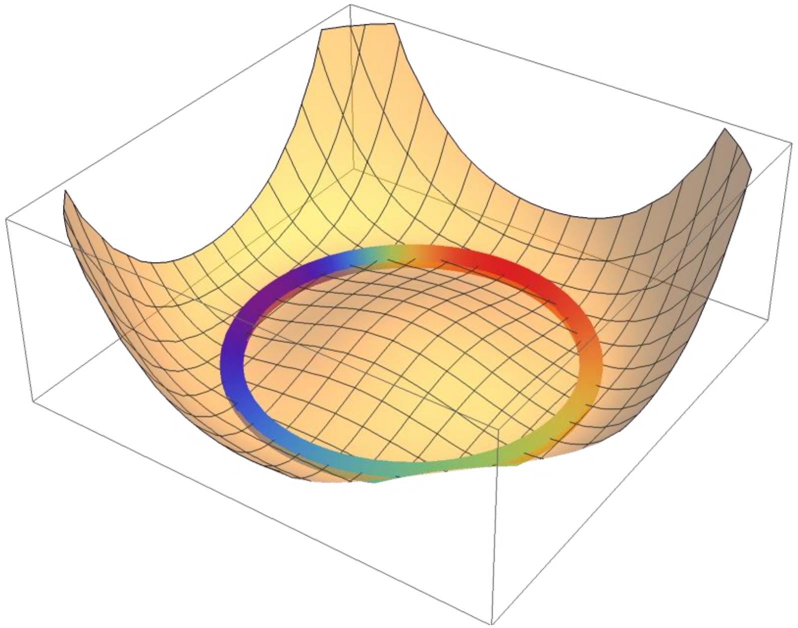


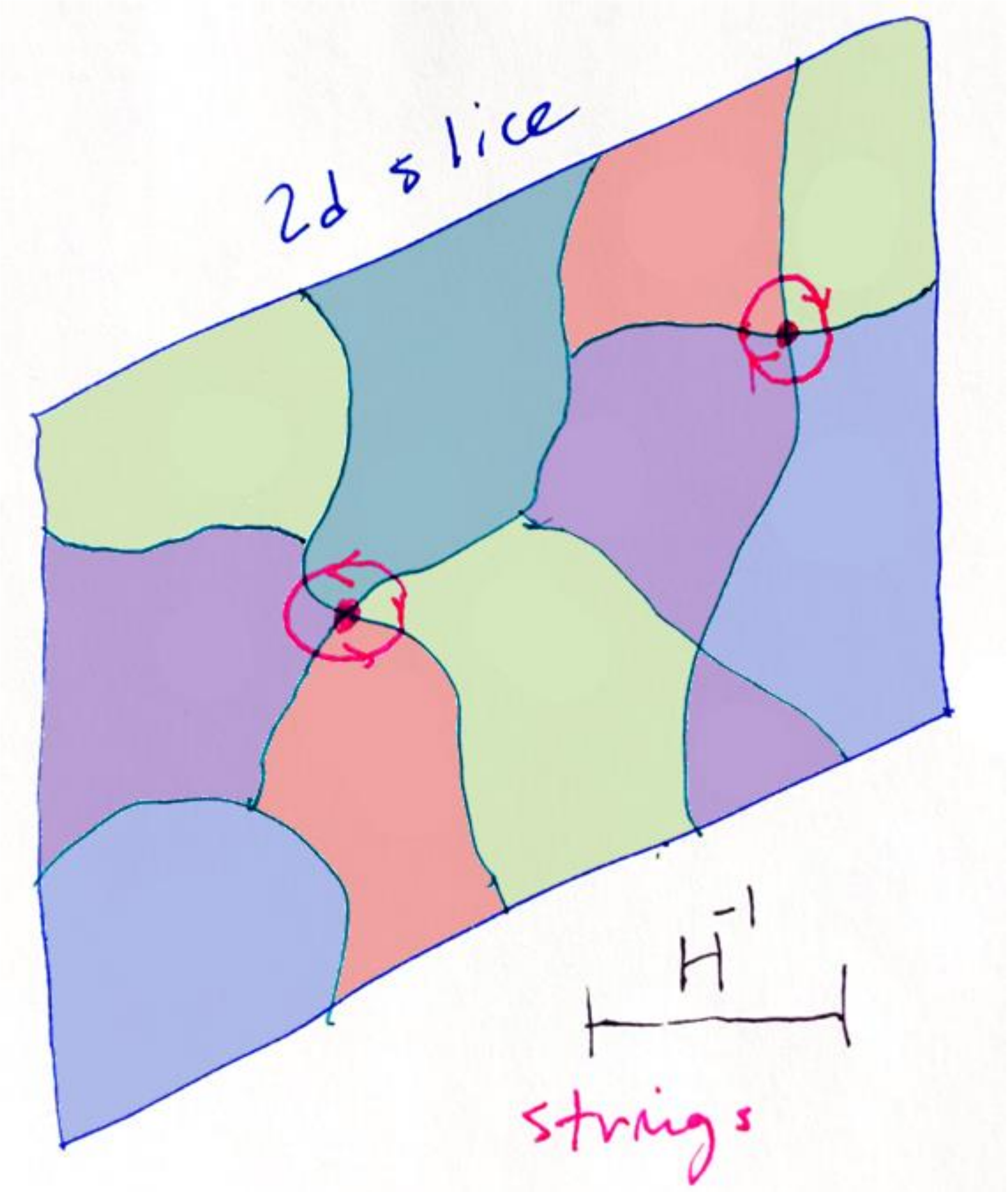




Defect Formation

In cosmology, thermal phase transitions occur dynamically!

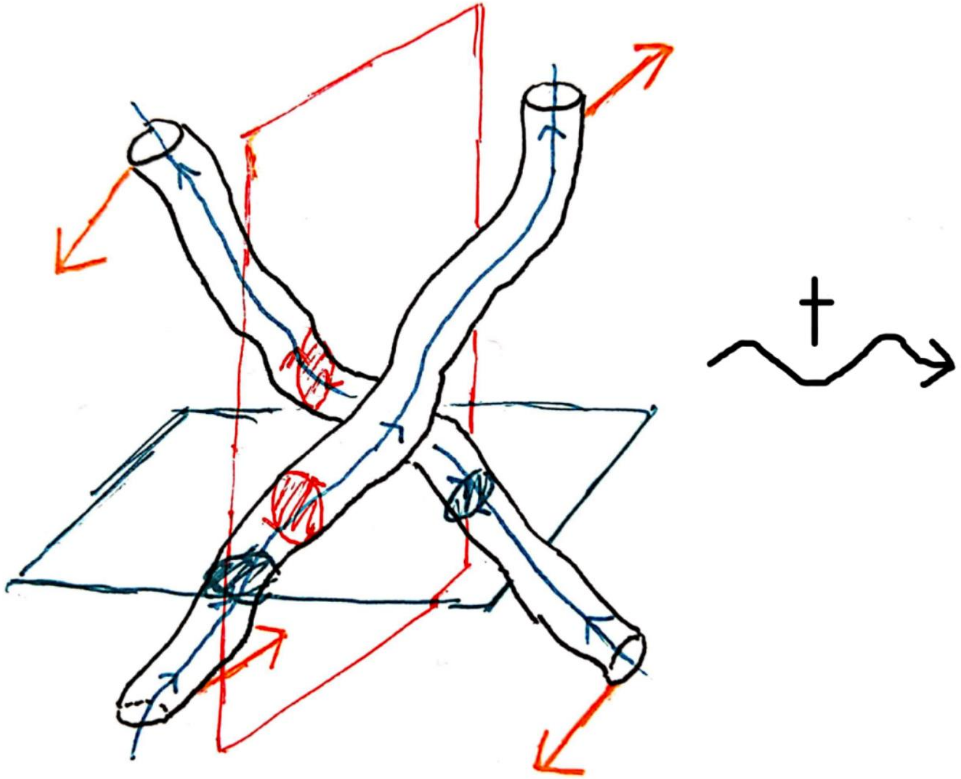




$$\rho_{string} \sim \frac{\mu H^{-1}}{(H^{-1})^3} = (G\mu)\rho_{tot}$$

Kibble '76, '80; Vachaspati & Vilenkin '84

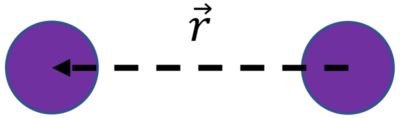
String interactions?



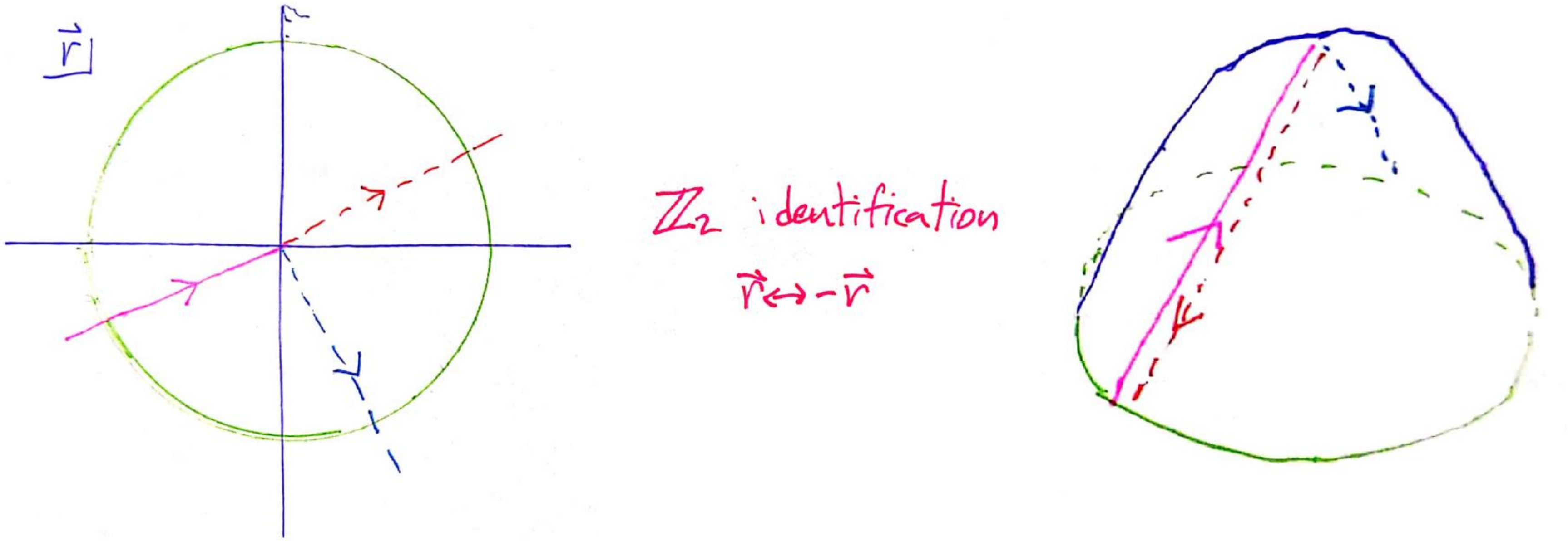
????

Low-energy soliton collisions

Warm-up: scattering of identical vortices in 2+1d Abelian Higgs

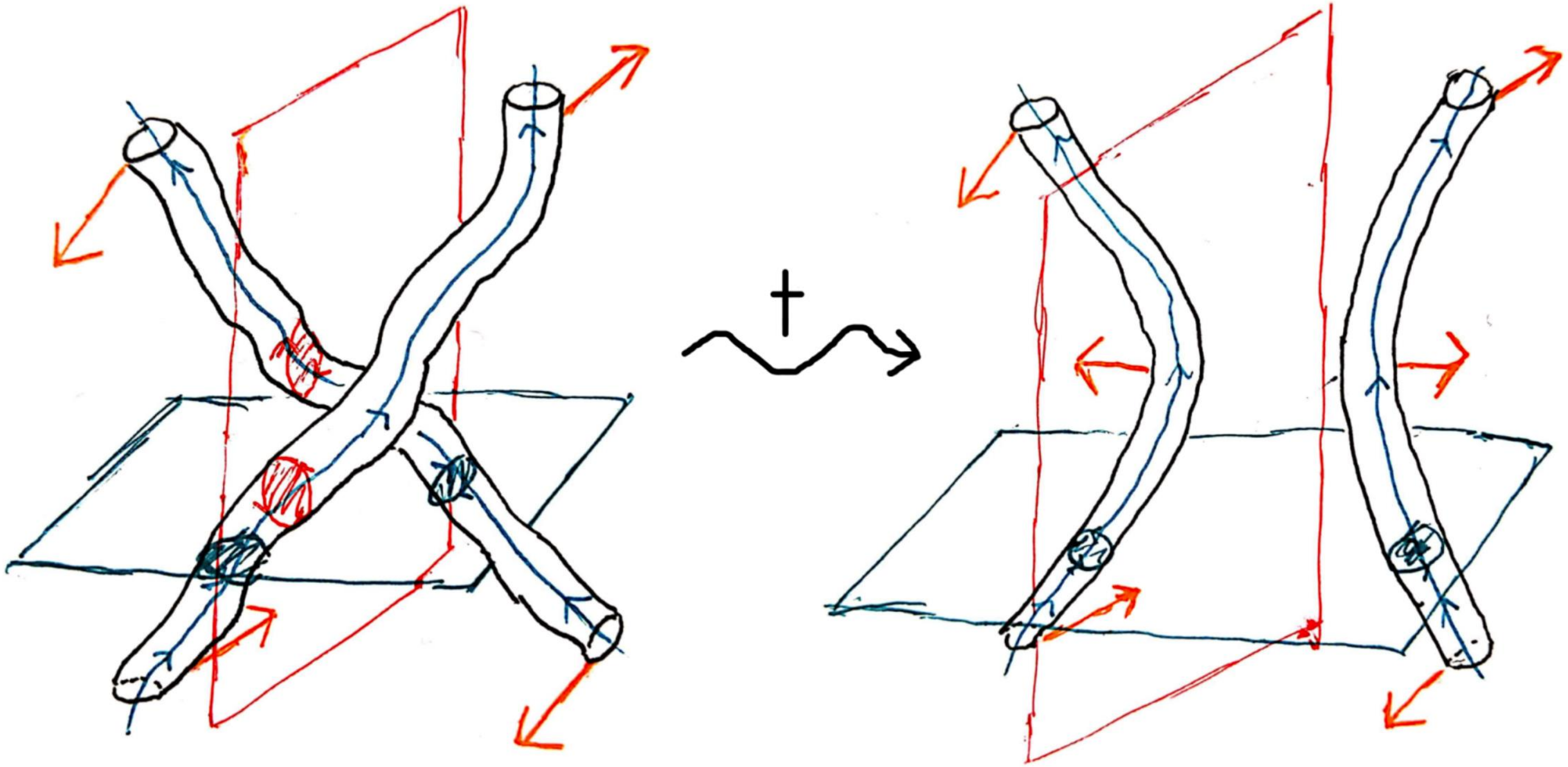


Supersymmetric limit -> geodesic motion in the n=2 moduli space!



Taubes '80; Manton '82; Atiyah & Hitchin '85; Gibbons & Manton '86, Ruback '88, Stuart '94

String intercommutation

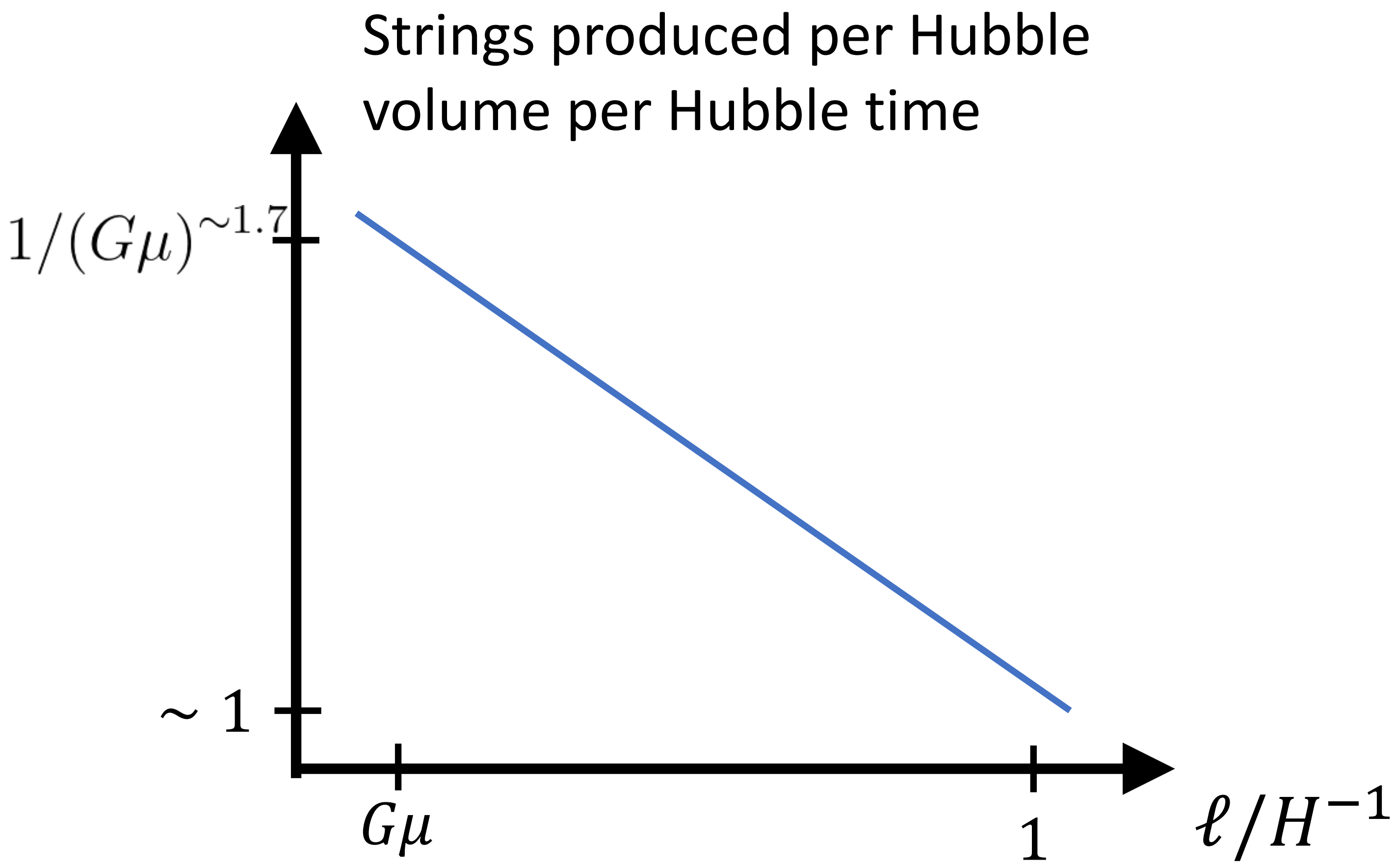


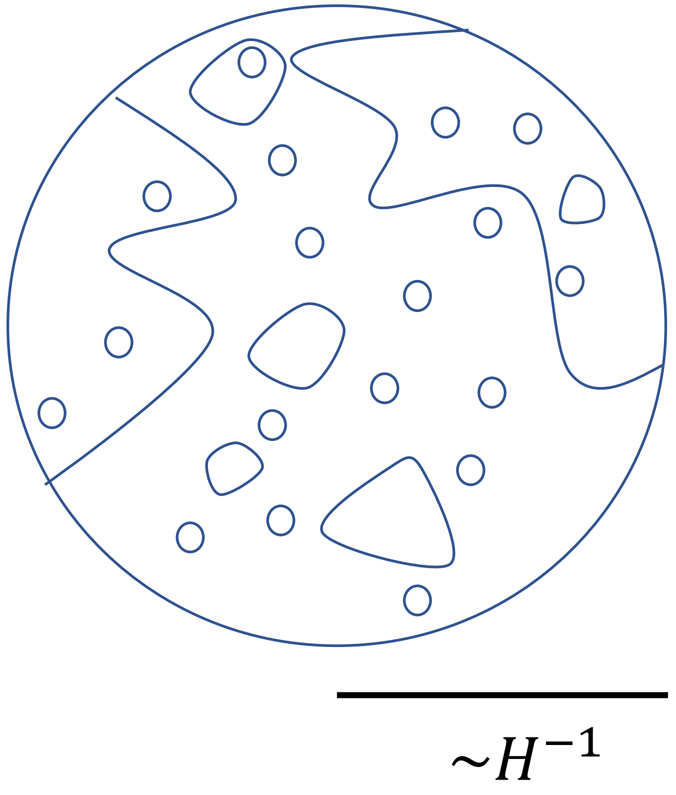
Strings must exchange partners!

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 inspired by Tong (2005)

‘Scaling’ Attractor Solution





Magnetic Monopoles Catalyze Proton Decay

Dirac, Fierz, Wilson, Saha, Zwanziger, Jackiw, Hasenfratz, ‘t Hooft, Goldhaber, Kazama, Yang, Sen, Rossi, Callias, Ross, Boulware, Lee, …, Csaki, Hong, Shirman, Telem, Terning, Waterbury

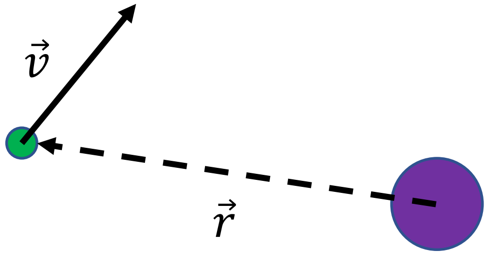
Magnetic Monopoles Catalyze Proton Decay

Infrared inelastic interactions

$$m\frac{d\vec{v}}{dt} = e\left(\vec{E} + \vec{v}\times\vec{B}\right) = eg\vec{v}\times\frac{\vec{r}}{r^3}$$

$$0 = \frac{d\vec{J}}{dt} = \frac{d}{dt}\left[\vec{r}\times m\vec{v} - eg\hat{r}\right]$$

$$\vec{J} = \vec{L} - eg\hat{r}$$



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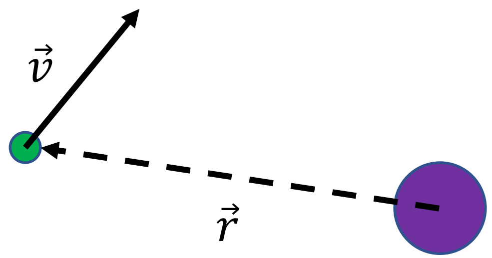


Callan, Rubakov effect: GUT boundary condition provides proton decay!

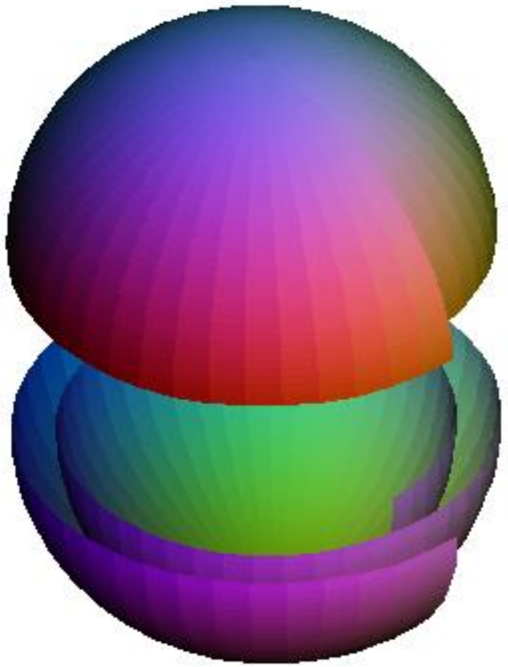
$$\sigma(p^+ + \text{ monopole} \to e^+ + \text{ monopole}) \sim \Lambda_{QCD}^{-2}$$

Unsuppressed by UV scales!

Dirac, Fierz, Wilson, Saha, Zwanziger, Jackiw, Hasenfratz, ‘t Hooft, Goldhaber, Kazama, Yang, Sen, Rossi, Callias, Ross, Boulware, Lee, …, Csaki, Hong, Shirman, Telem, Terning, Waterbury

Magnetic Monopoles Catalyze Proton Decay

Callan, Rubakov effect:
Quarks and leptons in same GUT multiplet, so monopole can relate them



Into the monopole

$$\Phi^a(x) : S^2_\infty \to SU(2)/U(1)$$

So a combined spatial and gauge rotation is needed to leave the background invariant

$$\vec{J} = \vec{L} + \vec{S} + \vec{T}$$

‘t Hooft, Polyakov, Arafune, Freund, Julia, Zee, Jackiw, Rebbi, Sommerfield, Blaer, Christ, Tomboulis, Woo, Callan, Gross, Witten, Goldstone, Coleman, Mandelstam, Polchinski, Rubakov, … Brennan

ENHANCED BARYON NUMBER VIOLATION DUE TO COSMIC STRINGS

M.G. ALFORD and John MARCH-RUSSELL

Lyman Laboratory of Physics, Harvard University, Cambridge, MA 02138, USA

Frank WILCZEK

Institute for Advanced Study, Princeton, NJ 08540, USA

Received 17 April 1989

$$\mathcal{L}_{int} = \lambda \left(\chi \bar{\psi}_q \psi_\ell + \chi^\star \bar{\psi}_\ell \psi_q \right)$$

$$\text{quark} \ + \ \text{string} \to \text{lepton} \ + \ \text{string}$$

Cosmic strings of some $\widetilde{U(1)} \to \mathbb{Z}_N$ with leptoquark condensed on core breaking EM, color, B+L

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$$\frac{d\sigma}{d\theta} \propto \frac{1}{p}\sin^2\left(\pi\frac{q}{N}\right)\left(\frac{p}{v}\right)^{4\left|\frac{q}{N}-\frac{1}{2}\right|}$$

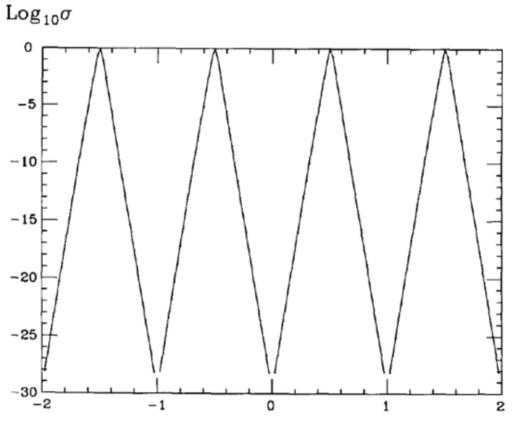
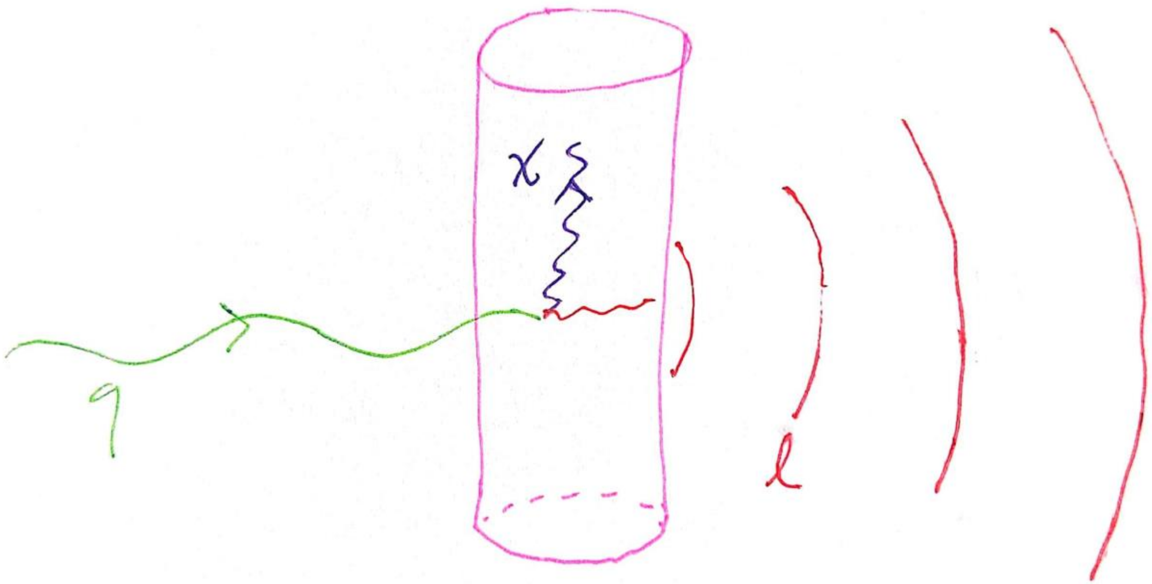


Fig. 5. Inelastic scattering cross section for the same case as fig. 4. Note that σ is unsuppressed by any factors of kR near half-integral flux.



Our case: Cosmic strings of $U(1)_{B-L}$ with χ condensed on core breaking $U(1)_{B+L}$ to SM $\mathbb{Z}_6^{B+L}$

	χ	ω_ℓ	ω_q	ω_s
$SU(3)_C$	$-$	3	3	$-$
$U(1)_B$	$+3$	$+1$	-2	$+3$
$U(1)_L$	$+3$	$+1$	0	$+1$

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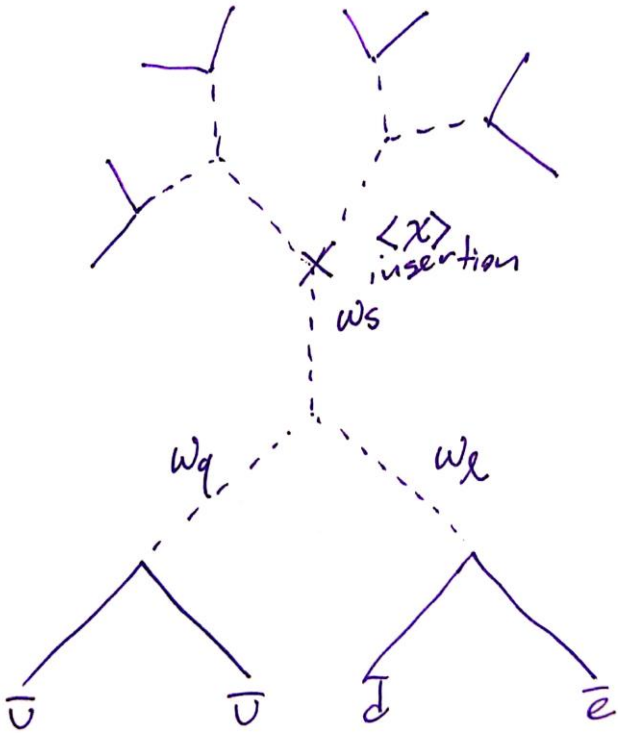
$$\mathcal{L}_{int} \sim \lambda \left(\chi \bar{\psi}_{3p} \psi_{3e} + \chi^\star \bar{\psi}_{3e} \psi_{3p} \right)$$

^{7}Li delivers just such an incoming state of three protons to the string!



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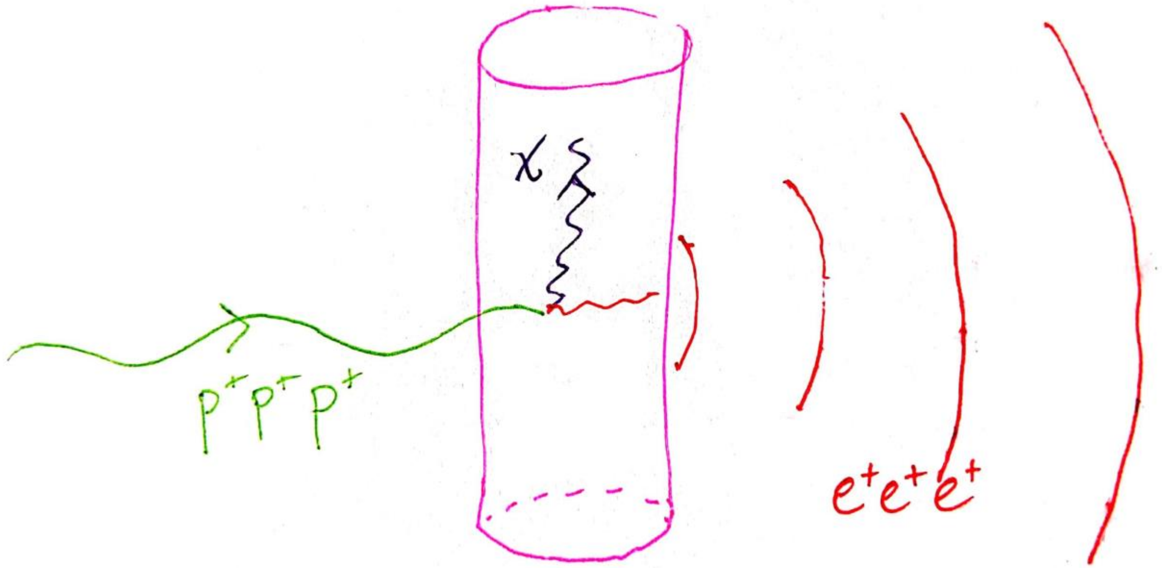

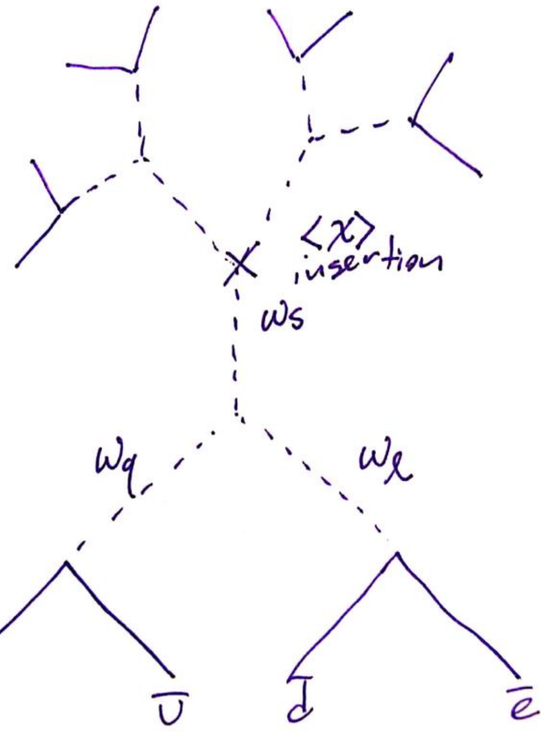

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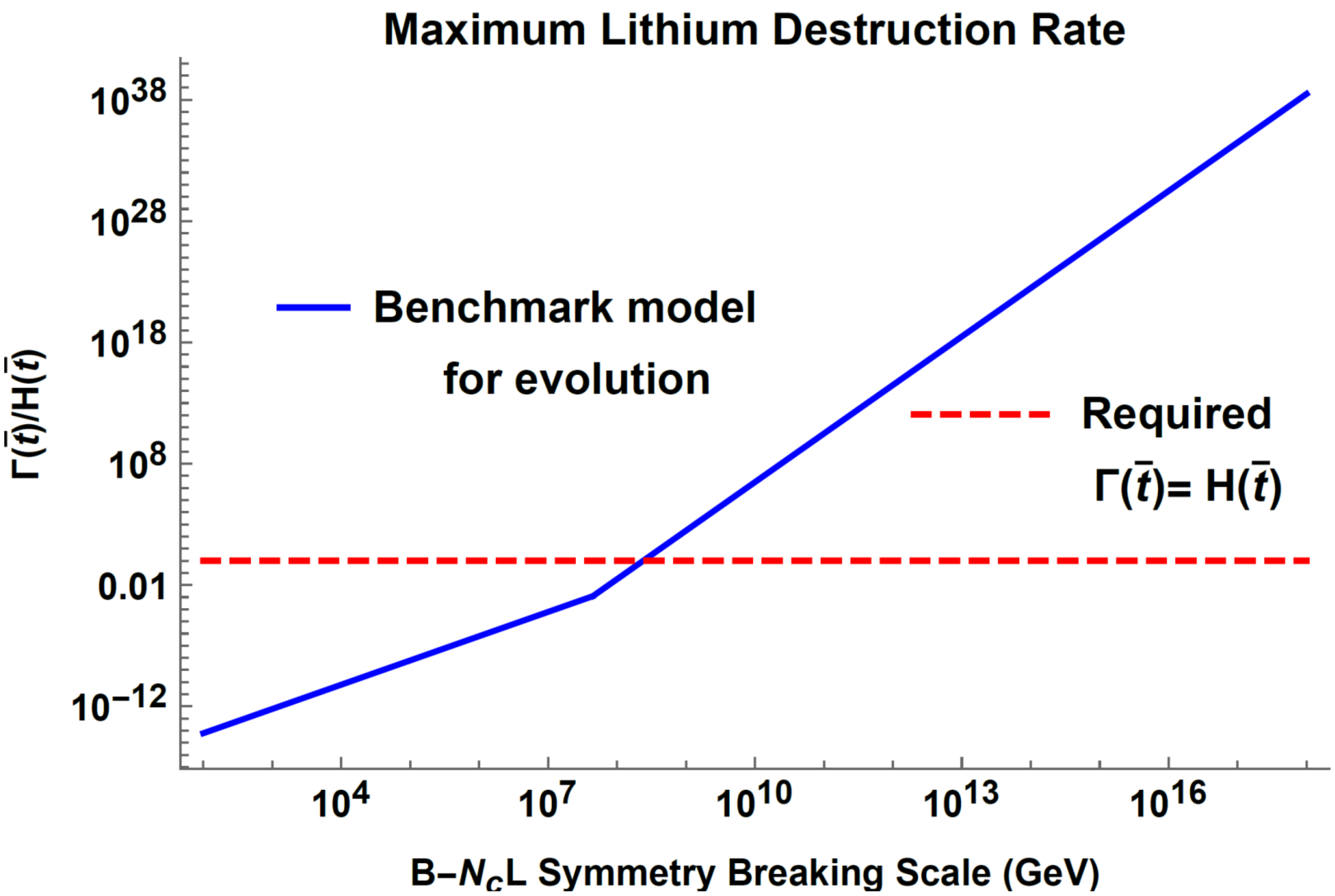
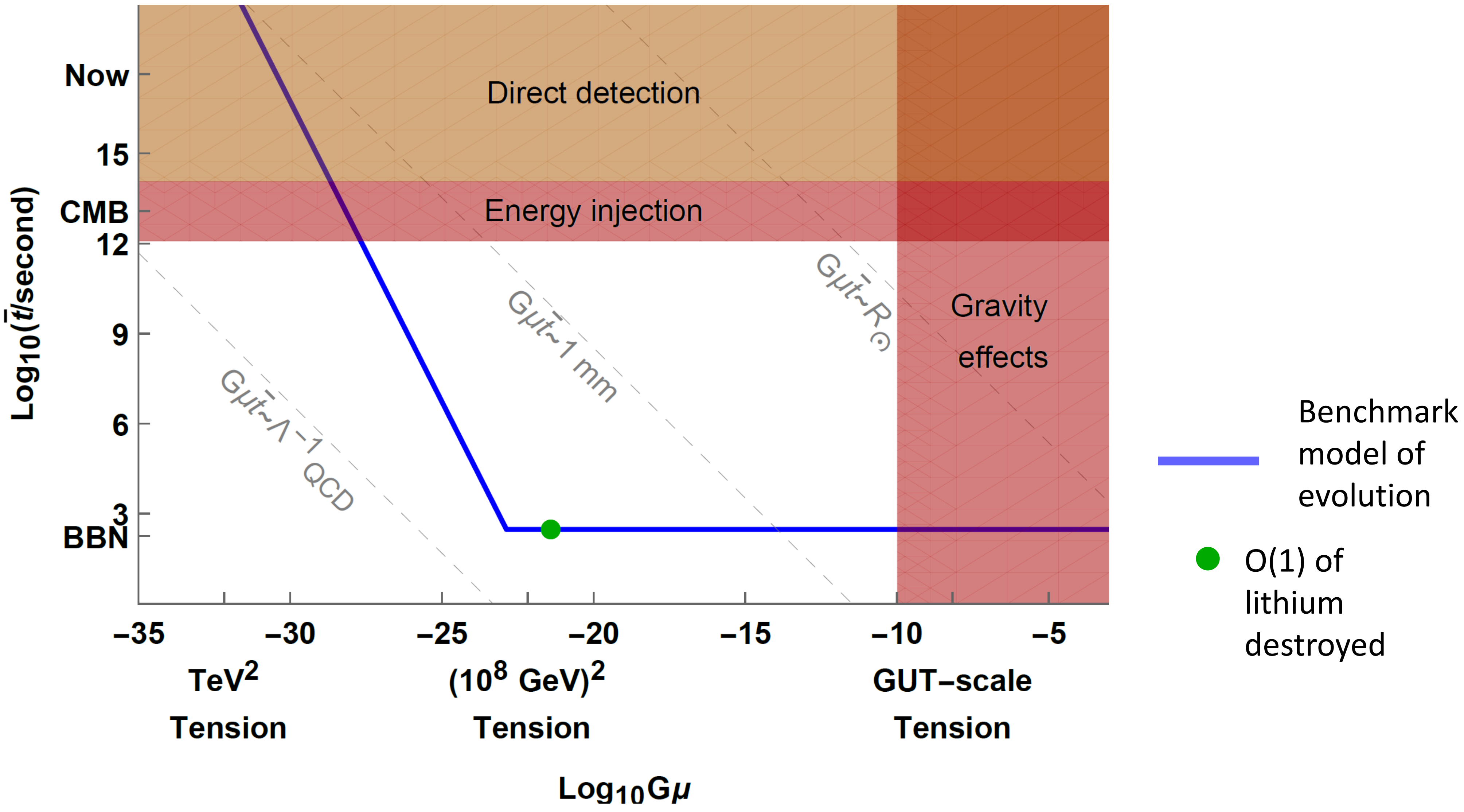
Can the rate be large enough to destroy O(1) of lithium?
TL;DR: Yes!



Treating the time at which lithium disintegrates as independent



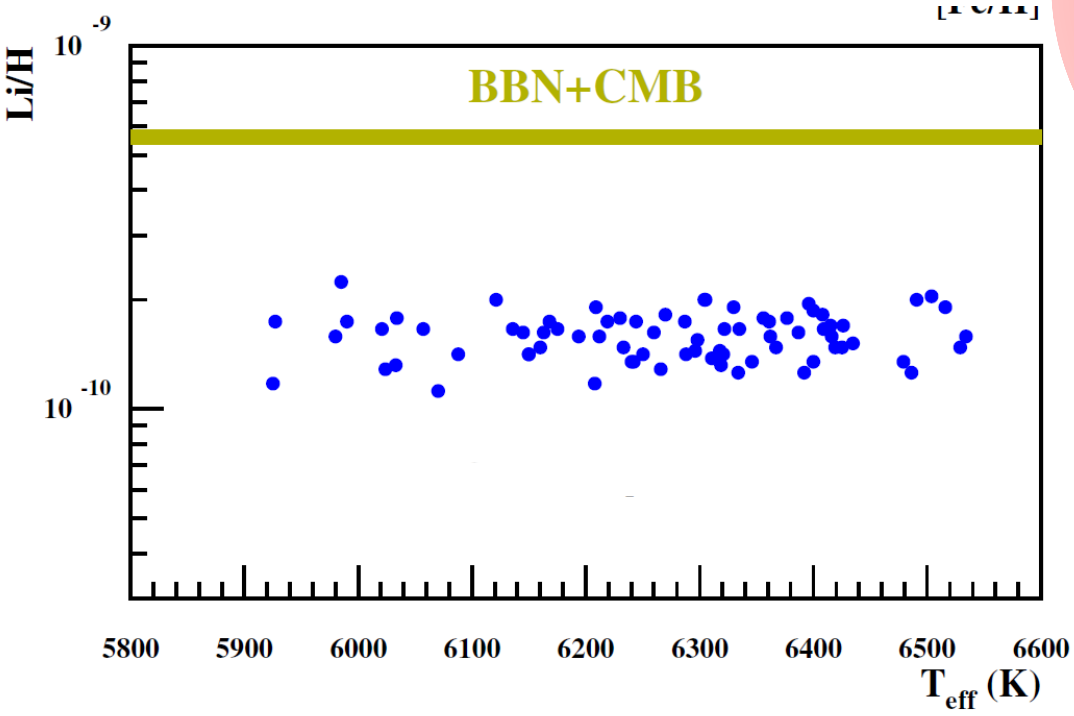
Conclusions

- Cosmic strings can have interesting non-gravitational interactions. B-L strings especially well-motivated.
- A plausible fundamental physics *raison d’être* for the lithium discrepancy. Remarkably close to the SM.
- Pb (Z=82) + string -> Au (Z=79) + string + 3 leptons! Alchemy!

Lithium abundance at the formation of the Galaxy

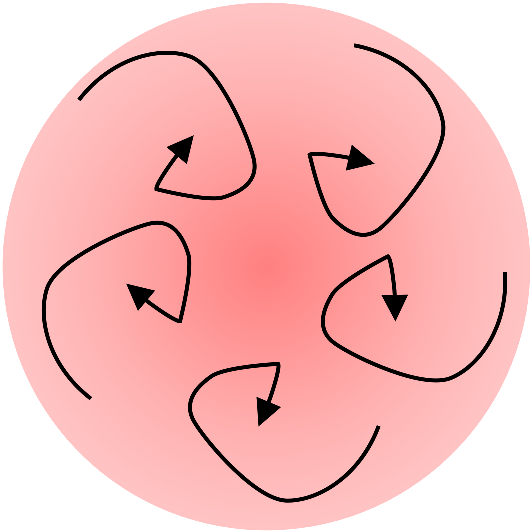
M. Spite & F. Spite 1982

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



Pitrou et al. (2018)

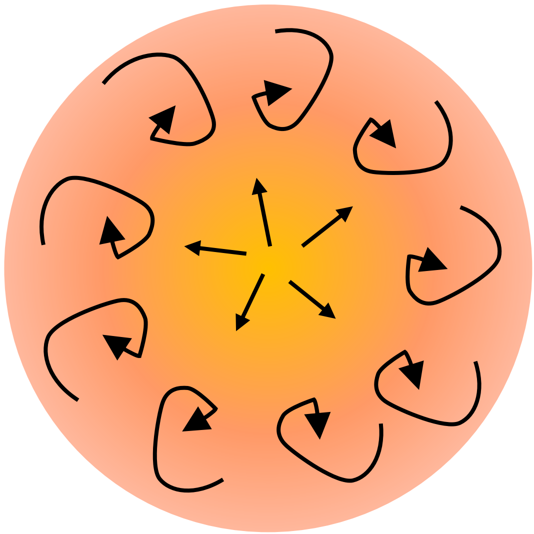
'Cold' stars



Fully convective

Li transported to core and destroyed

Hotter stars



Inner radiative zone is convectively stable

Atmospheric Li stays out of hottest region and reflects primordial abundance

First results from dark matter search experiment with LiF bolometer at Kamioka underground laboratory

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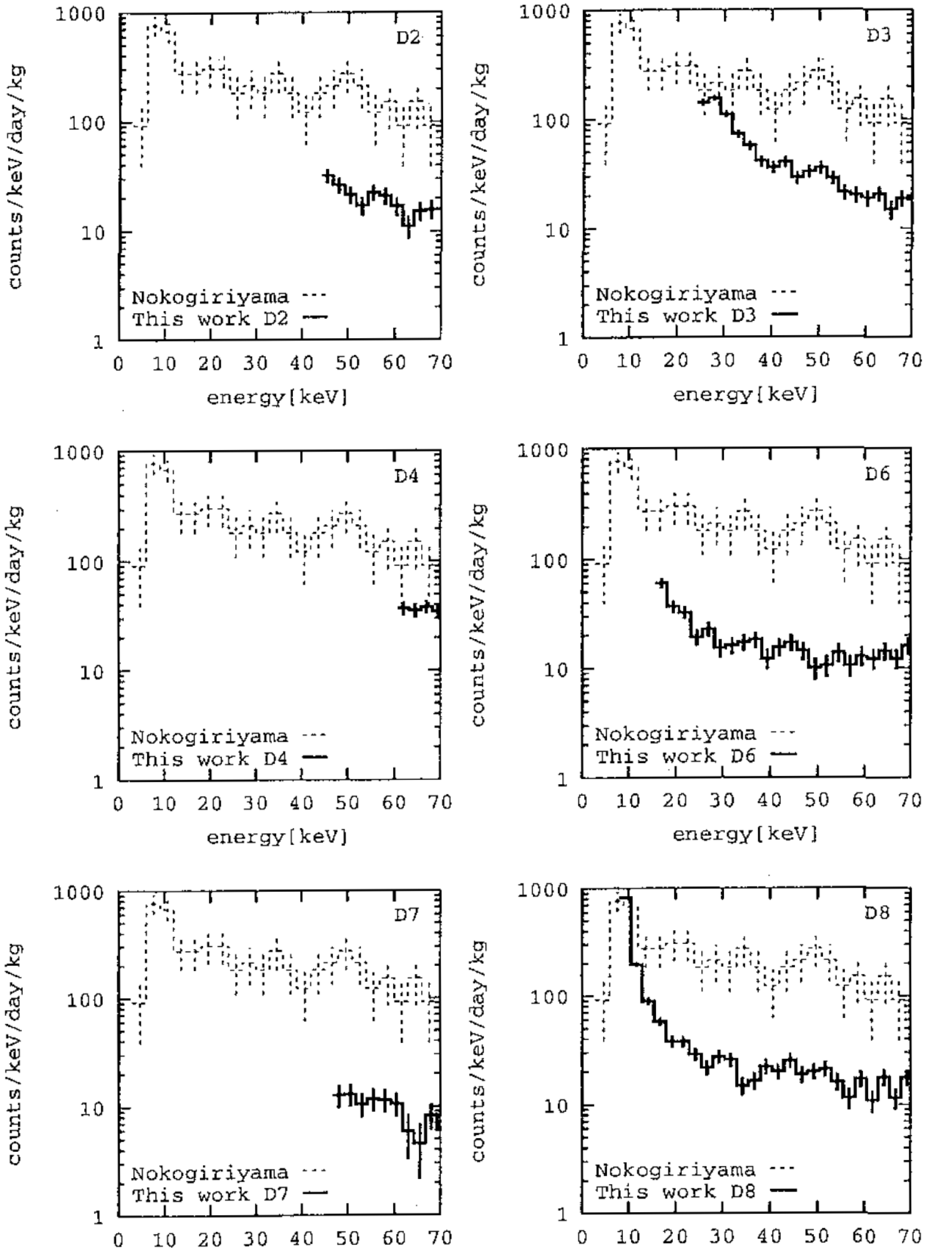
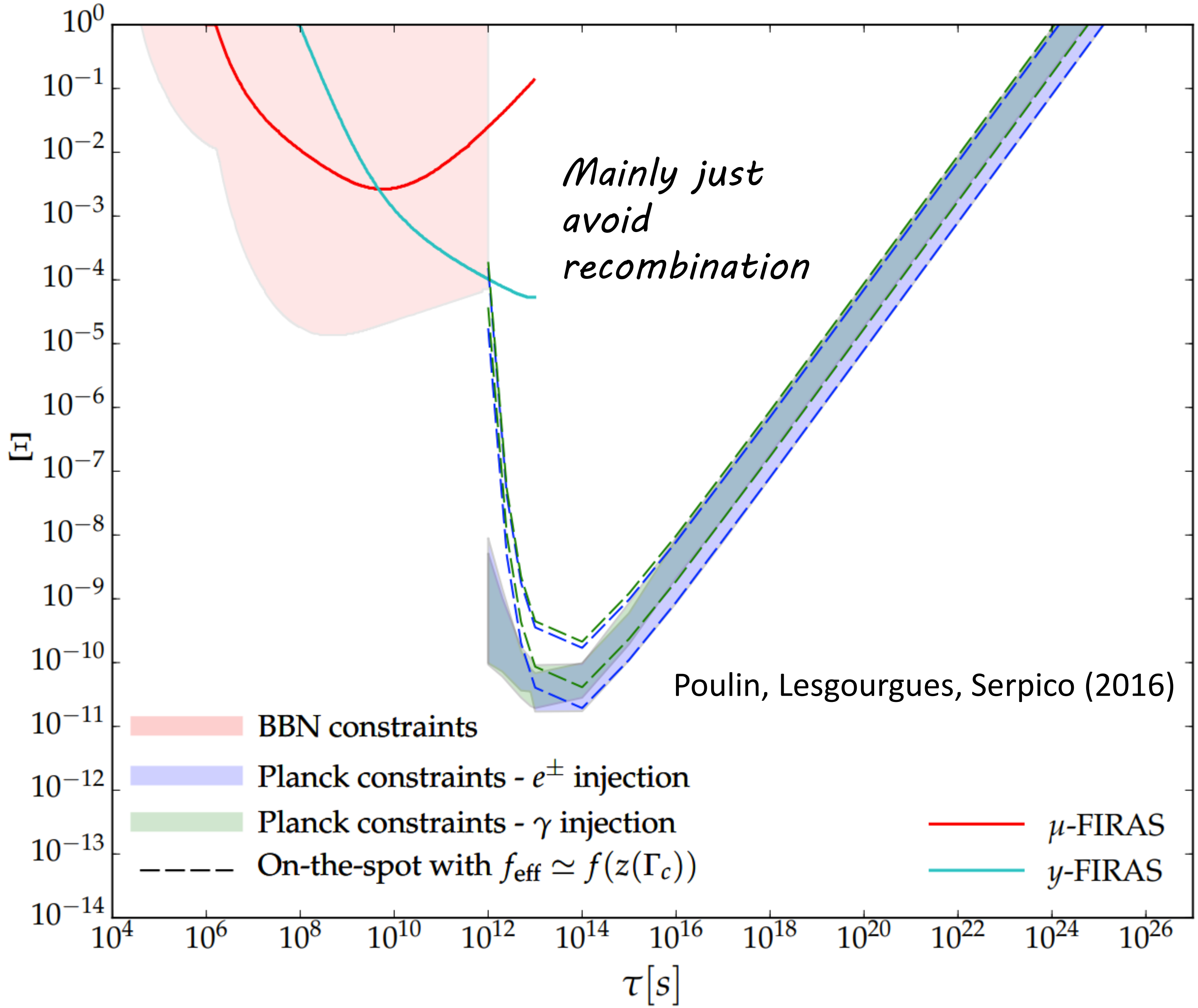
Abstract

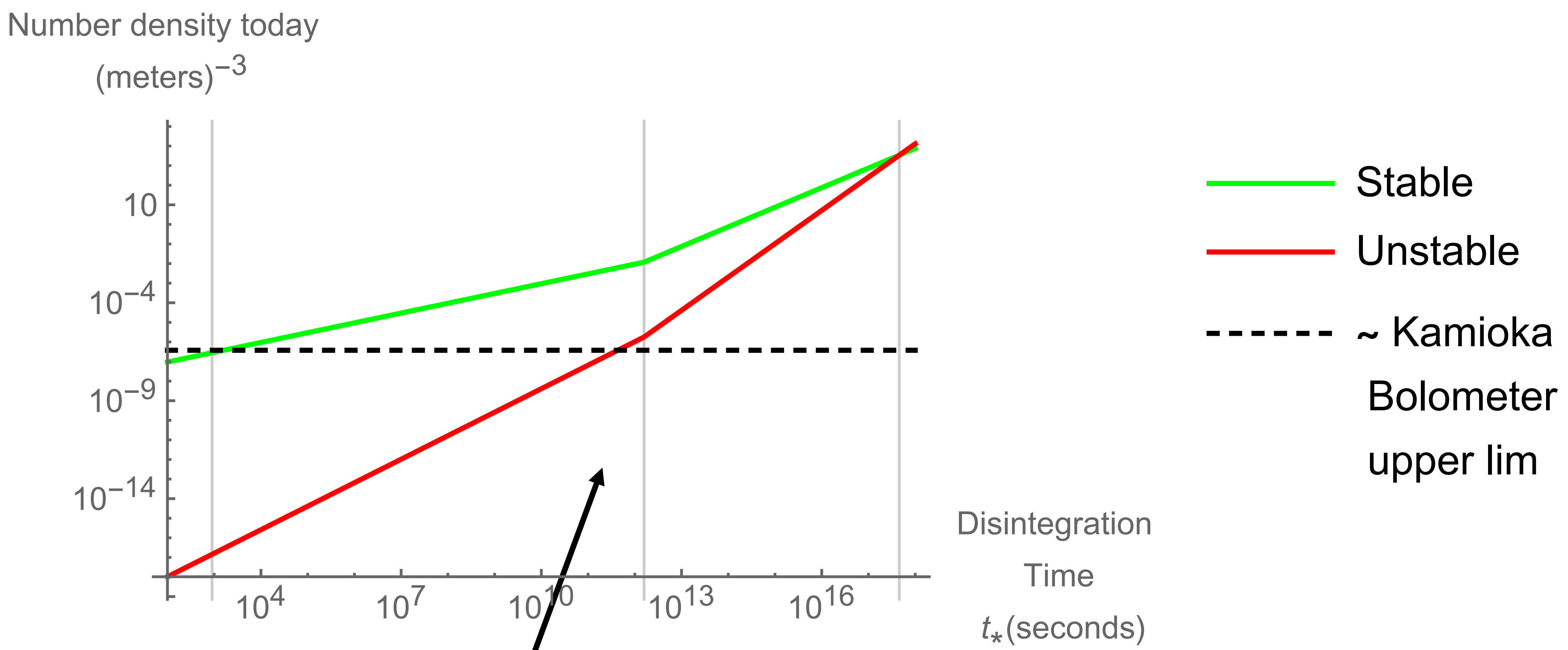
The Tokyo group has performed the first underground dark matter search experiment from 2001 through 2002 at Kamioka Observatory (2700 m.w.e). The detector is eight lithium fluoride bolometers with a total mass of 168 g and aims for the direct detection of weakly interacting massive particles (WIMPs) via spin-dependent interaction. With an exposure of 4.1 kg days, we derived the limits in the a_p–a_n (WIMP–nucleon couplings) plane and excluded a large part of the parameter space allowed by the UKDMC experiment.



Cosmological constraints are minor since

$$\frac{n_{Li}}{n_H} \sim 10^{-10}$$





So want to
disintegrate ~
during rad dom

$$\Gamma(t_\star) \sim H(t_\star)$$

Fermions are weird

$$\int \mathcal{D}\bar{\psi}\mathcal{D}\psi \; e^{-\int_{\mathcal{M}} \bar{\psi}\gamma_\mu D^\mu \psi} \supset \int d\xi^\dagger d\xi \; e^{-\lambda \xi^\dagger \xi} = \int d\xi^\dagger d\xi \; (1 - \lambda \xi^\dagger \xi)$$

$$\int d\xi = 0, \quad \int \xi d\xi = 1$$

Zero modes must be saturated!

$$\mathrm{index}(\gamma_\mu D^\mu) = \int \frac{F\tilde{F}}{16\pi^2} = \langle \partial_\mu J^\mu_X \rangle$$