IBS Conference on Dark World , Oct 27-30, 2025

Axion mass prediction from cosmic strings

Minho Son

Korea Adv. Inst. of Sci. and Tech. (KAIST)

Based on

arXiv > hep-ph > arXiv:2402.00741

High Energy Physics – Phenomenology

[Submitted on 1 Feb 2024 (v1), last revised 8 Feb 2024 (this version, v2)]

Axion Dark Matter from Cosmic String Network

Heejoo Kim, Junghyeon Park, Minho Son

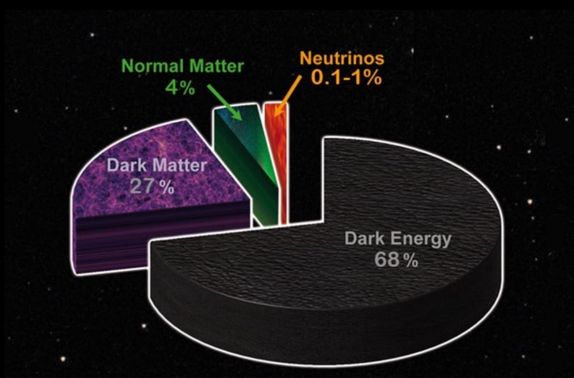
arXiv > hep-ph > arXiv:2411.08455

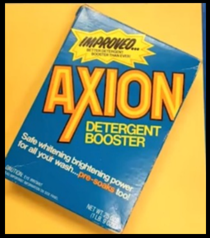
High Energy Physics – Phenomenology

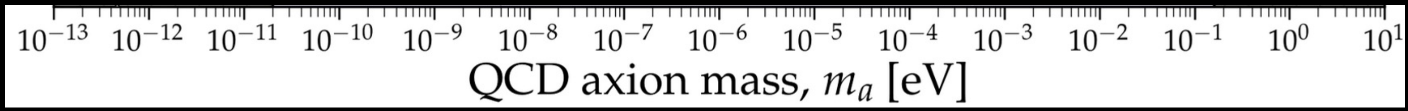
[Submitted on 13 Nov 2024]

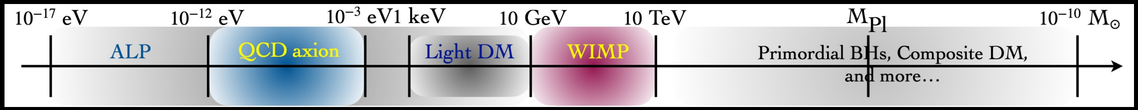
More Scalings from Cosmic Strings

Heejoo Kim, Minho Son



We will focus on QCD  of mass $\sim \mu eV$





Axion Dark Matter

Provides a solution to strong CP problem

Axion Dark Matter

One of the appealing qualities of the axion is that it can be dark matter

Pre-inflationary scenario

``PQ symmetry breaking before inflation"

VS

Post-inflationary scenario

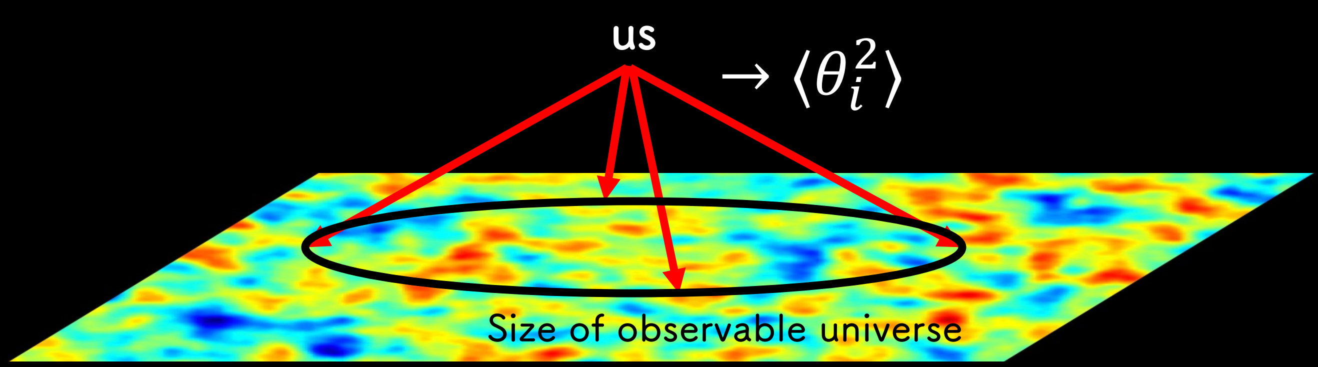
``PQ symmetry breaking after inflation"

$$\Omega_a h^2 = 0.12 \left(\frac{f_a}{10^{12} GeV}\right)^{7/6} \langle \theta_i^2 \rangle$$

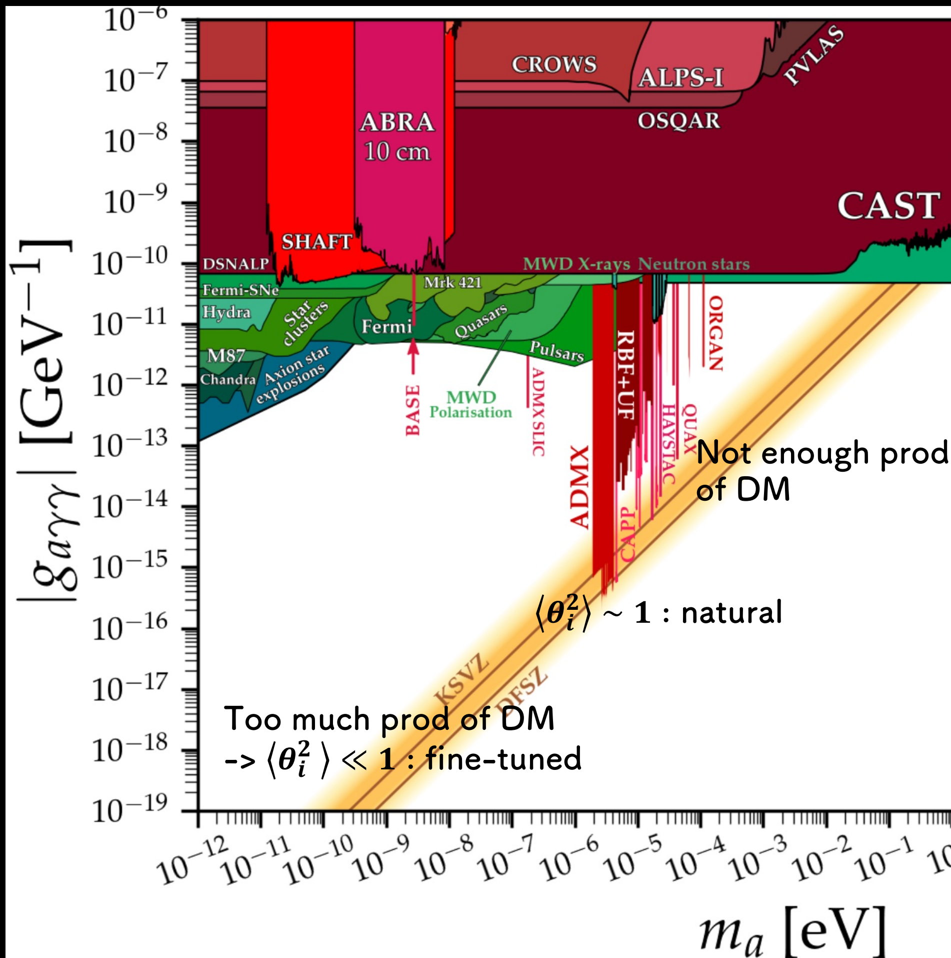
$$m_a \approx 5.7 \mu eV \left(\frac{10^{12}\ GeV}{f_a / N_W}\right)$$

Observable Universe

: includes many causally disconnected patches



$\rightarrow \langle \theta_i^2 \rangle$



Misalignment

$$\Omega_a^{\mathrm{mis}} h^2 = 0.12 \left(\frac{f_a}{10^{12} GeV}\right)^{7/6} \langle\theta_i^2\rangle$$

$$m_a \approx 5.7 \mu eV \left(\frac{10^{12}\ GeV}{f_a / N_W}\right)$$

Topological defects

$$0.12 \sim \Omega_a h^2 = \Omega_a^{\mathrm{mis}} h^2 + \Omega_a^{\mathrm{string}} h^2 + \Omega_a^{\mathrm{str-dw}} h^2$$

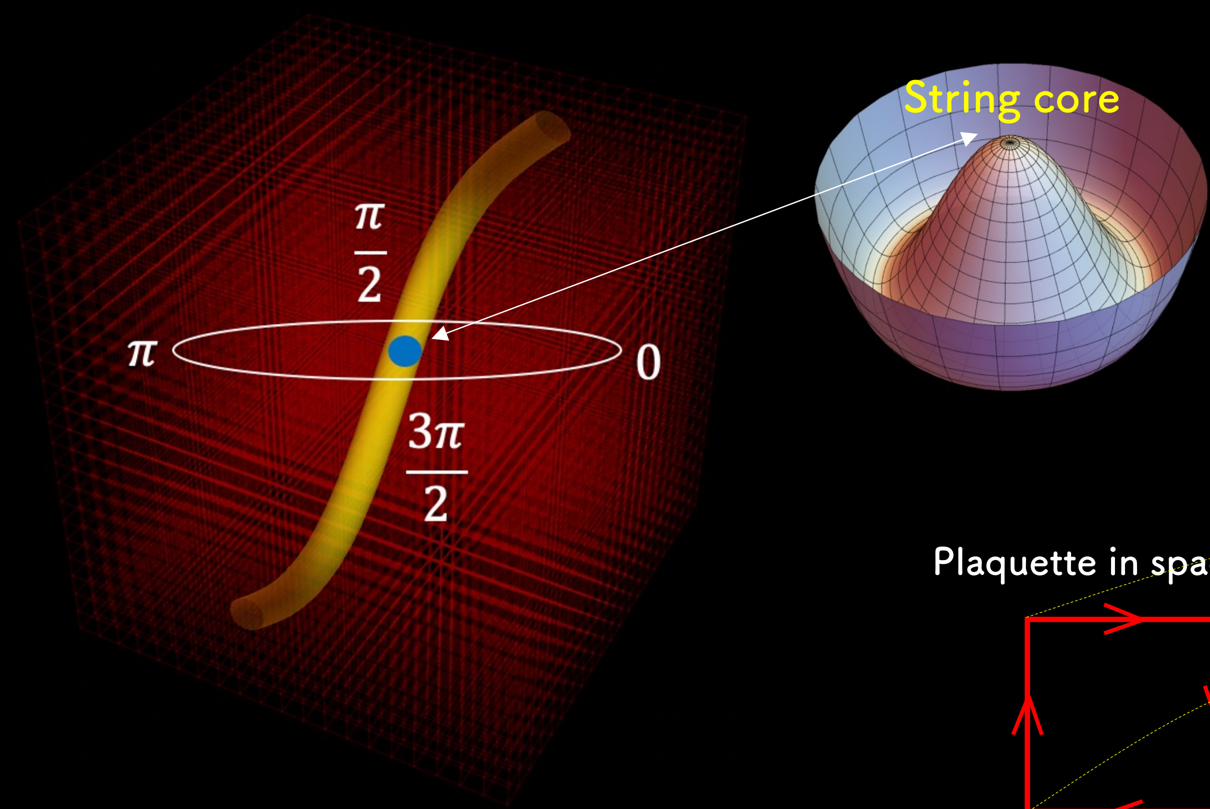
Situation of direct axion search dramatically changes depending on the size of this part

Formation of cosmic string

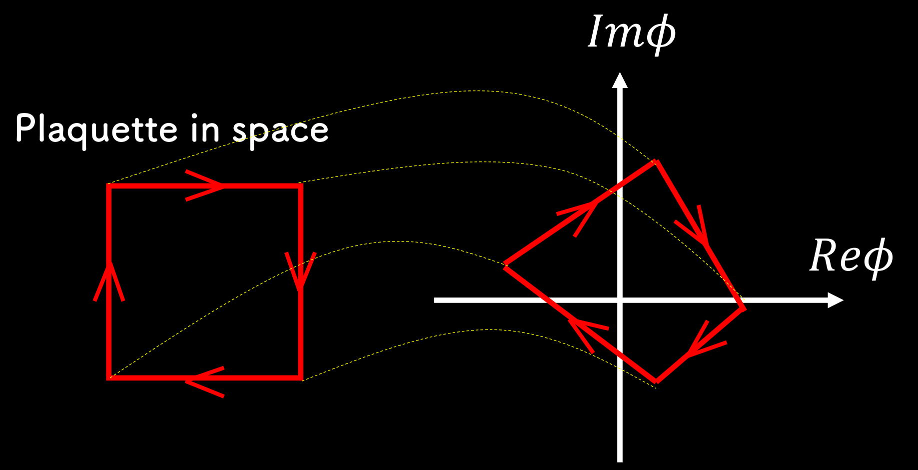
$$ds^2 = dt^2 - R^2(t)d\vec{x}^2$$

$$\ddot{\phi} + 3H\dot{\phi} - \frac{1}{R^2}\nabla^2\phi + \frac{m_r^2}{f_a^2}\left(|\phi|^2 - \frac{f_a^2}{2}\right)\phi = 0$$

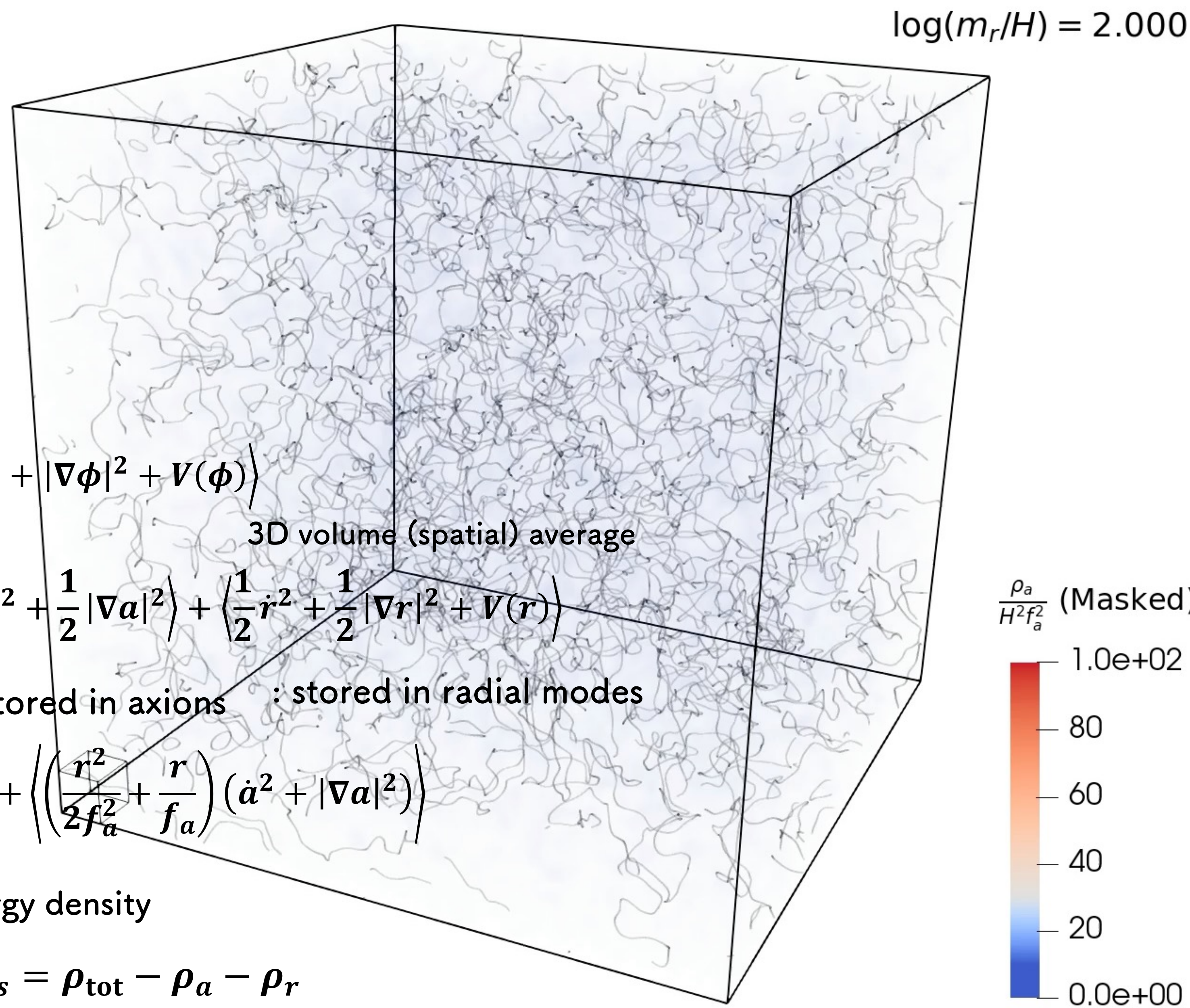
Evolution of this complex scalar field is highly non-linear and it can be done only numerically



$$\phi = \frac{r(x) + f_a}{\sqrt{2}} e^{i\frac{a}{f_a}}$$



See talk by Takahashi



$$\boldsymbol{\rho}_{\mathbf{tot}} = \left\langle \left|\dot{\boldsymbol{\phi}}\right|^2 + |\nabla\boldsymbol{\phi}|^2 + \boldsymbol{V}(\boldsymbol{\phi}) \right\rangle$$

3D volume (spatial) average

$$= \left\langle \frac{1}{2}\dot{\boldsymbol{a}}^2 + \frac{1}{2}|\nabla \boldsymbol{a}|^2 \right\rangle + \left\langle \frac{1}{2}\dot{\boldsymbol{r}}^2 + \frac{1}{2}|\nabla \boldsymbol{r}|^2 + \boldsymbol{V}(\boldsymbol{r}) \right\rangle$$

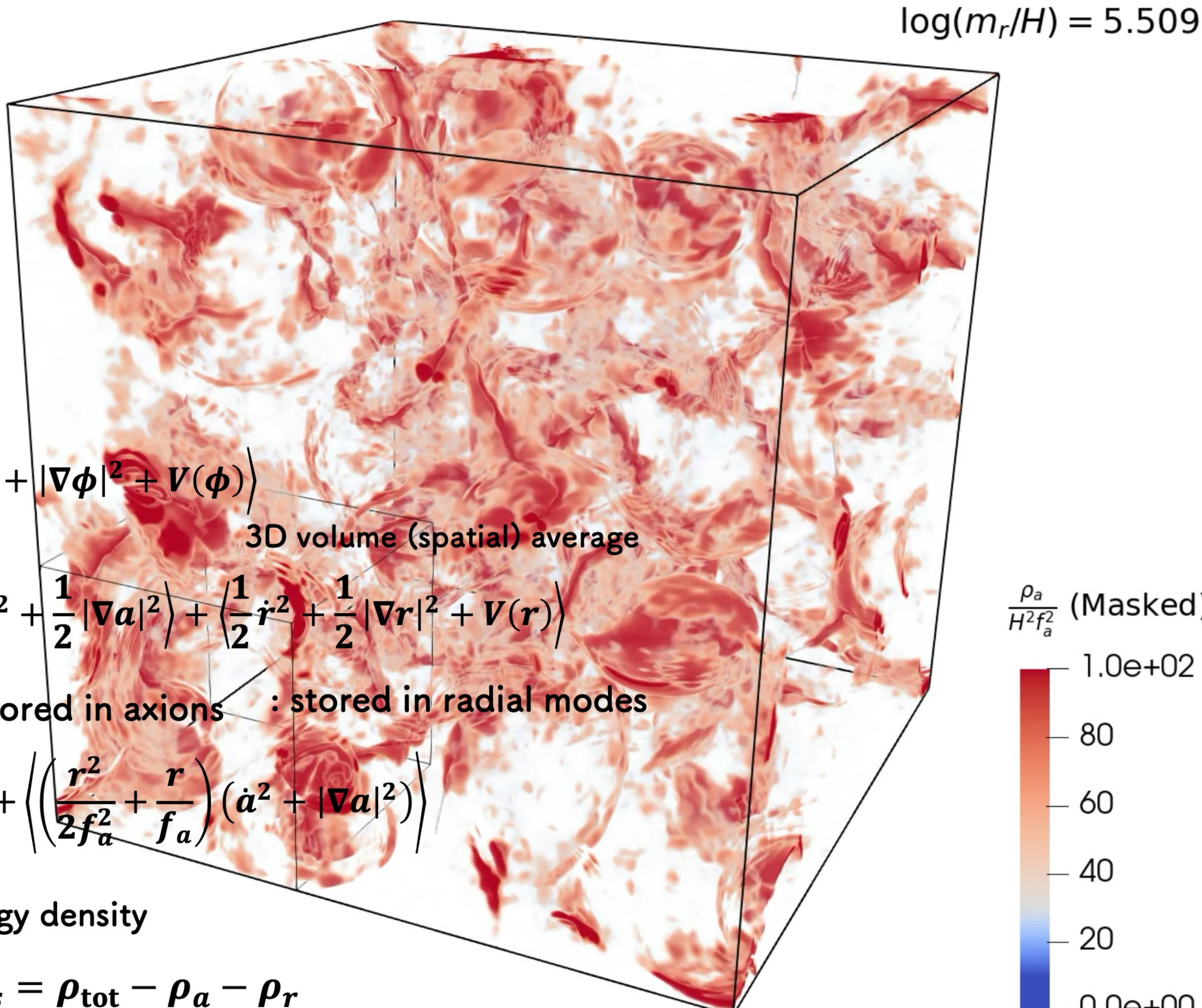
$2\times\frac{1}{2}\dot{\boldsymbol{a}}^2$: stored in axions

: stored in radial modes

$$+ \left\langle \left(\frac{\boldsymbol{r}^2}{2\boldsymbol{f}_{\boldsymbol{a}}^2} + \frac{\boldsymbol{r}}{\boldsymbol{f}_{\boldsymbol{a}}} \right) \left(\dot{\boldsymbol{a}}^2 + |\nabla \boldsymbol{a}|^2 \right) \right\rangle$$

String energy density

$$\boldsymbol{\rho}_{\boldsymbol{s}} = \boldsymbol{\rho}_{\mathbf{tot}} - \boldsymbol{\rho}_{\boldsymbol{a}} - \boldsymbol{\rho}_{\boldsymbol{r}}$$



$$\boldsymbol{\rho}_{\mathrm{tot}} = \left\langle |\dot{\boldsymbol{\phi}}|^2 + |\nabla \boldsymbol{\phi}|^2 + V(\boldsymbol{\phi}) \right\rangle$$

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$2 \times \frac{1}{2}\dot{a}^2$: stored in axions

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$$+ \left\langle \left(\frac{r^2}{2 f_a^2} + \frac{r}{f_a} \right) \left(\dot{a}^2 + |\nabla a|^2 \right) \right\rangle$$

String energy density

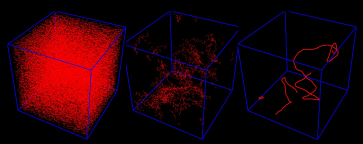
$$\rho_s = \rho_{\mathrm{tot}} - \rho_a - \rho_r$$

Cosmological evolution

$$\log \frac{m_r}{H} = \log \frac{t}{t_0} \lesssim \log N$$

QCD PT

$t \sim 10^{-5}$ sec



~ 1 ~ 10 ~ 70 $\log \frac{m_r}{H}$

lattice simulation

$H^{-1} \propto t$

$\Delta \propto R(t) = \sqrt{t}$

$m_r^{-1} \propto \mathrm{const}$

Multi-scale problem:
Even numerical simulation is very difficult and progress is very slow

Appearance of Scaling solution

: allows us to extrapolate all the way to QCD scale

Axions decayed from strings around this time contribute to DM

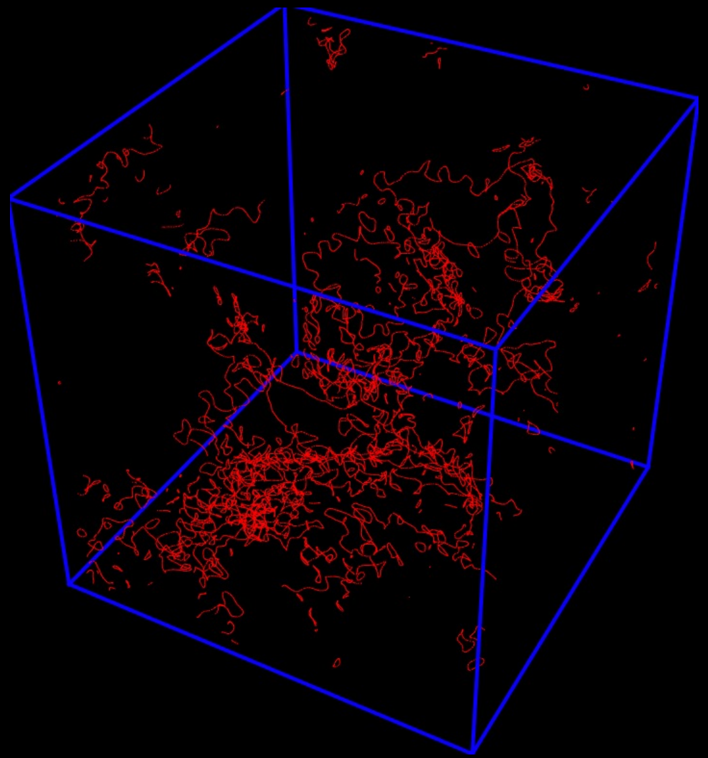
Two important scalings for axion mass prediction

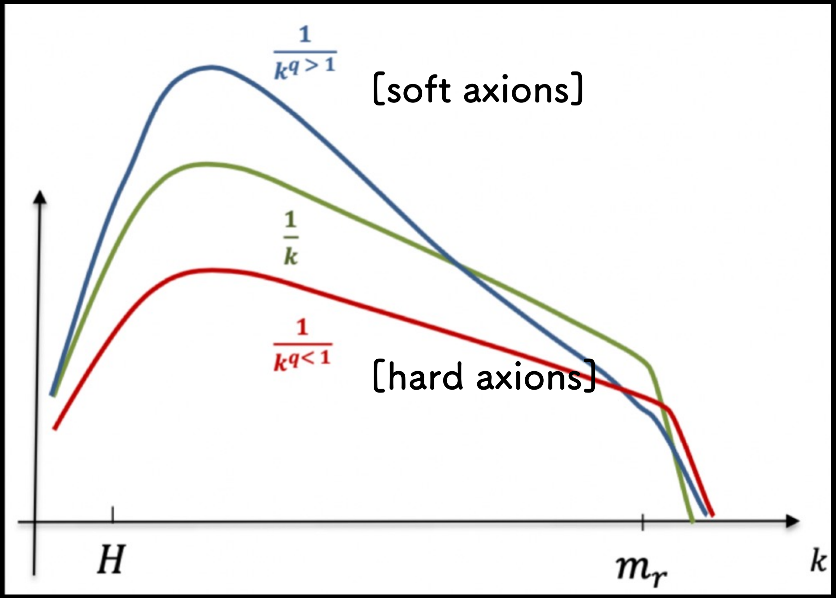
$$\xi \propto \frac{\ell_{\mathrm{tot}}(L)}{\left(L^3/(H^{-1})^3\right)} \frac{1}{H^{-1}} = \frac{\ell_{\mathrm{tot}}(L) t^2}{L^3}$$

: number of strings per Hubble patch

$$\frac{\partial^2 \rho_a}{\partial t \partial k} \propto \frac{1}{k^q}$$

: no new scale between m_r and H





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: number of strings
per Hubble patch

$$\frac{\partial^2 \rho_a}{\partial t \partial k} \propto \frac{1}{k^q}$$

: no new scale
between m_r and H

Interesting situation would be
this at the QCD crossover

$$\left.\frac{n_a^{\text{str},\, q>1}}{n_a^{\text{mis},\theta_0=1}}\right|_{t_\ell} > 1$$

Axion abundance

$$n_a = \int \frac{dk}{k} \frac{\partial \rho_a}{\partial k}$$

: should follow a **power law** due to absence of other non-trivial scales and sampling has to be done in scaling regime

$$\frac{\partial \rho_a}{\partial k} = \int^t dt' \frac{\Gamma[t']}{H(t')} \left(\frac{R(t')}{R(t)}\right)^3 F\left[\frac{k'}{H(t')}, \frac{m_r}{H(t')}\right]$$

: instantaneous emission function

$$\Gamma[t] \sim \frac{\xi \mu_{\mathrm{eff}}}{t^3} \sim 8\pi H^3 f_a^2 \, \xi \log \frac{m_r}{H}$$

$$F \sim \frac{1}{k^q}$$

Two most important scalings in ξ and spectral index q in cosmic string

E.g. $$\left.\frac{n_a^{q>1}}{n_a^{\mathrm{mis}}}\right|_{t_\ell} \propto \left(\xi_\star \log \frac{m_r}{H_\star}\right)^{\frac{1}{2}+\cdots}$$

Gorghetto, Hardy, Villadoro 20'
Kim, **SON**, Park 2024 (redone)

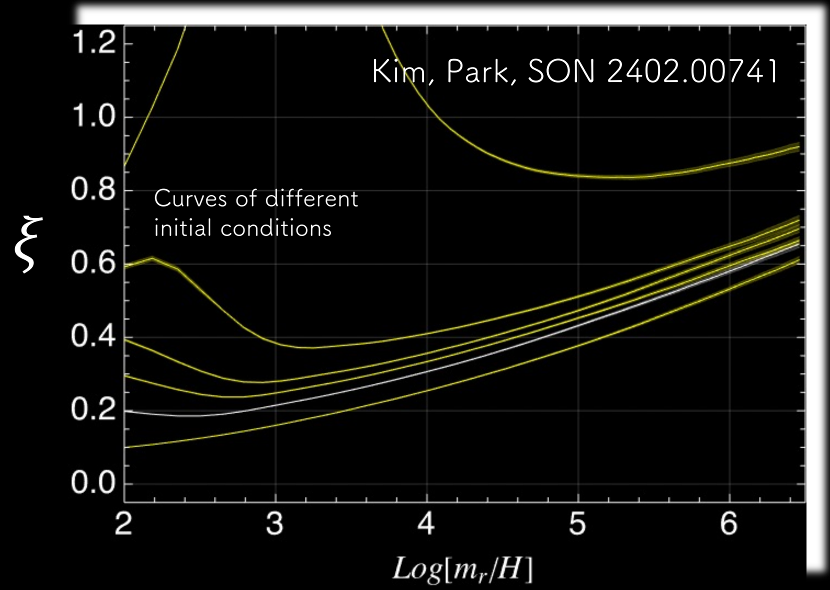
Recent intriguing observations are

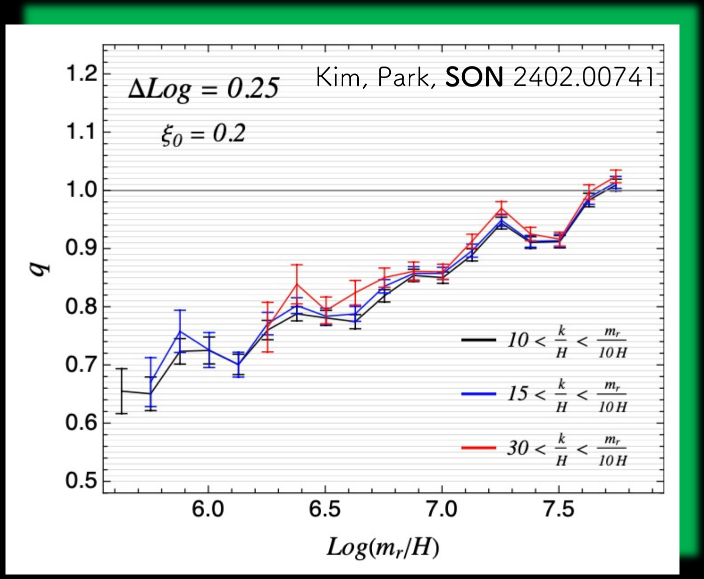
This is where simulation frontiers leads the theory.
These findings are not explained by theory yet

$$\xi = \beta + \alpha \log \frac{m_r}{H}$$

$$q = q_0 + \varepsilon \log \frac{m_r}{H}$$

Gorghetto, Hardy, Villadoro 18′,20′
Benabou, Buschmann, Foster, Hook, Peterson, Willcox, Zhang, Safdi 21′, 24′
Saikawa, Redondo, Vaquero, Kaltshmidt 24′





Kim, Park, **SON** 2402.00741

Extrapolates to

$$\xi \sim \mathcal{O}(10)$$

$$q > 1$$

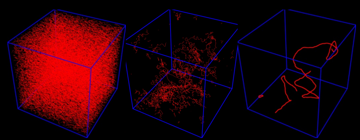
$$@\ m_r t = e^{70}$$

$$\left. \frac{n_a^{\text{str}, q>1}}{n_a^{\text{mis}, \theta_0 = 1}} \right|_{t_\ell} > 1$$

: soon after this time, axions become non-relativistic dark matter

QCD PT

$t \sim 10^{-5}$ sec



~ 1 $\quad\sim 10$ $\quad\sim 70$ $\quad\log \frac{m_r}{H}$

Supported by scaling solution

t_* ⟷ t_ℓ

lattice simulation → Extrapolation →

Nonlinearity may or may not kick in

$$\frac{\sqrt{\langle a^2 \rangle}}{f_a} \geq 1 \text{ vs } \leq 1$$

Gorghetto, Hardy, Villadoro 20′

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$$0.12 \sim \Omega_a h^2 = \Omega_a^{\mathrm{mis}} h^2 + \Omega_a^{\mathrm{str}} h^2 + \Omega_a^{\mathrm{str-dw}} h^2$$

Axions from strings in scaling regime @QCD PT

Gorghetto, Hardy, Villadoro 18′,20′
Saikawa, Redondo, Vaquero, Kaltshmidt 24′
Kim, Park, **SON** 24′

Axions from string-domain wall network @QCD phase transition

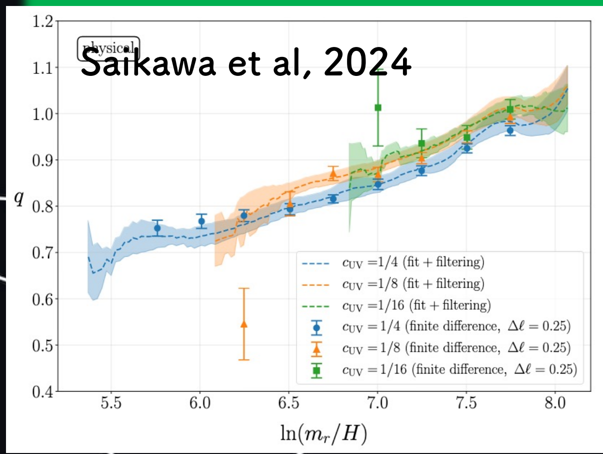
Gorghetto, Hardy, Villadoro 20′
Benabou, Buschmann, Foster, Safdi 24′

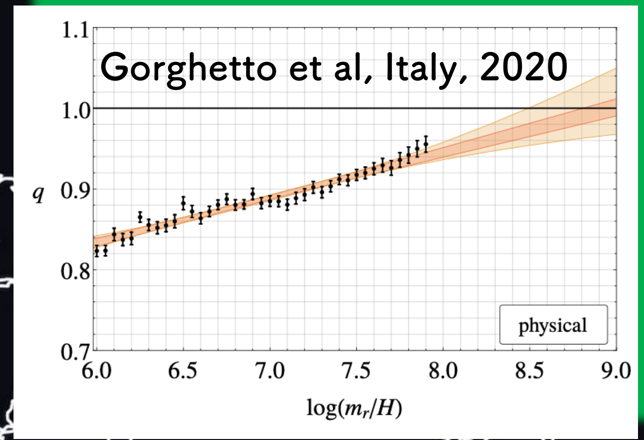
If $\Omega_a^{\mathrm{mis}} h^2, \Omega_a^{\mathrm{str-dw}} h^2 \ll \Omega_a^{\mathrm{str}} h^2$, $\quad \Omega_a^{\mathrm{str}} h^2 \approx \frac{n_a^{\mathrm{str}}}{n_a^{\mathrm{mis},\theta_0=1}} \Omega_a^{\mathrm{mis},\theta_0=1} h^2 \leq 0.12$

$\rightarrow m_a \geq$ ☐ μeV

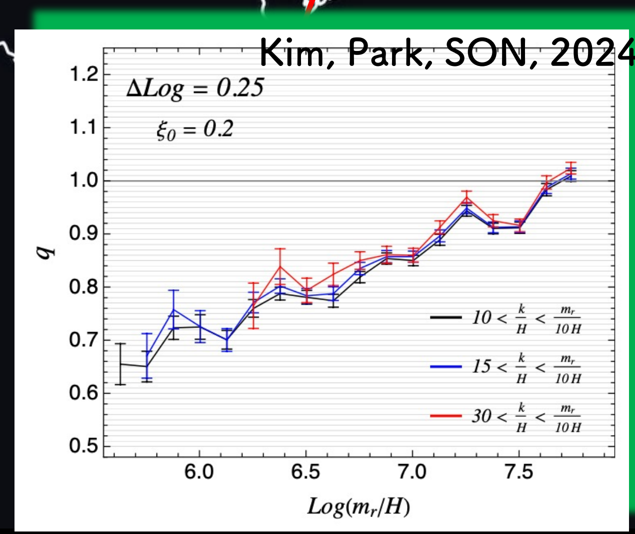
Recent results in cosmic string frontier

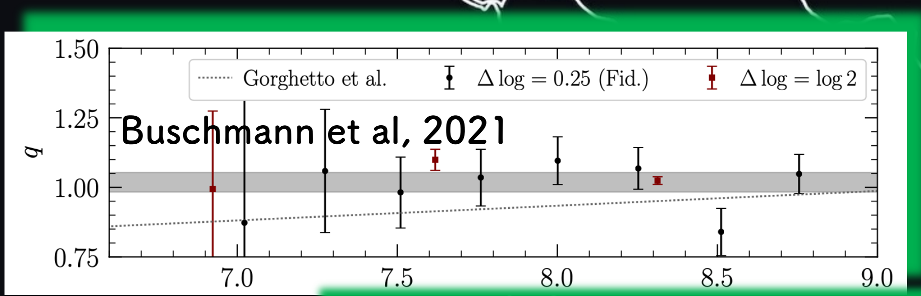
IR dominant axions, q > 1

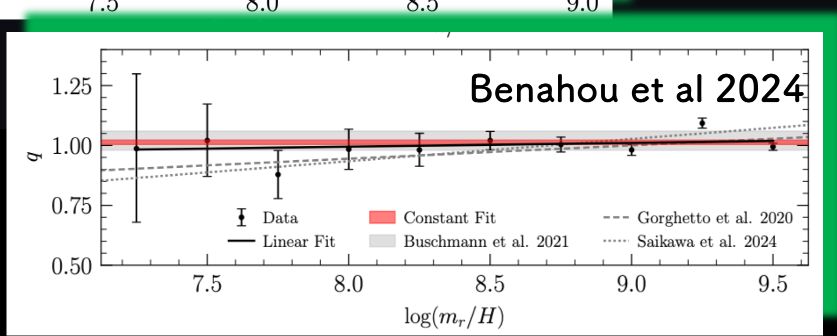




Nearly
conformal strings ,q ~ 1

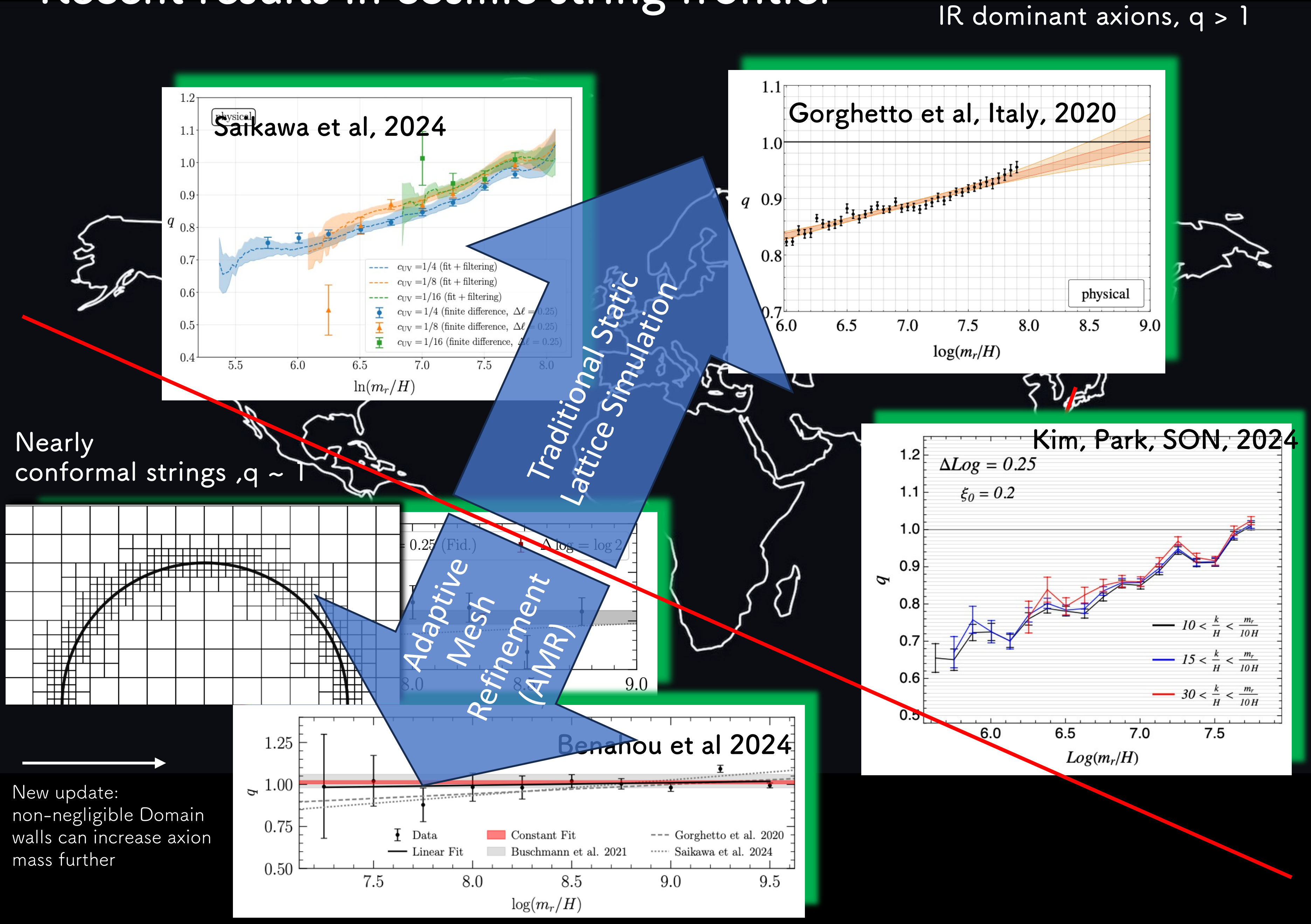






non-negligible Domain walls can increase axion mass further

Recent results in cosmic string frontier



Axion mass prediction

Axion Dark Matter from Cosmic String Network

Heejoo Kim[†], Junghyeon Park[†], and Minho Son[†]

[†]*Department of Physics, Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea*

Kim, Park, **SON** 2402.00741

$$m_a \geq 420\ \mu eV$$

Fat-string pre-evolution

$$m_a \geq 470\ \mu eV$$

Thermal pre-evolution

More Axions from Strings

Marco Gorghetto[a], Edward Hardy[b], and Giovanni Villadoro[c]

[a] *Department of Particle Physics and Astrophysics, Weizmann Institute of Science, Herzl St 234, Rehovot 761001, Israel*

[b] *Department of Mathematical Sciences, University of Liverpool, Liverpool, L69 7ZL, United Kingdom*

[c] *Abdus Salam International Centre for Theoretical Physics, Strada Costiera 11, 34151, Trieste, Italy*

Gorghetto et al 2020

$$m_a \geq 450\ \mu eV$$

Fat-string pre-evolution

Spectrum of global string networks and the axion dark matter mass

Ken'ichi Saikawa,[1] Javier Redondo,[2,3] Alejandro Vaquero,[3] and Mathieu Kaltschmidt[3]

[1]*Institute for Theoretical Physics, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan*

[2]*Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Boltzmannstr. 8, 85748 Garching, Germany*

[3]*CAPA & Departamento de Física Teórica, Universidad de Zaragoza, C. Pedro Cerbuna 12, 50009 Zaragoza, Spain*

(Dated: October 16, 2024)

Saikawa et al 2024

$$450\ \mu eV \geq m_a \geq 95\ \mu eV$$

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Axion mass prediction from adaptive mesh refinement cosmological lattice simulations

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[2]*Theoretical Physics Group, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, U.S.A.*

[3]*GRAPPA Institute, Institute for Theoretical Physics Amsterdam, University of Amsterdam, Science Park 904, 1098 XH Amsterdam, The Netherlands*

[4]*Astrophysics Theory Department, Theory Division, Fermilab, Batavia, IL 60510, USA*

[5]*Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637*

(Dated: December 13, 2024)

Benahou et al 2024

$$280 \leftarrow 65\ \mu eV \geq m_a \geq 45\ \mu eV$$

Buschmann et al 2021

$$180\ \mu eV \geq m_a \geq 40\ \mu eV$$

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Static Lattice Simulation

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Do not exceed current bound,
Only axion from strings in scaling regime
+ nonlinearity around QCD
[Domain-walls are sub-dominant]

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Account for 100% DM abundance,
Only axion from strings in scaling regime,
Mass range due to multiple ansatz for ξ and q + stat. + syst. errors

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AMR

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$$\xi_c^{\rm lin} = -0.19(3) + 0.205\,\ell$$

$$\xi_c^{\rm sat} = \frac{-0.25(15) + 0.23(6)\ell}{1 + 0.02(4)\ell}$$

$$\ell = \log \frac{m_r}{H}$$

$$q = q_0 + q_1/\ell^2 \text{ (Plateau)} \qquad q = q_0 + q_1\ell \text{ (Linear)}$$

TABLE II: Axion dark matter mass predicted at $\ln(m_r/H) = 70$ and its error budget. For each extrapolation of q (plateau extrapolation with $q = q_0 + q_1/\ell^2$ and linear extrapolation with $q = q_0 + q_1\ell$), we consider two models of ξ_c.

Parameter	m_a [μeV] (Plateau extrapolation)		m_a [μeV] (Linear extrapolation)	
	$\xi_c^{\rm lin}$	$\xi_c^{\rm sat}$	$\xi_c^{\rm lin}$	$\xi_c^{\rm sat}$
q	141–198	102–144	439	311
ξ	167–173	95–151	431–447	237–381
x_0	149–197	111–137	429–450	305–316
f_L	168–172	122–125	435–443	308–313
$n_{\rm QCD}$	138–175	101–127	379–449	268–317

Note that plateau (linear) model predicts smaller (larger) axion mass

Plateau ansatz :

$$95\ \mu eV \lesssim m_a \lesssim 198\ \mu eV$$

$$f_a \approx (2.9 - 6.0)\times 10^{10}\ {\rm GeV}$$

Linear ansatz :

$$237\ \mu eV \lesssim m_a \lesssim 450\ \mu eV$$

$$f_a \approx (1.3 - 2.4)\times 10^{10}\ {\rm GeV}$$

$$\rightarrow\ 95\ \mu eV \lesssim m_a \lesssim 450\ \mu eV$$

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AMR

Axion mass prediction from adaptive mesh refinement cosmological lattice simulations

Joshua N. Benabou,[1,2] Malte Buschmann,[3] Joshua W. Foster,[4,5] and Benjamin R. Safdi[1,2]

Account for 100% DM abundance,
Mass range due to the range of q from fitting,
Axions from strings scaling regime + string-domain walls,

Benahou et al 2024

$$280 \leftarrow 65\ \mu eV \geq m_a \geq 45\ \mu eV$$

Buschmann et al 2021

$$180\ \mu eV \geq m_a \geq 40\ \mu eV$$

Thermal pre-evolution

Exact scaling behavior has a dramatic impact on axion mass

String number density per Hubble

$$\xi = \beta + \alpha \log \frac{m_r}{H} \quad \text{vs} \quad \xi \sim \mathcal{O}(1)$$

A counter-study claiming a constant scaling of a unity
Correia, Hindmarsh, Lizarraga, Lopes-Eiguren, Rummukainen, Urrestilla, 2410.18064

Moving frame vs Rest frame

$$\xi_r = \xi \langle \gamma^{-1} \rangle$$

Spectral index of axion power spectrum

$$q = q_0 + q_1 \log \frac{m_r}{H} \quad , q = q_0 + \frac{q_1}{\log^2 \frac{m_r}{H}} \quad , q = \mathcal{O}(1)$$

- ✓ stronger disagreement in here

New independent scaling solution being consistent with ξ and $\boldsymbol{q}$ would be helpful for clarifying disagreements

New scaling in string fluctuations

arXiv > hep-ph > arXiv:2411.08455

High Energy Physics – Phenomenology

[Submitted on 13 Nov 2024]

More Scalings from Cosmic Strings

Heejoo Kim, Minho Son

Observed a new scaling consistent with spectral index of axion power spectrum

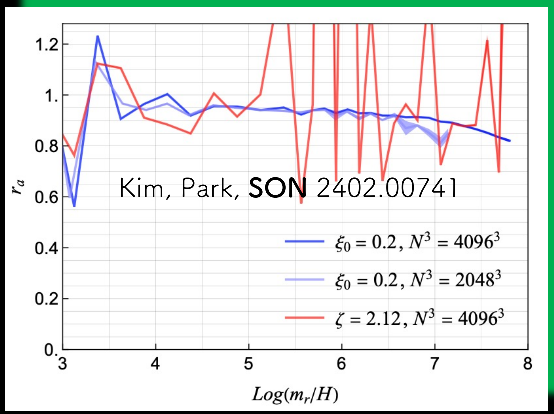
$$q = q_0 + q_1 \log \frac{m_r}{H}$$

New brand-new scaling consistent with q could be hinted from this observation

**Branching fraction of strings to axion

$$r_a = \frac{\Gamma_a}{\Gamma_a + \Gamma_r}$$

$$R^{-4}\partial_t(R^4\rho_a) \sim \Gamma_a$$



$$\rightarrow \Gamma = \Gamma_a + \Gamma_r \sim \Gamma_a$$

We speculate that axion power-law spectrum is originated from string power-law

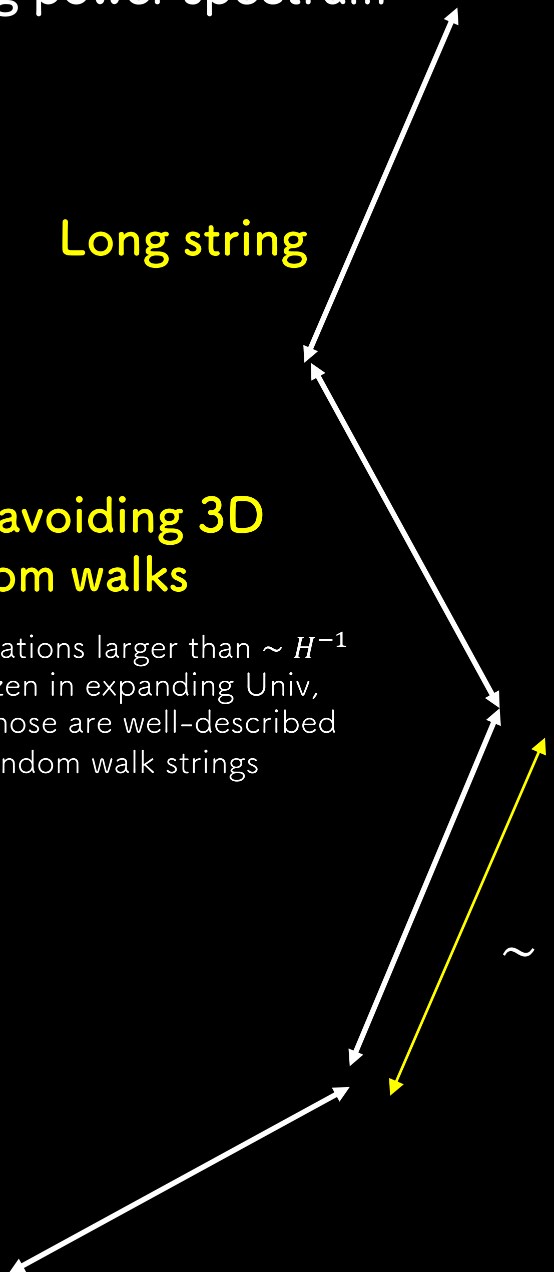
Looking into String power spectrum

Kim, **SON**, 2411.08455

Long string

Self-avoiding 3D random walks

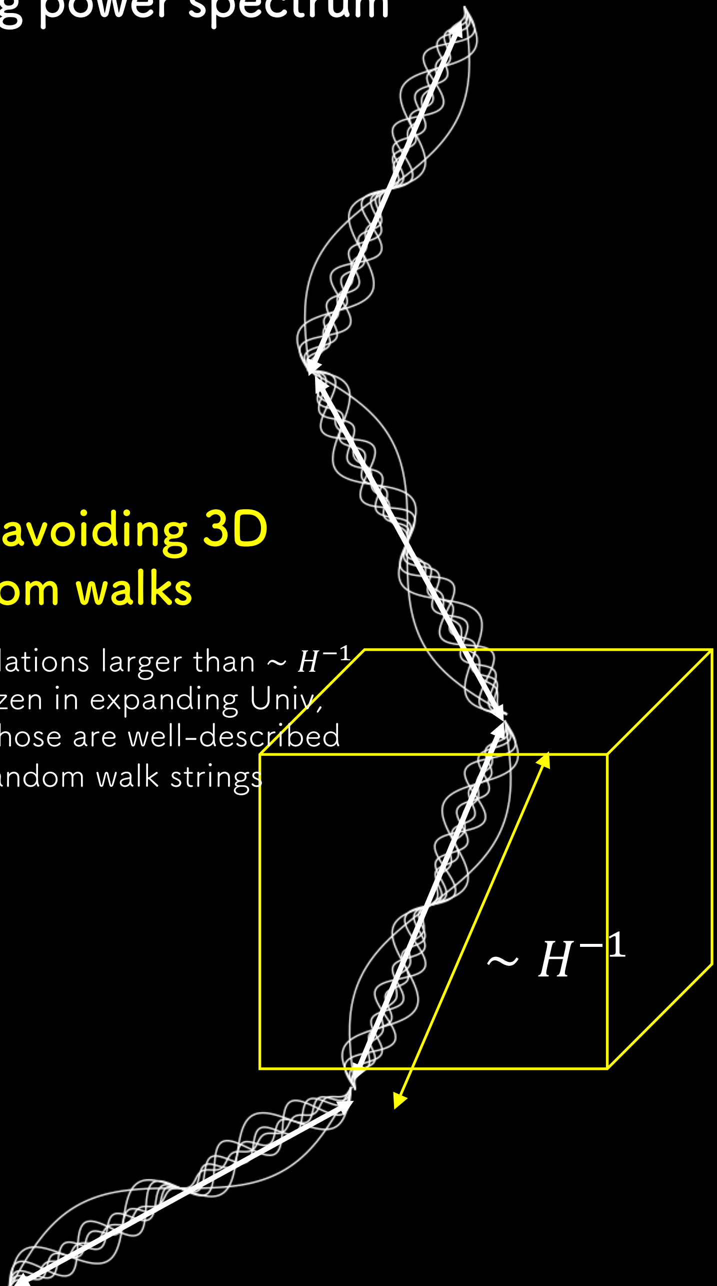
Oscillations larger than $\sim H^{-1}$ is frozen in expanding Univ, and those are well-described by Random walk strings



$\sim H^{-1}$: correlation length

Looking into String power spectrum

Kim, **SON**, 2411.08455



Self-avoiding 3D random walks

Oscillations larger than ~ H^{-1} is frozen in expanding Univ, and those are well-described by Random walk strings

We are interested in oscillations shorter than ~ H^{-1} that can contribute to axions

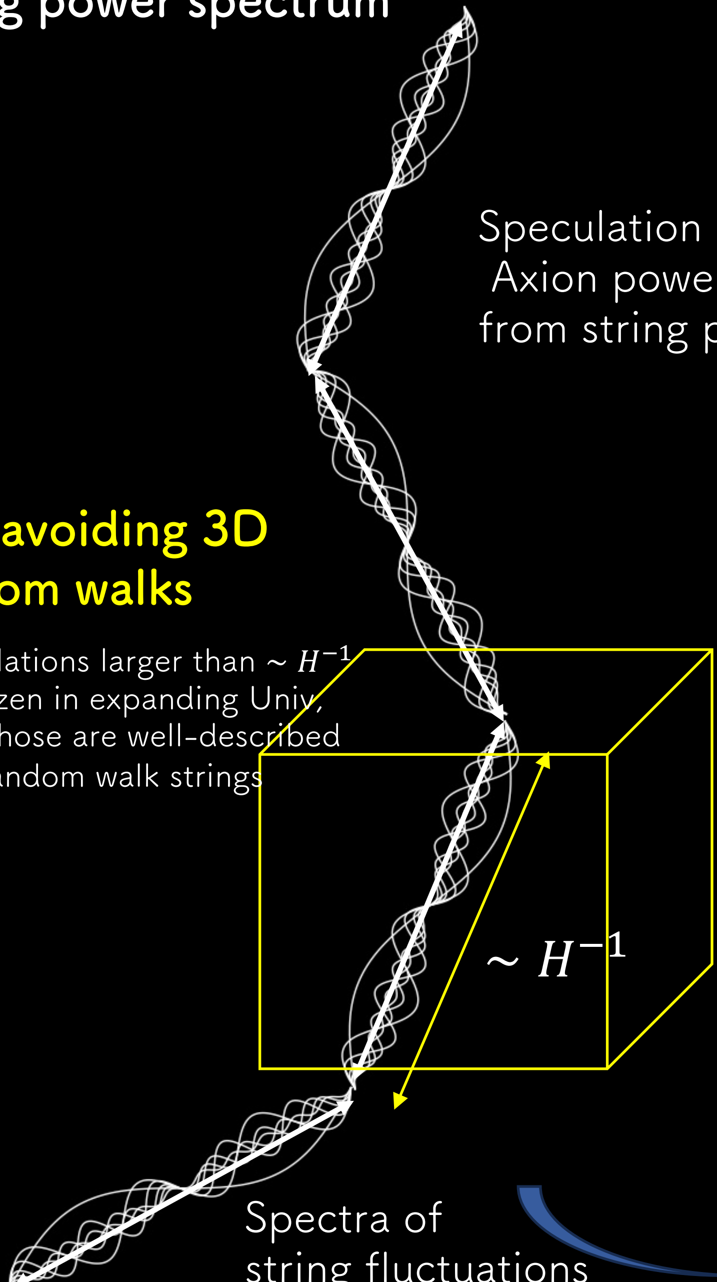
Looking into String power spectrum

Kim, **SON**, 2411.08455

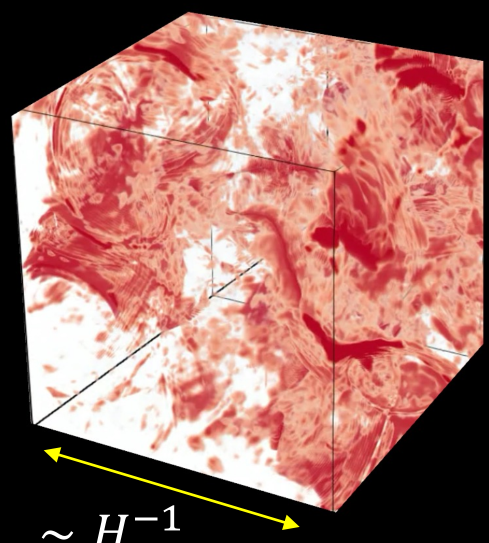
Speculation :
Axion power-law spectrum should be originated from string power-law behavior

Self-avoiding 3D random walks

Oscillations larger than $\sim H^{-1}$ is frozen in expanding Univ, and those are well-described by Random walk strings

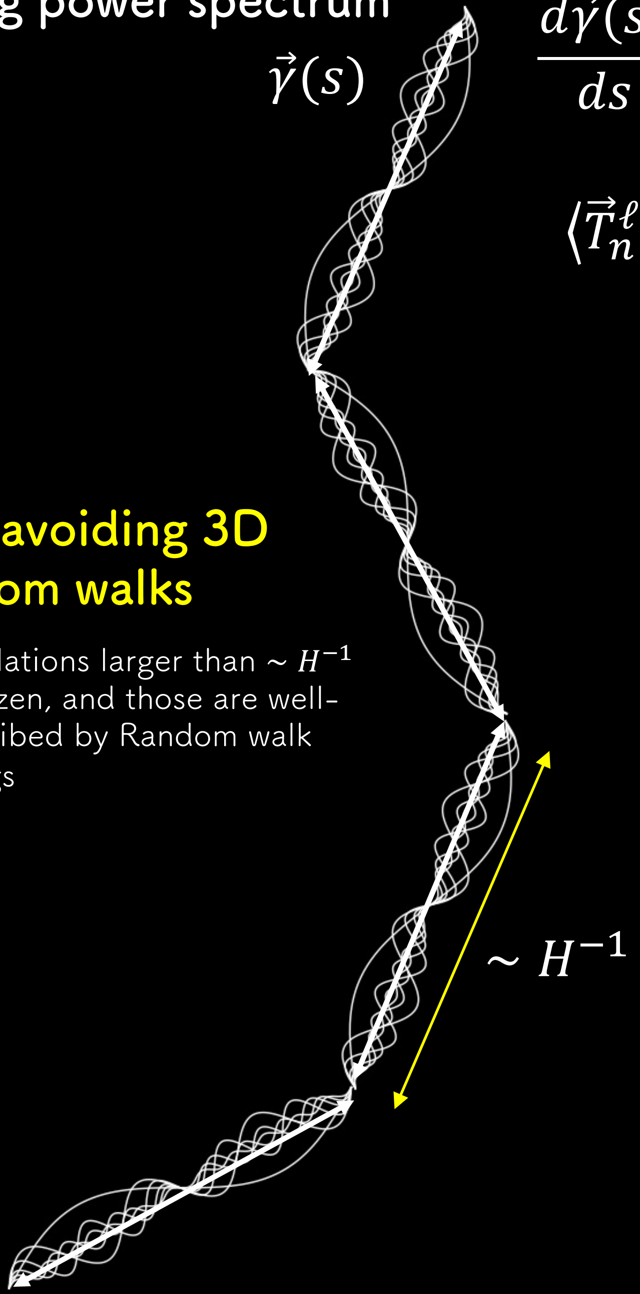


Axion energy density (red color) from cosmic strings inside one Hubble volume in real simulation



Spectra of string fluctuations → Axion spectra

Looking into String power spectrum

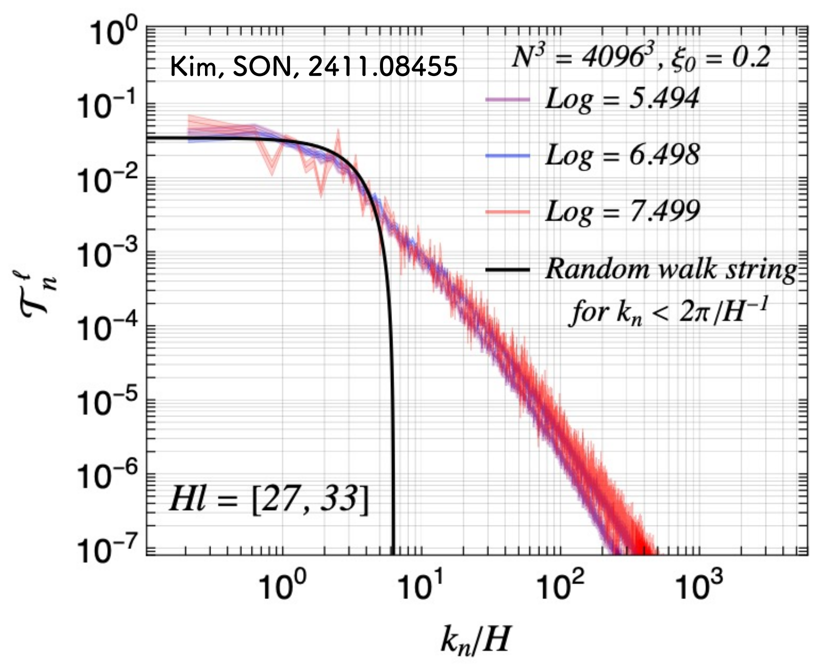


$$\frac{d\vec{\gamma}(s)}{ds} = \vec{t}(s) = \sum_{n=-\infty}^{\infty} \vec{T}_n^{\ell} e^{i\frac{2\pi n}{\ell}s}$$

$$\langle \vec{T}_n^{\ell} \cdot \vec{T}_{n'}^{\ell} \rangle = \mathcal{T}_n^{\ell} \delta_{(n+n')0}$$

Self-avoiding 3D random walks

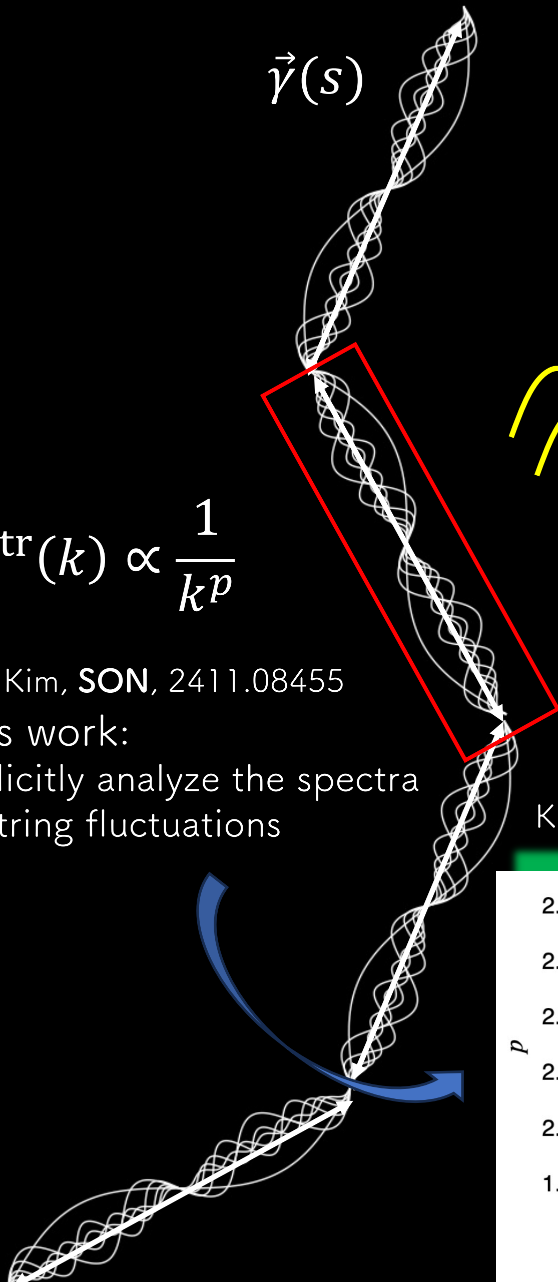
Oscillations larger than $\sim H^{-1}$ is frozen, and those are well-described by Random walk strings



Assume string fluctuation follows the power law similarly to axions

$$\mathcal{T}_n^{\ell} \sim \frac{1}{k^p}$$

String power spectrum



$$\Gamma_a^{\text{str}}(k) \propto \frac{1}{k^p}$$

Kim, **SON**, 2411.08455

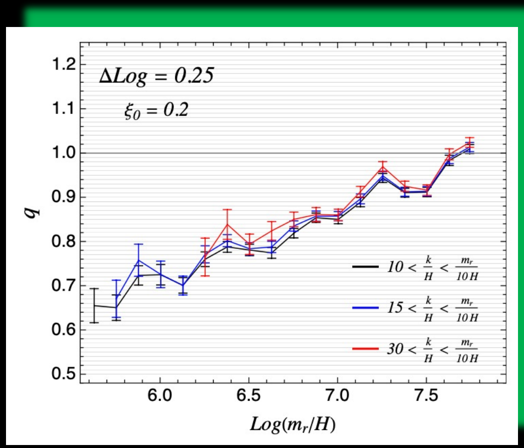
This work:
Explicitly analyze the spectra of string fluctuations

Radiation into Axions

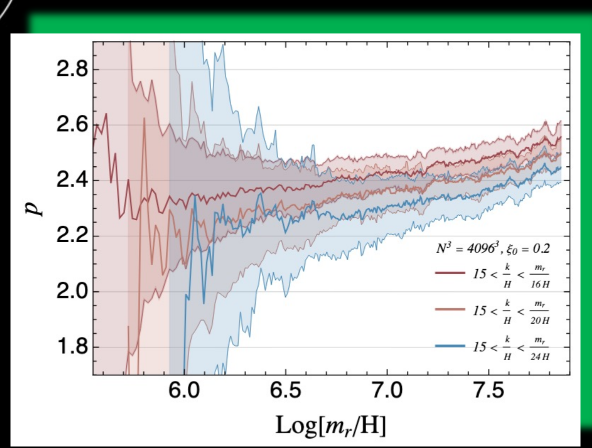
$$\Gamma_a \sim \frac{1}{k^q}$$

Traditional:
All literature analyze the axion spectra away from string cores

Kim, Park, SON 2402.00741

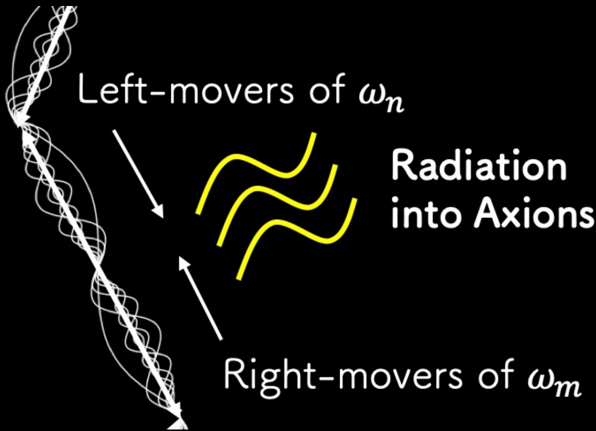


Kim, **SON**, 2411.08455



Question :
How q is related to p ?

Analytic connection between strings and axions



1. No Expansion of Universe
2. Almost straight string
3. Kalb-Ramond (KR) interaction in thin string Limit

$$\frac{\Gamma_a^{\rm str.}(k)}{m_r^2 f_a^2} = 8\pi^3 \xi \left(\frac{m_r}{H}\right)^{-2} \int_0^\infty \frac{d(H\ell)}{H\ell_{\rm ave.}} \frac{\rho(\ell)}{H} \sum_{n=1}^{\infty} nH\delta\left(k - \frac{2\pi n}{\ell}\right) \sum_{\substack{|m|<n,\\ m+n\ {\rm even}}} \mathcal{T}^\ell_{\frac{n+m}{2}} \mathcal{T}^\ell_{\frac{n-m}{2}} \ ,$$

$$\Gamma_a^{\rm str}(k = \frac{2\pi n}{\ell}) \propto n \sum_{m=1}^{n-1} \frac{1}{(n+m)^p (n-m)^p}$$

$$\mathcal{T}_n^\ell \sim \begin{cases} B_\ell \left(\frac{k_n}{H}\right)^{-p} & : k_{IR} < k < k_{UV} \\ 0 & : \text{otherwise} \end{cases}$$

$$\rightarrow \Gamma_a^{\rm str}(k) \propto k^{2-2p} \times k^{p-1} = \frac{1}{k^{p-1}}$$

$: \text{a few} \times (2k_{IR}) < \ k < k_{UV}$

$$q = p - 1 - \Delta^{\rm str.}_{\rm non-pert}$$

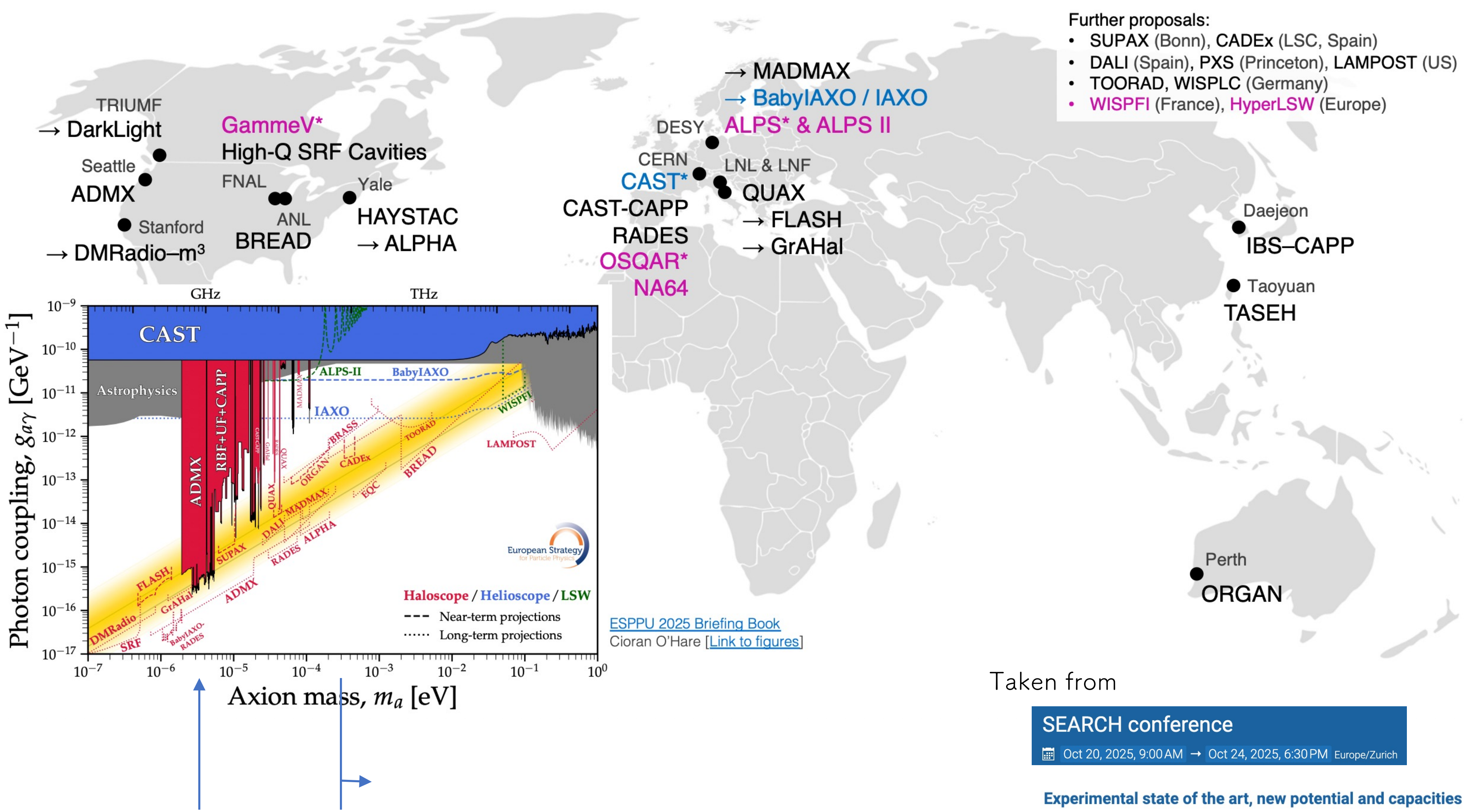
Part missed in our derivation

Low-mass Axion / ALP detection

Haloscopes (relic axions), Helioscopes (solar axions), Light shining through the wall (lab axions), '→' Future / proposed experiments, *Concluded exps (incomplete list)

Further proposals:

- SUPAX (Bonn), CADEx (LSC, Spain)
- DALI (Spain), PXS (Princeton), LAMPOST (US)
- TOORAD, WISPLC (Germany)
- WISPFI (France), HyperLSW (Europe)



ESPPU 2025 Briefing Book
Cioran O'Hare [Link to figures]

Taken from

SEARCH conference
Oct 20, 2025, 9:00 AM → Oct 24, 2025, 6:30 PM Europe/Zurich

Experimental state of the art, new potential and capacities

Speaker: Andreas Hoecker (CERN)

* CAPP -> DMAG (Dark Matter Axion Group)

Low-mass Axion / ALP detection

Haloscopes (relic axions), Helioscopes (solar axions), Light shining through the wall (lab axions), '→' Future / proposed experiments, *Concluded exps (incomplete list)

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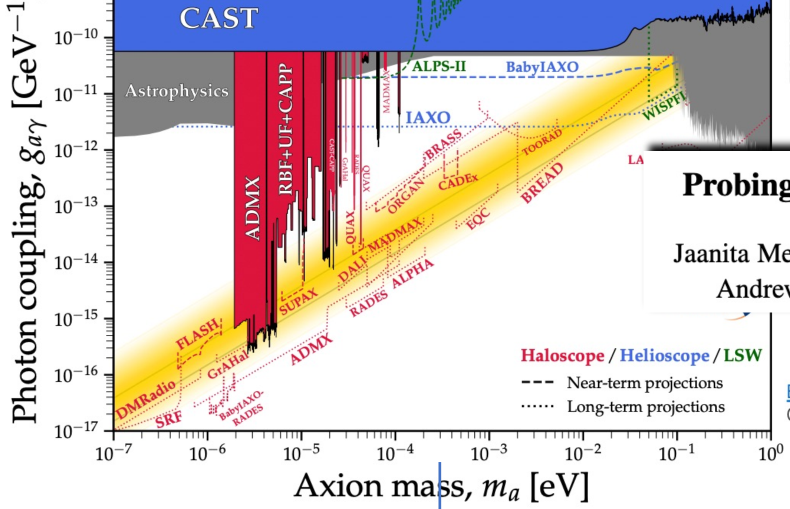

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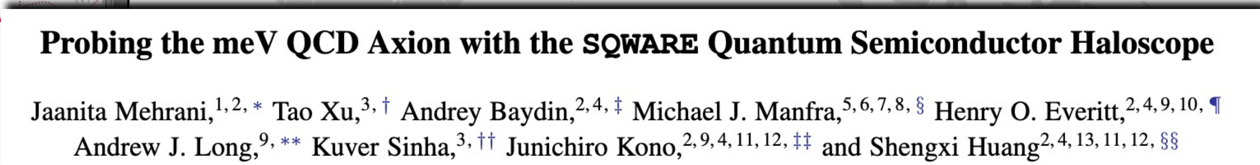
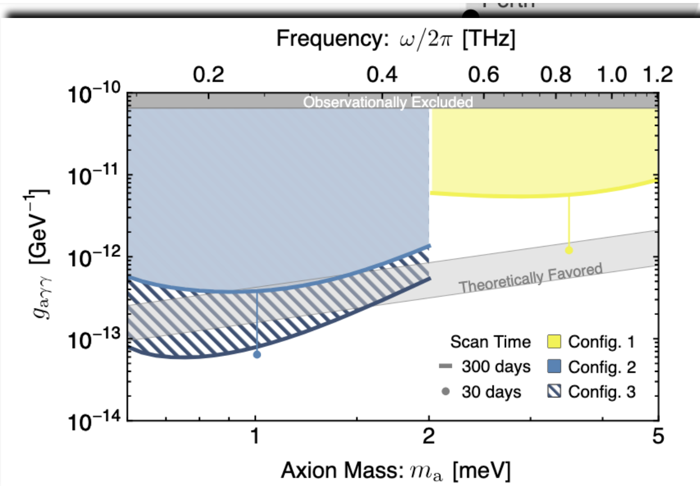

Probing the meV QCD Axion with the SQWARE Quantum Semiconductor Haloscope

Jaanita Mehrani,[1,2,*] Tao Xu,[3,†] Andrey Baydin,[2,4,‡] Michael J. Manfra,[5,6,7,8,§] Henry O. Everitt,[2,4,9,10,¶] Andrew J. Long,[9,**] Kuver Sinha,[3,††] Junichiro Kono,[2,9,4,11,12,‡‡] and Shengxi Huang[2,4,13,11,12,§§]



In near future

- ✓ Improve lattice resolution at least by 4x -> 16K each dimension

  Technically huge jump. Super-challenging

  Question : q is very close to touch the line of unity.
  will q keep growing above unity or get saturated ? 16K should help for this.

Supported by Static Lattice Simulations	VS	Supported by AMR (Adaptive Mesh Refinement)

- ✓ Numerical testing the collapse mechanism (while solving axion quality) of string-domain wall system with N > 1 might be interesting

  Question : is commercial method of gauged discrete symmetry actually working ?

  Lu, Reece, Sun, 2312.07650

- ✓ The statistical analysis of the string time evolution should be useful to understand the interaction between axion and strings.

  Question : any hint for better EFT description ?