THE SEARCH FOR AXIONS CIRCA 2023

BEN SAFDI

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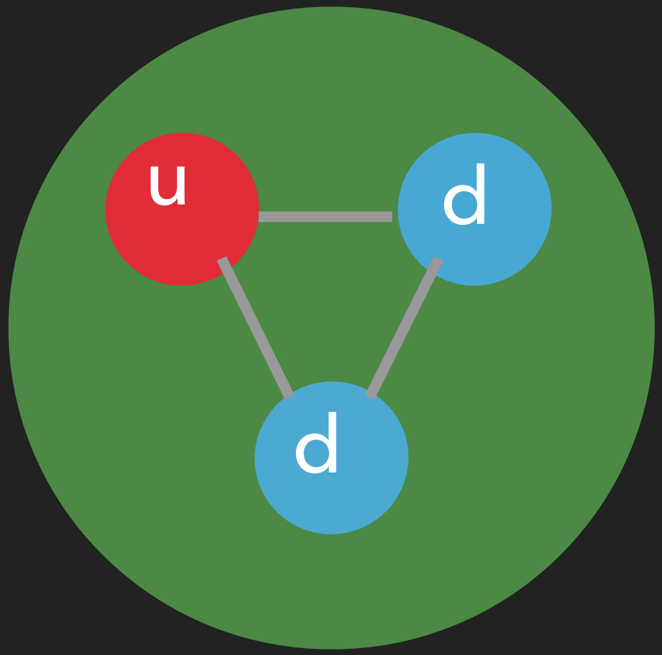
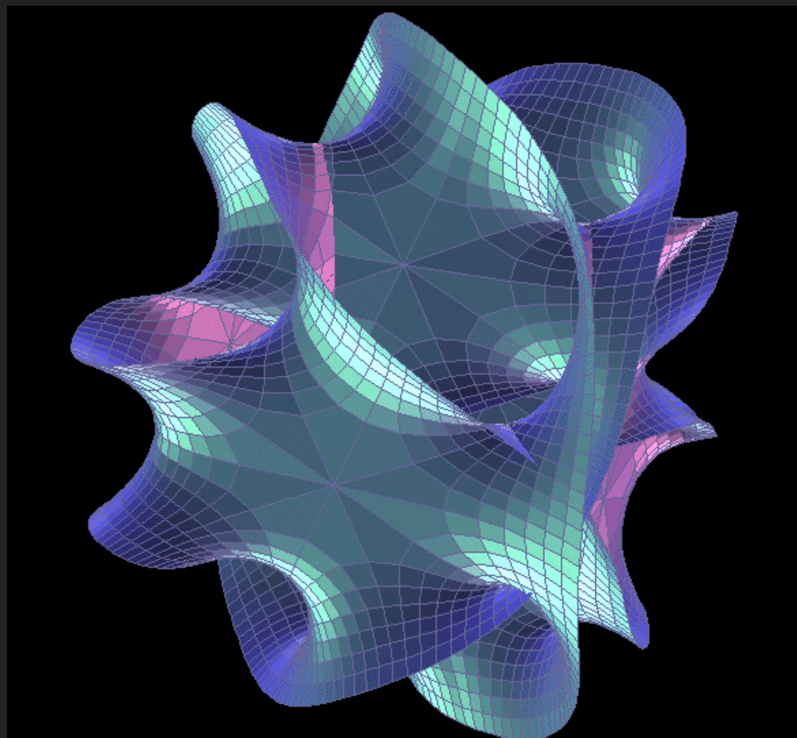
UNIVERSITY OF CALIFORNIA, BERKELEY

CHUNG-ANG UNIVERSITY BEYOND THE STANDARD MODEL WORKSHOP

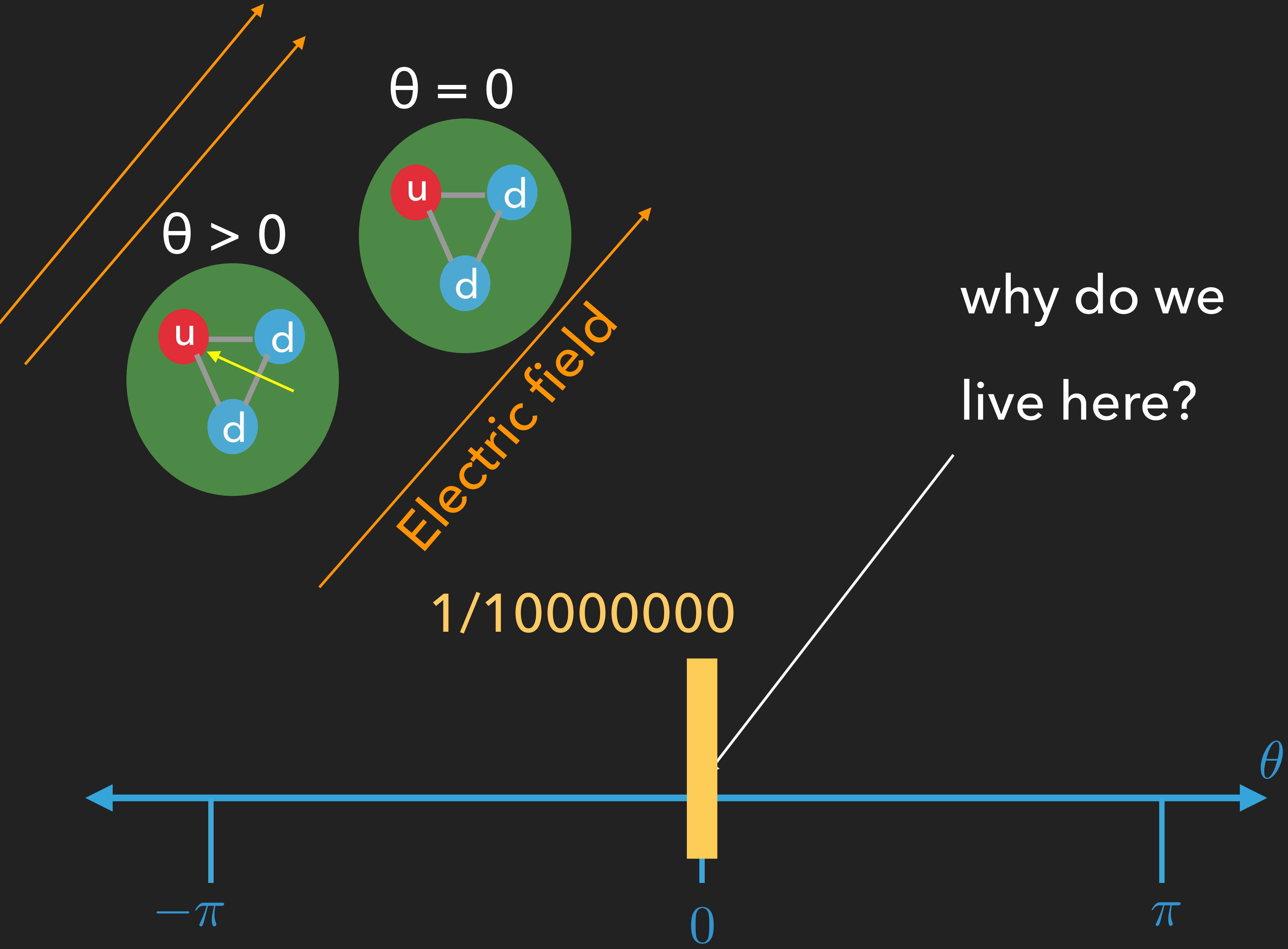
Reasons to think about axions

1. They solve the Strong-CP Problem
2. They can explain the observed dark matter
3. They arise generically in string theory
4. They may be connected to deep aspects of quantum gravity (see Matt Reece's talk)





The Strong CP Problem: no neutron EDM?



why do we live here?

The neutron electric dipole moment puzzle

Roberto Peccei

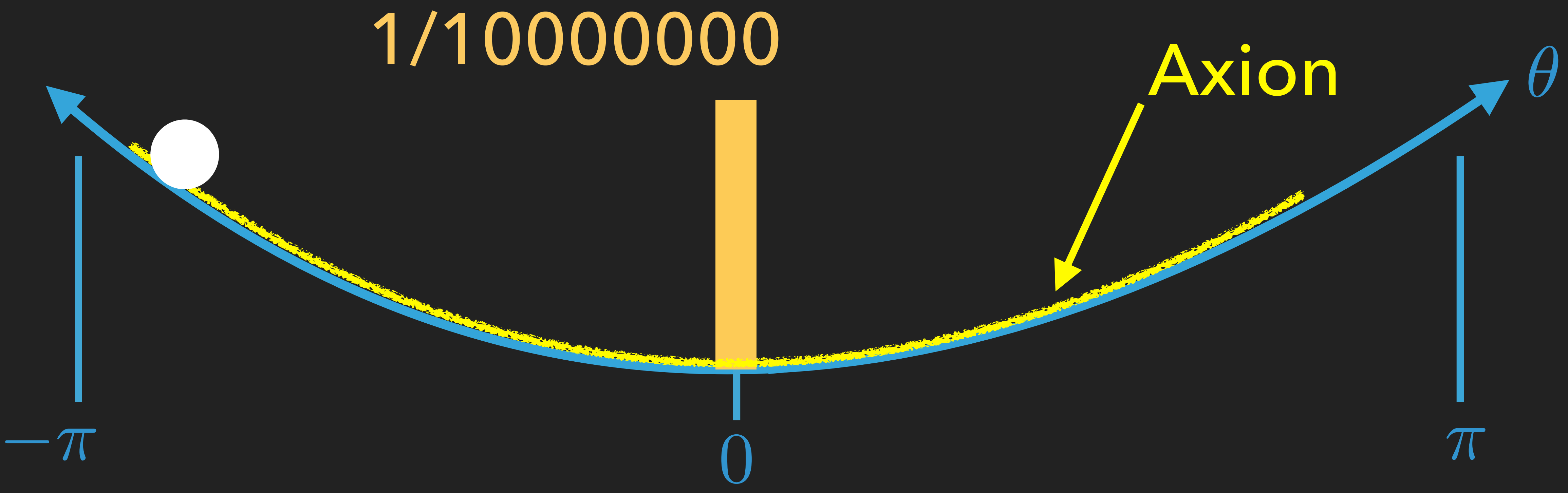
Helen Quinn

1977

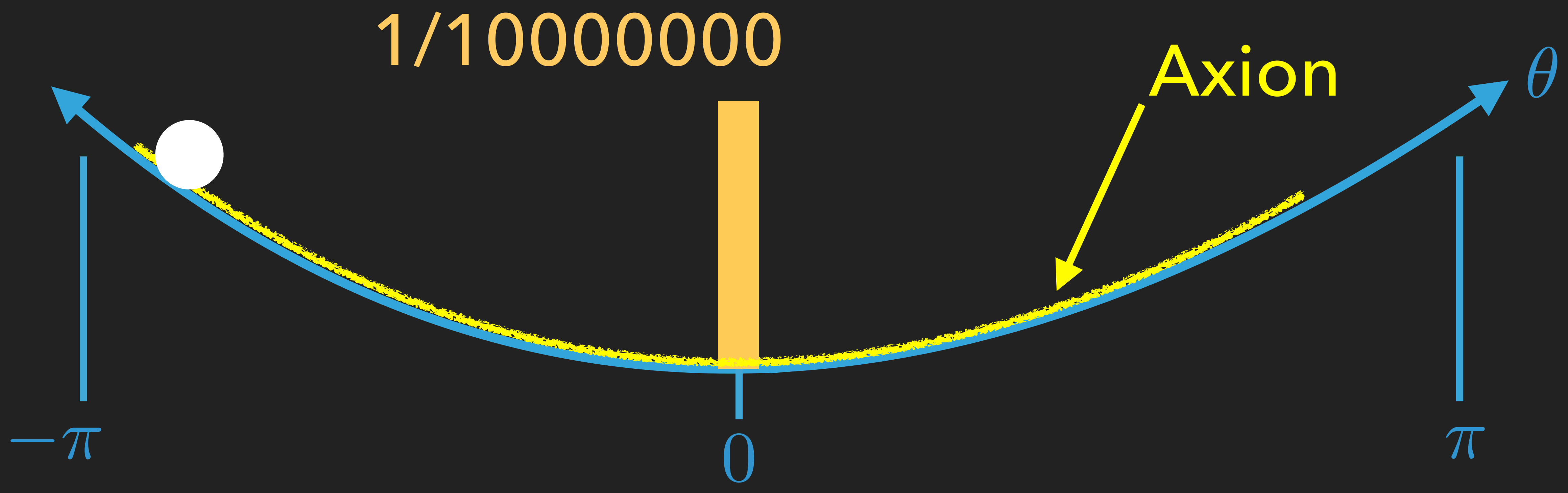
Steven Weinberg

Frank Wilczek

1978



Axion Solution to Strong CP (more precisely)



$$\mathcal{L} = -\frac{g^2}{32\pi^2}\left(\bar{\theta} + \frac{a}{f_a}\right) G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$f_a \gtrsim 10^9 \text{ GeV}$$

$$d_n \propto \left(\bar{\theta} + \frac{a}{f_a}\right)$$

$$V(a) \approx \frac{1}{2}\Lambda^4_{\text{QCD}}\left(\bar{\theta} + \frac{a}{f_a}\right)^2$$

Axion Solution to Strong CP (more precisely)

$$\mathcal{L} = -\frac{g^2}{32\pi^2}\left(\bar{\theta} + \frac{a}{f_a}\right) G_{\mu\nu}\tilde{G}^{\mu\nu}$$

$$\Big\downarrow$$

$$V(a) \approx \frac{1}{2}\Lambda_{\rm QCD}^4 \left(\bar{\theta} + \frac{a}{f_a}\right)^2$$

Axion mass: $m_a \approx \frac{\Lambda_{\rm QCD}^2}{f_a} \approx 10^{-5}\ \mathrm{eV}\left(\frac{10^{12}\ \mathrm{GeV}}{f_a}\right)$

Axions also couple to EM: $\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4} = g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$

$$g_{a\gamma\gamma} = \frac{C_\gamma \alpha_{\rm EM}}{2\pi f_a}\,, \qquad C_\gamma \sim \mathcal{O}(1)$$

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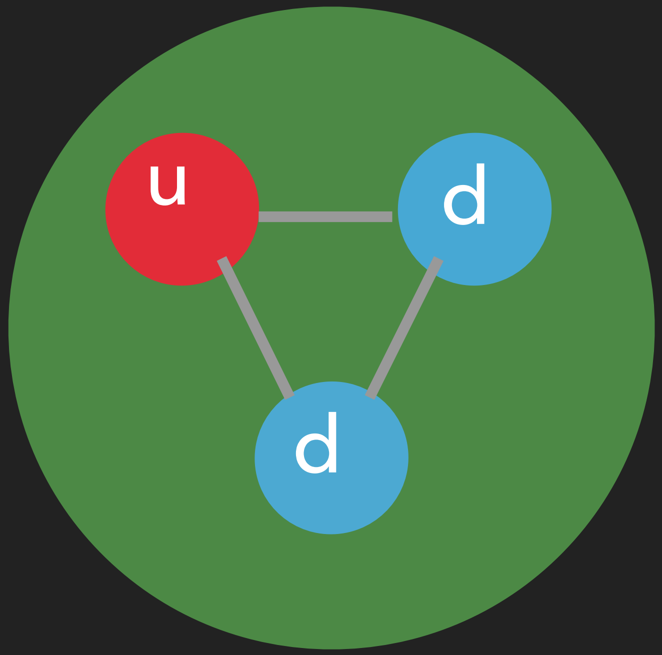
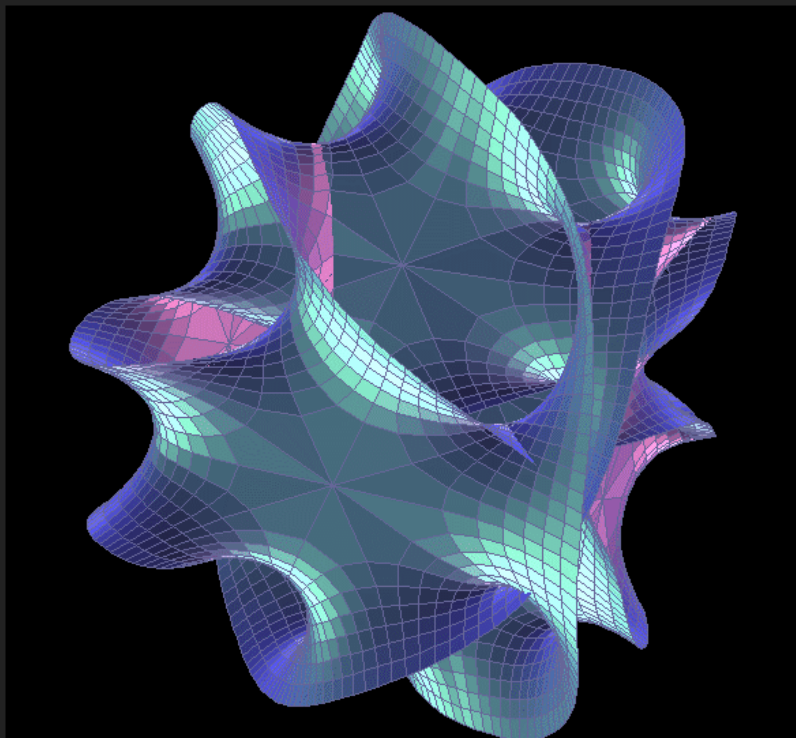
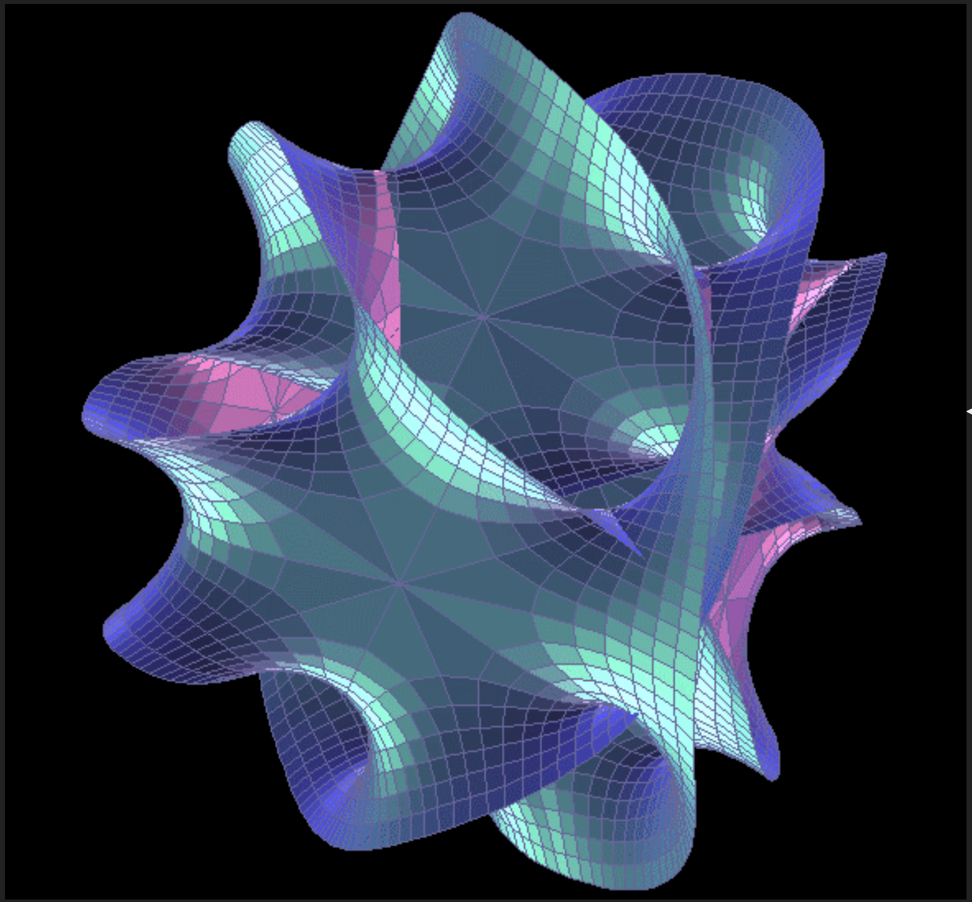
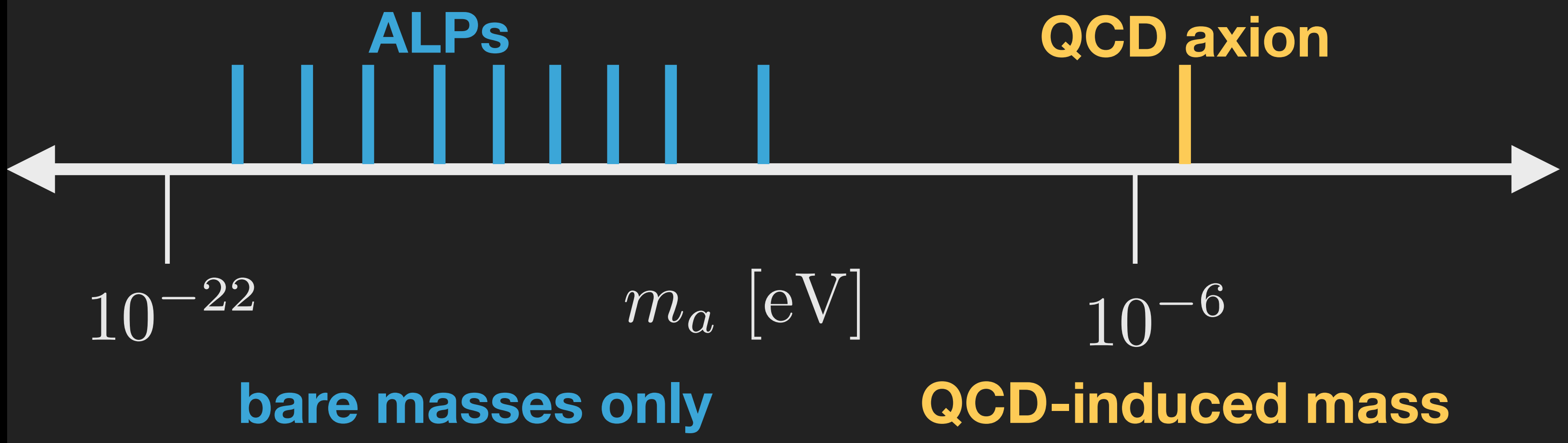




Axions Appear in String Theory

- Axions arise from compactified 2-form fields
- Perturbative masses protected by 10D gauge symmetry
- “Ultralight” non-perturbative masses (e.g. string instantons)





Axion-like particles versus QCD Axion

$$\mathcal{L} = \frac{-g^2}{32\pi^2}\xcancel{\frac{a}{f_a}}G_{\mu\nu}\tilde{G}^{\mu\nu} - \frac{C_\gamma \alpha_{\mathrm{EM}}}{8\pi f_a}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \sum_f \frac{C_f}{2f_a}\partial_\mu a \bar{f}\gamma^\mu\gamma_5 f$$

$$-\frac{1}{2}m_{\mathrm{bare}}^2 a^2$$

QCD axion only!

$$m_a^{\mathrm{QCD}} \gg m_{\mathrm{bare}}$$

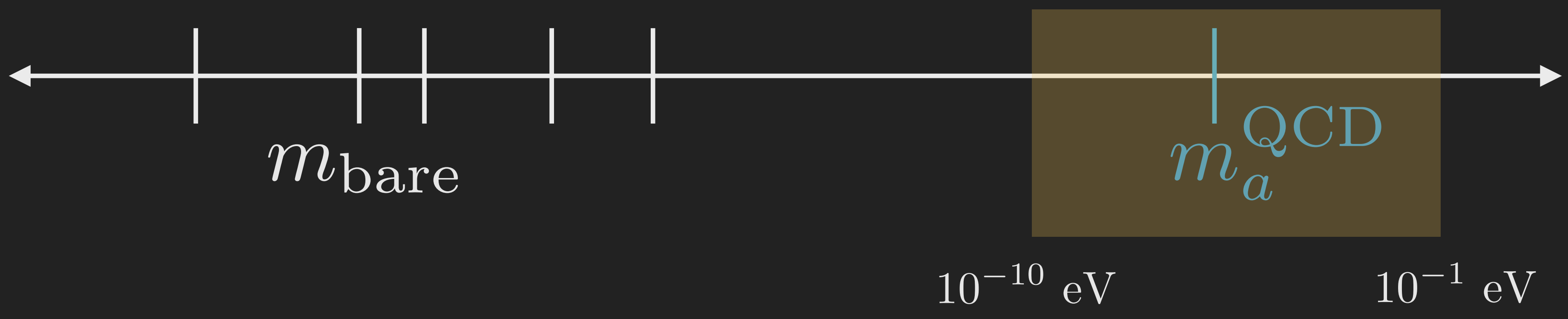
$g_{a\gamma\gamma}$

g_{aff}

small

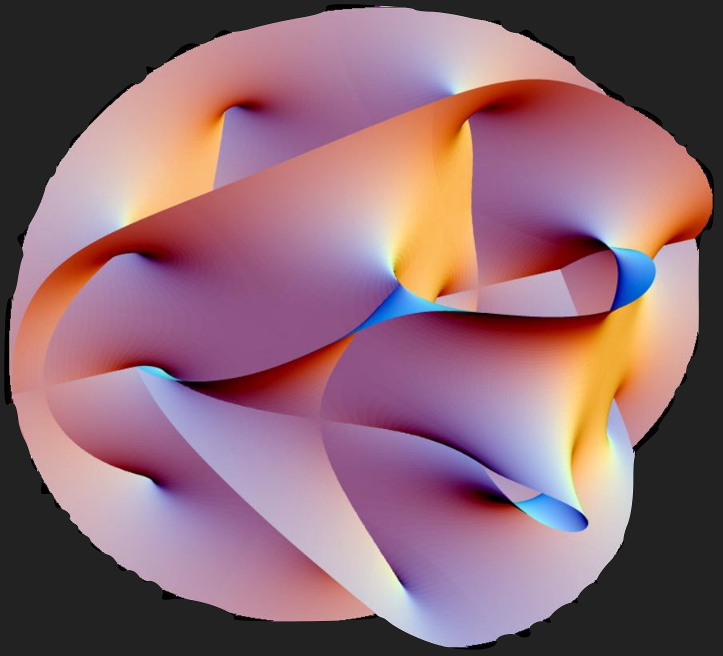
Sring Axiverse: *N* pseudo-scalars -> *N-1* ALPs + 1 QCD axion

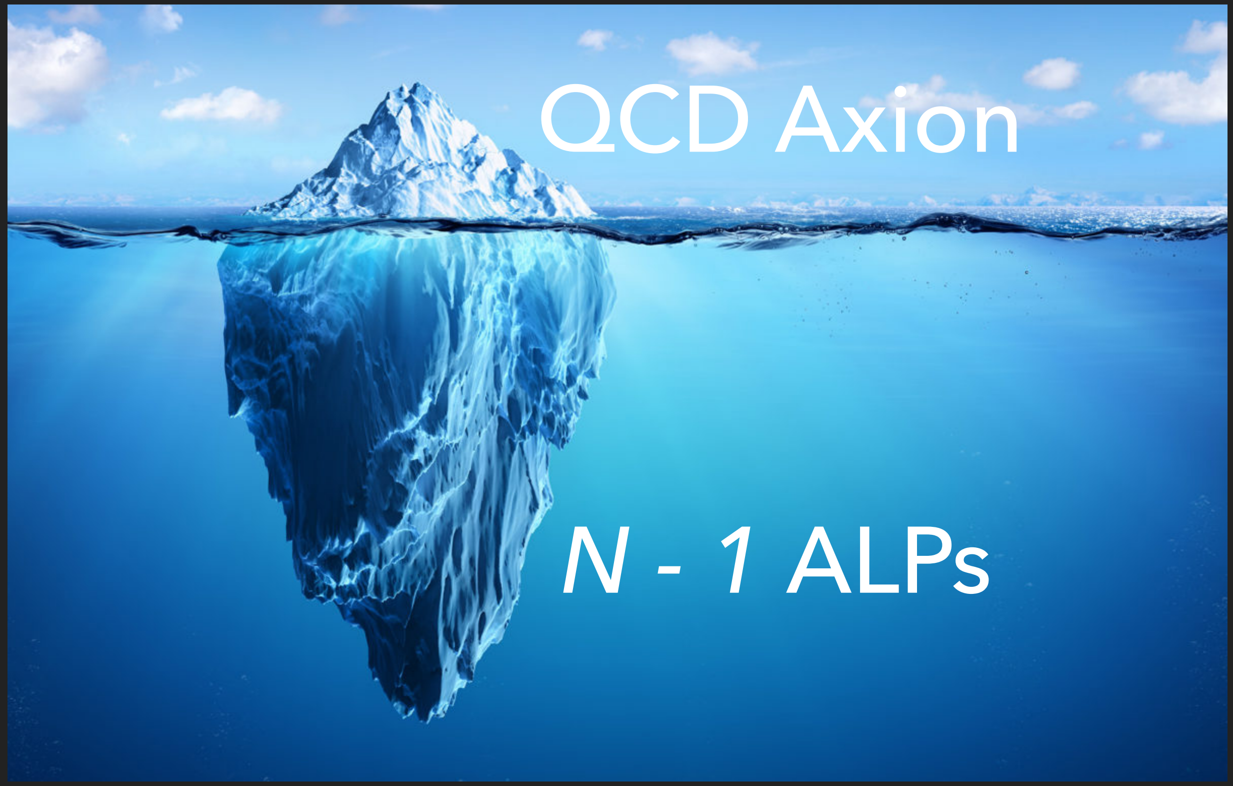
String theory provides answer to: why axions?



Axiverse: *N* pseudo-scalars -> *N-1* ALPs + 1 QCD axion

Zero modes of 2-form fields generate **10's - 100's of ALPs** from compactifion on internal space





Axions could be only way to experimentally probe string theory compactifications!

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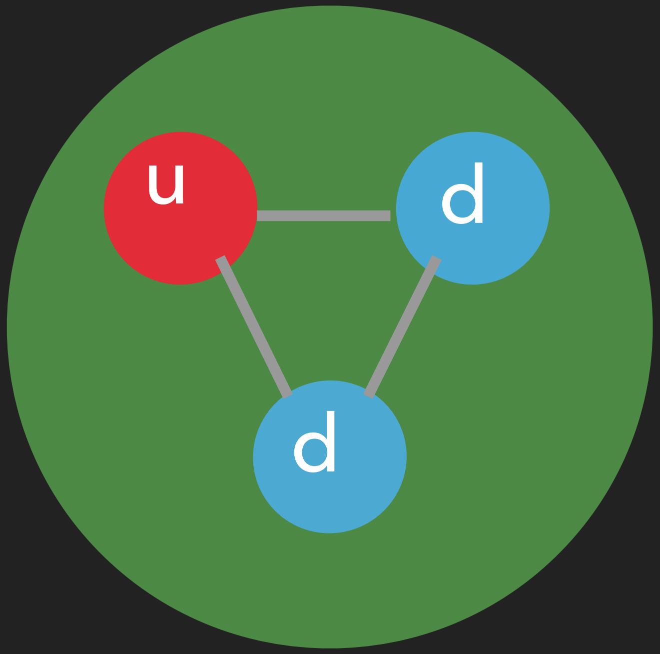
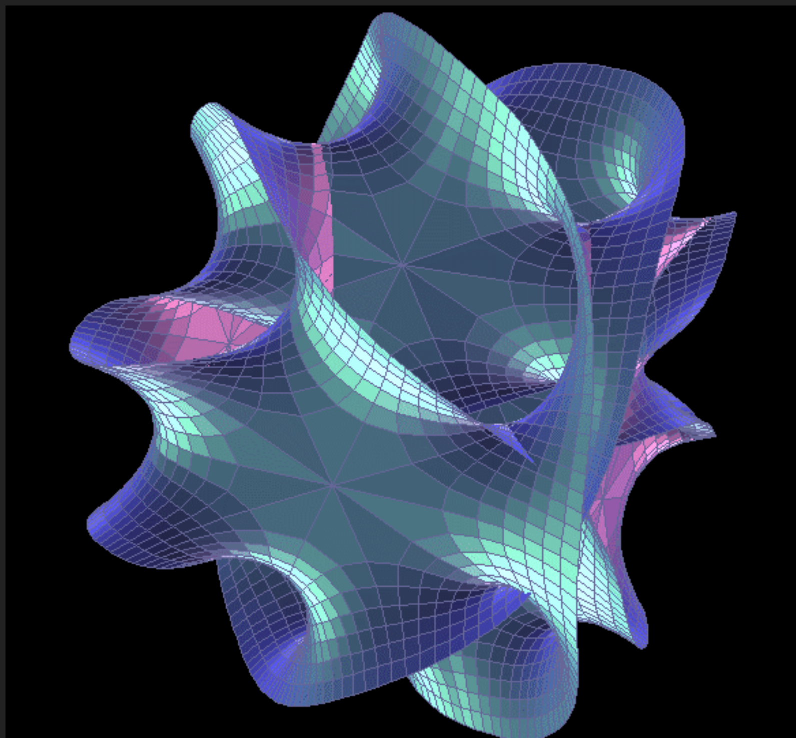
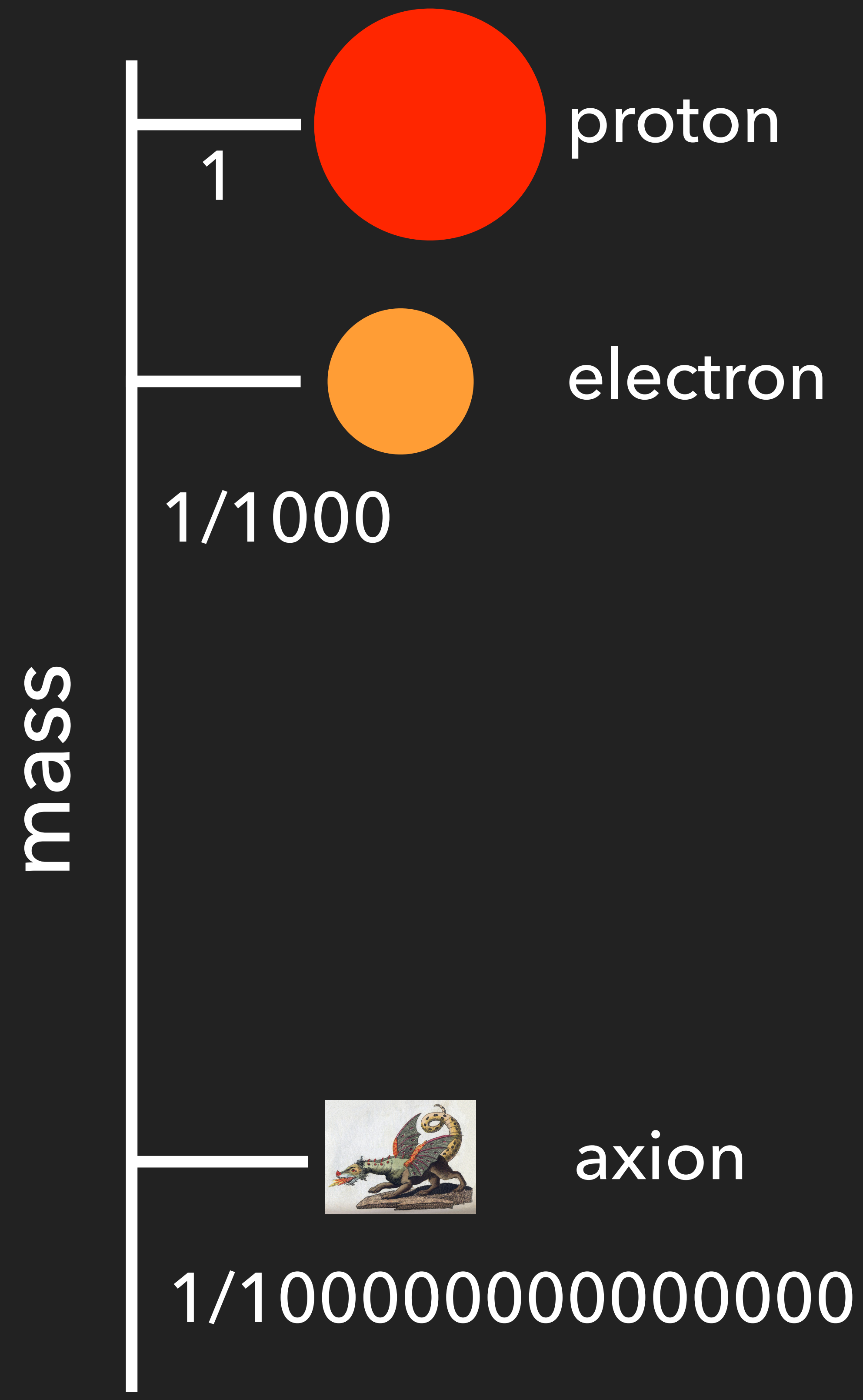
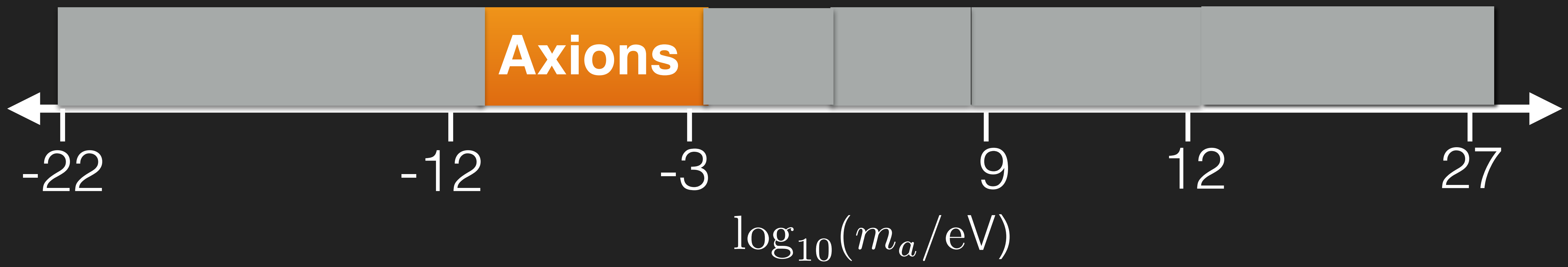




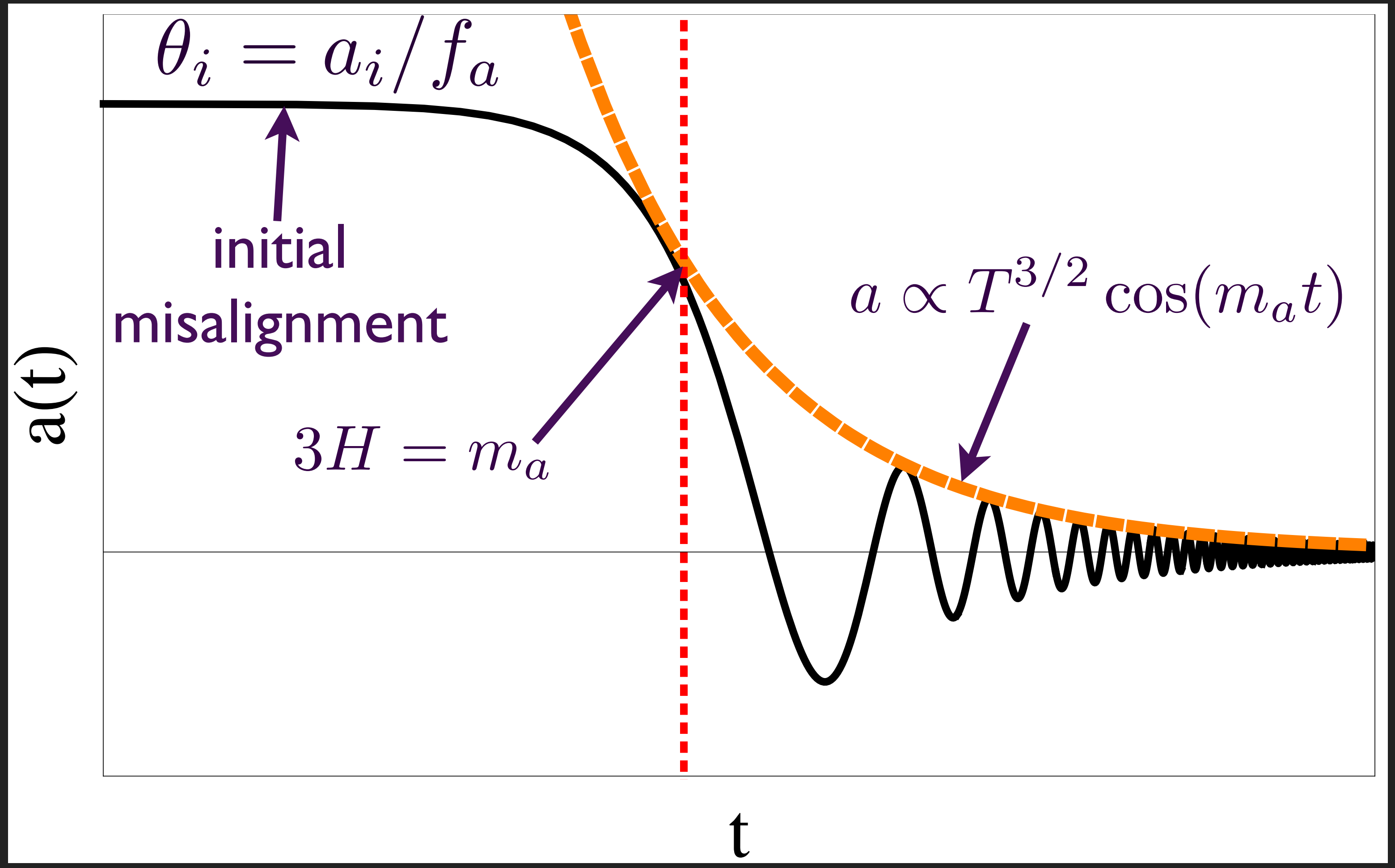
axion dark matter



1983



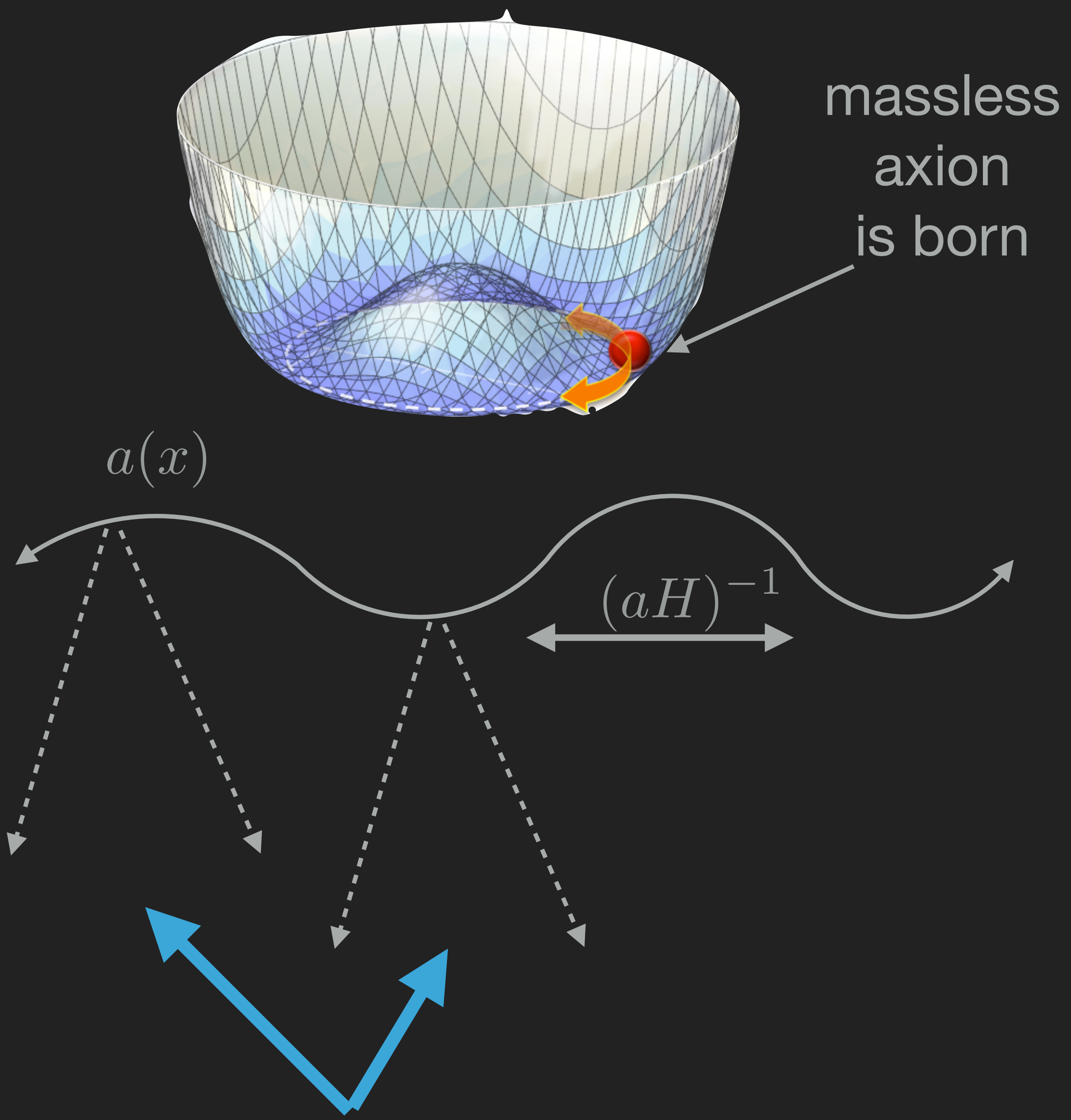
$$\sin a/f_a \sim a/f_a \;\; : \qquad \ddot{a} + 3H\dot{a} + m_a^2 a = 0$$



PQ broken before inflation!

$$\Omega_a h^2 \sim 0.1 \left(\frac{f_a}{10^{12}\ \mathrm{GeV}}\right)^{7/6} \theta_i^2$$

Axion generated before inflation



Causally disconnected regions with different homogeneous initial misalignment angles -> different DM densities

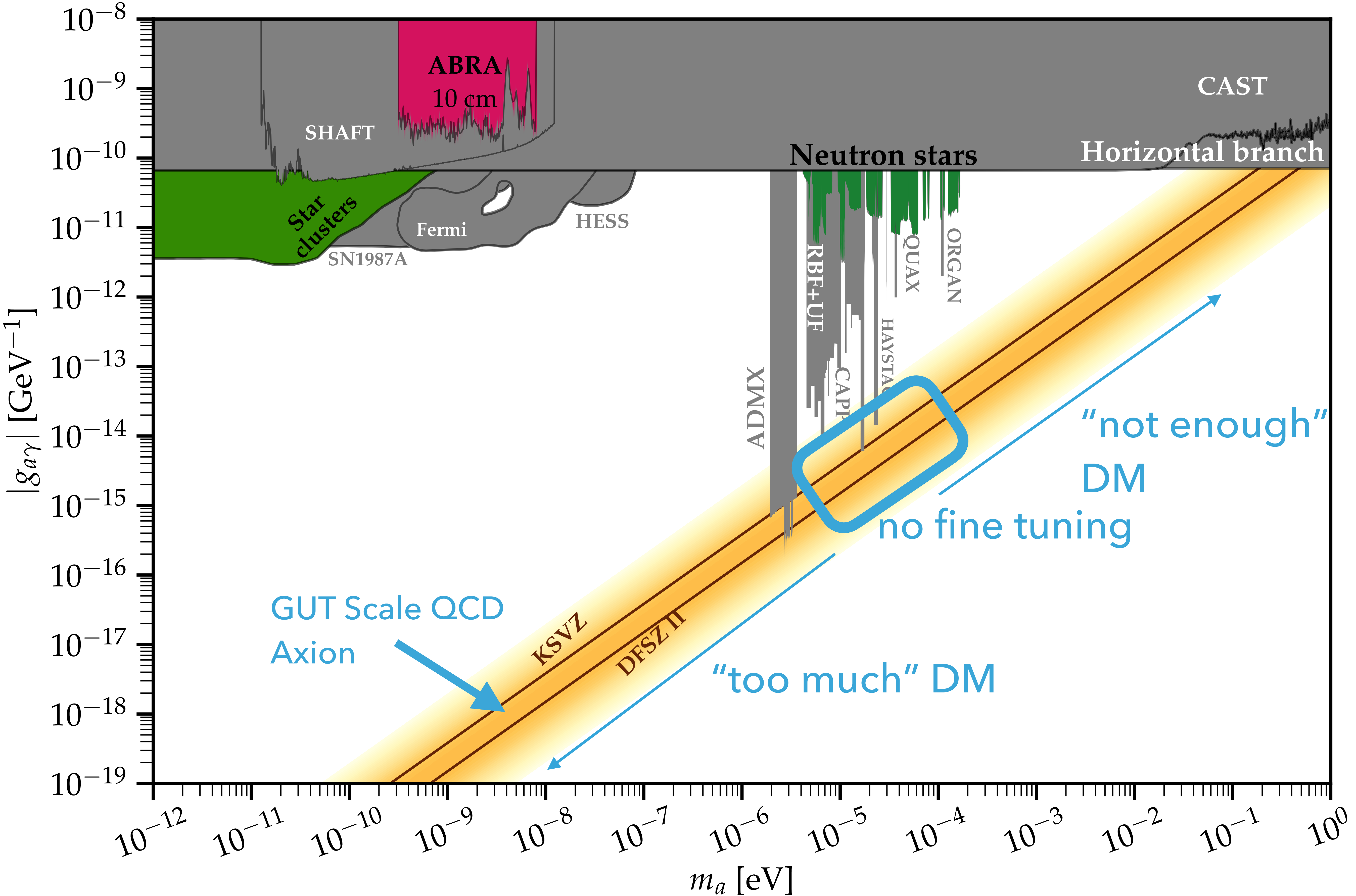
time

PQ symmetry breaking

Inflation

QCD Phase Transition

PQ Broken Before Inflation



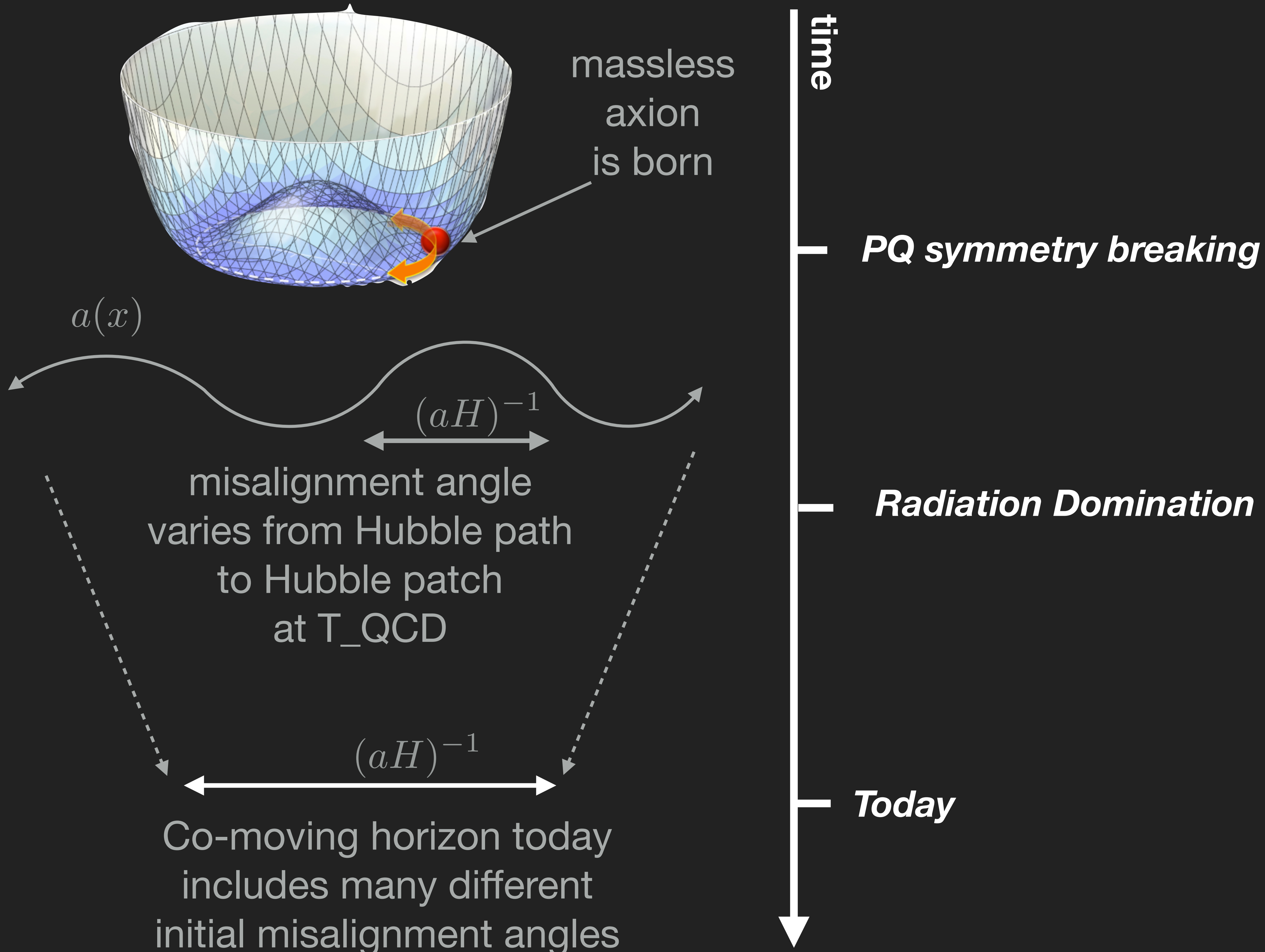
"not enough" DM

no fine tuning

GUT Scale QCD Axion

"too much" DM

Axion generated after inflation



massless
axion
is born

time

PQ symmetry breaking

$a(x)$

$(aH)^{-1}$

misalignment angle
varies from Hubble path
to Hubble patch
at T_QCD

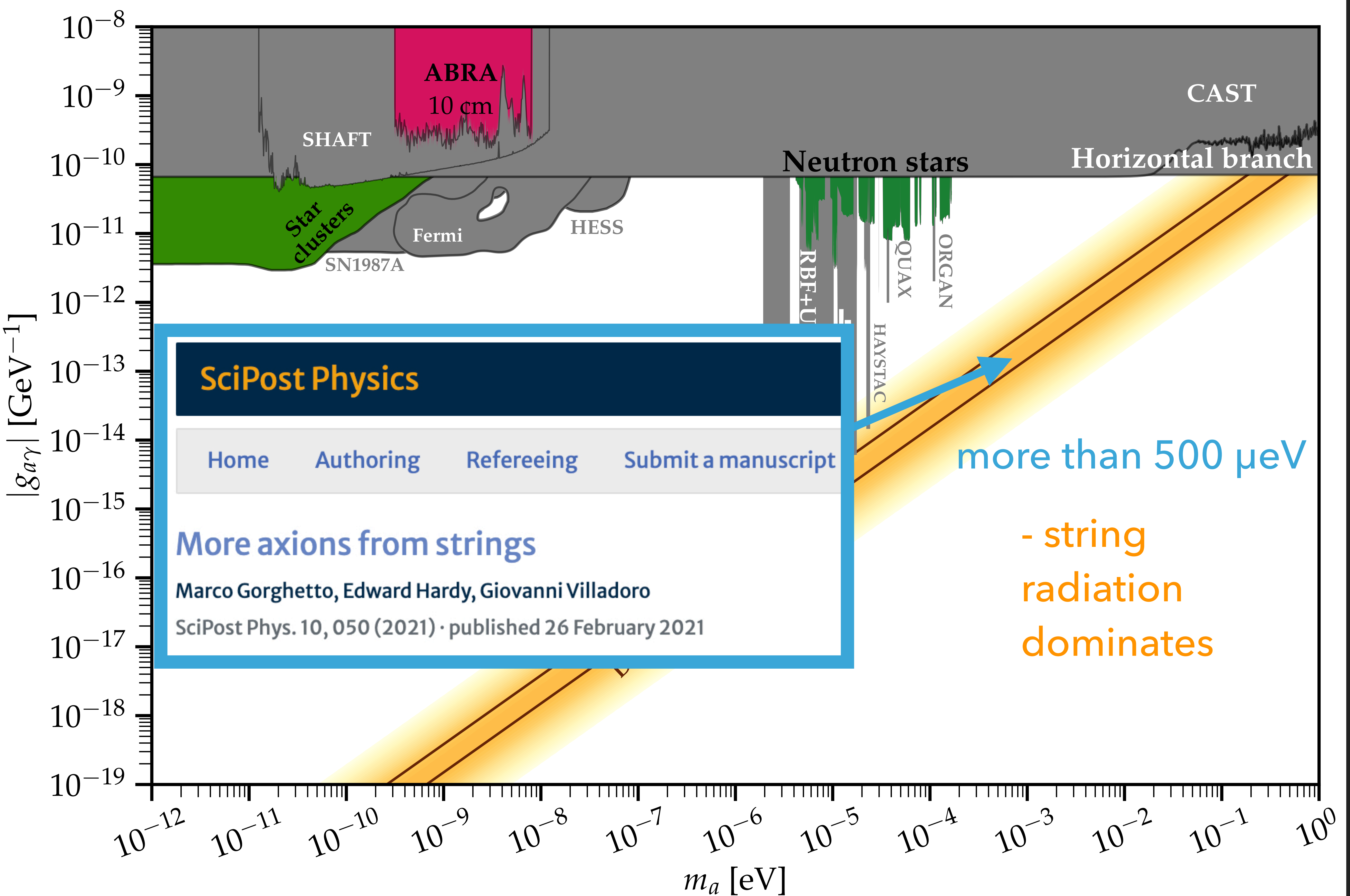
Radiation Domination

$(aH)^{-1}$

Co-moving horizon today
includes many different
initial misalignment angles

Today

What does the literature say?



SciPost Physics

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More axions from strings

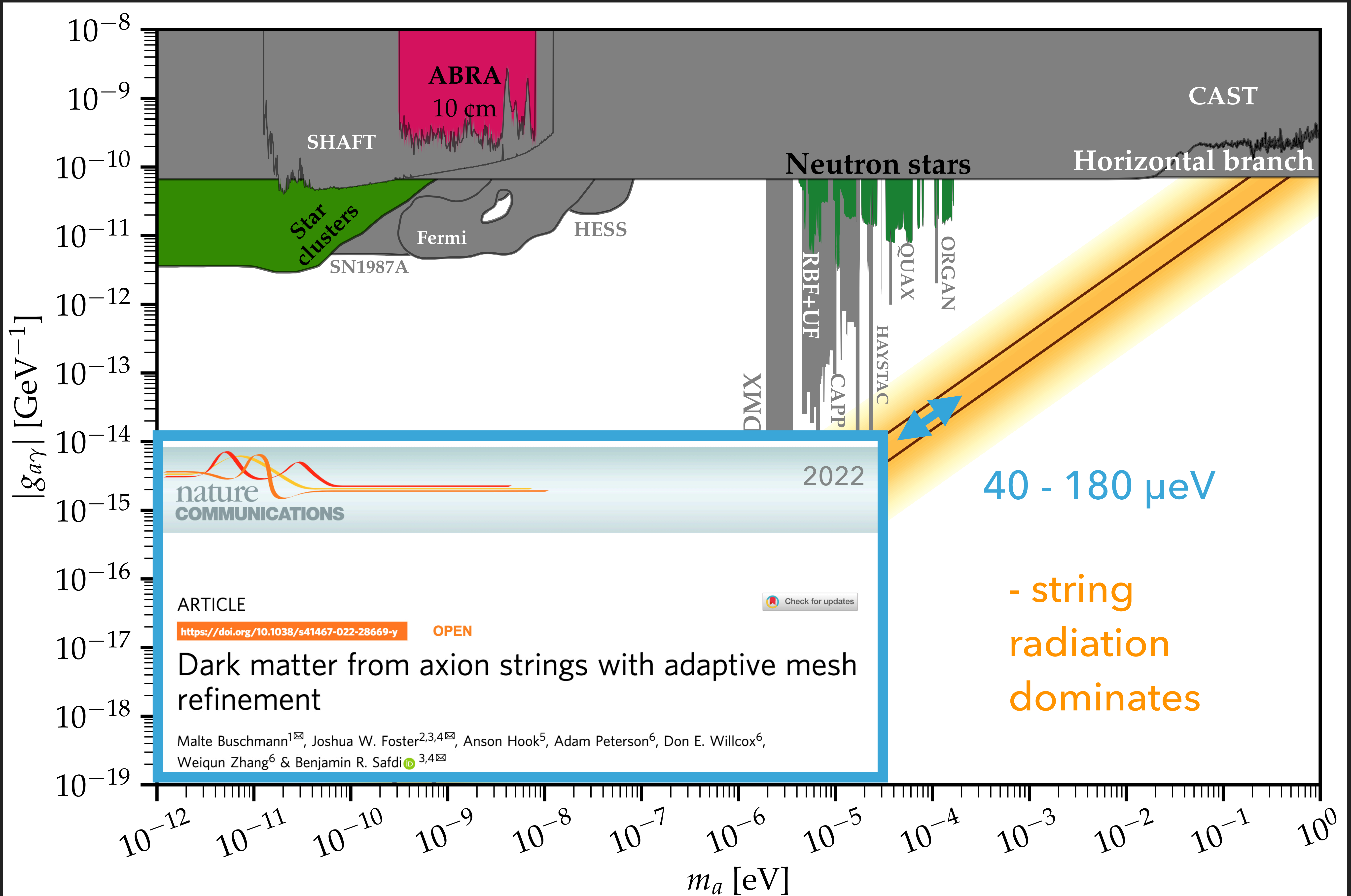
Marco Gorghetto, Edward Hardy, Giovanni Villadoro

SciPost Phys. 10, 050 (2021) · published 26 February 2021

more than 500 μeV

- string radiation dominates

What does the literature say?



2022

nature COMMUNICATIONS

ARTICLE

Check for updates

https://doi.org/10.1038/s41467-022-28669-y OPEN

Dark matter from axion strings with adaptive mesh refinement

Malte Buschmann[1]✉, Joshua W. Foster[2,3,4]✉, Anson Hook[5], Adam Peterson[6], Don E. Willcox[6], Weiqun Zhang[6] & Benjamin R. Safdi[3,4]✉

40 - 180 μeV

- string radiation dominates

Axion generated after inflation

M. Buschmann, J. Foster, **B.S.** PRL 2020

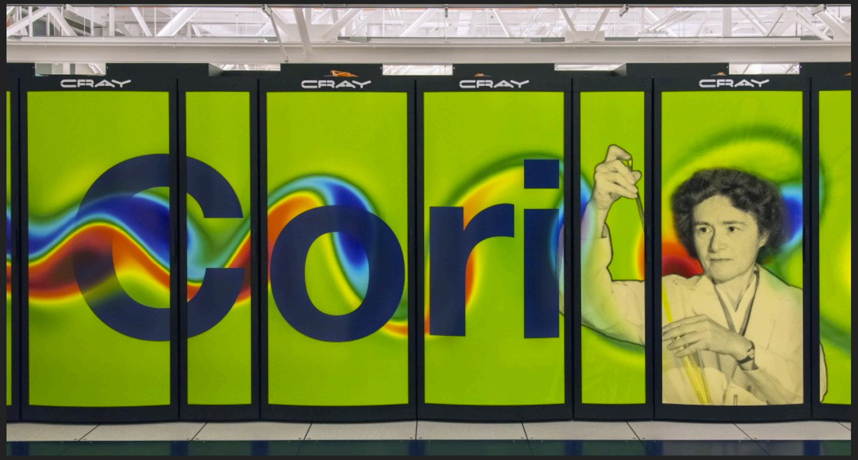
Simulate on static grid with ~10^{10} sites

Simulate from PQ phase transition to matter-radiation equality

M. Buschmann, J. Foster, **B.S.,** AMReX Collaboration, Nat. Comm. 2022

Simulate on adaptive grid equiv. to static grid with ~10^{15} sites

NERSC National Energy Research Scientific Computing Center

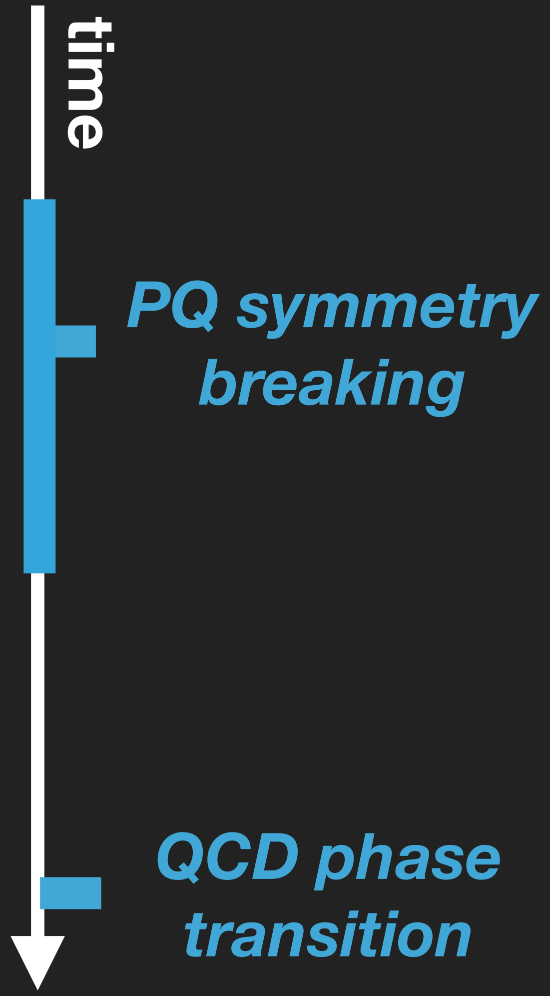


U.S. DEPARTMENT OF ENERGY | Office of Science

Axion dark matter primarily produced from strings

$$\mathcal{L}_{\rm PQ} = \frac{1}{2}|\partial\Phi|^2 - \frac{\lambda}{4}\left(|\Phi|^2 - f_a^2\right)^2 - \frac{\lambda T^2}{6}|\Phi|^2$$

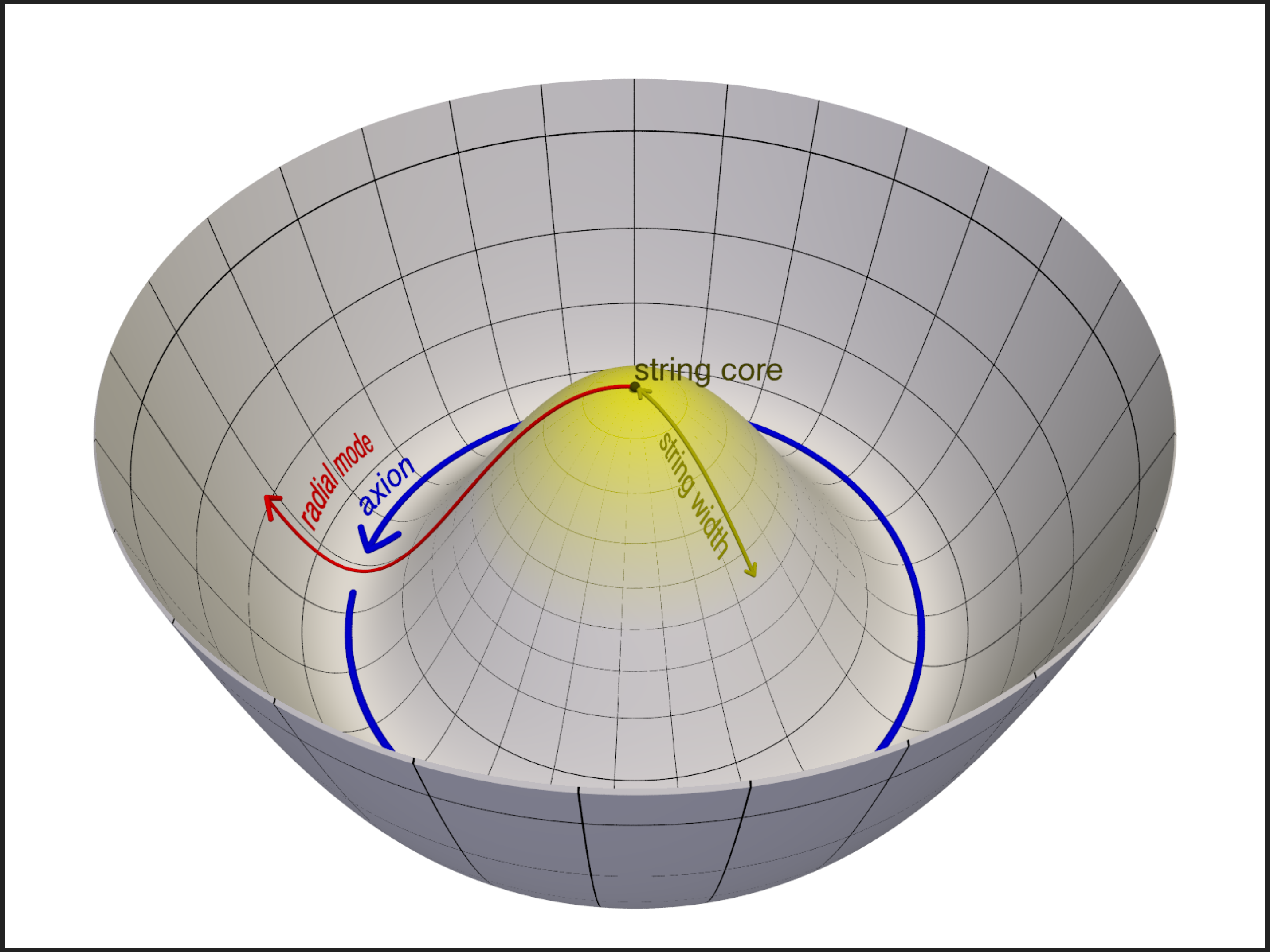
- symmetry broken for $T \lesssim f_a$
- write $\Phi(x) = \frac{r(x)+f_a}{\sqrt{2}}e^{ia(x)/f_a}$
- radial mode acquires mass: $m_r \sim \sqrt{\lambda}f_a \; (\text{take } \lambda \sim 1)$

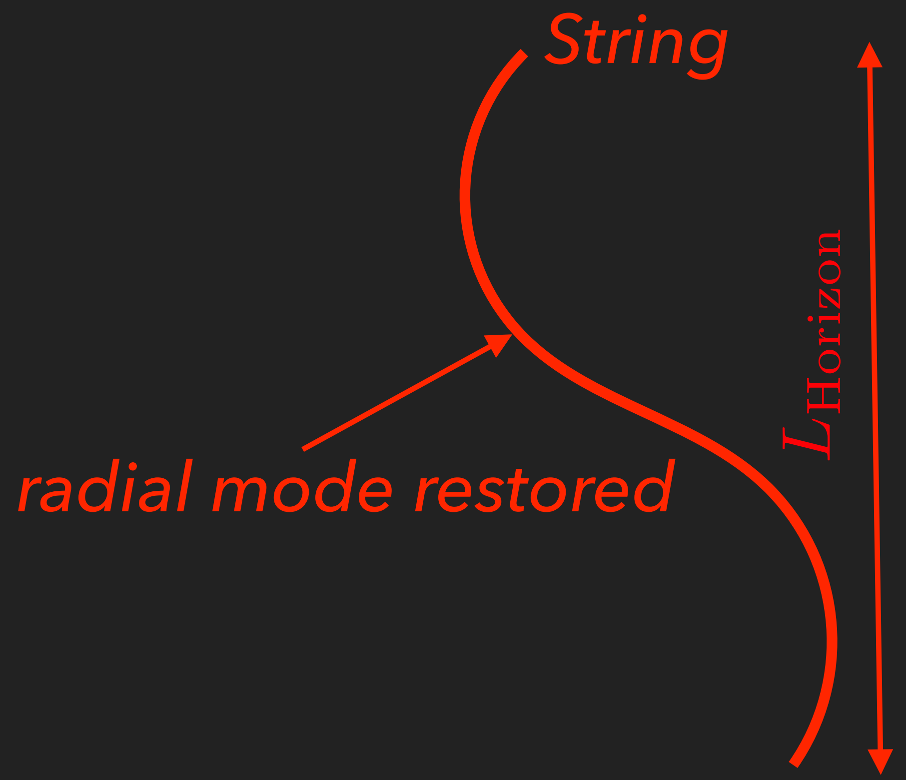


time

PQ symmetry breaking

QCD phase transition





String

radial mode restored

$L_{\rm Horizon}$

Axion dark matter primarily produced from strings

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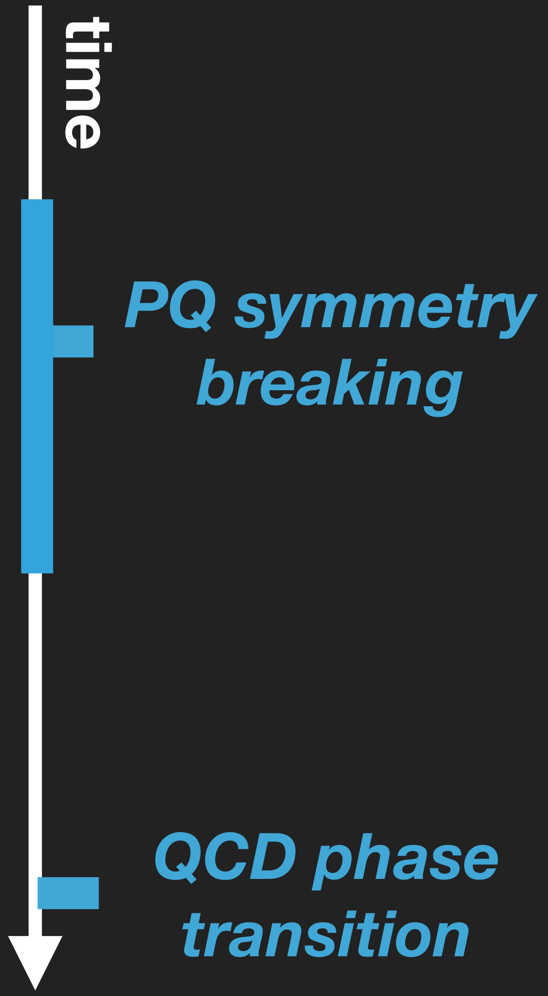

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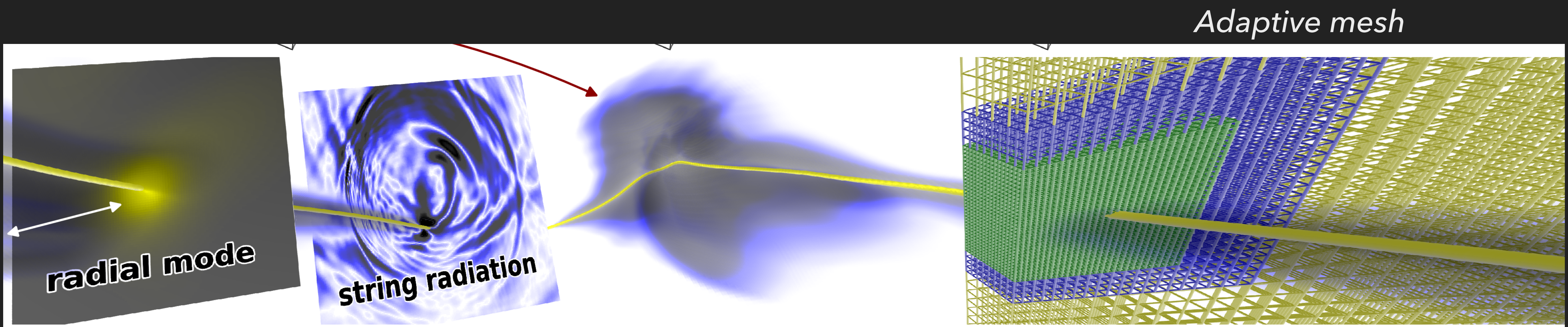
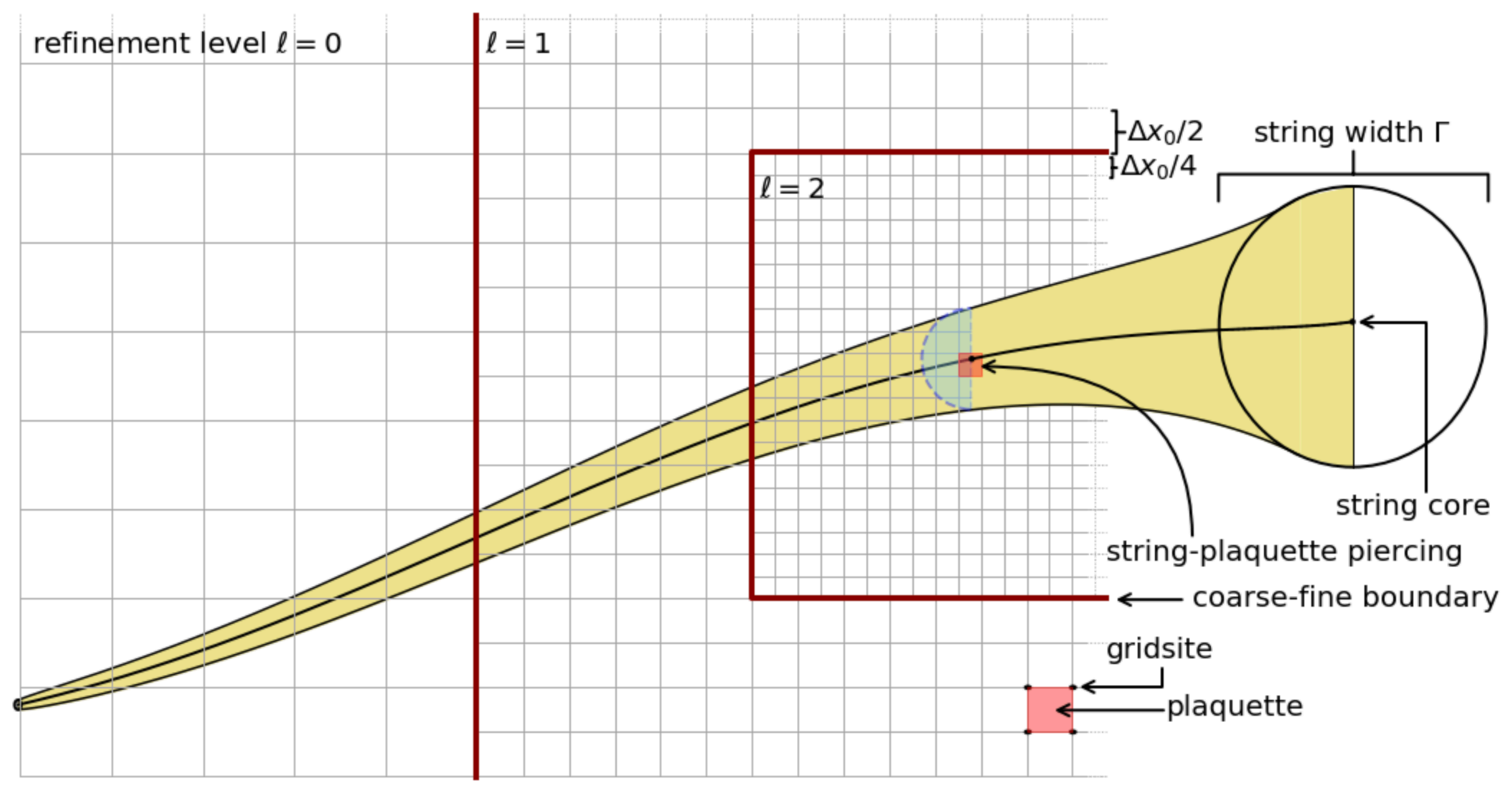
- radial mode acquires mass: $m_r \sim \sqrt{\lambda} f_a$ $(\text{take } \lambda \sim 1)$
- Adaptive mesh to maintain high resolution around strings
- 1e7 CPU-hours over ~100,000 CPUs and ~100 TB RAM
- Goal: measure axion radiation from strings to compute DM abundance

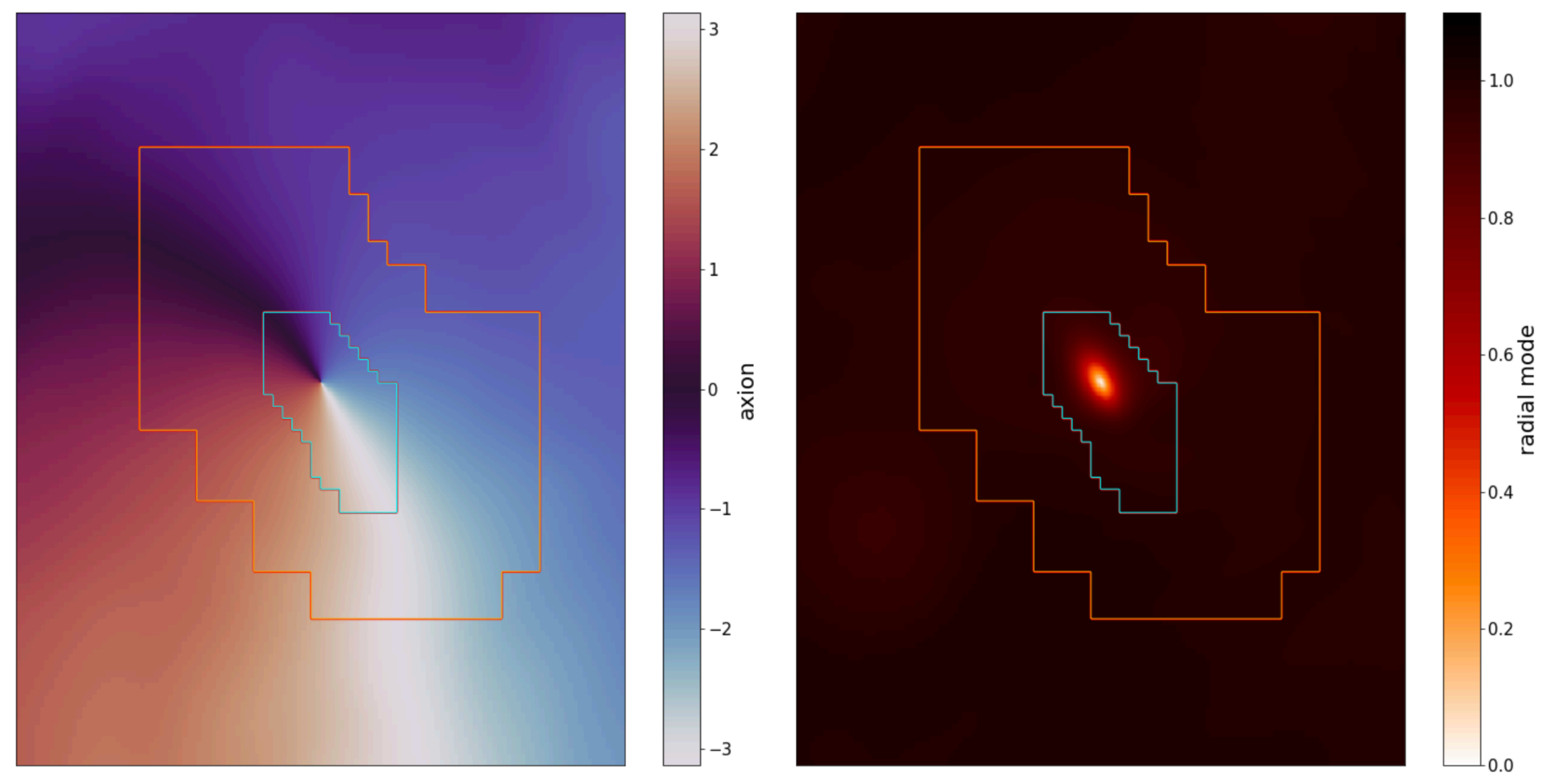


Answer with Adaptive Mesh Refinement Simulations (AMReX)

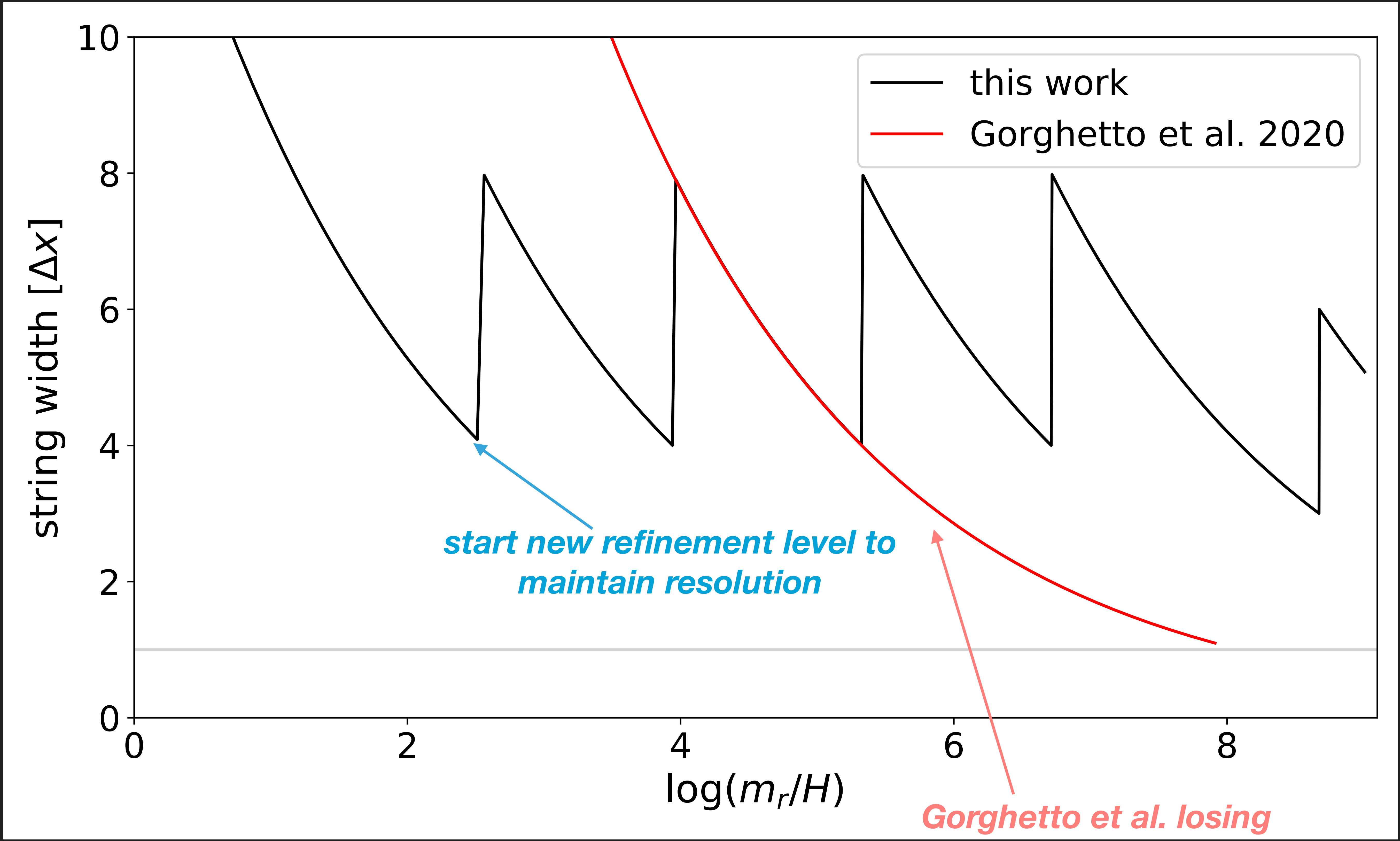
BERKELEY LAB CENTER FOR COMPUTATIONAL SCIENCES AND ENGINEERING



Answer with Adaptive Mesh Refinement Simulations (AMReX)

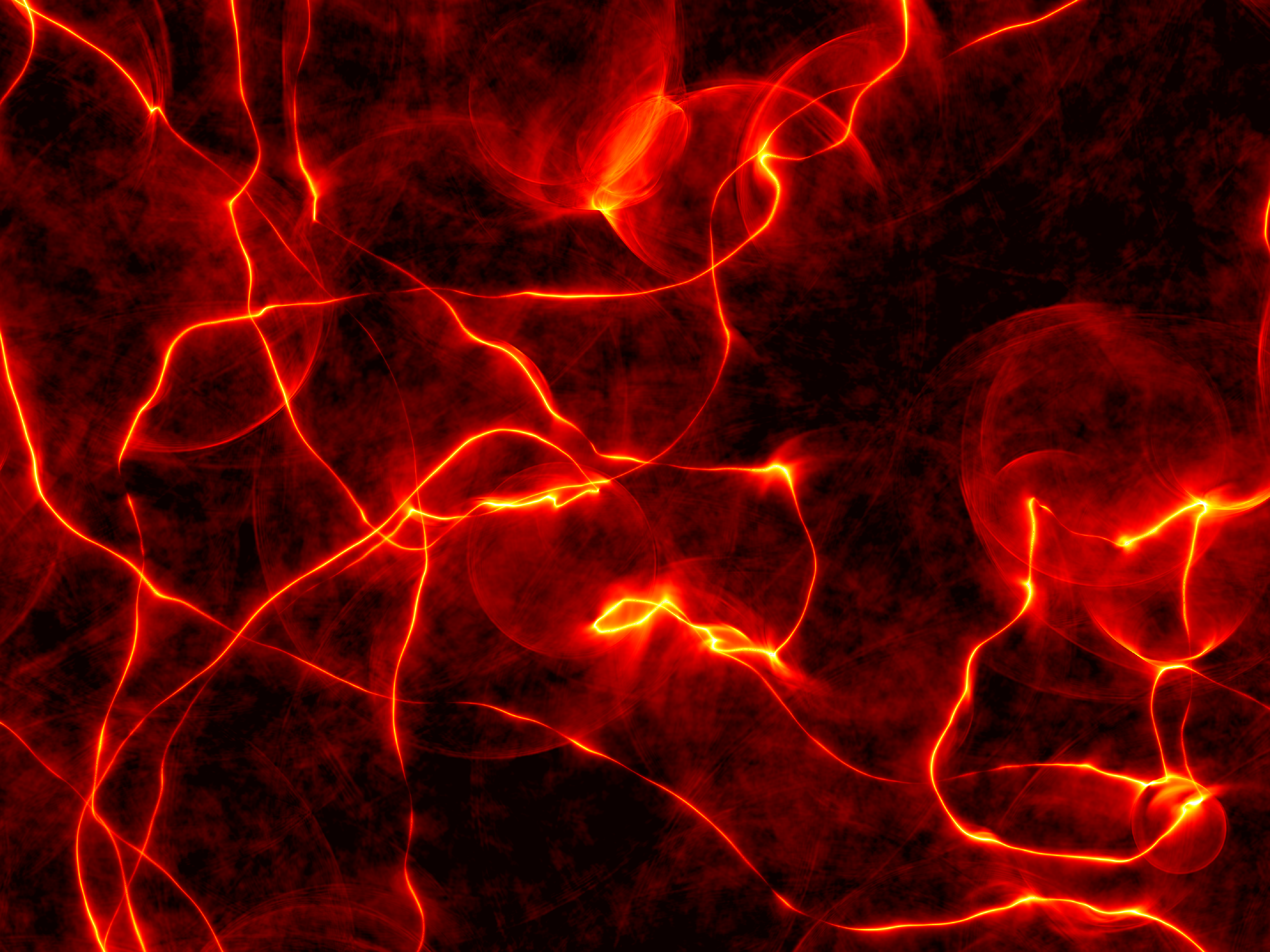


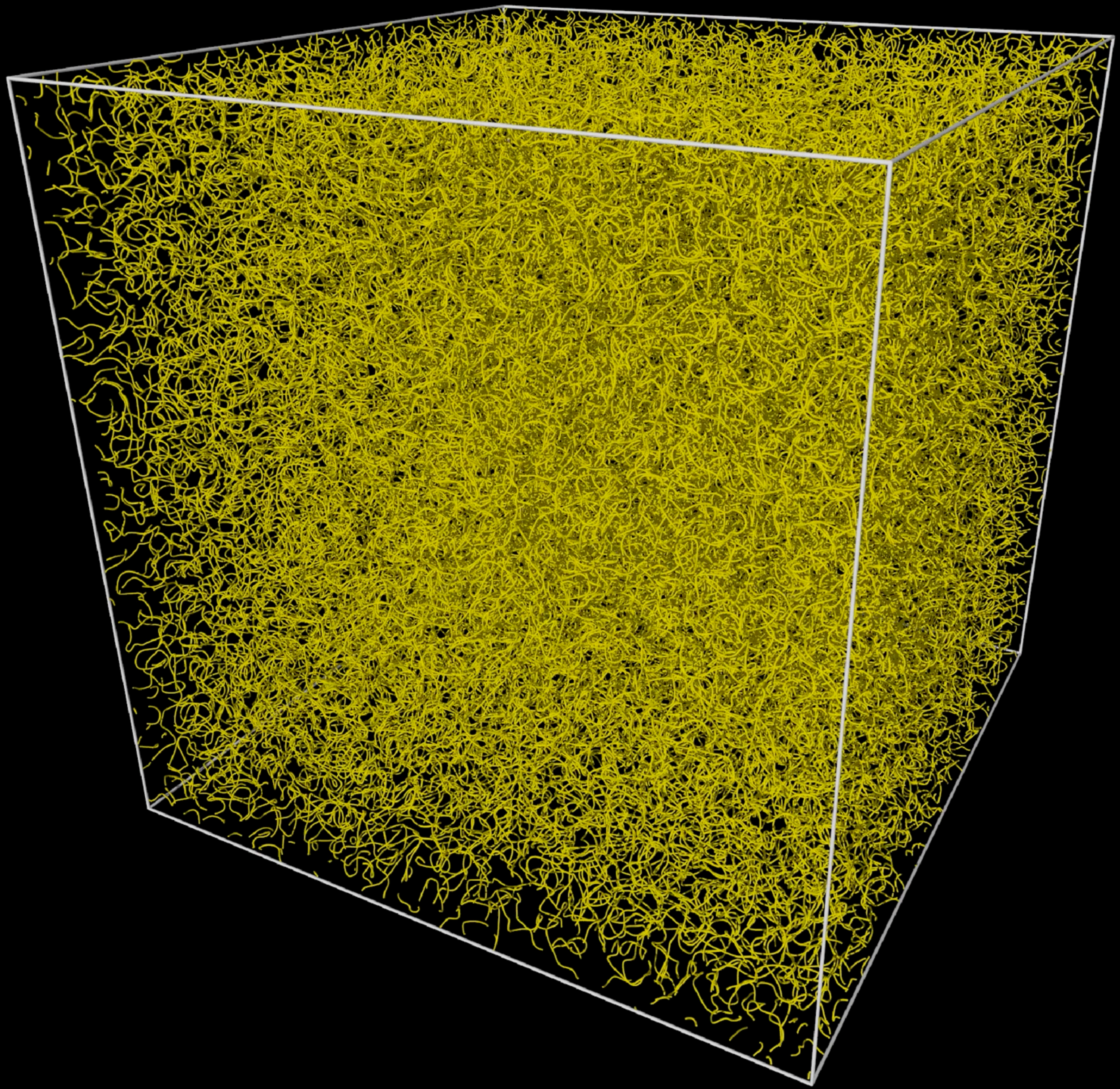
Axions with AMReX



start new refinement level to maintain resolution

Gorghetto et al. losing resolution to strings at late times



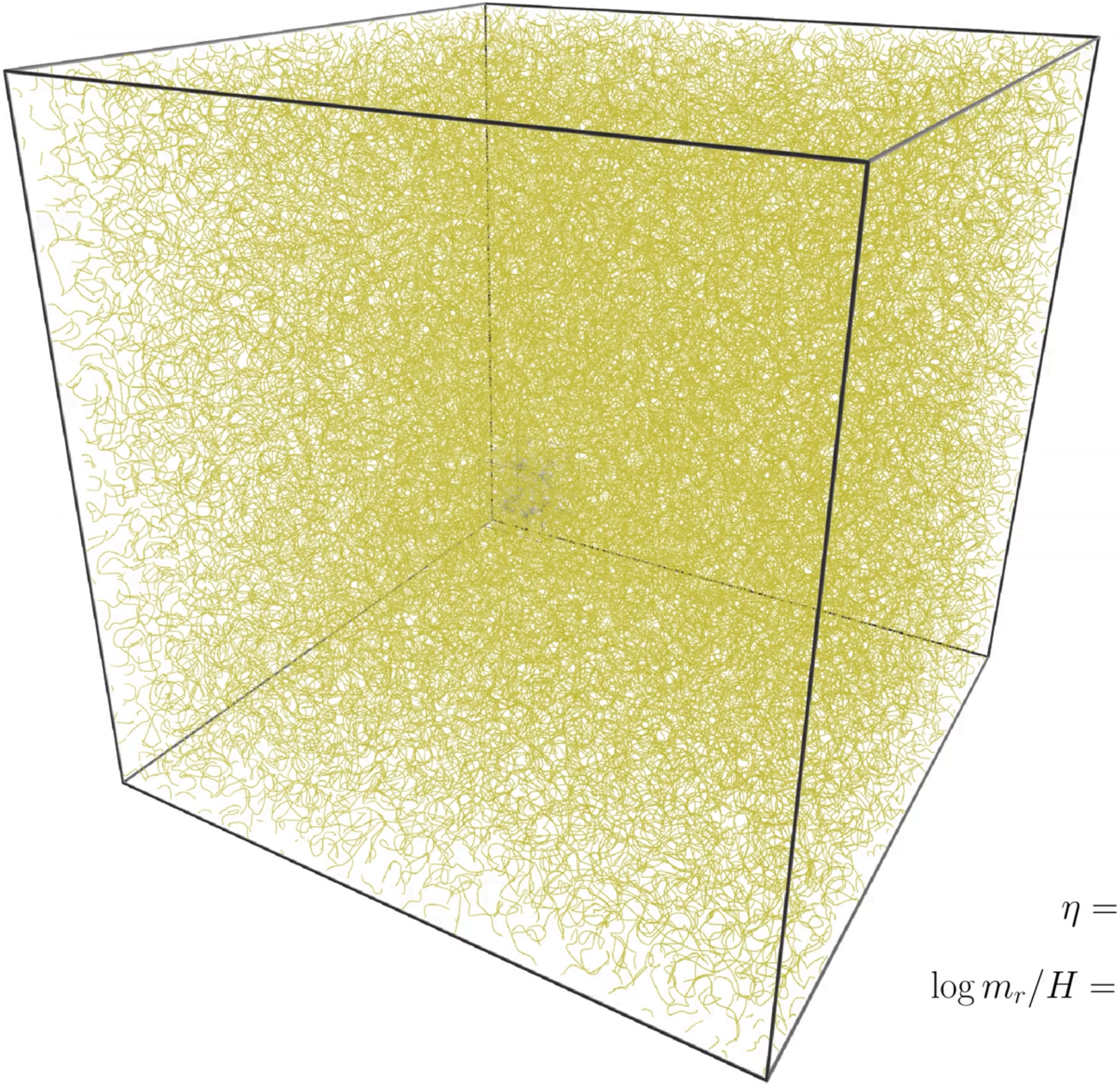


Simulation volume

Hubble volume

$\eta = 0.1$

$\log m_r/H = -3.58$



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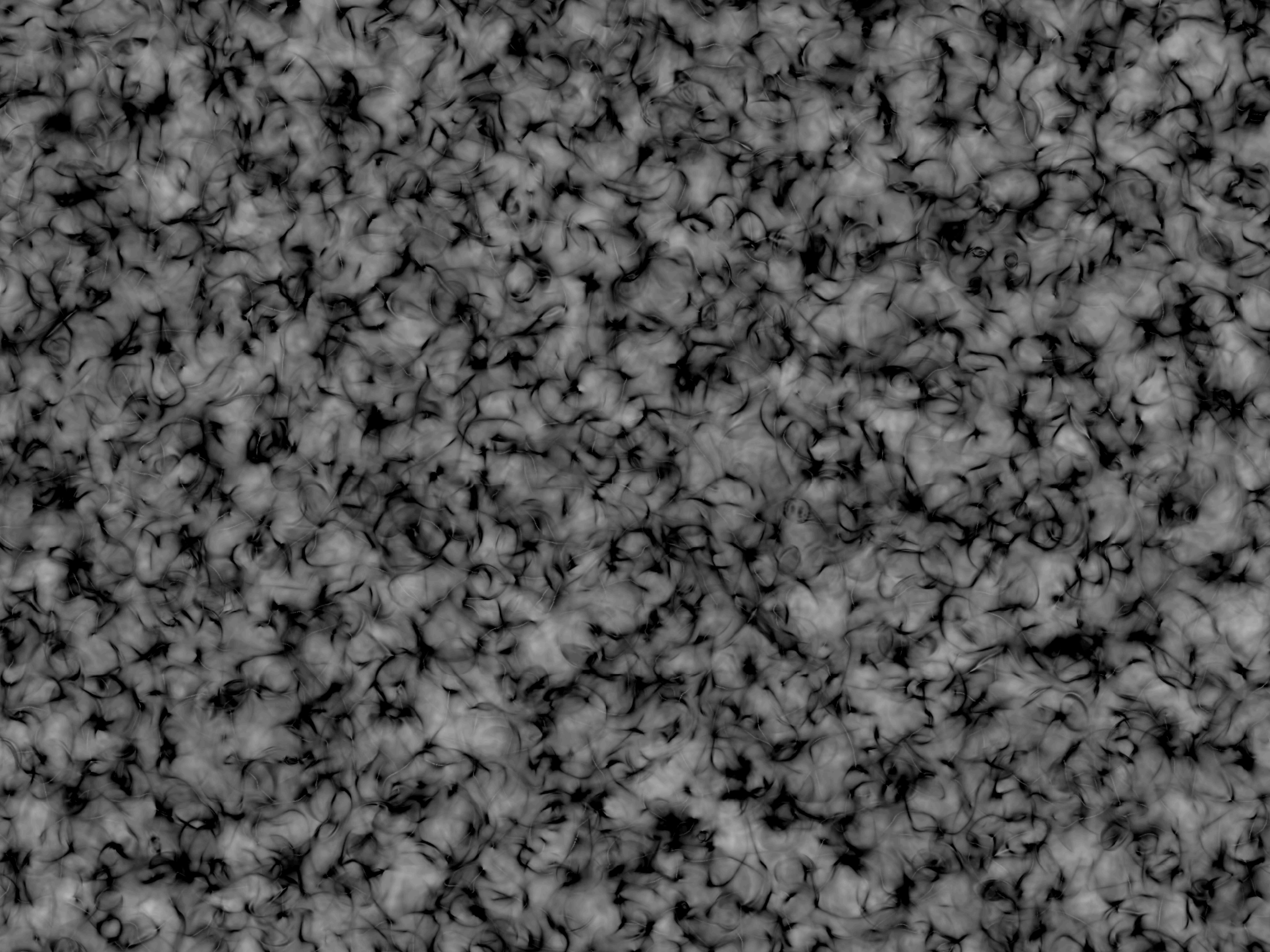
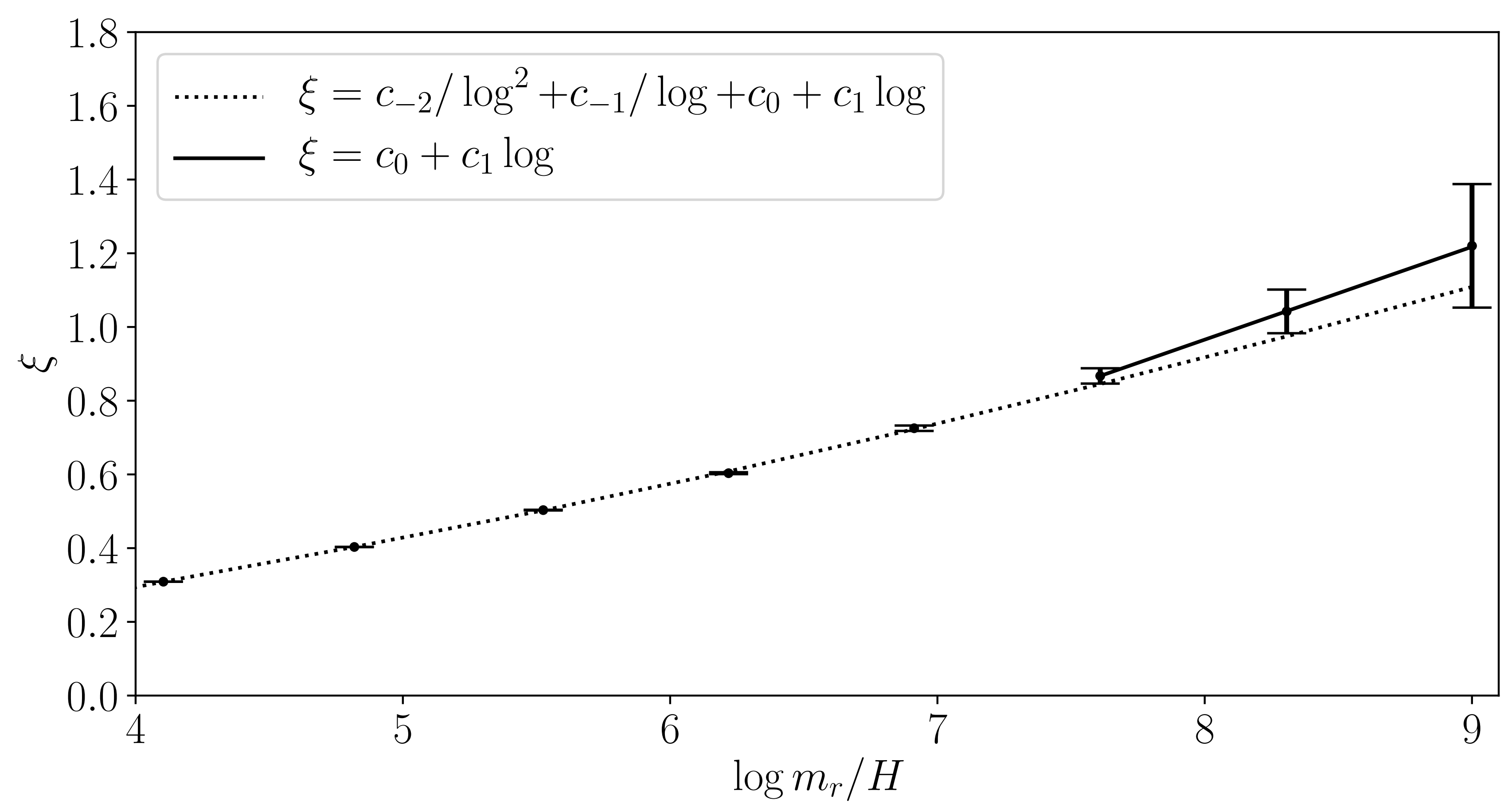


What do we find?

1. strings per Hubble increases logarithmically with time (and understand this analytically)



SciPost Physics

More axions from strings

Marco Gorghetto, Edward Hardy, Giovanni Villadoro

SciPost Phys. 10, 050 (2021) · published 26 February 2021

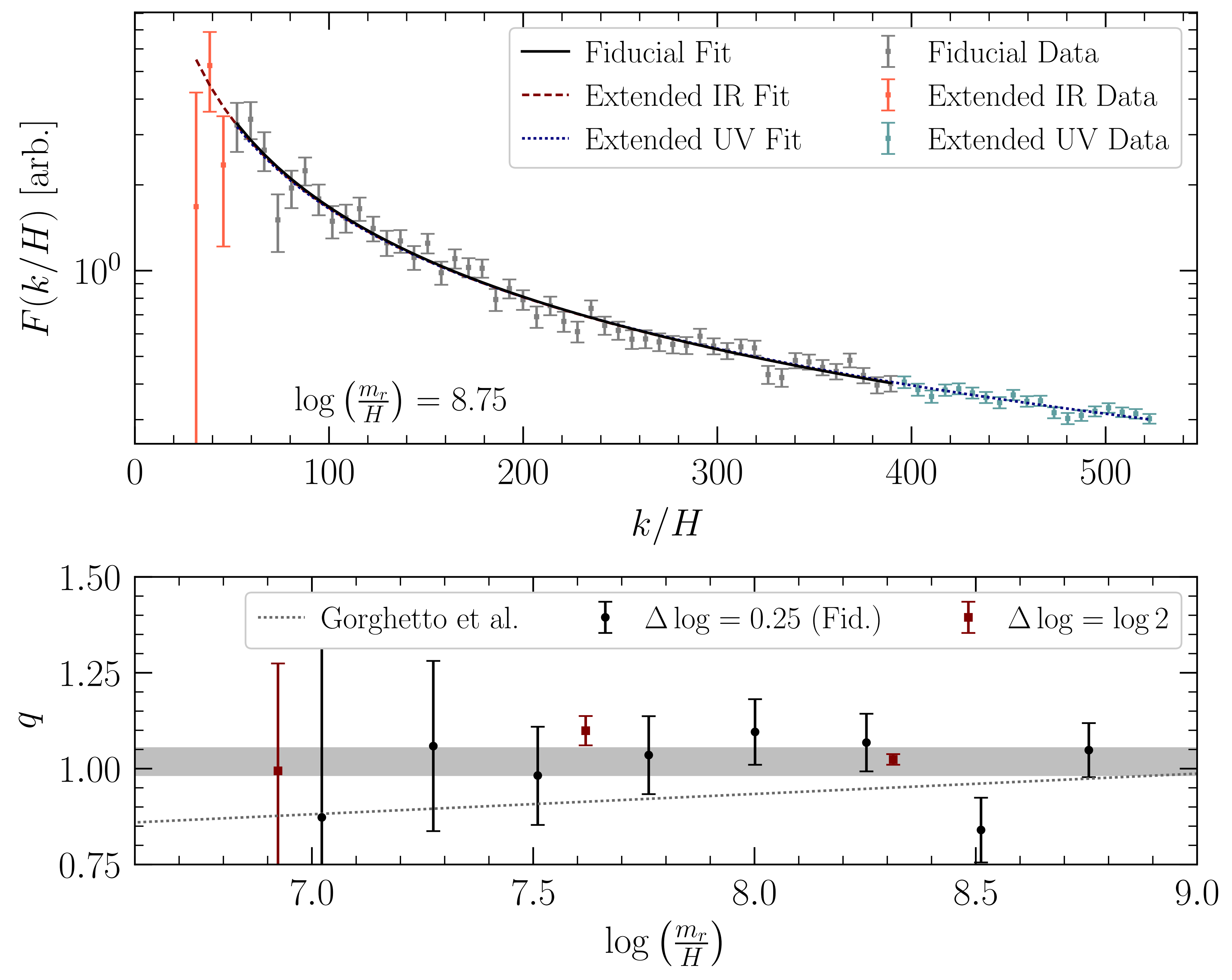
Pointed out here, and we confirm this!

What do we find?

2. radiation does not become IR dominated – conformal to within few %

$$\frac{\partial \rho}{\partial k} \sim \frac{1}{k^q}$$

$$q \in (0.98, 1.04)$$



$$m_a \in (40, 180)\ \mu\text{eV}$$

$$m_a = 65 \pm 6\ \mu\text{eV} \longleftarrow q = 1$$

What are we doing now?

Perlmutter + GPU acceleration

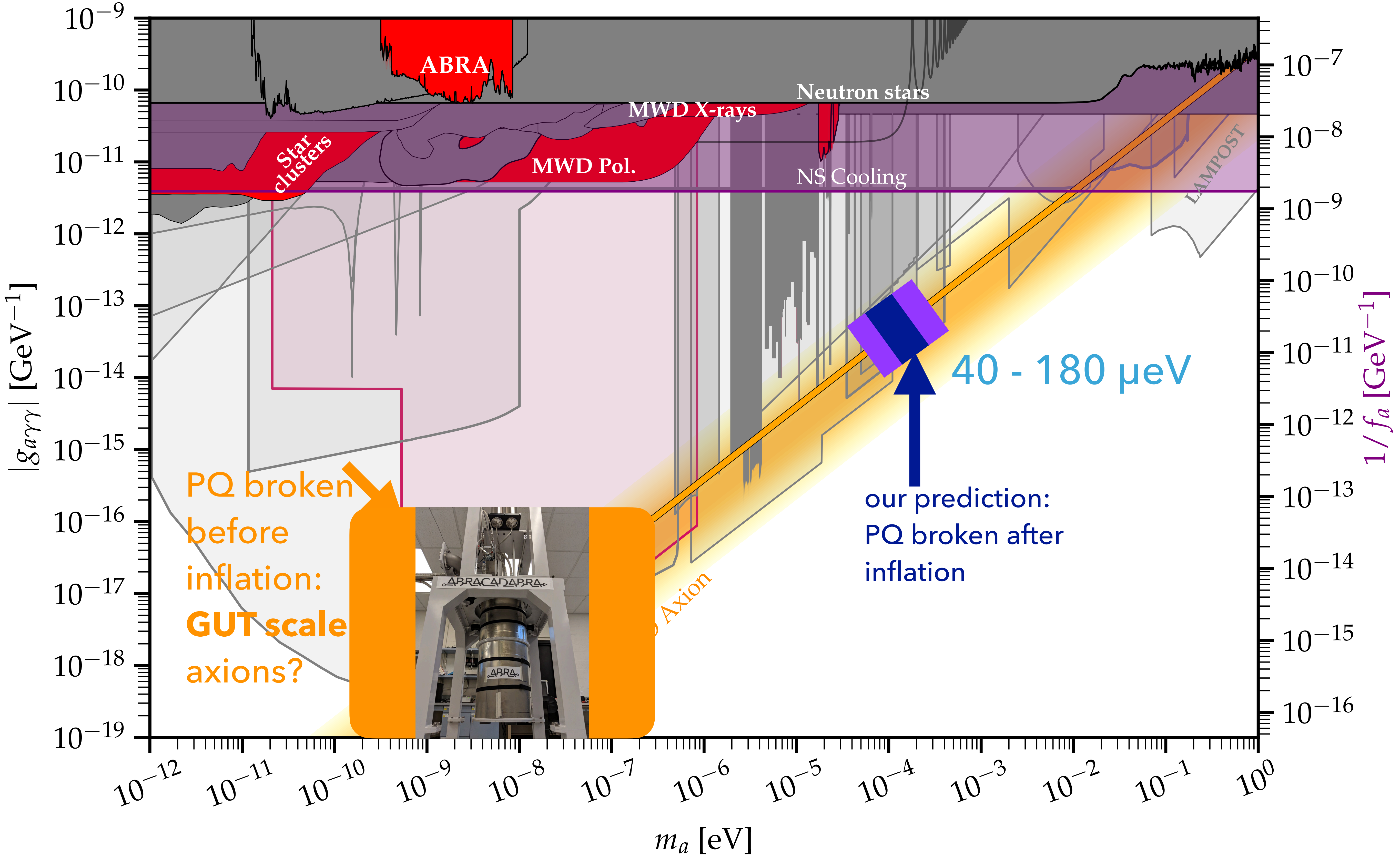
1. GPU cluster being commissioned now.
Already 5th most powerful supercomputer in world

2. our plan: ~10x increase in dynamic range

Why does this matter?

Motivated axion dark matter mass ranges

$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

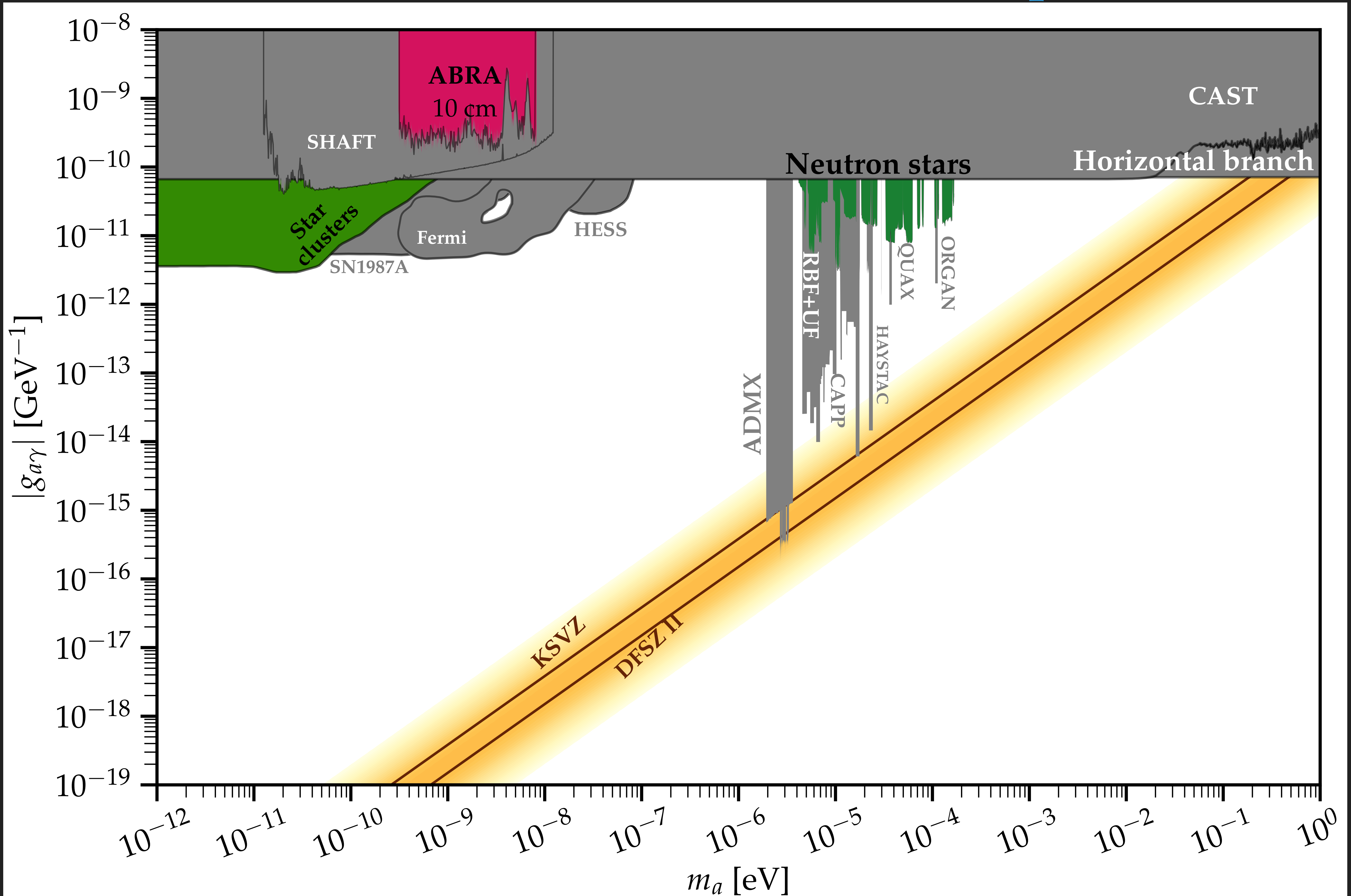


PQ broken before inflation: **GUT scale** axions?

40 - 180 μeV

our prediction: PQ broken after inflation

Existing Constraints: $\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4}$



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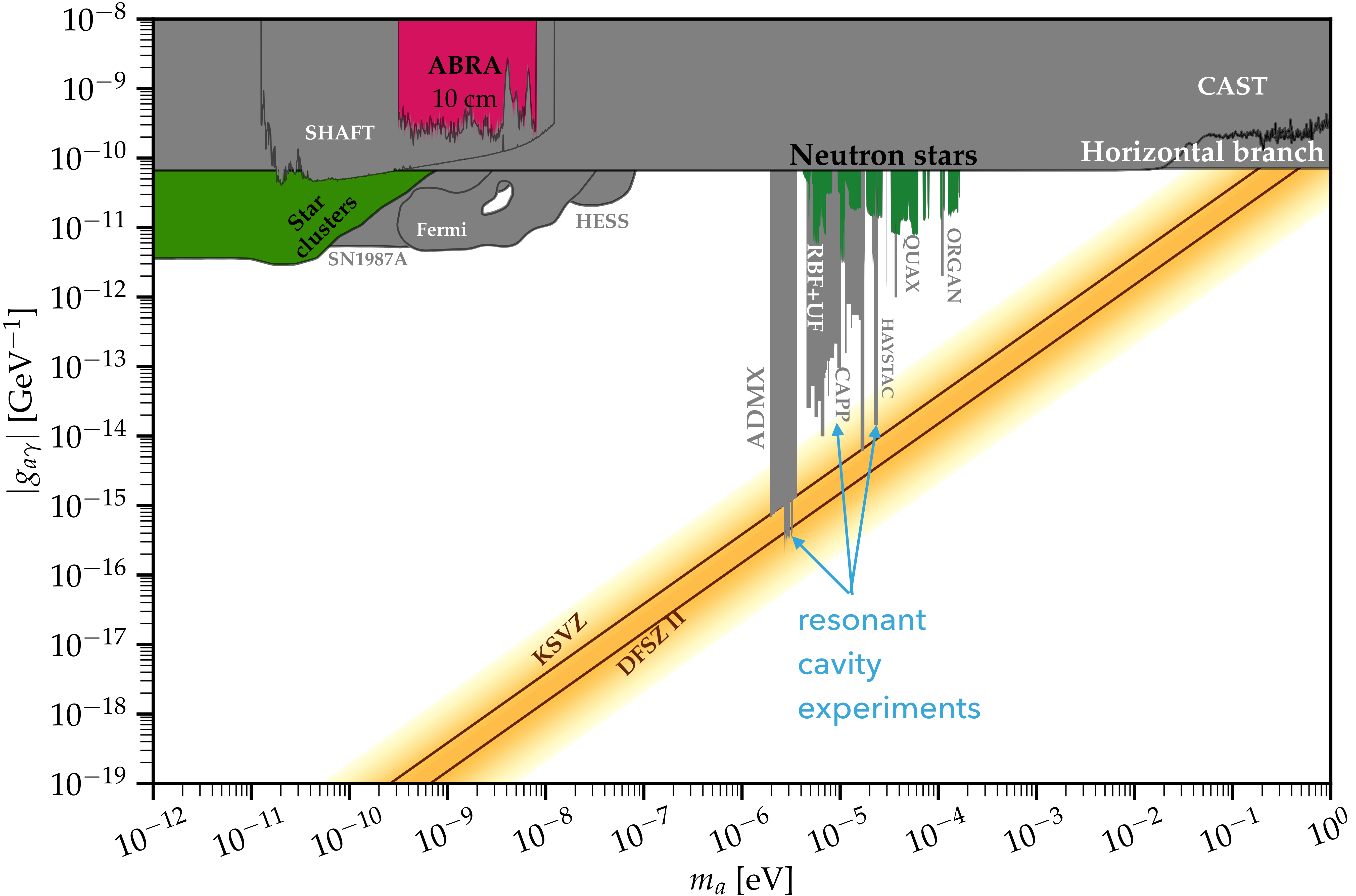
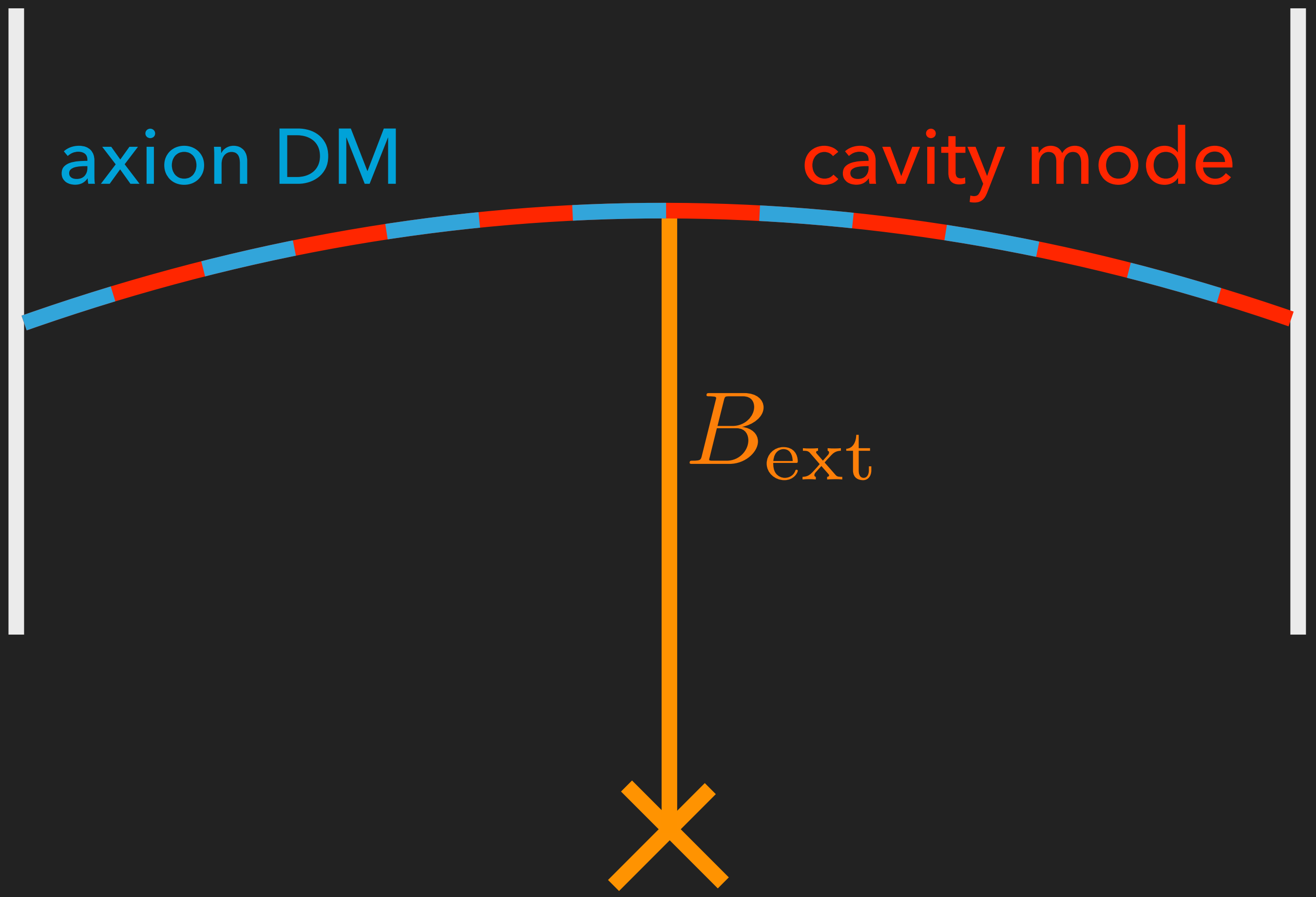


resonant cavity experiments

$$\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4} = g_{a\gamma\gamma}a\mathbf{E}\cdot\mathbf{B}$$



1. Axion coherence time limited by

$$\delta E/E \sim \left(\frac{v_{\text{DM}}}{c}\right)^2 \sim 10^{-6}$$

2. -> Q ~ 10^6 cavities ideal
3. m_a = 25 μeV -> 5 cm cavity

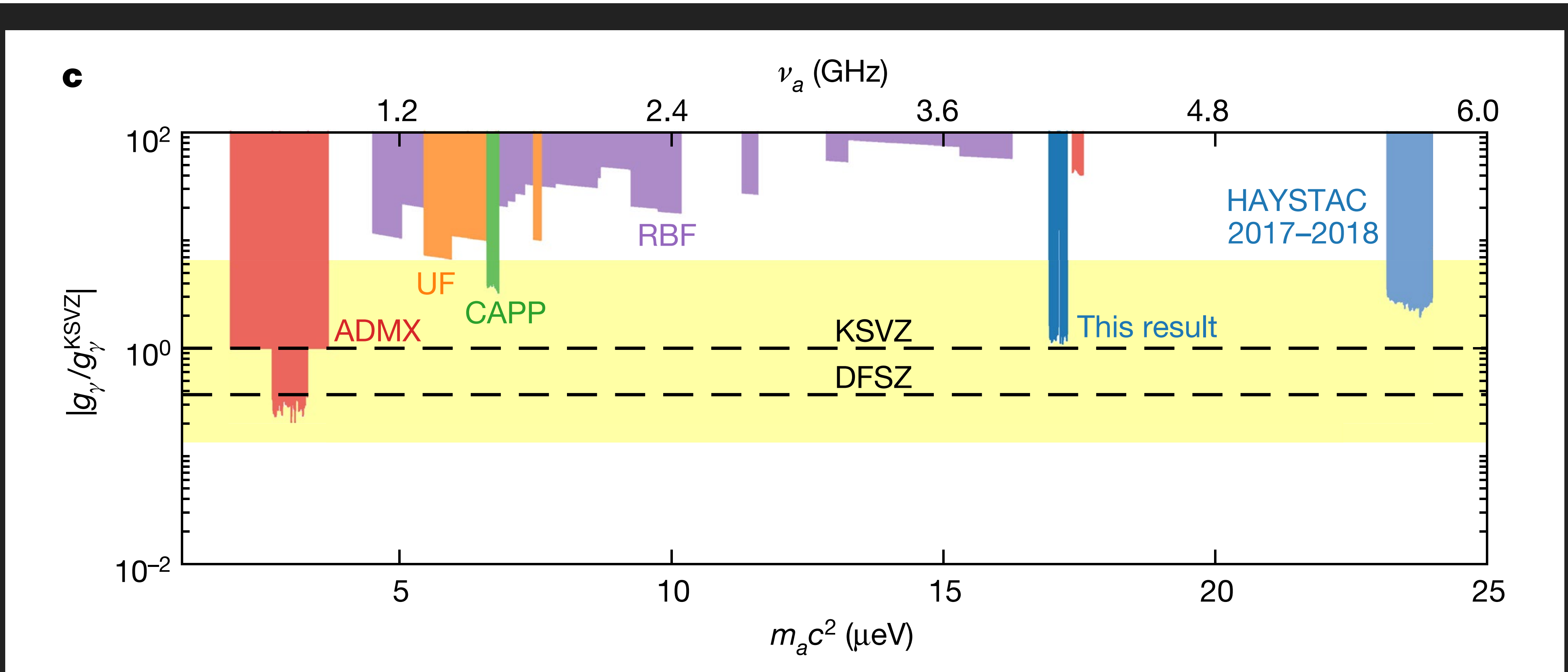
conversion probability – $p_{a\to\gamma} = g_{a\gamma\gamma}^2 B_{\text{ext}}^2 L^2$

cavity: converted power – $P_{a\to\gamma} \propto \frac{\rho_{\text{DM}}}{m_a} g_{a\gamma\gamma}^2 B_{\text{ext}}^2 VQ$

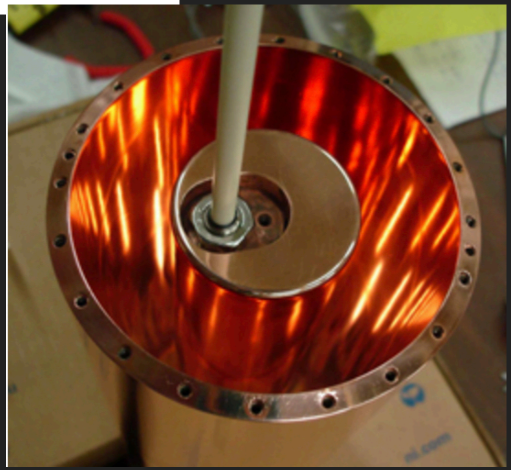
Example: HAYSTAC Experiment

Article Nature 2021

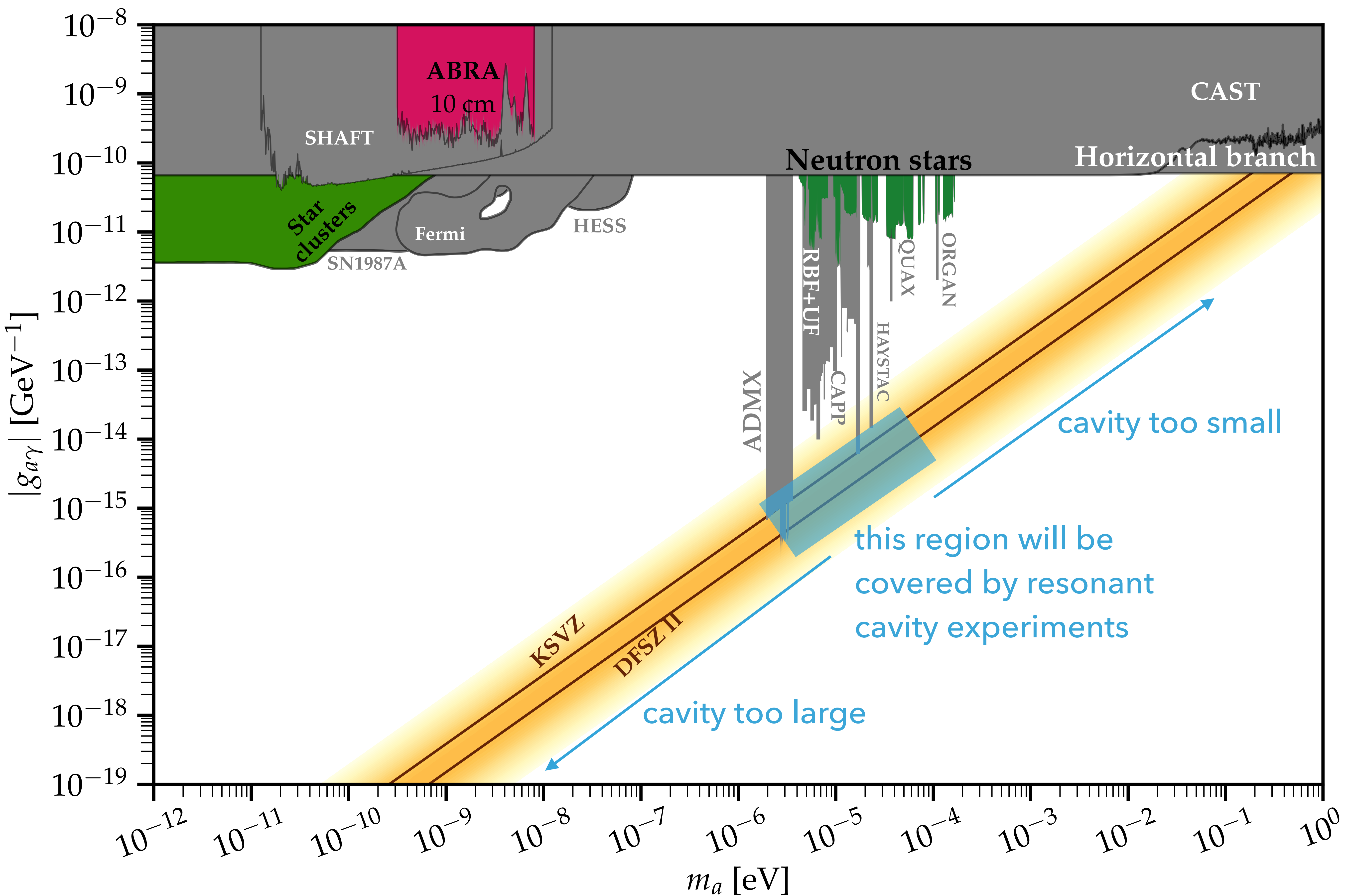
A quantum enhanced search for dark matter axions



Used quantum squeezed states in cavity to be more sensitive to axion signals



Going beyond the resonant cavity

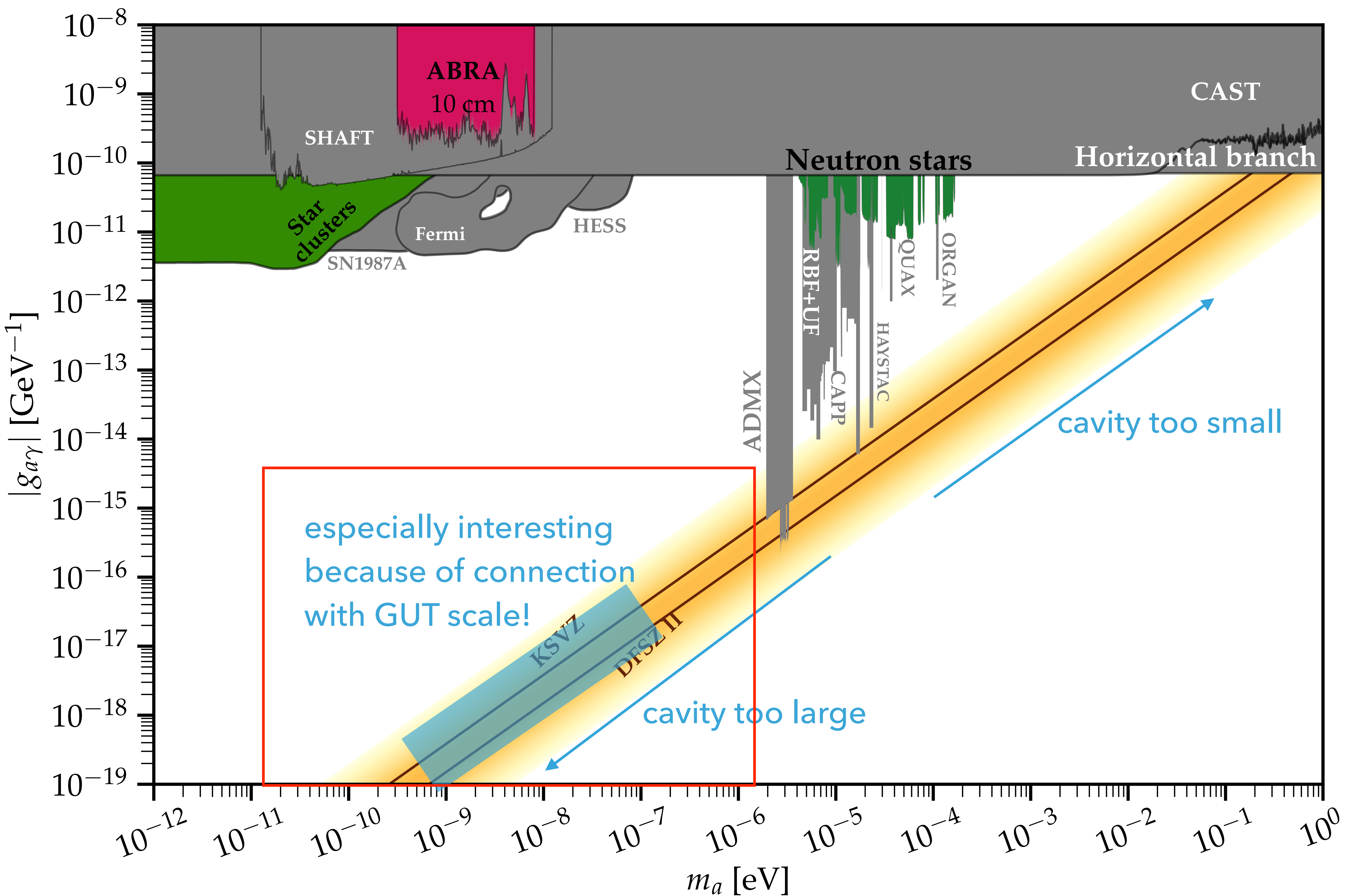


cavity too small

this region will be covered by resonant cavity experiments

cavity too large

Going beyond the resonant cavity



especially interesting because of connection with GUT scale!

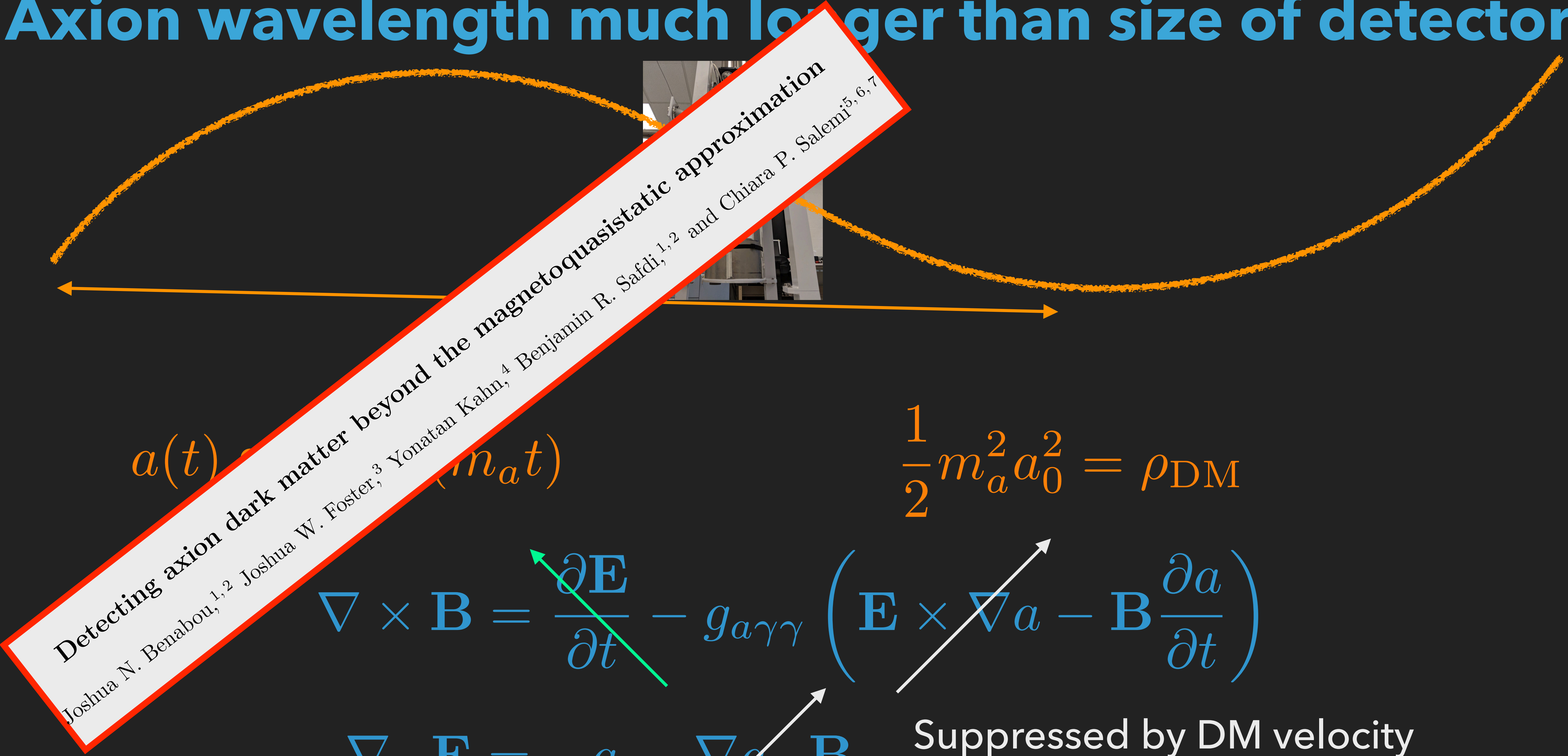
cavity too small

cavity too large

A Broadband / Resonant Approach to Cosmic Axion Detection with an Amplifying B-field Ring Apparatus

Y. Kahn, **B.S.** , J. Thaler (PRL 2016)

Axion wavelength much lo ger than size of detector



Detecting axion dark matter beyond the magnetoquasistatic approximation

Joshua N. Benabou,[1,2] Joshua W. Foster,[3] Yonatan Kahn,[4] Benjamin R. Safdi,[1,2] and Chiara P. Salemi[5,6,7]

$a(t)$ $m_a t)$

$$\frac{1}{2} m_a^2 a_0^2 = \rho_{\mathrm{DM}}$$

$$\nabla \times \mathbf{B} = \cancel{\frac{\partial \mathbf{E}}{\partial t}} - g_{a\gamma\gamma}\left(\mathbf{E} \times \cancel{\nabla a} - \mathbf{B}\frac{\partial a}{\partial t}\right)$$

$$\nabla \cdot \mathbf{E} = -g_{a\gamma\gamma}\cancel{\nabla a} \cdot \mathbf{B}$$

Suppressed by DM velocity
v / c ~ 0.001

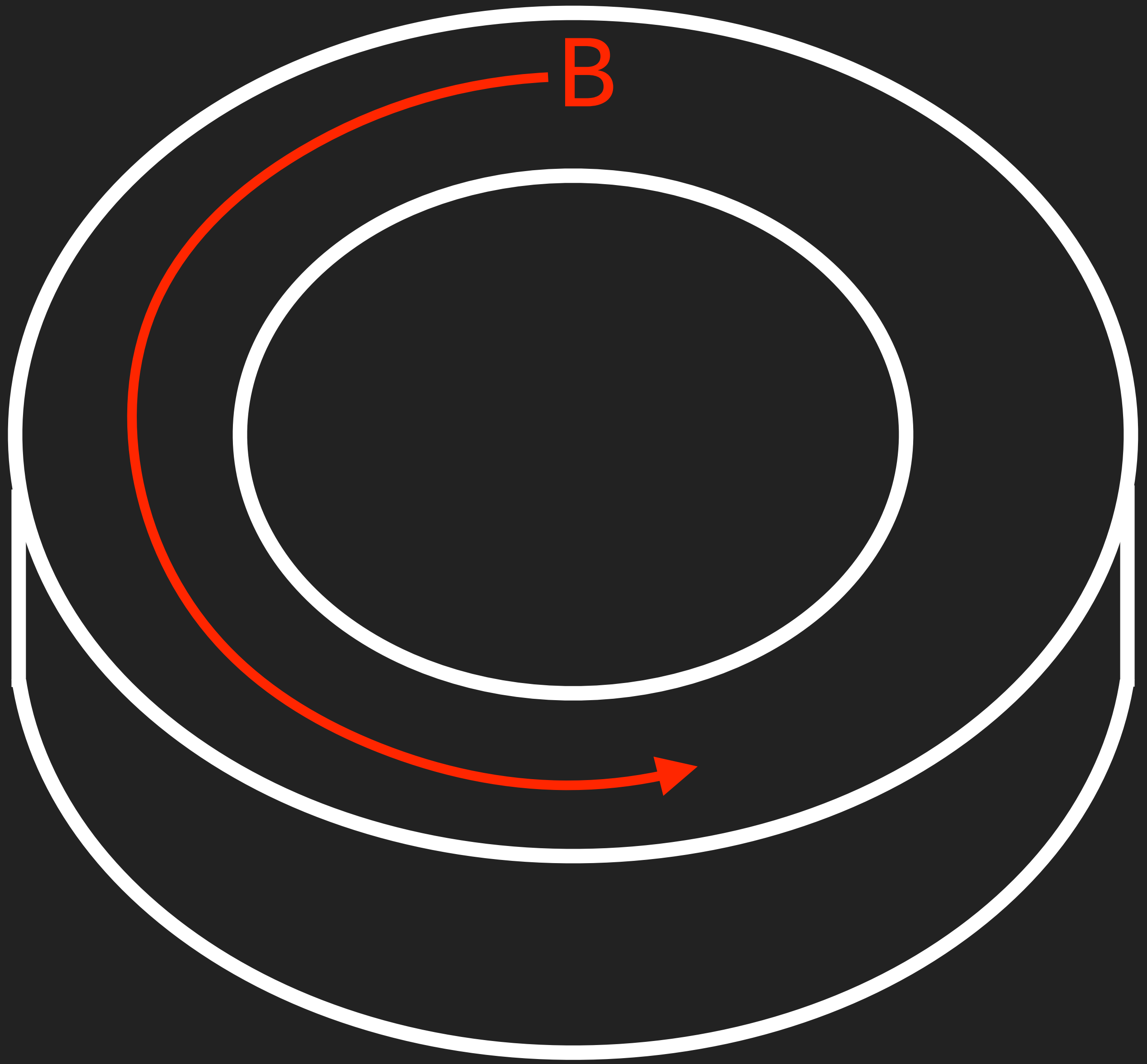
$$\nabla \times \mathbf{E} = -\cancel{\frac{\partial \mathbf{B}}{\partial t}}$$

$$\nabla \cdot \mathbf{B} = 0$$

Drop these terms in MQS approximation – long axion Compton wavelength

But see **B.S.** et al. 2022!

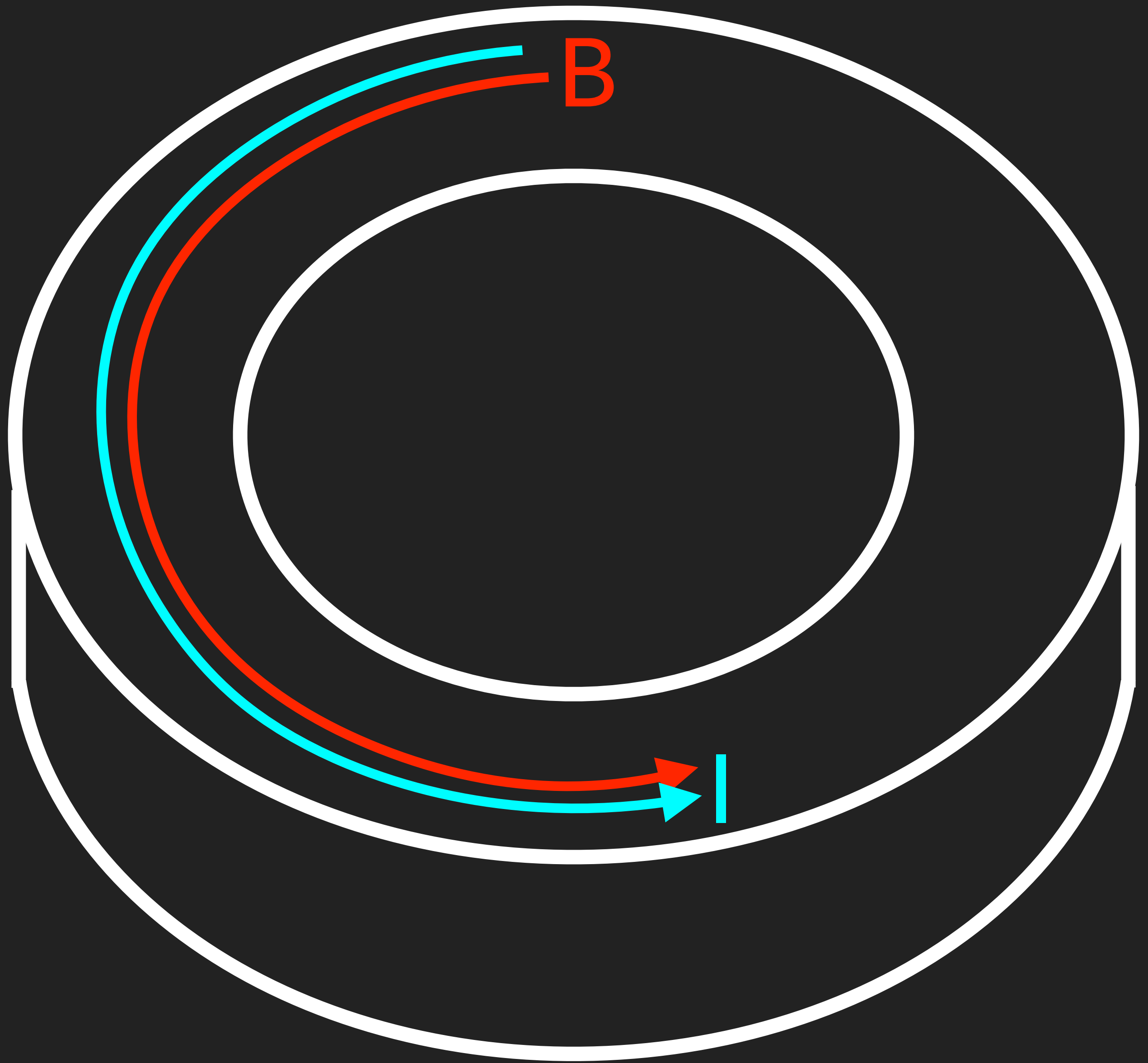
Toroidal Magnetic Field: B



$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

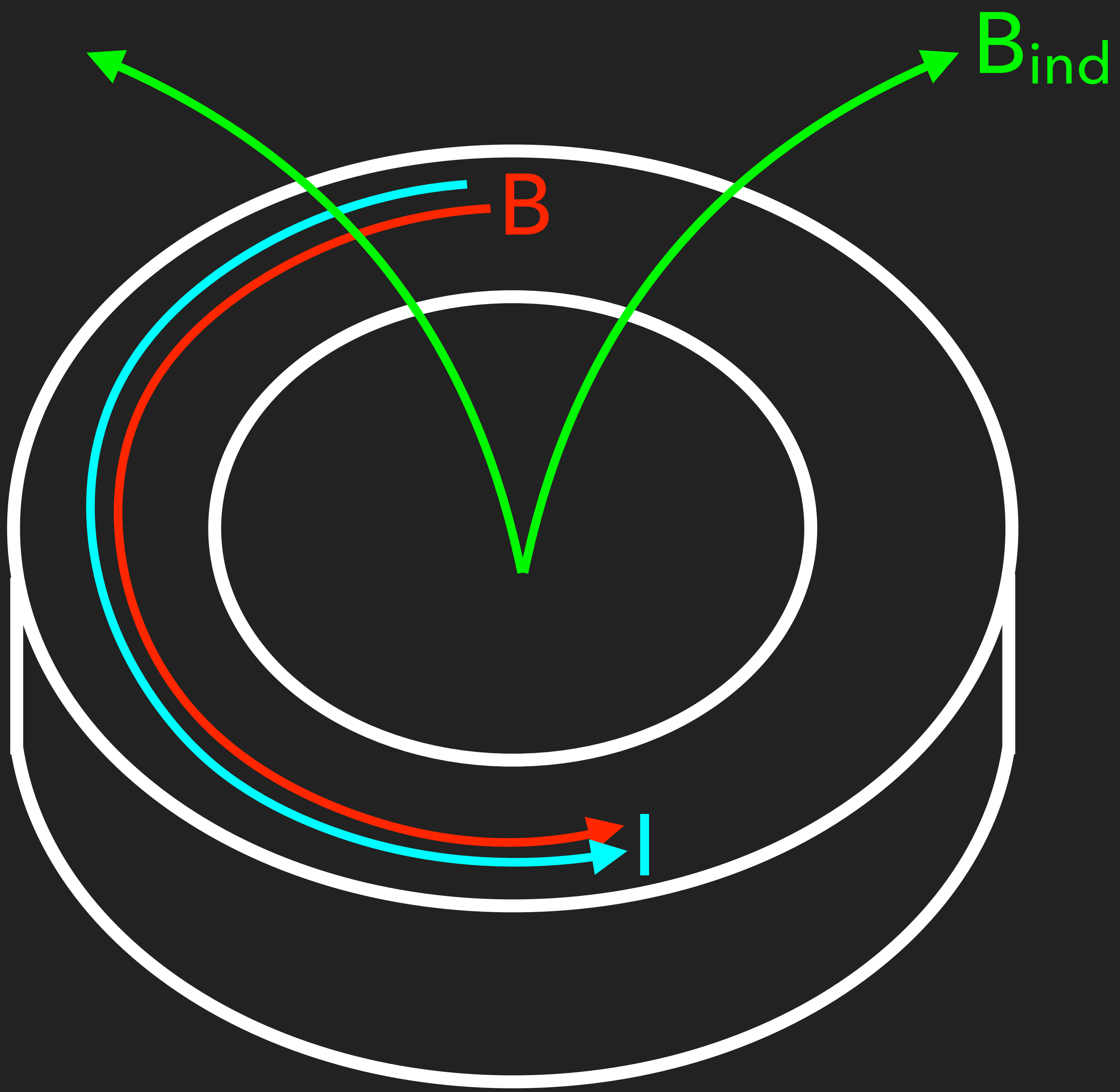
m_a^{-1} >> size of experiment: $\nabla \times \mathbf{B} = g_{a\gamma\gamma} \mathbf{B} \frac{\partial a}{\partial t}$

Axion Effective Electric Current: I



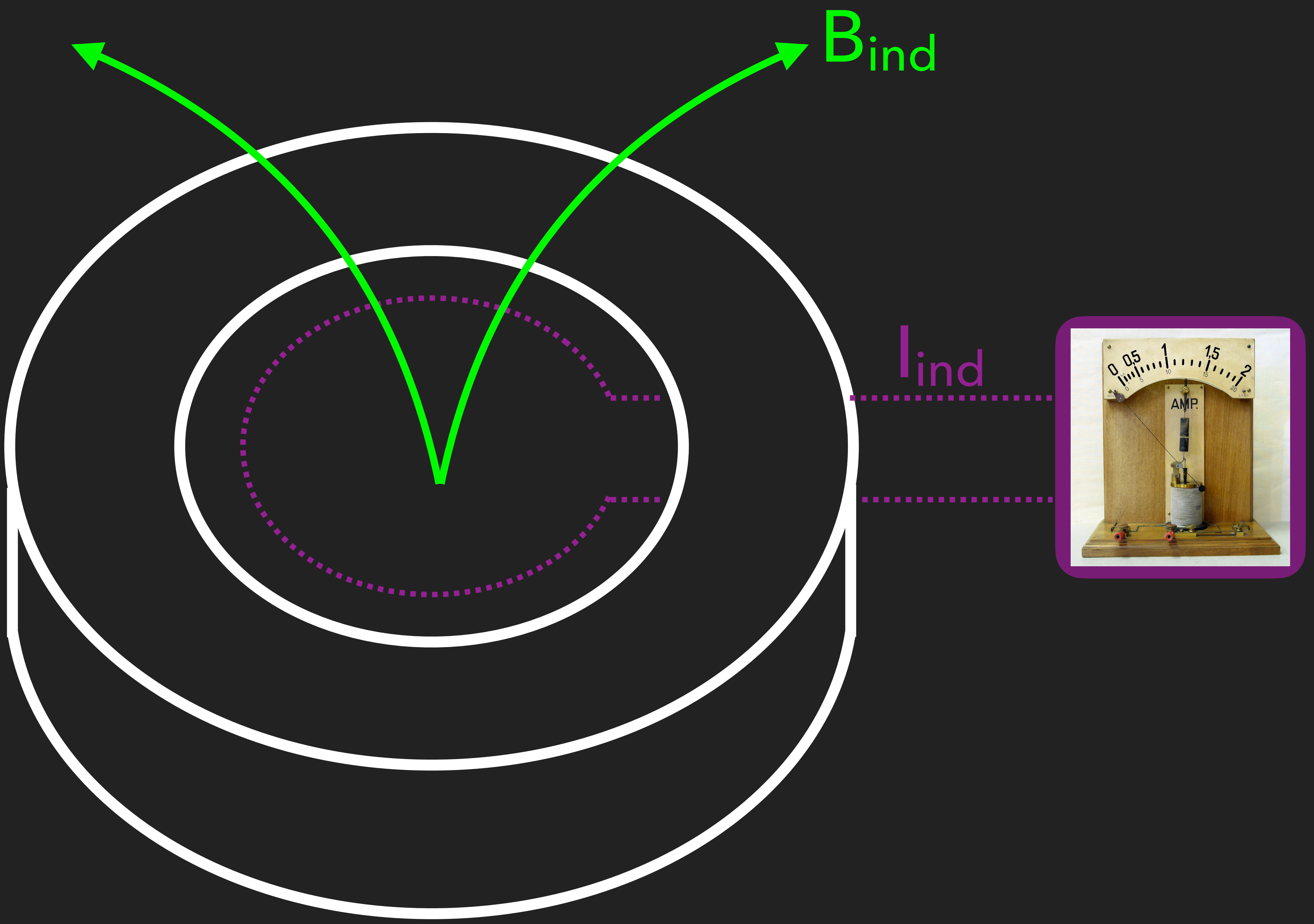
$$\mathcal{L} = g_{a\gamma\gamma} a \mathbf{E} \cdot \mathbf{B}$$

m_a^{-1} >> size of experiment: $\nabla \times \mathbf{B} = g_{a\gamma\gamma} \mathbf{B} \frac{\partial a}{\partial t}$



Secondary axion-induced B-field: B_{ind}

m_a^{-1} >> size of experiment: $\nabla \times \mathbf{B} = g_{a\gamma\gamma} \mathbf{B} \frac{\partial a}{\partial t}$

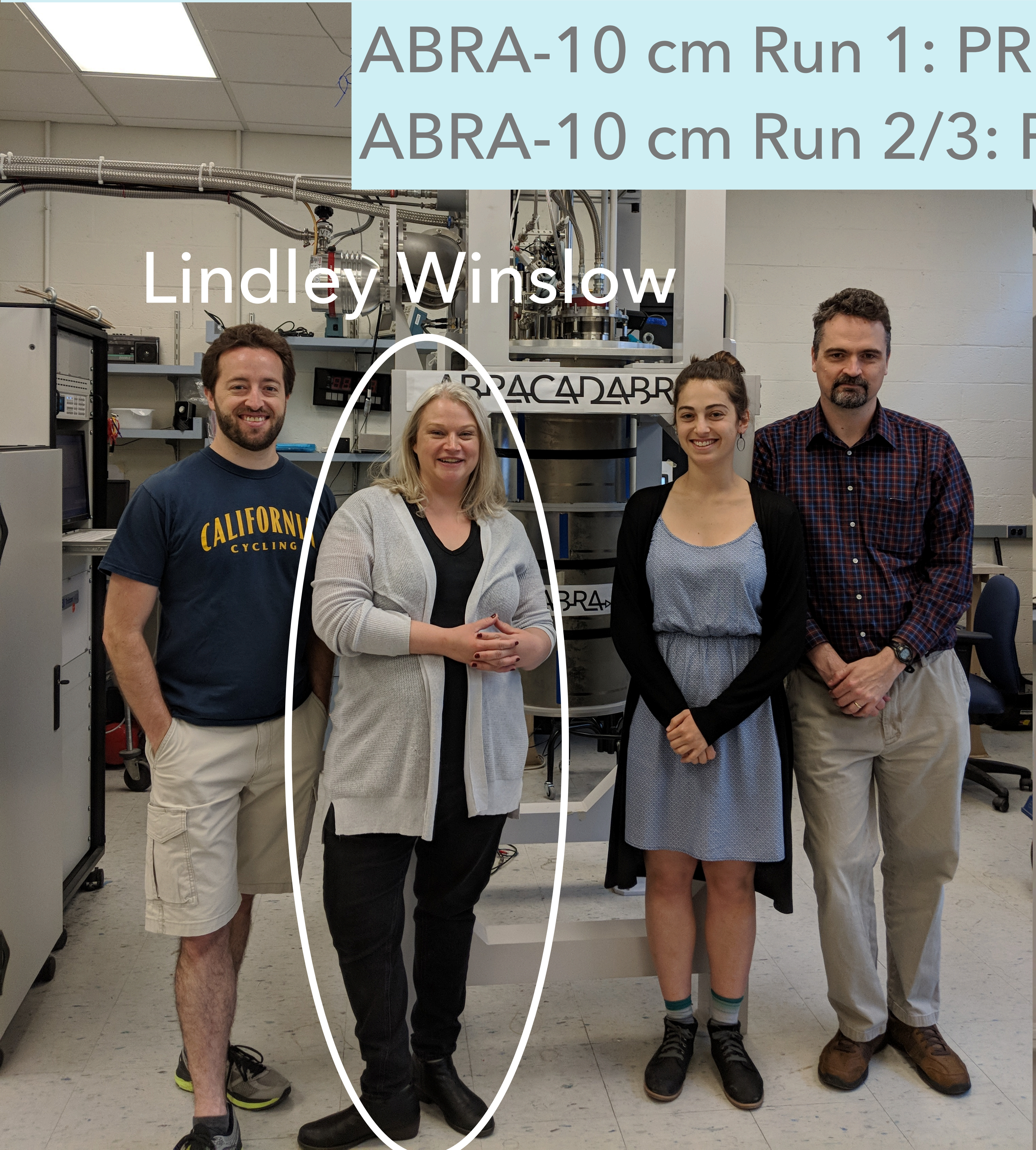


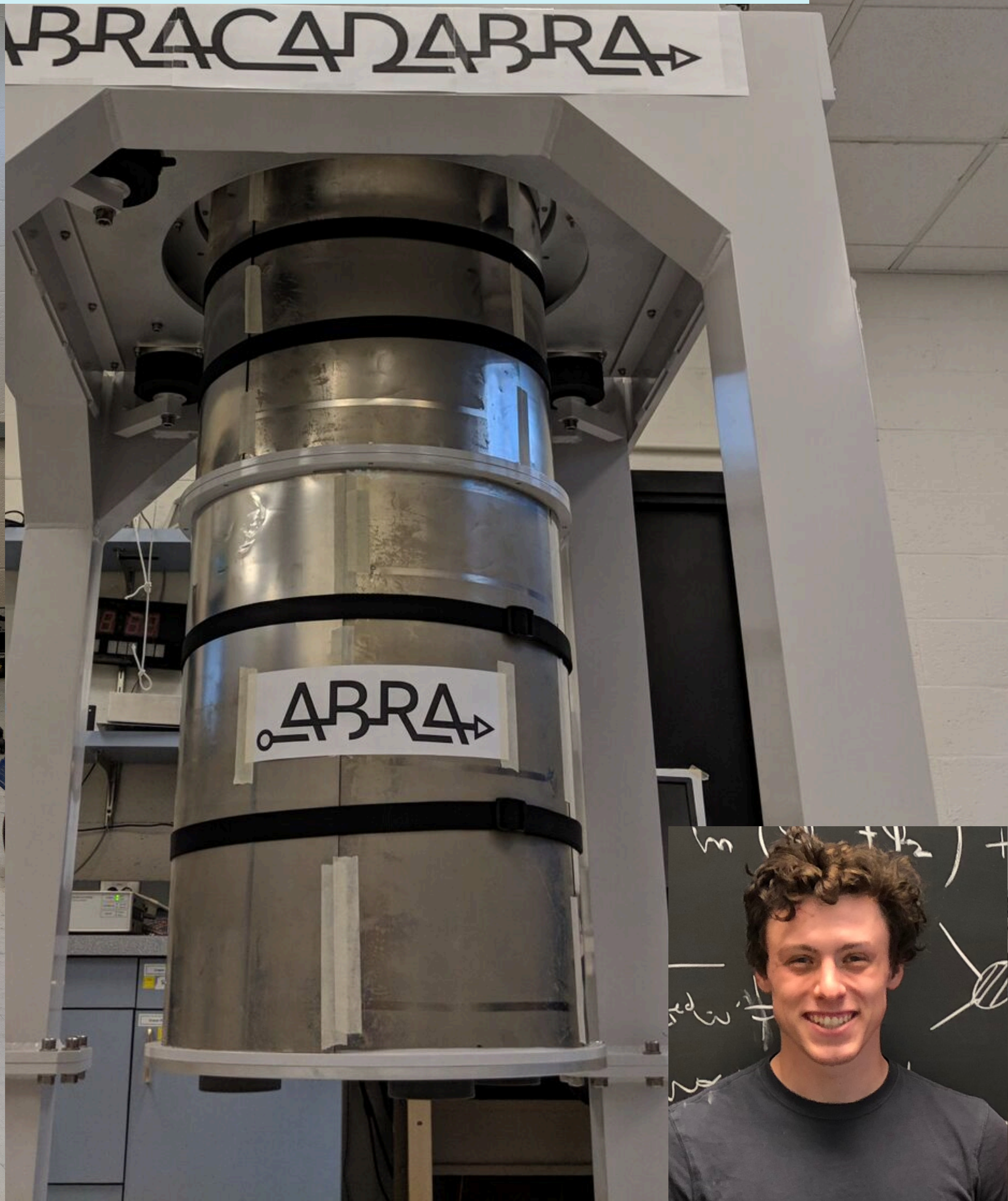
Pickup-loop current: I_{ind}

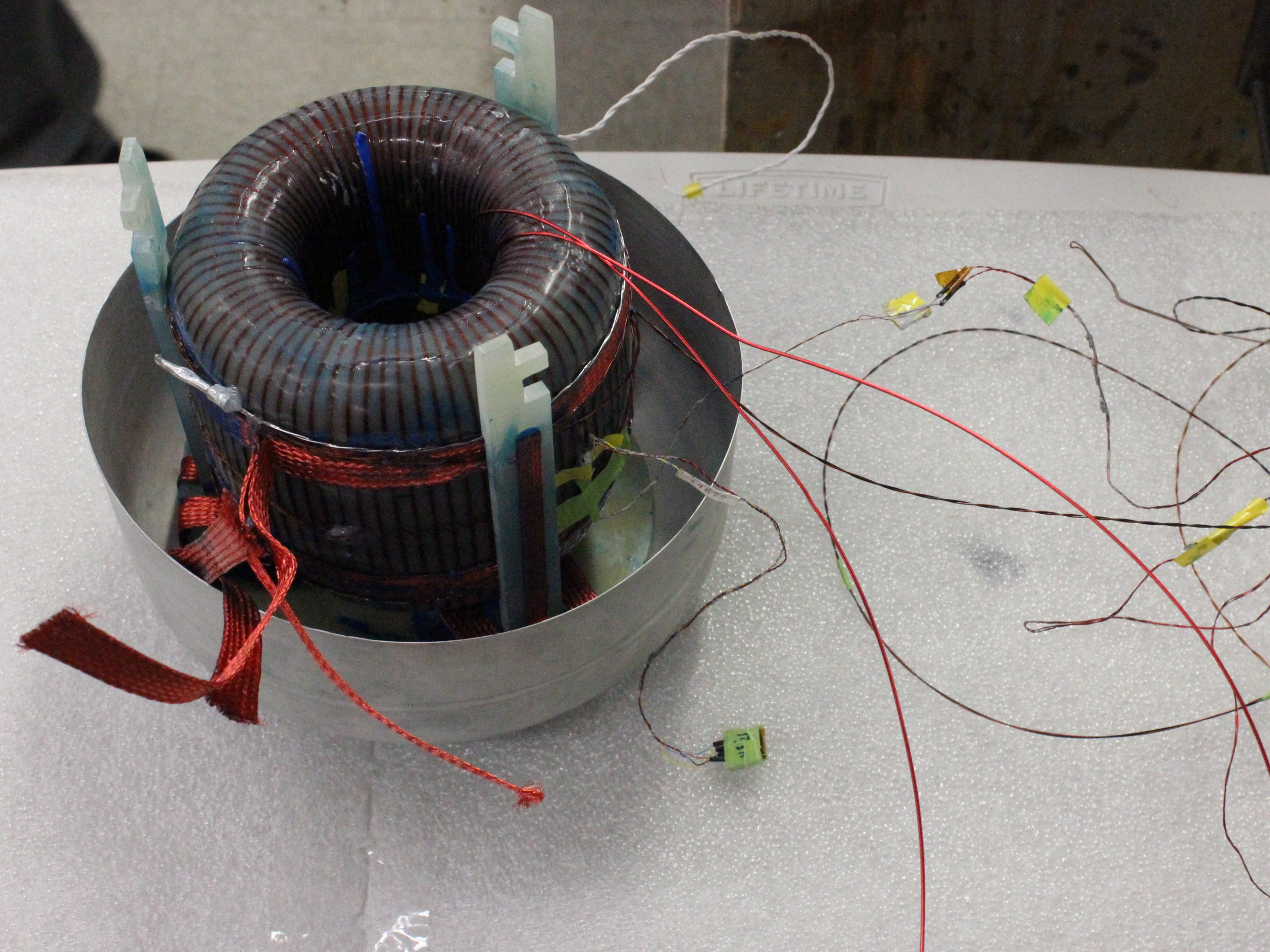
m_a^{-1} >> size of experiment: $\nabla \times \mathbf{B} = g_{a\gamma\gamma}\mathbf{B}\frac{\partial a}{\partial t}$

ABRA-10 cm Run 1: PRL 2018, PRD 2019

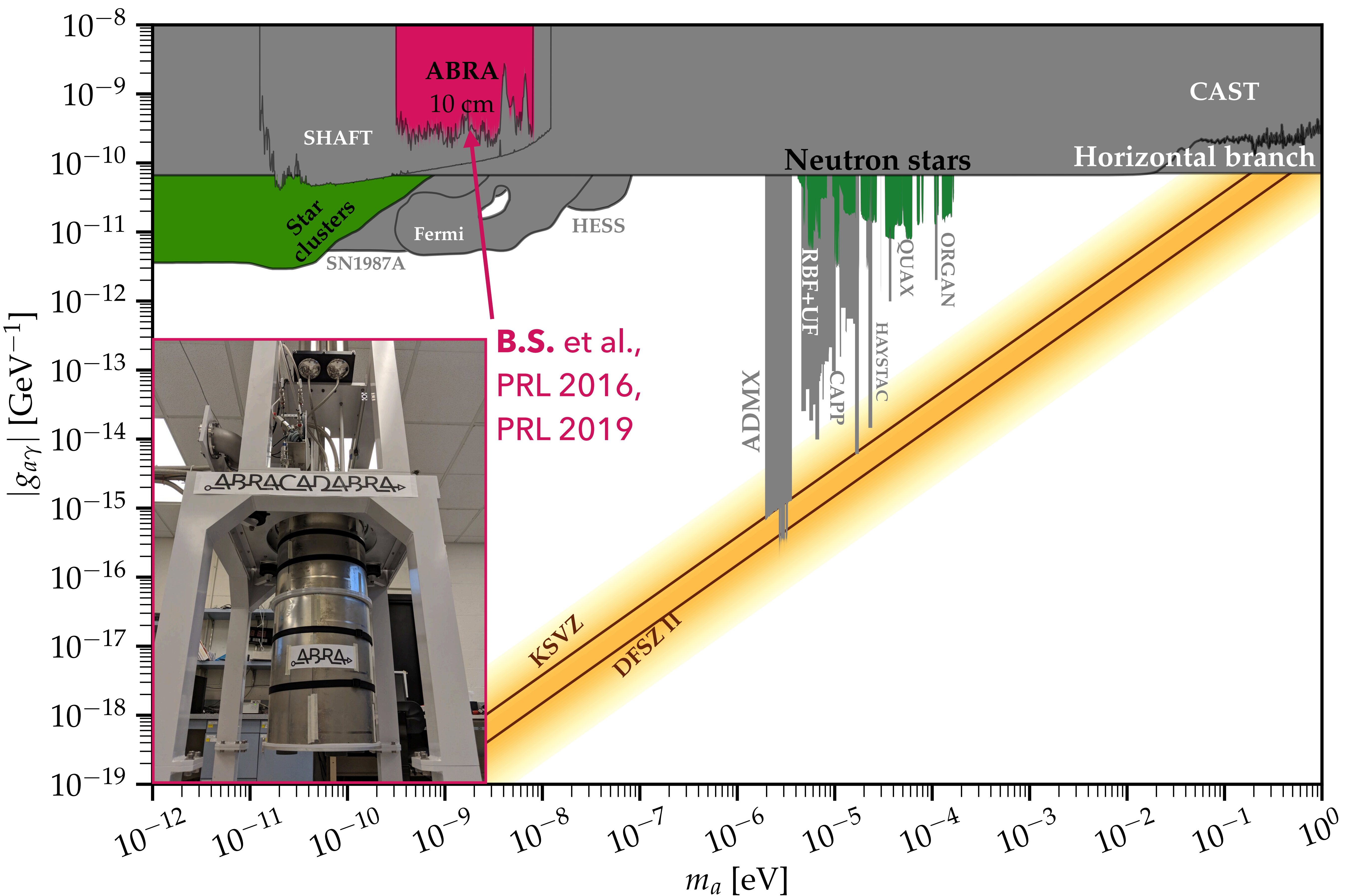
ABRA-10 cm Run 2/3: PRL 2021





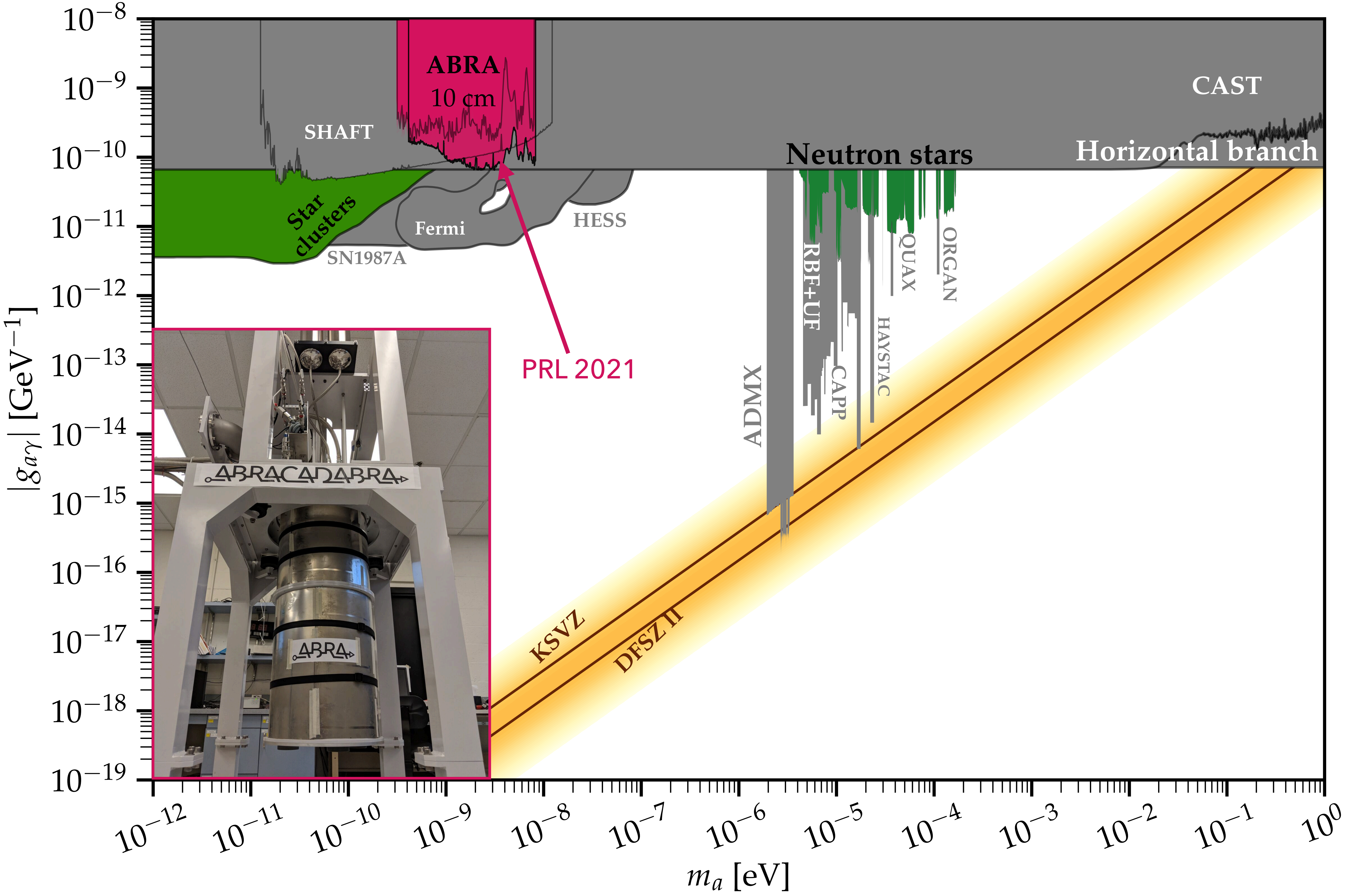

LIFETIME

$$\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4}$$

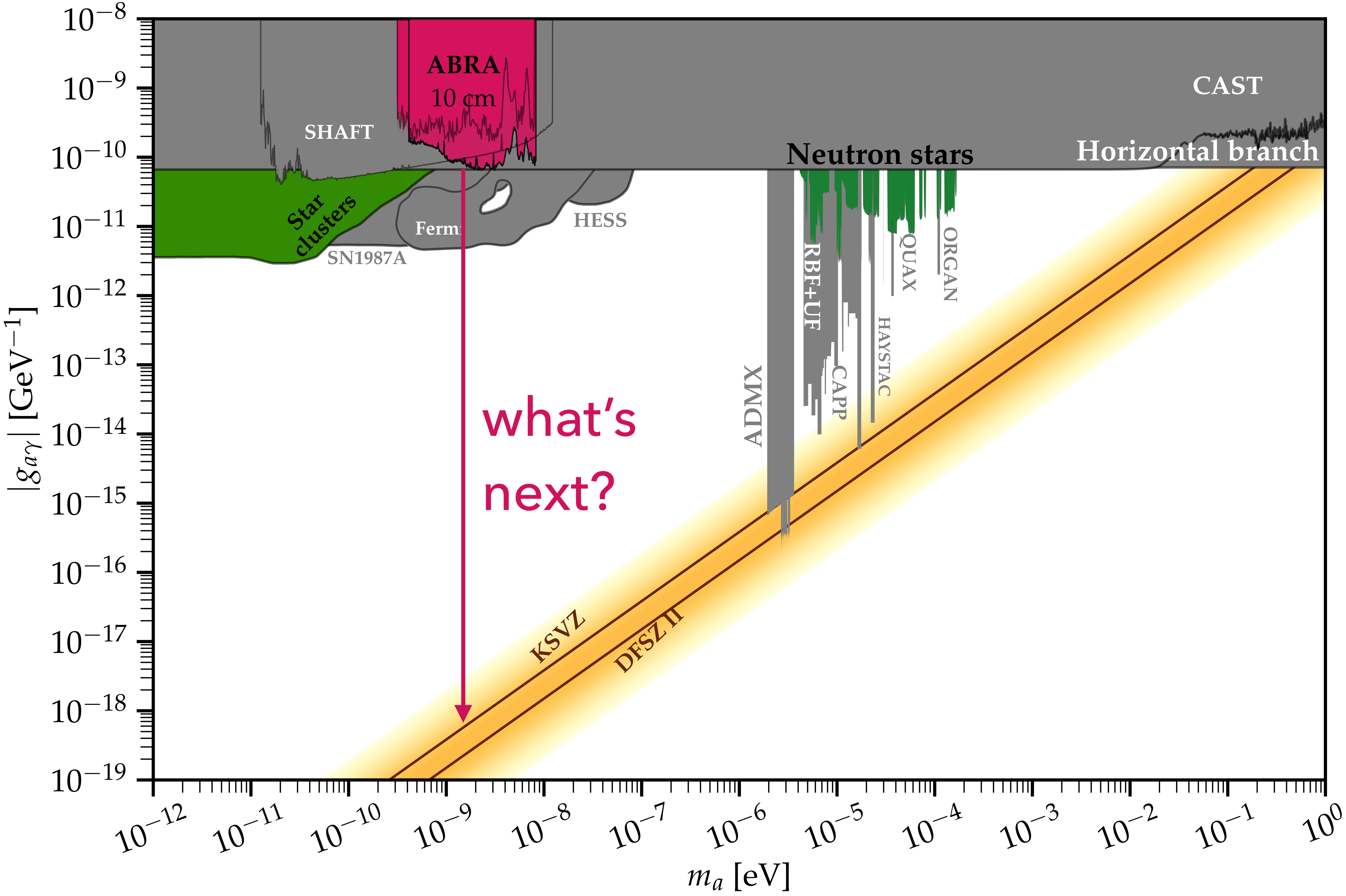


B.S. et al.,
PRL 2016,
PRL 2019

$$\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4}$$



$$\mathcal{L} = -g_{a\gamma\gamma}\frac{aF\tilde{F}}{4}$$



what's next?

DMRadio Collaboration

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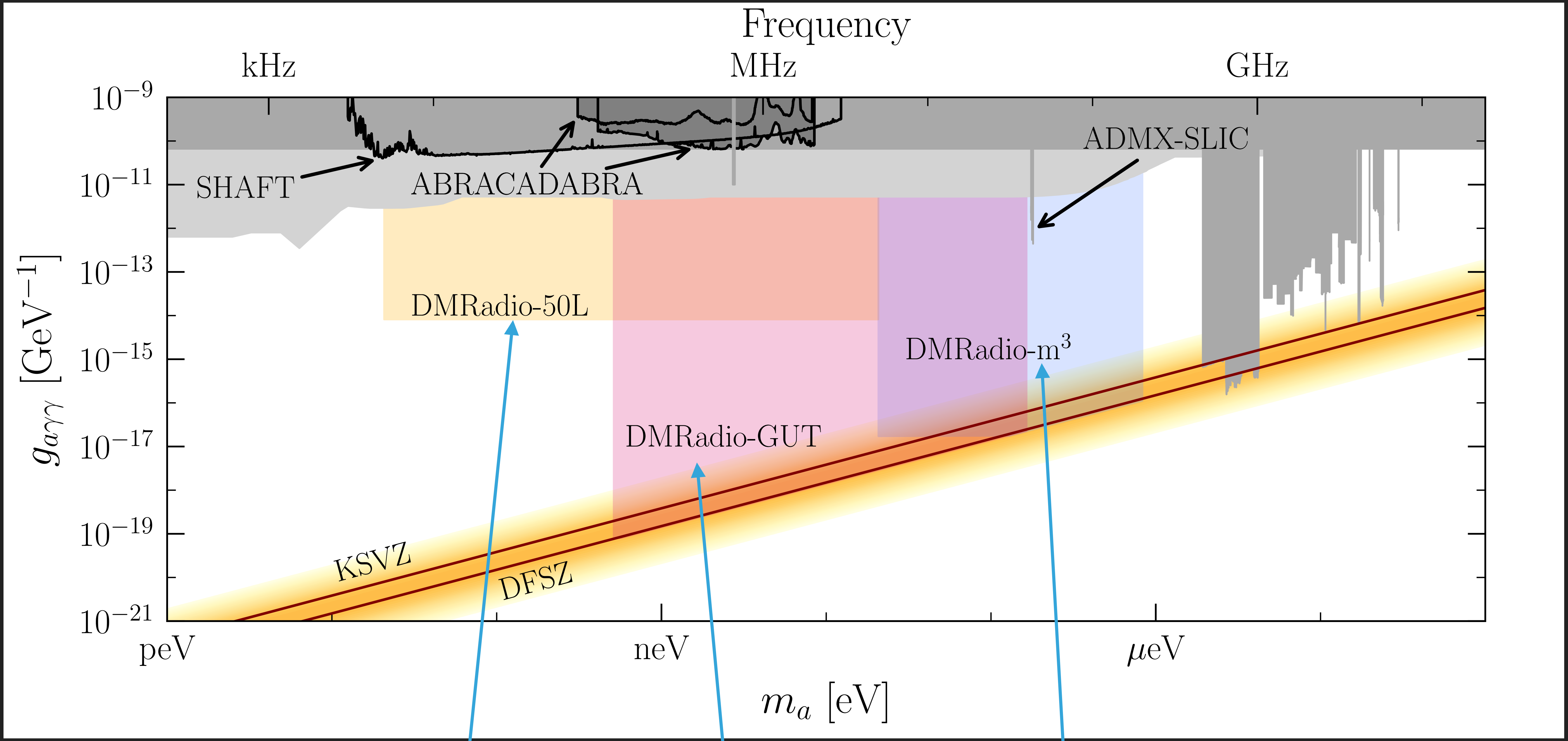
Berkeley UNIVERSITY OF CALIFORNIA
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
CAL STATE EAST BAY
PRINCETON UNIVERSITY
BERKELEY LAB
SANTA CLARA UNIVERSITY 1851
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
TUNL TRIANGLE UNIVERSITIES NUCLEAR LABORATORY
GORDON AND BETTY MOORE FOUNDATION
NSF
U.S. DEPARTMENT OF ENERGY Office of Science
HEISING-SIMONS FOUNDATION

DMRadio Science Plan

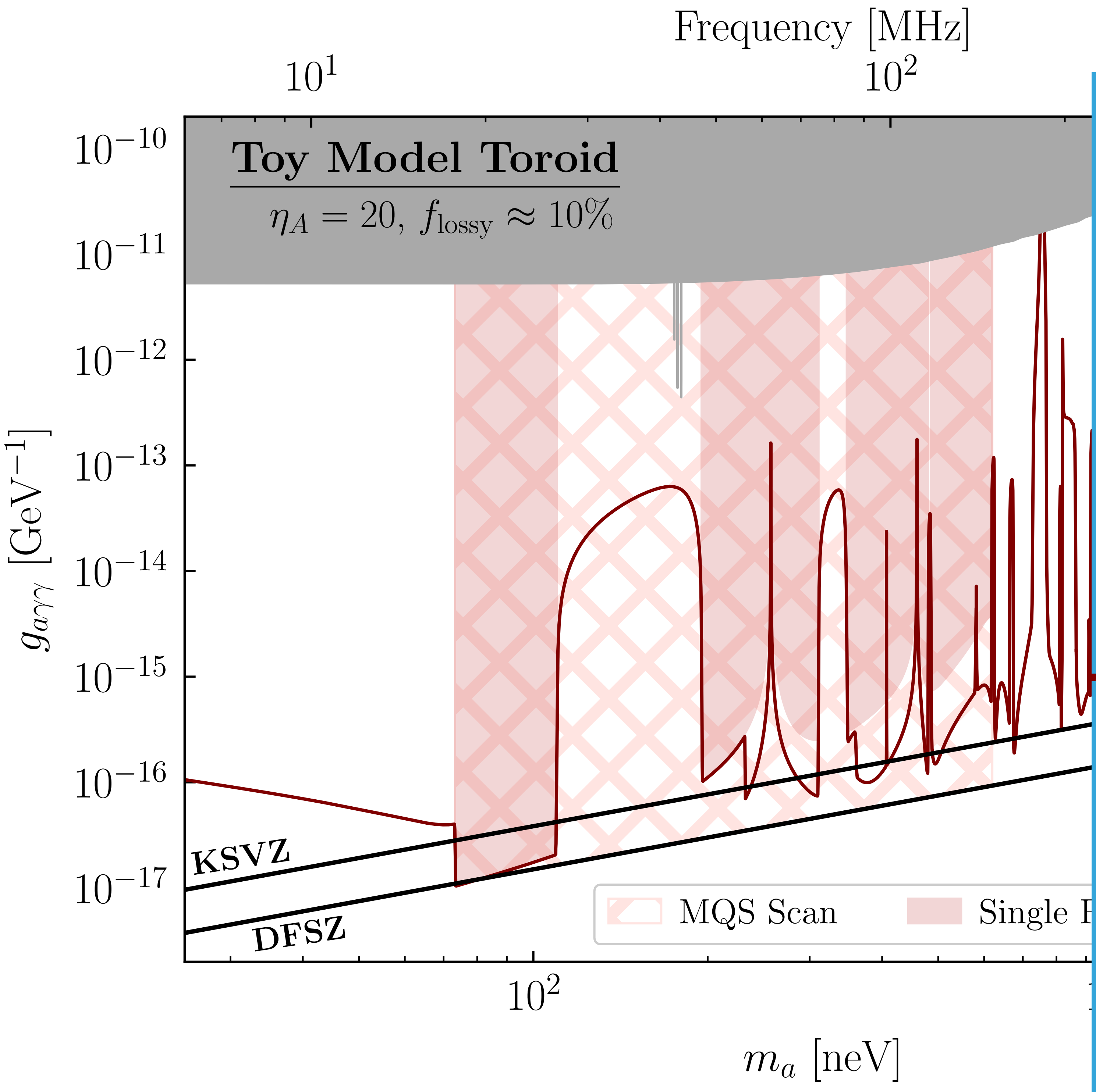


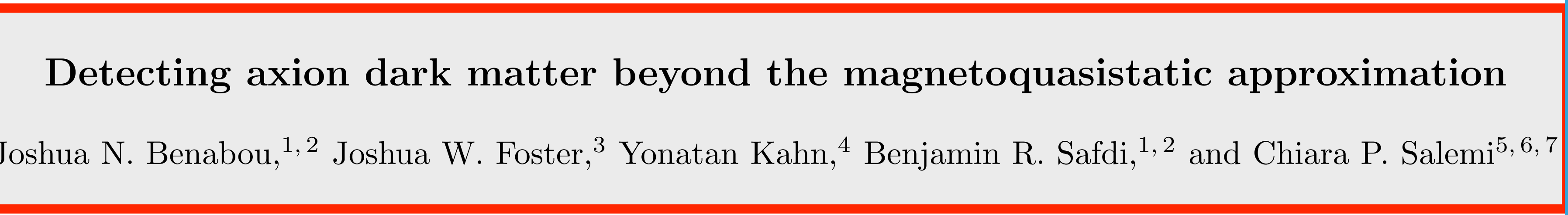
happening now

future aspirations

designing now

Caveat: Our simulations show beyond MQS Approximation, challenges emerge





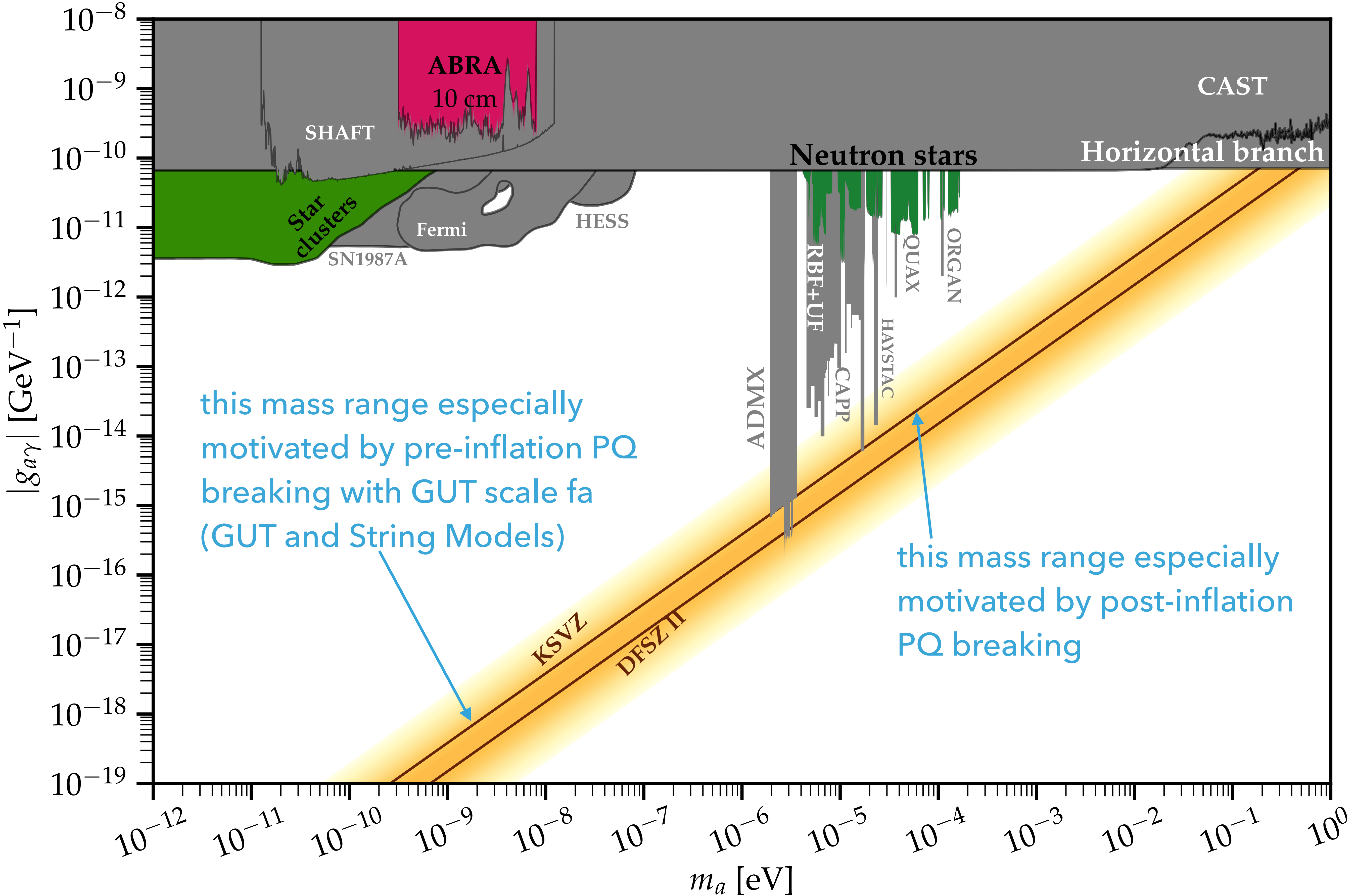
Detecting axion dark matter beyond the magnetoquasistatic approximation

Joshua N. Benabou,[1,2] Joshua W. Foster,[3] Yonatan Kahn,[4] Benjamin R. Safdi,[1,2] and Chiara P. Salemi[5,6,7]

DM Radio is actively engineering solutions to mitigate these previously unaccounted for effects

1. Radiation Losses
2. Toroid not ideal inductor
   1. At some frequencies toroid is capacitive!

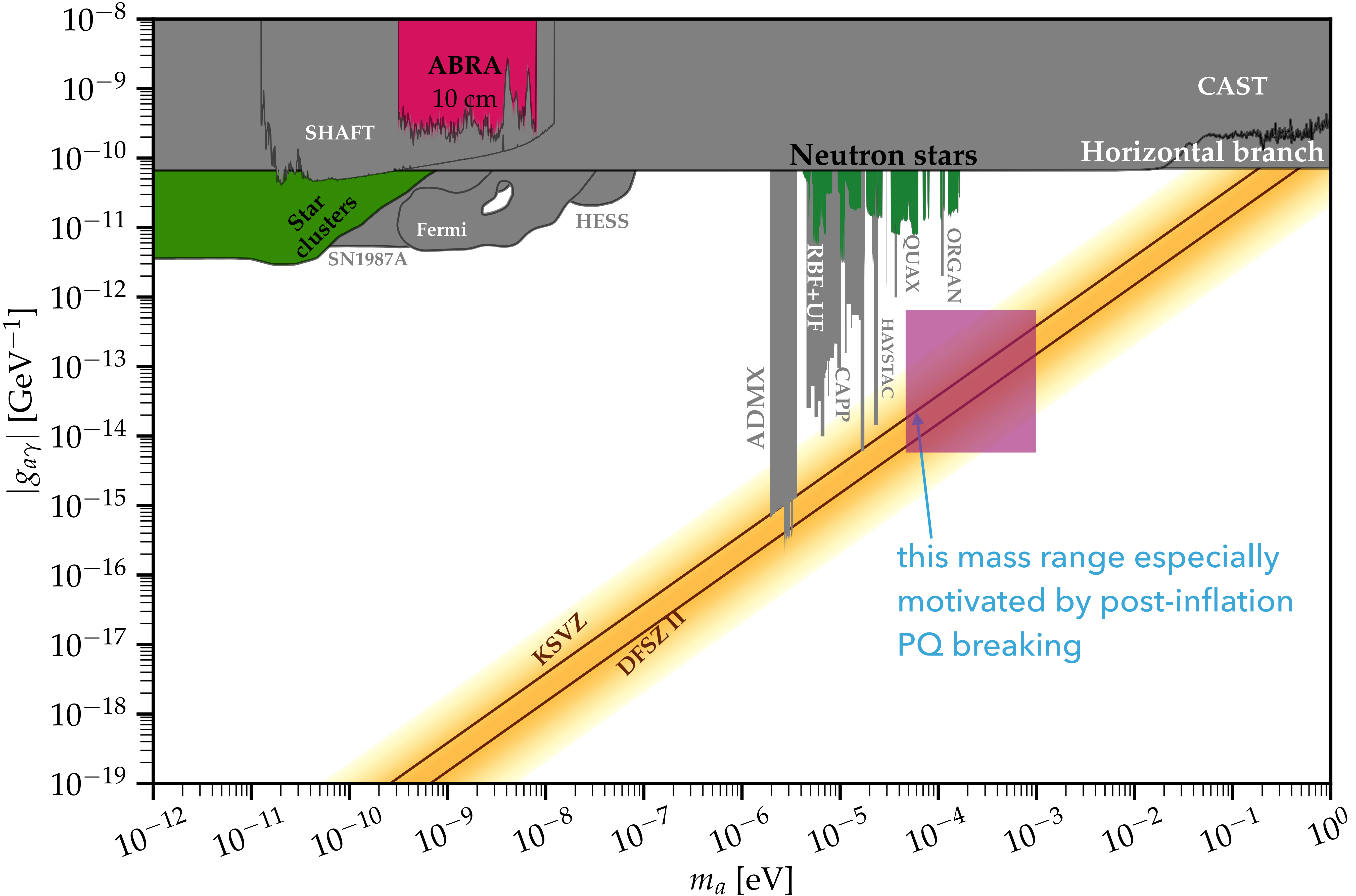
Motivated mass ranges



this mass range especially motivated by pre-inflation PQ breaking with GUT scale fa (GUT and String Models)

this mass range especially motivated by post-inflation PQ breaking

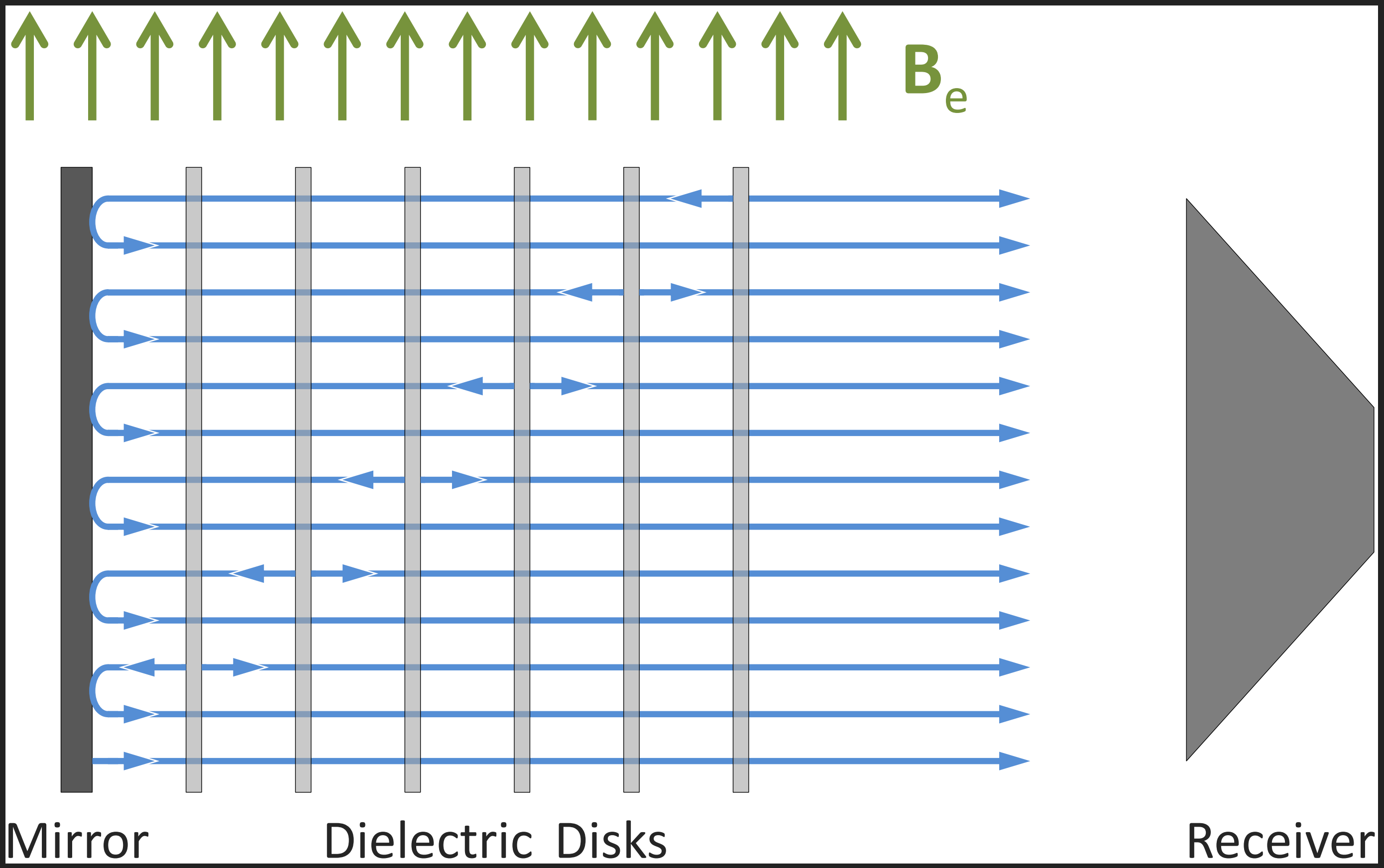
High-mass example: MADMAX

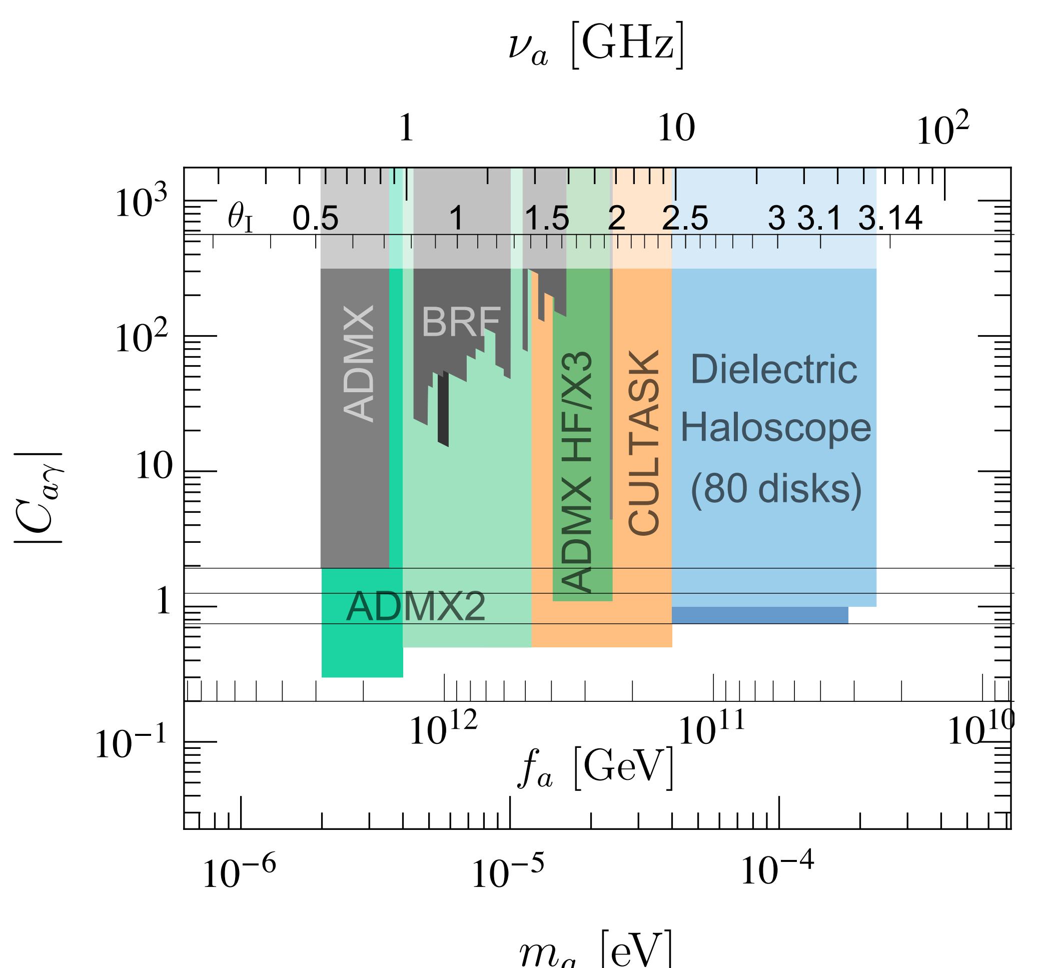


this mass range especially motivated by post-inflation PQ breaking

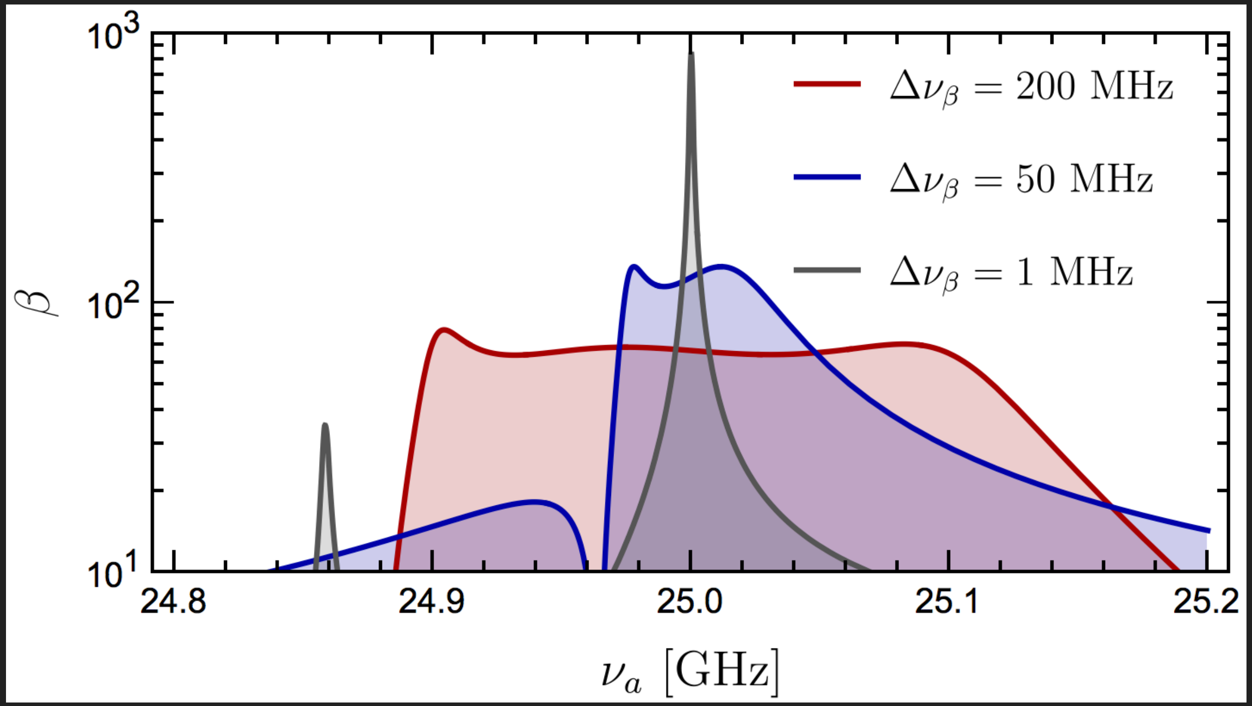
High-mass example: MADMAX, Caldwell et al. 2016

1. Cavities are too small at high mass
2. Need a way to have larger volume but also resonant enhancement





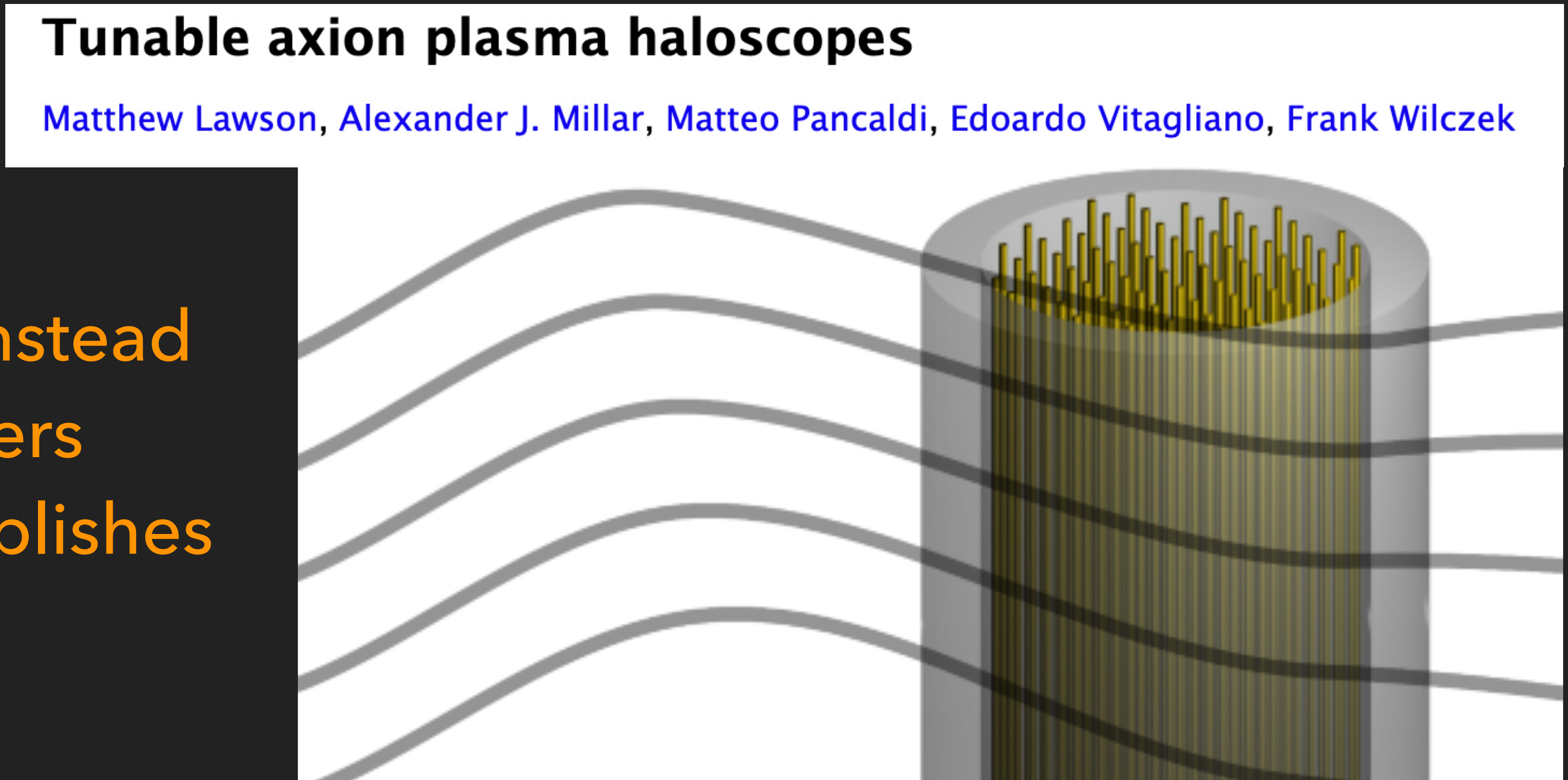
Resonant enhancement example: 20 layers



MADMAX is happening! DESY, Hamburg

MAgnetized Disc and Mirror Axion eXperiment

Other experiments in this range also:

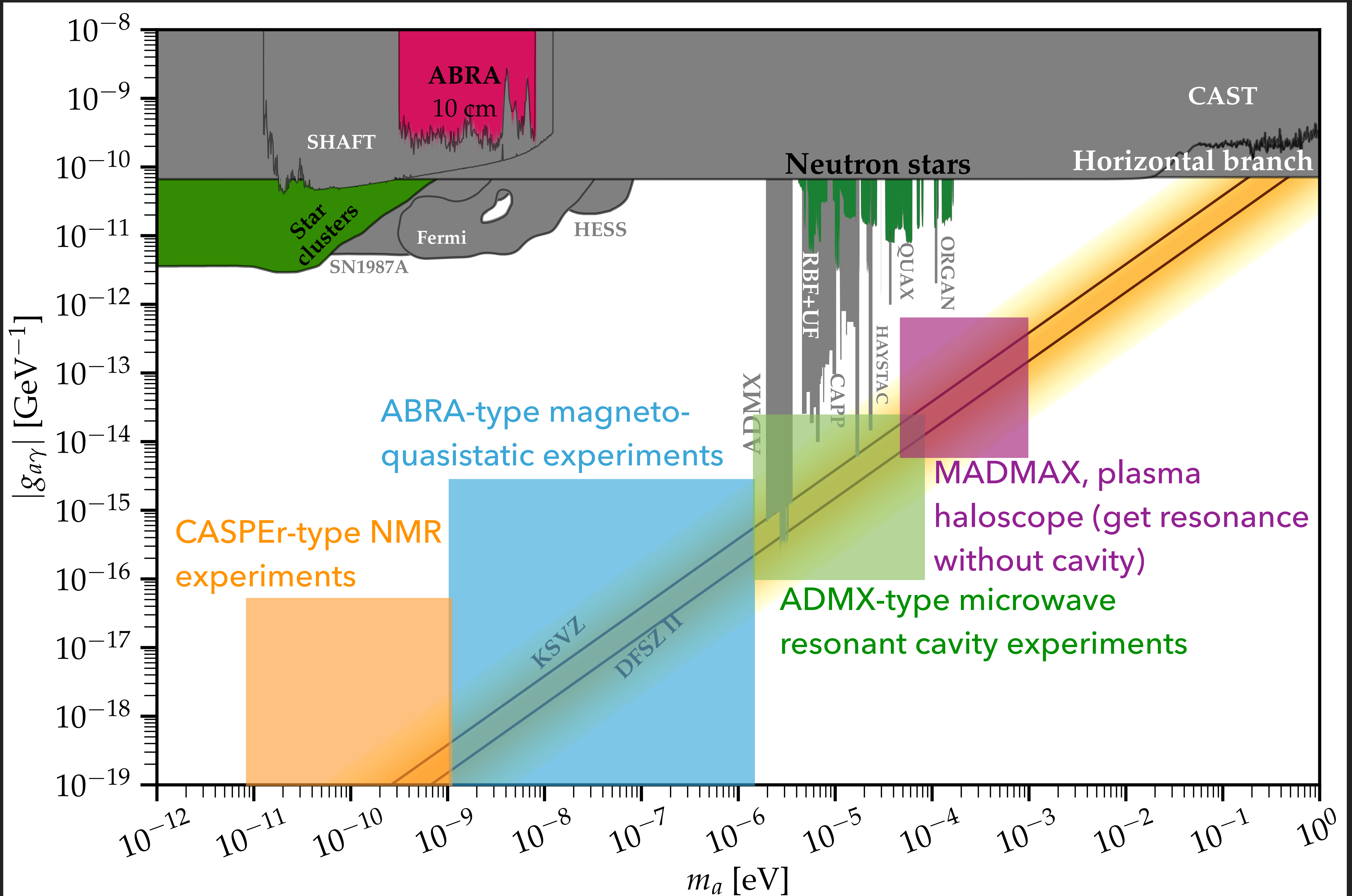


Tunable axion plasma haloscopes

Matthew Lawson, Alexander J. Millar, Matteo Pancaldi, Edoardo Vitagliano, Frank Wilczek

Array of wires instead of dielectric layers (morally accomplishes same result)

QCD Axion Direct Detection Summary



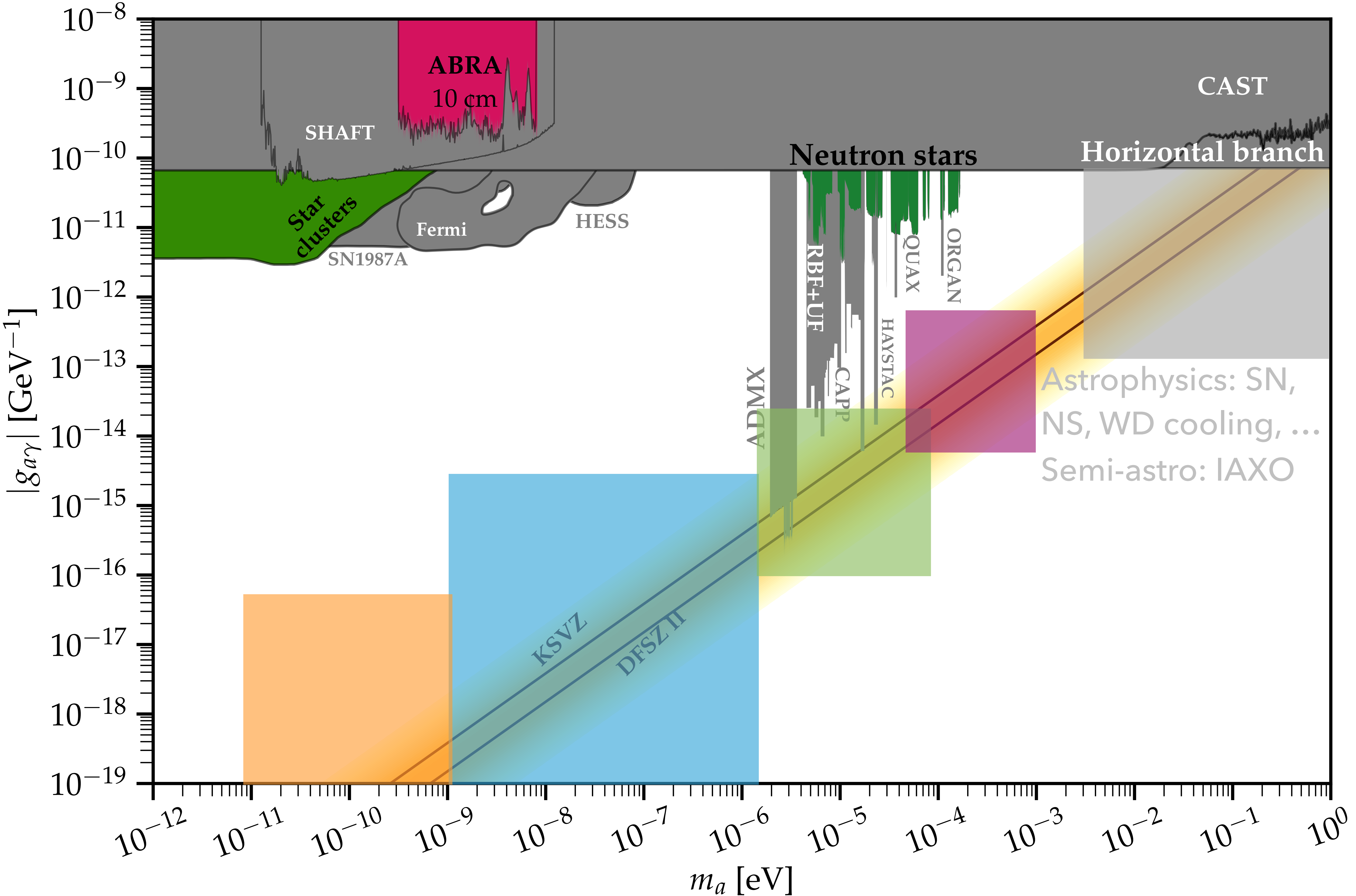
ABRA-type magneto-quasistatic experiments

CASPEr-type NMR experiments

MADMAX, plasma haloscope (get resonance without cavity)

ADMX-type microwave resonant cavity experiments

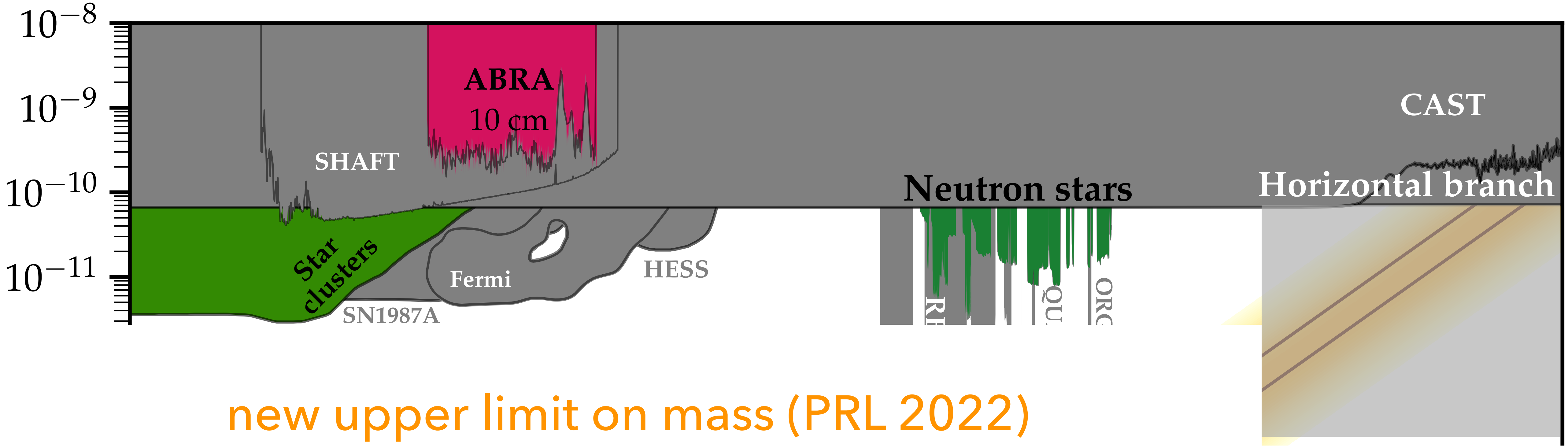
Astrophysical probes most relevant at high masses



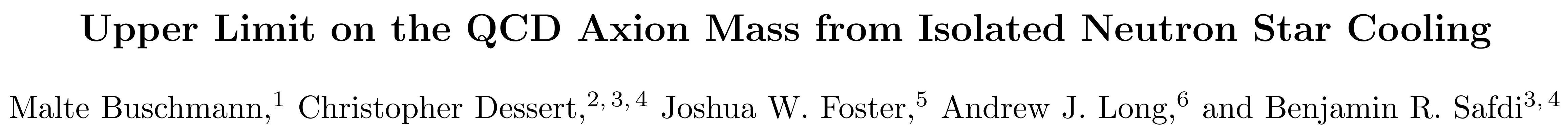
Astrophysics: SN, NS, WD cooling, …

Semi-astro: IAXO

Astrophysical probes most relevant at high masses

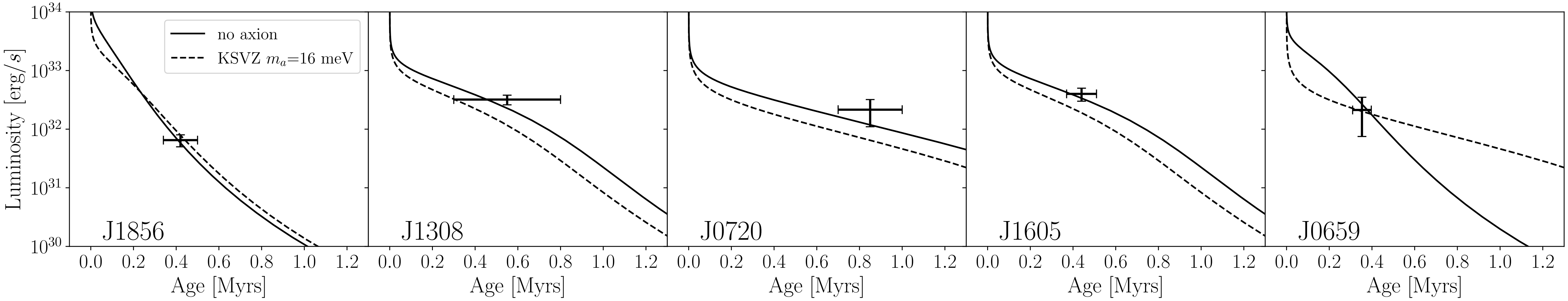


new upper limit on mass (PRL 2022)



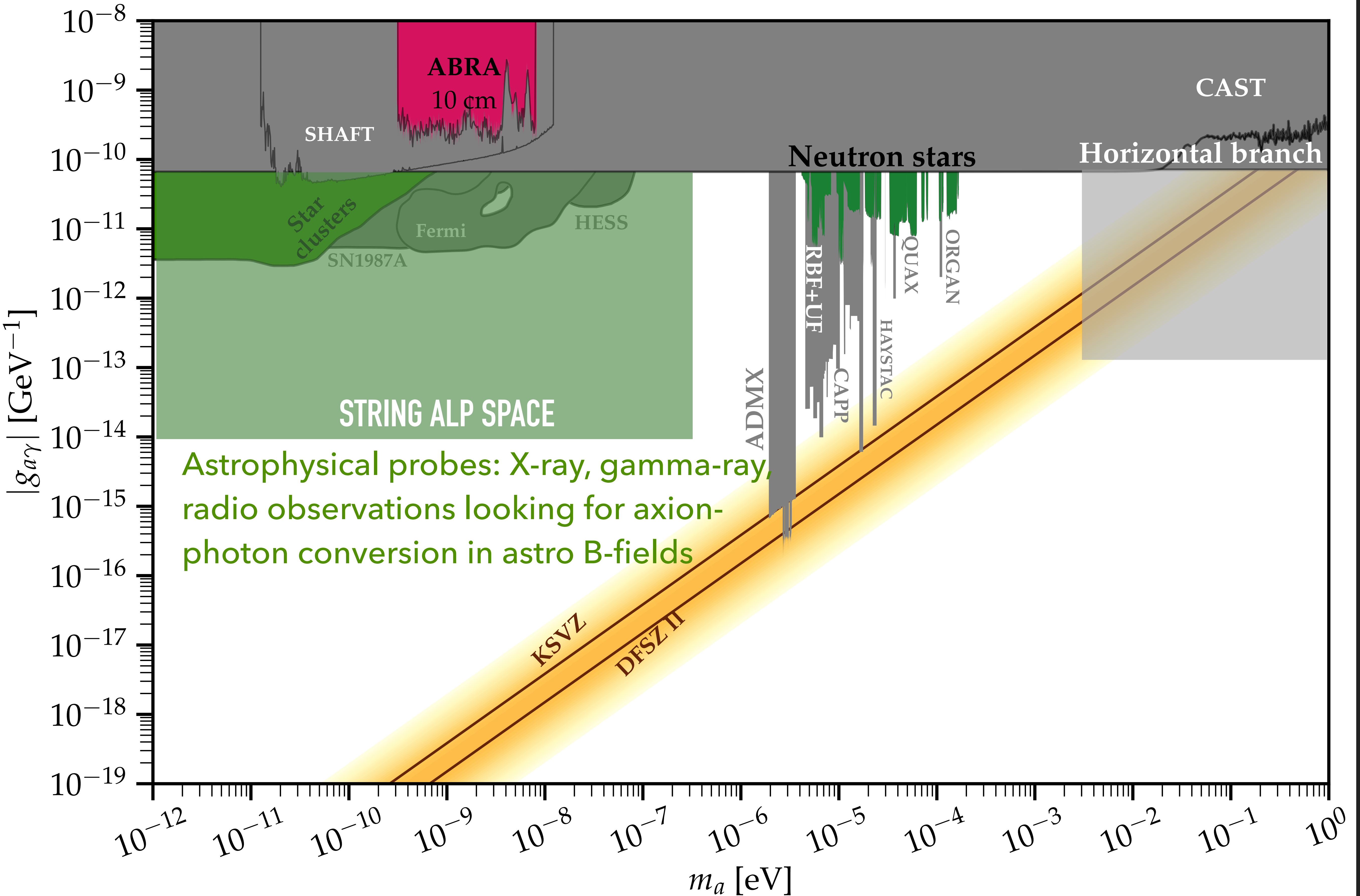
Upper Limit on the QCD Axion Mass from Isolated Neutron Star Cooling

Malte Buschmann,[1] Christopher Dessert,[2, 3, 4] Joshua W. Foster,[5] Andrew J. Long,[6] and Benjamin R. Safdi[3, 4]



m_a < (10 - 30) meV (depending of KSVZ/DFSZ)

Low-mass ALPs motivated by string theory

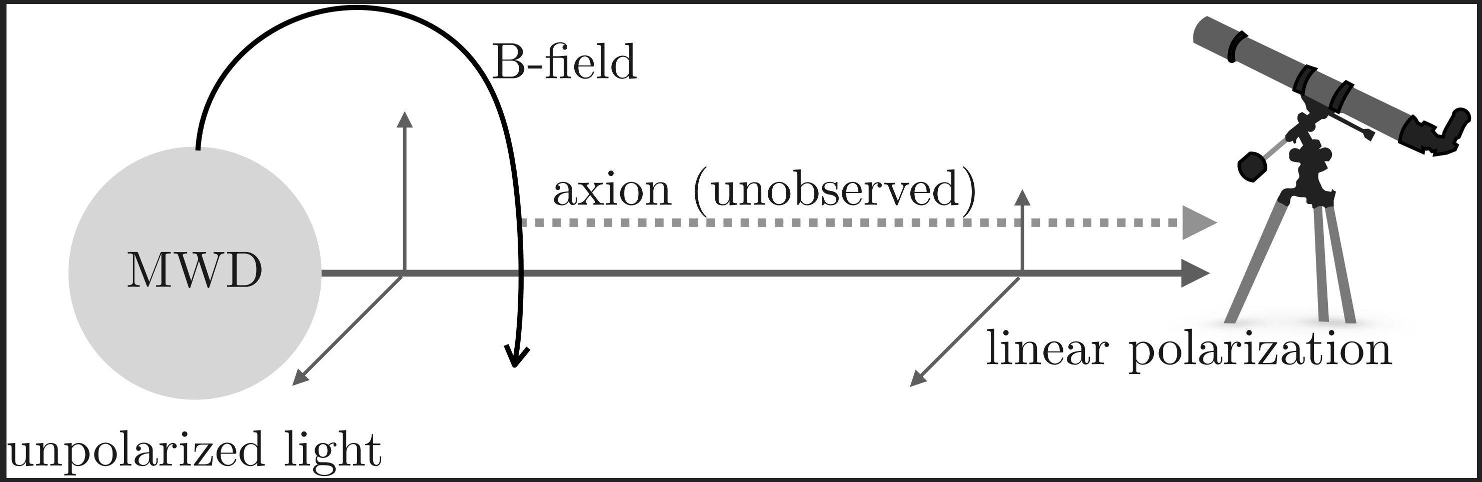


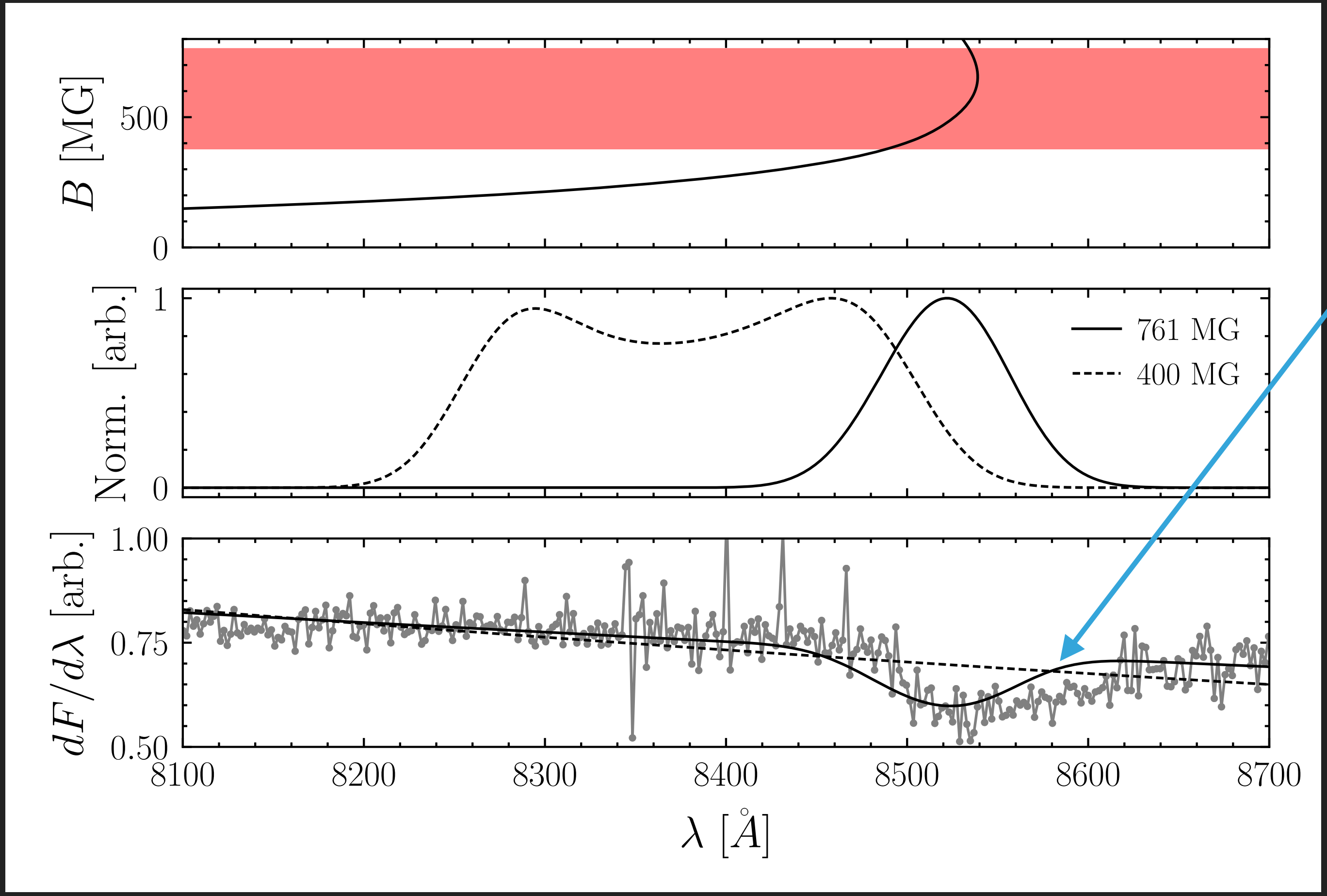
Astrophysical probes: X-ray, gamma-ray, radio observations looking for axion-photon conversion in astro B-fields

Example: Magnetic White Dwarf Polarization

C. Dessert. D. Dunsky, **B.S.**, 2022

Robust probes of ultra-light ALPs





Magnetic fields measured by Zeeman effect for absorption lines in MWD atmosphere

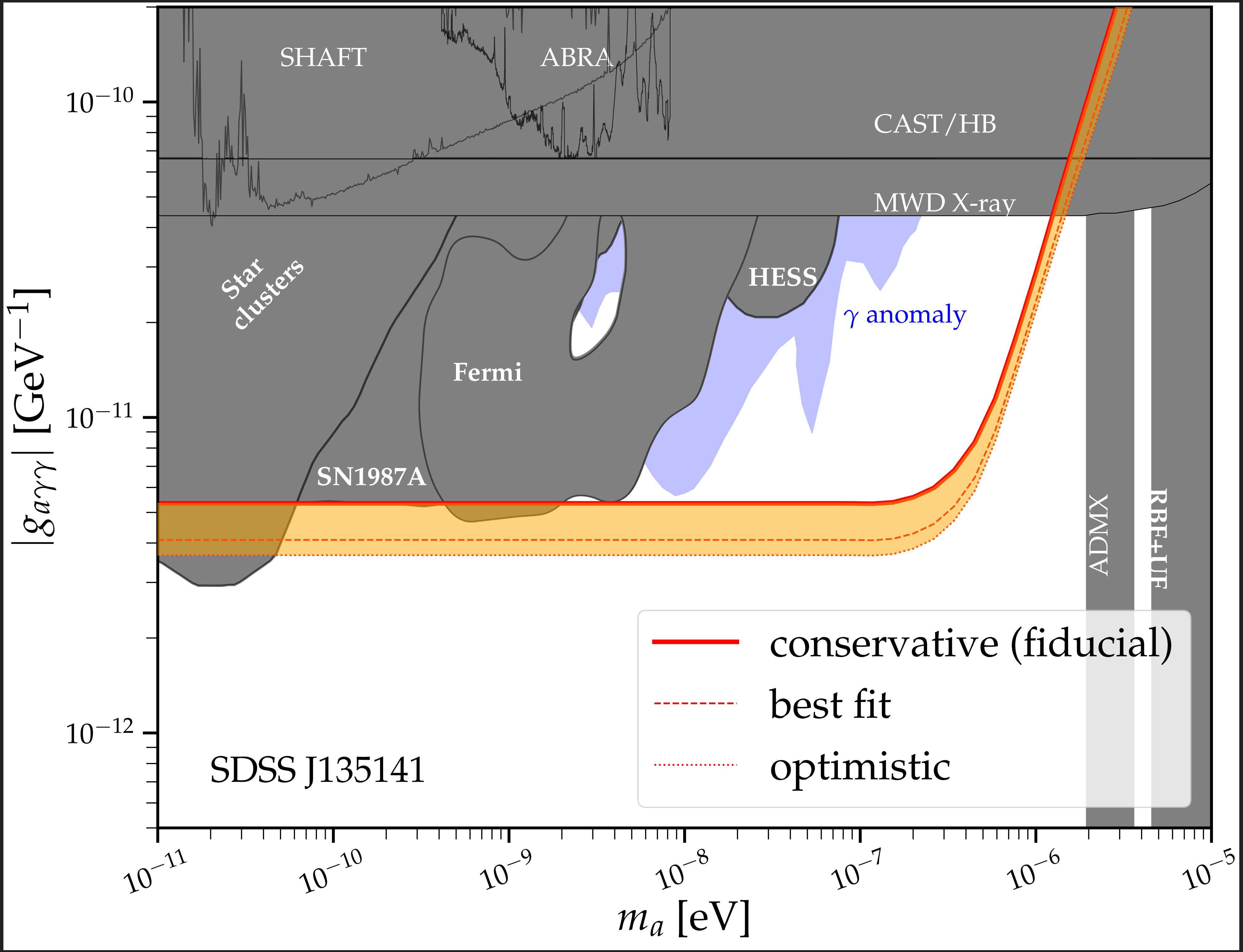
Astro contribution to linear polarization is negligible

1. current data is instrument-limited upper limit on polarization

Example: Magnetic White Dwarf Polarization

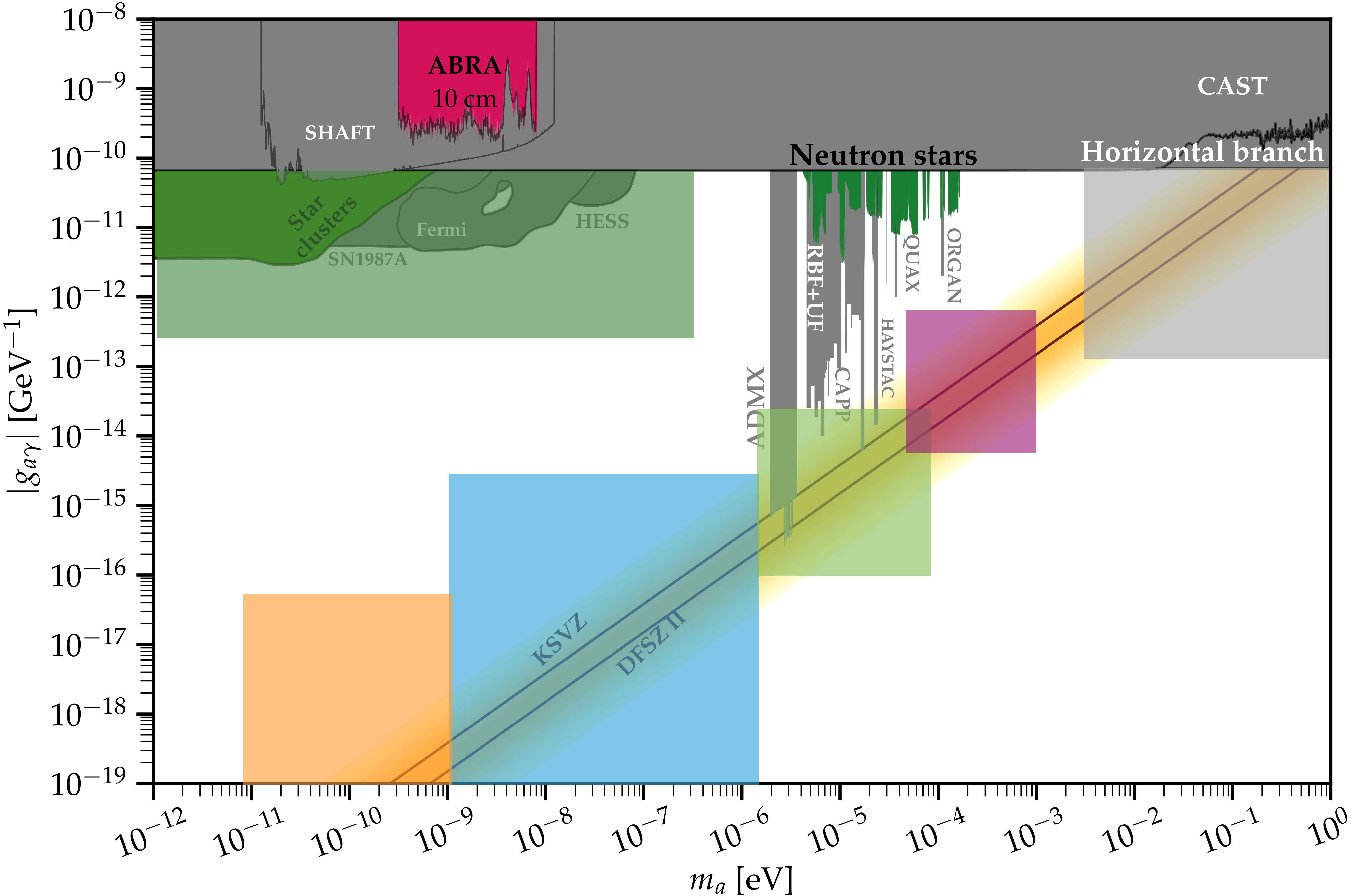
C. Dessert. D. Dunsky, **B.S.**, 2022

Robust probes of ultra-light ALPs



1. Order of magnitude improvement possible with dedicated data
2. **How do we move to parametrically smaller couplings?**

Summary


ABRA
10 cm
SHAFT
CAST
Neutron stars
Horizontal branch
Star clusters
Fermi
HESS
SN1987A
RBF+UF
QUAX
ORGAN
HAYSTAC
CAPP
ADMX
KSVZ
DFSZ II
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-12}
10^{-11}
10^{-10}
10^{-9}
10^{-8}
10^{-7}
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}

IF IT'S OUT THERE, WE WILL FIND IT!

QUESTIONS?