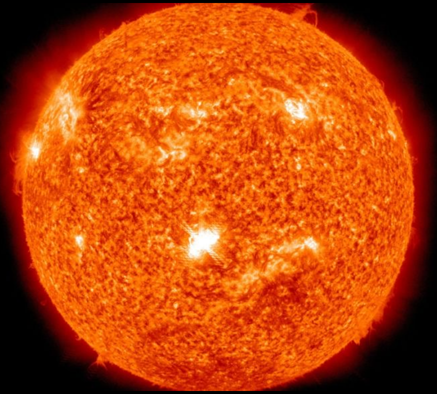
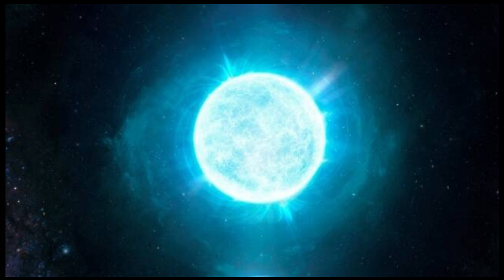
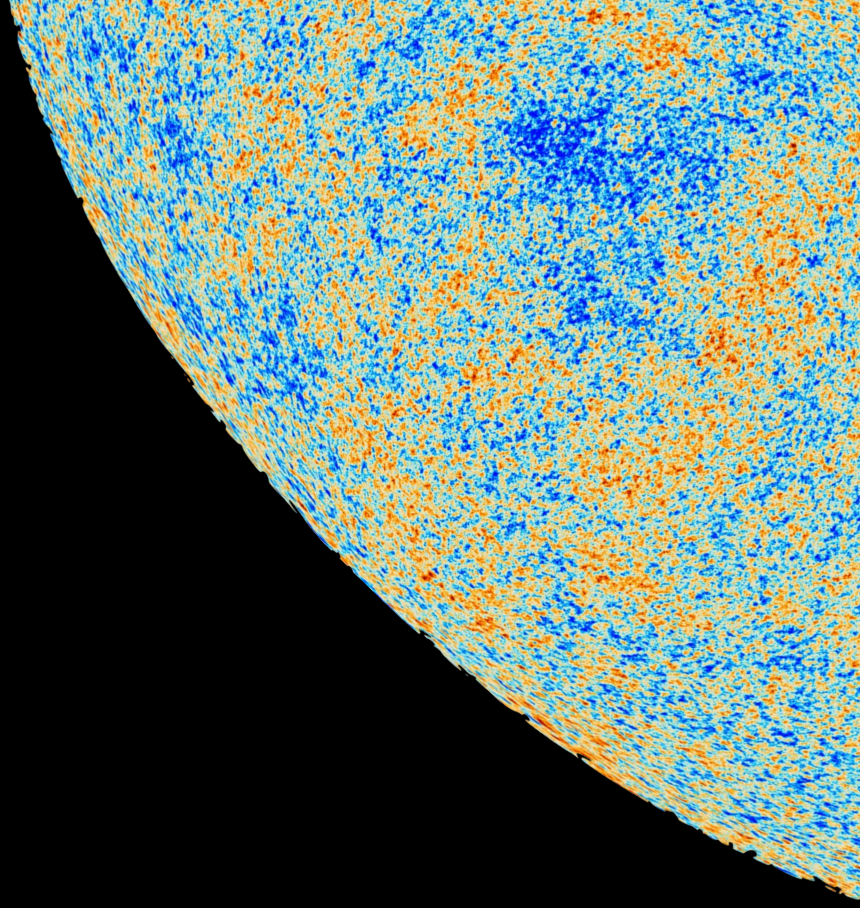
astrophysical
and
cosmological
probes of axions





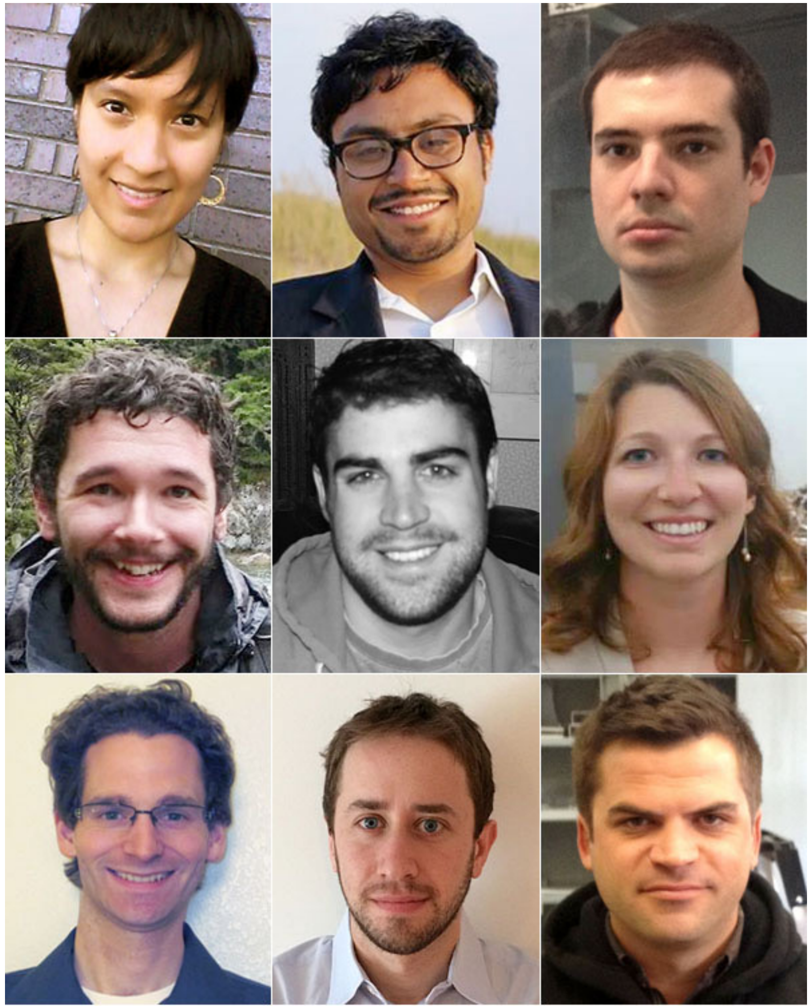


Andrew Long
Rice University

KICP Birthday Bash
June 6, 2024

the dream team

KICP Fellows circa 2015



fond memories

- KICP Jamboree + PD symposium
- Thunch … journal club
- KICP seminar run by fellows
- lunch with colloquium speakers
- the stitch + coffee
- support for workshops
- outreach: life-long learning
- interdisciplinary: particle physics + cosmology + astrophysics

A triumph of science!

Successes

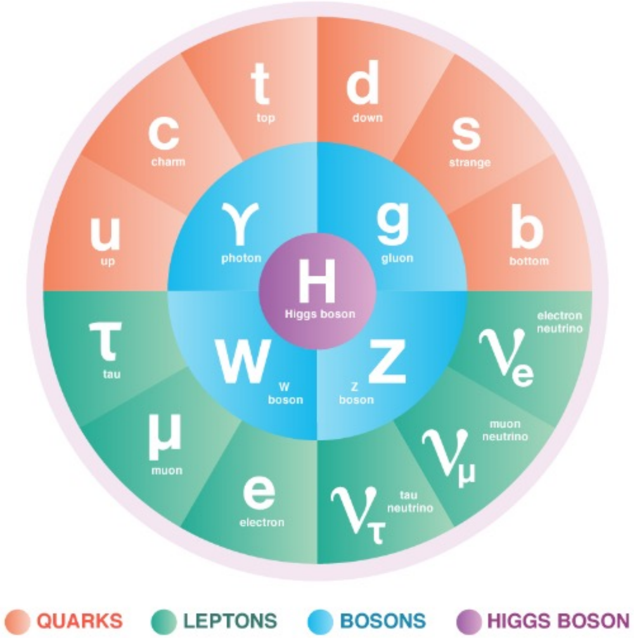
known physics

describes the properties of the known elementary particles and the forces by which they interact

allows for precision calculation

a predictive framework

Standard Model of the Elementary Particles

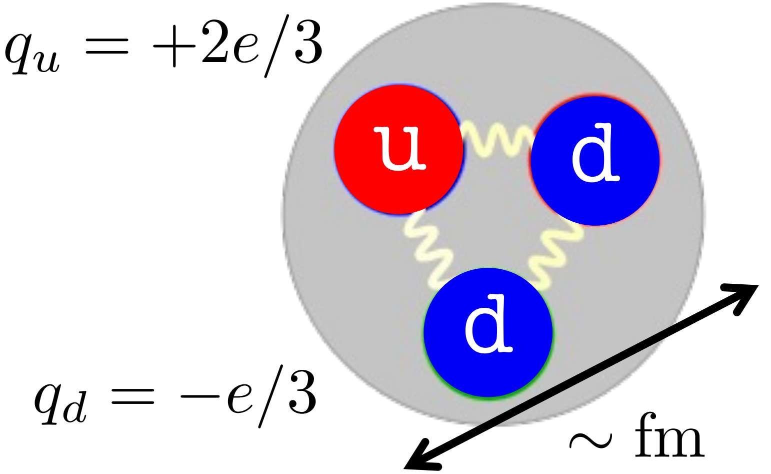


Puzzles

hints of *new* physics

Why is the Higgs light?
Why don't couplings unify?
Why are neutrinos massive?
Why three generations?
Why is there dark matter?
Why is there dark energy?
Why less antimatter?
Why homogenous & isotropic?
Why no strong CP violation?

A puzzle with the neutron's electric dipole moment



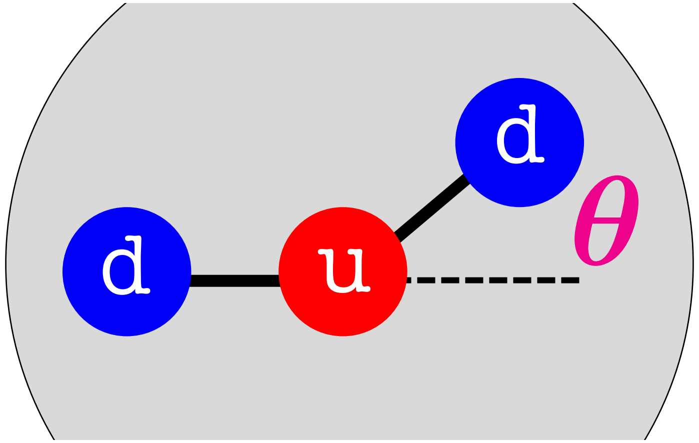
naïve dimensional analysis

$$d_n \sim e \times \text{fm} \sim 10^{-13} e\,\text{cm}$$

experiment

$$d_n < 10^{-26} e\,\text{cm}$$

consider this configuration:



$$d_n \to 0 \quad \text{as} \quad \theta \to 0$$

the strong nuclear force
exhibits a symmetry (CP)

Why does the strong nuclear force exhibit CP symmetry?

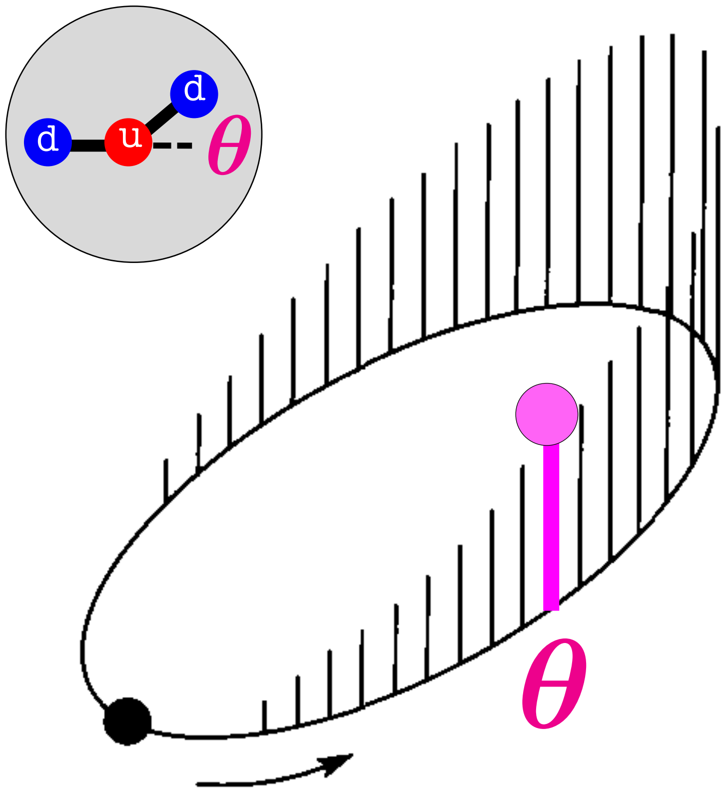
this is called the *Strong CP Problem*

* more precisely: why is $\bar{\Theta} = \Theta + \mathrm{Arg}\ \mathrm{det}\ M_q \ll 1$ fine-tuned?

Dynamical relaxation to zero

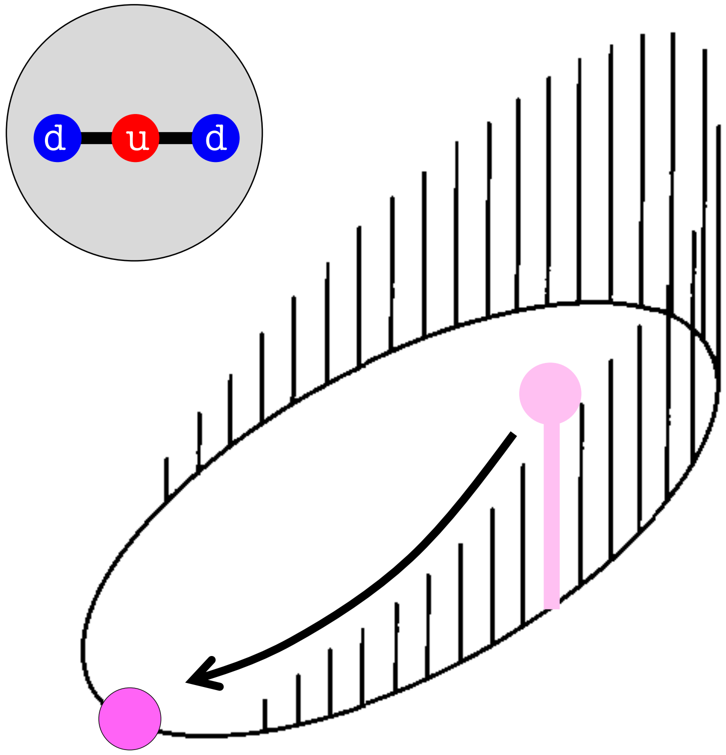
[Peccei, Quinn, Weinberg, Wilczek 1977-78]

It turns out that θ costs energy:



promote θ to a field

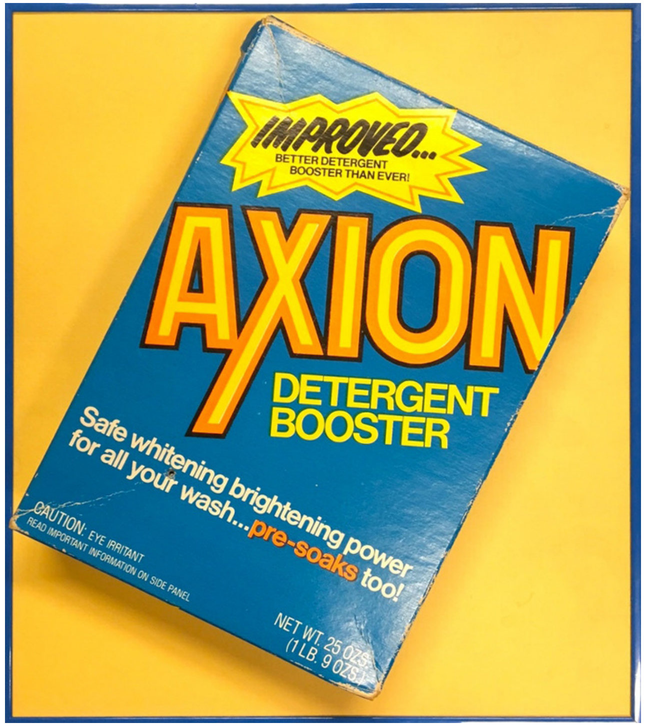
A dynamical θ relaxes to zero:



$\theta \approx 0$

By-product: a new particle

Quantum excitations around $\theta=0$
are a new kind of particle



Axion Fact Sheet

- SPIN = 0
- CHARGE = 0
- COLOR = 0

~~~~~~~~~~~~~~~~~~~~

(model-dep)

- MASS = ultralight (μeV)
- INTERACTIONS = feeble
- LIFETIME = cosmological
~~~~~~~~~~~~~~~~~~~~

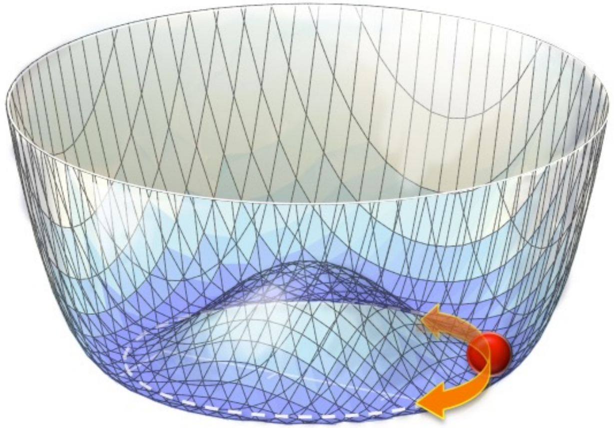
The QCD Axion's cousins: axion-like particles

[axions in string theory: Svrcek & Witten (2006), Arvanitaki et al (2009)]

Whereas the QCD Axion plays a special role of solving the Strong CP Problem, axion-like particles (ALPs) are generic in theories Beyond the Standard Model.

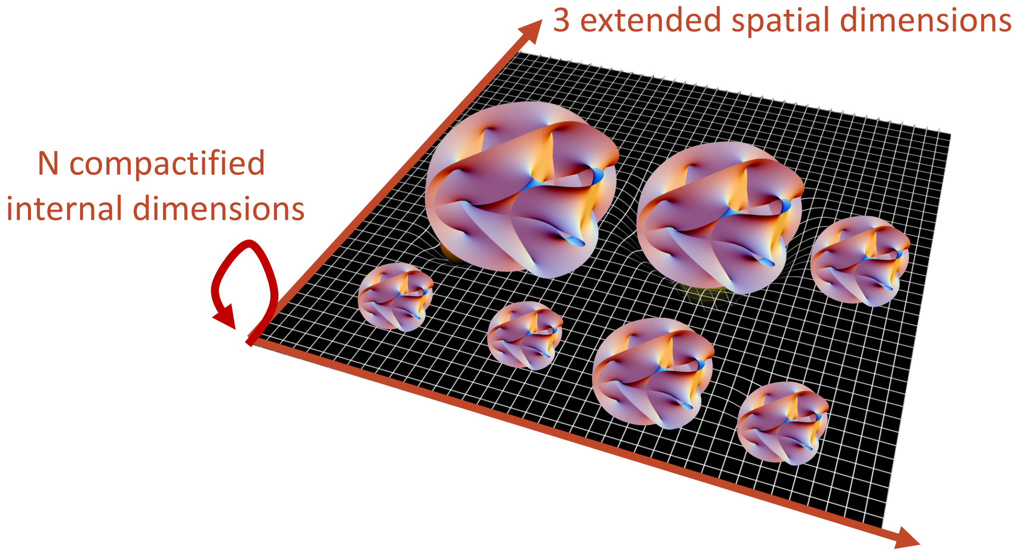
ALPs from symmetry breaking

(similar to pions in QCD)



ALPs from extra dimensions

(such as string theory)



Does the QCD axion or an ALP exist in nature?

What is its mass scale?

How does it interact with the SM?

Is it stable, or otherwise, what is its lifetime?

How is it produced in the Universe today?

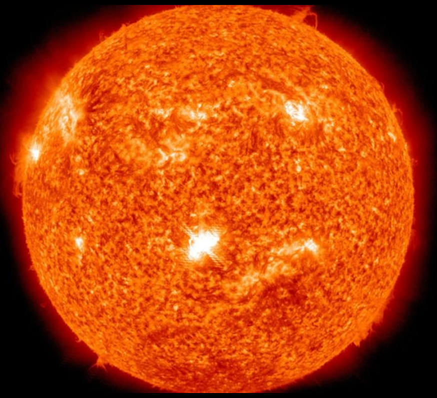
How was it produced in the early Universe?

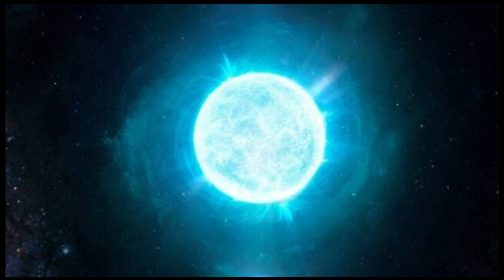
Is it connected to dark matter, baryogenesis, inflation, etc?

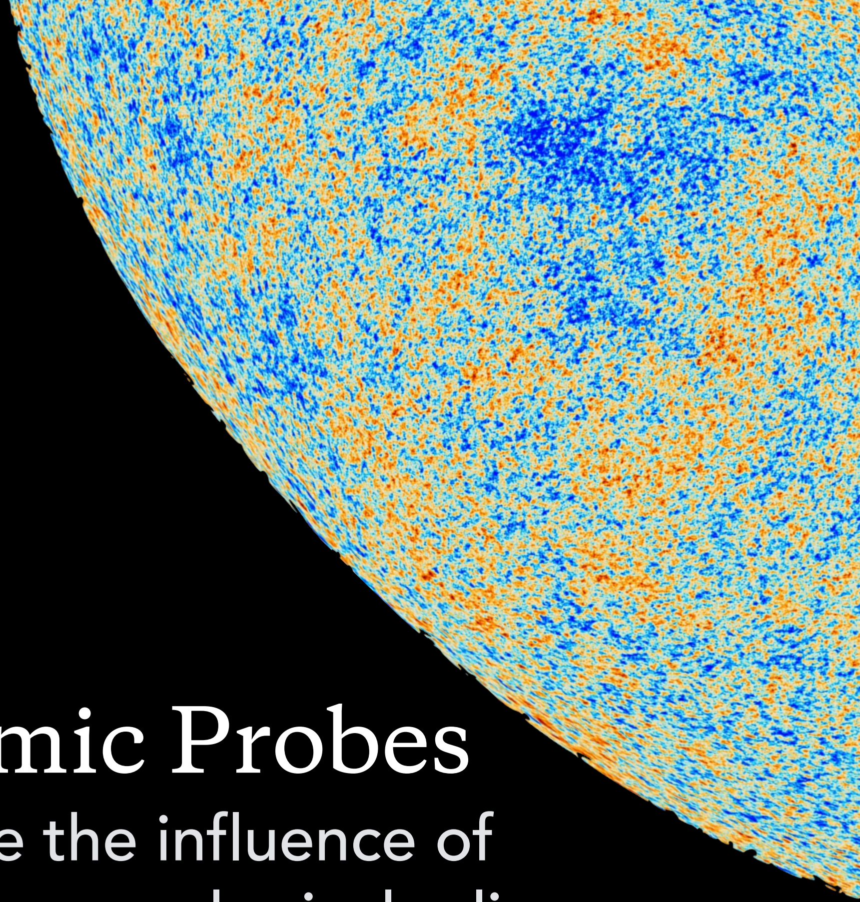
…

Astrophysical Probes

observe the influence of axions on stars, gas, & compact objects







Cosmic Probes

observe the influence of axions on cosmological relics

Terrestrial Probes

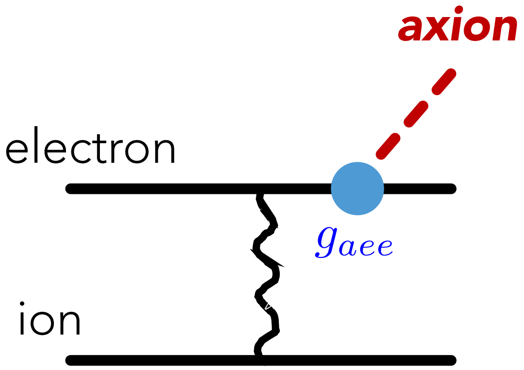
create axions on Earth or detect axions as they pass by the Earth

Stars emit axions

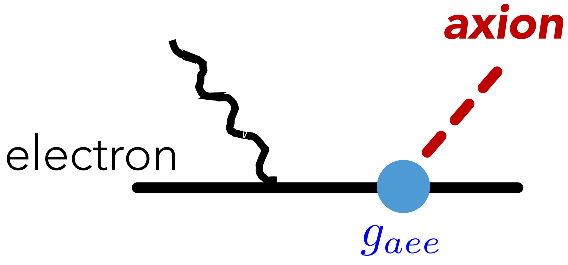
Various channels for axion emission

(different channels dominate for different star types)

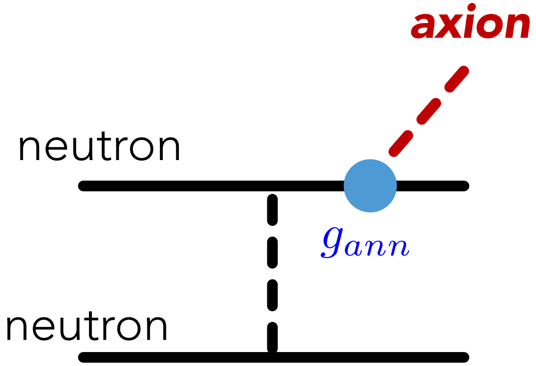
electron bremstrahlung
(white dwarf)



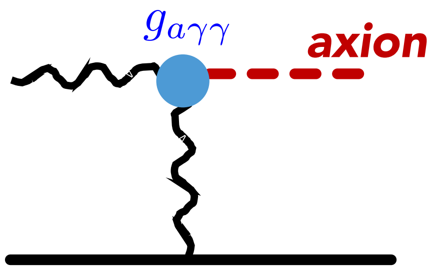
Compton
(main sequence, giants)



neutron bremstrahlung
(neutron star)



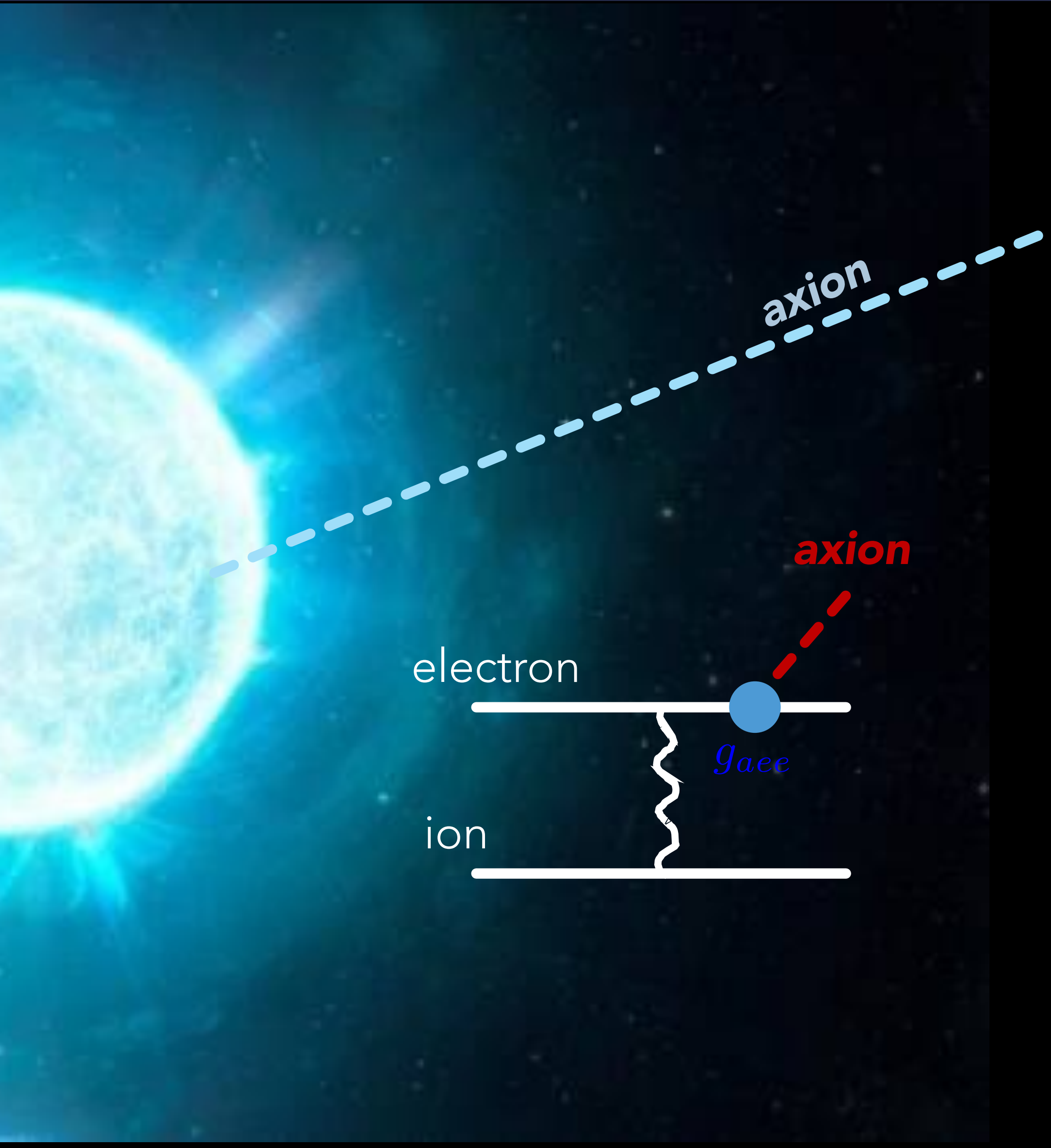
Primakoff effect
(main sequence, giants)



What kinds of stars emit axions?

let’s look at some examples

Example: white dwarf stars



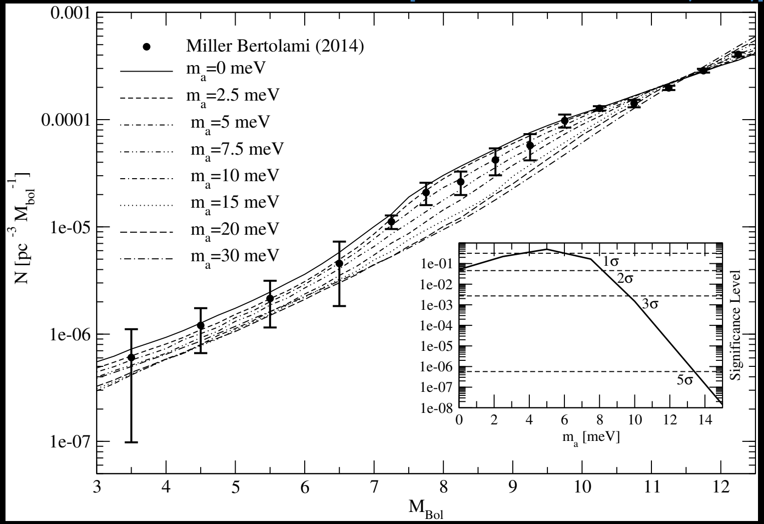
[Krauss, Moody, & Wilczek (1984)] [Raffelt (1986)]
[Nakagawa, Adachi, Kohyama, & Itoh (1987,88)]

axion luminosity *(for white dwarf stars)*

$$L_a \simeq (1.6 \times 10^{-4}\ L_\odot) \left(\frac{g_{aee}}{10^{-13}} \right)^2 \left(\frac{M_{\rm WD}}{1\ M_\odot} \right) \left(\frac{T_c}{10^7\ {\rm K}} \right)^4$$

constraints

[Miller Bertolami et. al. (2014)]



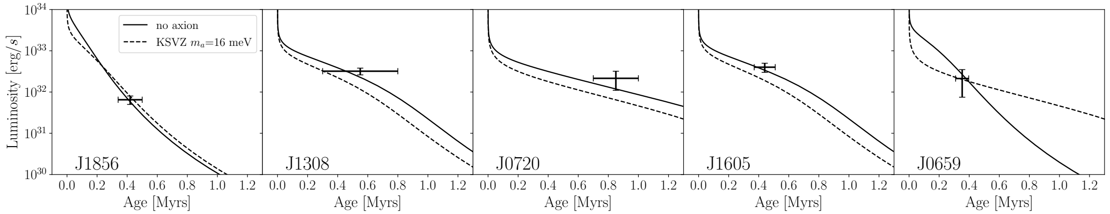
$$g_{aee} < 3 \times 10^{-13} \quad (3\sigma)$$

Example: neutron stars

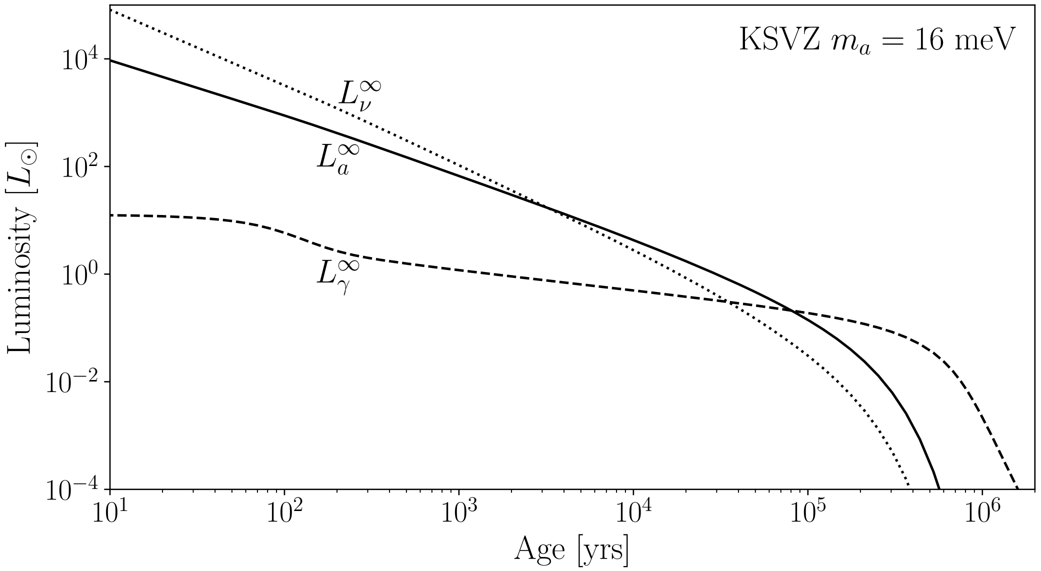
[Buschmann, Dessert, Foster, AL, & Safdi (2021)]

(a few of) The Magnificent 7

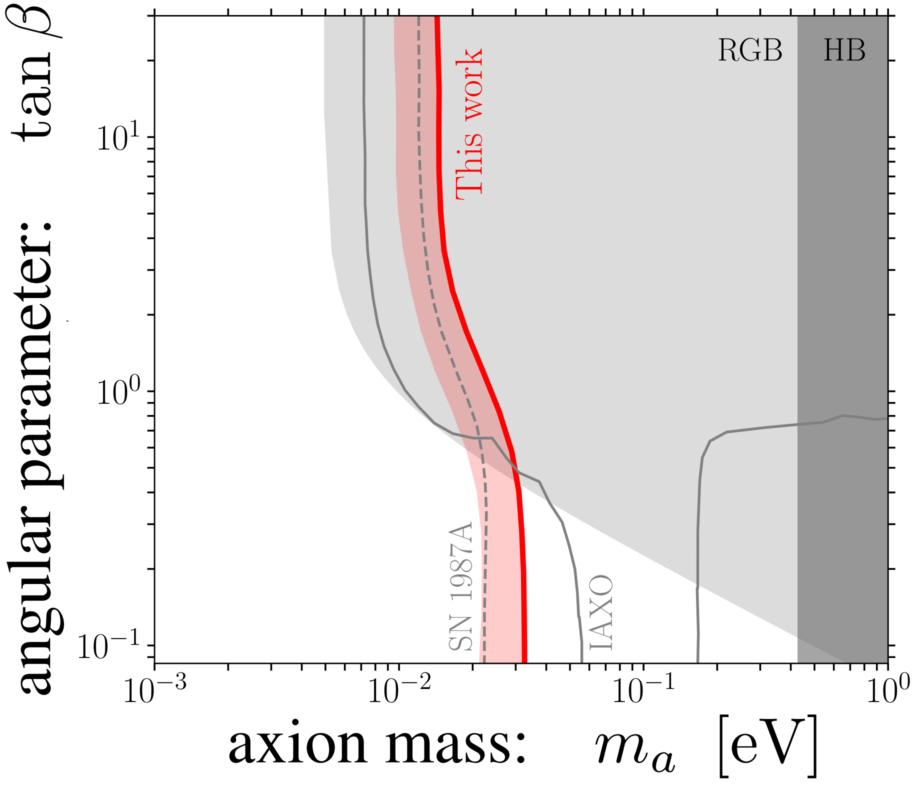
robust luminosity & age measurements



Comparison of emission channels



QCD Axion constraints

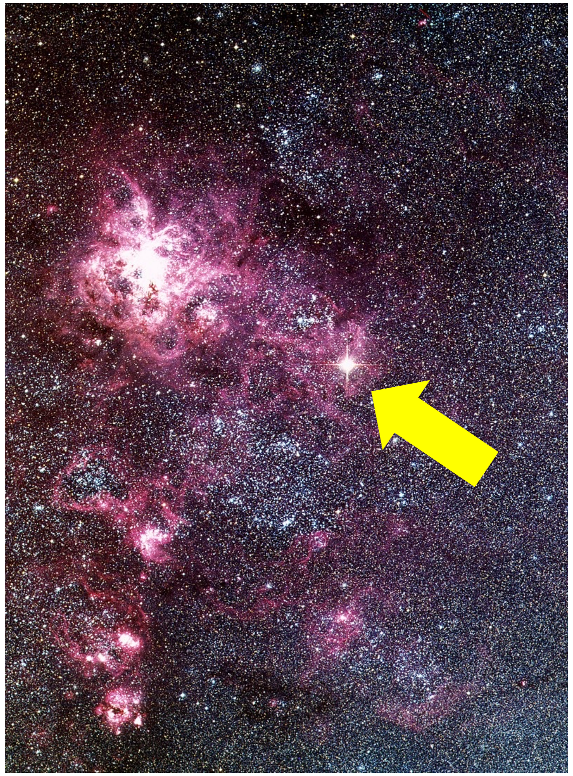


$$g_{ann} \lesssim 5 \times 10^{-10}$$

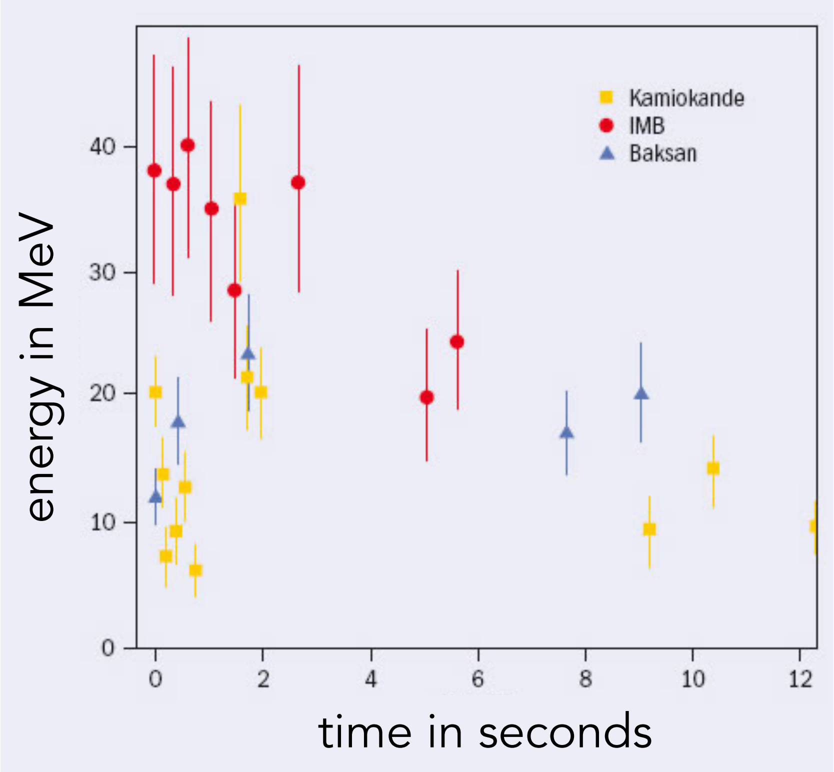
Example: supernovae

[constraints: Chang, Essig, McDermott (2018)]

SN 1987A

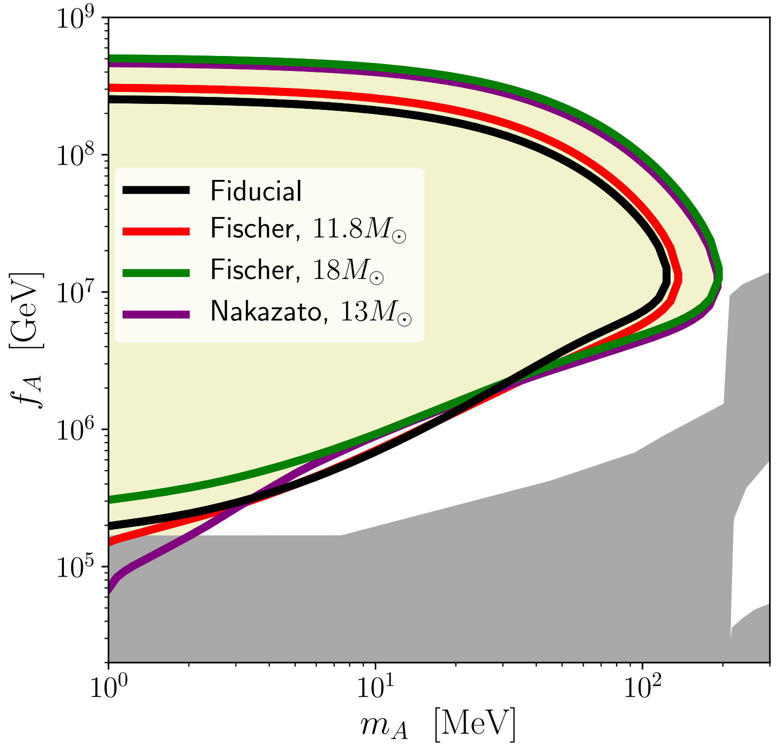


Neutrino burst



Constraints

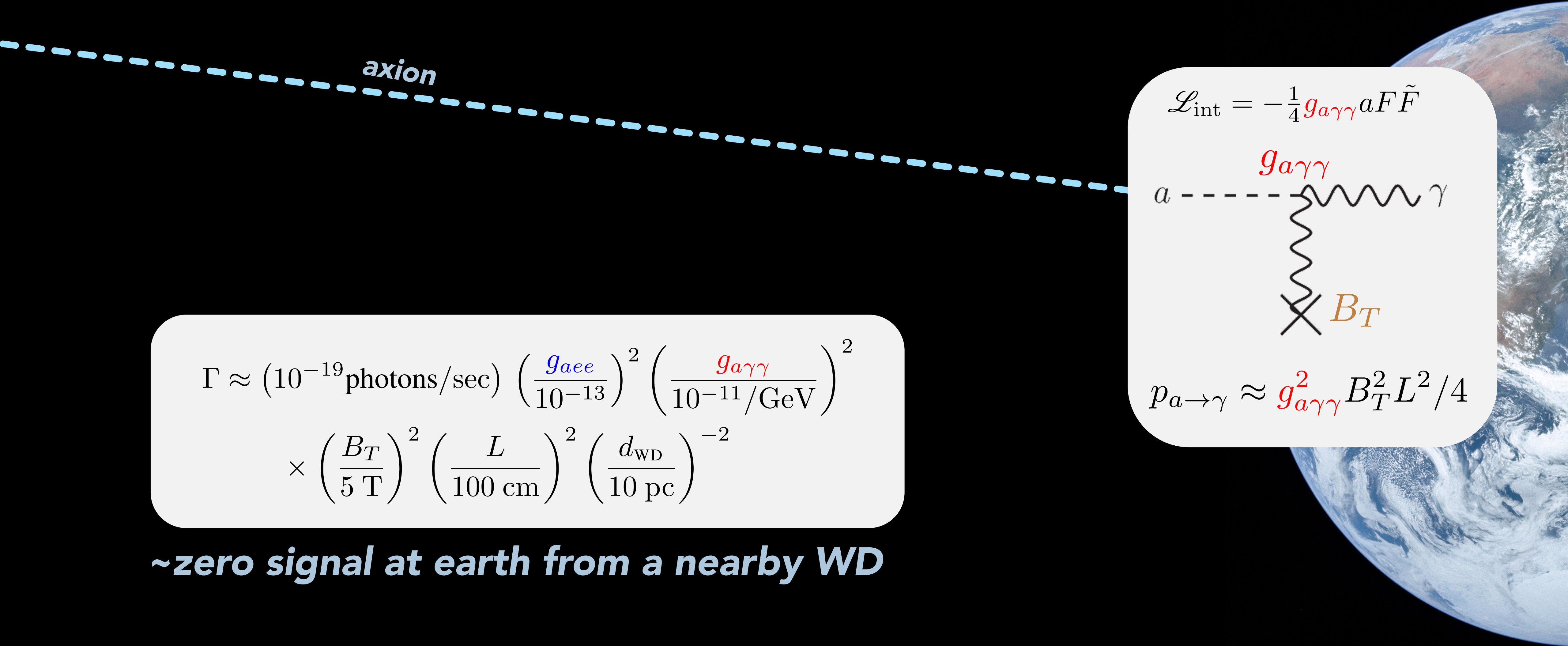
$$\dot{E}_{\text{axion}} \lesssim 5 \times 10^{52}\ \text{erg/sec}$$



how to test that stars emit axions?

we want a signal, not just a constraint!

Axions convert to photons in a B-field



$$\mathscr{L}_{\rm int} = -\tfrac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$

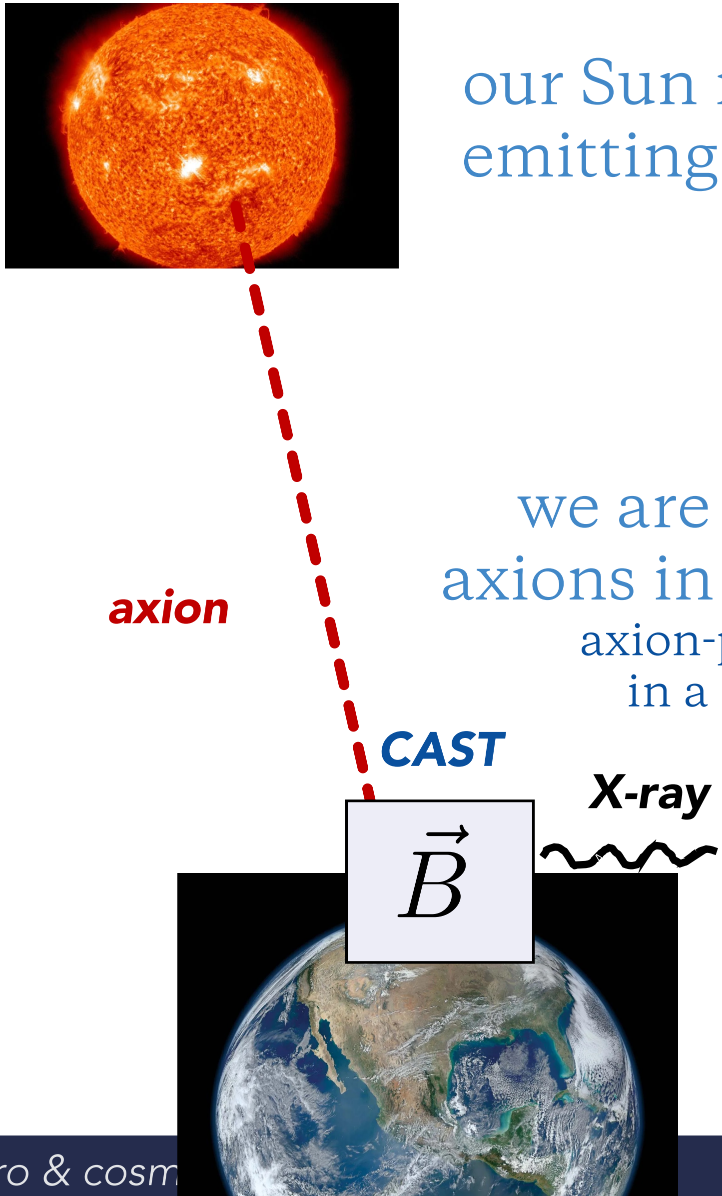
$$p_{a\to\gamma} \approx g_{a\gamma\gamma}^2 B_T^2 L^2 / 4$$

$$\Gamma \approx (10^{-19}\,\text{photons/sec}) \left(\frac{g_{aee}}{10^{-13}}\right)^2 \left(\frac{g_{a\gamma\gamma}}{10^{-11}/\text{GeV}}\right)^2 \times \left(\frac{B_T}{5\ \text{T}}\right)^2 \left(\frac{L}{100\ \text{cm}}\right)^2 \left(\frac{d_{\rm WD}}{10\ \text{pc}}\right)^{-2}$$

~zero signal at earth from a nearby WD

Example: our Sun

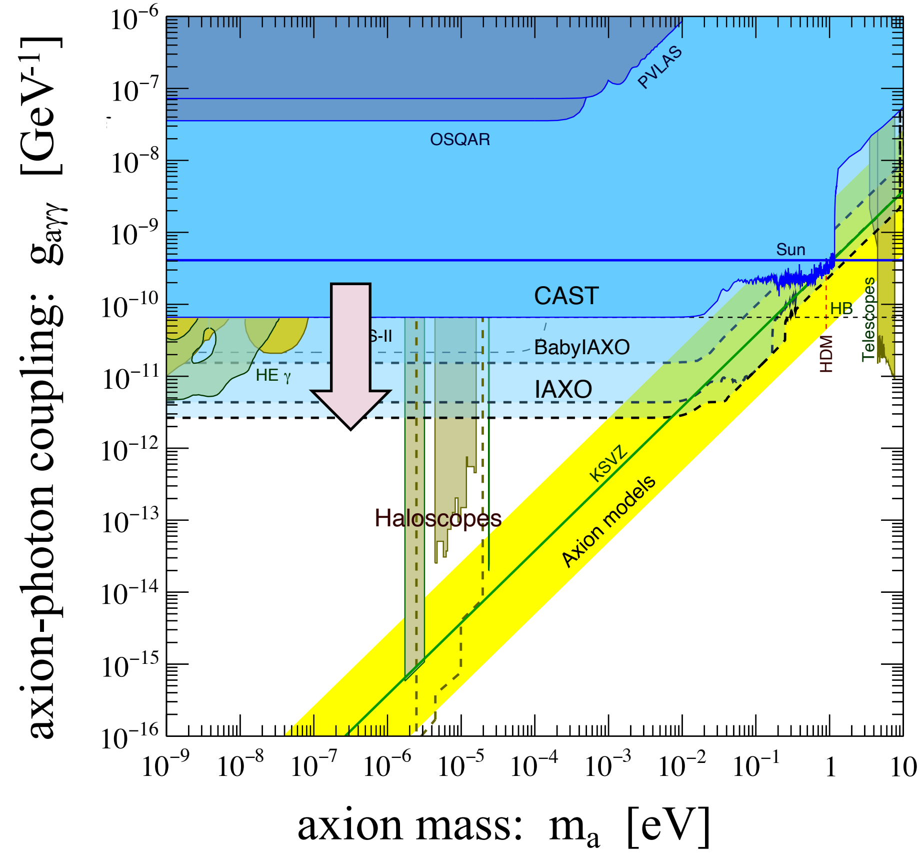
our Sun may be emitting axions



we are searching for these axions in laboratories on Earth

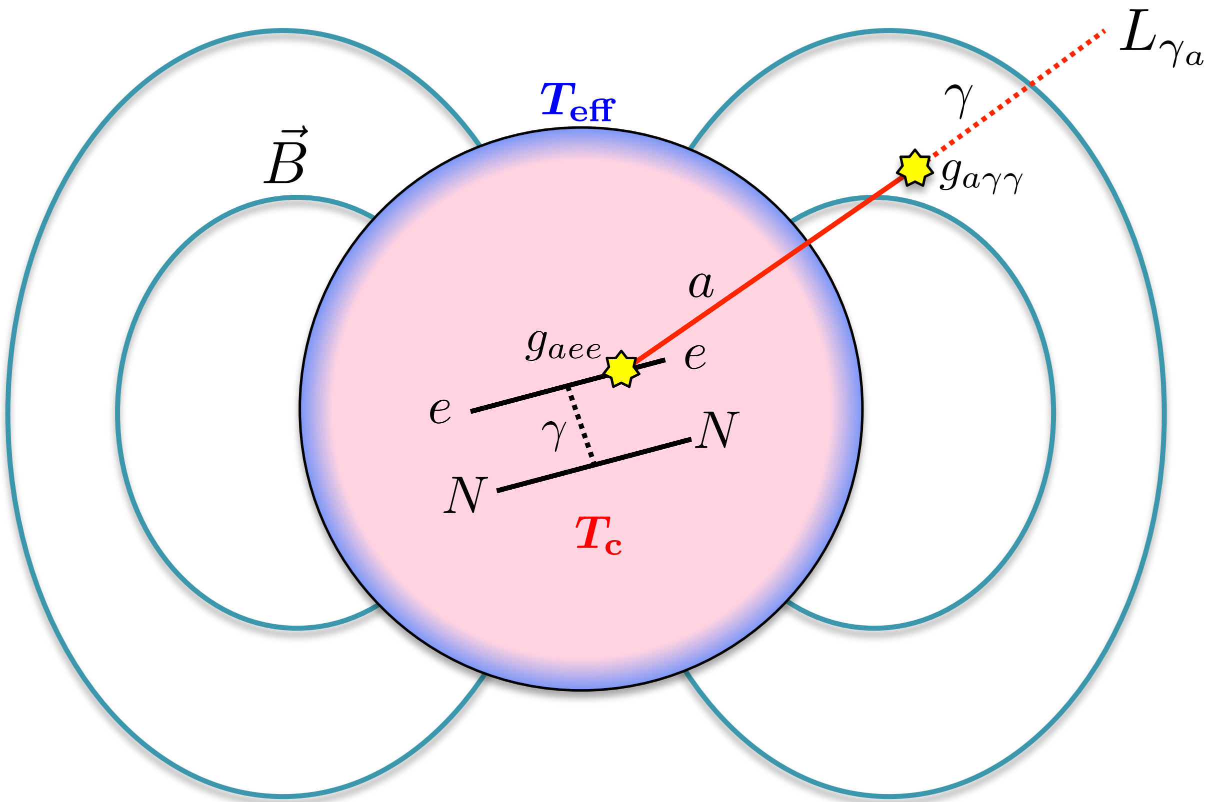
axion-photon interconversion in a strong magnetic field

helioscopes



Axion-photon conversion at compact stars

[D. E. Morris (1986)] [Raffelt & Stodolsky (1987)]
[Gill & Heyl (2011)] [Fortin & Sinha (2018)]



Strong magnetic field:
- ➔ Neutron stars (magnetars): ~10^{12} – 10^{15} G
- ➔ Magnetic white dwarfs: ~10^{6} – 10^{9} G

Filling large volume:
- ➔ Neutron stars (magnetars): ~10 km
- ➔ Magnetic white dwarfs: ~ 0.01 R_{sun}

Hot plasma radiates axions:
- ➔ Core temperature: 10^7 K ~few keV

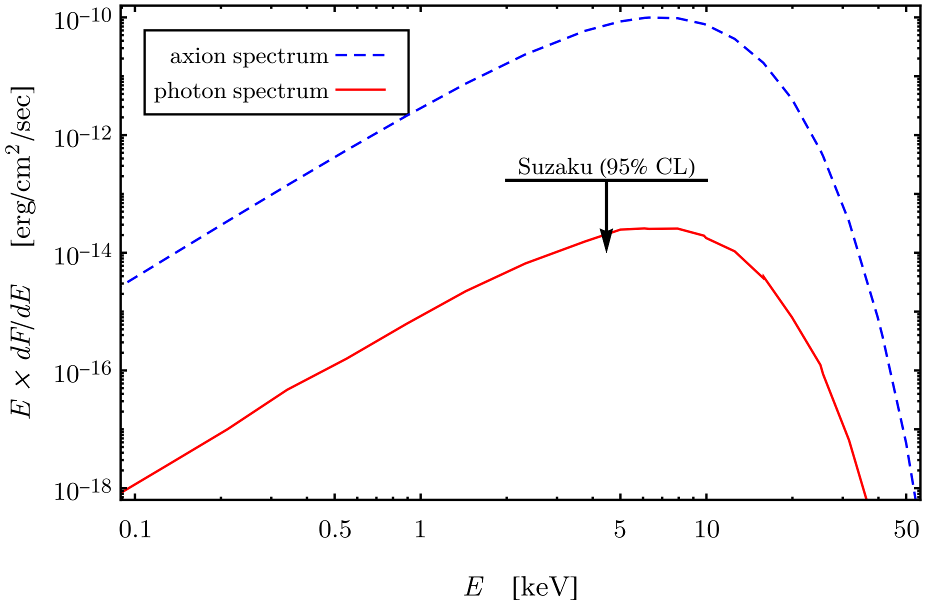
$$E_a = T_{\text{core}} = E_\gamma = \text{X-ray}$$

signal = thermal X-ray emission (T_{core} ~ 10^7 K ~ keV)
background = surface emission negligible (T_{surface} ~ 10^4 K)

Expected X-ray signal from MWDs

[Dessert, AL, Safdi, arXiv:1903.04088]

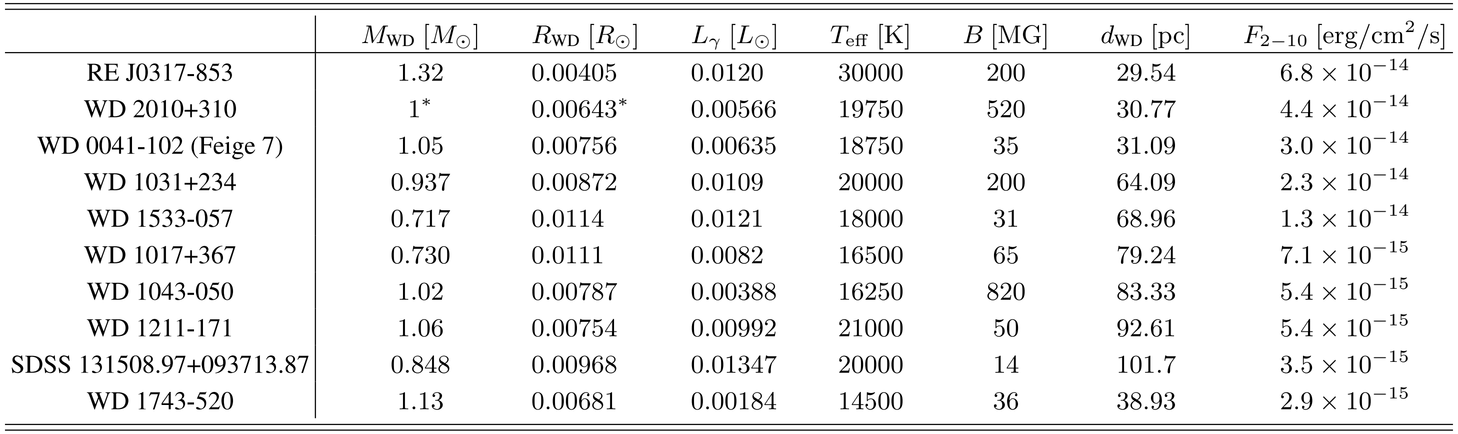
quasi-thermal spectrum



$g_{aee} = 10^{-13}$
$g_{a\gamma\gamma} = 10^{-11}\ \mathrm{GeV}^{-1}$
$M_{\rm WD} = 1.32\ M_\odot$
$d_{\rm WD} = 29.54$ pc
$T_c = 2 \times 10^7$ K
$= 1.7$ keV

rising through 1-10 keV where backgrounds are falling

top 10 magnetic white dwarf candidates



	$M_{\rm WD}$ [$M_\odot$]	$R_{\rm WD}$ [$R_\odot$]	L_γ [$L_\odot$]	$T_{\rm eff}$ [K]	B [MG]	$d_{\rm WD}$ [pc]	F_{2-10} [erg/cm^2/s]
RE J0317-853	1.32	0.00405	0.0120	30000	200	29.54	6.8×10^{-14}
WD 2010+310	1*	0.00643*	0.00566	19750	520	30.77	4.4×10^{-14}
WD 0041-102 (Feige 7)	1.05	0.00756	0.00635	18750	35	31.09	3.0×10^{-14}
WD 1031+234	0.937	0.00872	0.0109	20000	200	64.09	2.3×10^{-14}
WD 1533-057	0.717	0.0114	0.0121	18000	31	68.96	1.3×10^{-14}
WD 1017+367	0.730	0.0111	0.0082	16500	65	79.24	7.1×10^{-15}
WD 1043-050	1.02	0.00787	0.00388	16250	820	83.33	5.4×10^{-15}
WD 1211-171	1.06	0.00754	0.00992	21000	50	92.61	5.4×10^{-15}
SDSS 131508.97+093713.87	0.848	0.00968	0.01347	20000	14	101.7	3.5×10^{-15}
WD 1743-520	1.13	0.00681	0.00184	14500	36	38.93	2.9×10^{-15}

1000's of known WDs (Gaia), but only 100's have B-field measurements

rank by expected X-ray flux

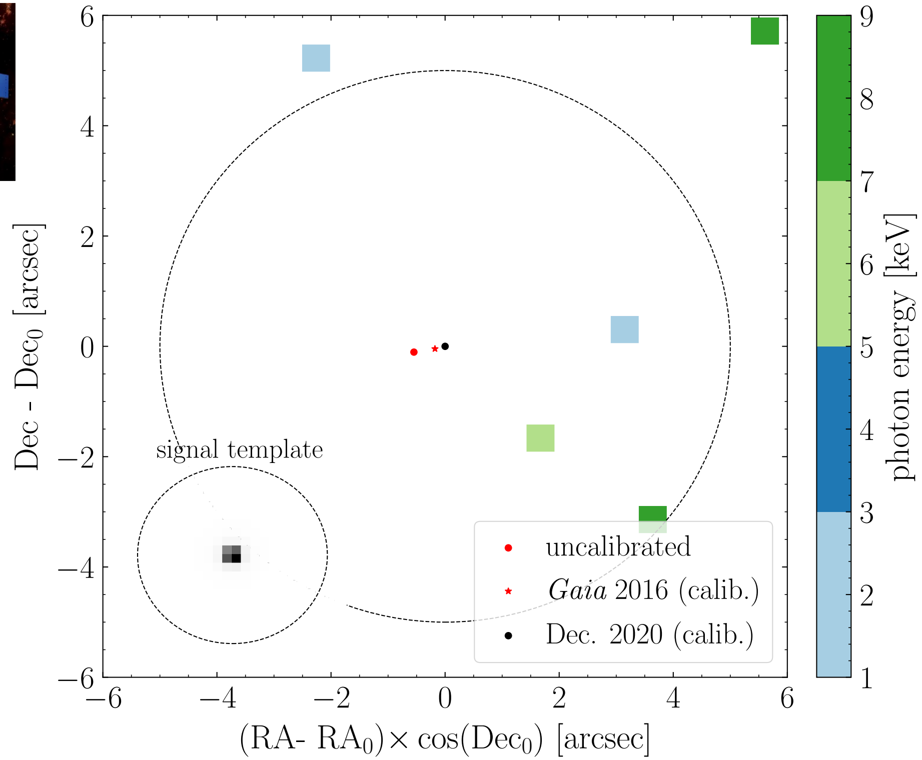
(for $m_a = 10^{-9}$ eV and $|g_{aee}\, g_{a\gamma\gamma}| = 10^{-24}\ \mathrm{GeV}^{-1}$)

Searching for X-rays from Magnetic White Dwarfs

[Dessert, AL, Safdi (2019, 2021)]

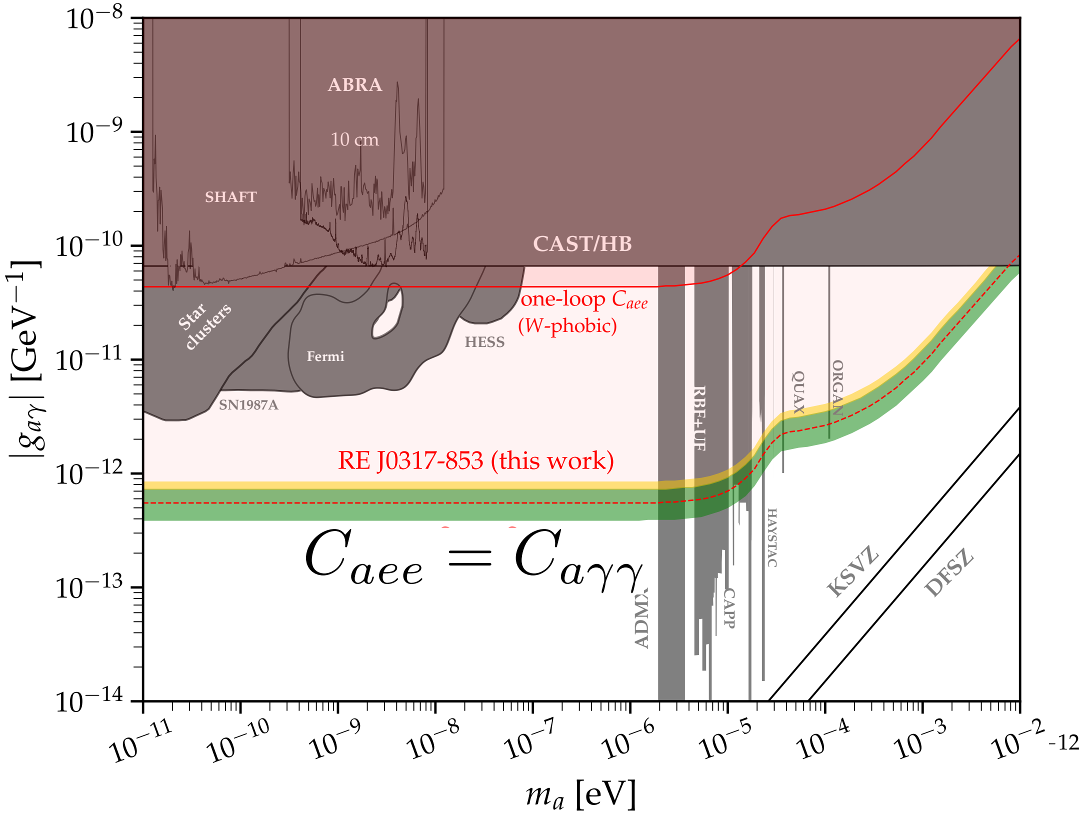
Chandra observation

- ➔ 37.42 ks (~10 hr) of data, Dec 18, 2020
- ➔ No photon counts observed near source



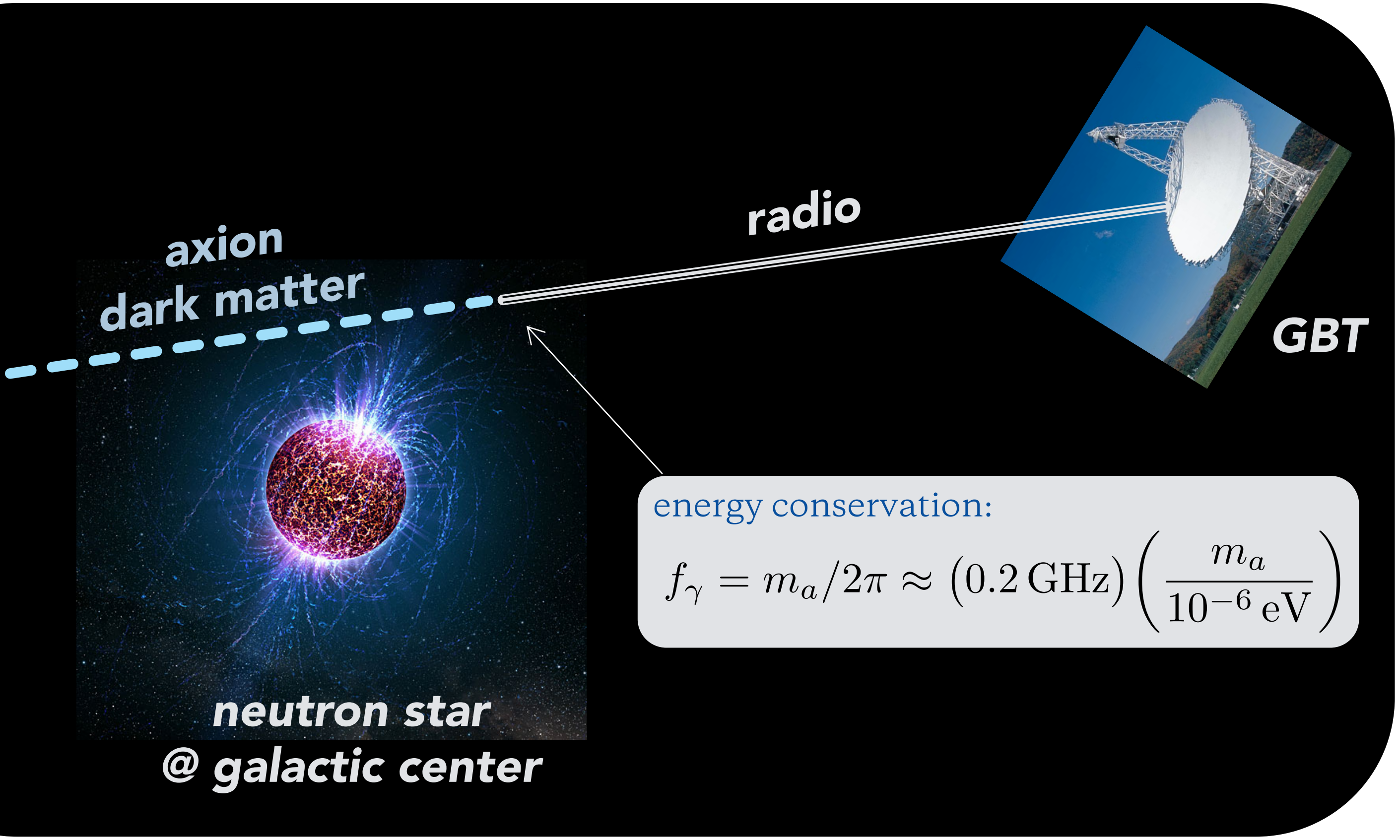
Constraints on axion emission / X-ray conversion

- ➔ Upper limit on product of couplings $g_{aee} * g_{a\gamma\gamma}$
- ➔ Can be recast as a limit in $g_{a\gamma\gamma}$ alone



Radio from the galactic center probes axion dark matter

[Hook, Kahn, Safdi, Sun (2018)], [Safdi, Sun, Chen (2018)], [Foster et al (2022)]

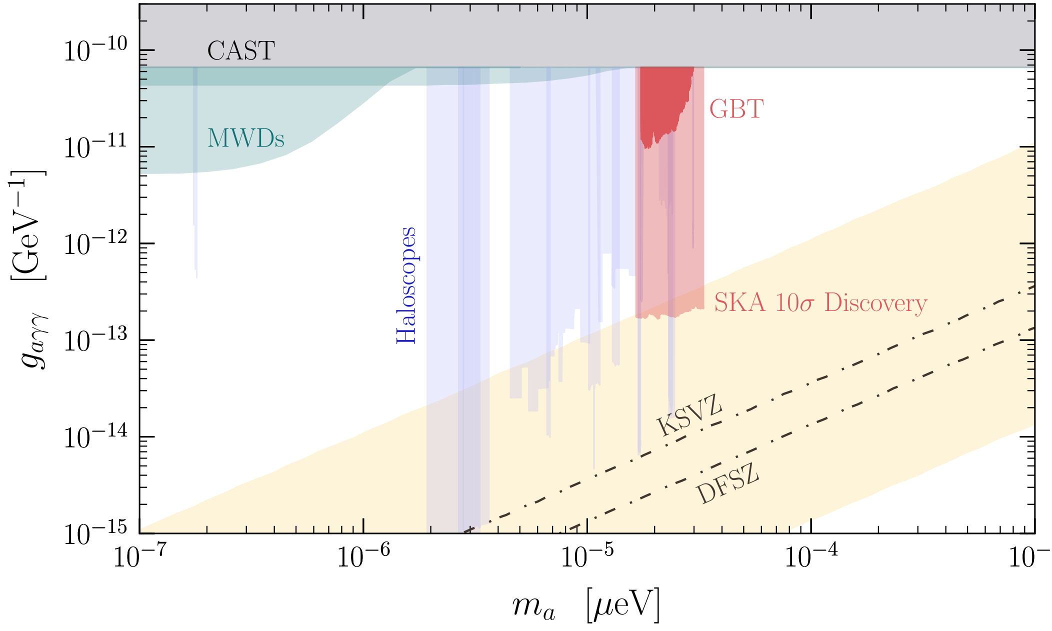


energy conservation:

$$f_\gamma = m_a/2\pi \approx (0.2\,\mathrm{GHz})\left(\frac{m_a}{10^{-6}\,\mathrm{eV}}\right)$$

The galactic center neutron star population provides a strong magnetic field to resonantly convert axion dark matter into radio emission

constraints derived from an analysis of archival Green Bank Telescope data



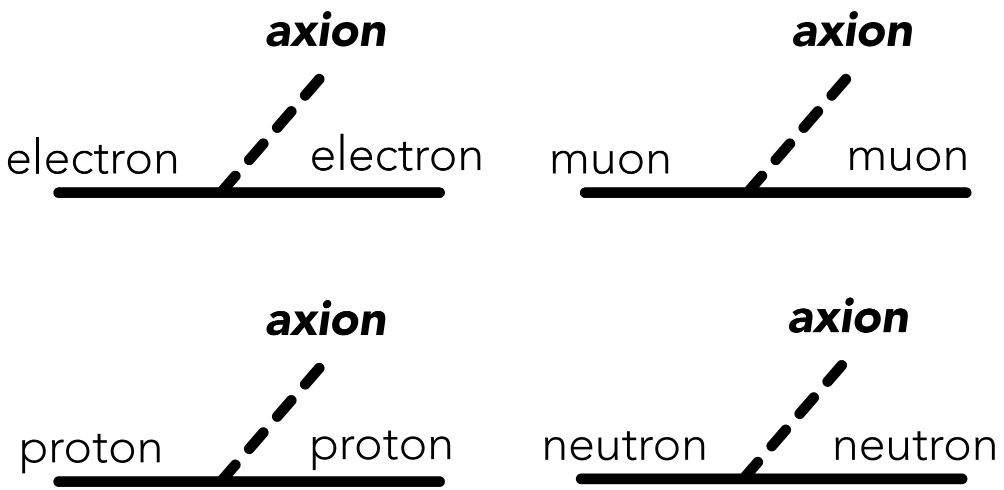
have we missed any interesting channels?

let's look at exotic axion couplings

ALP emission from exotic couplings

[Zhang, Hagimoto, & AL, 2309.03889]

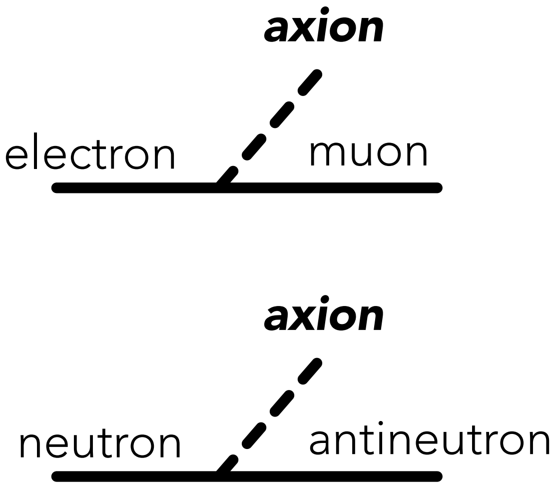
standard axion couplings



exotic axion couplings

LFV:

BNV:



$$\mathscr{L}_{\mathrm{int}} = g_{a\psi\psi}\, \partial_\mu a\, \bar{\psi}\gamma^\mu\gamma_5\psi / 2m_\psi$$

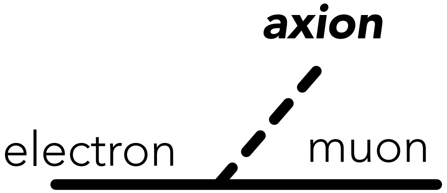
astro implications:

- axion emission off of muons in a neutron star
- baryon-destruction in a neutron star & heating
- connections with lab probes of axion LFV & BNV interactions

ALP emission from exotic couplings

[Zhang, Hagimoto, & AL, 2309.03889]

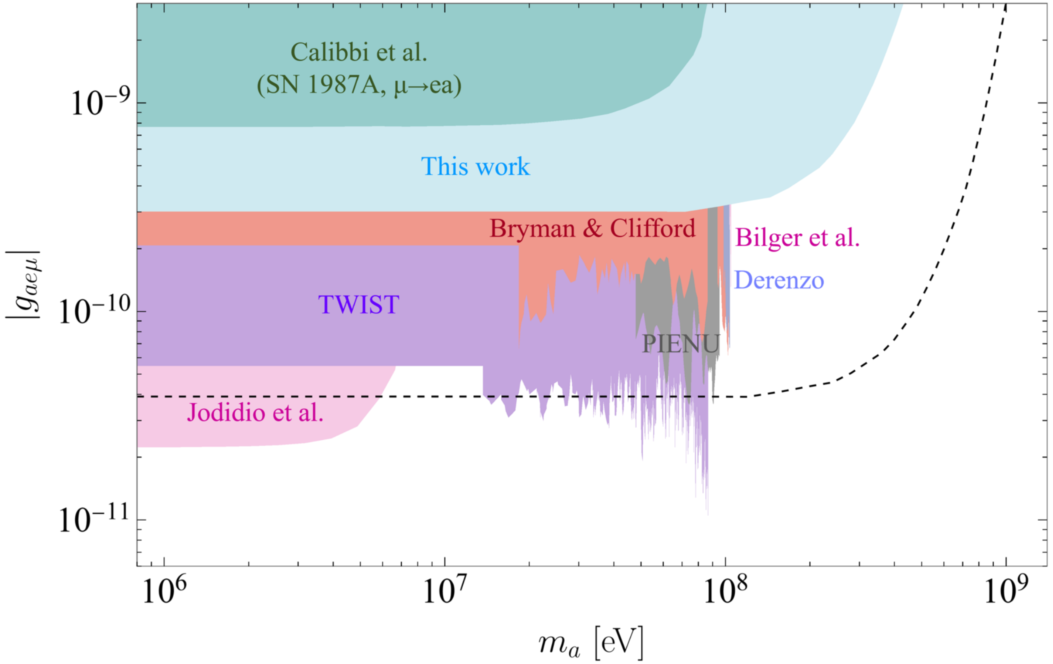
LFV:



axion emissivity

$$\varepsilon_a^{\mathrm{LFV}} \approx (4.8 \times 10^{10}\ \mathrm{erg/cm^3/sec}) \left(\frac{g_{ae\mu}}{10^{-11}} \right)^2 \left(\frac{T}{10^9\ \mathrm{K}} \right)^8$$

constraints on axion-LFV interactions



- for a neutron star, strong lab limits imply that axion emission is subdominant to standard neutrino emission via the Murca processes
- due to the strong temperature dependence, much stronger limits can be derived from SN 1987A by considering its hot proto-neutron star

$$|g_{ae\mu}| \lesssim (4 \times 10^{-11}) \left(\frac{T}{50\ \mathrm{MeV}} \right)^{-4}$$

$10^9\ \mathrm{K} \approx 86.2\ \mathrm{keV}$

can axions source their own electromagnetic radiation

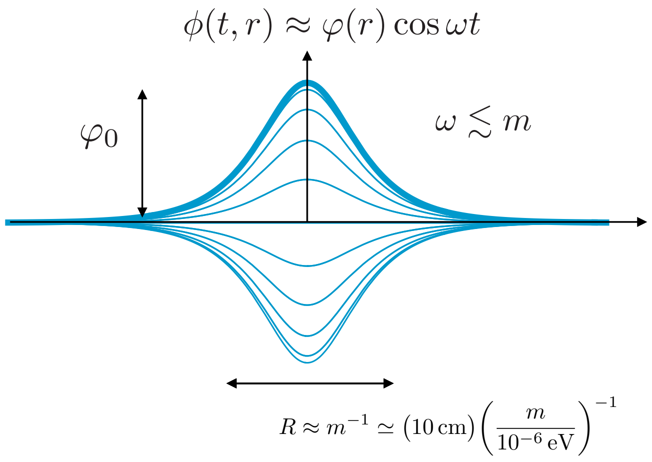
let's look at compact clumps of cold axions

What if the axion DM is clumped up?

[Amin, AL, Mou, Saffin, arXiv:2103.12082]

dense axion star:

a coherent "clump" of axion dark matter

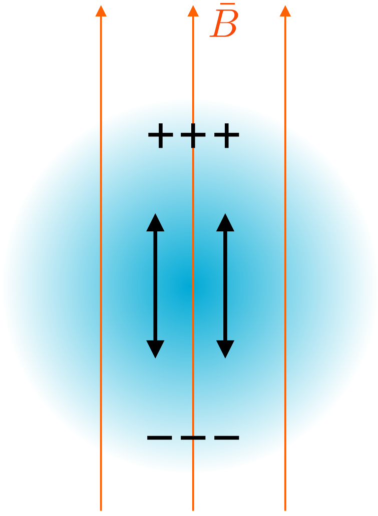


coupling to electromagnetism:

new terms in Maxwell's equations

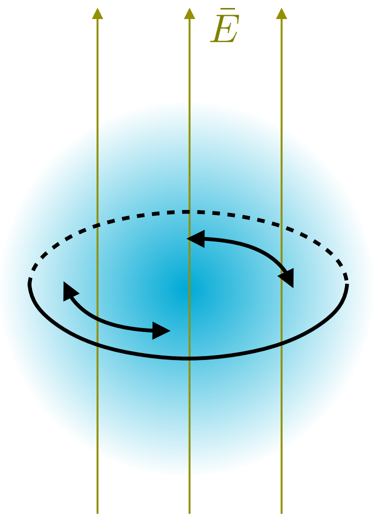
$$\mathscr{L}_{\mathrm{int}} = -\tfrac{1}{4} g_{a\gamma} \phi F \tilde{F} \quad \left\{ \begin{aligned} & \ddot{\phi} - \nabla^2 \phi + \partial_\phi V = g_{a\gamma} \boldsymbol{E} \cdot \boldsymbol{B} \,, \\ & \dot{\boldsymbol{E}} = \nabla \times \boldsymbol{B} - \underbrace{g_{a\gamma} \left(\dot{\phi} \boldsymbol{B} + \nabla \phi \times \boldsymbol{E} \right)}_{\text{effective current density}} \,, \\ & \dot{\boldsymbol{B}} = -\nabla \times \boldsymbol{E} \,, \\ & \nabla \cdot \boldsymbol{E} = \underbrace{-g_{a\gamma} \nabla \phi \cdot \boldsymbol{B}}_{\text{effective charge density}} \,, \\ & \nabla \cdot \boldsymbol{B} = 0 \,. \end{aligned} \right.$$

background magnetic field



induced electric dipole

background electric field



induced magnetic dipole

a source of EM radiation!

EM radiation from an axion clump

[Amin, AL, Mou, Saffin, arXiv:2103.12082]

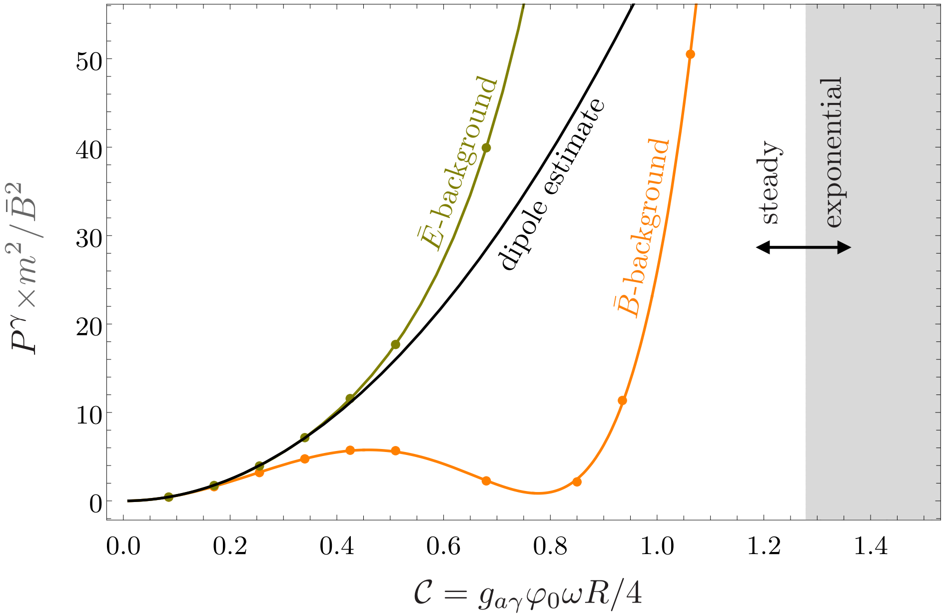
lattice simulation:

radiation from clump in external B/E fields

shading shows intensity of EM field

EM power radiated:

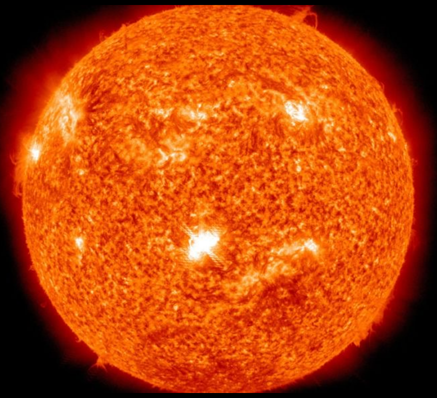
departure from dipole approx. at larger coupling

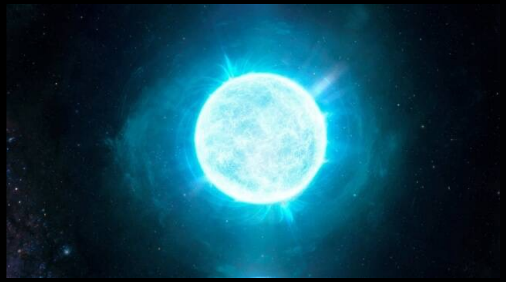


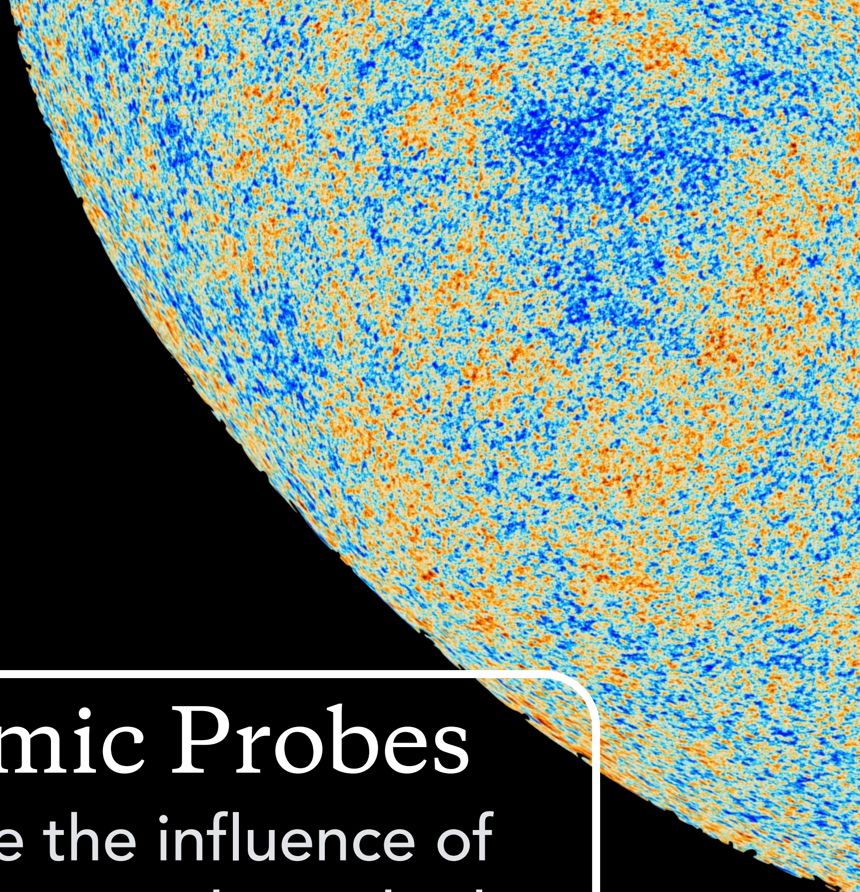
$$P_{\text{dipole}} = \frac{g_{a\gamma}^2 \omega^4 \tilde{\varphi}^2(\omega)}{12\pi} \left(|\bar{\boldsymbol{B}}|^2 + |\bar{\boldsymbol{E}}|^2\right)$$

Astrophysical Probes

observe the influence of axions
on stars, gas, & compact objects







Cosmic Probes

observe the influence of
axions on cosmological relics

Terrestrial Probes

create axions on Earth or detect
axions as they pass by the Earth

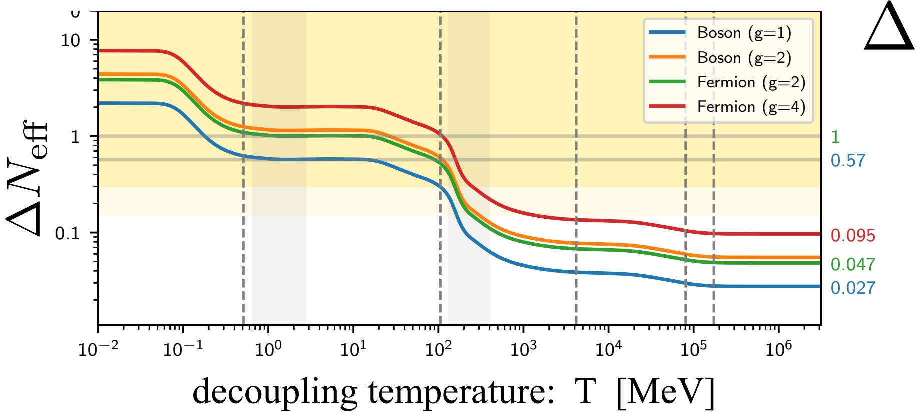
Axion dark radiation influence on CMB

[Baumann, Green, & Wallisch (2016)]
[CMB S4 Science Book (2016)]

Precision CMB measurements constrain the presence of a "dark radiation" in the Universe

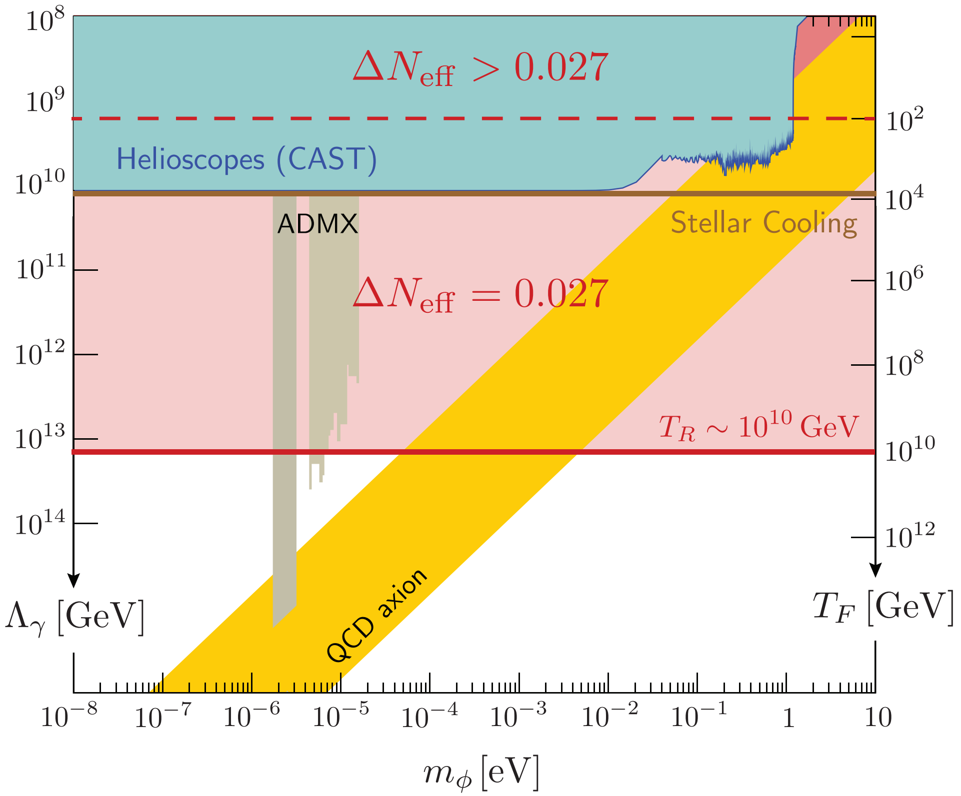
$$\Delta N_{\rm eff} \approx \frac{\rho_{\rm dark}}{\rho_{one\ \nu}} \lesssim 0.3$$ (Planck 2018)

For thermalized axions we expect:



$$\Delta N_{\rm eff} > 0.027$$

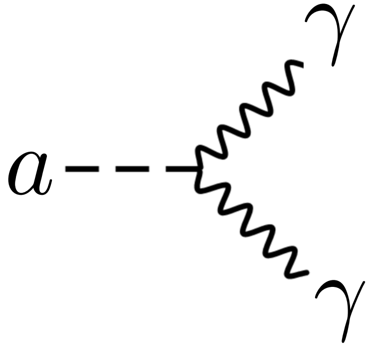
testable parameter space



Decaying axion radiation & BBN

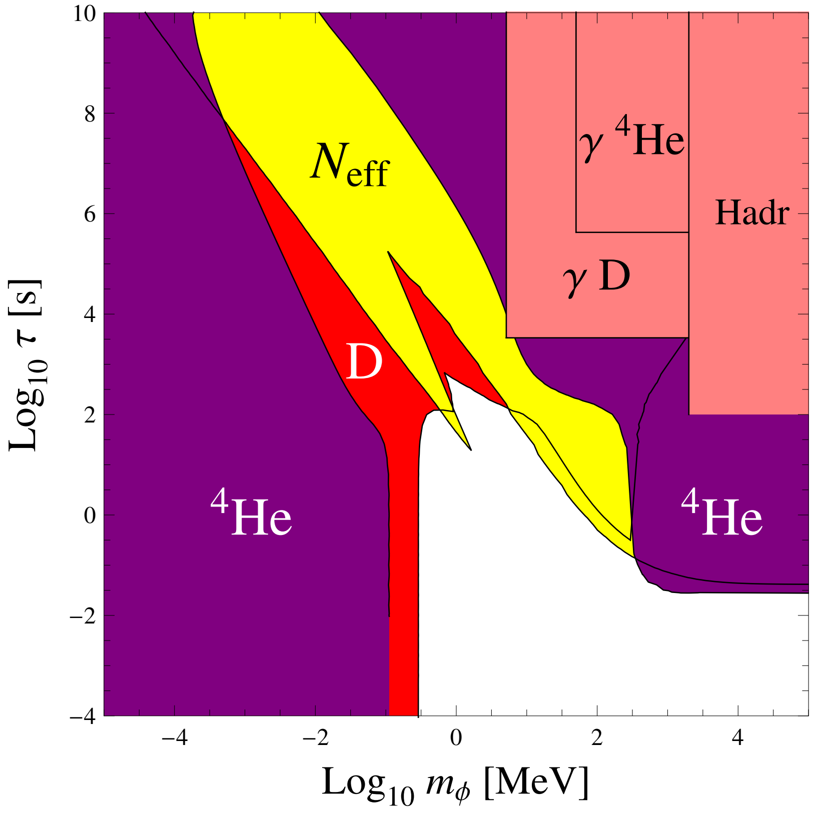
[Cadamuro & Redondo (2011)]

Axions decay through their coupling to photons



$$\Gamma_a \propto g_{a\gamma\gamma}^2 m_a^3$$

Axion decays during nucleosynthesis would disrupt the abundance of light elements.



Another way of probing axions with the CMB

[Harvey & Naculich (1989)], [Carroll, Field, Jackiw (1990,91)], [Harari, Sikivie (1992)]
[Fedderke, Graham, Rajendran (2019)], [Agrawal, Hook, Huang (2019)]
[Yin, Dai, Ferraro (2021) & (2023)]

assume interaction with electromagnetism:

standard Chern-Simons coupling

$$\mathscr{L}_{\text{int}} = -\tfrac{1}{4} g_{a\gamma\gamma} a F \tilde{F}$$

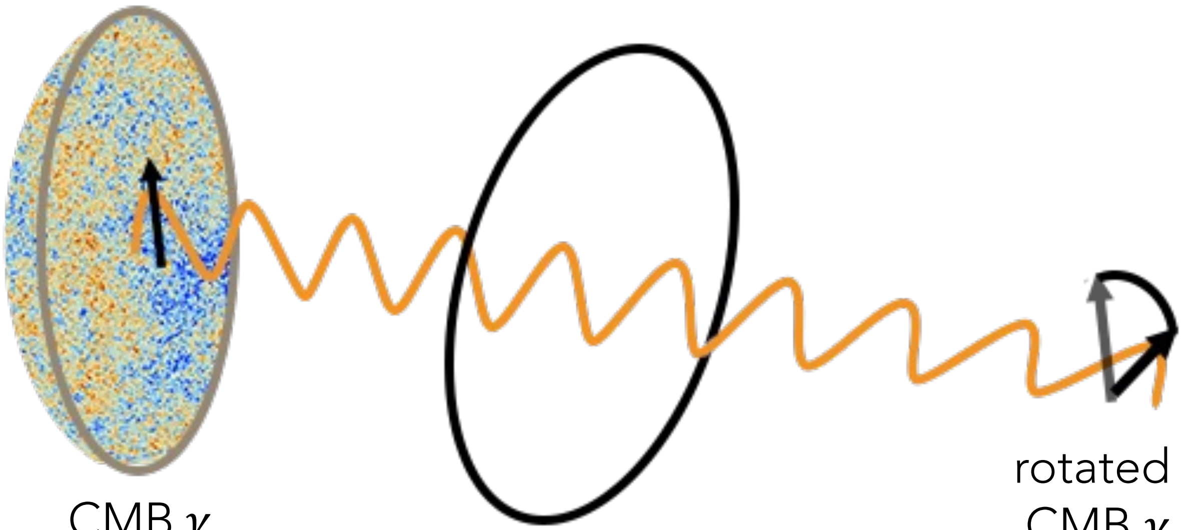
$$g_{a\gamma\gamma} = -\mathcal{A} \frac{\alpha_{\text{em}}}{\pi f_a}$$

$$\mathcal{A} = \sum Q_{\text{PQ}} Q_{\text{em}}^2 \sim \#/9$$

axion-induced birefringence:

an electromagnetic wave traveling through a varying axion field has its plane of polarization rotated

$$\alpha = \tfrac{1}{2} g_{a\gamma\gamma} \int_C \mathrm{d}X^\mu \, \partial_\mu a(X)$$



axion string loop

$$\Delta a = 2\pi f_a$$

rotation angle

$$\alpha = g_{a\gamma\gamma} \pi f_a \equiv -\mathcal{A}\alpha_{\text{em}} \approx -0.42^\circ \, \mathcal{A}$$

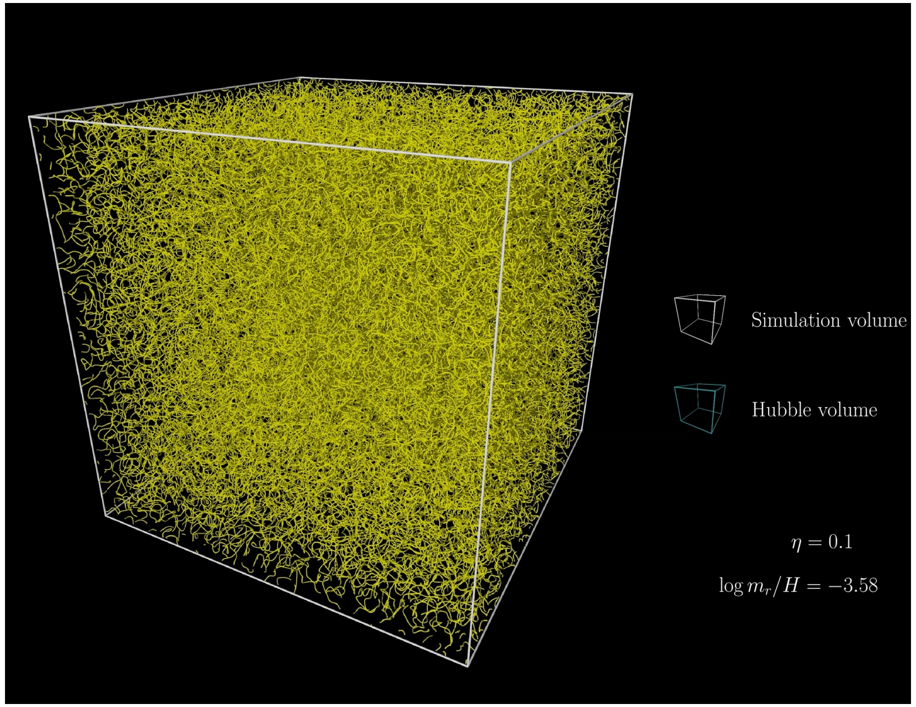
* birefringence can be measured through E-B cross correlation

Birefringence from an axion string network

[Jain, Hagimoto, AL, Amin]
[simulation: Buschmann et. al. (2022)]

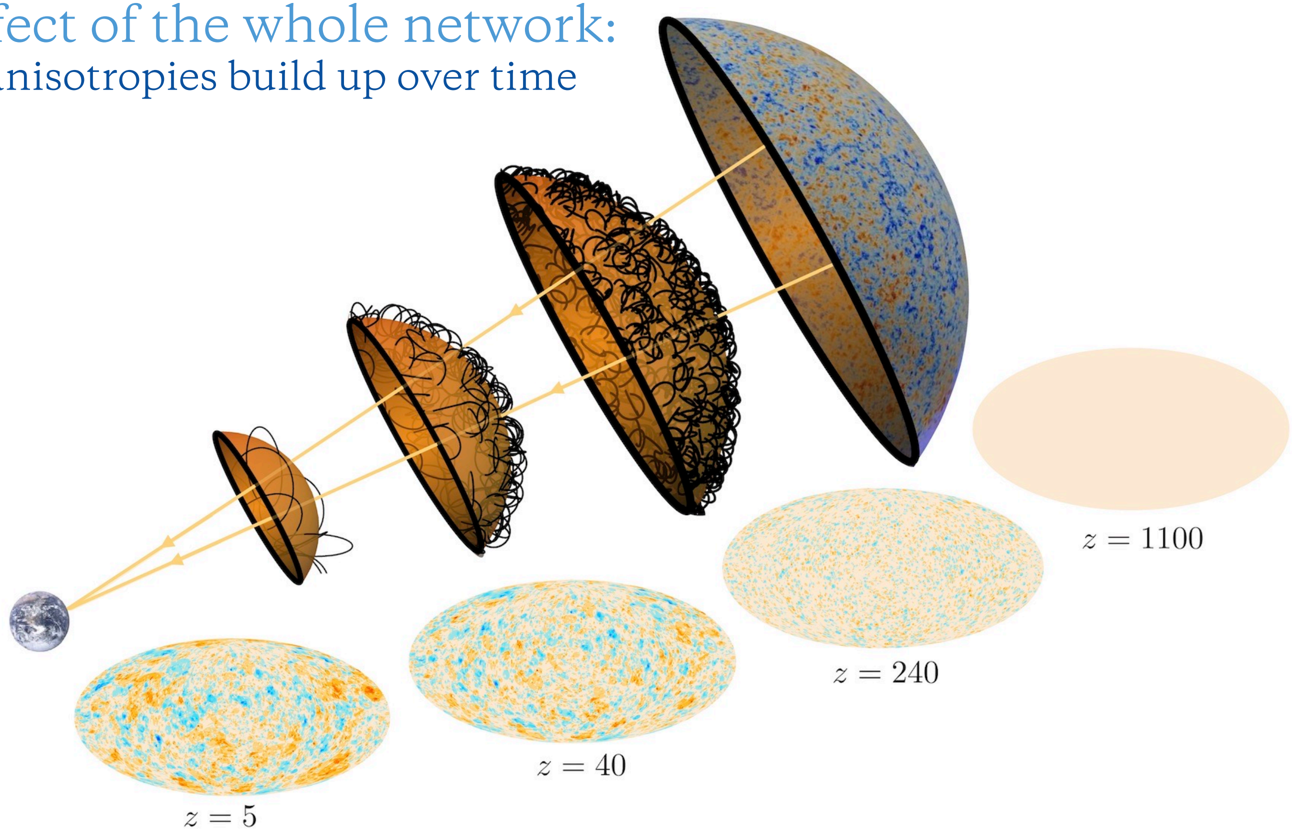
axions can form cosmic strings

network evolves throughout the cosmic history



effect of the whole network:

anisotropies build up over time



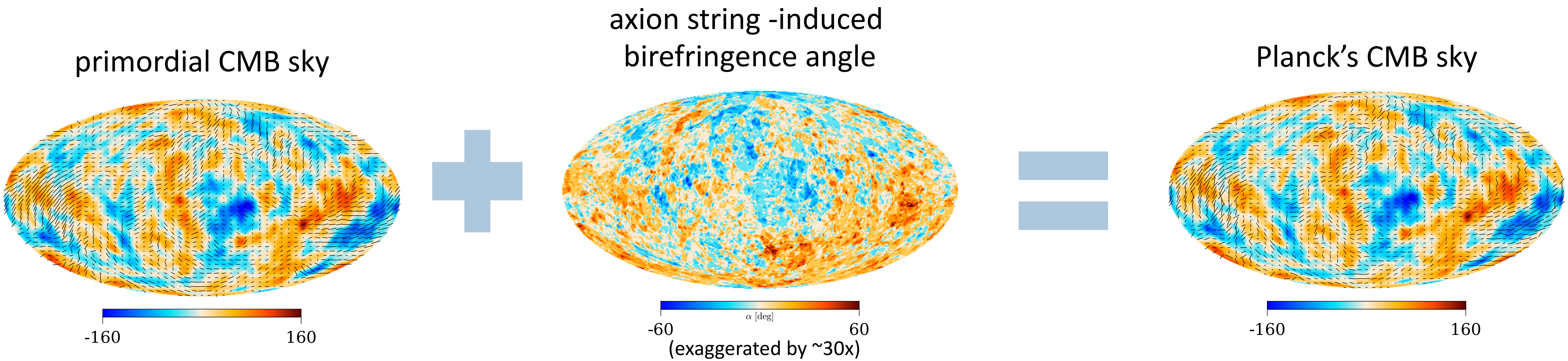
$*$ need $m_a \lesssim 3H_{\rm cmb} \approx 10^{-28}$ eV for the network to survive until after recombination

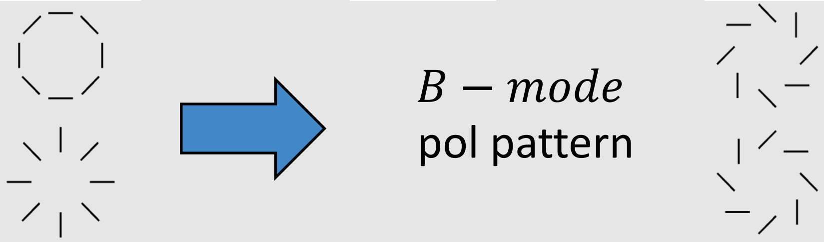
Effect on CMB polarization

How does birefringence affect the CMB's temperature and polarization?

$$T(\hat{\boldsymbol{n}}) \to T(\hat{\boldsymbol{n}})$$

$$[Q \pm iU](\hat{\boldsymbol{n}}) \to [(Q \pm iU)e^{\pm 2i\Delta\Phi}](\hat{\boldsymbol{n}})$$





$E - mode$ pol pattern

$B - mode$ pol pattern

Signal of axion string-induced cosmological birefringence

$$\begin{cases} \langle TB \rangle \neq 0 \\ \langle EB \rangle \neq 0 \end{cases}$$

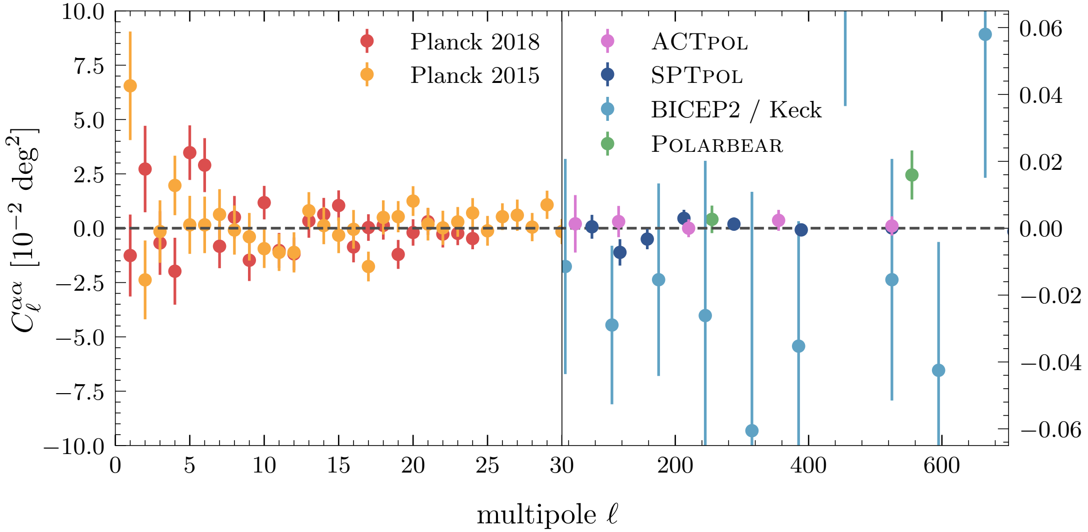
$$C_\ell^{\mathrm{EB}} \sim \sin(4\alpha)\left(C_\ell^{\mathrm{EE}} - C_\ell^{\mathrm{BB}}\right)$$

Constraints on axion string networks

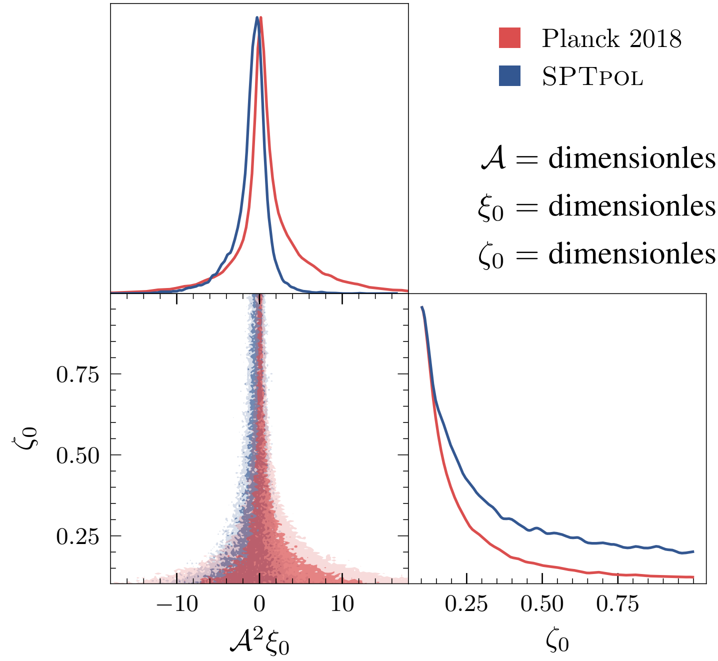
[Jain, Hagimoto, AL, Amin]

measurements of CMB polarization:

no evidence for anisotropic birefringence



a constraint on axion strings networks & their coupling to electromagnetism:



$\mathcal{A}$ = dimensionless axion-photon coupling

ξ_0 = dimensionless loop density (Hubble units)

ζ_0 = dimensionless loop length (Hubble units)

already valuable constraints: SPTPol: $\mathcal{A}^2\xi_0 < 3.7$ at 95% CL

Implications

CMB observations constrain:

$$\text{SPT}\textsc{pol}\text{:}\ \mathcal{A}^2\xi_0 < 3.7 \text{ at } 95\% \text{ CL}$$

Typical axion-photon coupling:

$$\mathcal{A} = 1/3$$

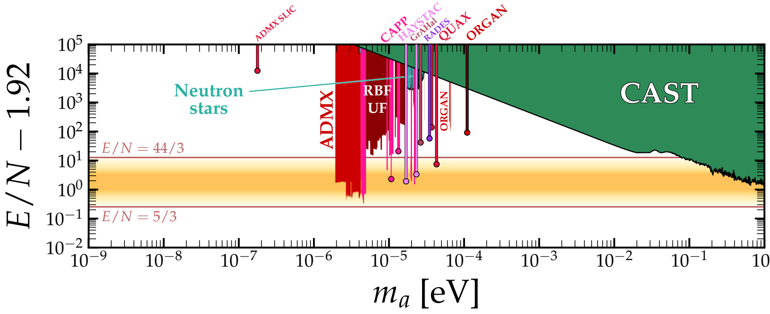
Typical loop abundance:

$$\xi_0 = 30$$

$$\mathcal{A}^2\xi_0 \approx 3.3$$

… already probing an O(1) anomaly coefficient!

… but still large uncertainties in ξ_0 (from sims)

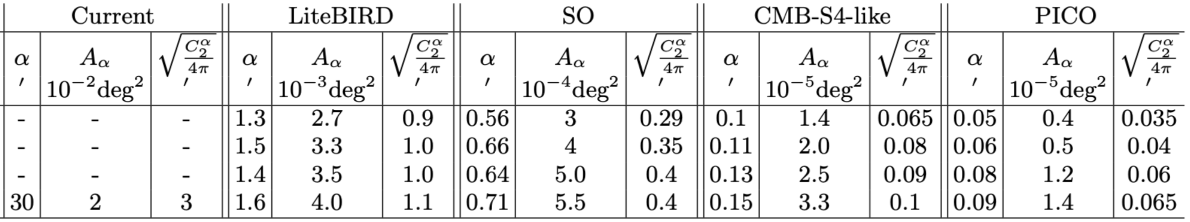


Projected sensitivity

Pogosian et. al. (2019)

future telescopes

probes of isotropic + aniso. birefringence



Current			LiteBIRD			SO			CMB-S4-like			PICO		
α $'$	A_α $10^{-2}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$	α $'$	A_α $10^{-3}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$	α $'$	A_α $10^{-4}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$	α $'$	A_α $10^{-5}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$	α $'$	A_α $10^{-5}\mathrm{deg}^2$	$\sqrt{\frac{C_2^\alpha}{4\pi}}$ $'$
-	-	-	1.3	2.7	0.9	0.56	3	0.29	0.1	1.4	0.065	0.05	0.4	0.035
-	-	-	1.5	3.3	1.0	0.66	4	0.35	0.11	2.0	0.08	0.06	0.5	0.04
-	-	-	1.4	3.5	1.0	0.64	5.0	0.4	0.13	2.5	0.09	0.08	1.2	0.06
30	2	3	1.6	4.0	1.1	0.71	5.5	0.4	0.15	3.3	0.1	0.09	1.4	0.065

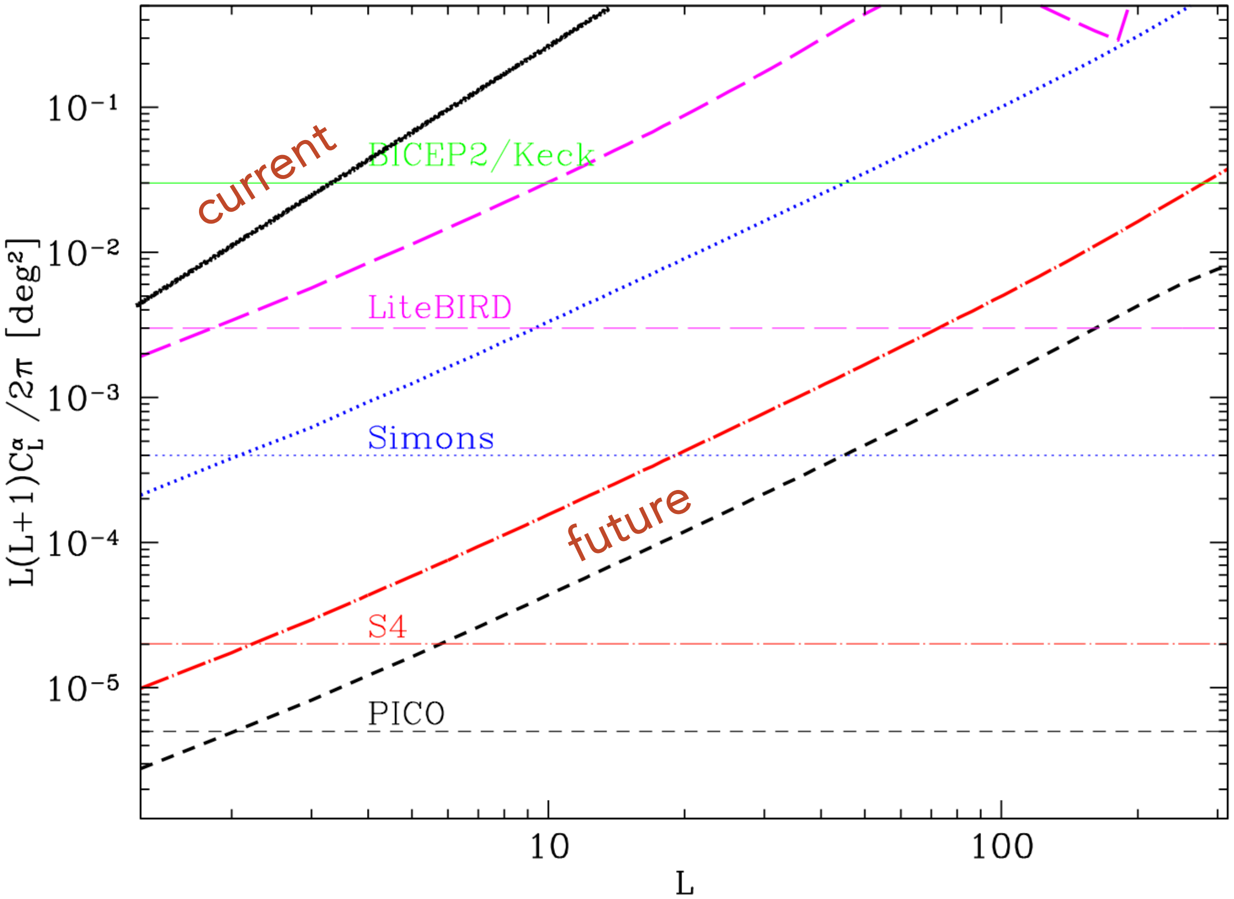
BLE II. Current and forecasted 68% CL bounds on the uniform and the anisotropic CPR parameters.

$$A_\alpha = L(L+1)C_L^\alpha/2\pi$$

future CMB polarization measurements will drastically improve sensitivity to axion-string induced anisotropic birefringence

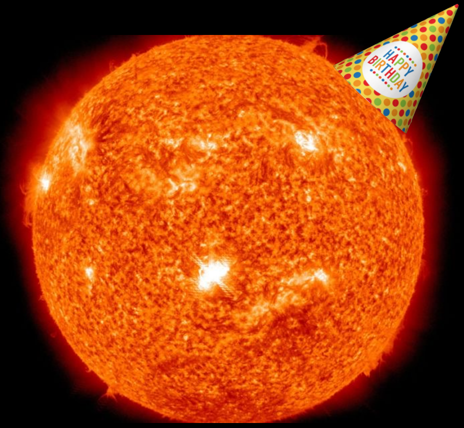
diagonal = allows multipoles to vary independently

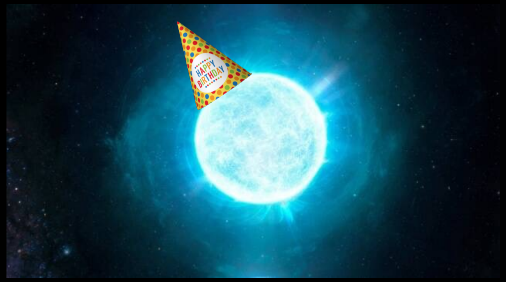
horizontal = restricts to a scale invariant spectrum

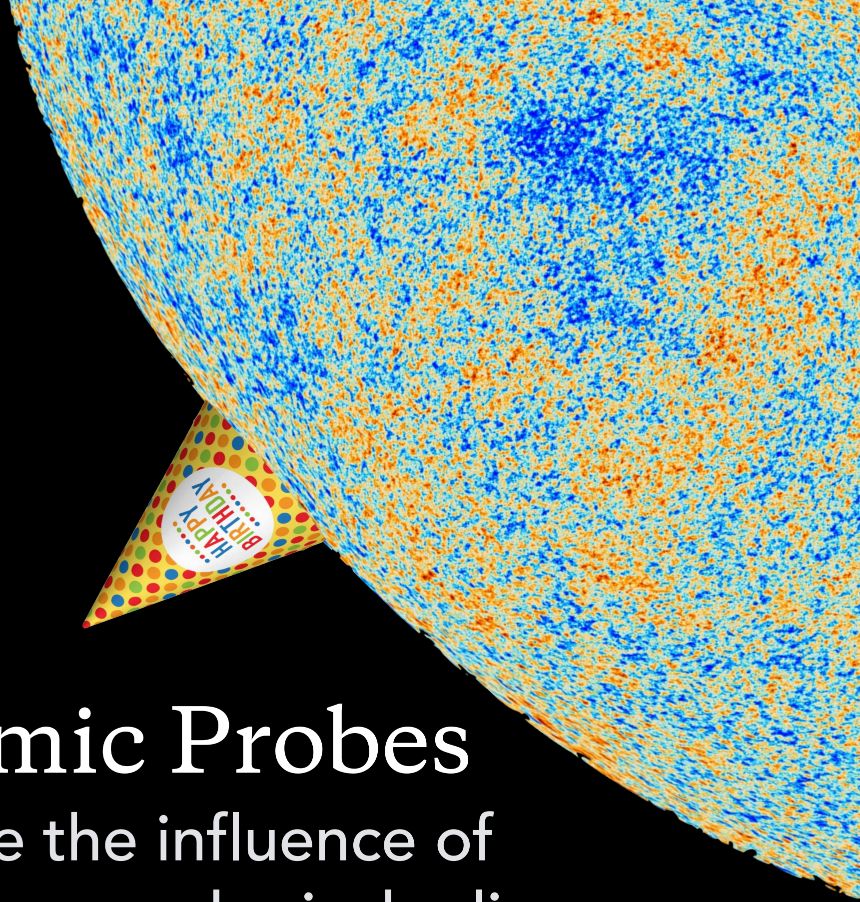


Astrophysical Probes

observe the influence of axions on stars, gas, & compact objects







Cosmic Probes

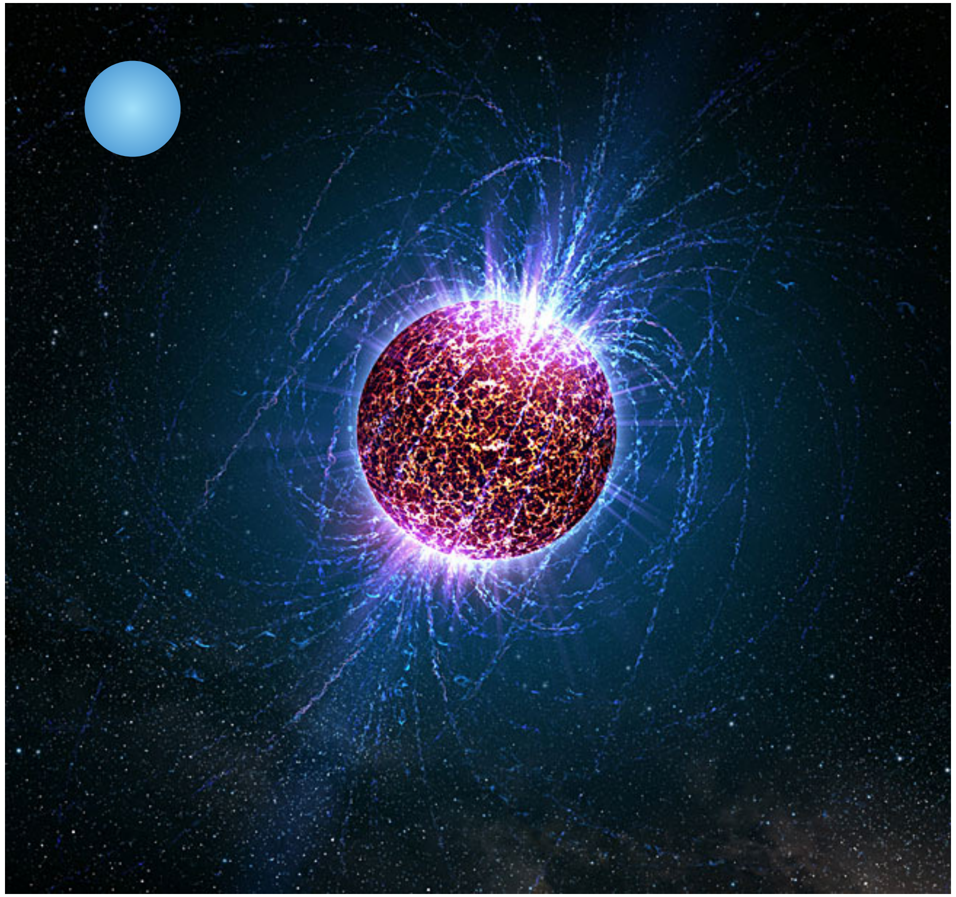
observe the influence of axions on cosmological relics

Terrestrial Probes

create axions on Earth or detect axions as they pass by the Earth

backup slides

Connection with astrophysics



Astrophysical implications worth exploring more closely:

- Radio bursts from NS encounters
- Transient rather than stochastic
- NS environment contains plasma allowing for resonant conversion (not considered here)
- Robust rate estimates require careful population modeling

the loop crossing model
simplified string network

The loop-crossing model

Assumptions

- All loops are circles
- Randomize loop orientation
- Randomize loop location in space
- All loops same radius at any time
- Loop radius evolves tracking Hubble

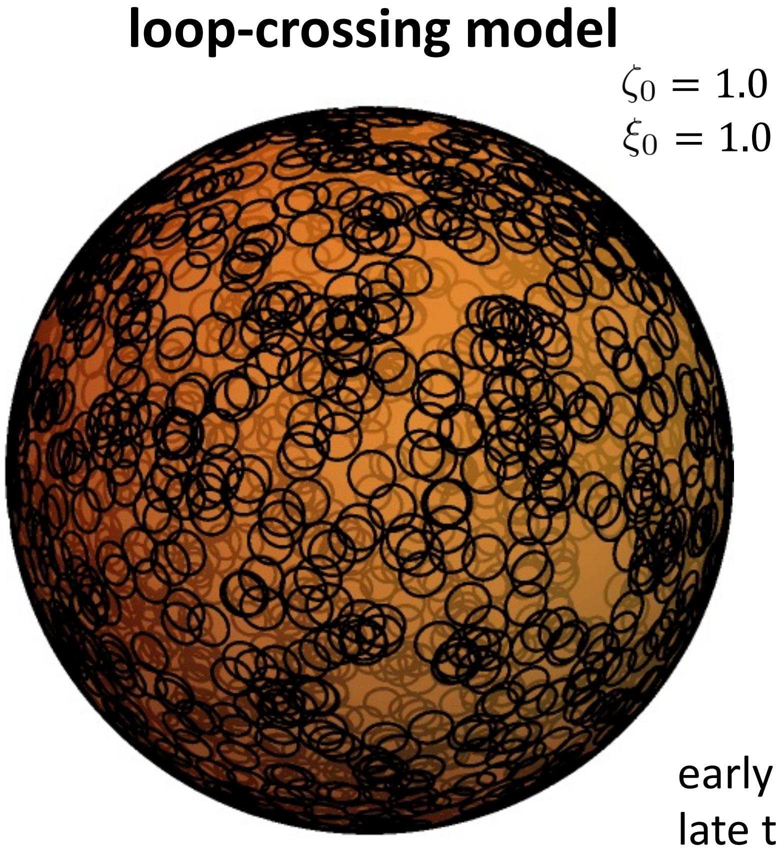
$$R(t) = \zeta_0 / H(t)$$

- Number of loops tracks Hubble

$$\rho(t) = \xi_0 \mu(t) H(t)^2$$

Model Parameters

$$\{m_a,\ \mathcal{A},\ \zeta_0,\ \xi_0\}$$



early time -> small loops
late time -> large loops

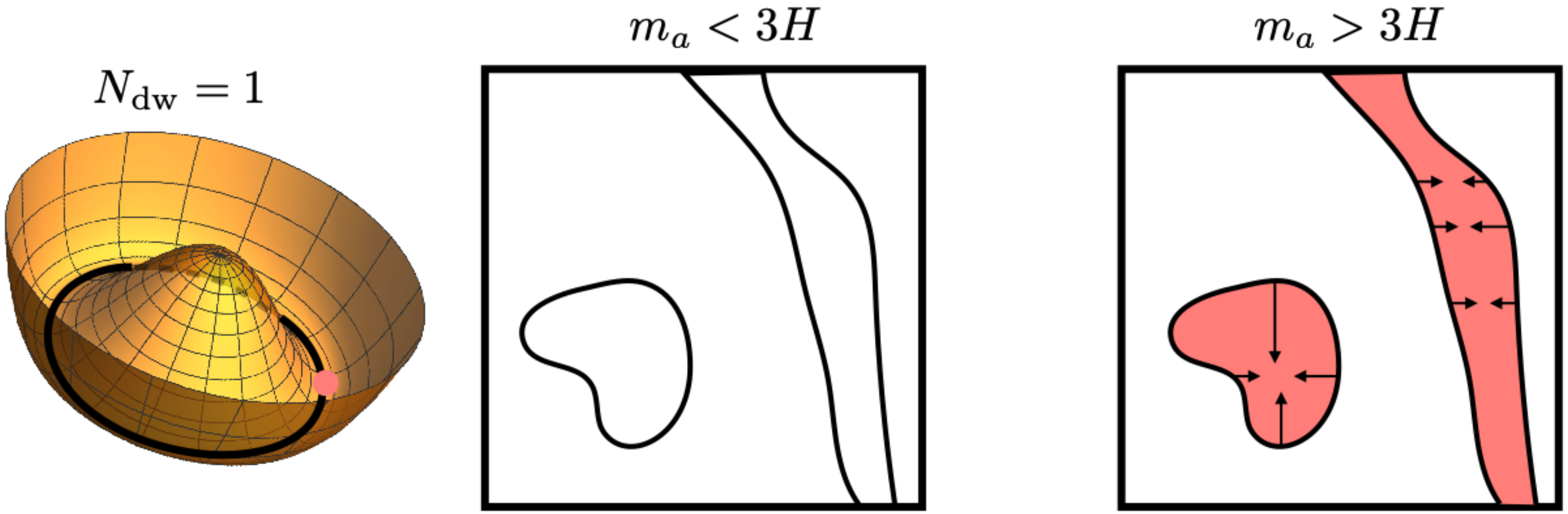
effect of
varying ALP mass

Collapse of the string-wall network

[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

Axion strings become connected together by domain walls

… the string-wall network collapses (for $N_{dw} = 1$)



let's consider:
$$\begin{cases} m_a \lesssim 3H_{\rm CMB} \simeq 3 \times 10^{-29}\ \mathrm{eV} & \text{(string network survives until after recombination)} \\ m_a \gtrsim 3H_0 \simeq 5 \times 10^{-33}\ \mathrm{eV} & \text{(string network collapses before today)} \end{cases}$$

Impact on birefringence

(assuming $N_{\mathrm{DW}} = 1$)

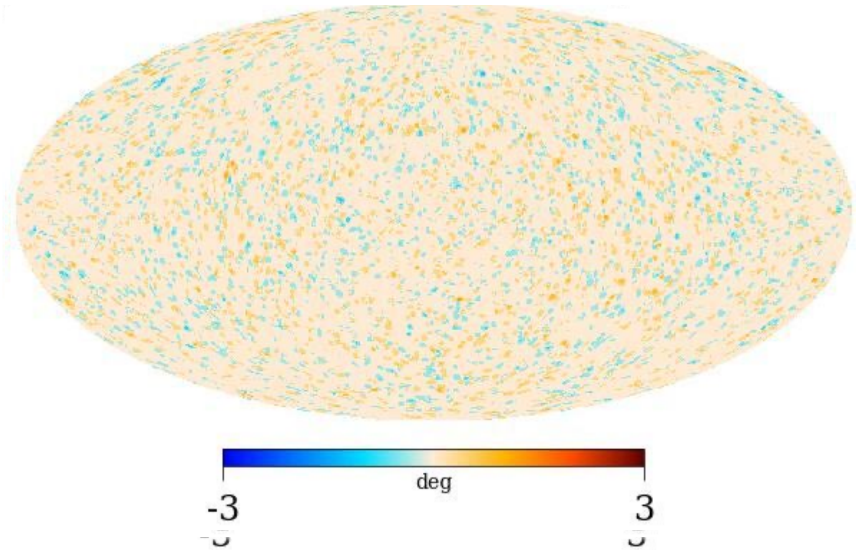
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

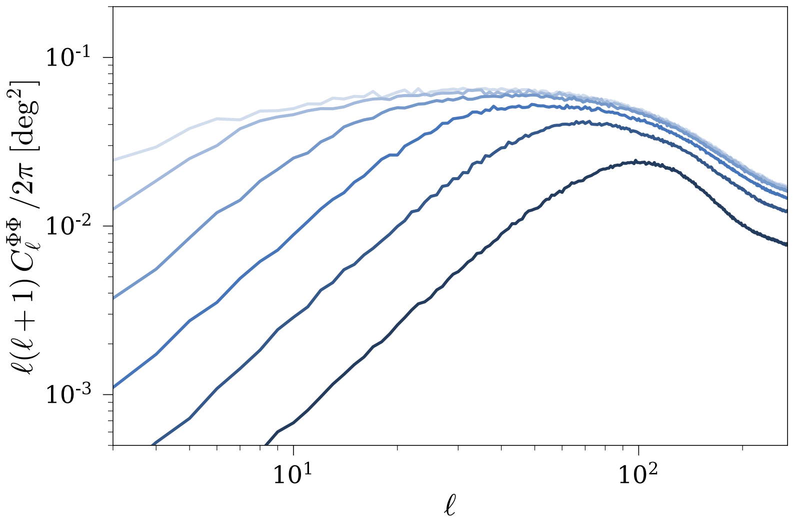
see also: [Ferreira, Gasparotto, Hiramatsu, Obata, & Pujolas (2023)]

raise the ALP mass

(network collapses earlier)

$$m_a = 2 \times 10^{-29}\ \mathrm{eV} \quad (z_c = 404)$$





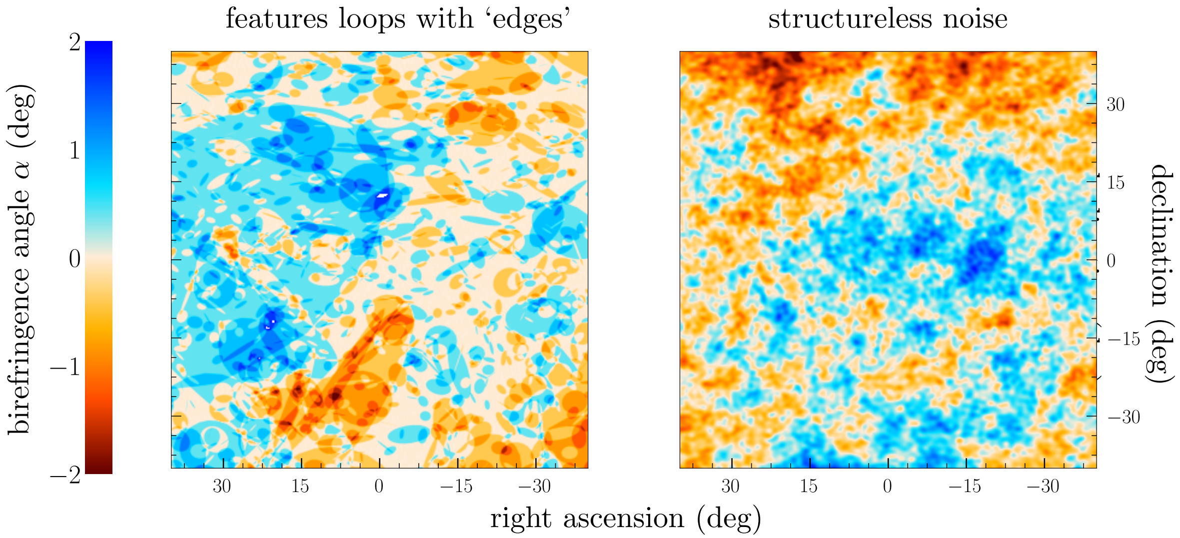
strong scale dependence ➔ possible to measure m_a

signatures of non-Gaussianity

Birefringence non-Gaussianity

[Hagimoto & AL, arXiv:2306:07351]
see also: Yin, Dai, Ferraro (2305.02318)

axion-string induced birefringence:
loop-like features are visibly non-Gaussian



Non-Gaussian axion birefringence map

Gaussian random field with same power spectrum

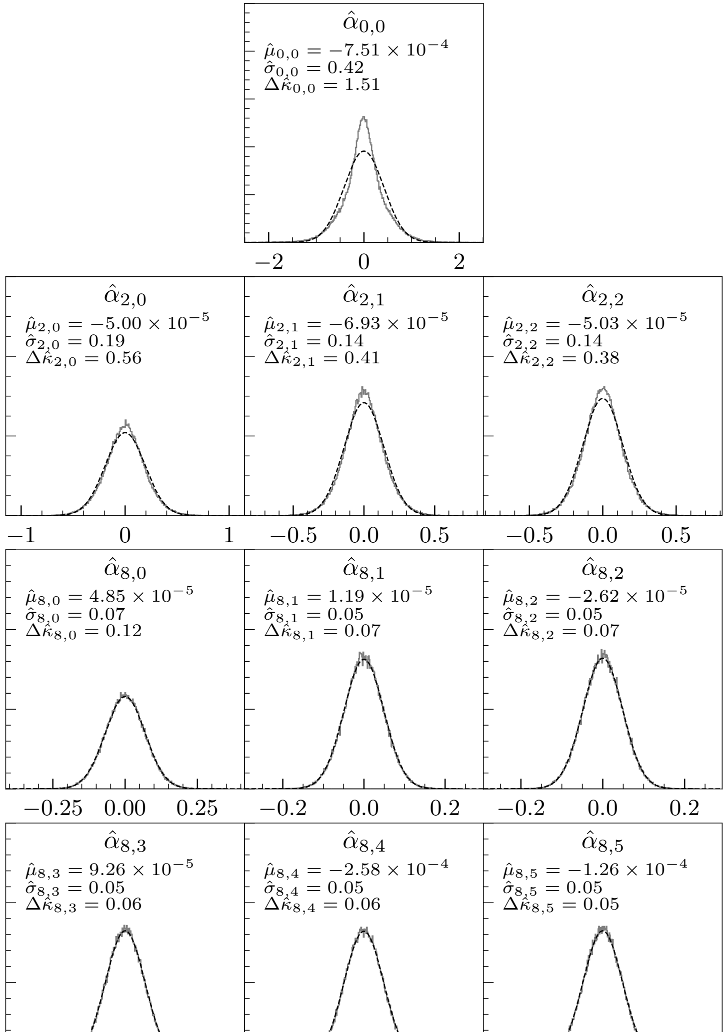
How to best quantify the non-Gaussian birefringence and develop tests to extract these features from the data?

Measures of NG 1: kurtosis

[Hagimoto & AL, arXiv:2306:07351]

distribution over a_{lm}'s

less Gaussian at lower ell



kurtosis

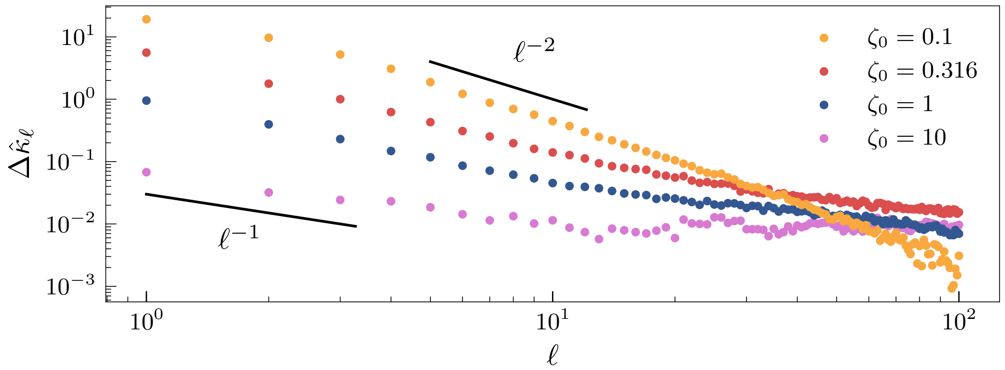
a measure of Gaussianity

$$\kappa_{\ell m} = \frac{\left\langle \left|\hat\alpha_{\ell m} - \langle\hat\alpha_{\ell m}\rangle\right|^4\right\rangle}{\left\langle \left|\hat\alpha_{\ell m} - \langle\hat\alpha_{\ell m}\rangle\right|^2\right\rangle^2}$$

= 3 for Gaussian

scaling with multipole index

more Gaussian on smaller scales



analytical model

~ inverse with # loops

$$\Delta\hat\kappa_\ell \sim \frac{\zeta_0}{8\xi_0}\left(1 + \frac{\pi}{\lambda\zeta_0\ell}\right)^2$$

recall: $R(t) = \zeta_0/H(t)$

Measures of NG 2: bispectrum

[Hagimoto & AL, arXiv:2306:07351]

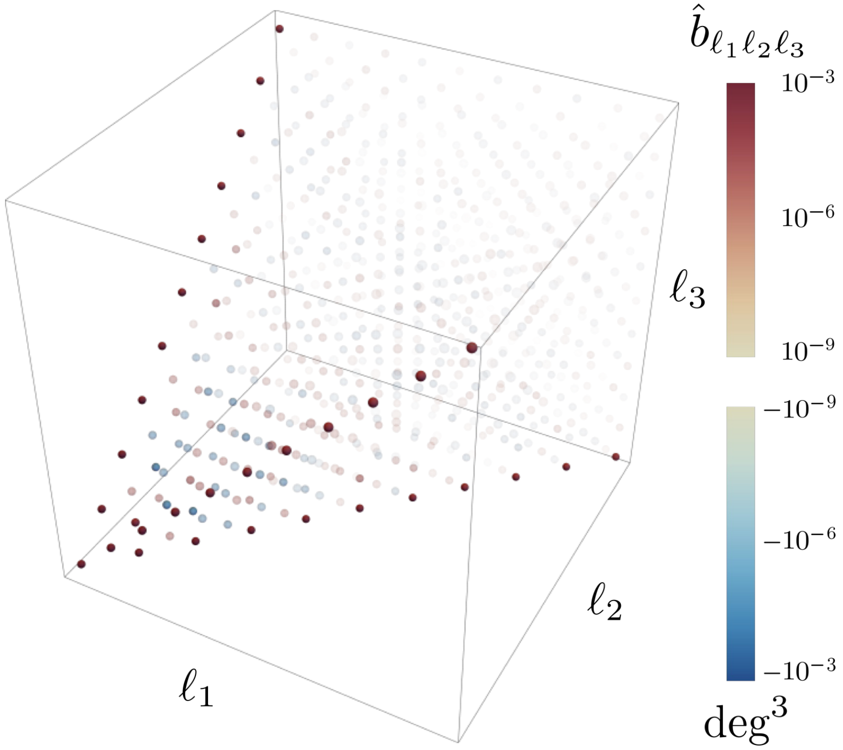
bispectrum

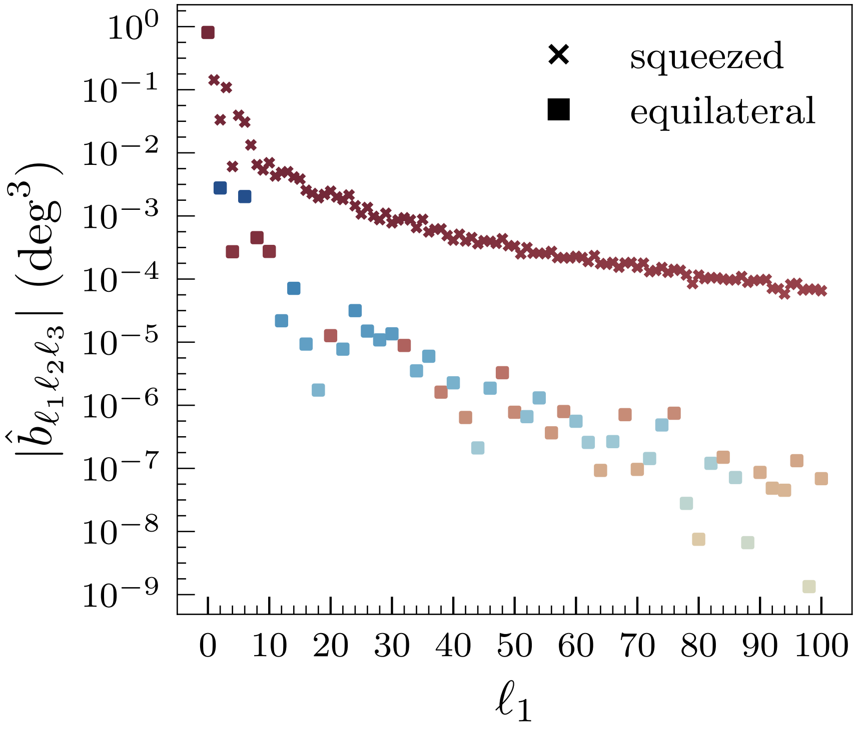
3-point correlations

$$\hat{b}_{\ell_1\ell_2\ell_3} = h^{-1}_{\ell_1\ell_2\ell_3} \sum_{m_1=-\ell_1}^{\ell_1}\sum_{m_2=-\ell_2}^{\ell_2}\sum_{m_3=-\ell_3}^{\ell_3} \begin{pmatrix}\ell_1 & \ell_2 & \ell_3\\ m_1 & m_2 & m_3\end{pmatrix} \hat{\alpha}_{\ell_1 m_1}\hat{\alpha}_{\ell_2 m_2}\hat{\alpha}_{\ell_3 m_3}$$

single realization

largest in squeezed triangle form





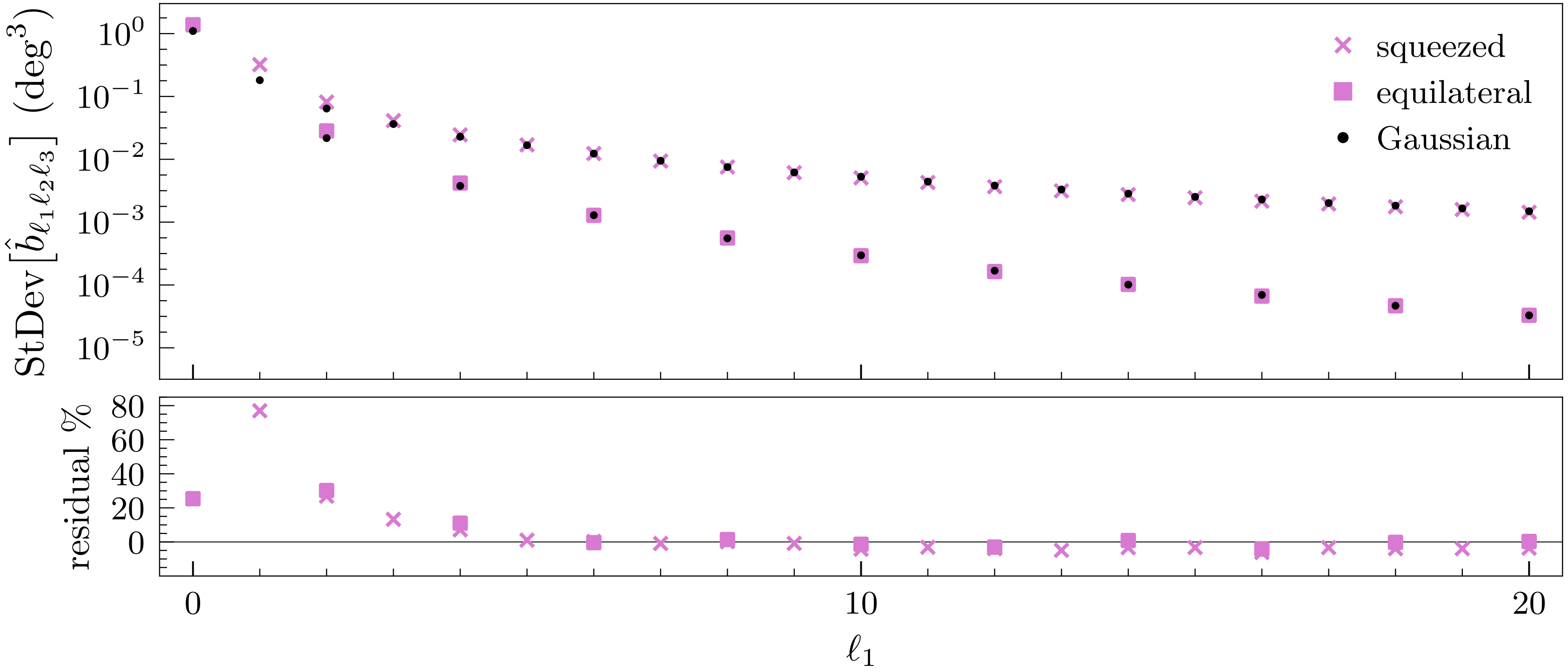
Measures of NG 2: bispectrum

[Hagimoto & AL, arXiv:2306:07351]

bispectrum
3-point correlations

$$\hat{b}_{\ell_1\ell_2\ell_3} = h^{-1}_{\ell_1\ell_2\ell_3} \sum_{m_1=-\ell_1}^{\ell_1} \sum_{m_2=-\ell_2}^{\ell_2} \sum_{m_3=-\ell_3}^{\ell_3} \begin{pmatrix} \ell_1 & \ell_2 & \ell_3 \\ m_1 & m_2 & m_3 \end{pmatrix} \hat{\alpha}_{\ell_1 m_1} \hat{\alpha}_{\ell_2 m_2} \hat{\alpha}_{\ell_3 m_3}$$

average bispectrum
and comparison with Gaussian random field



Measures of NG 3: scattering transform

Yin, Dai, Ferraro (2023

std. method

power spectrum

$$\text{signal:} \quad I_0(\mathbf{x})$$

$$\text{plane wave:} \quad \phi_{\mathbf{k}}(\mathbf{x})$$

$$P_{\mathbf{k}}(\mathbf{x}) = \langle |I_0 * \phi_{\mathbf{k}}|^2 \rangle(\mathbf{x})$$

new method

scattering transform

$$\text{wavelet:} \quad \psi^{j.l}(\mathbf{x})$$

$$I_1^{j,l}(\mathbf{x}) = \langle |I_0 * \psi^{j,l}|^2 \rangle(\mathbf{x})$$

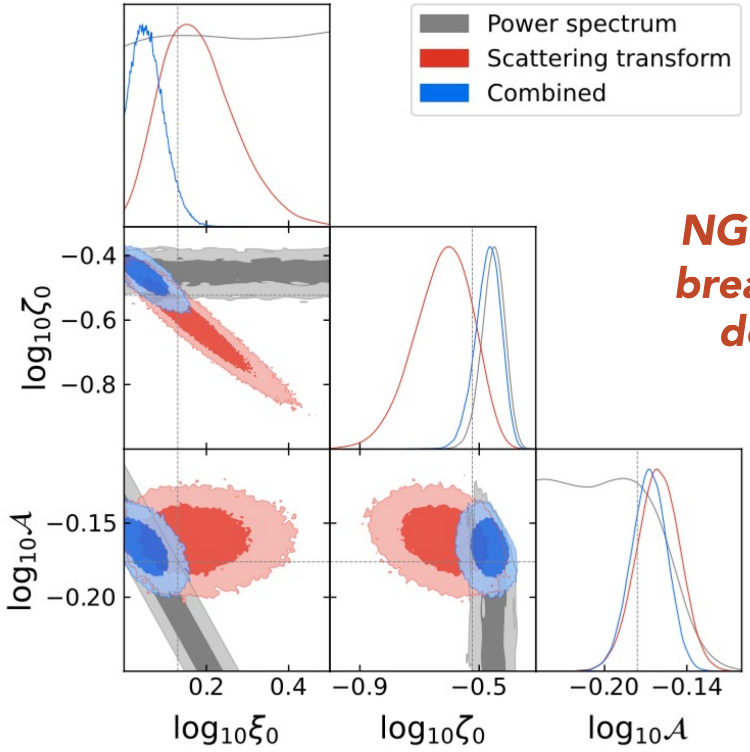
$$I_2^{j_1,l_1,j_2,l_2}(\mathbf{x}) = \langle |I_1^{j_1,l_1} * \psi^{j_2,l_2}|^2 \rangle(\mathbf{x})$$

$$s_1^{j} = \langle I_1^{j,l} \rangle_{\mathbf{x},l}$$

$$s_2^{j_1,j_2} = \langle I_2^{j_1,l_1,j_2,l_2} \rangle_{\mathbf{x},l_1,l_2}$$

comparison

pow-spec vs. scatt-transform



(b) $\mathcal{A}^2\xi_0 = 0.6,\ \mathcal{A} = 2/3,\ \zeta_0 = 0.3$

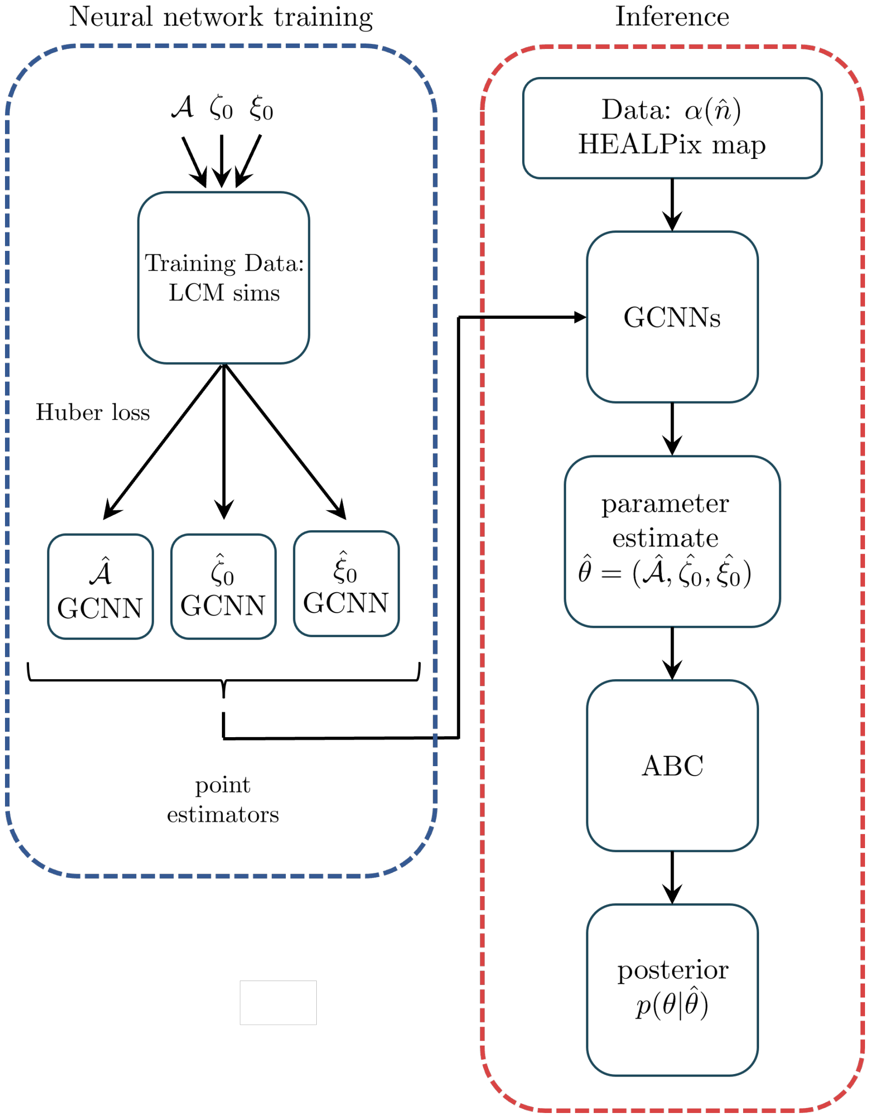
NG information breaks the $A^2\ \xi_0$ degeneracy

machine learning
for axion string identification

Machine learning for axion strings

--- early stages ---

goal: to train an AI to identify features of axion strings in CMB polarization maps



Neural network training

$\mathcal{A}$ ζ_0 ξ_0

Training Data: LCM sims

Huber loss

$\hat{\mathcal{A}}$ GCNN

$\hat{\zeta}_0$ GCNN

$\hat{\xi}_0$ GCNN

point estimators

Inference

Data: $\alpha(\hat{n})$ HEALPix map

GCNNs

parameter estimate $\hat{\theta} = (\hat{\mathcal{A}}, \hat{\zeta}_0, \hat{\xi}_0)$

ABC

posterior $p(\theta|\hat{\theta})$

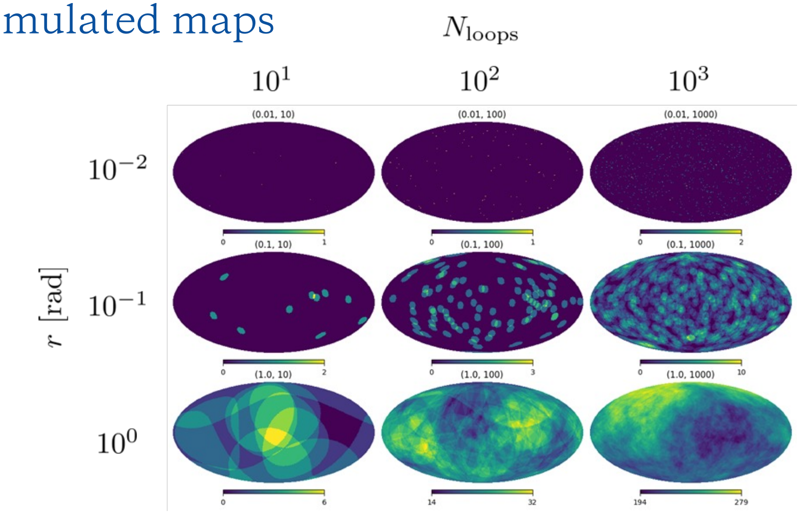
Ray Hagimoto (Rice U grad)

Machine learning for axion strings

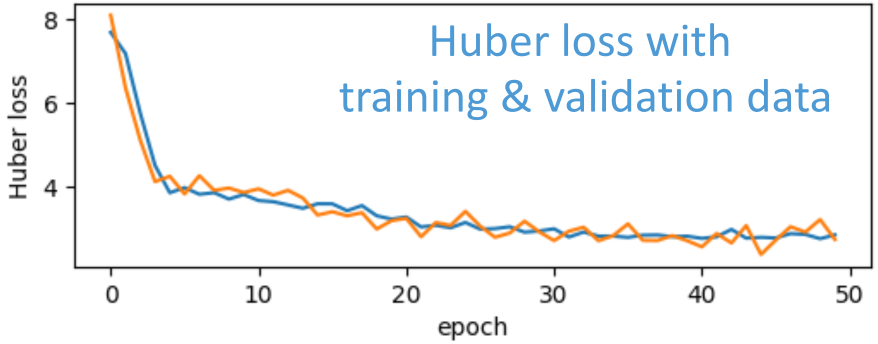
--- early stages ---

Ray Hagimoto
(Rice U grad)

simulated maps

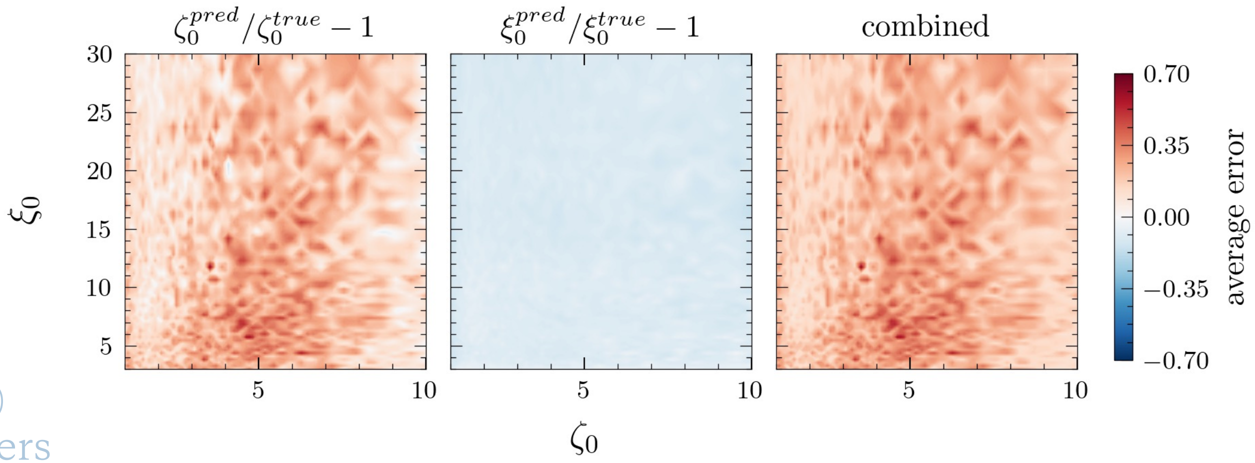


training



Huber loss with training & validation data

how well is it working? … not bad!



things to do & where we're going:

- -- detector noise
- -- beyond LCM sims
- -- real CMB data
- -- projections

package: DeepSphere (Python)
architecture: 3 conv + 3 pool layers

what about isotropic birefringence

Are strings responsible for isotropic birefringence?

[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

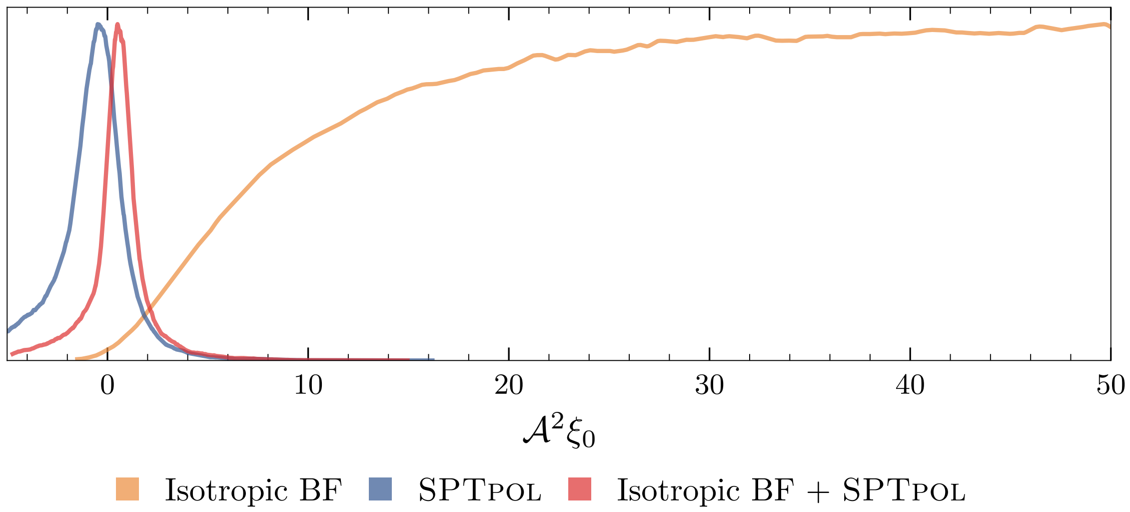
reported detection of isotropic birefringence:

same rotation angle across the whole sky
(using *Planck* & *WMAP* data)

$$\alpha_{00} = -1.21^{\circ}{}^{+0.33^{\circ}}_{-0.32^{\circ}} \ (68\% \text{ CL})$$

[Minami & Komatsu (2020)]
[Diego-Palazuelos et. al. (2022)]
[Eskilt (2022)], [Eskilt & Komatsu (2022)]
[Eskilt et. al. (2023)]

our conclusion: the isotropic signal is in tension with limits on anisotropic BF if they both arise from axion-string induced birefringence



note that: $\beta = -\alpha_{00}/\sqrt{4\pi} \approx 0.34^{\circ}$

Are strings responsible for isotropic birefringence?

[Ferreira, Gasparotto, Hiramatsu, Obata, & Pujolas (2023)]

reported detection of isotropic birefringence:

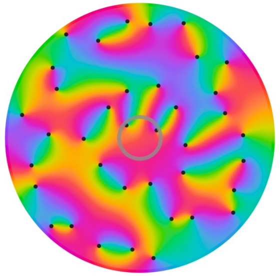
same rotation angle across the whole sky
(using *Planck* & *WMAP* data)

$$\alpha_{00} = -1.21^{\circ}{}^{+0.33^{\circ}}_{-0.32^{\circ}} \ (68\% \ \mathrm{CL})$$

[Minami & Komatsu (2020)]
[Diego-Palazuelos et. al. (2022)]
[Eskilt (2022)], [Eskilt & Komatsu (2022)]
[Eskilt et. al. (2023)]

loopholes allowing large iso-BF

(1) environmental effects
a nearby loop in our Hubble volume
would dominate the isotropic signal



(2) Hubble-scale gradients
the massless axion field is expected to be
inhomogeneous on the Hubble scale

(3) late-forming network
if the string network is not present just after
recombination, the small-scale BF is suppressed

note that: $\beta = -\alpha_{00}/\sqrt{4\pi} \approx 0.34^{\circ}$

Constraints from anisotropic birefringence