astrophysical and cosmological probes of axions

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Recontres du Vietnam
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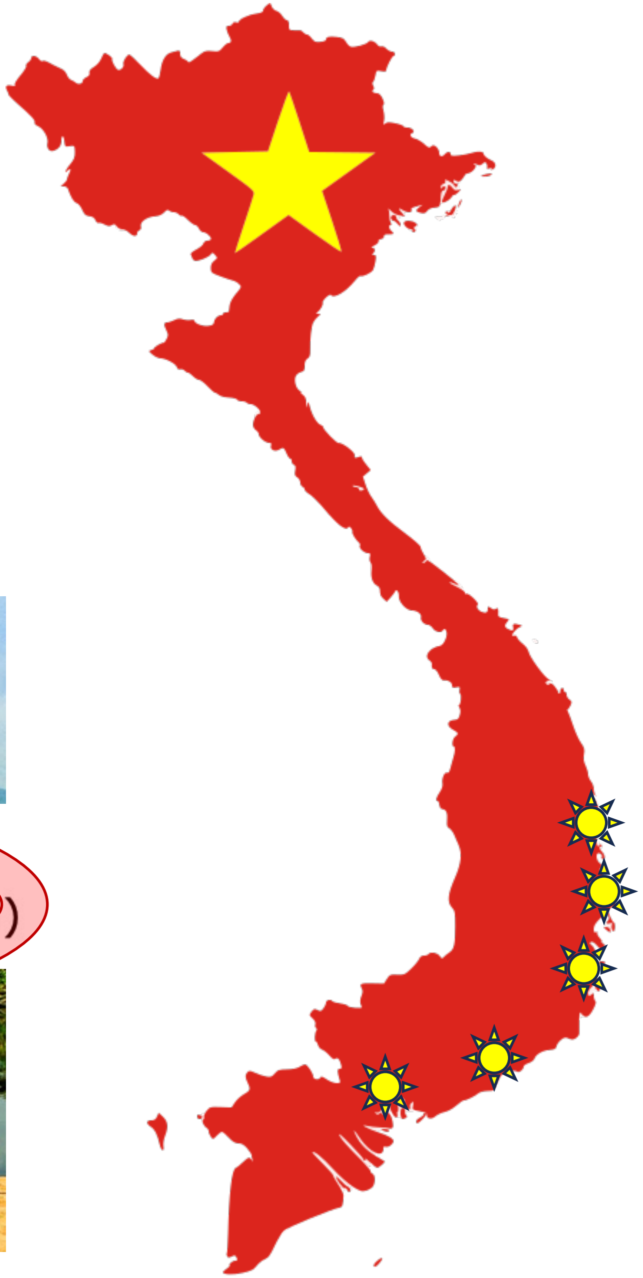
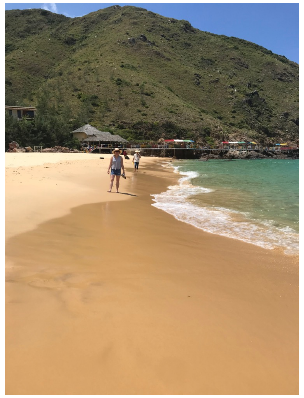
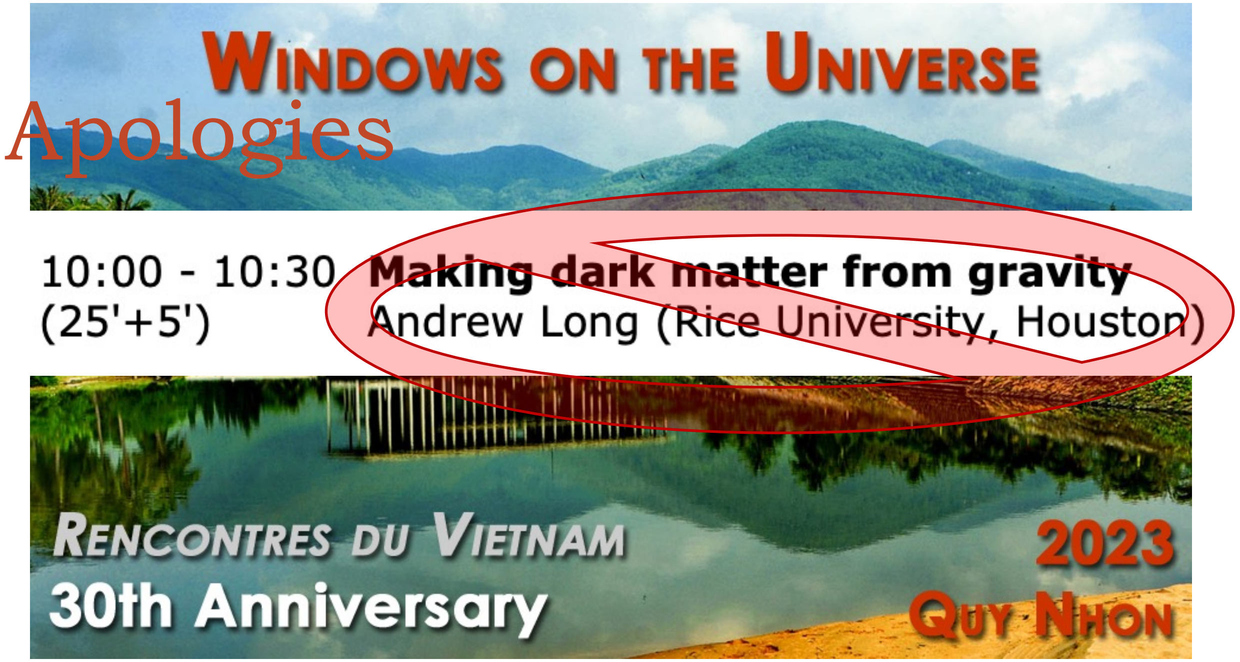
Thanks



Excuses



Apologies



“A triumph of science!”

[quoting Tao Han’s talk]

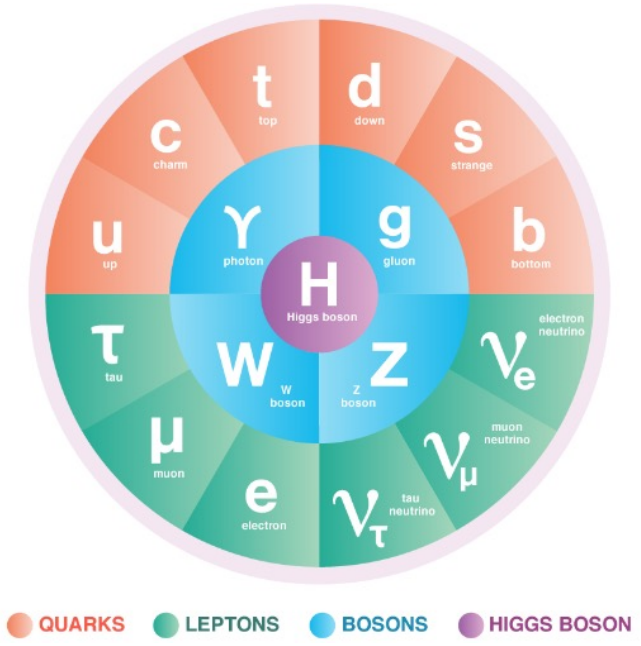
Successes
known physics

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

allows for precision calculation

a predictive framework

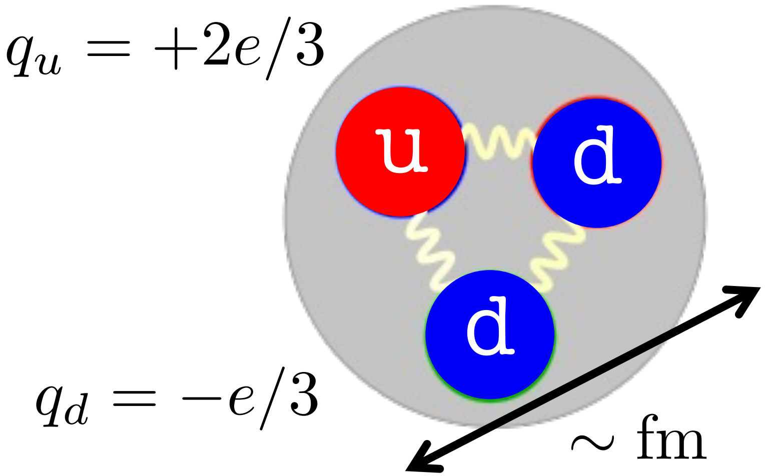
Standard Model of the Elementary Particles



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



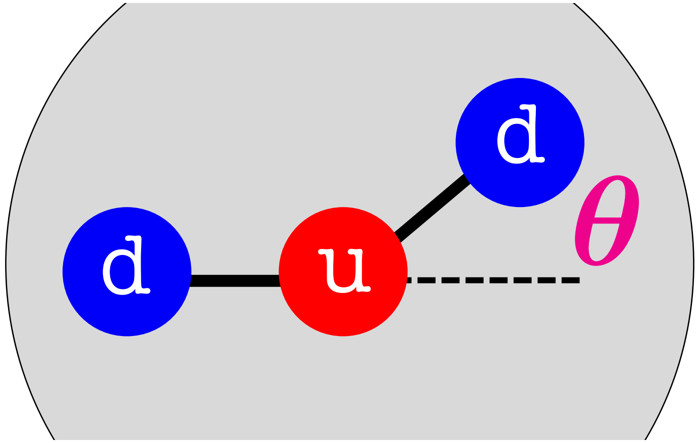
naïve dimensional analysis

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

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?

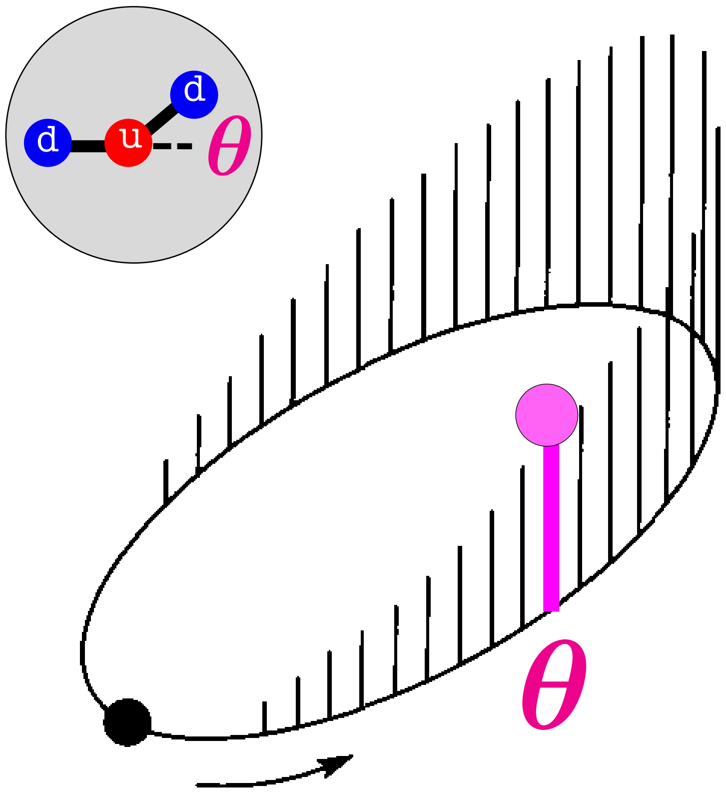
this is called the *Strong CP Problem*

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

Dynamical relaxation to zero

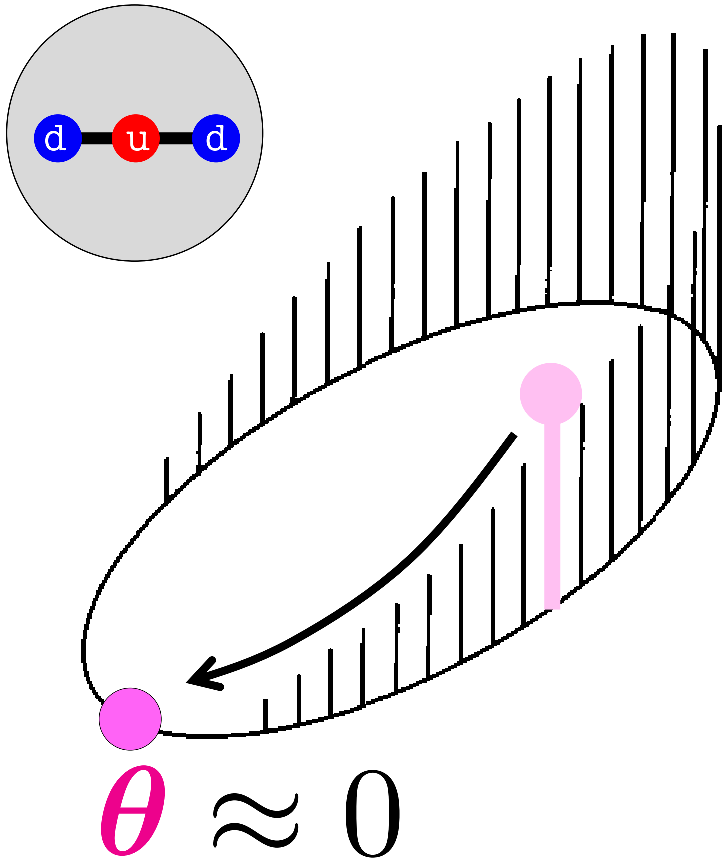
[Peccei, Quinn, Weinberg, Wilczek 1977-78]

It turns out that θ costs energy:



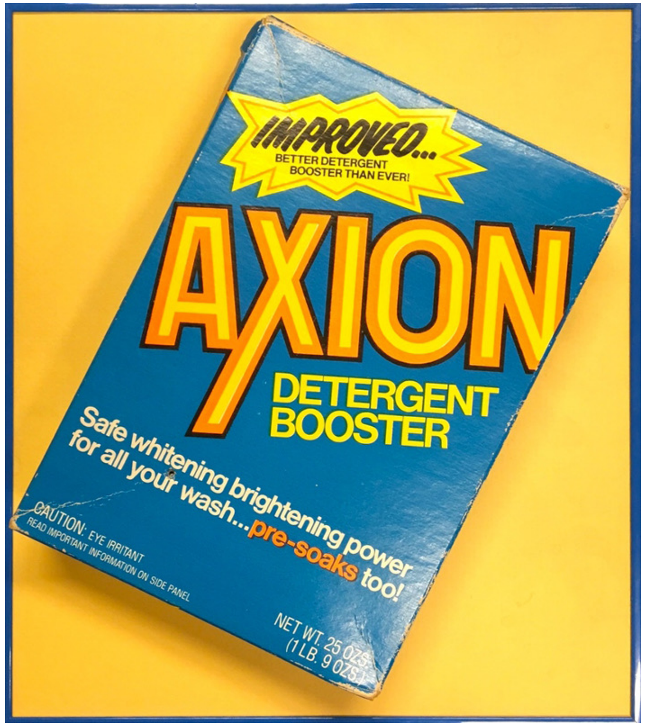
promote θ to a field

A dynamical θ relaxes to zero:



By-product: a new particle

Quantum excitations around θ=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
~~~~~~~~~~~~~~~~~~~~

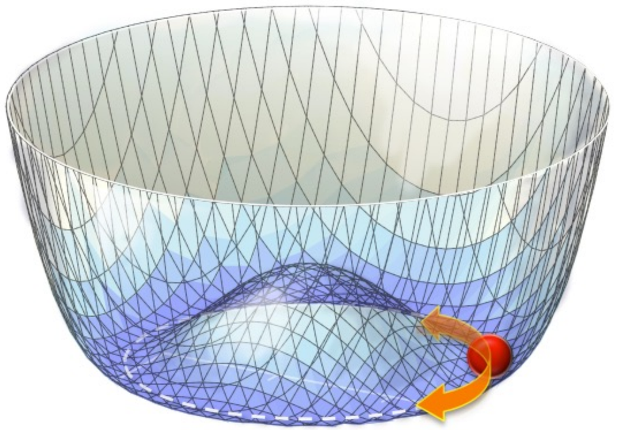
The QCD Axion's cousins: axion-like particles

[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.

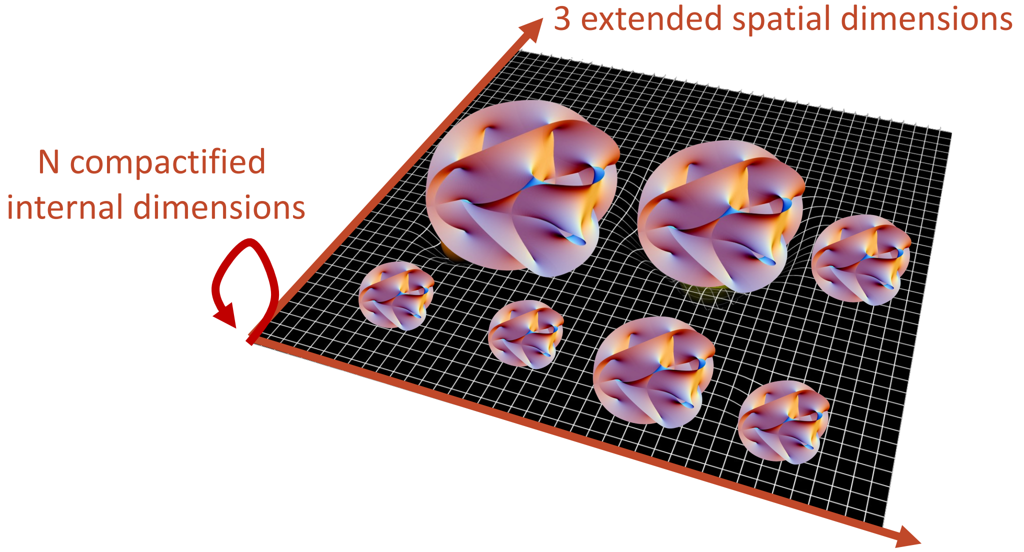
ALPs from symmetry breaking

(similar to pions in QCD)



ALPs from extra dimensions

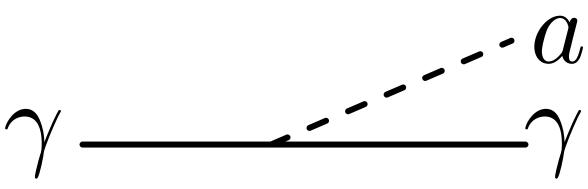
(such as string theory)



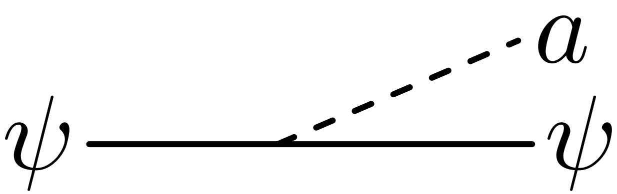
Axions interact with light and matter

mass | axion-photon | axion-electron | axion-neutron | etc

$$\mathscr{L}_{\text{axion}} = -\tfrac{1}{2}m_a^2 a^2 - \tfrac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{m_e}g_{aee}\bar{e}\gamma^\mu\gamma_5 e\partial_\mu a + \frac{1}{m_n}g_{ann}\bar{n}\gamma^\mu\gamma_5 n\partial_\mu a + \cdots$$

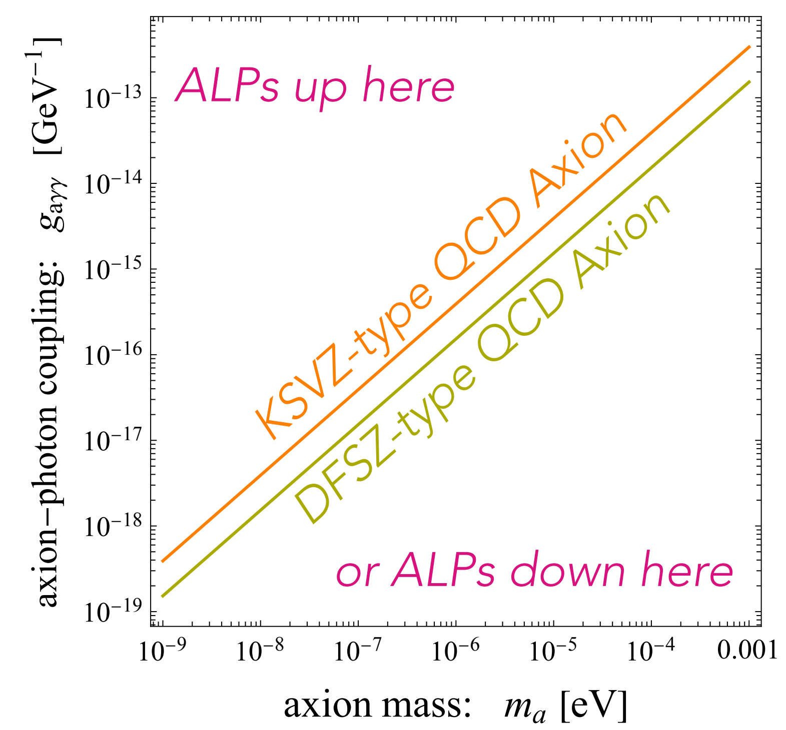


$$g_{a\gamma\gamma} = C_\gamma \frac{\alpha_{\text{em}}}{2\pi f_a}$$



$$g_{a\psi\psi} = C_\psi \frac{m_\psi}{f_a}$$

for the QCD Axion: $m_a \simeq (5.7\,\mu\text{eV})\left(f_a/10^{12}\ \text{GeV}\right)^{-1}$



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?

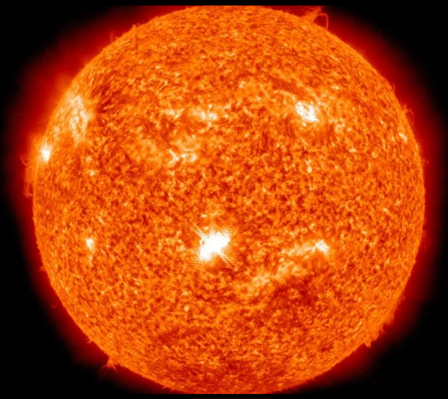
How was it produced in the early Universe?

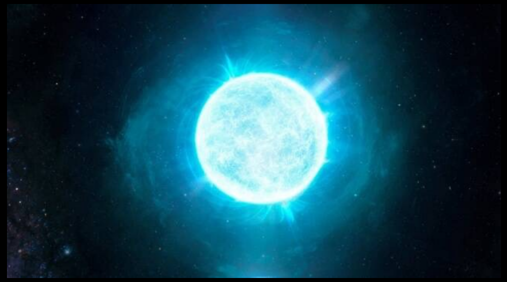
Is it connected to dark matter, baryogenesis, inflation, etc?

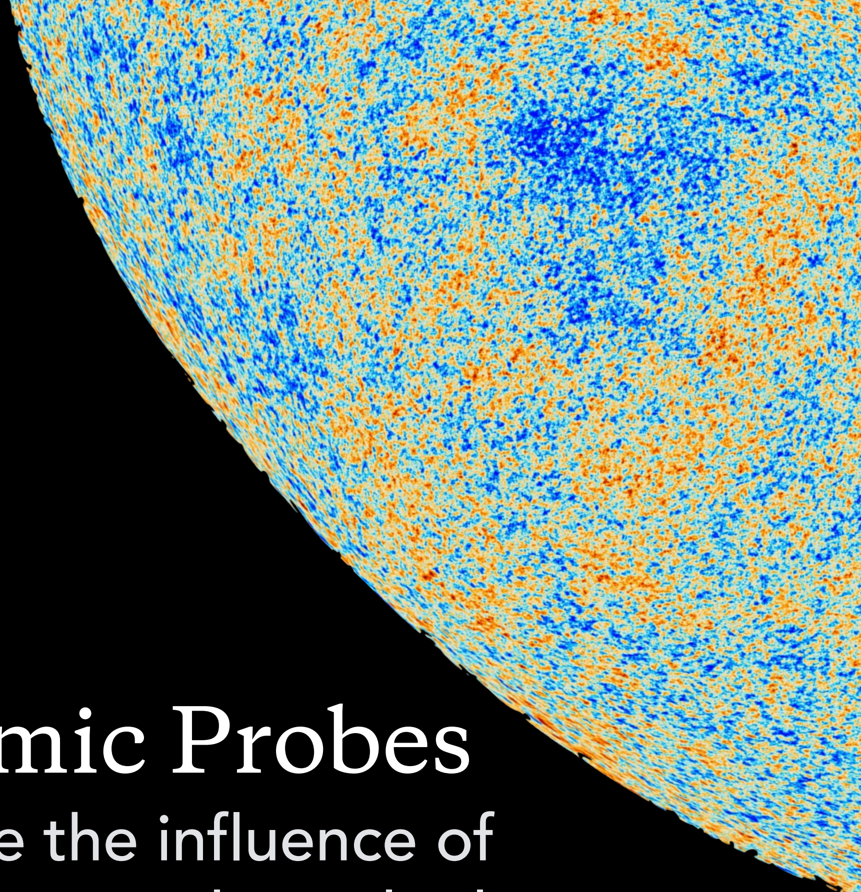
…

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

Terrestrial probes

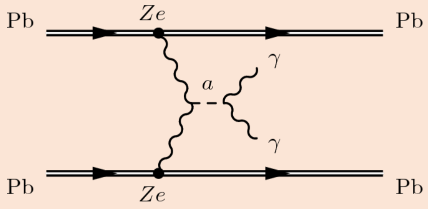
[see talks by Matthew Citron, Boris Ivanov, Nhan V Tran]

accelerator / collider

rare meson decay

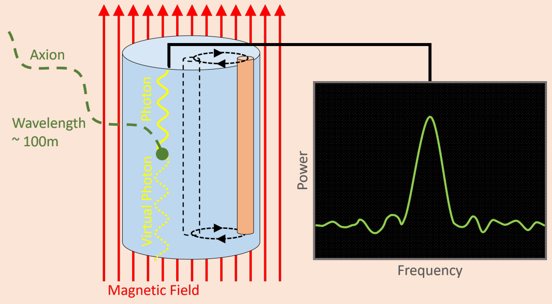
ultra-peripheral heavy ion

FASER, milliQan, FPS



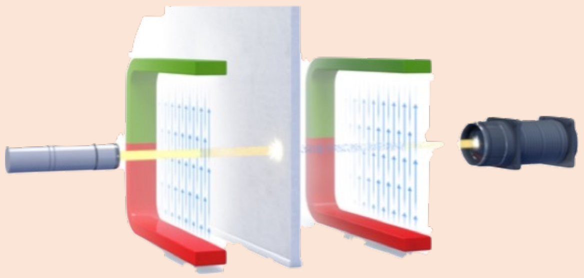
resonant cavity

ADMX, haloscopes



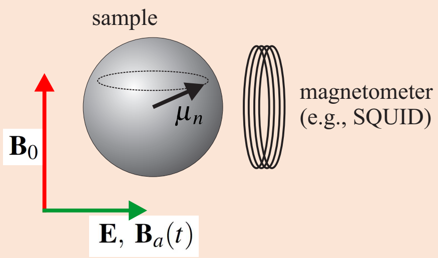
light through wall

ALPS-II

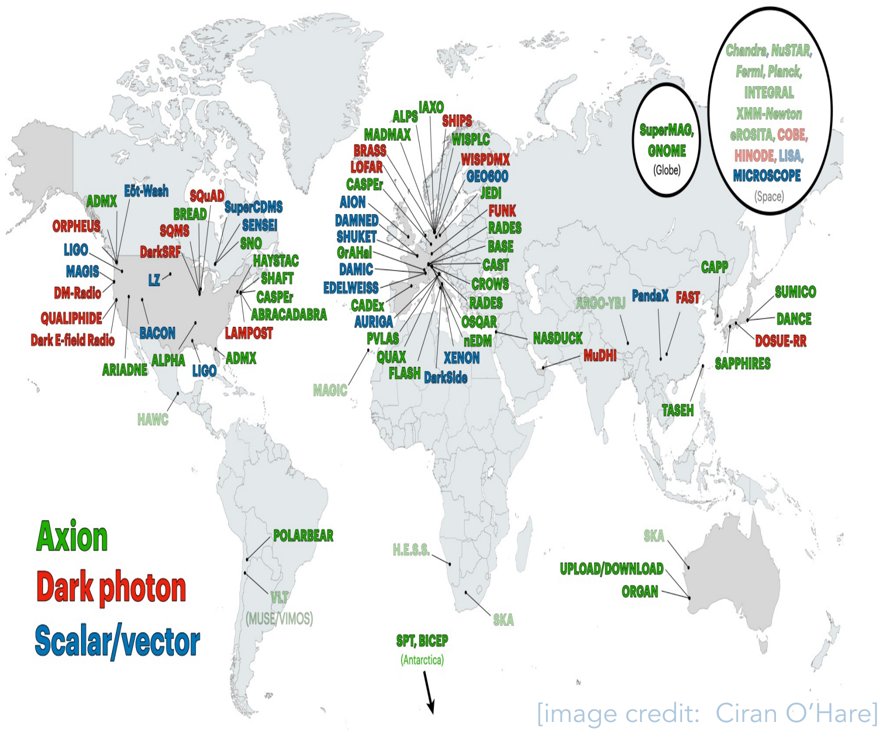


broadband

CASPEr, Abra, ...



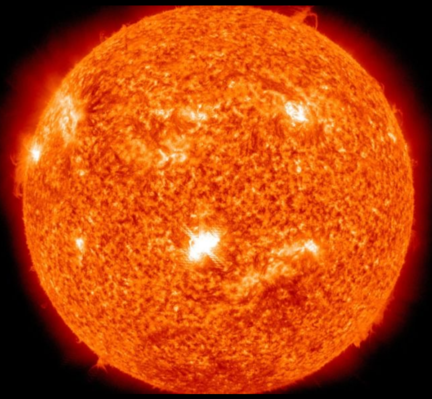
a worldwide campaign

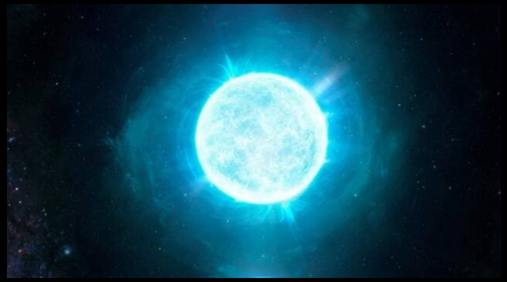


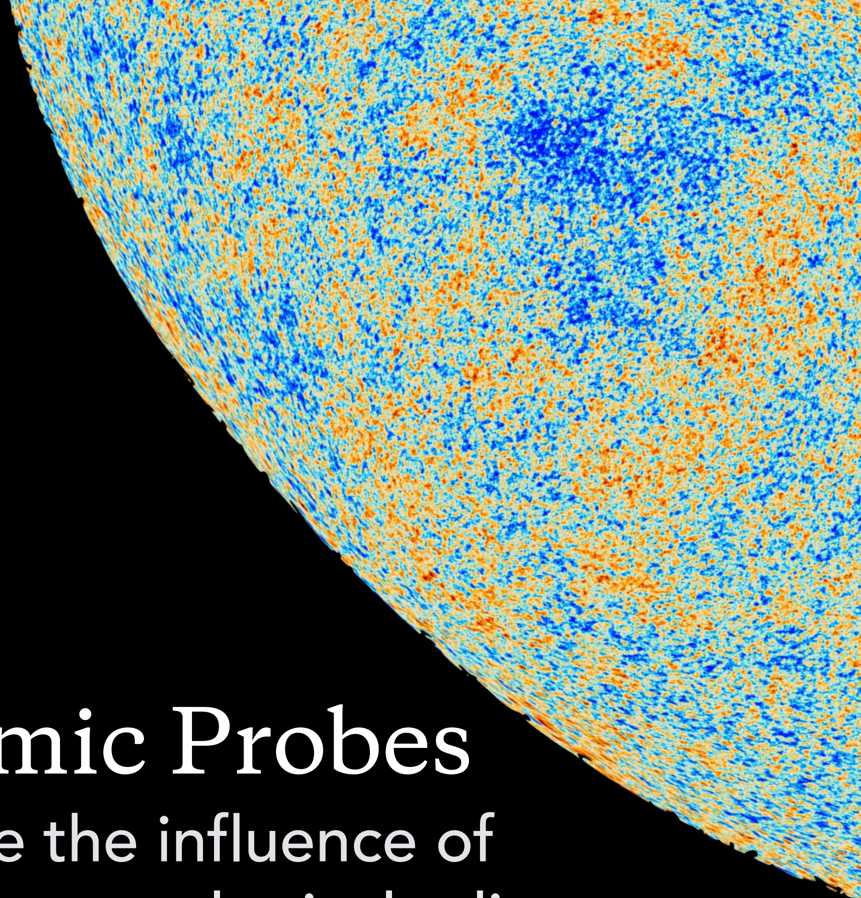
[image credit: Ciran O'Hare]

Astrophysical Probes

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







Cosmic Probes

observe the influence of axions on cosmological relics

Terrestrial Probes

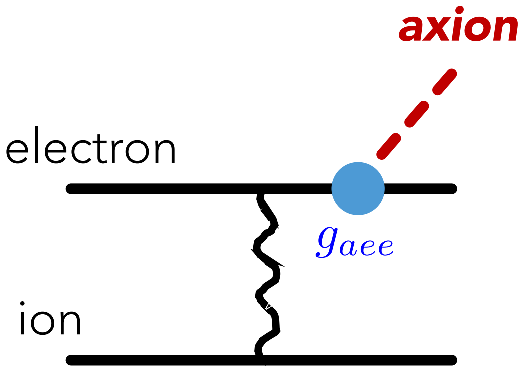
create axions on Earth or detect axions as they pass by the Earth

Stars emit axions

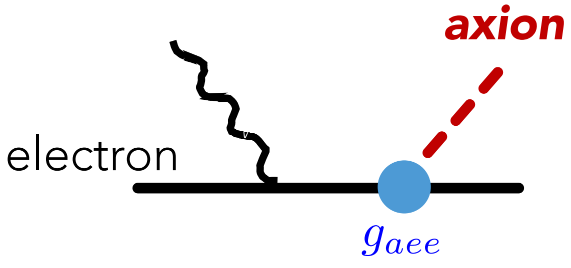
[see talk by Ngan Nguyen after coffee]

Various channels for axion emission
(different channels dominate for different star types)

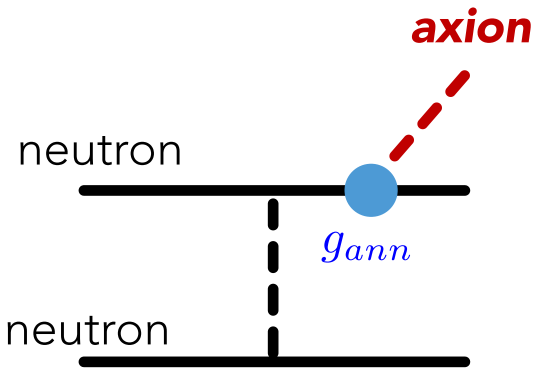
electron bremstrahlung
(white dwarf)



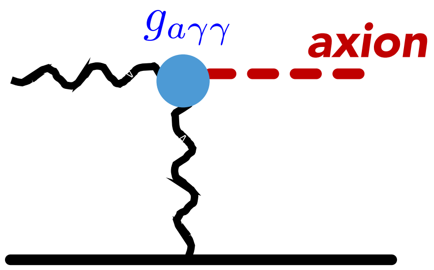
Compton
(main sequence, giants)



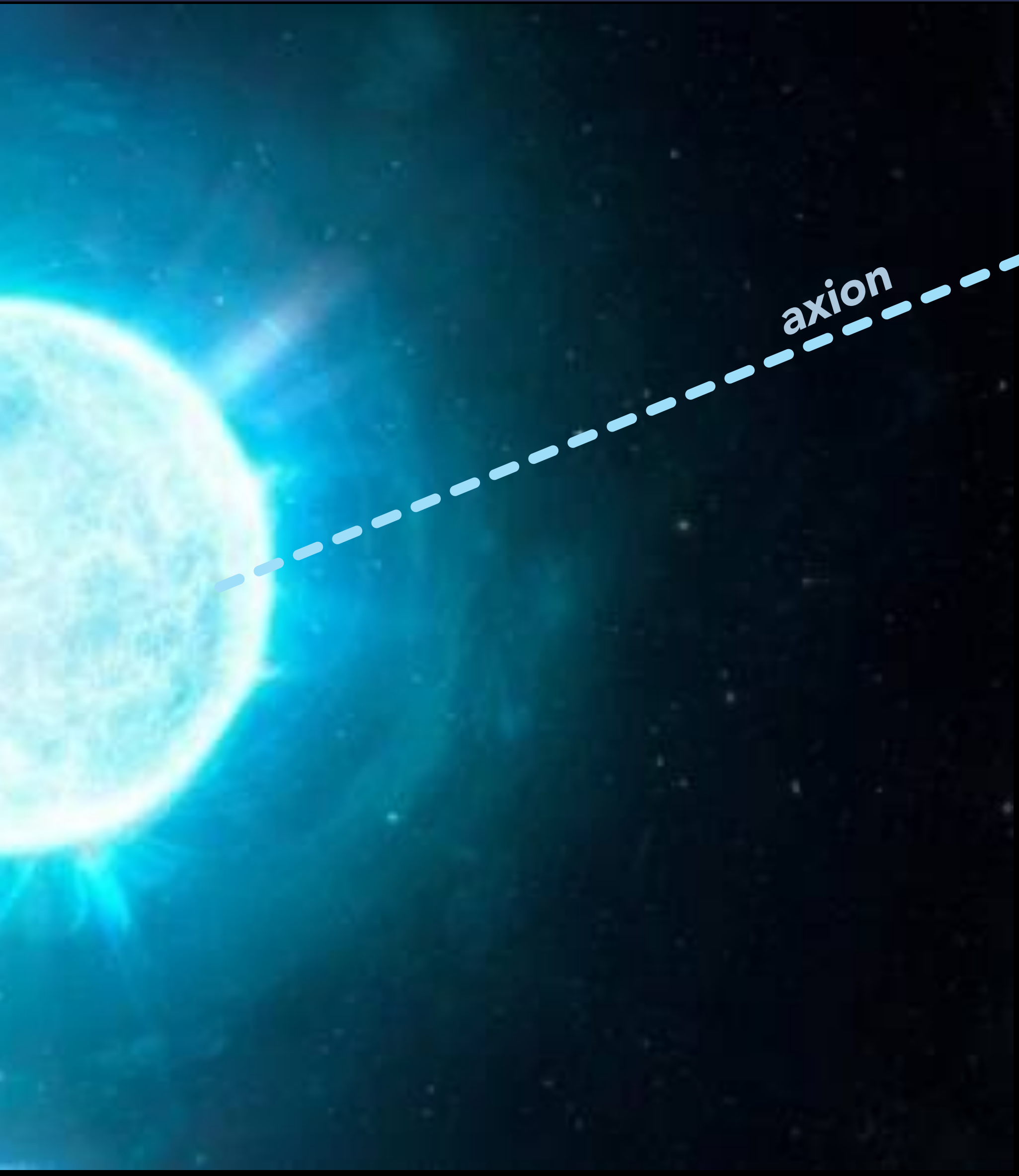
neutron bremstrahlung
(neutron star)



Primakoff effect
(main sequence, giants)



Example: white dwarf stars



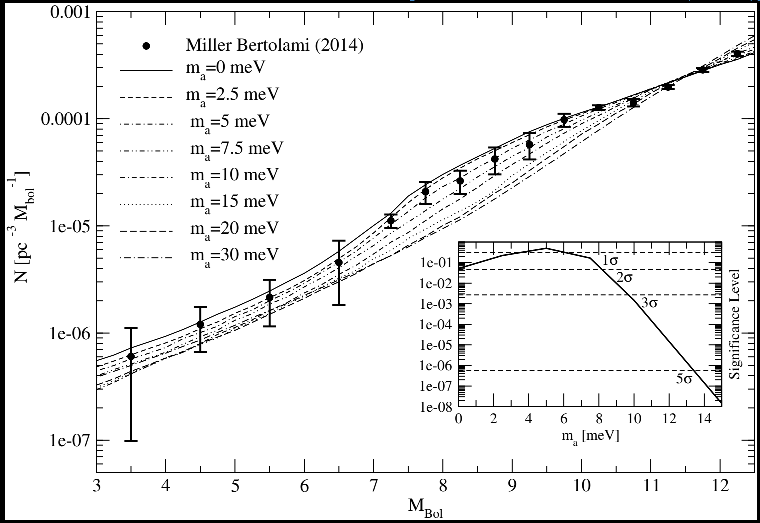
[Krauss, Moody, & Wilczek (1984)] [Raffelt (1986)]
[Nakagawa, Adachi, Kohyama, & Itoh (1987,88)]

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)]

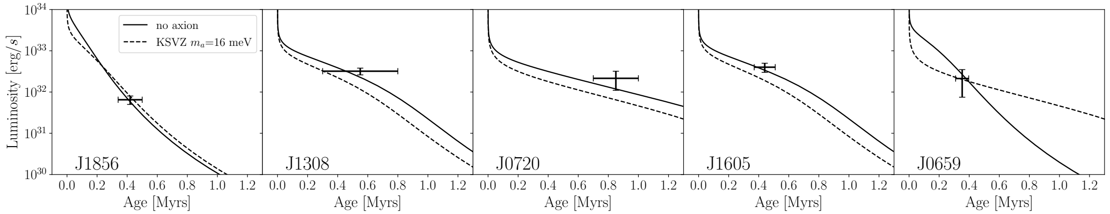


$$g_{aee} < 3 \times 10^{-13} \quad (3\sigma)$$

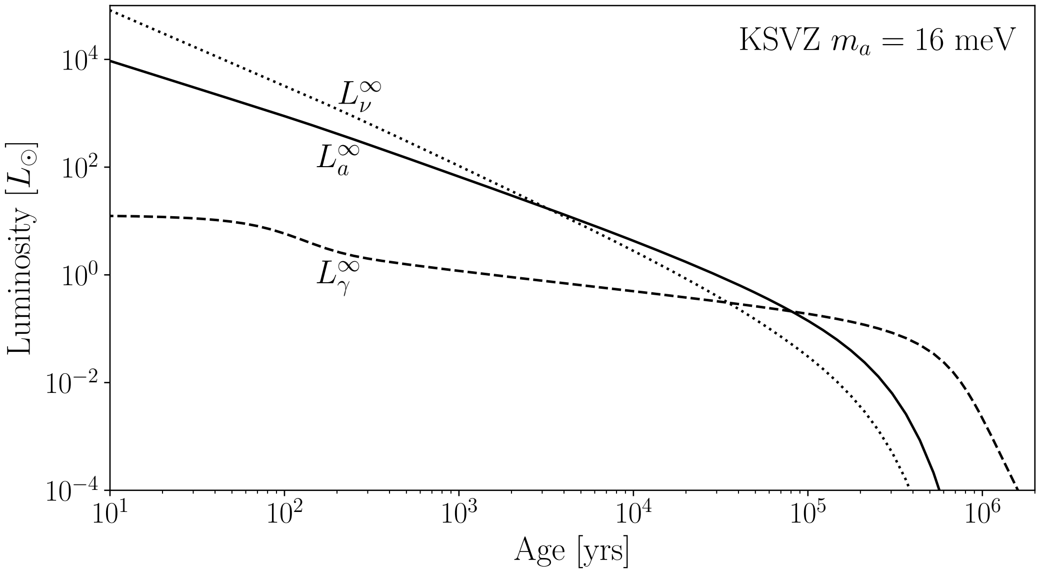
[Buschmann, Dessert, Foster, AL, & Safdi (2021)]

(a few of) The Magnificent 7

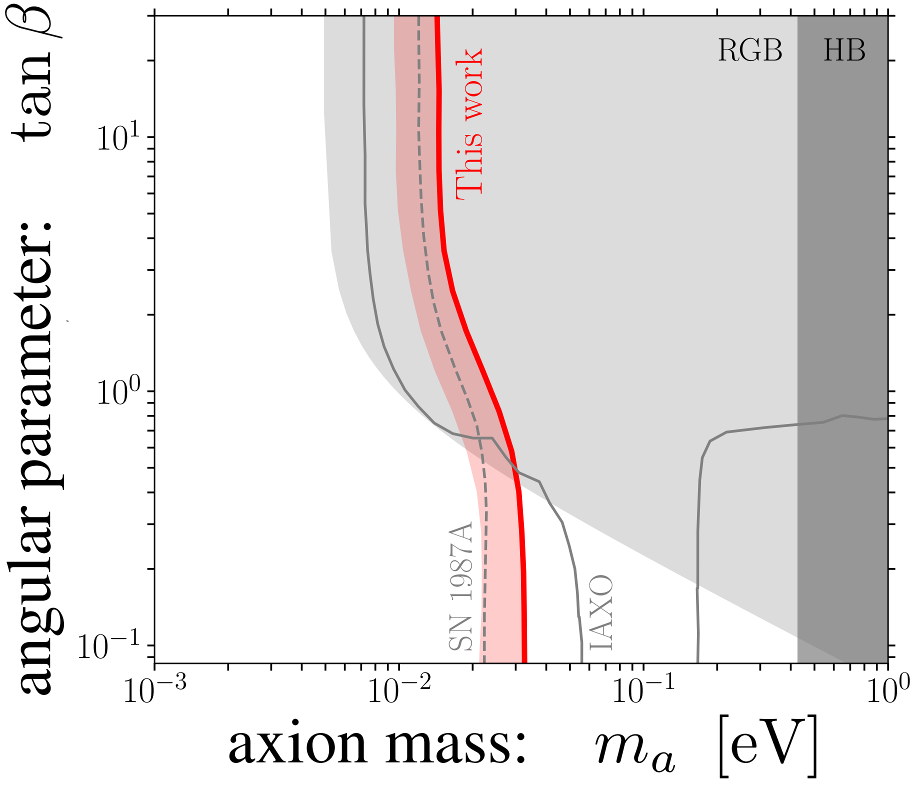
robust luminosity & age measurements



Comparison of emission channels



QCD Axion constraints

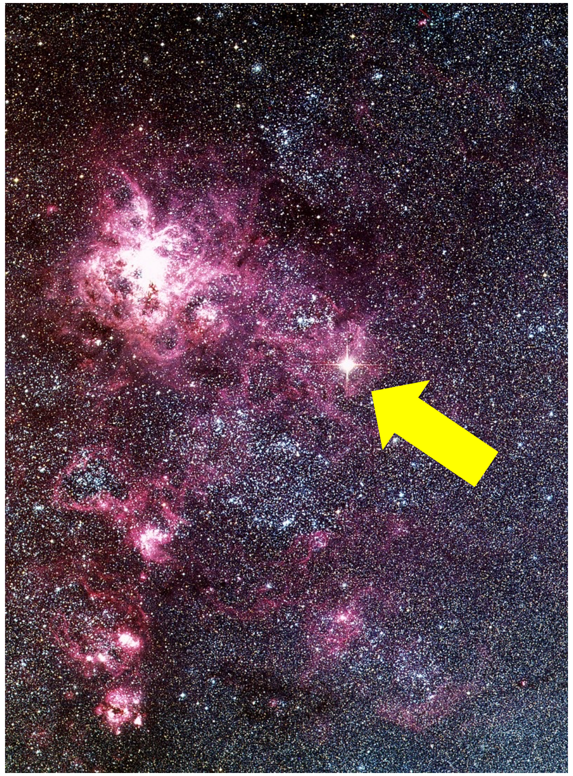


$$f_a \gtrsim 5 \times 10^8 \text{ GeV}$$

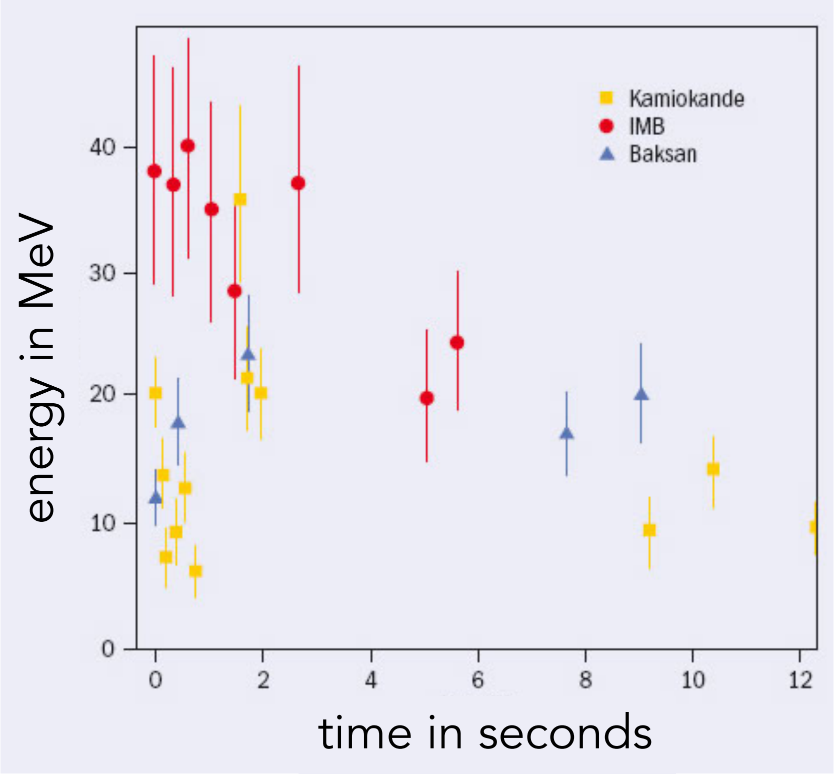
Example: supernovae

[constraints: Chang, Essig, McDermott (2018)]
[see talk by Koichi Hamaguchi after coffee]

SN 1987A

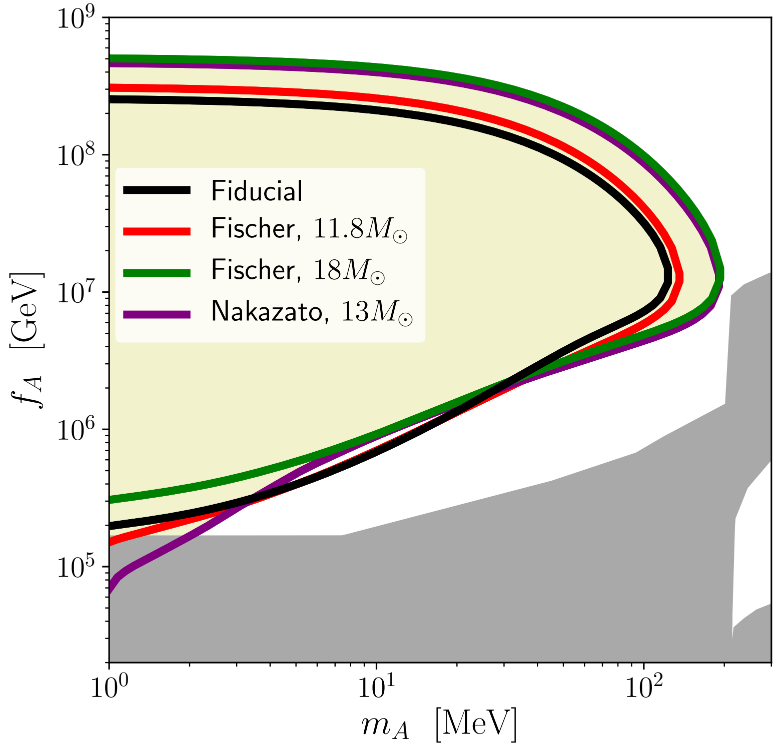


Neutrino burst

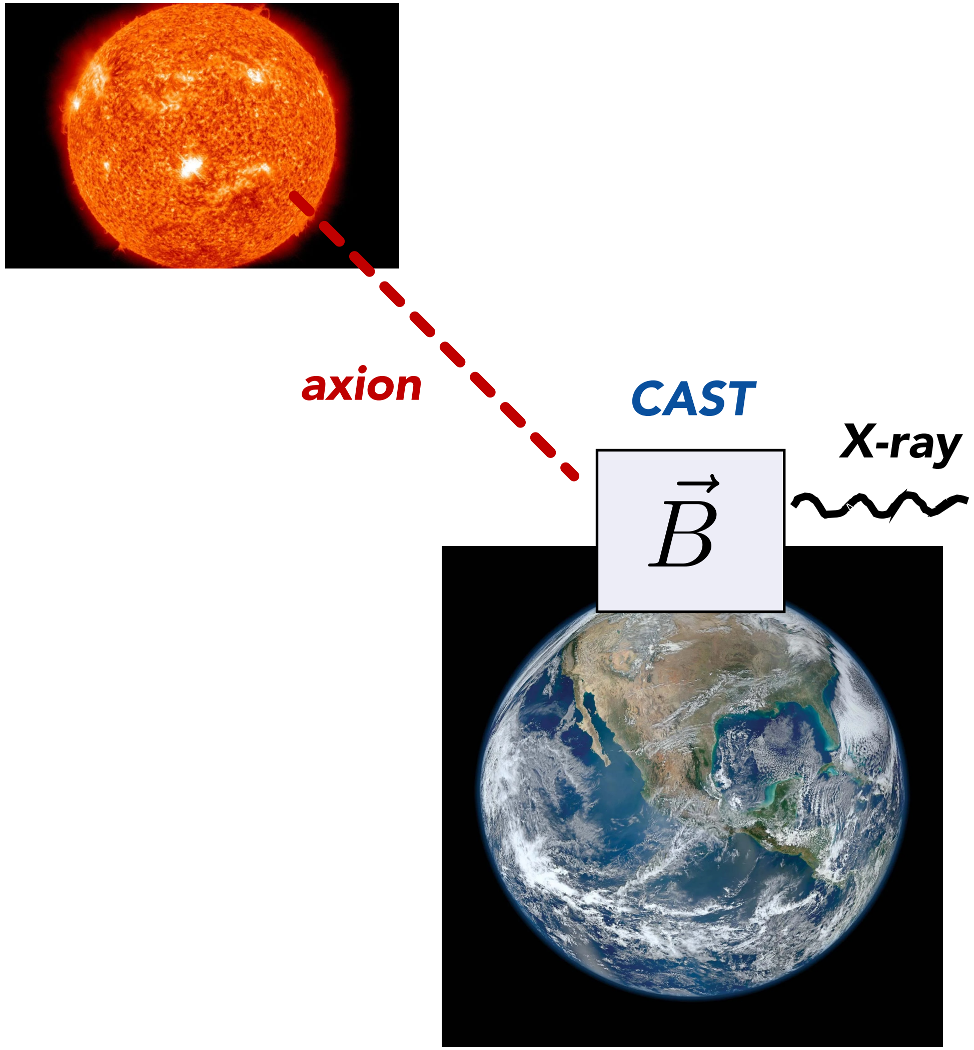


Constraints

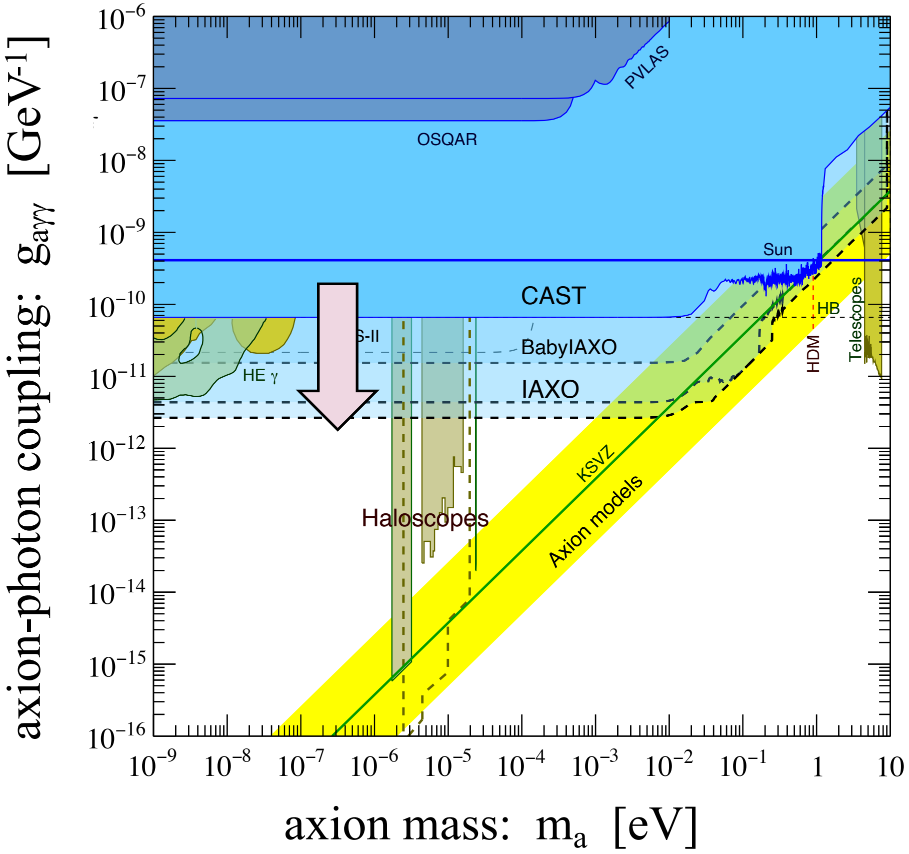
$$\dot{E}_{\rm axion} \lesssim 5 \times 10^{52}\ {\rm erg/sec}$$



Searching for axions from our Sun

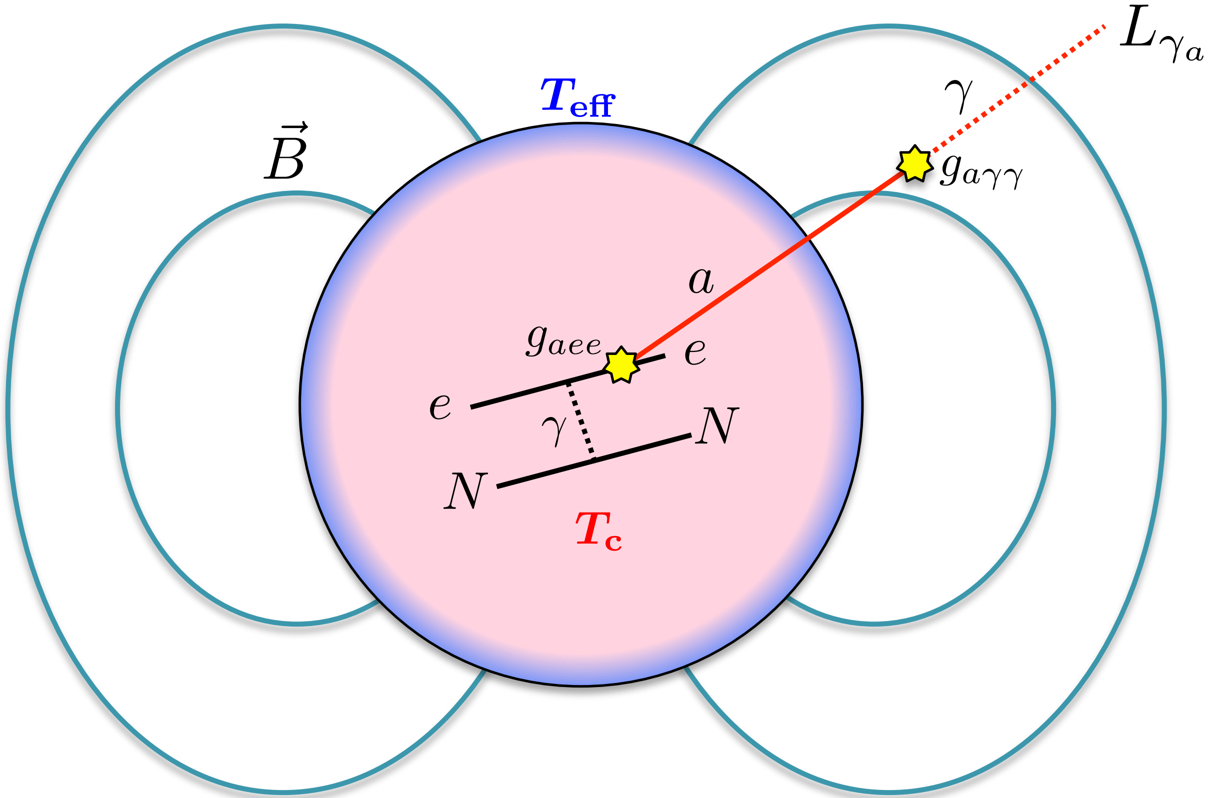


Helioscopes



Axion-photon conversion at the star

[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

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

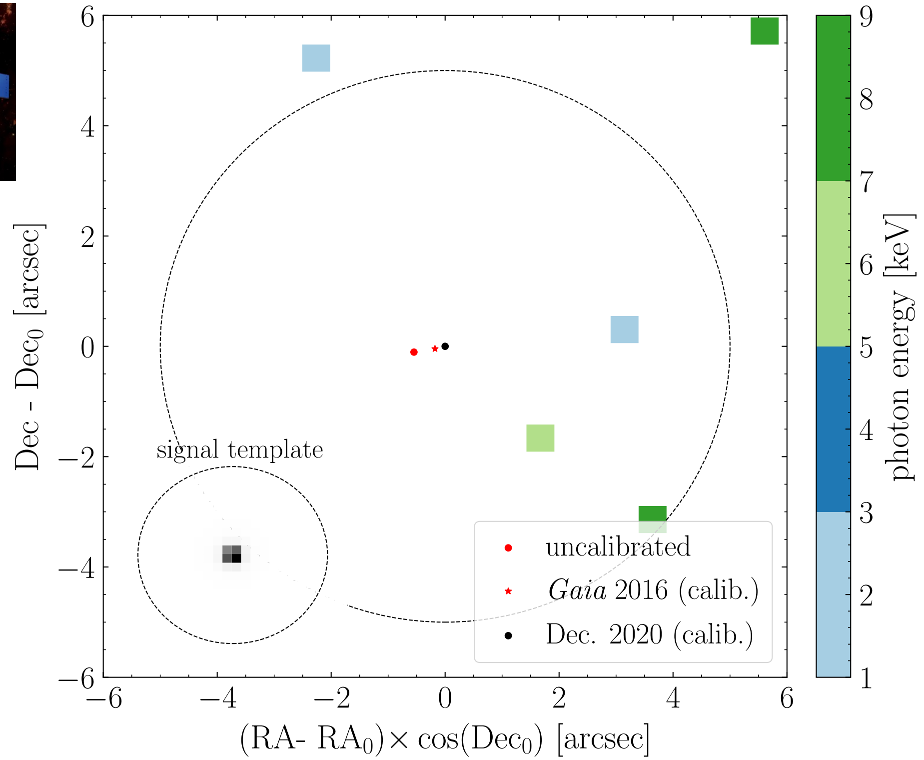
signal = thermal X-ray emission (T_{core} ~ 10^7 K ~ keV)
background = surface emission negligible ($T_{surface}$ ~ 10^4 K)

Searching for X-rays from Magnetic White Dwarfs

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

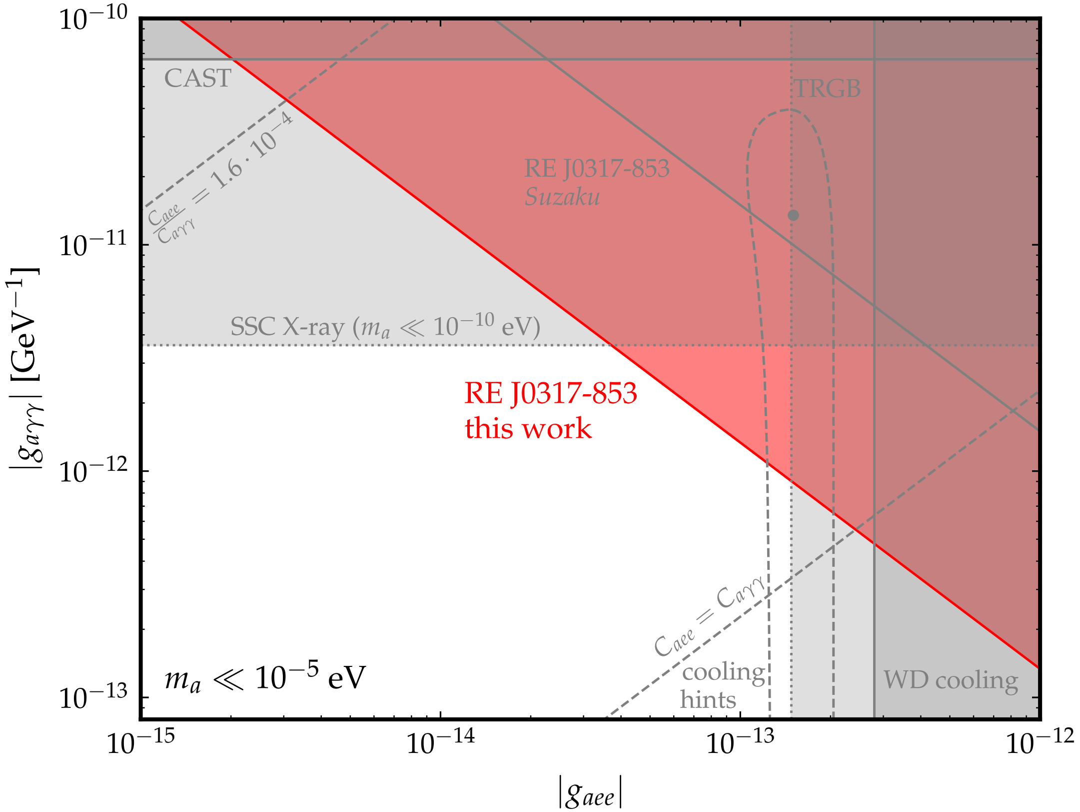
Chandra observation

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



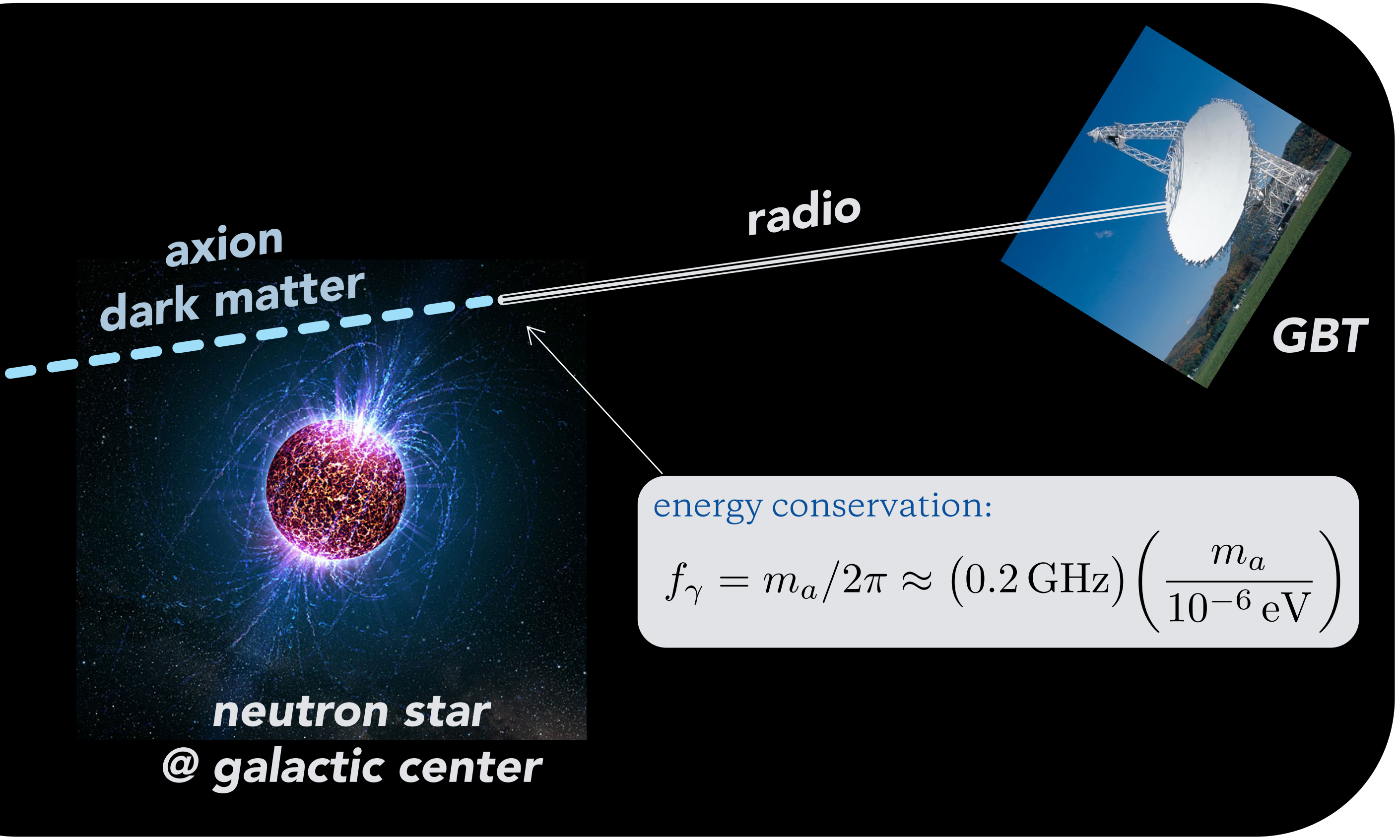
Constraints on axion emission / X-ray conversion

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



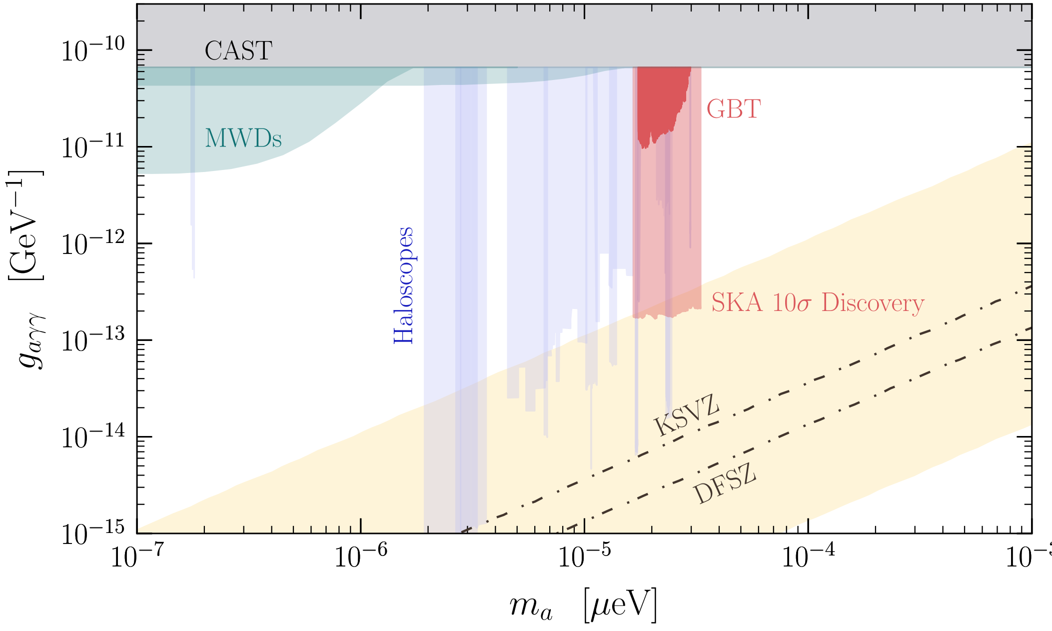
Radio from the galactic center probes axion dark matter

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



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

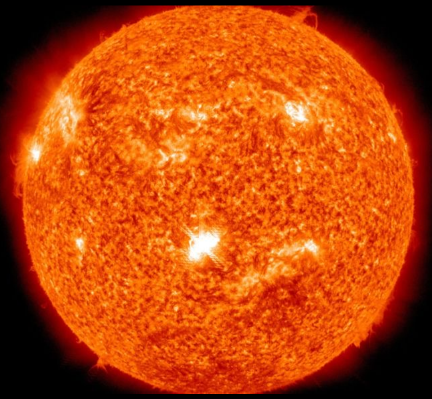
constraints derived from an analysis of archival Green Bank Telescope data

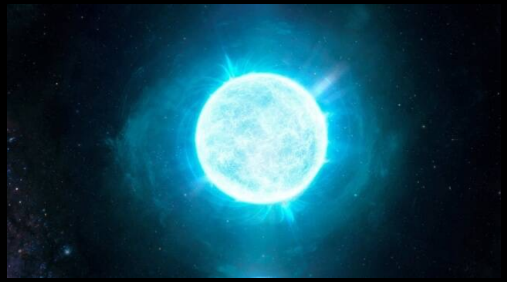


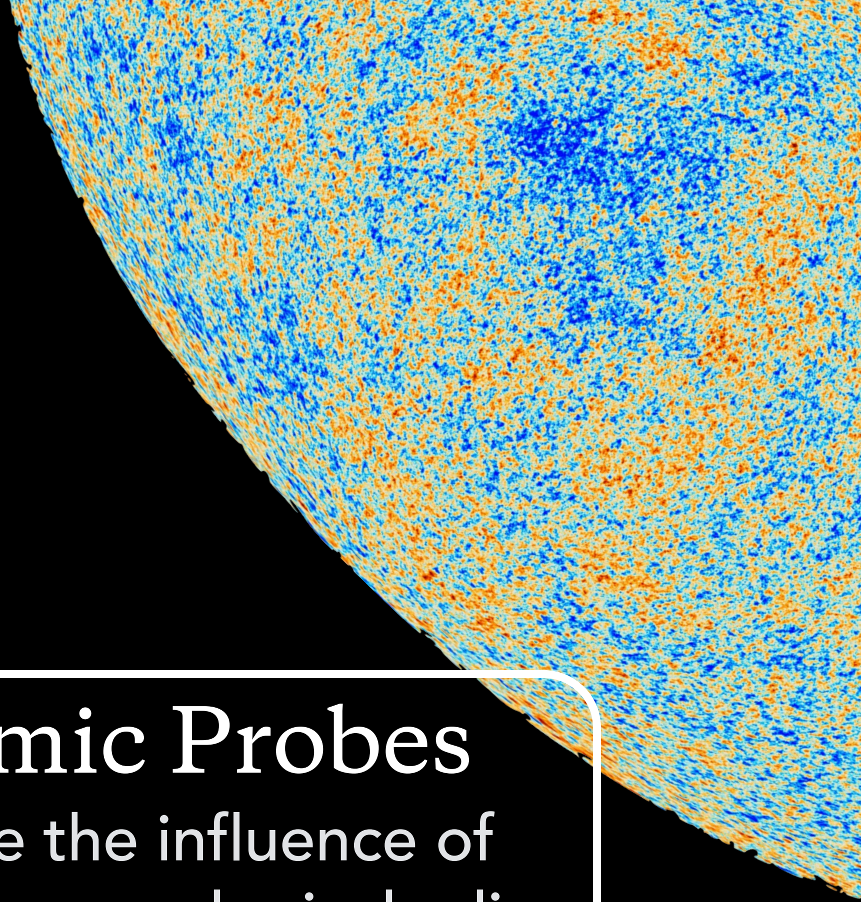
Astrophysical Probes

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

see Ranjan Laha's talk this afternoon for GWs







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

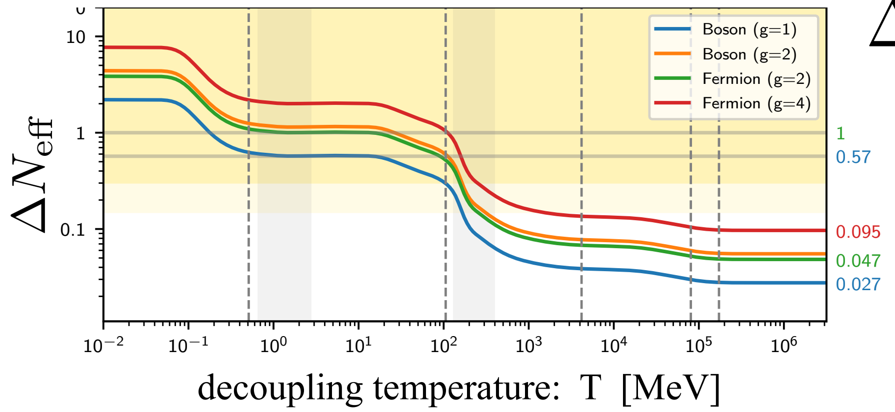
Axion dark radiation influence on CMB

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

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

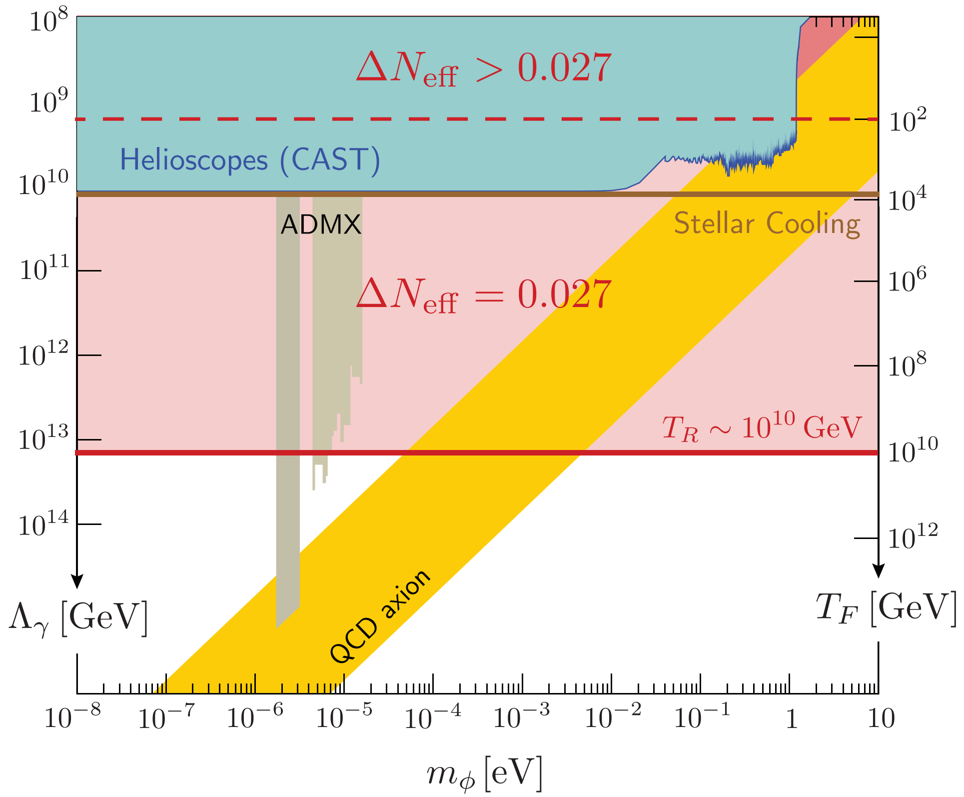
$$\Delta N_{\mathrm{eff}} \approx \frac{\rho_{\mathrm{dark}}}{\rho_{one\ \nu}} \lesssim 0.3 \quad \text{(Planck 2018)}$$

For thermalized axions we expect:



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

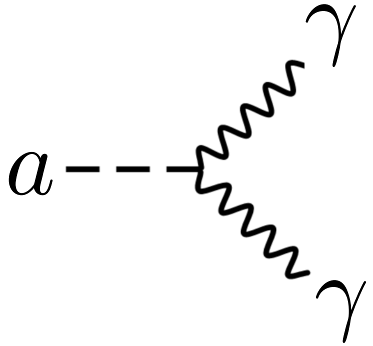
testable parameter space



Decaying axion radiation & BBN

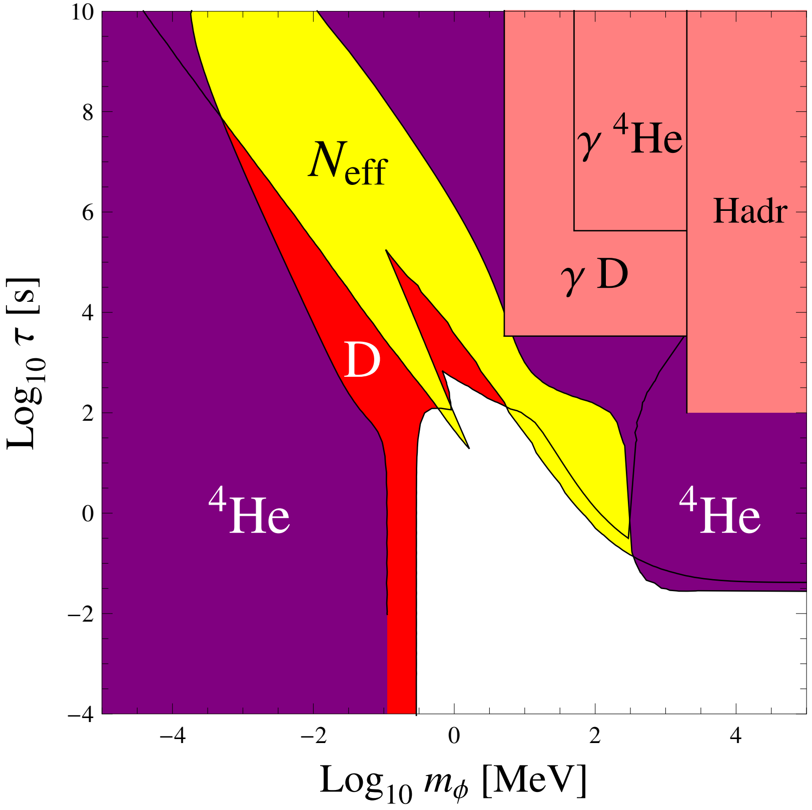
[Cadamuro & Redondo (2011)]

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.



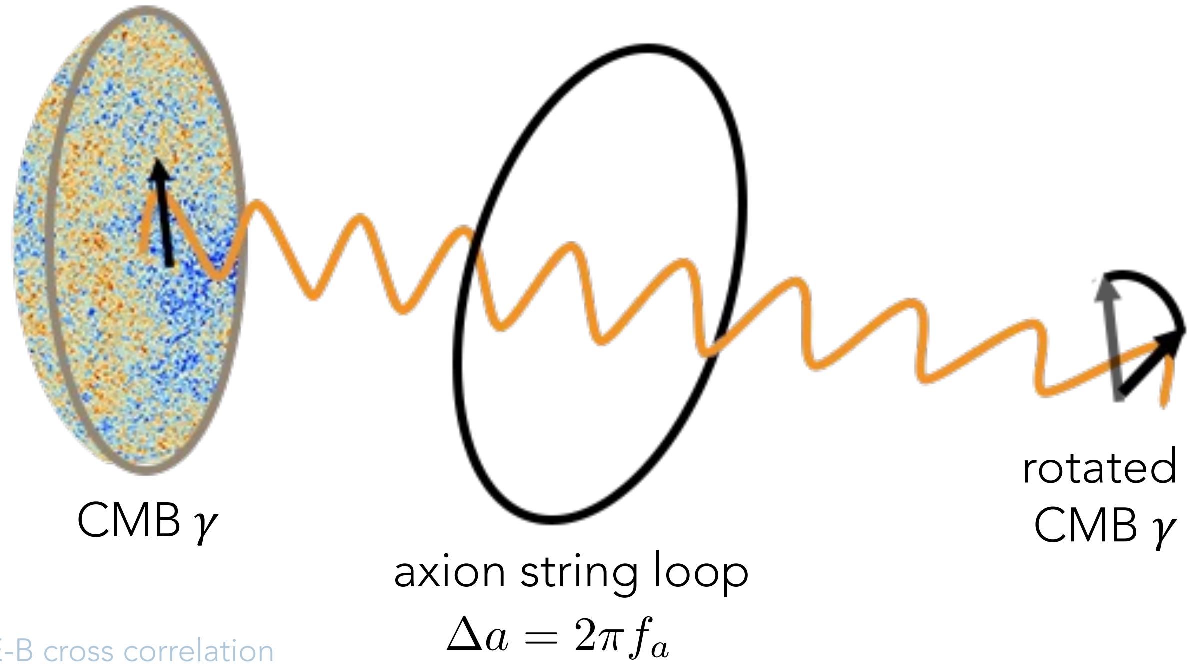
Axions in the foreground lead to birefringence

[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

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

axion-induced birefringence:
an electromagnetic wave
traveling through a varying axion field
has its plane of polarization rotated



rotation angle

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

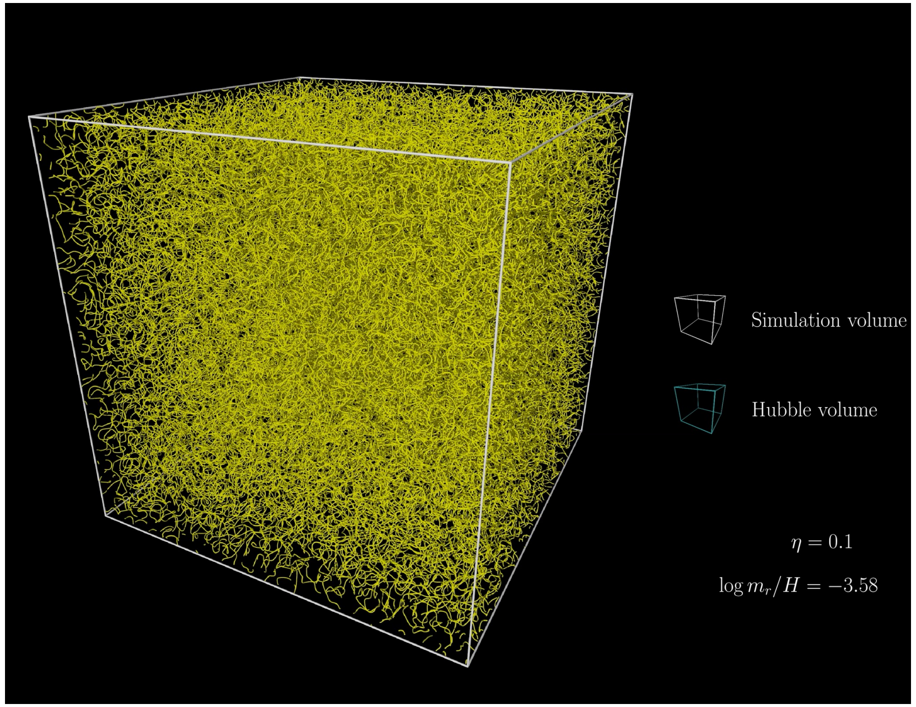
* birefringence can be measured through E-B cross correlation

Birefringence from an axion string network

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

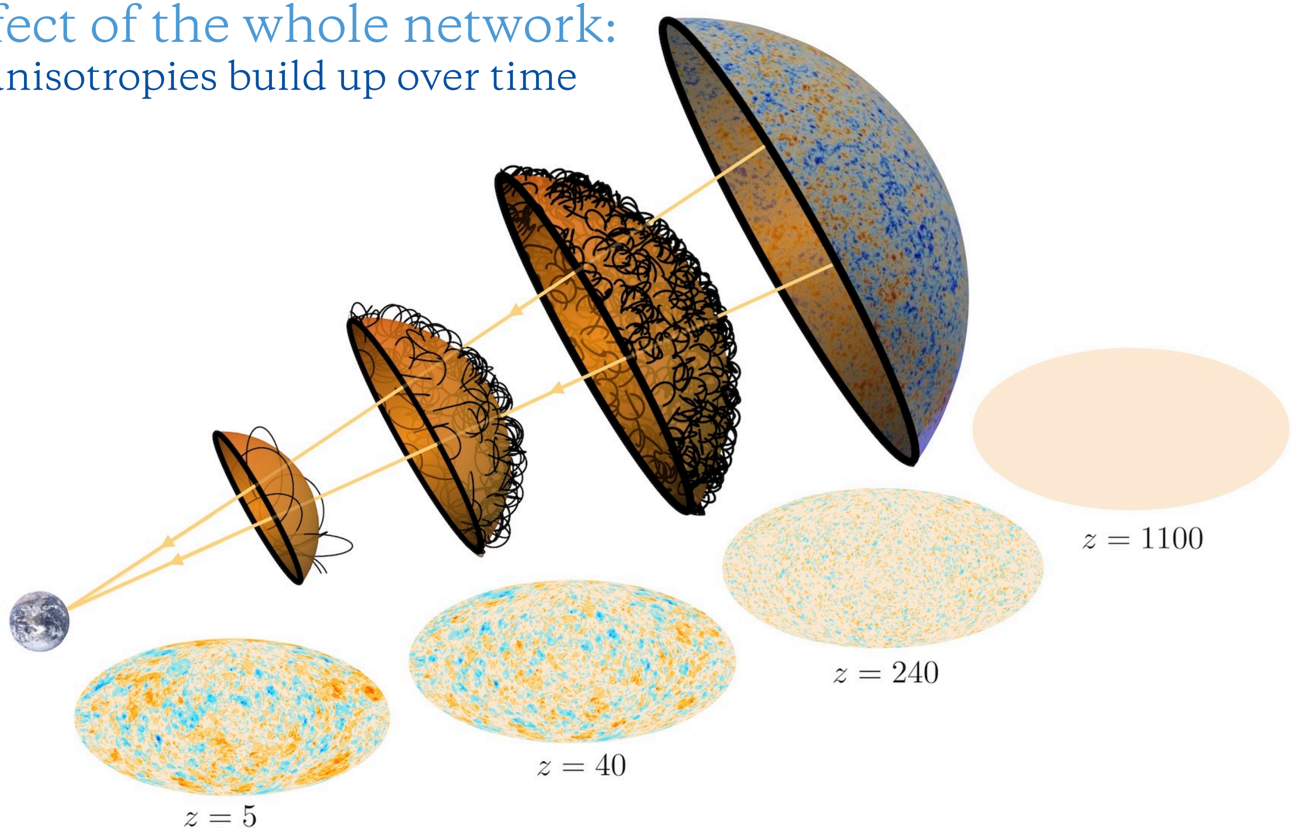
axions can form cosmic strings

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

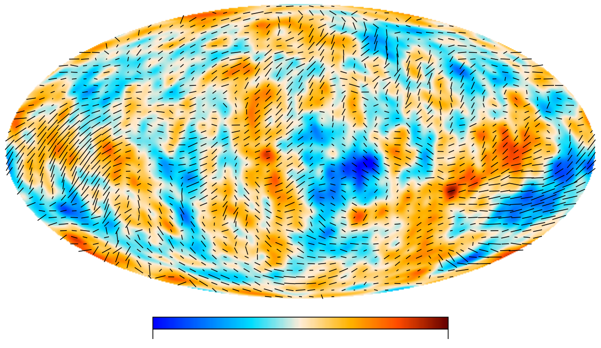
Effect on CMB polarization

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

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

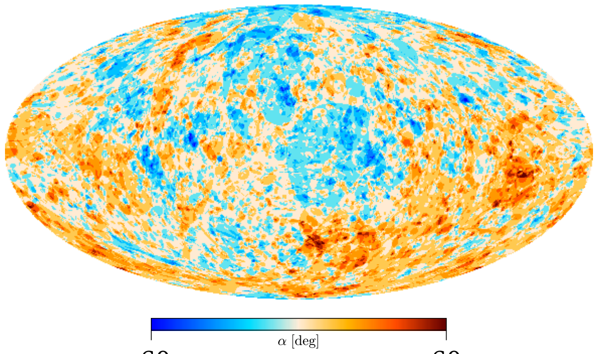
$$[Q \pm iU](\hat{\boldsymbol{n}}) \to [(Q \pm iU)e^{\pm 2i\Delta\Phi}](\hat{\boldsymbol{n}})$$

primordial CMB sky



+

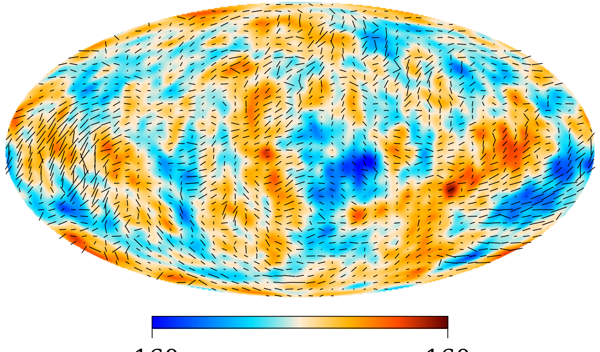
axion string -induced birefringence angle



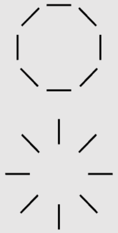
(exaggerated by ~30x)

=

Planck's CMB sky

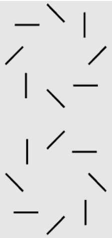


$E-mode$ pol pattern



→

$B-mode$ pol pattern



Signal of axion string-induced cosmological birefringence

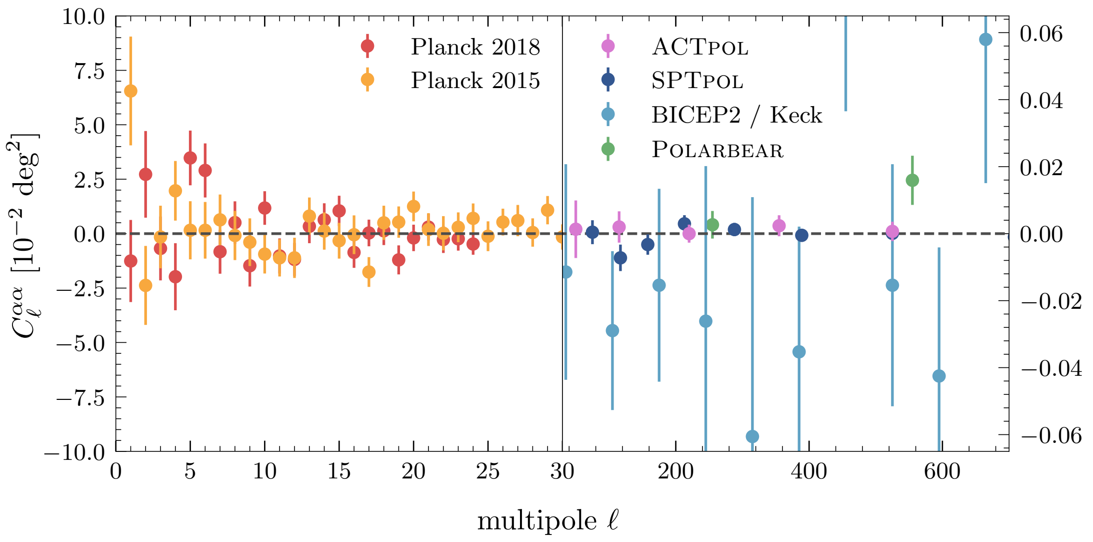
$$\begin{cases} \langle TB \rangle \neq 0 \\ \langle EB \rangle \neq 0 \end{cases}$$

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

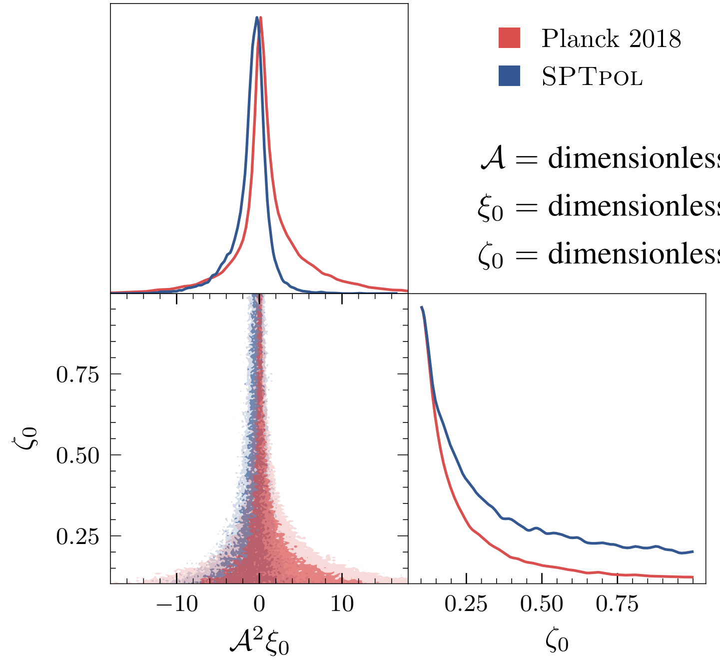
Constraints on axion string networks

[Jain, Hagimoto, AL, Amin]

measurements of CMB polarization:
no evidence for anisotropic birefringence

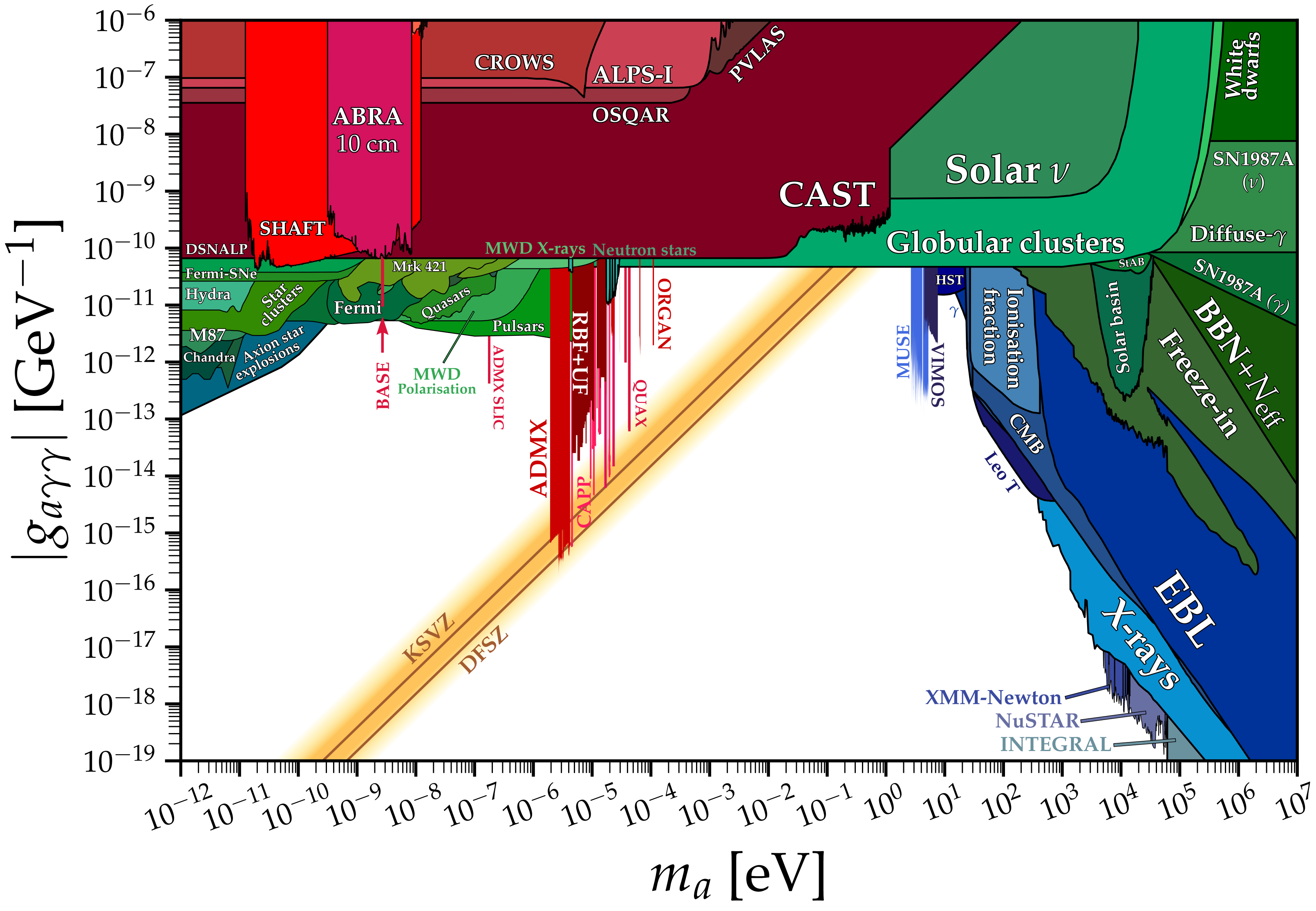


a constraint on axion strings networks & their coupling to electromagnetism:



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

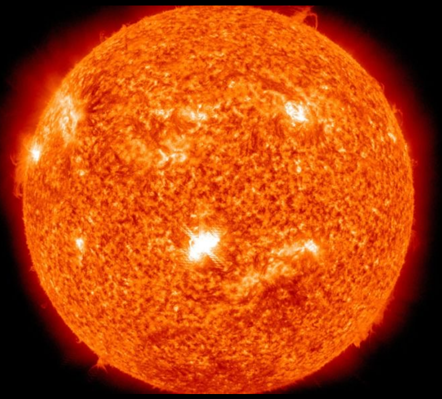
Big Picture

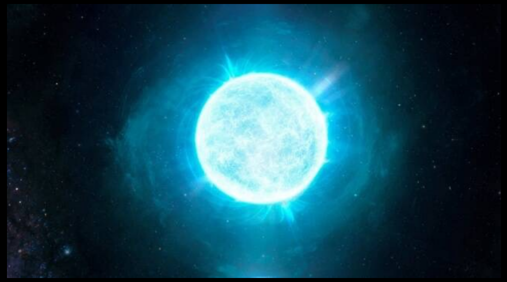


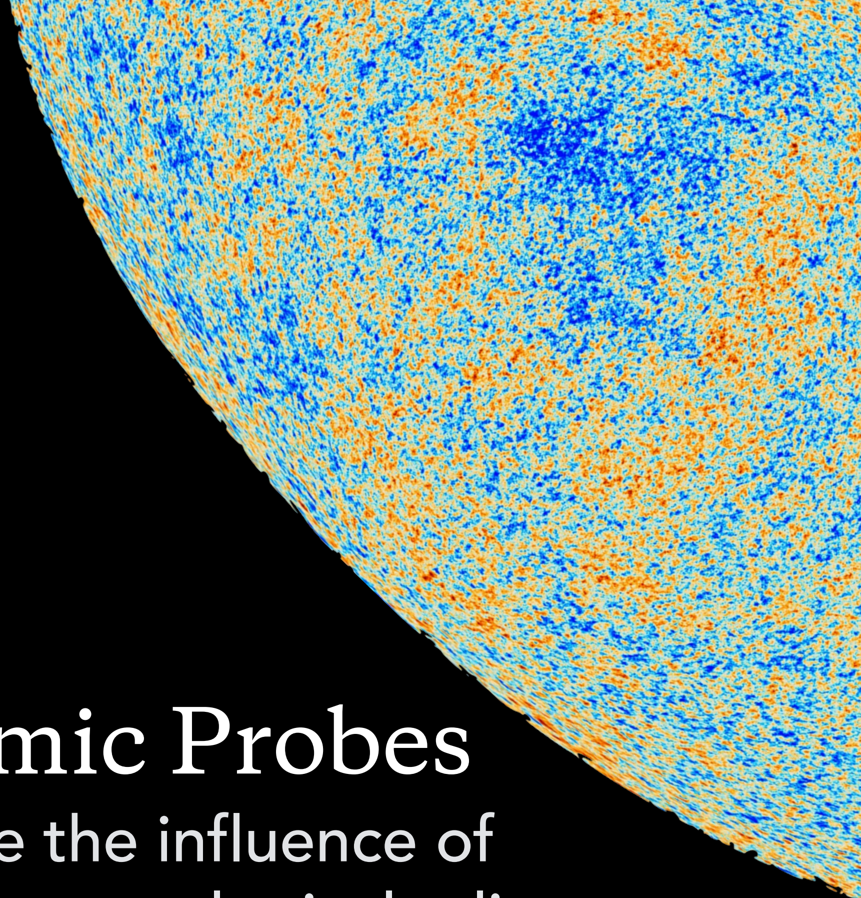
CROWS
ALPS-I
PVLAS
OSQAR
ABRA
10 cm
SHAFT
DSNALP
CAST
Solar ν
White dwarfs
SN1987A (ν)
Diffuse-γ
Globular clusters
MWD X-rays
Neutron stars
Mrk 421
Fermi-SNe
Hydra
Star clusters
Fermi
Quasars
Pulsars
M87
Chandra
Axion star explosions
BASE
MWD
Polarisation
ADMX SLIC
ADMX
RBF+UF
CAPP
QUAX
ORGAN
KSVZ
DFSZ
MUSE
VIMOS
HST
γ
Ionisation fraction
StAB
Solar basin
SN1987A (γ)
BBN+Neff
Freeze-in
CMB
Leo T
EBL
X-rays
XMM-Newton
NuSTAR
INTEGRAL
$|g_{a\gamma\gamma}|$ [GeV^{-1}]
m_a [eV]

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

I hope you've enjoyed the tour.

Cảm ơn