astrophysical and cosmological probes of axion-like particles and dark photons

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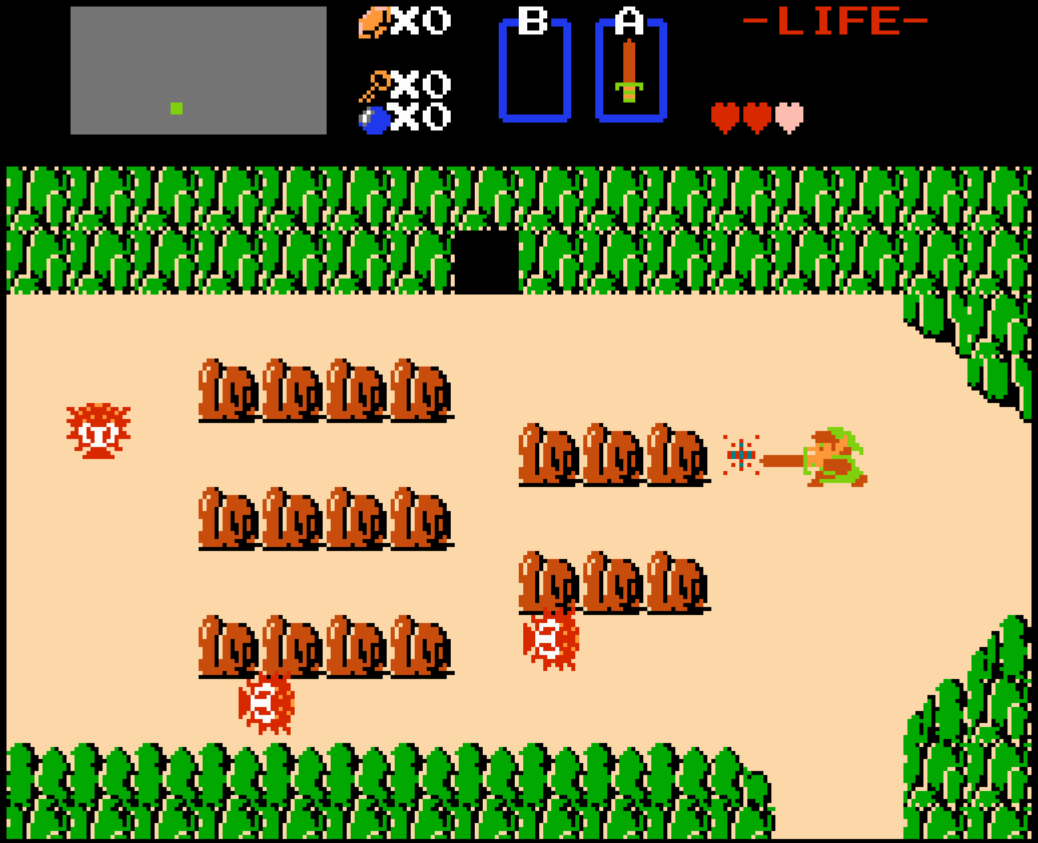
@ Phenomenology 2023 Symposium
May 9, 2023

this talk is dedicated to Susan Long (1952-2022) who always encouraged me to keep adventuring



“explore the dungeon”
“discover the treasure”

How will we discover new physics?

What dungeons must we
explore to find this treasure?

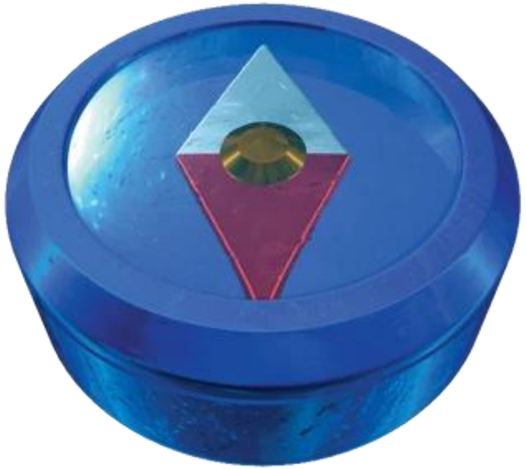
adventuring gear

a map

the maps contains clues …

the treasure is out there somewhere, we just don't know how to reach it

a compass

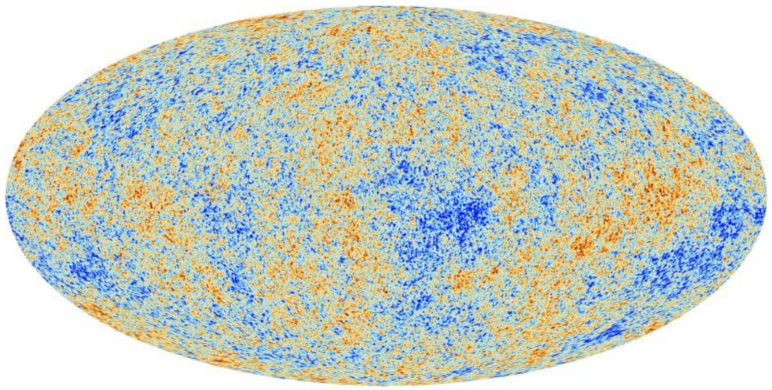


the compass guides our path …

it points the shortest way to reach the treasure

adventuring gear

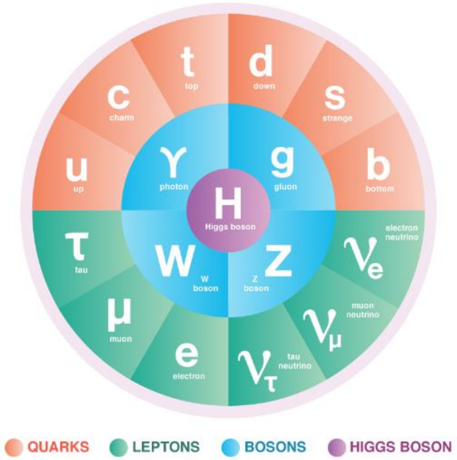
a map



the maps contains clues …

data reveals the presence of new physics, but a full understanding is still out of reach

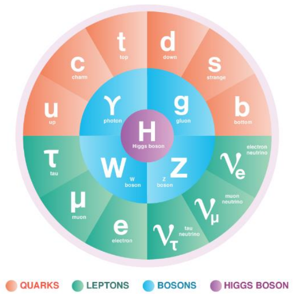
a compass



the compass guides our path …

the success of existing theory furnishes organizing principles and points a way forward

Symmetry & symmetry breaking determine the structure of the Standard Model including the properties and interactions of its particles



Let symmetry guide our search for new physics!

Standard Model

↓

chiral symmetry breaking

↓

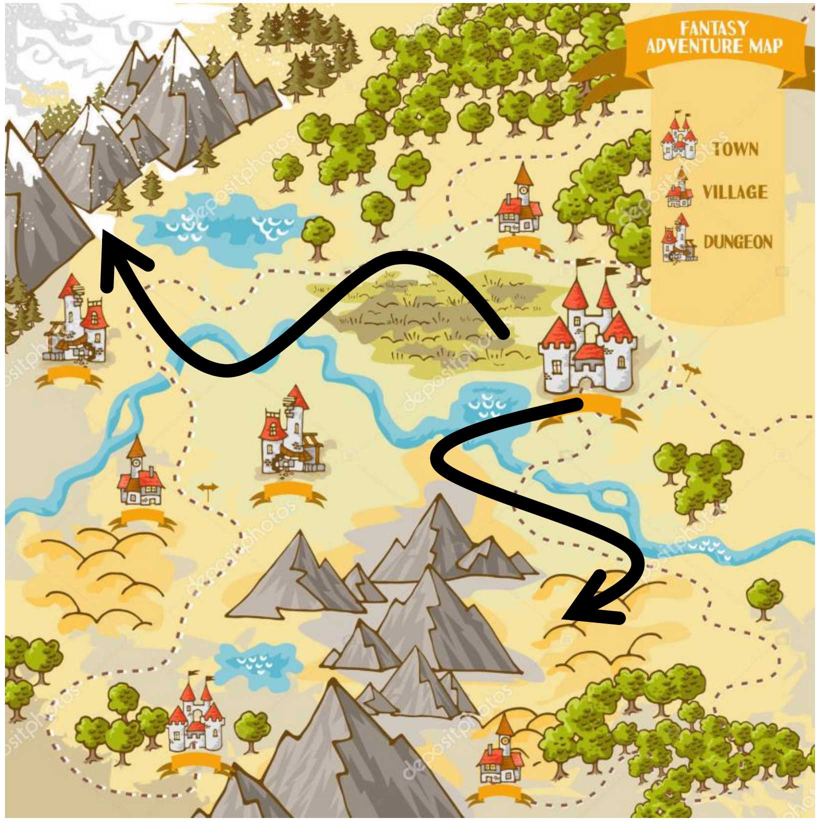
light pions

↓

light axion-like particles

↓

BSM theory



Standard Model

↓

electroweak symmetry breaking

↓

massive W/Z bosons

↓

massive hidden/dark photons

↓

BSM theory

light axion-like particles

(1) Axion-enhanced X-rays from compact stars

(2) Radio emission from axion clumps

(3) CMB birefringence from axion strings

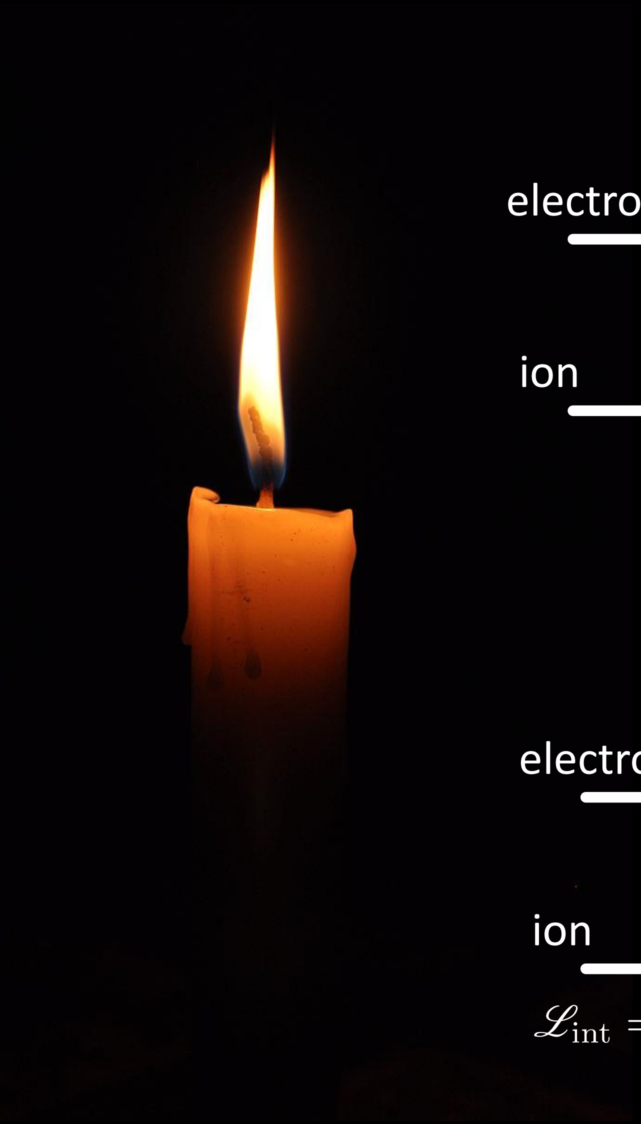
light hidden/dark photons

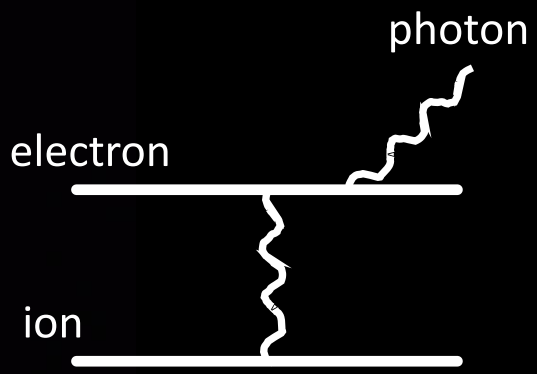
(4) Producing dark photon dark matter

(5) Radio bursts from dark photon stars

(1) Axion-enhanced X-rays from compact stars

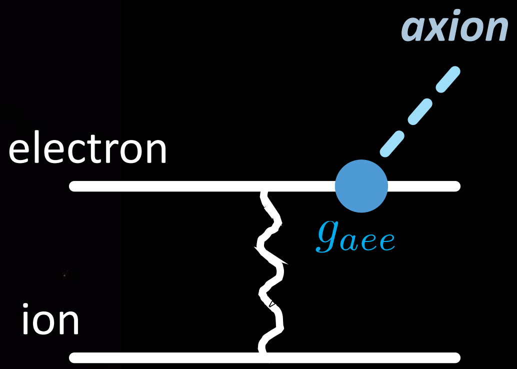
Where do axions come from?





$$P = A\sigma T^4 \approx (5\,\mathrm{Watt})\left(\frac{A}{1\,\mathrm{cm}^2}\right)\left(\frac{T}{10^3\,\mathrm{K}}\right)^4$$

$$\Rightarrow \sim 10^{19}\ \text{photons per second}$$



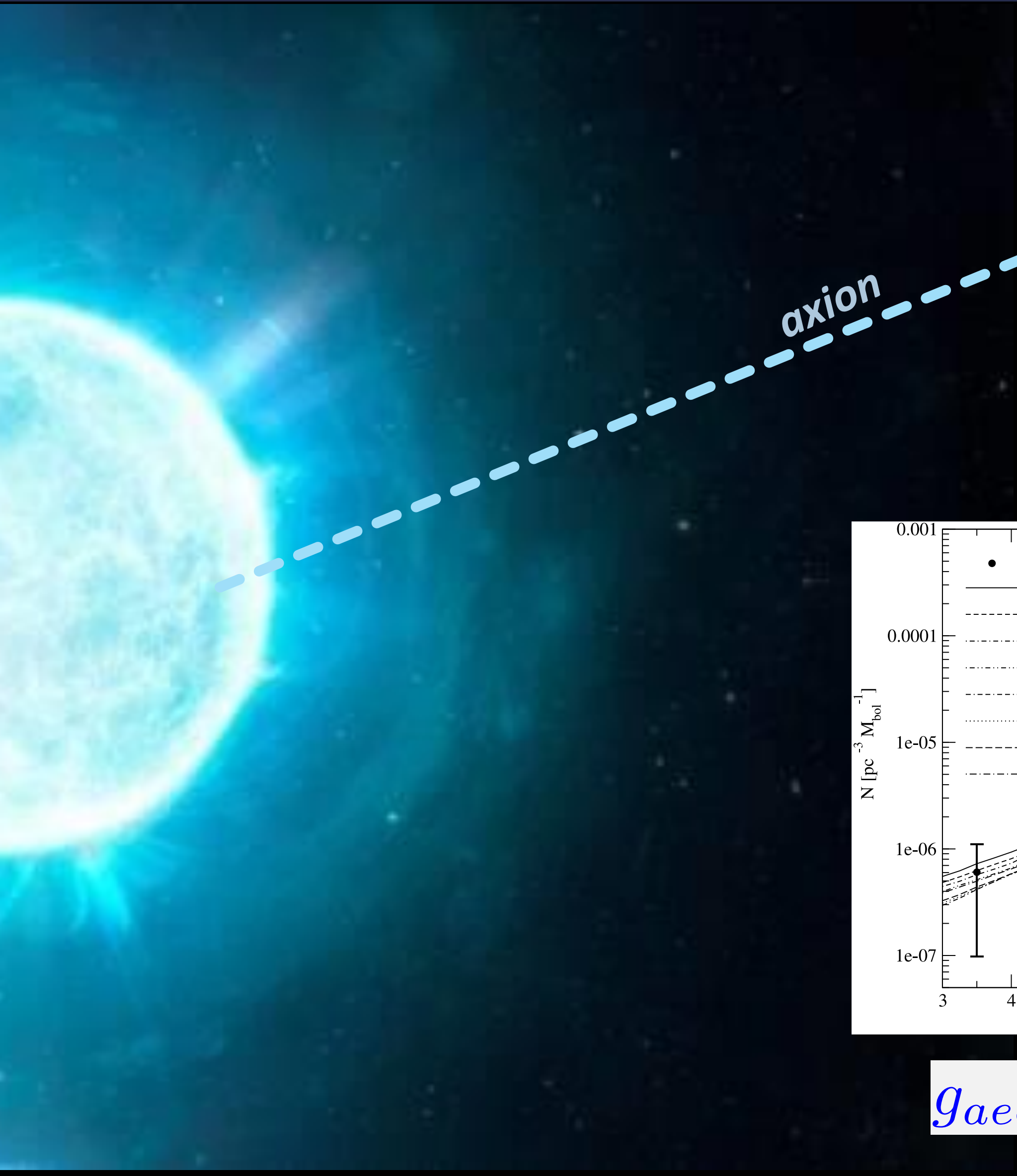
$$\mathscr{L}_{\text{int}} = g_{aee}\,\partial_\mu a\,\bar{\psi}\gamma^\mu\gamma_5\psi/2m_e$$

$$P = \frac{g_{aee}^{\ 2}}{e^2} A\sigma T^4 \approx (10^{-25}\,\mathrm{Watt})\left(\frac{g_{aee}}{10^{-13}}\right)^2$$

$$\Rightarrow \sim 10^{-6}\ \text{axions per second}$$

not a lot of axions!

Where can we find a stronger source of ALPs?



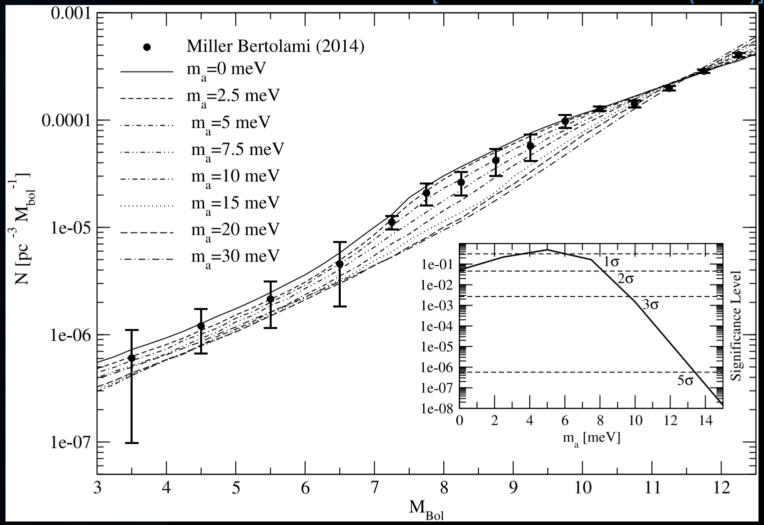
[Krauss, Moody, & Wilczek (1984)] [Raffelt (1986)]
[Nakagawa, Adachi, Kohyama, & Itoh (1987,88)]

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

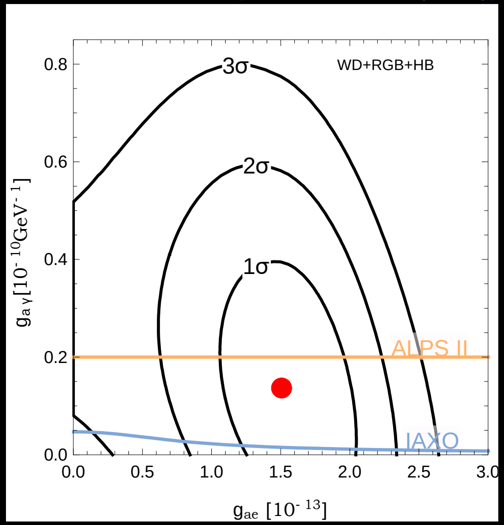
[Miller Bertolami et. al. (2014)]



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

hints

[Giannotti et. al. (2017)]

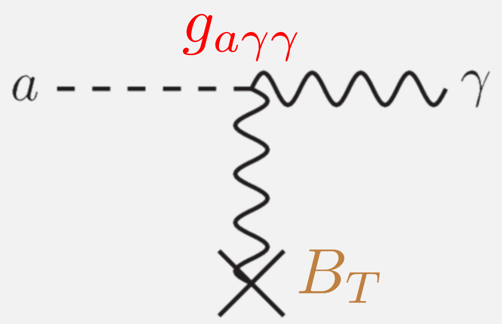


$$g_{aee} \neq 0 \quad (\sim 2\sigma)$$

How to test that ALPs cause cooling?

axion

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



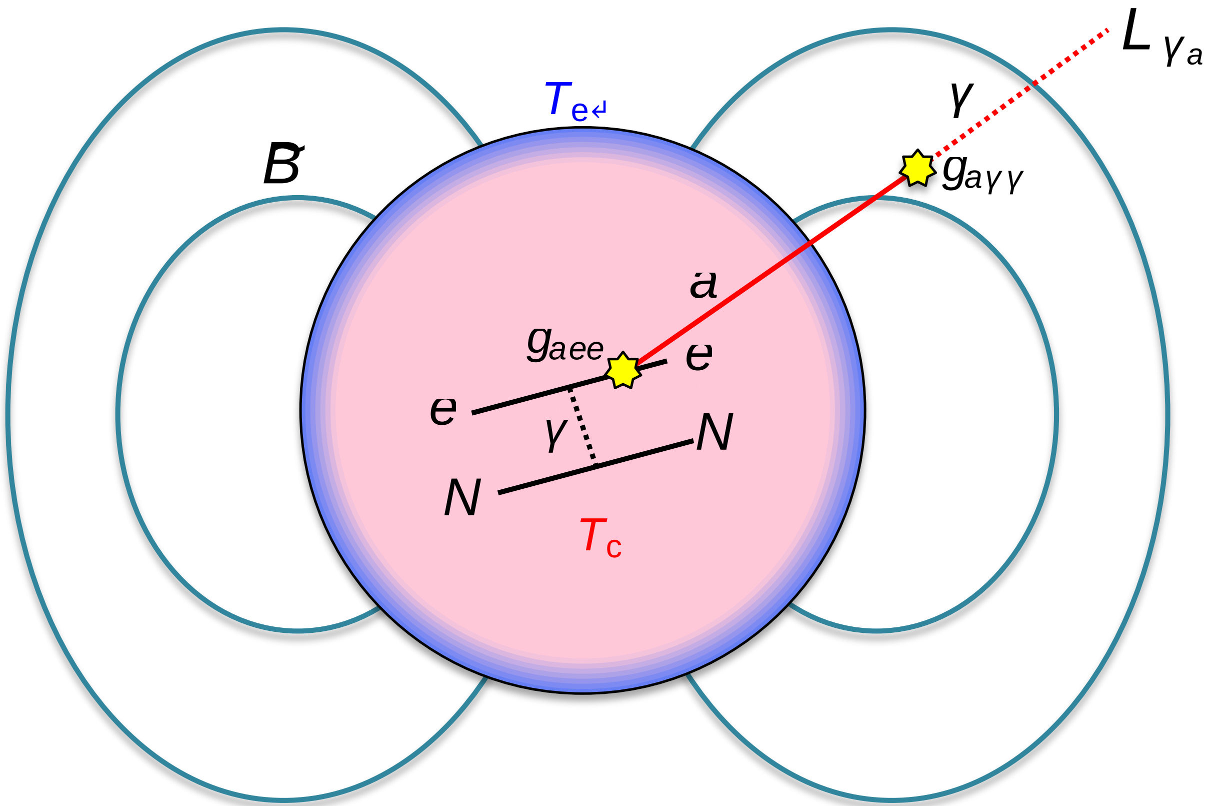
$$p_{a\to\gamma} \approx g_{a\gamma\gamma}^2 B_T^2 L^2 / 4$$

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

we can’t wait till the axions reach Earth!

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): $\sim 10^{12} - 10^{15}$ G
- ➔ Magnetic white dwarfs: $\sim 10^{6} - 10^{9}$ 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

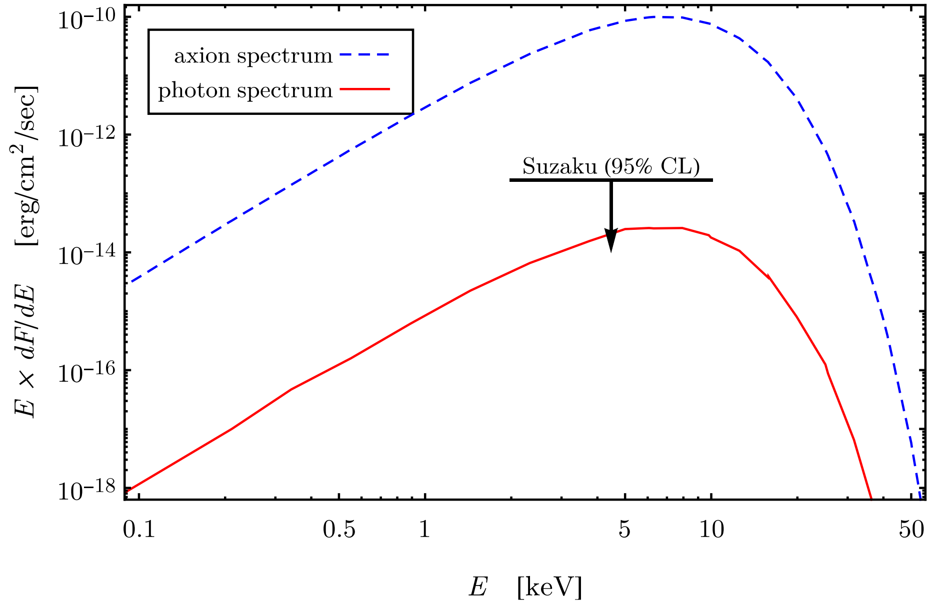
$$E_a = T_{\text{core}} = E_\gamma = \text{X-ray}$$

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



$g_{aee} = 10^{-13}$
$g_{a\gamma\gamma} = 10^{-11}$ 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 MWD 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

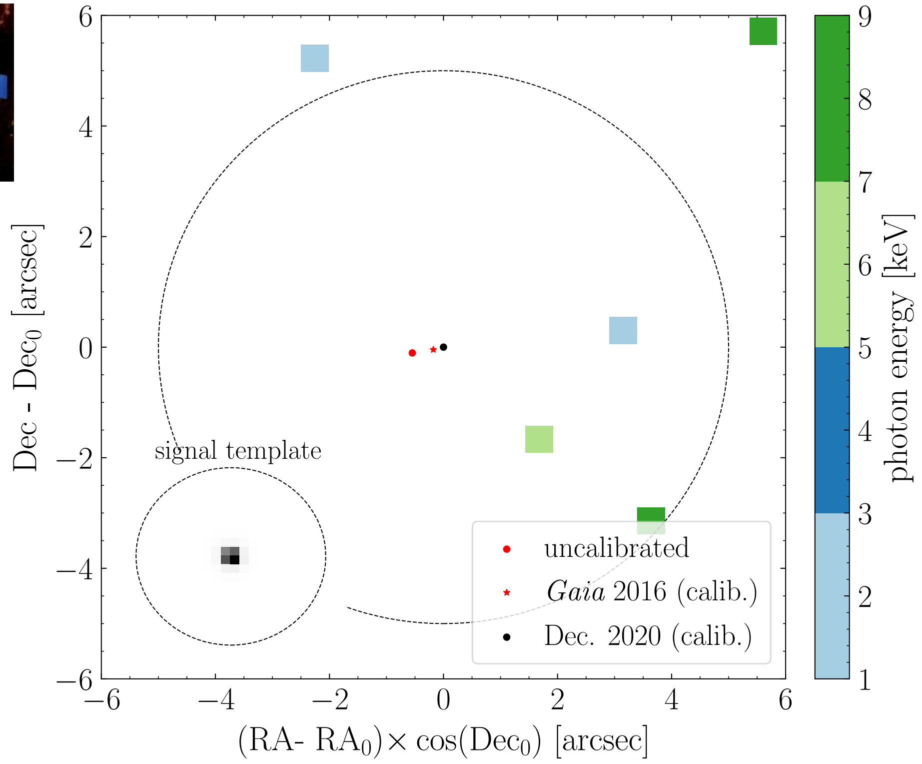
(for $m_a = 10^{-9}$ eV and $|g_{aee}\, g_{a\gamma\gamma}| = 10^{-24}$ GeV^{-1})

What do we learn from Chandra observations?

[Dessert, AL, Safdi, arXiv:2104.12772]

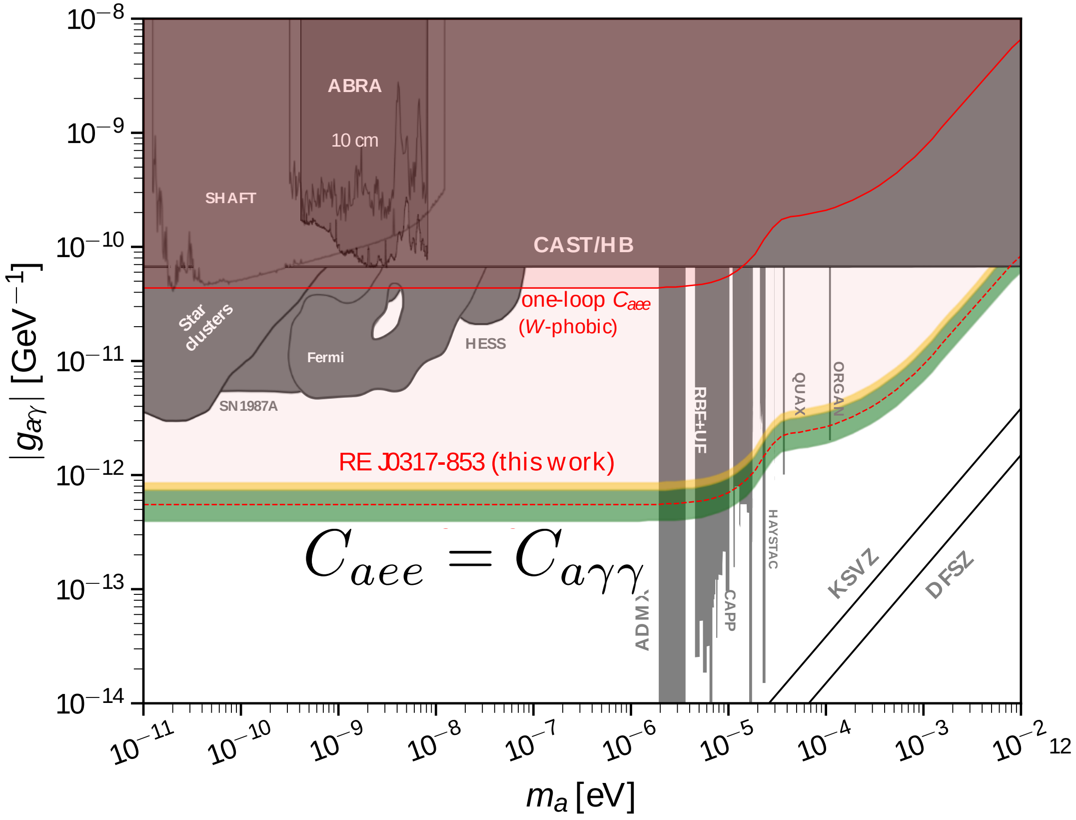
Chandra observation

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



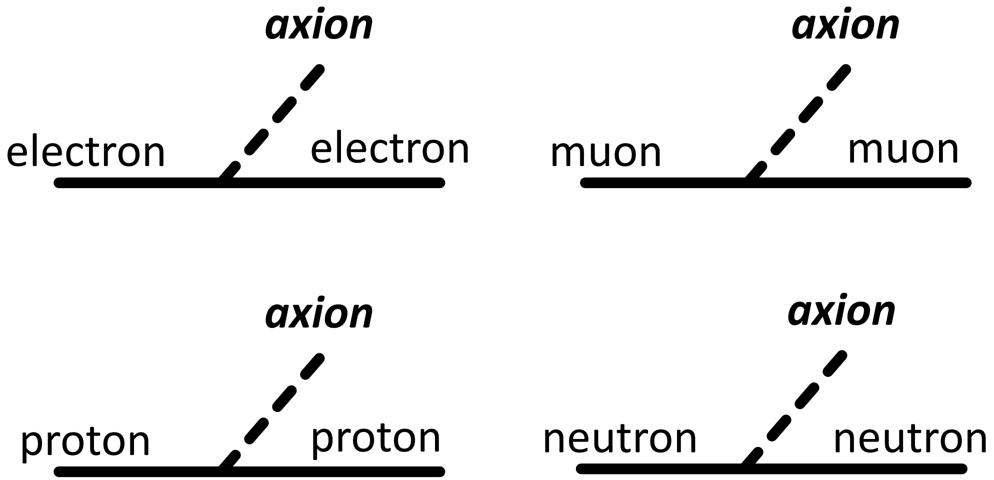
Constraints on axion emission / X-ray conversion

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



ALP emission from exotic couplings (ongoing work)

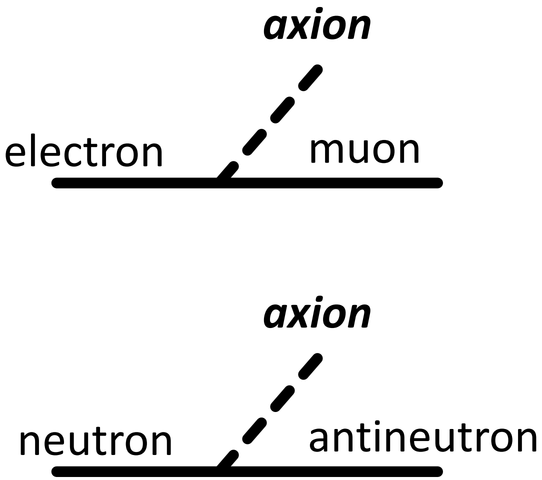
standard axion couplings



exotic axion couplings

LFV:

BNV:



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

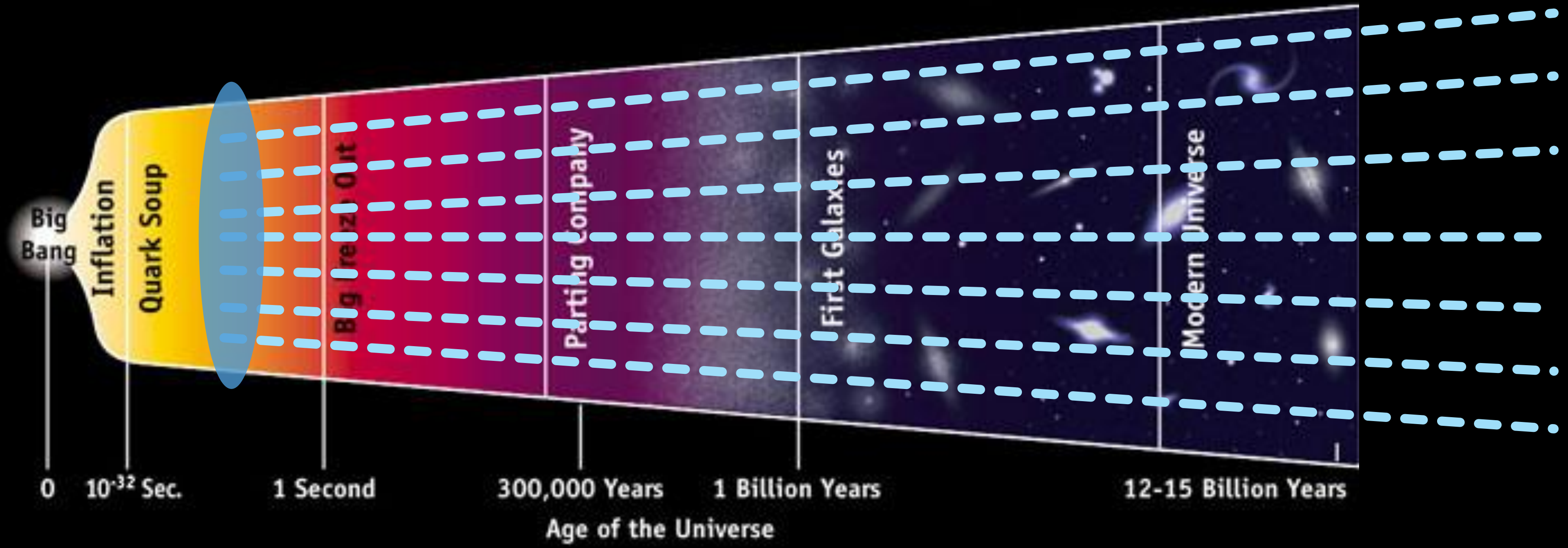
Hong-Yi Zhang
(Rice U grad)

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

(2) Radio emission from axion clumps

Axion-like particles as dark matter

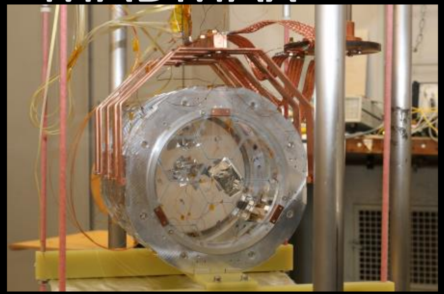


axion dark matter

ADMX

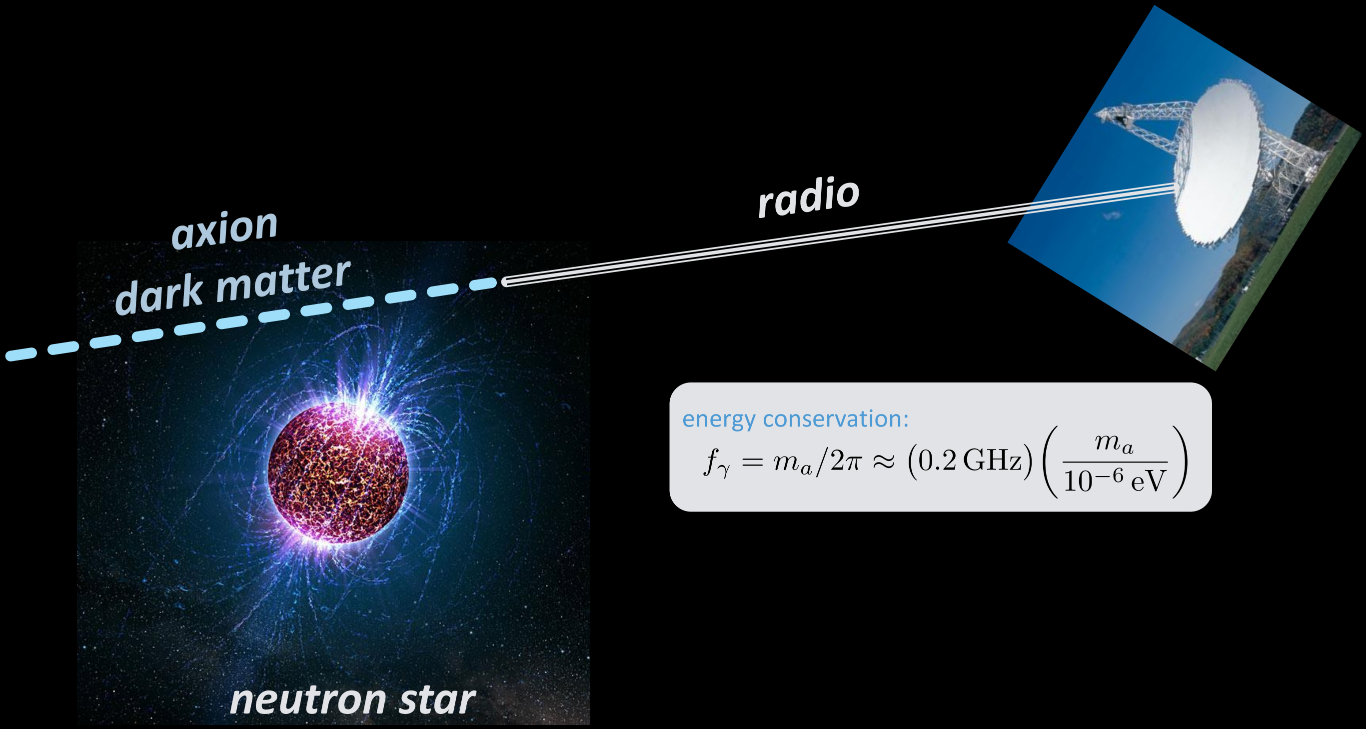
Abra

MADMAX



Conversion in neutron star magnetospheres

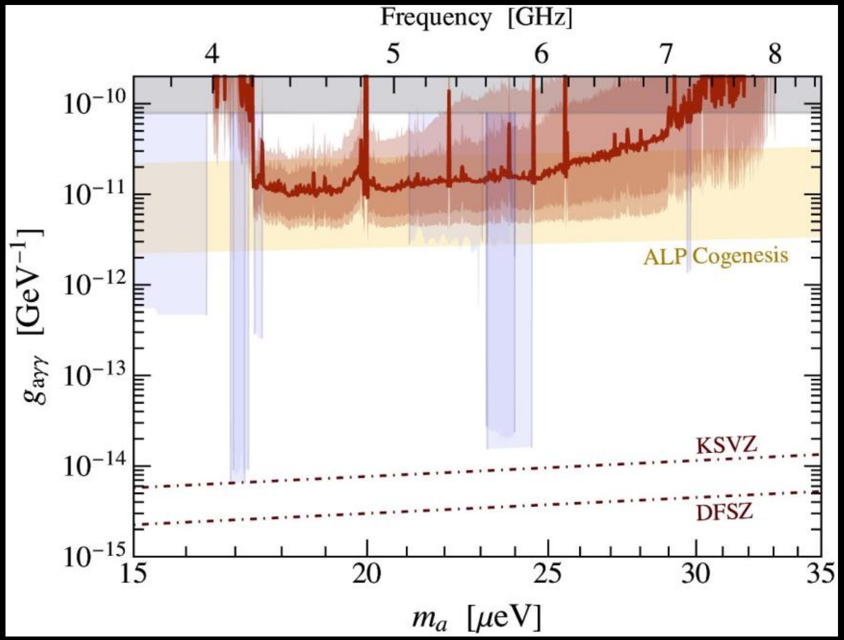
[Hook, Kahn, Safdi, Sun (2018)], [Safdi, Sun, Chen (2018)], [Foster et al (2022)]



energy conservation:

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

constraints derived from an analysis of archival Greenbank Telescope data



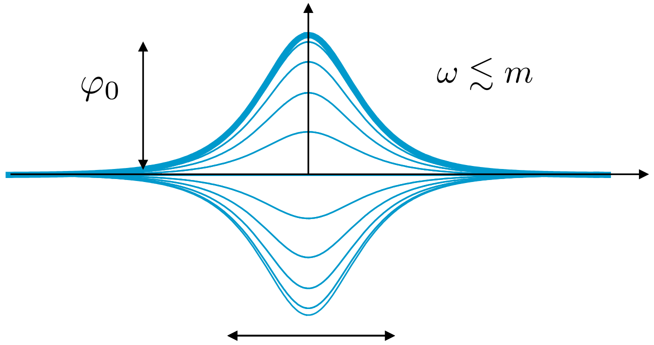
What if the axion DM is clumped up?

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

dense axion star:

a coherent "clump" of axion dark matter

$$\phi(t,r) \approx \varphi(r)\cos\omega t$$



$$R \approx m^{-1} \simeq (10\,\mathrm{cm})\left(\frac{m}{10^{-6}\,\mathrm{eV}}\right)^{-1}$$

coupling to electromagnetism:

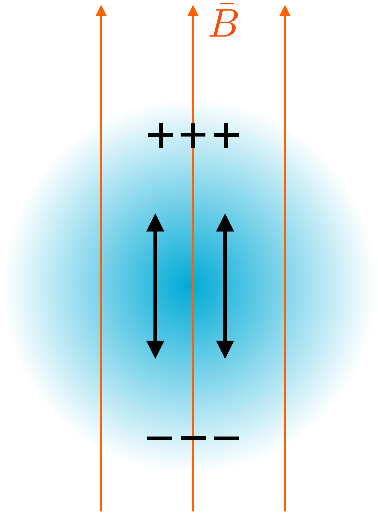
new terms in Maxwell's equations

$$\mathscr{L}_{\rm int} = -\tfrac{1}{4} g_{a\gamma}\phi F\tilde{F} \quad \begin{cases} \ddot{\phi} - \nabla^2\phi + \partial_\phi V = g_{a\gamma}\boldsymbol{E}\cdot\boldsymbol{B}\,, \\ \dot{\boldsymbol{E}} = \nabla\times\boldsymbol{B} - g_{a\gamma}\left(\dot{\phi}\boldsymbol{B} + \nabla\phi\times\boldsymbol{E}\right)\,, \\ \dot{\boldsymbol{B}} = -\nabla\times\boldsymbol{E}\,, \\ \nabla\cdot\boldsymbol{E} = -g_{a\gamma}\nabla\phi\cdot\boldsymbol{B}\,, \\ \nabla\cdot\boldsymbol{B} = 0\,. \end{cases}$$

effective current density

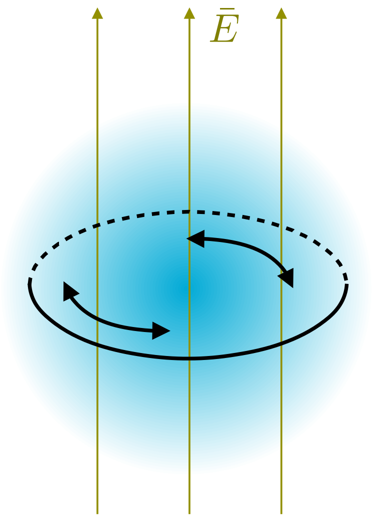
effective charge density

background magnetic field



induced electric dipole

background electric field



induced magnetic dipole

a source of EM radiation!

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

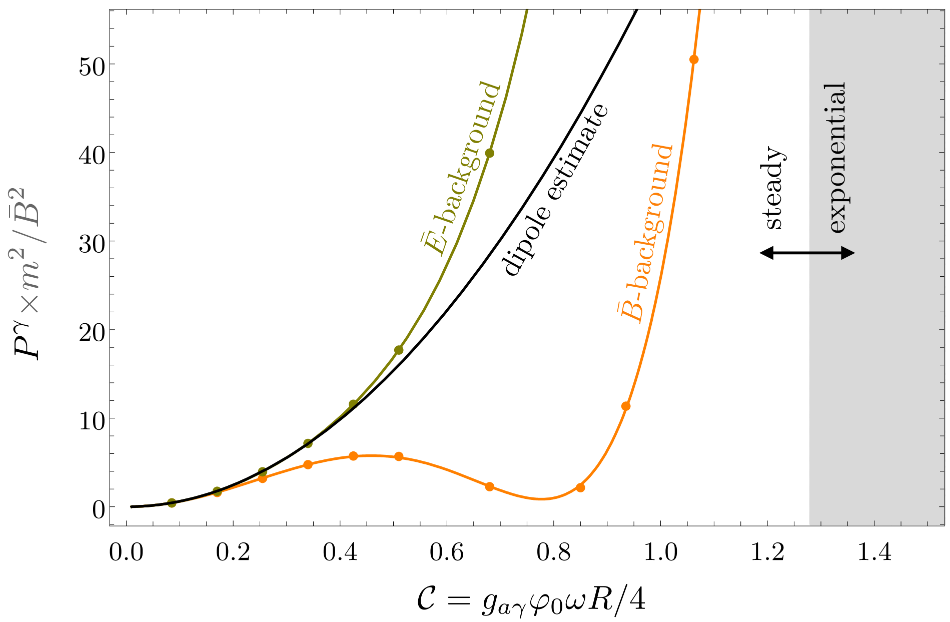
lattice simulation:

radiation from clump in external B/E fields

shading shows intensity of EM field

EM power radiated:

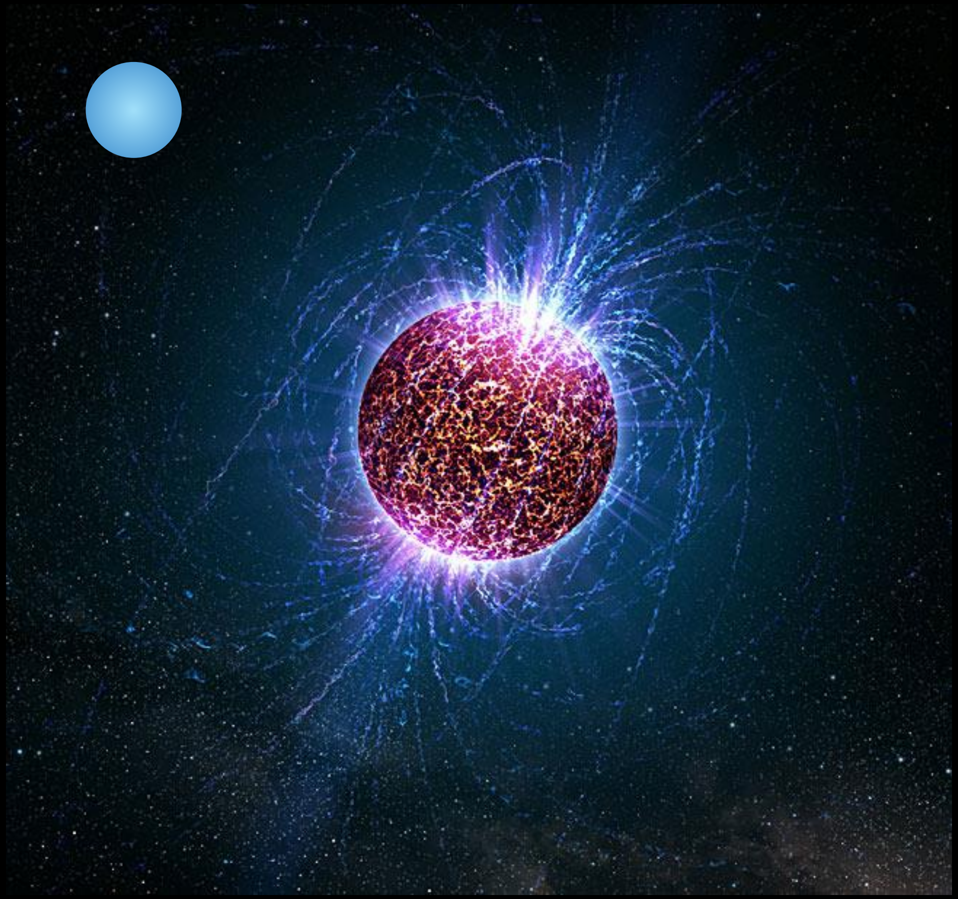
departure from dipole approx. at larger coupling



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

Zong-Gang Mou
(Rice U postdoc)

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

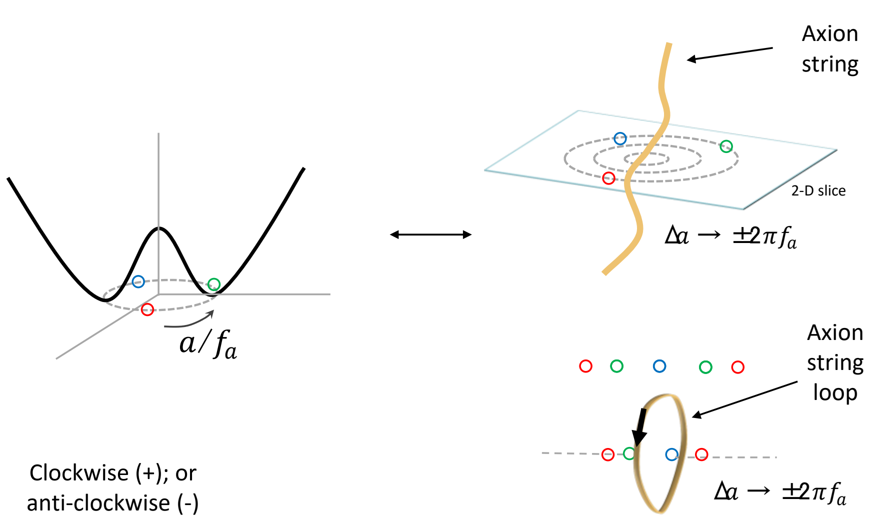
(3) CMB birefringence from axion strings

How do axions make strings?

[Buschmann et. al. (2022)]

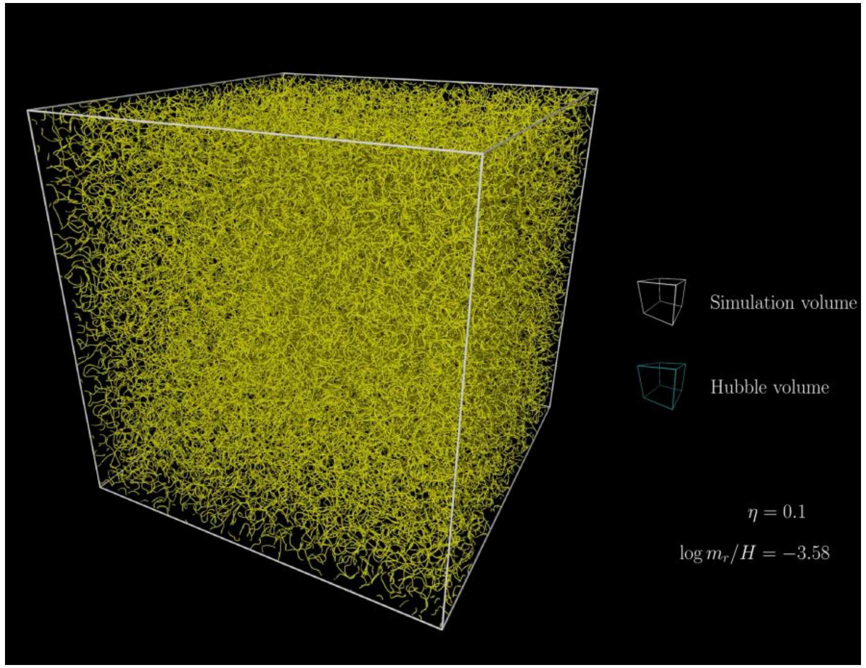
string formation:

early-universe phase transition



[graphic thanks to Mudit Jain (2021)]

string network simulation:



- string network is in scaling
- new loops are formed from reconnection
- loops emit axions and collapse
- typical string length tracks Hubble
- average energy density tracks Hubble

How can we detect axion strings in the Universe today?

How could we detect an axion string?

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

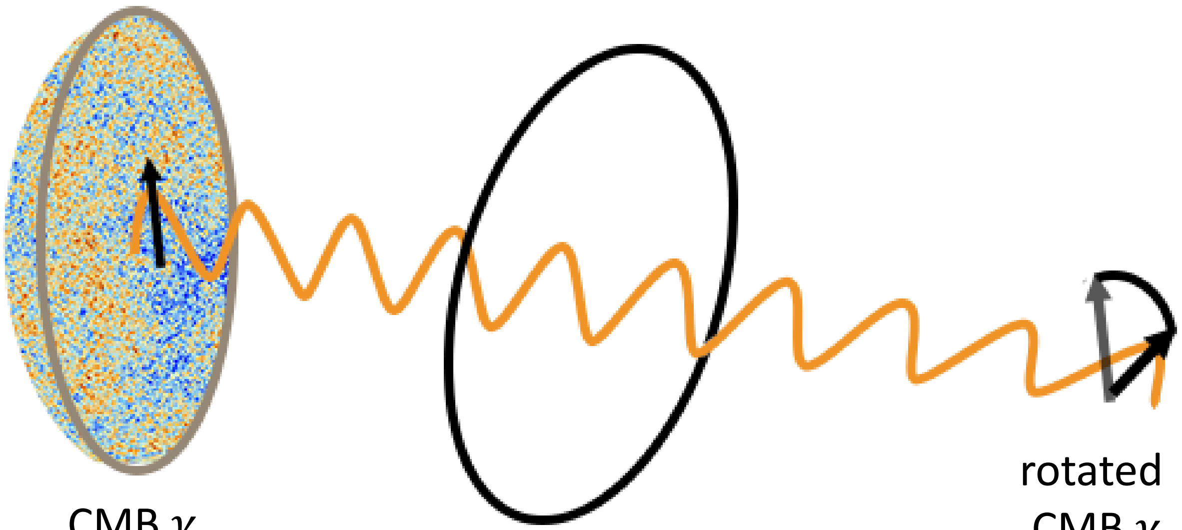
assume interaction
with electromagnetism:

standard Chern-Simons coupling

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

axion-induced birefringence:

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



rotation angle

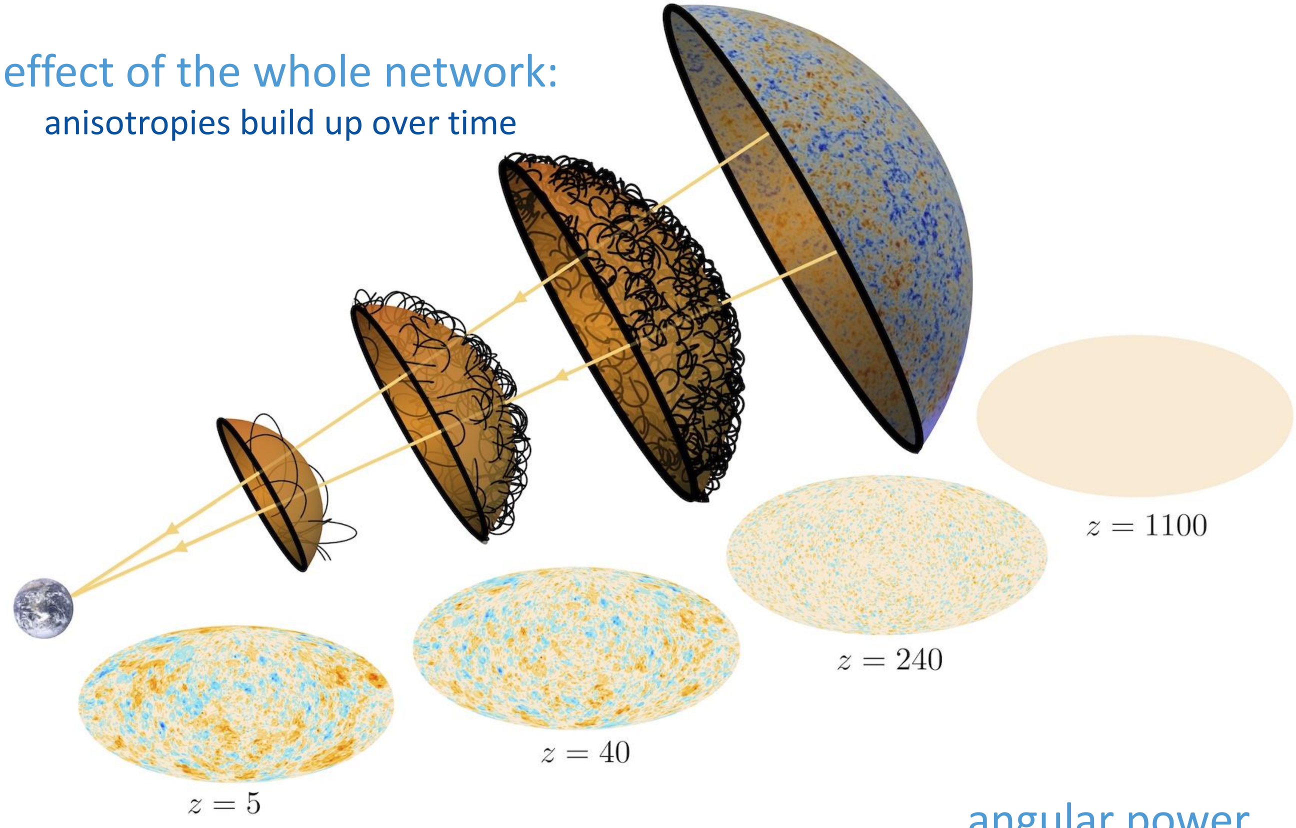
$$\alpha = g_{a\gamma\gamma} \pi f_a$$
$$\equiv \mathcal{A} \alpha_{\text{em}}$$
$$\approx 0.42^\circ \, \mathcal{A}$$

* birefringence can be measured through E-B cross correlation

Birefringence signal & measurement

[Jain, AL, Amin, arXiv:2103:10962]
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

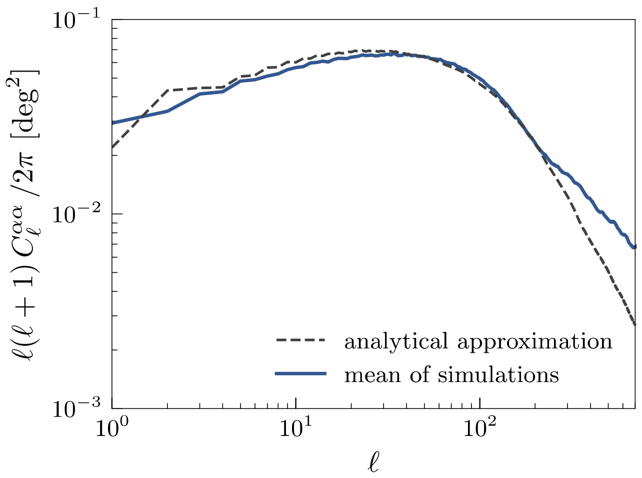
effect of the whole network:
anisotropies build up over time



Ray Hagimoto
(Rice U grad)

Mudit Jain
(Rice U postdoc)

angular power spectrum:

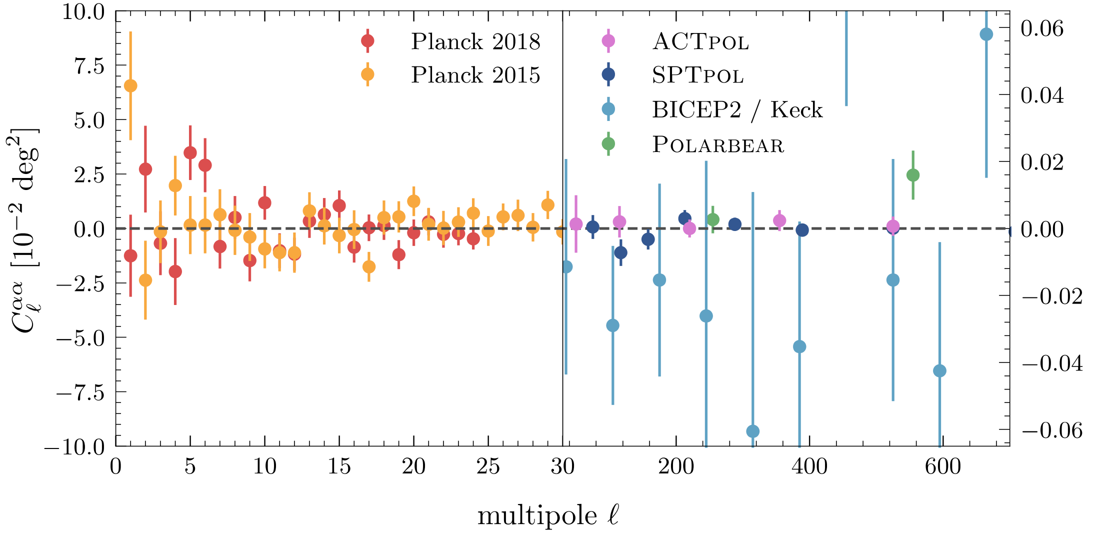


$*$ need $m_a \lesssim 3H_{\rm cmb} \approx 10^{-28}$ eV for the network to survive until after recombination

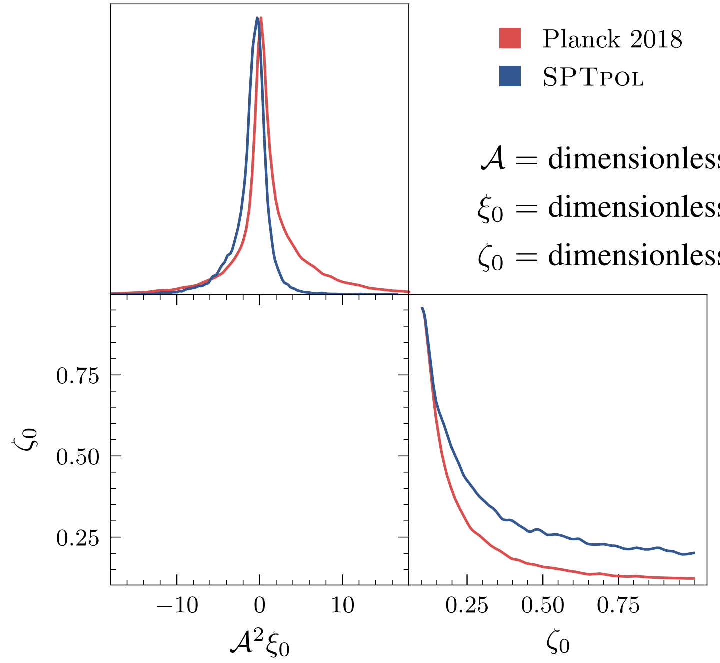
Constraints on axion string networks

[Jain, AL, Amin, arXiv:2103:10962]
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

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)

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

Incompatibility with isotropic birefringence

[Jain, AL, Amin, arXiv:2103:10962]
[Jain, Hagimoto, AL, Amin, arXiv:2208.08391]

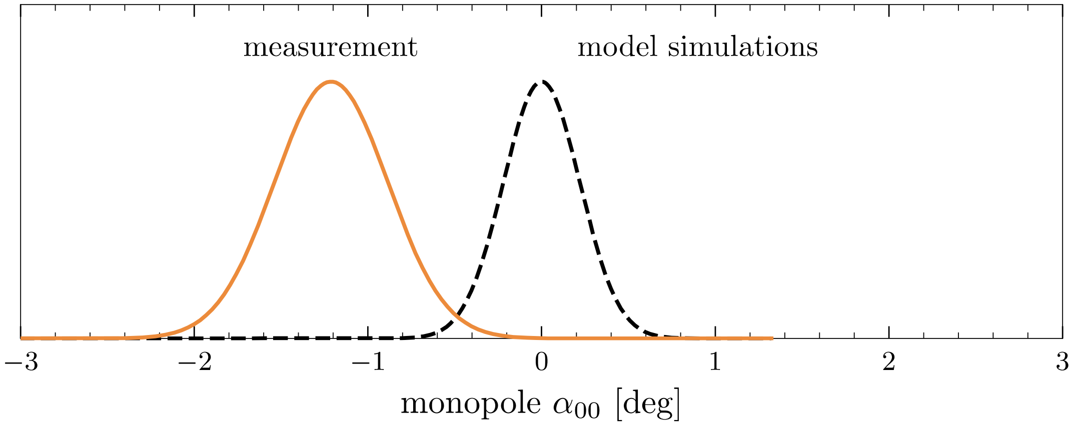
claimed detection of isotropic birefringence:

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)]

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



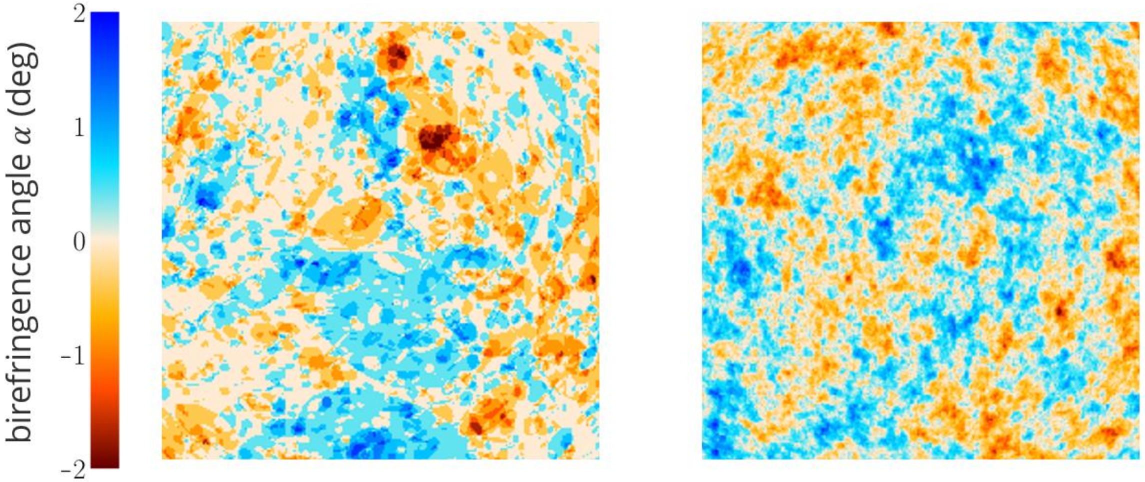
Birefringence non-Gaussianity (ongoing work)

we're working to quantify the non-Gaussianity and develop tests to extract these features from the data

Ray Hagimoto
(Rice U grad)

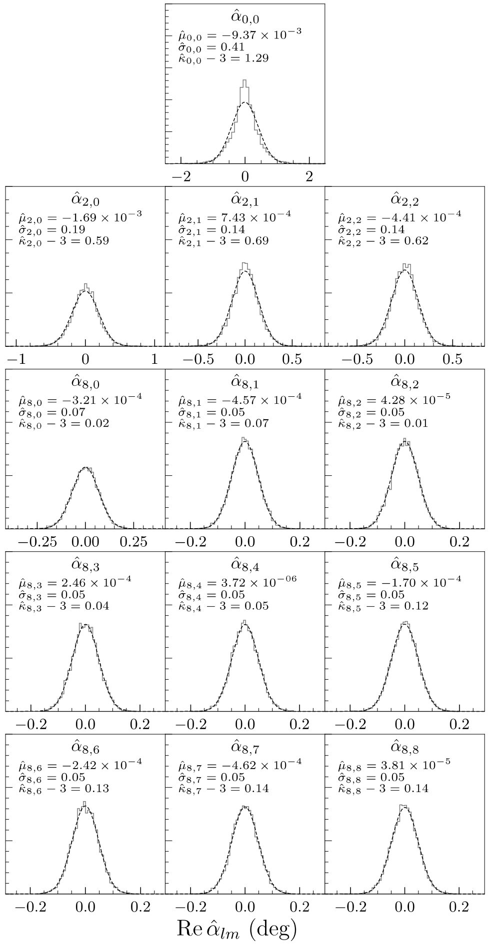
axion-string induced birefringence:

loop-like features are visibly non-Gaussian



Non-Gaussian axion birefringence map

Gaussian random field with same power spectrum



(4) Producing dark photon dark matter

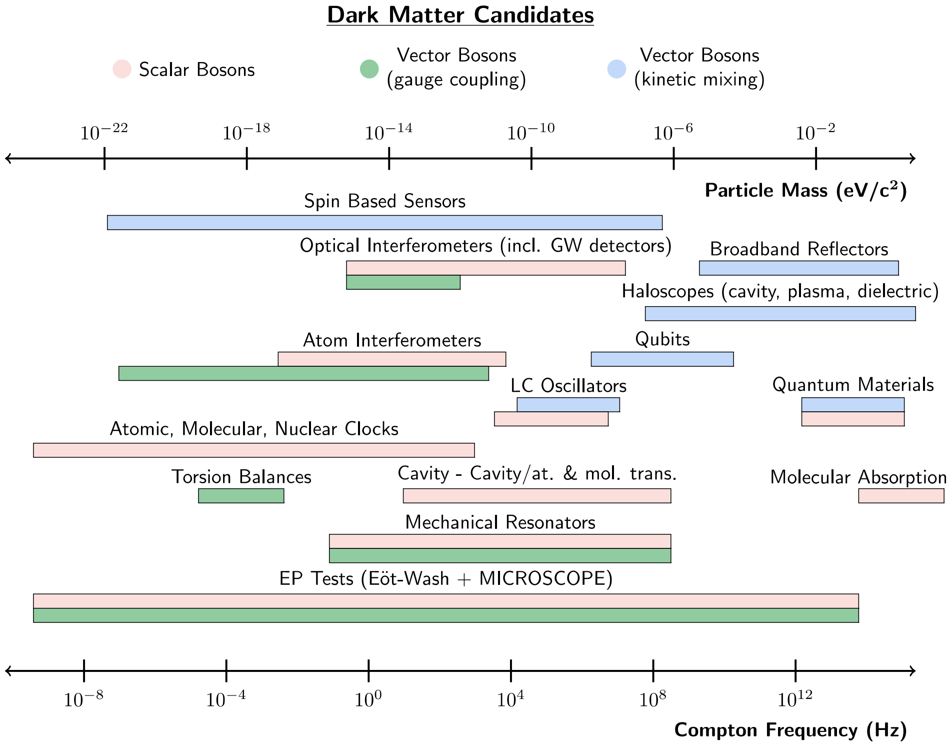
Growing interest in wave-like vector dark matter

[Snowmass 2021 – Wave Dark Matter report]

Impressive abundance and diversity of detection strategies in the lab

Whereas making a vector out of scalar dark matter requires taking a gradient, vector dark matter avoids this velocity suppression

A playground of couplings to explore:
kinetic mixing, gauged B-L, gauged L_e-L_μ, …



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A dark photon production problem

[Nelson & Scholtz (2011)], [Arias, Cadamuro, Goodsell, Jaeckel, & Redondo (2012)]
[Co, Pierce, Zhang, & Zhao (2018)] (plot)
[Agrawal, Kitajima, Reece, Sekiguchi, & Takahashi (2018)]
[Bastero-Gil, Santiago, Ubaldi, & Vega-Morales (2018)]
[Dror, Harigaya, & Narayan (2018)]

Misalignment production?

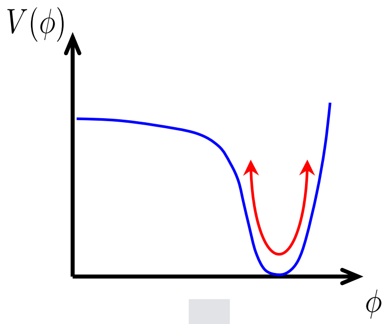
- Not viable for vectors!
- Potential energy redshifts away during inflation

$$\rho_\phi \sim m^2 \phi^2 \sim a^0$$

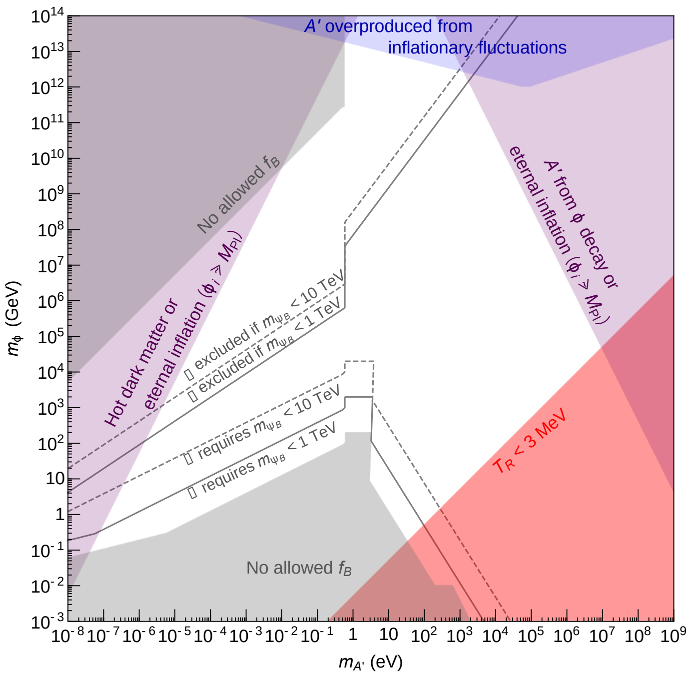
$$\rho_A \sim g^{\mu\nu} m^2 A_\mu A_\nu \sim a^{-2}$$

Transfer from a scalar?

- Burst of activity in 2018



$$\mathscr{L}_{\text{int}} = -\frac{\phi}{M} F_{\mu\nu}\tilde{F}^{\mu\nu}$$

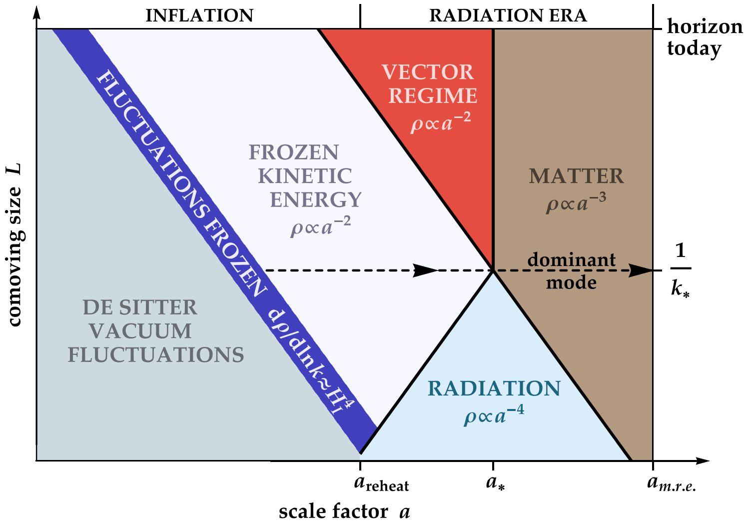


Gravitational production of dark photons

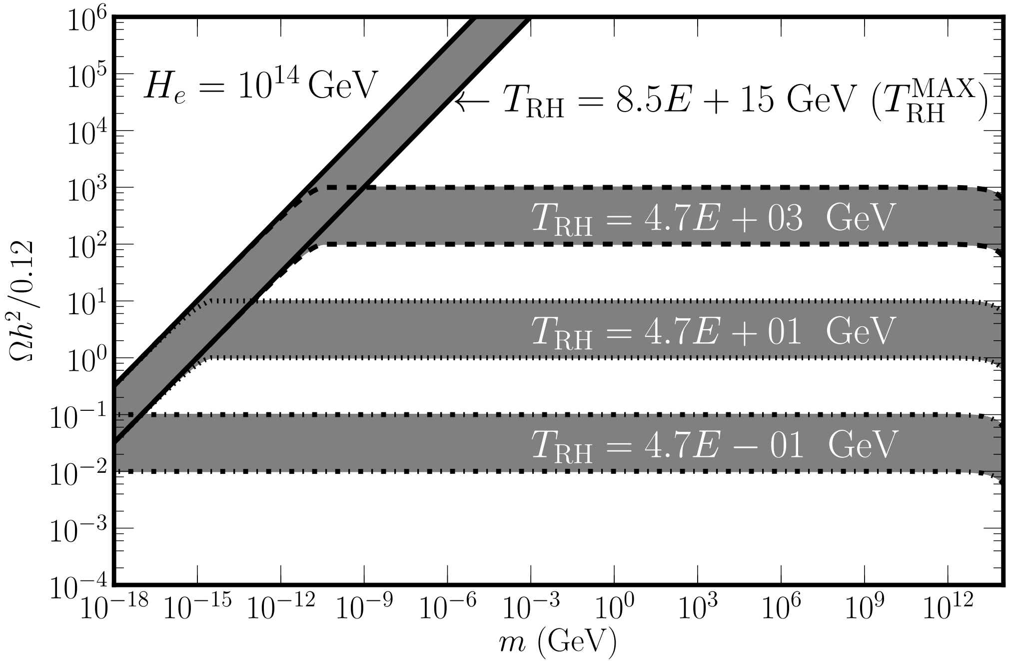
[Graham, Mardon, Rajendran (2015)], [Ahmed, Grzadkowski, Socha (2000)]
[Kolb & Long, arXiv:2009.03828]

Ask: how does a massive vector field behave in an inflationary cosmology?

Quantum field fluctuations during inflation survive as dark matter density perturbations today



relic abundance



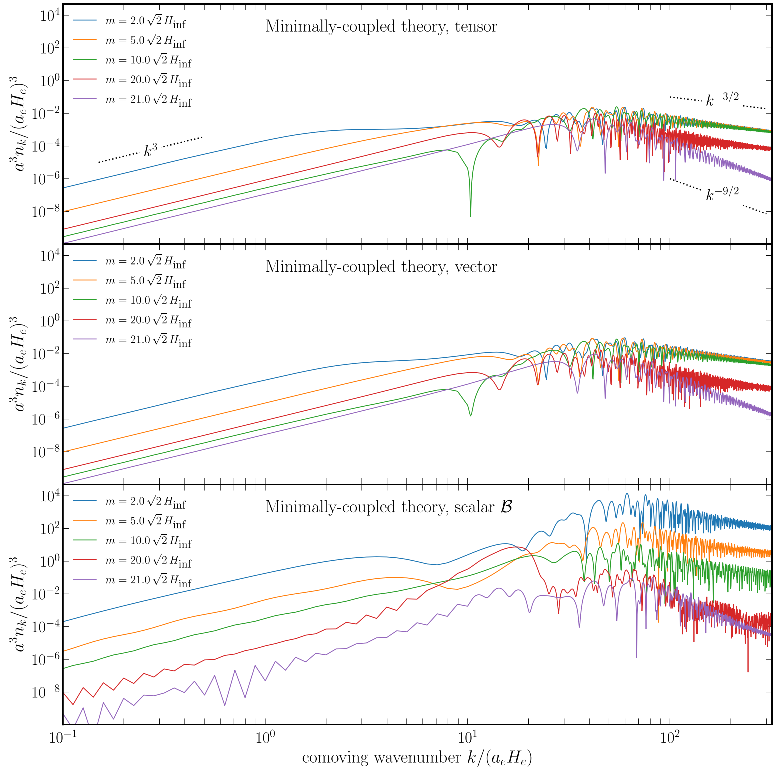
$$\frac{\Omega h^2}{0.12} \approx \begin{cases} \left(\frac{m}{10^{-6}\,\text{eV}}\right)^{1/2}\left(\frac{H_{\text{inf}}}{10^{14}\,\text{GeV}}\right)^2 , & \text{high } T_{\text{RH}} \\ \left(\frac{T_{\text{RH}}}{10\,\text{GeV}}\right)\left(\frac{H_{\text{inf}}}{10^{14}\,\text{GeV}}\right)^2 , & \text{low } T_{\text{RH}} \end{cases}$$

Dark photon dark matter with m > 10^{-6} eV may arise from gravitational interactions alone

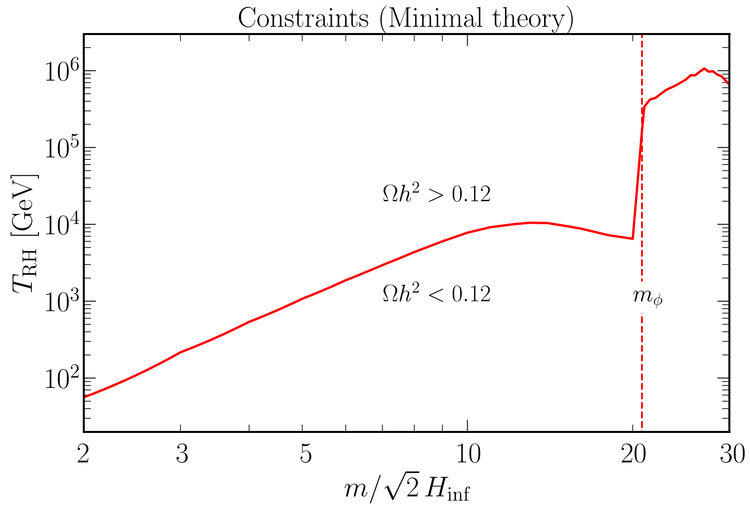
Gravitational production of massive spin-2

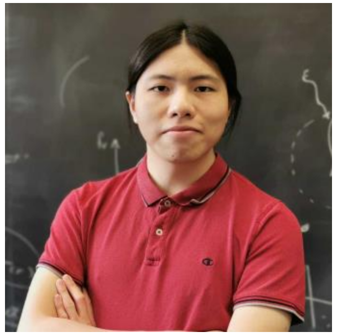
[Kolb, Ling, AL, & Rosen, arXiv:2302.04390]

spectrum



relic abundance





Siyang Ling
(Rice U grad)

FRW Higuchi bound

$$m^2 > 2H^2(1-\epsilon)$$

Dark photon emission from cosmic strings

[AL & Wang, arXiv:1901.03312]

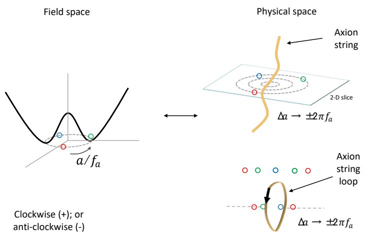
Ultra-light dark photons may arise from an Abelian-Higgs model with a tiny gauge coupling.

$$\mathscr{L} = \left|D_\mu \Phi\right|^2 - \tfrac{1}{4} F_{\mu\nu}F^{\mu\nu} - \lambda\left(|\Phi|^2 - v^2/2\right)^2$$

$$D_\mu \Phi = \partial_\mu \phi + ieA_\mu \Phi$$

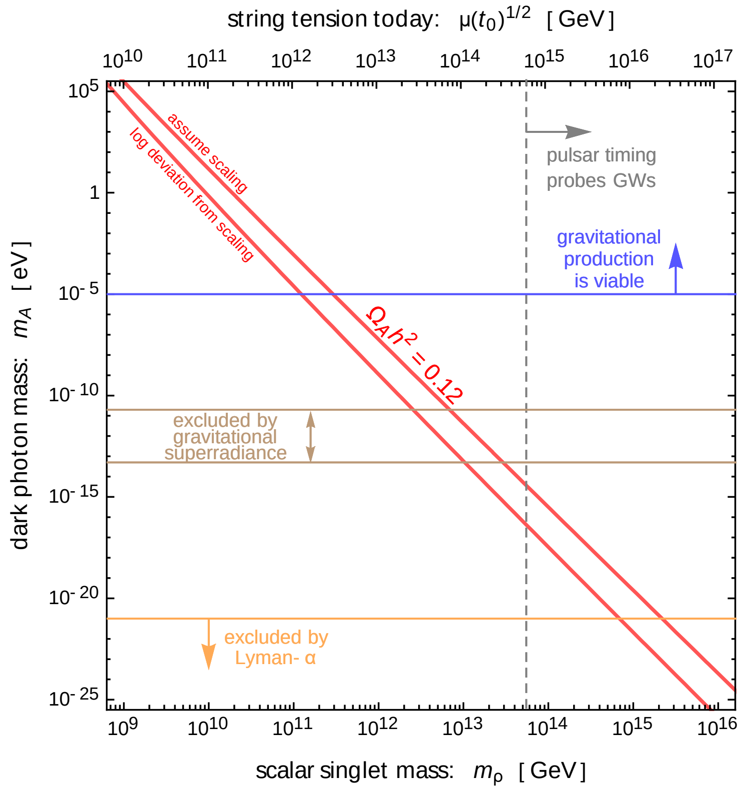
$$(m_A = ev) \ll (m_\rho = \sqrt{2\lambda}v)$$

The early-universe symmetry breaking phase transition creates a network of cosmic strings.



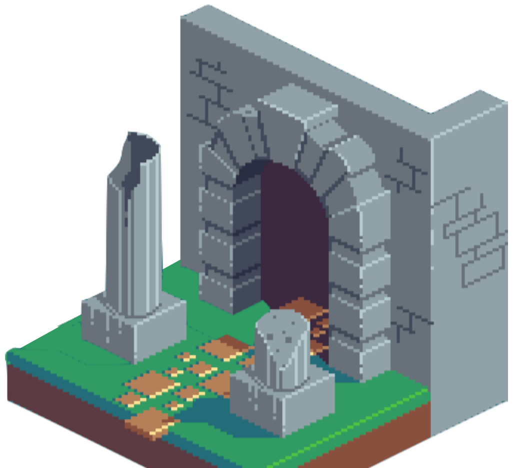
Dark photons are emitted efficiently from the string network – like Goldstone emission from global strings – and become nonrelativistic before today.

relic abundance



Production from strings can explain the origin of dark photon dark matter for a wide range of masses

(5) Radio bursts from dark photon stars



A dark matter clump with spin

[Brito & et. al. (2015)], [Aoki et. al. (2017)], [Adsheaed & Lozanov (2021)], [Chen et. al. (2023)]
[Jain & Amin (2021)], [Zhang, Jain, & Amin (2021)], [Jain (2022)], [Amin, Jain, Karur, Mocz (2022)]

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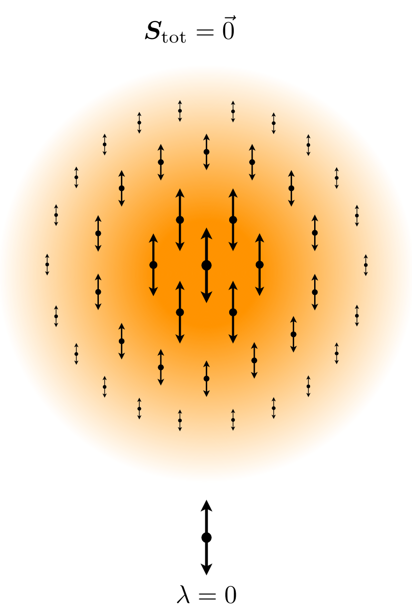
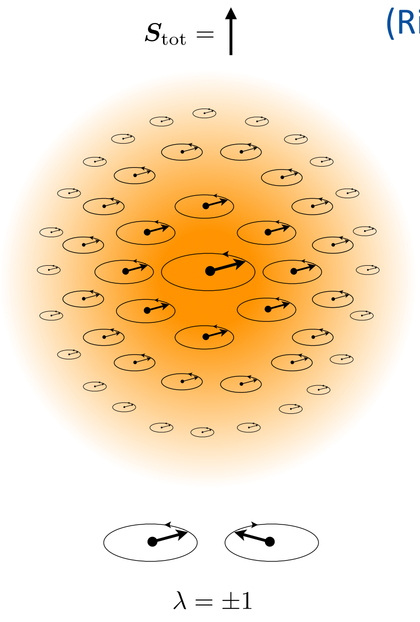
spatially-coherent clump of dark photons:

- bounded by gravity or nongravitational self-interaction
- lowest-energy configurations carry macroscopic spin
- form during structure formation (seen in simulations)
- if gravitationally bounded …

$$M \sim (10^{-7}\, M_\odot)(m/10^{-6}\,\mathrm{eV})^{-1}$$
$$S \sim (10^{65}\hbar)(m/10^{-6}\,\mathrm{eV})^{-2}$$
$$R \sim (1\ \mathrm{km})(m/10^{-6}\,\mathrm{eV})^{-1}$$





How can we detect these objects in galaxy halos?

Electromagnetic radiation signal

[Amin, AL, & Schiappacasse, arXiv:2301:11470]

assume coupling
to electromagnetism:
via dimension-6 operators

$$\mathcal{O}_1 = -\tfrac{1}{2} F_{\mu\nu} \tilde{F}^{\mu\nu} (X \cdot X) \approx 2(\boldsymbol{E} \cdot \boldsymbol{B})(\boldsymbol{X} \cdot \boldsymbol{X})$$
$$\mathcal{O}_2 = -\tfrac{1}{2} F_{\mu\nu} F^{\mu\nu} (X \cdot X) \approx (\boldsymbol{E} \cdot \boldsymbol{E})(\boldsymbol{X} \cdot \boldsymbol{X}) - (\boldsymbol{B} \cdot \boldsymbol{B})(\boldsymbol{X} \cdot \boldsymbol{X})$$
$$\mathcal{O}_3 = F_{\mu\rho} F^{\nu\rho} X^\mu X_\nu \approx (\boldsymbol{B} \cdot \boldsymbol{B})(\boldsymbol{X} \cdot \boldsymbol{X}) - (\boldsymbol{E} \cdot \boldsymbol{X})^2 - (\boldsymbol{B} \cdot \boldsymbol{X})^2$$
$$\mathcal{O}_4 = \tilde{F}_{\mu\rho} \tilde{F}^{\nu\rho} X^\mu X_\nu \approx (\boldsymbol{E} \cdot \boldsymbol{E})(\boldsymbol{X} \cdot \boldsymbol{X}) - (\boldsymbol{E} \cdot \boldsymbol{X})^2 - (\boldsymbol{B} \cdot \boldsymbol{X})^2$$
$$\mathcal{O}_5 = F_{\mu\rho} F^{\nu\rho} \partial^\mu X_\nu \approx (\boldsymbol{E} \times \boldsymbol{B}) \cdot \dot{\boldsymbol{X}}\ .$$

Enrico
Schiappacasse
(Rice U postdoc)

radiation from solitons in vacuum:

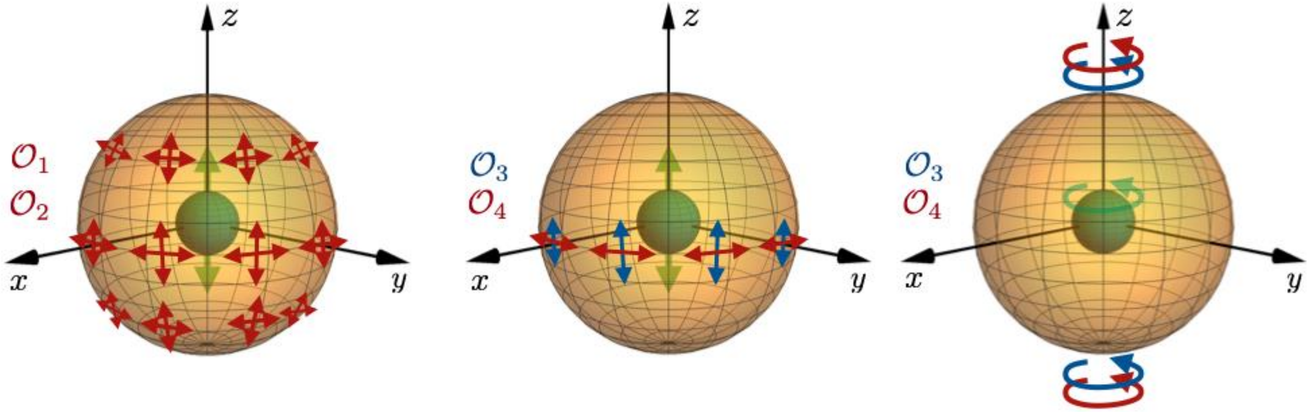
- oscillating dark photon field triggers parametric resonance in the electromagnetic field
- we derive condition for parametric resonance:

$$g^2 \bar{X}^2 m R \gtrsim 1$$

- emission is a narrow radio line

$$f_\gamma \approx m/2\pi \approx \big(0.2\ \mathrm{GHz}\big)\big(m/10^{-6}\ \mathrm{eV}\big)$$

radiation pattern:
depends on the operator
& polarization of the soliton



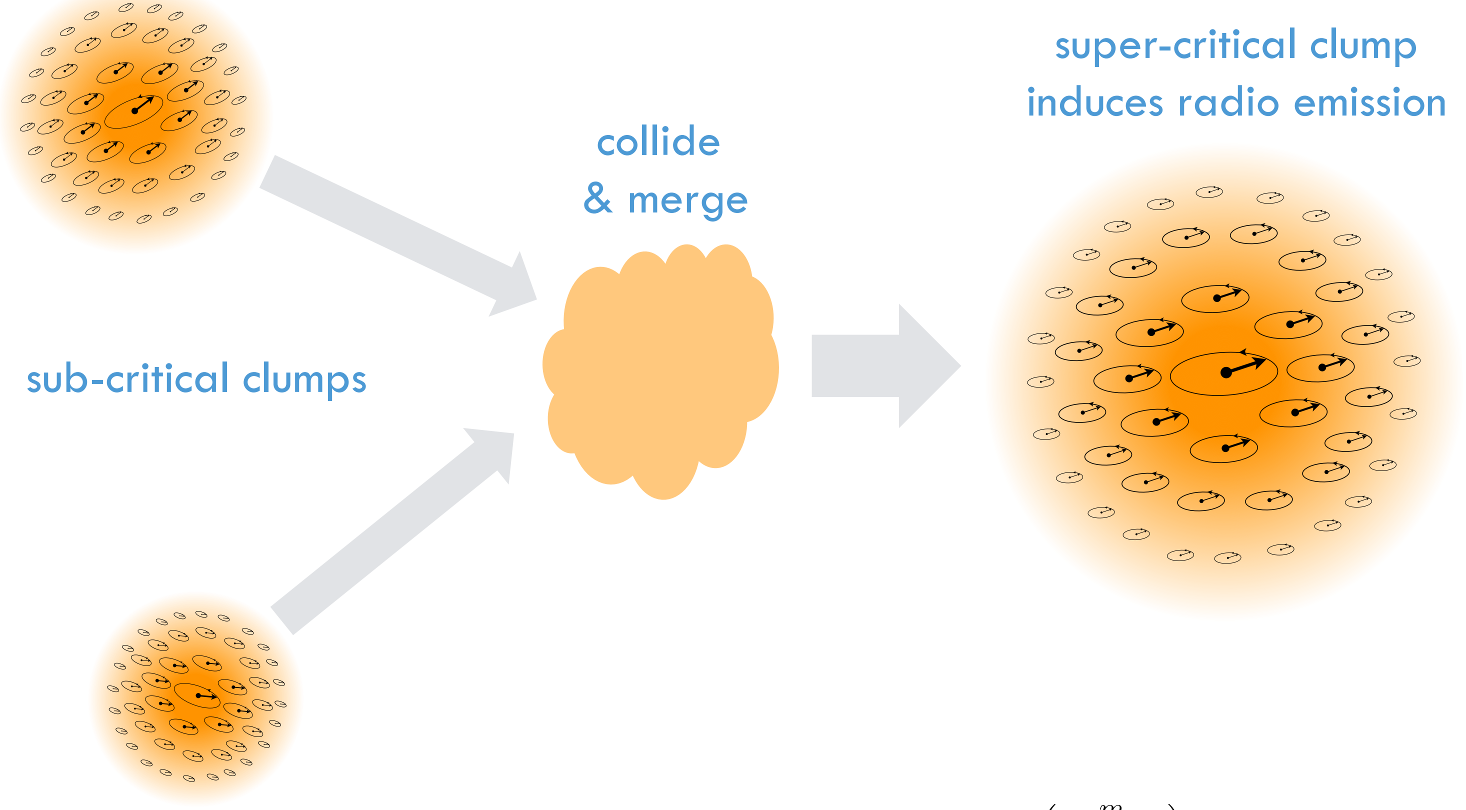
Astrophysical implications

[Tkachev (2014)], [Levkov, Panin, & Tkachev (2000)], [Hertzberg & Schiappacasse (2018)]
[Amin, AL, & Schiappacasse, arXiv:2301:11470]

to activate parametric resonance, the clump mass must exceed a threshold value

$$M \gtrsim (2 \times 10^{-9}\ M_\odot)\,(m/10^{-6}\,\mathrm{eV})^{-1}\,(g/10^{-10}\,\mathrm{GeV}^{-1})^{-2/3}$$

this may occur when clumps merge in galaxy halos today



signal: strong, transient, narrow radio burst

$$\nu_0 \sim (200\ \mathrm{MHz})\left(\frac{m}{10^{-6}\ \mathrm{eV}}\right) ,$$

$$\Delta\nu \sim (40\ \mathrm{kHz})\left(\frac{g}{10^{-10}\ \mathrm{GeV}^{-1}}\right)^{-2/3}\left(\frac{m}{10^{-6}\ \mathrm{eV}}\right)$$

summary & conclusion

Symmetry principles guide us to explore extensions of the Standard Model containing light axion-like particles and hidden/dark photons

We must 'delve into every dungeon' if we seek to explore these particles through their myriad manifestations:

dark radiation, dark matter, clumps / solitons, strings, …

Astrophysical and cosmological observables (X-ray, radio, birefringence) will continue to be a pathway to discovery