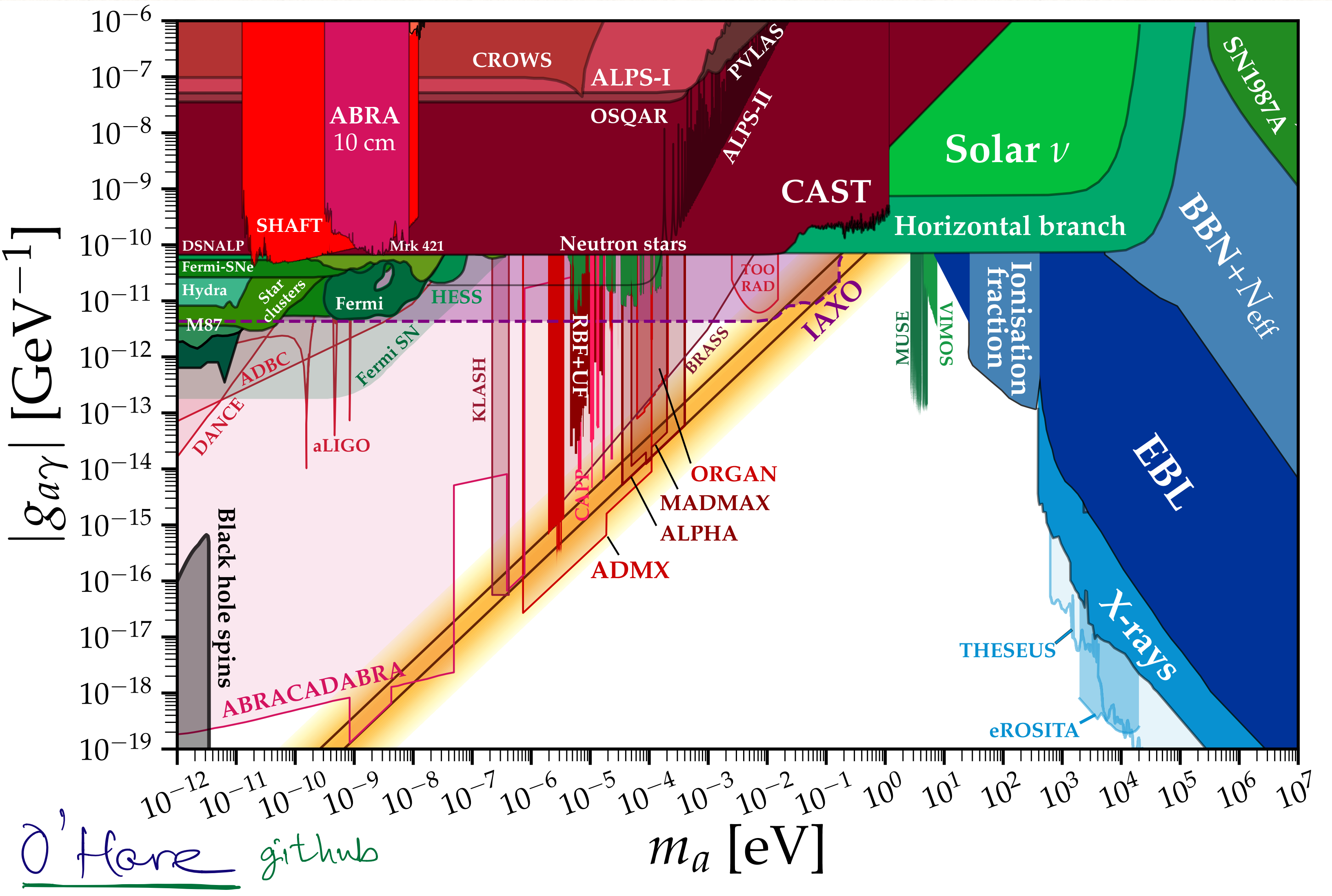
Workshop Seminar DESY + UHH 18 May 21

ASTROPHYSICAL CONSTRAINTS ON AXIONS

by PRANJAL TRIVEDI

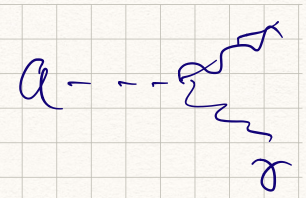
References:

- Sikivie : Invisible Axion Search Methods 2003.02206
- Ringwald, Rosenburg, Rybka PDG – Axions 2020
- Marsh : Axion Cosmology 1510.07633
- Sigl : Astroparticle Physics (Atlantis 2016)
- Raffelt : Astrophysical axion Bounds 0611350



CROWS
ALPS-I
PVLAS
ALPS-II
OSQAR
ABRA
10 cm
SHAFT
CAST
Solar ν
Horizontal branch
SN1987A
BBN+$N_{\rm eff}$
DSNALP
Mrk 421
Neutron stars
Fermi-SNe
Hydra
Star clusters
Fermi
HESS
M87
TOO RAD
IAXO
ADBC
Fermi SN
BRASS
KLASH
RBF+UF
CAPP
MUSE
VIMOS
Ionisation fraction
DANCE
aLIGO
ORGAN
MADMAX
ALPHA
ADMX
EBL
Black hole spins
ABRACADABRA
X-rays
THESEUS
eROSITA
$|g_{a\gamma}|$ [GeV^{-1}]
m_a [eV]
O'Hare
github

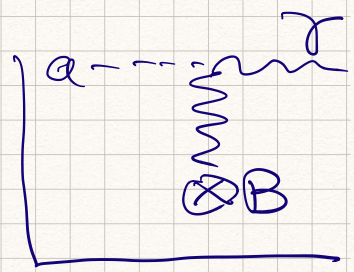
- Axions ⟷ Astrophysics



aDM is not really 'DM'

$\Omega_{DM} = 0.26$

- a → aDM / $a_{\odot}$ / CaB / burst (transient)



γ → a Primakoff

a → γ Sikivie

- QCD axion

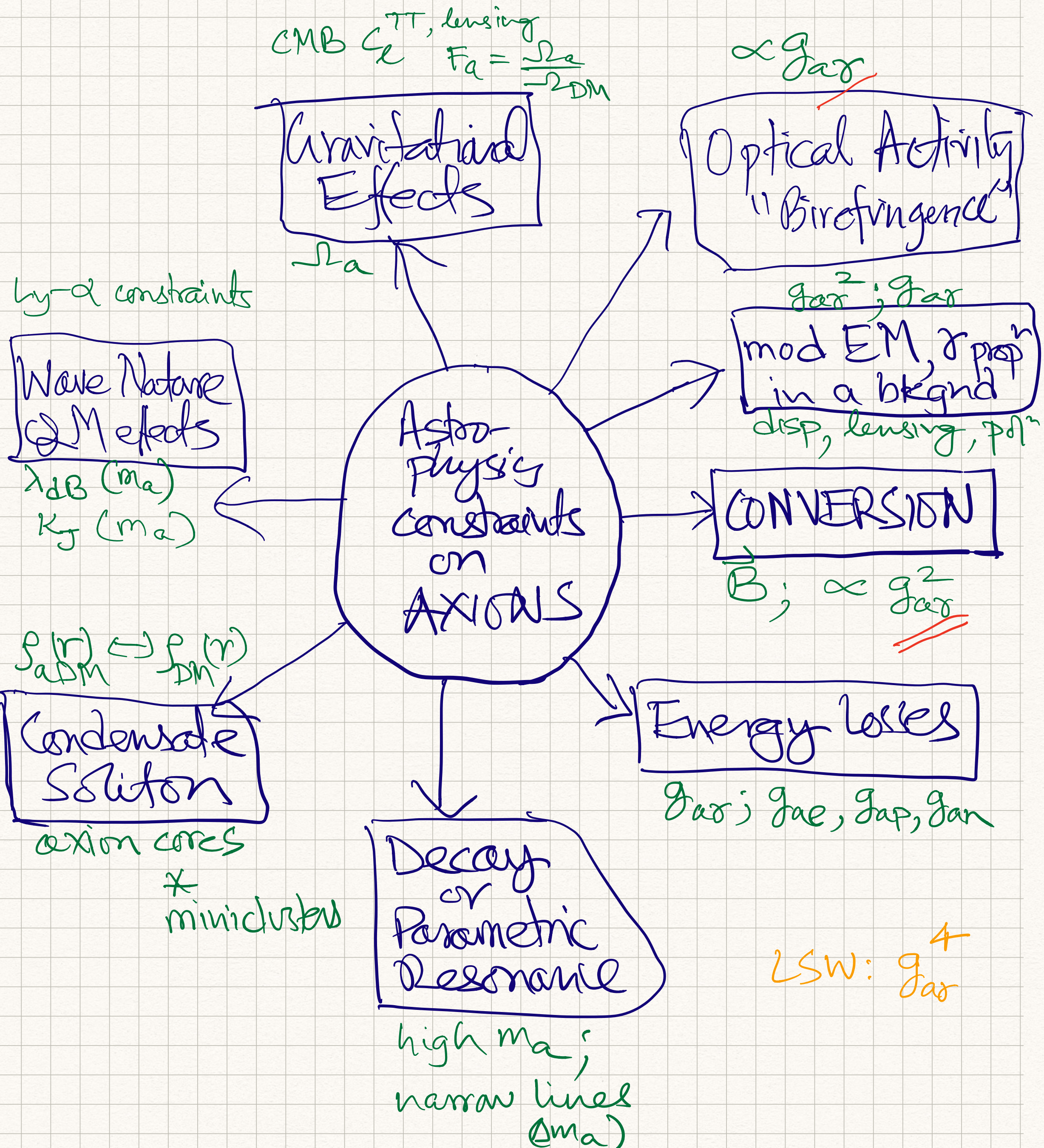
$10^{-13}\,eV \longleftrightarrow 10^{-2}\,eV$

m_a

$f_a < f_{Pl}$

stellar evolution

$$m_a \simeq 6\,\mu eV \left(\frac{10^{12}\,GeV}{f_a}\right)$$



Astro-physics constraints on AXIONS
Gravitational Effects
CMB C_ℓ^{TT}, lensing
$F_a = \frac{\Omega_a}{\Omega_{DM}}$
Ω_a
Optical Activity "Birefringence"
$\propto g_{a\gamma}$
mod EM, γ prop^n in a bkgnd
$g_{a\gamma}^2$; $g_{a\gamma}$
disp, lensing, pol^n
CONVERSION
$\vec{B}$; $\propto g_{a\gamma}^2$
Energy Losses
$g_{a\gamma}$; g_{ae}, g_{ap}, g_{an}
Decay or Parametric Resonance
high m_a; narrow lines (Δm_a)
Condensate Soliton
$\rho_{aDM}(r) \leftrightarrow \rho_{DM}(r)$
axion cores * miniclusters
Wave Nature QM effects
Ly-α constraints
$\lambda_{dB}(m_a)$
$k_J(m_a)$
LSW: $g_{a\gamma}^4$

New + Improved Astro probes

- Resonant conversion NS, WD : $B_{NS} \sim 10^{12}$ G
  ↓ $B_{Magnetars} \sim 10^{15}$ G
  MWD
- SN a — γ-ray limits
  burst duration
- Conversion in $\vec{B}_{Gal}$, $\vec{B}_{IGMF}$, $\vec{B}_{Solar}$
  $\vec{B}_{Gal}$ → $\sim 10^{-6}$ G
  $\vec{B}_{IGMF}$ → $10^{-18} - 10^{-15}$ G
  $\vec{B}_{Solar}$ → $\sim$ Gauss $- 10^{5}$ Gauss
- Dwarf Galaxies : survival of star clusters : grav. heating by soliton oscillations

$\rho_{DM\,local} \sim 0.45$ GeV/cm^3

$\rho_{DM,\,dwarf\,gal} \sim$ upto 100 GeV/cm^3

Marsh + Niemeyer 1810.08543 ← opposite conclusions → Chiang et al 2104.13359

3D FDM Simulations + analytics : Schive + collab. find negligible grav. heating

- Mocz et al. structure formation FDM

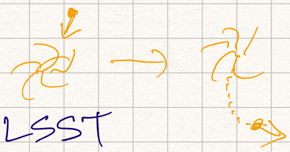
$\lambda_{dB}(m_a) \longrightarrow$ observable? fringes in $\rho_{DM} \longrightarrow$ fringes in ρ_* — coherent interference pattern unaffected by baryonic feedback

1910.01653

JWST observability of DM fringes

related $\ell_{coh} \sim \dfrac{1}{m_a v_a}$

- Tidal effects: Satellite gal of MW

Tidal Streams.  eg. 1811.03631 (Bonaca et al.)
SDSS, Gaia, LSST

- Local DM wind: structure

basic models: Gal DM halo M-B distrib^n
dispersion $\sqrt{\vec{v}\cdot\vec{v}} \sim 270$ km s^{-1}

BUT substructure DM halo

⟶ calculation of interference effects in wave DM

eg: vortices

Hui et al 2004.01188

$$\mathcal{L}_{a\gamma} = \frac{1}{4} g_{a\gamma} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma} a(\vec{x}) \vec{E}(\vec{x}) \cdot \vec{B}(\vec{x})$$

$\hookrightarrow (+,-,-,-)$

$$g_{a\gamma} \equiv \frac{s\, \alpha_{em}}{2\pi f_a}$$

$$s = \begin{cases} 0.72 & \text{DFSZ} \\ -1.94 & \text{KSVZ} \end{cases}$$

$$\vec{\nabla} \times \vec{E} = -\partial_t \vec{B}$$

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

$$\vec{\nabla} \cdot \vec{E} = \frac{\rho_{em}}{\epsilon} + \frac{g_{a\gamma}}{\epsilon} \vec{B} \cdot \vec{\nabla} a$$

$$\vec{\nabla} \times \vec{B} = \partial_t \vec{E} + \mu \vec{J}_{em} + \frac{g_{a\gamma}}{\epsilon} \left(\vec{E} \times \vec{\nabla} a - \vec{B} \partial_t a \right)$$

$$\Box a + \frac{\partial V_a}{\partial a} \cdot a = -g_{a\gamma} \vec{E} \cdot \vec{B}$$

$$\partial_t^2 a - \nabla^2 a + m_a^2 a = -g_{a\gamma} \vec{E} \cdot \vec{B}$$

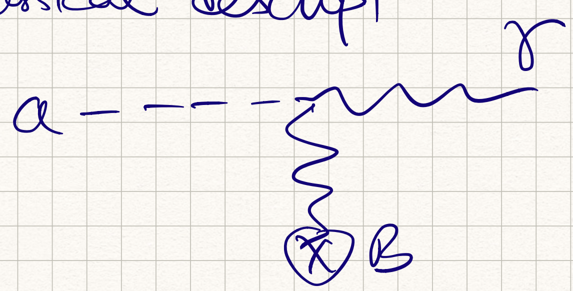
in bkgnd $\vec{B}_0(\vec{x},t)$, $\vec{E}_0(\vec{x},t)$

$$\rho_a = g_{a\gamma} \vec{B}_0 \cdot \vec{\nabla} a$$

$$\vec{j}_a = g_{a\gamma}(\vec{E}_0 \times \vec{\nabla} a - \vec{B}_0 \partial_t a)$$

a acts as a src of EM waves
(sources a-induced EM current)

classical descript^n



conversion
axion energy → photon energy

axion plane wave $a(\vec{x},t) = \mathrm{Re}\left[A e^{i(\vec{k}_a \cdot \vec{x} - \omega t)}\right]$

$$\omega^2 = m_a^2 + \vec{k} \cdot \vec{k}$$

assumptions

$\vec{E}_0 = 0$
↑ cond. plasma

$\vec{B}_0$ static

$\rho_{em} = 0$
$j_{em} = 0$

$\Delta t_{astro} \gg \Delta t_{obs}$
ignore backreaction

$$\vec{E} = -\nabla\Phi - \partial_t \vec{A}$$
$$\vec{B} = \vec{\nabla} \times \vec{A}$$

solve for $A(\vec{x})$
obtain $\vec{j}_a(\vec{k}_a)$

$\Big\} \rightarrow \frac{dP}{d\Omega} \propto \vec{j}_a^{\,2}$

$\propto g_{a\gamma}^2$

$$\frac{d\sigma}{d\Omega}(a \rightarrow \gamma) = \frac{1}{|\vec{P}_a|}\frac{dP}{d\Omega}$$

$\beta_a = \frac{|\vec{k}_a|}{\omega}$

$$= \frac{g_{a\gamma}^2 \mu k \omega}{16\pi^2 \beta_a} \sum_{\lambda=1,2} \left| \int_V d x^3 \, e^{i(\vec{k}_a - \vec{k})\cdot\vec{x}} \, \hat{e}_\lambda(\hat{n}) \cdot \vec{B}_0(\vec{x}) \right|^2$$

$$\frac{d\sigma}{d\Omega}(a \rightarrow \gamma) \propto |B(q)|^2 g_{a\gamma}^2 \frac{k\omega}{\beta_a}$$

In general $\vec{k}$, $\vec{k}_a$ will be distinct

⊛ Momentum conservation must be ensured by $\vec{B}$ capturing / providing the $|\vec{q}|$

$\vec{q} \equiv \vec{k} - \vec{k}_a$

$\vec{B}$-field
- have power in $\vec{B}$ @ scale $|\vec{q}|$
- inhomogeneity in B-field

Can be UNCERTAIN: is $\left(\frac{B(q)}{B_{rms}}\right)^2 = f(q) = f(m_a)$
~ 0.1 ?

OR $f(a) << 1$ (?) // → see Sigl (2017) Astrophysical Haloscopes 1708.08908

$$P_{res}(a \to \gamma) = \frac{g_{a\gamma}^2}{4 p_a} \sqrt{\frac{\mu}{\epsilon}}\, B_0^2 L^2$$

$L^2 \downarrow$ if $\ell < L$: ℓL

see detailed discussion of $P(a\to\gamma)$ for non-relativistic axions @resonance in Hook et al 1804.03145 (conversion in NS)

$P(a\to\gamma) \approx B_0^2 L^2 g_{a\gamma}^2$ for relativistic axions in $\vec{B}$ in vacuum

L : extent of B_{ext}

coherence $a \leftrightarrow \gamma$ only till $\ell < L$

$$\ell_{osc} = \frac{\pi}{q}$$

Limiting factors on $\ell_{coherence}$ in astrophysical conversion:

- absorpt^n, scattering γ
- turbulence of medium
- non-stationary $\vec{B}_{ext}$

Important to note: Energy conservation includes the Kinetic Energy of a

$$\hbar\omega = m_a c^2 + KE_a$$

Cosmic Birefringence

γ EoM in an ALP bkgnd

$$\omega \simeq k \mp \frac{g_{a\gamma} m_a a_0}{2}$$

phase difference:

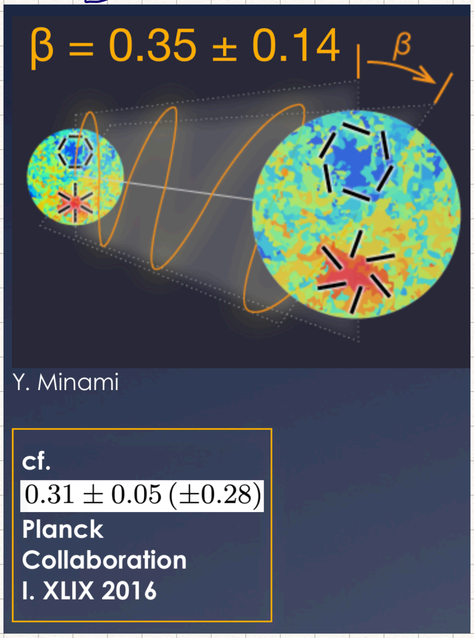
$$\Delta\phi = \int \Delta\omega \, dt$$

$$\sim g_{a\gamma} \Delta a$$

Birefringence angle

$$\beta = \frac{1}{2}\Delta\phi \simeq \frac{g_{a\gamma}\Delta a}{2}$$

between obs. and src.



Minami Komatsu PRL 2020 2011.11254

Tentative Evidence for isotropic birefringence CMB

PLANCK: 1605.08633 $\beta = (0.31 \pm_{\text{stat}} 0.05 \pm_{\text{syst}} 0.28)^\circ$

MK20 $\beta = (0.35 \pm_{\text{stat}} 0.14)$ → 2.4σ

⊕ Instrument miscalib^r uncertainty:

MK20 mitigate by comparing CMB w. Gal. foregnd.

$$C_\ell^{EB,0} = \frac{1}{2}\sin(4\beta)\left[C_\ell^{EE} - C_\ell^{BB}\right]$$

↑ measure of birefringence

Fujita: constrain ALPs: $10^{-33}\,\text{eV} \lesssim m_a \leq 10^{-28}\,\text{eV}$

2011.11894
2008.02473

for ALP DE: (i) $V(a) = \frac{1}{2}m^2 a^2$

(ii) $V(a) = m^2 f_a^2\left[1 - \cos\left(\frac{a}{f_a}\right)\right]$

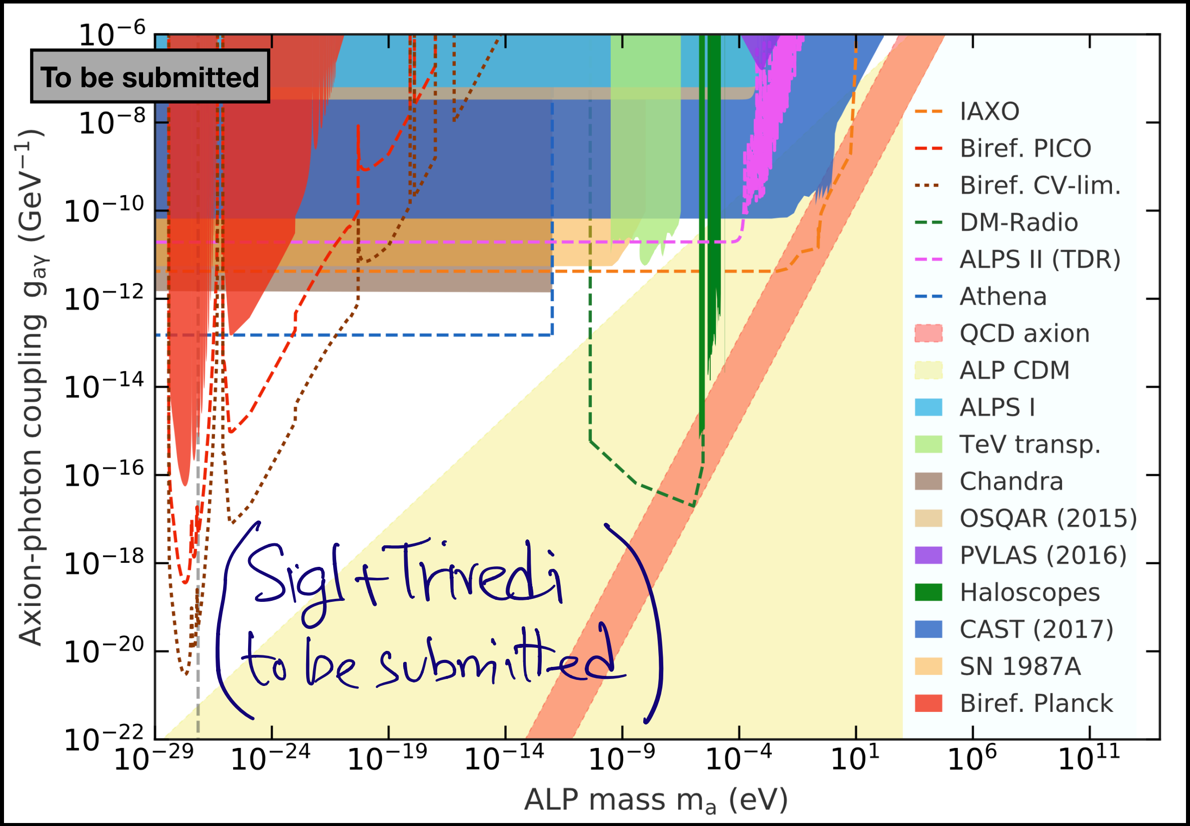
also find for ALP EDE

iso. biref $\Rightarrow g_{a\gamma} \sim f_a^{-1}$

Sigl + Trivedi (to be submitted): iso. birefringence can also constrain ALP DM

$10^{-29}\,\text{eV} \lesssim m_a < 10^{-20}\,\text{eV}$

Isotropic Birefringence from aDM: Constraints &Forecasts



Comparing CMB to other pol^n astro sources used to measure birefringence or other astro axion probes:

CMB β is indep. of uncertainties in

- $\tilde{B}_{ext}$, $B(\vec{q})$
- ρ_a overdensities
- $PA_{intrinsic}$ of source polarization

Namikawa: 2105.03367

can cross check MK20 $\beta = (0.35 \pm 0.14)^\circ$ by mode-coupling from parity violation

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(*) MK20: assumed EB cross-correl^n from foregrd = 0

however, they also found that

- dust foreground could possibly explain β
- depends on sign of dust rotation γ

Clearly, dust foreground contribution to birefringence signal + systematics needs to be addressed in detail

[cf. CMB B-mode + dust signal]

Clark, Kim, Hill, Hensley 2105.00120

- used H I Stokes parameter maps + Planck Gal $\vec{B}$-field obs.
- misalignment betn dust poln emission and $B_{Gal,\perp}$ can induce parity violation in foregnd.

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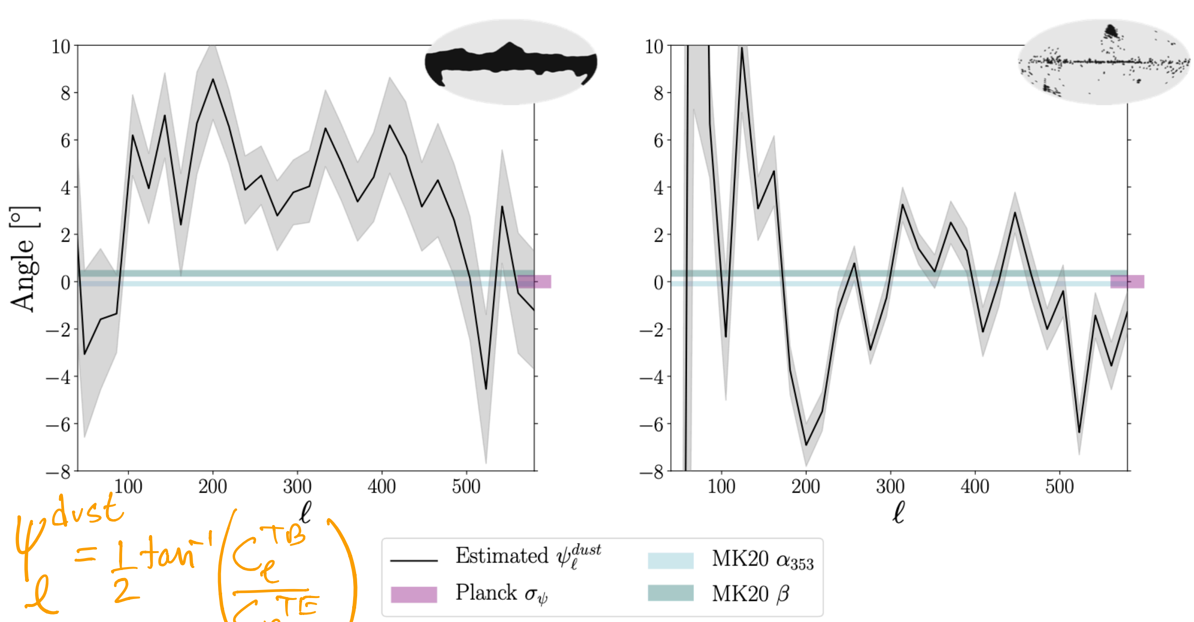
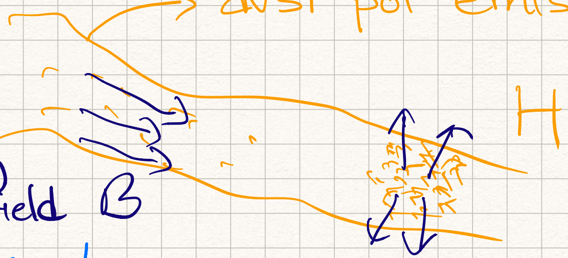


$$\psi_\ell^{dust} = \frac{1}{2}\tan^{-1}\left(\frac{C_\ell^{TB}}{C_\ell^{TE}}\right)$$

Figure 9. A comparison of our prediction for ψ_ℓ^{dust}, the effective magnetic misalignment angle, to values from the MK20 analysis. Black line is the effective ψ_ℓ^{dust} calculated from the ratio of TB and TE at 353 GHz. Gray band indicates the propagated 1σ error. Left: ψ_ℓ^{dust} computed over the mask considered in this work ($f_{sky} \sim 0.69$, upper righthand corner). Right: the same analysis calculated with PR3 data over the 353 GHz masks used in MK20 (HM1 mask, with $f_{sky} \sim 0.92$, pictured in upper righthand corner). Light blue band indicates the MK20 value calculated for the polarization angle miscalibration at 353 GHz, $\alpha_{353} = -0.09^\circ \pm 0.11^\circ$. Teal band denotes the MK20 inference of the isotropic cosmic birefringence angle, $\beta = 0.35^\circ \pm 0.14^\circ$. Purple band indicates the Planck polarization angle calibration uncertainty, $\sigma_\psi = 0.28^\circ$.

dust pol^n emission, correlated with ρ_H distributed in filaments



plane-of-sky magn. field B

In general,

- obs. trend in HI filaments with Gal. dust emission: $\uparrow \rho_H$: $\vec{B} \parallel$ filament
  $\downarrow \rho_H$: $\vec{B} \perp$ filament

- ISM properties det^n by MHD turbulence.

- Both sign + amplitude of Gal foreground EB parity violation signal seen to vary a lot with
  - sky patch
  - sky mask

$\Rightarrow$ no simple theory available as a guide!