李政道研究所
TSUNG-DAO LEE INSTITUTE

When stars dim into axions:
A time-domain window on new physics

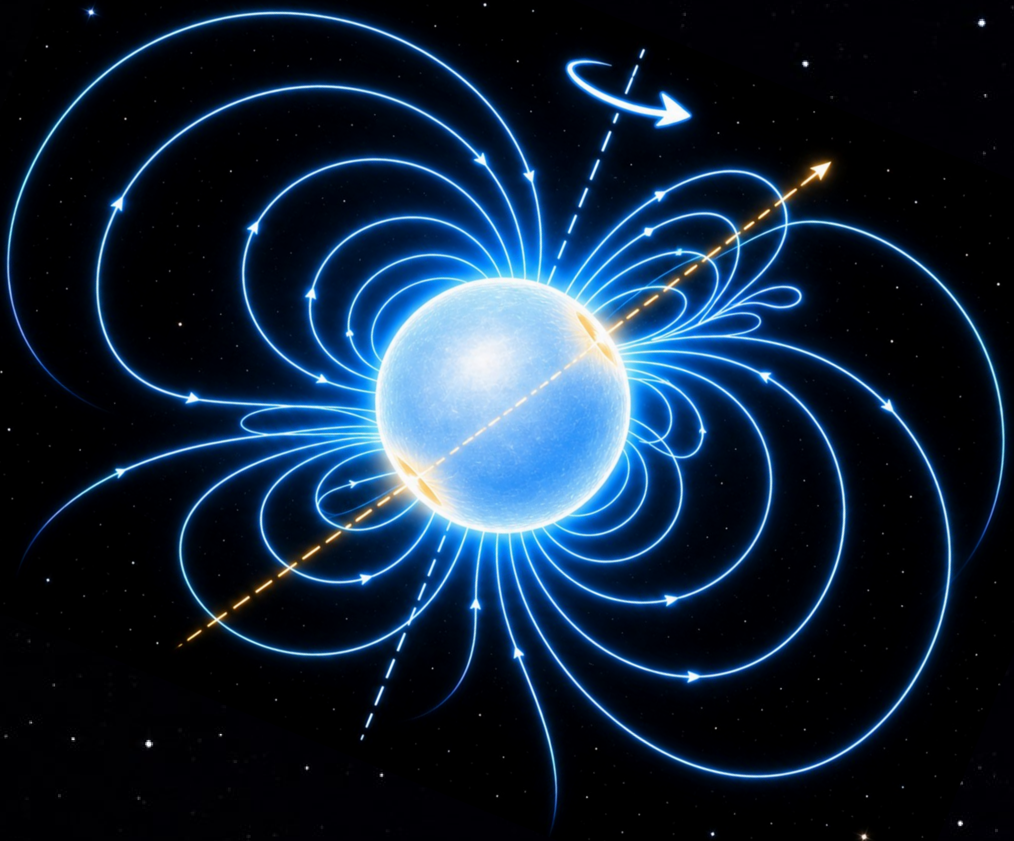
Hong-Yi Zhang (张闳一)

Tsung-Dao Lee Institute, Shanghai Jiao Tong University

https://hongyi18.github.io

@ Axion 2026; Aug 11, 2026

Mainly based on **HYZ**, Heng Bian, Zhao-Yu Zuo (2607.18647)



A magnetic white dwarf

- A compact object

  $M_\star \sim M_\odot \quad R_\star \sim R_\oplus$

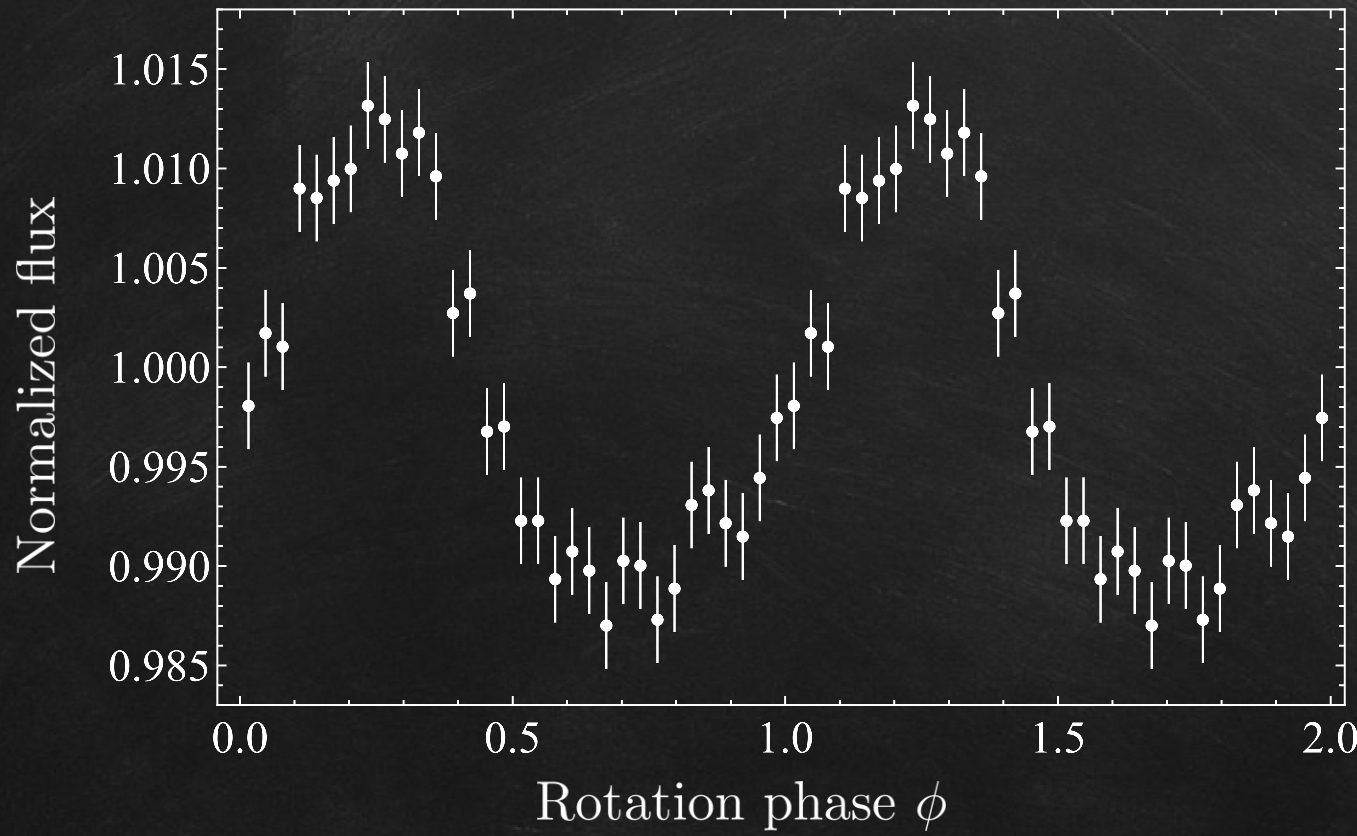
- A strong magnetic field

  $B \sim 10^3\text{–}10^9\,\mathrm{G}$

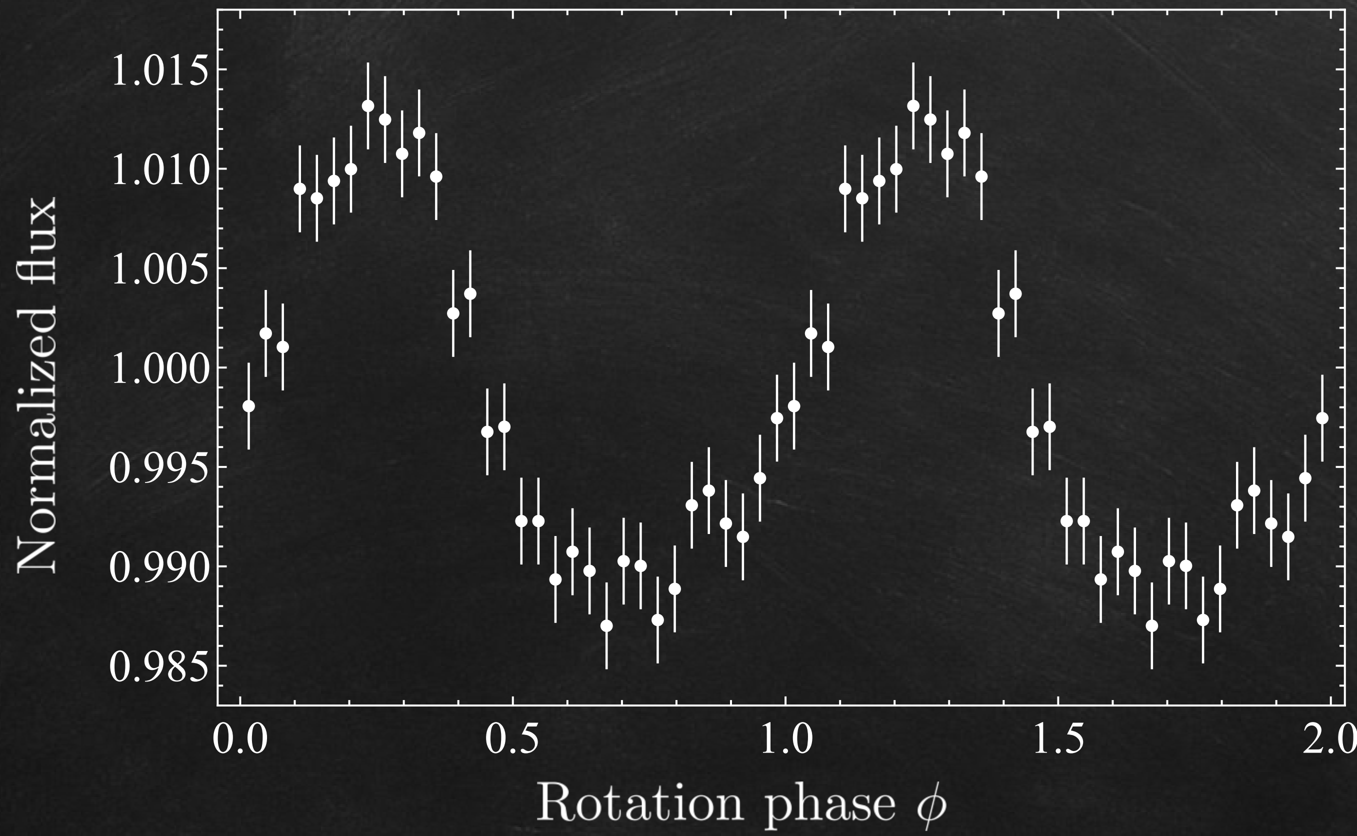
- A periodic lock

  $P \sim$ mins–years

Why does the star brighten and dim?



Why does the star brighten and dim?



Surface is not uniform:

- Temperature inhomogeneities
- Magnetic bright/dark spots
- Magnetic field dependent opacity and conductivity
- Other complex stellar physics...

A light curve is a rotating surface integral

intensity (emitted energy per unit time, area, solid angle, frequency bandwidth)

$$F_{\mathrm{obs}}(\phi) = \int d\omega\, R(\omega)\, \frac{1}{D^2} \int_{\mu>0} I_{\mathrm{S}}(\hat{\boldsymbol{n}}, \boldsymbol{r}, \omega; \phi)\, \mu\, dS$$

direction to observer

photon frequency

position on stellar surface

A light curve is a rotating surface integral

intensity (emitted energy per unit time, area, solid angle, frequency bandwidth)

projection factor $\hat{\boldsymbol{n}} \cdot \hat{\boldsymbol{r}}$

surface element

$$F_{\text{obs}}(\phi) = \int d\omega \, R(\omega) \, \frac{1}{D^2} \int_{\mu>0} I_{\text{S}}(\hat{\boldsymbol{n}}, \boldsymbol{r}, \omega; \phi) \, \mu \, dS$$

direction to observer

photon frequency

visible hemisphere

position on stellar surface

A light curve is a rotating surface integral

intensity (emitted energy per unit time, area, solid angle, frequency bandwidth)

instrumental response

projection factor $\hat{\boldsymbol{n}} \cdot \hat{\boldsymbol{r}}$

surface element

$$F_{\mathrm{obs}}(\phi) = \int d\omega\, R(\omega)\, \frac{1}{D^2} \int_{\mu>0} I_{\mathrm{S}}(\hat{\boldsymbol{n}}, \boldsymbol{r}, \omega; \phi)\, \mu\, dS$$

propagation distance

visible hemisphere

direction to observer

position on stellar surface

photon frequency

A light curve is a rotating surface integral

intensity (emitted energy per unit time, area, solid angle, frequency bandwidth)

instrumental response

projection factor $\hat{\boldsymbol{n}} \cdot \hat{\boldsymbol{r}}$

surface element

$$F_{\text{obs}}(\phi) = \int d\omega \, R(\omega) \, \frac{1}{D^2} \int_{\mu>0} I_{\text{S}}(\hat{\boldsymbol{n}}, \boldsymbol{r}, \omega; \phi) \, \mu \, dS$$

propagation distance

visible hemisphere

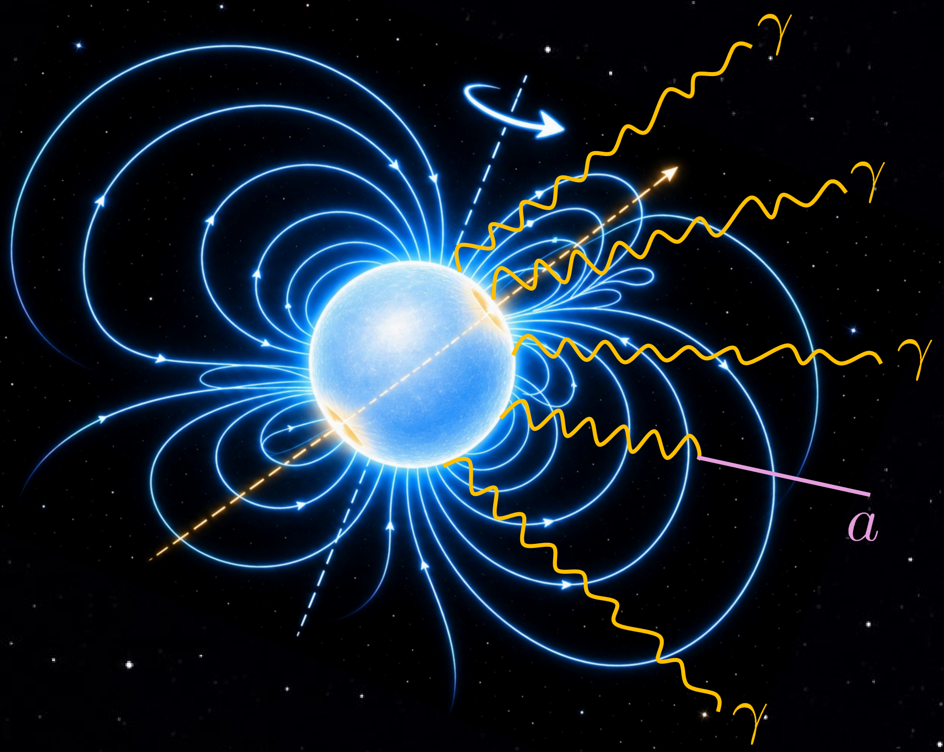
direction to observer

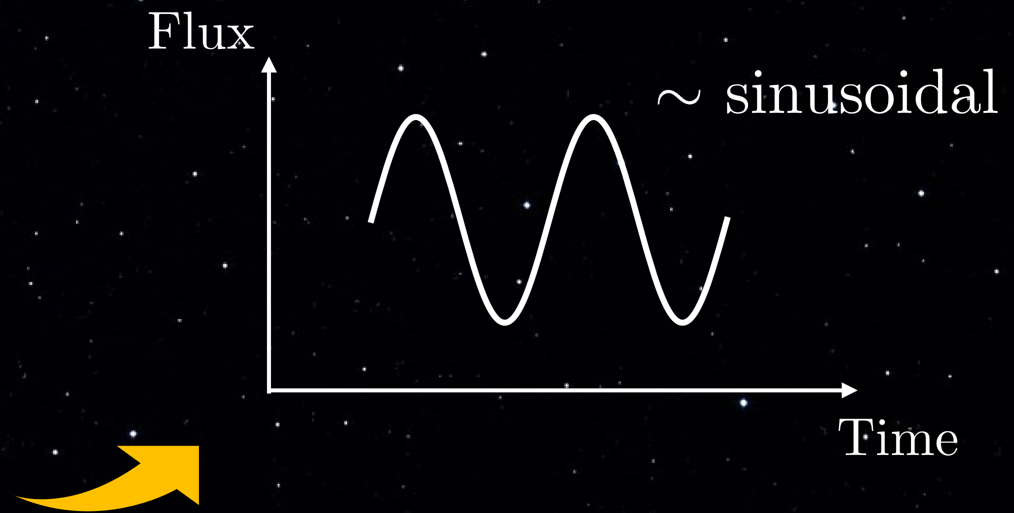
position on stellar surface

photon frequency

Light curve is obtained by painting an intensity map on the stellar surface, rotating the star, and integrating everything that is visible

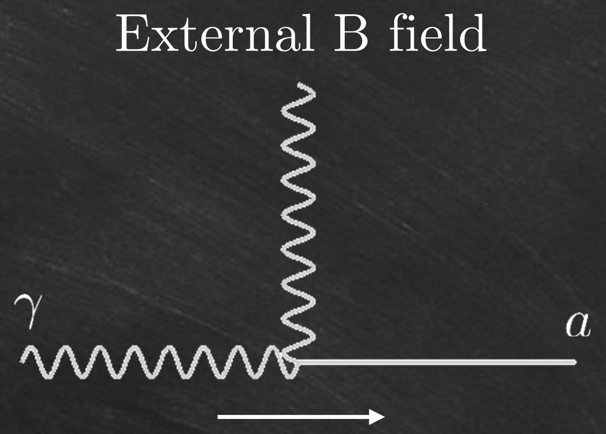
But photons can change identity on the way out...





Axion-photon conversion

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} a \underbrace{F_{\mu\nu} \widetilde{F}^{\mu\nu}}_{\substack{\text{EM tensor} \\ \text{\& dual tensor}}} = g_{a\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$$

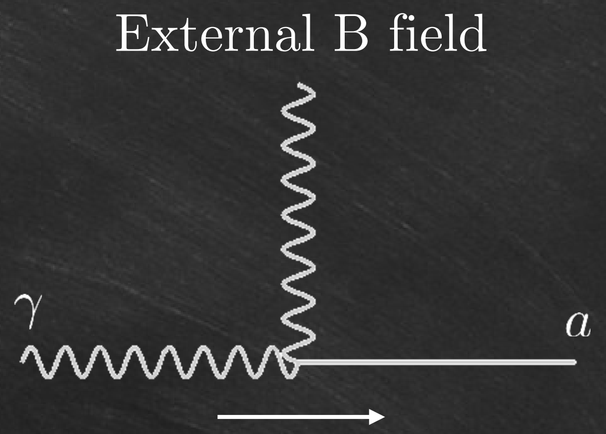


Similar to neutrino oscillations

Raffelt & Stodolsky (PRD, 1988)

Axion-photon conversion

$$\mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} a \underbrace{F_{\mu\nu}\widetilde{F}^{\mu\nu}}_{\substack{\text{EM tensor} \\ \text{\& dual tensor}}} = g_{a\gamma} a \boldsymbol{E}\cdot\boldsymbol{B}$$



Conversion probability

for photons with polarization parallel to B_T

neglecting plasma and nonlinear QED effects

$$P_{a\gamma} = \frac{1}{4} g_{a\gamma}^2 \left| \int_0^s \underbrace{B_T(s')}_{\text{Transverse to trajectory}} \exp\left(i \frac{m_a^2}{2\omega} s' \right) ds' \right|^2$$

Photon survival probability

assuming initially unpolarized light

$$P_{\gamma\gamma} \simeq 1 - \frac{1}{2} P_{a\gamma}$$

Raffelt & Stodolsky (PRD, 1988)

Flux in the presence of axions

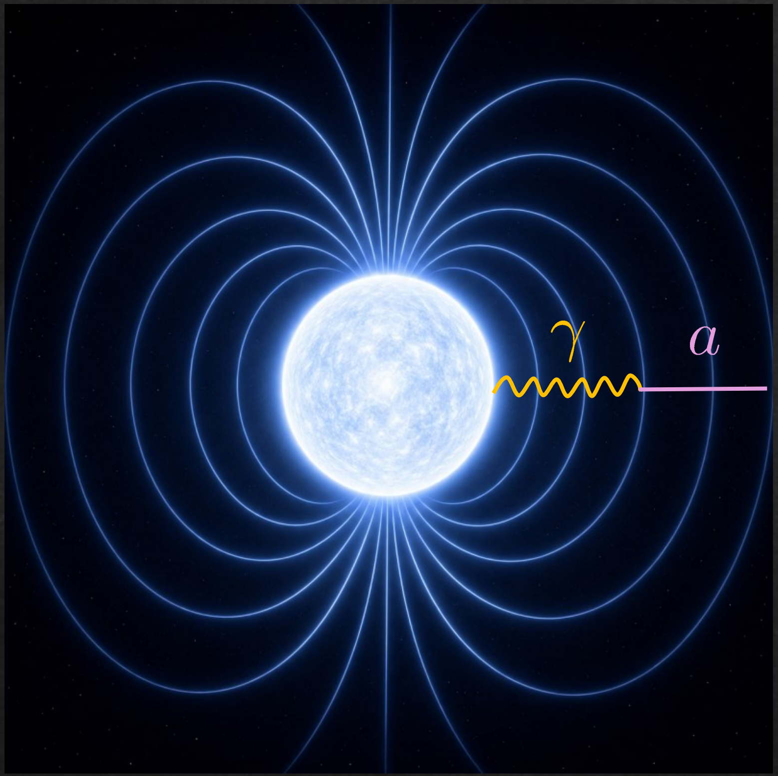
$$F_{\text{obs}}(\phi) = \int d\omega\, R(\omega)\, \frac{1}{D^2} \int_{\mu>0} I_{\text{S}}(\hat{\boldsymbol{n}}, \boldsymbol{r}, \omega; \phi)\, P_{\gamma\gamma}(\boldsymbol{r}; \phi)\, \mu\, dS$$

$$\equiv F_{\text{bkg}}(\phi) \langle P_{\gamma\gamma} \rangle_{\text{S}}(\phi)$$

$$\text{Phase dependence} \begin{cases} \text{originates at stellar surface } F_{\text{bkg}}(\phi) \\ \text{(conventional interpretation)} \\ \\ \text{modulated in the magnetosphere } \langle P_{\gamma\gamma} \rangle_{\text{S}}(\phi) \\ \text{(with axions)} \end{cases}$$

How important is axion-photon conversion?

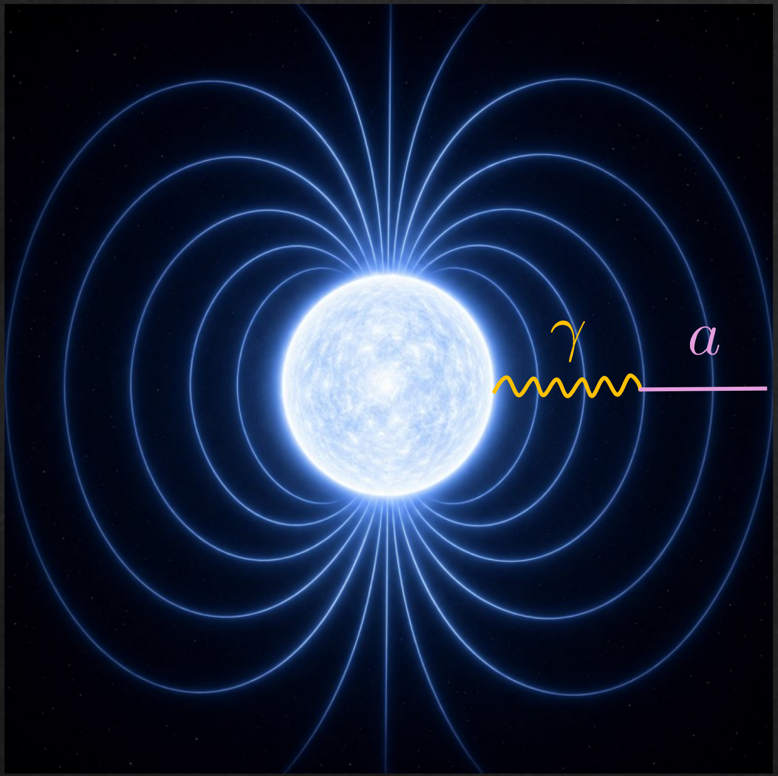
A magnetic dipole



$$B_{\mathrm{T}}(s) \sim B_0 \left(\frac{R_\star}{R_\star + s} \right)^3$$

How important is axion-photon conversion?

A magnetic dipole



$$B_{\mathrm{T}}(s) \sim B_0 \left(\frac{R_\star}{R_\star + s}\right)^3$$

$$P_{a\gamma} = \frac{1}{4} g_{a\gamma}^2 \left| \int_0^s B_{\mathrm{T}}(s') \underbrace{\exp\left(i \frac{m_a^2}{2\omega} s'\right)}_{} ds' \right|^2$$

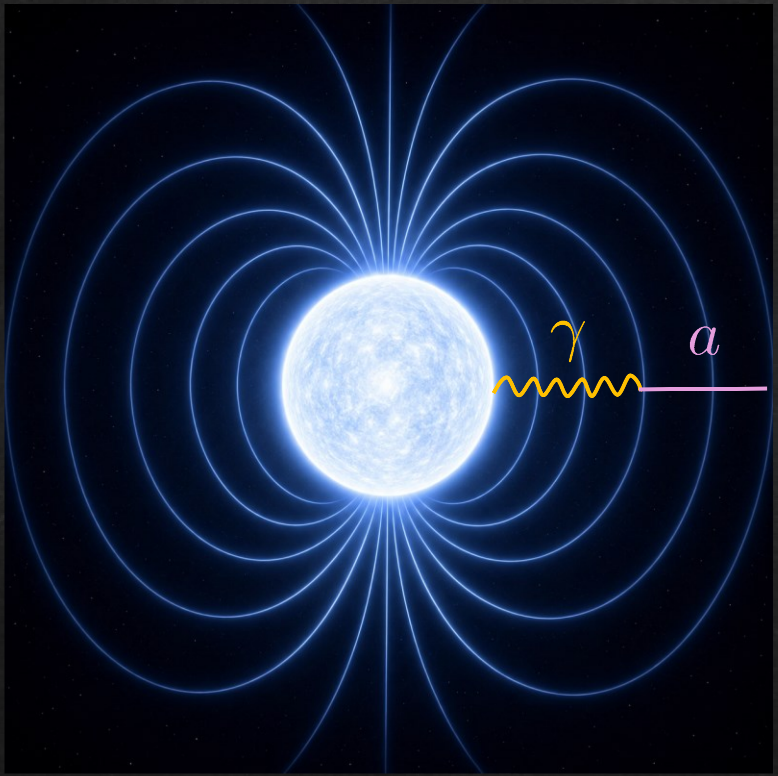
mass-dependence is negligible for

$$m_a \ll 2 \times 10^{-7} \mathrm{eV} \left(\frac{\omega}{1\,\mathrm{eV}}\right)^{1/2} \left(\frac{0.01 R_\odot}{R_\star}\right)^{1/2}$$

$$P_{a\gamma} \sim 0.03 \left(\frac{g_{a\gamma}}{10^{-11}\mathrm{GeV}^{-1}}\right)^2 \left(\frac{B_0}{100\,\mathrm{MG}}\right)^2 \left(\frac{R_\star}{0.01 R_\odot}\right)^2$$

How important is axion-photon conversion?

A magnetic dipole



$$P_{a\gamma} = \frac{1}{4} g_{a\gamma}^2 \left| \int_0^s B_{\mathrm{T}}(s') \exp\left(i \frac{m_a^2}{2\omega} s' \right) ds' \right|^2$$

mass-dependence is negligible for

$$m_a \ll 2 \times 10^{-7}\mathrm{eV} \left(\frac{\omega}{1\,\mathrm{eV}} \right)^{1/2} \left(\frac{0.01 R_\odot}{R_\star} \right)^{1/2}$$

$$P_{a\gamma} \sim 0.03 \left(\frac{g_{a\gamma}}{10^{-11}\mathrm{GeV}^{-1}} \right)^2 \left(\frac{B_0}{100\,\mathrm{MG}} \right)^2 \left(\frac{R_\star}{0.01 R_\odot} \right)^2$$

$$B_{\mathrm{T}}(s) \sim B_0 \left(\frac{R_\star}{R_\star + s} \right)^3$$

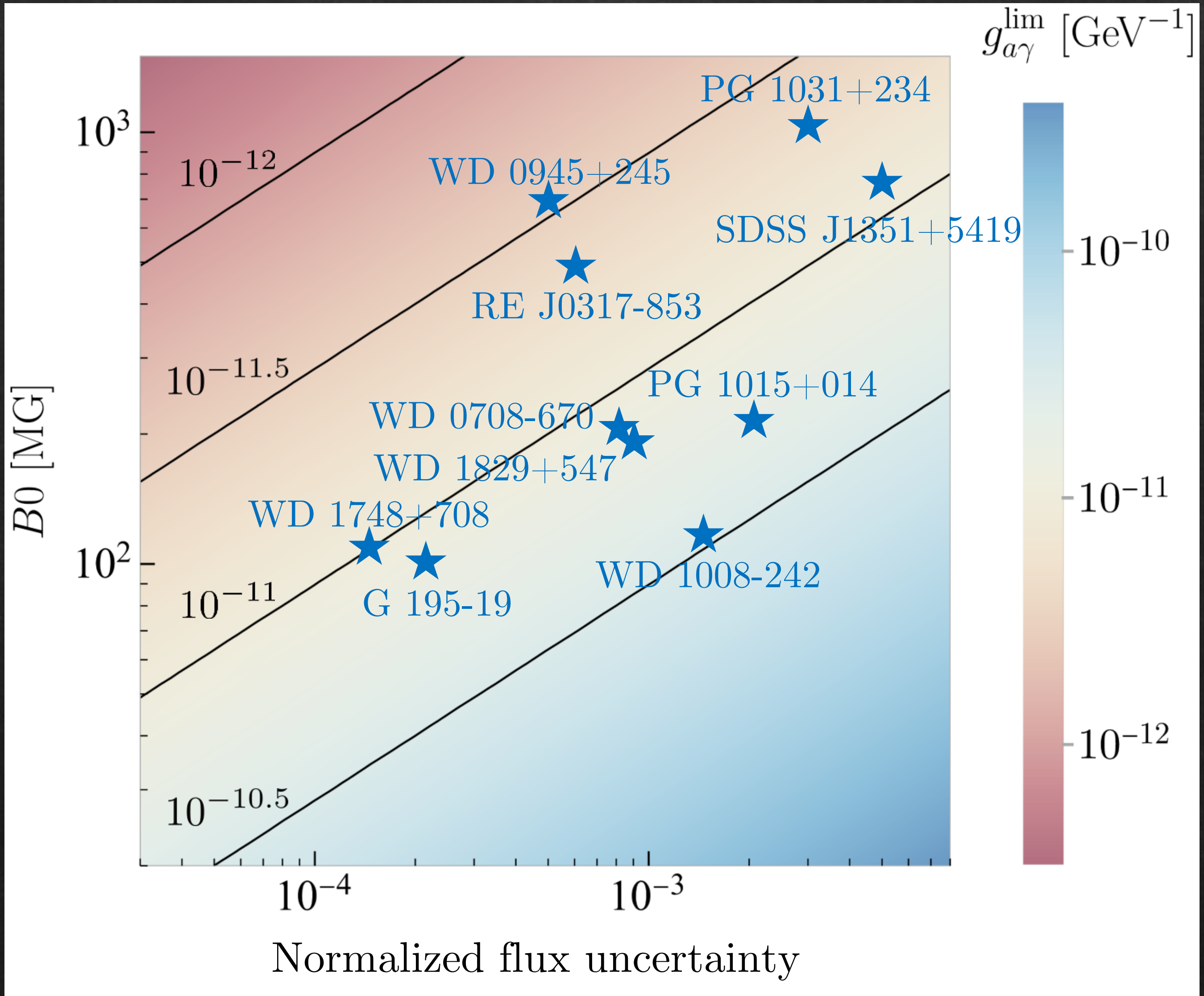
$$\langle P_{a\gamma} \rangle_{\mathrm{S}} \equiv x P_{a\gamma}$$

surface-averaging factor
(i.e., not every location has strong B fields)

Is this research worth pursuing?

The modulation can be probed if

$$\text{data uncertainty} \lesssim \frac{1}{2}\langle P_{a\gamma}\rangle\text{s}$$



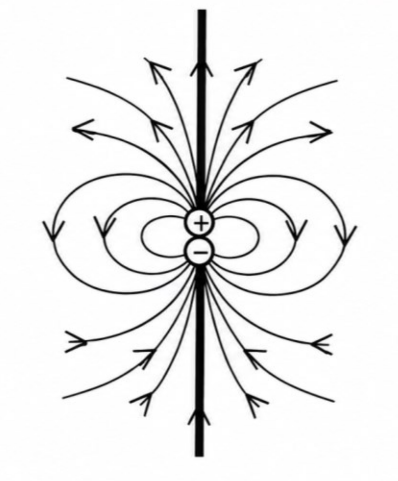
Magnetic fields are taken from Ferrario+ (Space Sci. Rev., 2015), Bagnulo+ (A&A, 2024)

assuming $R_\star = 0.009 R_\odot\,,\ x = 0.05$

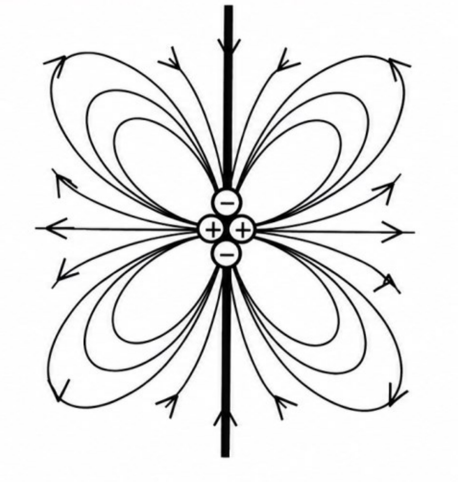
But real MWDs are not centered dipoles...

Current-free magnetosphere: $\boldsymbol{B} = -\nabla \Phi_B$

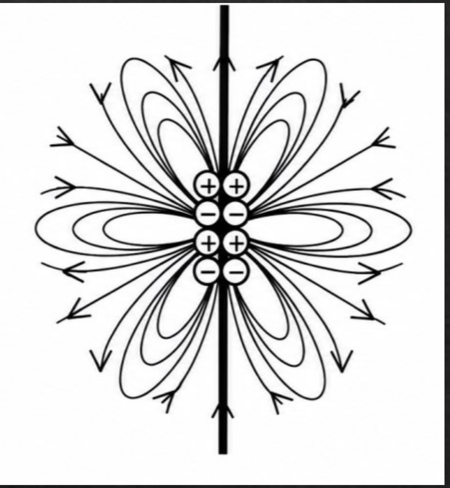
$$\Phi_B = -R_\star \sum_{l=1}^{l=l_{\max}} \sum_{m=0}^{l} \left(\frac{R_\star}{r'}\right)^{l+1} P_l^m(\cos\theta')[g_l^m \cos(m\varphi') + h_l^m \sin(m\varphi')]$$



Dipole
$l = 1$



Quadrupole
$l = 2$



Octupole
$l = 3$

Determining magnetic geometry from Zeeman tomography

$B(\theta, \varphi)$

↓

Local Zeeman spectra

↓

Disk-integrated
flux & circular pol.

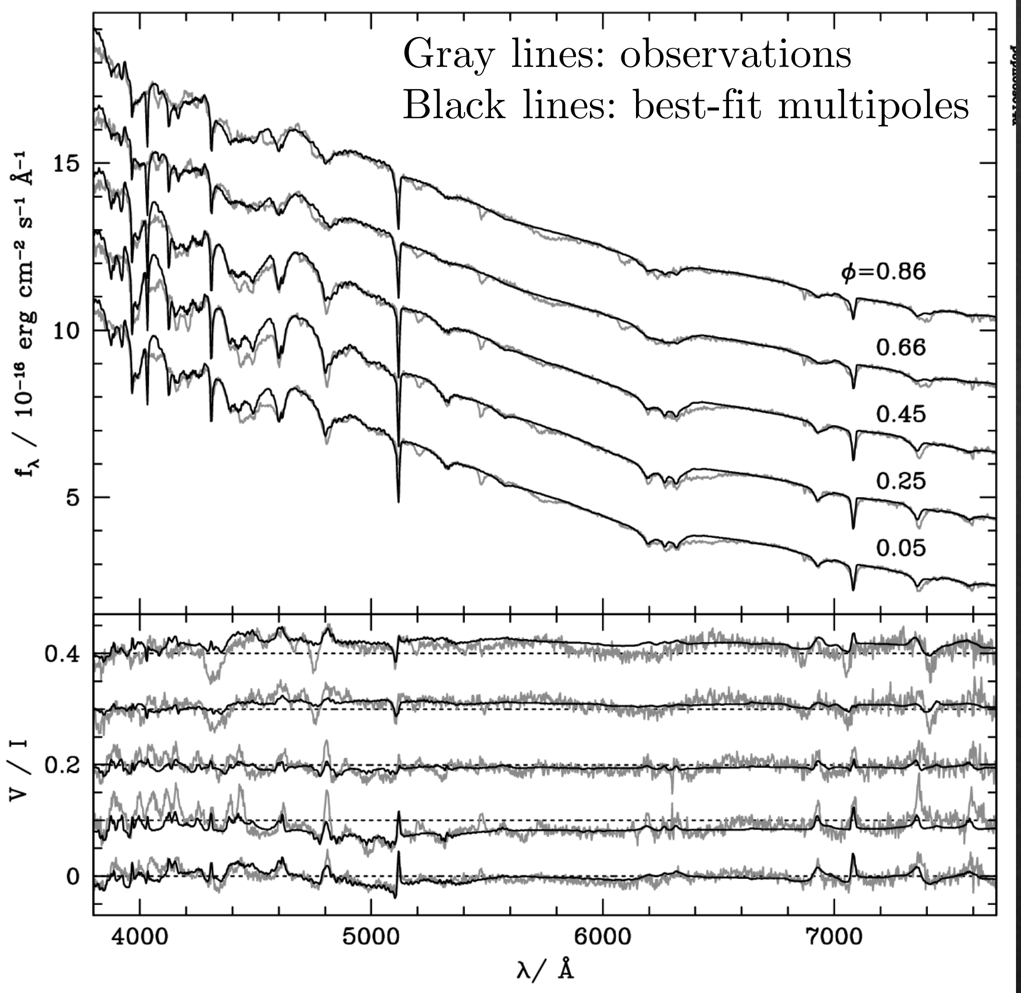
↓

Rotational modulation

↓

Inverse reconstruction

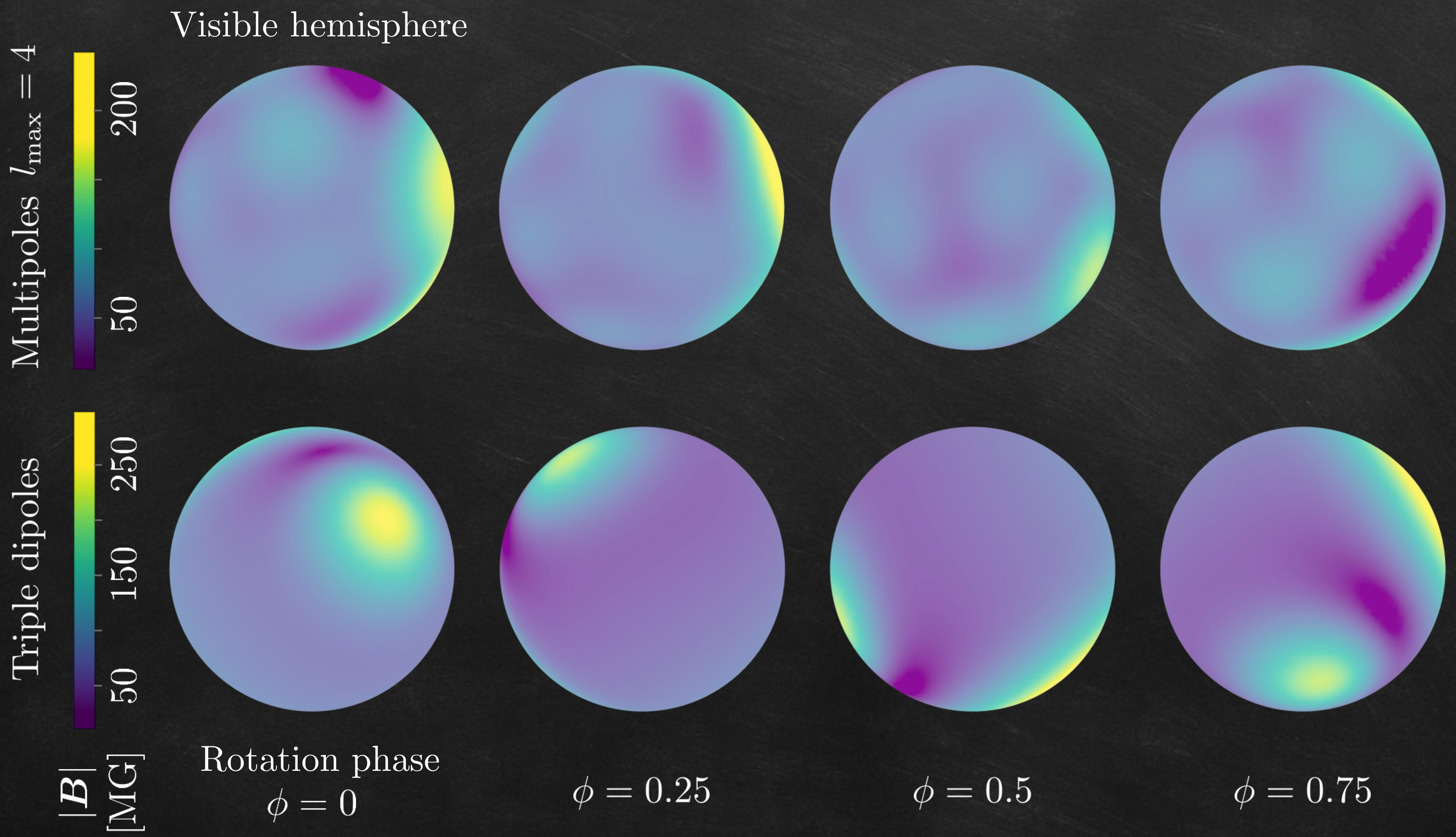
Flux and circular pol. spectra of PG1015+014



Three off-centered dipoles & multipoles both fit well

Euchner+ (A&A, 2006)

Surface magnetic fields for PG 1015+014



From a magnetic map to a synthetic light curve

$$F_{\rm obs}(\phi) \left\{ \begin{array}{l} \text{A phenomenological background light curve model } F_{\rm bkg}(\phi) \\ \text{Surface-averaged photon's survival probability } \langle P_{\gamma\gamma}\rangle_{\rm S}(\phi) \end{array} \right.$$

A phenomenological background light curve model $F_{\rm bkg}(\phi)$

$$F_{\rm bkg}(\phi) = \theta_0 + \sum_{n=1}^{N_{\rm bkg}} \left[\theta_{2n-1}\sin(2\pi n\phi) + \theta_{2n}\cos(2\pi n\phi)\right]$$

($N_{\rm bkg}$ encodes uncertainties about intrinsic stellar variability, e.g., radiative transport, surface temperature, Zeeman opacity, limb-darkening, etc.)

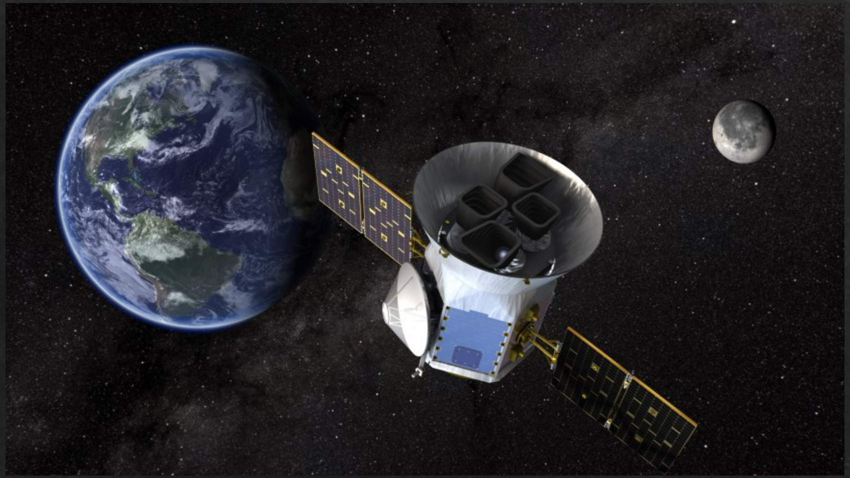
(Approximately sinusoidal for a sizable fraction of MWDs)

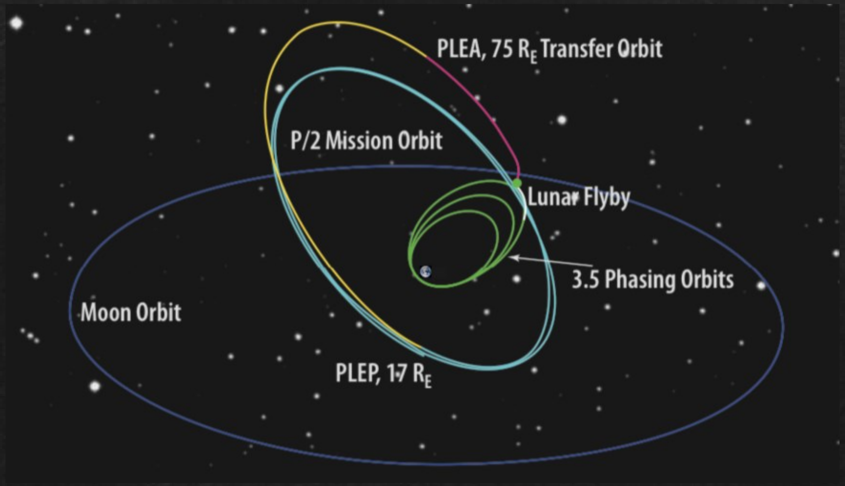
Surface-averaged photon's survival probability $\langle P_{\gamma\gamma}\rangle_{\rm S}(\phi)$

(Surface rays $\to \boldsymbol{B}(s) \to \gamma - a$ evolution $\to$ disk integration)

(Typically polychromatic due to complex magnetic geometry)

Transiting Exoplanet Survey Satellite (TESS)



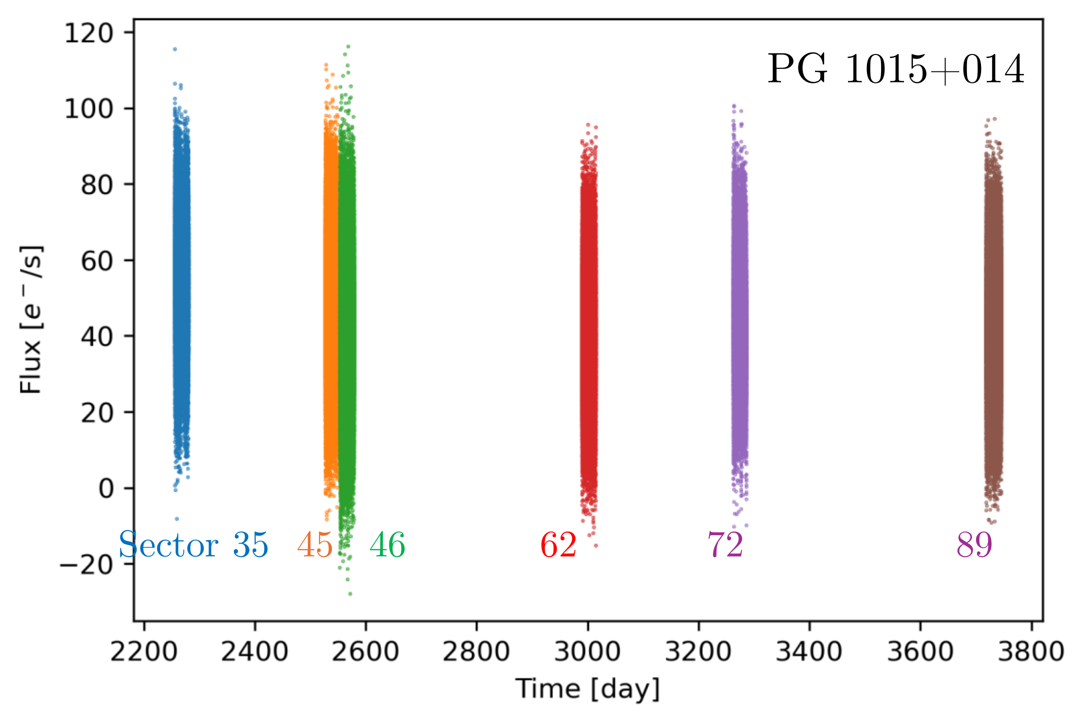


- Launched on a SpaceX Falcon 9 Rocket in 2018
- Scientific goals: Exoplanets, stars, supernovae, galaxies, asteroids
- Measures brightness variations in an optical band, $\lambda \sim 600 - 1000\text{nm}$
- High cadence, including 20s/120s products for selected targets
- Robust pipelines to remove photometry systematics
- Supports python module "lightkurve" for data downloads

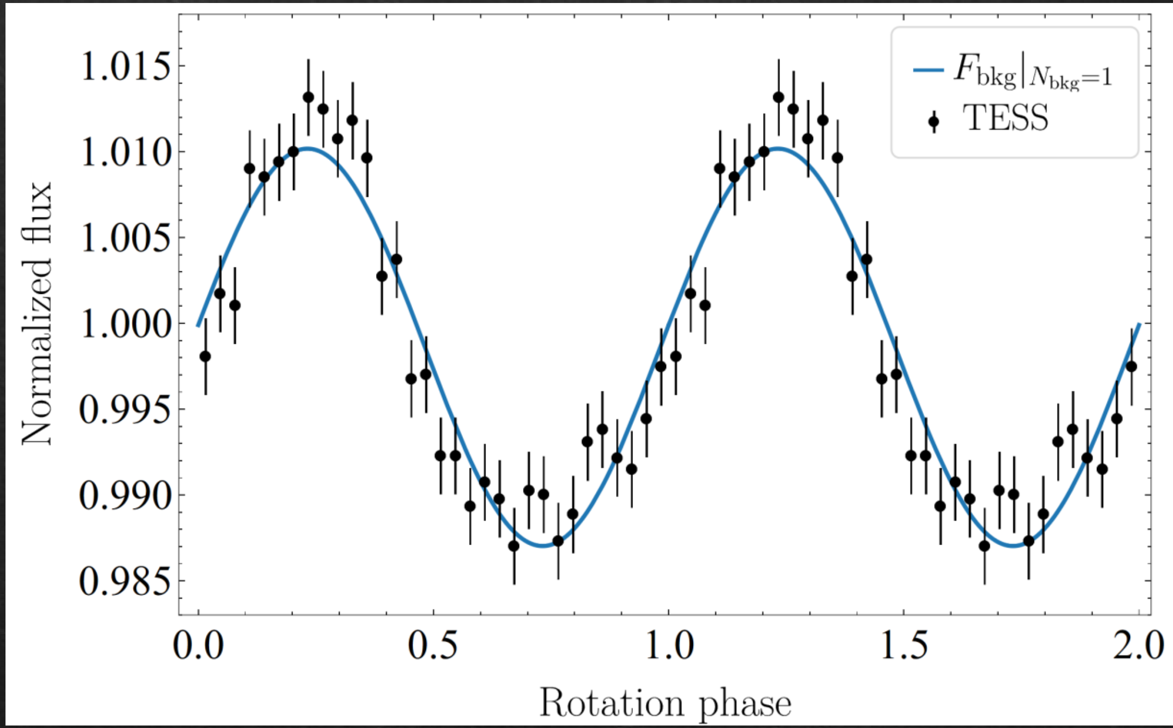
https://tess.mit.edu/mission-overview/
https://heasarc.gsfc.nasa.gov/docs/tess/what-is-tess.html

What the telescope actually reports

Phase folding: $\phi = \mathrm{mod}\left(\frac{t - t_0}{P}, 1\right)$

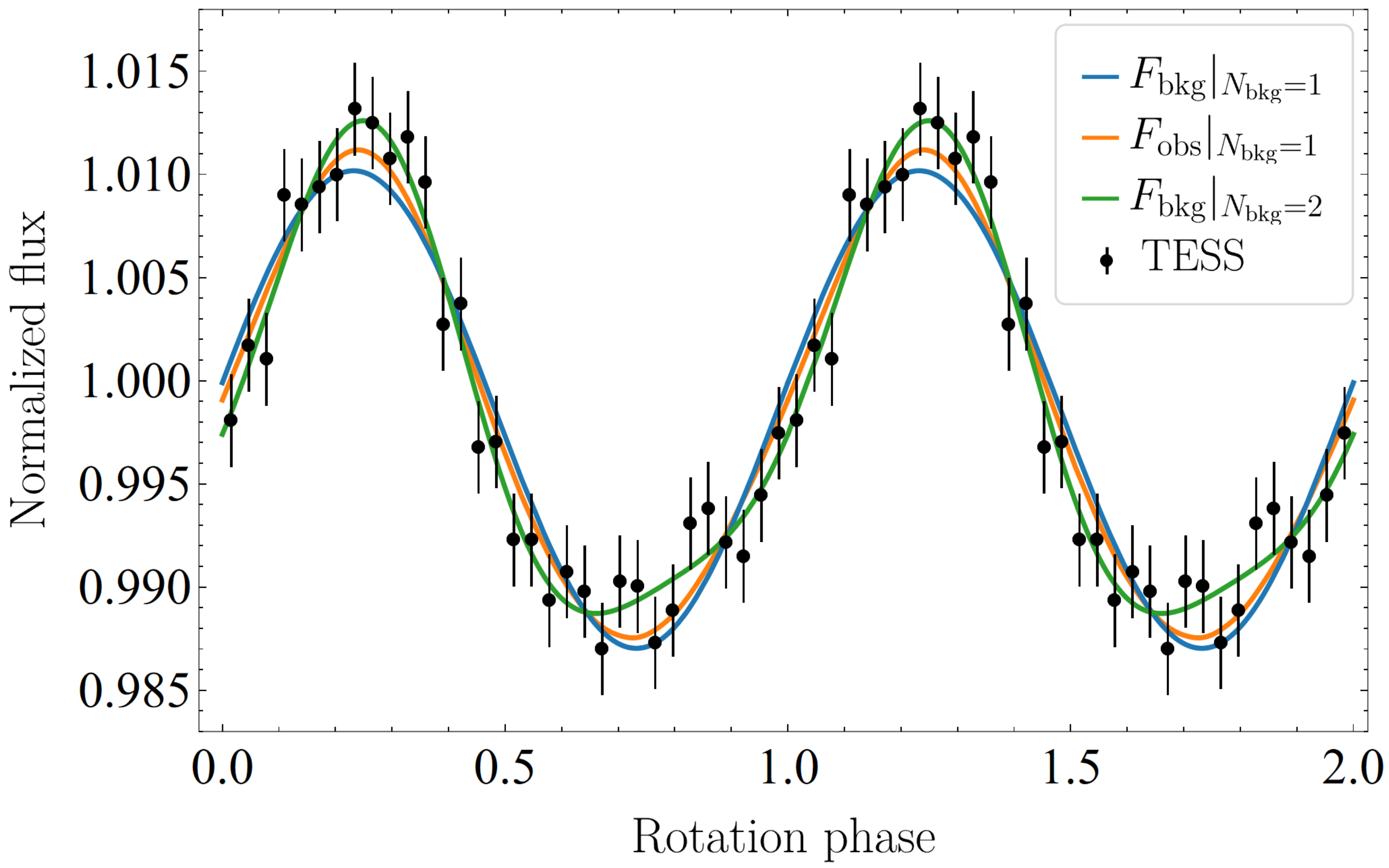


Each sector ~ 27 days



Data suggests deviations from a simple sinusoidal curve (N_{bkg}=1)

One deviation, two possible explanations



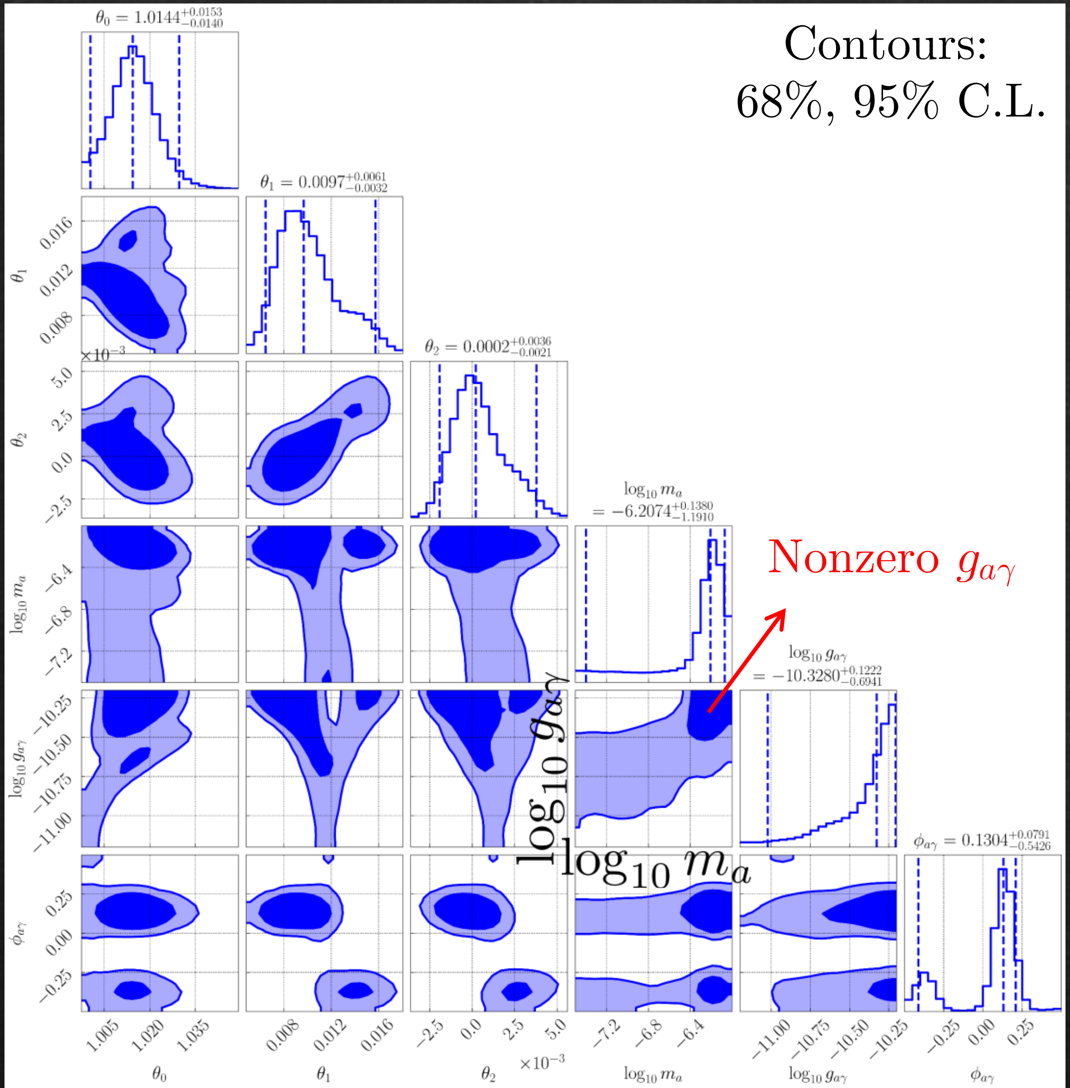
Sinusoidal bkg

Sinusoidal bkg + axion

Two-harmonic bkg

What produces the deviation from a sinusoidal?

Posterior distribution for sinusoidal bkg + axion



Background model

Axion portal

Comparing to Nbkg=2 background-only model:

$\Delta\chi^2 = 9.94$ (Chi-square)

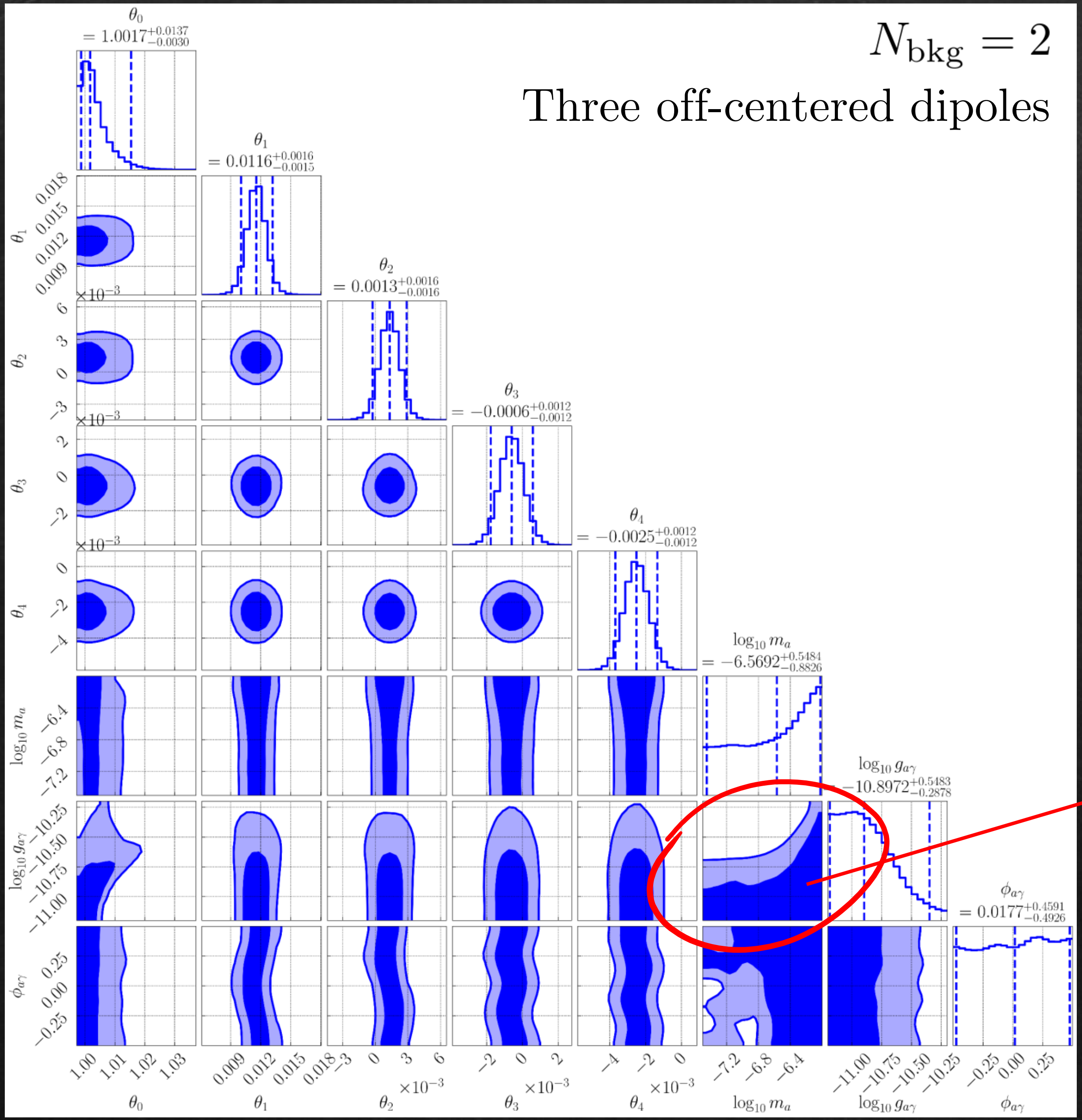
$\Delta\mathrm{AIC} = 11.94$ (Akaike Information Criterion)

$\Delta\mathrm{BIC} = 13.52$ (Bayesian Information Criterion)

Both AIC and BIC penalize for more model parameters; $\Delta > 10$ indicates strong preference

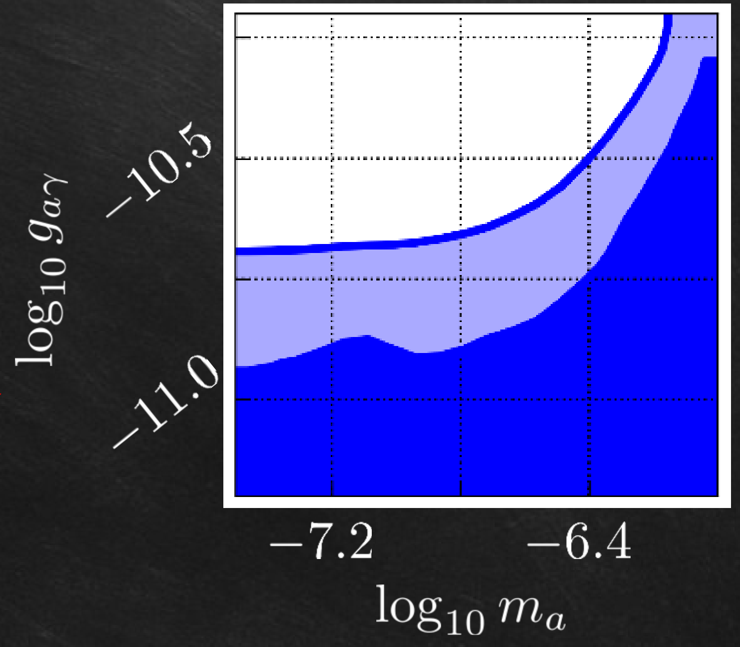
Axion explanation for the deviation from a sinusoidal is highly disfavored

Axion constraints from PG 1015+014

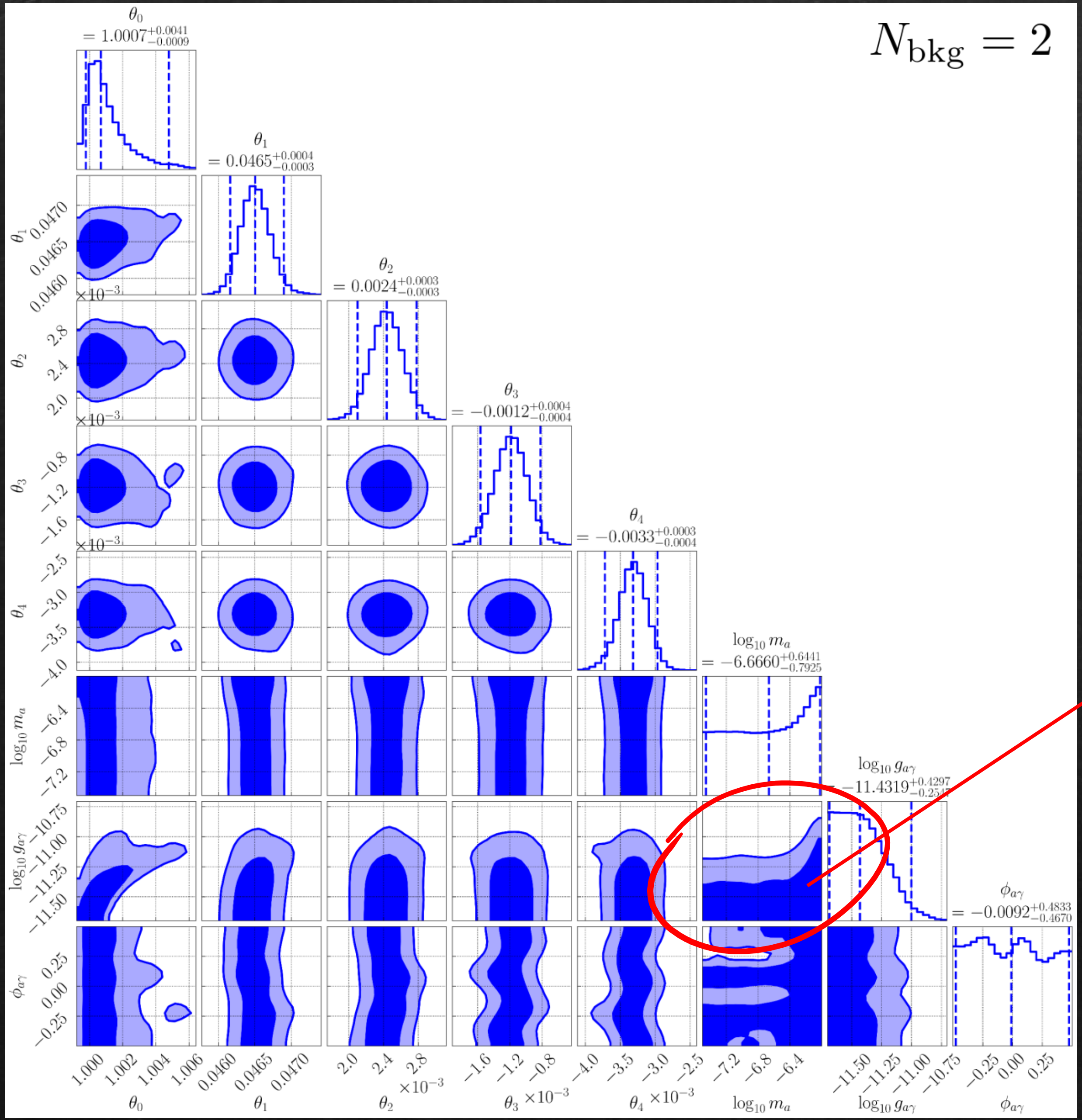


For $m_a < 2 \times 10^{-7}\text{eV}$

$g_{a\gamma} < 2 \times 10^{-11}\text{GeV}^{-1}$ (95% C.L.)

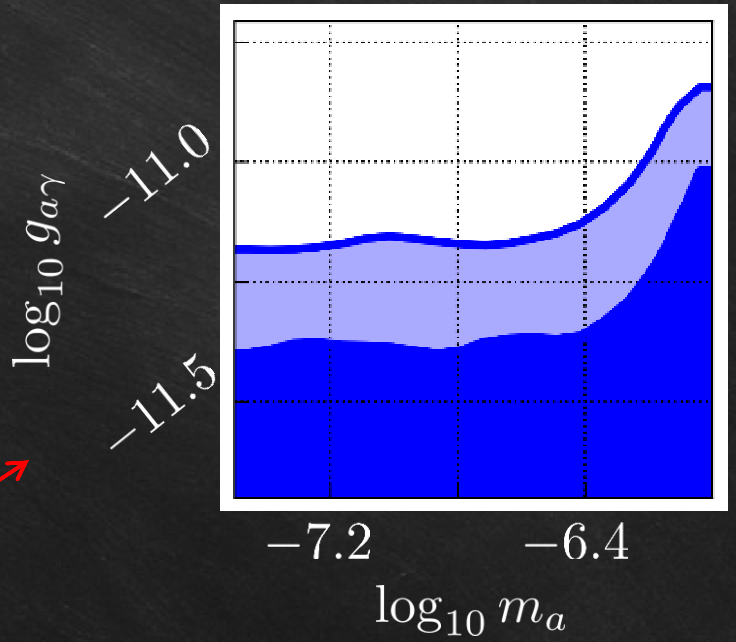


Axion constraints from RE J0317-853



For $m_a < 2 \times 10^{-7}\,\mathrm{eV}$

$g_{a\gamma} < 6 \times 10^{-12}\,\mathrm{GeV}^{-1}$ (95% C.L.)

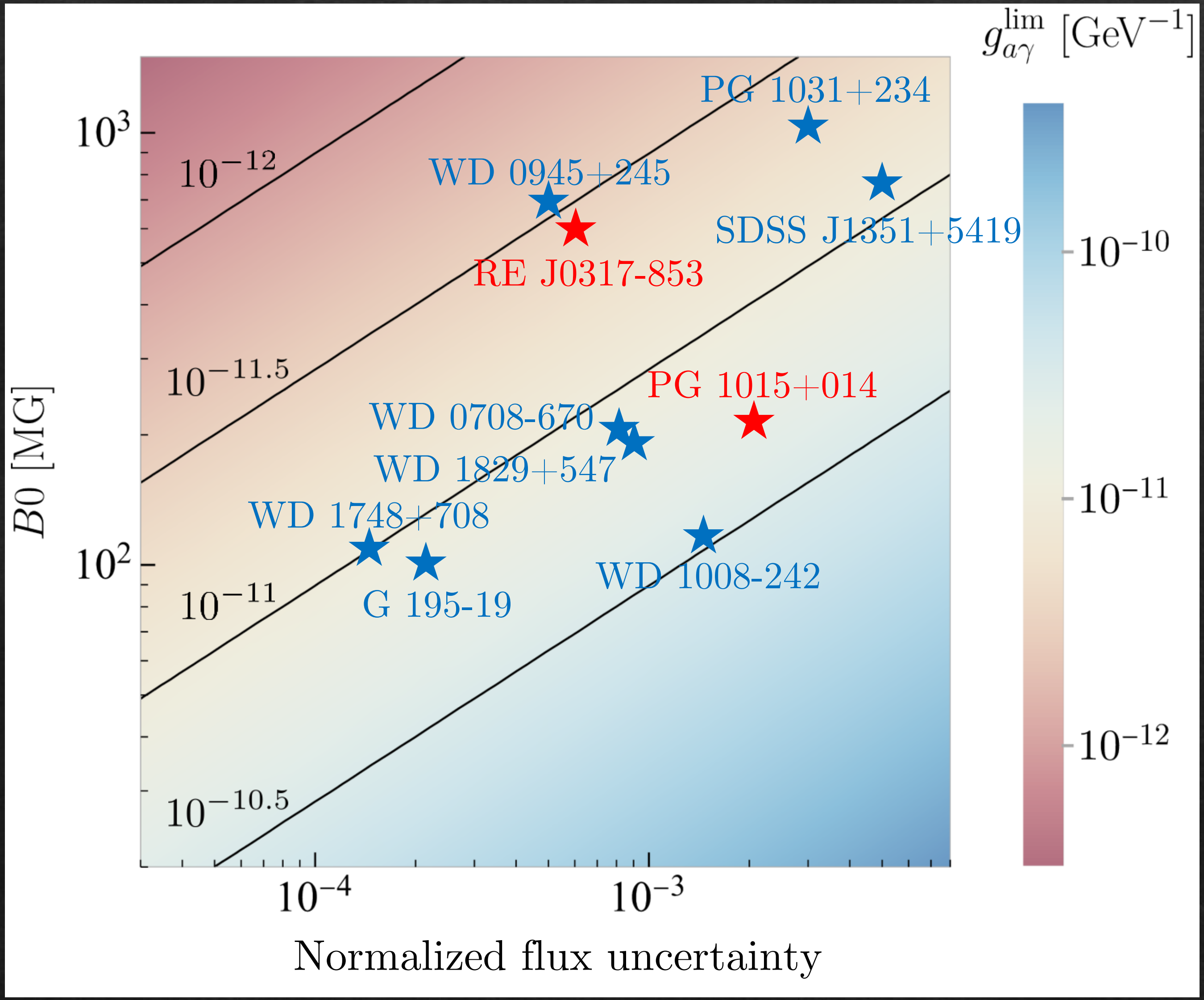


Current best bound for sub-μeV axions

MWD polar.: $g_{a\gamma} \lesssim 2 \times 10^{-12}\,\mathrm{GeV}^{-1}$

Benabou+ (2504.12377)

Outlook

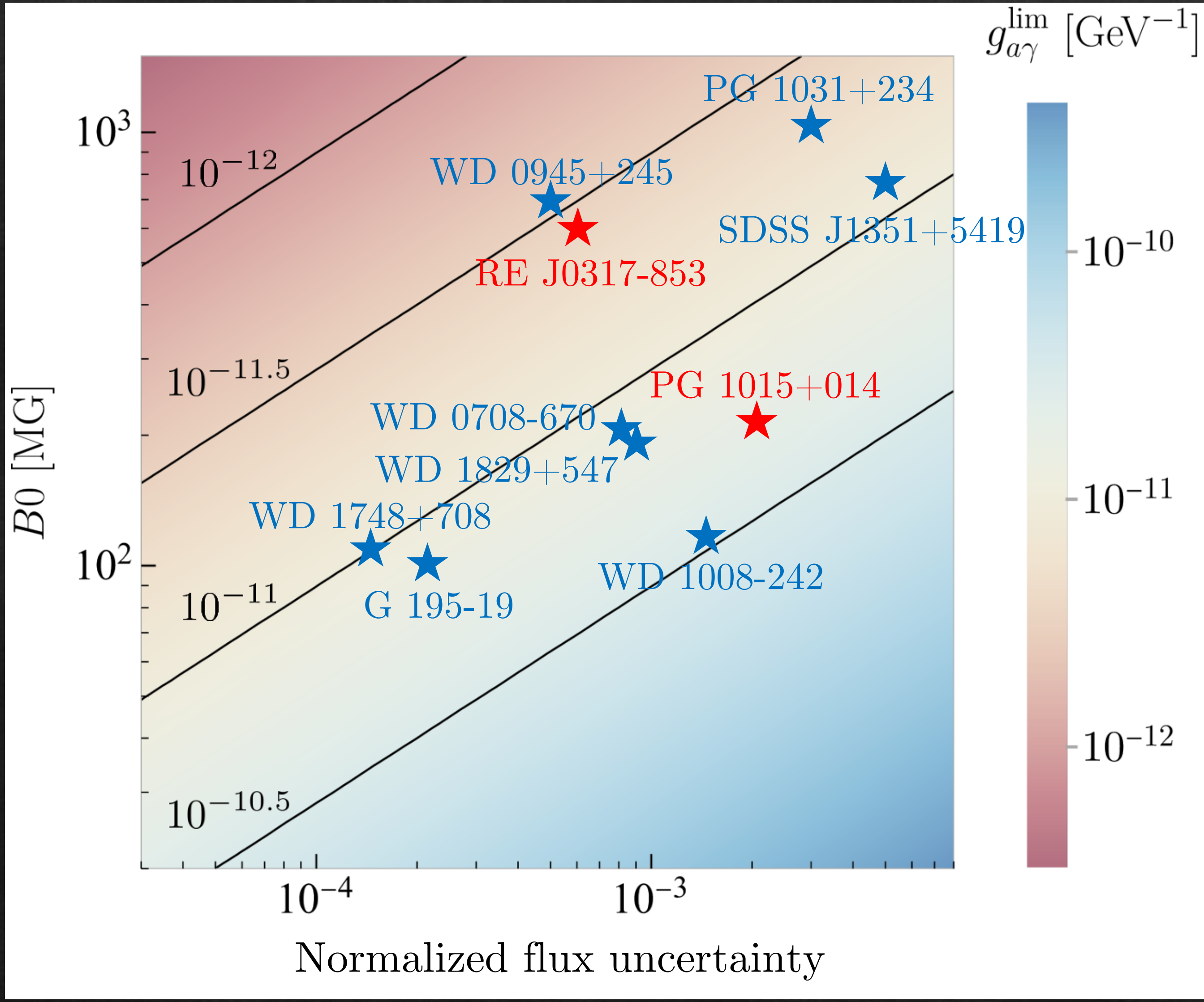


Data number ↑
Flux uncertainty ↓
Axion sensitivity ↑

“We will win by waiting”

Proj. based on existing TESS data and dipolar field assumptions

Outlook



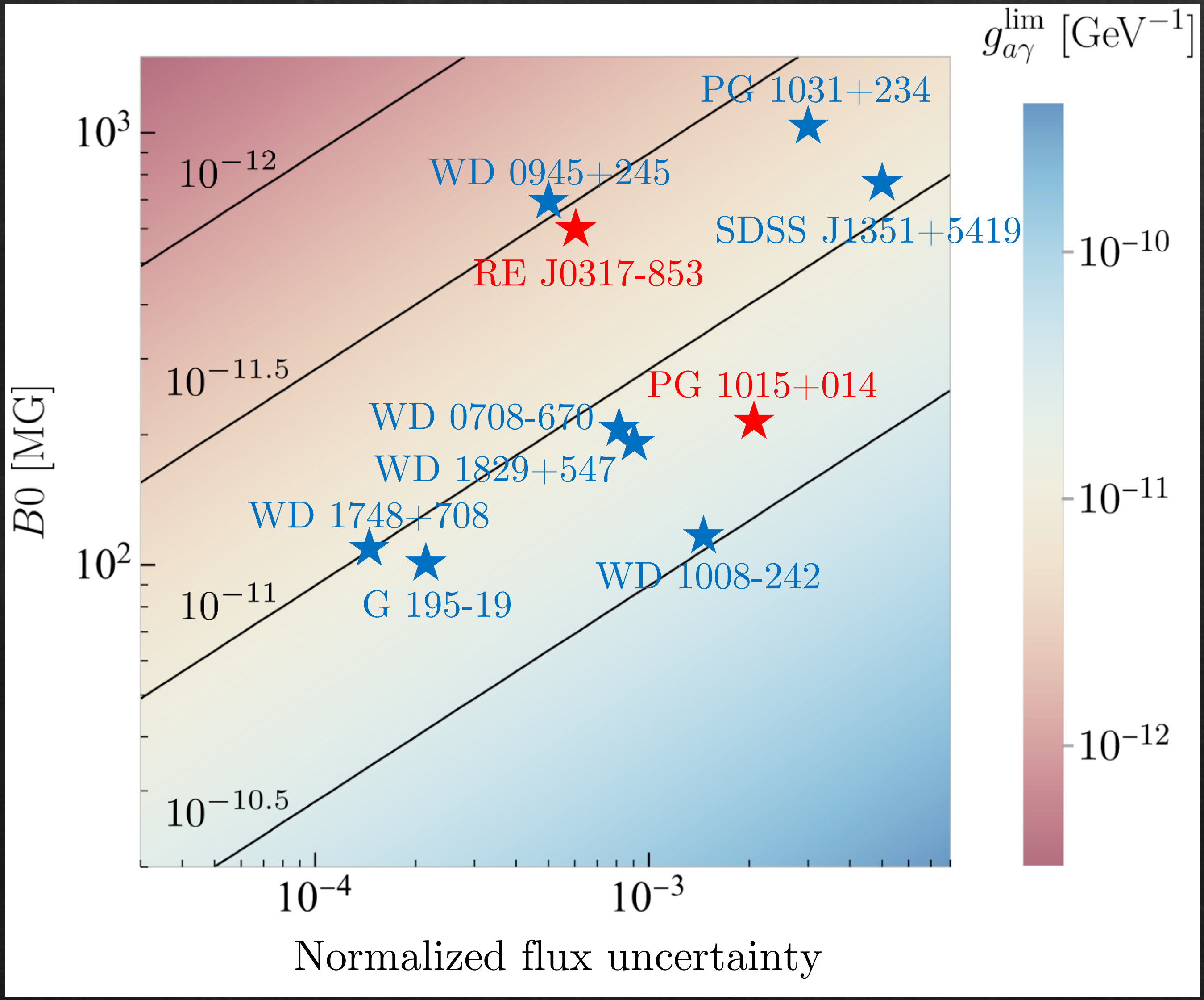
$$\sigma \propto \frac{1}{\sqrt{N}} \propto \frac{1}{\sqrt{t}}$$

$\gtrsim \mathcal{O}(100)\mathrm{yr}$ for OoM improvements

"Waiting was our strategy,
madness was the outcome"

Proj. based on existing TESS data and dipolar field assumptions

Outlook



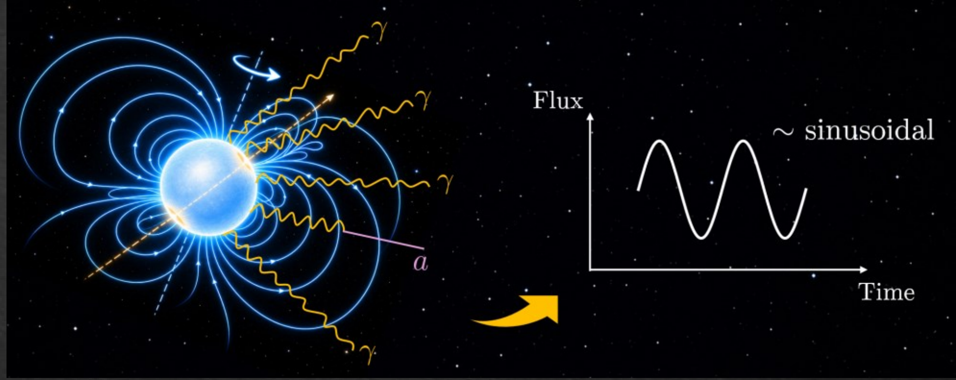
New surveys:

- Rubin/LSST (Chile, began on Jun 2026)
- Roman/WFIRST (NASA, to be launched Aug 2026)
- Xuntian/CSST (China, to be launched in 2027)

new MWDs
+
better precision

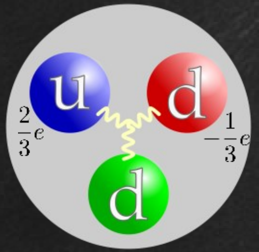
Proj. based on existing TESS data and dipolar field assumptions

Summary

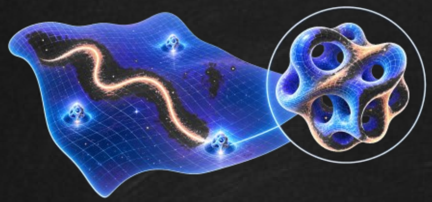


- MWDs as time-domain axion laboratories:
  - Strong B fields
  - Phase-resolved magnetic models by Zeeman tomography
  - Rich data availability (TESS, Rubin, Roman, Xuntian)
  - Targets with ~ sinusoidal light curves
- A controlled background-degeneracy framework:
  - Flexible background light curve
  - Modulation from photon-axion conversion
- What we can learn: Axion constraints & evidence

Why care about all of these? Top-down vs. bottom-up



✓ Strong CP problem



✓ String compactification

✓ A minimal, model-independent extension of the Standard Model (EFT)

✓ Good dark matter candidates with natural production mechanisms

✓ Low-hanging fruit: theoretically well-motivated, experimentally inexpensive

✓ Intellectual benefits: new theory, pheno, method for wavelike massive particles

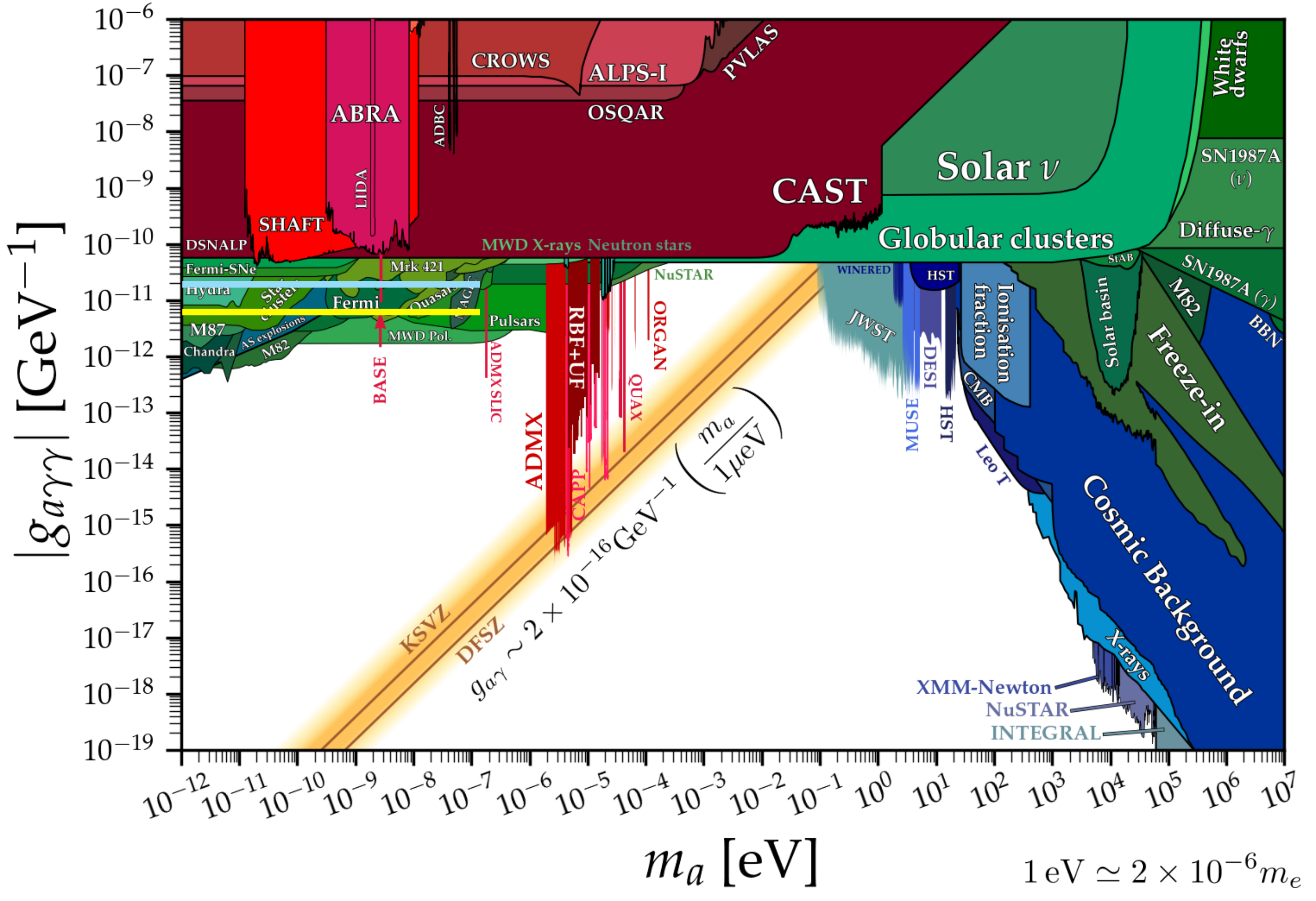
Where do our bounds sit?

Red: Terrestrial experiments

PG 1015+014

RE J0317-853

Yellow: QCD axions



Green: Cosmo/astro (w/o assuming axion DM)

Blue: Cosmo/astro (assuming axion DM)

https://cajohare.github.io/AxionLimits