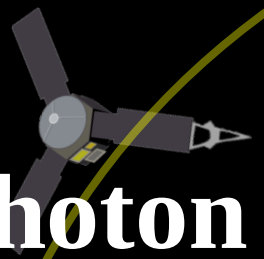


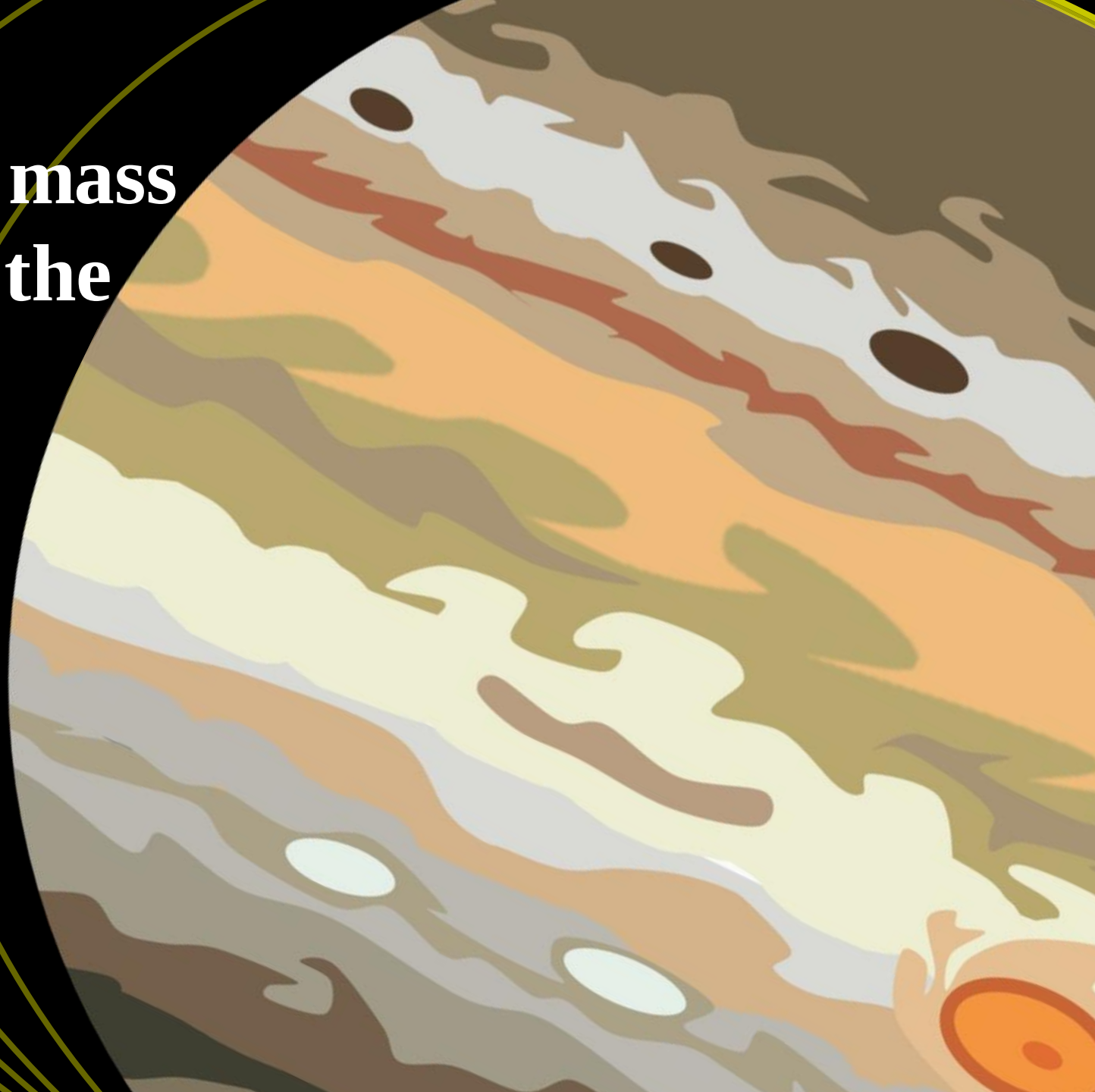
Constraints on photon mass and dark photon from the Jovian magnetic field

Shi Yan Brown University

May.16’th 2024

PHENO

Based on arXiv:2312.06746, accepted by JHEP with Lingfeng Li and JiJi Fan



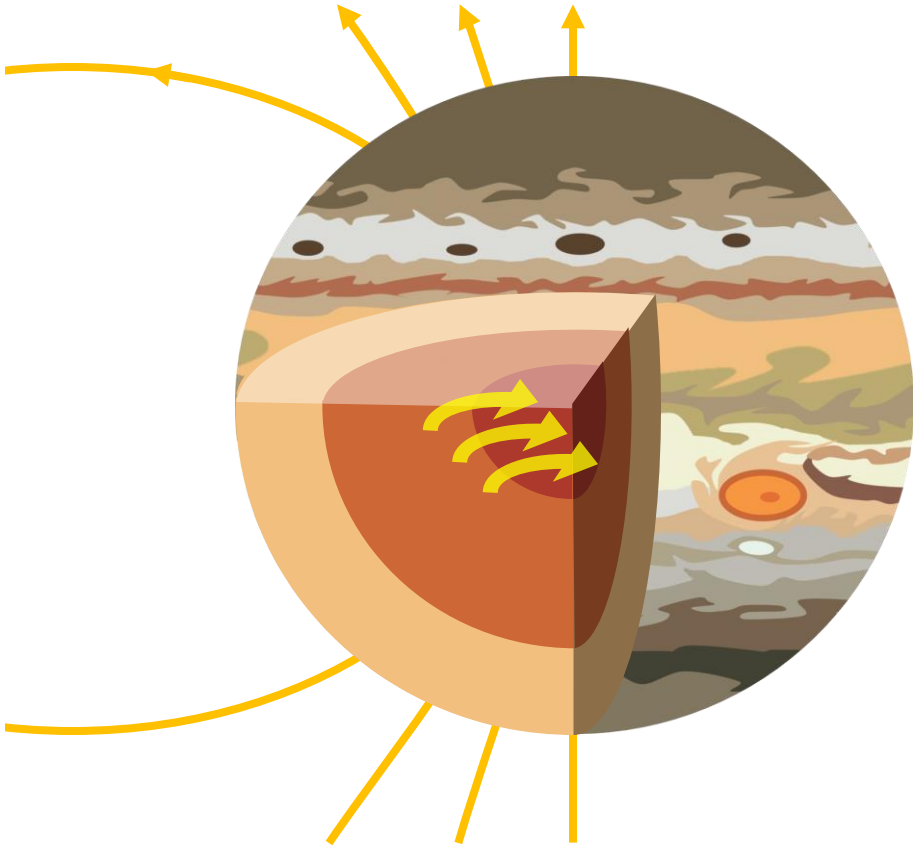
Why Jupiter

- Ideal way to test Maxwell equation
- Largest planet in solar system
- Strong magnetic field
- Relatively stable
- Enough *in situ* measurements (Pioneer, Galileo, Juno etc.)

New Physics and Jupiter

Massive Photon $\longrightarrow \mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{m_\gamma^2}{2}A^\mu A_\mu$ (Mass Term)

Dark Photon $\longrightarrow \mathcal{L} \supset -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}X^{\mu\nu}X_{\mu\nu} + \frac{\epsilon}{2}F^{\mu\nu}X_{\mu\nu} + \frac{m_X^2}{2}X^\mu X_\mu$ (Mixing Term)



Dynamo Current ⟶ B field

$$\Delta B_{dark} \propto \epsilon^2 e^{-m_X r}$$

$\epsilon \to 0$

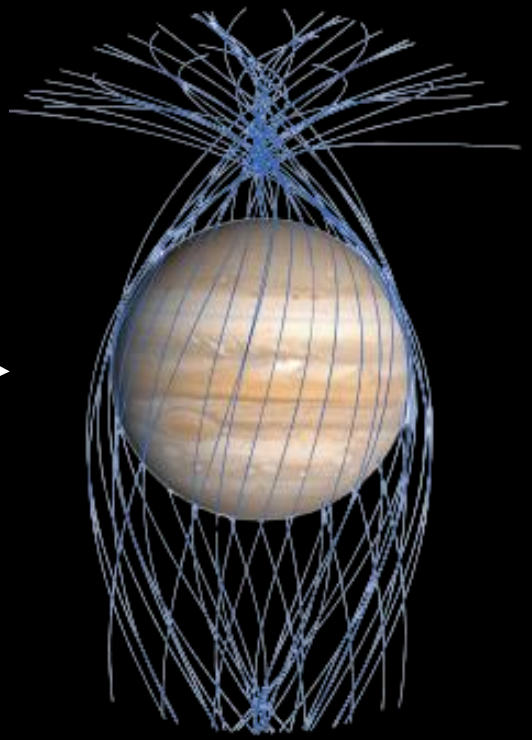
$m_X \to 0$ ⟶ $\Delta B_{dark} \to 0$

$m_X \to \infty$

Juno Mission (2011-)

Closest Approach 3000 km

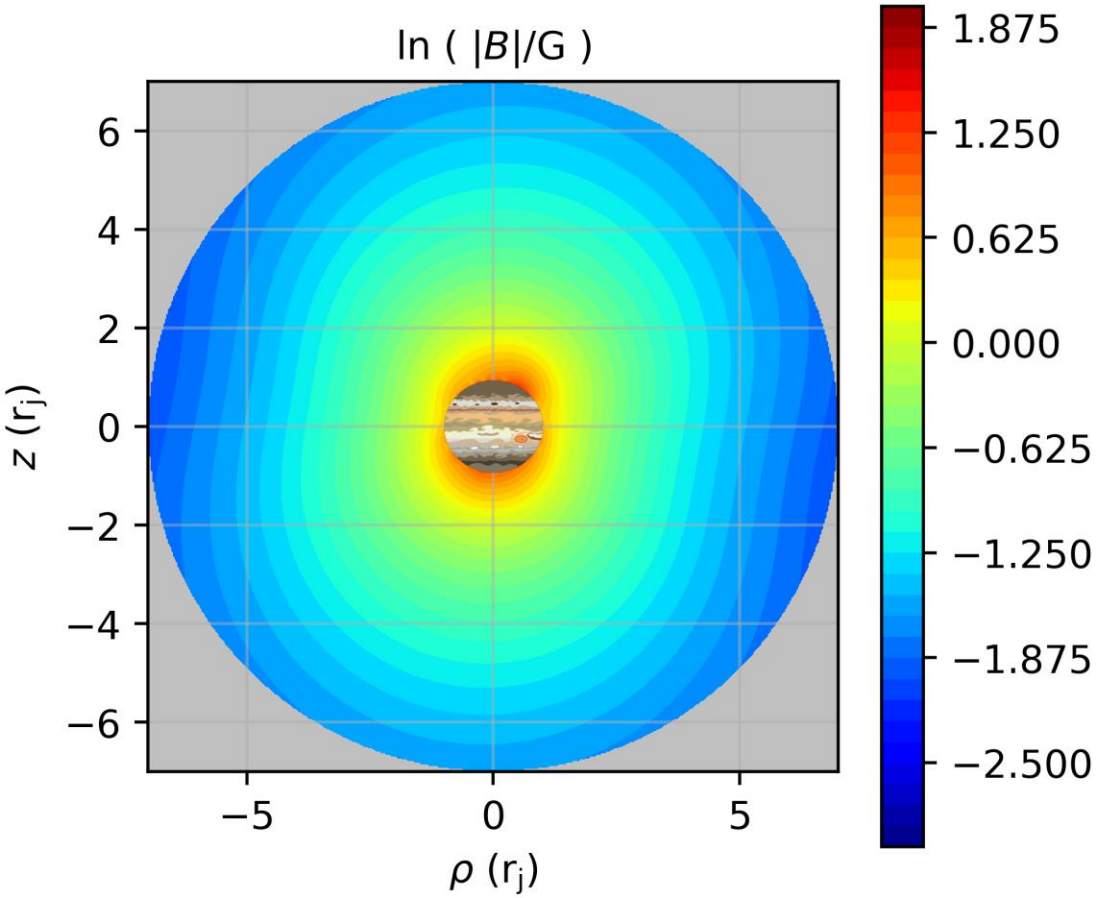
Wide Spatial Coverage



Rich Data Base
From 40 Orbits
2016-2023

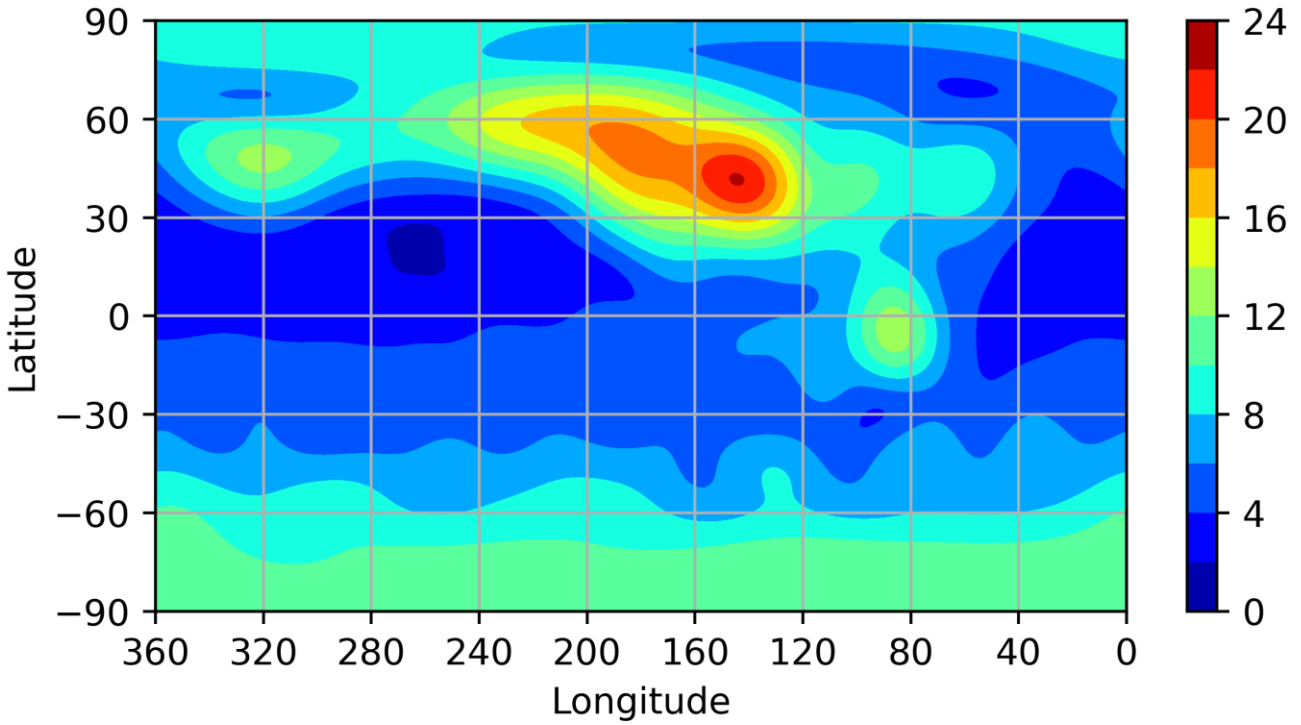
Reconstruction of the Field

Spherical harmonic expansion $B = \sum_{n=1}^{n_{\max}} R_n \sum_{l=1}^{n} c_n^l Y_n^l(\theta, \varphi)$



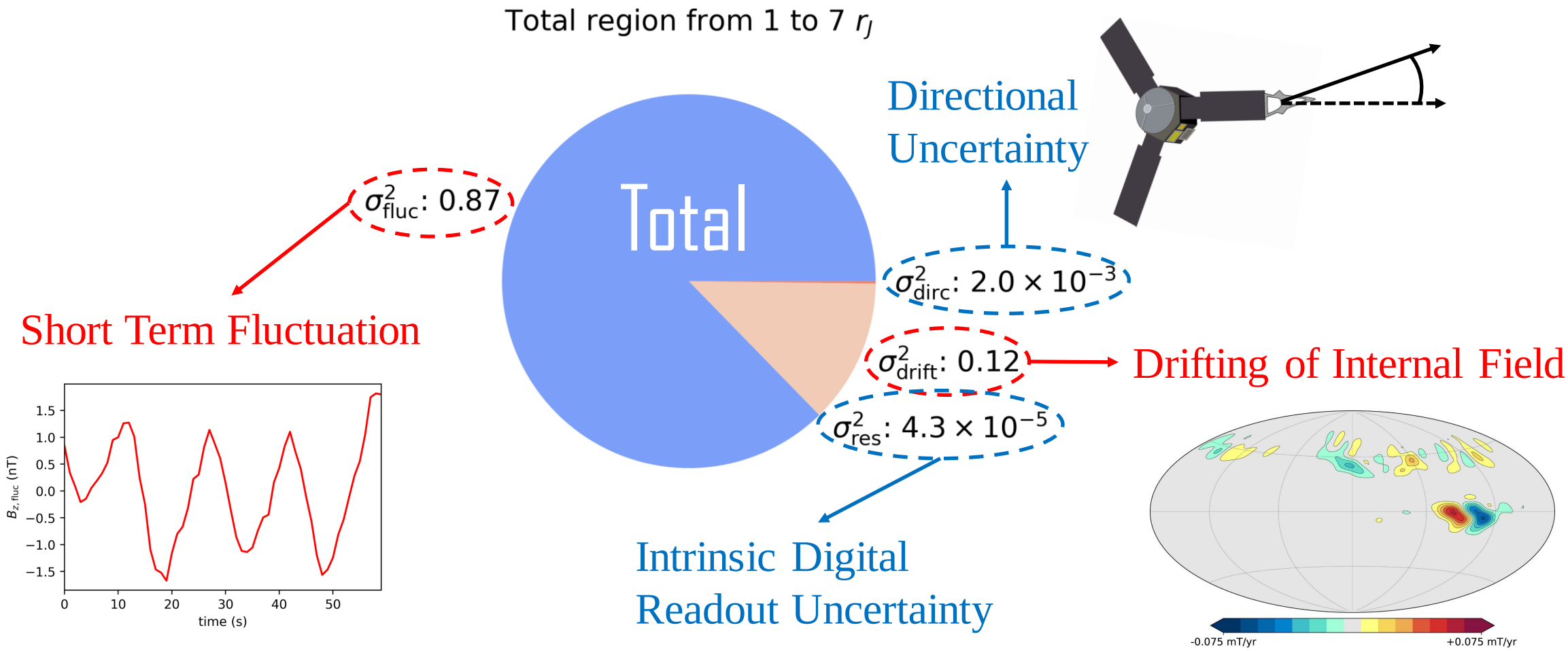
Logarithmic of Planar Field

Multipole with $n_{\max} = 18$



Field on Jupiter's Surface

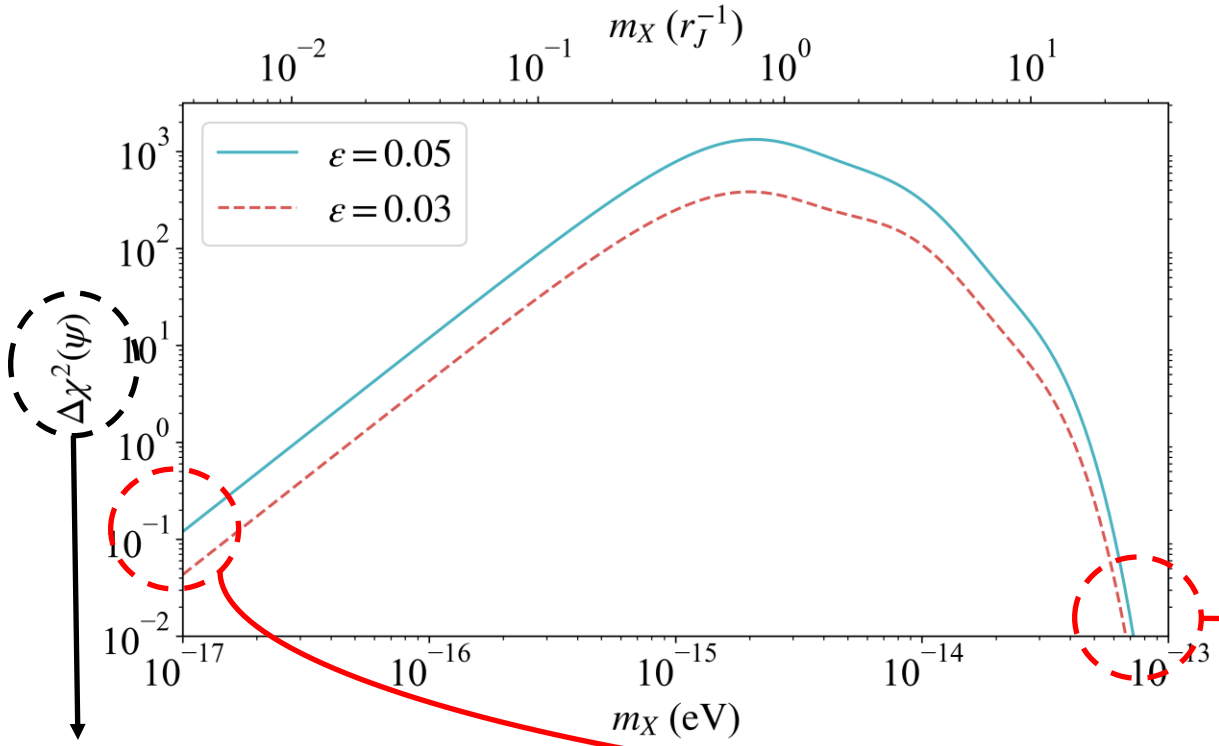
Variances Analysis



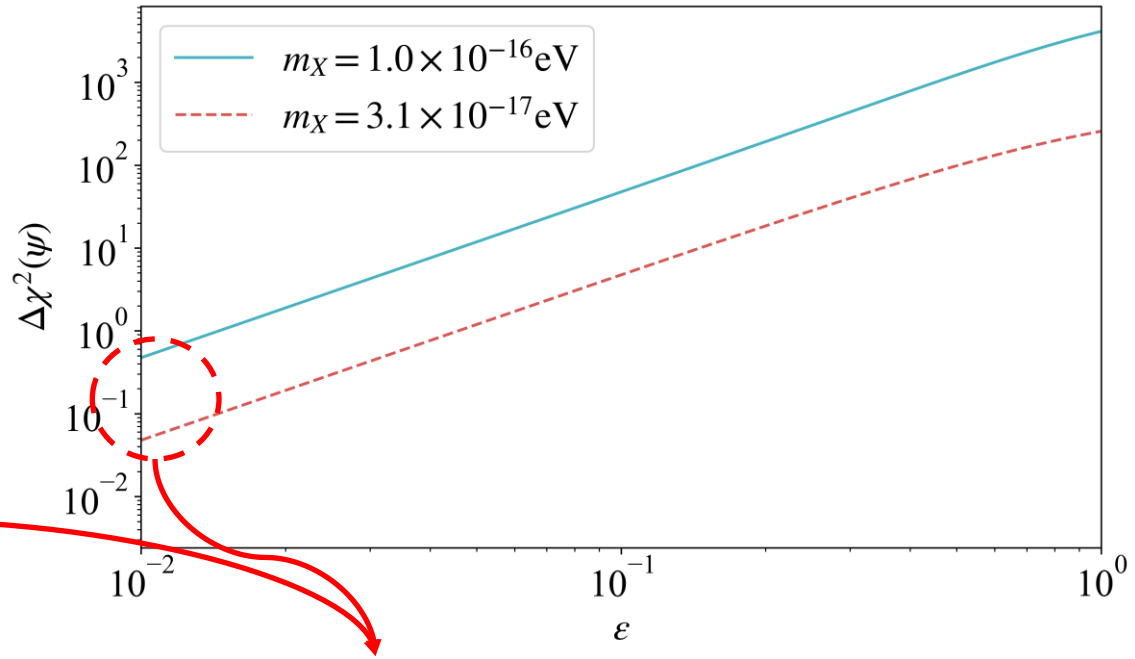
Statistic Method

Scan of $\min \chi^2(\psi)$ in dark photon case

Scan of m_X



Scan of ϵ



$$\Delta\chi^2 = \min \chi^2(\psi) - \min \chi^2$$

$\min \chi^2$ in SM-like limit

Constraint Results

Photon mass constraint:

Pioneer 1975:

$$m_\gamma \leq 6 \times 10^{-16}\text{eV}$$

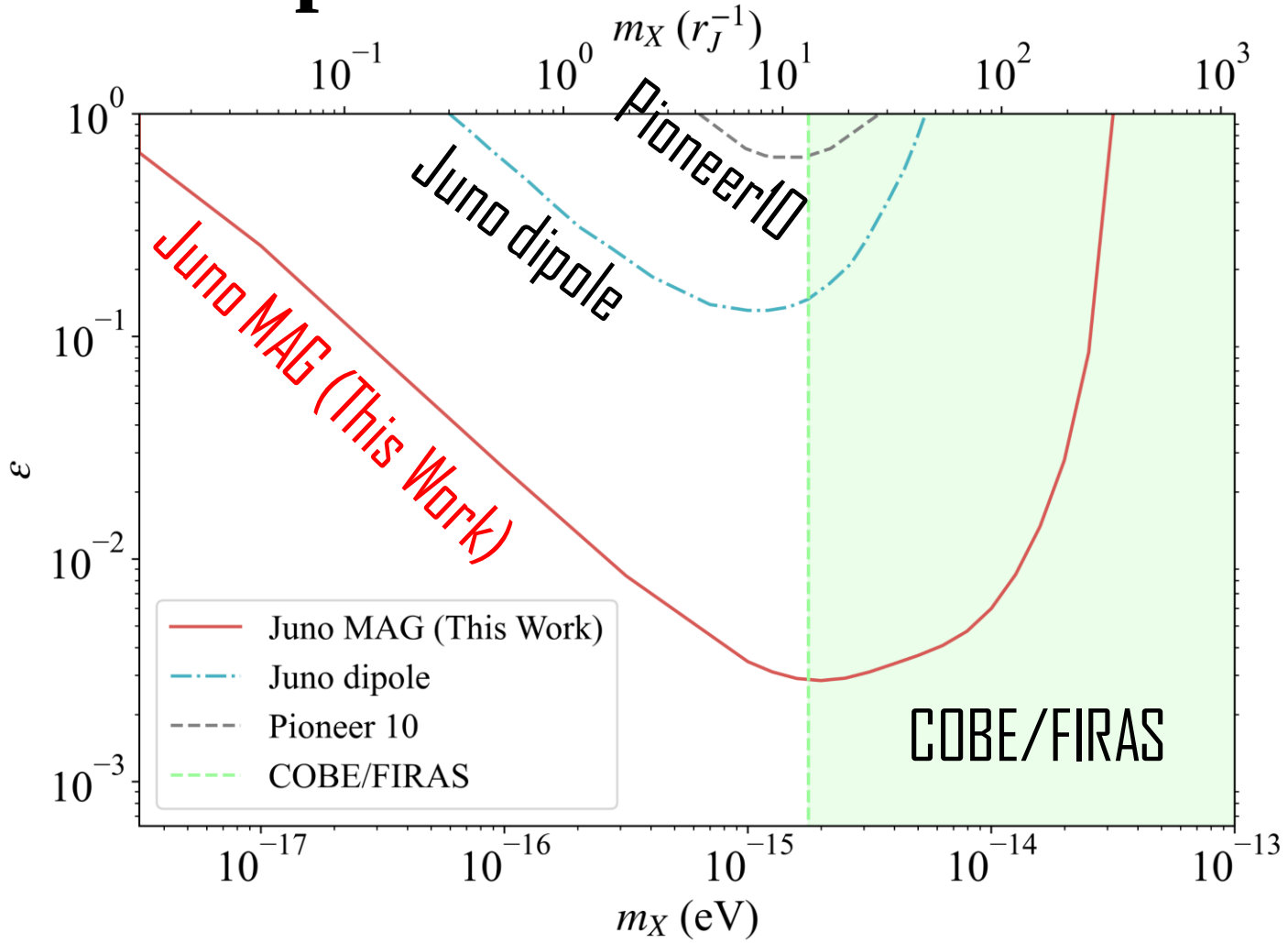
Our Result:

$$m_\gamma \leq 3 \times 10^{-17}\text{eV}$$

Best Limit Ever: Ryutov, D. D. (1997)

$$m_\gamma \leq 1 \times 10^{-18}\text{eV}$$

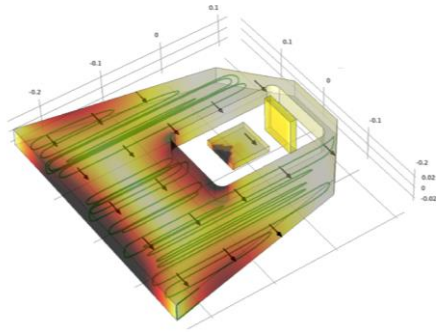
Dark photon constraint:



Thanks for Listening!

Back Up Slides

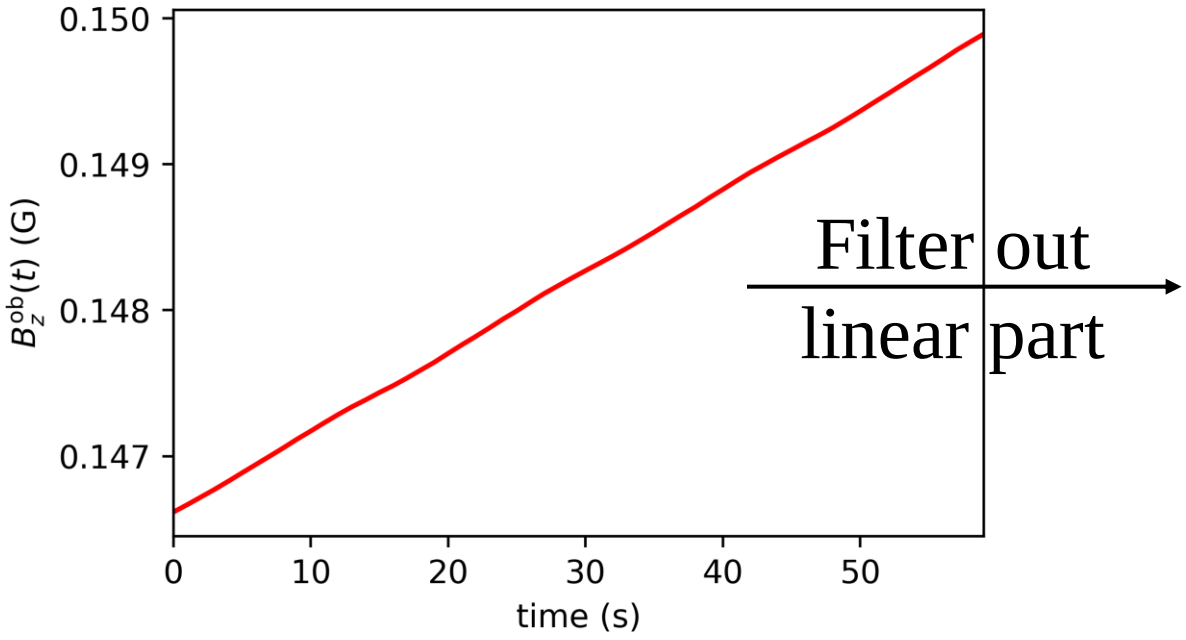
Short-Term Fluctuation



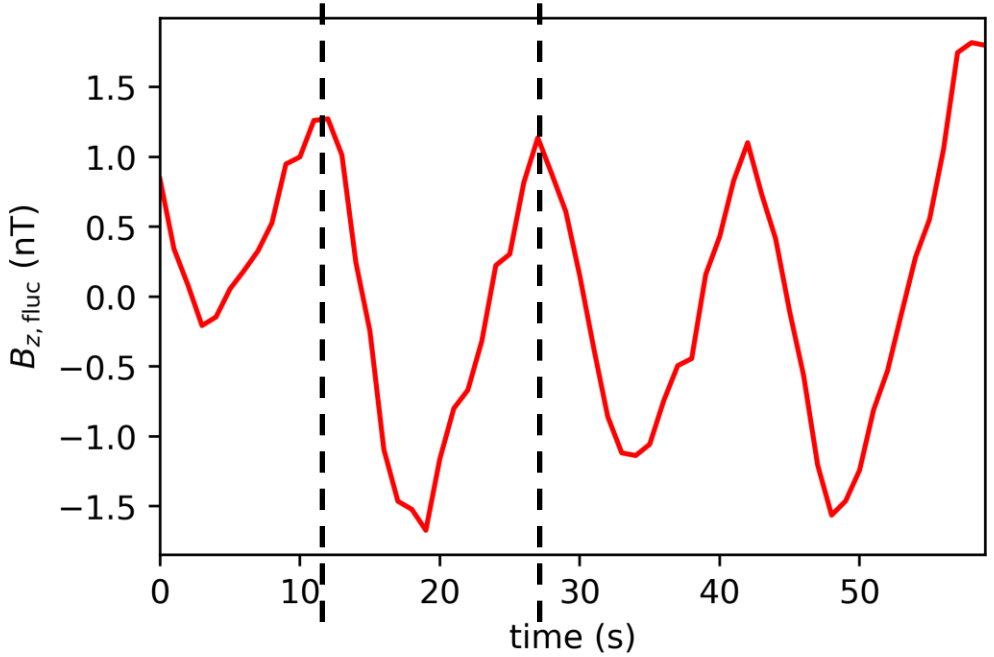
Eddy Current

~15s

Kotsiaros, Stavros, et al. (2020)



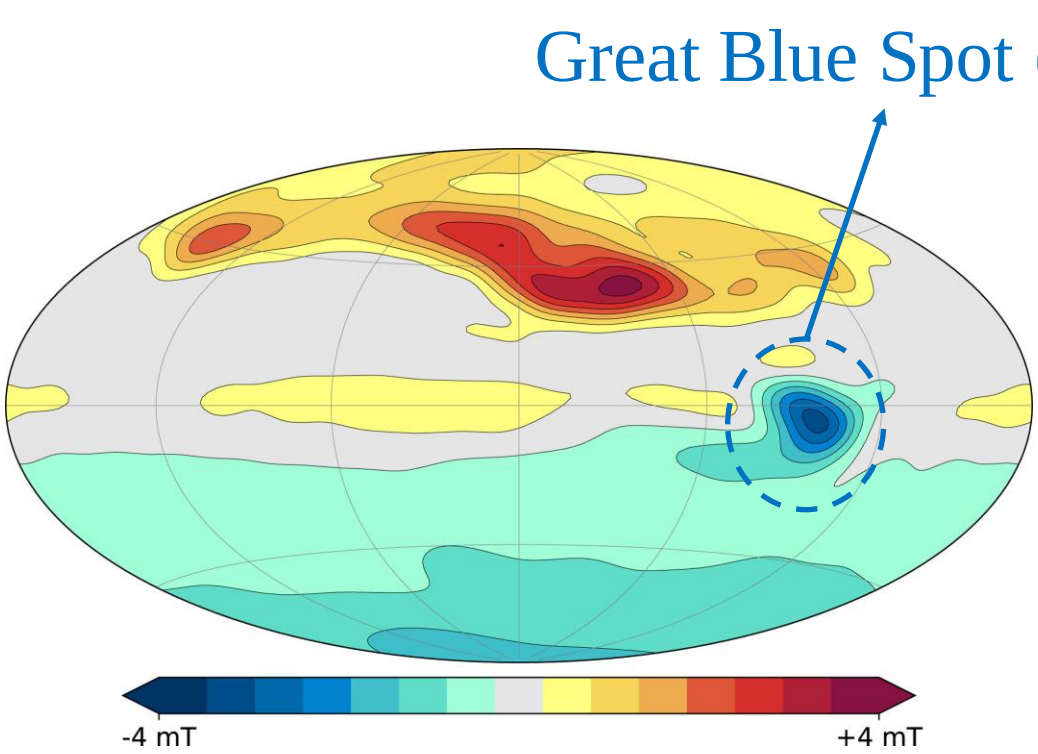
Filter out linear part



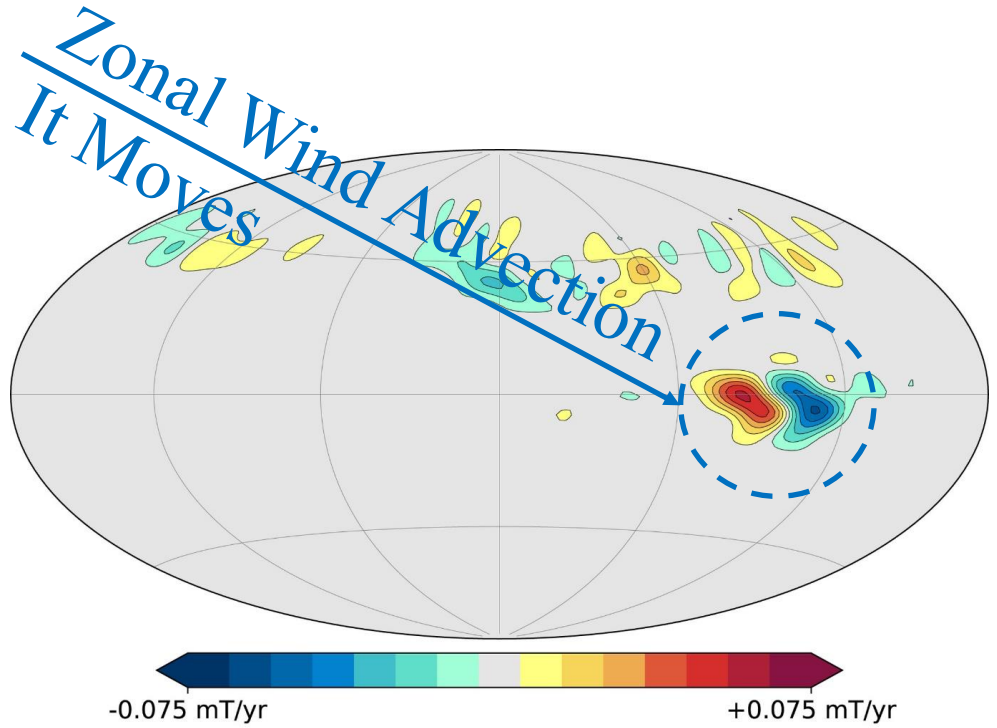
Observed B_z within 1 min

Fluctuation

Drifting of Internal Field

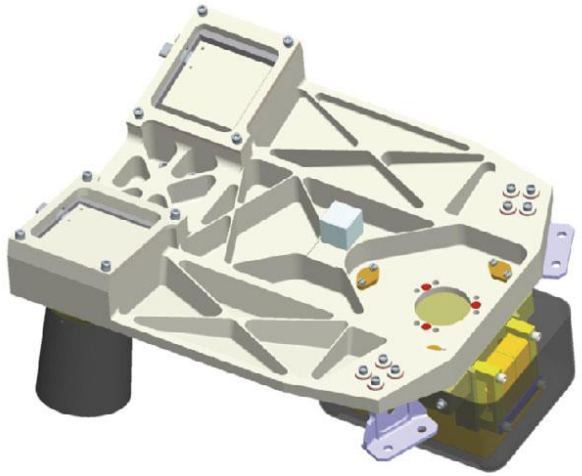


Standard Model B_r at 0.9 r_J at 2016.5.



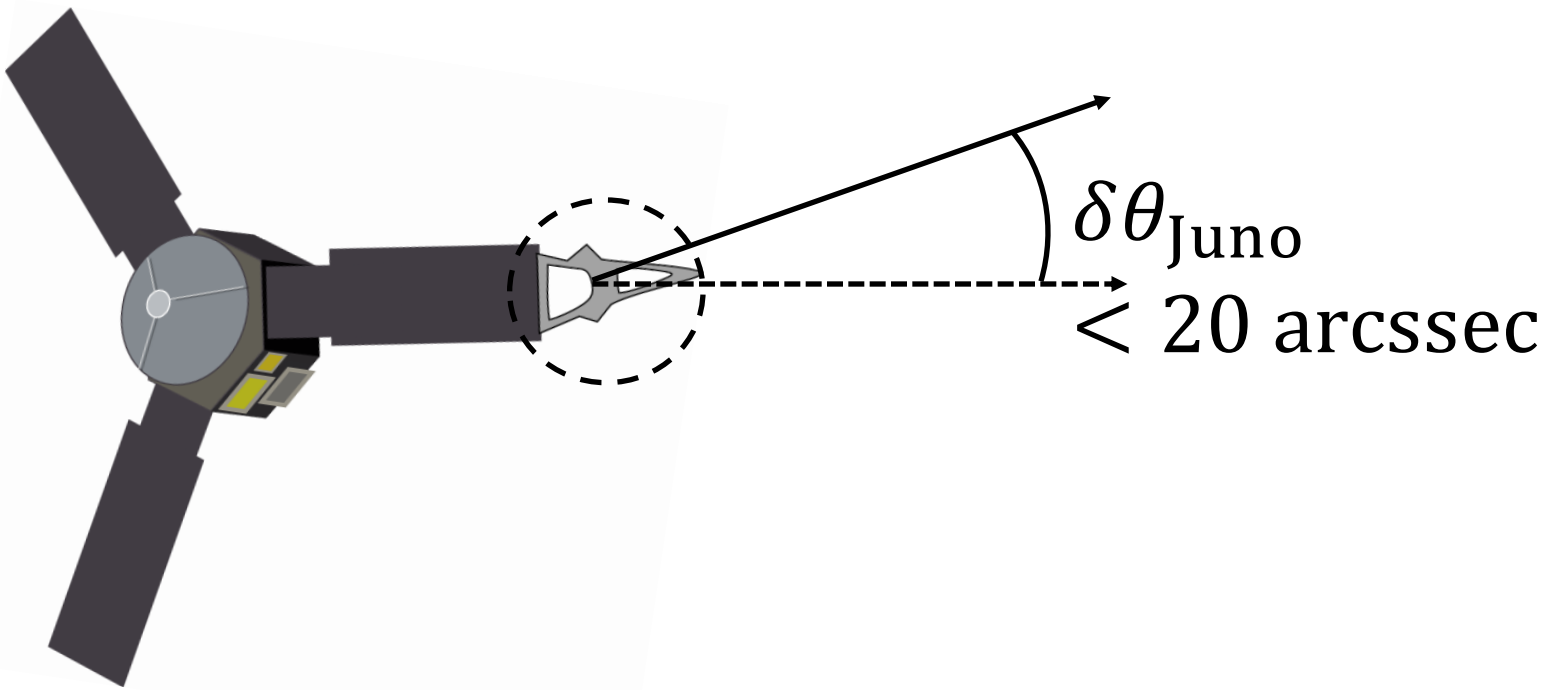
Secular variation of the B_r at 0.9 r_J from the DFR model.
Bloxham, Jeremy, et al. (2022)

Directional Uncertainty

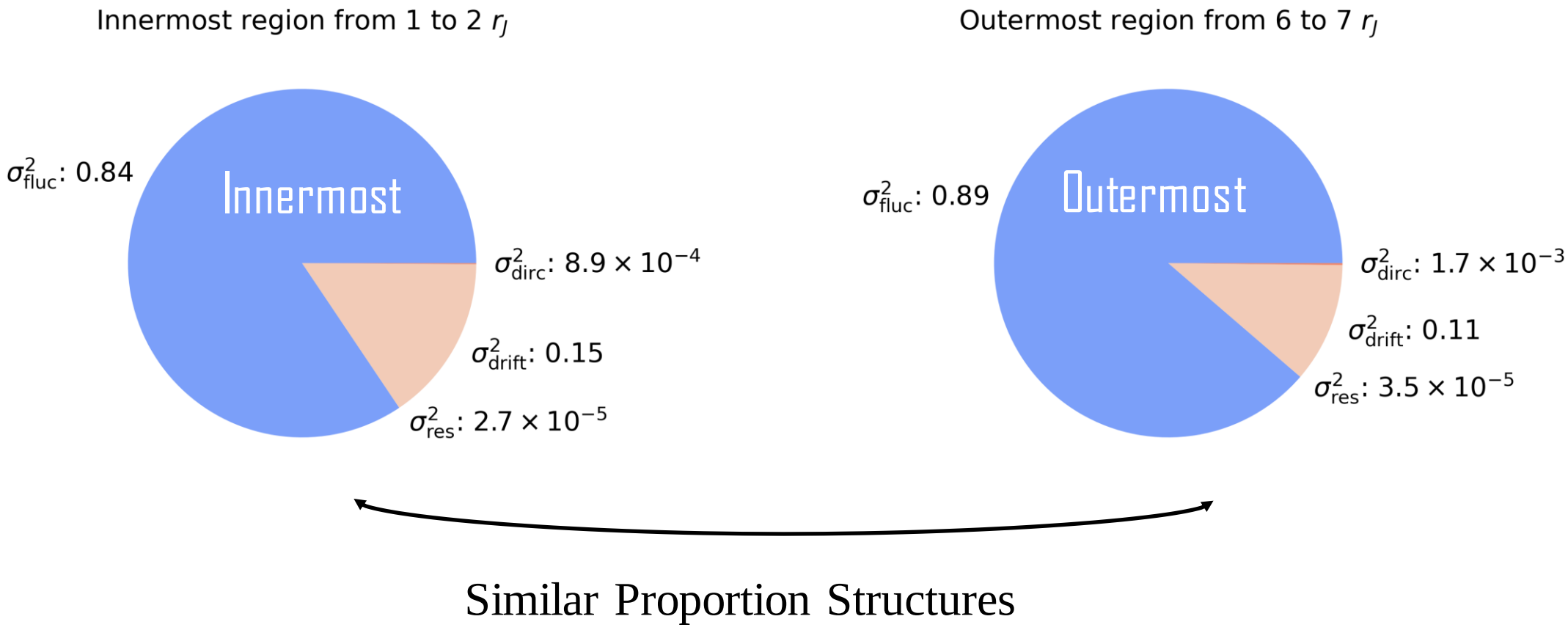


Advanced Stellar Compass (ASC)

Connerney, J. E. P., et al. (2017)

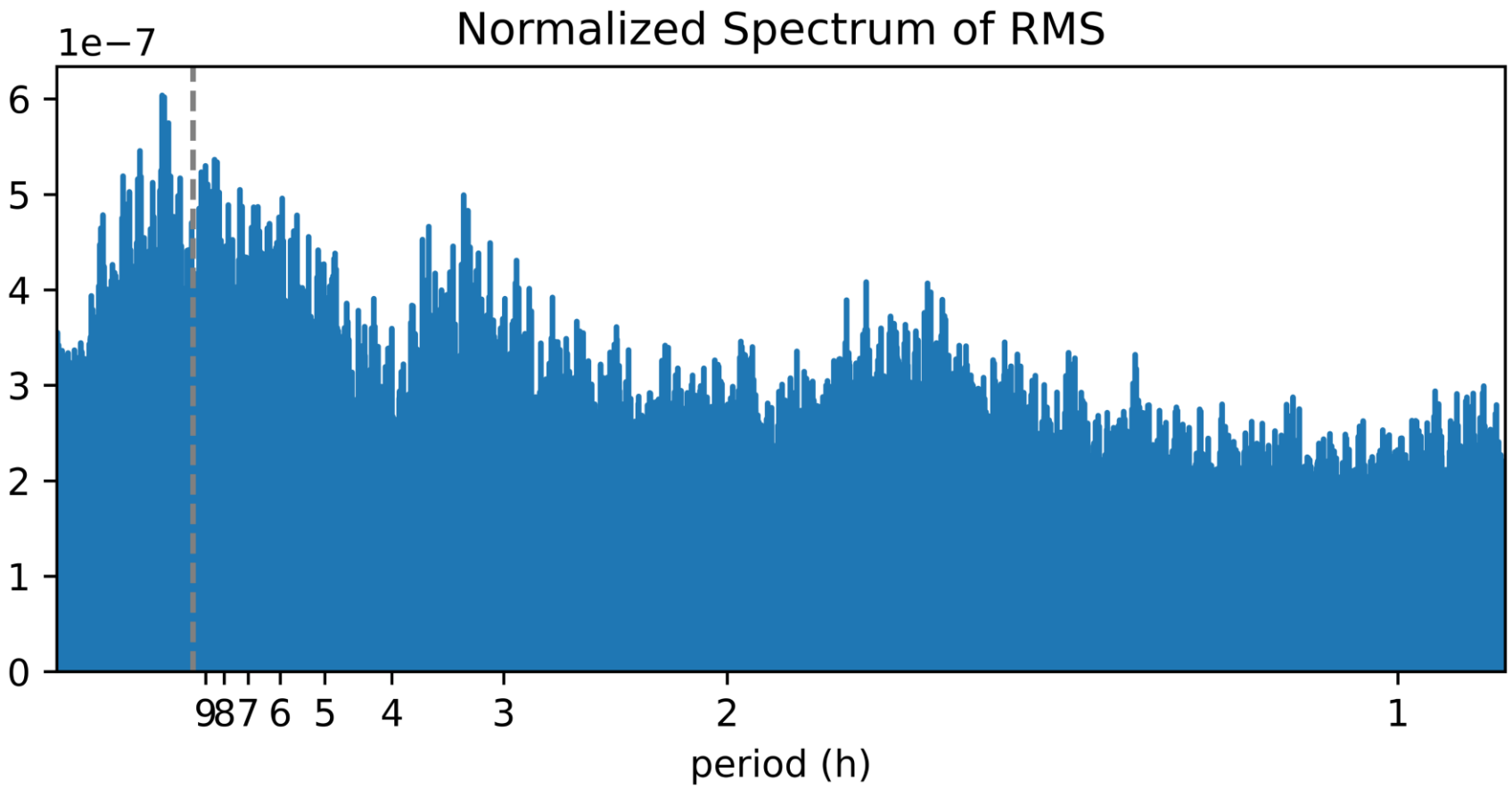


Relative Importance of Each Variance



Similar Proportion Structures

Temporial Analysis



Fourier transform of the RMS. The grey dashed line indicate the period of Jupiter spin.

Statistic Method

Spherical harmonic expansion

$$B^{\mathrm{fit}}(\eta) = \sum_{n=1}^{n_{\max}} R_n(\psi, r) \sum_{l=1}^{n} c_n^l Y_n^l(\theta, \varphi)$$

Parameters $\eta = \{\psi, c_n^l\}$

Nuisance parameters c_n^l
(Describe the Field)

Parameters of interest ψ
(Describe New Physics)

Massive photon $\psi = \{m_\gamma\}$

Dark photon $\psi = \{m_X, \epsilon\}$

Statistic Method

B^{ob} are independent and residual are Gaussian distributed

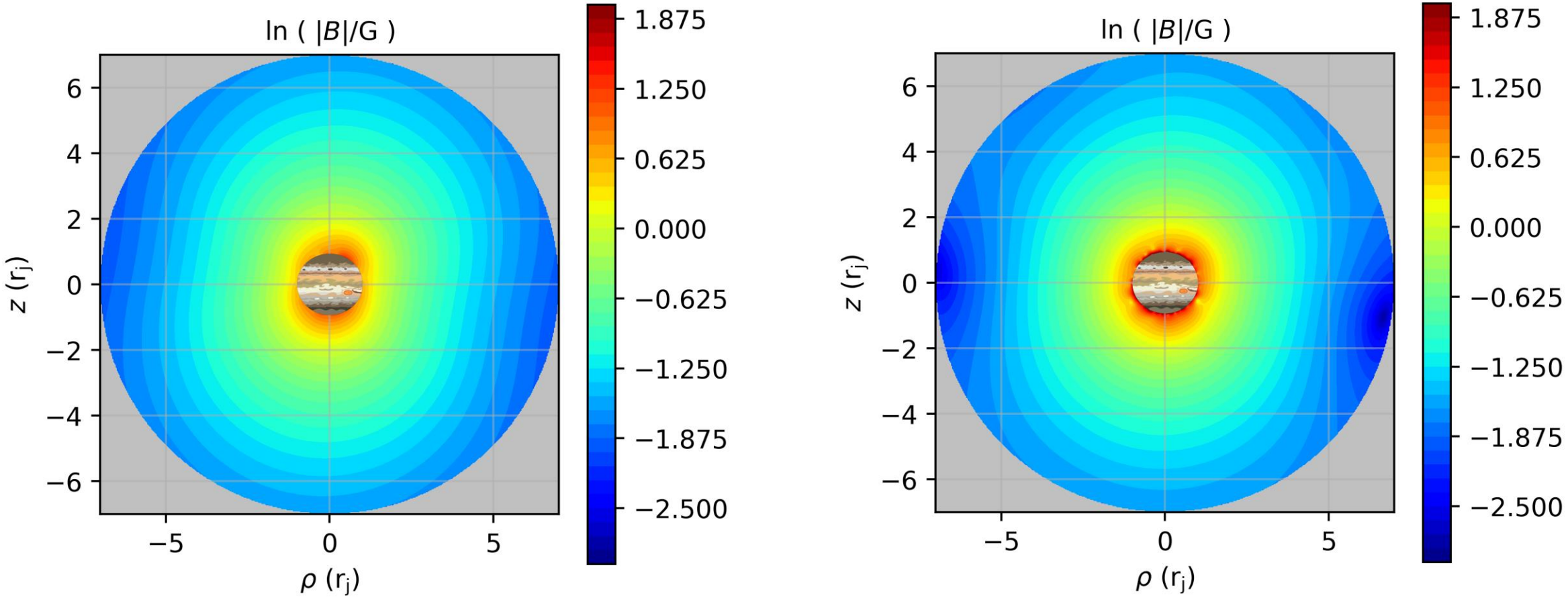
$$\chi^2(\eta) = \sum \frac{(B^{\mathrm{ob}} - B^{\mathrm{fit}}(\eta))^2}{\sigma^2}$$

$$\min \chi^2(\psi) \longrightarrow \text{Constraints}$$

Reconstruction of the Field

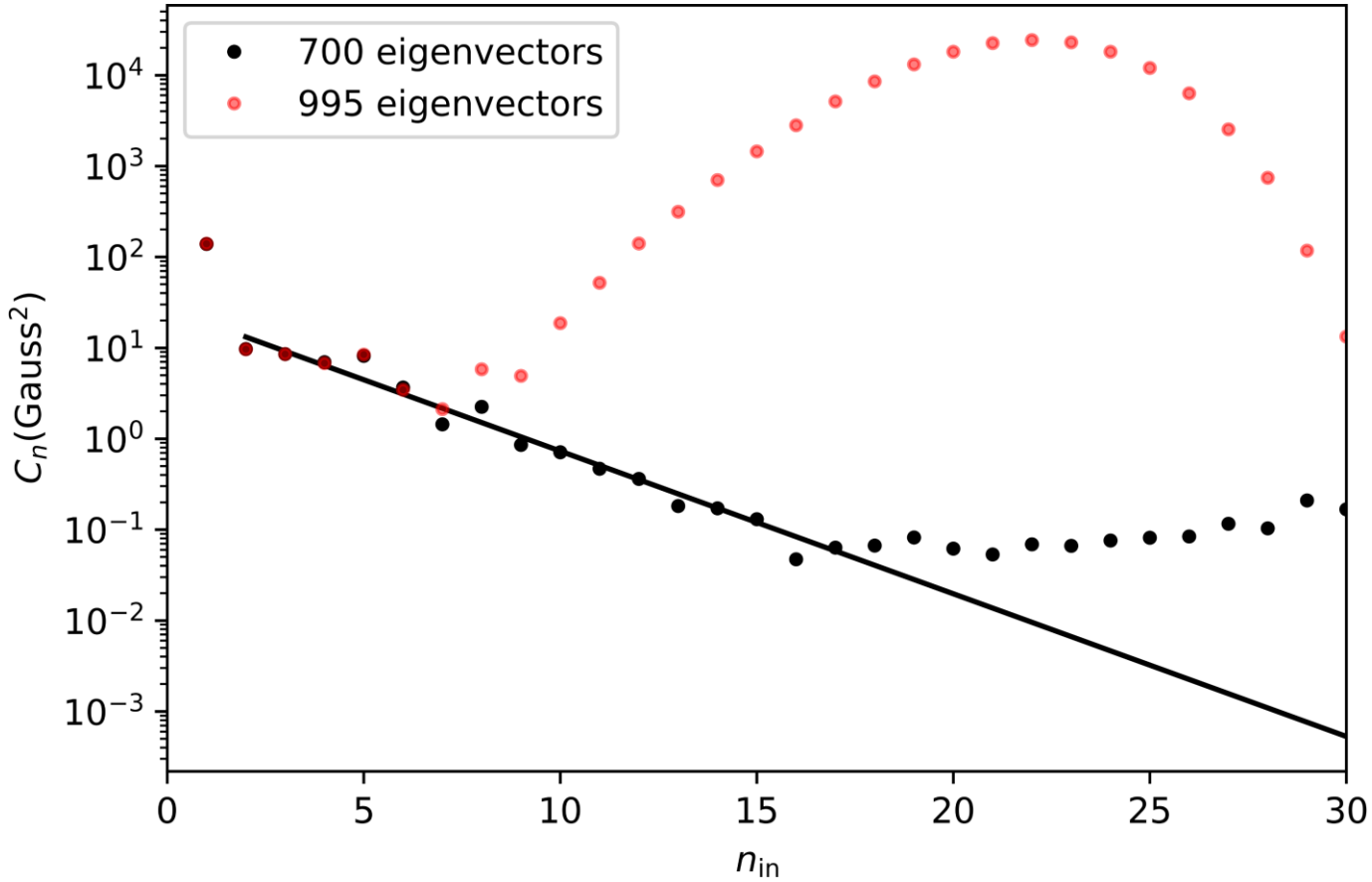
Standard Model

$\epsilon = 1;\ m_X = 10^{-14.5}\text{eV}$



Longitudes 150° and 330°

Spectrum of Multiples



Lowes' plot of the magnetic spectrum for a model fit to Juno observations