Constraining the multipolar magnetic field of MSP J0030+0451 via *NICER* X-ray light curve fitting

NWU
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SA-GAMMA
THE SOUTH AFRICAN GAMMA-RAY ASTRONOMY PROGRAMME

Fermi

Anu Kundu*, North-West University

TEAM:
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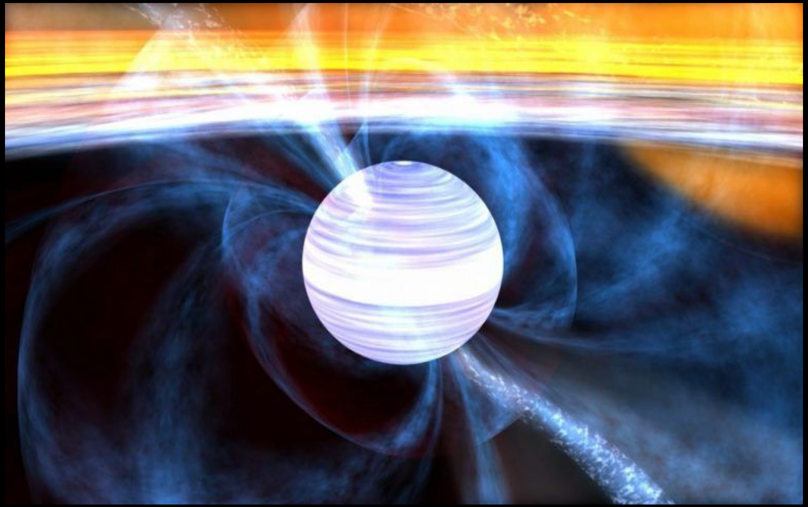
Outline

- Introduction
- Multipolar magnetic field
- Methods
- Markov chain Monte Carlo (MCMC) runs
- Summary

Introduction: MSP PSR J0030+0451

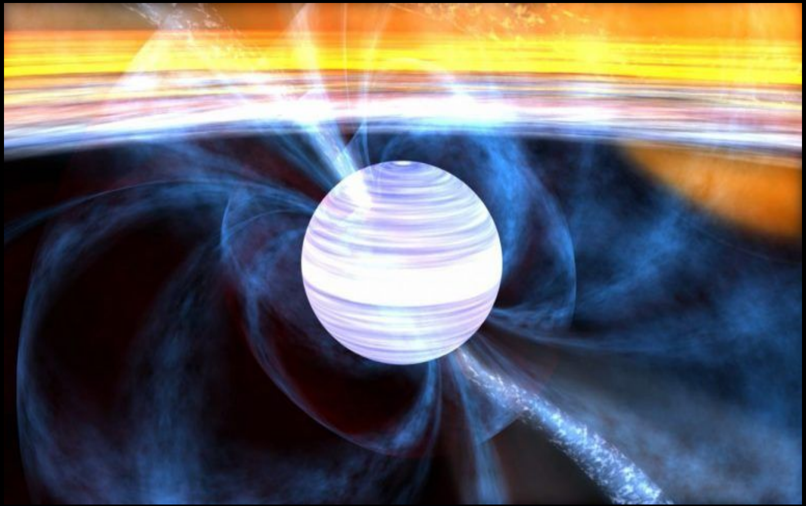
- **Millisecond pulsars (MSPs)**
  - **Old pulsars**
  - **Period < 10 ms**



Lommen et al. (2000), Arzoumanian et al. (2018), Becker et al. (2000), Abdo et al. (2009), NASA (https://asd.gsfc.nasa.gov/blueshift/index.php/2017/08/03/rxtes-greatest-pulsar-hits/)

Introduction: MSP PSR J0030+0451

- Millisecond pulsars (MSPs)
  - Old pulsars
  - Period < 10 ms
- J0030: Isolated MSP, minority in MSP population
- Spin period 4.865 ms
- Multiwavelength emission:
  - discovered as a radio pulsar using *Arecibo*
  - identified as an X-ray pulsar with *ROSAT*
  - first gamma-ray MSP announced by *Fermi*



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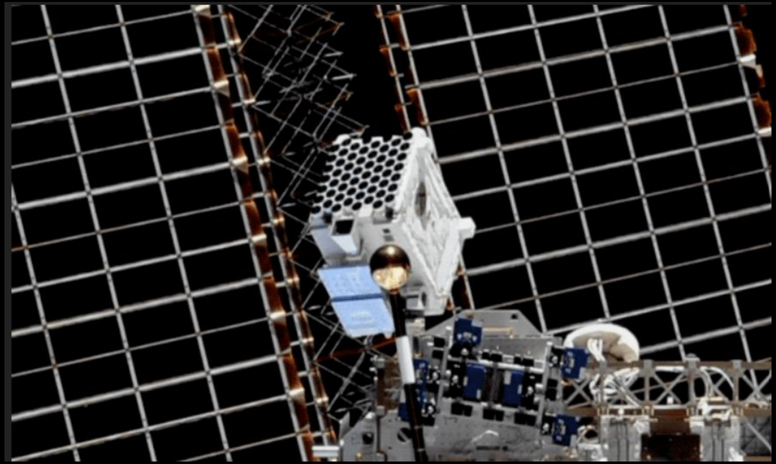
Introduction: NICER view of J0030

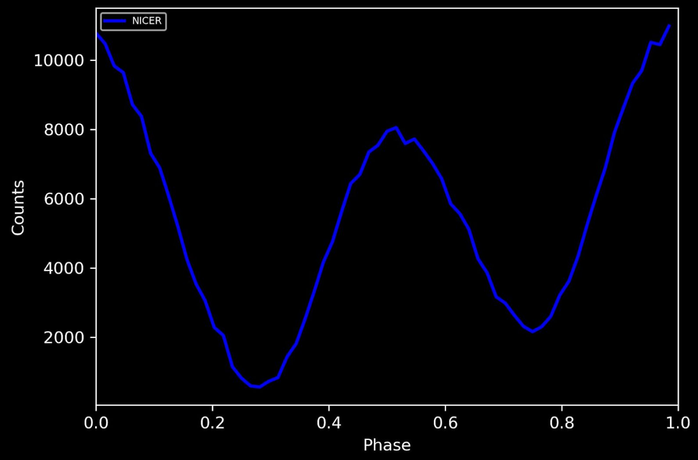
- Neutron star Interior Composition Explorer (*NICER*)
  - Soft X-ray band (0.2–12 keV)
  - Science goal: Constrain the equation of state

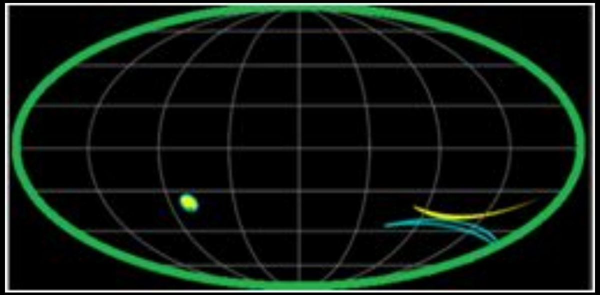


Gendreau et al. (2016), https://heasarc.gsfc.nasa.gov/docs/nicer/

Introduction: NICER view of J0030

- Neutron star Interior Composition Explorer (*NICER*)
  - Soft X-ray band (0.2–12 keV)
  - Science goal: Constrain the equation of state
- Light curve (LC) of J0030: two peaks
- Possible origin: hotspots on surface
- Fit the light curve, model hotspots on the surface
  - Kalapotharakos et al. (2021): static offset dip+quad magnetic field
  - Updating magnetic field: retarded centred multipolar field, up to l=3; Pétri (2015)





Kalapotharakos et al. (2021)

Multipolar magnetic field equations

Multipolar magnetic field outside neutron star

$$B(r,\theta,\phi,t) = \sum_{l=1}^{\infty} \sum_{m=-l}^{l} [B_r(r,\theta,\phi,t) + B_\theta(r,\theta,\phi,t) + B_\phi(r,\theta,\phi,t)]$$

where,

$$B_r = -\frac{\sqrt{l(l+1)}}{r} f^B_{lm} Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t}$$

$$B_\theta = -\frac{\partial_r (r f^B_{lm})}{r\sqrt{l(l+1)}} \partial_\theta (Y_{lm}(\theta)) e^{im\phi} e^{-im\Omega t} + \frac{i\mu_0 m\Omega f^D_{lm}}{\sin\theta \sqrt{l(l+1)}} im Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t}$$

$$B_\phi = -\frac{\partial_r (r f^B_{lm})}{r \sin\theta \sqrt{l(l+1)}} im Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t} - \frac{i\mu_0 m\Omega f^D_{lm}}{\sqrt{l(l+1)}} \partial_\theta (Y_{lm}(\theta)) e^{im\phi} e^{-im\Omega t}$$

Pétri 2012, 2015

Multipolar magnetic field equations

Multipolar magnetic field outside neutron star

l = 1: Dipole
l = 2: Quadrupole
l = 3: Octopole
...
m = - l to l : different orientations for the corresponding multipolar component

Terms with r dependence

$$B_r = -\frac{\sqrt{l(l+1)}}{r} f^B_{lm} Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t}$$

$$B_\theta = -\frac{\partial_r (r f^B_{lm})}{r\sqrt{l(l+1)}} \partial_\theta (Y_{lm}(\theta)) e^{im\phi} e^{-im\Omega t} + \frac{i\mu_0 m\Omega f^D_{lm}}{\sin\theta\sqrt{l(l+1)}} im Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t}$$

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Pétri 2012, 2015

Multipolar magnetic field equations

Multipolar magnetic field outside neutron star

Terms with r dependence
Terms with (ϑ, φ) dependence

l = 1: Dipole
l = 2: Quadrupole
l = 3: Octopole
...
m = - l to l : different orientations for the corresponding multipolar component

$$B_r = -\frac{\sqrt{l(l+1)}}{r} f_{lm}^B Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t}$$

$$B_\theta = -\frac{\partial_r (r f_{lm}^B)}{r\sqrt{l(l+1)}} \partial_\theta (Y_{lm}(\theta)) e^{im\phi} e^{-im\Omega t} + \frac{i\mu_0 m\Omega f_{lm}^D}{\sin\theta\sqrt{l(l+1)}} im Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t}$$

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Pétri 2012, 2015

Multipolar magnetic field equations

Multipolar magnetic field outside neutron star

Terms with r dependence
Terms with (ϑ, φ) dependence
Terms with (l,m) dependence

l = 1: Dipole
l = 2: Quadrupole
l = 3: Octopole
...
m = - l to l : different orientations for the corresponding multipolar component

$$B_r = -\frac{\sqrt{l(l+1)}}{r} f^B_{lm} Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t}$$

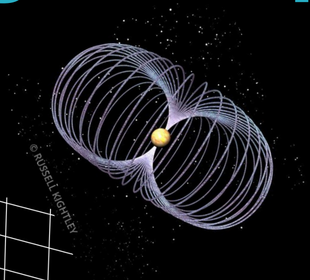
$$B_\theta = -\frac{\partial_r (r f^B_{lm})}{r\sqrt{l(l+1)}} \partial_\theta (Y_{lm}(\theta)) e^{im\phi} e^{-im\Omega t} + \frac{i\mu_0 m \Omega f^D_{lm}}{\sin\theta \sqrt{l(l+1)}} im Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t}$$

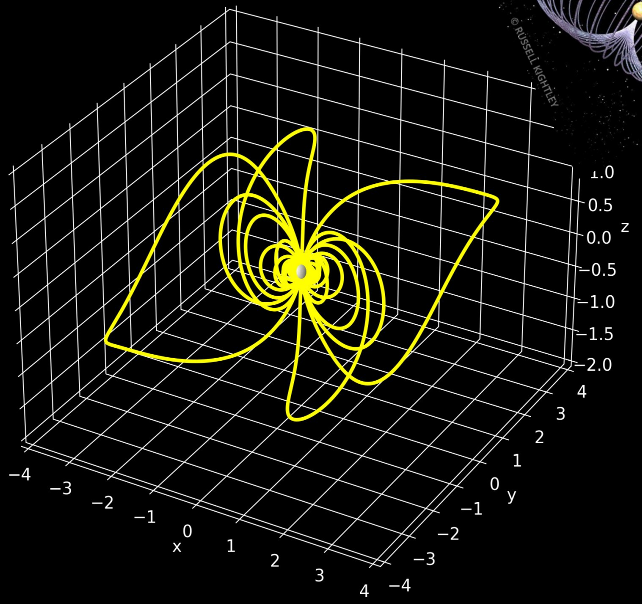
$$B_\phi = -\frac{\partial_r (r f^B_{lm})}{r \sin\theta \sqrt{l(l+1)}} im Y_{lm}(\theta) e^{im\phi} e^{-im\Omega t} - \frac{i\mu_0 m \Omega f^D_{lm}}{\sqrt{l(l+1)}} \partial_\theta (Y_{lm}(\theta)) e^{im\phi} e^{-im\Omega t}$$

Pétri 2012, 2015

Visualizing multipolar field lines

l = 1



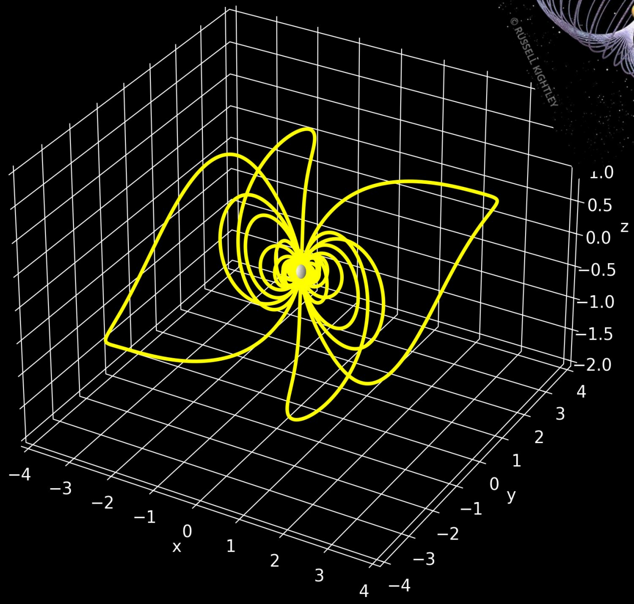


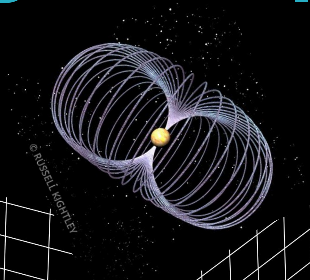
Retarded vs static field line geometry

http://d3e1m60ptf1oym.cloudfront.net/60e36a4e-fb28-11e2-95d3-553510e1e033/Magnetar_0_sec_blur_large.jpg

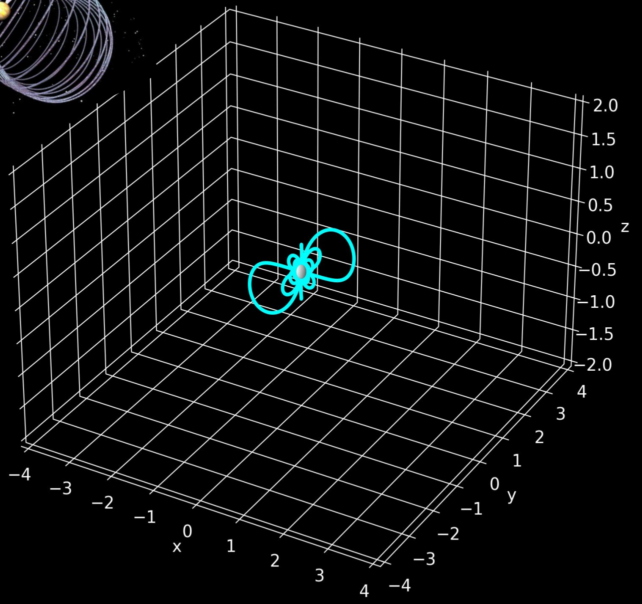
Visualizing multipolar field lines

l = 1





l = 2



Retarded vs static field line geometry

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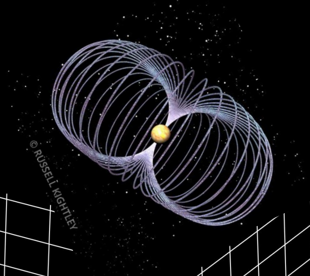
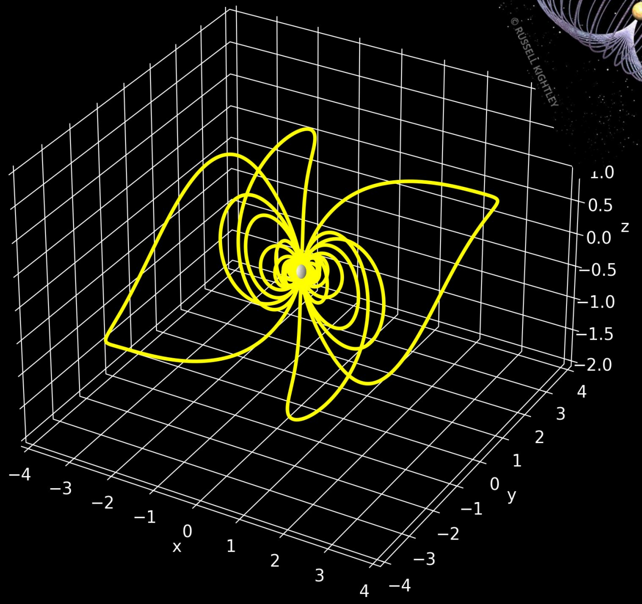
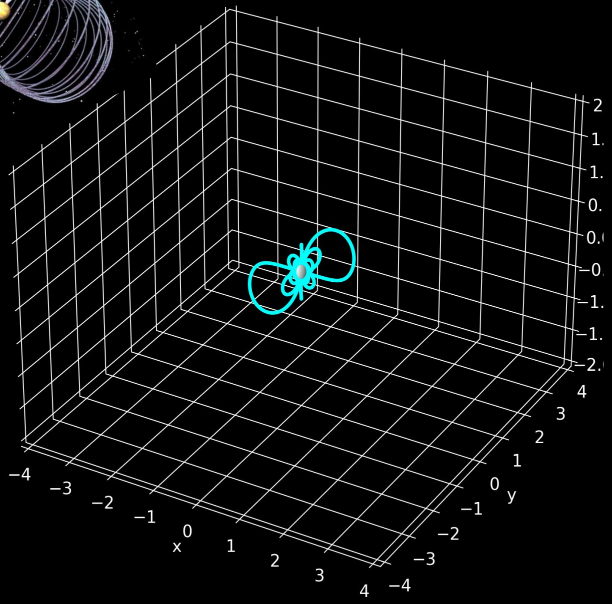
Visualizing multipolar field lines



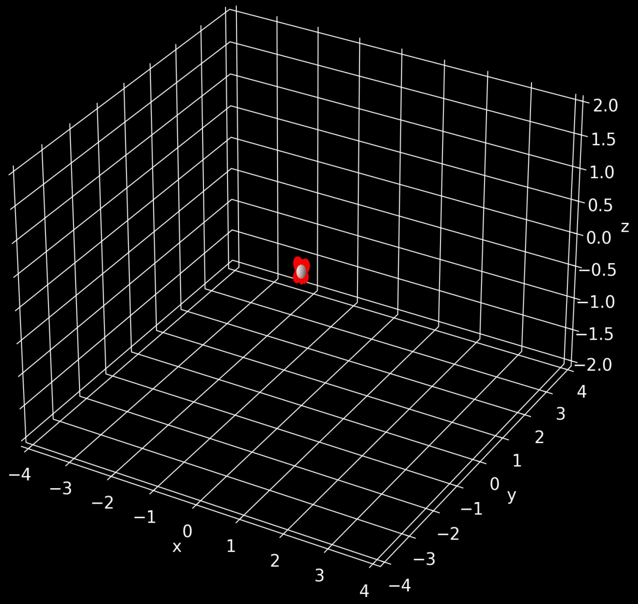
l = 1



l = 2



l = 3



Retarded vs static field line geometry

$\frac{1}{r^{l+1}}$ **dependence**

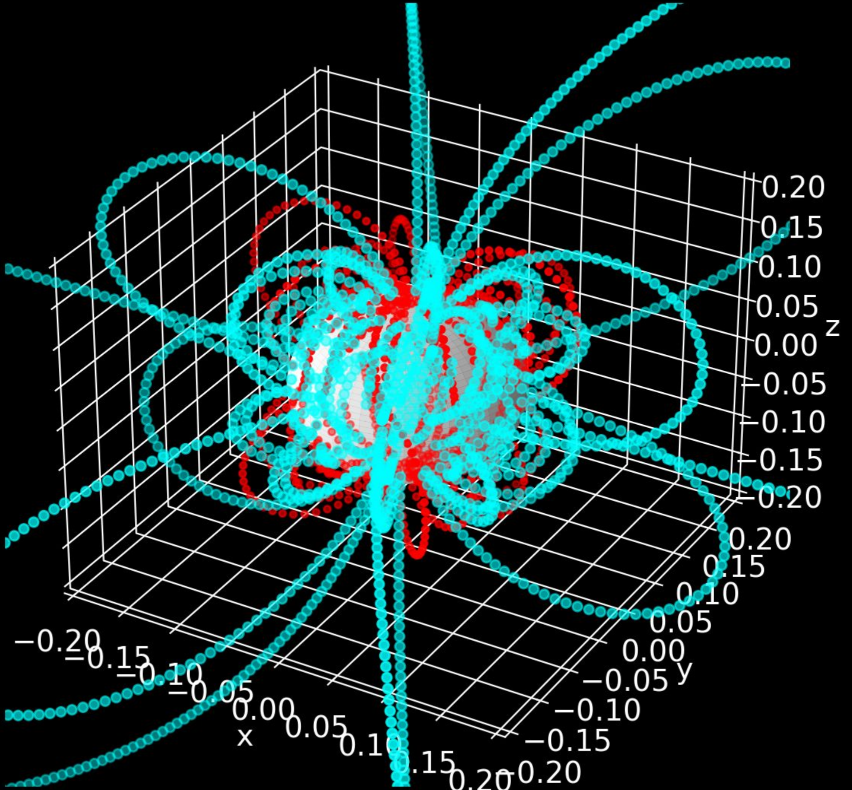
http://d3e1m60ptf1oym.cloudfront.net/60e36a4e-fb28-11e2-95d3-553510e1e033/Magnetar_0_sec_blur_large.jpg

Visualizing multipolar field lines

l = 2, 3 overlap

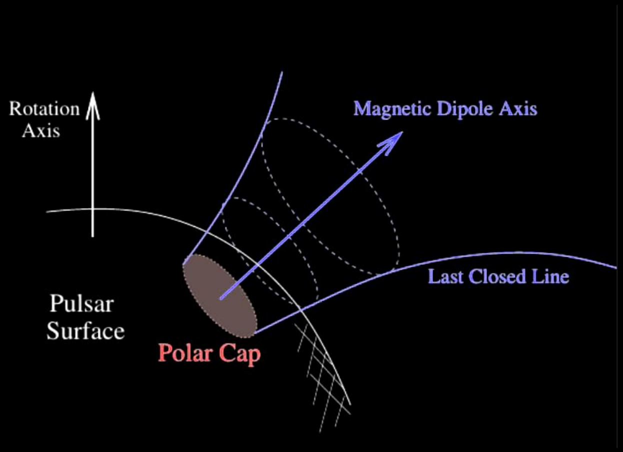
l2 in cyan

l3 in red



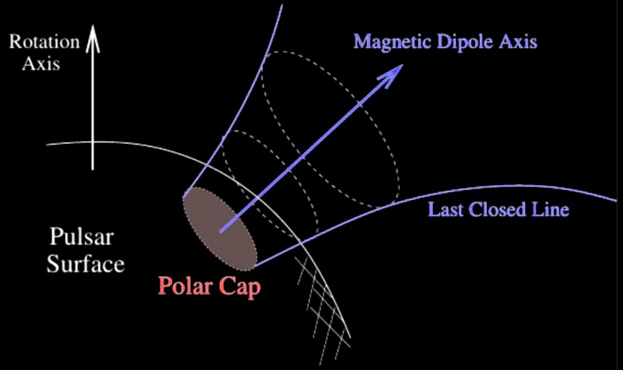
Close to the surface, higher components contribute

Testing multipolar field: Polar caps

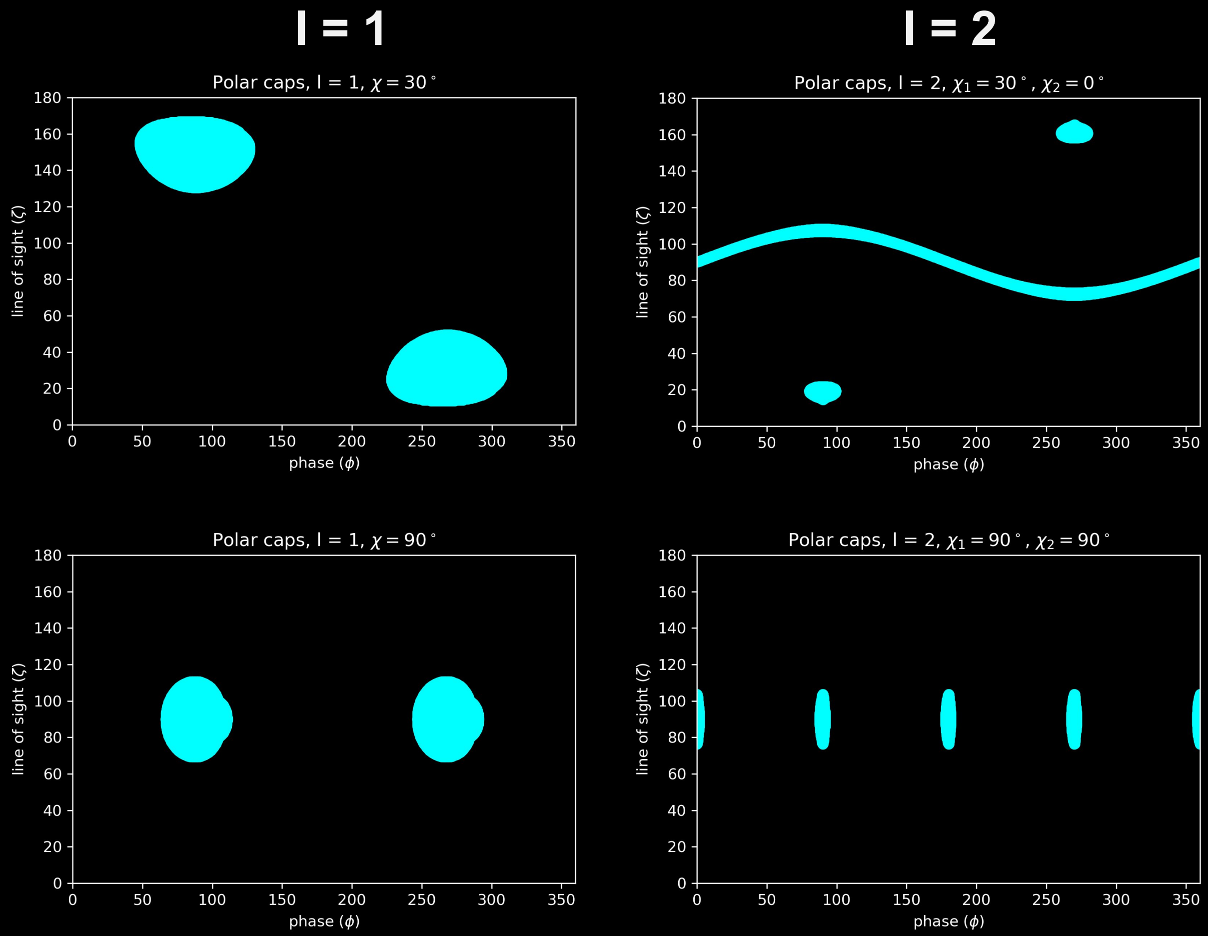


Saito (2011)

Testing multipolar field: Polar caps

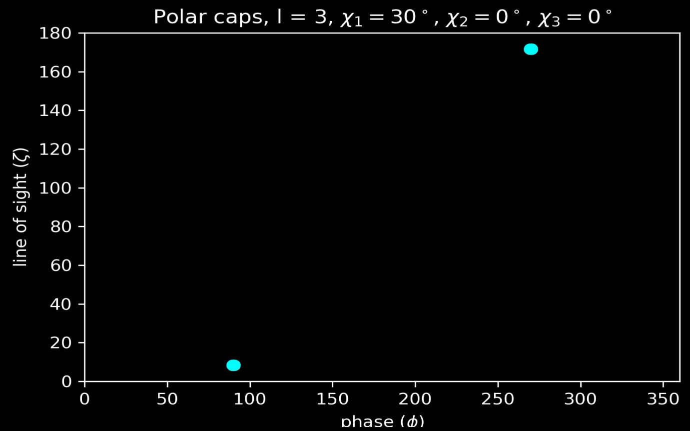


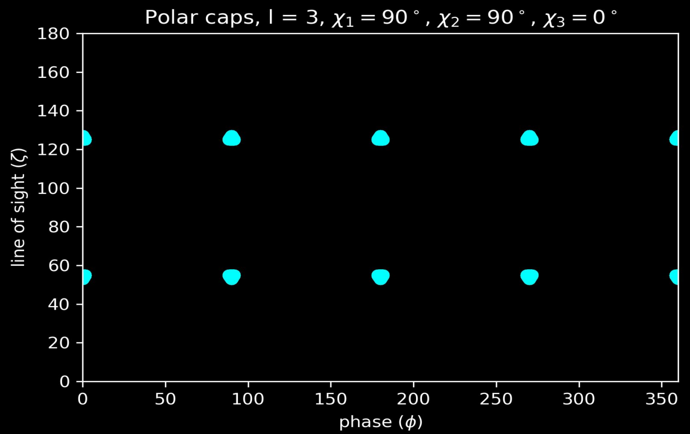
Saito (2011)

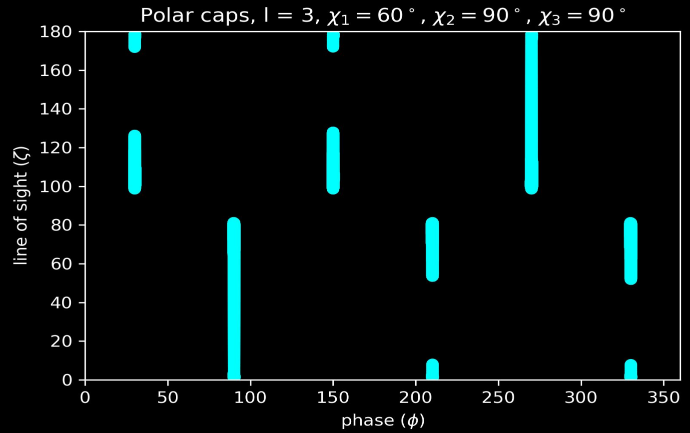


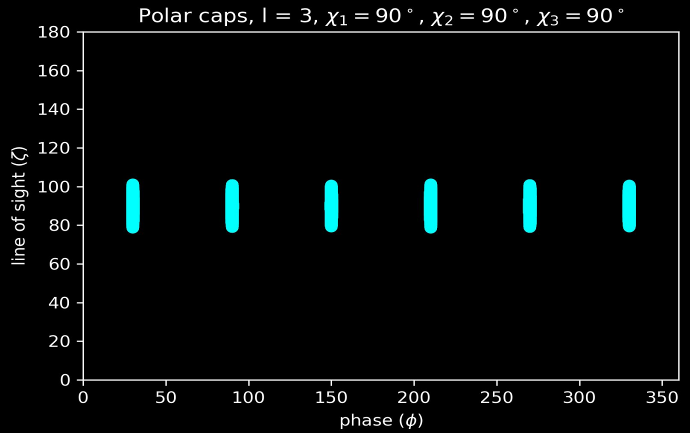
Testing multipolar field: Polar caps

l = 3









Methods

Retarded multipolar magnetic field

Geodesic Integration in Kerr Spacetime (GIKS) ray-tracing:

- **Find hotspots on the surface -> Produce corresponding light curve**

MCMC: updated code from Kalapotharakos et al. (2021)

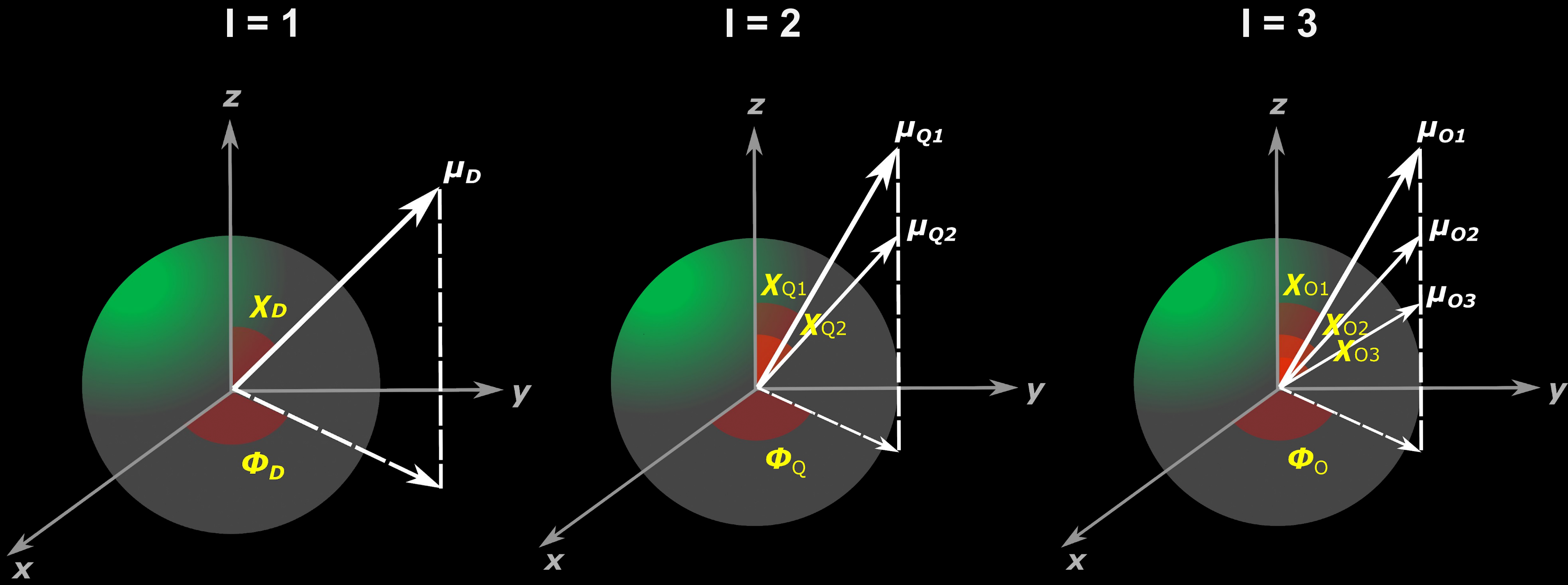
Kalapotharakos et al. (2021)	Current work
l1 + l2	l1 + l2 + l3
Static	Retarded
Offset	Centred (offset later)
11 parameters	11 parameters (6 up to l2)

Methods: MCMC parameter space

Phase - 3 parameters: $\varphi_{D}, \varphi_{Q}, \varphi_{O}$

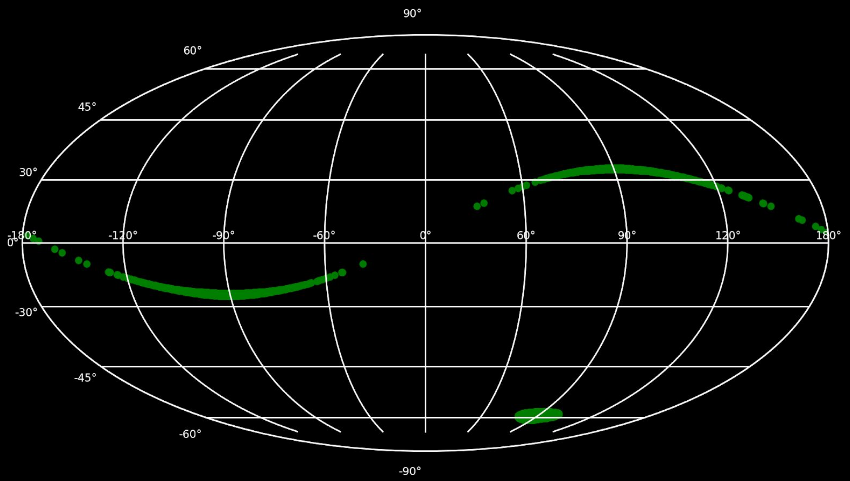
Angular - 6 parameters: $\chi_{D}, \chi_{Q1}, \chi_{Q1}, \chi_{O1}, \chi_{O2}, \chi_{O3}$

Field strength - 2 parameters: B_Q/B_D, B_O/B_D



MCMC runs: l = 1+2

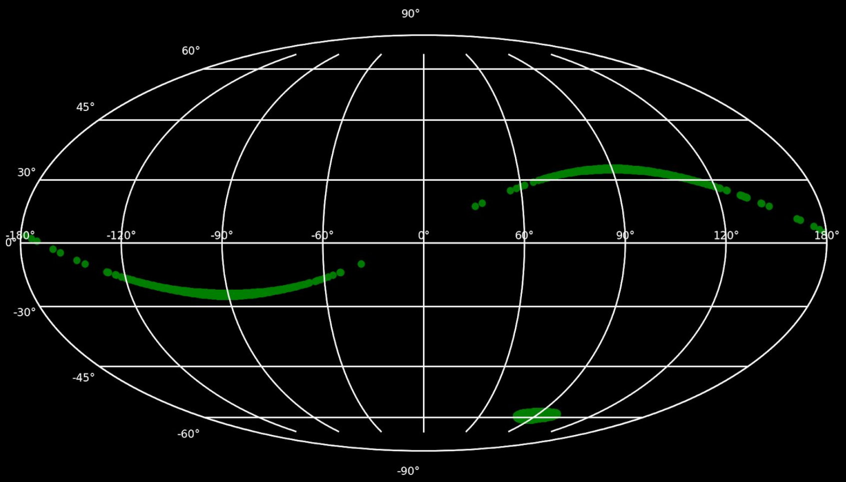
Mollweide projection showing hotspots



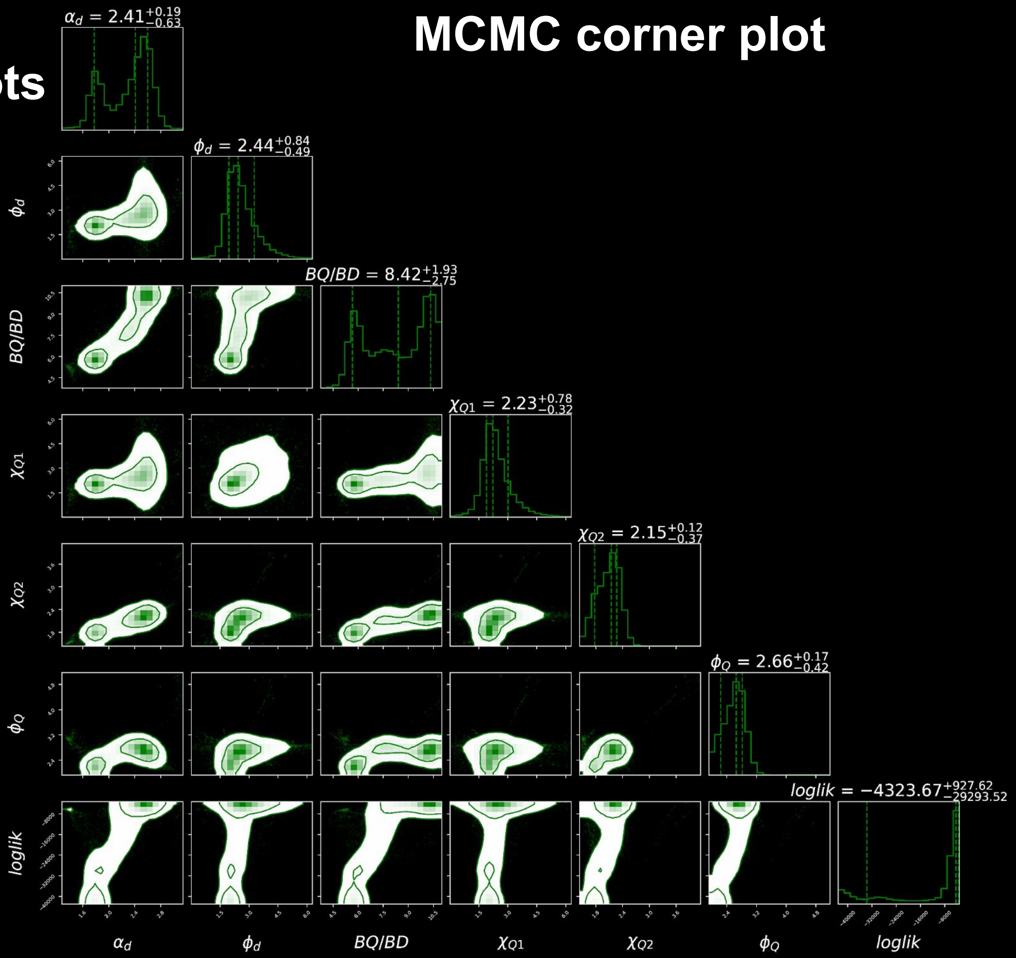
Low resolution

MCMC runs: l = 1+2

Mollweide projection showing hotspots



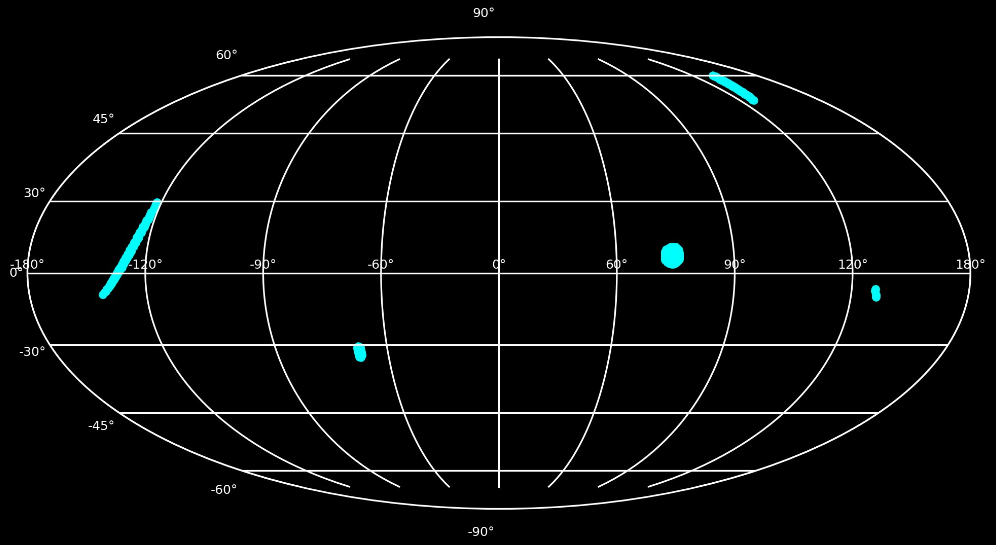
MCMC corner plot



Low resolution
Bimodal!

MCMC runs: l = 1+2+3

Mollweide projection showing hotspots

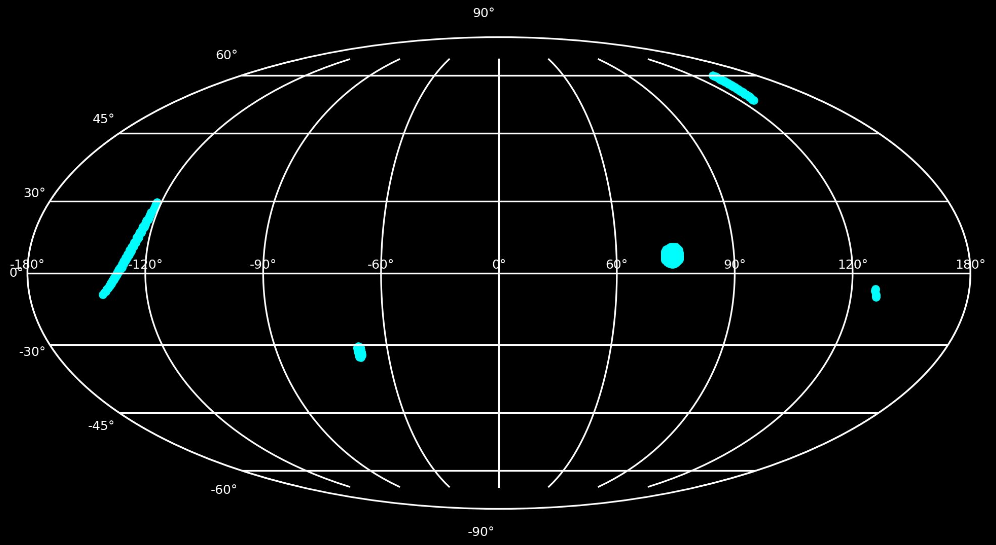


Work in progress…

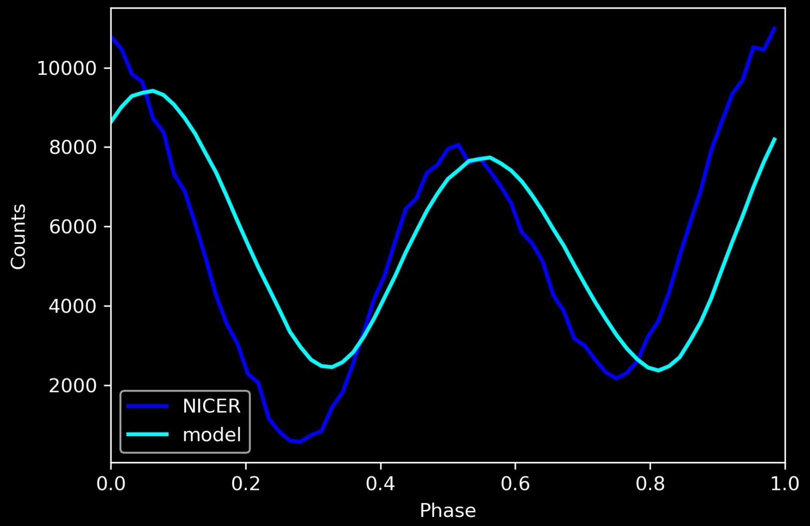
20 chains: 100 or 200 iterations
Grid size: 1000x1000 grid or 800x800

MCMC runs: l = 1+2+3

Mollweide projection showing hotspots



Light curve, model in cyan



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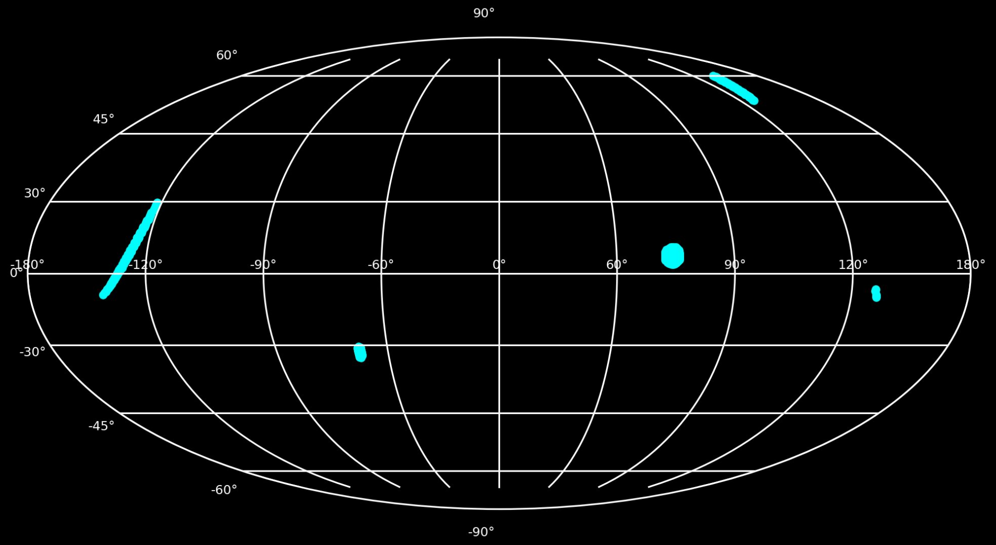
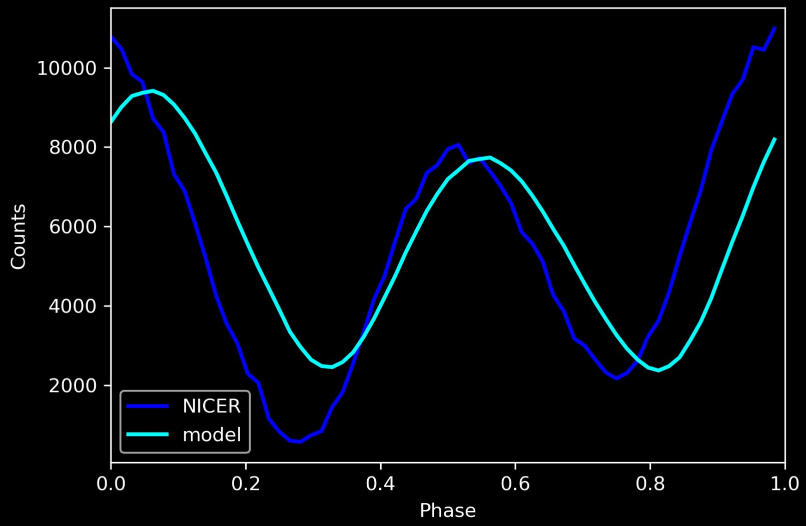
MCMC runs: l = 1+2+3

Mollweide projection showing hotspots



Light curve, model in cyan



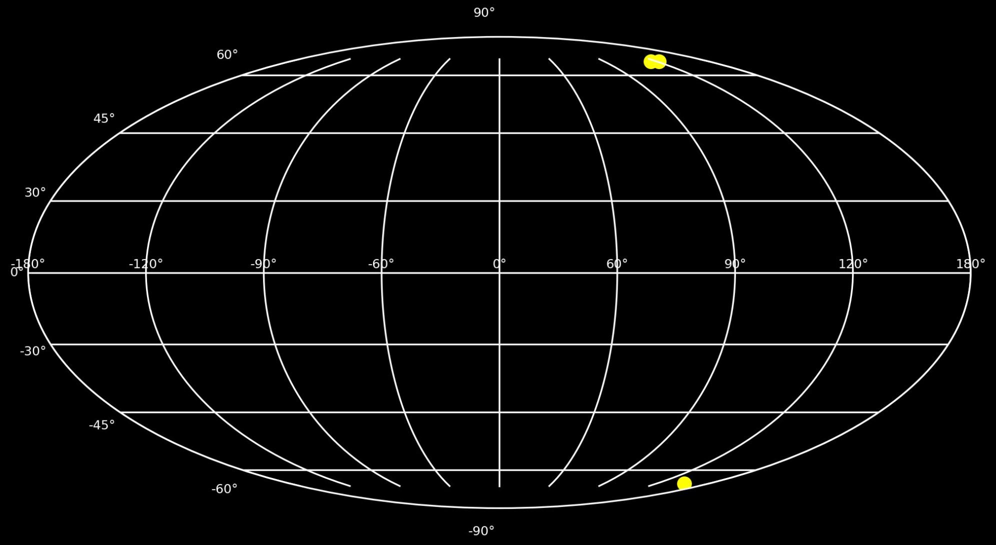
Incorrect phase transformation…

Work in progress…

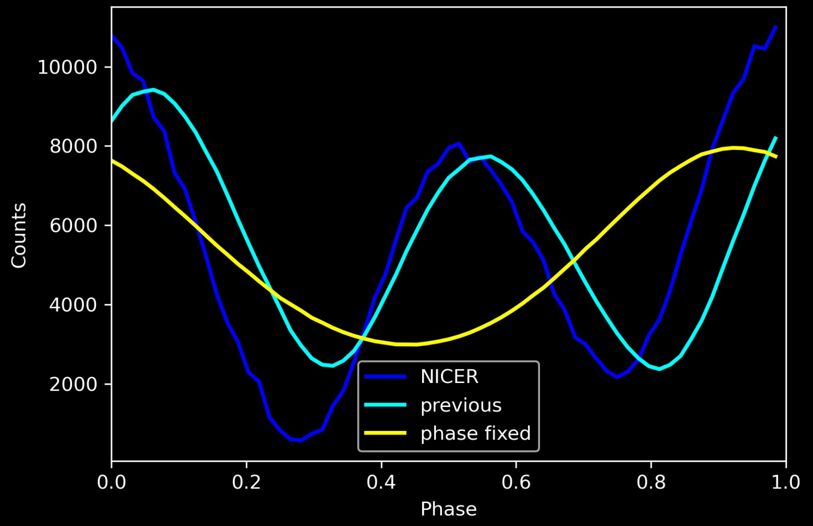
20 chains: 100 or 200 iterations
Grid size: 1000x1000 grid or 800x800

MCMC runs: l = 1+2+3

Mollweide projection showing hotspots



Light curve, model in cyan, yellow



Incorrect phase transformation…

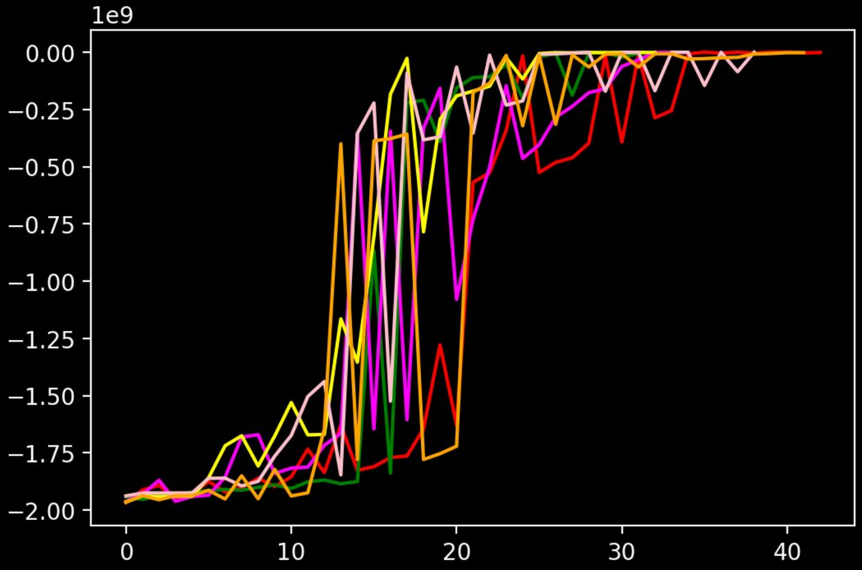
After the fixes…

Work in progress…

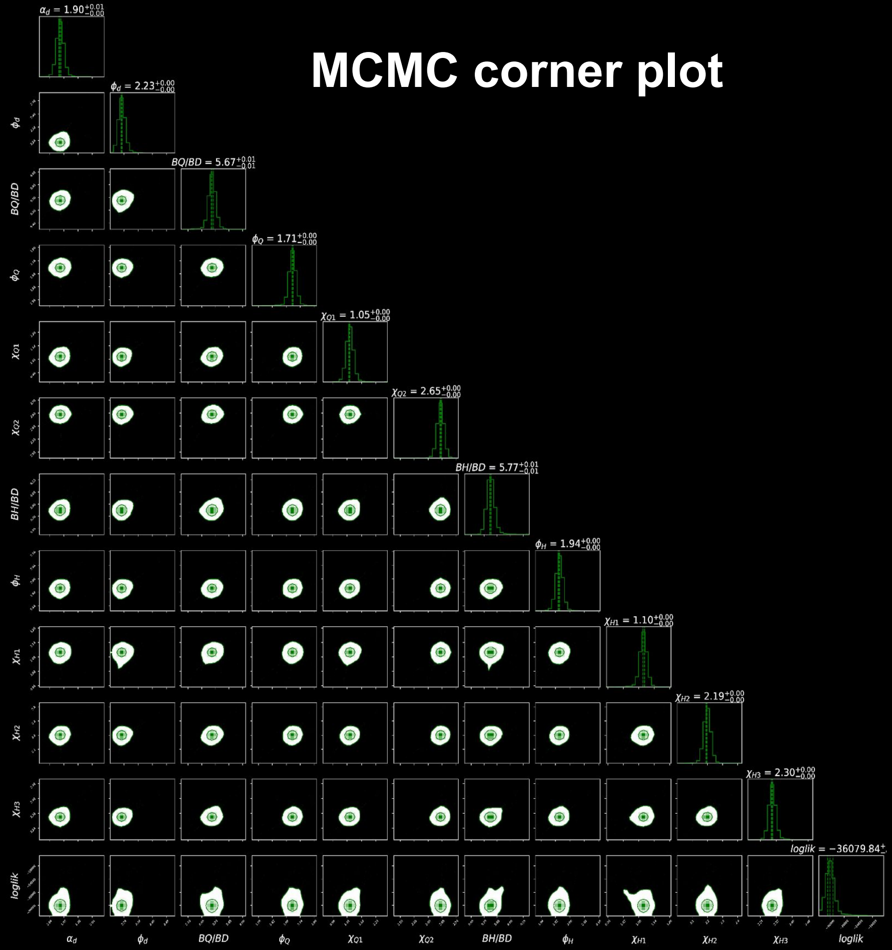
Grid size: 600x600, 50x50

MCMC runs: l = 1+2+3

Trace plot for log-likelihood



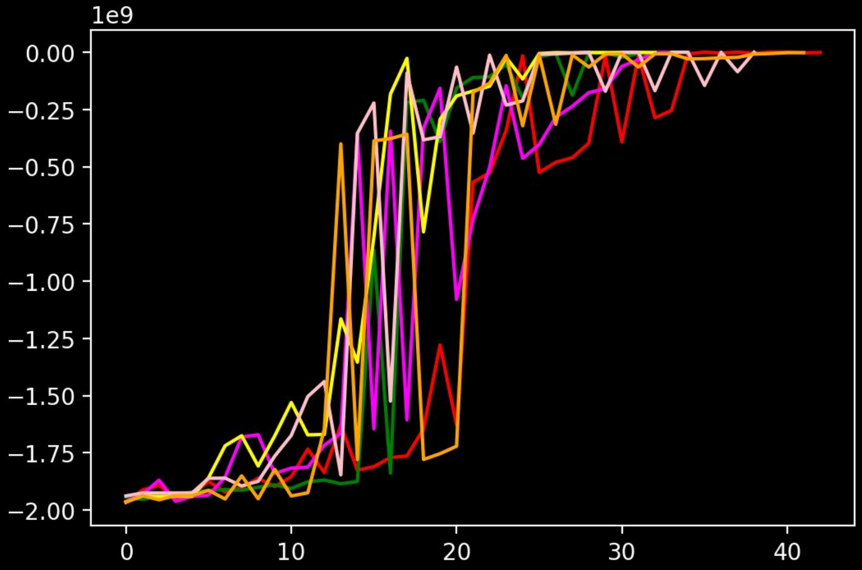
MCMC corner plot



Maximizing negative log-likelihood :
For 50 steps, from order of billion to 1000

MCMC runs: l = 1+2+3

Trace plot for log-likelihood

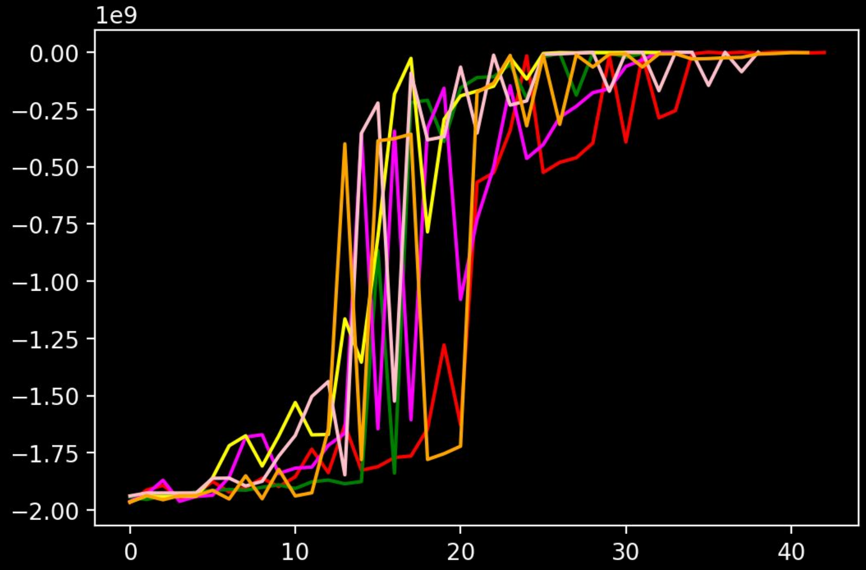


Current focus:

- **Number of iterations, runtime**
- **Decent set of initial conditions**

MCMC runs: l = 1+2+3

Trace plot for log-likelihood



Current focus:

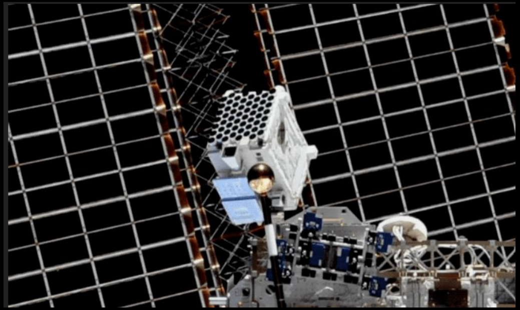
- Number of iterations, runtime
- Decent set of initial conditions

Current limitations:

- Cluster resources, limits
- Loadshedding, resulting in longer queues

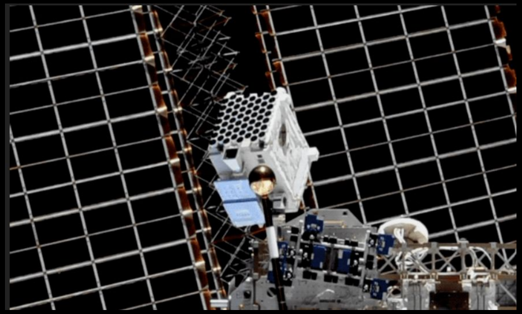
The full story…

Constraining the multipolar magnetic field of MSP J0030+0451 via *NICER* X-ray light curve fitting



The full story…

Constraining the multipolar magnetic field of MSP J0030+0451 via *NICER* X-ray light curve fitting



Constraining the multipolar magnetic field of MSP J0030+0451 via combined *NICER* X-ray and *Fermi* gamma-ray light curve fitting

https://heasarc.gsfc.nasa.gov/docs/nicer/
https://www.nasa.gov/sites/default/files/thumbnails/image/glap0588.jpg

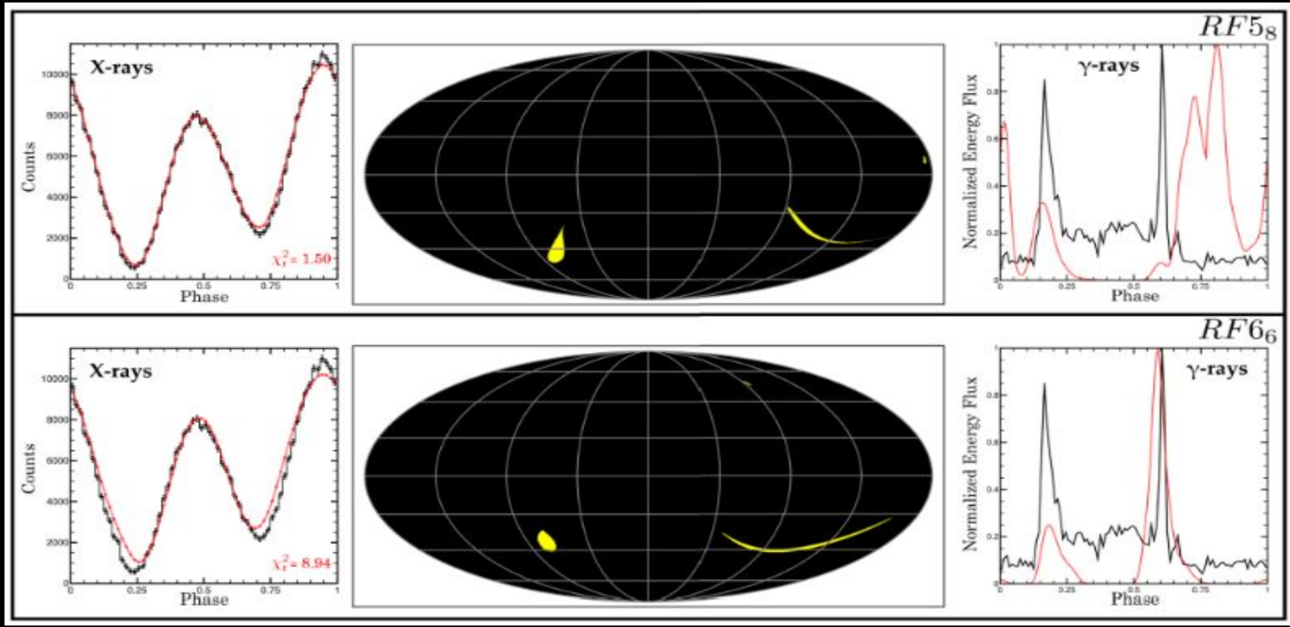
The full story…

Yellow:
Hotspots

LCs:
Black: NICER/Fermi data
Red: Model

X-ray LCs:
Field degeneracies

Gamma-ray LCs:
Lifts the degeneracies



Kalapotharakos et al. (2021)

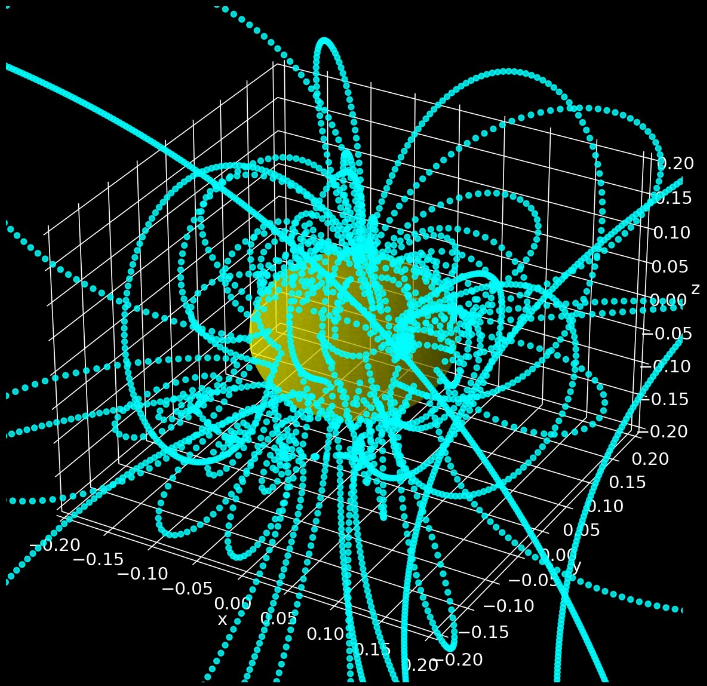
Summary and outlook

Now: Multipolar field + MCMC runs:

- Runtime optimization: Ideas?
- Constrain by simultaneous fitting with *Fermi* gamma-ray data: Degeneracies?
- Offset multipolar field

Next: Constraining equation of state:

- Self-consistent mass and radius determination
- Apply to other *NICER* MSPs



Thank you for your attention!

NWU
NORTH-WEST UNIVERSITY
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UNIBESITI YA BOKONE-BOPHIRIMA

SA-GAMMA
THE SOUTH AFRICAN GAMMA-RAY ASTRONOMY PROGRAMME

Fermi

Anu Kundu*, North-West University

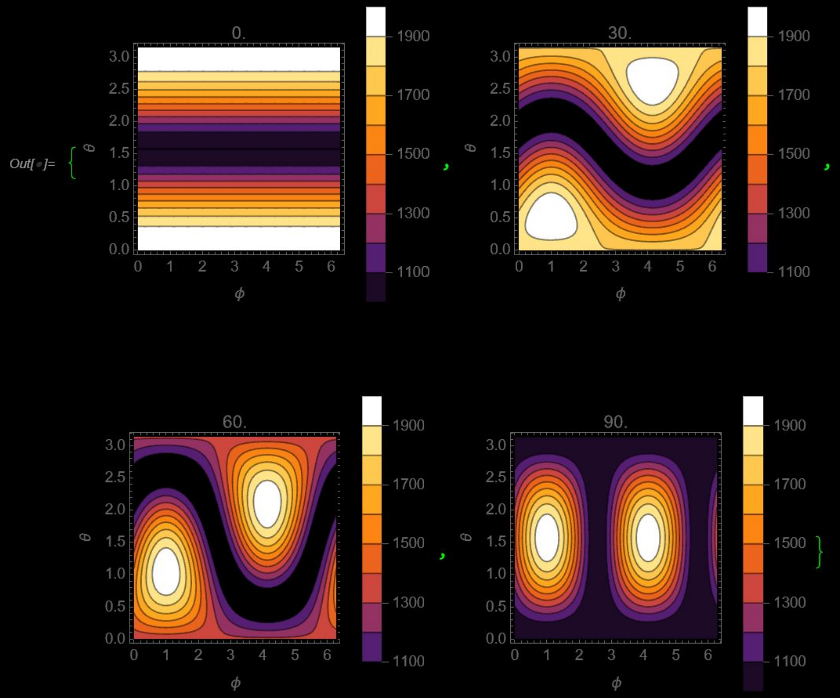
Can't think of any questions? Maybe you are curious about:

1. *"Normalization of the field strength of the different components?"*
2. *"Difference from what NICER team is doing?"*
3. *"Are you crazy enough to activate l4 and higher components?"*
4. *"What is this… loadshedding?"*
5. *(If you attended HEASA 2022:) "Updates on the lost peak…?"*

*anukundu02@yahoo.com

Extra slides

Surface magnetic field for l = 1



Surface magnetic field for l = 2