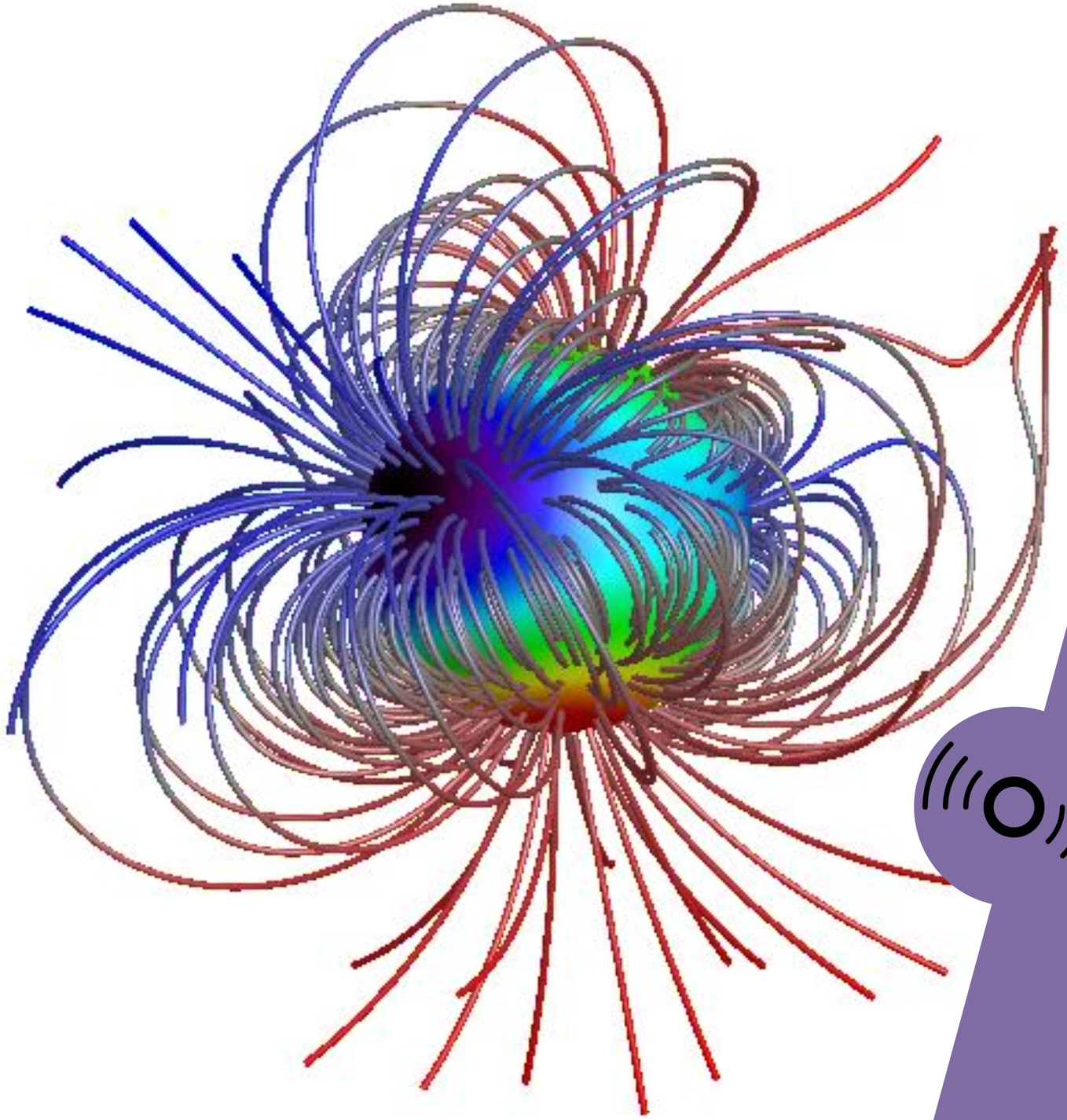
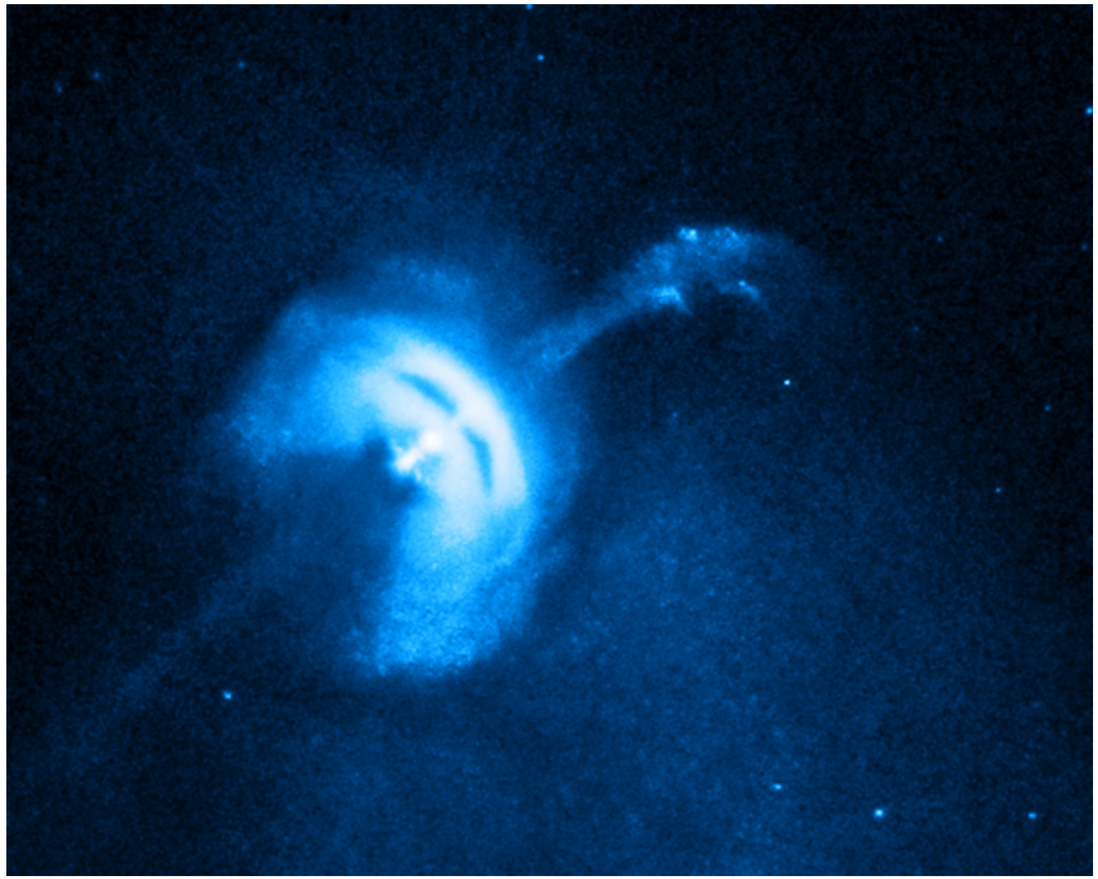


Assessing the Evidence of Multipolar Fields in Pulsars

Prakash Arumugasamy
Dipanjan Mitra,
Oleg Kargaltsev, George Pavlov, Bettina Posselt

NECESSITY OF MULTIPOLAR FIELDS

- Pulsar Wind Nebulae
  - Pair cascades



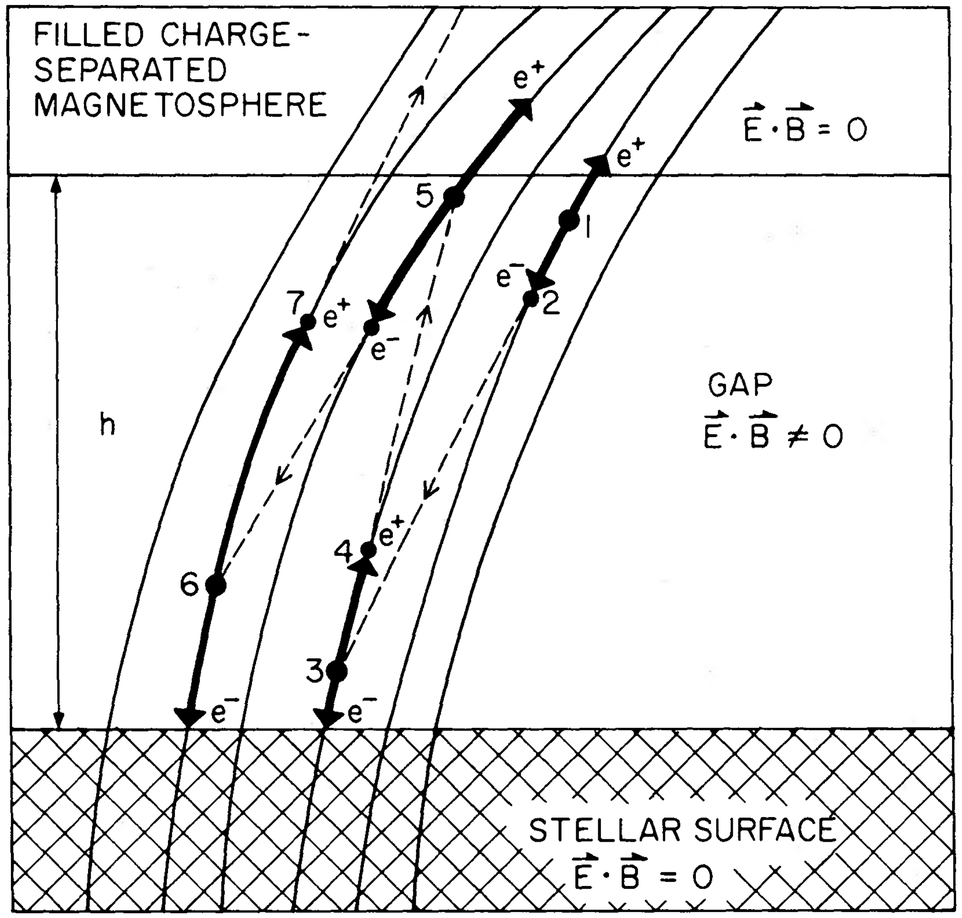
Vela Pulsar and Wind Nebula in the X-rays *gsfc@NASA*

NECESSITY OF MULTIPOLAR FIELDS

Pulsar Wind Nebulae

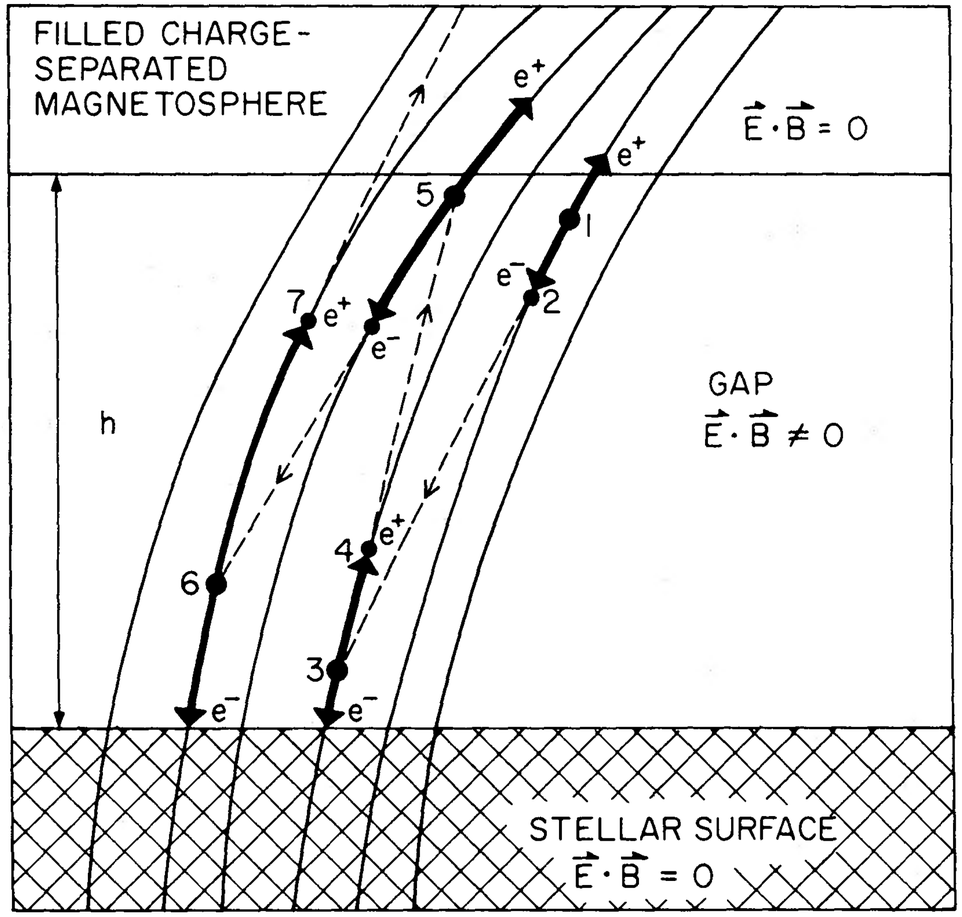
Pair multiplicity factor ~ 10^5

- Mean free path for magnetic pair production decreases with curvature
- High pair multiplicity cannot be achieved with dipolar fields.



Ruderman & Sutherland, 1974

NECESSITY OF MULTIPOLAR FIELDS

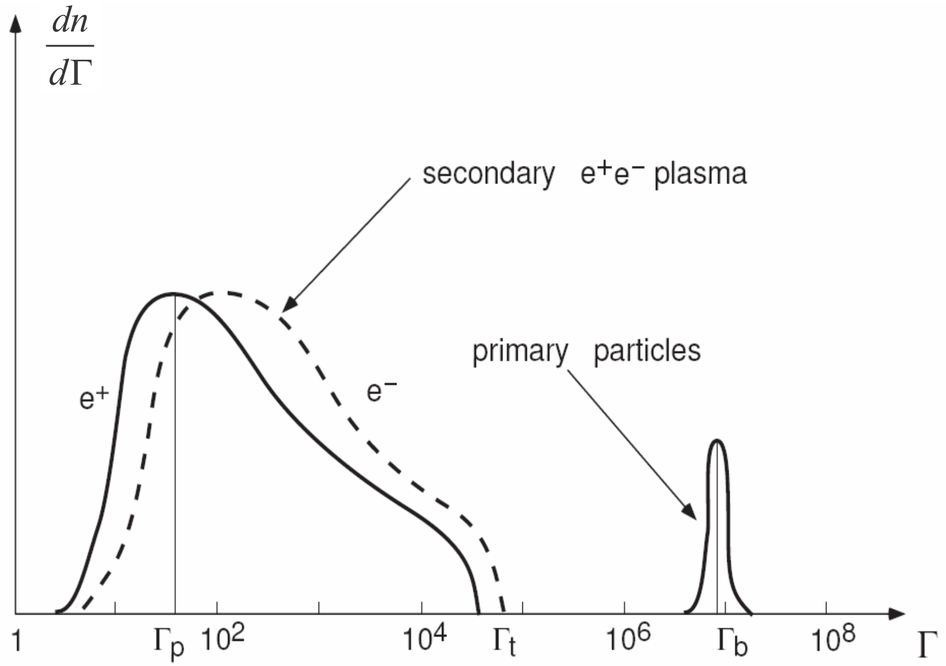


Ruderman & Sutherland, 1974

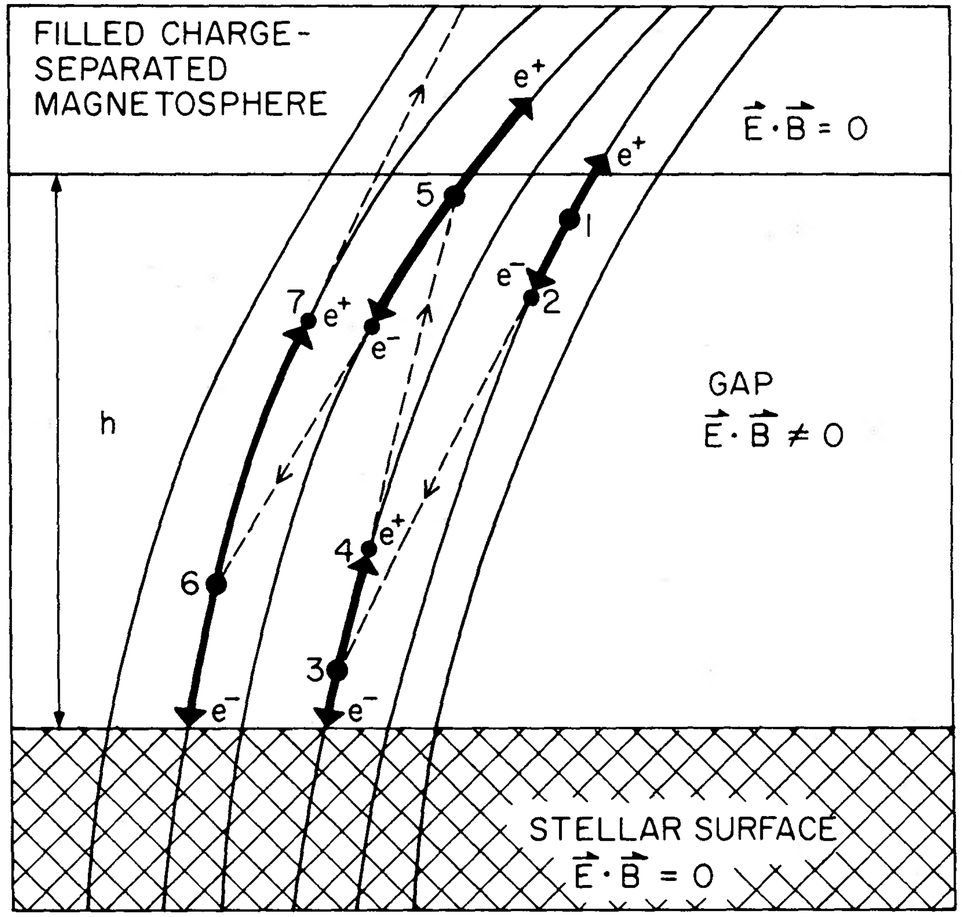
Coherent Radio Emission

Pair multiplication

Two stream instability



NECESSITY OF MULTIPOLAR FIELDS

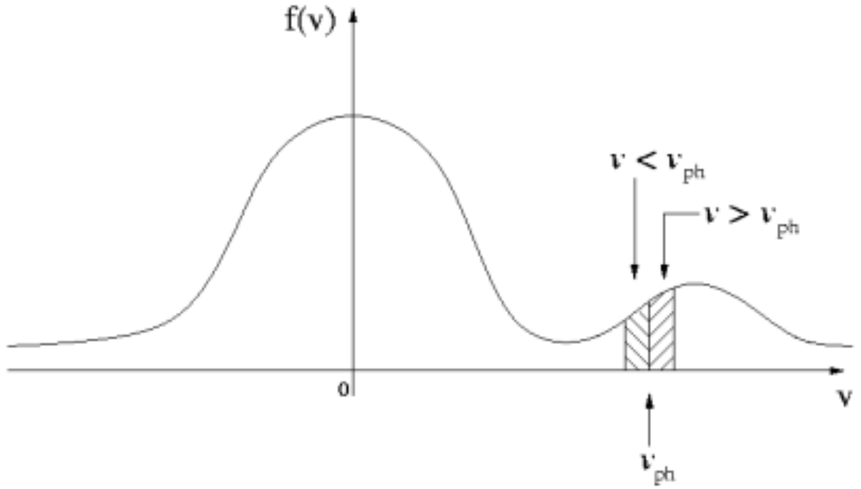


Ruderman & Sutherland, 1974

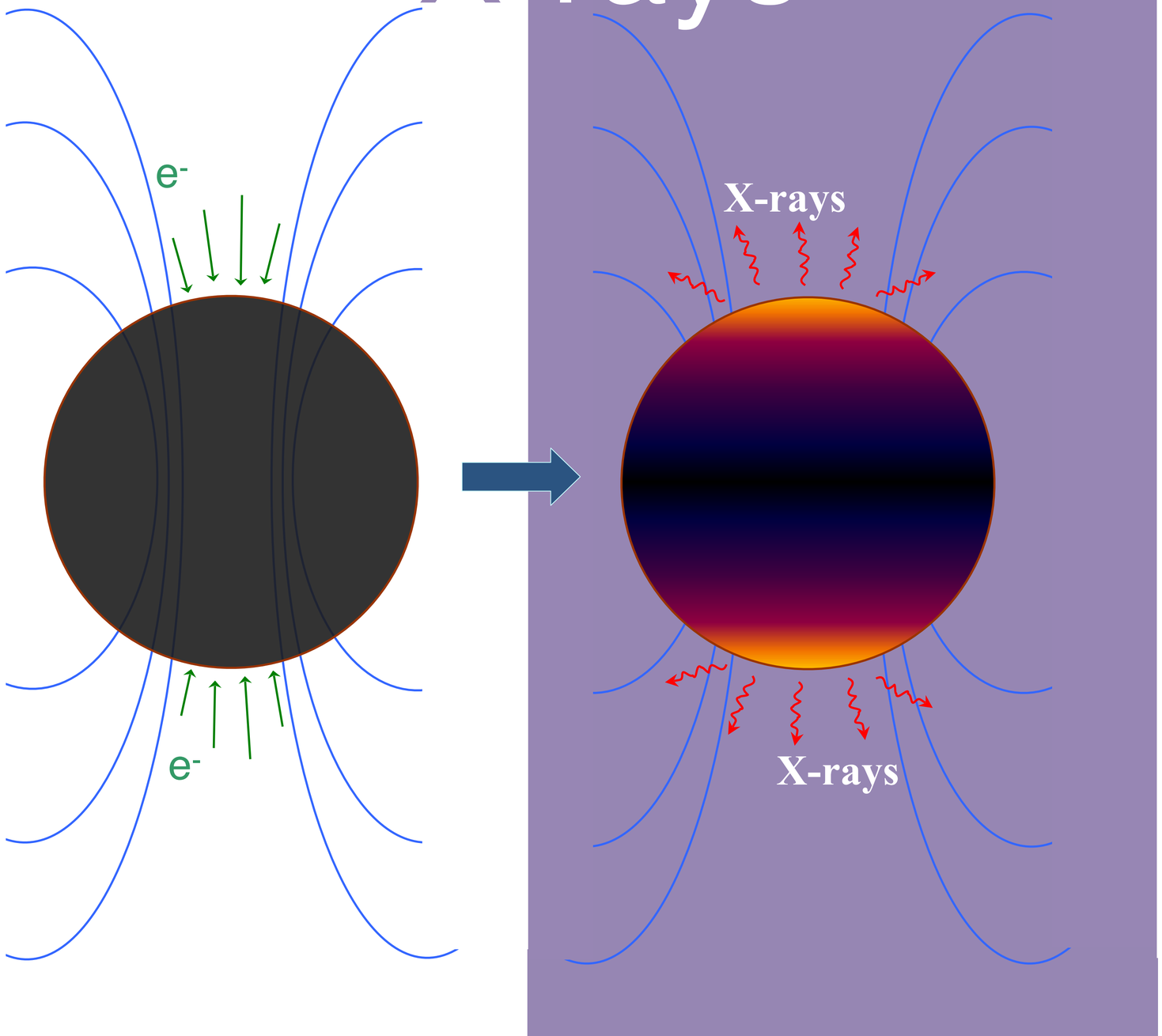
Coherent Radio Emission

Pair multiplication

Two stream instability



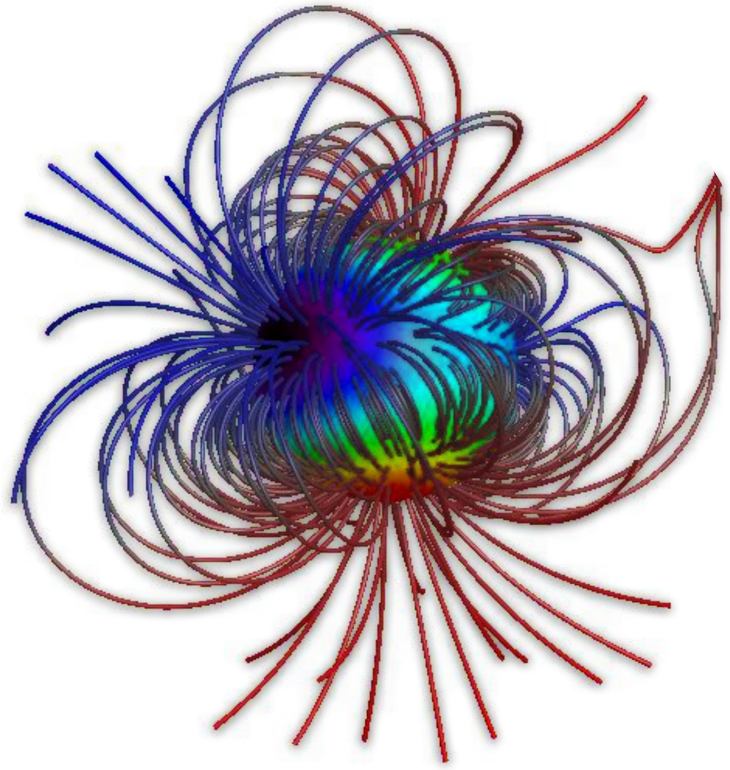
X-rays



X-ray Emission from near the Neutron star surface

- Charged particles accelerated in a gap close to the poles
- Charge bombardment on polar cap leads to local heating
- At ~ 1 million K, predominantly X-rays

THE TRADITIONAL METHOD



MEASURE THE
POLAR CAP AREA

MEASURE THE POLAR CAP AREA

Conservation of Magnetic Flux

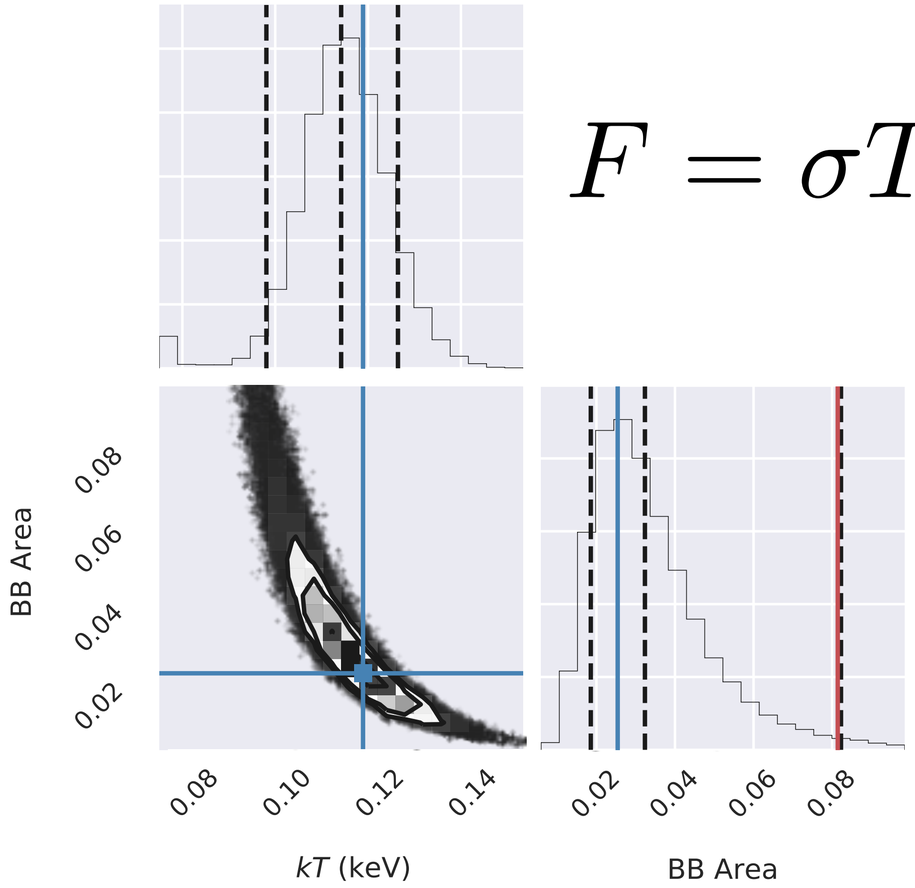
$$B_{\mathrm{Surf}} \cdot A_{\mathrm{pc}} = B_{\mathrm{dip}} \cdot A_{\mathrm{pc,dip}}$$

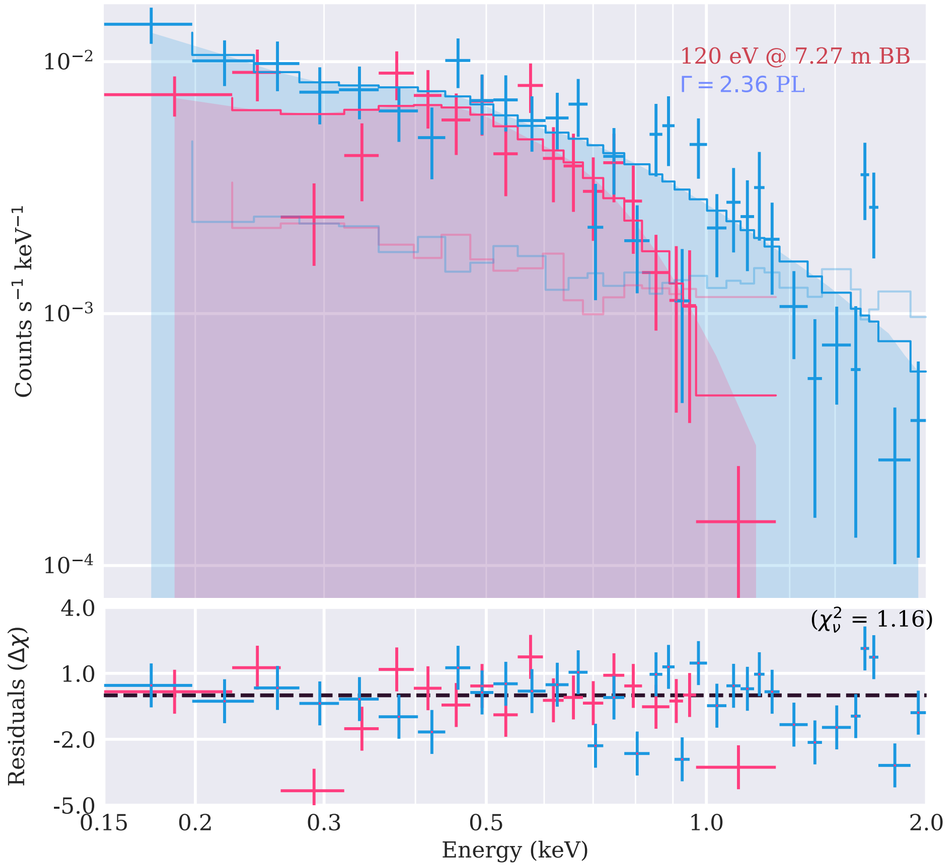
$> 10^{12}\mathrm{G} \quad < A_{\mathrm{pc,dip}} \quad \sim 10^{12}\mathrm{G} \quad \frac{2\pi^2 R^3}{cP}$

MEASURE THE BLACKBODY AREA

Blackbody Emission

$$F = \sigma T^4 A$$

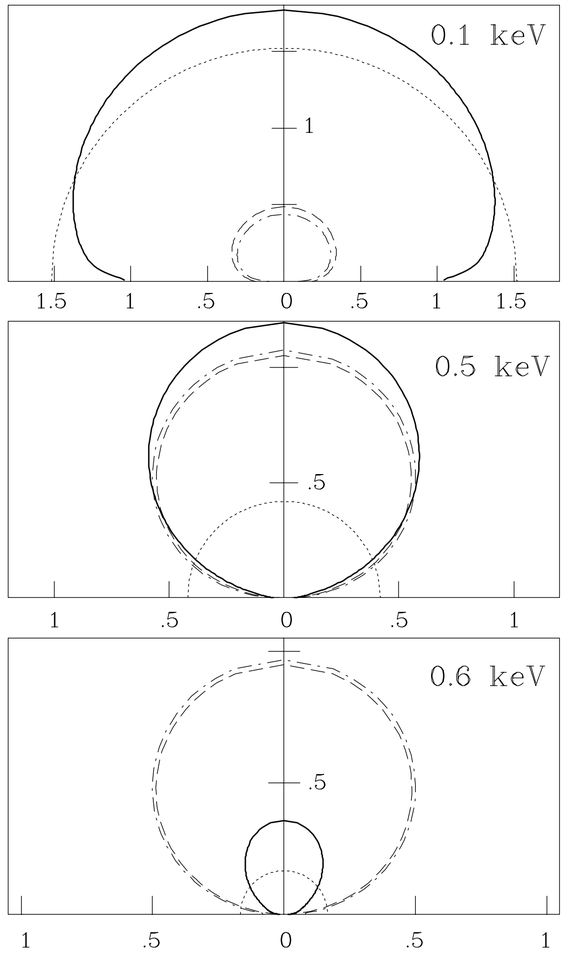




BEAMED EMISSION MODELS

Beamed Emission

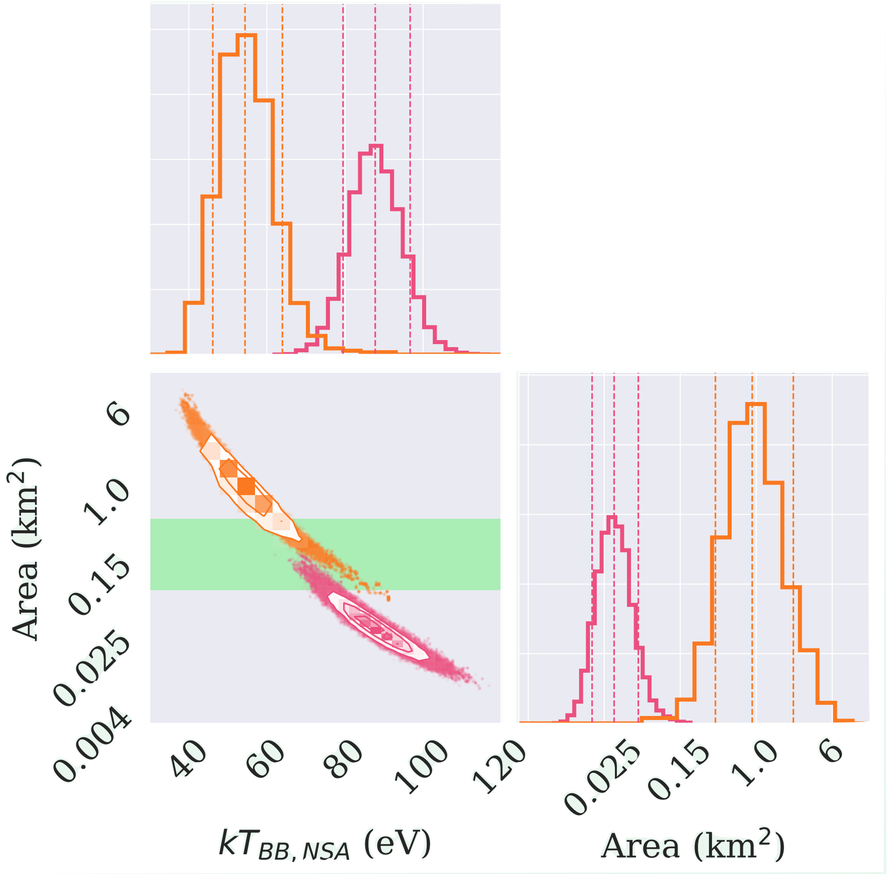
- Blackbody emission is isotropic
- Reprocessed BB emission anisotropy in energy dependent.



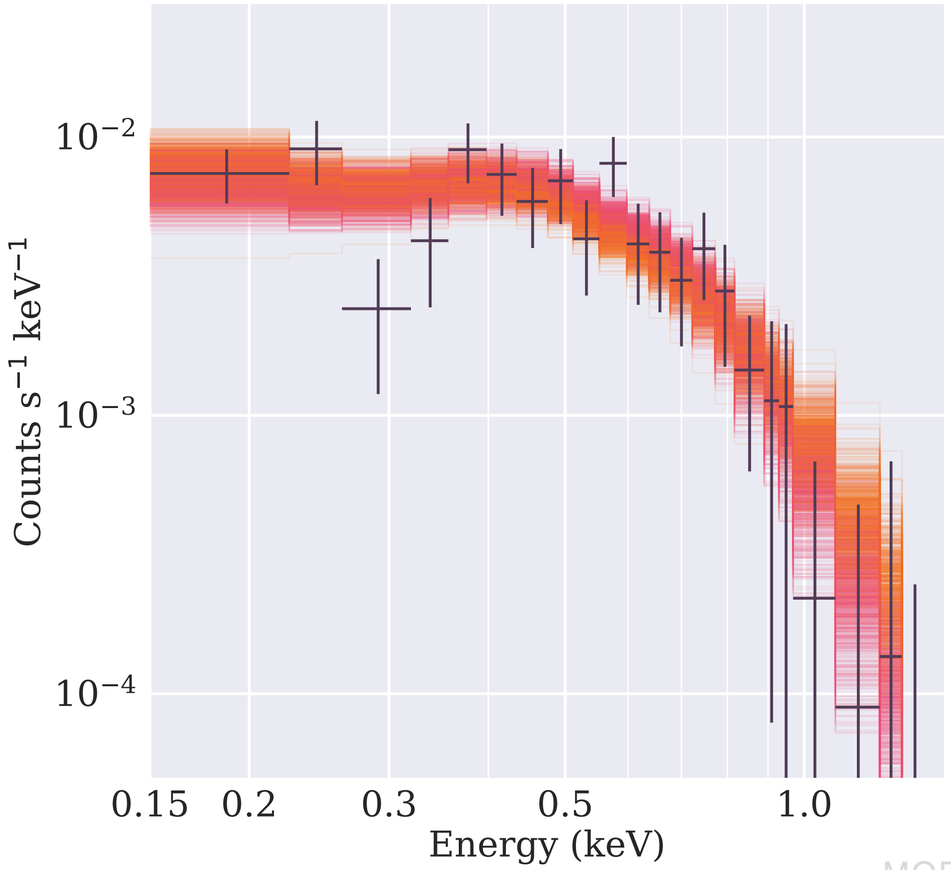
Polar plots of specific intensity from Hydrogen, Helium, and Iron atmospheres (dash-dotted, dashed, and solid) *Zavlin, Pavlov, & Shibanov, 1996*

MEASURE THE POLAR CAP AREA

Blackbody and Atmosphere models are degenerate
Polar cap area estimate is unreliable



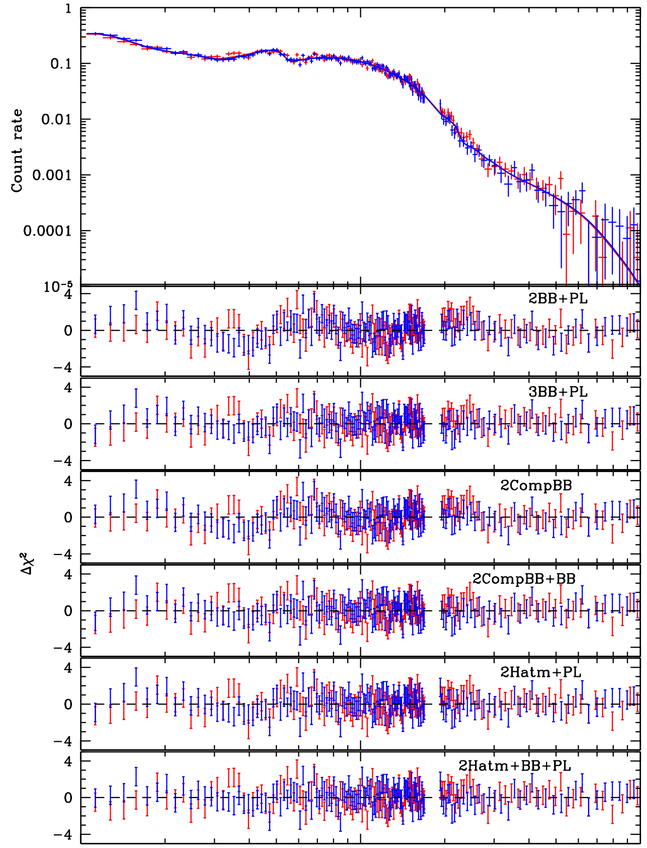
Blackbody and Atmosphere emission area compared to Dipolar polar cap area



Spectra fit with Blackbody and Atmosphere models

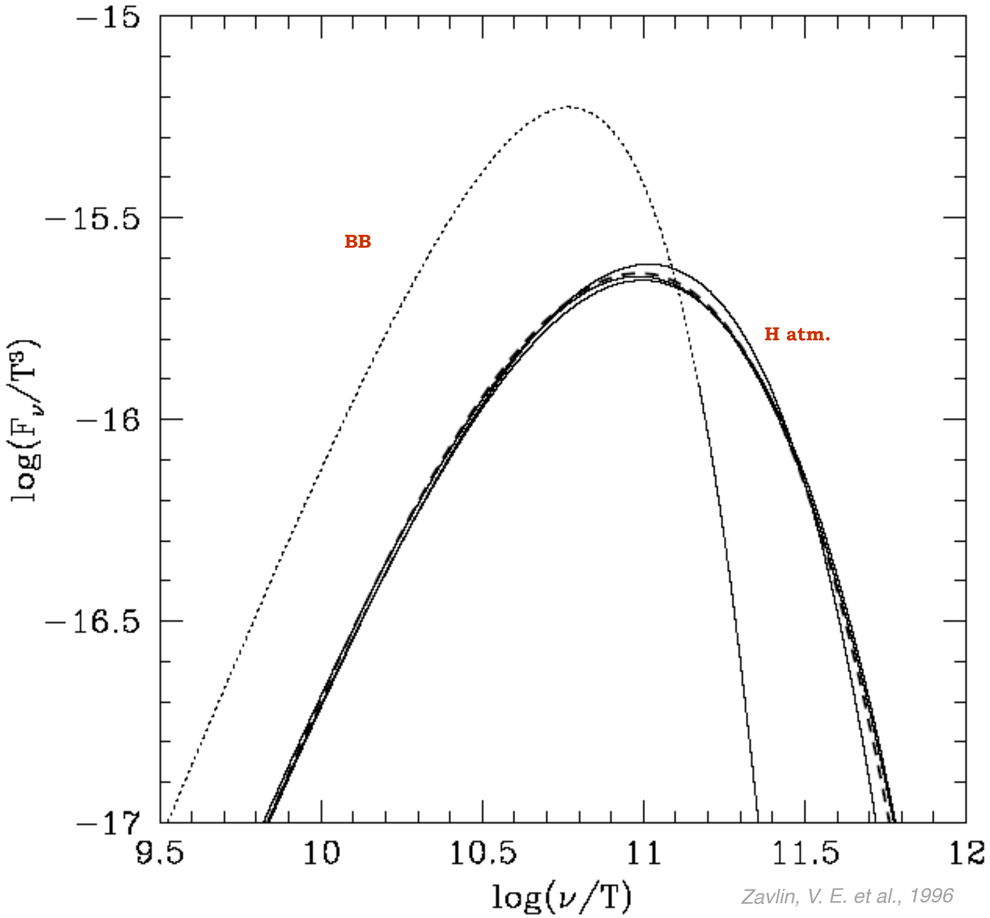
EVIDENCE FOR BLACKBODY

Spectral analysis degenerate even for high S/N spectra



Spectral fits for J0437-4715

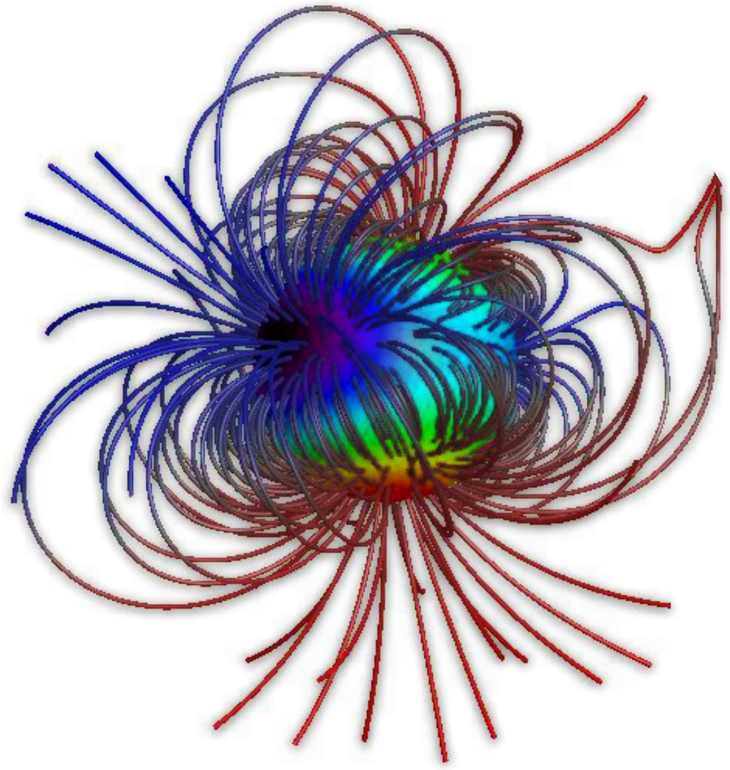
Bogdanov, S., 2012



Zavlin, V. E. et al., 1996

Blackbody and Hydrogen atmosphere spectrum

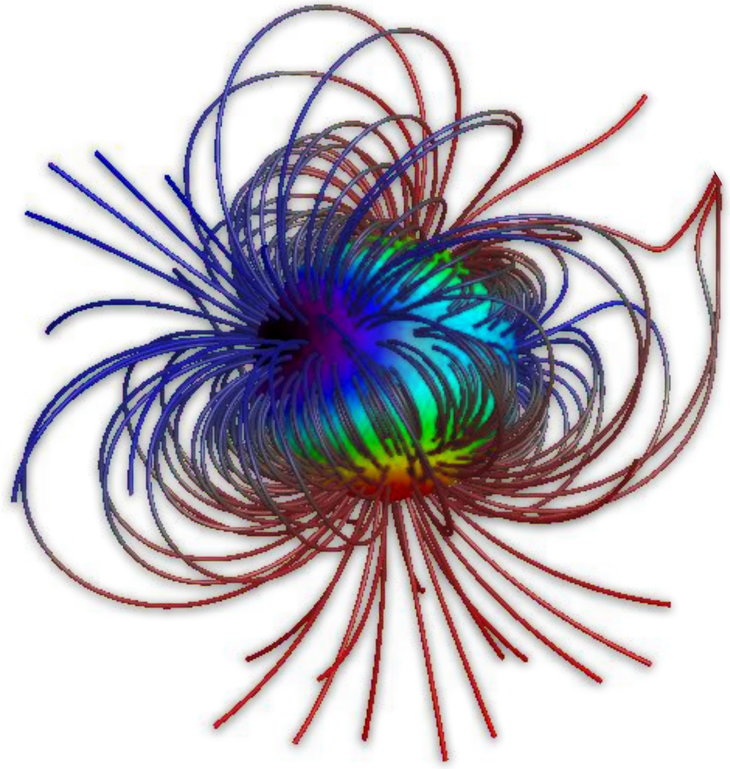
THE TRADITIONAL METHOD



Polar Cap Area

- Requires high S/N observations at energies in which thermal PC emission dominates.
- Weak predictive power with current data and telescopes.
- We are trying to show how the method is usually misused in current literature.

THE ALTERNATIVE METHOD

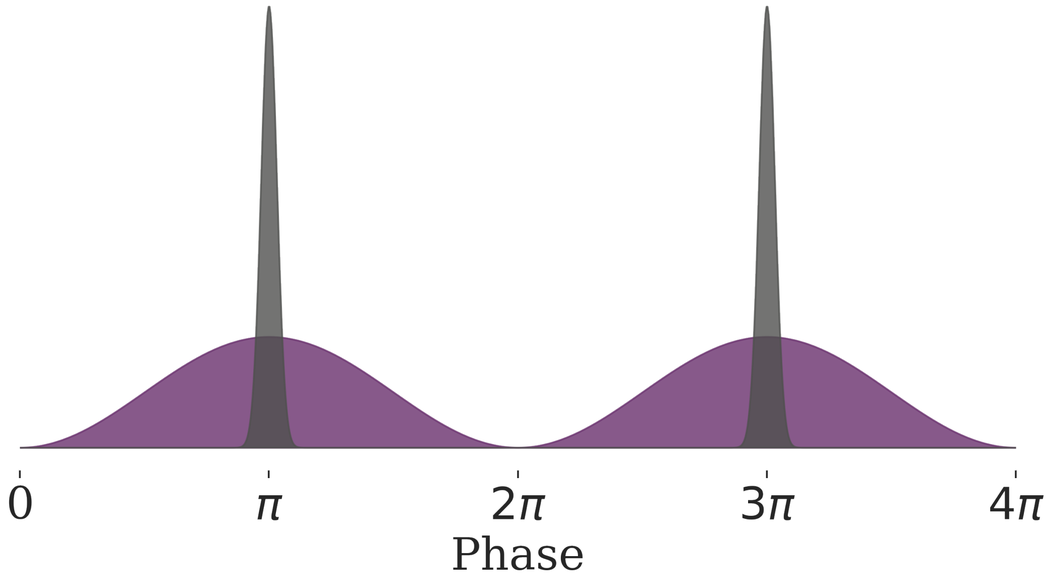


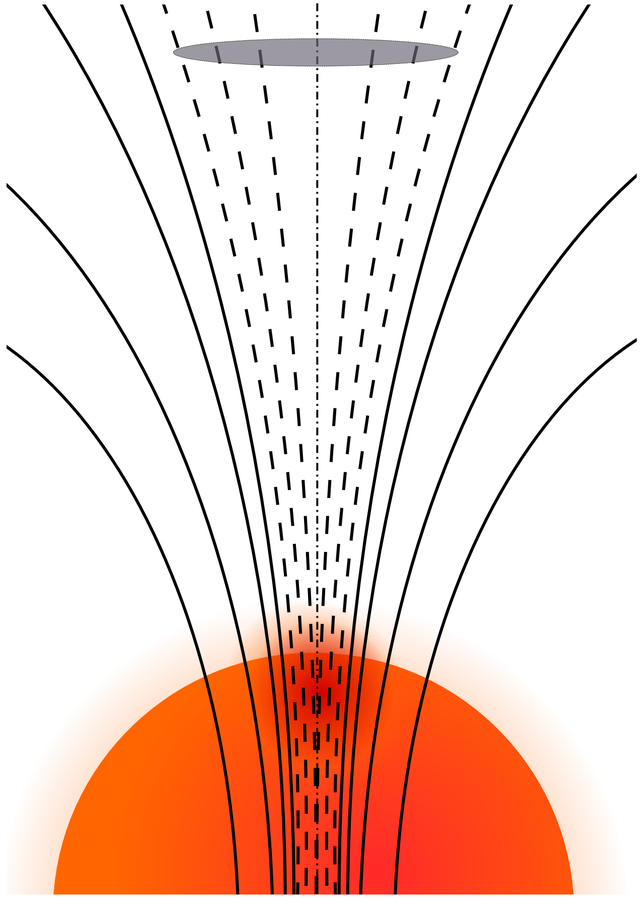
MEASURE THE OFFSET
THERMAL EMISSION
AND
RADIO EMISSION

MEASURE THE X-RAY RADIO OFFSET

Predictable Alignments of Emission from Dipolar Region

- Thermal radiation from the surface and radio emission regions see a dipole
- Close alignment of thermal emission peak and radio emission core components

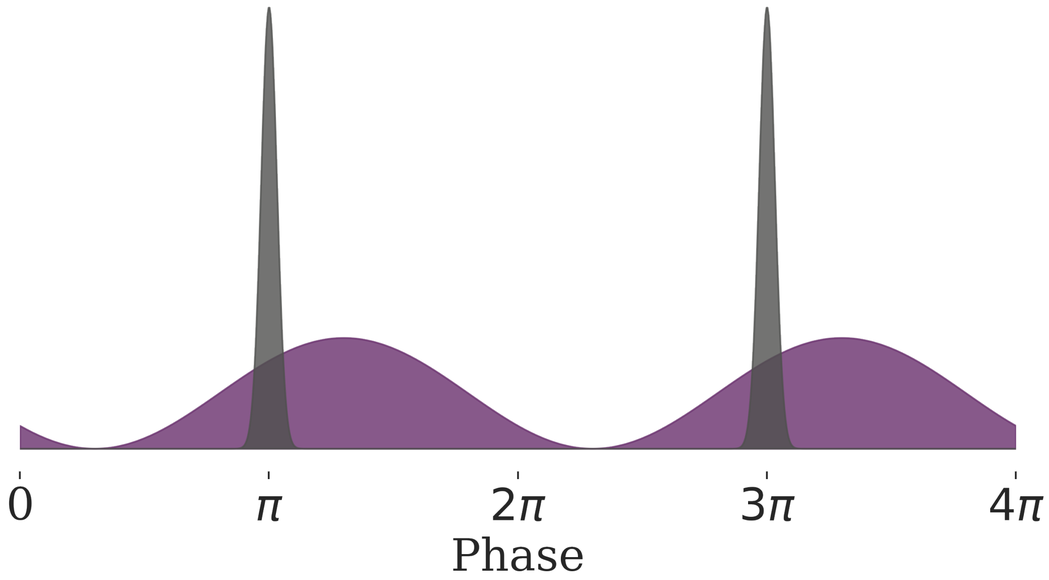


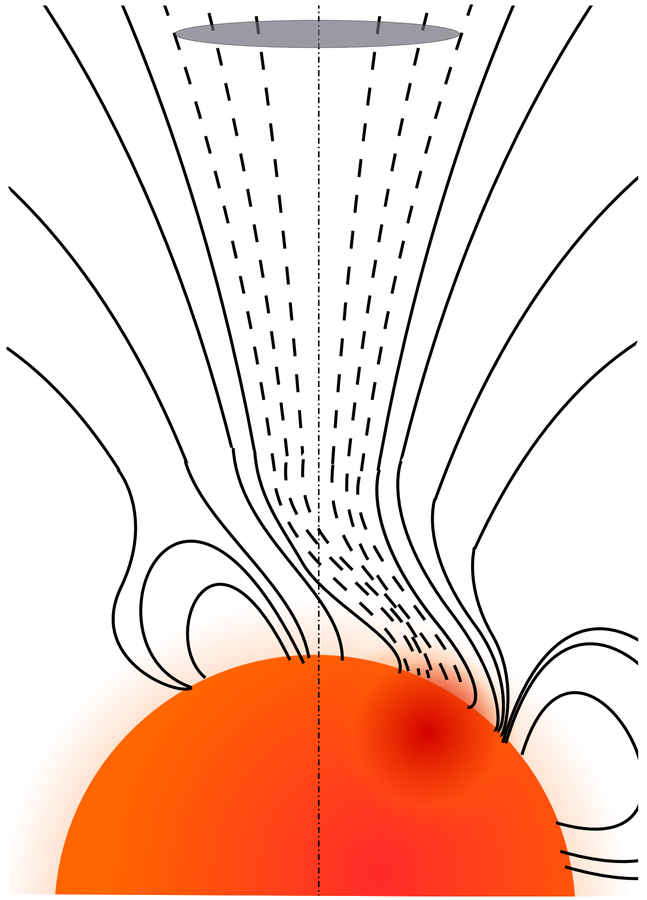


MEASURE THE X-RAY RADIO OFFSET

Thermal X-ray and Radio Offset from Non-dipolar Fields

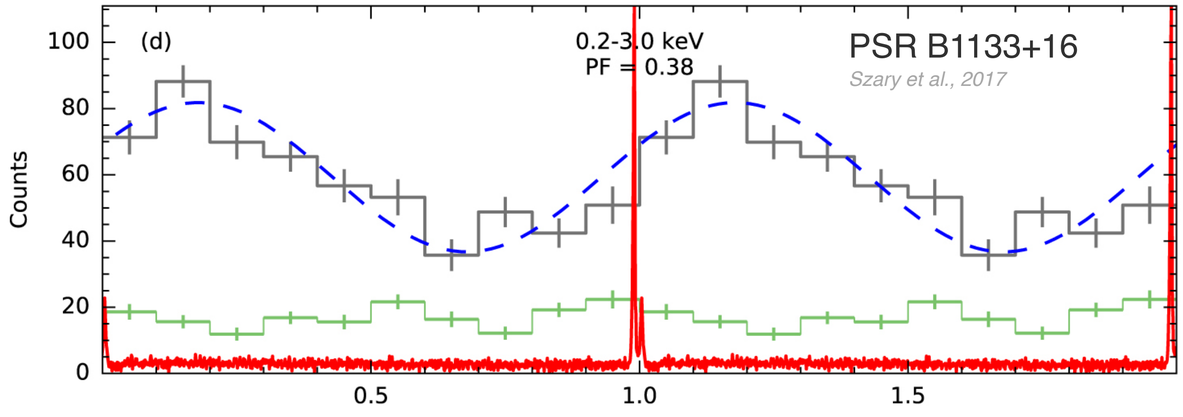
- Radio emission regions still from dipolar region
- Thermal emission from foot of open field lines

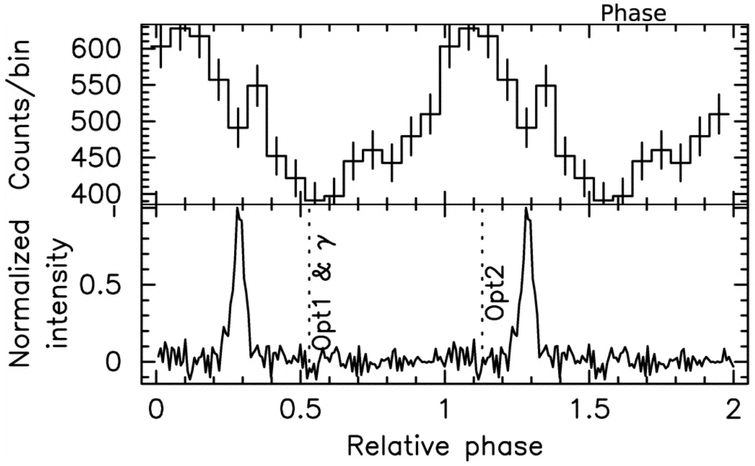




MEASURE THE X-RAY RADIO OFFSET

X-ray — Radio Phase-Aligned Profiles



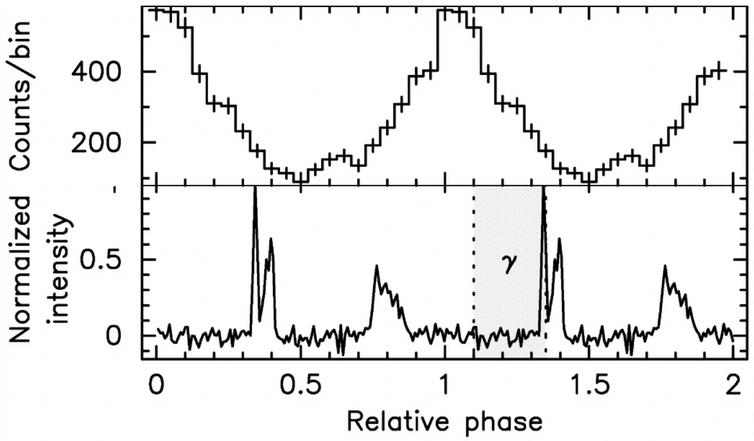


0.70−1.50 keV
Hot blackbody
PF=(21.3±2.5)%

Radio 0.67 GHz

PSR B0656+14

De Luca et al., 2005
Also, see Arumugasamy et al., 2018



0.70−1.50 keV
Hot blackbody
PF=(67±3)%

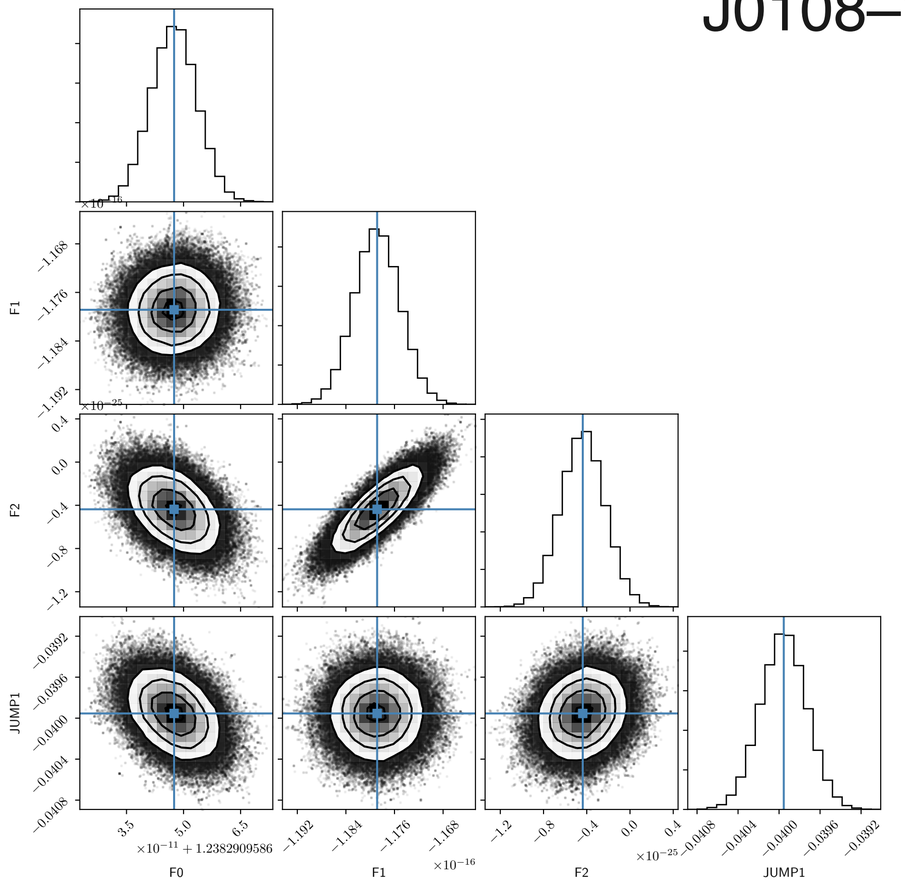
Radio 0.67 GHz

PSR B1055-52

De Luca et al., 2005

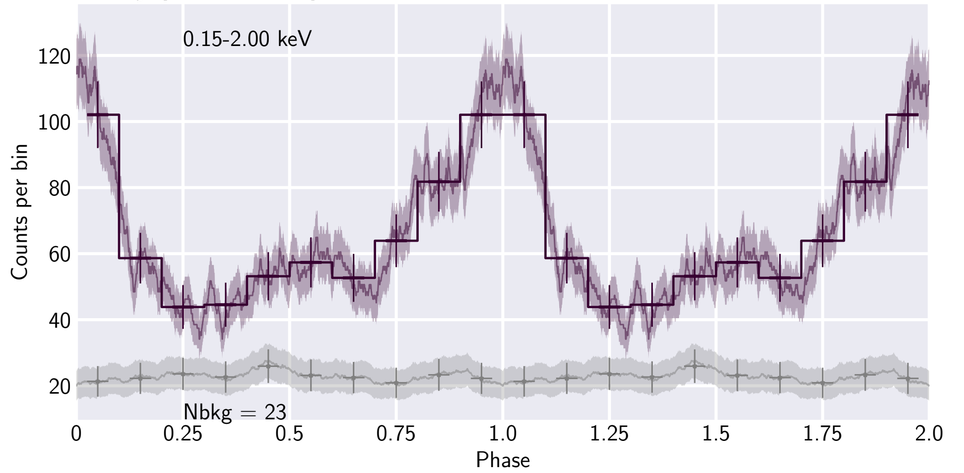
MEASURE THE X-RAY RADIO OFFSET

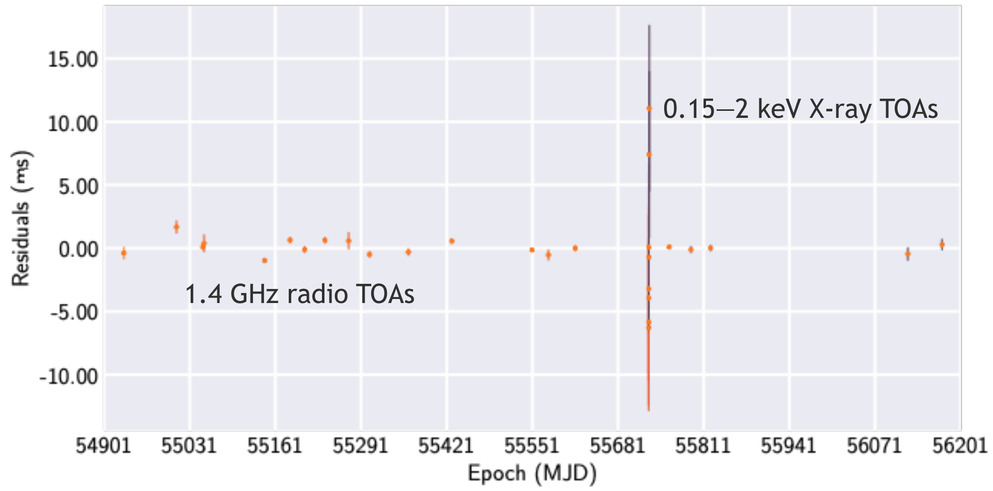
X-ray — Radio Offset Measurement J0108–1431



Radio timing solution for J0108-1431 with X-ray pulse offset measurement

X-ray pulsation profile

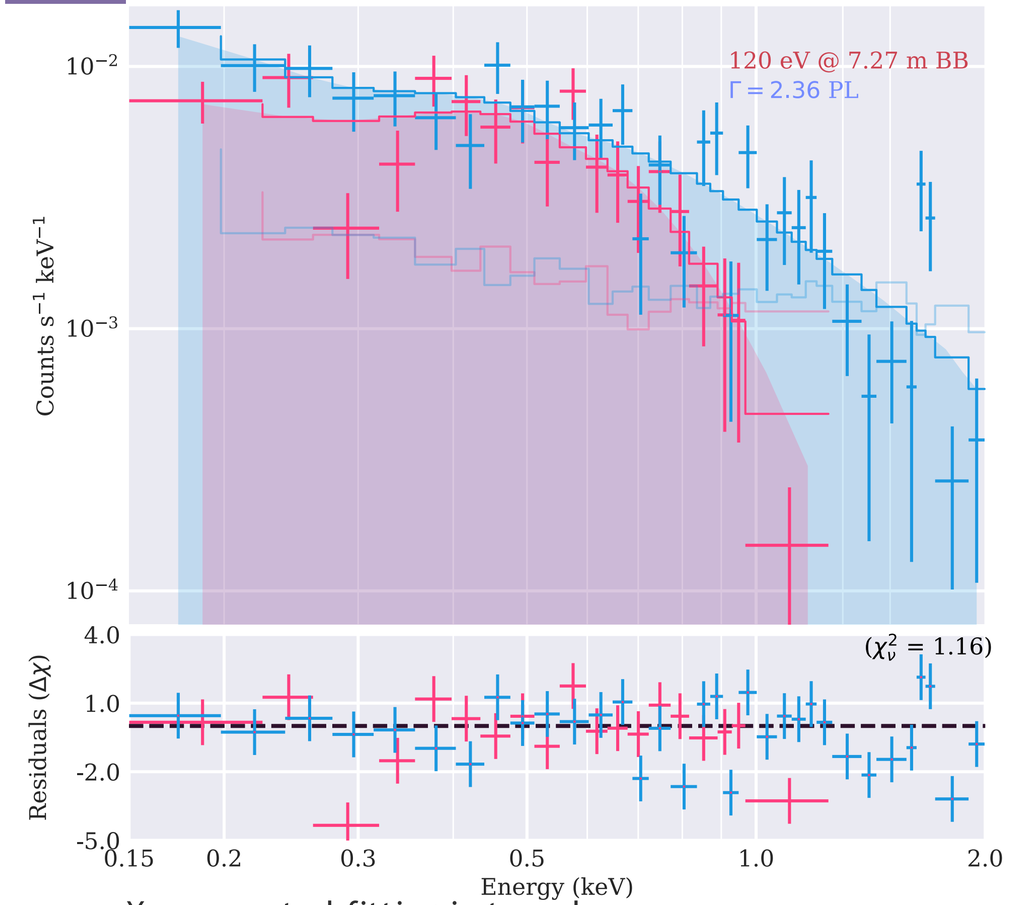




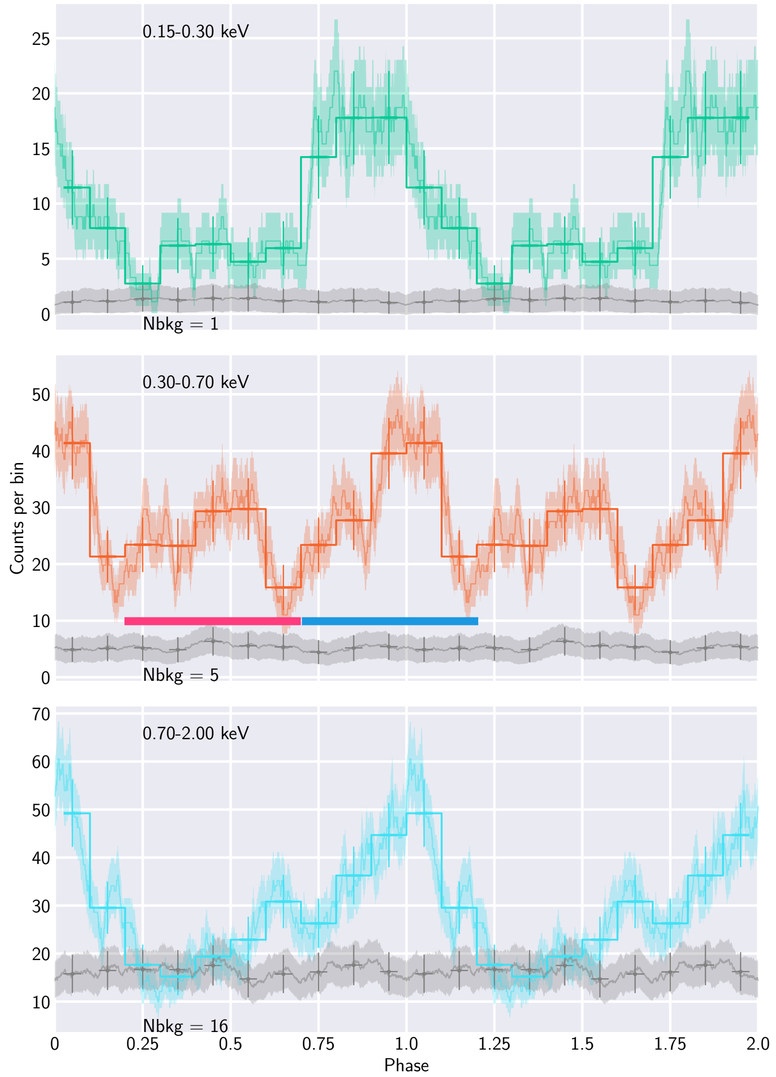
Residuals after fitting radio TOAs

MEASURE THE X-RAY RADIO OFFSET

X-ray — Radio Offset Measurement



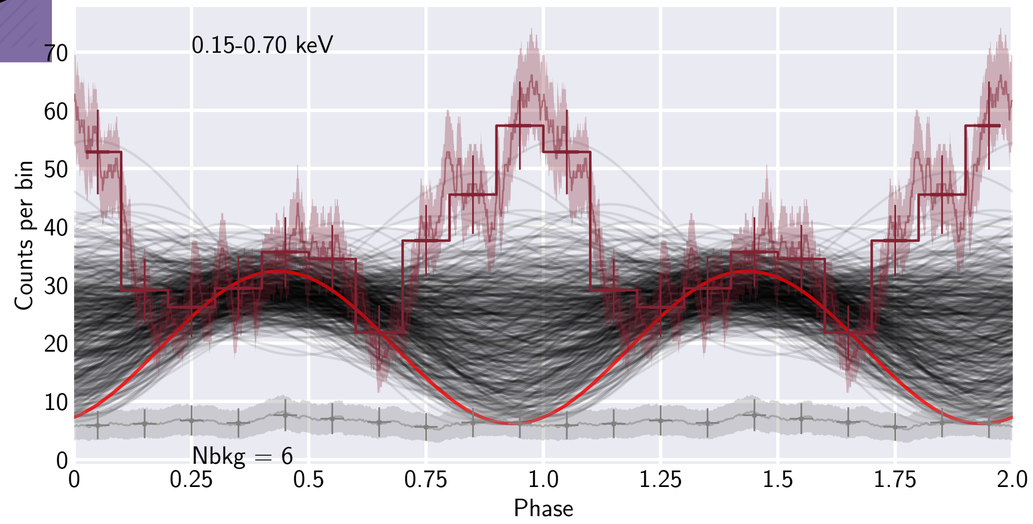
X-ray spectral fitting in two phases



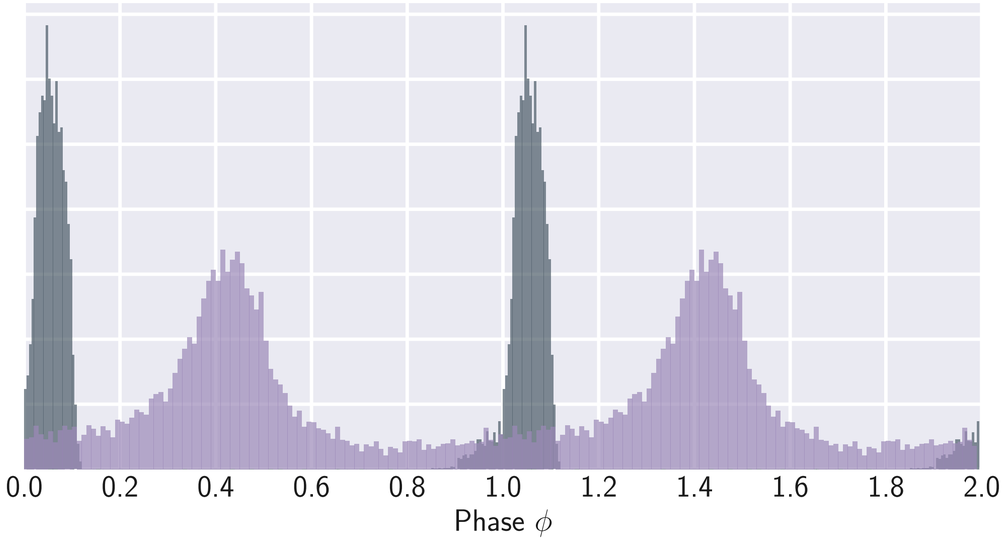
Energy-resolved X-ray pulsation

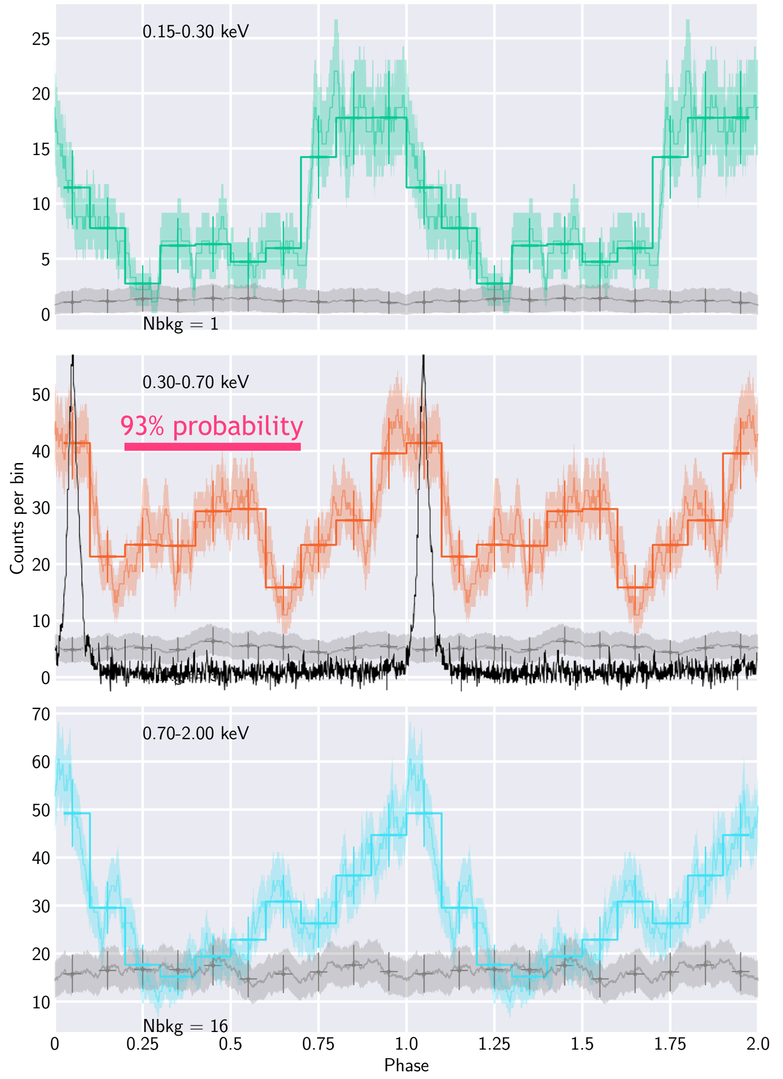
MEASURE THE X-RAY RADIO OFFSET

Fitting Sine curves to find thermal pulsations peak



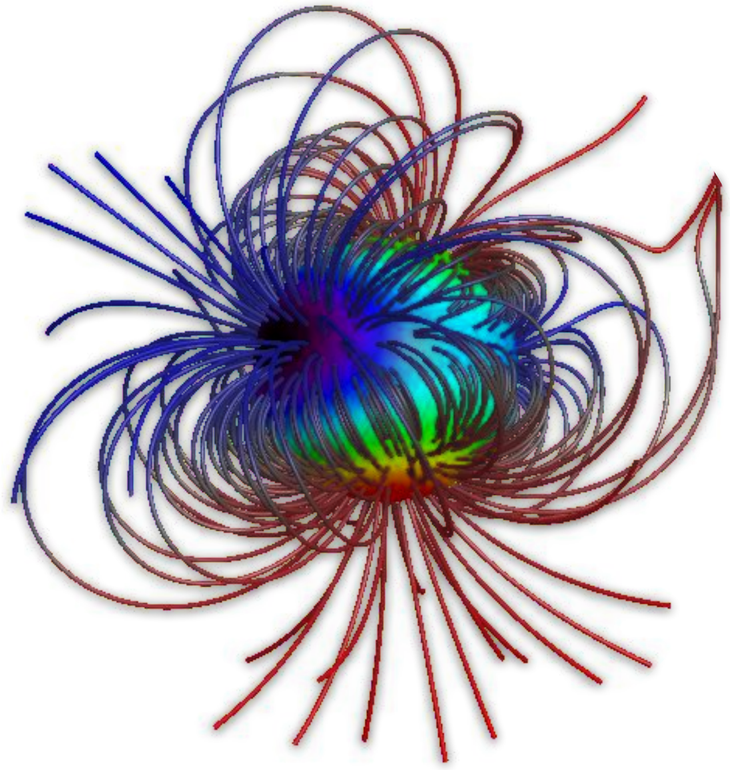
Distribution of thermal and radio peaks





Energy-resolved X-ray pulsation

THE ALTERNATIVE METHOD

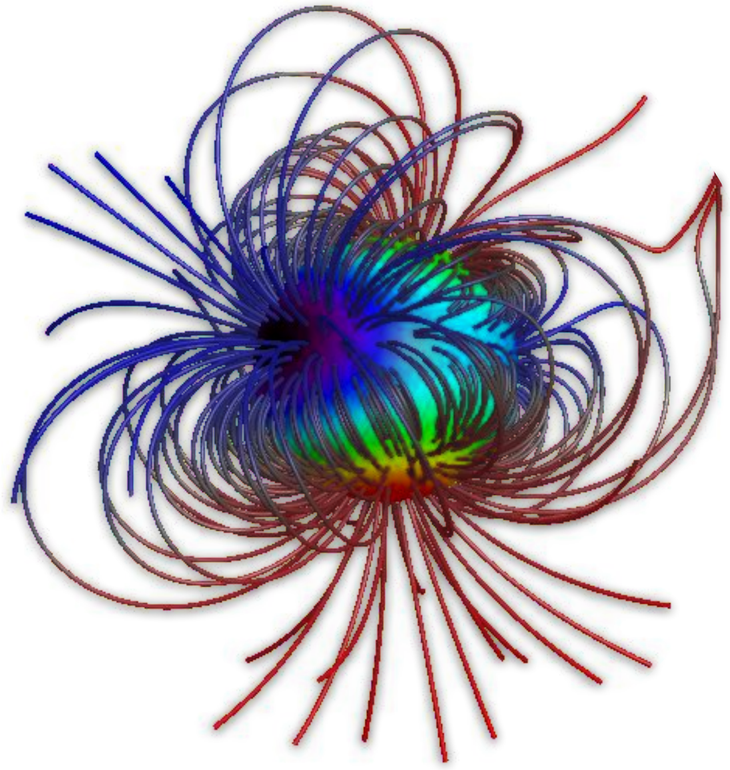


Need a good sample with reliable thermal X-ray and radio offsets

Alignment =/= Dipolar
Mis-alignment == Multipolar

Emission Profile Offset

EVIDENCE OF MULTIPOLAR FIELDS



Polar Cap Area

Weak predictive power with current data and telescopes

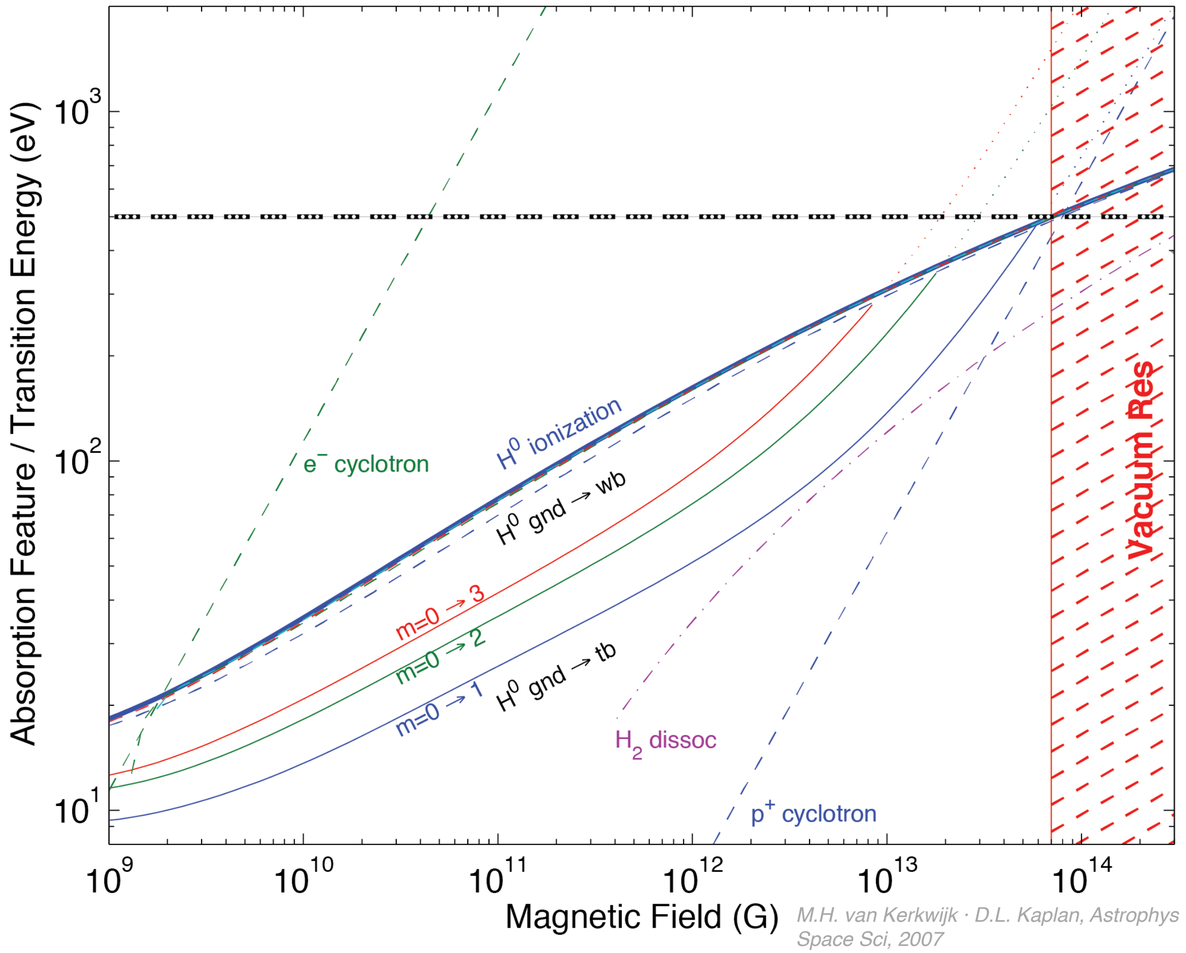
Emission Profile Offset

Qualitative but very promising method

MEASURE THE CYCLOTRON LINE

Landau Level Transition in High B-field

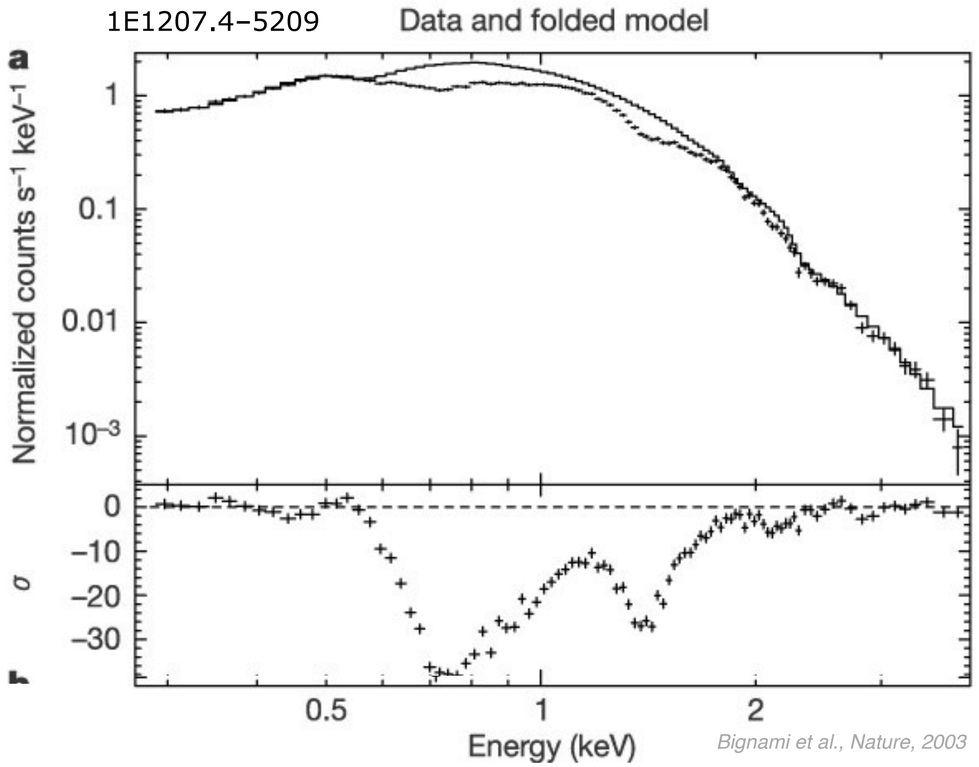
$$\Delta E = \frac{\hbar e B}{mc}$$



M.H. van Kerkwijk · D.L. Kaplan, Astrophys Space Sci, 2007

MEASURE THE CYCLOTRON LINE

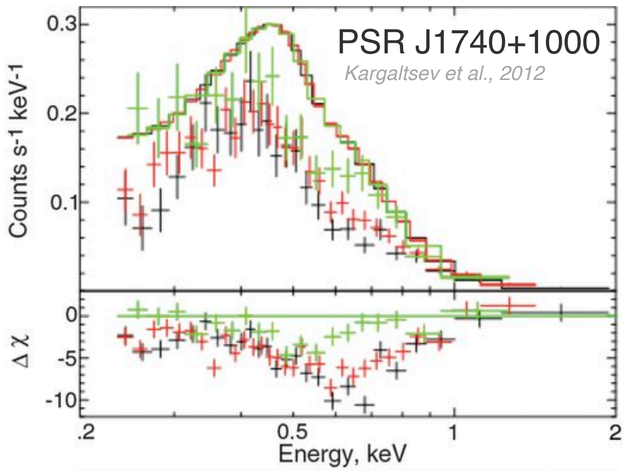
Proton Cyclotron Lines in High-B Neutron Stars

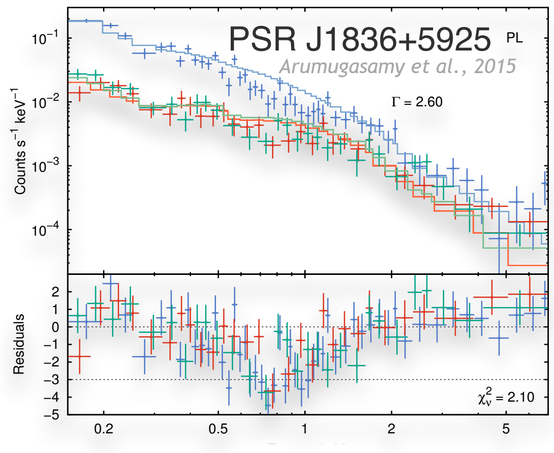


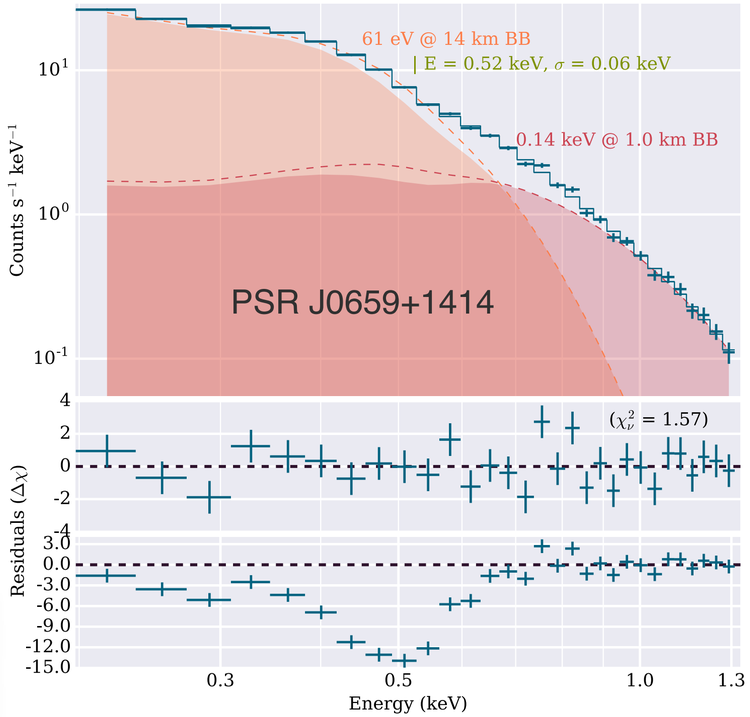
Bignami et al., Nature, 2003

MEASURE THE CYCLOTRON LINE

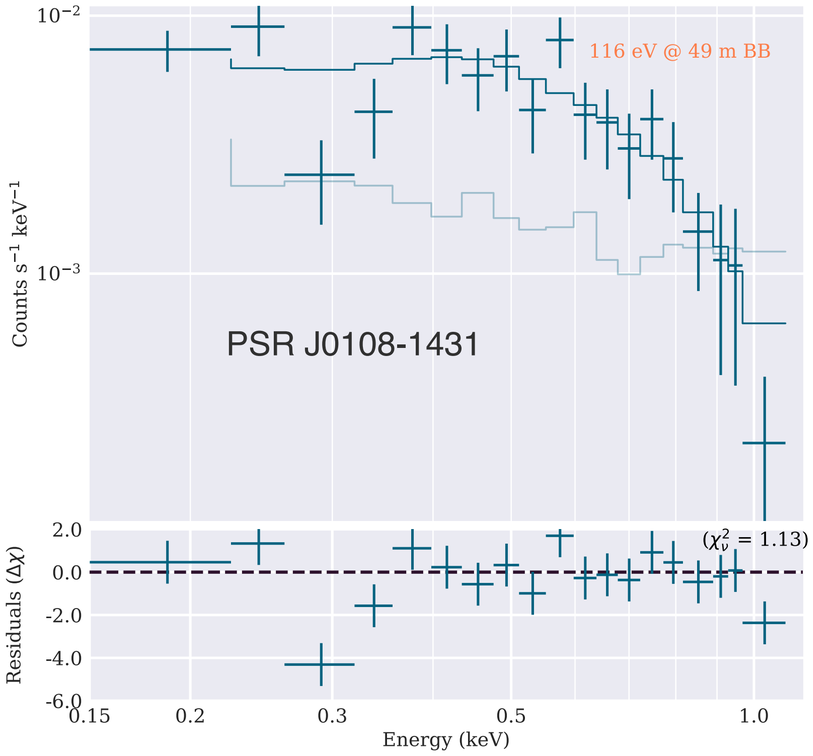
Weak Absorption (-like) Features in Radio Pulsars







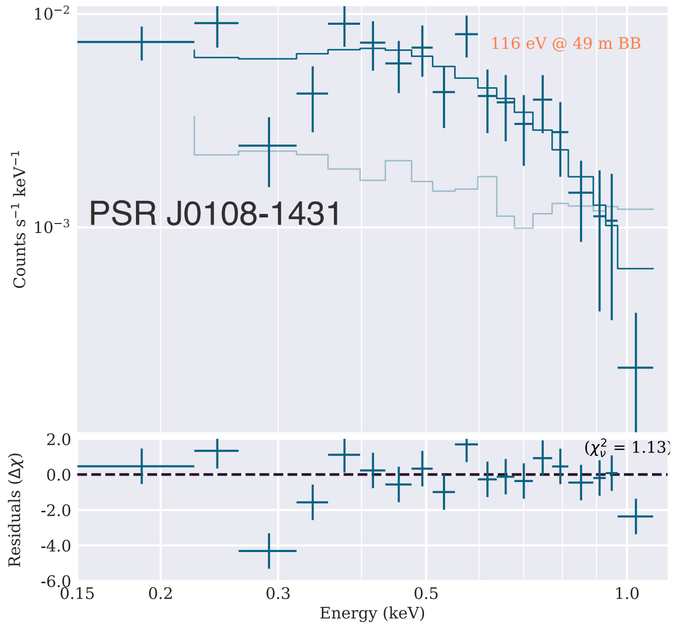
Arumugasamy et al., 2018



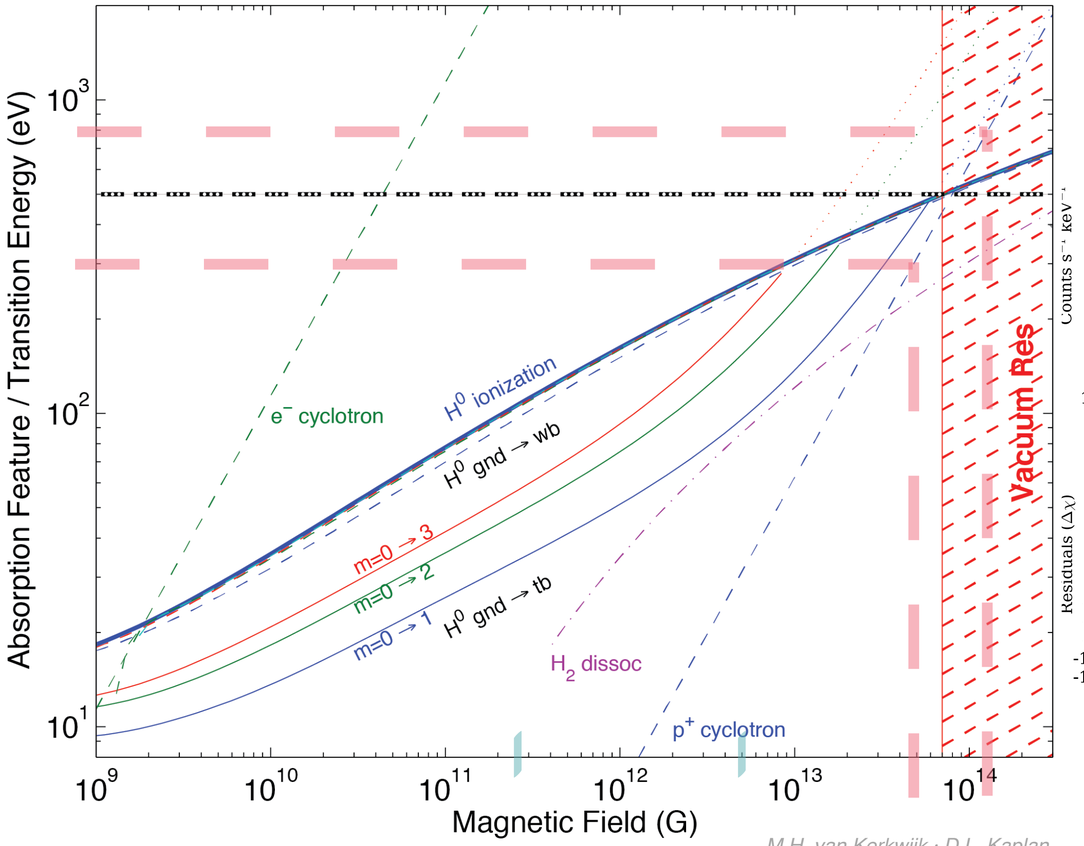
Arumugasamy et al., 2019, In prep.

MEASURE THE CYCLOTRON LINE

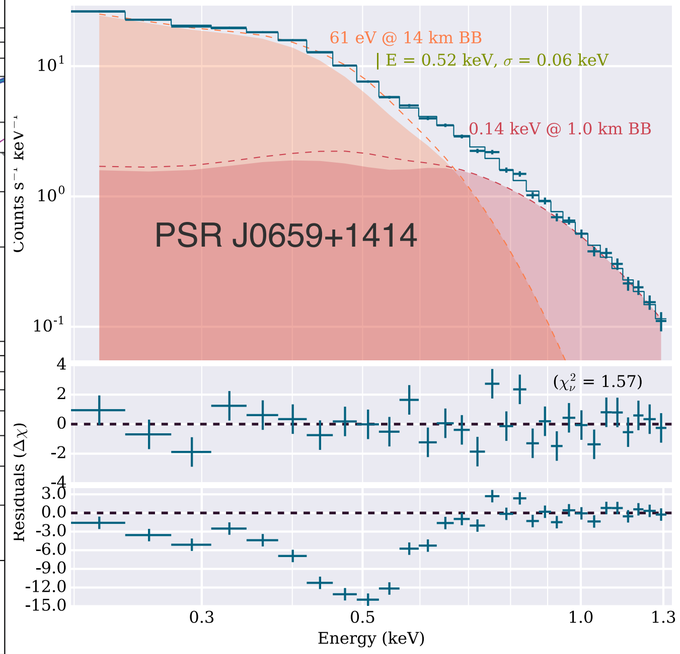
Proton Cyclotron Interpretation



Arumugasamy et al., 2019, In prep.

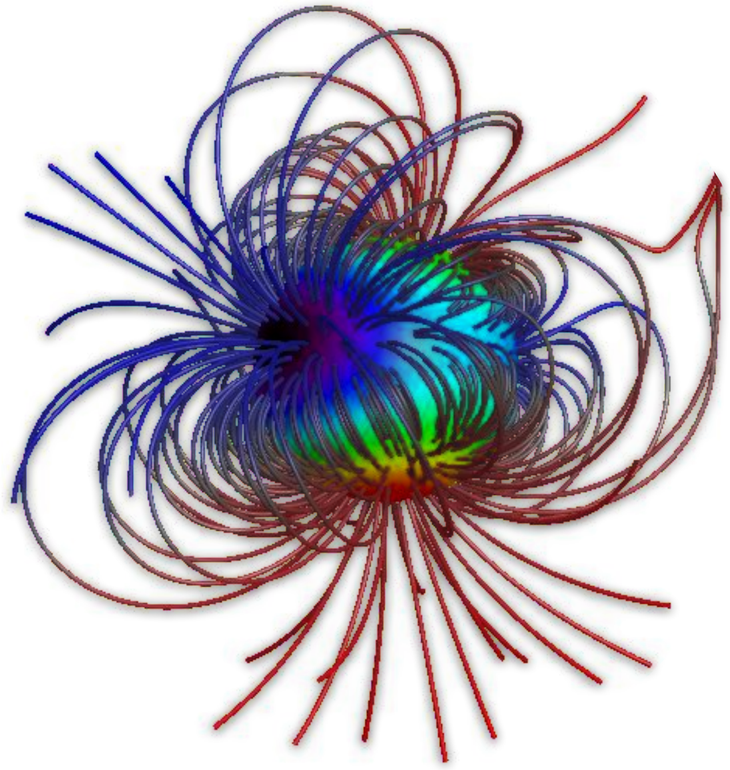


M.H. van Kerkwijk · D.L. Kaplan, Astrophys Space Sci, 2007



Arumugasamy et al., 2018

ALTERNATIVE 2

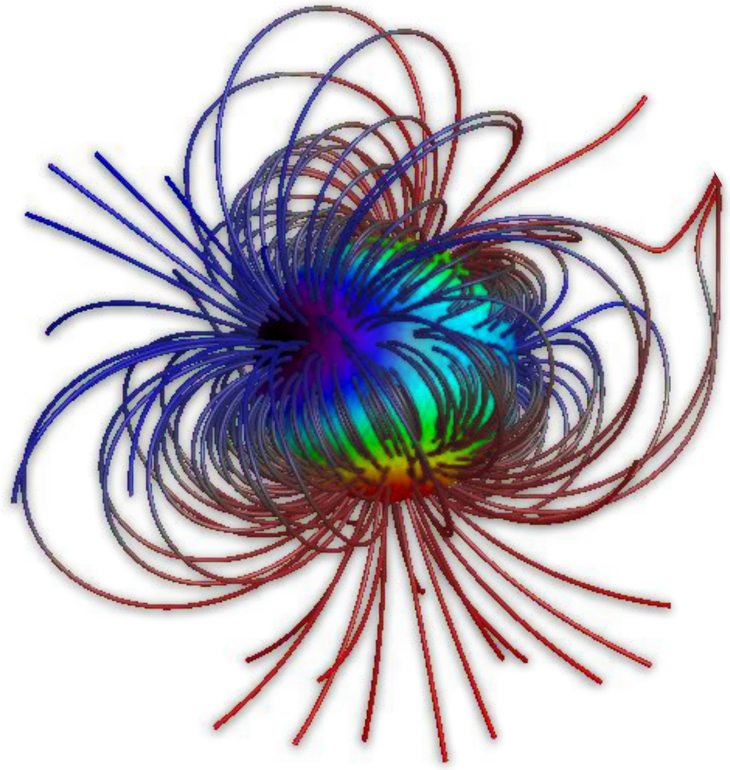


- Stronger evidence and detailed modelling needed for confirmation

Cyclotron Absorption

- Very few detections

EVIDENCE OF MULTIPOLAR FIELDS



Polar Cap Area

Weak predictive power with current data and telescopes

Cyclotron Absorption

Stronger evidence from 1-2 sources likely

Emission Profile Offset

Qualitative but very promising method