Modeling Jovian Magnetospheres Beyond the Solar System

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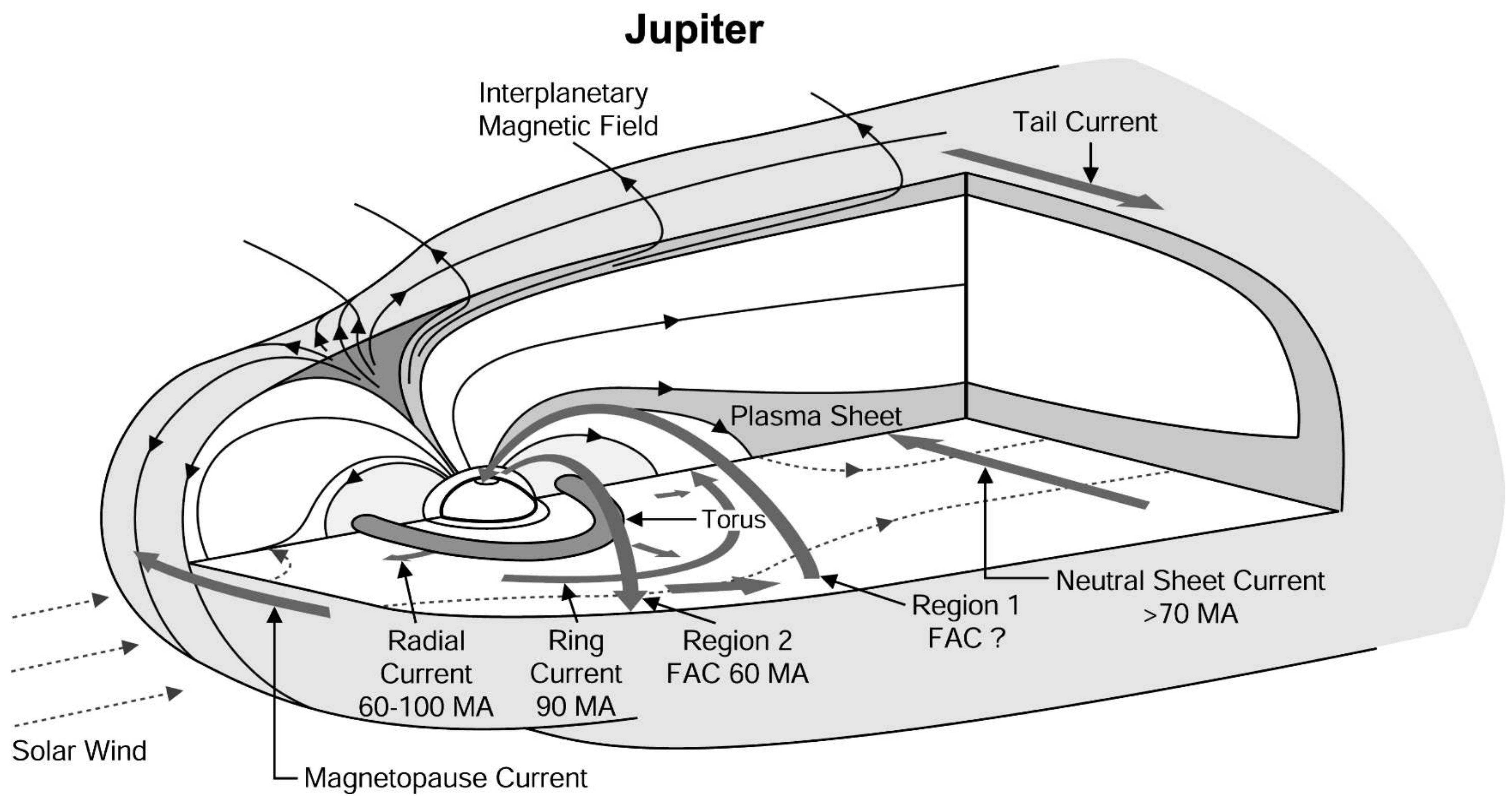
Planetary magnetospheres are complex, dynamic systems.

And they are embedded in helio/asterospheres, adding another layer of complexity!



Khurana+ (2004)

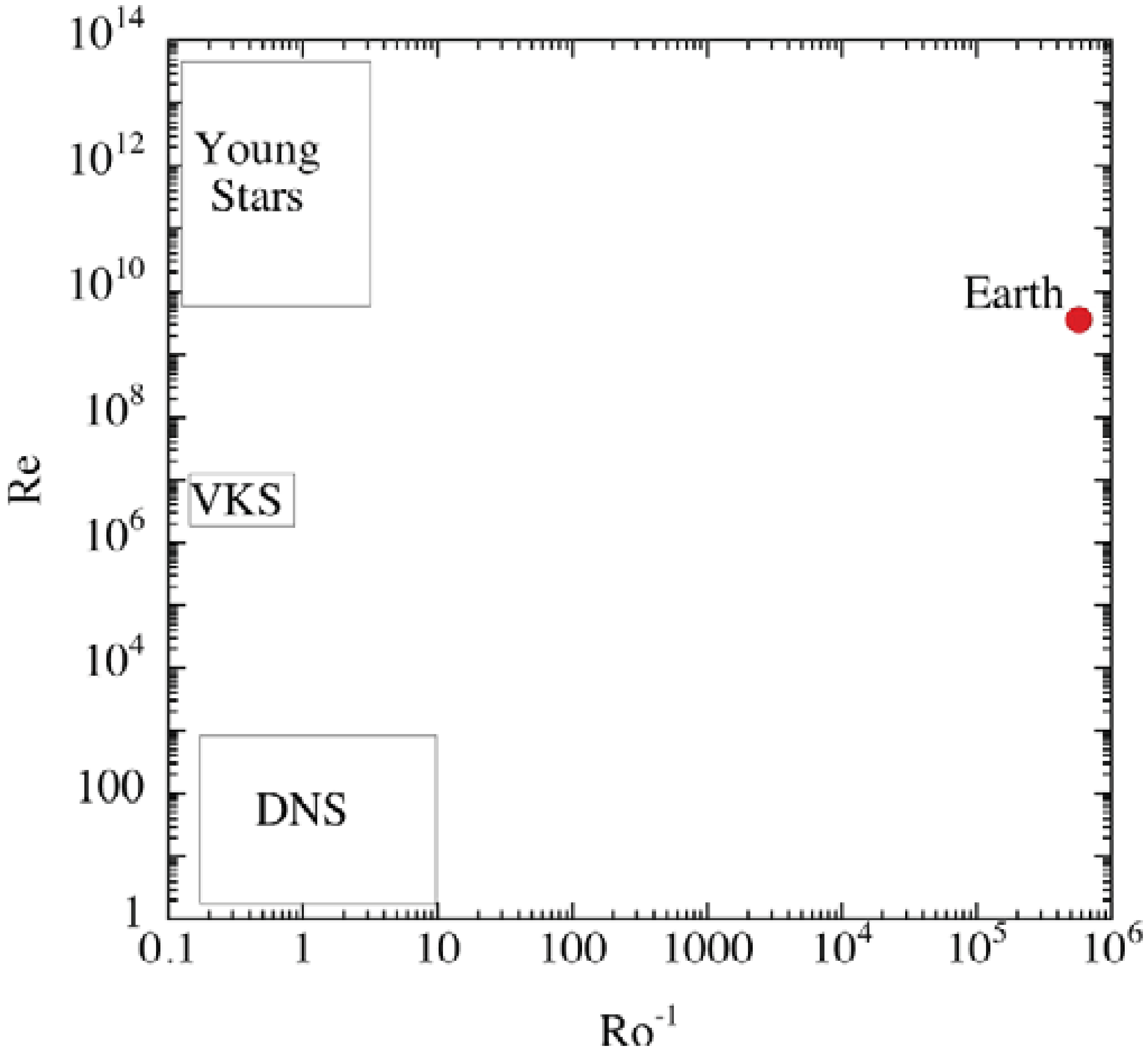
Here, Jupiter's volcanic moon Io makes things extra messy.

It will be challenging to understand exo-magnetospheres in detail.

“First principles” theory will be important, but empirical characterization will be essential.

The underlying dynamo process is notoriously difficult to analyze; astrophysical examples span a huge parameter space ⇒

What other methods could we use to remote-sense these structures?



Dubrulle (2010)

I believe that radiation belts will yield powerful diagnostics.

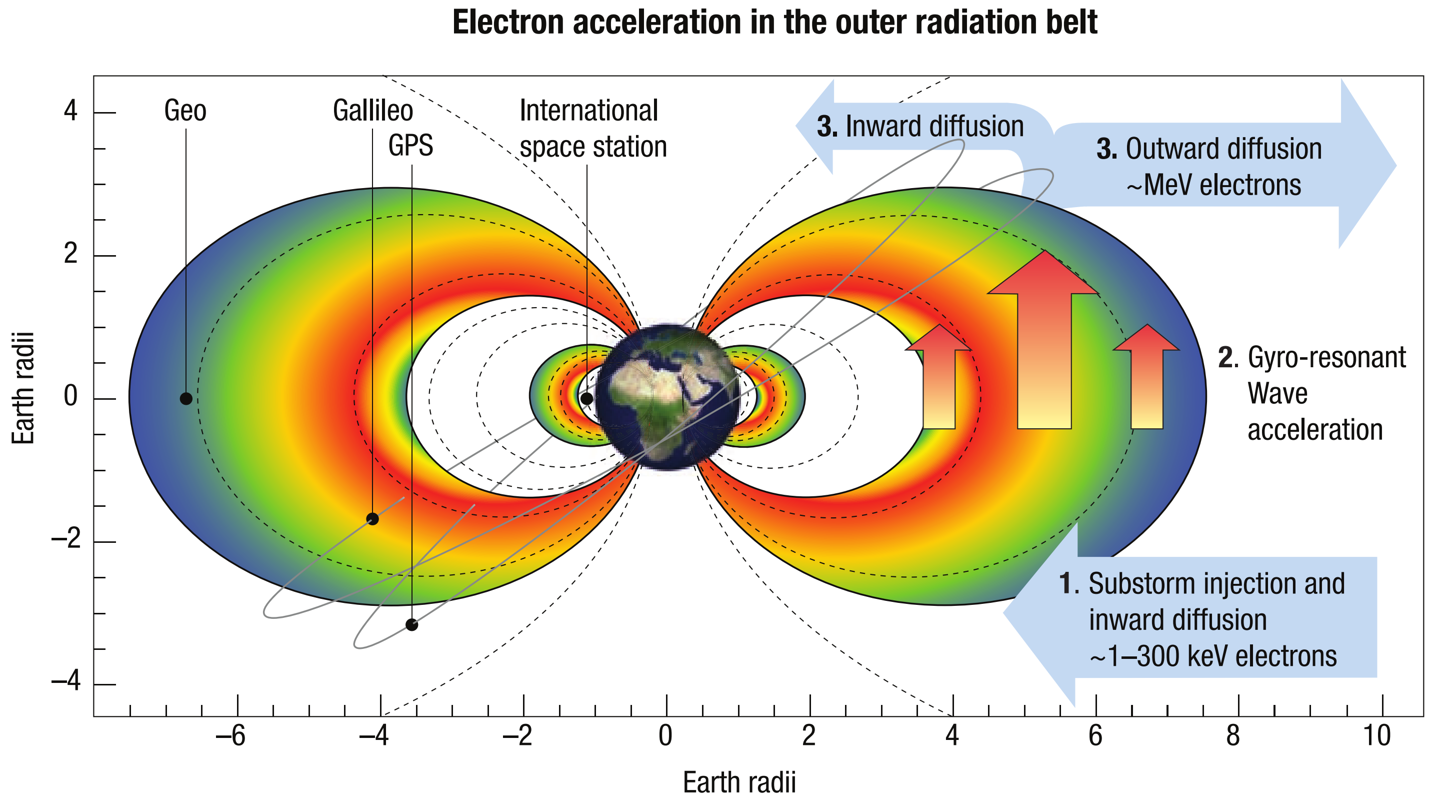
AKA “Van Allen belts” — the populations of high-energy particles trapped in Solar System magnetospheres.

In situ measurements in the Solar System anchor a detailed theory of radiation belt dynamics.

Dynamics dominated by two orthogonal diffusion processes operating on three action-angle coordinates:

- Radial diffusion (1D)
- Energy/pitch-angle diffusion (2D)

The particles can be probed remotely through their synchrotron emission.



Horne 2007

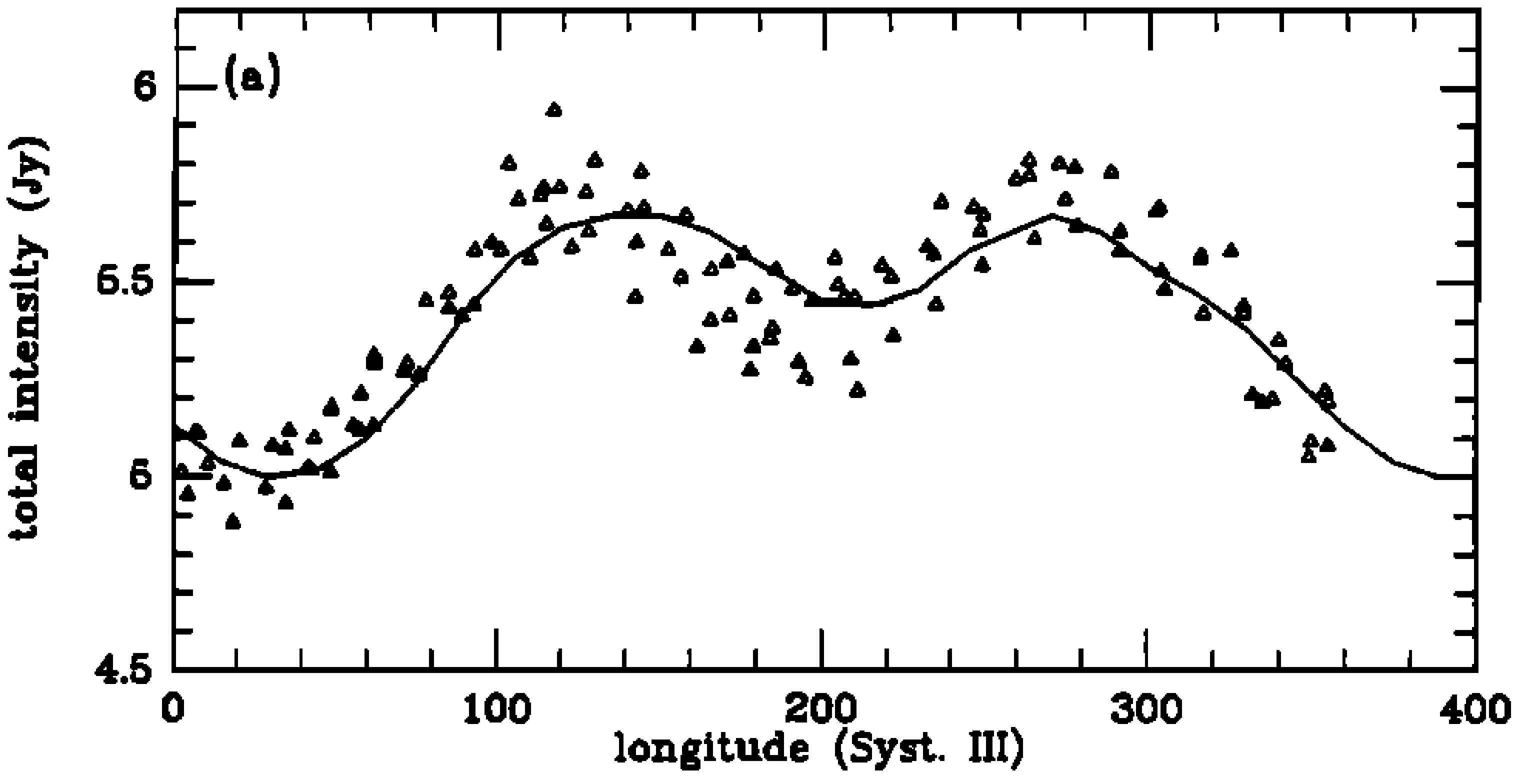
Motion	Timescale
Gyromotion	μs
Latitudinal bounce	seconds
Longitudinal drift	days

The “ultra-cool dwarfs” are perfect test cases for this approach.

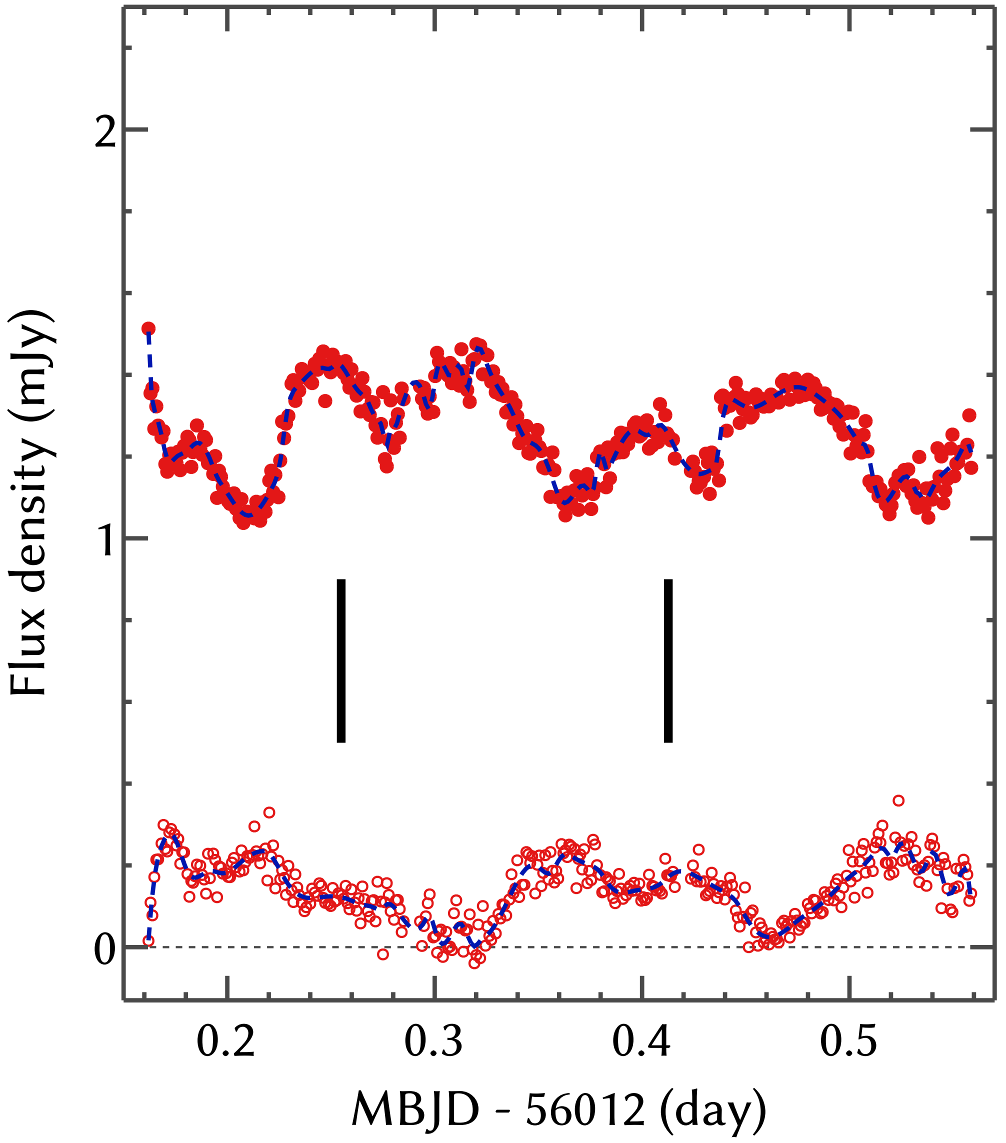
The “UCDs” are stars and brown dwarfs cooler than ~2700 K.

They can sustain magnetospheres that are essentially planetary in nature (e.g. Hallinan+ 2007, Schrijver 2009).

The non-burst emission of the best-studied example, NLTT 33370 B (M7), is strongly reminiscent of Jupiter's.

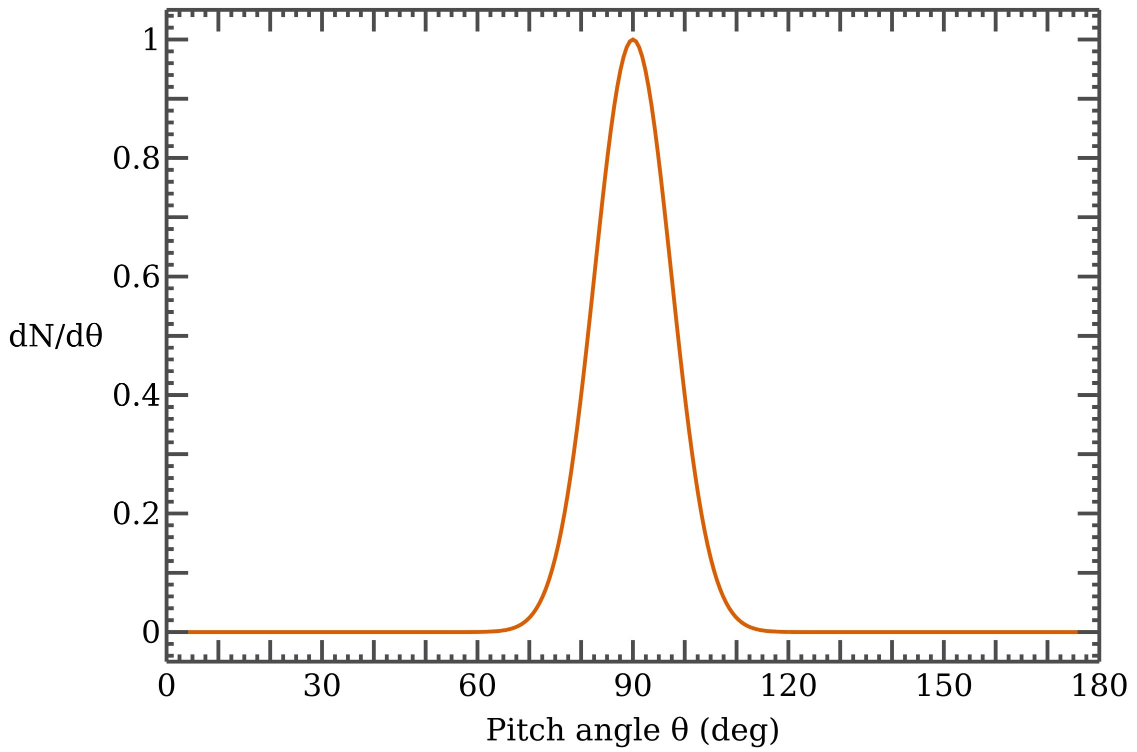


De Pater+ 1997



adapted from PKGW+ (2015)

To match theory and data, new calculations are needed.



Radiation belt electron populations are highly anisotropic, a case rarely handled by existing synchrotron codes or approximations.

The fully generic polarized radiative transfer equation is:

$$\frac{\mathrm{d}}{\mathrm{d}s}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} j_I \\ j_Q \\ j_U \\ j_V \end{pmatrix} - \begin{pmatrix} \alpha_I & \alpha_Q & \alpha_U & \alpha_V \\ \alpha_Q & \alpha_I & \rho_V & -\rho_U \\ \alpha_U & -\rho_V & \alpha_I & \rho_Q \\ \alpha_V & \rho_U & -\rho_Q & \alpha_I \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

We can choose the linear polarization basis such that there are just *eight* unique coefficients. But they’re hard to compute!

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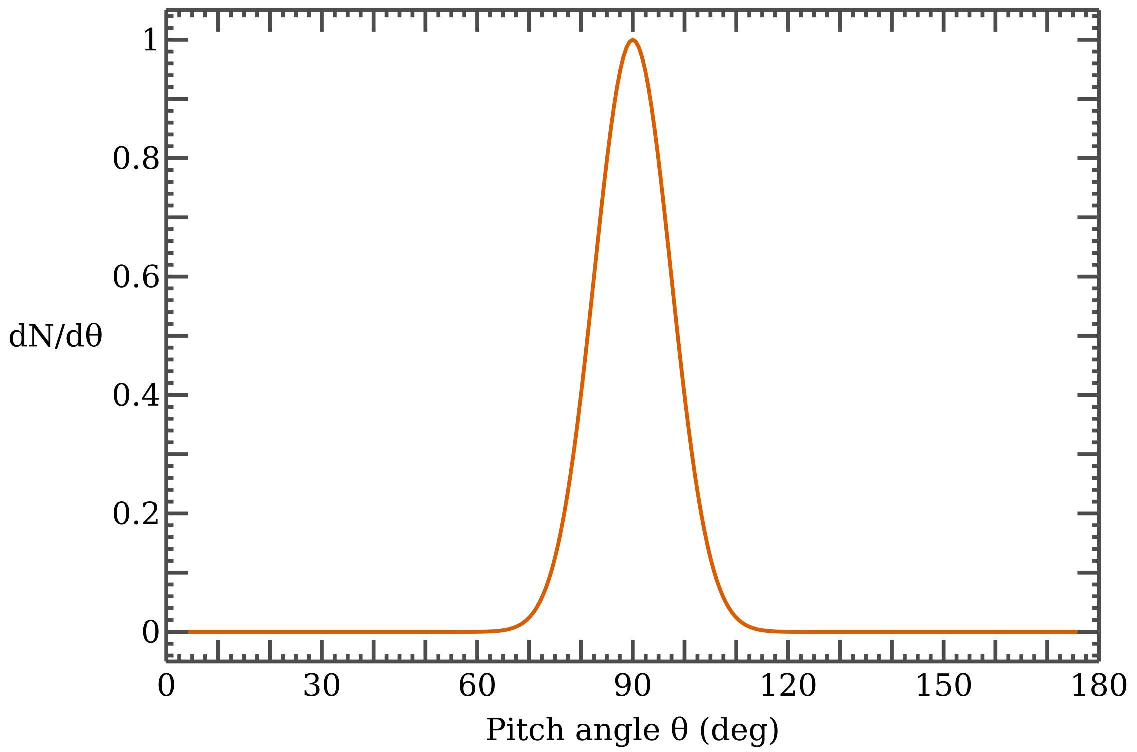

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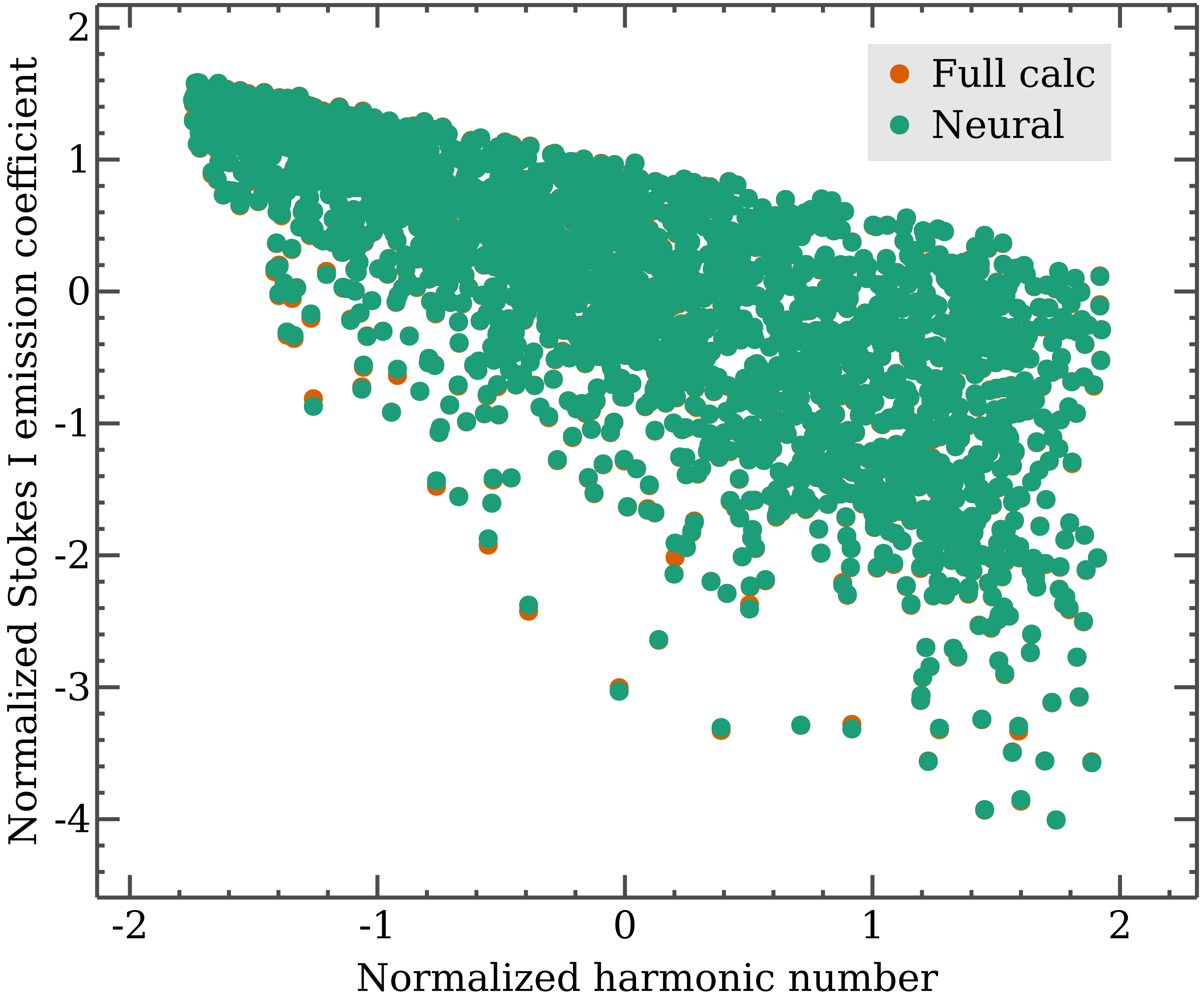
I’ve developed a new synchrotron code.

Rimphony derives from Symphony (Pandya+ 2016) but adds:

- Anisotropic particle distributions.
- Faraday conversion terms — all eight coefficients! (Heyvaerts+ 2013)
- A neural network approximator for speed ⇨
- Interface with *grtrans* (Dexter 2016) RT integrator.
- Redesigned, modular implementation of core algorithms in the Rust language.

https://github.com/pkgw/rimphony

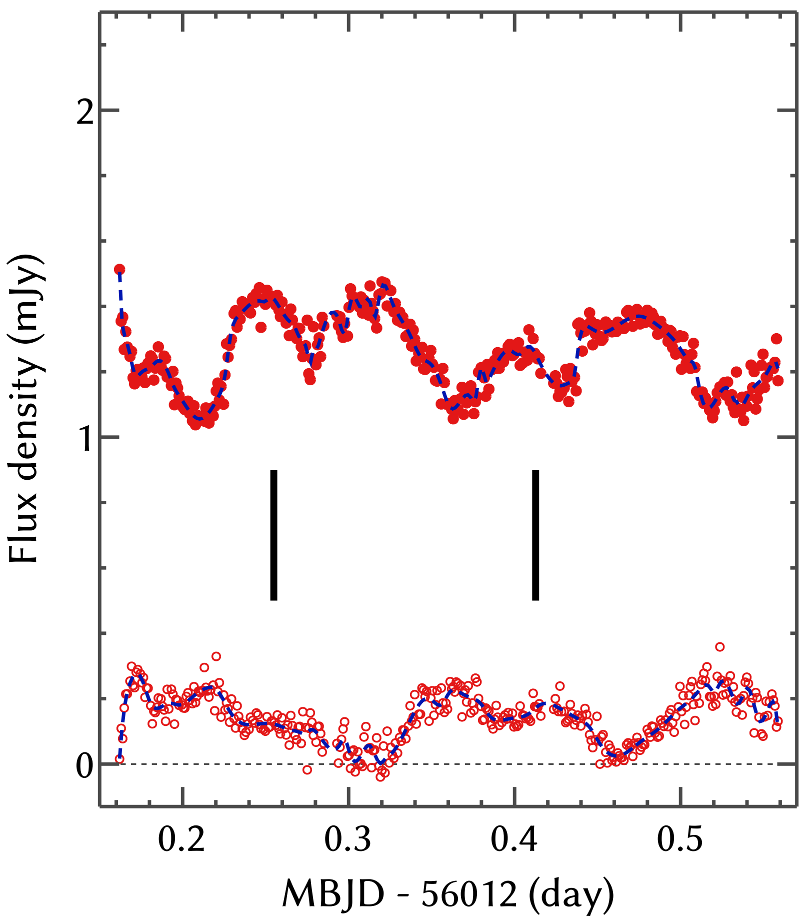


PKGW+ in prep.

Indeed, “pancake” distributions are needed to match the data.

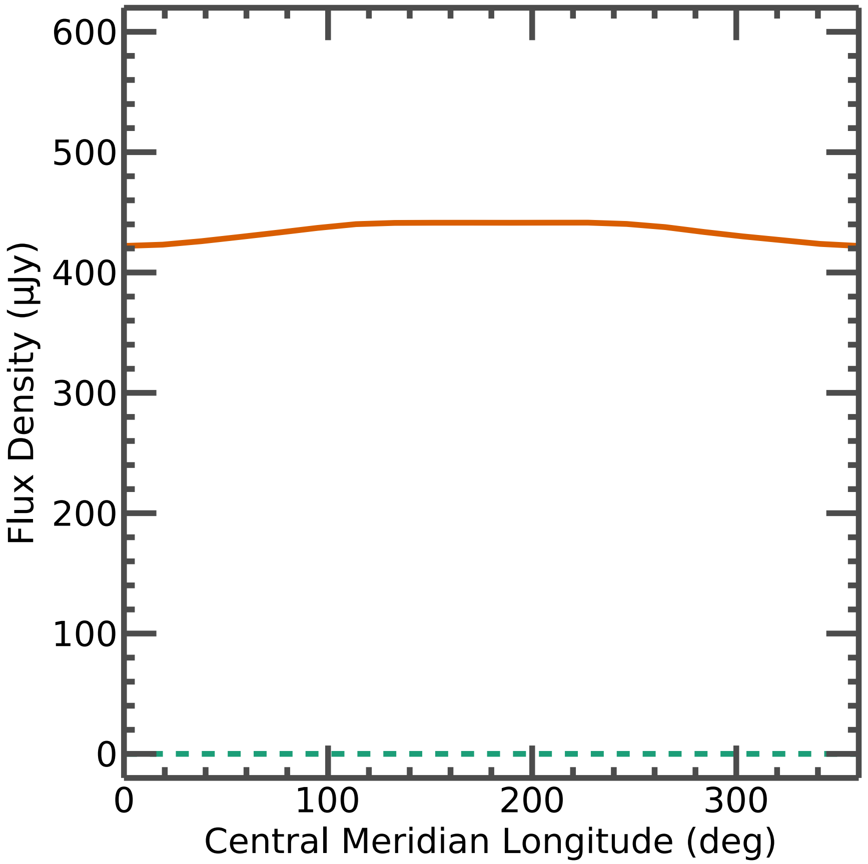
Isotropic pitch-angle distributions can’t reproduce the observed variability amplitude.

Observed:

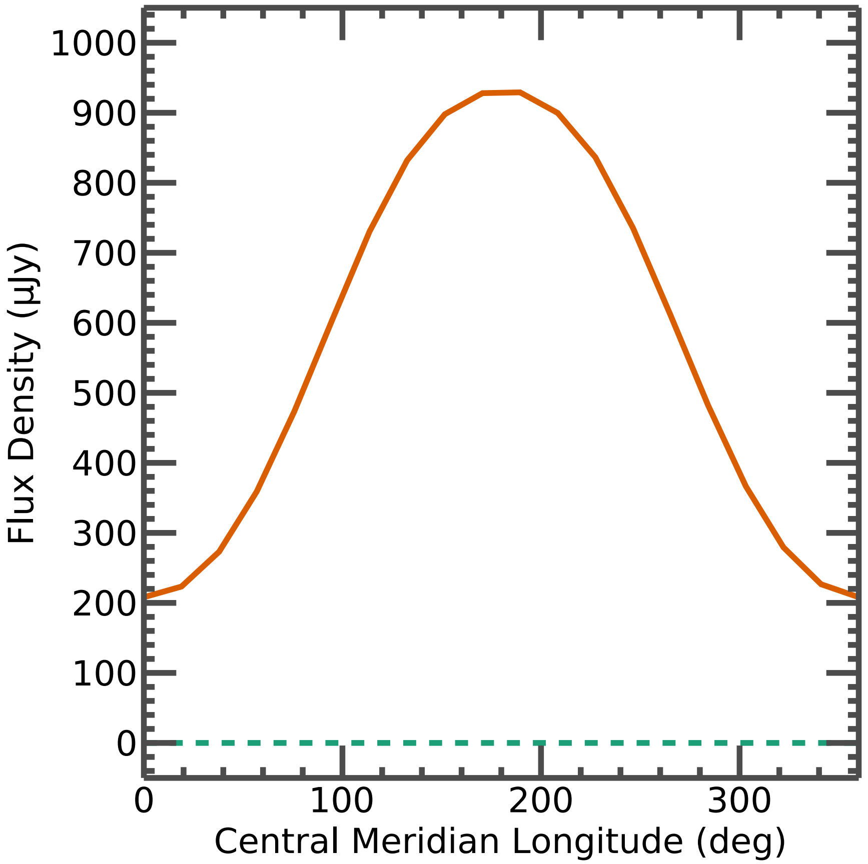


adapted from PKGW+ (2015)

Isotropic:

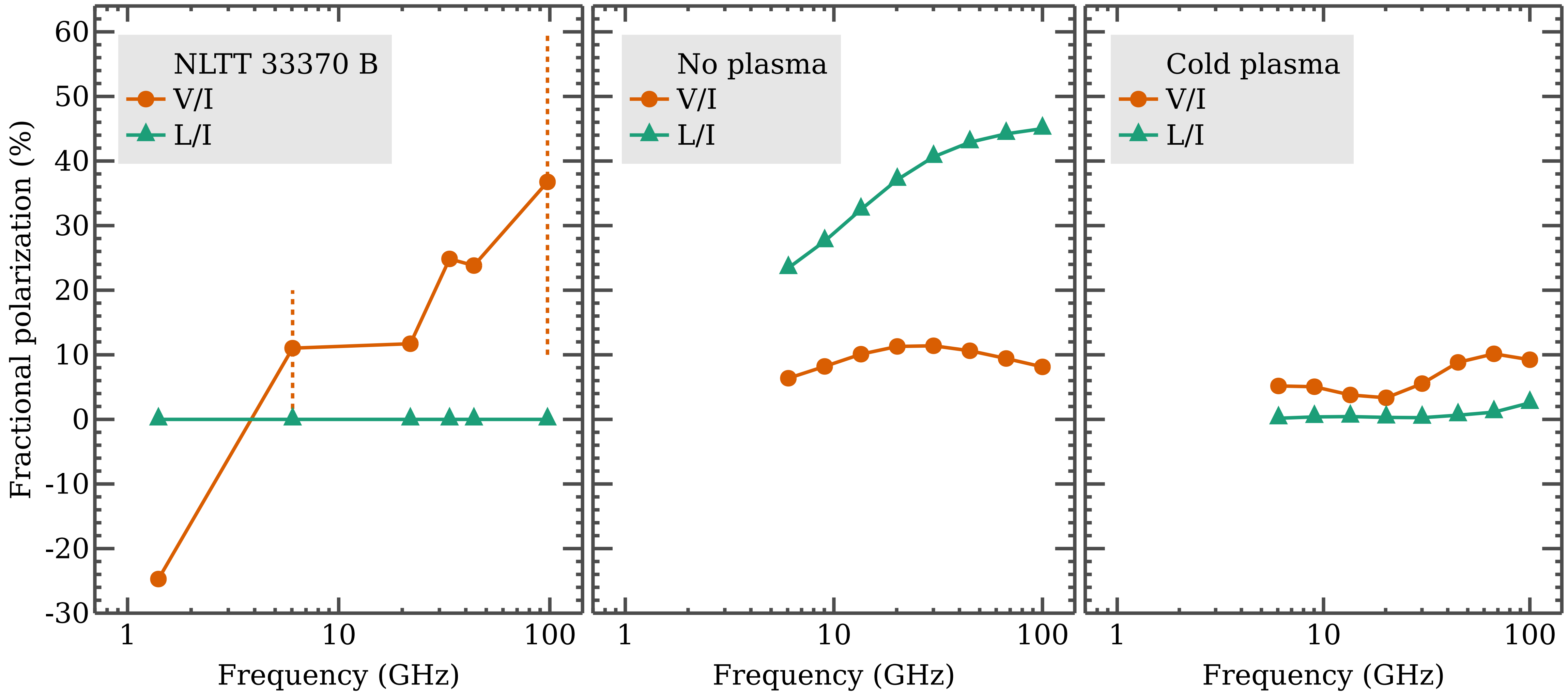


$\sin^8(\theta)$ anisotropic:



Substantial cold plasma is needed to erase linear polarization.

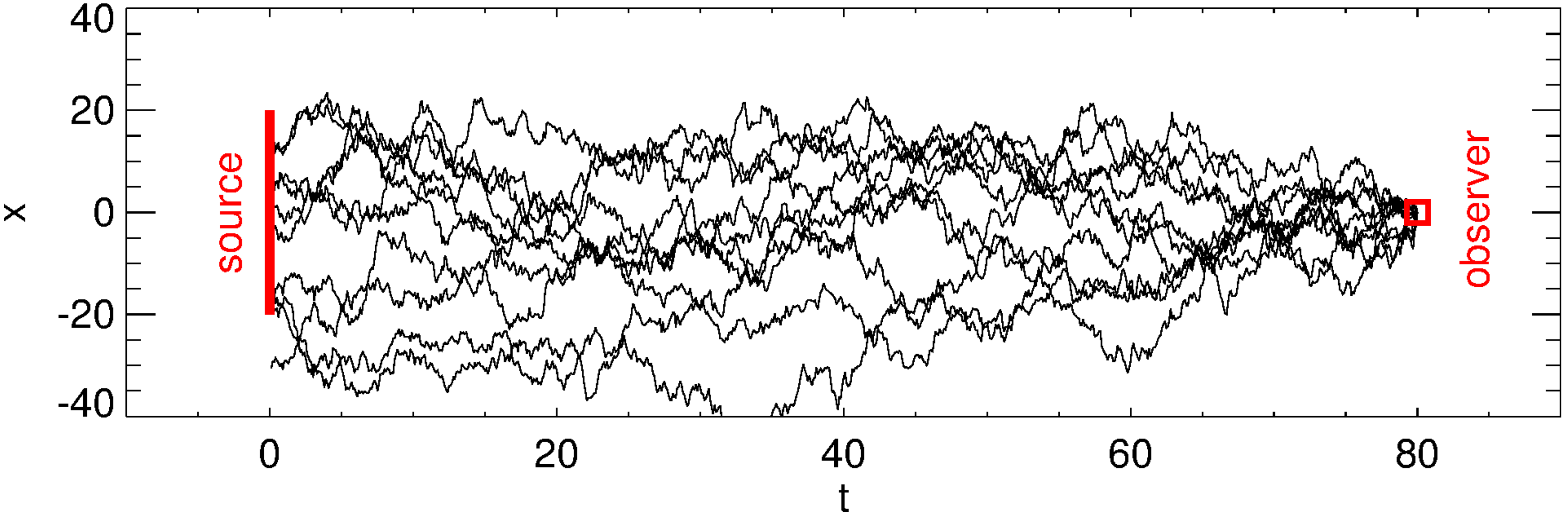
Without its Faraday rotation, expect substantial linear polarization at high frequencies.



Faraday conversion may explain increasing circular polarization in optically thin regime, but fine-tuning seemingly needed.

Numerical models can tie the data to basic physical quantities.

As of now: magnetic moment, angle between field and rotation axis, etc.



adapted from Du Toit Strauss (2017)

With *stochastic differential equation* diffusion model: spectrum of magnetosphere MHD waves, presence of moons (?! — Santos-Costa & Bolton 2008)

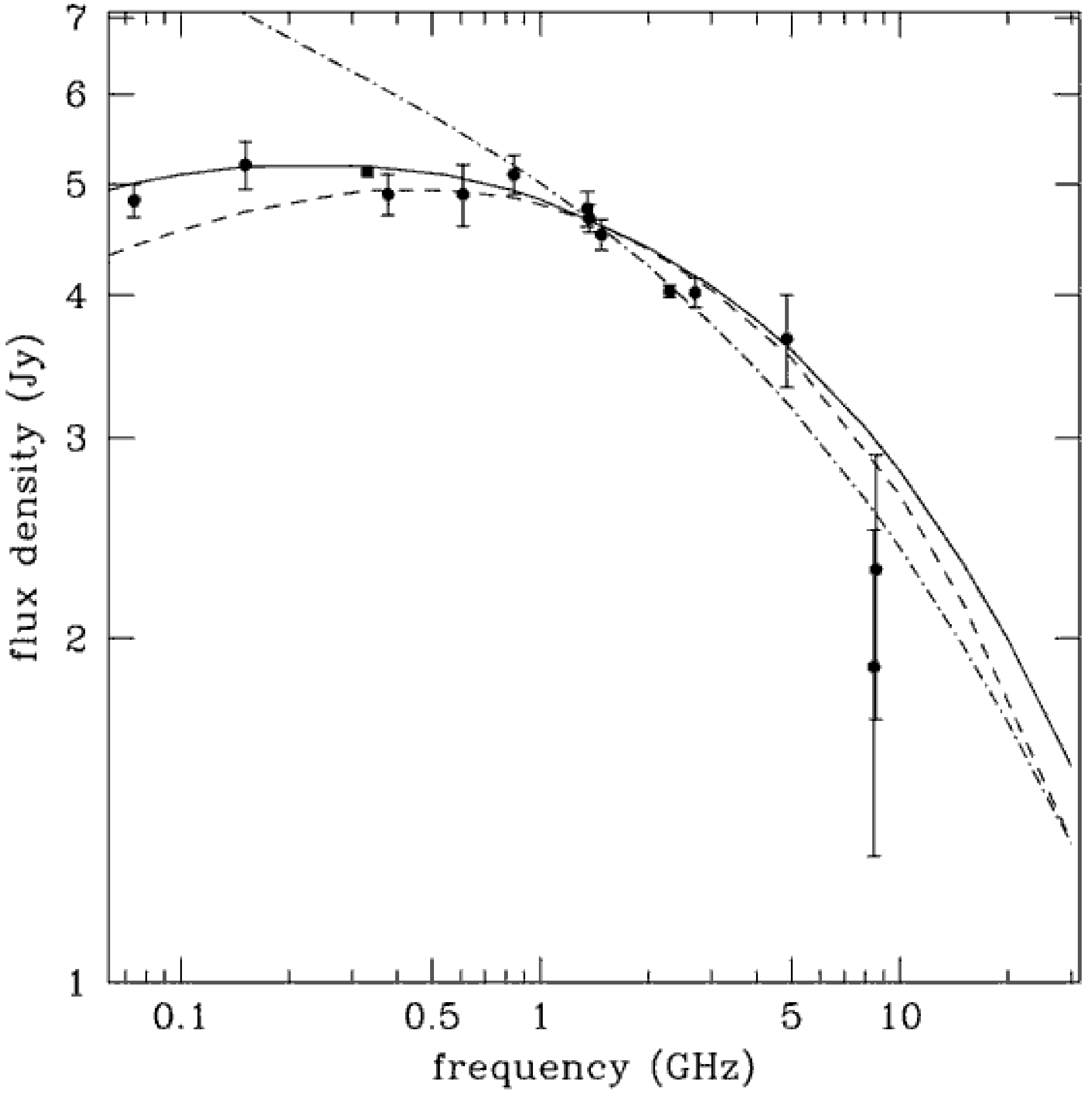
Modeling at lower frequencies is challenging.

Jupiter's radiation-belt spectrum has a broad peak at 100-500 MHz $\Rightarrow$

Refractive indices of X and O modes diverge $\rightarrow$ modes propagate separately $\rightarrow$ Stokes RT formalism breaks down!

Start having to worry about modeling gyroresonance layers, plasma emission.

... not to mention the challenges that arise in low-frequency radio astronomy in general.



De Pater+ 2003

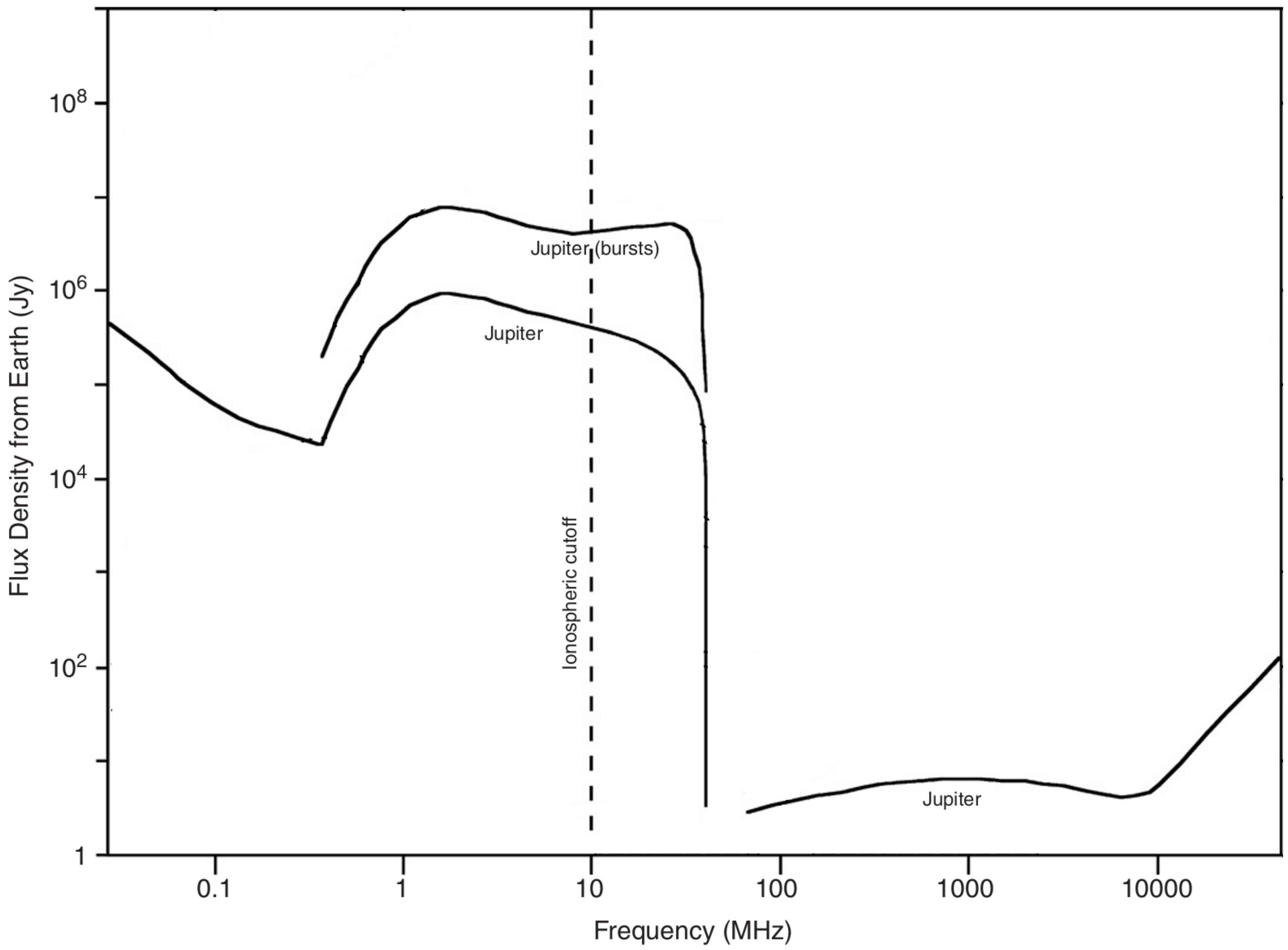
Detecting exoplanetary radiation belts is likely to be even harder.

Pros of ECMI (inexhaustive):

- Intensity!
- Diagnoses characteristics of physically small regions

Pros of radiation-belt synchrotron:

- Persistence
- Diagnoses overall characteristics of magnetosphere
- *Diagnoses system in more-or-less steady state*



adapted from Zarka (2007)

Here's a summary.

- *rimphony* delivers synchrotron coefficients for fully-polarized RT with unprecedentedly flexible particle distributions.
- NLTT 33370 B probably has a Jovian-type magnetosphere with a magnetodisk, a scattered electron population, and substantial quantities of cold plasma.
- Future work will connect theory and data self-consistently through detailed particle diffusion models.
- Characterizing the radiation belts of space-discovered exoplanets can provide insight not available from auroral observations …
- … but it will be extremely challenging.

Thanks for your attention!

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HTML talk info: https://tinyurl.com/htmltalk • *Design credits*: Hakim El Hattab ("white" theme), Julieta Ulanovsky (Montserrat font), Steve Matteson (Open Sans font) • *Tech credits*: git, reveal.js, KaTeX, Firefox developer tools.

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