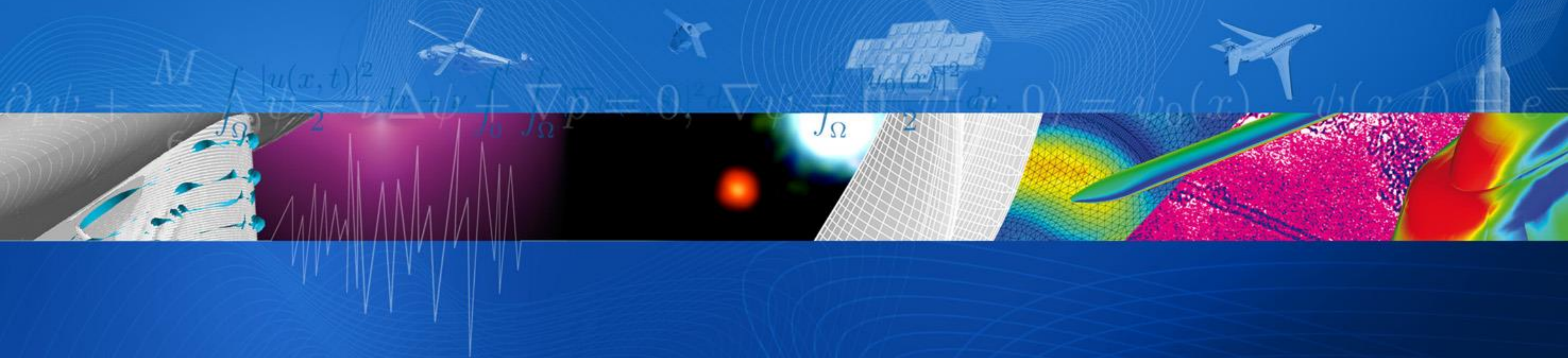

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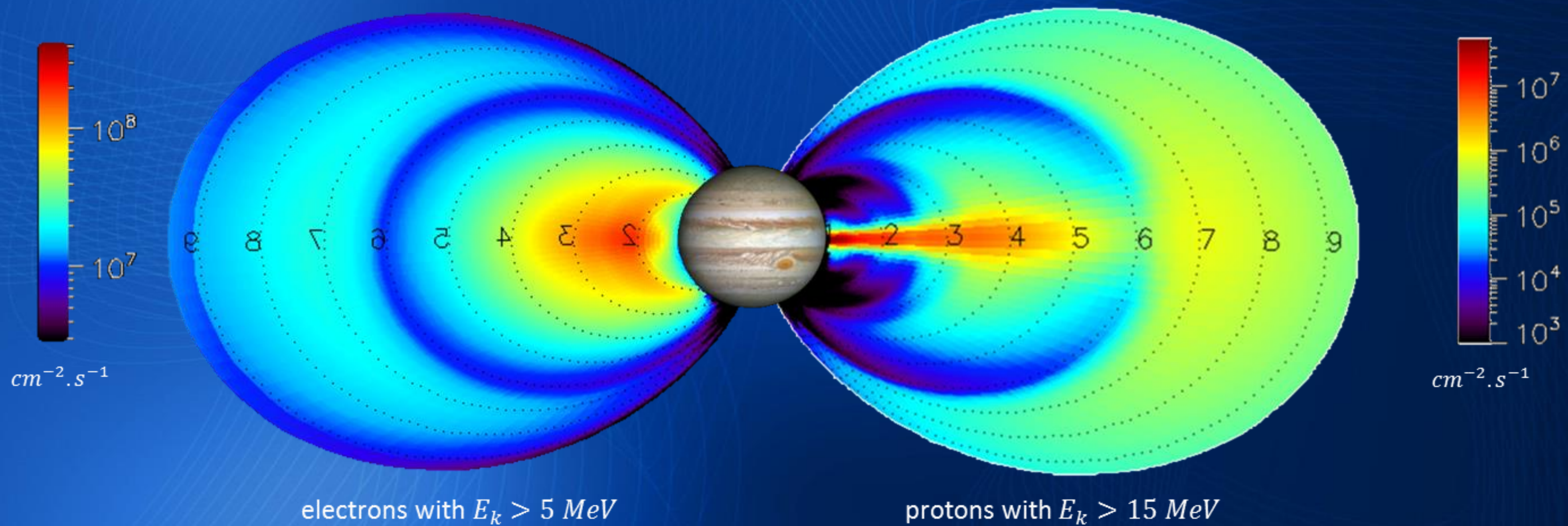
Space and time variability of the Jovian radiation belts as seen by the physical model Salammbô



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[1] ONERA, Toulouse, France

[2] The John Hopkins University, Applied Physics Laboratory, Laurel, USA

return on innovation

Quentin Nénon[1], A. Sicard[1], P. Kollmann[2] and C. Paranicas[2]

Introduction: the physical model Salammbô

Salammbô: a time-invariant 3D physical model of the Jovian **electron and proton** radiation belts inside Europa's orbit (L<9.5)

- Time-invariant: we compute a mean or « balanced » state of the belts
- 3D (E_k, α_{eq}, L): no longitude or MLT dependency, longitude homogeneity is ensured by the trapped particles drift
- Physics-based: the physical processes which shape the belts are modeled and their balance is evaluated with the diffusion theory

Applications

- Complements the empirical models, for instance see the « hybrid model » JOSE [Sicard-Piet et al., 2011], and addresses **the space variability,** anywhere for L<9.5
- Enables to discuss the importance of the different physical processes, which may drive **the time variability** of the belts

3D (E_k, α_{eq}, L) time-invariant model **Salammbô-Jupiter**

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Electrons

Outer Boundary condition: source

Chorus and Hiss waves: $D_{EE}, D_{\alpha\alpha}$

Synchrotron radiation: $\frac{dy}{dt}, \frac{dE}{dt}$

Protons

Outer boundary condition: source

Europa and Io neutral gas torus: $\frac{1}{\Gamma}$

EMIC waves: $D_{EE}, D_{\alpha\alpha}$

CRAND (Cosmic Ray Albedo Neutron Decay): source

Both

Radial diffusion: D_{LL}

Cold plasma: $\frac{dE}{dt}, D_{\alpha\alpha}$

Sweeping by Io: $\frac{1}{\Gamma}$

Small moons: $\frac{1}{\Gamma}$

Dust rings: $\frac{1}{\Gamma}, \frac{dE}{dt}, D_{\alpha\alpha}$

Atmosphere: loss cone, D_{yy}, $\frac{dE}{dt}$

3D (E_k, α_{eq}, L) time-invariant model **Salammbô-Jupiter**

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Electrons

Outer Boundary condition: source

Radial diffusio

Chorus and Hiss waves: $D_{EE}, D_{\alpha\alpha}$

Cold plasma:

Sweeping by

Small moon

Synchrotron radiation: $\frac{dy}{dt}, \frac{dE}{dt}$

Dust rings: $\frac{1}{\Gamma},$

Atmosphere: loss co

Only electrons and a bit of EM waves today, but we might have great « radiation belt » discussions on protons and other processes around a coffee

Today’s planning

1) Validation of Salammbô electron: do we correctly address the **space variability** ?

2) **Time variability** above Io’s orbit
    1) In the particle observations: Galileo/EPD
    2) Of the wave-particle interaction
    3) Any link with solar wind ? Tentative study of the C22 storm

3) Conclusions and future work

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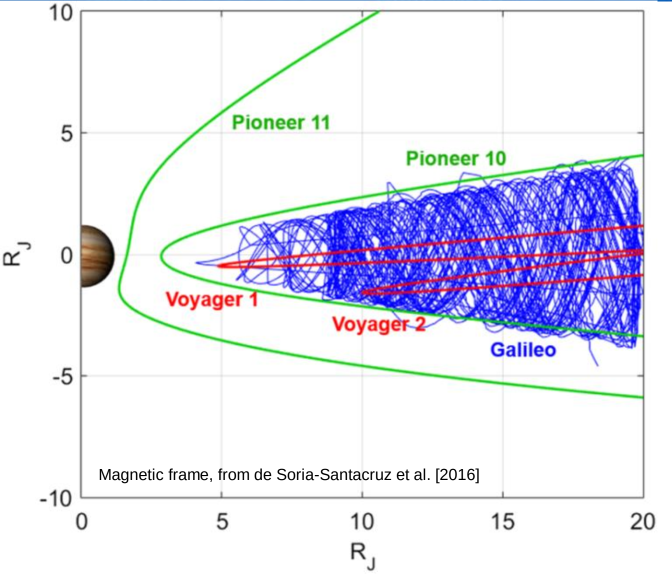

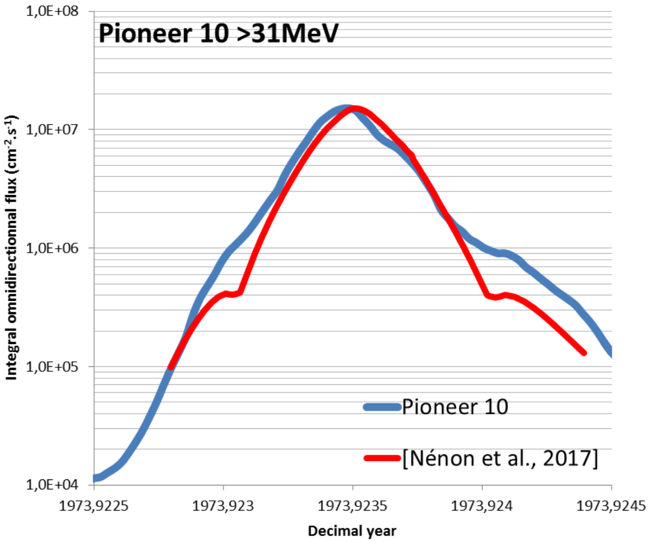

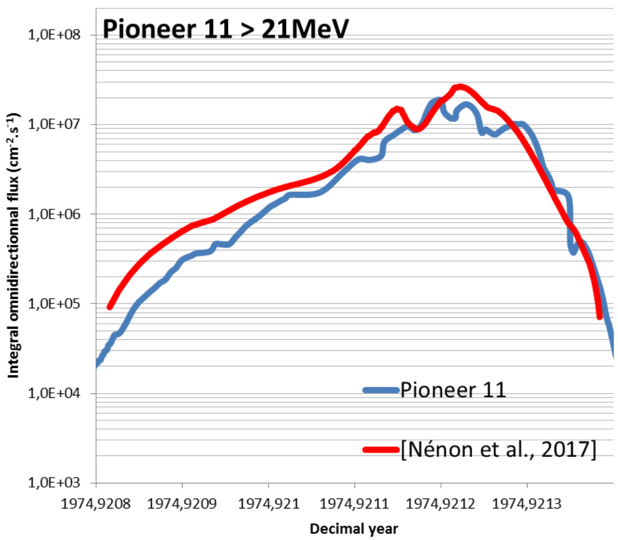

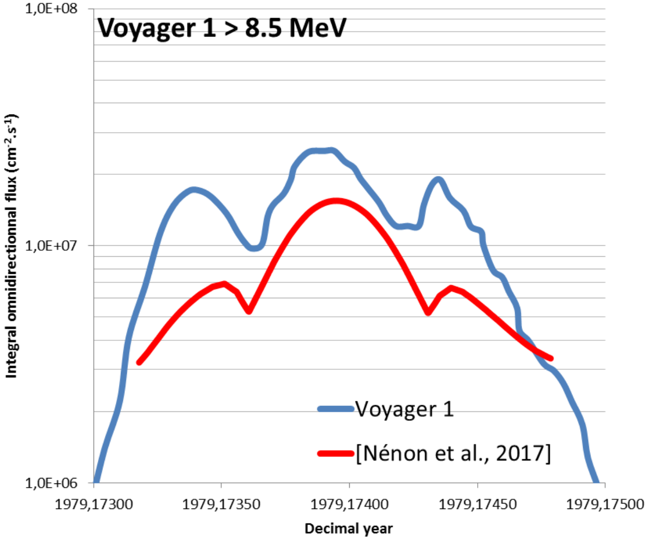

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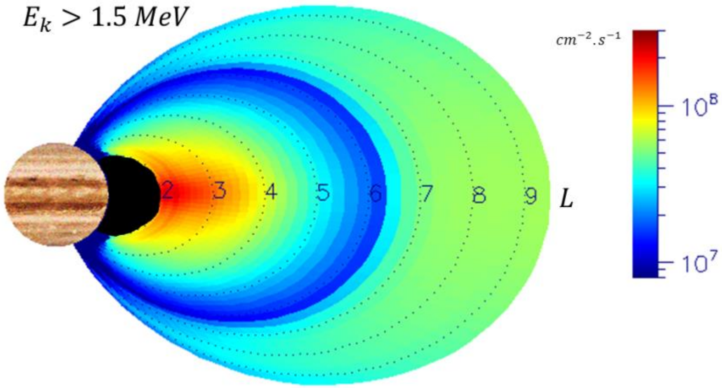
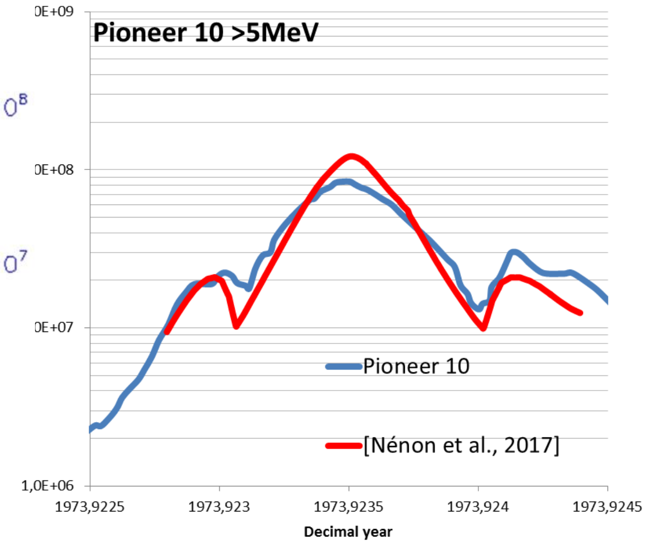
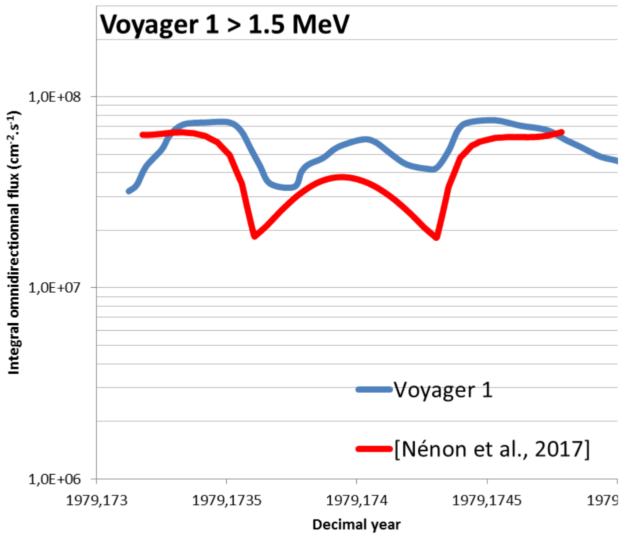
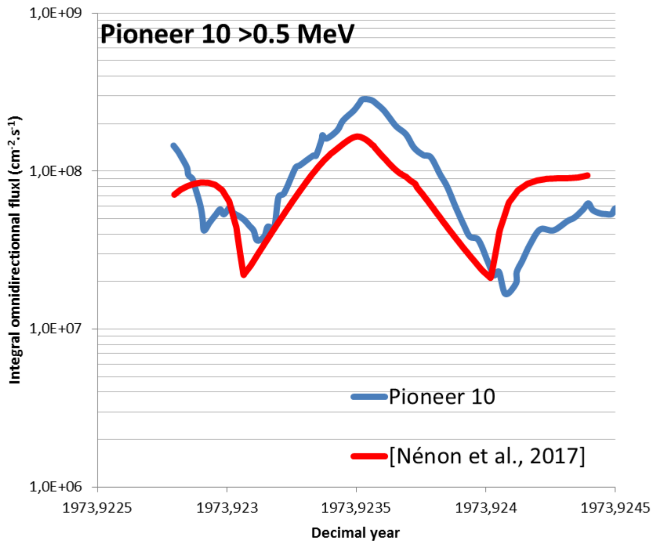
1) Validation: Salammbô-electron









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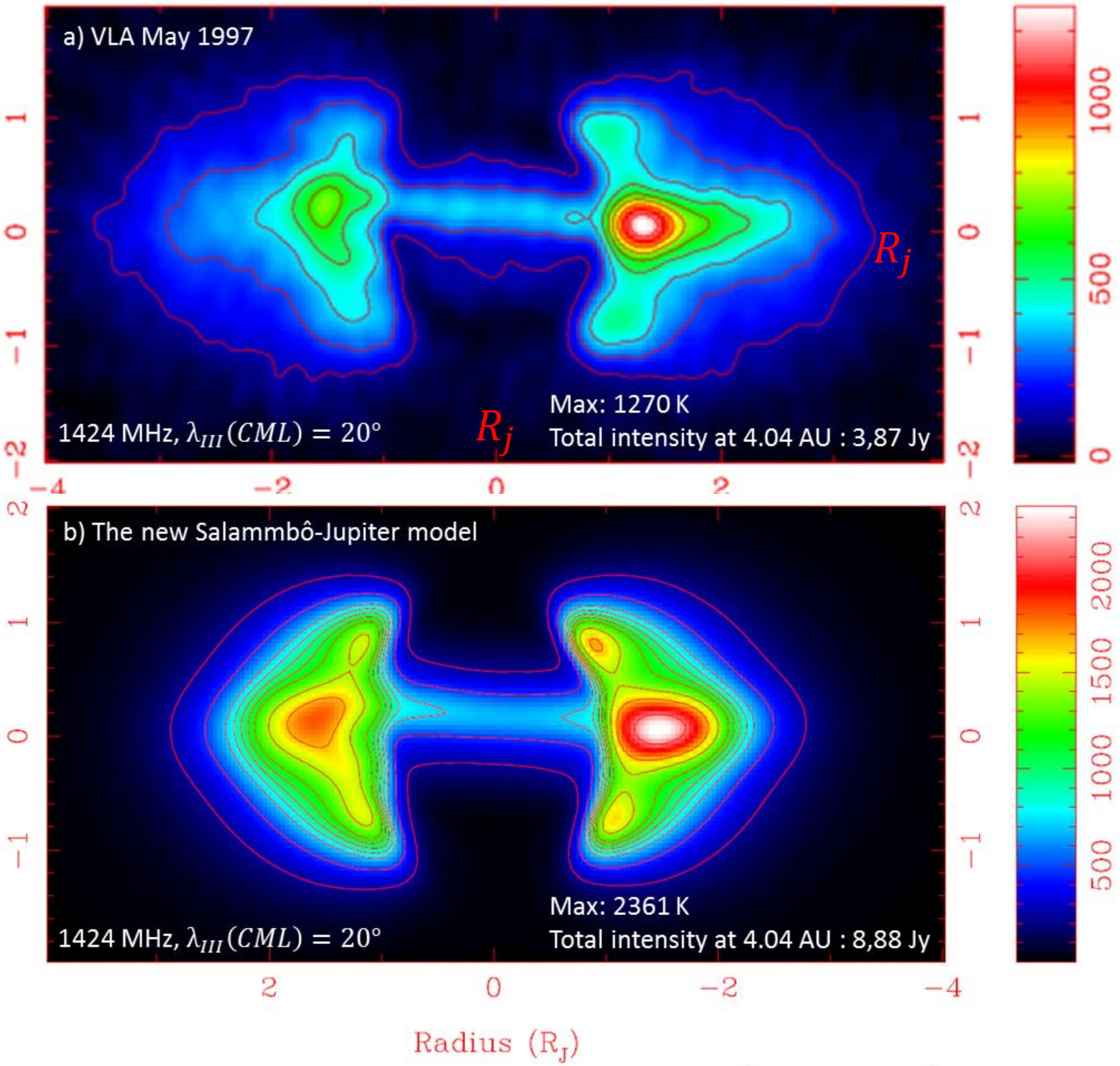
2) Validation: Salammbô-electron

Very Large Array, New Mexic



Salammbô is valid within a factor 2 to 3 against all the existing synchrotron measurements (resolved or integrated): VLA, LOFAR, GMRT, Cassini…

1) Validation: Salammbô-electron

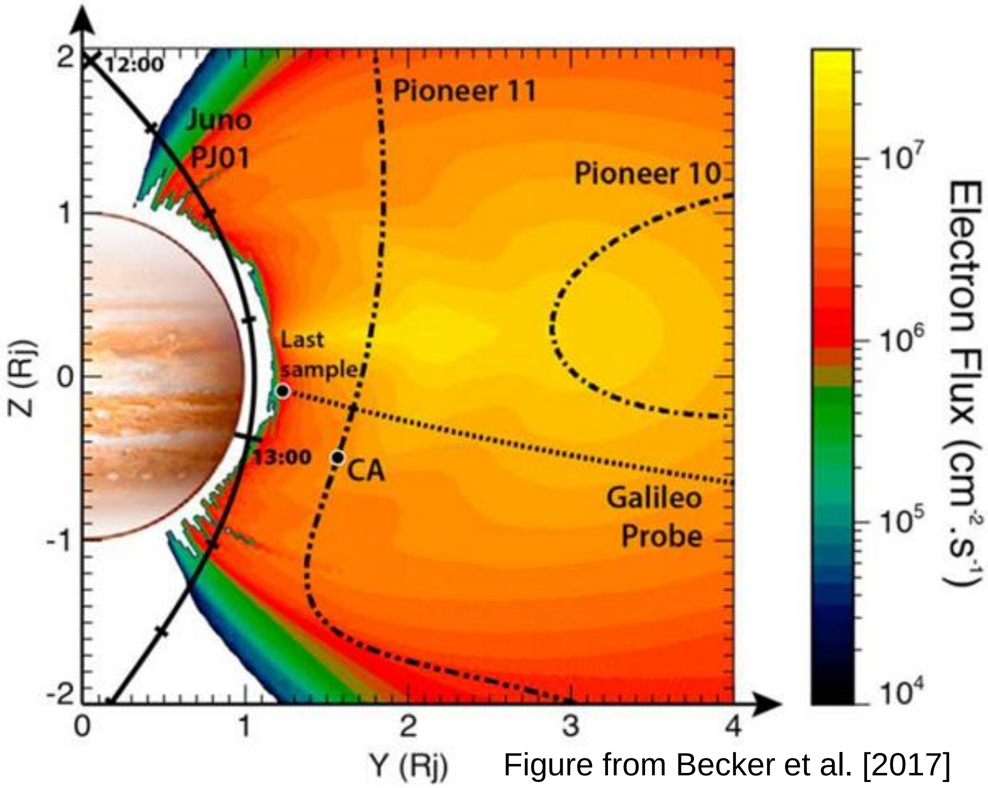


Figure from Becker et al. [2017]

1) Validation: Salammbô-electron

- The computation grid of Salammbô has to be refined to properly predict fluxes along Juno’s orbit
- Then, in future work: any missing physical process at high latitudes ? Wave-particle interaction (only modeled close to the equator in Salammbô thanks to Galileo) ?

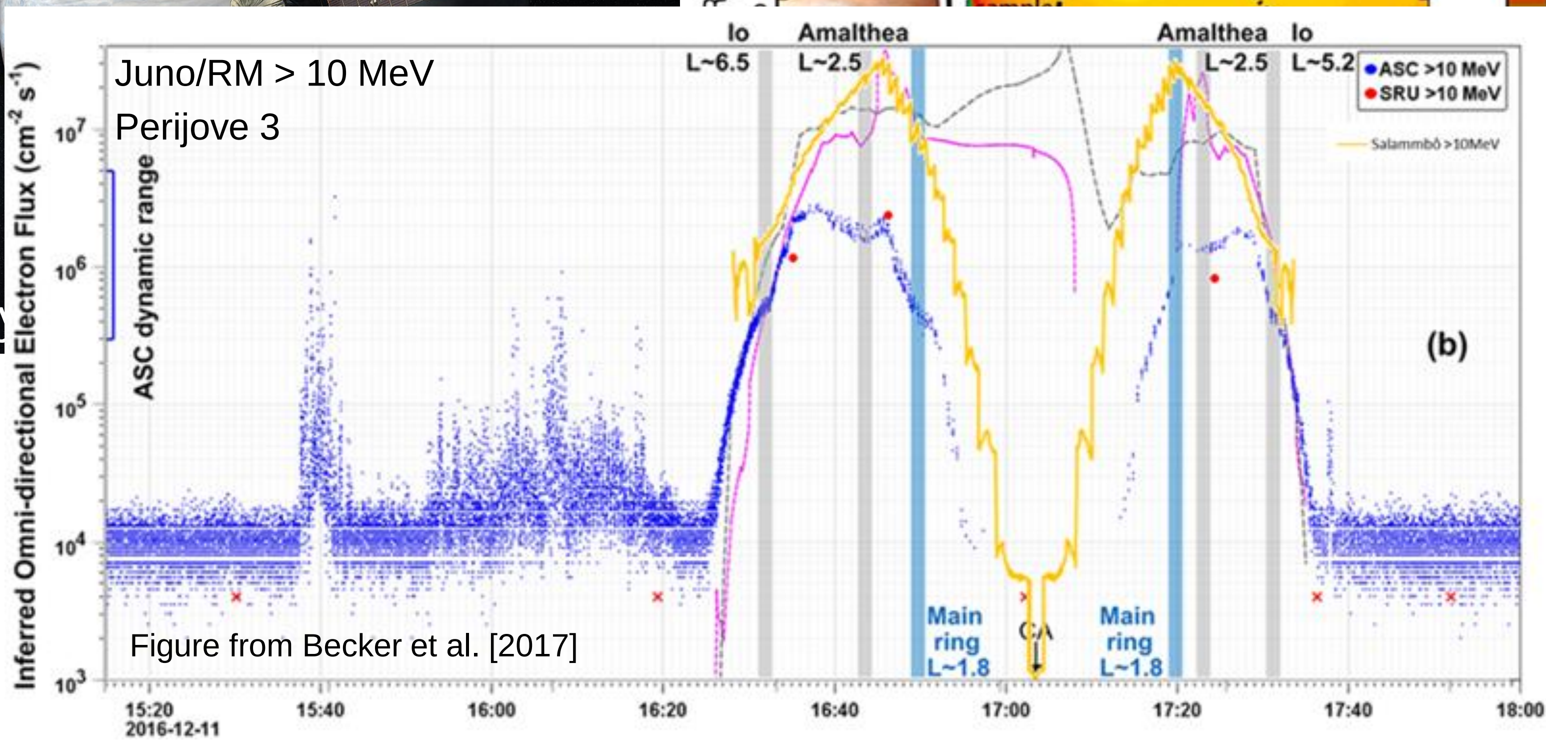
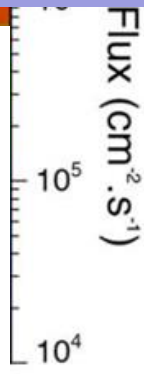


Figure from Becker et al. [2017]

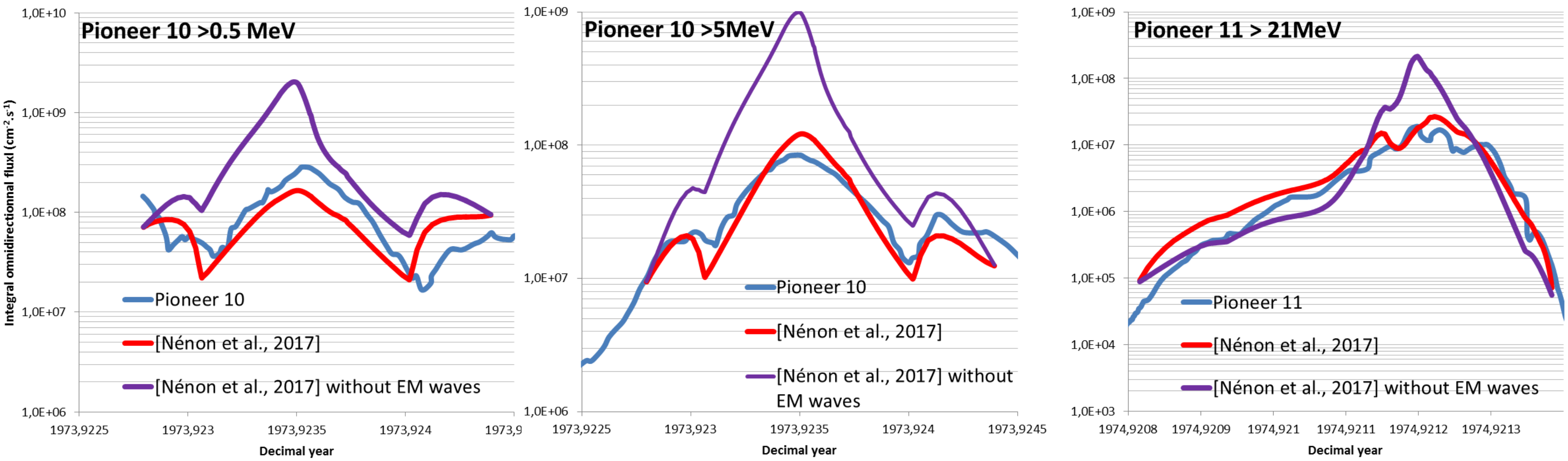


[2017]

1) Validation: Salammbô-electron

Importance of the hiss and chorus waves against observations

By « switching off » the process in Salammbô



With a realistic boundary condition at Europa, hiss and chorus waves are crucial to be able to reproduce in-situ fluxes.

- **Between Io and Europa, hiss and chorus waves play a leading role !**

See the JGR article [Nénon et al., 2017]

1) Validation: Salammbô-electron

Electrons

Wave-particle interaction is a leading process

Salammbô is a good mean model of the trapped electrons, reproduces **all** the existing measurements within a factor 2 to 3 except Juno's ones

Space variability quite correctly adressed by Salammbô !

Today's planning

1) Validation of Salammbô electron: do we correctly address **the space variability** ?

2) **Time variability above Io's orbit**
    1) In the particle observations: Galileo/EPD
    2) Of the wave-particle interaction
    3) Any link with solar wind ? Tentative study of the C22 storm

3) Conclusions and future work

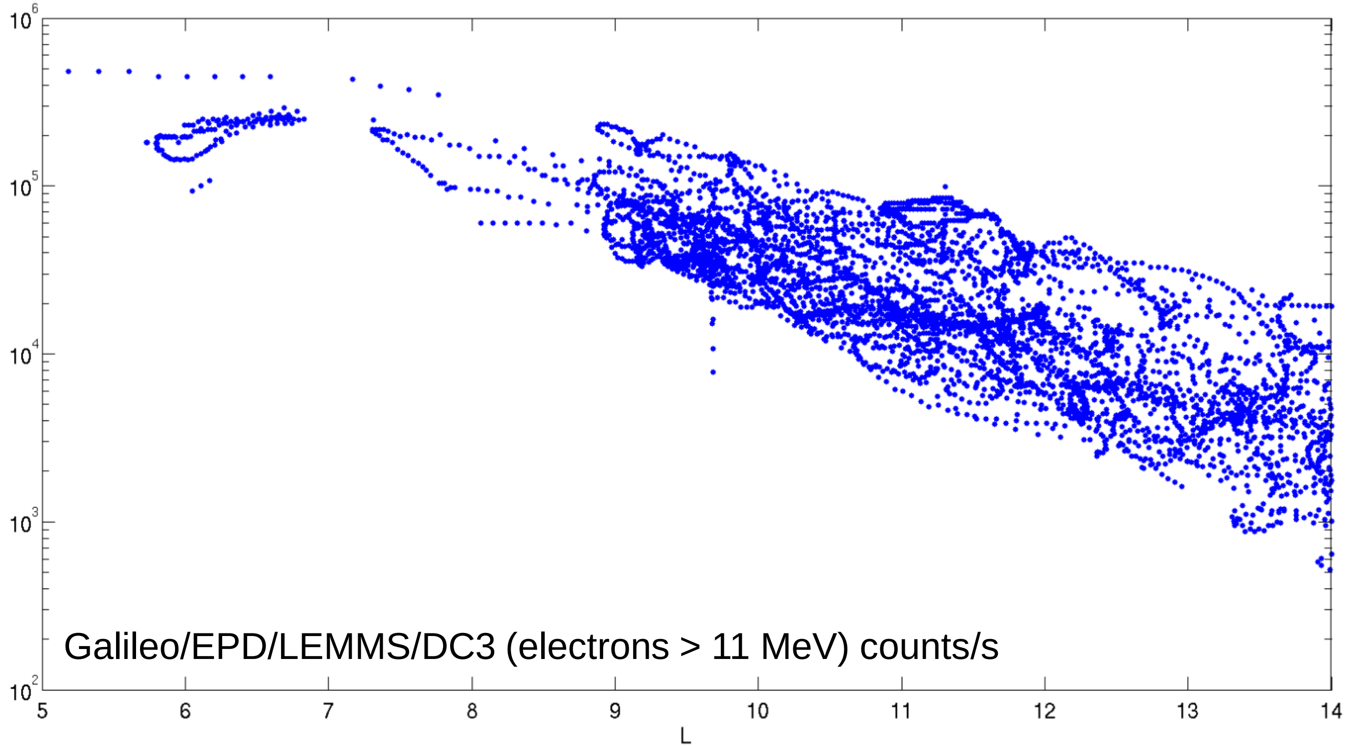
2) Time variability: Galileo EPD

Galileo remained more than 7 years in orbit around Jupiter

Below 1 MeV, « substorm » injections exist (backup slide)

Above 1 MeV, there is an observable **time variability**, not an effect of latitude

≈≈ 1 order of magnitude



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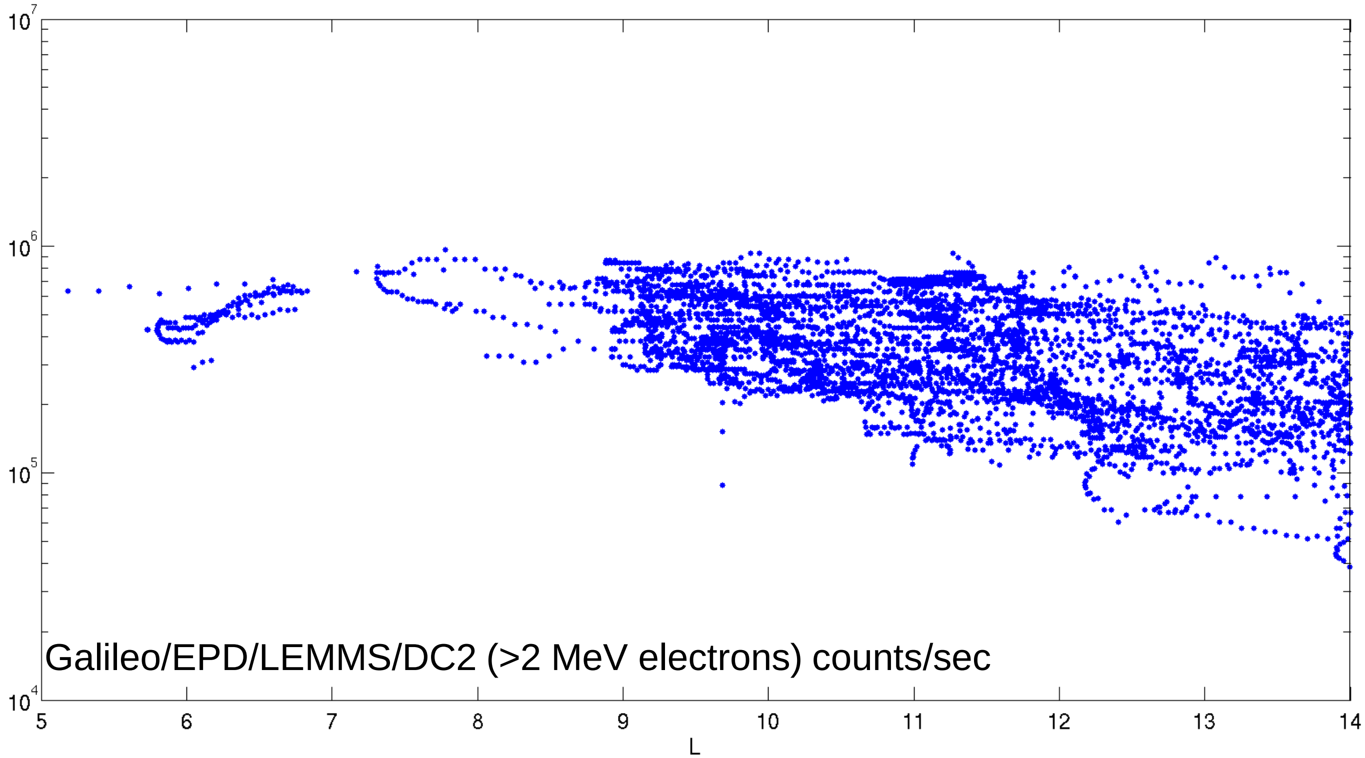

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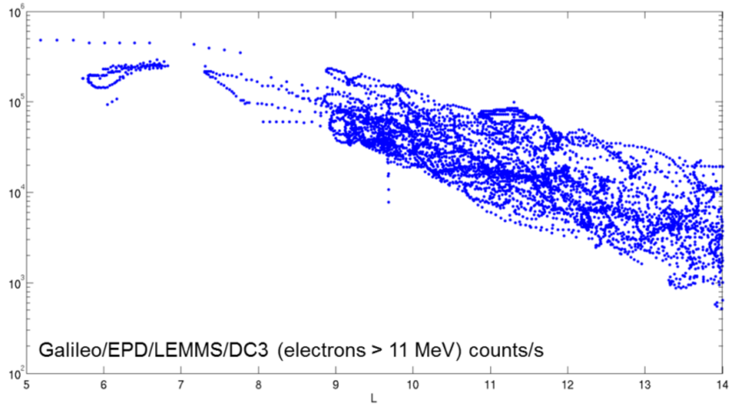

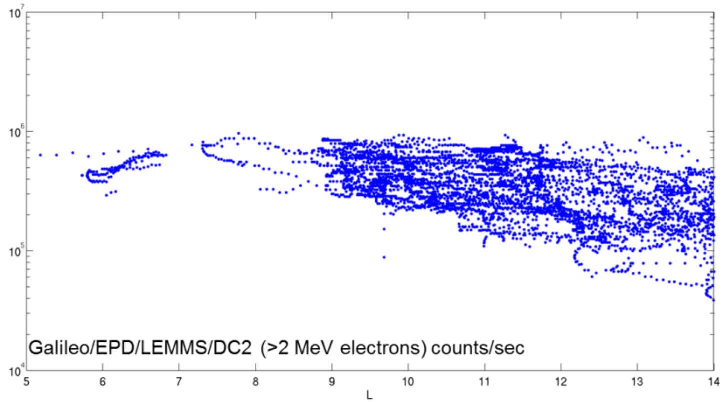

There is an observable time variability above the orbit of Io

➢ Any link with the observed variability of synchrotron emissions ?

Conclusion: for environment specification and shielding design, no worries:

- Close to the planet: time variability within a factor 2 (synchrotron)
- Within L<20: time variability within a decade (Galileo/EPD)

Except…

2) Time variability: Galileo EPD

Galileo remained more than 7 years in orbit around Jupiter

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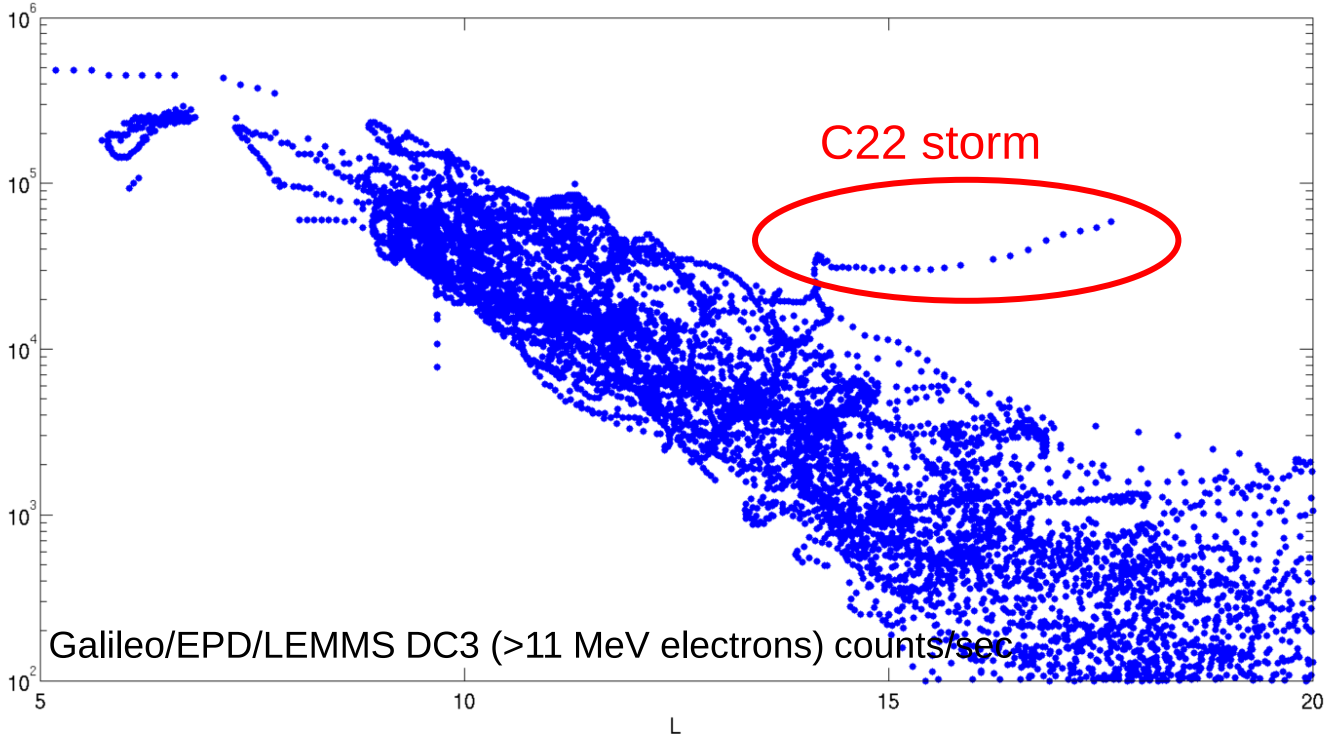

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Conclusion :

- Close to t
- Within L<

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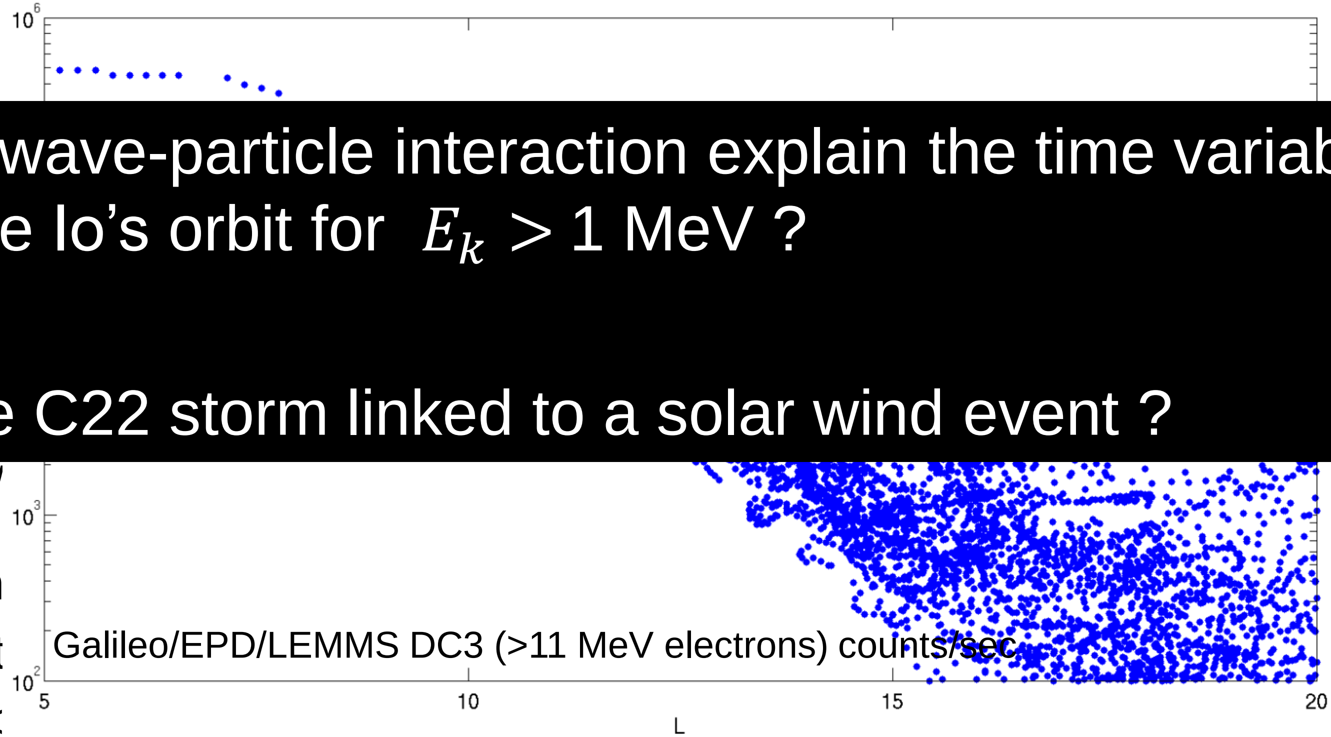

- May wave-particle interaction explain the time variability above Io's orbit for $E_k > 1$ MeV ?
- Is the C22 storm linked to a solar wind event ?

Th

➢ Any link w

Conclusion :

- Close to t
- Within L<

Except…

Today's planning

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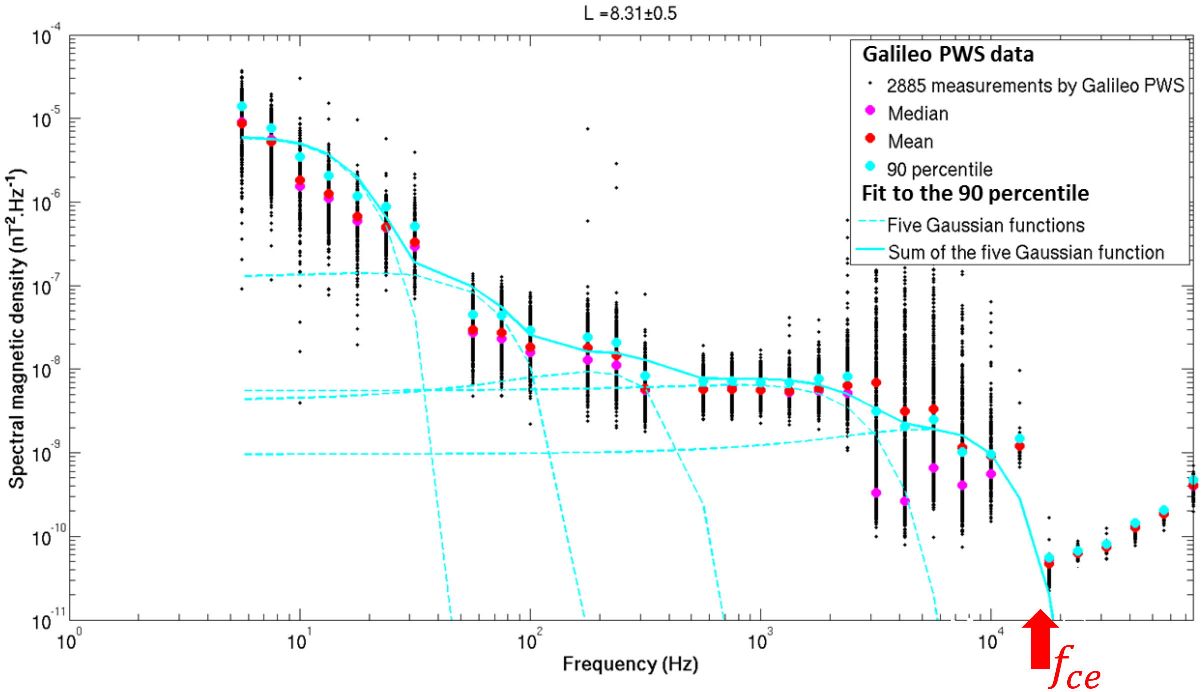
2) Time variability: wave-particle interaction

- Do the EM wave magnetic spectral densities evolve with time ? **YES**, see for instance Galileo/PWS data: **time variability**



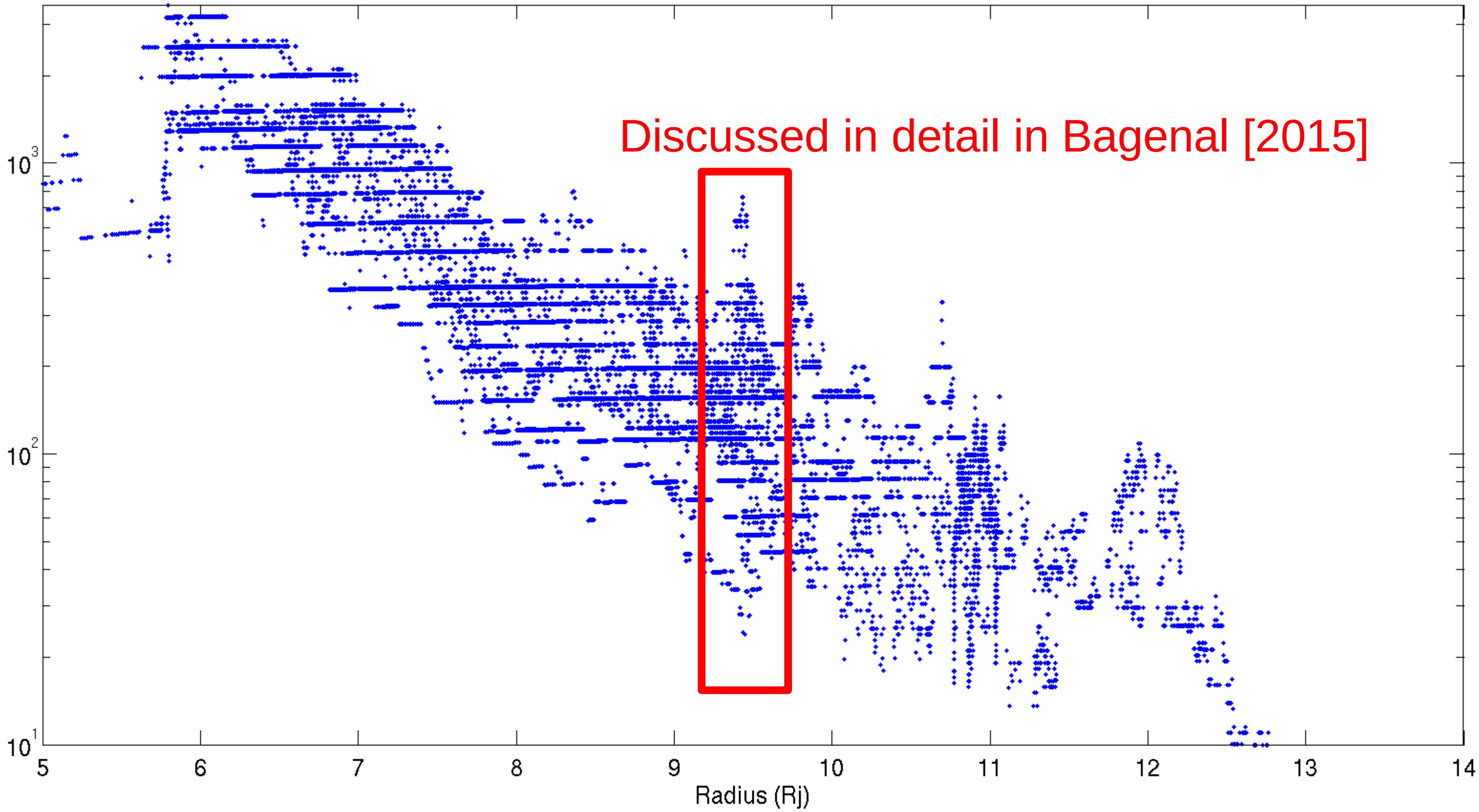
- Wave-particle interaction: fundamental link between the cold plasma and the radiation belts !

➢ Cold electron density is now seen as a key parameter of the Jovian radiation belts

Does it evolve with time ?

2) Time variability: wave-particle interaction

YES, it does. Electron density (cm^{-3}) from identification of the upper hybrid frequency in Galileo PWS, released on NASA PDS on March 2017



The variability is not only an effect of latitude: **time variability**

2) Time variability: wave-particle interaction

YES, it does. Electron density (cm^{-3}) from identification of the upper hybrid frequency in Galileo PWS, released on NASA PDS on March 2017

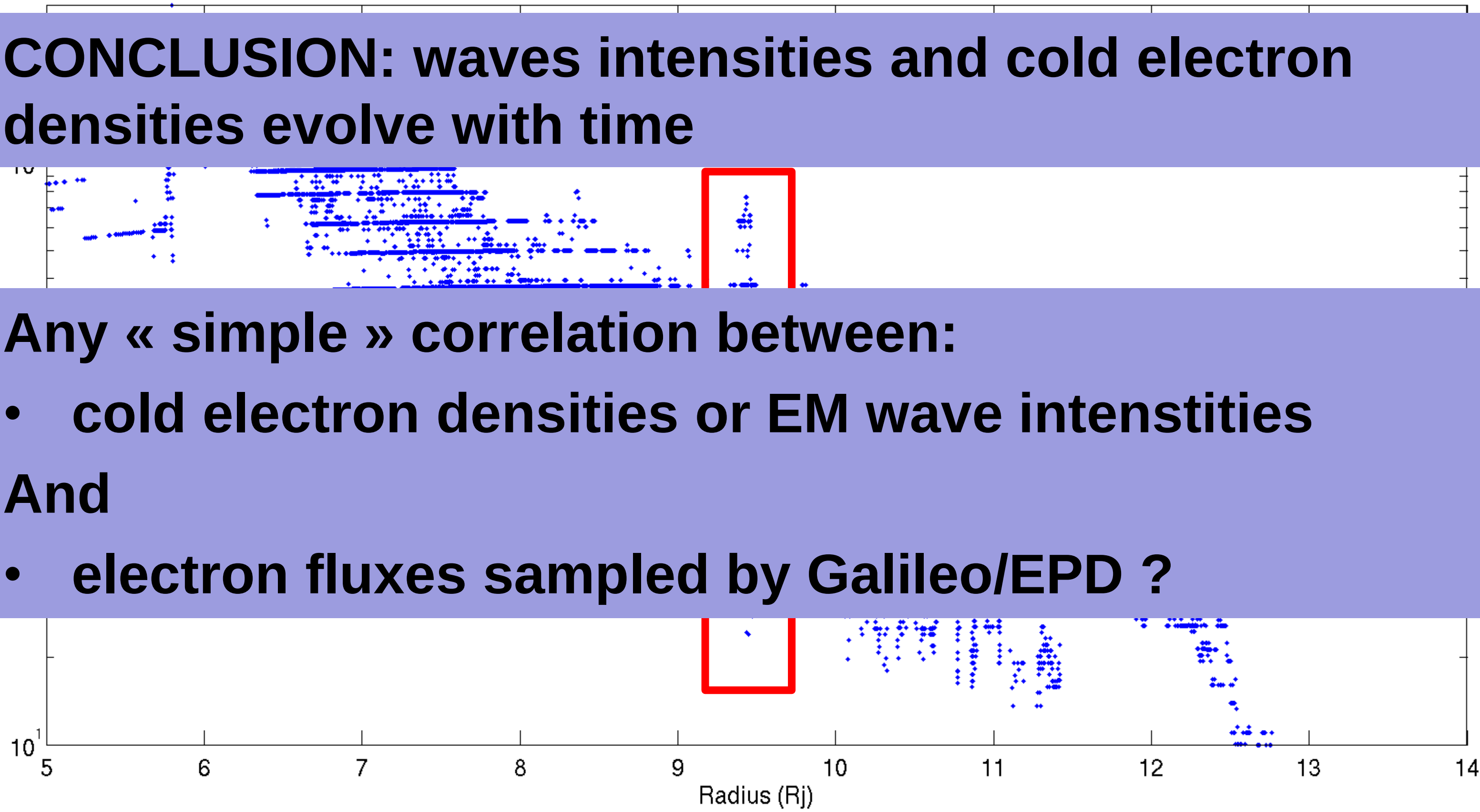
CONCLUSION: waves intensities and cold electron densities evolve with time

Any « simple » correlation between:

- **cold electron densities or EM wave intenstities**

And

- **electron fluxes sampled by Galileo/EPD ?**

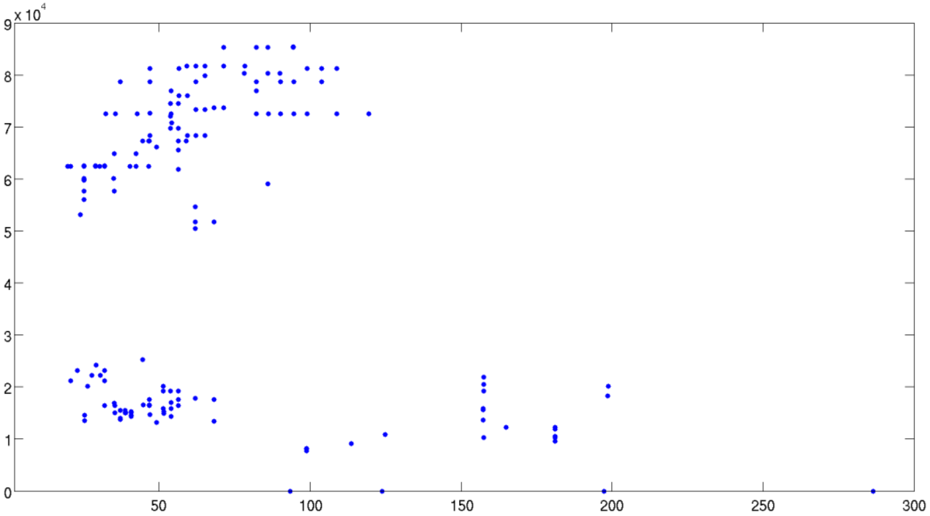


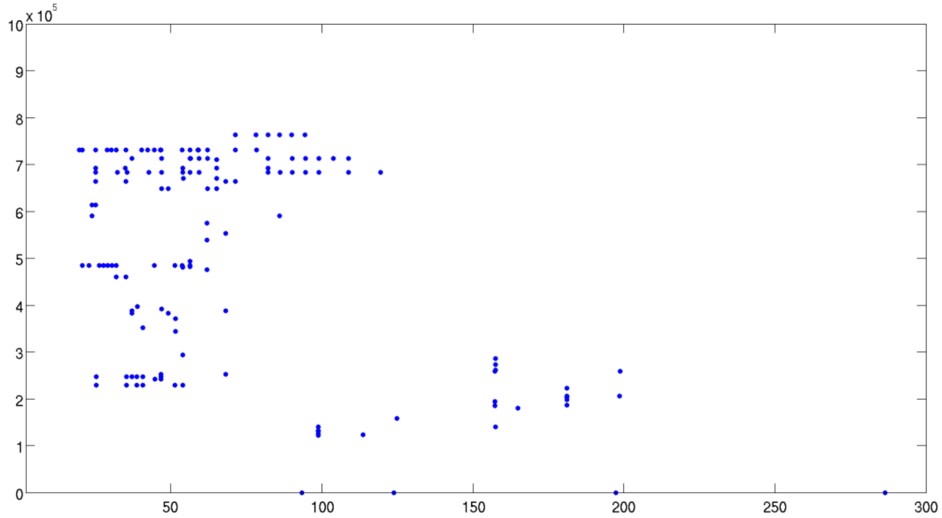
The variability is not only an effect of latitude: **time variability**

2) Time variability: wave-particle interaction

For $11.0 \leq L \leq 11.5$, we plot Galileo/EPD counts and cold electron density n_e if:

$$|date(EPD) - date(n_e)\,| < 30\,minutes$$





DC3 (>11 MeV electrons) counts (s^{-1})
vs $n_e\ (cm^{-3})$

DC2 (> 2 MeV electrons) (s^{-1})
vs $n_e(cm^{-3})$

« Physically », an increase in n_e might lead to an increase in DC3 and DC2 counts

Not obvious at all…

2) Time variability: wave-particle interaction

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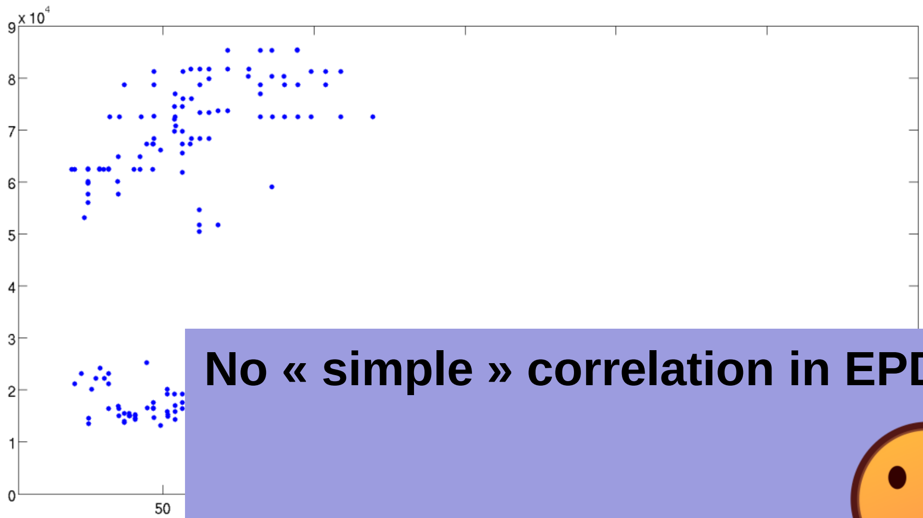

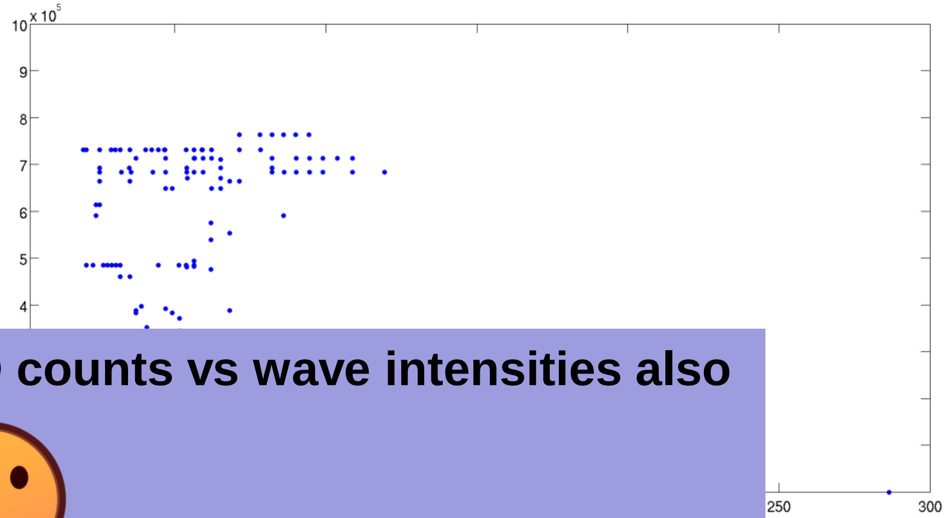

No « simple » correlation in EPD counts vs wave intensities also

DC3 (>11 MeV electrons) counts (s^{-1}) vs $n_e\ (cm^{-3})$

DC2 (> 2 MeV electrons) (s^{-1}) vs $n_e(cm^{-3})$

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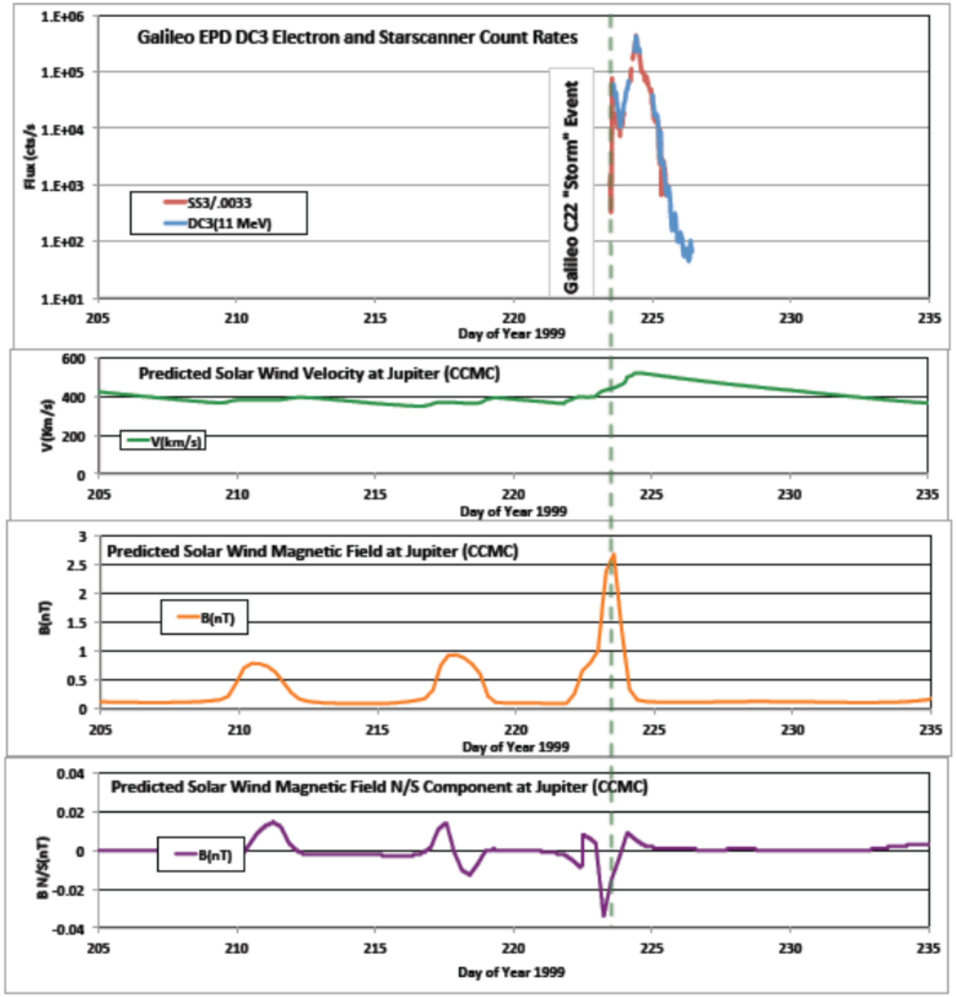
2) Time variability: a solar wind effect ? C22 storm

The Community Coordinated Modeling Center (CCMC) provided Dr. H. B. Garrett and JPL with solar wind predictions at Jupiter's orbit [Garrett et al., 2012]

For instance, the « C22 storm » seems to be correlated with a big peak in solar wind magnetic field



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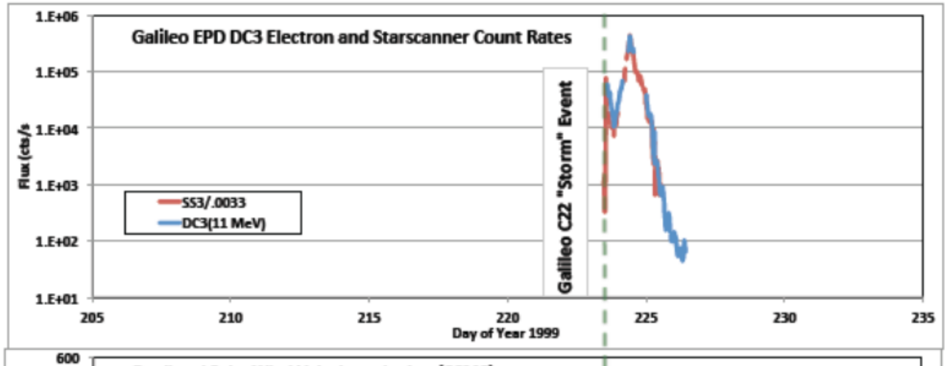
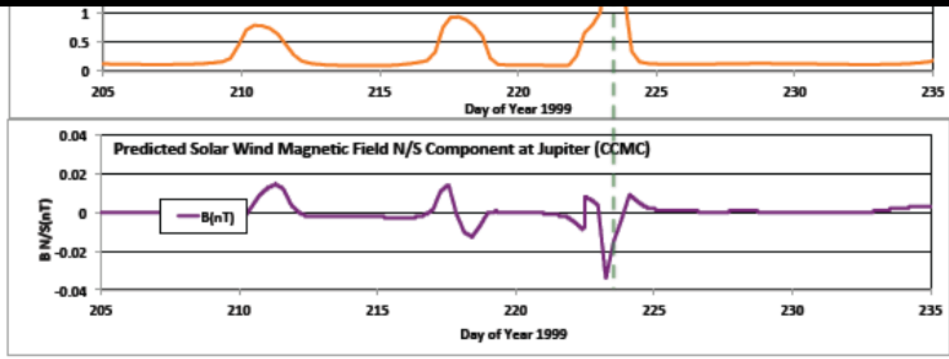


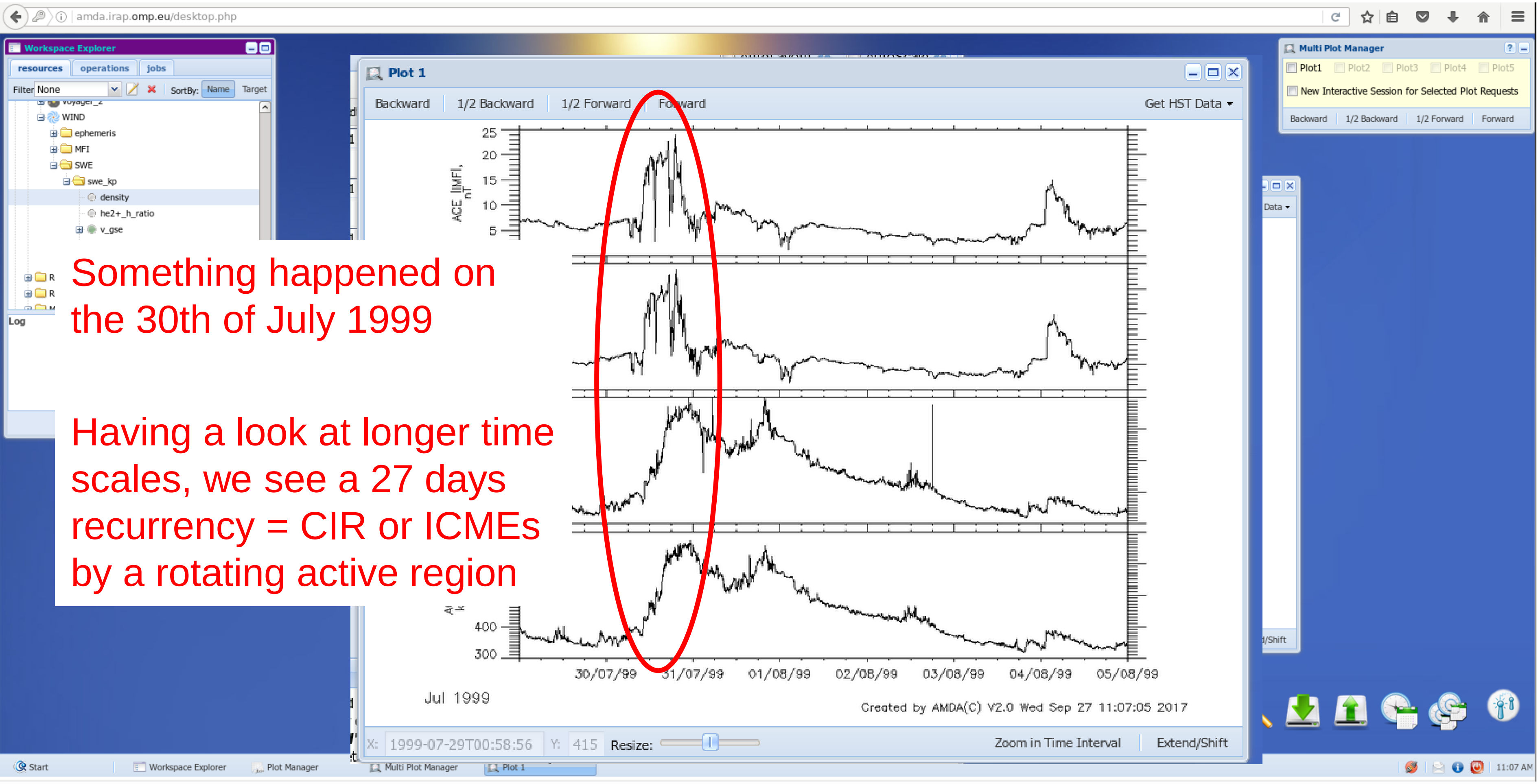
Let's do the prediction by ourself with the CDPP tools !

1) Find the event at L1 with **AMDA** database
2) Propagate the event towards Jupiter's orbit with **CDPP Solar Wind propagation tool**



2) Time variability: a solar wind effect ? C22 storm

AMDA database: ACE and WIND (L1) magnetic field and velocity measurements

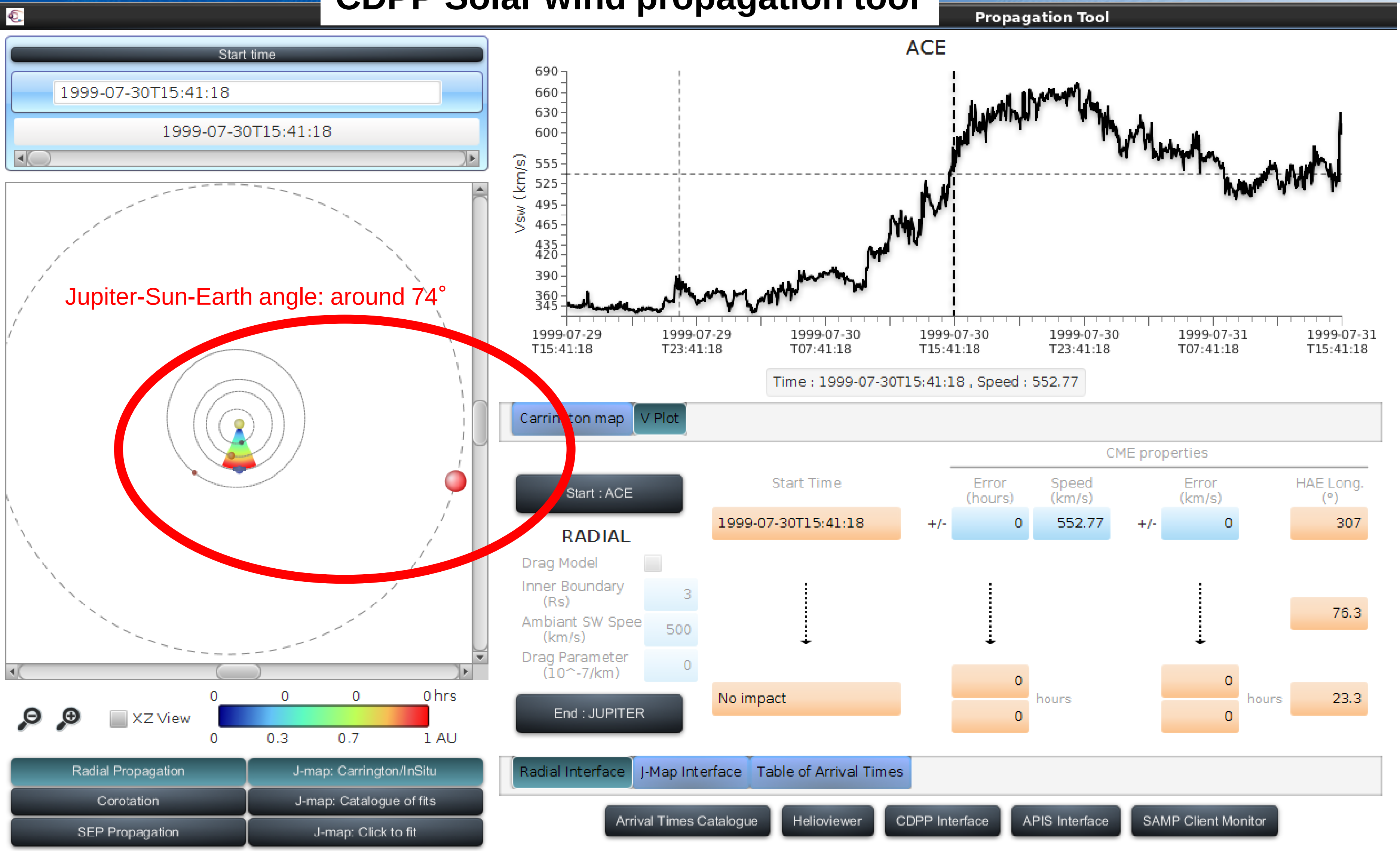


Something happened on the 30th of July 1999

Having a look at longer time scales, we see a 27 days recurrency = CIR or ICMEs by a rotating active region

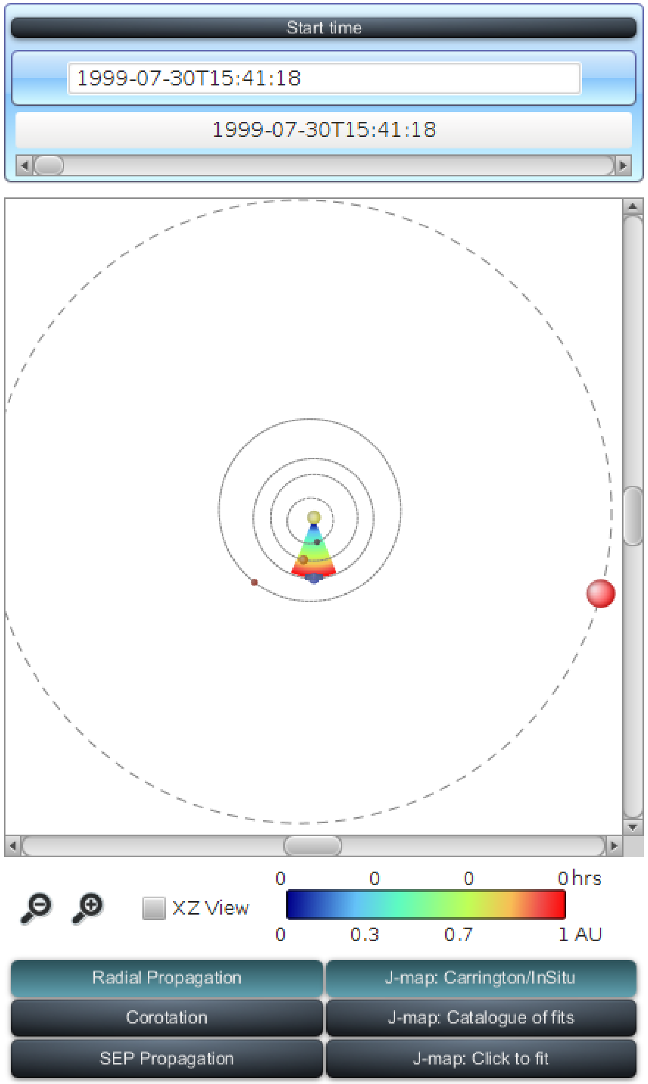
2) Time variability: a solar wind effect ? C22 storm

CDPP Solar wind propagation tool



2) Time variability: a solar wind effect ? C22 storm

Propagation Tool



Target	t'	t'min(Δt)	t'max(Δt)	t'min(ΔV)	t'max(ΔV)	φEnd(t')-φStart(t)	r(End-Sun)	φCME(t)	Δ(
		(hrs)	(hrs)	(hrs)	(hrs)	(°)	(AU)	(°)	(°)
SUN	1999-07-27T12:...	0	0	0	0	71.15	0	307.01	45
Probes									
WIND	1999-07-30T15:...	0	0	0	0	0.04	1	307.01	45
ACE	1999-07-30T15:...	0	0	0	0	0	1	307.01	45
SOHO	1999-07-30T15:...	0	0	0	0	0.19	1	307.01	45
Planets									
MERCURY	1999-07-28T19:...	0	0	0	0	3.32	0.41	307.01	45
VENUS	1999-07-29T18:...	0	0	0	0	345.7	0.72	307.01	45
EARTH	1999-07-30T16:...	0	0	0	0	0.08	1.01	307.01	45
MARS	1999-08-01T02:...	0	0	0	0	318.18	1.46	307.01	45
JUPITER	1999-08-12T00:...	0	0	0	0	76.26	4.95	307.01	45
SATURN	1999-08-25T09:...	0	0	0	0	94.06	9.21	307.01	45
URANUS	1999-09-27T20:...	0	0	0	0	8.37	19.9	307.01	45
NEPTUNE	1999-10-29T20:...	0	0	0	0	356.54	30.12	307.01	45
PLUTO	1999-10-30T00:...	0	0	0	0	303.12	30.17	307.01	45
Comets									

Time of arrival at Jupiter's **orbit**: 12th of August !

Beginning of the event: 11th of August
End of the event: 13th of August
C22 storm: 12th of August

Given defined

Radial Interfa

Arrival Times Catalogue | Helioviewer | CDPP Interface | APIS Interface | SAMP Client Monitor

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CONCLUSIONS

- CCMC and Solar Wind Propagation tool

If the event observed by ACE and WIND on 30th July 1999 is an ICME with a 74° opening angle, then the C22 storm might be a response to this event

- <u>Michigan model (found on AMDA also)</u> and Solar Wind Propagation tool

However, 74° is a big opening angle ! If the event rotates with the Sun (CIR or active region), then it impacts the Jupiter magnetosphere **<u>5 days after</u>** the C22 storm

Important conclusion :

Easy to « play » with the CDPP tools !

Conclusions

Time variability above Io's orbit

Wave-particle observation may drive the time variability observed by Galileo/EPD

No simple correlation, future wave-particle interaction simulations might help

CDPP tools may be useful to study any link with solar activity

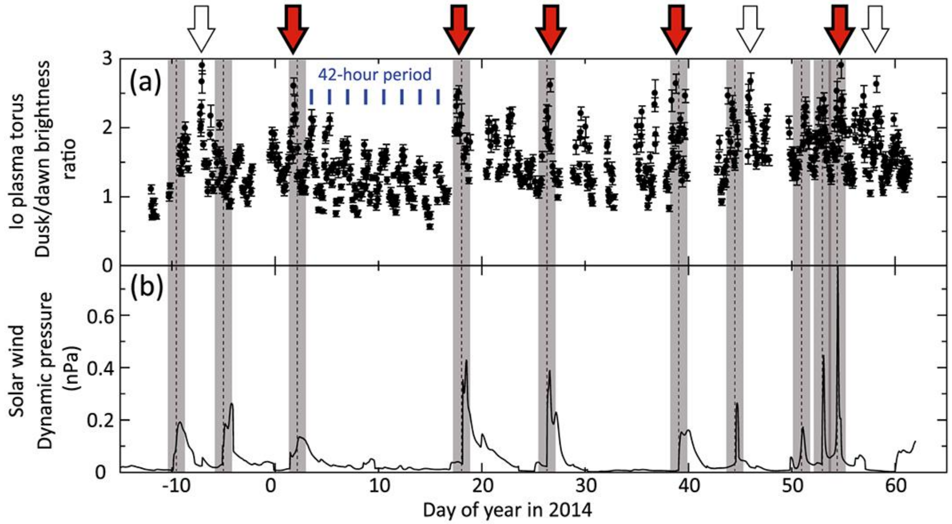
Future work

- Variability of the magnetodisck densities seen by HISAKI/EXCEED ?

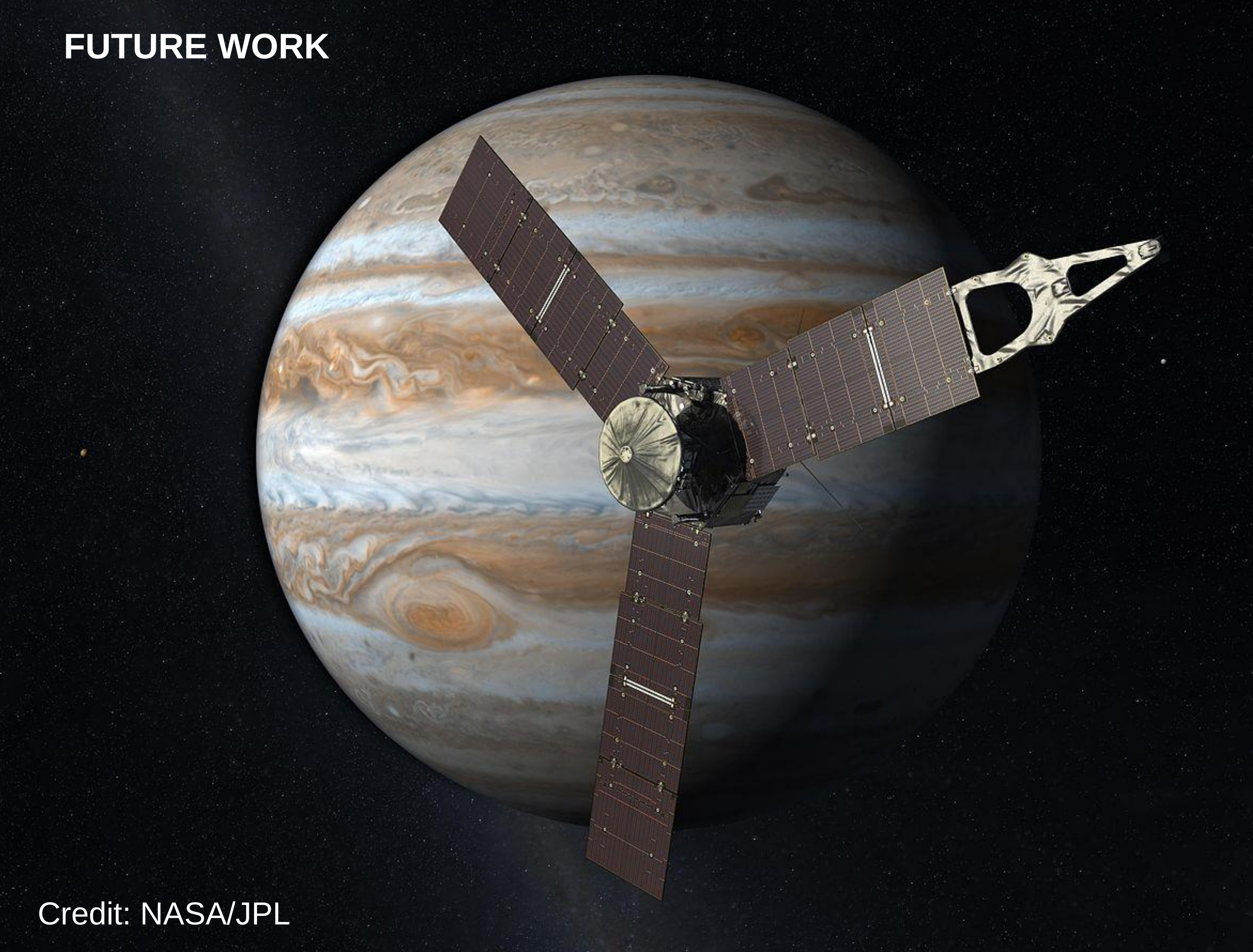
Response to solar wind are known to exist ! [Murakami et al., 2016; Tschuiya et al., 2017]

Maybe also responses to the Io volcanic activity [Yoshikawa et al., 2017]

[Murakami et al., 2016]



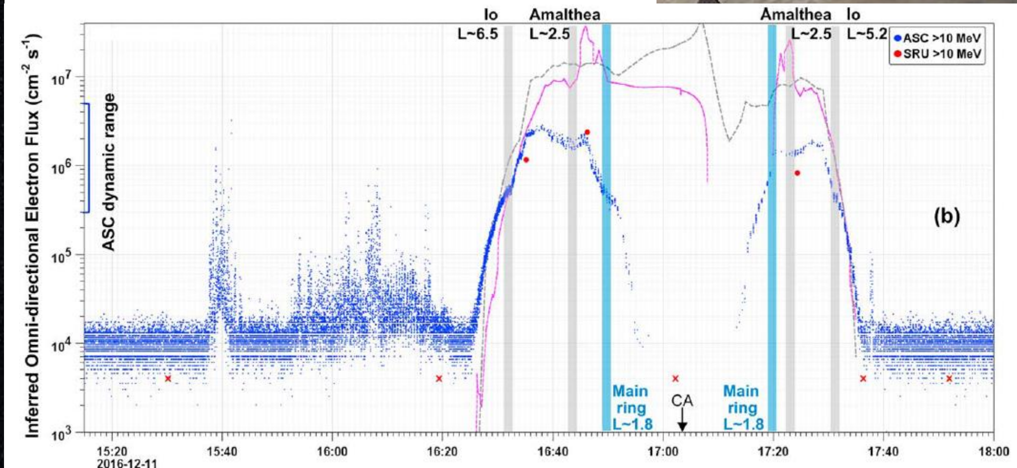
FUTURE WORK



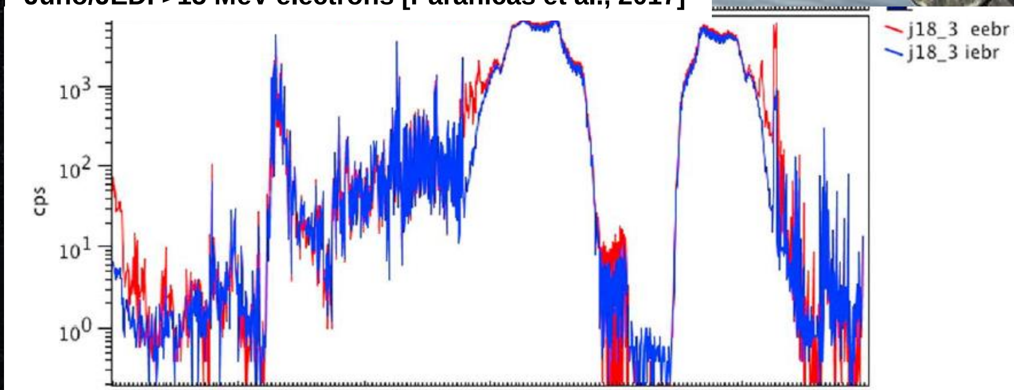
Credit: NASA/JPL

FUTURE WORK

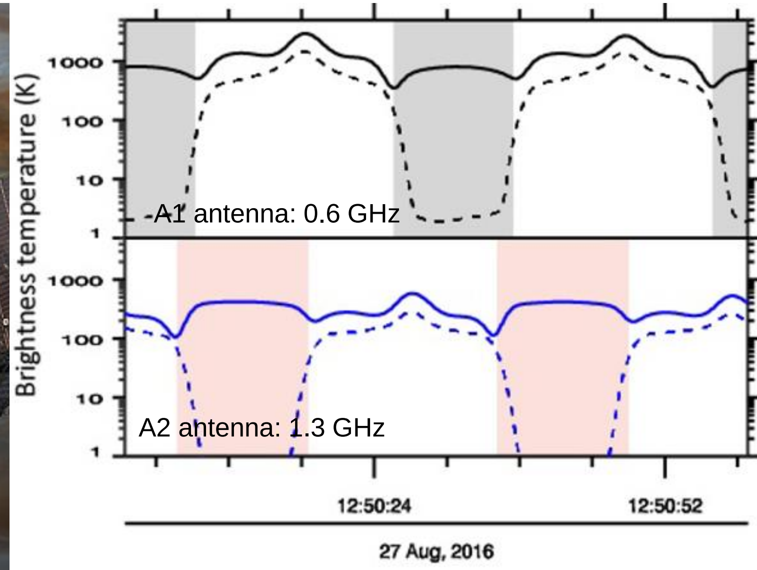
Juno/RM >10 MeV electrons [Becker et al., 2017]



Juno/JEDI >15 MeV electrons [Paranicas et al., 2017]



Juno/MWR synchrotron observations [Santos-Costa et al., 2017]



+ Juno/JEDI electrons and protons below 1 MeV [Kollmann et al., 2017] [Paranicas et al., 2017]

+wave-particle interaction at high latitudes ?