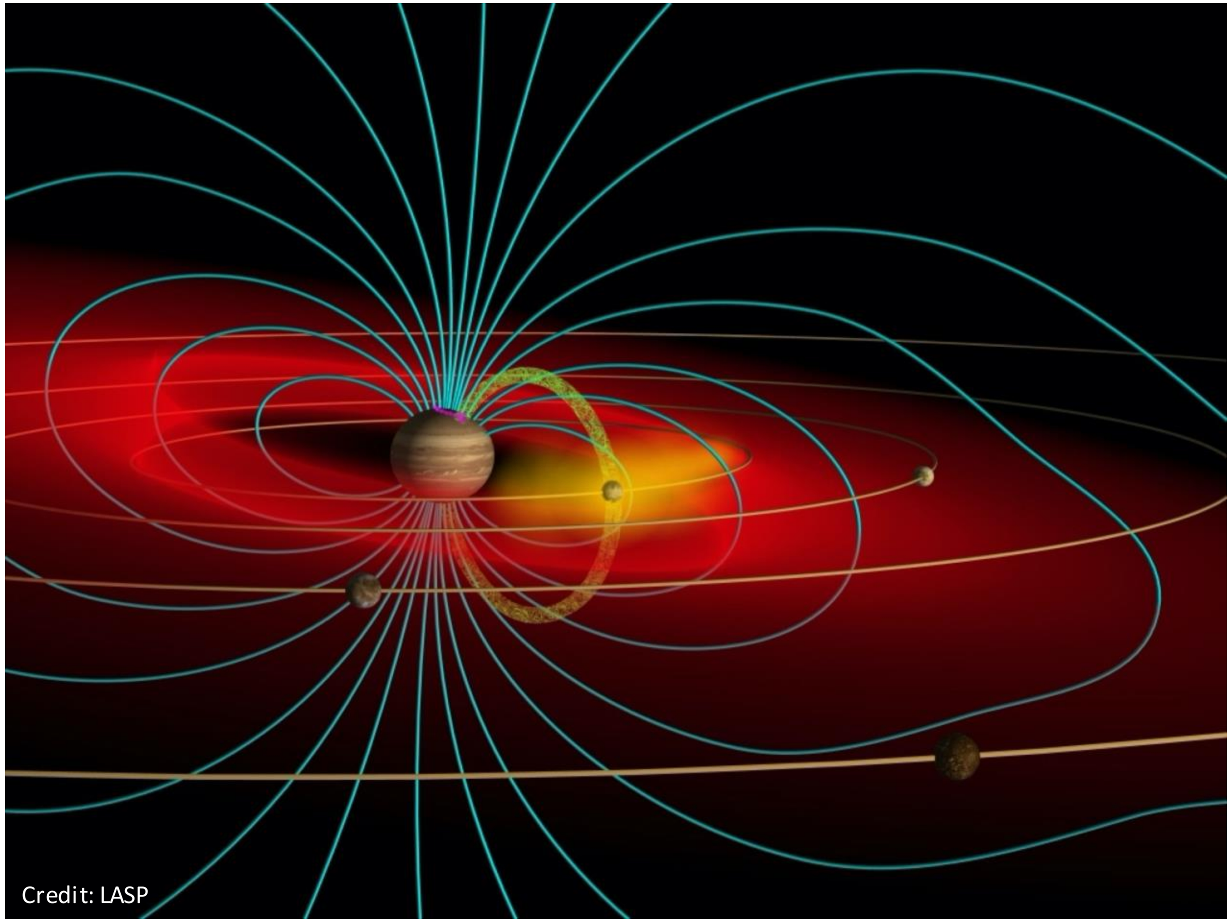
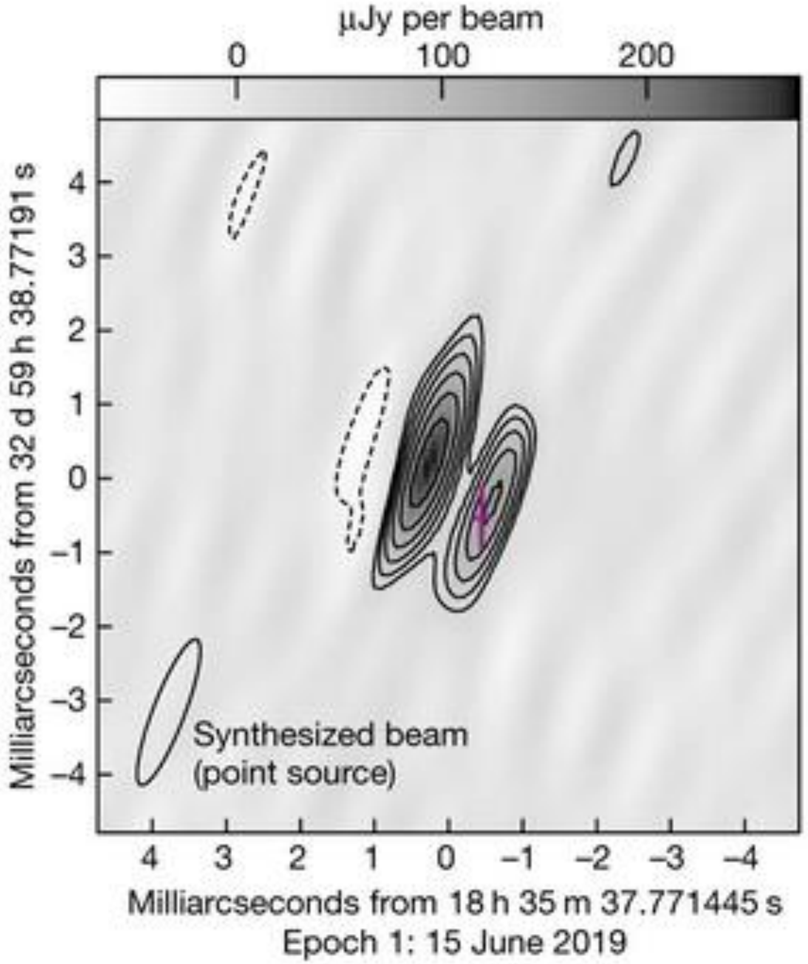
Electron radiation belts of Jupiter
Anisotropy of >1 MeV electrons

Quentin Nénon, IRAP-CNRS, Toulouse, France

Jupiter: analogue for extra-solar radiation belts



Brown dwarf radiation belts [Kao+2023, Nature]



Why study the Jovian radiation belts?

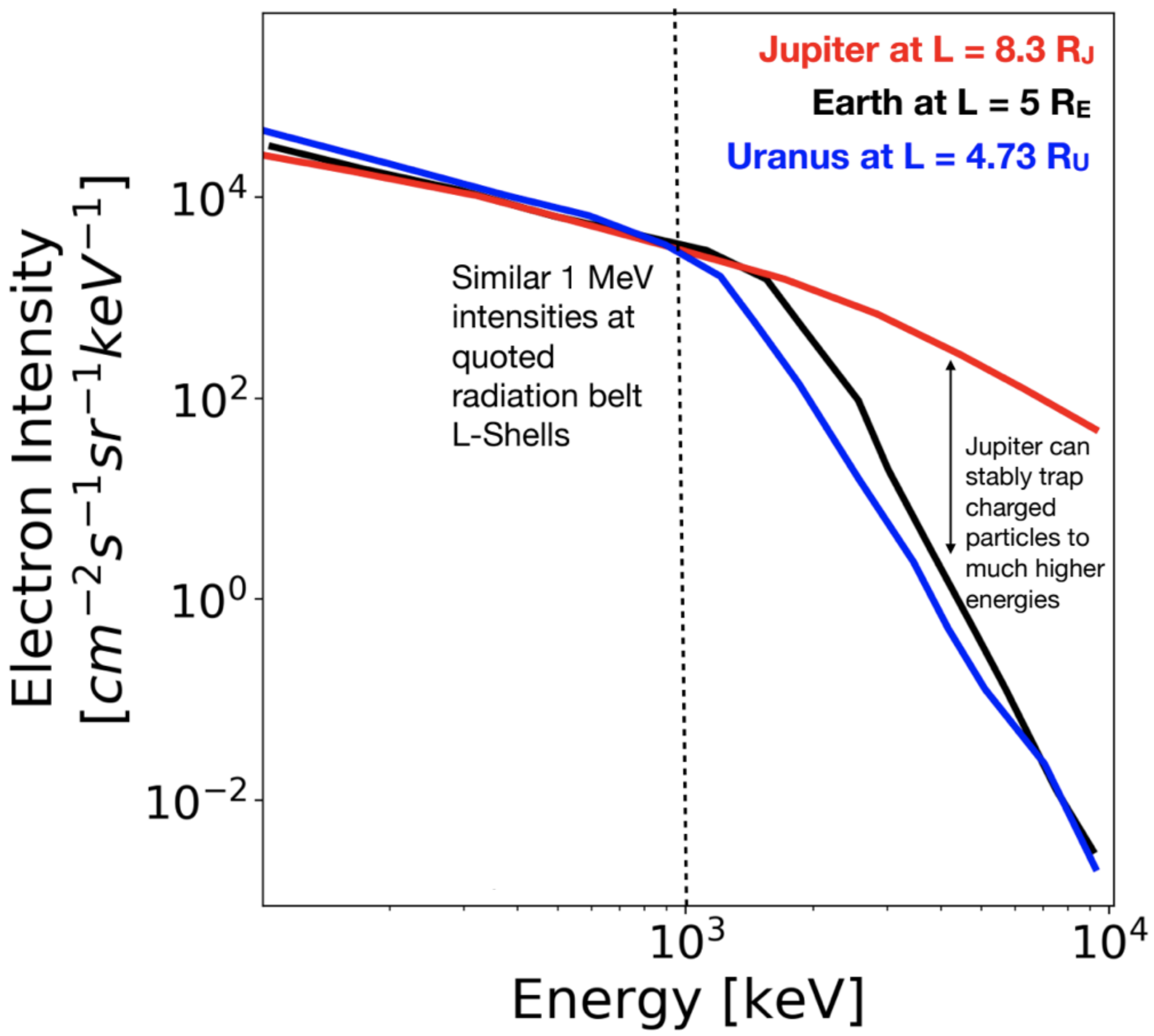
1) Space plasma physics in a unique natural laboratory

To answer to the **universal** **question**: where do energetic charged particles come from, how are they accelerated, transported, and lost?

Unique configuration: strong magnetic field, fast planetary rotation, volcanic moon, rings…

Unique regime: high fluxes at high kinetic energies

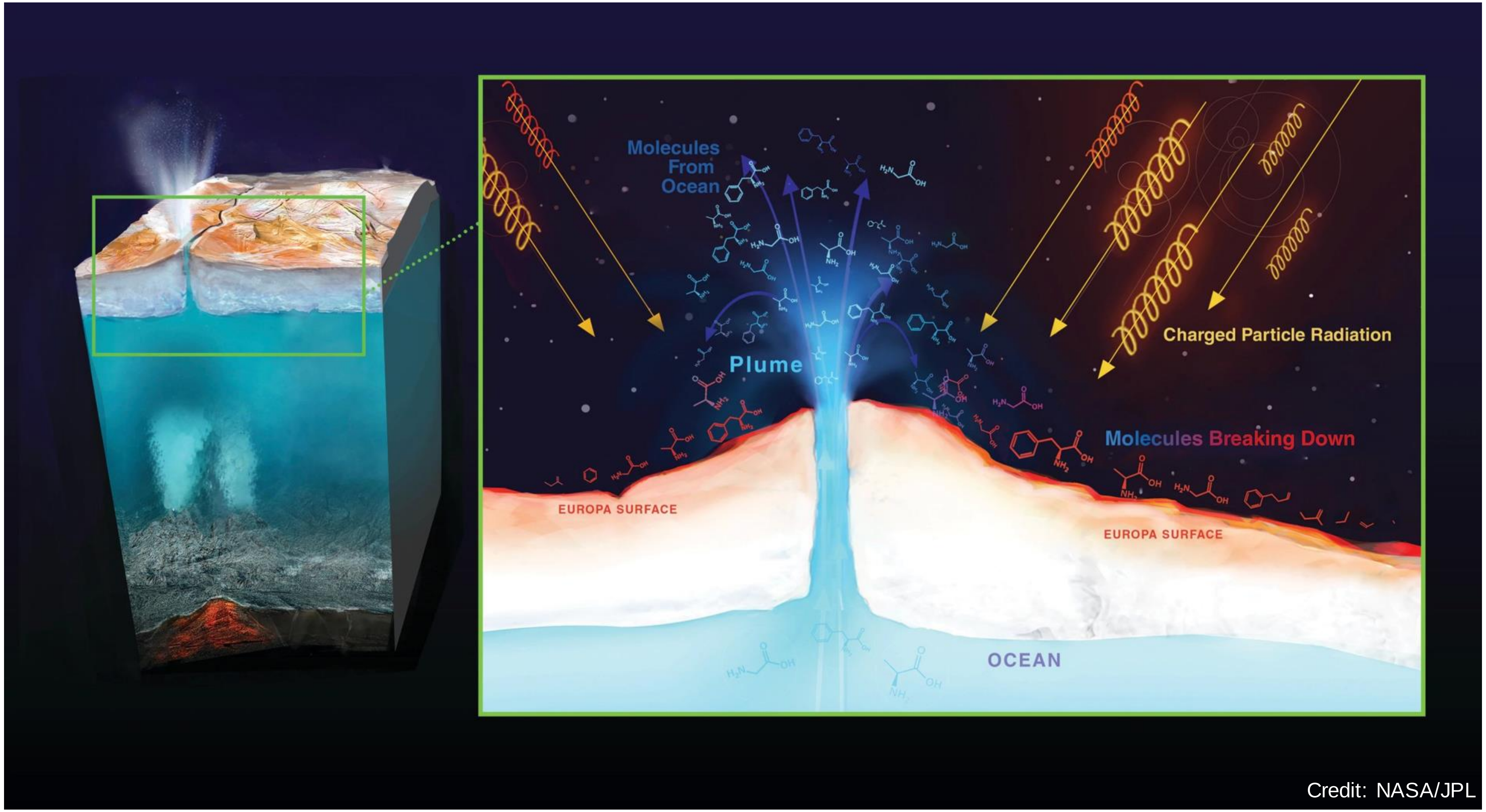
- Electron **Pitch Angle Distribution** provide insight into the dominant physical processes



Why study the Jovian radiation belts?

2) Planetary science: weathering of the moon surfaces

- Electron **Pitch Angle Distribution** defines the dose received at each location on a moon surface



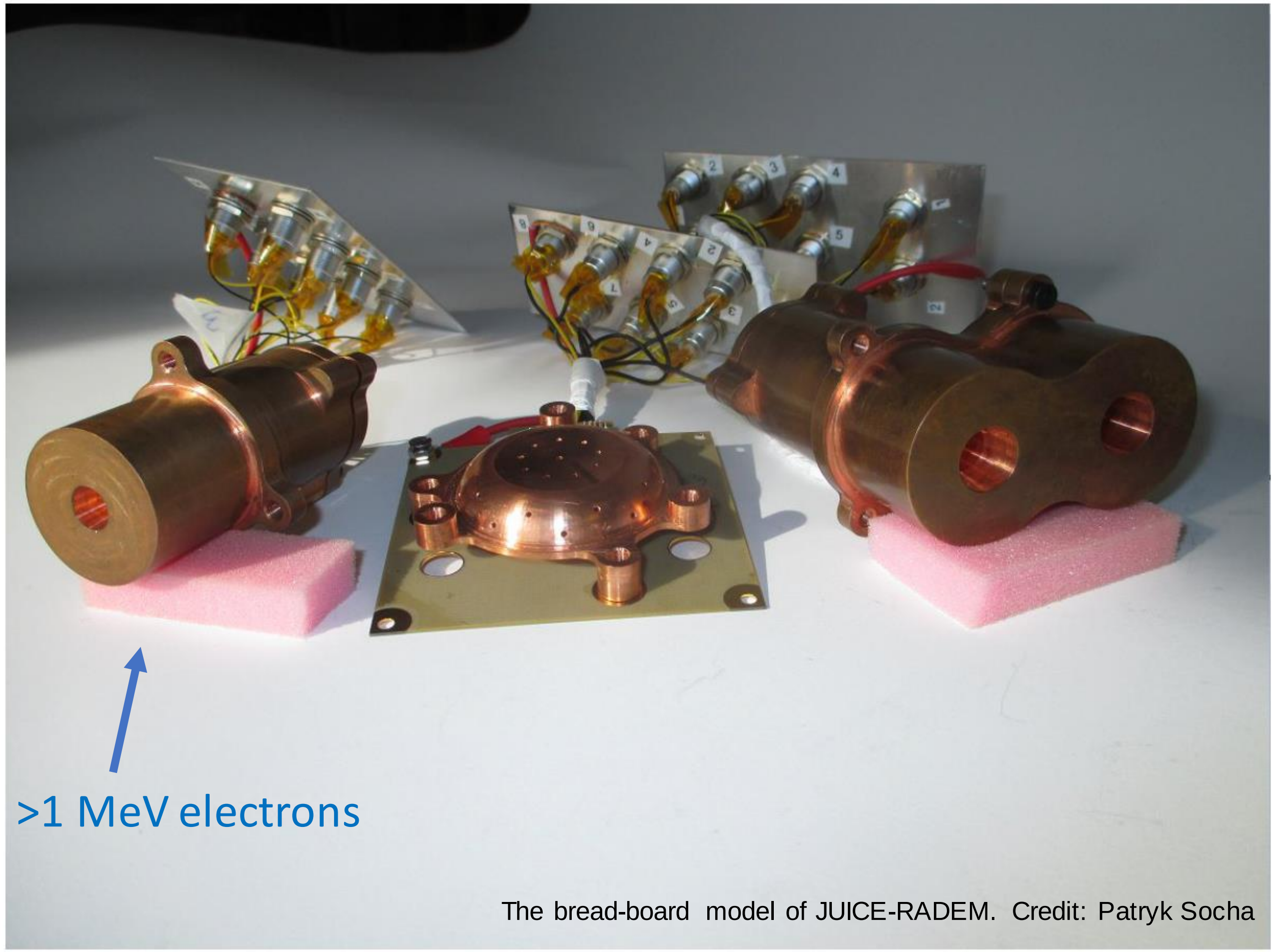
Why study the Jovian radiation belts?

By studying the Jovian radiation belts:

1) Space plasma physics
2) Planetary science: moon weathering
3) Hazard for artificial satellites (electronics, solar panels)

- The Radiation Monitor of **JUICE (RADEM)** will observe 0.5% of the sky.

Anisotropy of the radiation?



In-situ exploration of the Jovian radiation belts

Energetic charged particle detectors onboard:

Past

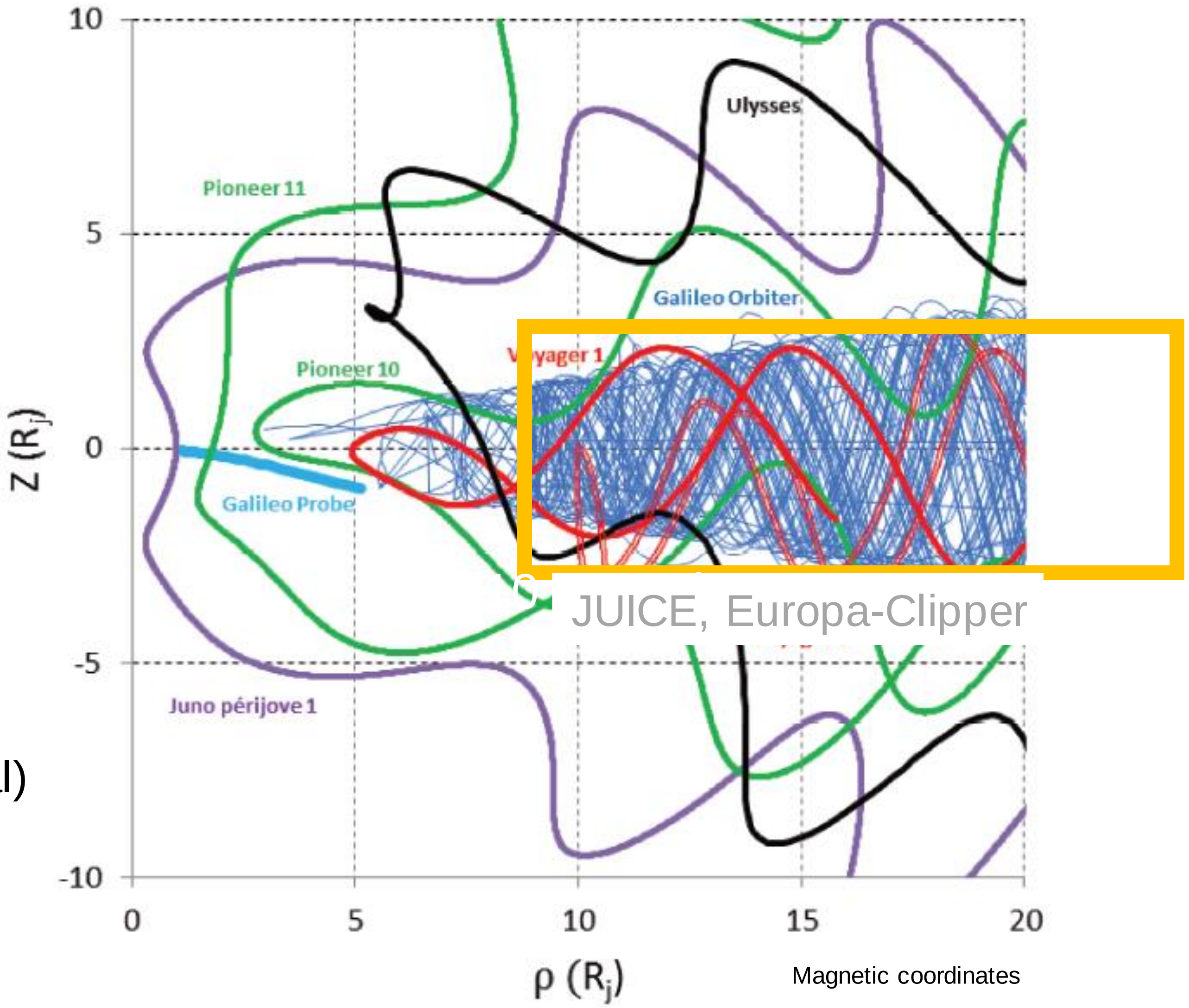
- 1970s: NASA Pioneer 10-11, Voyager 1-2
- 1992: ESA Ulysses
- 1995-2003: NASA **Galileo** (equatorial orbiter)

Present

- 2016 – now: NASA **Juno** (polar orbiter)

Future

- 2030s: ESA **JUICE**, NASA **Europa-Clipper** (equatorial)



Magnetic coordinates

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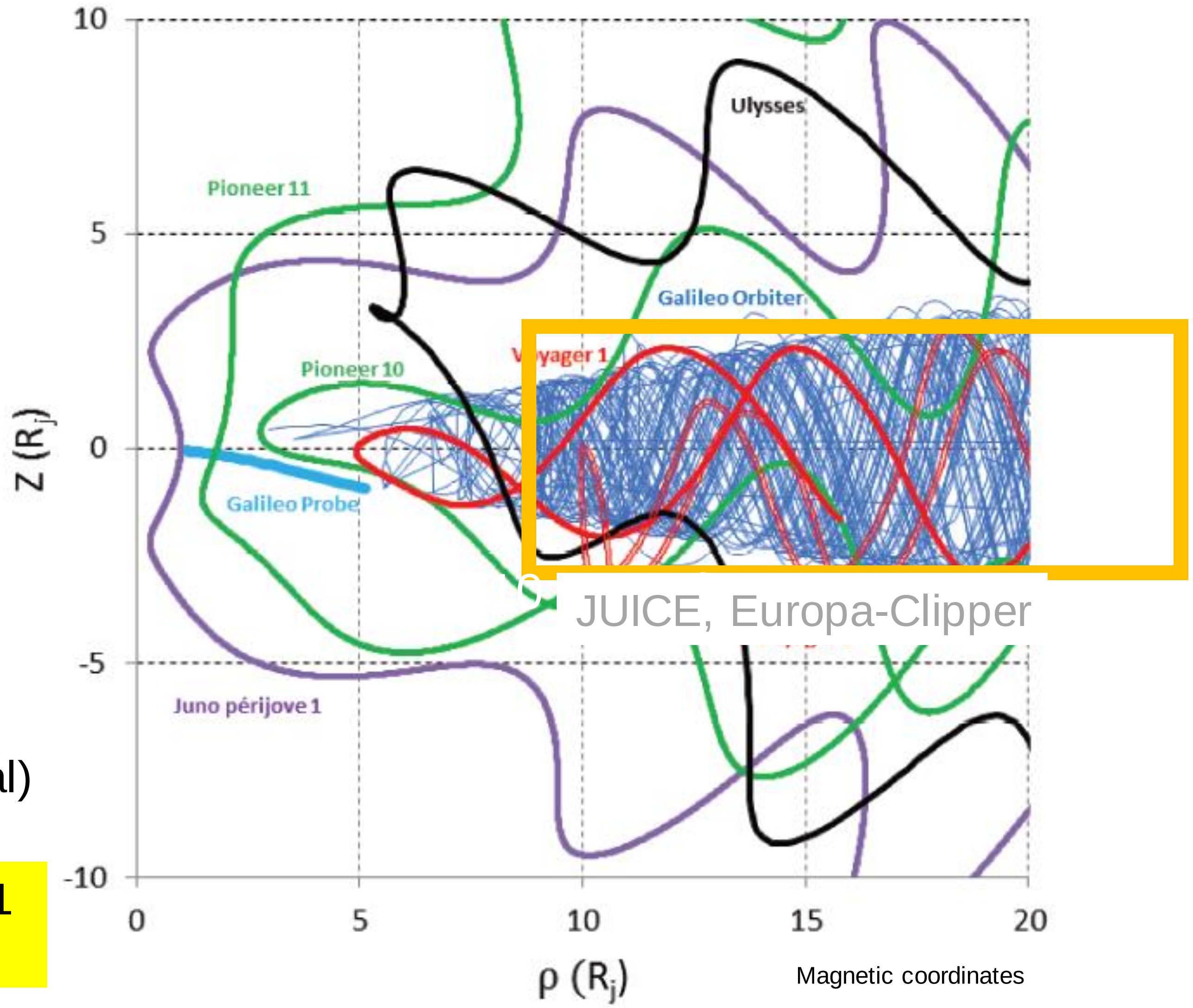
➢ Amongst orbiters, **only Galileo** for the anisotropy of >1 MeV electrons



Magnetic coordinates

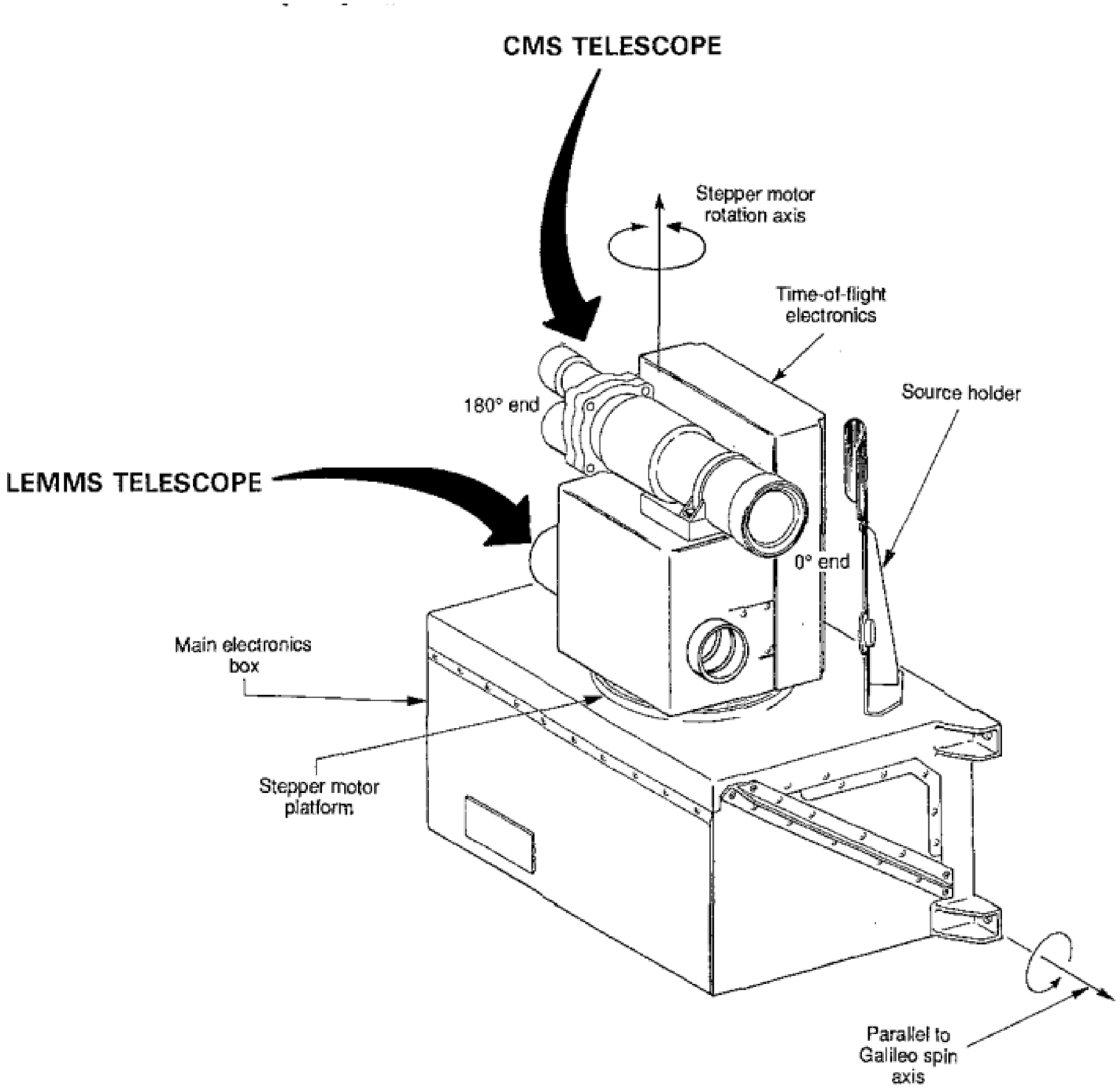
Galileo – EPD (1995-2003)

The Galileo Energetic Particle Detector (EPD)

- On the spinning platform of Galileo (spin period of 20 seconds).
- 4π sr coverage every 160 seconds

- EPD-LEMMS for electrons:

Energy-resolved channels from 20 keV to 1 MeV
Integral channels for >1 MeV and >10 MeV electrons



Galileo-EPD, Figure from Williams+1992

Results: The anisotropy of >1 MeV electrons at Jupiter

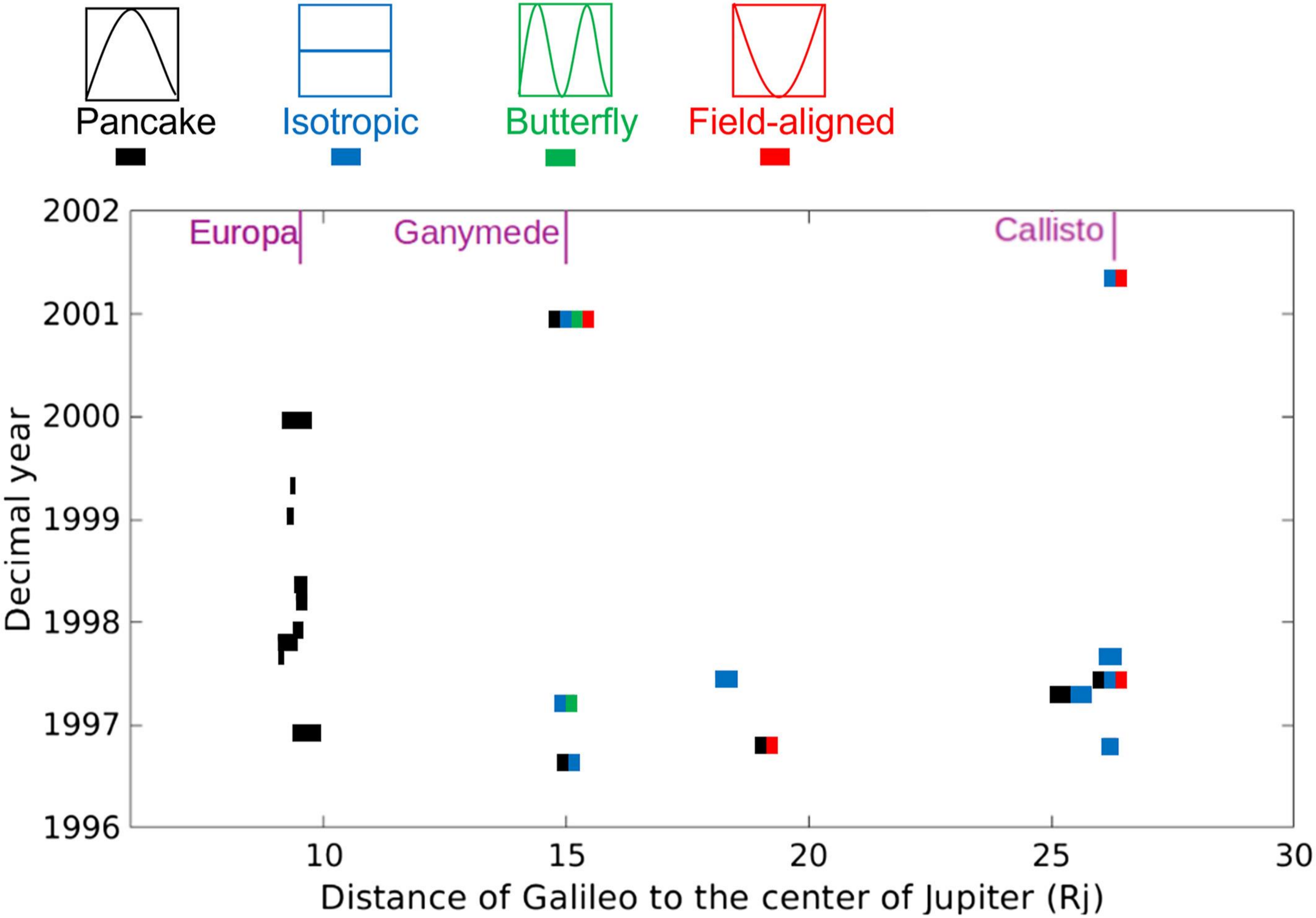
- **Only 26 hours of data in total**

Pancake = normal and/or wave acceleration?

Isotropic = PA scattering?

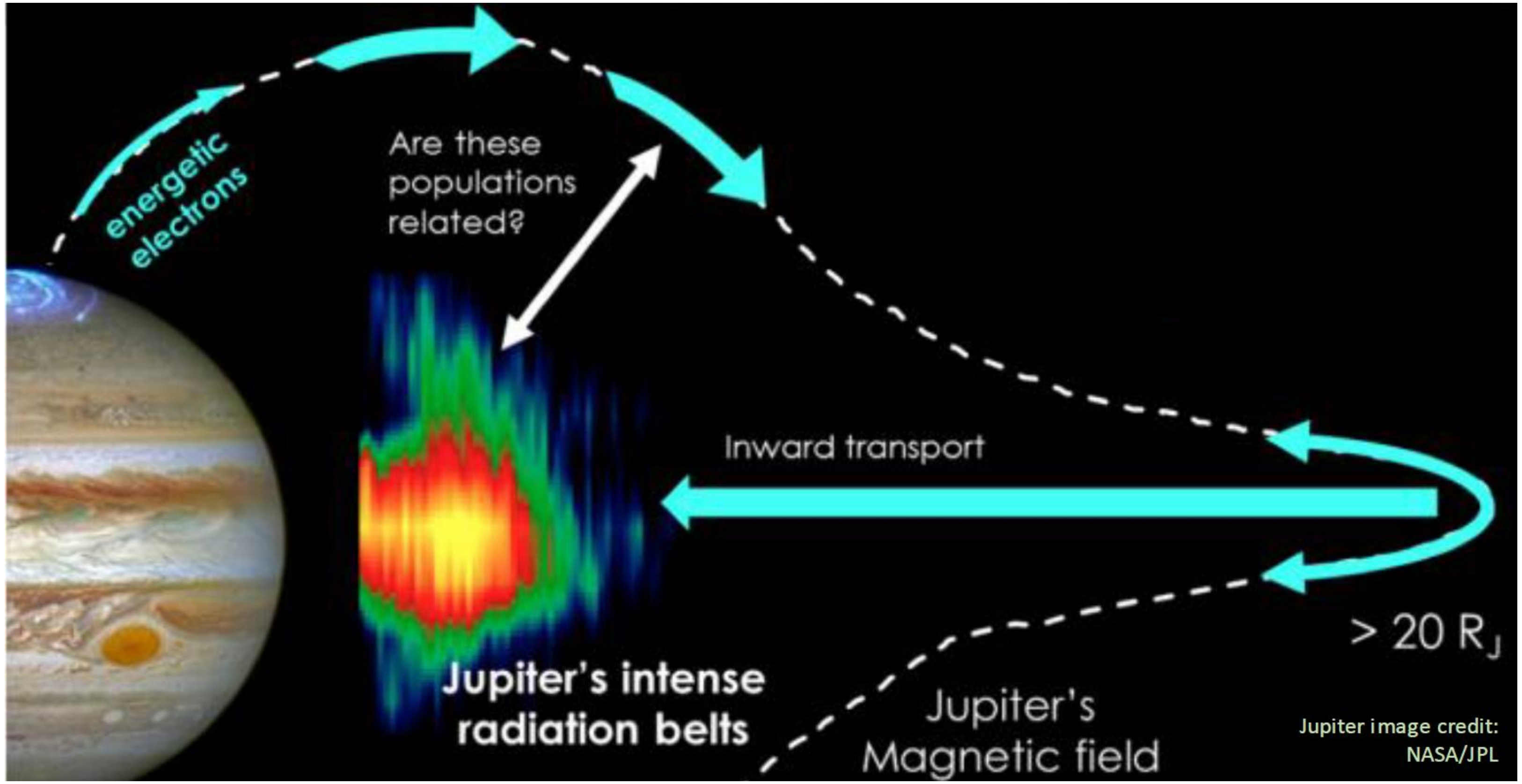
Butterfly = wave acceleration?

Field-aligned = auroral acceleration?



Results: Field-aligned distributions of >1 MeV electrons

- Galileo-EPD reveals that auroral acceleration injects >1 MeV electrons in the Jovian magnetosphere
- Do these electrons remain trapped?



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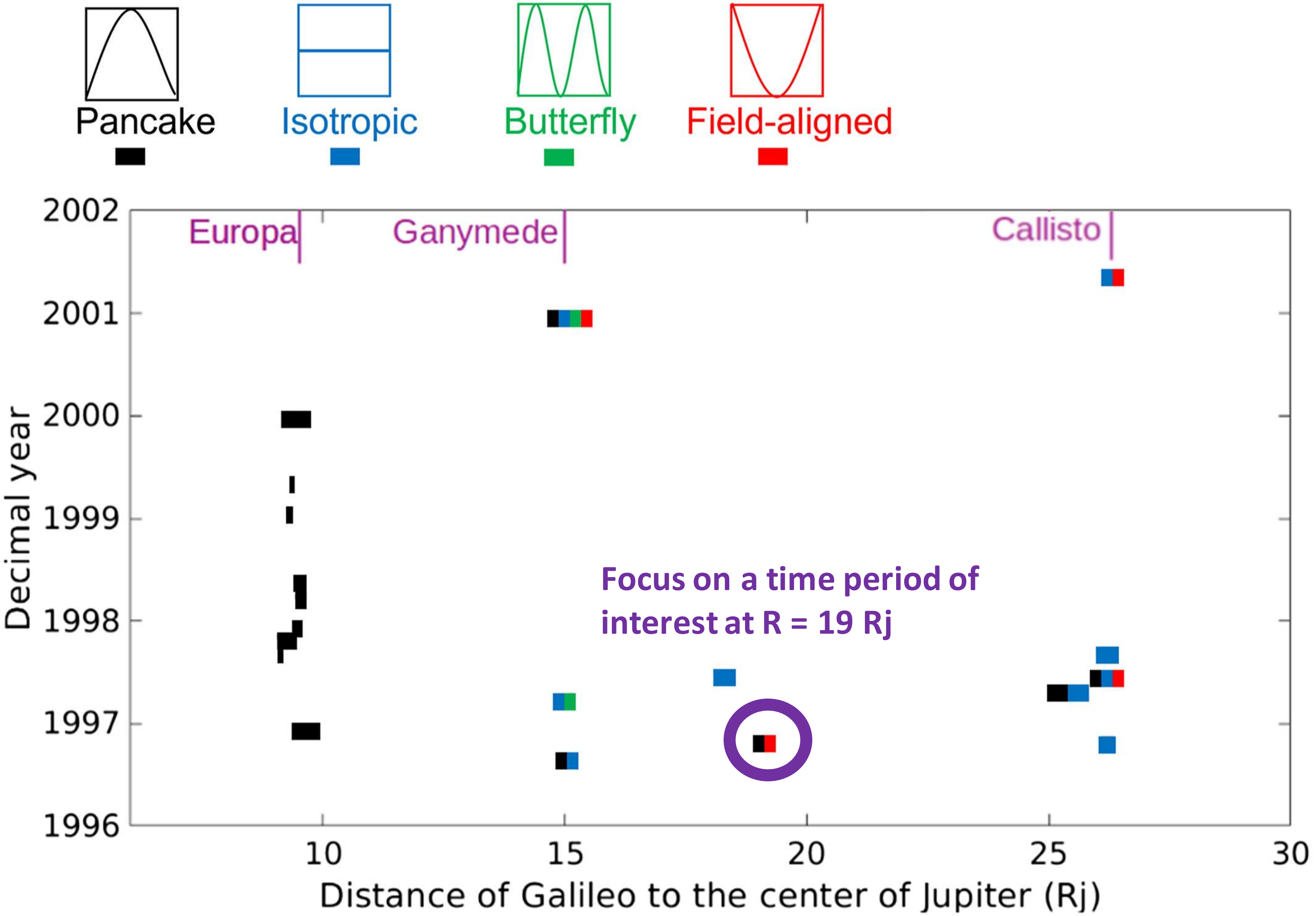
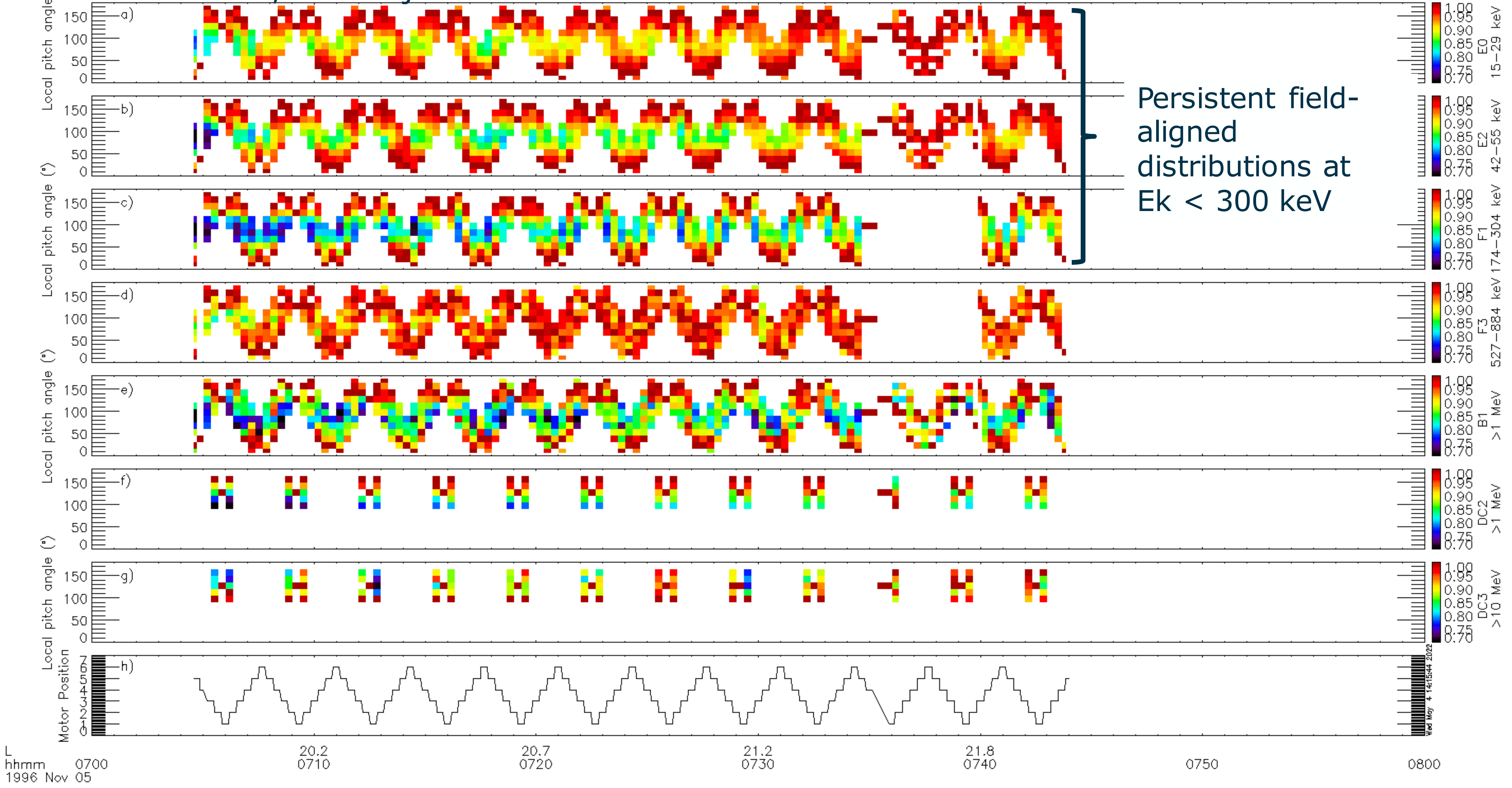


1996-310, R=18 Rj



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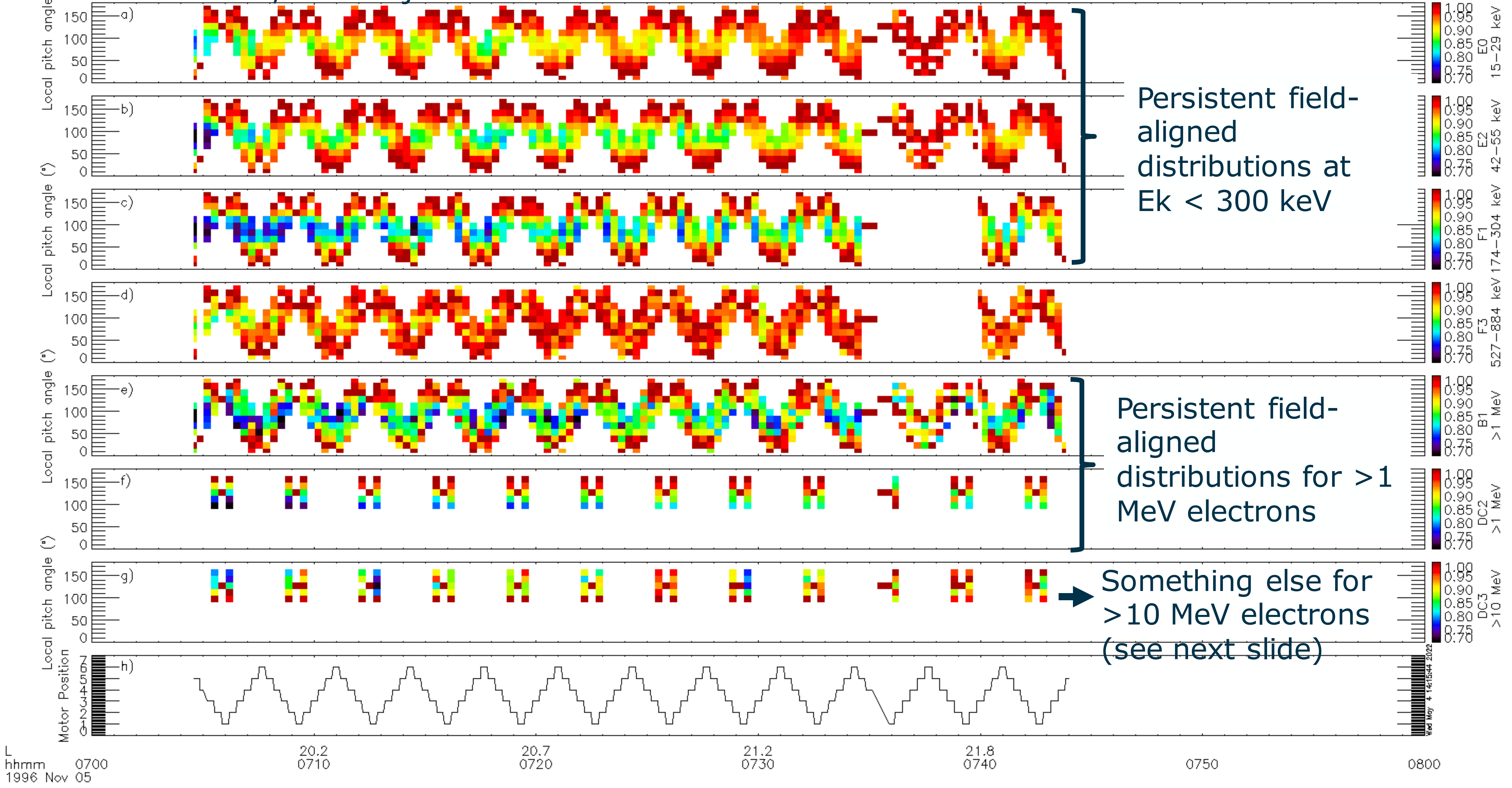
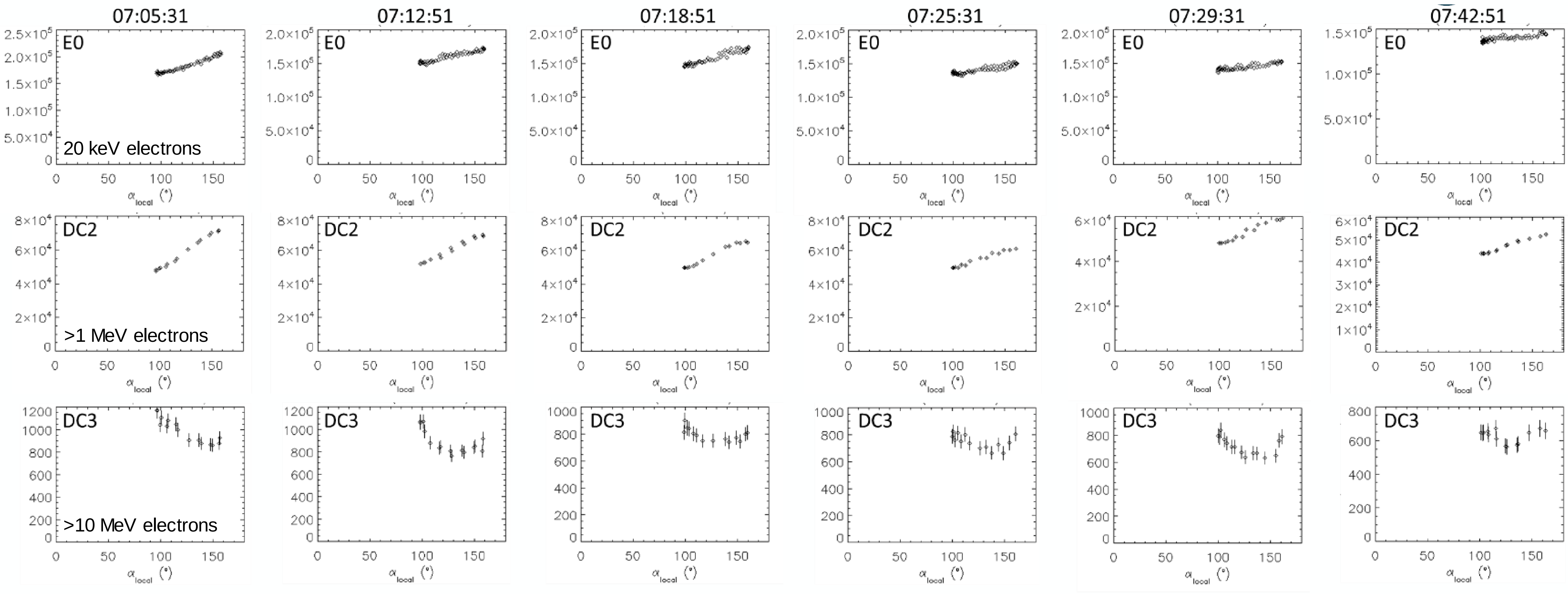


Results: Electron PADs observed at R=18 Rj in 1996-310



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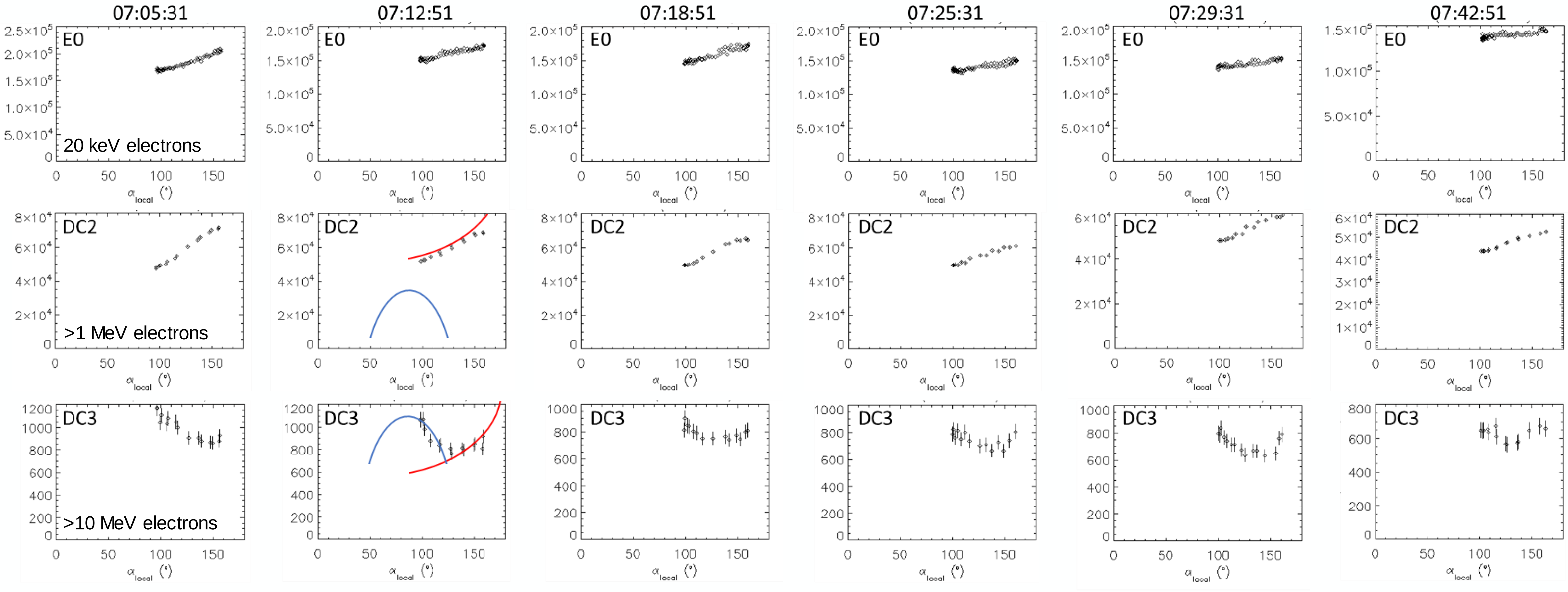


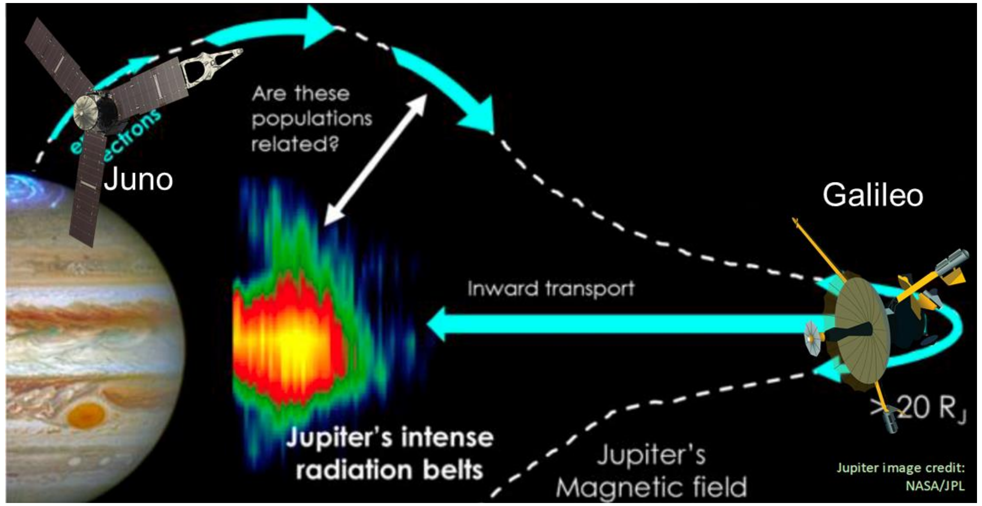
- For >1 MeV and >10 MeV electrons, we may have the superposition of:
  - A pancake (in blue)
  - A field-aligned distribution (in red)

Conclusions and future work

During its 8-year tour, Galileo collected 26 hours of >1 MeV electron anisotropy data.

1) Space plasma physics:

- The Jovian aurorae may be a significant source of trapped MeV electrons in the middle magnetosphere



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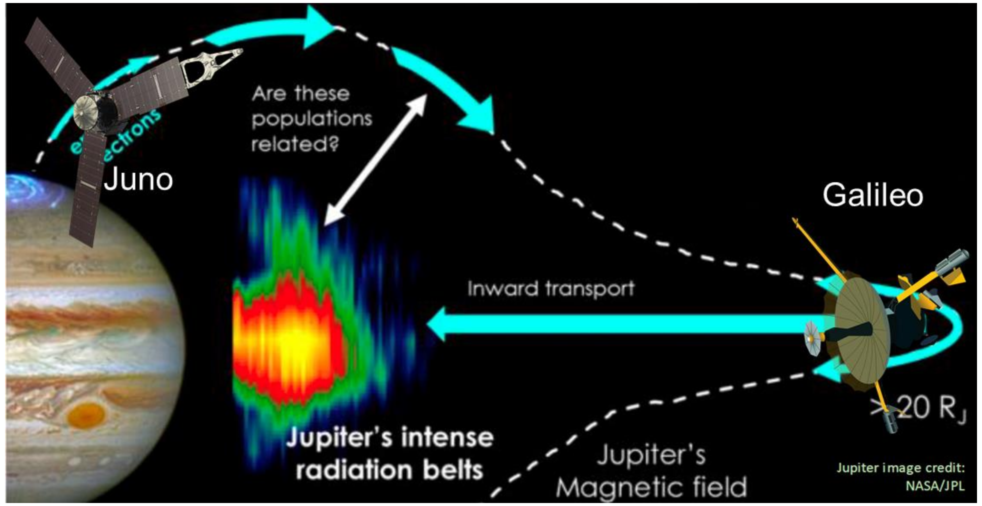
The Pitch Angle Distribution of >1 MeV electrons is now constrained. How does it change our understanding of moon surface weathering?

-> Collaborations with UC Berkeley and Georgia Tech



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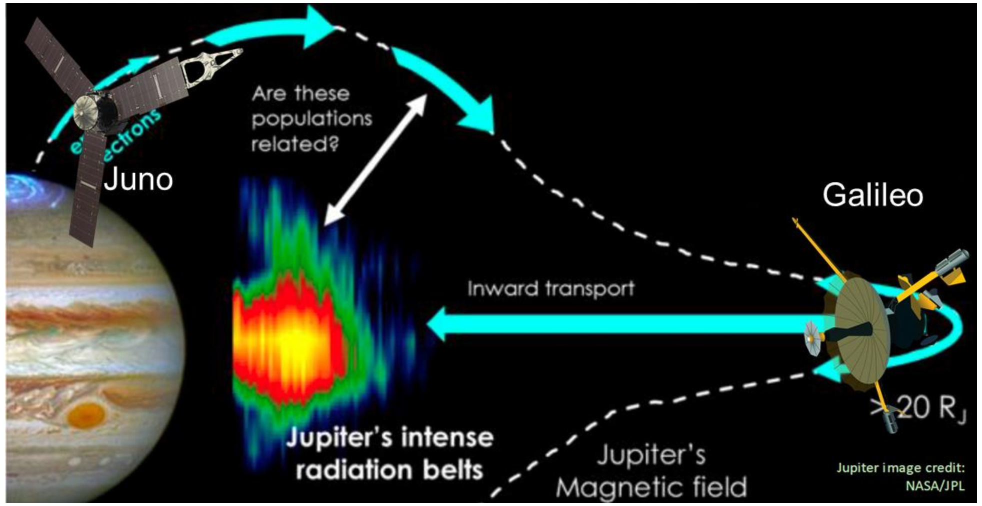

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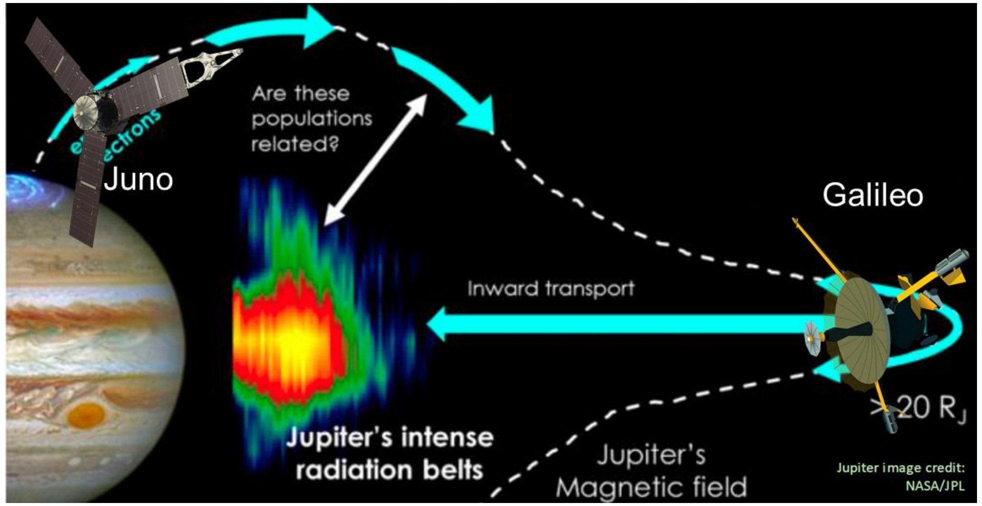

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JUICE-RADEM will indeed inform on the omnidirectional flux.

However, the Jovian radiation belts will remain largely unexplored and poorly understood…

- **The COMPASS mission proposal**

COMPASS: exploring the extremes of **Jupiter's radiation belts**

(**C**omprehensive **O**bservations of **M**agnetospheric **P**article **A**cceleration, **S**ources, and **S**inks)

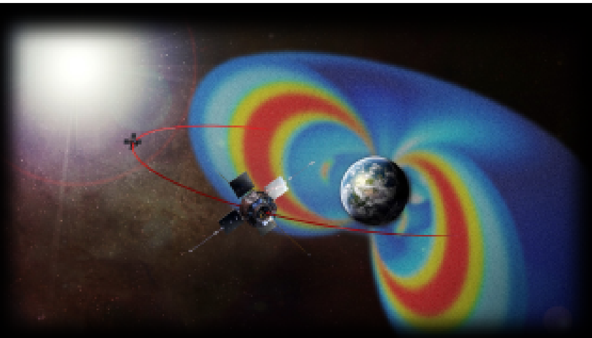
A Heliophysics **Mission Concept Study** for the American Heliophysics decadal survey

PI: George Clark, JHU/APL

Presented by Quentin Nénon, IRAP, on behalf of the COMPASS team

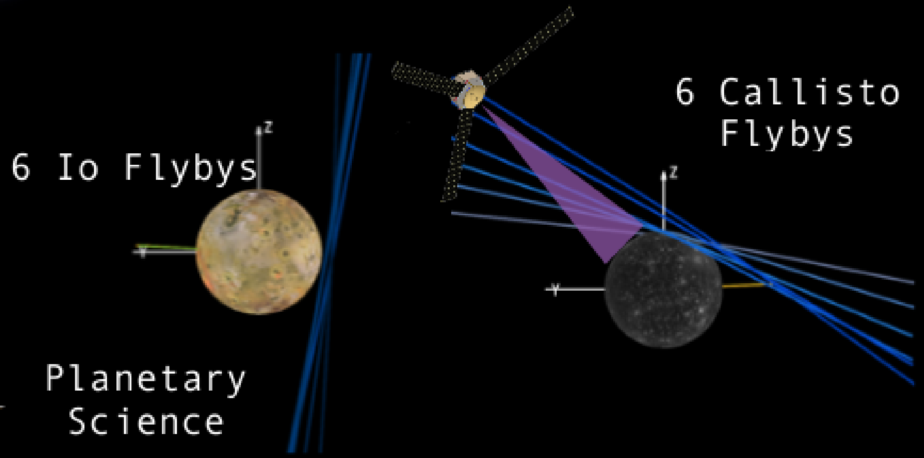
Cross-Disciplinary Science Approach

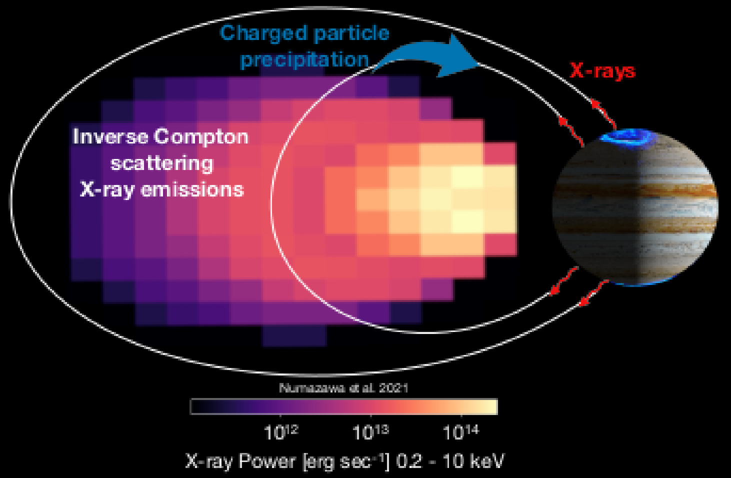
Jupiter's trapped radiation & X-ray emissions make it an ideal stepping stone for using fundamental plasma physics to bridge the gaps between planetary magnetospheres and astrophysical systems.



COMPASS will extend what Van Allen Probes has accomplished at Earth to Jupiter's extreme environment.

Heliophysics





Astrophysics

Planetary Science

COMPASS

COMPASS can probe elemental and chemically specific X-ray fluorescence lines with its X-ray imager.

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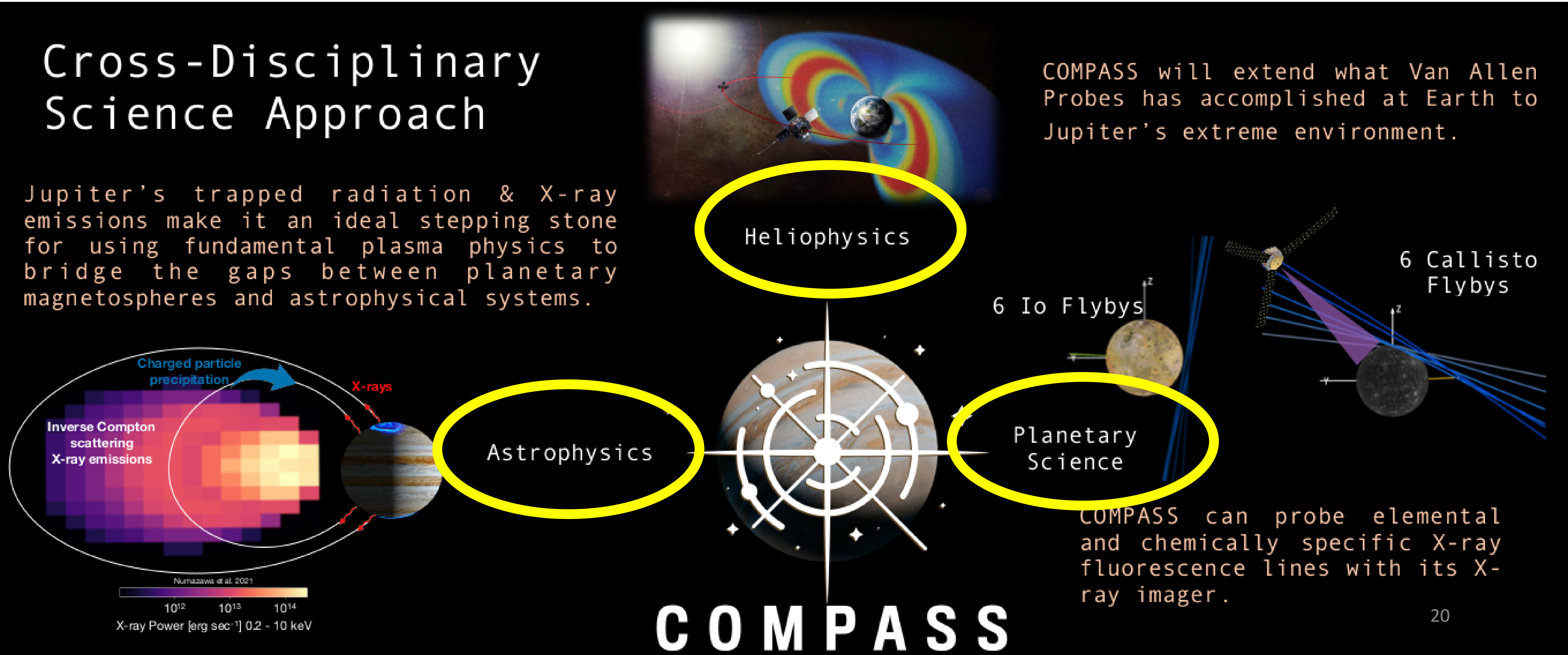

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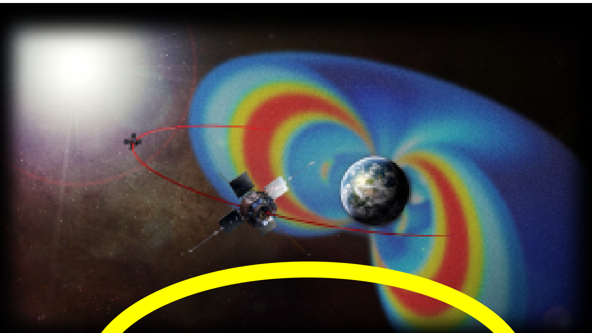

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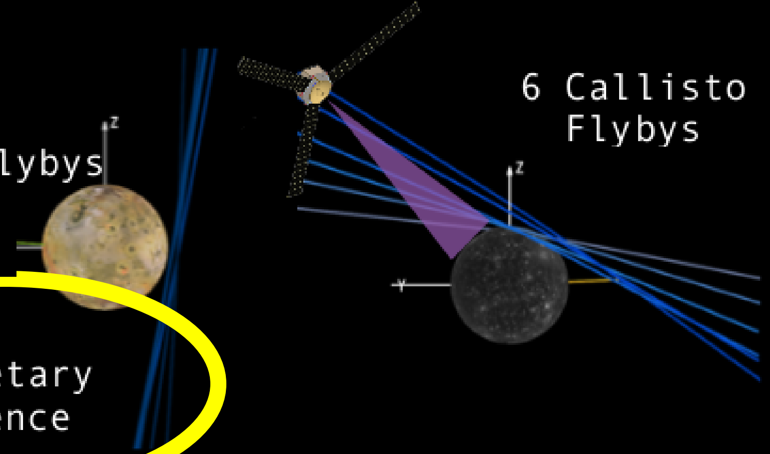
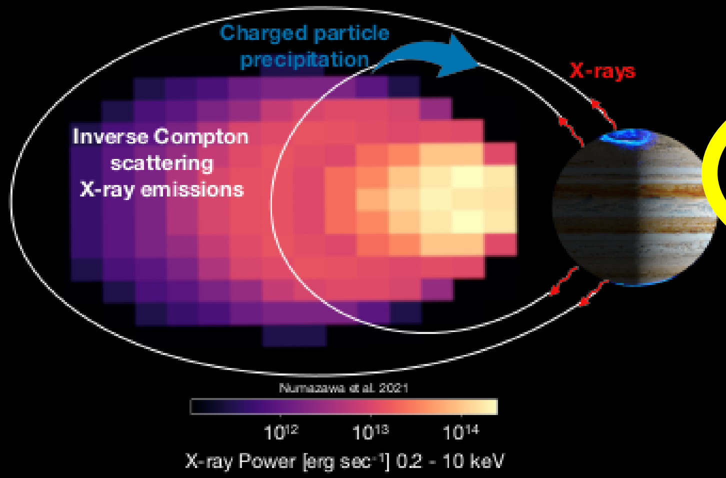


+ PLANETARY SPACE WEATHER



Astrophysics

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COMPASS can probe elemental and chemically specific X-ray fluorescence lines with its X-ray imager.

COMPASS

COMPASS: a single satellite that would explore the radiation belts of Jupiter

Science Goals

Origins

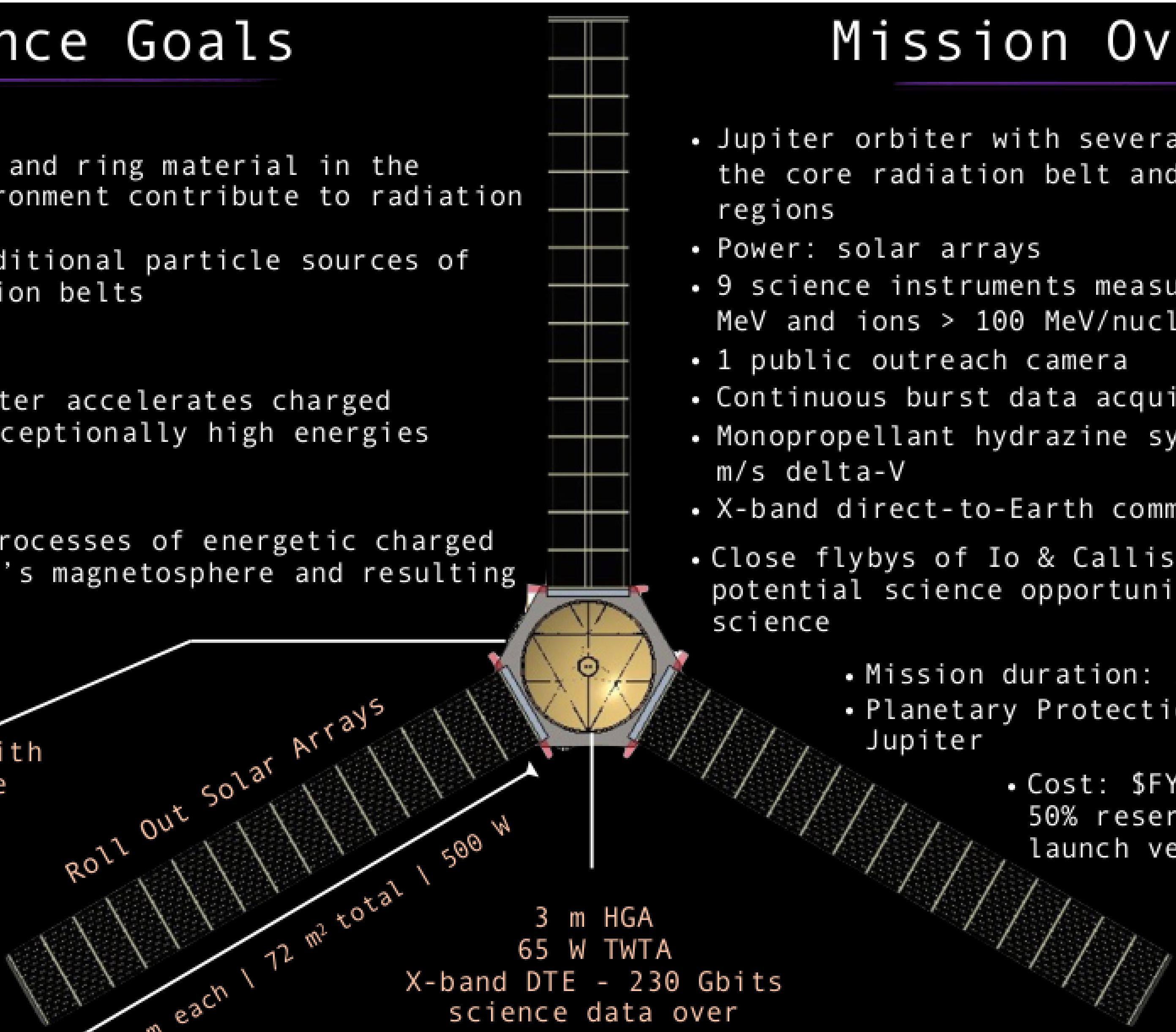
1. Discover how moon and ring material in the Jovian space environment contribute to radiation belts
2. Understand the additional particle sources of the Jovian radiation belts

Acceleration

3. Discover how Jupiter accelerates charged particles to such exceptionally high energies

Loss

4. Reveal the loss processes of energetic charged particles in Jupiter's magnetosphere and resulting X-ray emissions



Mission Overview

- Jupiter orbiter with several deep dives into the core radiation belt and synchrotron regions
- Power: solar arrays
- 9 science instruments measuring electrons > 50 MeV and ions > 100 MeV/nucleon
- 1 public outreach camera
- Continuous burst data acquisition
- Monopropellant hydrazine system provides 1,500 m/s delta-V
- X-band direct-to-Earth communications
- Close flybys of Io & Callisto enable potential science opportunities of moon science
- Mission duration: 514 days, 15 orbits
- Planetary Protection: Impact with Jupiter
- Cost: $FY22 1.2B—Phases A-F, 50% reserves, including launch vehicle

COMPASS: Payload tailored to radiation belts

Science Payload

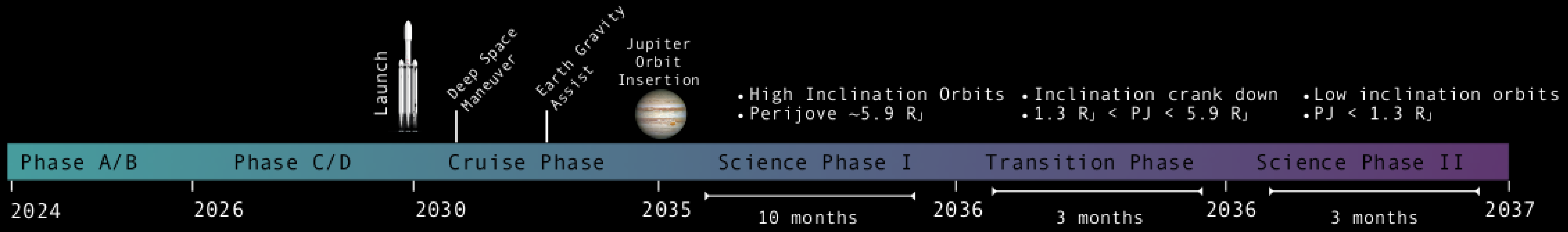
Instruments		Mass* (MEV)	Power
TPD:	Thermal Plasma Detector	7.7 kg x2	6 W x2
SPD:	Suprathermal Particle Detector	19.0 kg	11.0 W
EPD:	Energetic Particle Detector	10.3 kg	3.6 W
RPD:	Relativistic Particle Detector	17.8 kg	7.1 W
UPD:	Ultra-relativistic Particle Detector	13.3 kg	16.5 W
FGM:	Fluxgate Magnetometer	1.8 kg x2	4.8 W x2
SCM:	Search Coil Magnetometer	7.9 kg	1.2 W
EFW:	Electric Field Waves	14.6 kg	17.7 W
XRI:	X-Ray Imager	16.5 kg	6.9 W
EPOC:	Education & Public Outreach Camera	6.5 kg	2.7 W

* *includes shielding mass*

Planetary space weather:

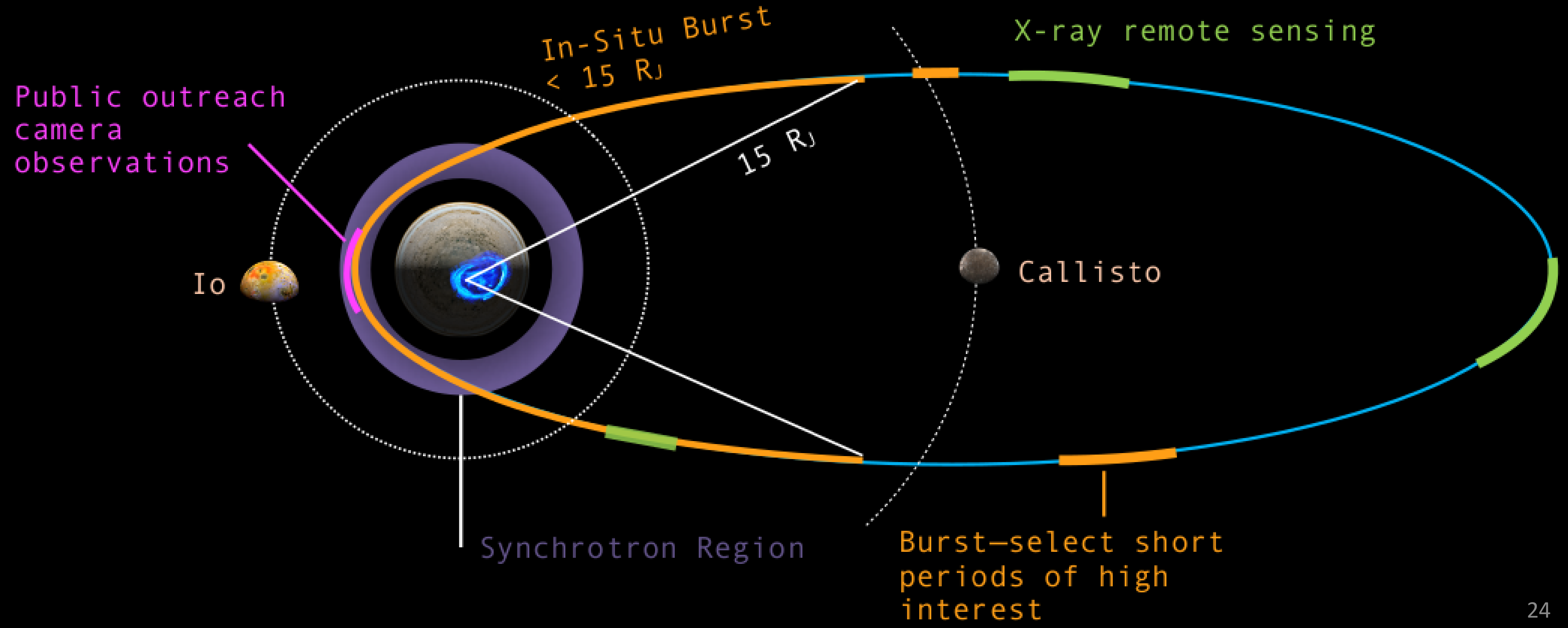
- How can we constrain the interplanetary conditions upstream of the Jovian magnetosphere? (solar wind propagation? ENA observations?)
- What is the influence of interplanetary conditions on the Jovian radiation belts?

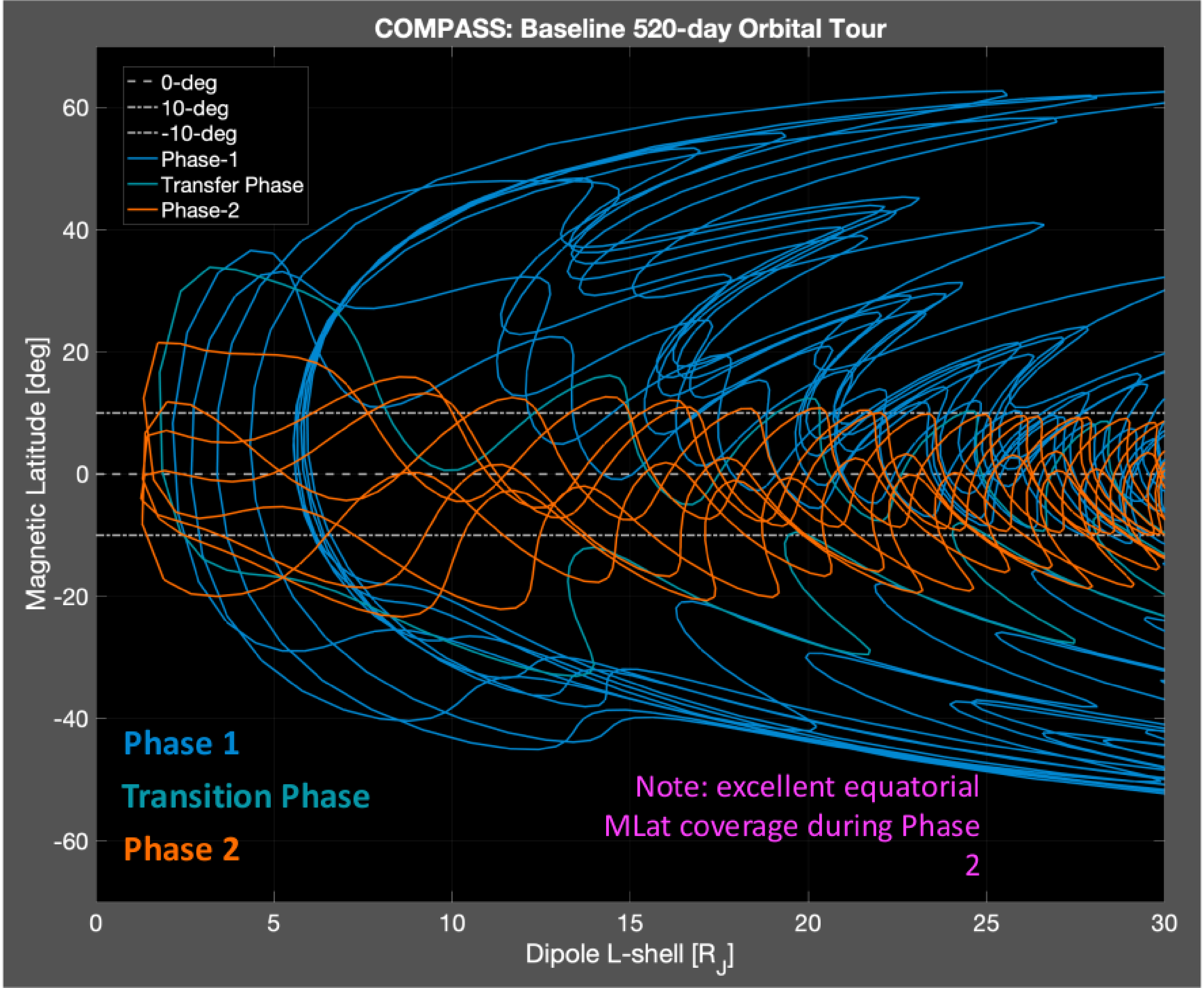
Mission Timeline*



** representative timeline: mission design is extremely flexible with multiple launch windows*

Concept of Operations




COMPASS: Baseline 520-day Orbital Tour
0-deg
10-deg
-10-deg
Phase-1
Transfer Phase
Phase-2
Magnetic Latitude [deg]
60
40
20
0
-20
-40
-60
0
5
10
15
20
25
30
Dipole L-shell [R_J]
Phase 1
Transition Phase
Phase 2
Note: excellent equatorial MLat coverage during Phase 2

The COMPASS team

European partners

Concept Study Team

Name	Role	Affiliation
George Clark	Principal Investigator	Johns Hopkins Applied Physics Laboratory (APL)
Jim Kinnison	Study Design Lead	APL
Dan Kelly	Study Design Lead	APL
Peter Kollmann	Topic Lead: Acceleration	APL
Wen Li		Boston University
Allison Jaynes	Topic Lead: Origins	University of Iowa
Lauren Blum	Topic Lead: Loss	University of Colorado Boulder
Robert Marshall		University of Colorado Boulder
Drew Turner	Project Science	APL
Ian Cohen		APL
Sasha Ukhorskiy	Science Mentorship	APL
Barry Mauk		APL
Elias Roussos	Jupiter & Earth Radiation Belt Expertise	Max Planck Institute for Solar System Research
Quentin Nénon		Research Institute in Astrophysics and Planetology
Sasha Drozdov		University of California Los Angeles
Xinlin Li		University of Colorado Boulder
Emma Woodfield	X-ray Science & Astrophysics Expertise	British Antarctic Survey
Will Dunn		University of College London
Grant Berland		University of Colorado Boulder
Ralph Kraft		Harvard University
Peter Williams		Harvard University
Todd Smith	Theory & Modeling Expertise	APL
Kareem Sorathia		APL
Anthony Sciola		APL
George Hospodarsky	Particle & Field Instrumentation Leads	University of Iowa
Xin Wu		University of Geneva
Paul O'Brian		The Aerospace Corporation
Mark Looper		The Aerospace Corporation
Angelica Sicard	Salammbô Simulation Support	The French Aerospace Lab (ONERA)
Andy Santo	Project Management	APL
Meagan Leary	Design Study Team	APL
Amanda Haapala	Design Study Team	APL
Fazle Siddique	Design Study Team	APL
Michelle Donegan	Design Study Team	APL
Ben Clare	Design Study Team	APL
Derek Emmell	Design Study Team	APL
Kim Slack	Design Study Team	APL
John Wirzburger	Design Study Team	APL
Daniel Sepulveda	Design Study Team	APL