Jupiter Missions as Probes of Dark Matter

JiJi Fan

Brown University

TDLI/SJTU DM+nu Forum, Nov 8, 2022

Jupiter missions as probes of dark matter

Lingfeng Li
(postdoc at Brown)

arXiv: 2207.13709 [hep-ph], to appear in JHEP

Outline

— Introduction

- Why Jupiter (木星) ?
- GeV-scale dark matter (DM)

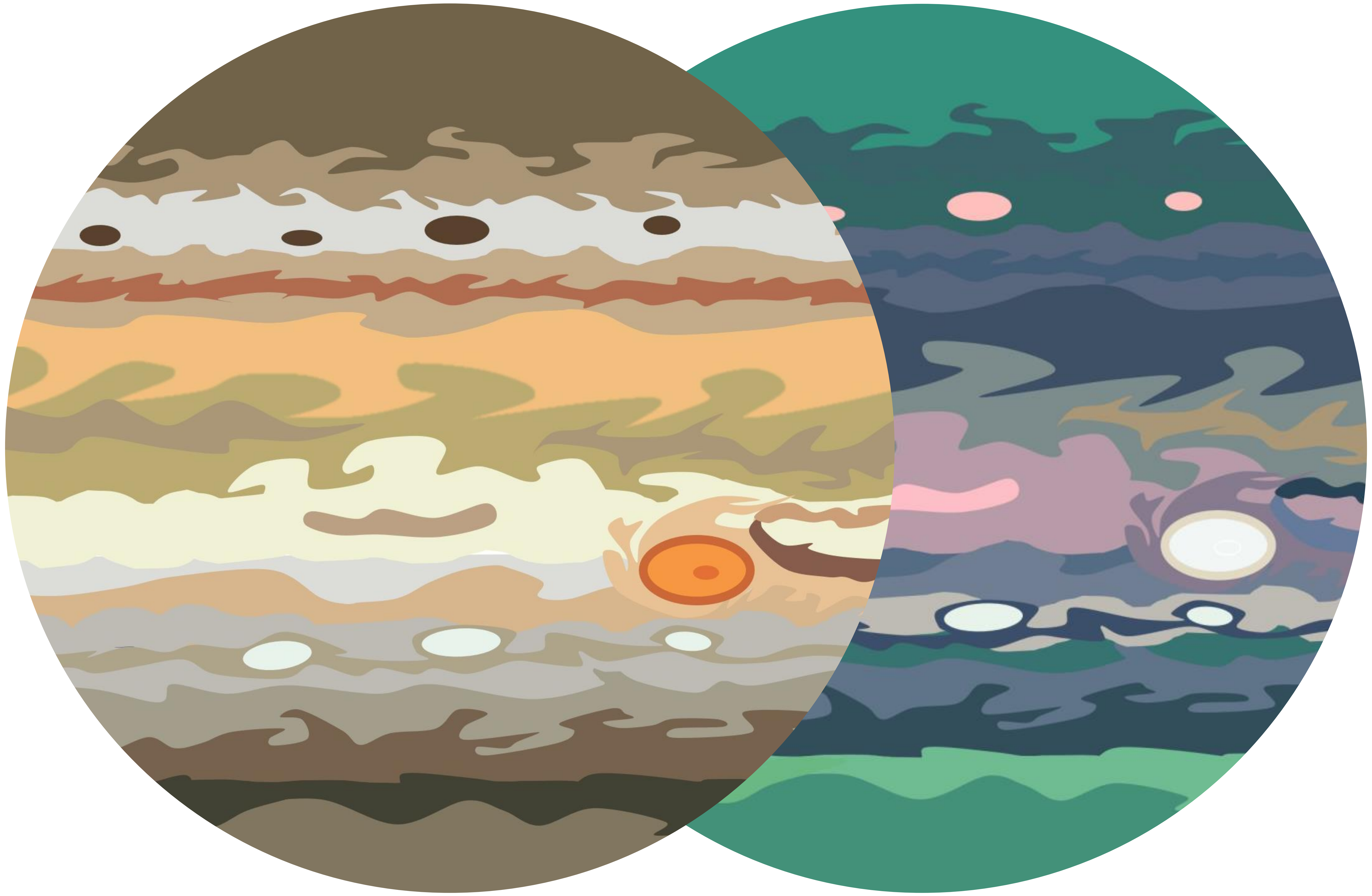
— Scenario

- DM captured in Jupiter
- DM annihilation into $e^{-}e^{+}$

— Motions of $e^{-}(e^{+})$ in the Jovian magnetosphere

— Results

— Summary



Hubble space telescope (visible)

James Webb space telescope (IR)

Why Jupiter?

— Most massive planet in the solar system: a big detector;

— "Clean" background: not as active as a star, e.g., the Sun;

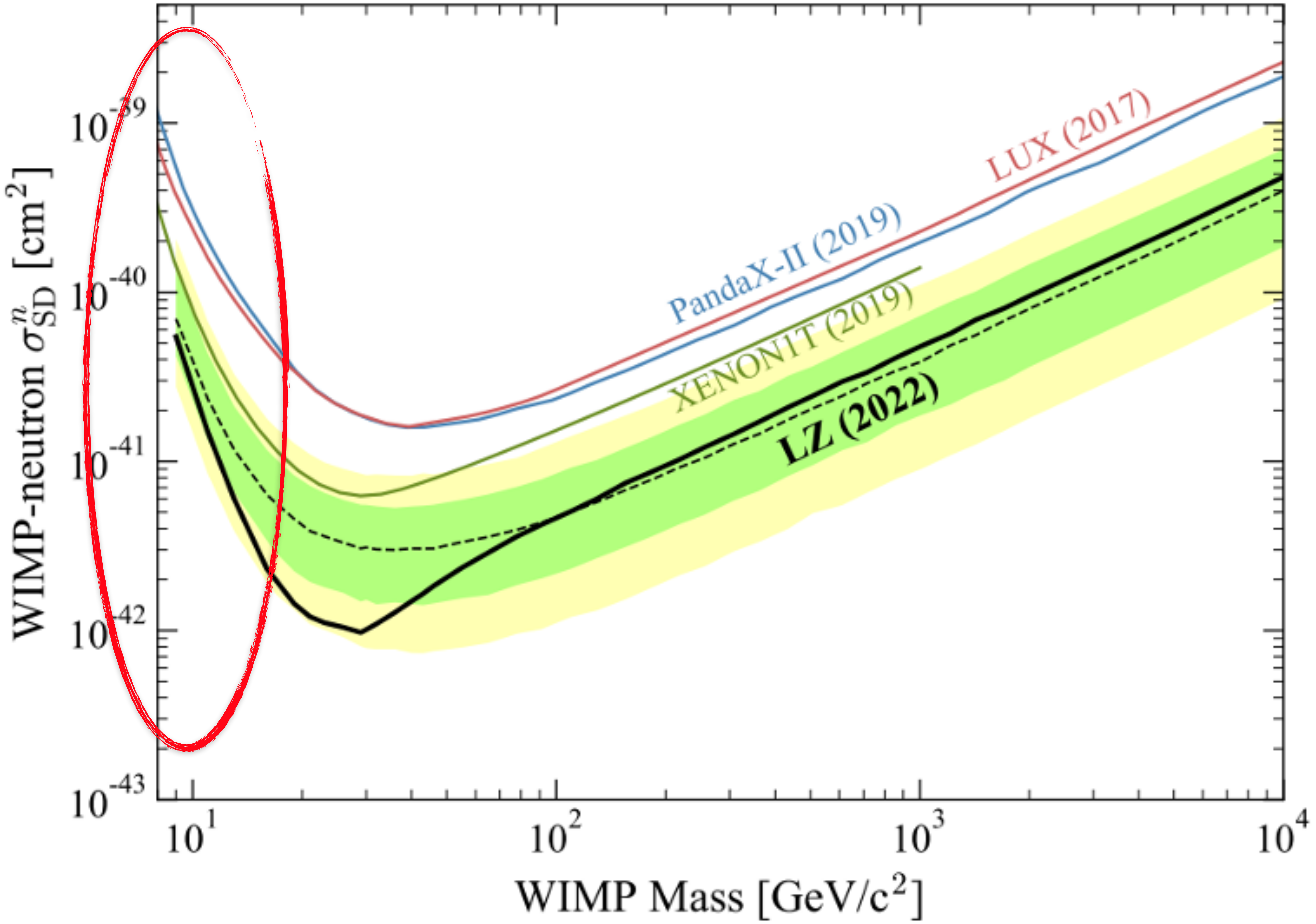
— Relatively close to us: easier for both *in situ* (at Jupiter) and *ex situ* (away from Jupiter, i.e., close to the Earth) measurements.

A lot of data for planetary science


Jupiter. The color spectra are sampled from images
taken by the nine spacecraft that visited the gas giant
since 1973, as well as the Hubble Space Telescope.
TELESCOPE OBSERVATION
FLYBY
ORBIT
1610 | Galileo Galilei | Telescope
1973 | Pioneer 10 | Flyby
1974 | Pioneer 11 | Flyby
1979 | Voyager 1 | Flyby (gravity assist)
1979 | Voyager 2 | Flyby (gravity assist)
1992 | Ulysses | Flyby (gravity assist)
NO CAMERA
1995 to 2003 | Galileo | Orbit
2000 | Cassini-Huygens | Flyby (gravity assist)
2007 | New Horizons | Flyby
2015 | Hubble Space Telescope | Telescope observation
2016 | Juno Mission | Orbit
COMING SOON
till 2025
Any other use?
Dark matter?

GeV-scale dark matter

Lots of efforts to search for GeV and sub-GeV scale dark matter



Dark mediator

Dark sector

Visible sector

dark mediator:

e.g., dark photon

γ_D ***through*** $\epsilon F F_D$.

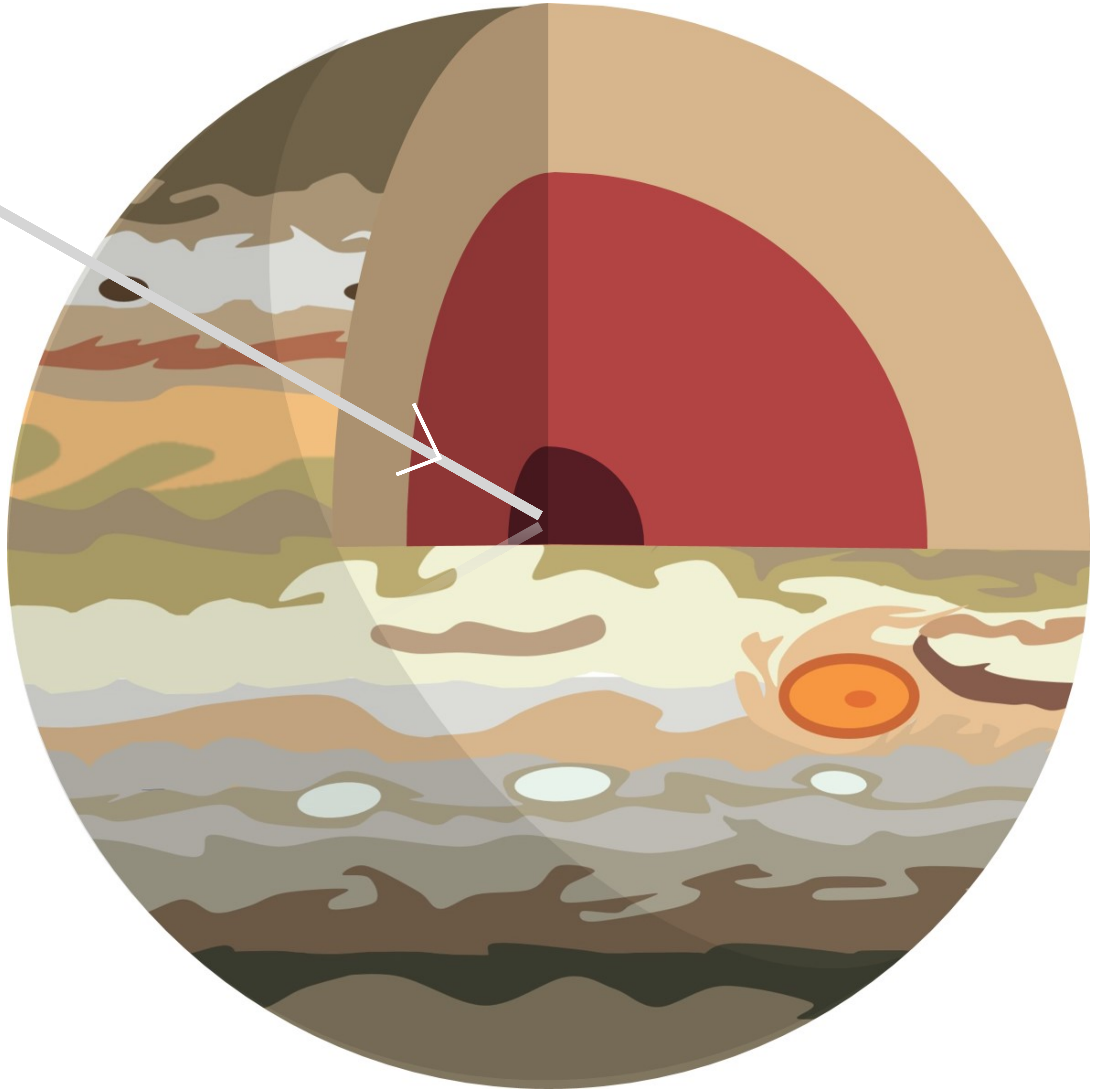
(Kobazarev et.al 1966; Okun 1982; Galison eta.al 1984; Holdom 1986)

Weakly-coupled

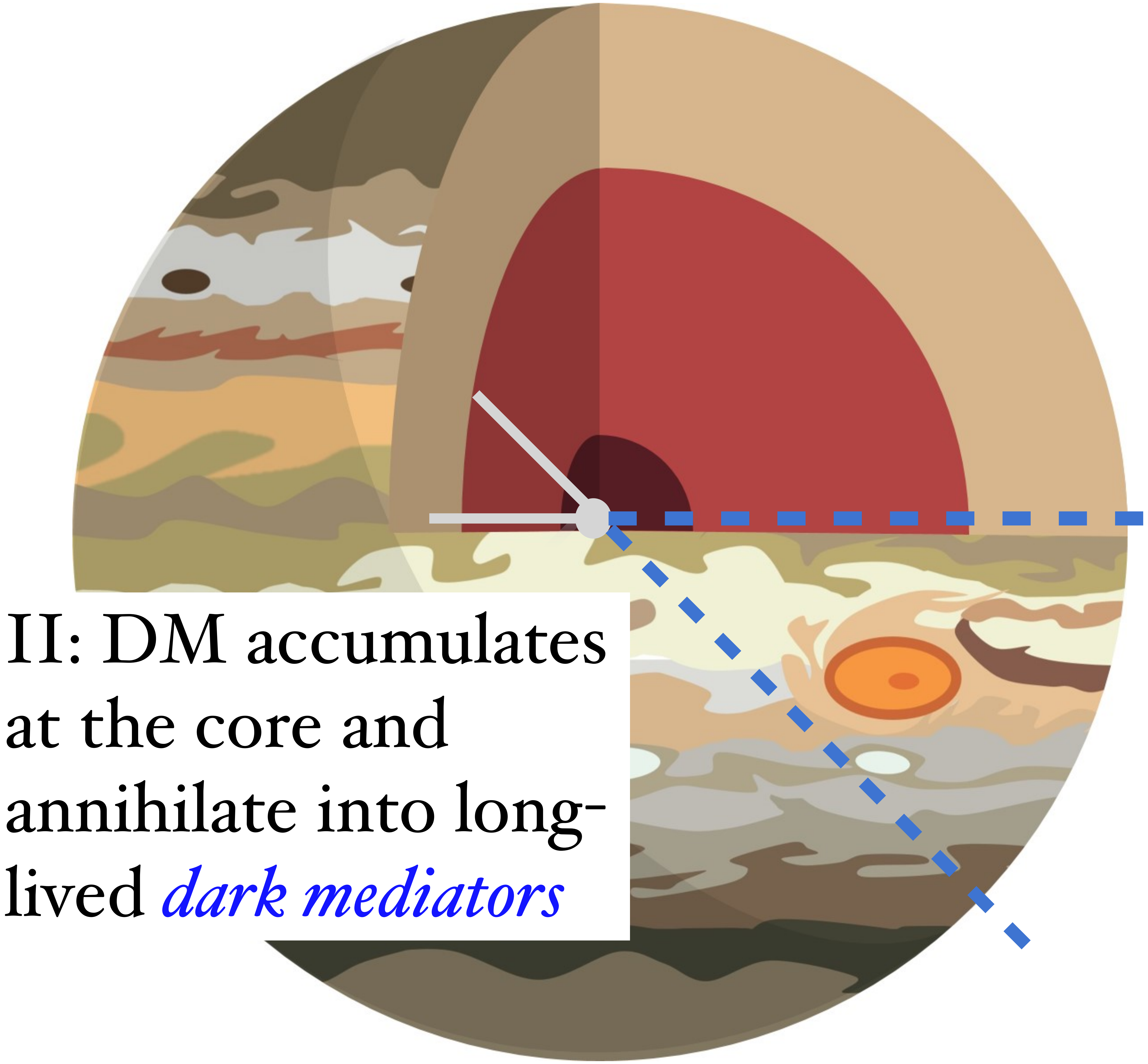
$\Rightarrow$ ***long-lived***

Scenario

I: DM captured by the gravitational potential well after elastic scattering with Jovian matter

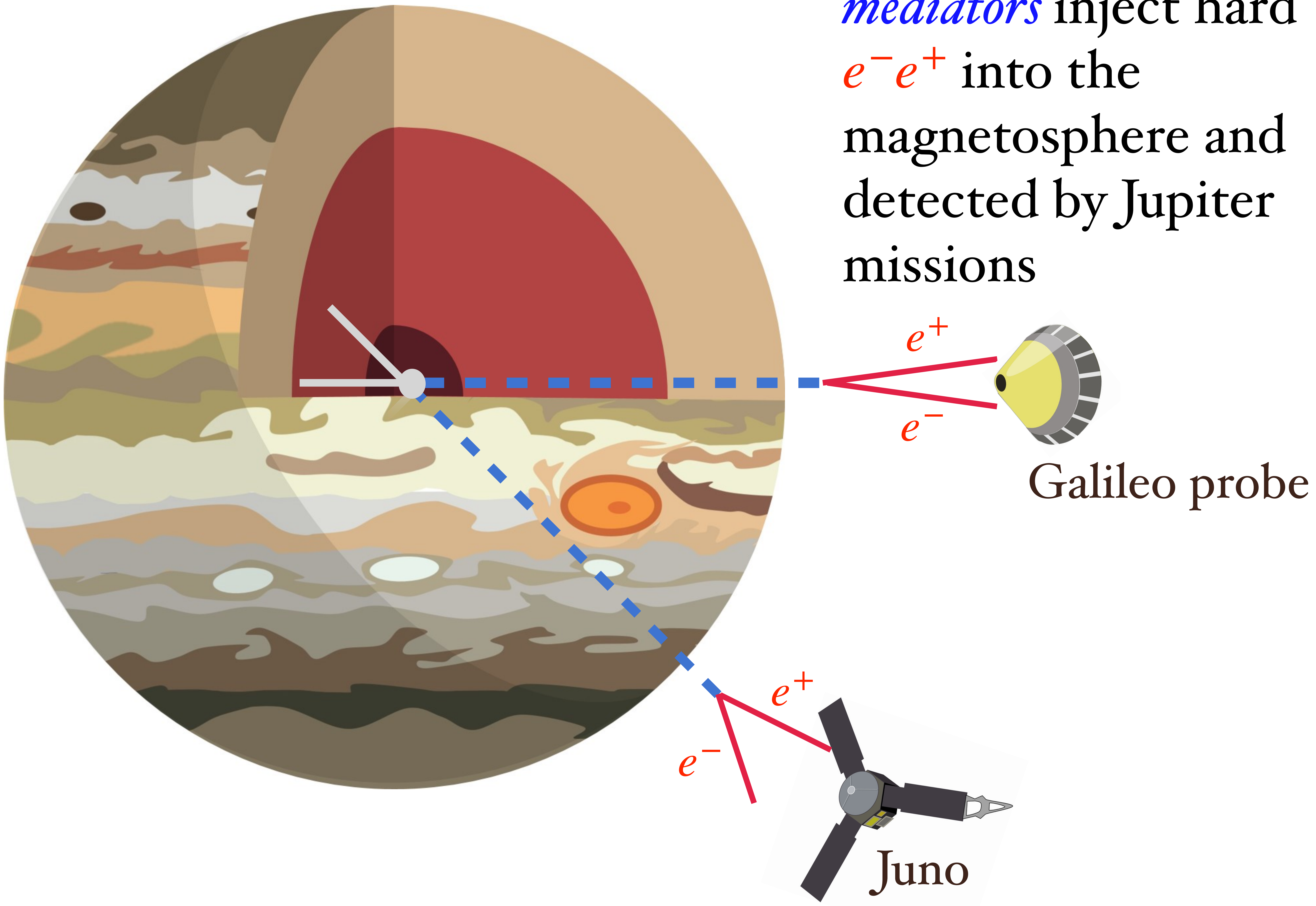


Scenario


II: DM accumulates at the core and annihilate into long-lived *dark mediators*

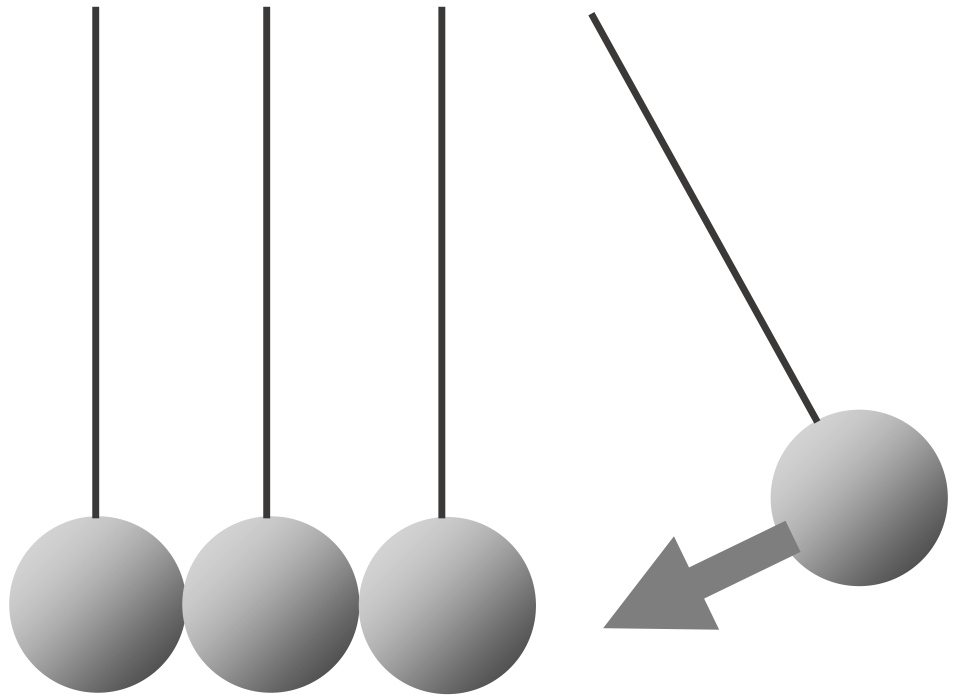
Scenario

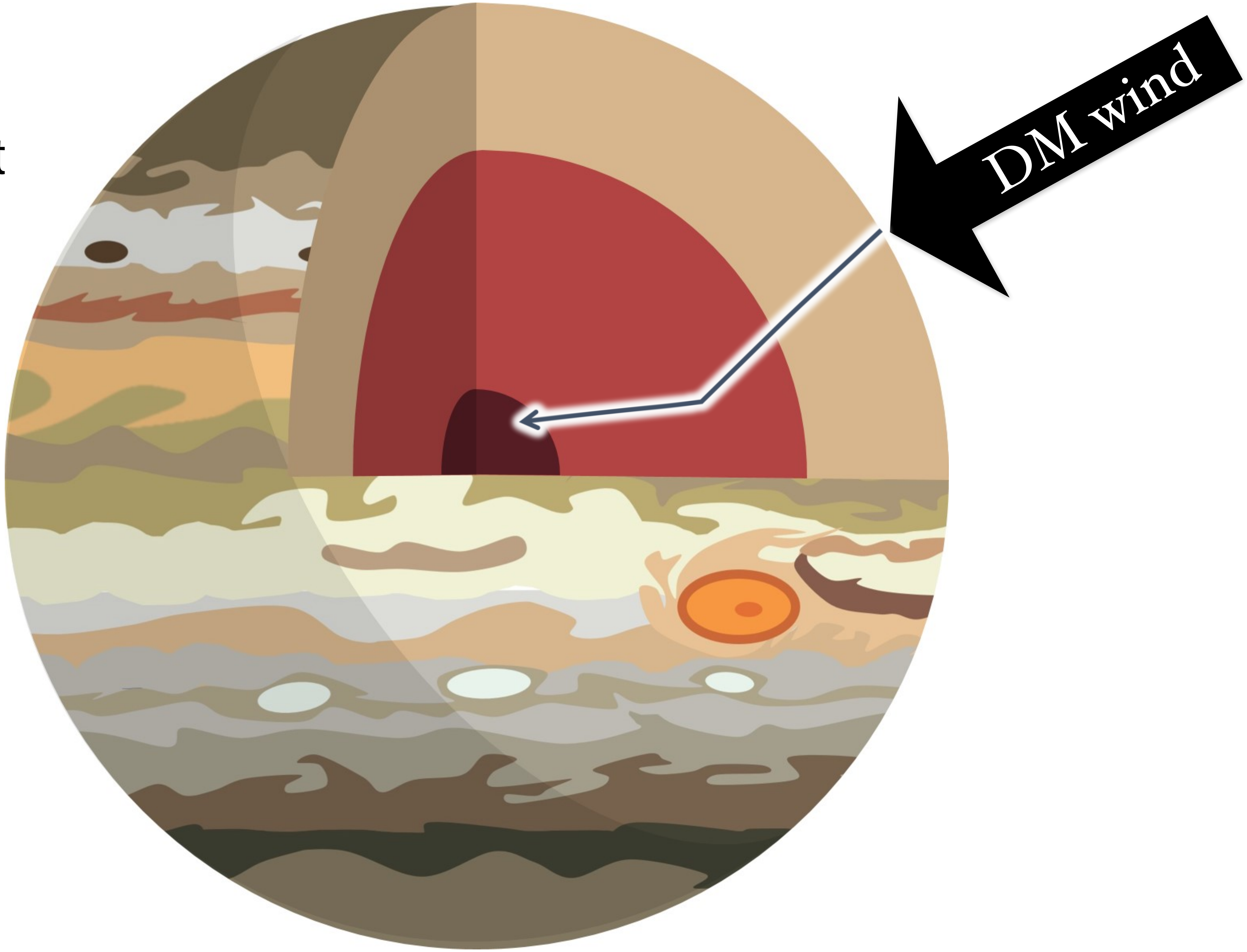
III: long-lived *dark mediators* inject hard e^-e^+ into the magnetosphere and detected by Jupiter missions



DM capture

DM transfers energy to nucleons by scattering and slows down, most efficient when $m_\chi \sim 1\text{GeV}$ $\sim m_N$





DM capture

Gould 1987, 1988, 1990

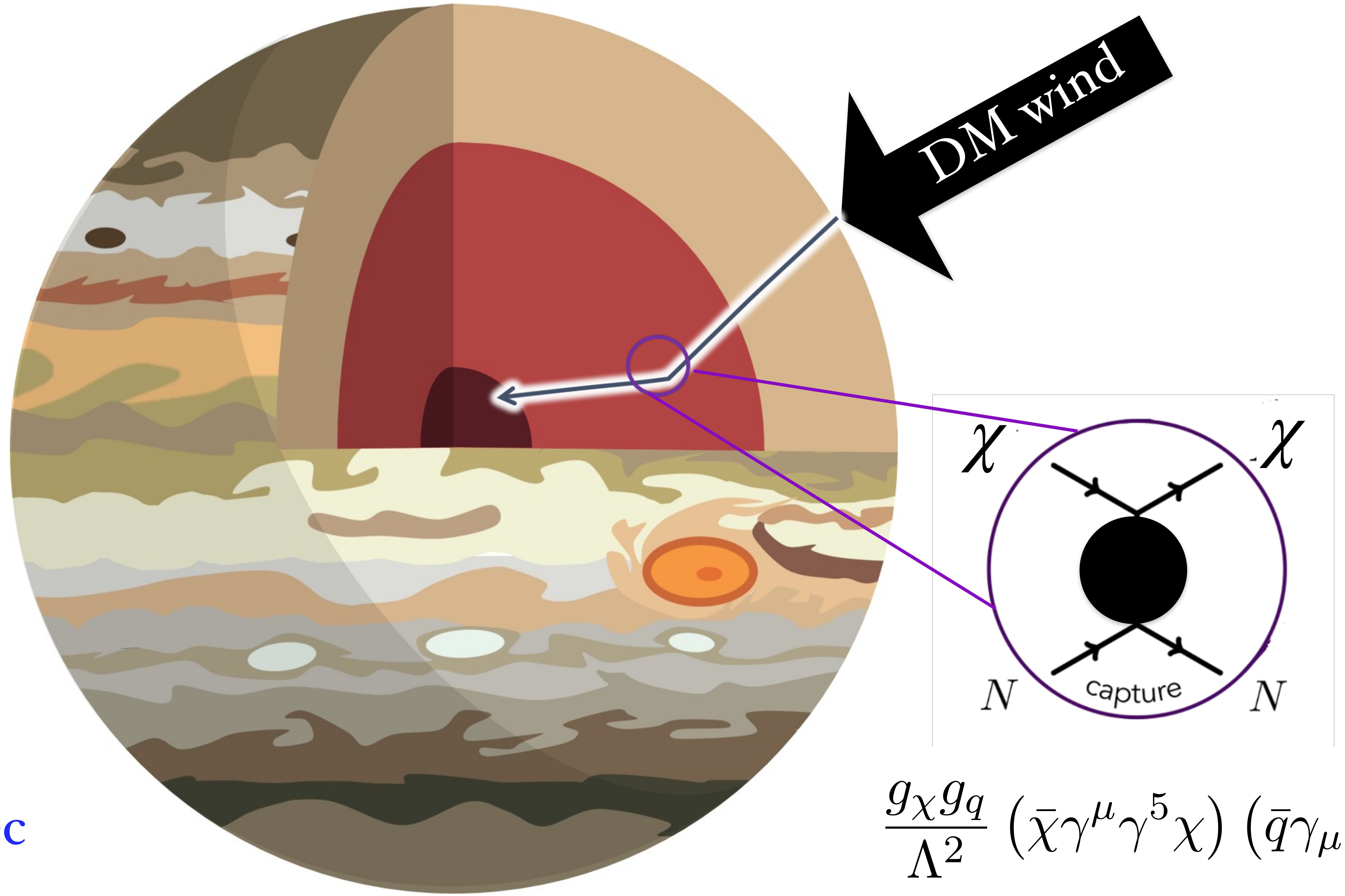
Captured when DM velocity drops below the escape velocity (~60 km/s at surface).

Single scattering (optically thin)

DM-nucleon scattering xsec

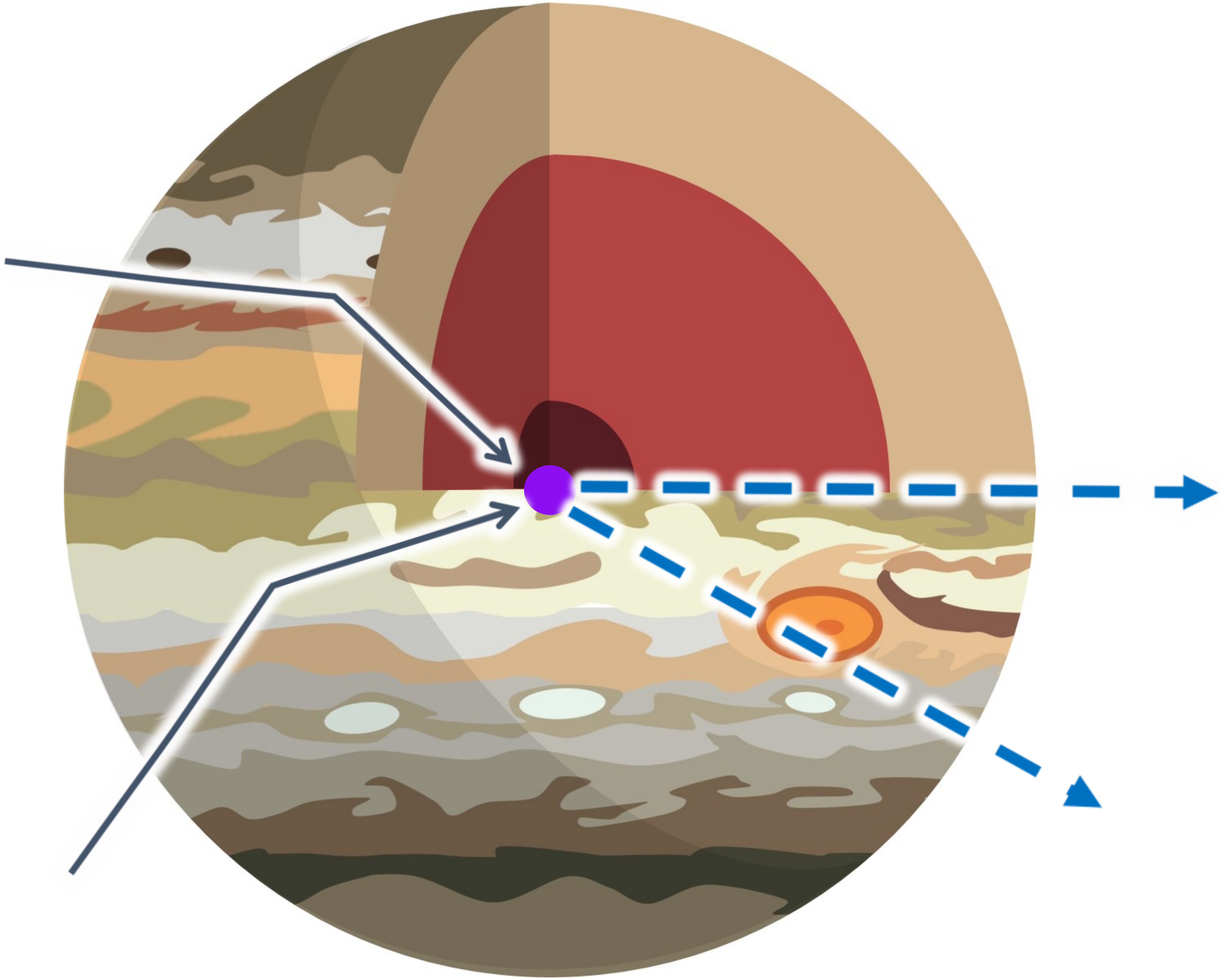
$$\tau_J \propto \frac{\sigma_{\chi n}}{\sigma_{\rm sat}} \ll 1$$

geometric saturation xsec $\sim 10^{-34}\,\mathrm{cm}^2$



$$\frac{g_\chi g_q}{\Lambda^2}\left(\bar{\chi}\gamma^\mu\gamma^5\chi\right)\left(\bar{q}\gamma_\mu\gamma^5 q\right)$$

DM annihilation



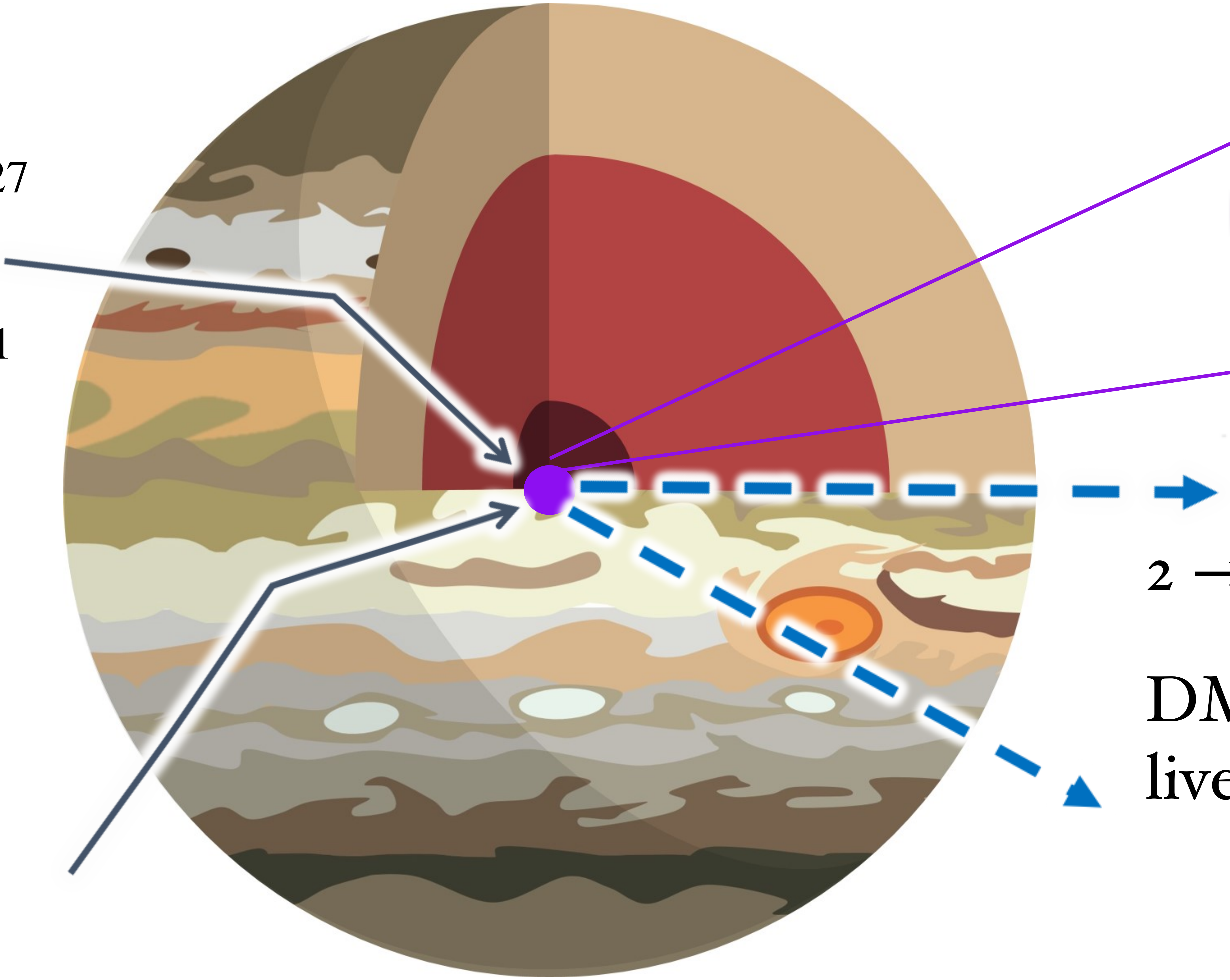
DM annihilation

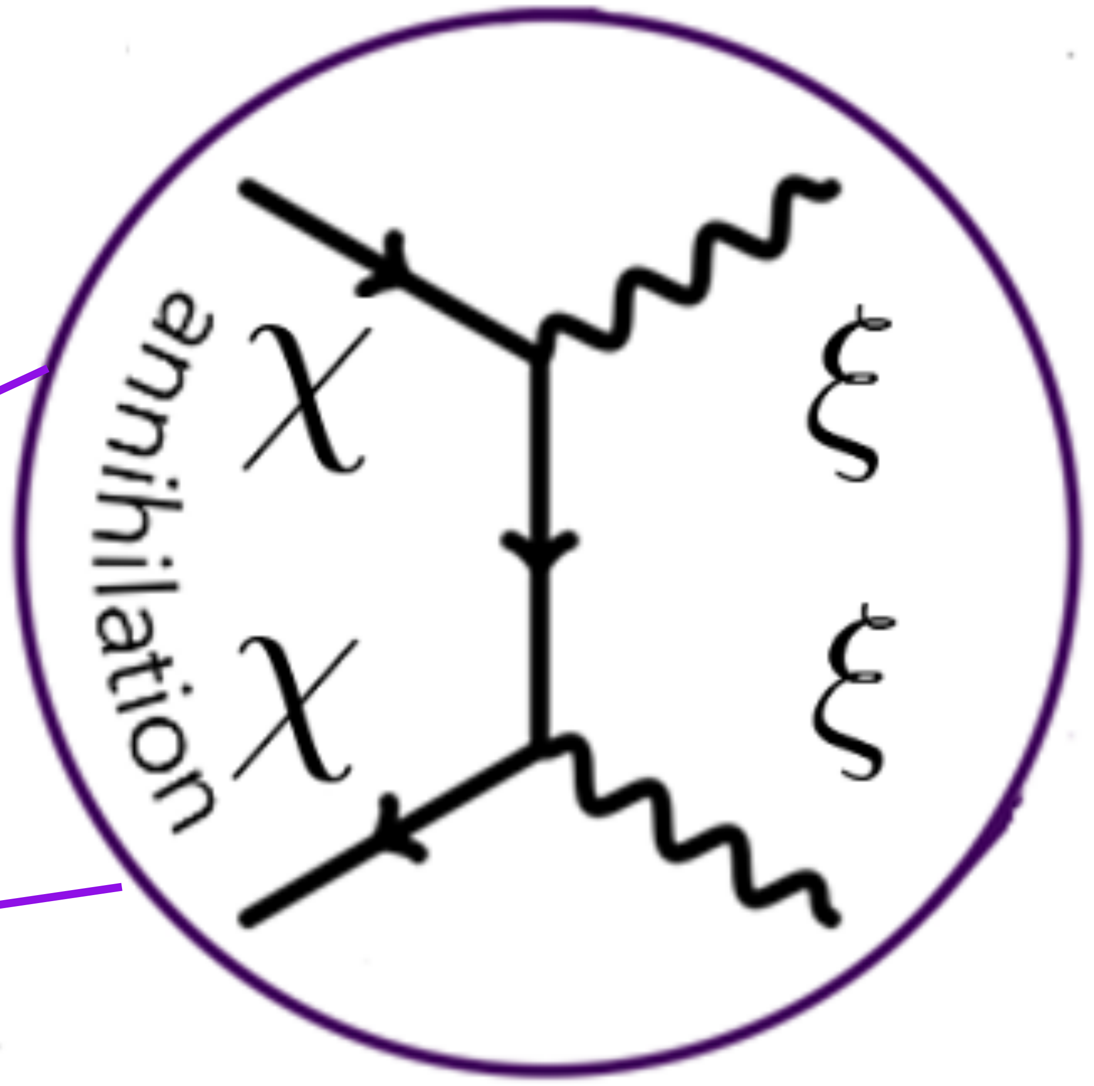
CMB bound:

$\langle \sigma_{ann} v \rangle \lesssim 5 \times 10^{-27}$

$\left(\frac{m_\chi}{\text{GeV}} \right) \text{cm}^3 \text{ s}^{-1}$

Leane et.al 2018

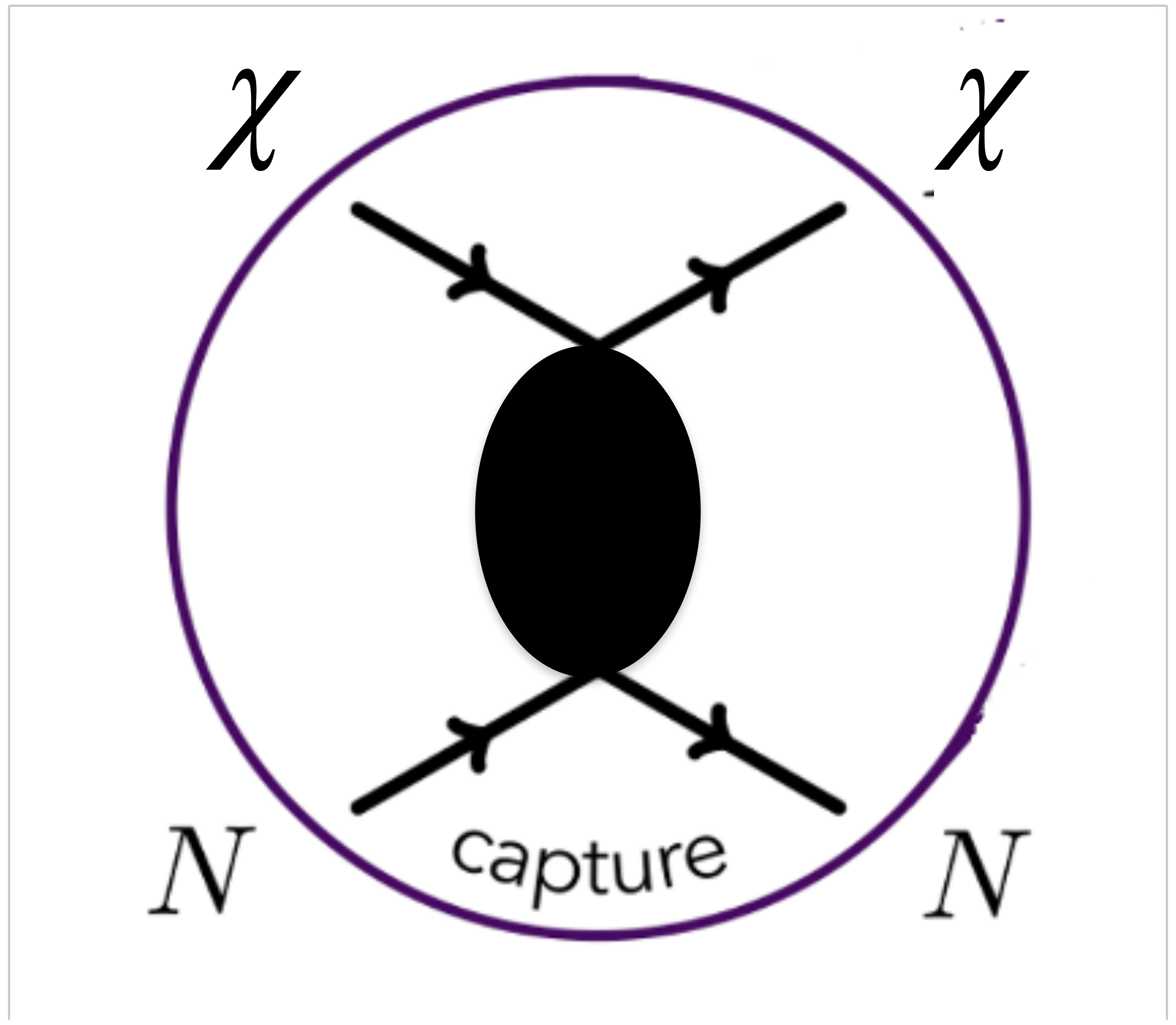




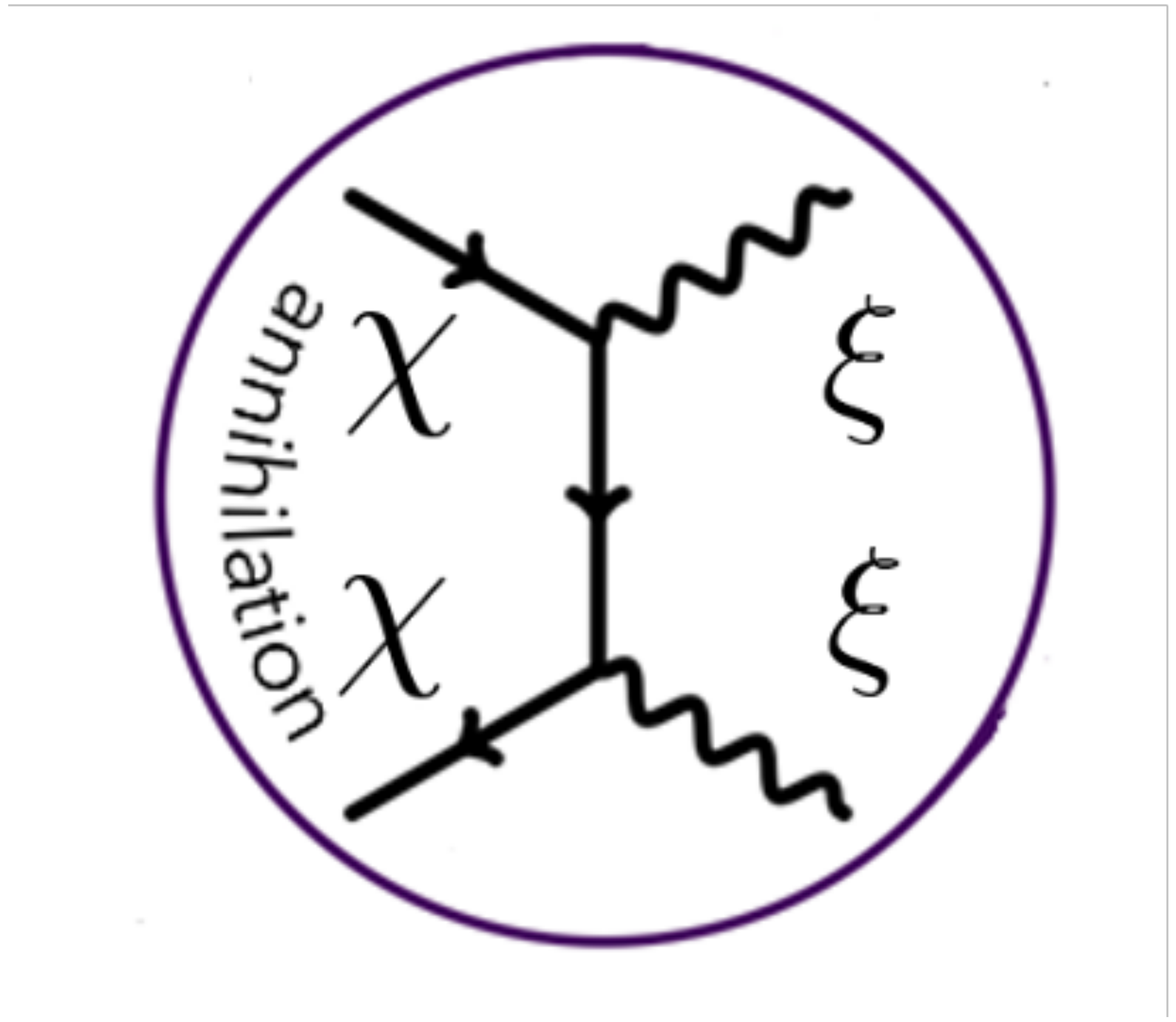
2 →2 annihilation:

DM DM → 2 long-lived *dark mediators*

DM capture



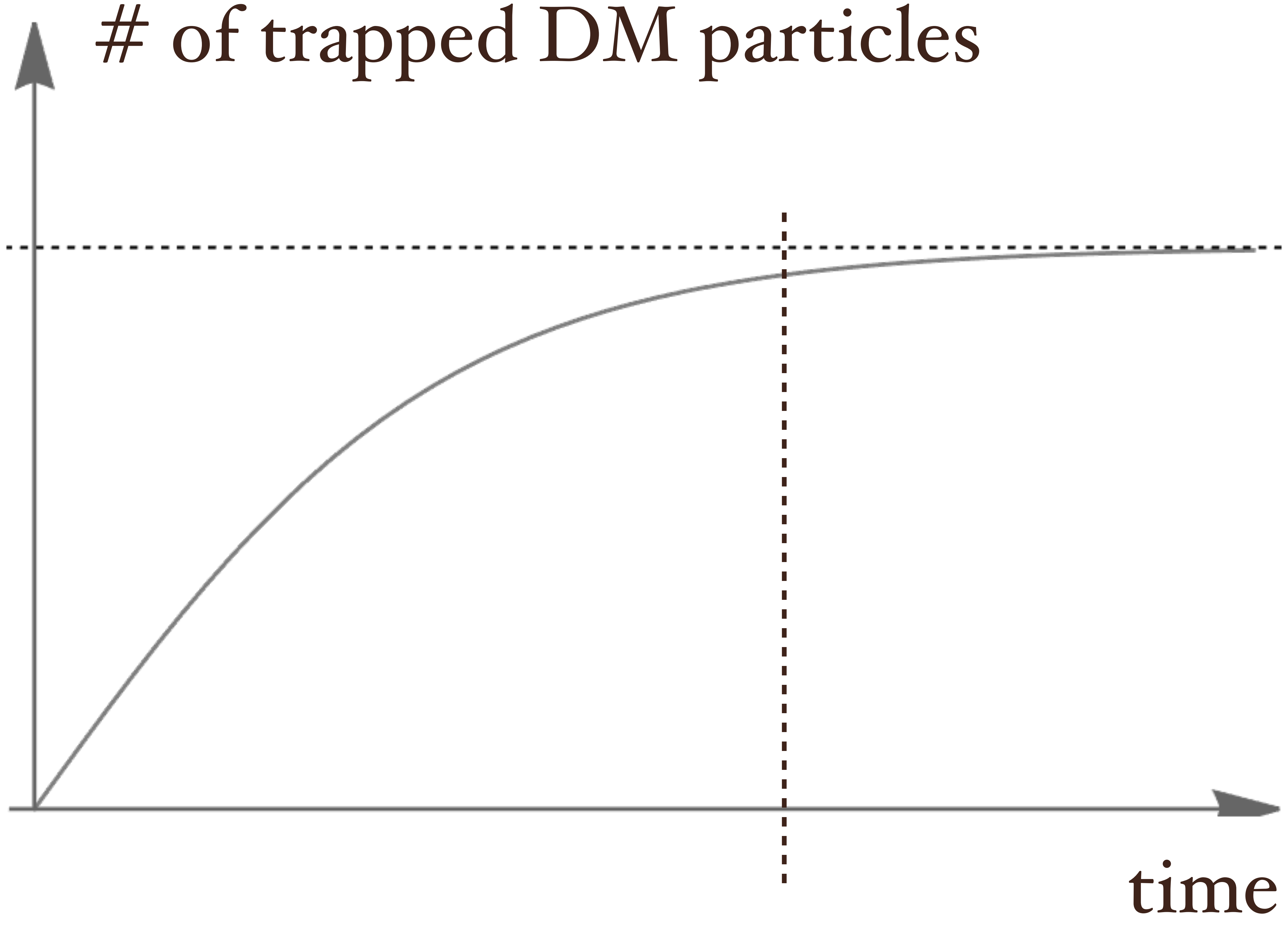
DM annihilation



$\bar{\chi}\chi \to \bar{q}q$ through $\frac{g_\chi g_q}{\Lambda^2}\left(\bar{\chi}\gamma^\mu\gamma^5\chi\right)\left(\bar{q}\gamma_\mu\gamma^5 q\right)$

is suppressed by $m_\chi^2 m_q^2/\Lambda^4$ and $(g_\chi g_q)^2$.

Capture and annihilation equilibrium



$t_{\text{eq}} \propto (\text{capture rate})^{-1/2}$

Equilibrium: capture rate = annihilation rate/2

For 1 GeV DM, $t_{\text{eq}} \approx 10^{16}\,\text{s} < (t_J \sim 10^{17}\,\text{s})$, Jupiter lifetime.

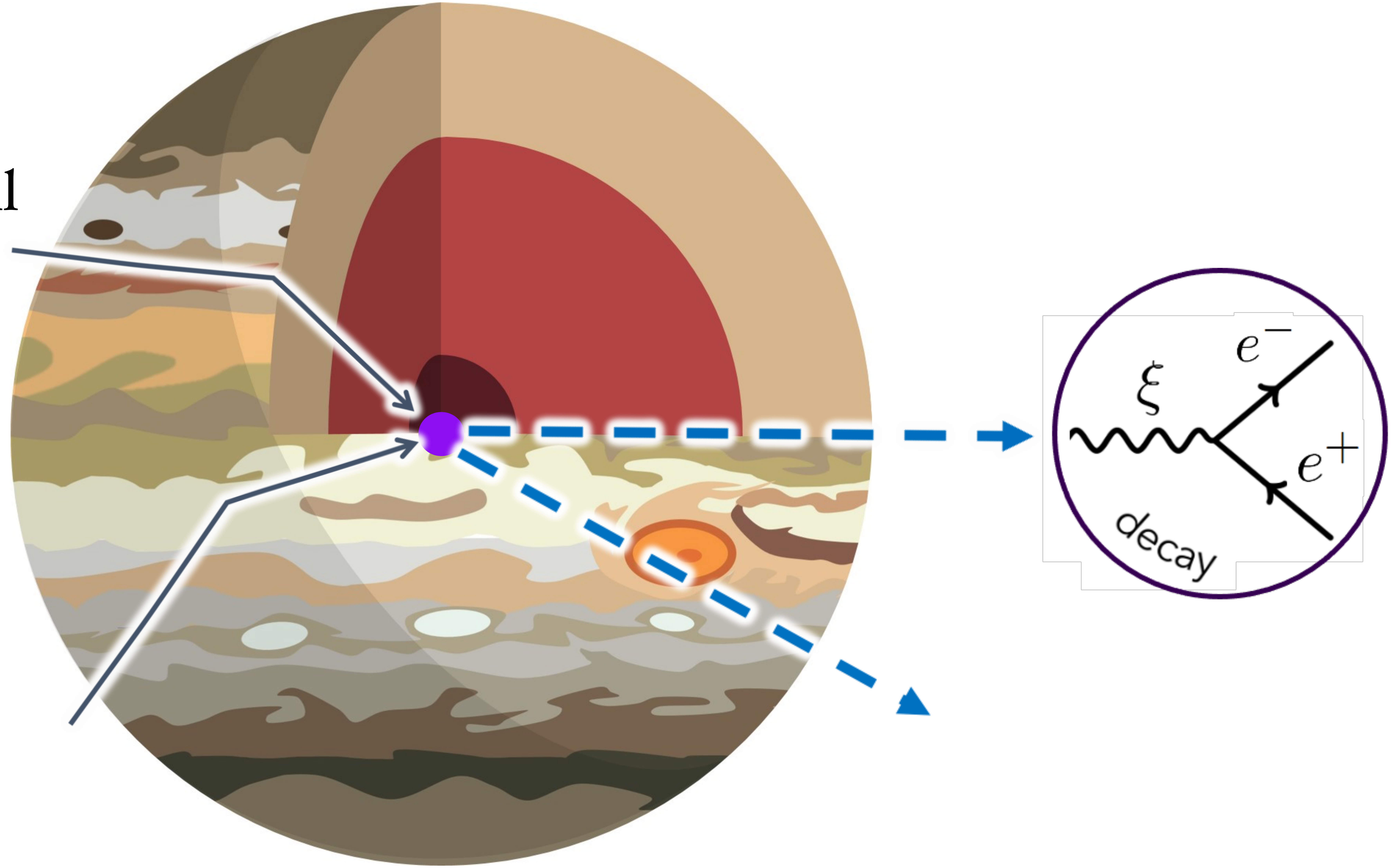
DM could leak out via exponential tails in kinematic distributions: DM lighter than 1 GeVcould evaporate (significantly). Gould 1990, Garani et. al 2021

Dark mediator decays

Benchmark for dark mediators (sub-GeV): dark photon with a small kinetic mixing ϵ to SM photons,

$c\tau \sim \mathcal{O}(10^4)\,\text{km}$
$\Rightarrow \epsilon \lesssim 10^{-9}$

* Elusive at lab
* Go through Jupiter without being absorbed



Previous studies on DM capture: signal

Most studied: gamma-rays

— Good *ex situ* measurements, e.g., Fermi-LAT, HAWC;

— Photons travel in straight lines;

— Spectroscopy & morphology.

Other signals: neutrinos…

Our study: electrons with non-trivial motions in the magnetic field

Previous studies on DM capture: source

Sun:

🙂 Massive and close

😞 Higher background, higher temperature that evaporates light DM

Neutron stars:

🙂 Massive and dense

😞 Too far away and systematics

Our study: Jupiter

Motion of $e^-(e^+)$ in the magnetosphere

Magnetic bottle effect:

trap e^-e^+ inside for a long time.

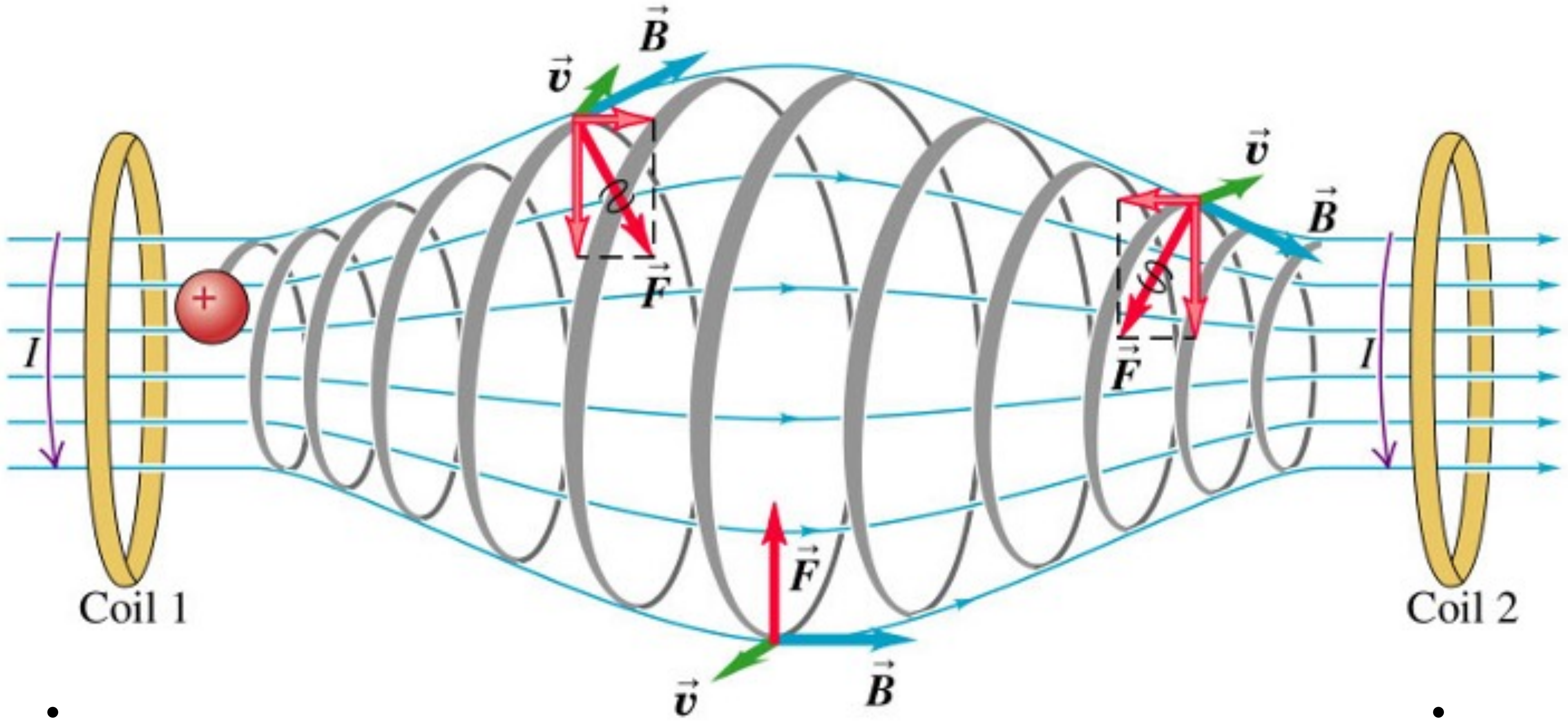
$\mu = \dfrac{mv_\perp^2}{2B}$ adiabatic constant;

Total energy:

$$\frac{1}{2}mv_\parallel^2 + \frac{1}{2}mv_\perp^2 = \frac{1}{2}mv_\parallel^2 + \mu B$$

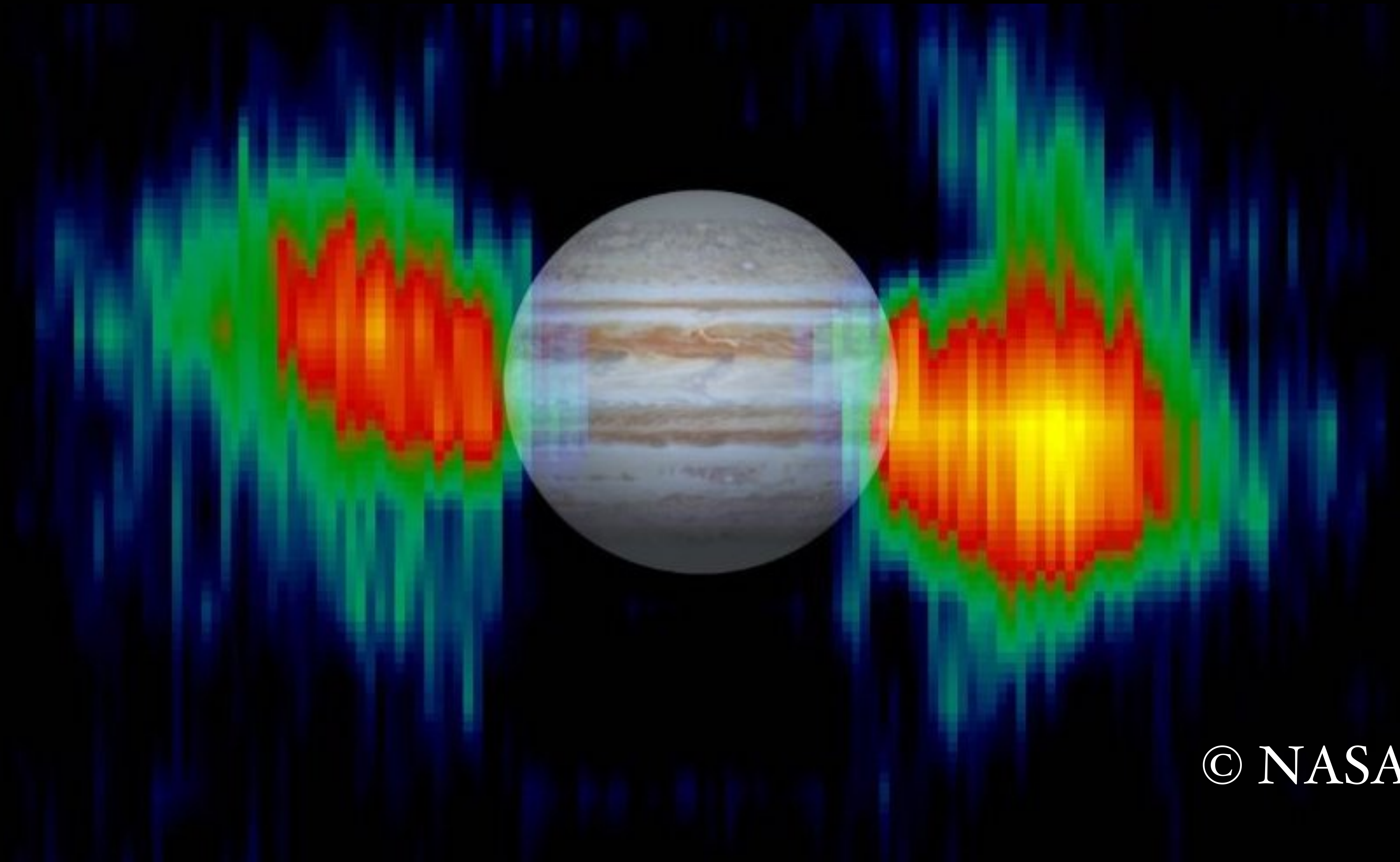
conserved;

$B\uparrow$, $v_\parallel\downarrow$ till e^-, e^+ are repelled from the dense field region.



mirror mirror

Origin of planet’s radiation belts: Van Allen radiation belts



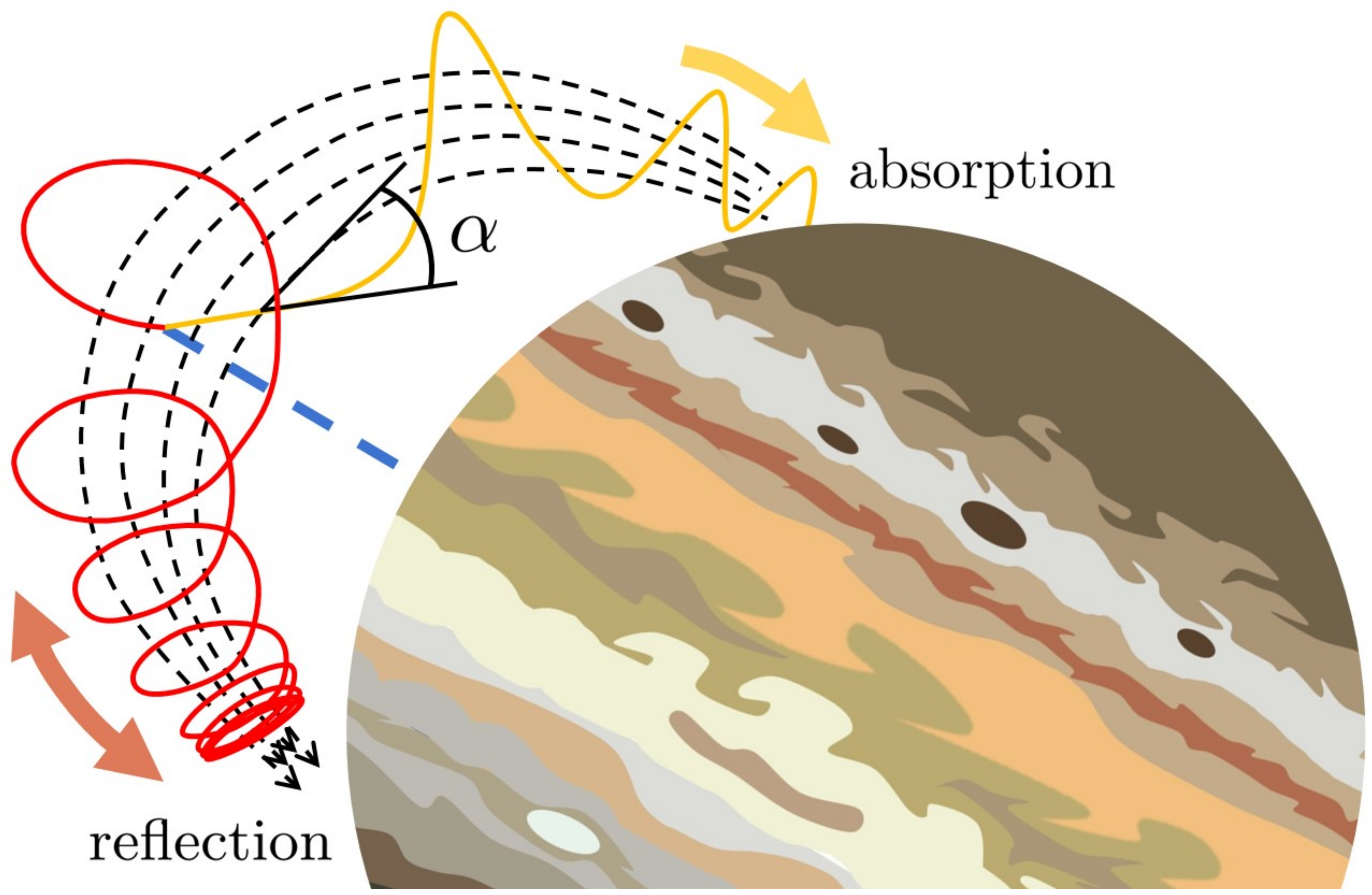
Three possible modes in B field

1. ***Gyration*** around field lines ($\gg$ kHz) : Lorentz force;

2. ***Bounce*** between two mirror points (~Hz) : magnetic bottle effect, depending on the pitch angle;

3. ***Drift*** in the azimuthal/longitudinal direction (< mHz) : gradience of the B field;

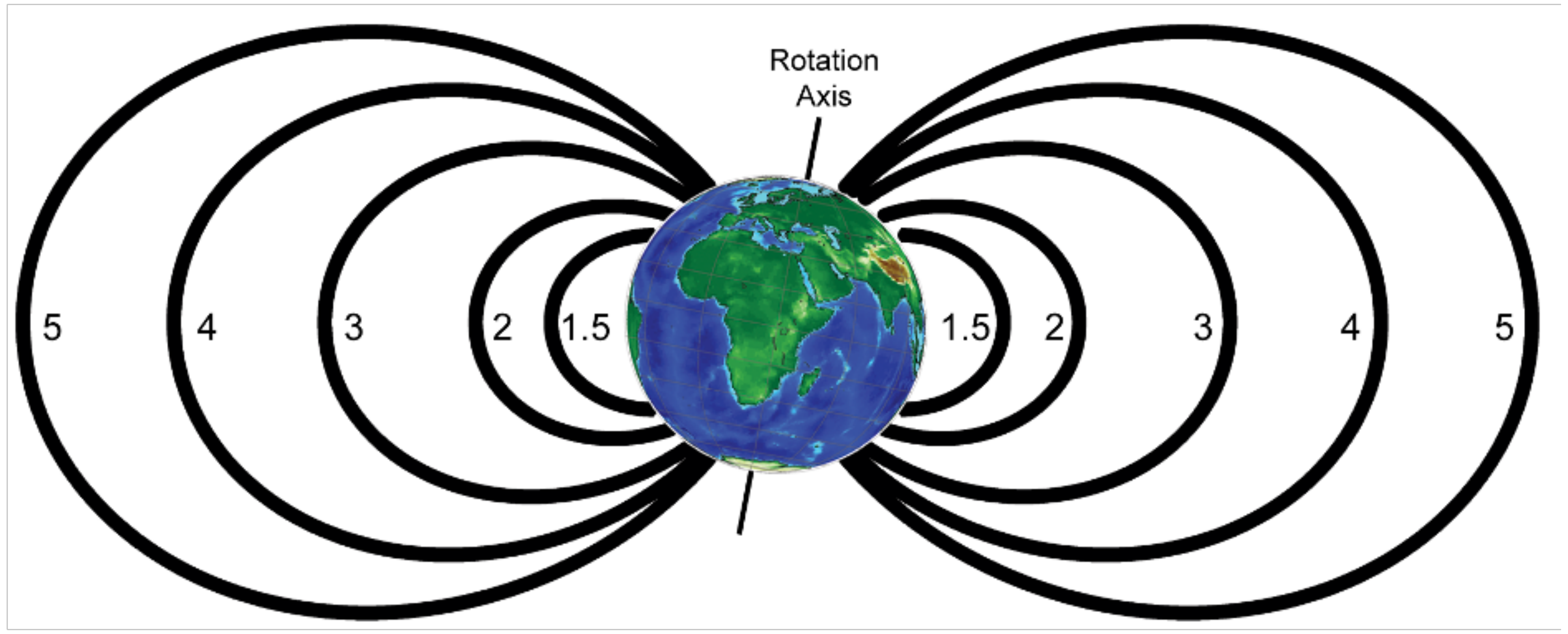
Schulz and Lanzerotti, 1974



Phase space parameters

1) **Kinetic energy**: E

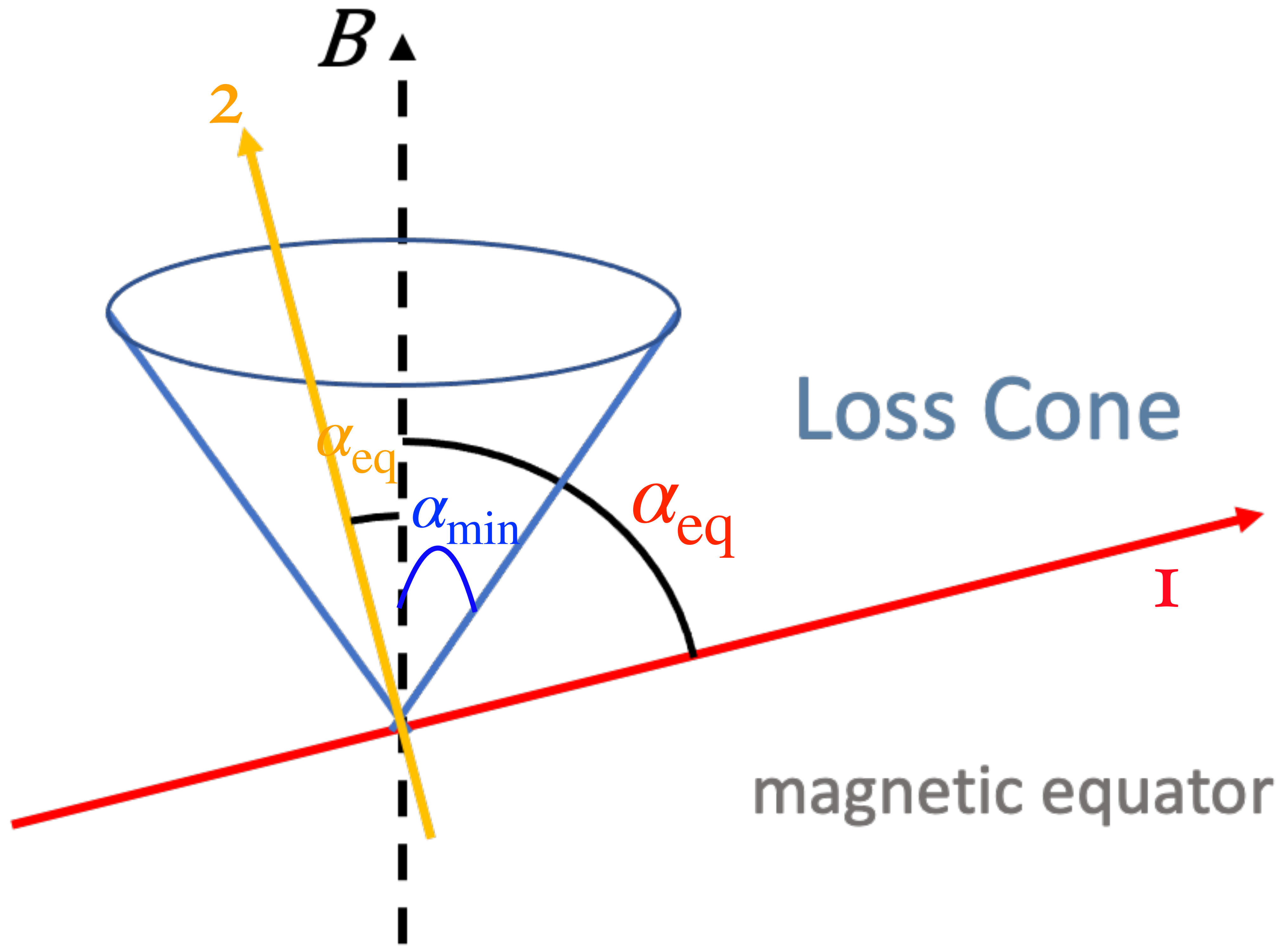
2) **Mcilwain parameter**: L Mcilwain 1961

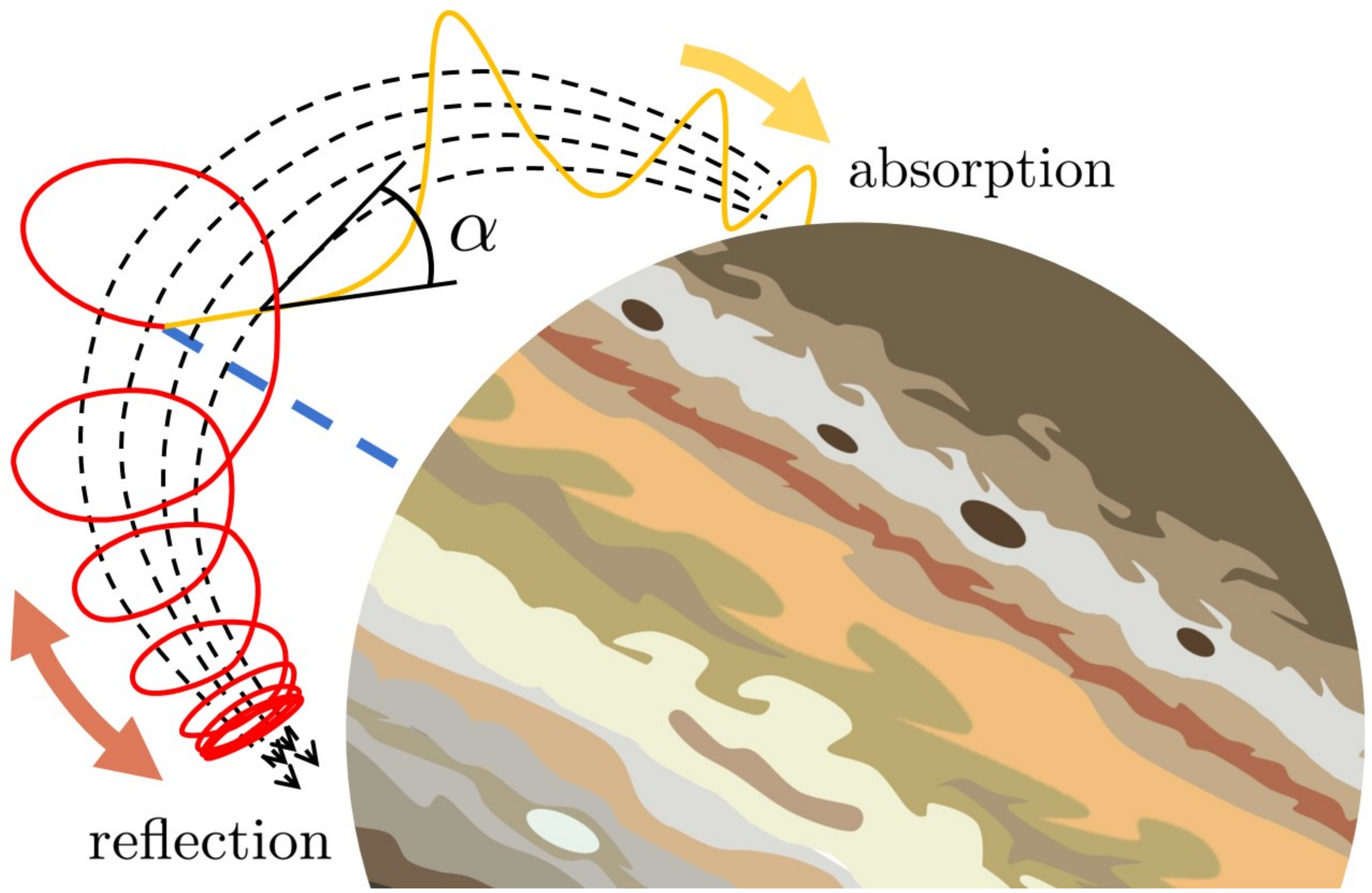


Lines with $L \times$ radius in the magnetic equator in a dipole field

For the time scales of hard electrons, they are limited on the same L-shell.

3) **Equatorial pitch angle**: α_{eq} , angle between the electron momentum and the magnetic field at the magnetic equator.





Electrons with small α_{eq} : mirror points are inside Jupiter. Thus they hit Jupiter first and be absorbed.

$\alpha_{eq} \leq \alpha_{min}$: loss cone.

Dynamics

Diffusion equation

phase space density

$$\frac{df(L, E, \sin\alpha_{\rm eq})}{dt} = \langle I \rangle_{\rm trajectories}$$

source term averaged over trajectories: injected by decays of dark mediators

friction terms: energy loss or $\alpha_{\rm eq}$ variation with time (electron number conservation)

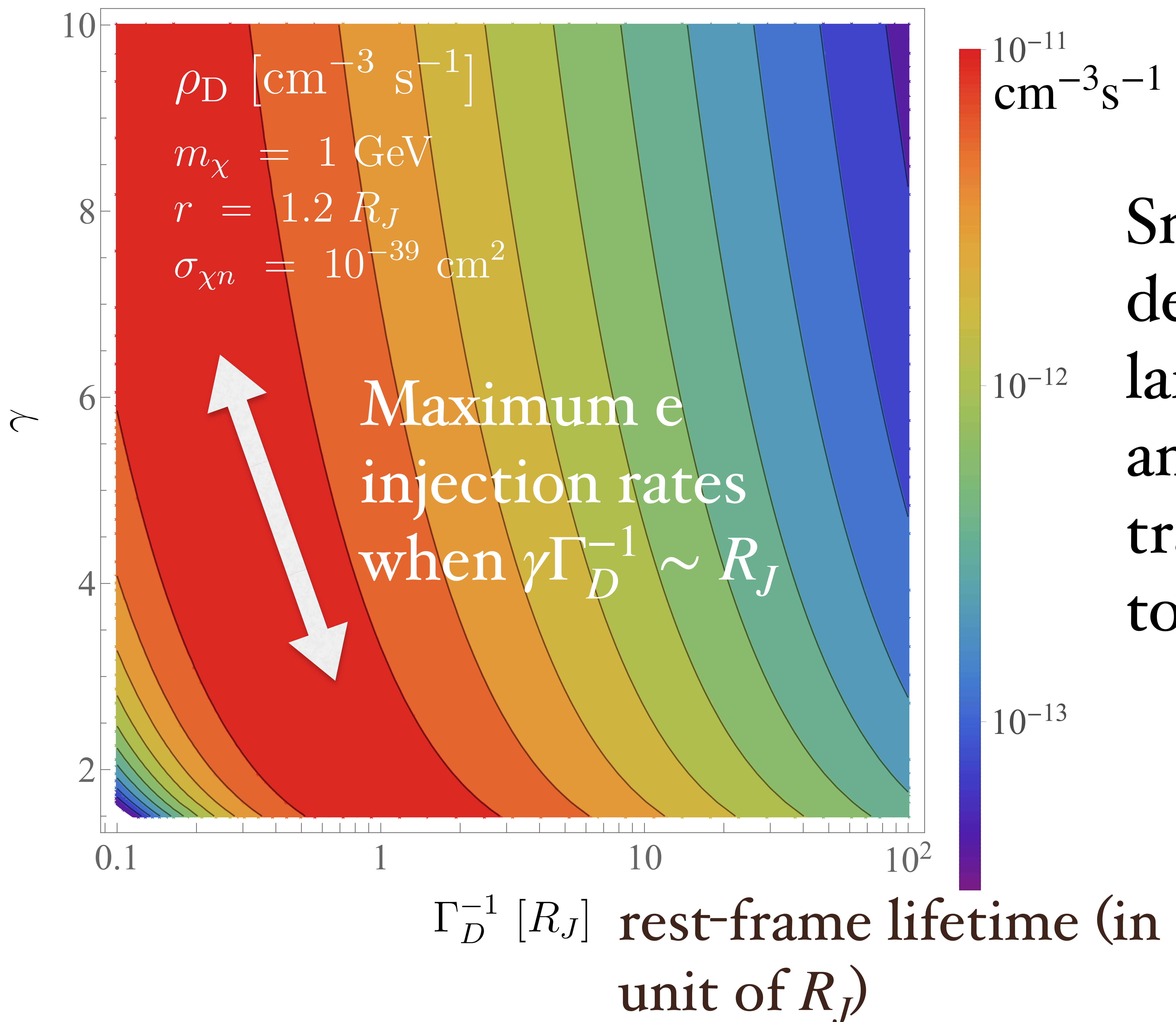
$$-\frac{\partial}{\partial E}\left(\frac{dE}{dt} f\right) - \frac{\partial}{\partial \sin\alpha_{\rm eq}}\left(\frac{d\sin\alpha_{\rm eq}}{dt} f\right)$$

$$+\tau_{\rm loss}^{-1} f + \cdots$$

Electron number loss term with time scale $\tau_{\rm loss}$

Source term

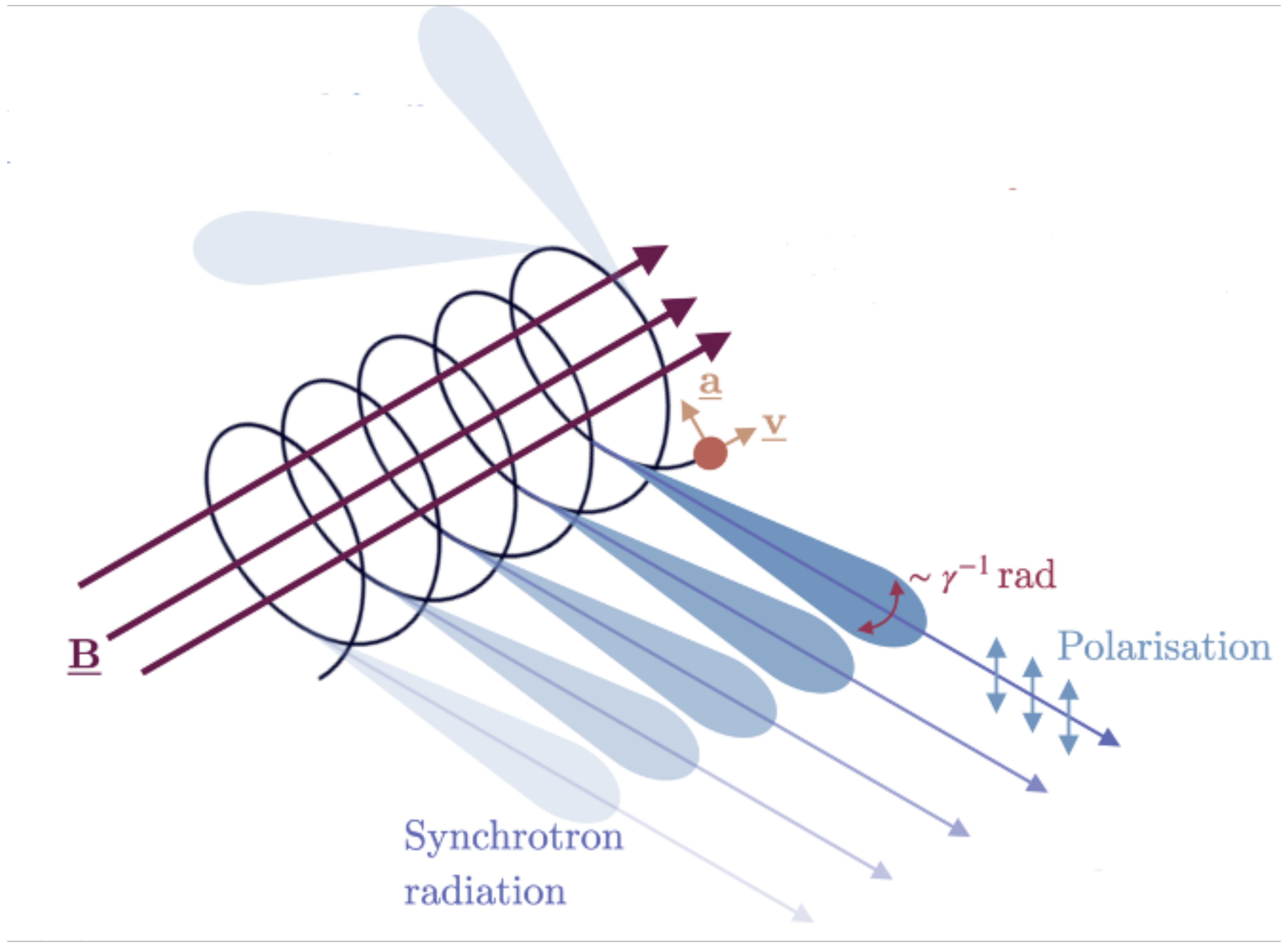
Mediator decay rate density

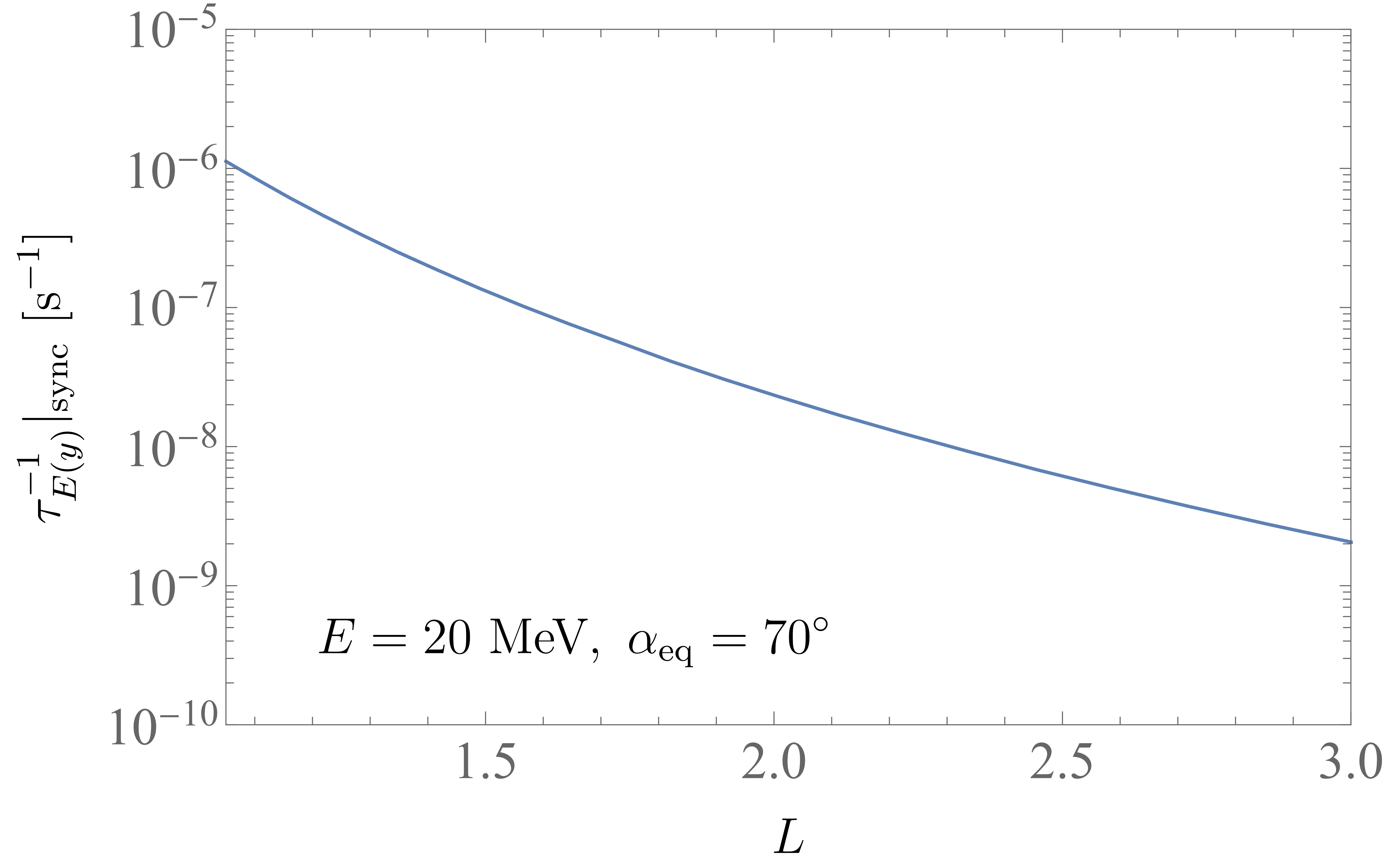


Small rate density, but large volume and long trapping time to compensate

Synchrotron friction

Fast energy loss/α_{eq} variation dominantly through *synchrotron radiation* for hard electrons > $\mathcal{O}(10)$ MeV ($|B| \sim \mathcal{O}$ (Gauss); $E \gg m_e$).

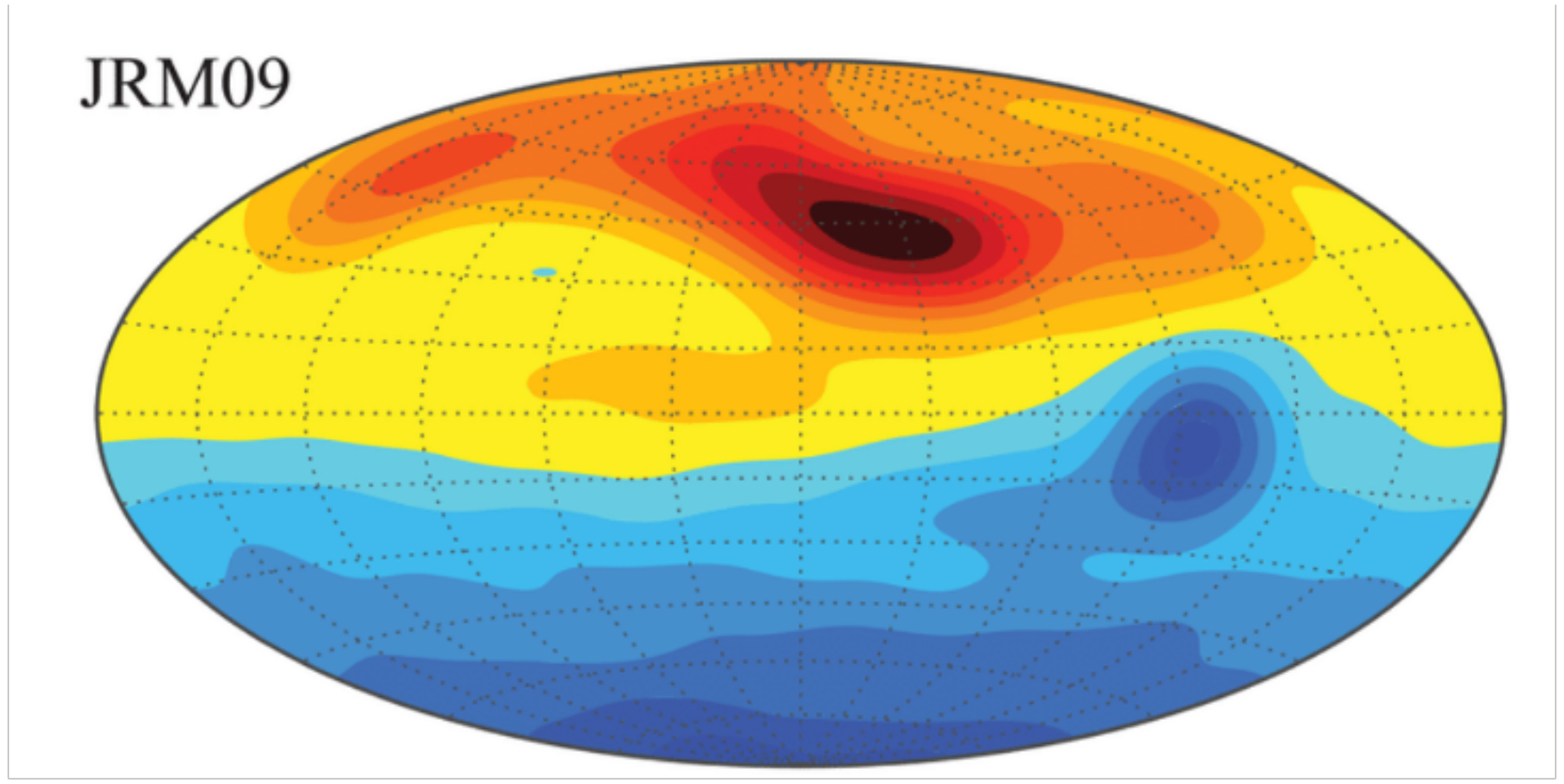




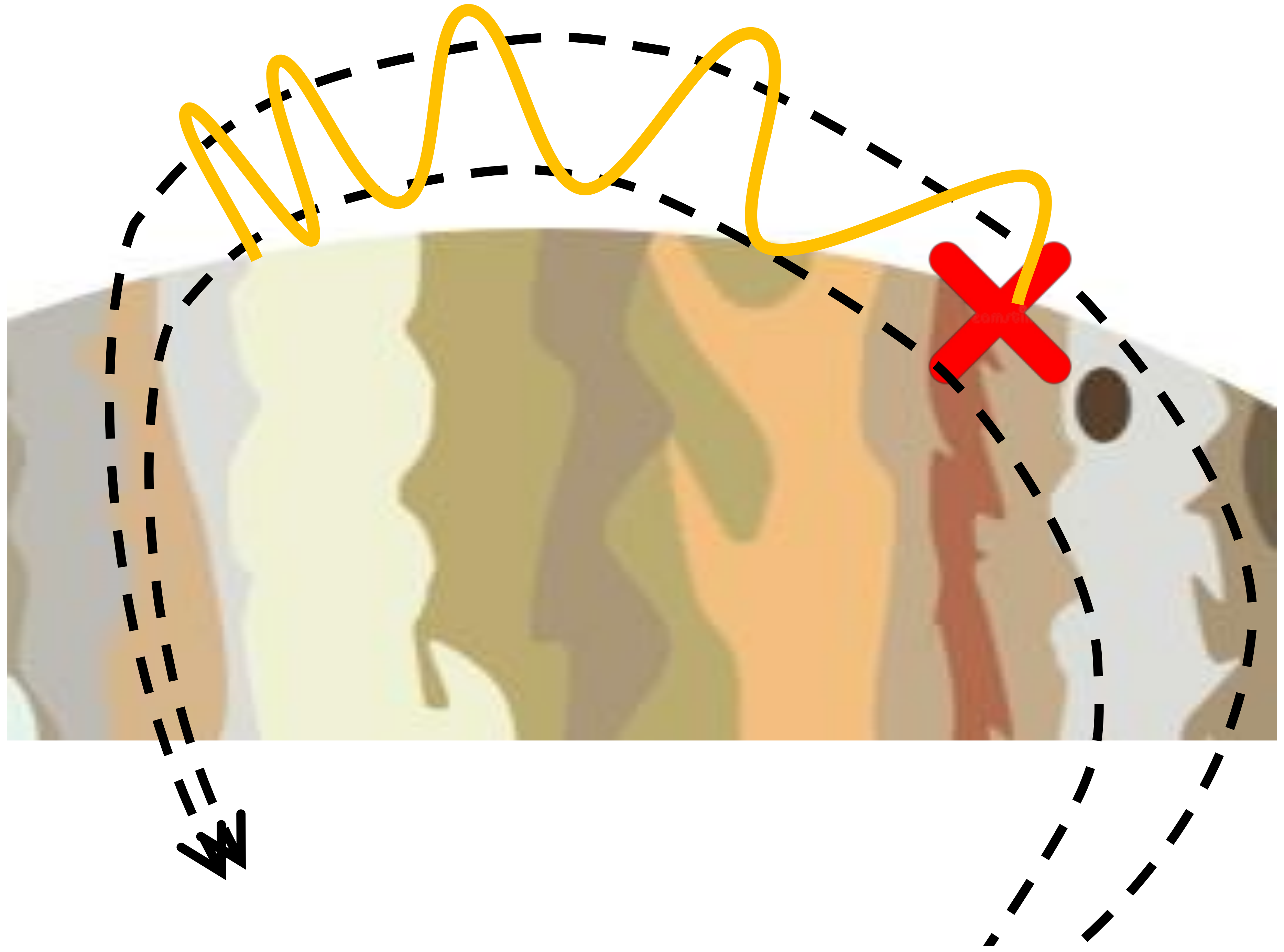
Time scale $\tau_E \gtrsim \mathcal{O}(10^5)$ s for hard electrons > $\mathcal{O}(10)$ MeV

Electron loss

Case 1: untrapped region



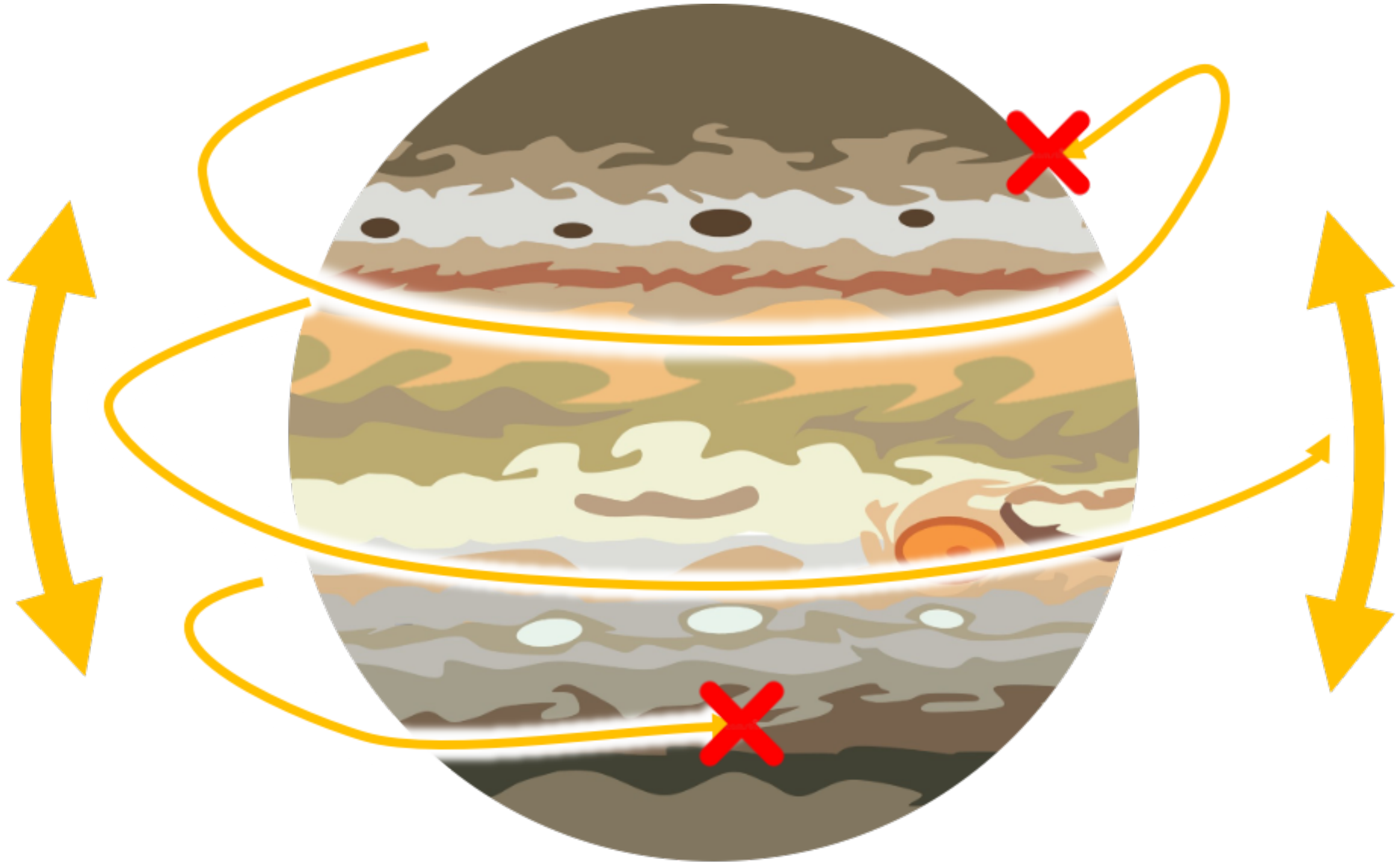
Not a perfect dipole field, twisted by higher moments
Connerney et.al 2018



Close to the surface where field line minimum close to or inside Jupiter ($L \sim 1$): no reflection, $\tau_{\rm loss} \sim 0.2$ s.

Case 2: quasi-trapped region

A bit further away from surface, $r < 1.3R_J$, electrons fall in the local loss cone during the azimuthal drifting.

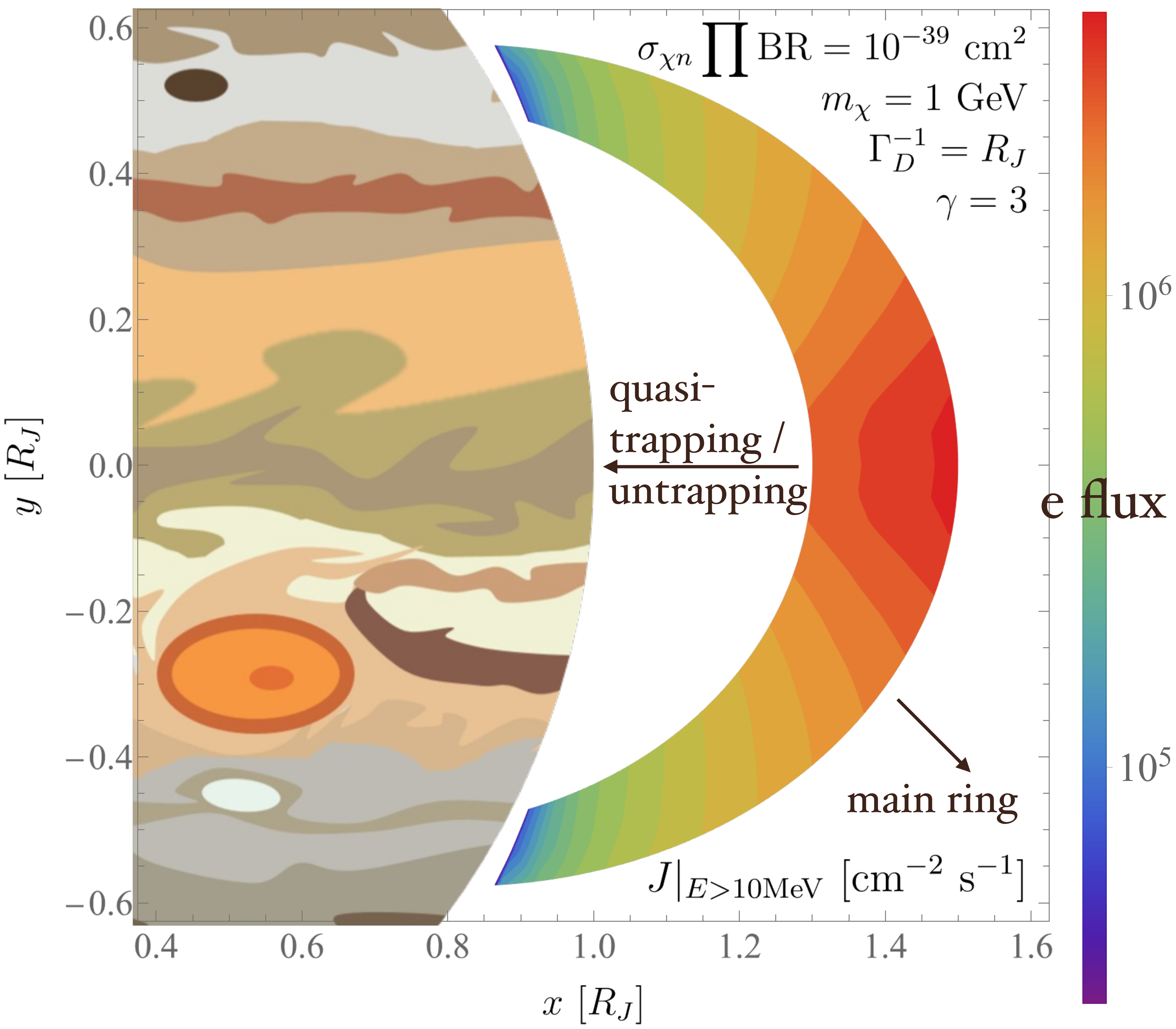


Electron trapping lifetime set by the drift period: electrons lost before losing energy significantly via synchrotron radiation

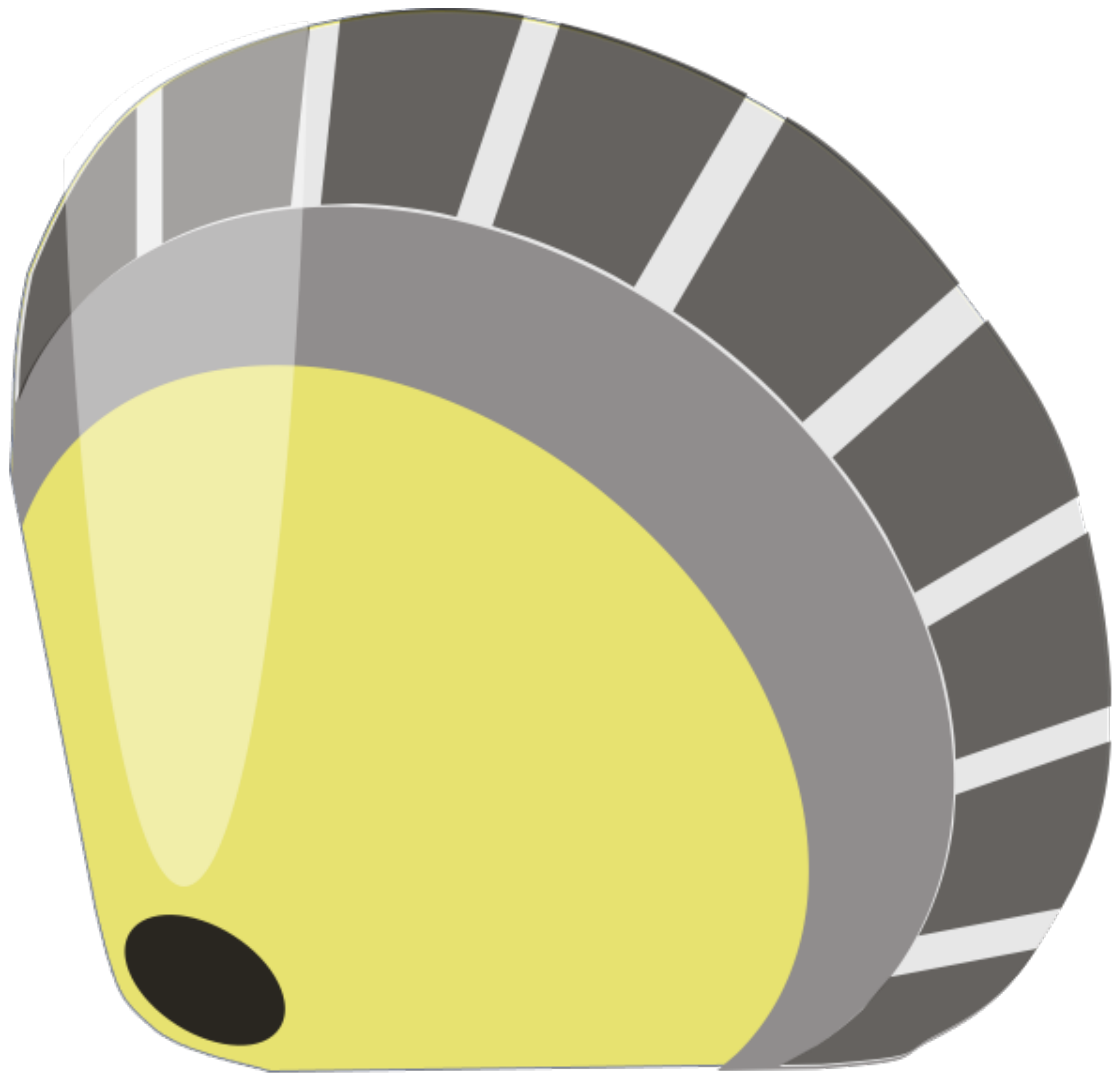
$$\tau_{\rm loss} \lesssim \frac{\mathcal{O}(10^4)}{E/100\,{\rm MeV}}\,{\rm s} \ll \tau_E|_{\rm sync}$$

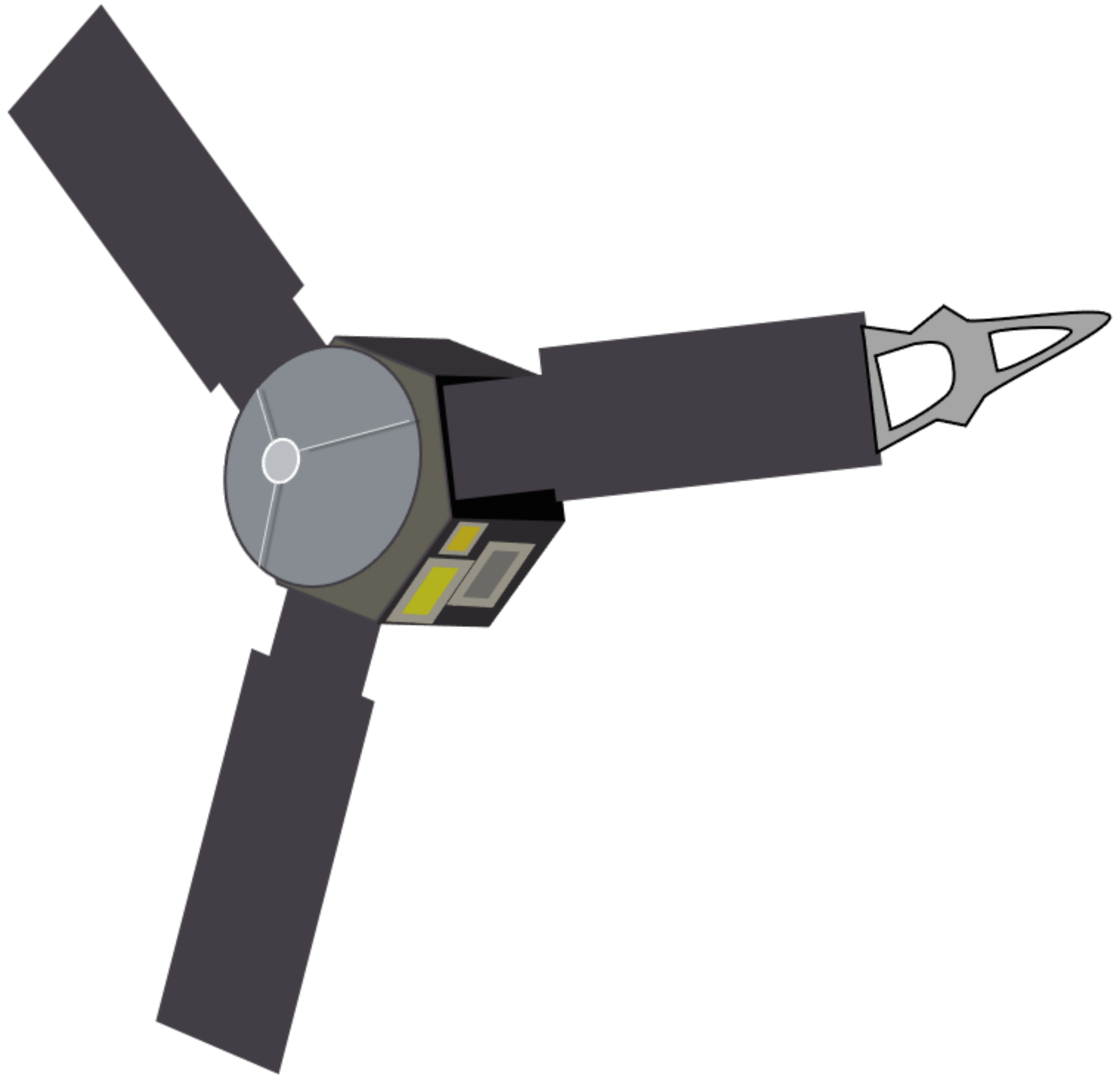
Case 3: fully-trapped region

$L \subset (1.3, 1.5)$, away from the surface (smaller L) and away from the main ring, moons etc. (larger L). Close to the magnetic equator, electron loss not as important as synchrotron friction:
$\tau_{\rm loss} \gtrsim \mathcal{O}(10^5)\,{\rm s} \gtrsim \tau_E|_{\rm sync}$.



Mission overview

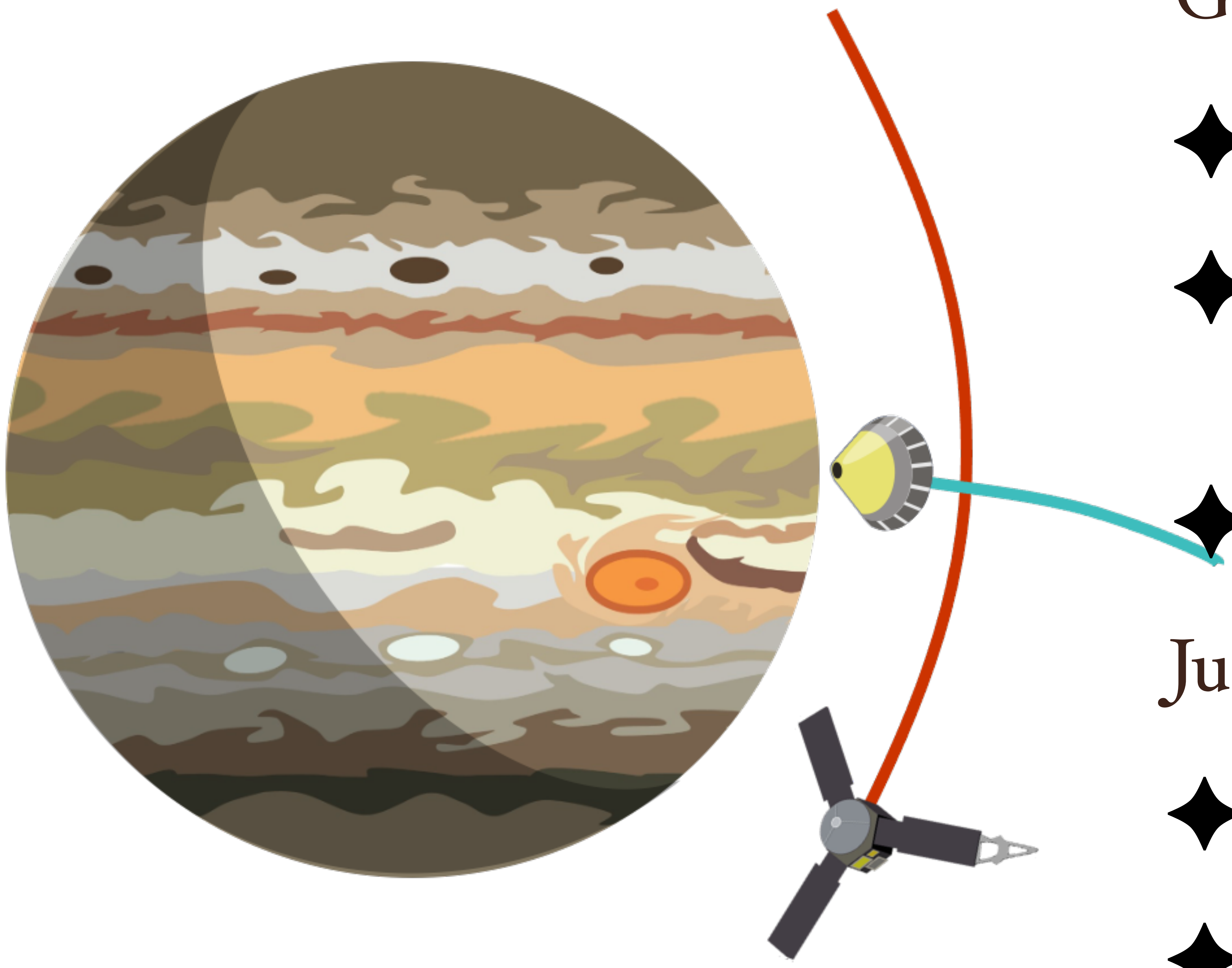




Galileo probe
(1989-1995)

Juno mission
(2011 -)

Mission overview



Galileo probe: one way trip

- ✦ Dive into the atmosphere;
- ✦ Energetic particle investigation (EPI): "calorimeters";
- ✦ Sensitive to MeV-GeV charged particles;

Juno: orbiter still in work

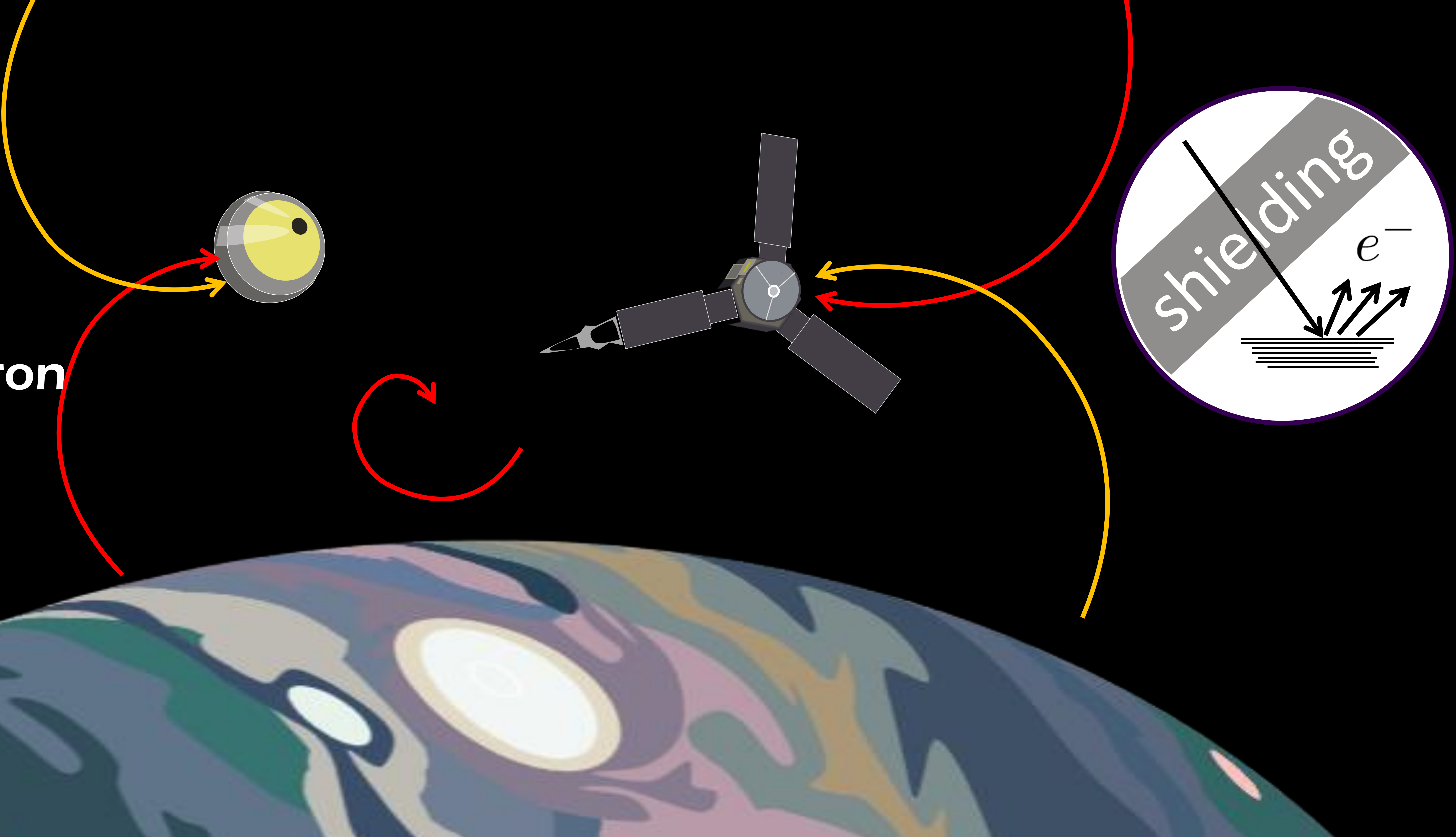
- ✦ Can be very close to the surface;
- ✦ No specific relativistic particle detector;
- ✦ Radiation monitoring (RM) investigation detects hard electron: CCD cameras.

Relate DM Model with Data

(never used for HEP)

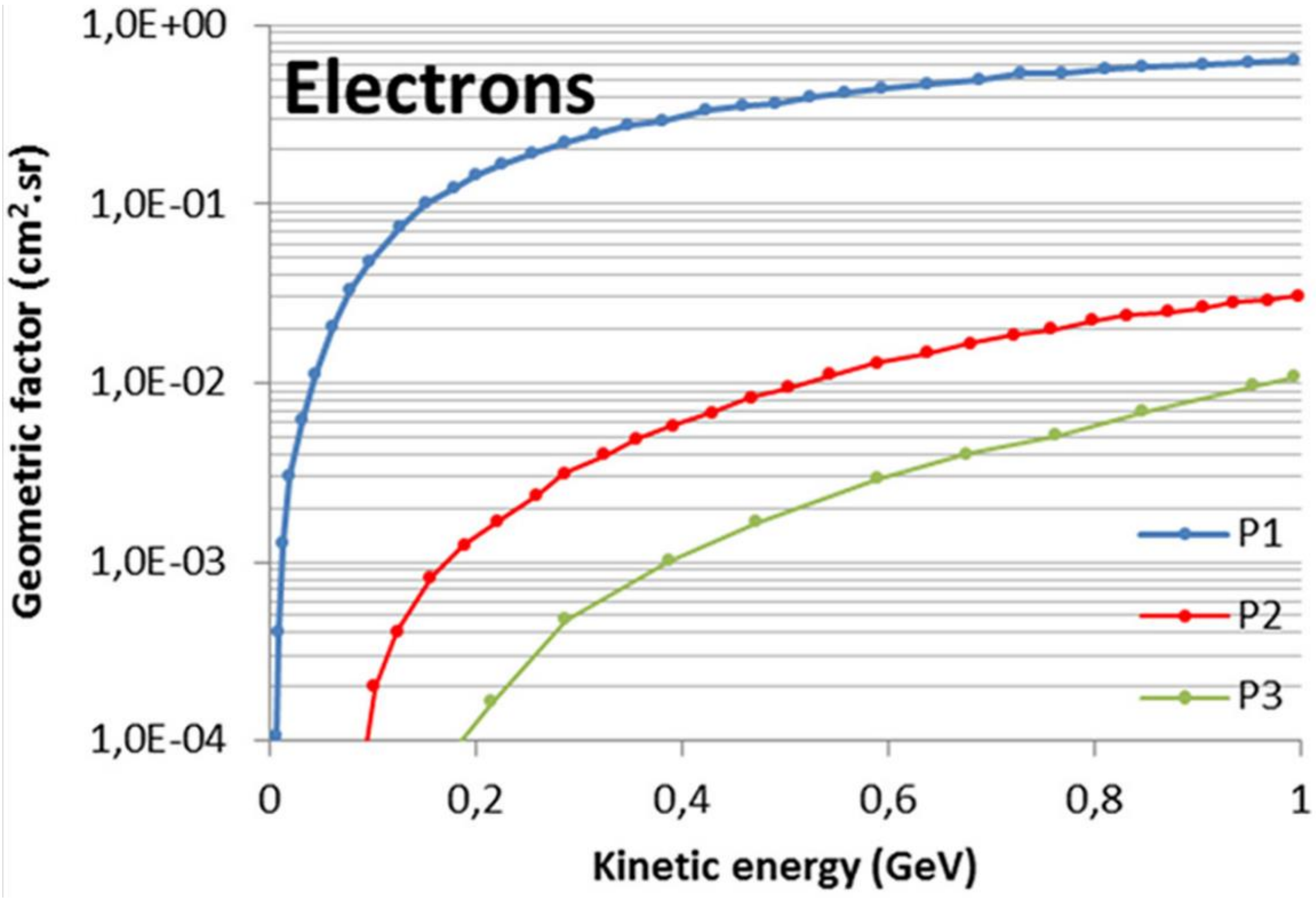
GeV-scale electrons leave data with precise space/time stamps.

Hit rate (s^{-1}) = electron flux ($cm^{-2}\ s^{-1}$)× effective area of detection (cm^2)



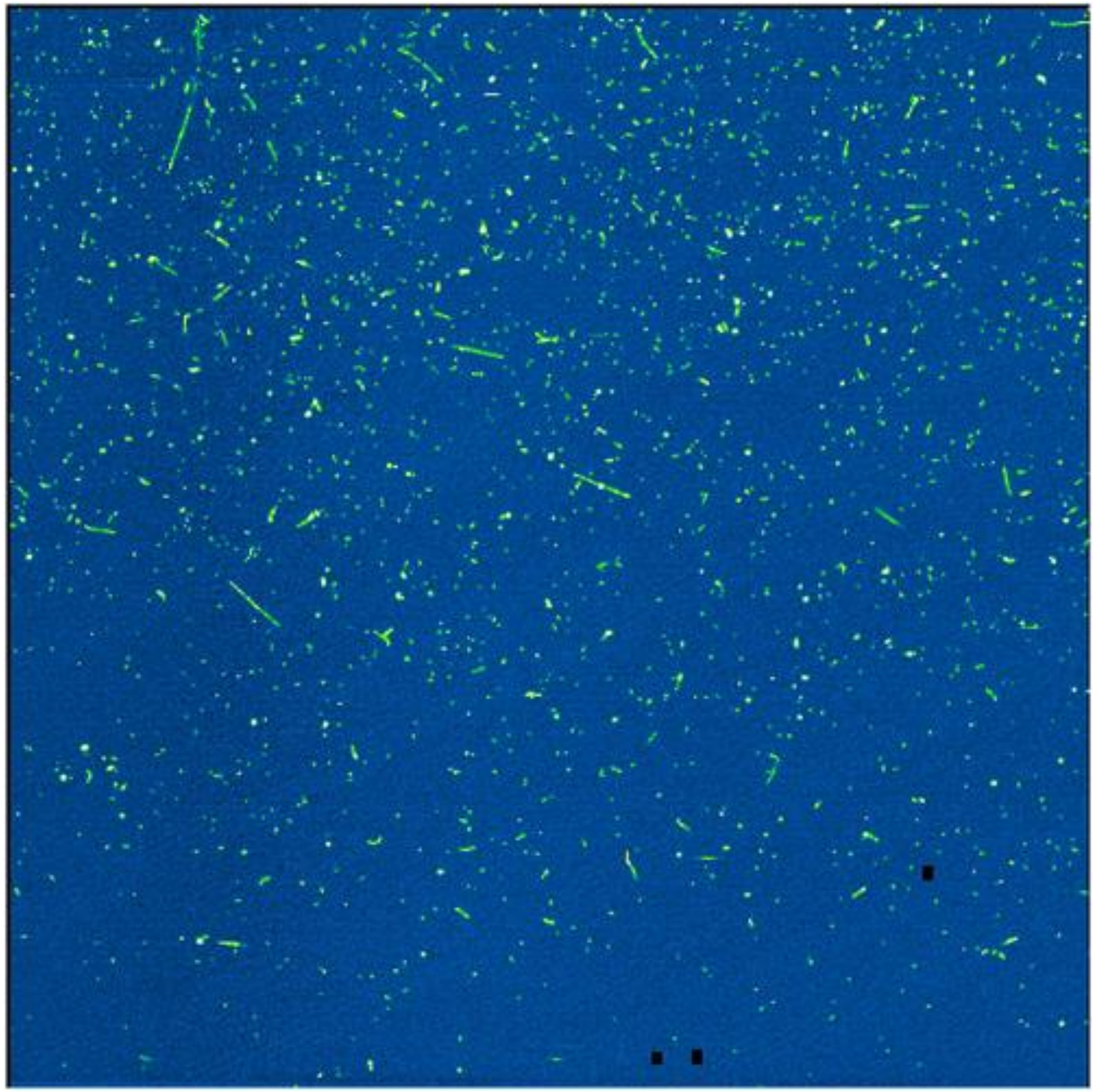
Sensitivity

No precise spectroscopy: higher energy → higher penetration rate → higher sensitivity;



Nenon et.al. 2018

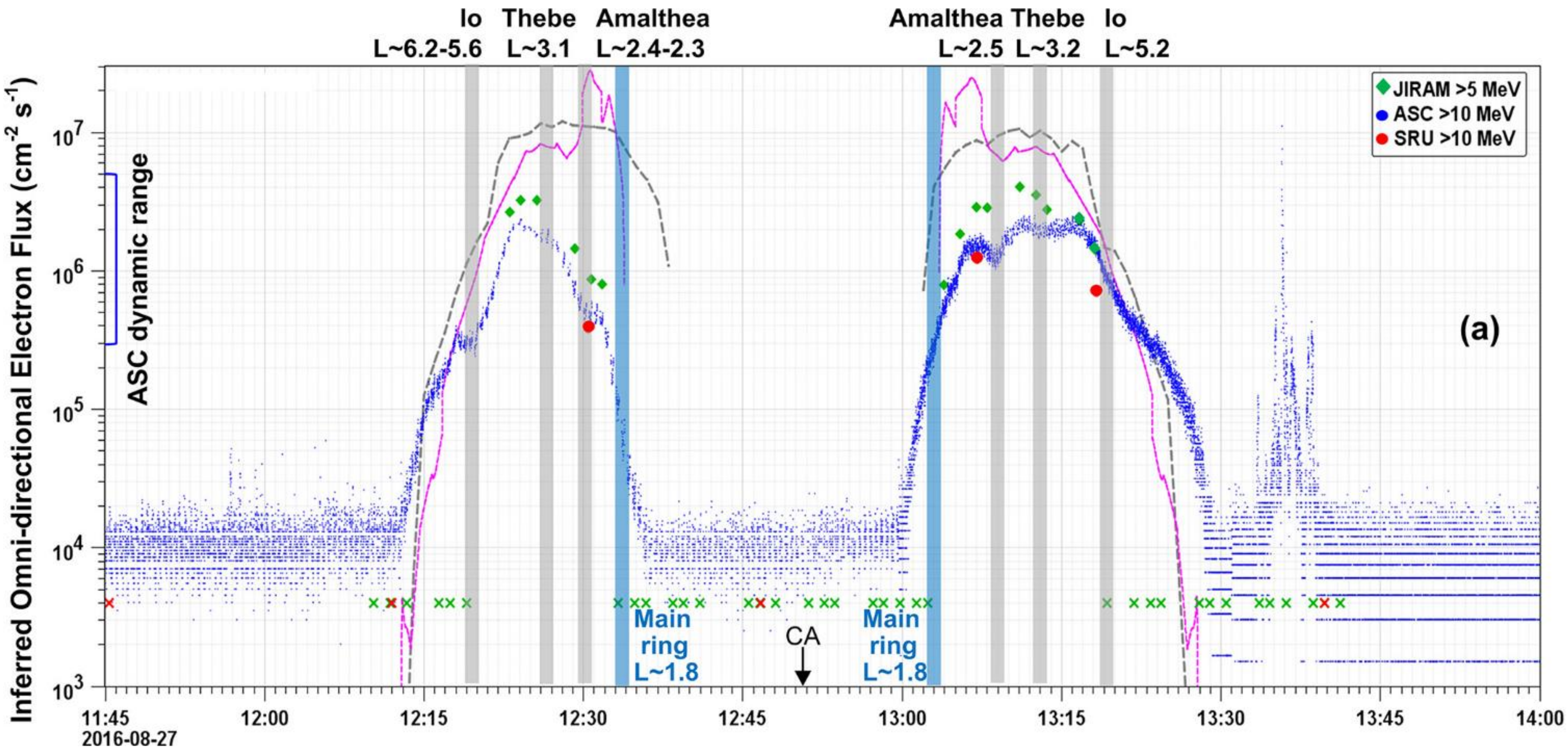
Data



Juno CCD image from relativistic particles

Becker et. al. 2017

Data

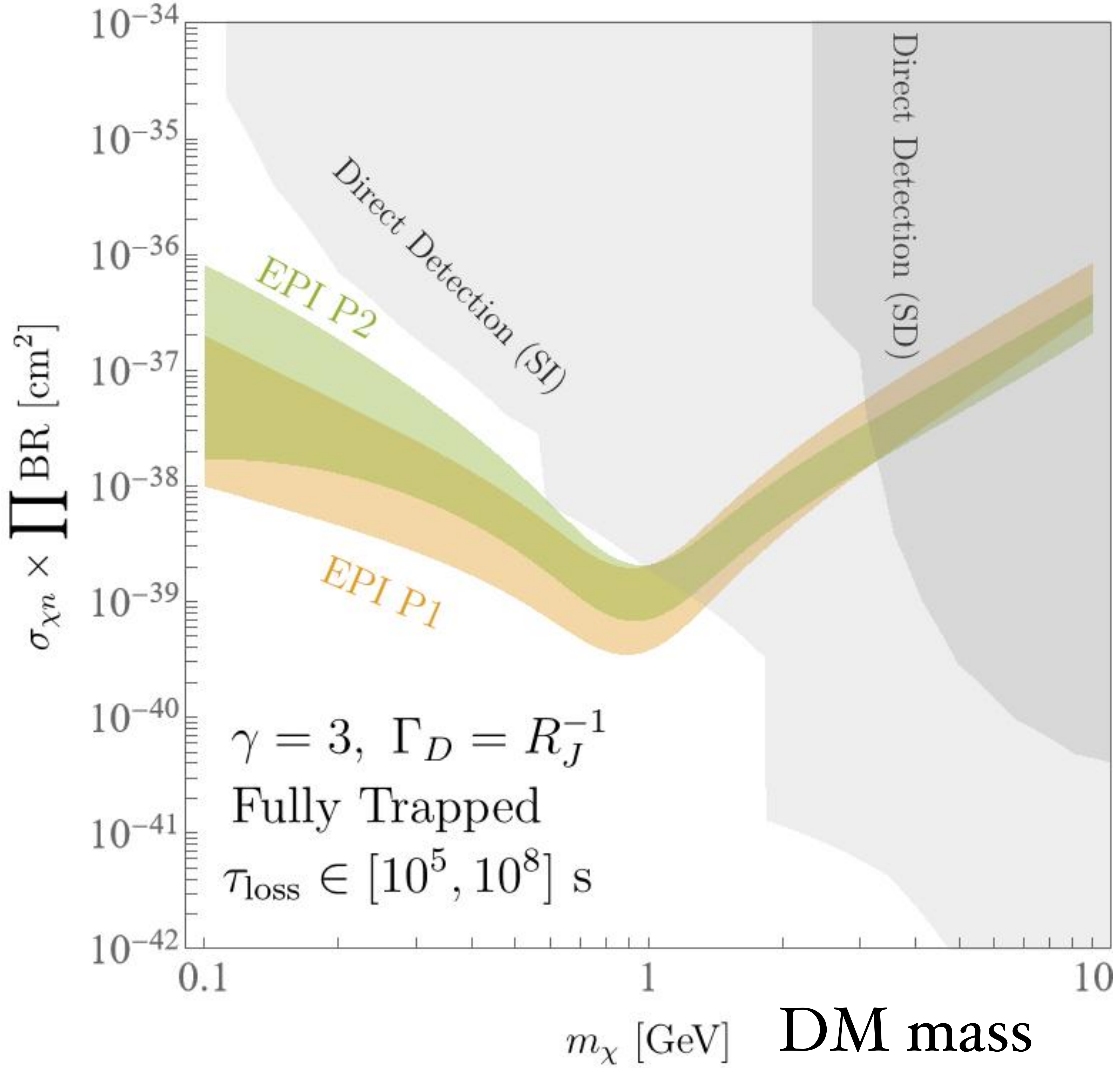


Becker et.al 2017

Results

Currently only the Galileo probe data covers region where electrons could be fully-trapped ($L \subset (1.3, 1.5)$ & close to the magnetic equator; small electron loss rate);

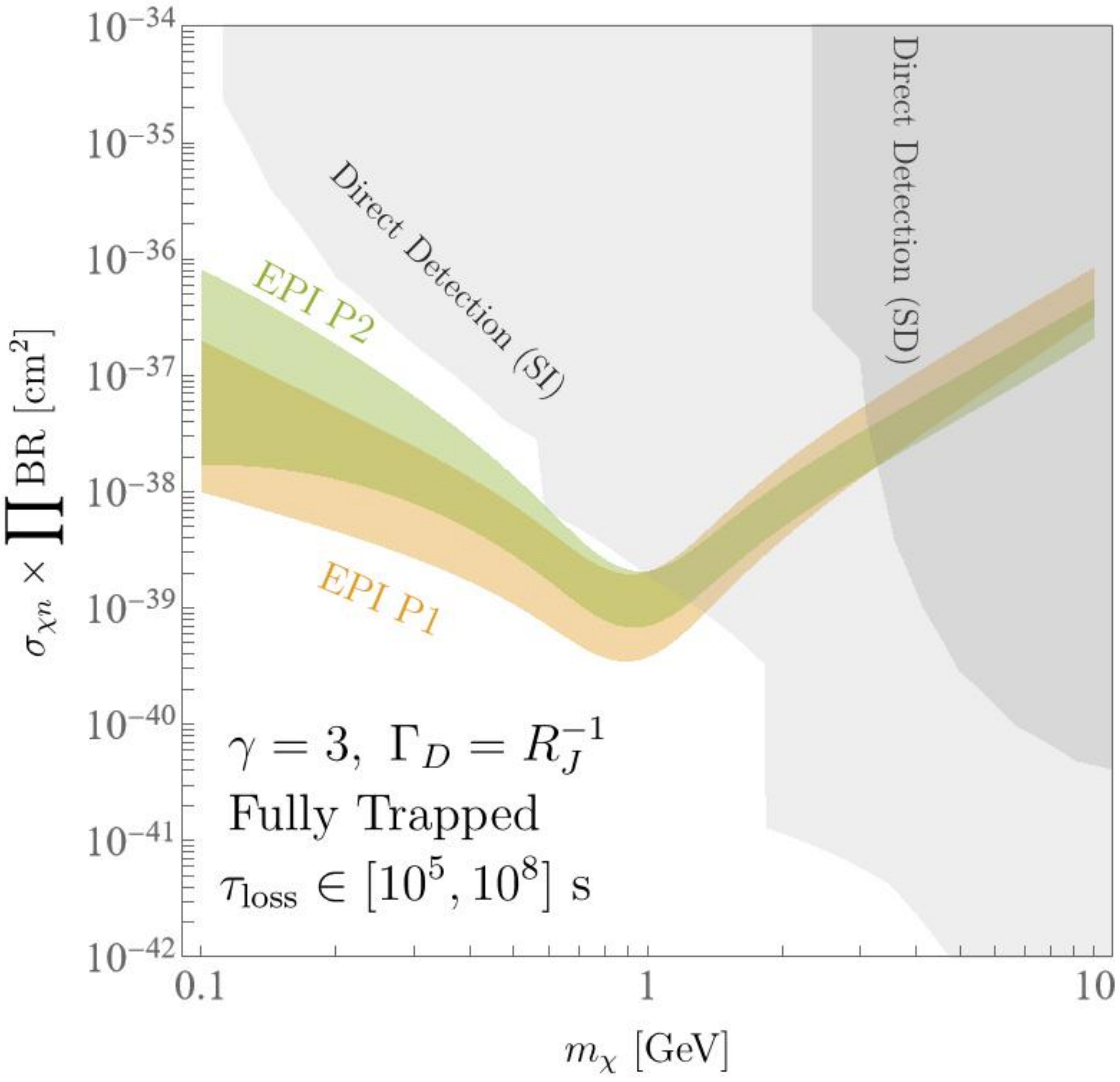
electron flux from dark mediator decays ∝ DM-nucleon scattering xsec × BR (DM →mediator → e^-e^+)



DM mass

Results

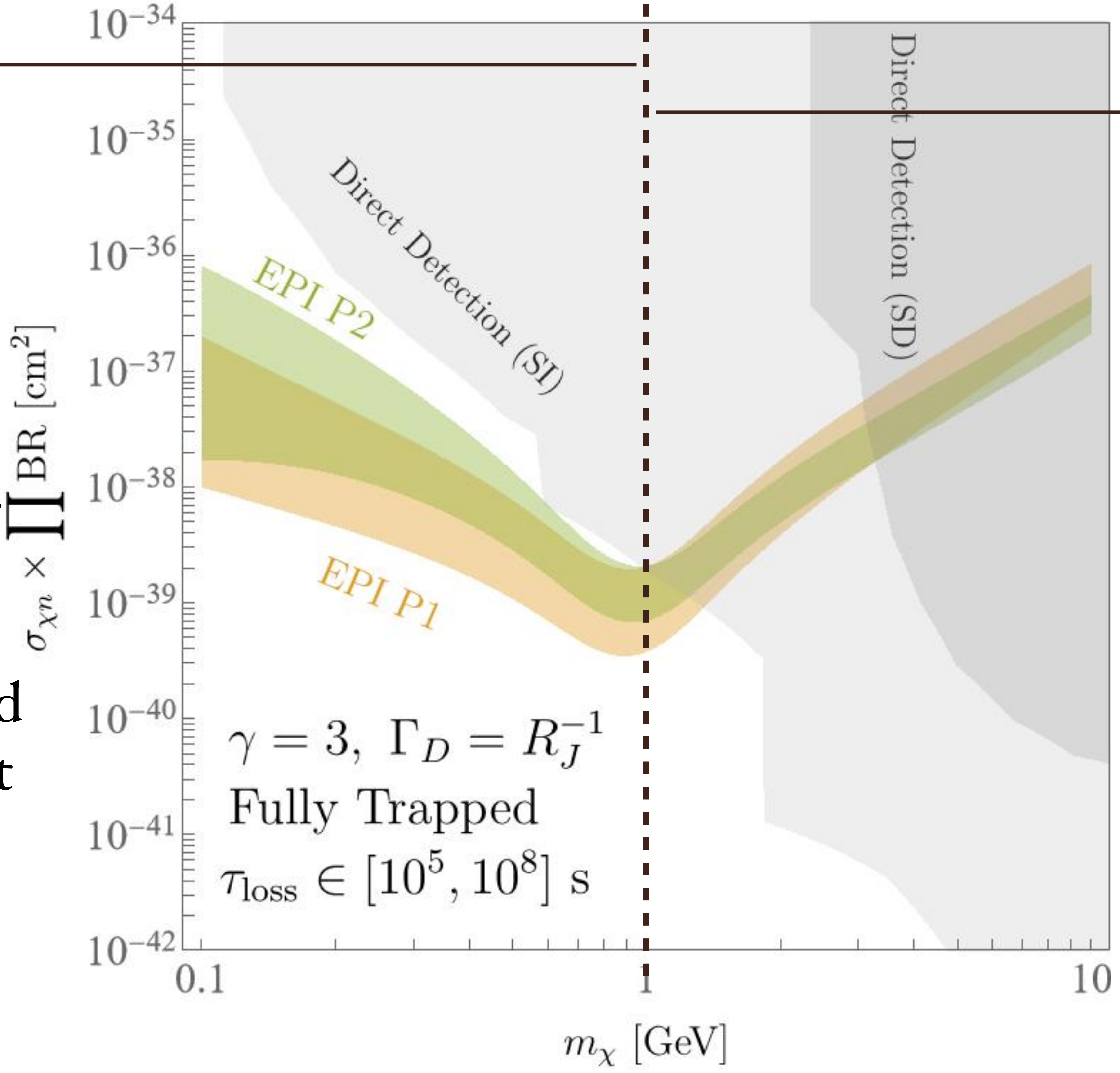
Since Jupiter is mostly made up of hydrogen, DM capture is insensitive to either spin-independent (SI) or spin-dependent (SD) scattering. The bounds apply to both. Compared to direct detection experiments, this could be a more sensitive probe to SD scattering.



Results

Below 1 GeV:

- DM number density increases but capture efficiency drops;
- softer electrons: lower sensitivity;
- Evaporation rates could become important (not accounted for in the plot).



Above 1 GeV:

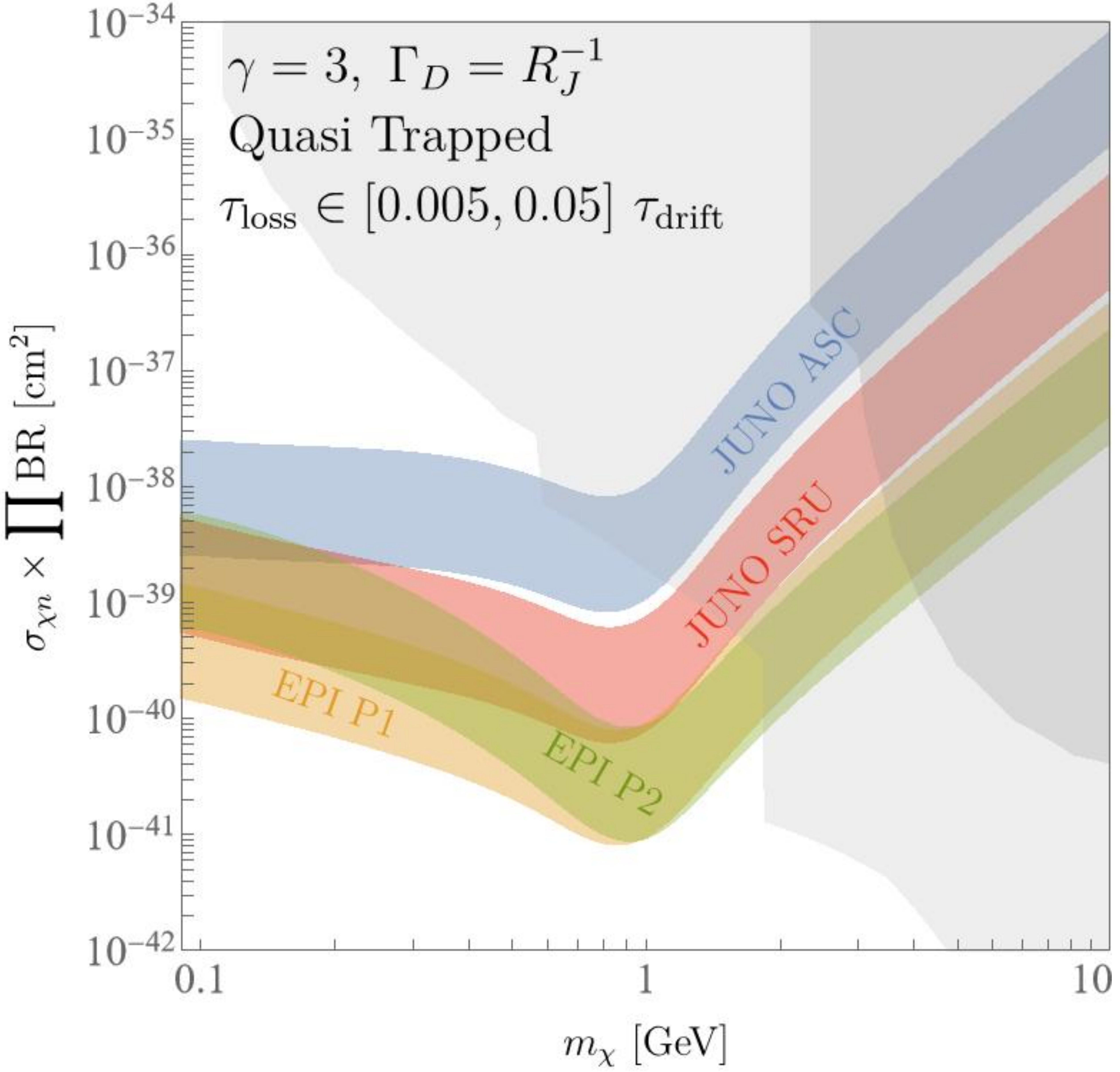
- DM number density and capture efficiency drops.
- Harder electrons: may improve with better detector knowledge.

Results

Both Galileo probe and Juno mission probe quasi-trapped region (e.g. $L \sim 1.1$).

Bounds could be stronger but also higher systematics;

need more precise magnetic field modeling and numerical simulations.



Summary

— Jupiter could be a powerful capturer of GeV-scale DM;

— DM could annihilate into long-lived dark mediators. For a dark mediator with lifetime $\sim \mathcal{O}(0.1-1)\,\mathrm{s}$, its decays could inject hard electrons into the radiation belts. Such kind of model is well motivated in the context of the relatively new DM paradigm and the parameter space could be challenging to be probed via terrestrial experiments.

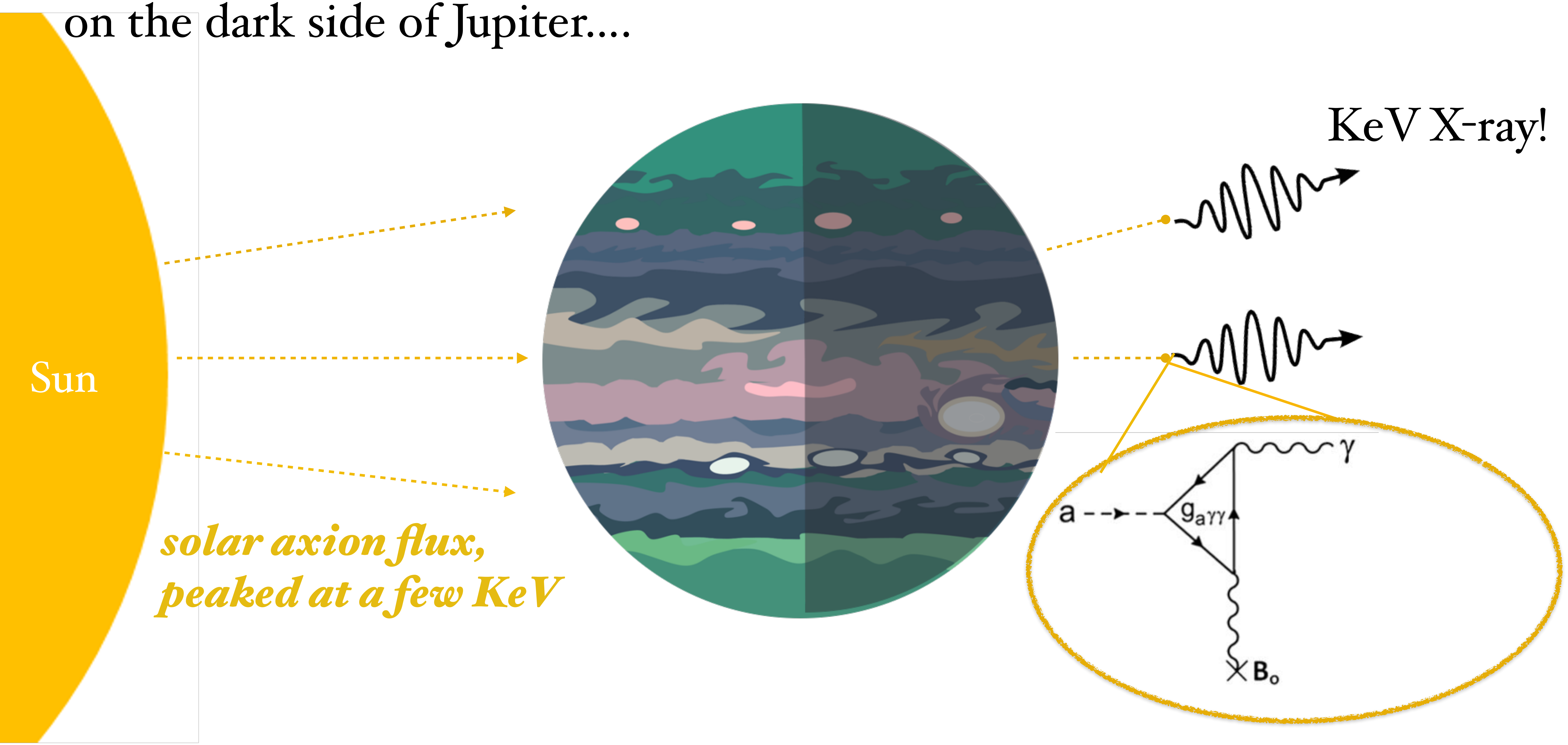
— *In situ* limits on DM-nucleon scattering from Jupiter missions could be comparable to or better than direct detection limits, in particular, for SD scattering.

— This only serves as a first step and an example to use the unusual dataset (e.g. from planetary science) to probe high energy physics!

Thank you!

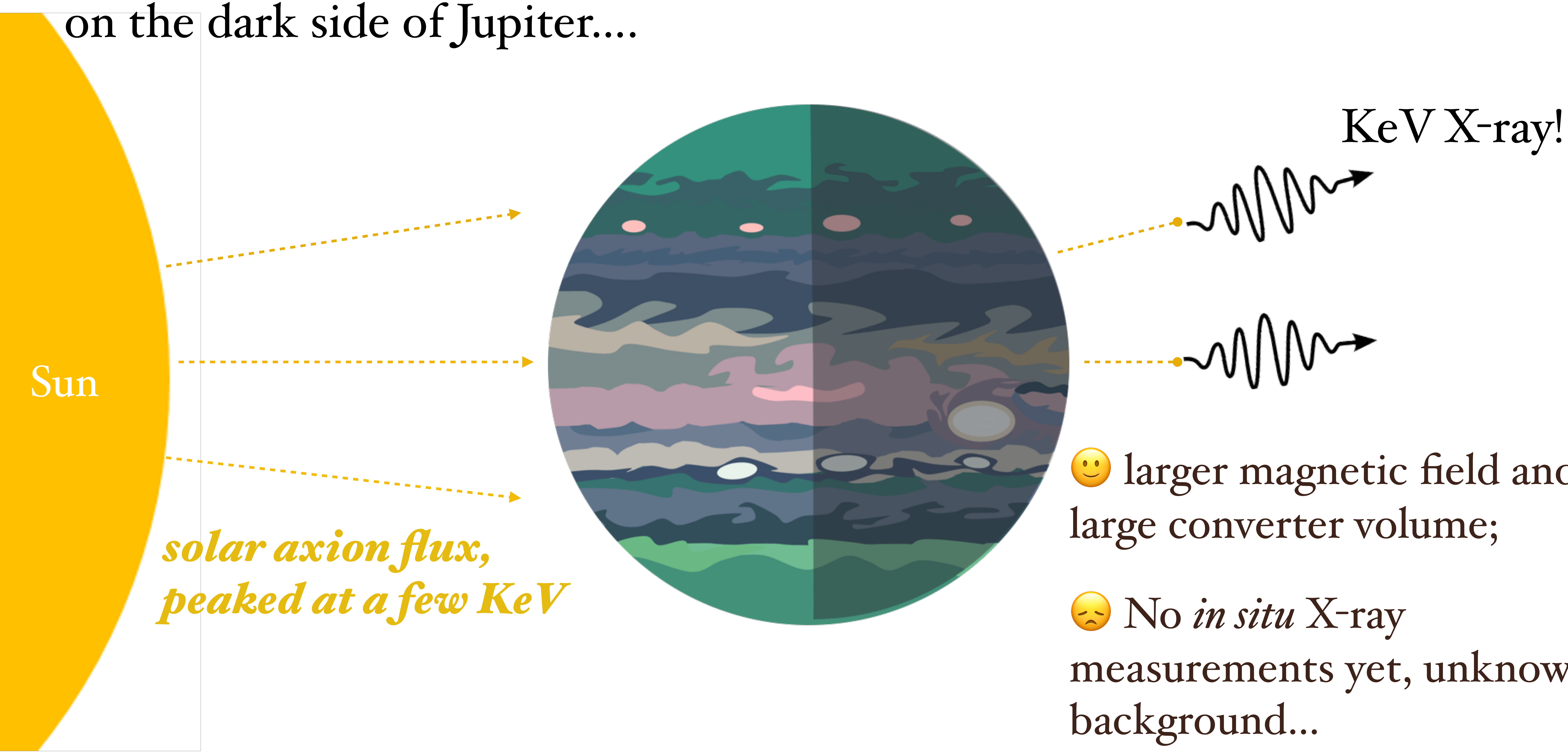
Outlook

Only a first step to use Jupiter data, many other possibilities: X-ray emission on the dark side of Jupiter....



Outlook

Only a first step to use Jupiter data, many other possibilities: X-ray emission on the dark side of Jupiter....



🙂 larger magnetic field and large converter volume;

😞 No *in situ* X-ray measurements yet, unknown background...