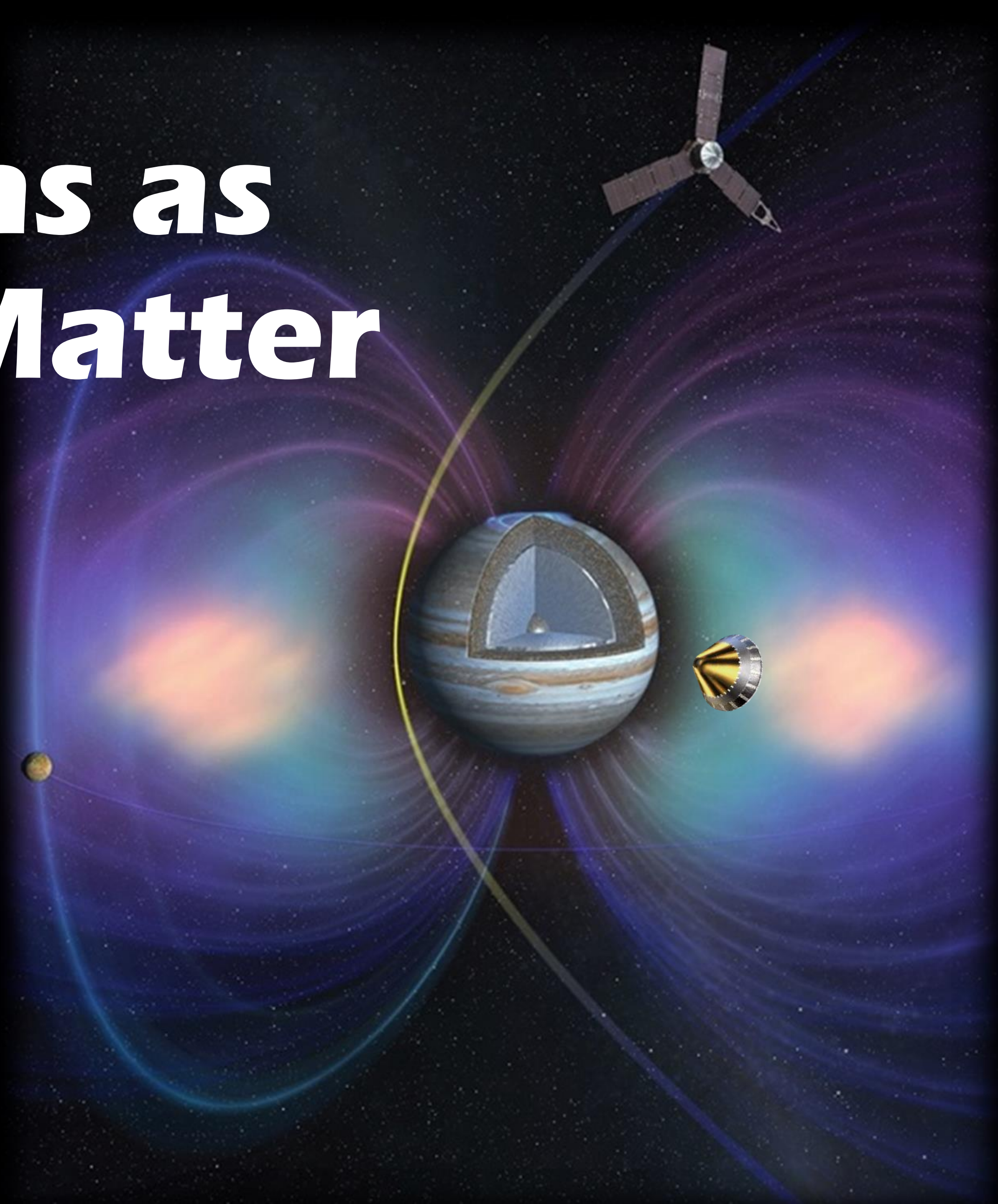
Jupiter Missions as Probes of Dark Matter

Lingfeng Li   Brown University

Sep 15th 2022

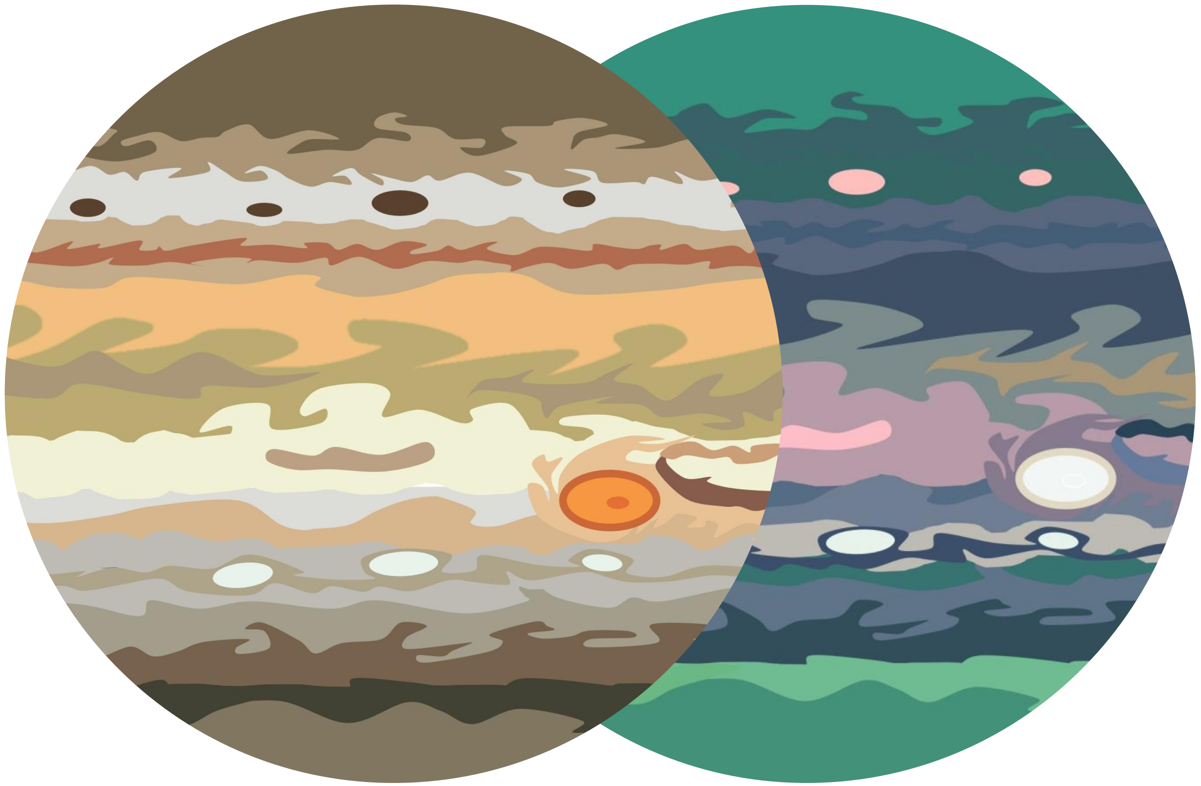
Brookhaven National Lab

Based on arXiv:2207.13709 with JiJi Fan



Outline

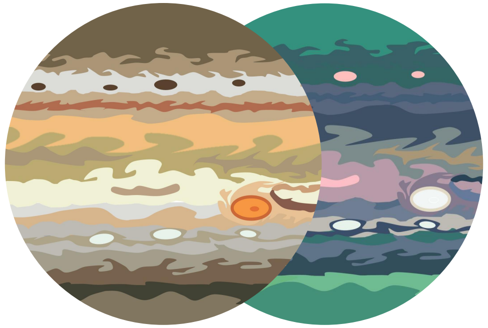
- Introduction
  - About Jupiter
  - About DM
- DM capture by Jupiter and annihilation
- Motion & flux of electron in the magnetosphere
- Numerical results
- Summary & outlook



"HST" (VIS)

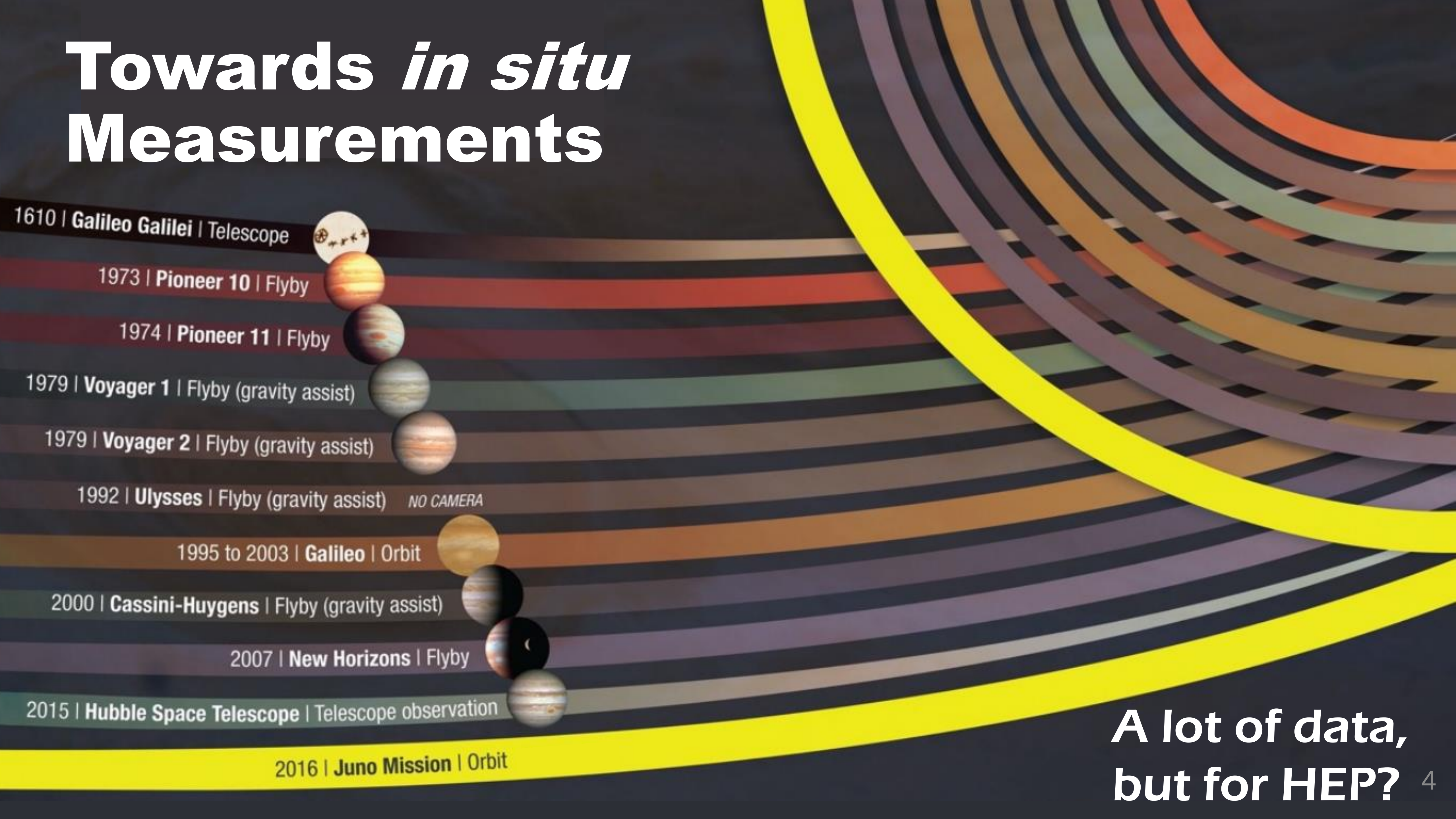
"JWST" (IR)

Why Jupiter?



- ☐ Most massive planet in the solar system: a big detector
- ☐ “Clean” background: not as active as a star
- ☐ Relatively close: easier for both *in situ* and *ex situ* measurements
- ☐ A small and thin main ring

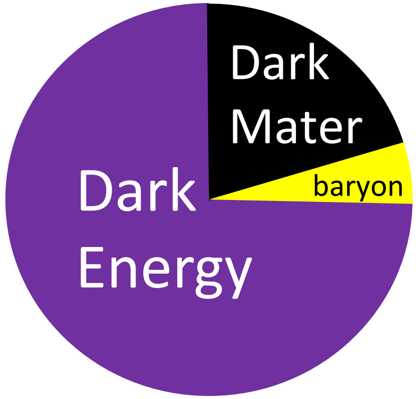
Towards *in situ* Measurements

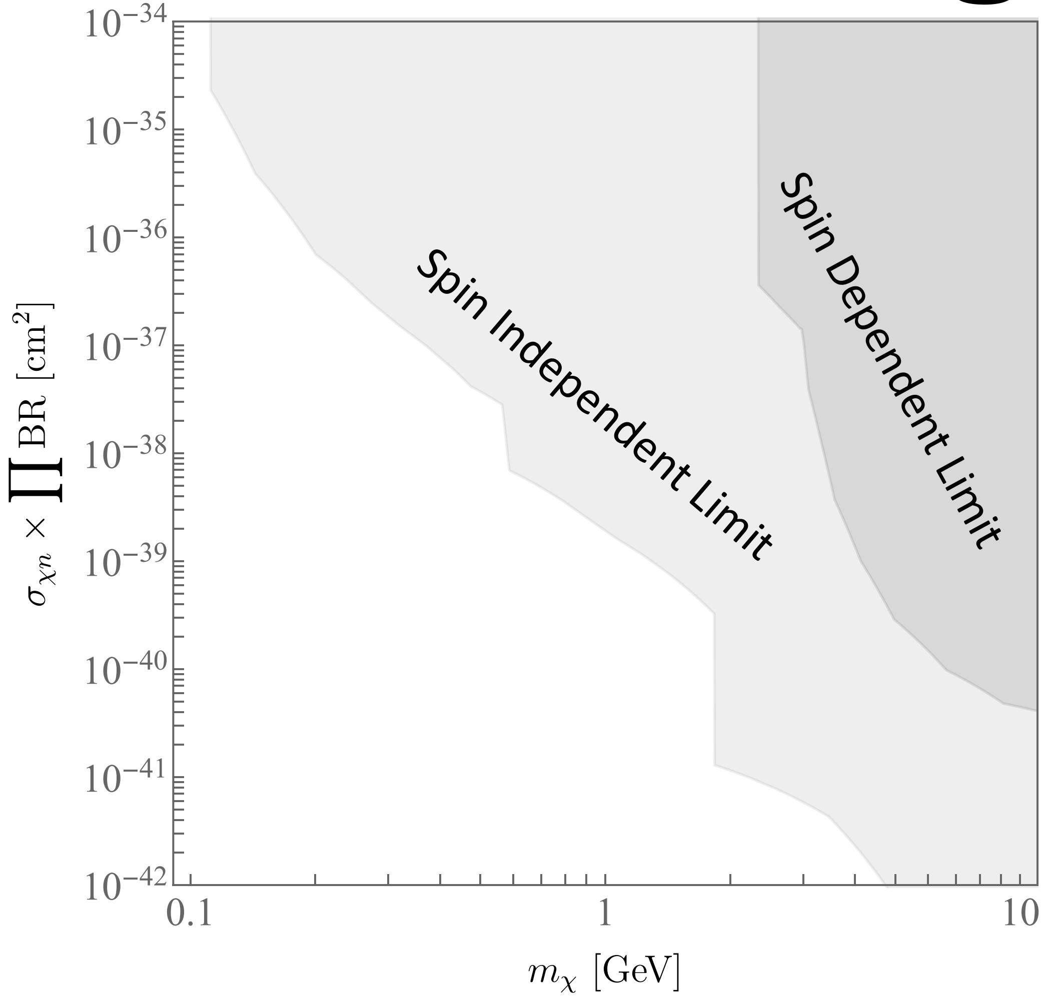


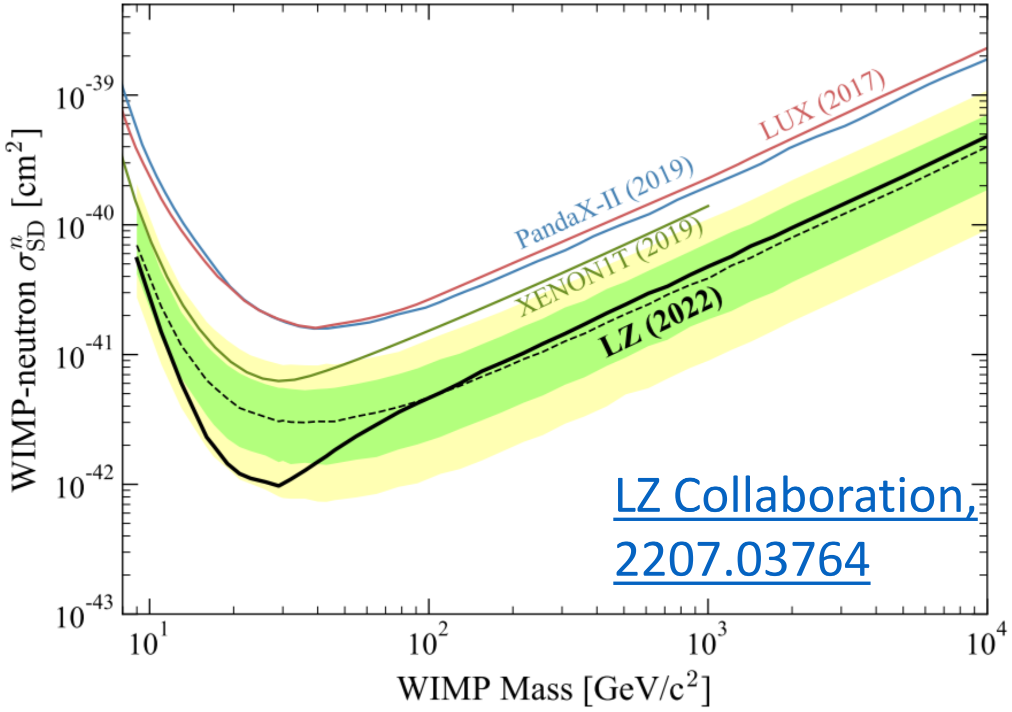
A lot of data,
but for HEP?

Dark Matter in the GeV Range

May I skip ☞ this part?





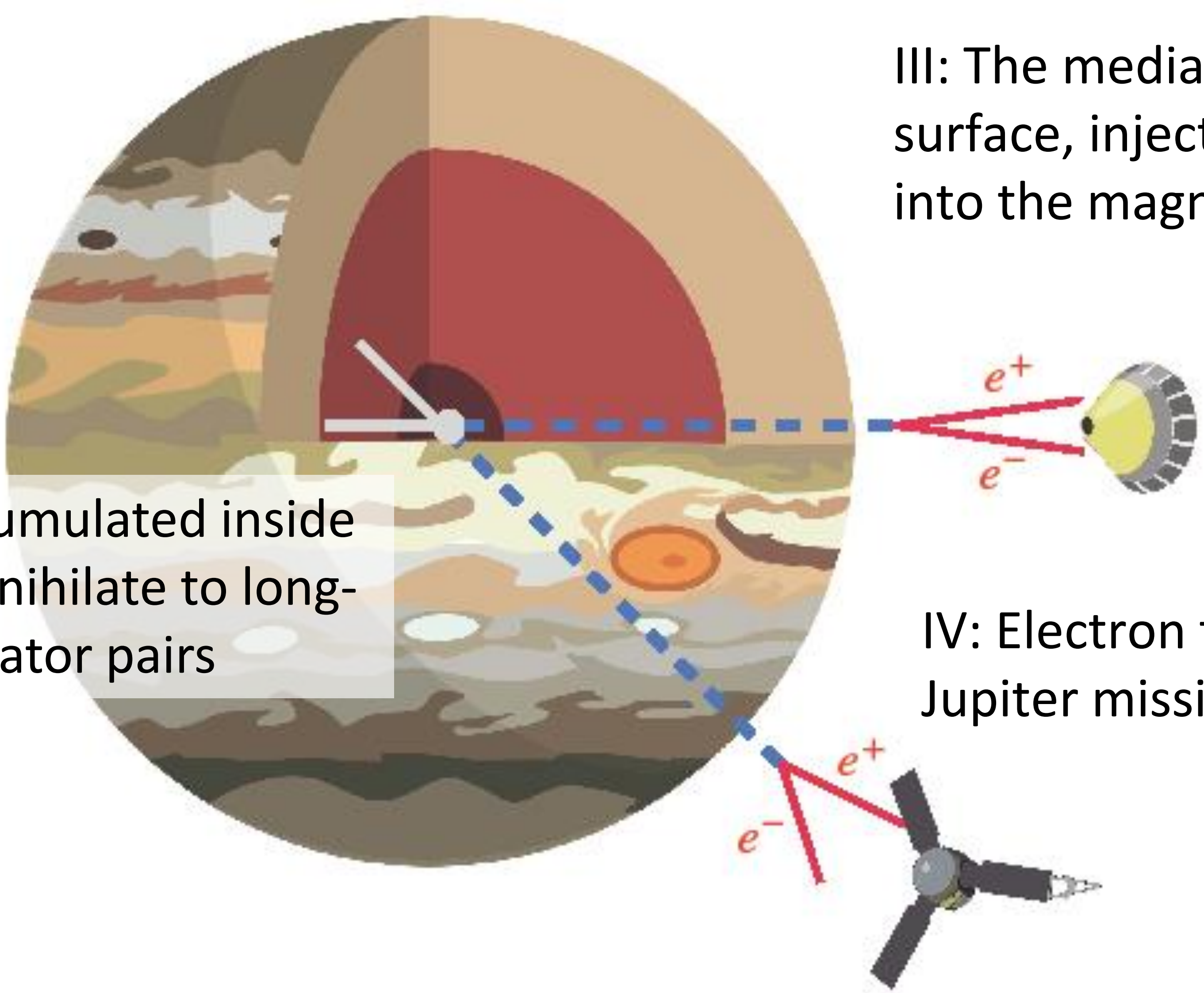


LZ Collaboration, 2207.03764

Direct detection bounds weakens for light DM as the recoiling energy softens

Lingfeng Li 2207.13709

In a Nutshell



I: DM captured by the potential well after elastic scatterings

II: DM accumulated inside Jupiter, annihilate to long-lived mediator pairs

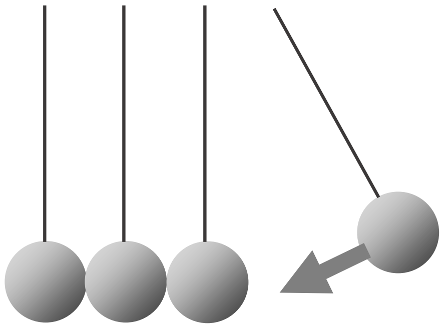
III: The mediators reach the surface, injecting hard electrons into the magnetosphere

IV: Electron flux detected by Jupiter missions

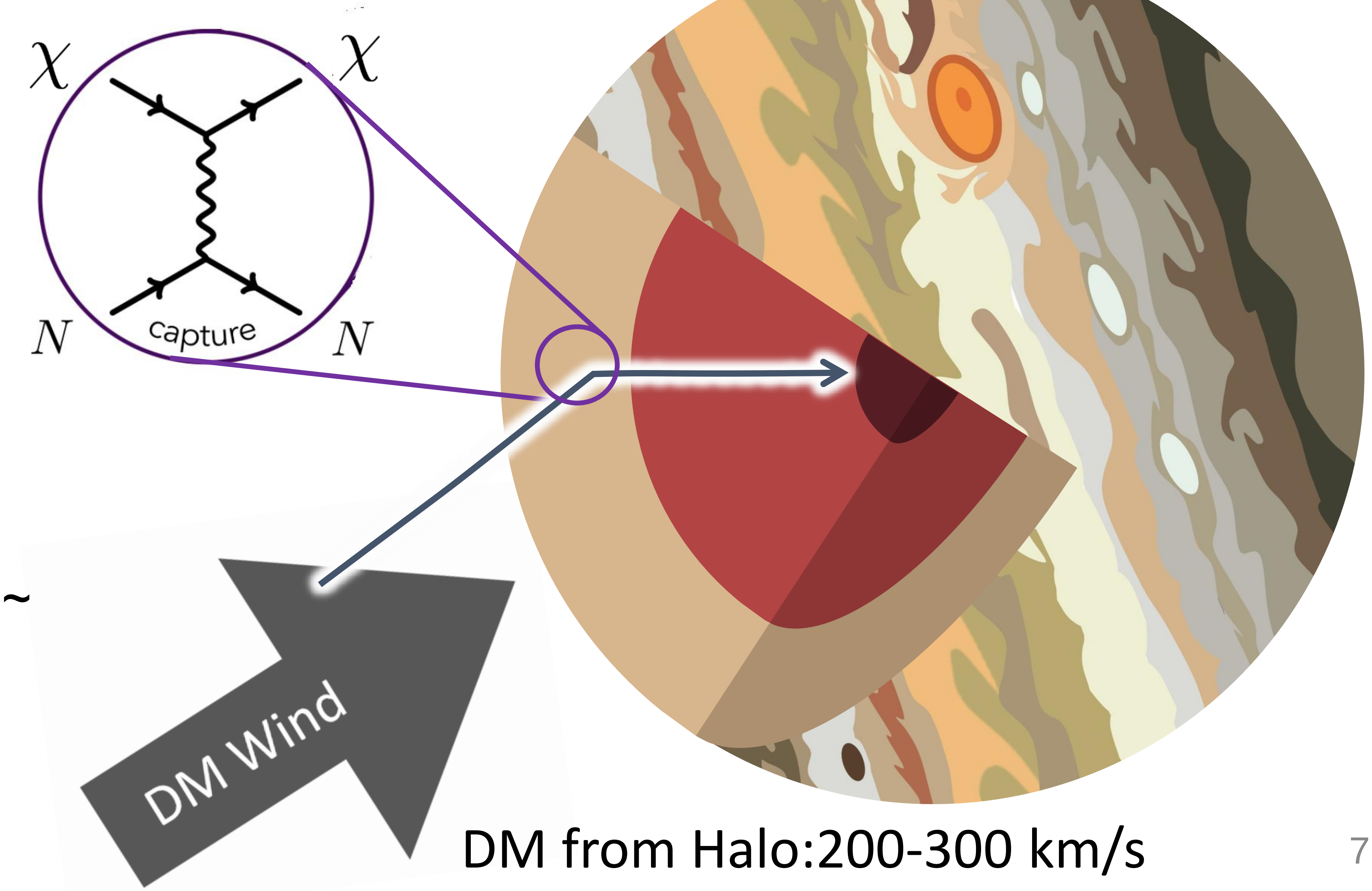
DM Capture

Mostly hydrogen

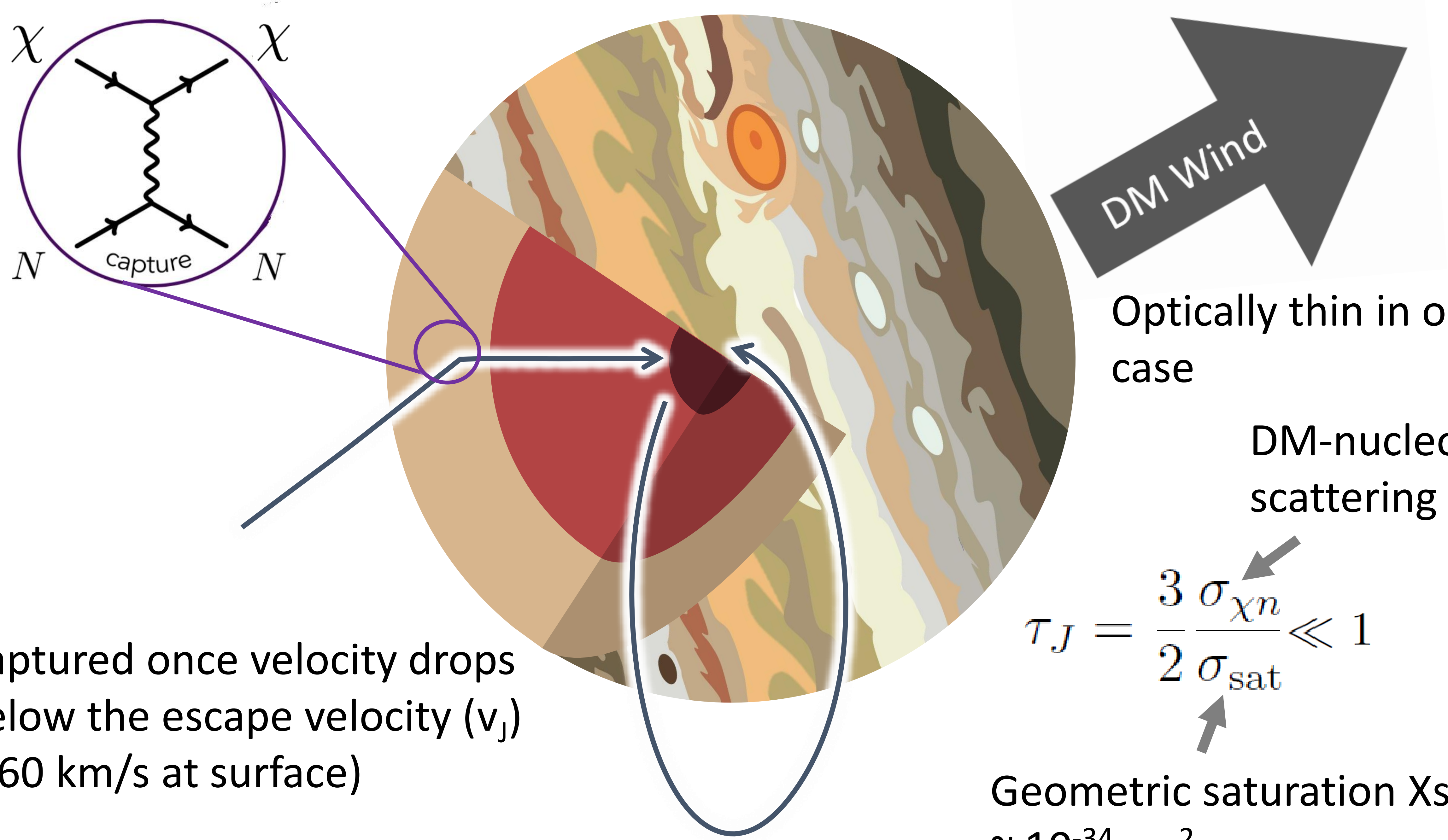
DM transfers energy to nucleons by scattering and slows down



Most efficient when $m_\chi \sim$ 1GeV, comparable to nucleon masses



DM from Halo:200-300 km/s



Optically thin in our case

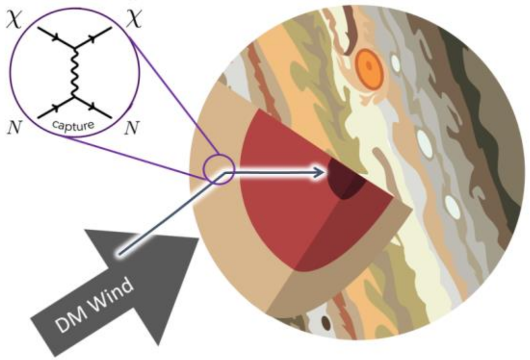
DM-nucleon scattering Xsec

$$\tau_J = \frac{3}{2}\frac{\sigma_{\chi n}}{\sigma_{\rm sat}} \ll 1$$

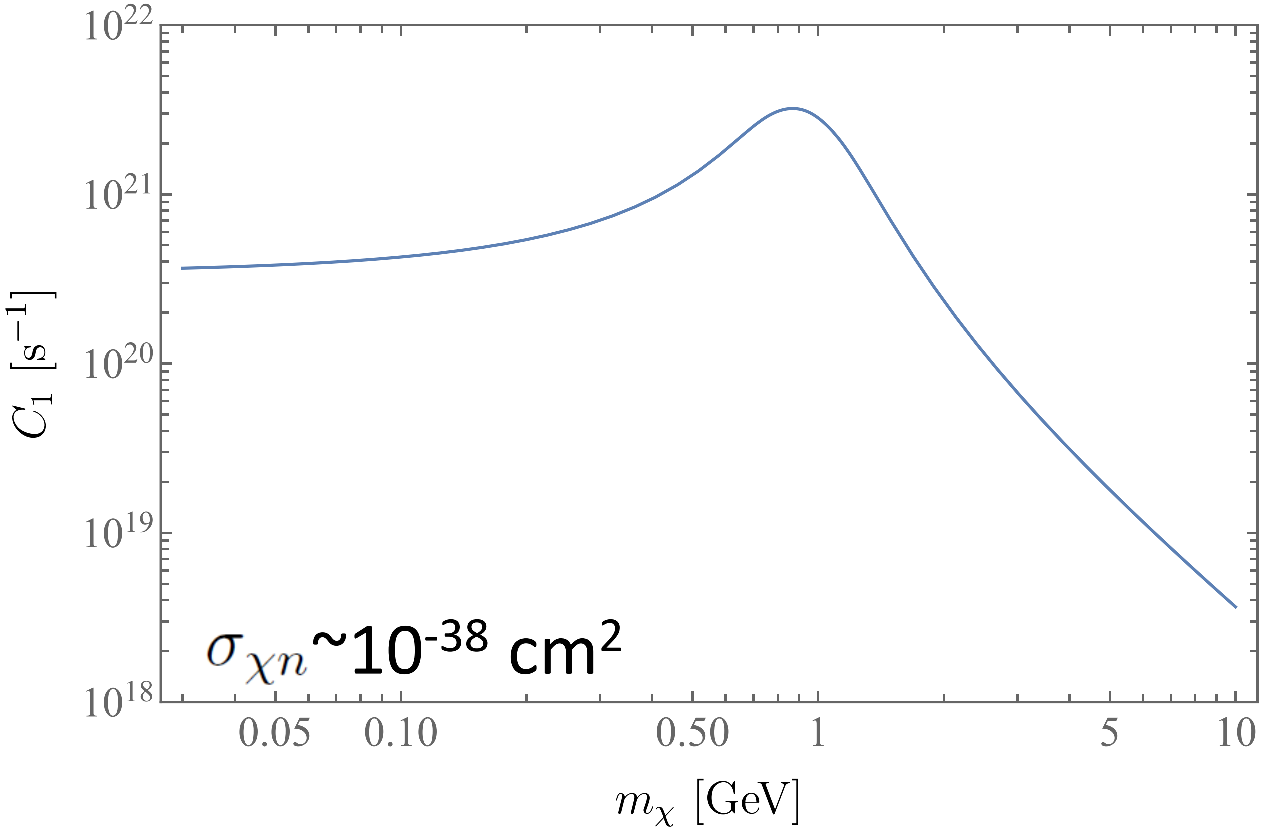
Geometric saturation Xsec ~ 10^{-34} cm^2

Captured once velocity drops below the escape velocity (v_J) (~60 km/s at surface)

DM Capture Rate



Single scattering rate following [A. Gould, Astrophys. J., 321, 1987]



$\sigma_{\chi n}$~10^{-38} cm^2

For multiple scattering, see

[J. Bramante, A. Delgado A. Martin, 1703.04043]

[C. Ilie, J. Pilawa, S. Zhang, 2005.05946]

Spin dependent scattering for weaker constraints: axial-vector type interaction

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

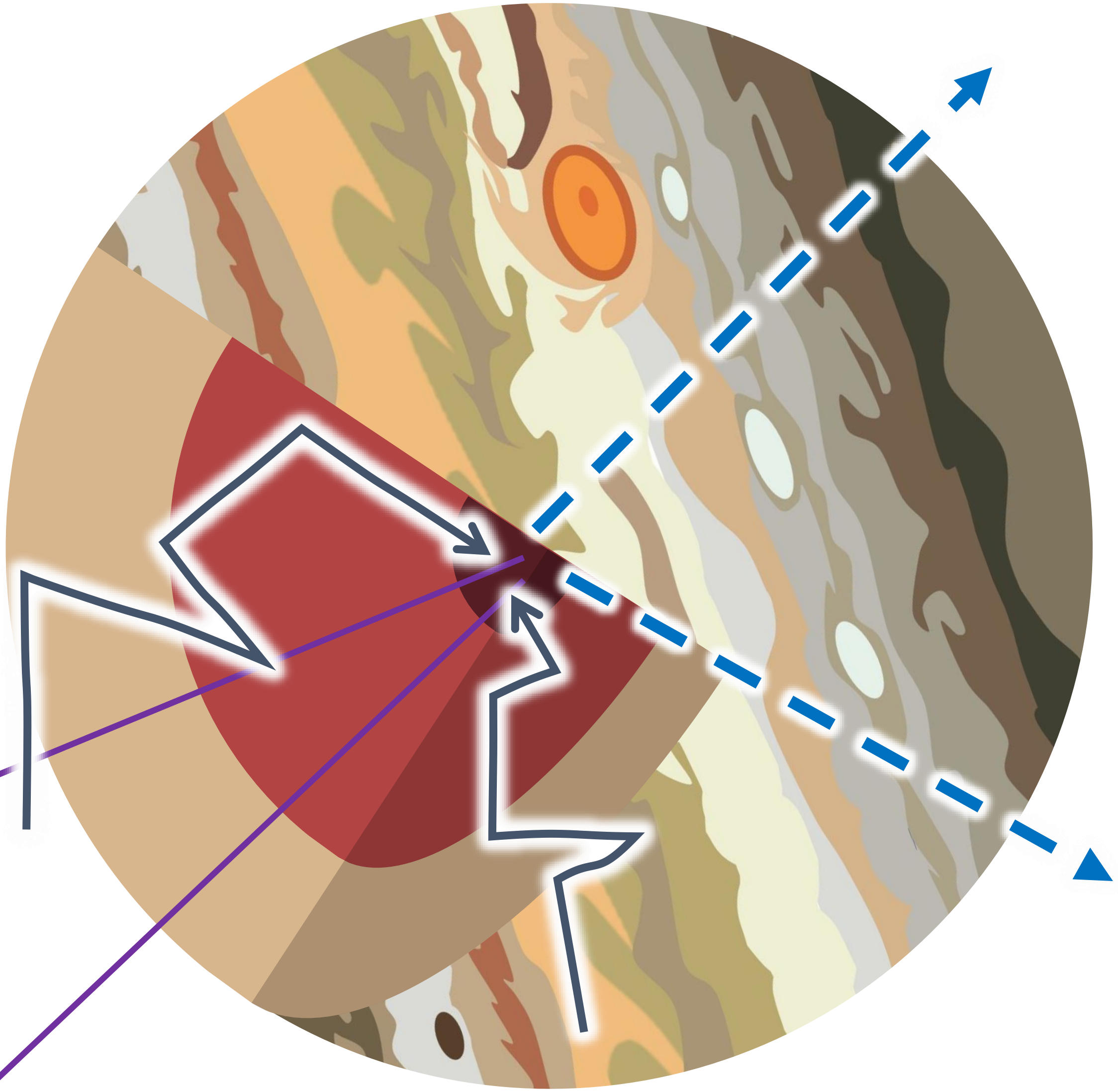
$$\sigma_{\chi n} \approx 3.8\times 10^{-39}\,\mathrm{cm}^2\left(\frac{\mu_{\chi n}}{\mathrm{GeV}}\right)^2\left(\frac{g_\chi g_q}{10^{-3}}\right)^2\left(\frac{10\,\mathrm{GeV}}{\Lambda}\right)^4$$ without violating collider bounds

DM Annihilation inside Jupiter

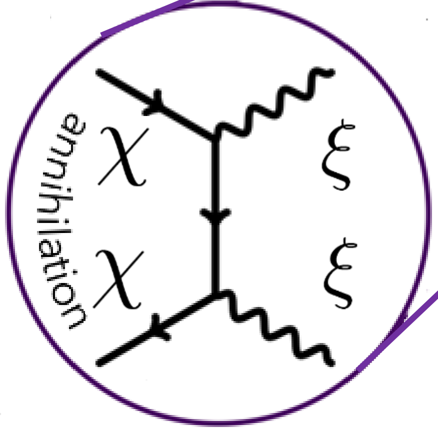
Multiple scattering after capture, high density around the core

$\langle \sigma_{\rm ann} v \rangle \lesssim O(10^{-27})$ cm^3 s^{-1}, mostly from CMB spectrum distortion

R. K. Leane, T. R. Slatyer, J. F. Beacom, K. C. Y. Ng, 1805.10305

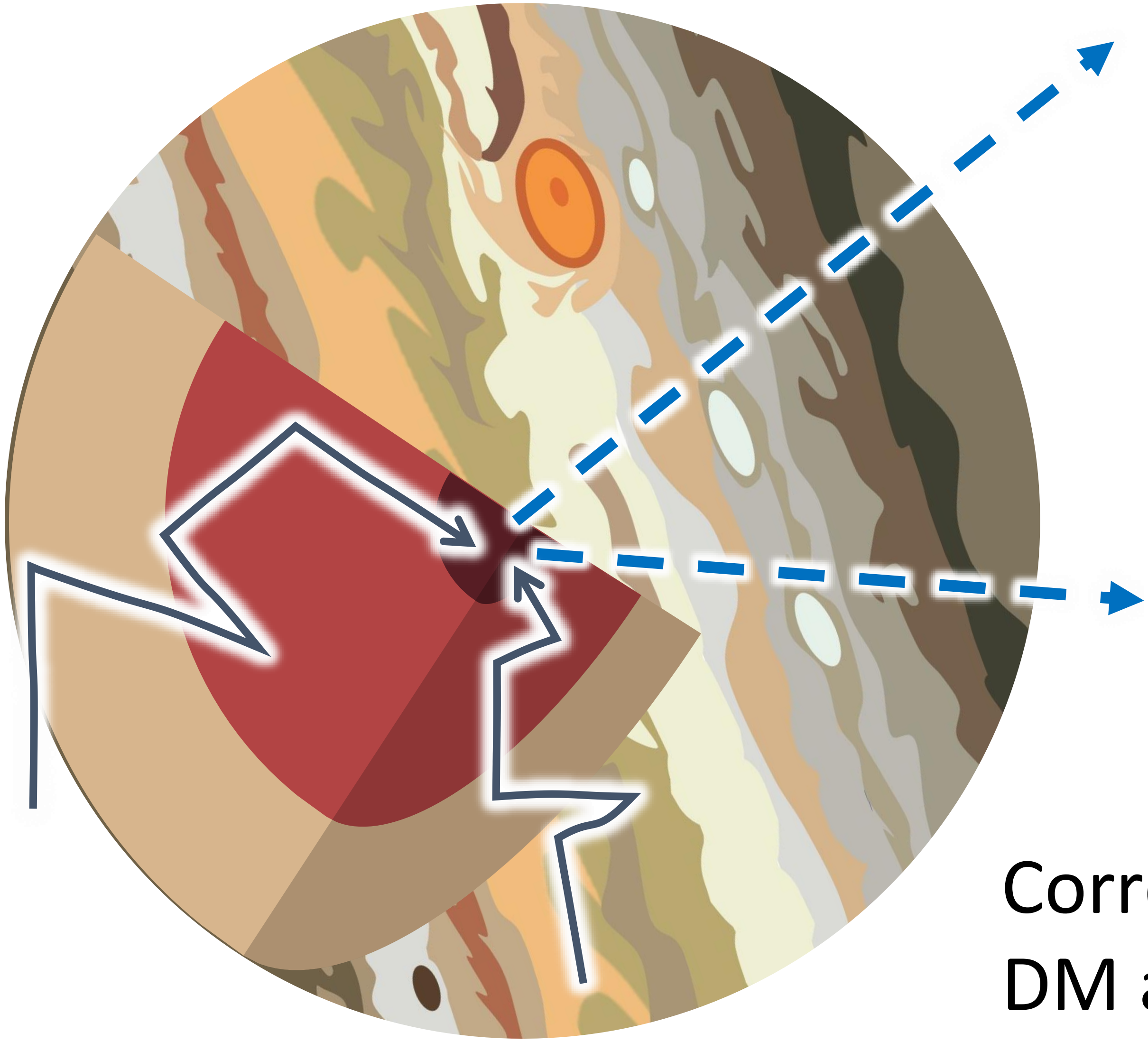


2→2 annihilation to long-lived messengers ξ



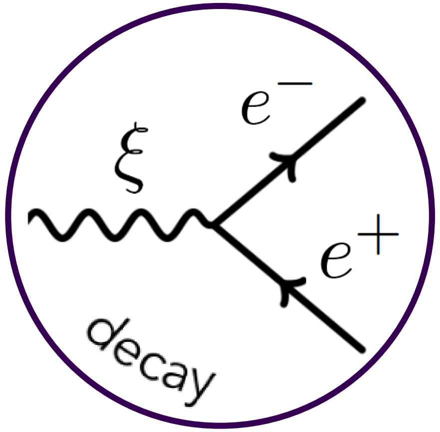
$\bar{\chi}\chi \to \bar{q}q$ through $\frac{g_\chi g_q}{\Lambda^2}\left(\bar{\chi}\gamma^\mu\gamma^5\chi\right)\left(\bar{q}\gamma_\mu\gamma^5 q\right)$

is “forbidden”, suppressed by $m_\chi^2 m_q^2/\Lambda^4$ & $(g_\chi g_q)^2$



For a dark photon with kinetic mixing ε to SM photon, $c\tau$ ~$O(10^4)$ km means $\varepsilon<10^{-9}$:

- ☐ Very elusive for lab experiments
- ☐ Too small for DM capture
- ☐ Go though Jupiter easily

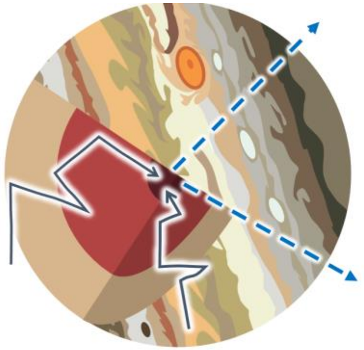


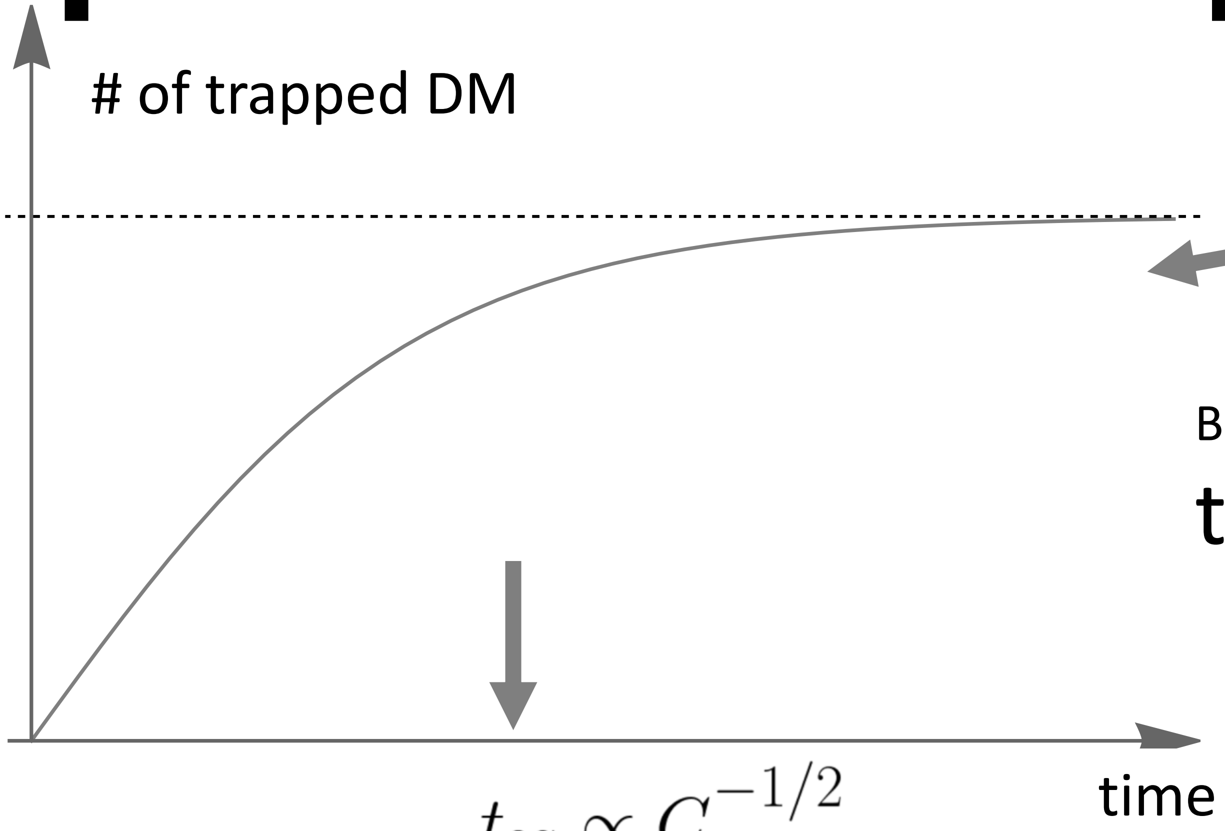
Decay to electrons: also final states for leptonic (μ→eνν) & hadronic (π→μν, K→ππ)

Correction due to branching ratios of DM annihilation & mediator decays

$$\prod \mathrm{BR} \equiv \mathrm{BR}(2\chi \to 2\xi) \times \mathrm{BR}(\xi \to e^+e^-)$$

Equilibrium and Evaporation





$t_{\mathrm{eq}} \propto C_1^{-1/2}$

Equilibrium: Capture rate simply = annihilation rate/2

Benchmark (m_χ=1 GeV)

$t_{eq} \sim 10^{16}$ sec

$\lesssim$

Jupiter lifetime

$t_J \sim 1.5 \times 10^{17}$ sec

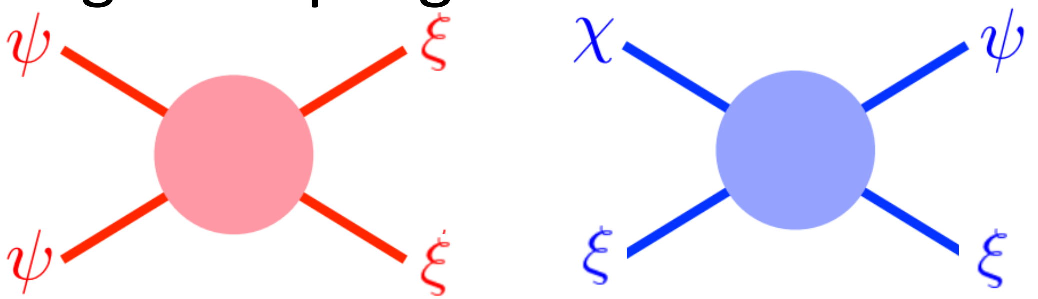
As DM thermalizes, they "leak out" via exponential tails in kinematic distributions: DM lighter than ~1 GeV evaporates significantly A. Gould, 1990

R. Garani, S. Palomares-Ruiz, 2104.12757

A Right Ω_{CDM}?

Small annihilation for “WIMP miracle”, may overclose the universe

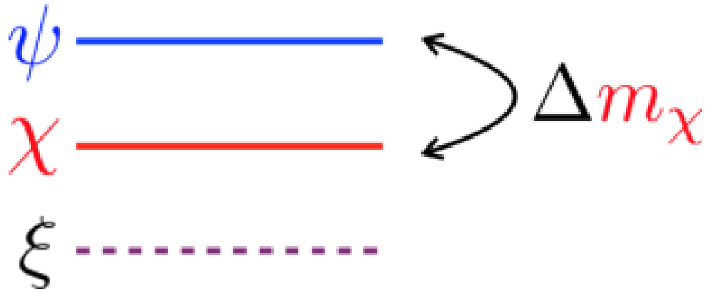
Thermal way out: dark partner (ψ) with stronger coupling to the mediator:



Coannihilation / Coscattering

M. Garny, J. Heisig, B. Lülf, S. Vogl, 1705.09292
R. D’Agnolo, D. Pappadopulo, J. Ruderman, 1705.08450
R. D’Agnolo, C. Mondino, J. Ruderman, P. Wang 1803.02901
H.C. Cheng, LFL, R. Zheng 1805.12139 ……

Exponentially sensitive to the mass gap and the mediator mass, large flexibility……



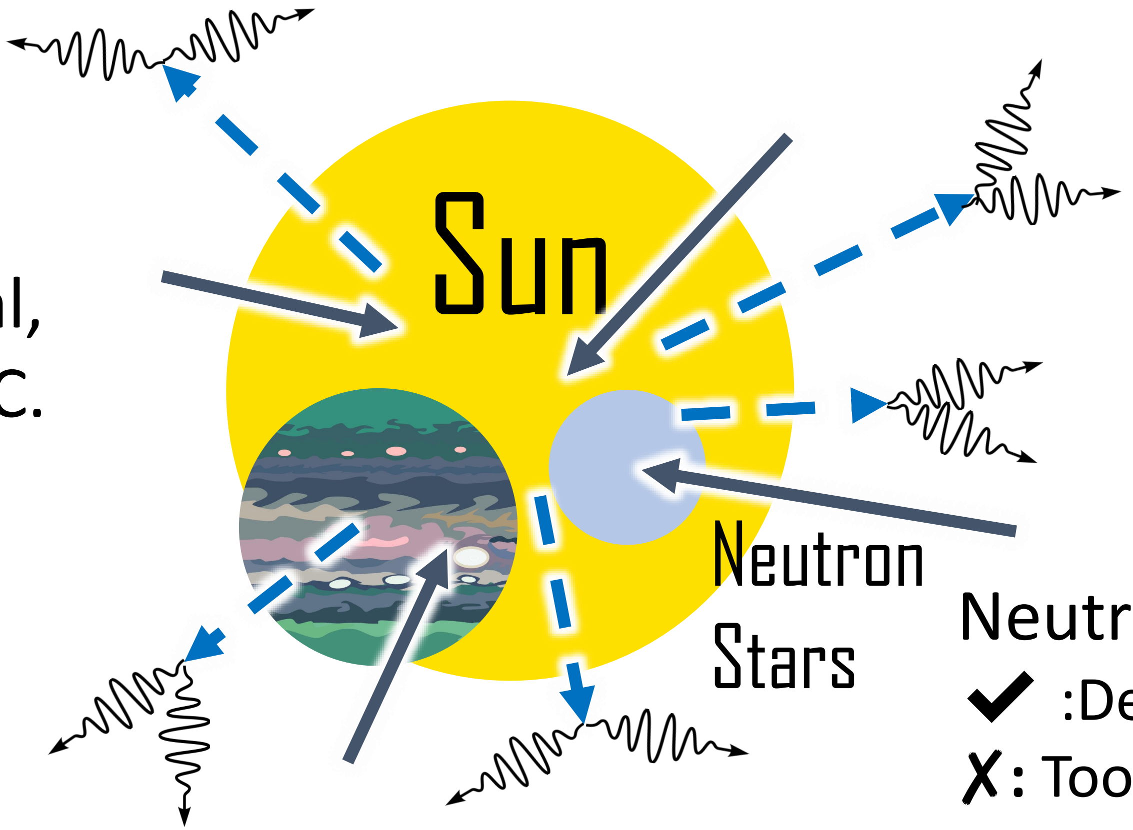
Non-thermal way out: early matter domination diluting DM generated

* We stay agnostic about DM production in this talk

Previous Studies on DM Capture

Gamma-Ray signals are most studied:

- ☐ Good *ex situ* potential, e.g., Fermi-LAT, HAWC.
- ☐ Easy to understand: Photons travel in straight lines
- ☐ Spectroscopy & morphology



The Sun

✓: Massive and close.

✗: Higher background, high temperature that evaporates light DM

Neutron stars:

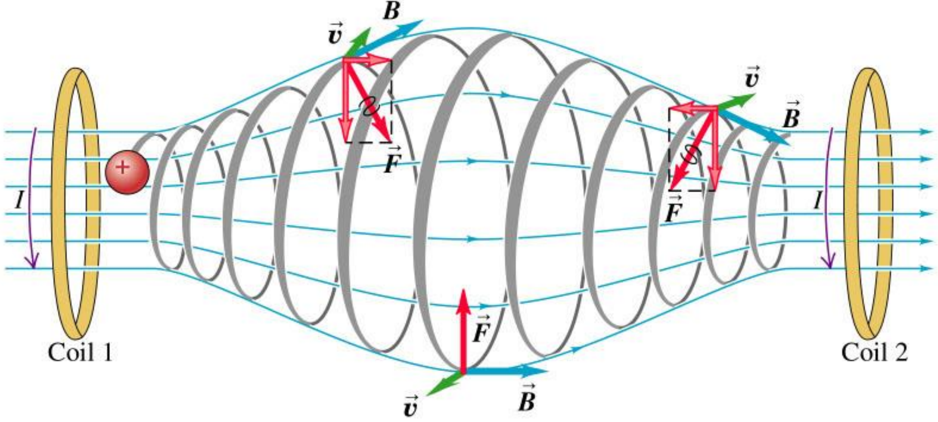
✓ :Dense and massive

✗: Too far away & systematics

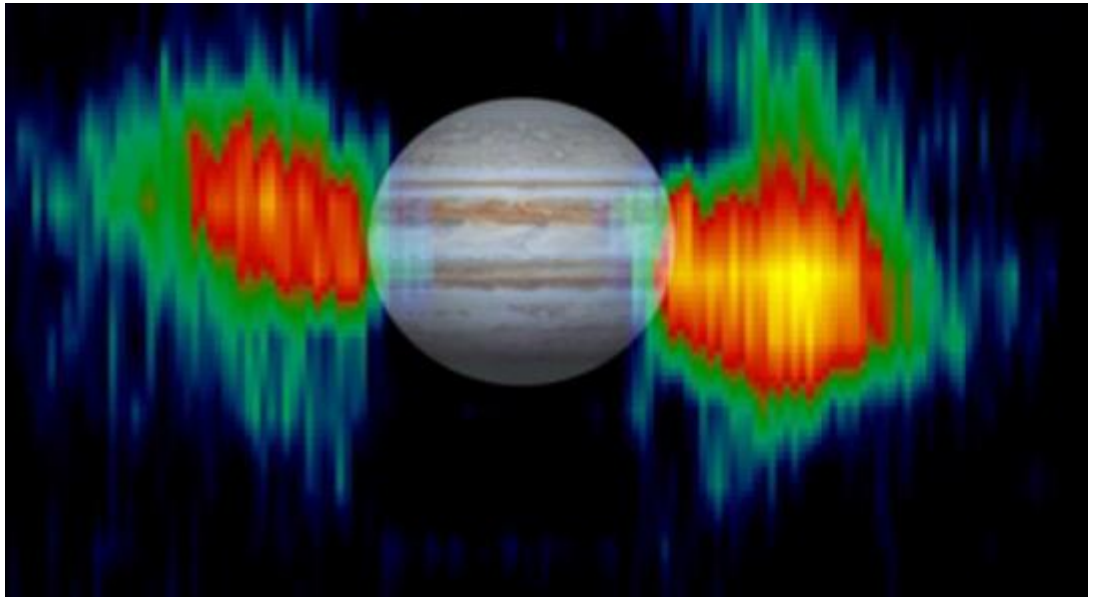
N. Giglietto, 0907.0541 B. Batell, M. Pospelov, A. Ritz, Y. Shang, 0910.1567 P. Schuster, N. Toro, N. Weiner, I. Yavin, 0910.1839 J. L. Feng, J. Smolinsky, P. Tanedo 1602.01465 V. Brdar, J. Kopp, J. Liu, 1607.04278 R. K. Leane, K. C. Y. Ng, J. F. Beacom, 1703.04629 HAWC collaboration, 1808.05624 R. K. Leane, T. Linden, 2104.02068 and many more!

Motion in the Magnetosphere

Electrons/positrons produced will be hold by the magnetic bottle effect.



Copyright © 2004 Pearson Education, Inc., publishing as Addison Wesley.



Trapped inside for a long time (≫ sec) rather than escaping

→ The origin of the radiation belt

Three basic modes inside an approximate dipole field

Lorentz force

- ☐ **Gyration** around field lines (≫ kHz)

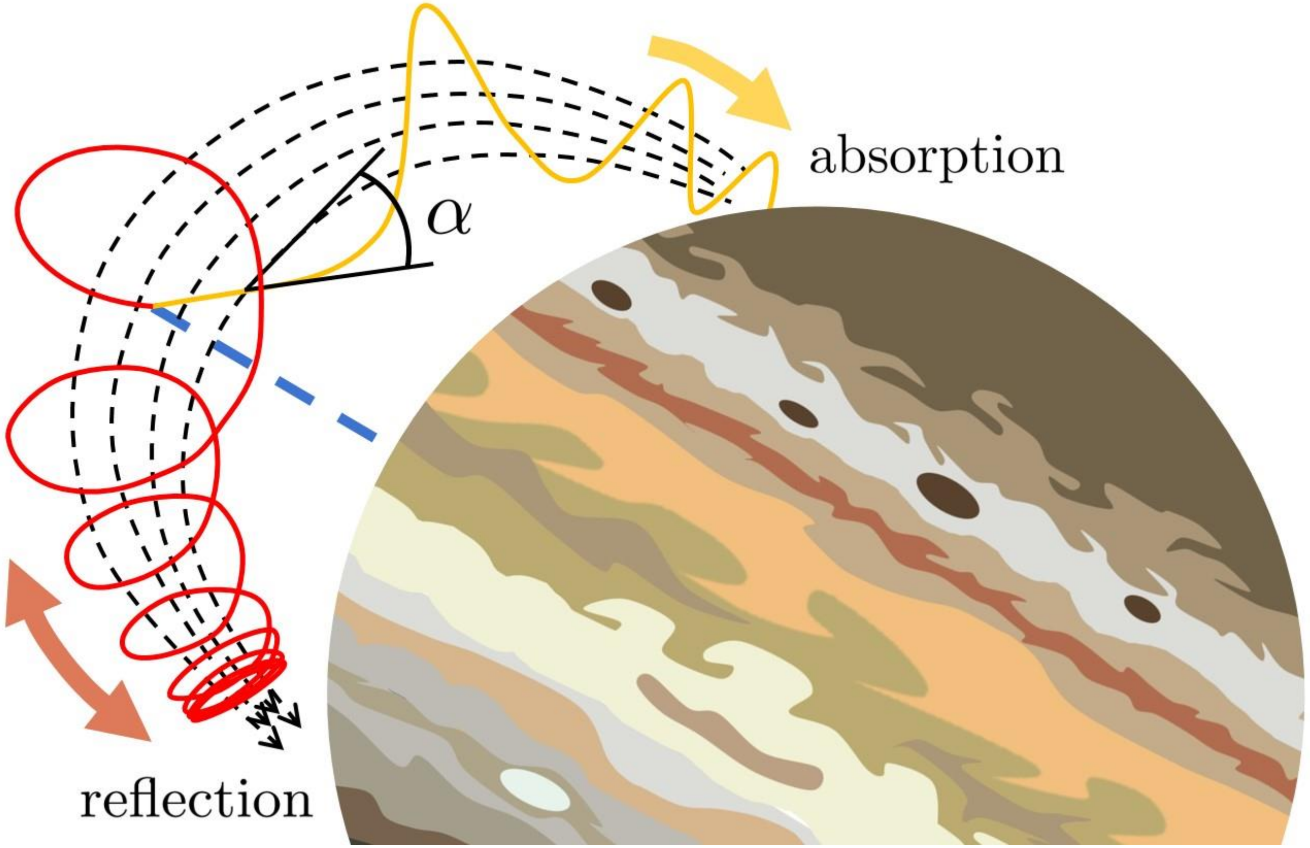
Magnetic mirror/bottle effect

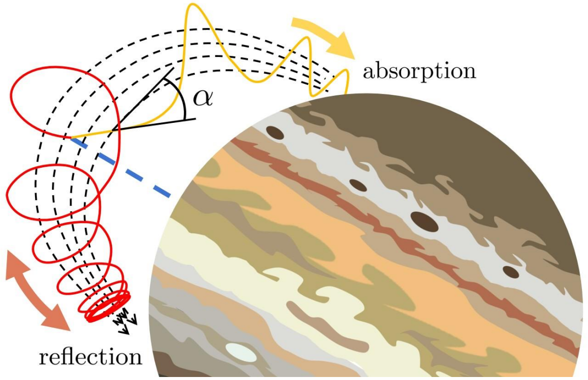
- ☐ **Bounce** between two mirror points (~ Hz)

Gradience of the B field

- ☐ **Drift** in the azimuthal/longitudinal direction (< mHz)

M. Schulz, L. J. Lanzerotti, 1974

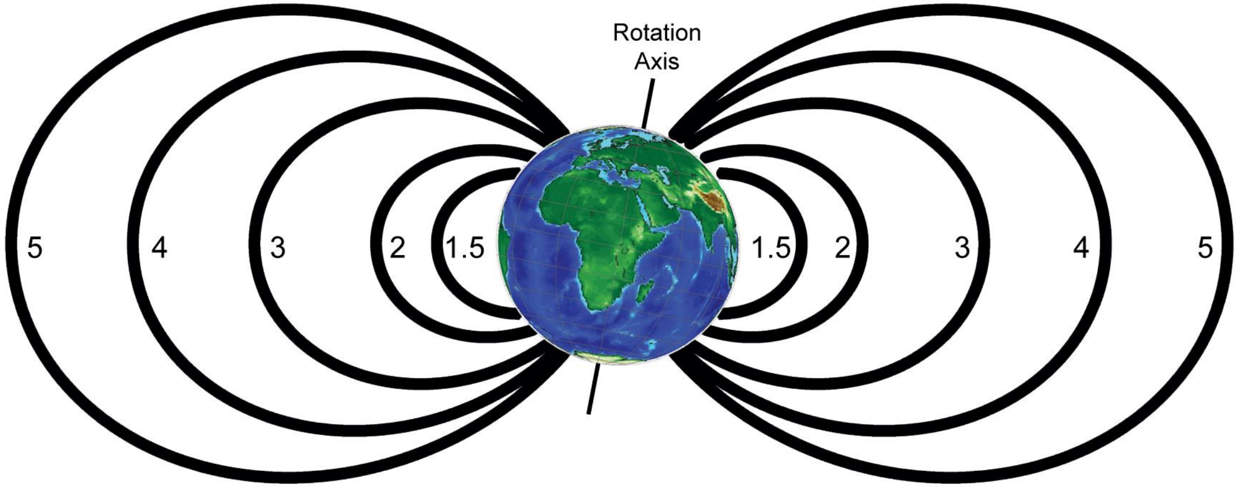




Phase Space Parameters

At least 3 “physical” parameters to describe the phase space:

1) E: Kinetic energy



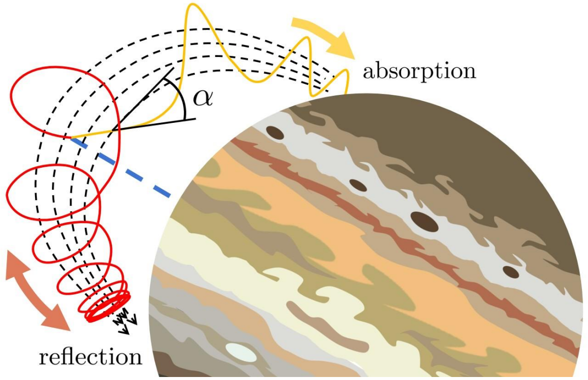
2) L: Mcilwain L-parameter

[C. E. McIlwain, 1961]

Lines with L × radius in the magnetic equator plane if it is dipole

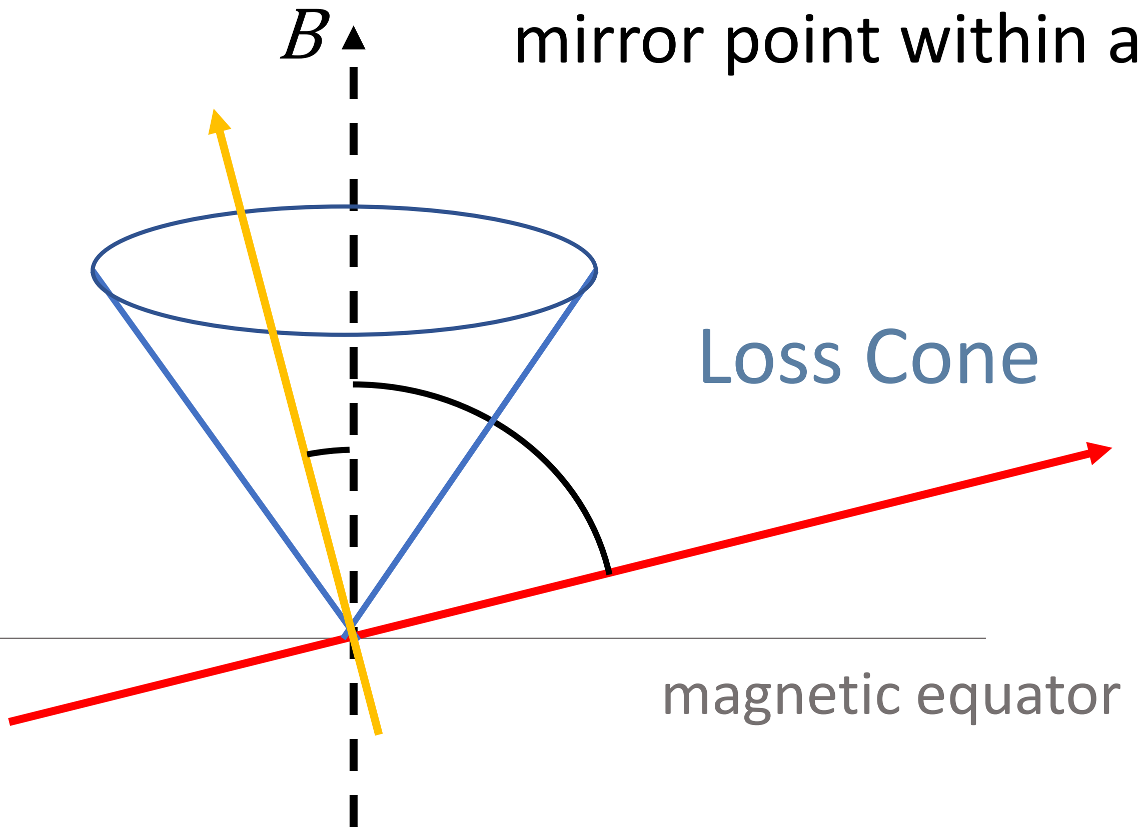
For the time scale considered for hard electrons, limited on the same L-shell for all the time (bounce & drift)

Phase Space Parameters



3) α_{eq}: Equatorial pitch angle

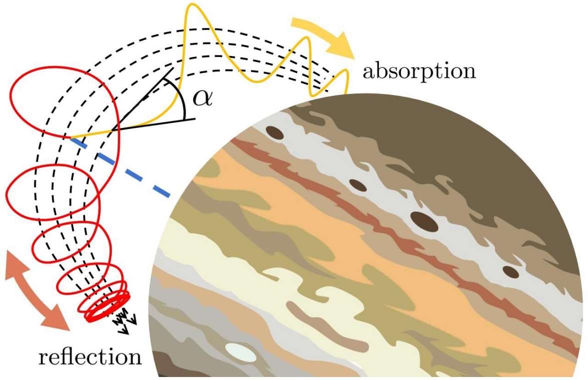
Small α_{eq}: inside loss cone
mirror point within atmosphere



Large α_{eq}: outside loss cone
mirror point away from the
atmosphere & long-lived

The loss cone shrinks with L
e.g., $\alpha_{eq} > 0.75$ (0.47) for L=1.2 (1.5)

Diffusion Equation



A. M. Lenchek, S. F. Singer, R. C. Wentworth, 1961

f = Phase space density

Source term: averaged over trajectories

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

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

Friction terms: energy loss with time (number conserving)

D. Santos-Costa, S. A. Bourdarie, 2001

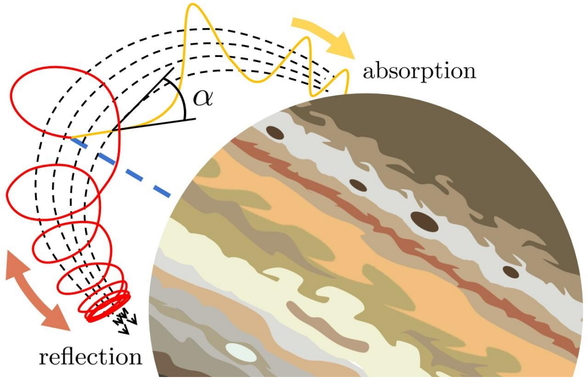
$$\tau_{\rm loss}^{-1}f \quad + \quad \text{diffusion terms}$$

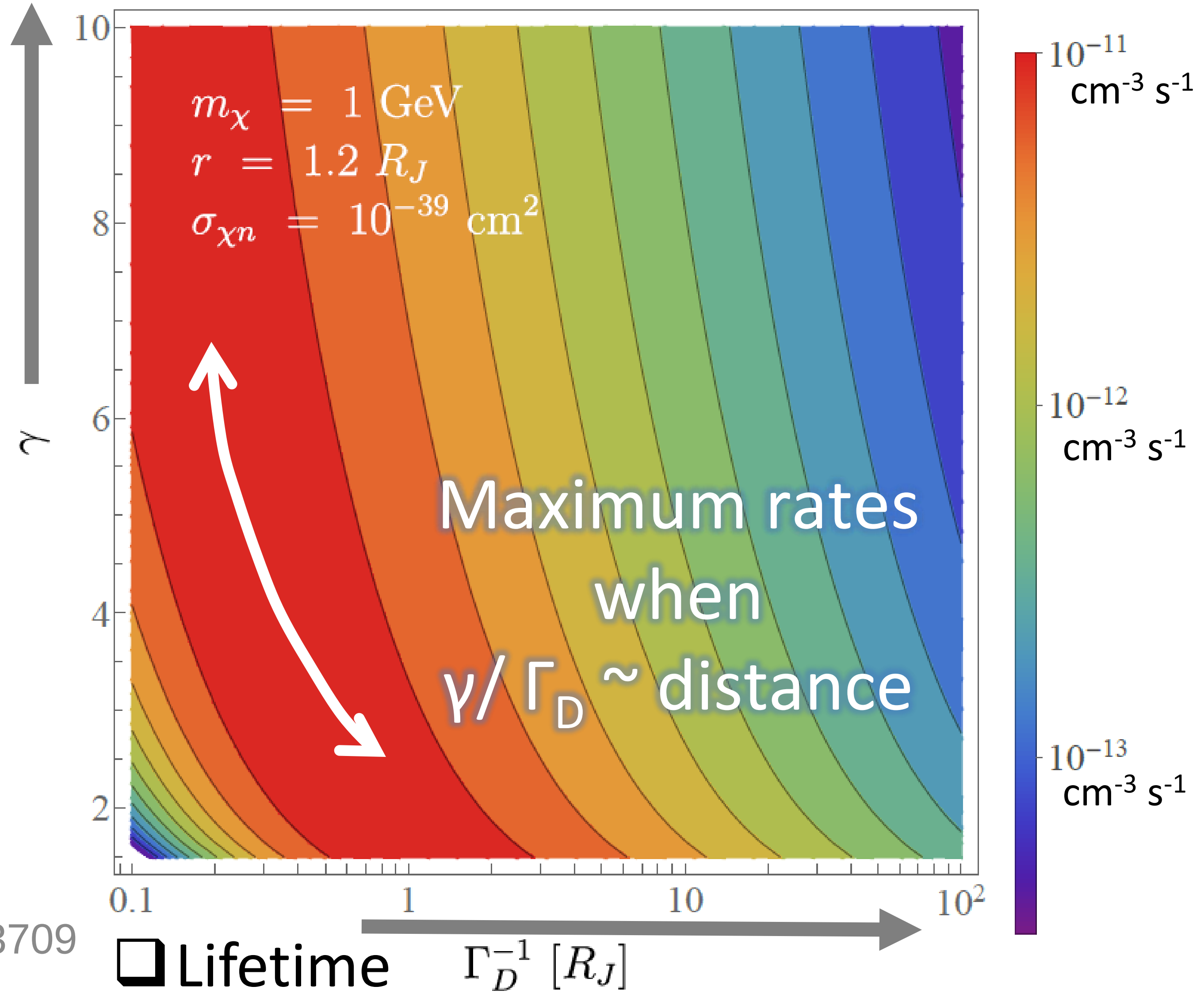
Electron number loss (and its time scale)

Suppressed for our discussion

Q. Nenon, A. Sicard, S. Bourdarie, 2017

Decay Rate Density



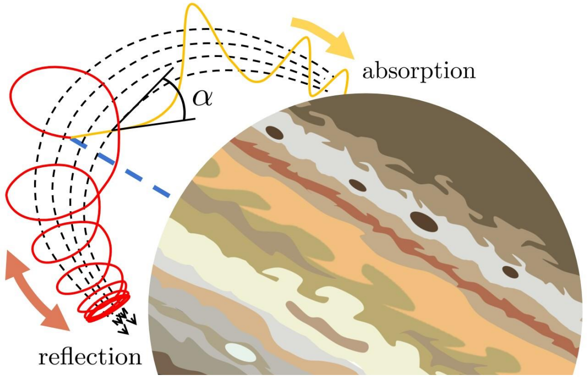


☐Boost ~ m_χ/m_ξ

☐Lifetime

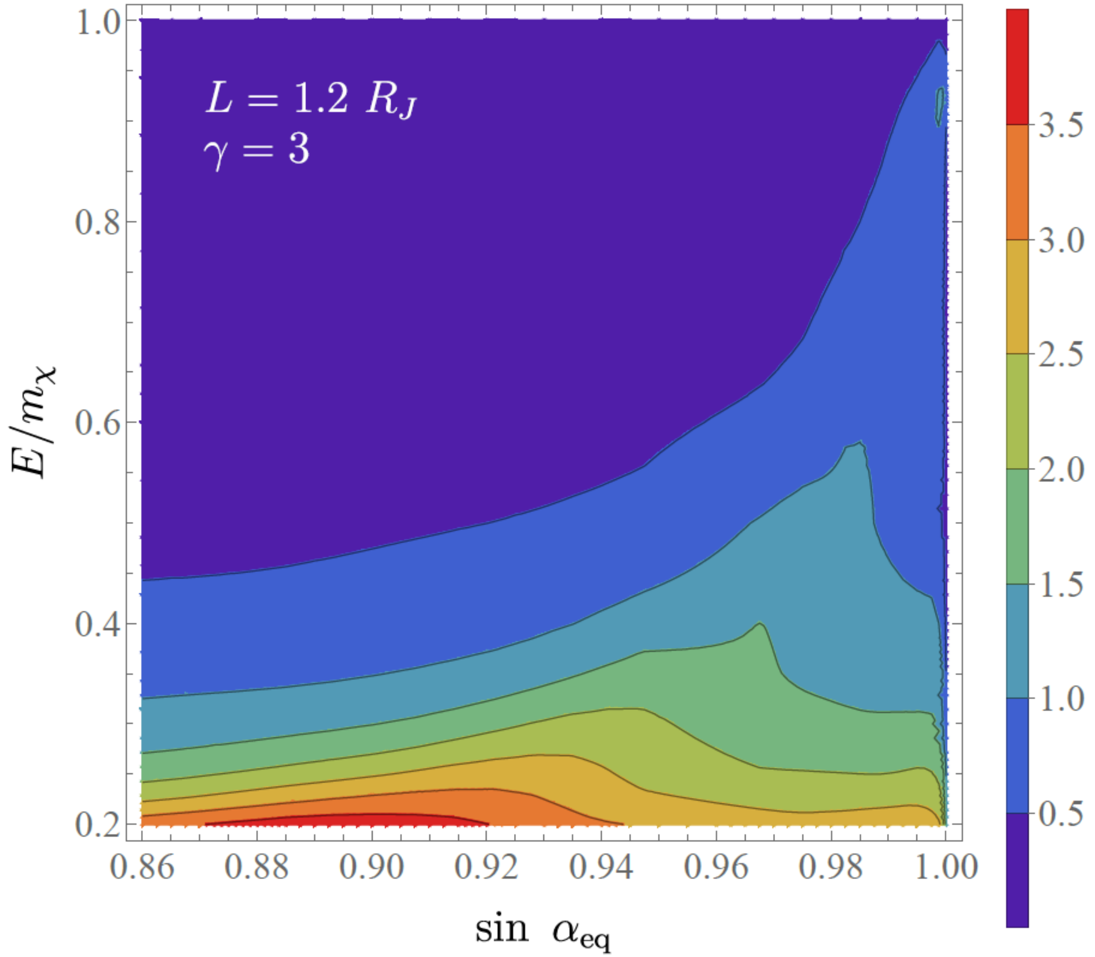
Maximum rates when γ/Γ_D ~ distance

* The volume is large to compensate

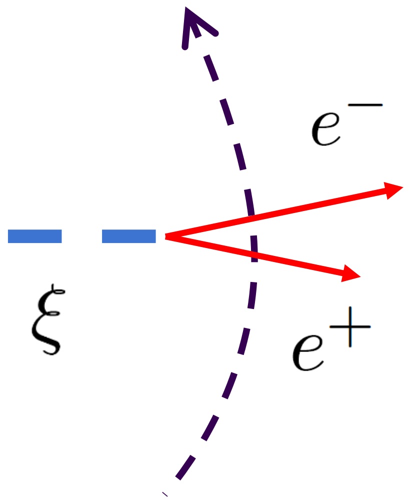


Source Term

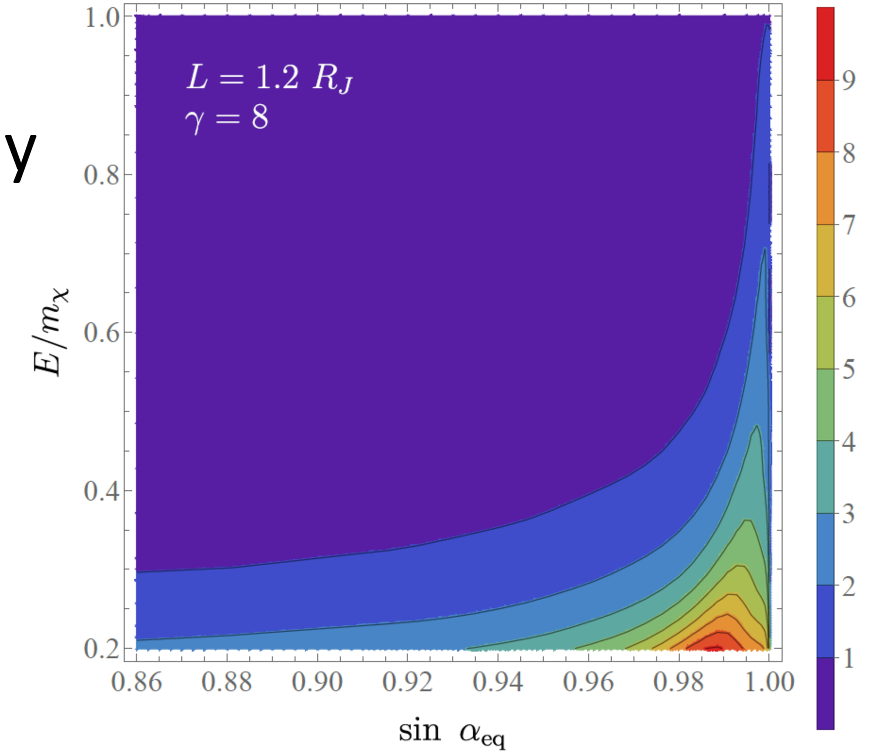
Injected electrons' phase space distribution



Dimensionless form for unit decay rate density

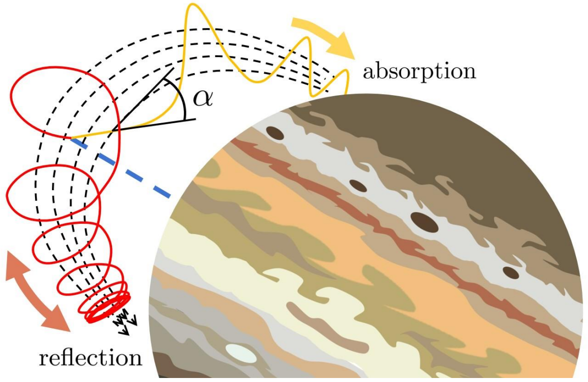


Tends to have high α_{eq}: boost $\gamma>1$



Scales as E^{-2} before integration

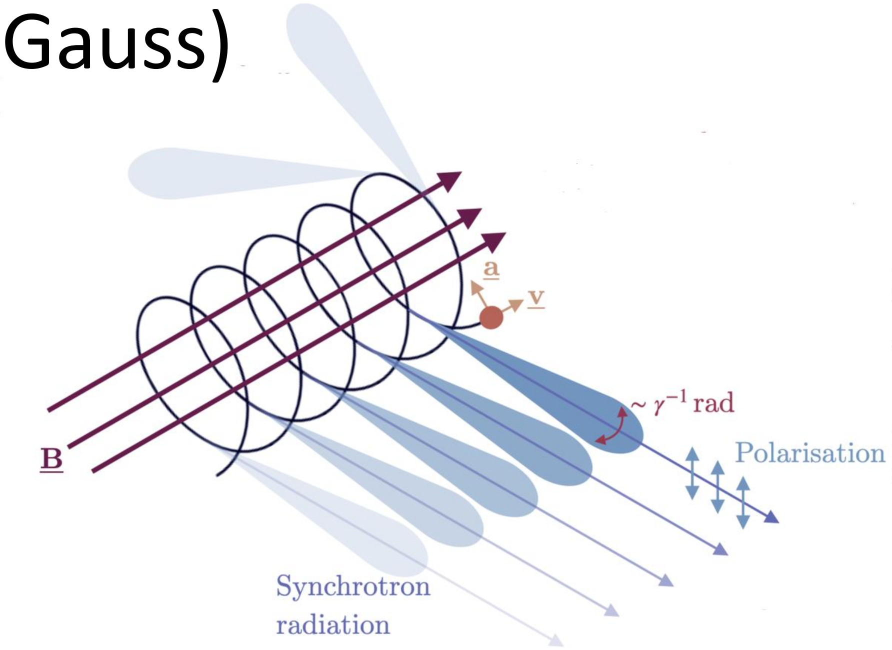
Synchrotron Friction



Fast energy loss for hard electrons > O(10) MeV

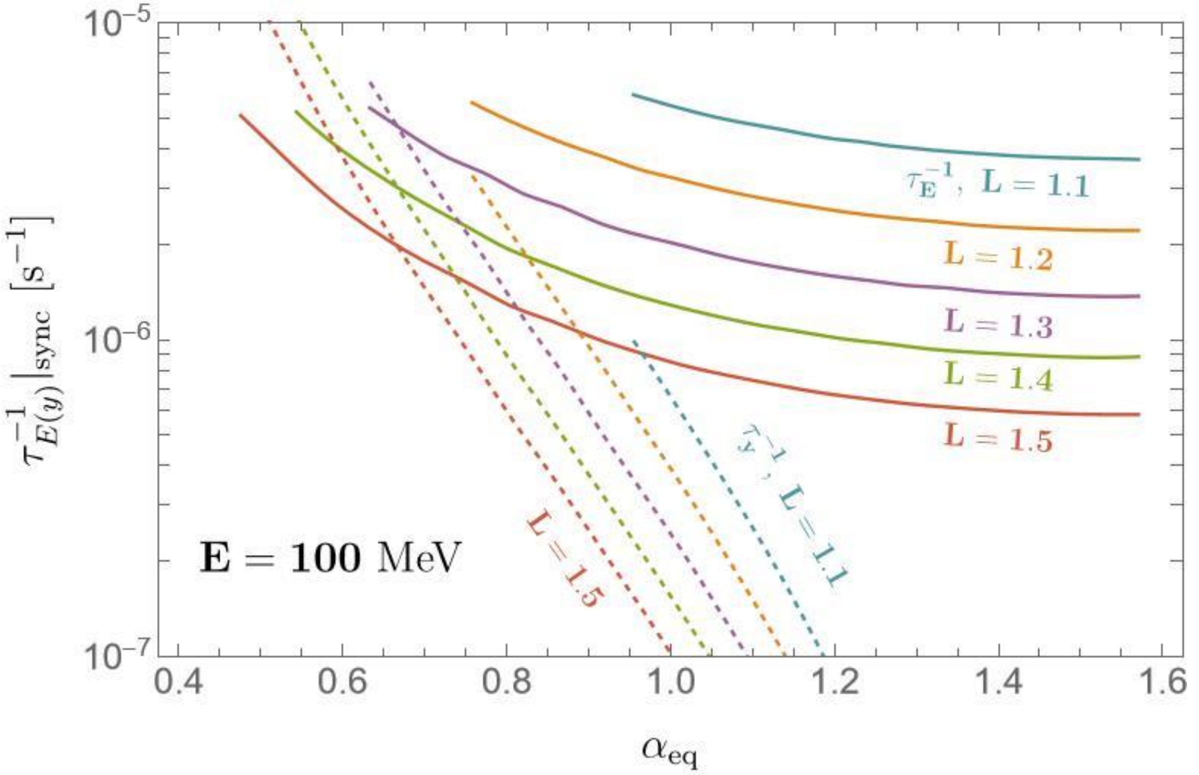
☐ |B|~O(Gauss)

☐ E≫ m_e



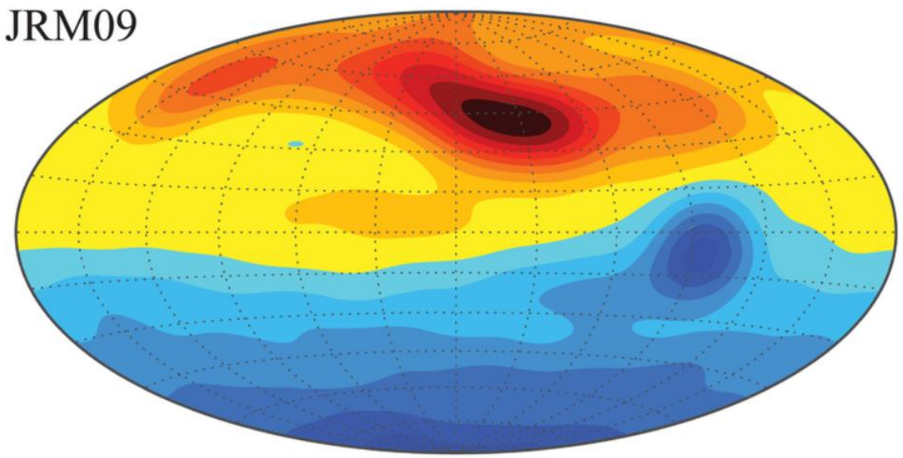
Dominant friction when r ≳ 1.03 R_J

$$\tau_E^{-1}|_{\text{sync}} \equiv \left\langle \frac{1}{E}\frac{dE}{dt}\bigg|_{\text{sync}} \right\rangle \propto E$$



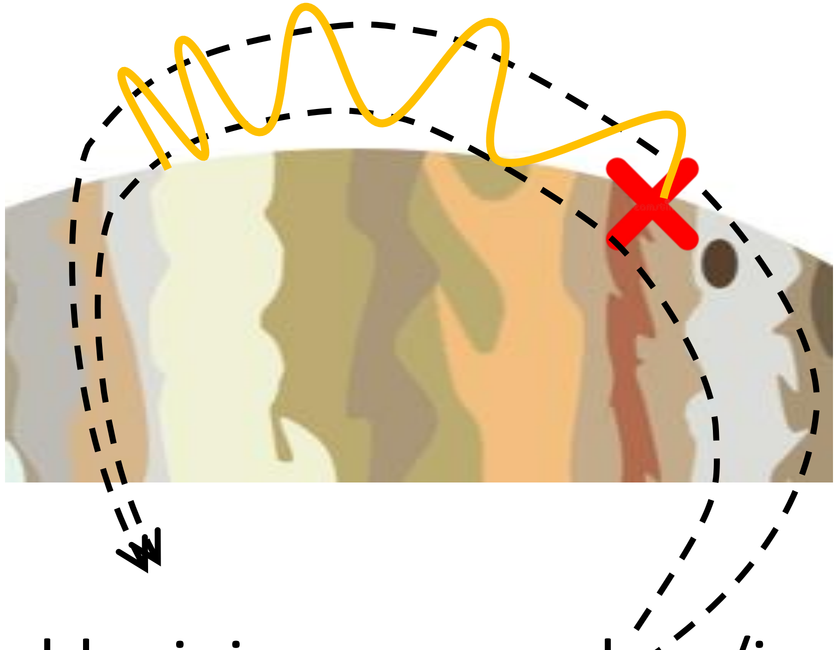
Time scale $\tau_E|_{\text{sync}}$≳ O(10^5) sec for 100 MeV electrons

Loss Term: Untrapped Scenario



Surface field twisted by higher moments

J. E. P. Connerney, S. Kotsiaros, R. J. Oliversen, J. R. Espley, J. L. Joergensen, P. S. Joergensen et al., 2018



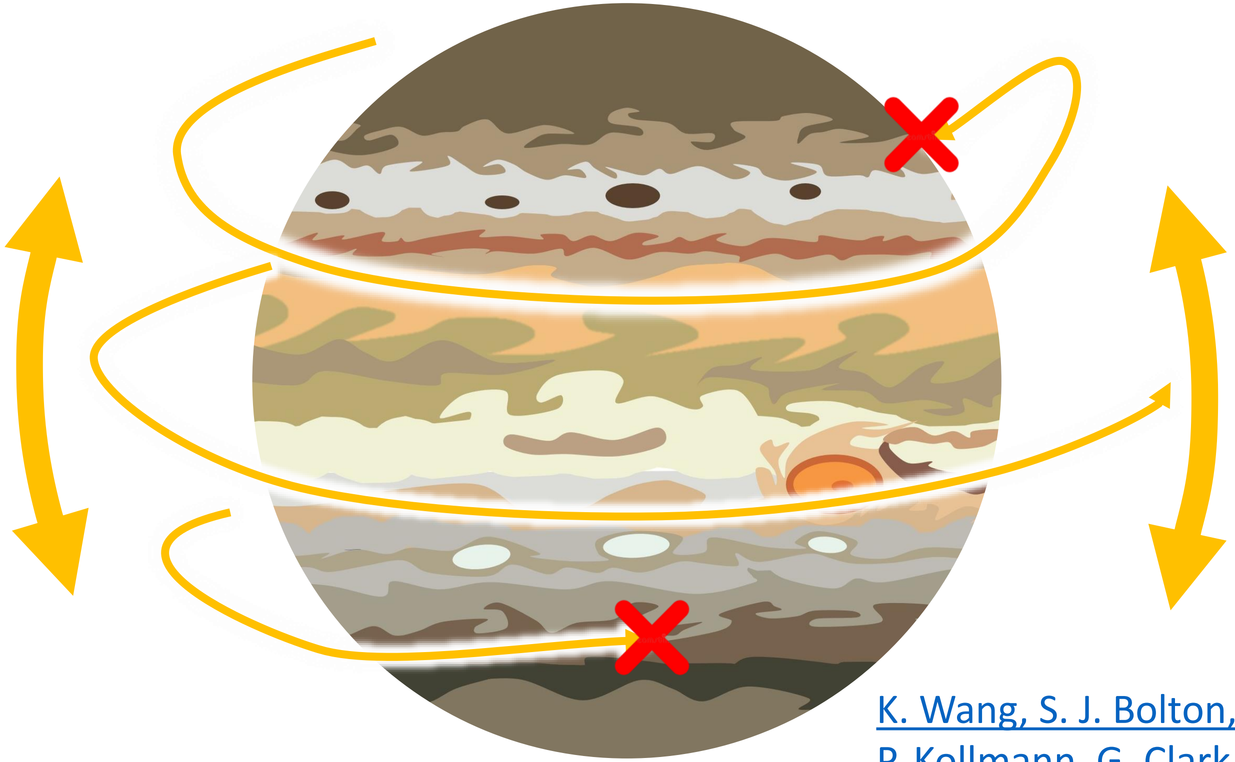
Field minimum very close/inside Jupiter: Impossible for reflection

$$\tau_{\text{loss}} \sim R_J \sim \mathcal{O}(0.2)\ \text{sec}$$

(Expected lifetime of electrons)

Quasi-Trapped Scenario

Meet untrapped regions/ fall in the local loss cone during the azimuthal drifting



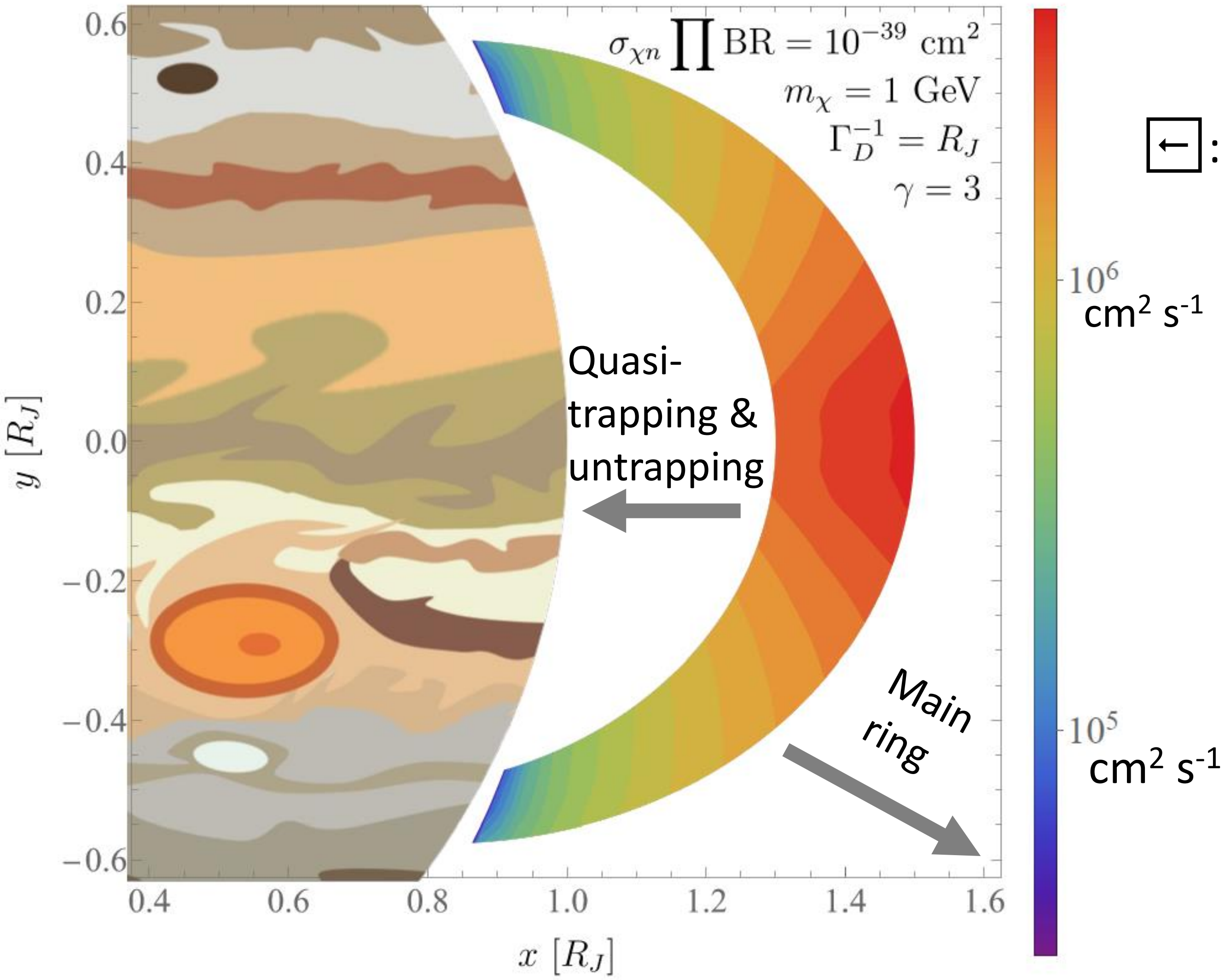
Electron lifetime set by drift period, lost before losing energy significantly via synchrotron radiation

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

K. Wang, S. J. Bolton, S. M. Gulkis, S. M. Levin, 2002

P. Kollmann, G. Clark, C. Paranicas, B. Mauk, E. Roussos, Q. Nenon et al, 2021

Fully-Trapped: Spatial Distributions



$\boxed{\leftarrow}$: Flux predicted in each position

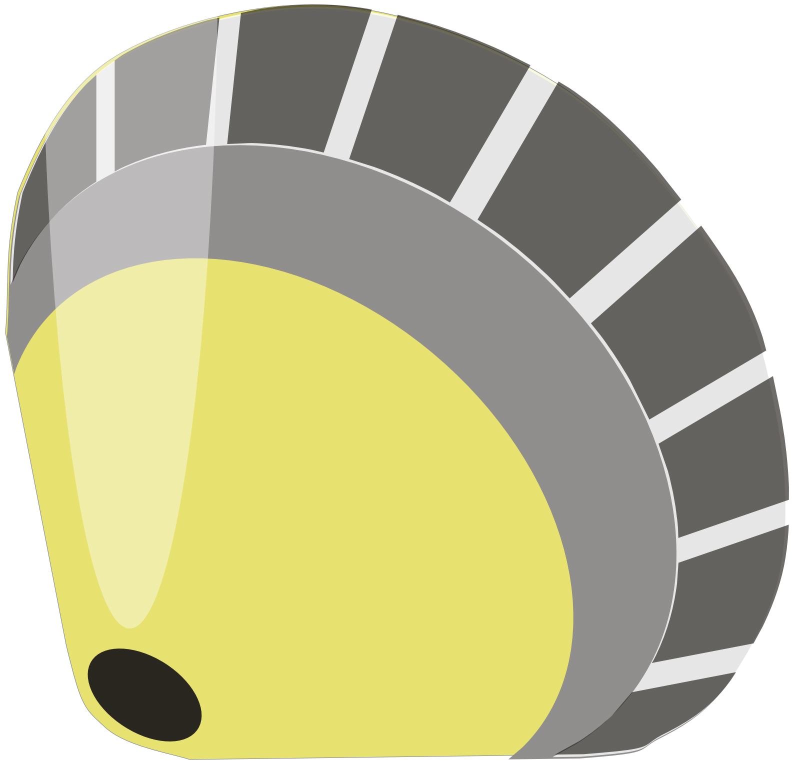
When L ∈ [1.3, 1.5$^+$] and near the magnetic equator, the loss effect is not as significant as the synchrotron friction:

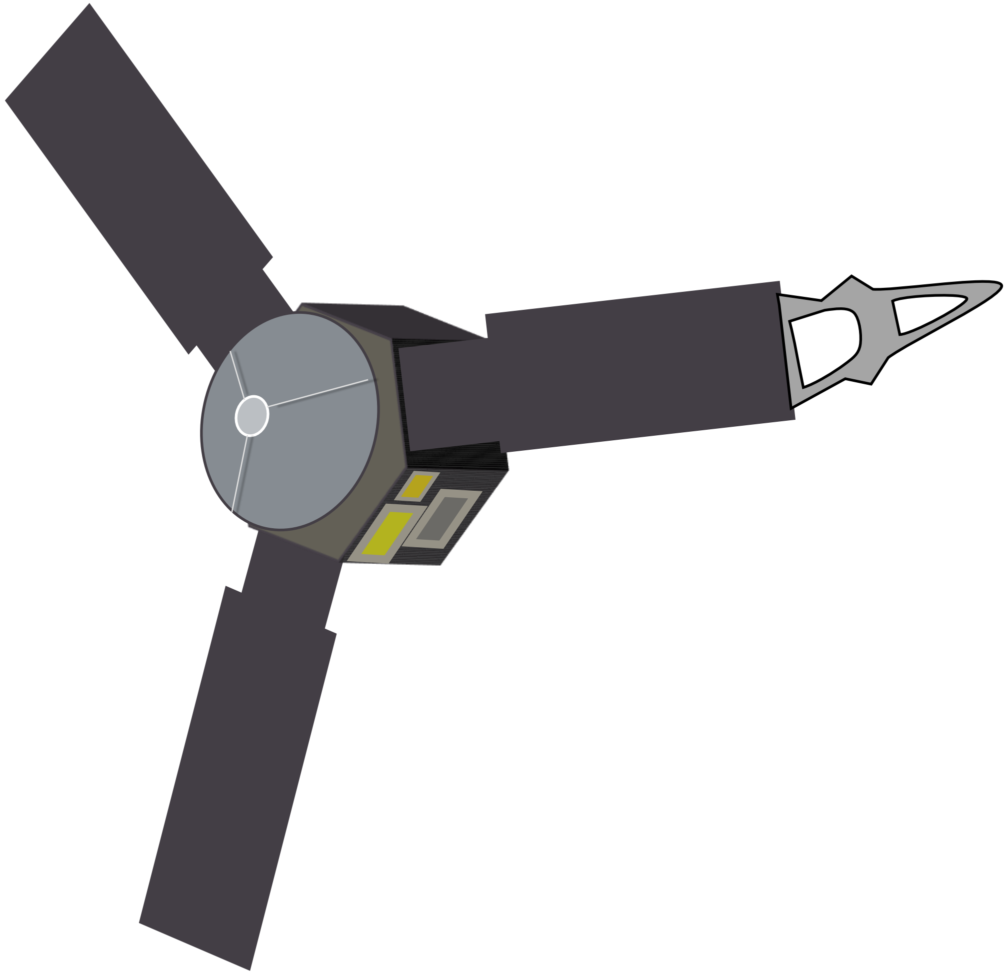
$$\tau_{\mathrm{loss}} \gtrsim \mathcal{O}(10^5)\ \mathrm{sec} \gtrsim \tau_E|_{\mathrm{sync}}$$

Enough paper & pencil works on Earth

Let's launch to Jupiter now!

Aug. 05, 2011
Launch of Juno





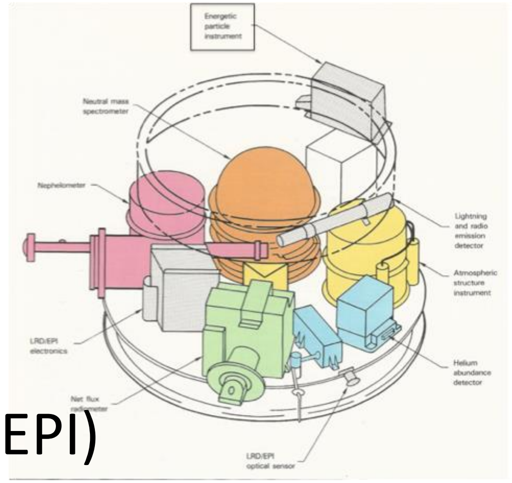
Galileo Probe

(1989-1995)

Juno Mission

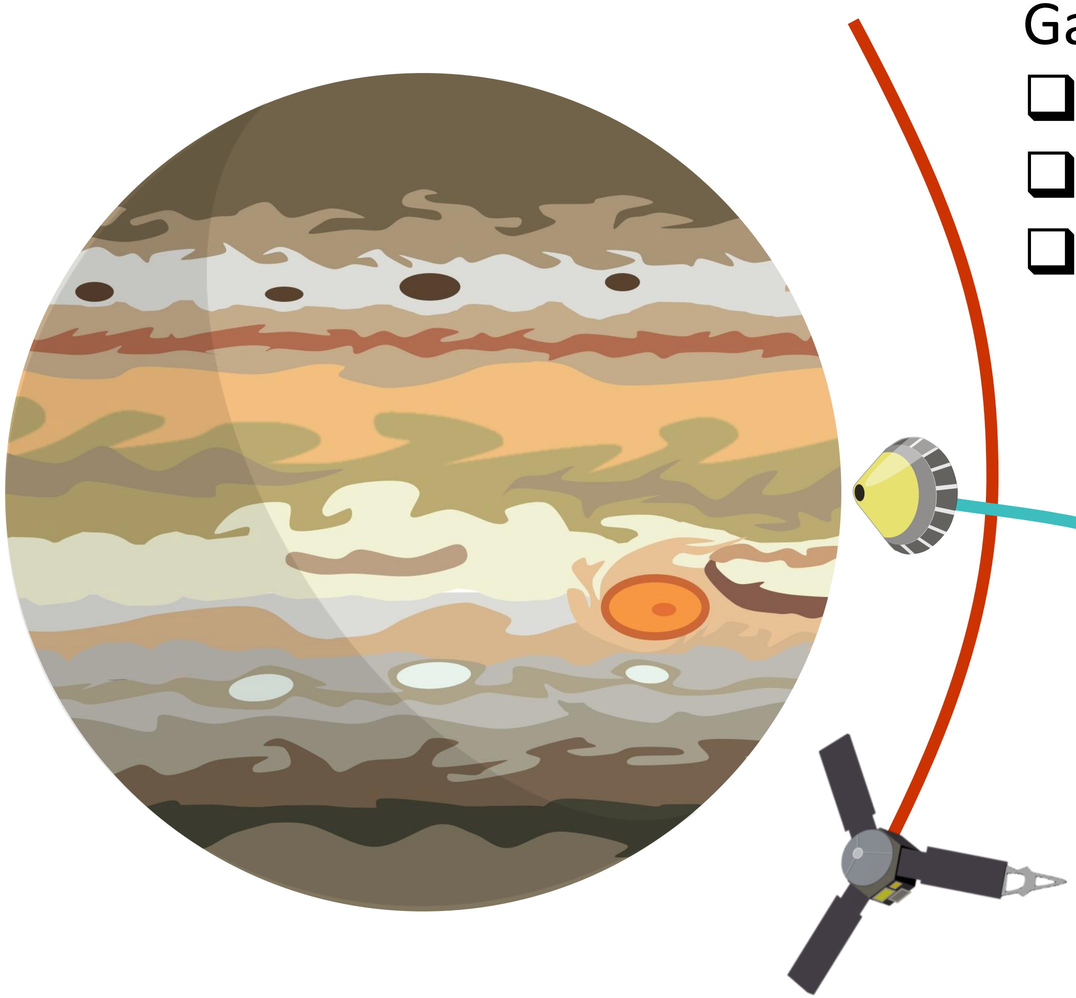
(2011-)

Mission overview



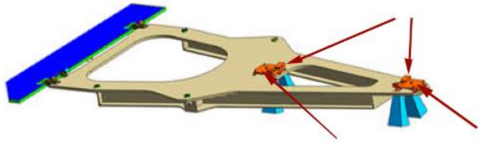
Galileo probe: one way mission

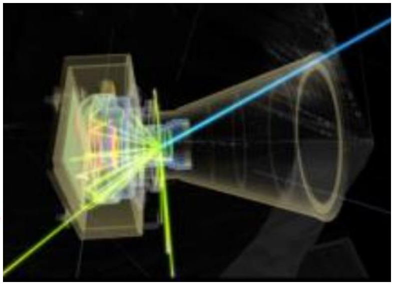
☐ Dive into the atmosphere
☐ Energetic Particle Investigation (EPI)
☐ Sensitive to MeV-GeV charged particles



Juno: orbiter still works

☐ Can be very close to the surface
☐ No specific relativistic particle detectors
☐ Hard electron from Radiation Monitoring (RM) investigation

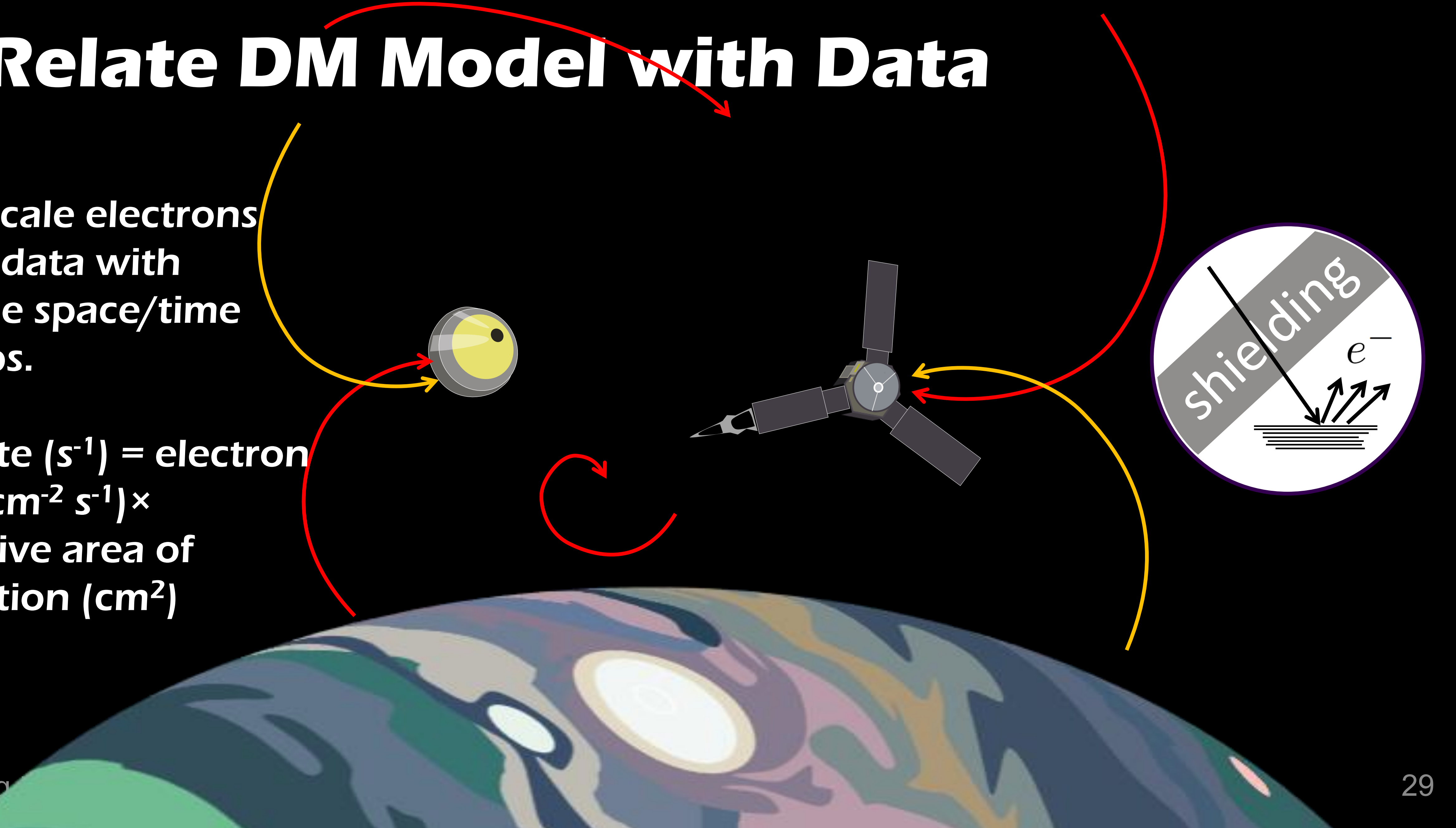




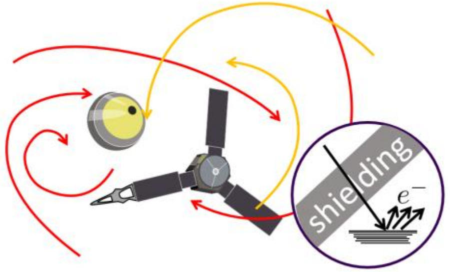
Relate DM Model with Data

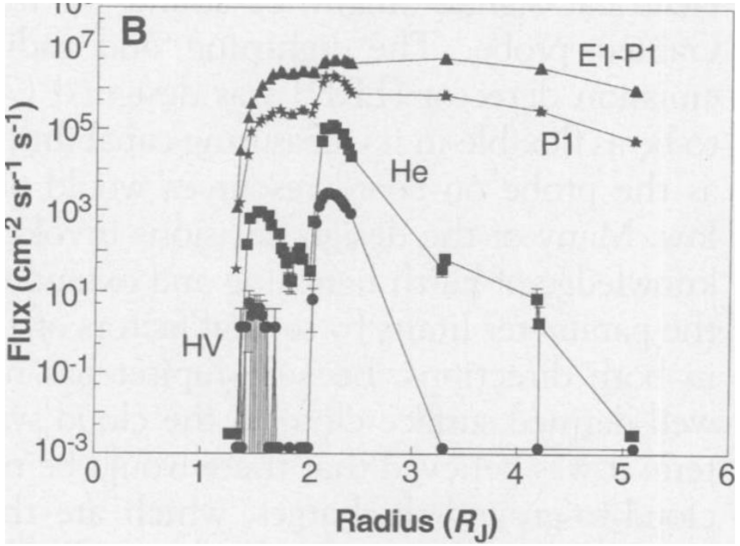
GeV-scale electrons leave data with precise space/time stamps.

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



Jupiter Mission Readouts

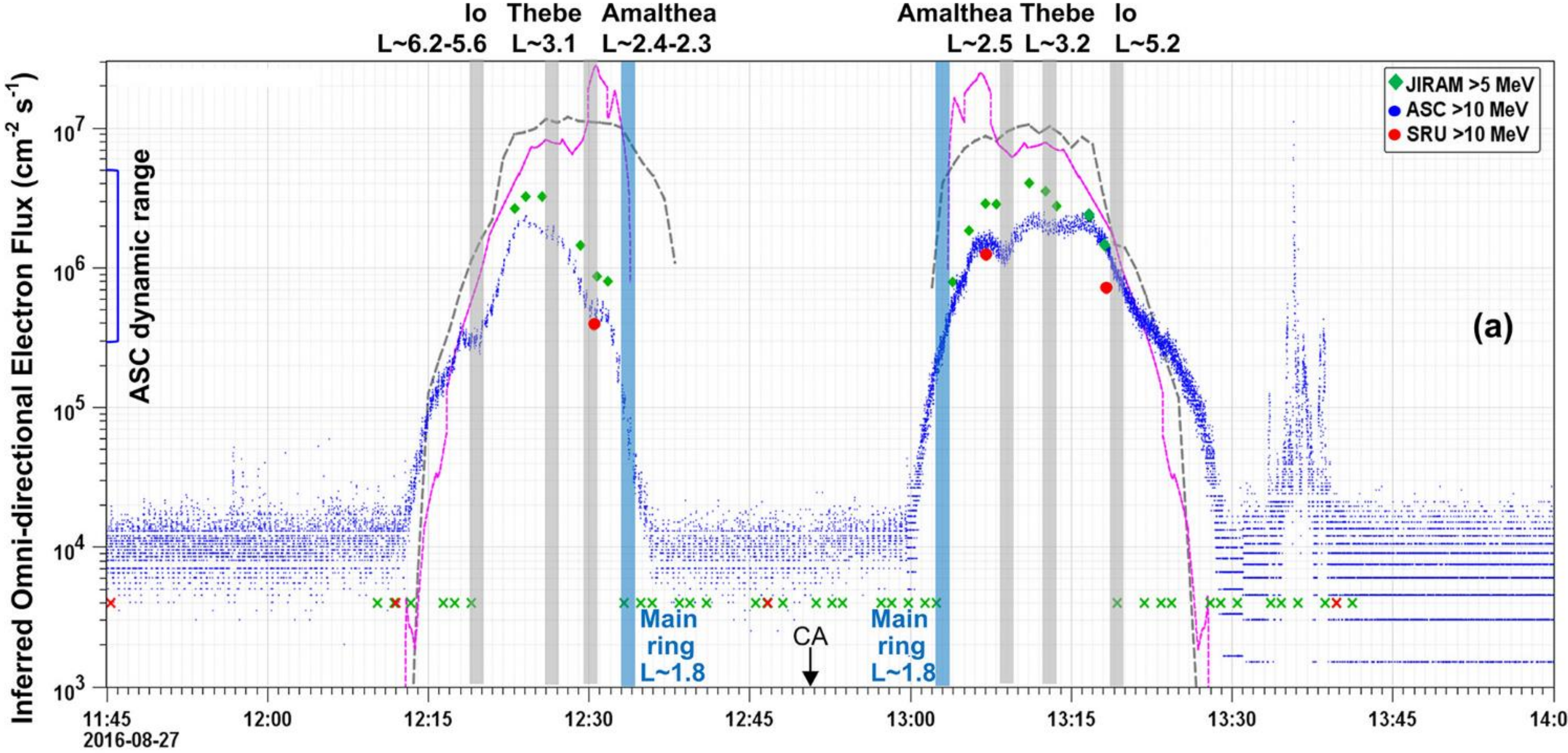




H. M. Fischer, E. Pehlke, G. Wibberenz, L. J. Lanzerotti, J. D. Mihalov, Science 272, 1996

Data never used for HEP before

- ❑Galileo Probe EPI: “Calorimeters”
- ❑Juno RM: CCD cameras

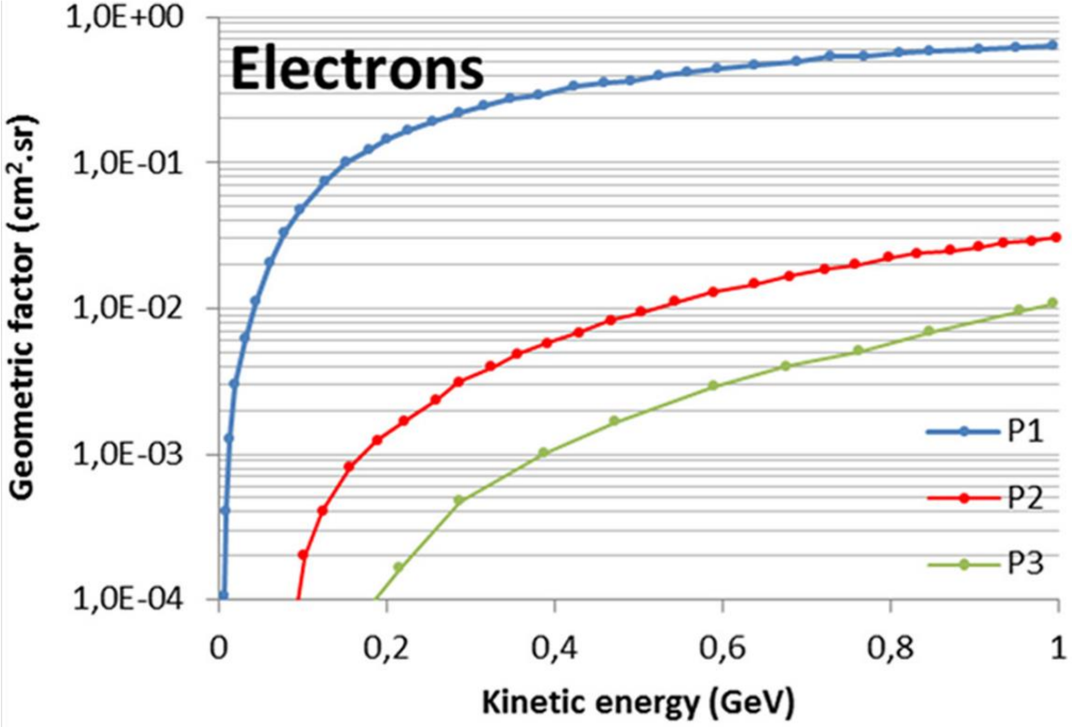


H.N. Becker, D. Santos-Costa et al., Geophys. Res. Lett. 44, 2017

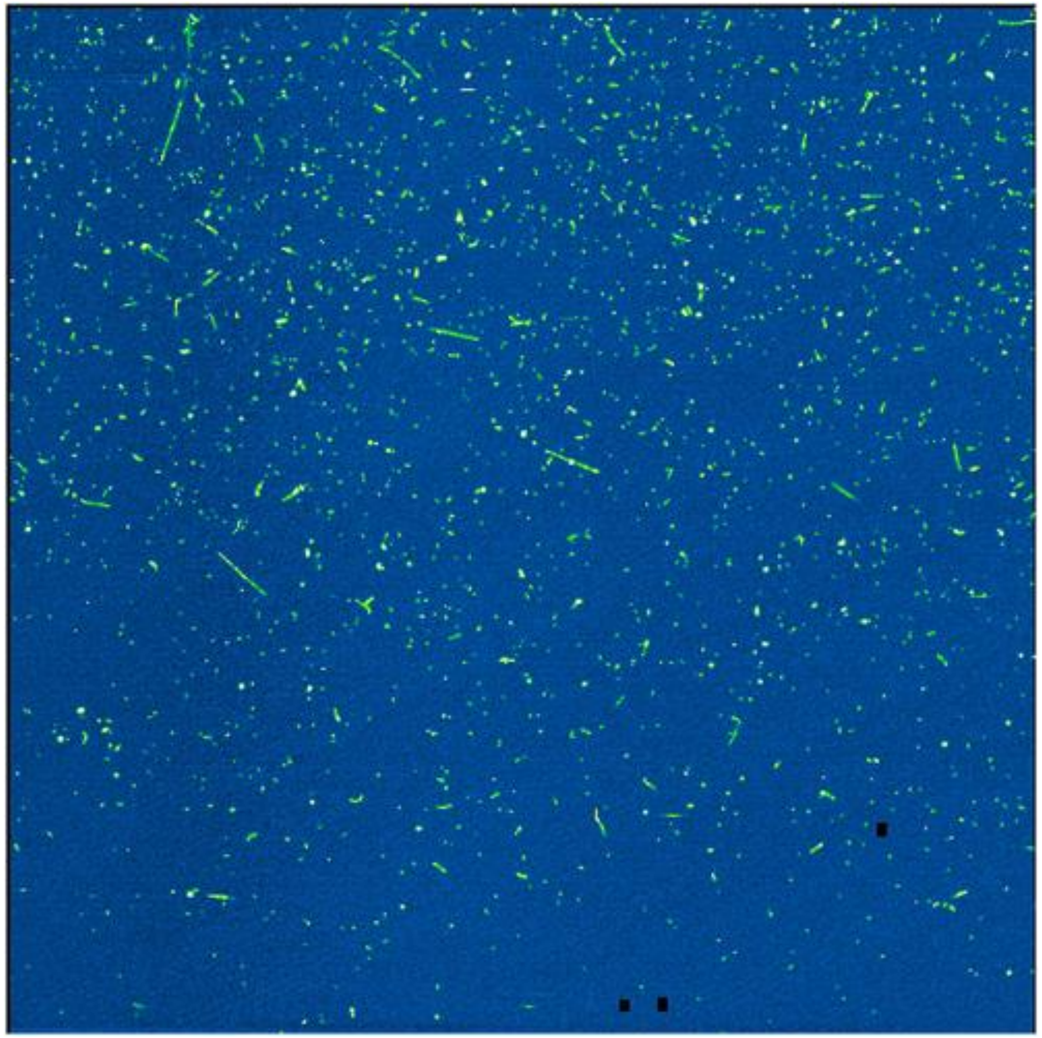
Sensitivity

No precise spectroscopy:

Higher energy → higher penetration rates



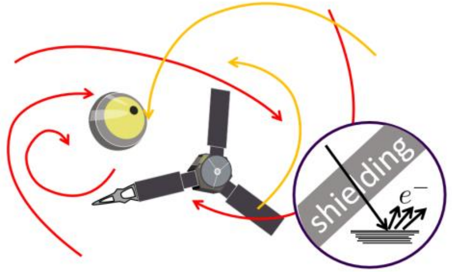
[Q. Nenon, A. Sicard, P. Kollmann, H. B. Garrett, S. P. A. Sauer, C. Paranicas, 2018]()



Juno SRU CCD image from relativistic particles @ Perijove 1, around maximum radiation intensity

[H.N. Becker, D. Santos-Costa et al., Geophys. Res. Lett. 44, 2017]()

Limit (Fully Trapped)



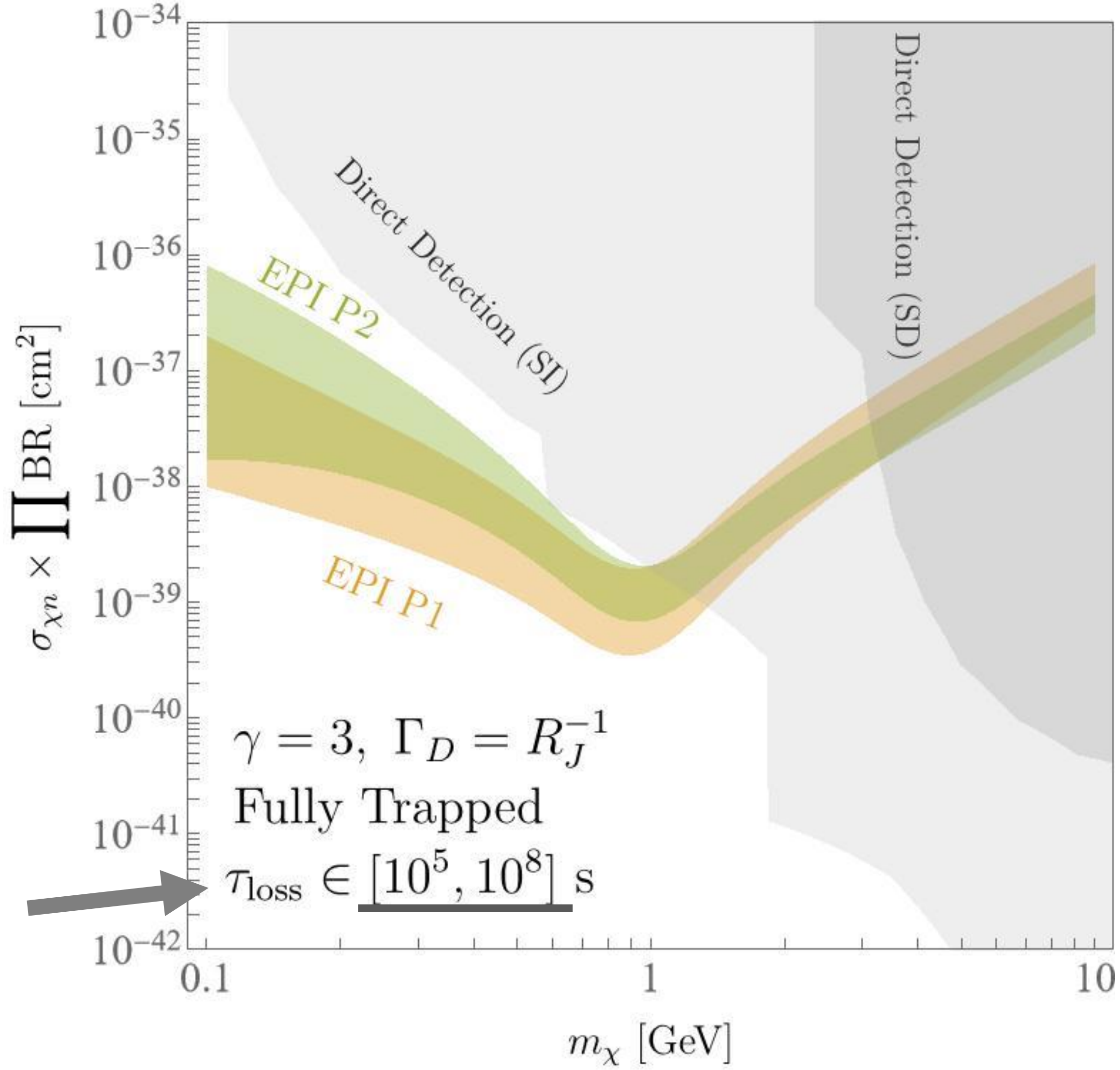
Currently only Galileo probe data available covers the area L > 1.3 & close to the magnetic equator

Large count rates

P1: O(10^5 s^{-1}) & P2: O(10^3 s^{-1}),

Conservative but reliable

Not very sensitive to a varying τ_{loss} :



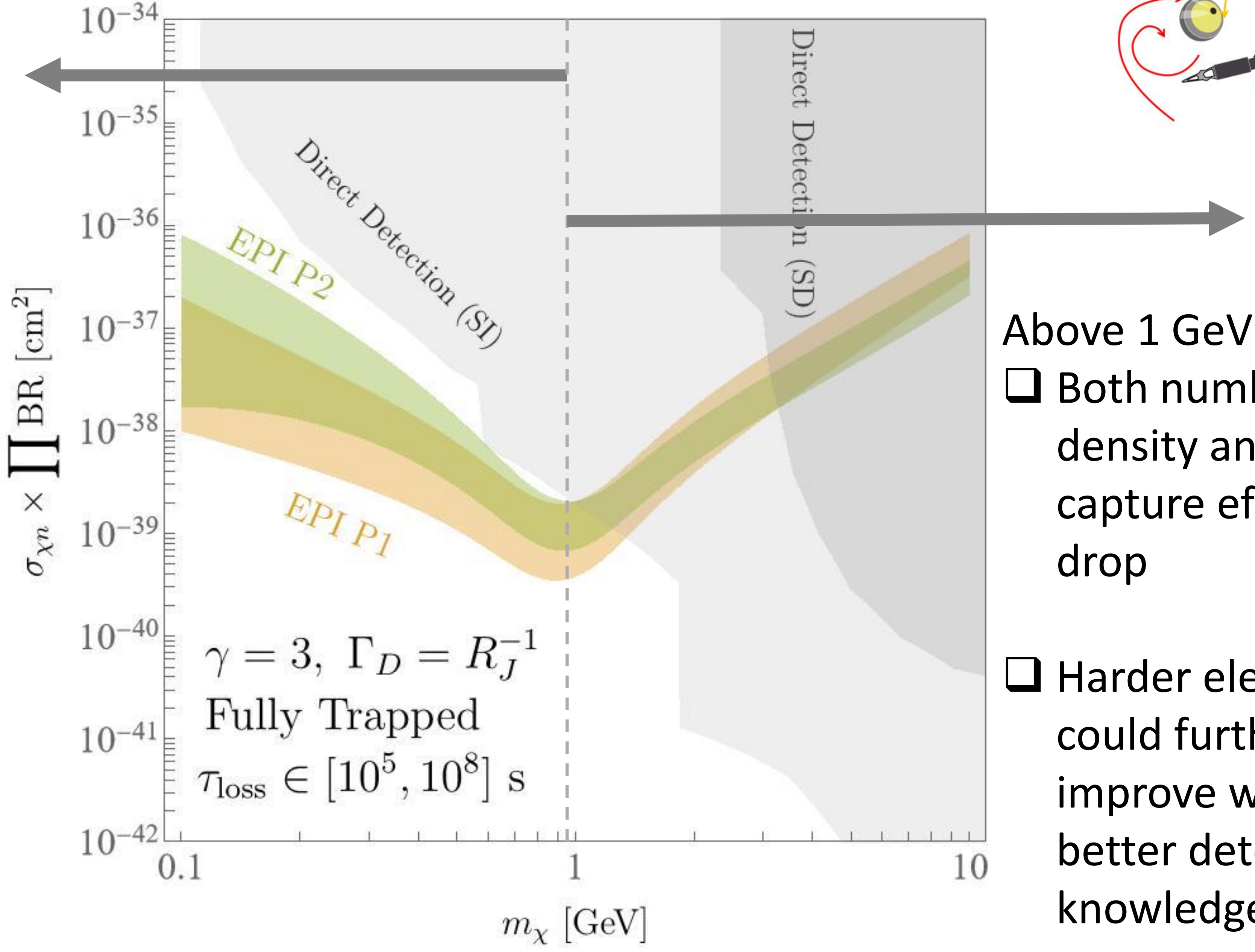
Lingfeng Li 2207.13709

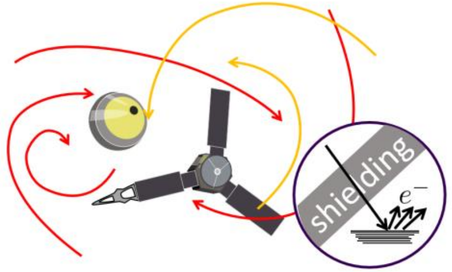
Below 1 GeV:

☐ DM number density increases but capture efficiency drops.

☐ Softer electron →weaker bounds

☐ Stronger evaporation effect (not accounted for in the plot)

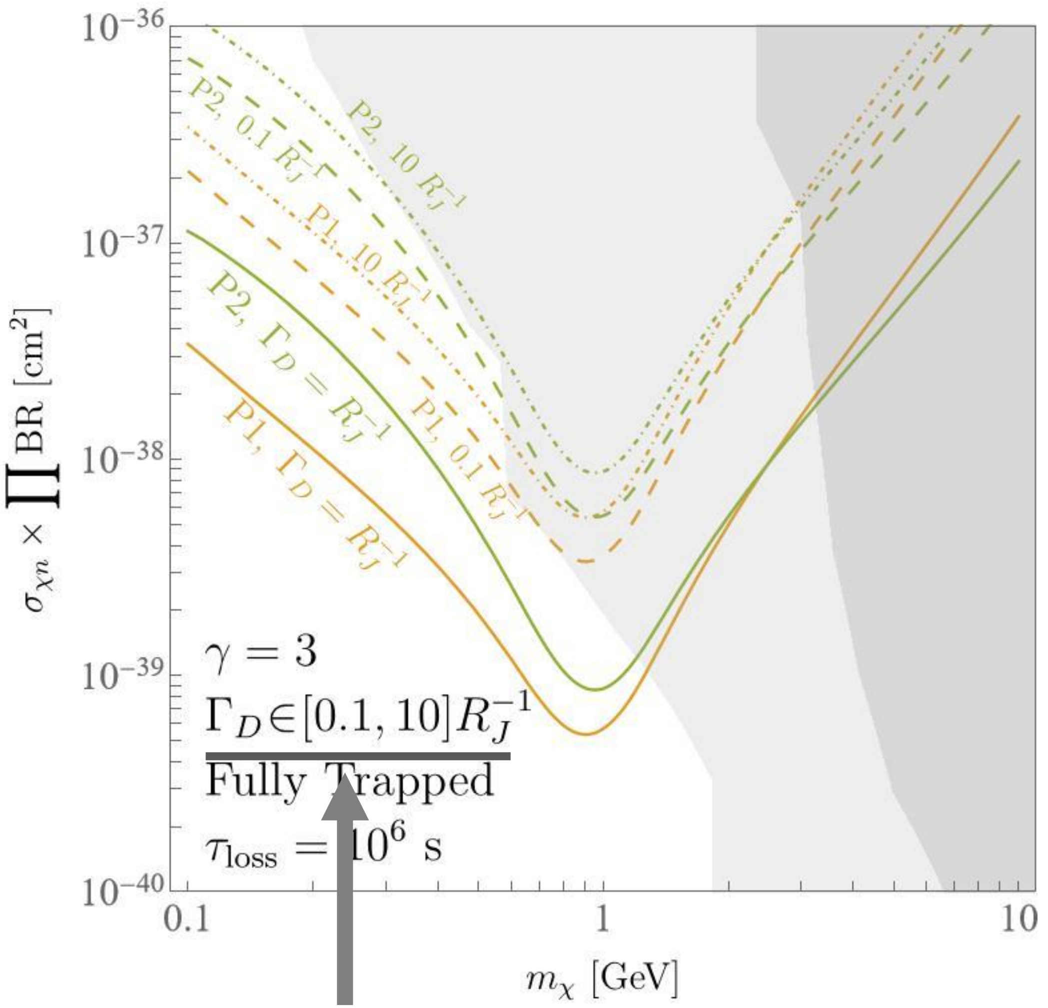




Above 1 GeV:

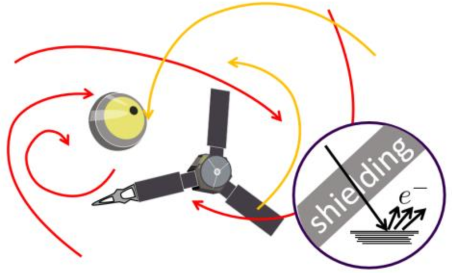
☐ Both number density and capture efficiency drop

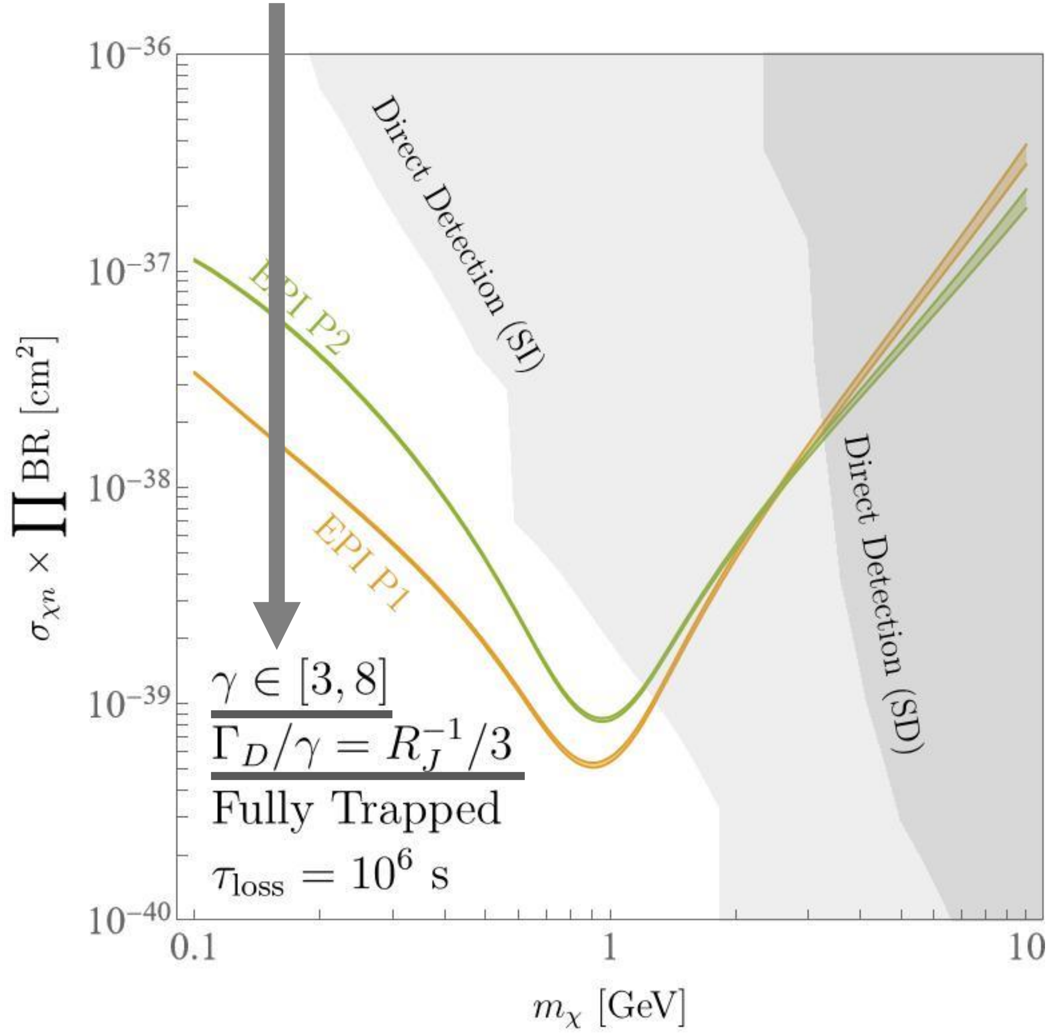
☐ Harder electrons, could further improve with better detector knowledge



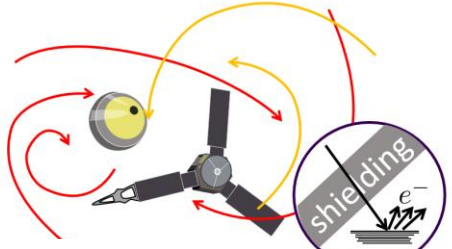
Limit also dependent on mediator decay length: chances to reach an L shell

Insensitive to boost once the proper decay length is fixed





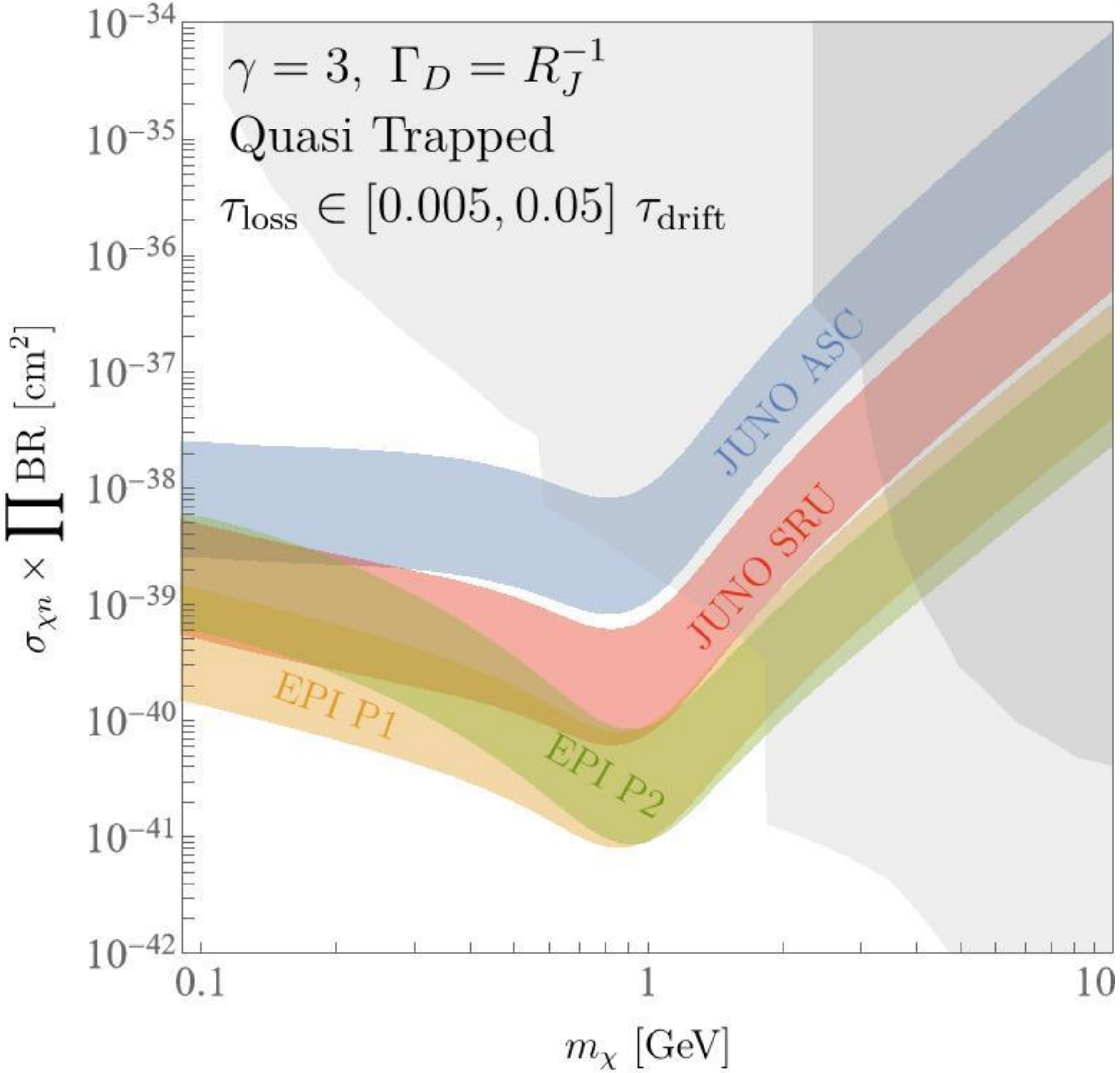
Limit (Quasi Trapped)



Both Juno (away from magnetic equator & the main radiation belt) and Galileo Probe (L ~ 1.1) provide quasi-trap region data

Bounds are stronger but higher systematics: only suggestive values

Need very precise magnetic field model and numerical simulations to find out.



Summary

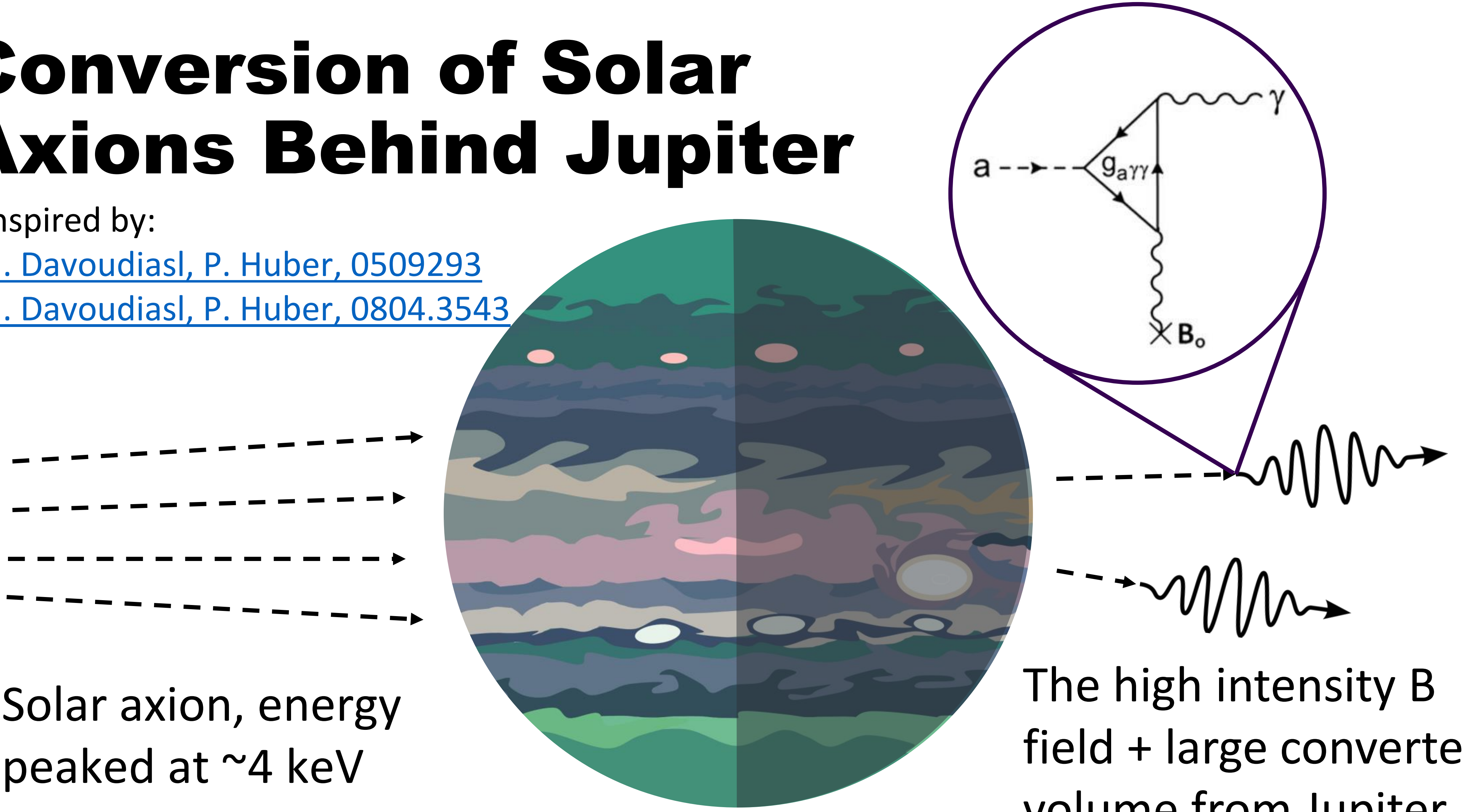
- ❑DM accumulation inside Jupiter is a general prediction for GeV-scale DM, greatly enhancing annihilation rates.
- ❑Long-lived mediator with lifetime ~R_J decaying to electrons inject hard electrons to the radiation belt.
- ❑*In situ* limits on DM-nucleon scattering Xsec comparable (spin-independent) or even stronger (spin-dependent) than best direct detection bounds.

Conversion of Solar Axions Behind Jupiter

Inspired by:

[H. Davoudiasl, P. Huber, 0509293]()

[H. Davoudiasl, P. Huber, 0804.3543]()



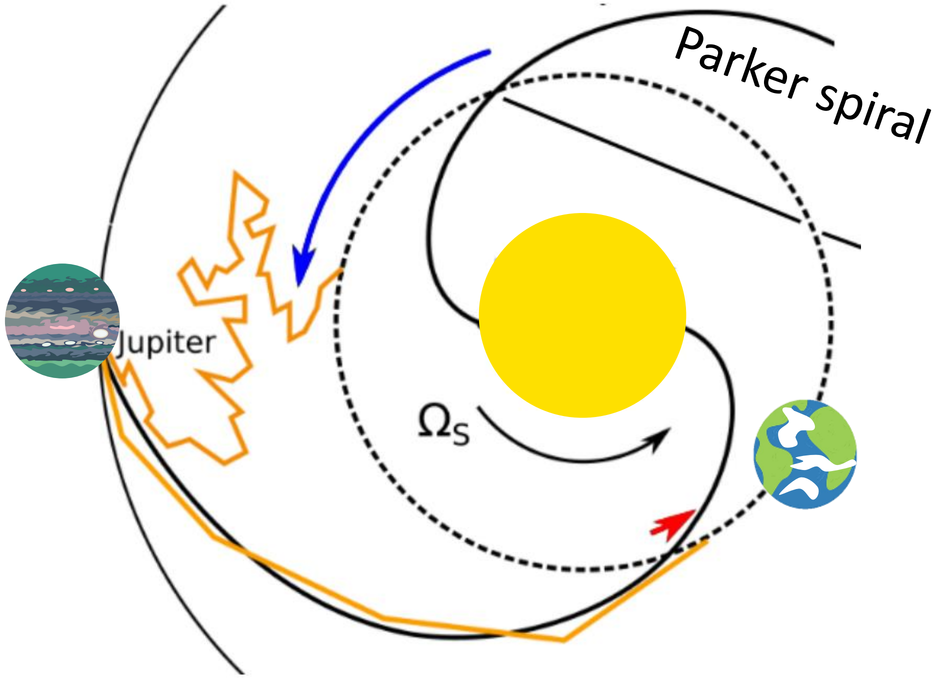
Solar axion, energy peaked at ~4 keV

The high intensity B field + large converter volume from Jupiter

Difficulties: need high angular/energy resolution with hard X-rays, unknown Jupiter background, small window of observation……

Positron Signal from Jupiter

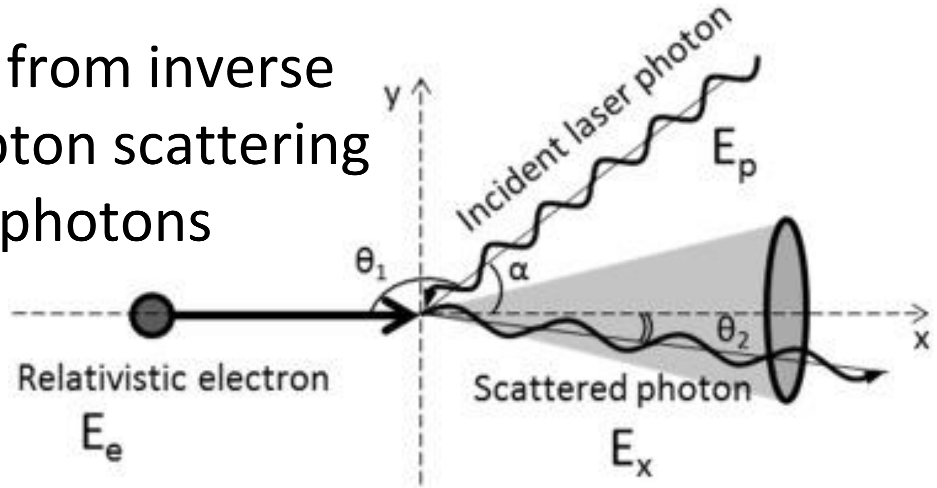
Positrons escaping the magnetosphere hit earth orbit E. N. Parker, 1958

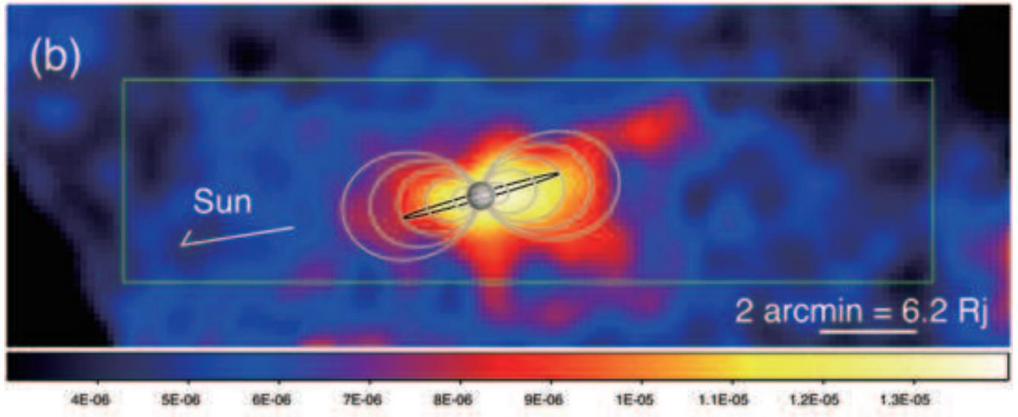


~13 month period of Jovian positrons, see e.g.
A. Vogt, N. E. Engelbrecht, B. Heber, A. Kopp, K. Herbst, 2110

X-ray from Electrons

X-ray from inverse Compton scattering solar photons

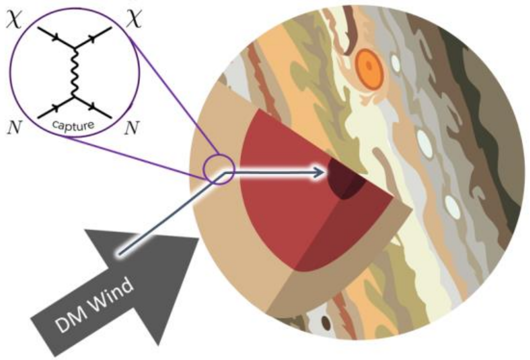




1-5 keV diffuse X-ray @ Suzaku
Y. Ezoe, K. Ishikawa, T. Ohash, 1001.0800

Backup Slides

DM Capture Rate



In the optical thin limit, DM captured with single scattering, described in A. Gould, Astrophys. J., 321, 1987

Optical depth $$\tau_J = \frac{3}{2}\frac{\sigma_{\chi n}}{\sigma_{\rm sat}}$$

DM-nucleon scattering Xsec

Geometric saturation Xsec ~ 10^{-34} cm^2

Capture rate of the whole planet:

$$C_1 = \sqrt{\frac{8\pi}{3}}\frac{n_\chi \tau_J R_J^2}{\bar{v}_\chi}\int_0^{R_J}\frac{4\pi r^2 n_n(r)}{N_{n,J}}v_J^2(r)\left(1-\frac{1-e^{-A(r)^2}}{A(r)^2}\right)X[A(r)]dr$$

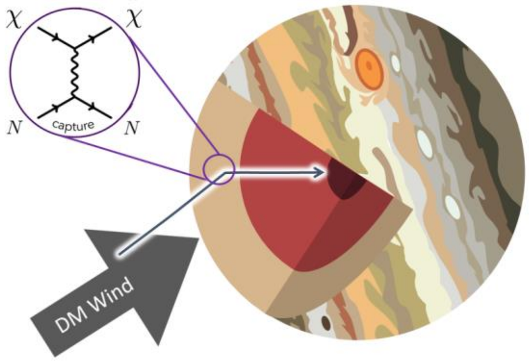
$$A(r)^2 \equiv 6v_J(r)^2 m_n m_\chi/[\bar{v}_\chi^2(m_n-m_\chi)^2]$$

The exponential factor that maximizes when DM has the same mass as a nucleon

Suppression factor comes from the relative speed between Jupiter and the DM Halo

For multiple scattering, see
J. Bramante, A. Delgado A. Martin, 1703.04043
C. Ilie, J. Pilawa, S. Zhang, 2005.05946

DM Capture Rate



After including the internal density profile & relative velocity, the capture rate takes the numerical form

$$C_1 \gtrsim 0.28\sqrt{\frac{8\pi}{3}}\frac{n_\chi \tau_J R_J^2 v_J^2(R_J)}{\bar{v}_\chi}\left(1-\frac{1-e^{-A(R_J)^2}}{A(R_J)^2}\right)$$

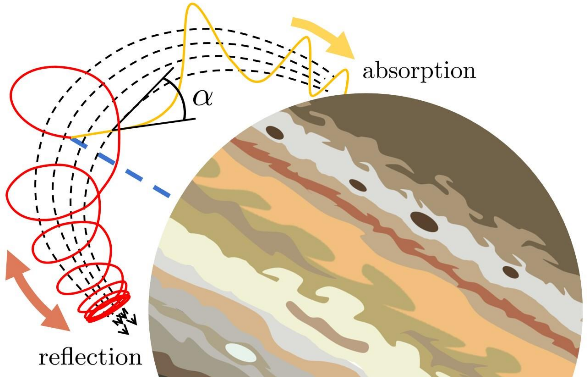
To get spin dependent rates for weaker constraints: axial-vector type interaction

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

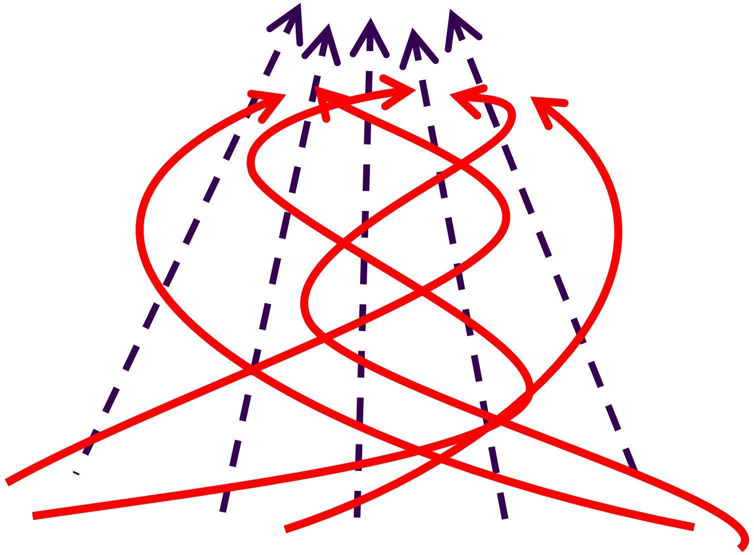
$$\sigma_{\chi n} \approx 3.8\times 10^{-39}\,\mathrm{cm}^2\left(\frac{\mu_{\chi n}}{\mathrm{GeV}}\right)^2\left(\frac{g_\chi g_q}{10^{-3}}\right)^2\left(\frac{10\,\mathrm{GeV}}{\Lambda}\right)^4$$

Possible to get a relevant scattering rate without violating collider bounds

Spatial Distribution

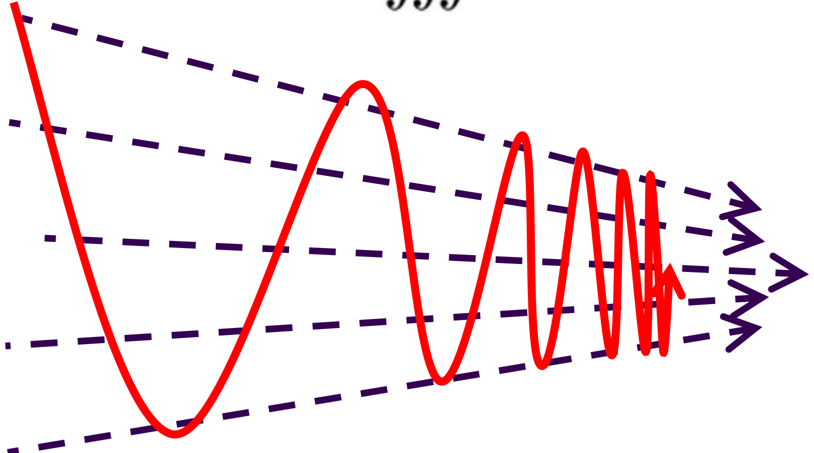


The (omnidirectional) electron flux is NOT the same along the same L-shell



The tube narrows as the field goes stronger

$$J(L,\theta_p) \simeq \iiint E^2\, dE\, d\cos\alpha_{\rm eq} \frac{dA_{\rm eq}}{dA} \frac{(dt/dS)}{(dt/dS)_{\rm eq}} f$$



The coil gets denser when the field is strong

Speed ∝ cos $^{-1}$ α