Jupiter Missions as Probes of Dark Mediators

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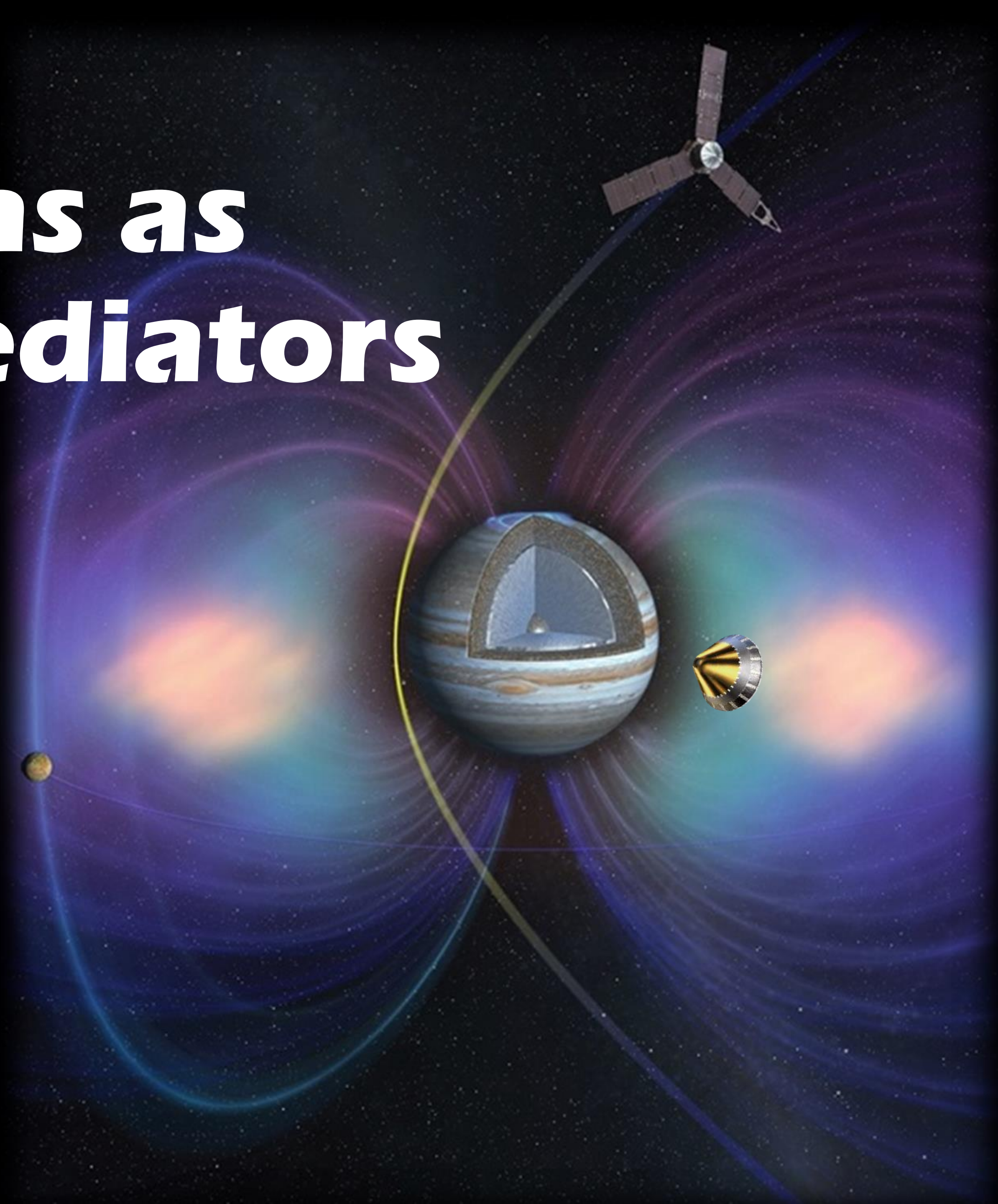
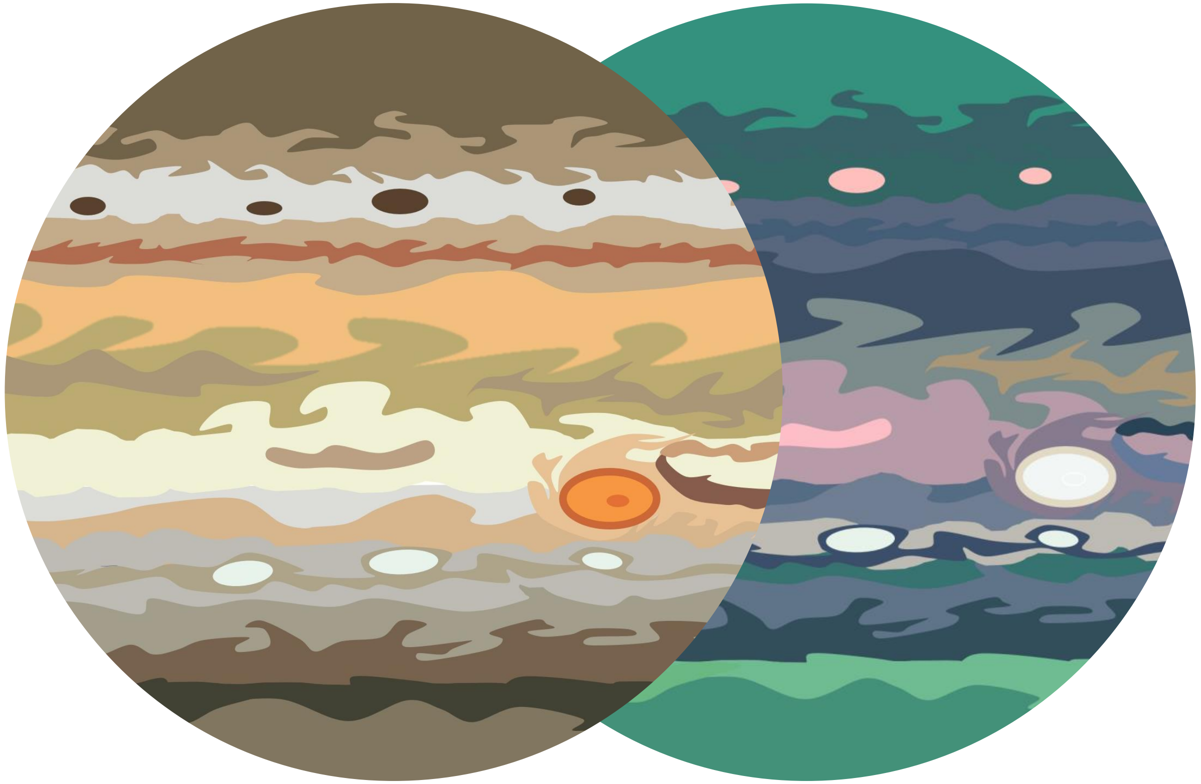
FIPs 2022 Workshop, CERN

Based on arXiv:2207.13709 with JiJi Fan



Why Jupiter?

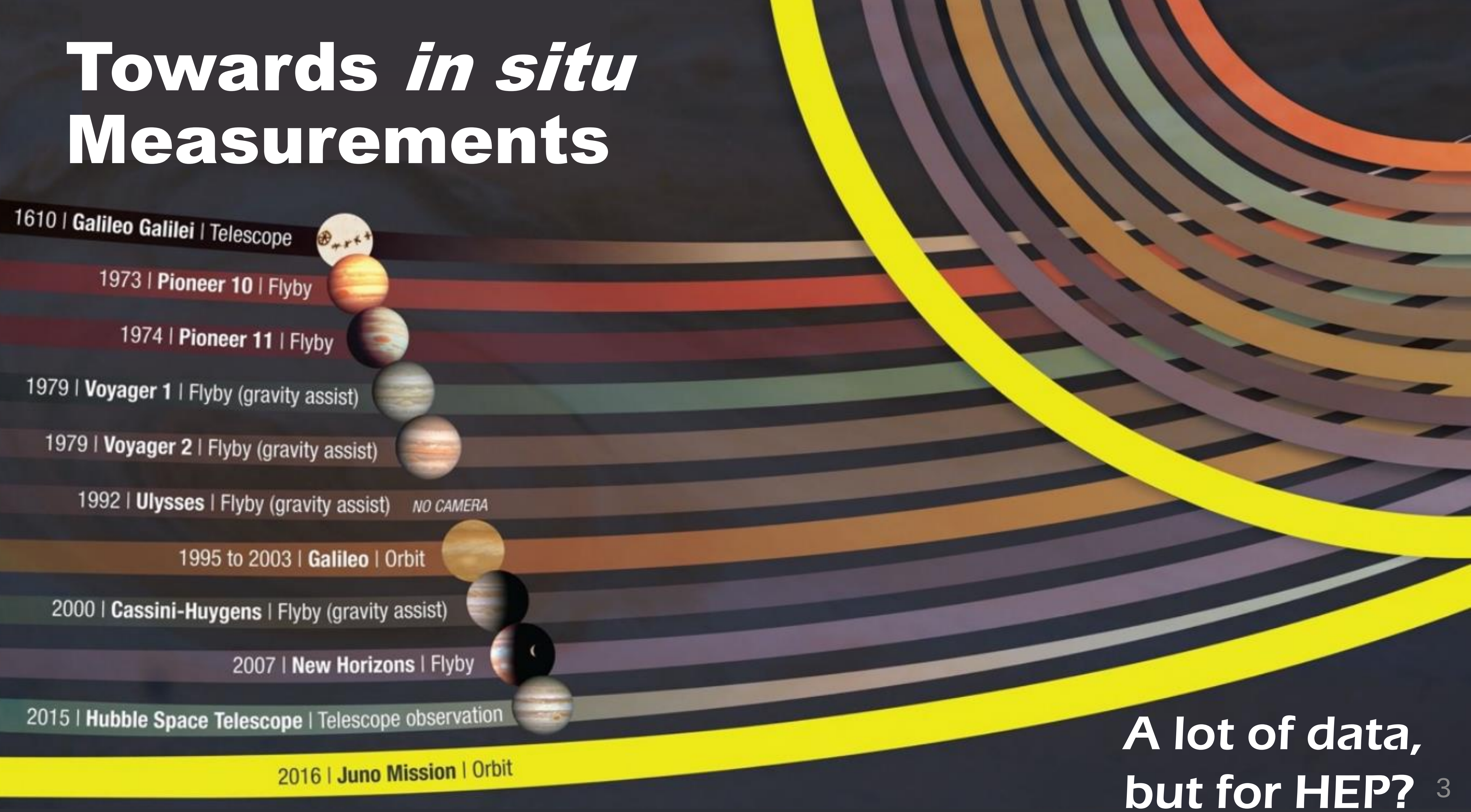
- ☐ Most massive planet in the solar system: a big detector
- ☐ "Clean" background: not as active as a star
- ☐ Relatively close: easier for both *in situ* and *ex situ* measurements
- ☐ A small and thin main ring



"HST" (VIS)

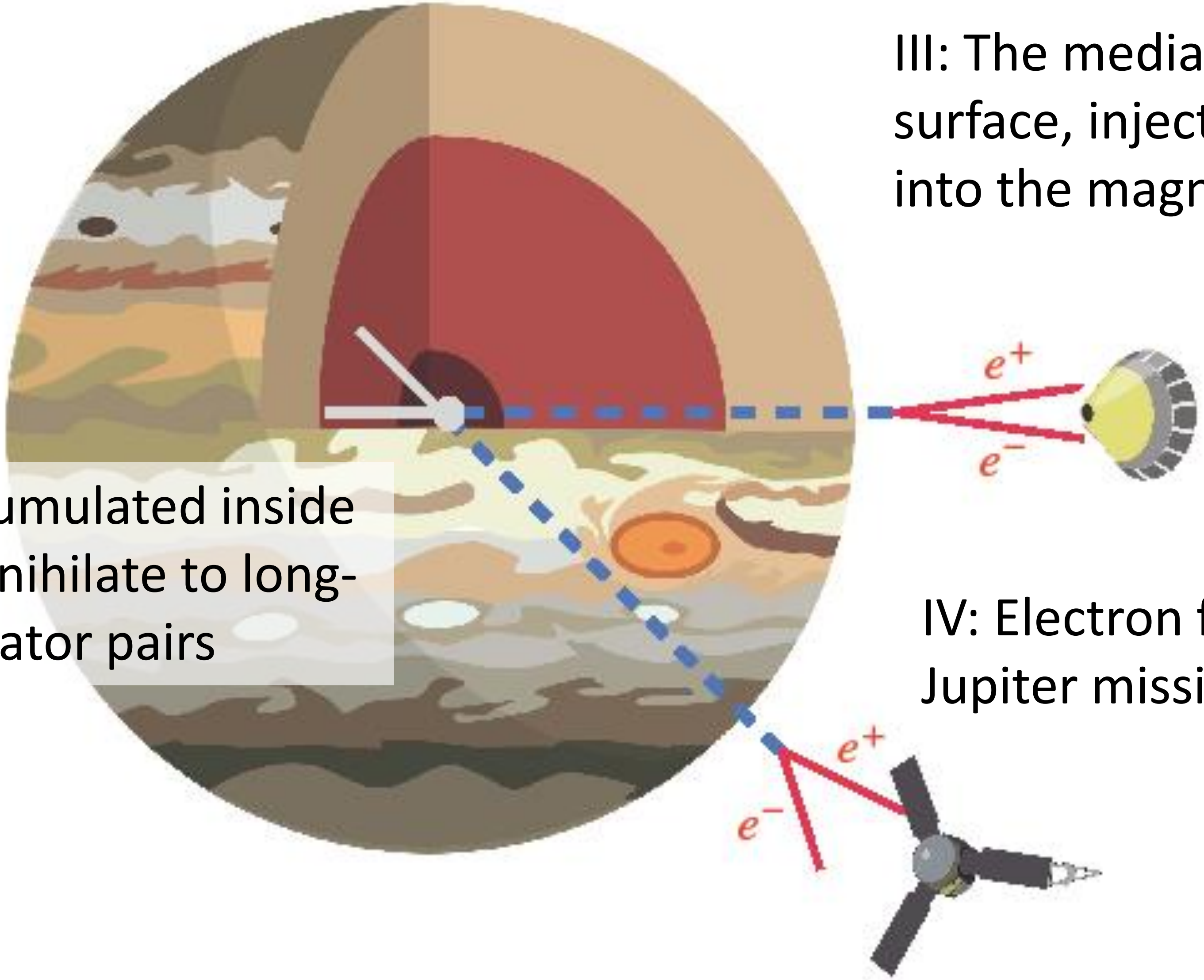
"JWST" (IR)

Towards *in situ* Measurements



A lot of data, but for HEP?

In a Nutshell



I: DM captured by the potential well after elastic scatterings

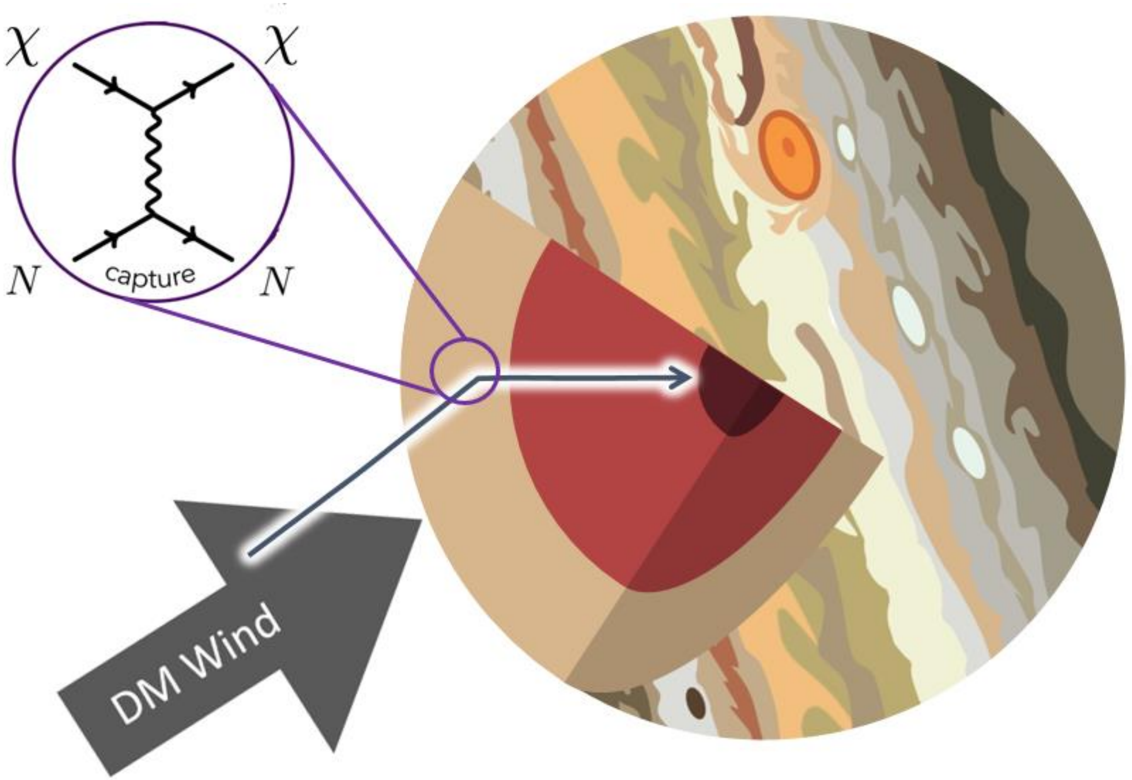
II: DM accumulated inside Jupiter, annihilate to long-lived mediator pairs

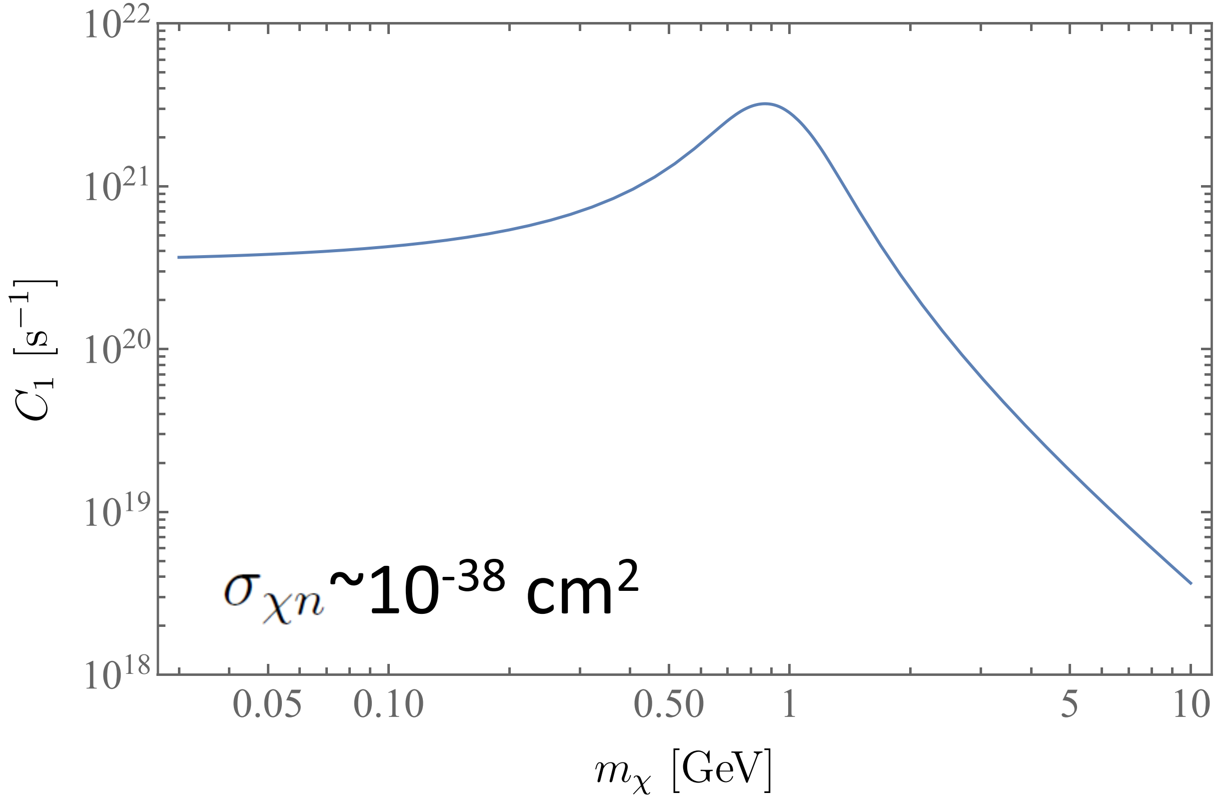
III: The mediators reach the surface, injecting hard electrons into the magnetosphere

IV: Electron flux detected by Jupiter missions

DM Capture Rate

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





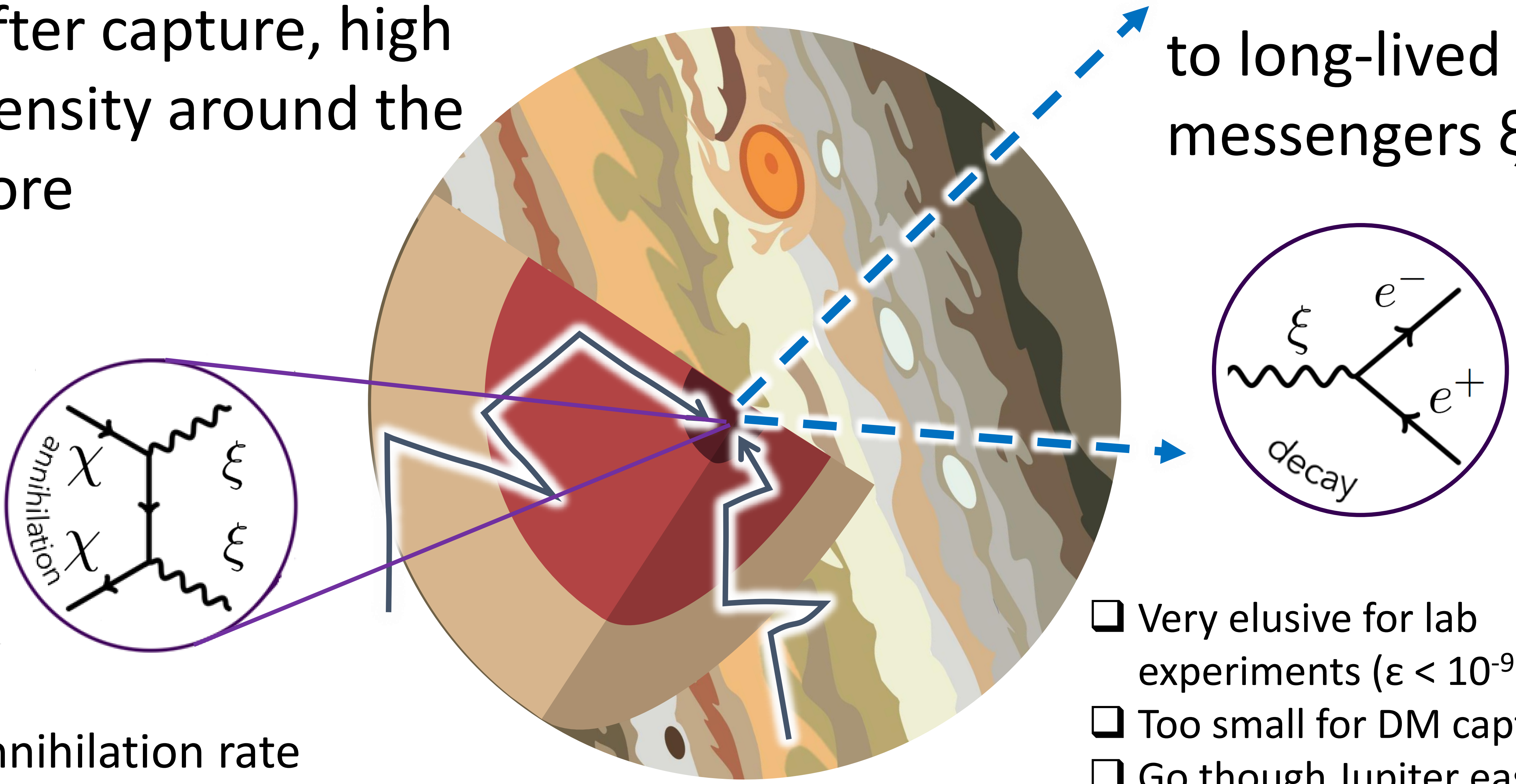
$\sigma_{\chi n}$~10^{-38} cm^2

Geometric saturation Xsec ~ 10^{-34} cm^2
Below this, Jupiter is optically thin

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

Multiple scattering after capture, high density around the core

2→2 annihilation to long-lived messengers ξ



- ☐ Very elusive for lab experiments ($\varepsilon < 10^{-9}$ for DP)
- ☐ Too small for DM capture
- ☐ Go though Jupiter easily

Annihilation rate
~capture rate/2 after reaching equilibrium

Three basic modes inside an approximate dipole field

Lorentz force

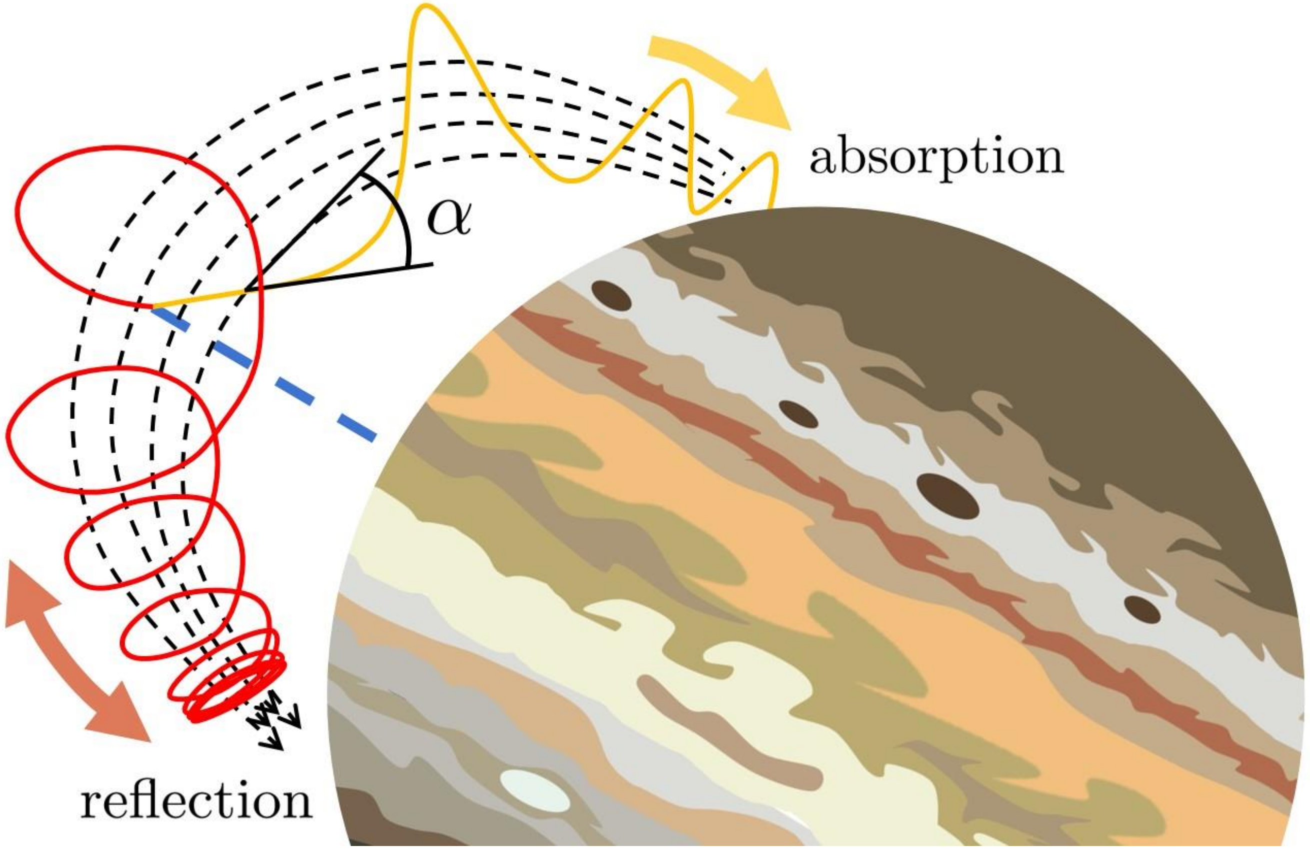
- **Gyration** around field lines ($\gg$ kHz)

Magnetic mirror/bottle effect

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

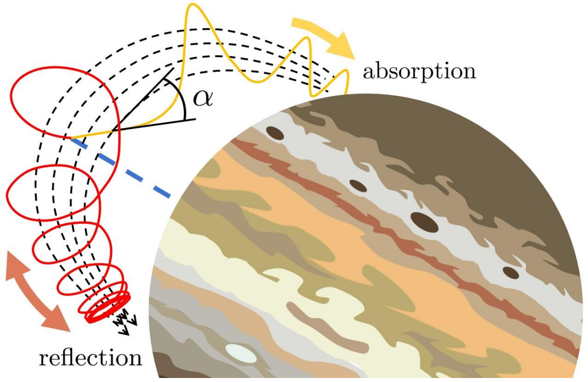
Gradience of the B field

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



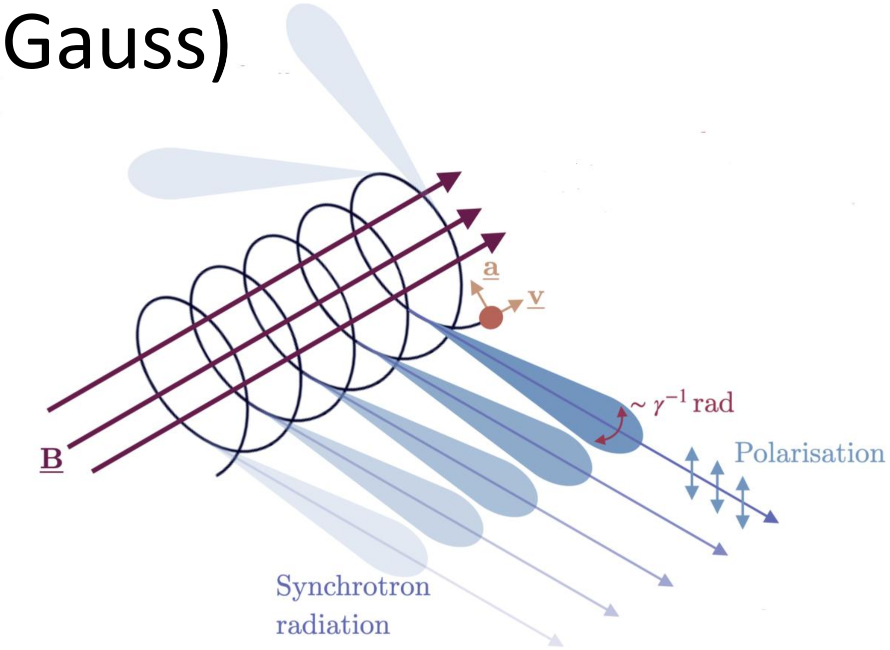
M. Schulz, L. J. Lanzerotti, 1974

Synchrotron Friction



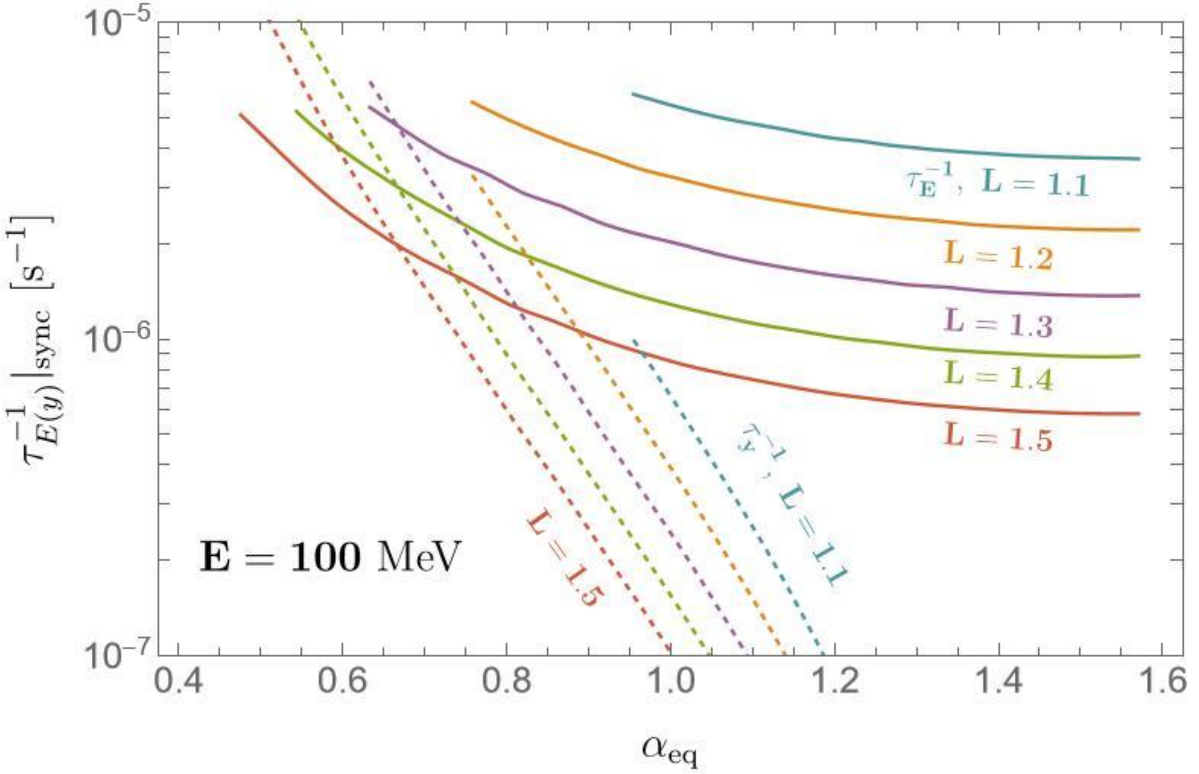
Fast energy loss for hard electrons > O(10) MeV

- ❑ |B|~O(Gauss)
- ❑ E≫ m_e



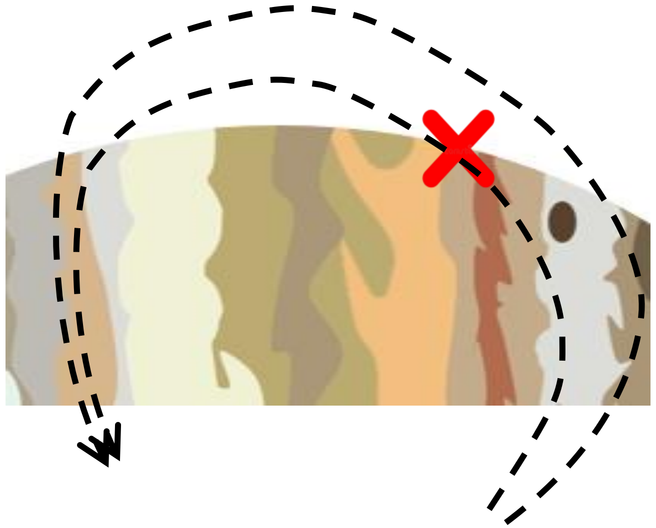
Dominant friction when r $\gtrsim$ 1.03 R_J

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



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

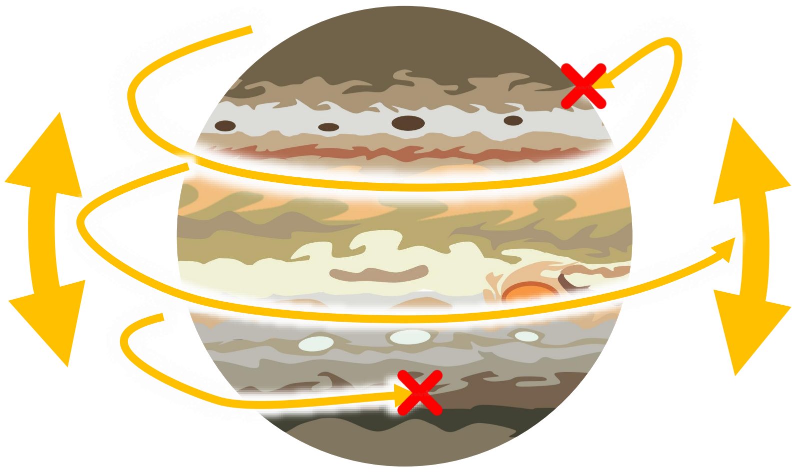
Three Scenarios of Trapping



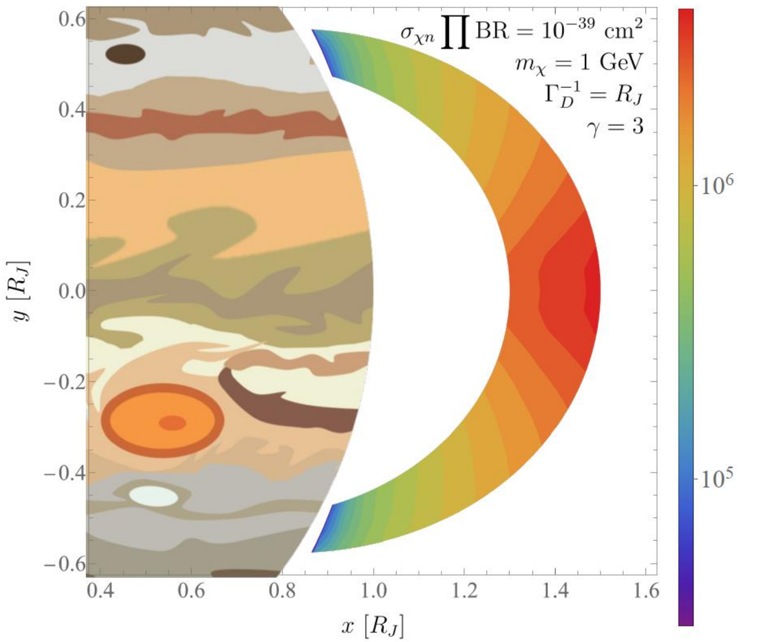
Untrapped scenario: electron absorption when meeting twisted field lines

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

Quasi-Trapping: electron trapped locally but eventually loss when drifting around Jupiter



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



Full-Trapping: electron losing energy via synchrotron radiation before being absorbed

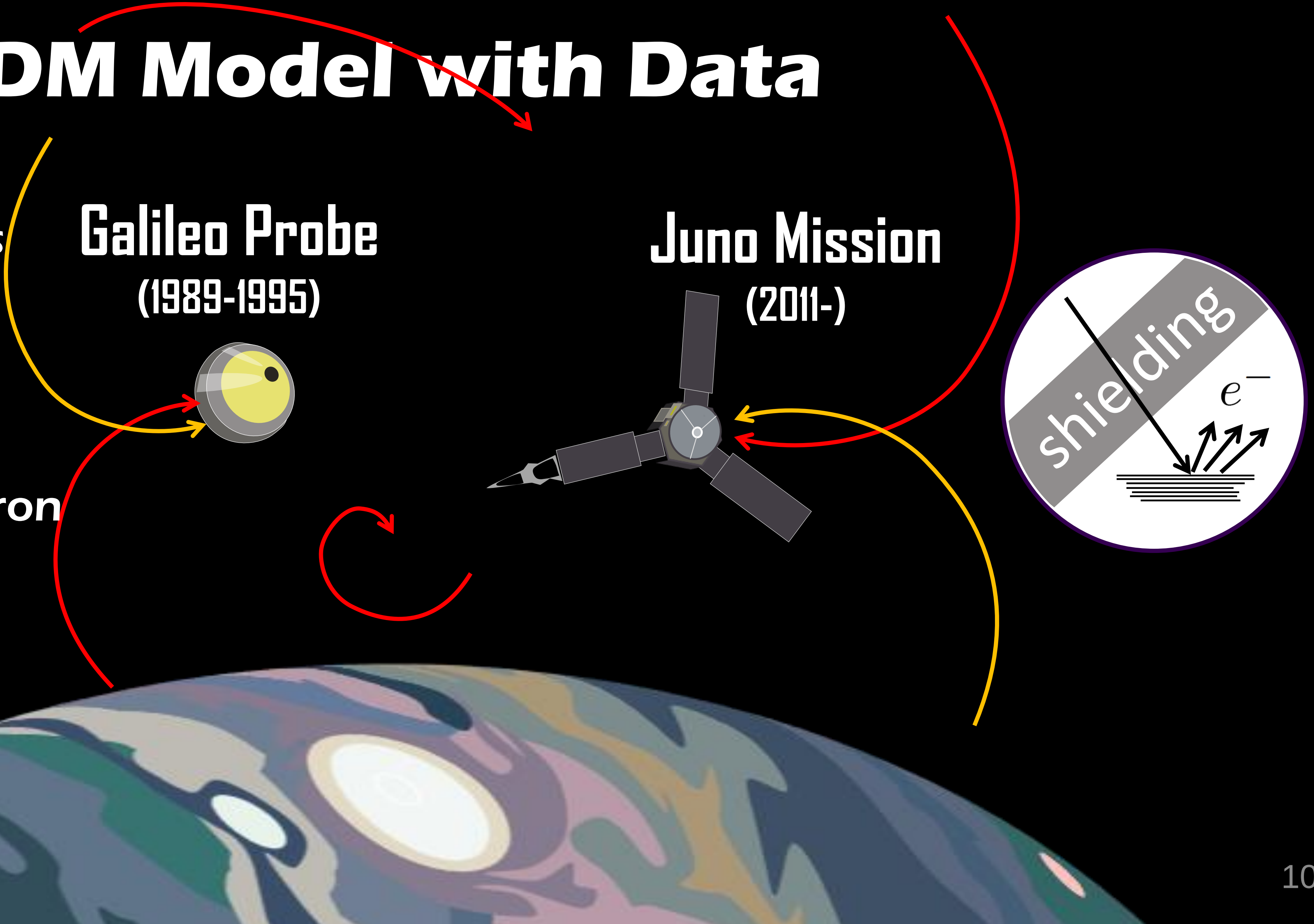
$$\tau_{\rm loss} \gtrsim \mathcal{O}(10^5)\ \text{sec} \gtrsim \tau_E|_{\rm sync}$$

Lingfeng Li 2207.13709

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)



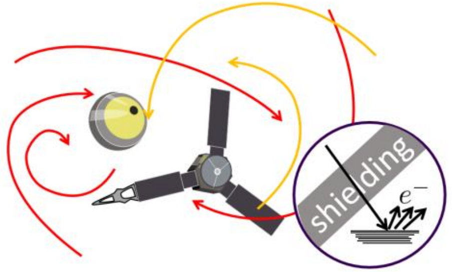
Galileo Probe

(1989-1995)

Juno Mission

(2011-)

Limit (Fully Trapped)



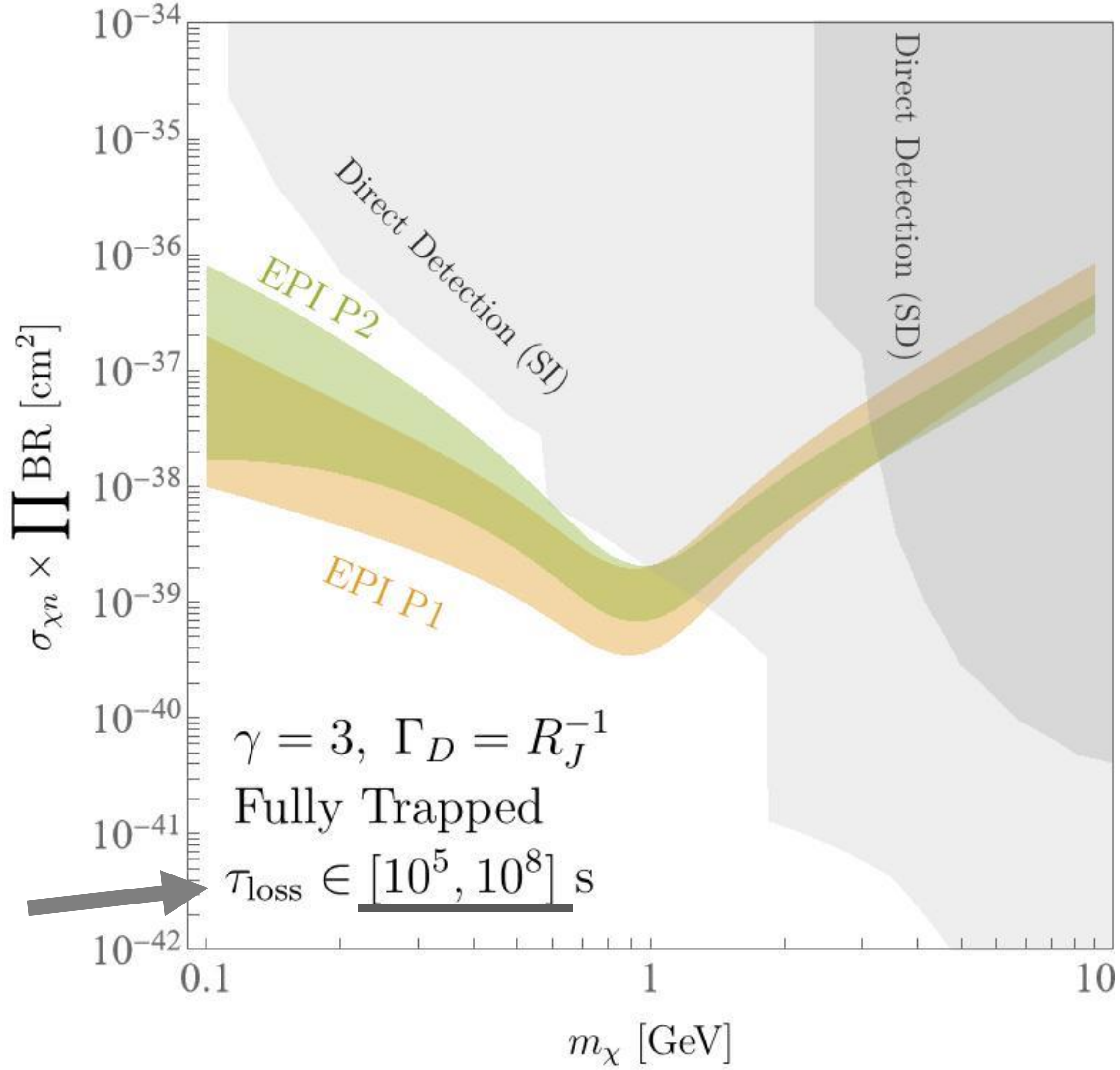
Currently only Galileo probe data available covers the area L > 1.3 & close to the magnetic equator

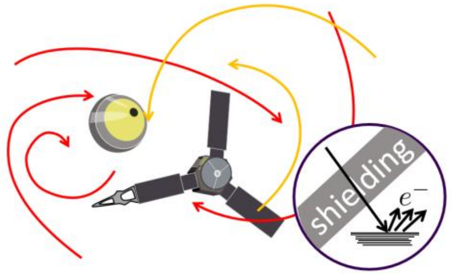
Large count rates

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

Conservative but reliable

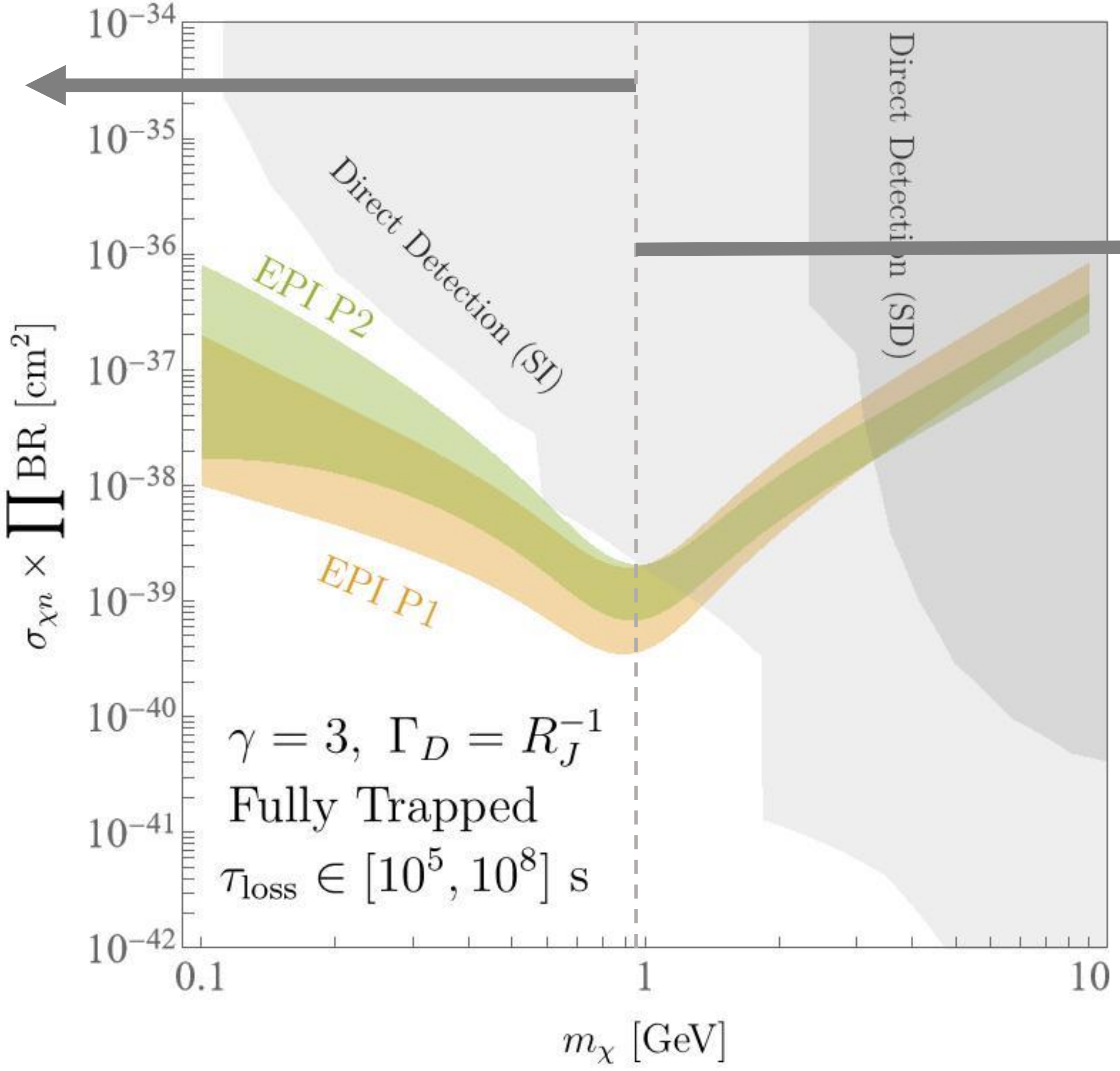
Not very sensitive to a varying τ_{loss} :





Below 1 GeV:

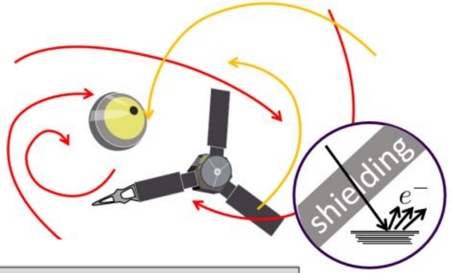
- ☐ DM number density increases but capture efficiency drops.
- ☐ Softer electron →weaker bounds
- ☐ Stronger evaporation effect (not accounted for in the plot)



Above 1 GeV:

- ☐ Both number density and capture efficiency drop
- ☐ Harder electrons, could further improve with better detector knowledge

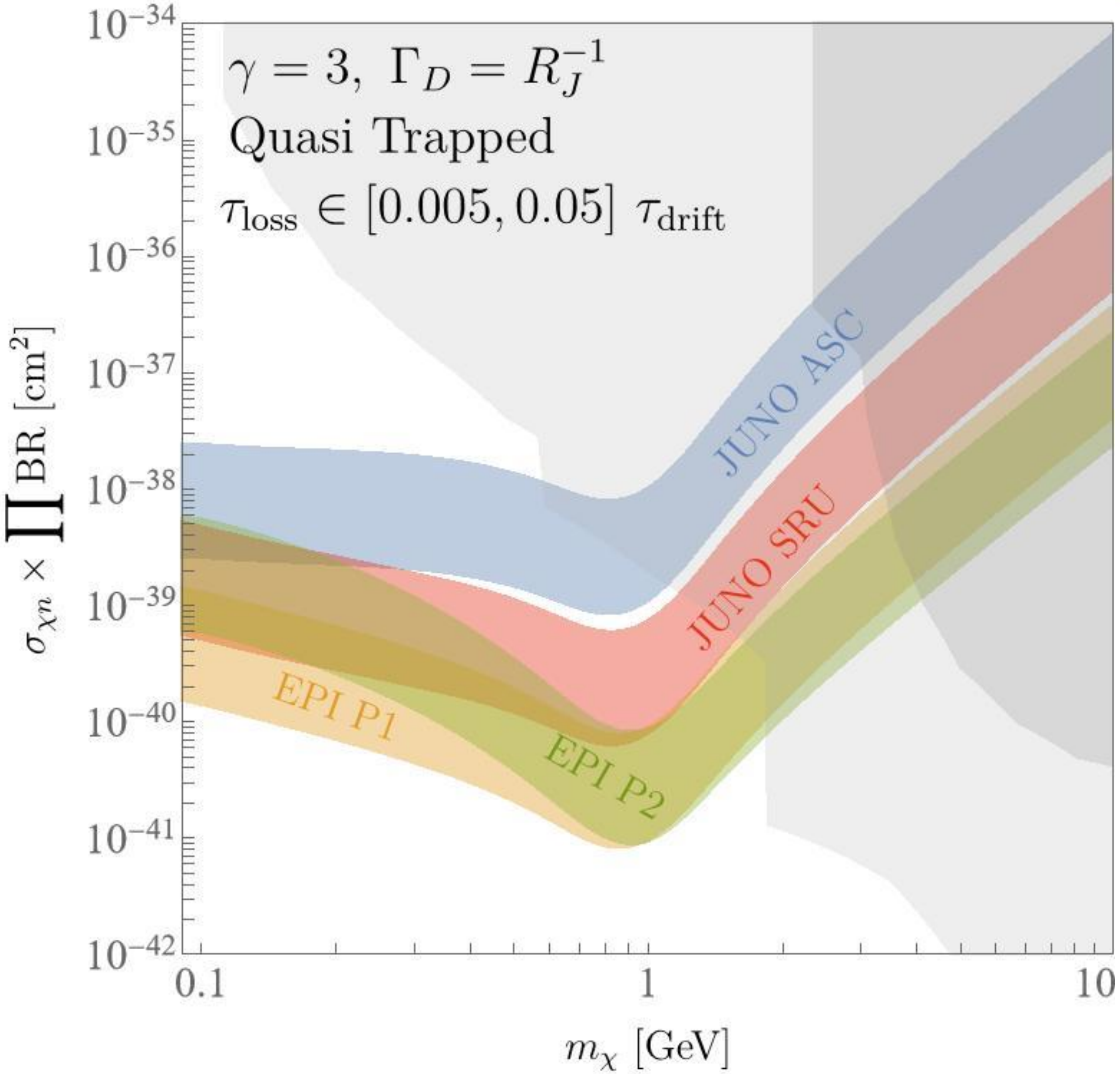
Limit (Quasi Trapped)



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.



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Summary

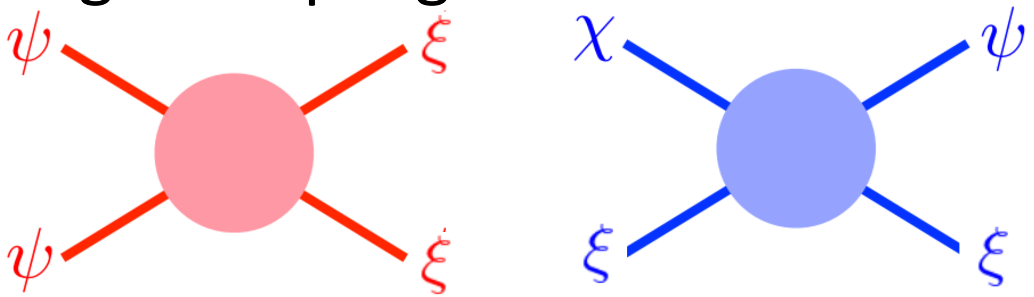
- ❑DM accumulation inside Jupiter is a general prediction for GeV-scale DM, greatly enhancing annihilation rates.
- ❑Long-lived mediator with lifetime ~R_J decaying to electrons inject hard electrons to the radiation belt.
- ❑*In situ* limits on DM-nucleon scattering Xsec comparable (spin-independent)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

Backup Slides

A Right Ω_{CDM}?

Small σ_{ann} for the "WIMP miracle", may overclose the universe

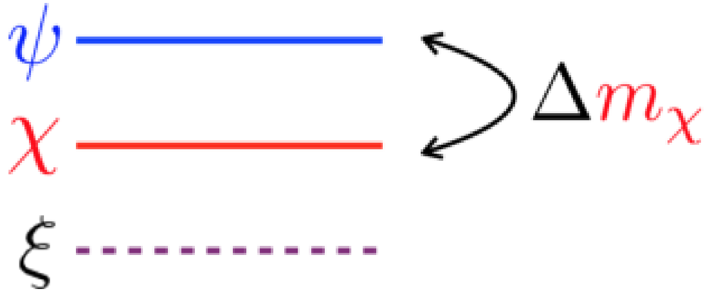
Thermal way out: dark partner (ψ) with stronger coupling to the mediator:



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……

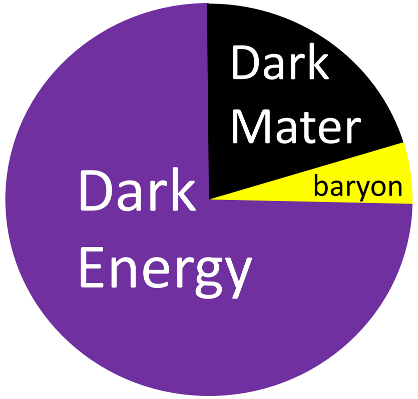


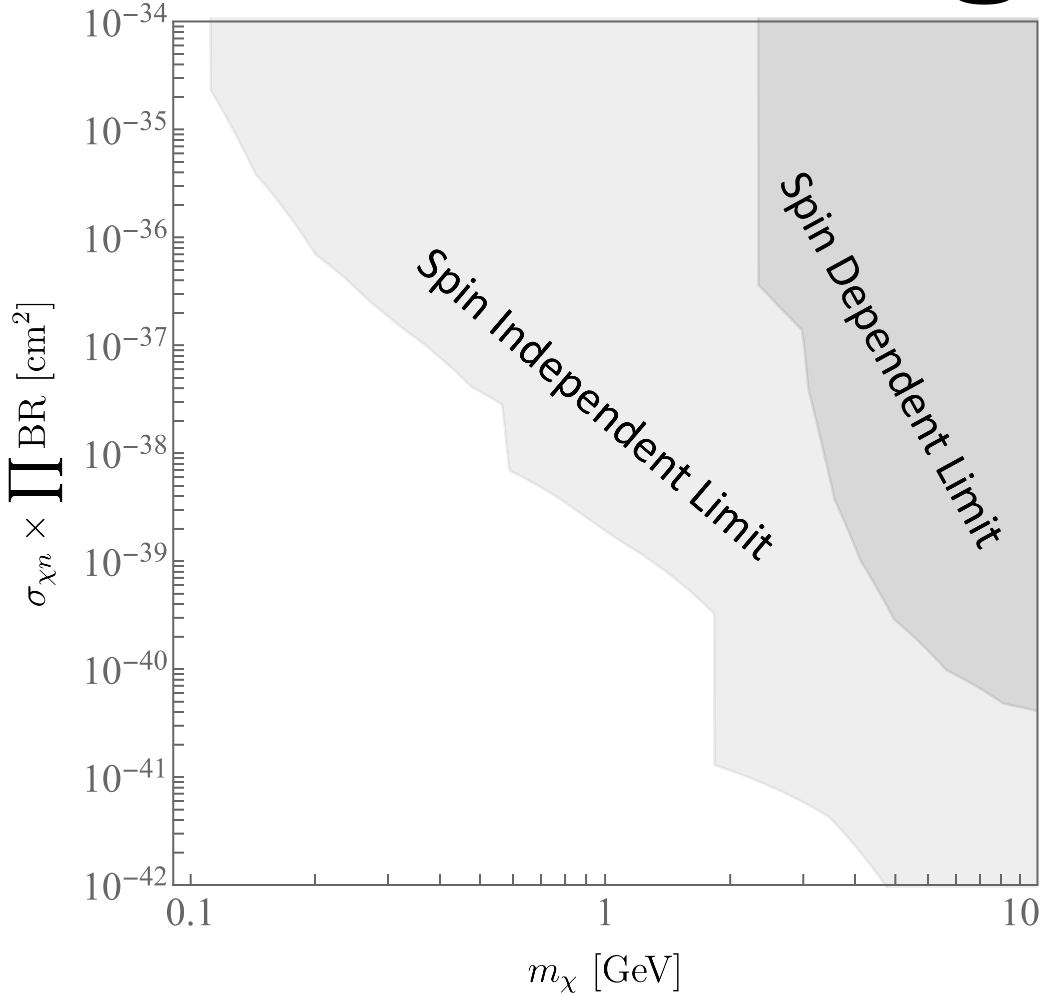
Non-thermal way out: early matter domination diluting DM generated

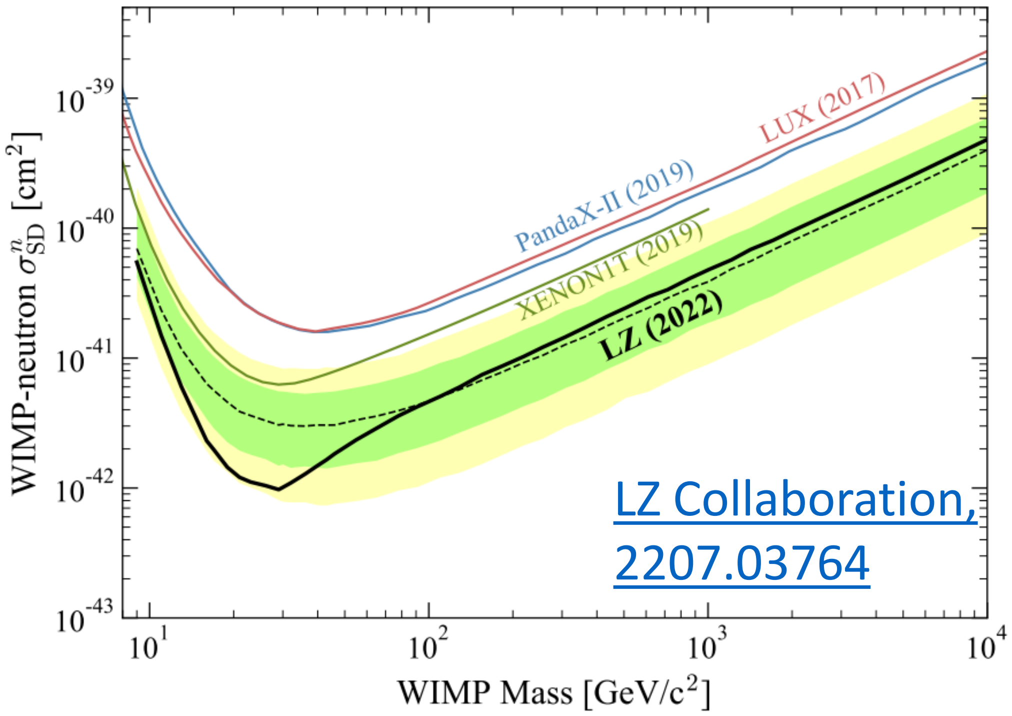
* We stay agnostic about DM production in this talk

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

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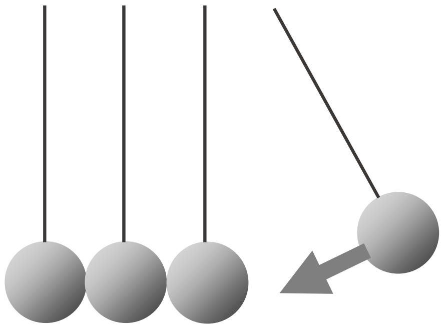
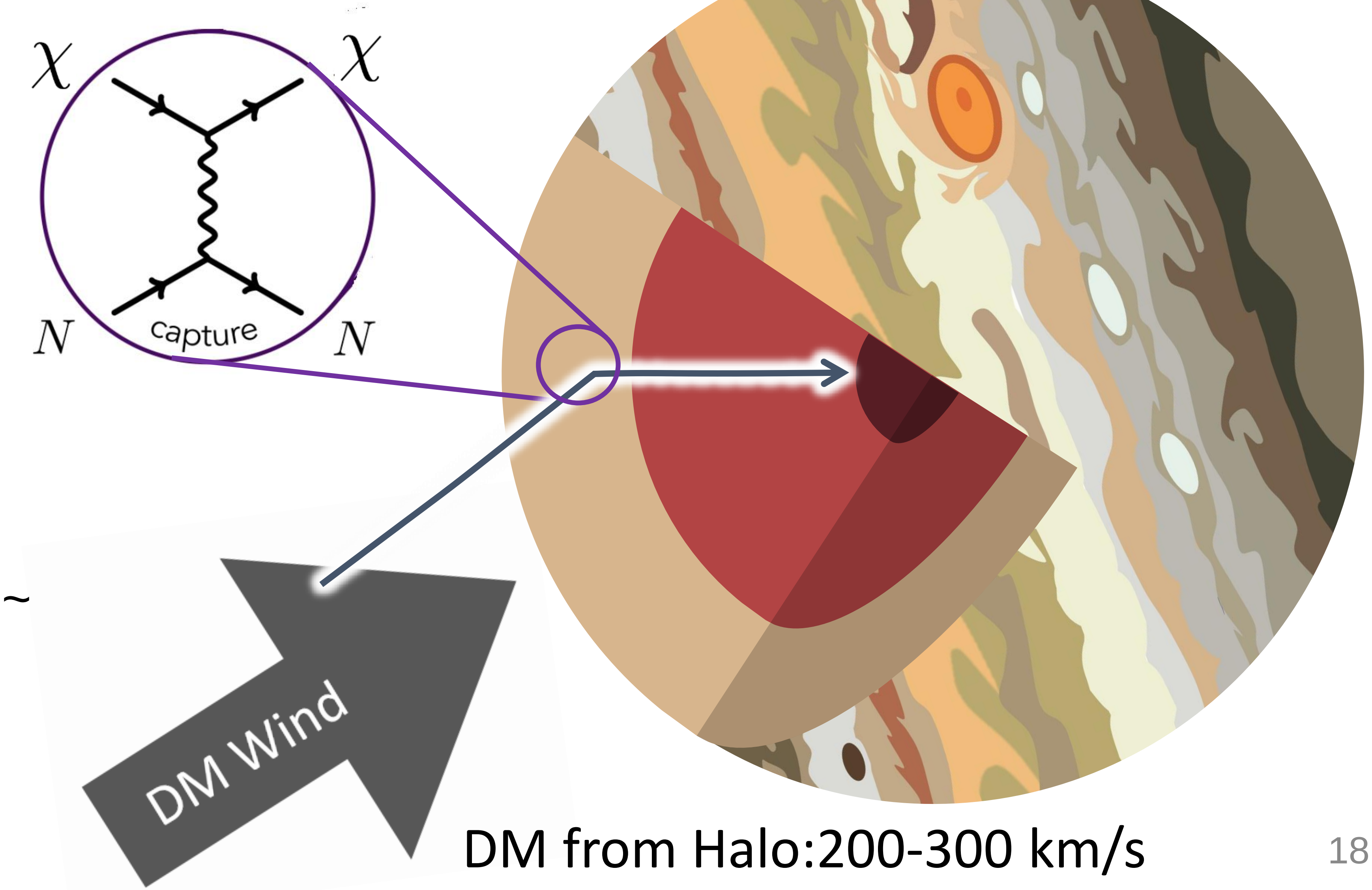
DM Capture

DM transfers energy to nucleons by scattering and slows down

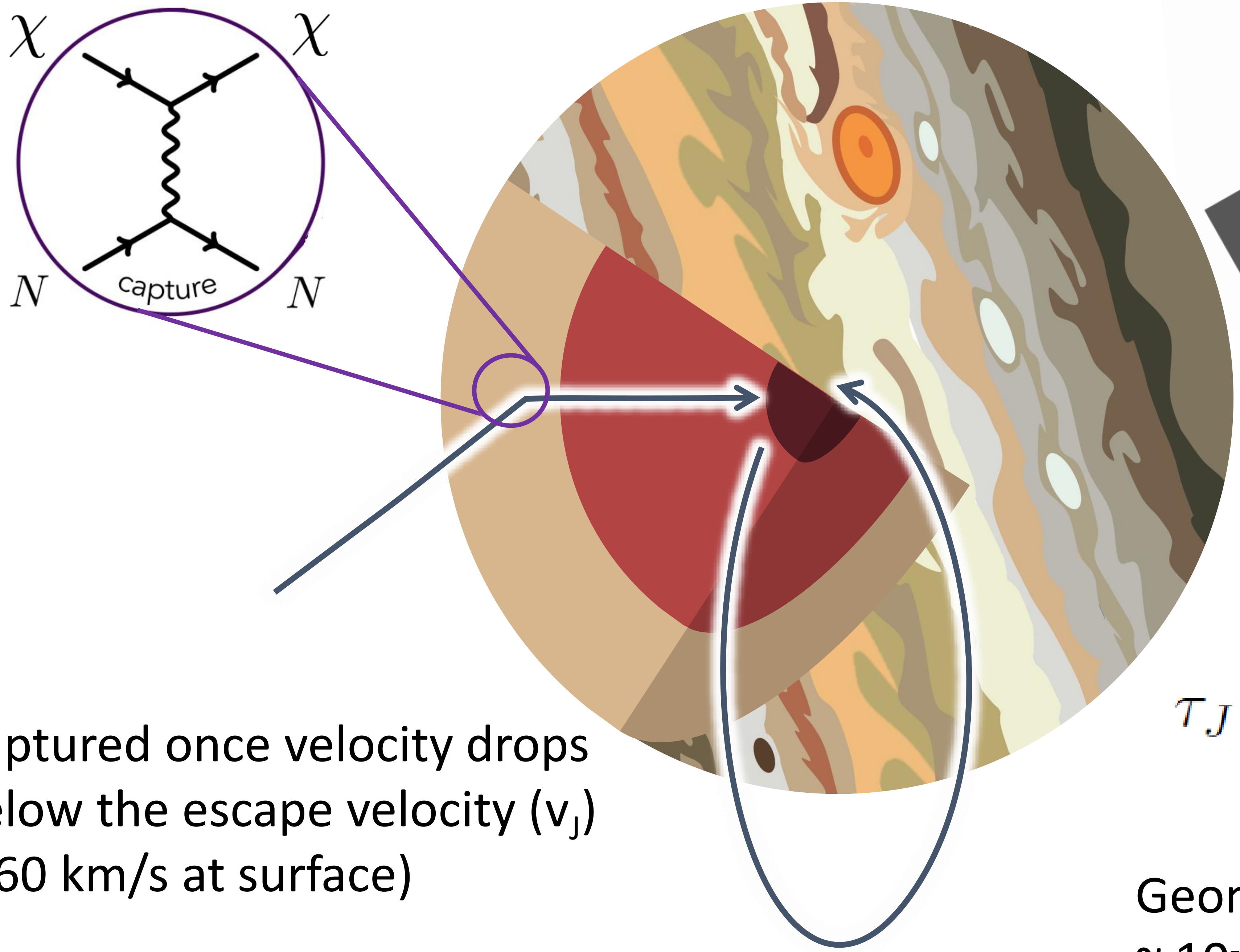


Most efficient when m_χ ~ 1GeV, comparable to nucleon masses

Mostly hydrogen



DM from Halo:200-300 km/s



Optically thin in our case

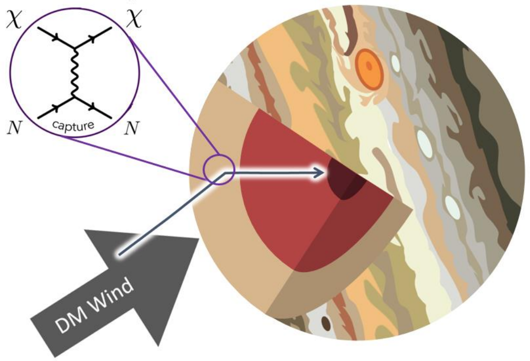
DM-nucleon scattering Xsec

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

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



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

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

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

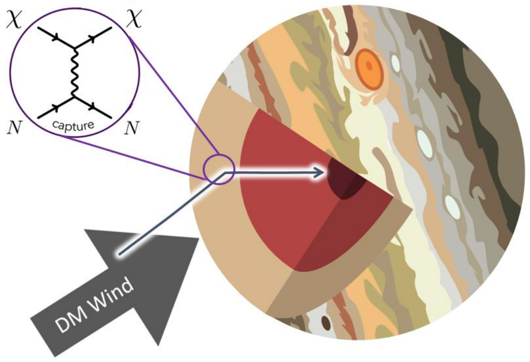
Suppression factor comes from the relative speed between Jupiter and the DM Halo

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

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

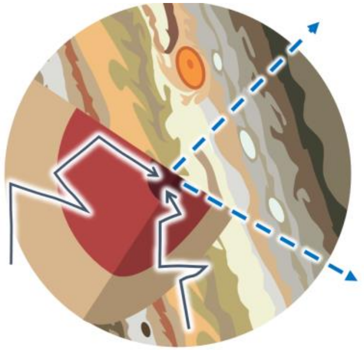
To get spin dependent rates for weaker constraints: axial-vector type interaction

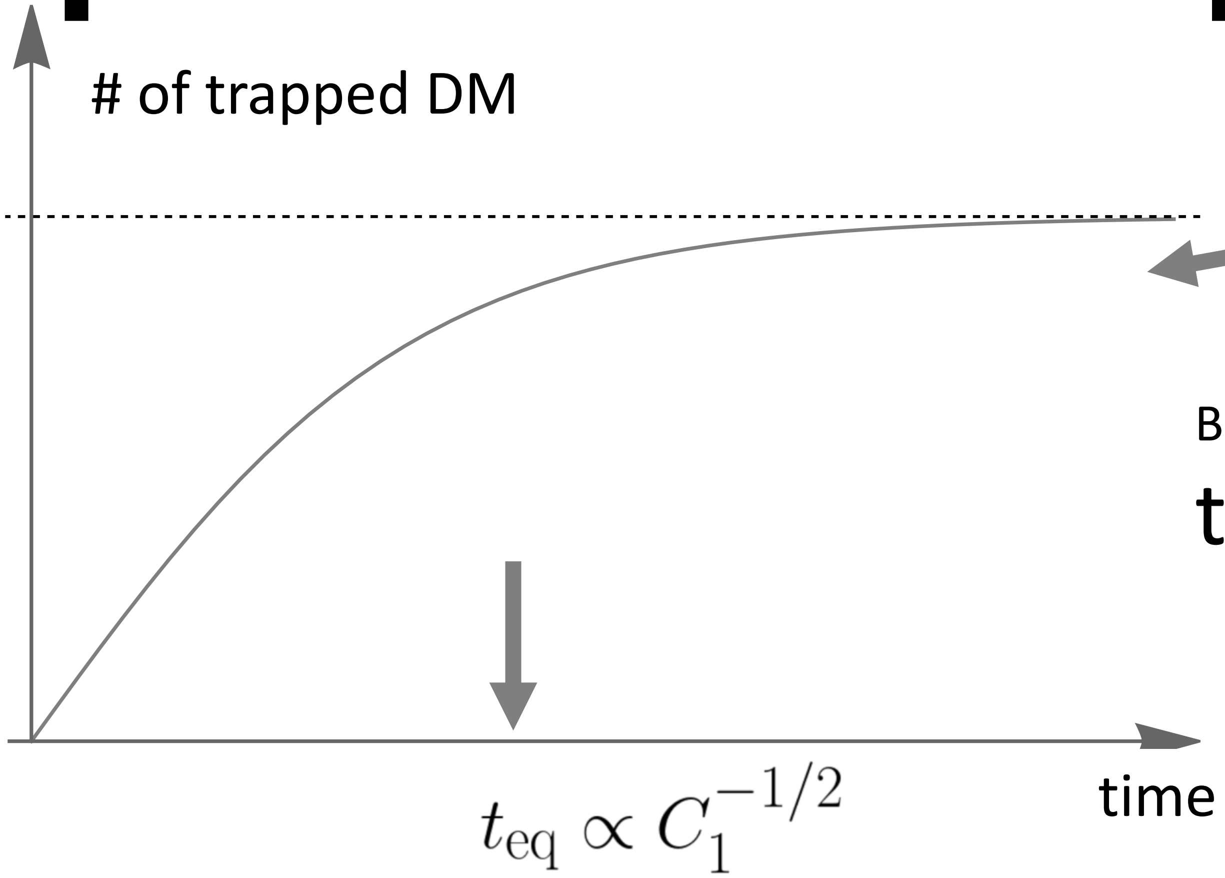
$$\frac{g_\chi g_q}{\Lambda^2}\left(\bar{\chi}\gamma^\mu\gamma^5\chi\right)\left(\bar{q}\gamma_\mu\gamma^5 q\right)$$

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

Possible to get a relevant scattering rate without violating collider bounds

Equilibrium and Evaporation





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

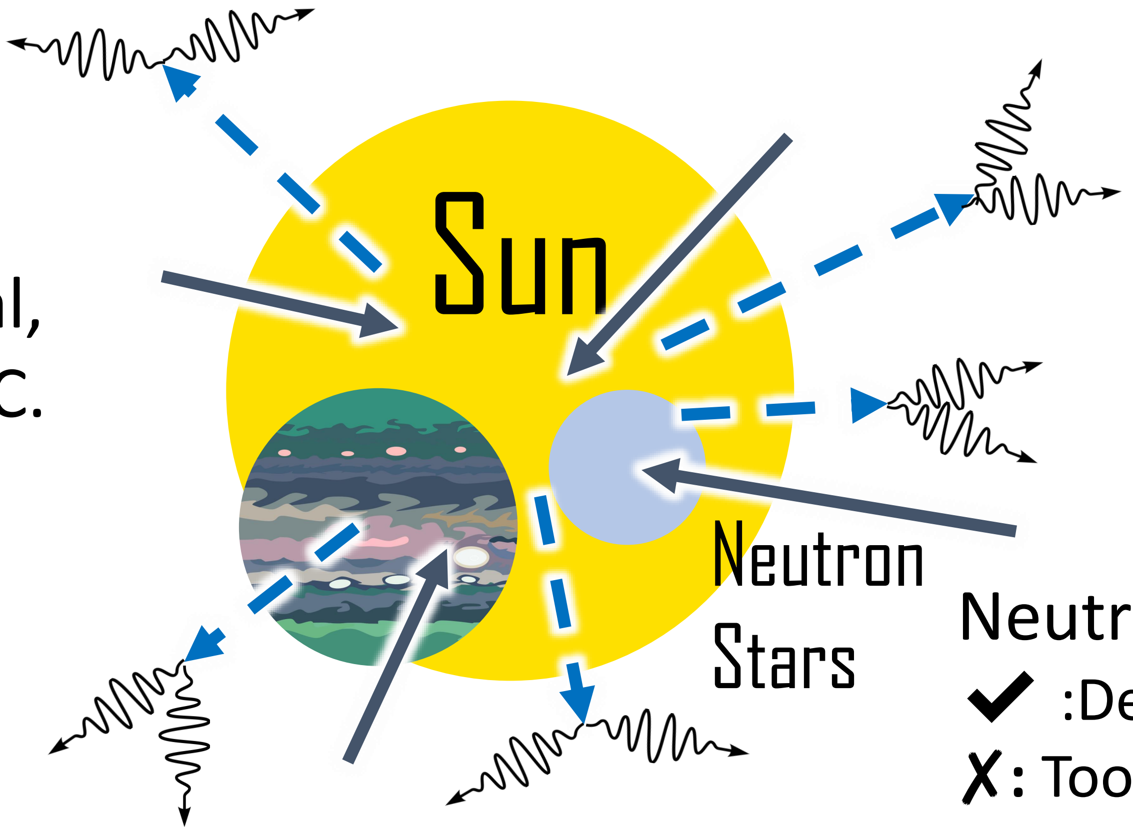
A. Gould, 1990

R. Garani, S. Palomares-Ruiz, 2104.12757

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

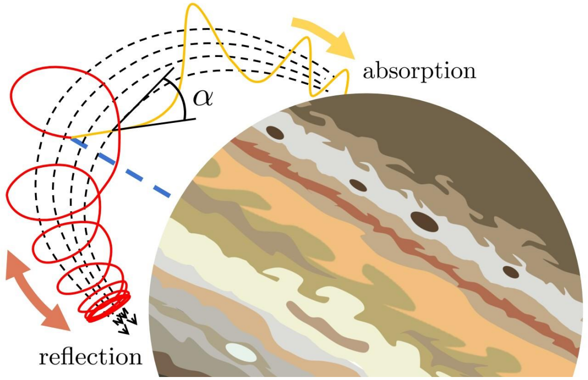
Neutron stars:

✓ :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!

Diffusion Equation



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

f = Phase space density

Source term: averaged over trajectories

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

Friction terms: energy loss with time (number conserving)

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

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

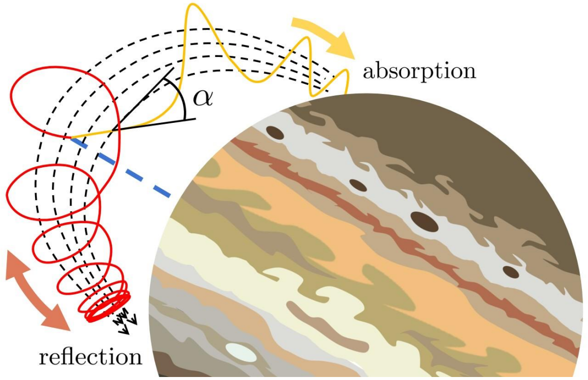
$$\tau_{\rm loss}^{-1} f \quad + \quad \text{diffusion terms}$$

Electron number loss (and its time scale)

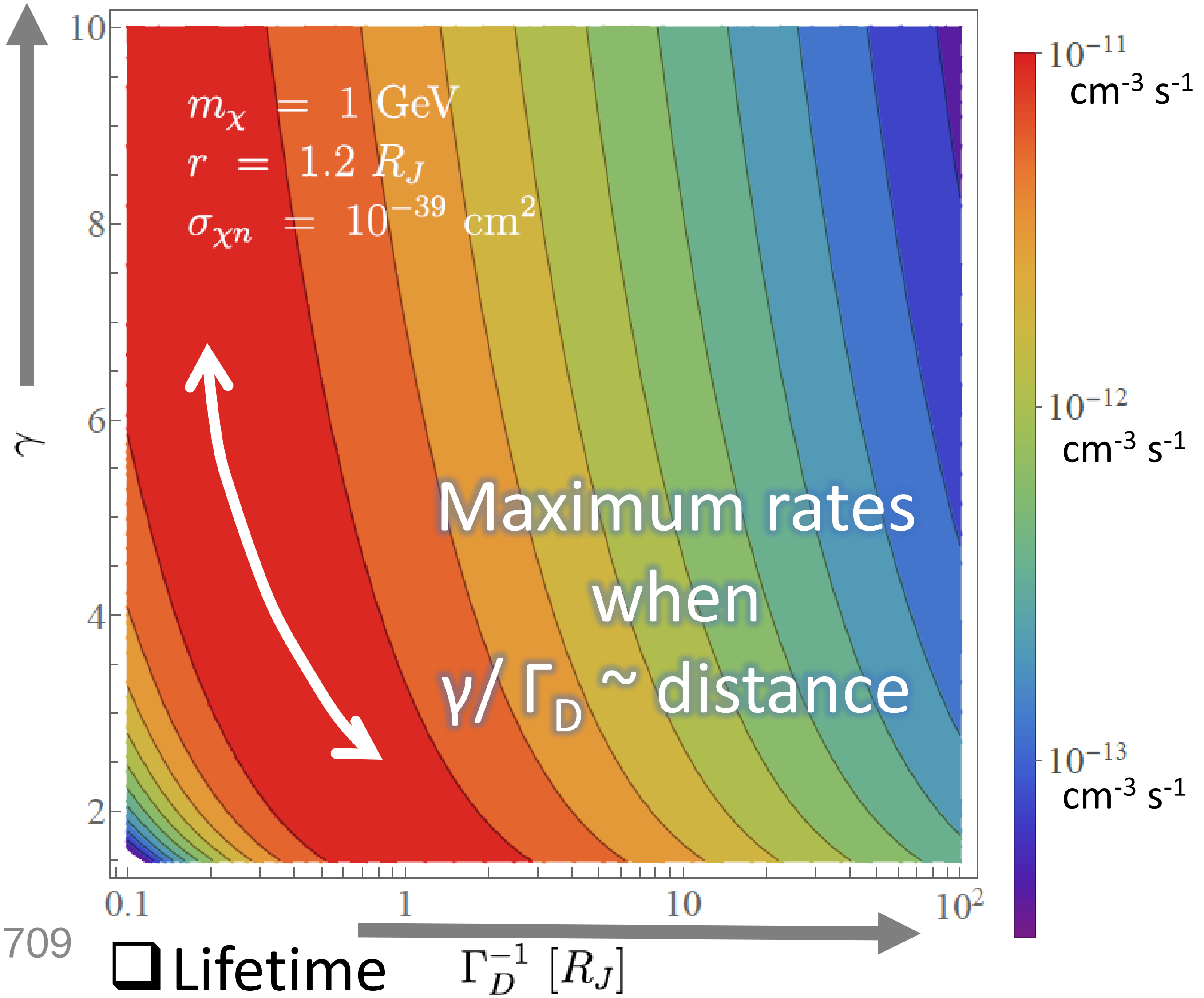
Suppressed for our discussion

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

Decay Rate Density



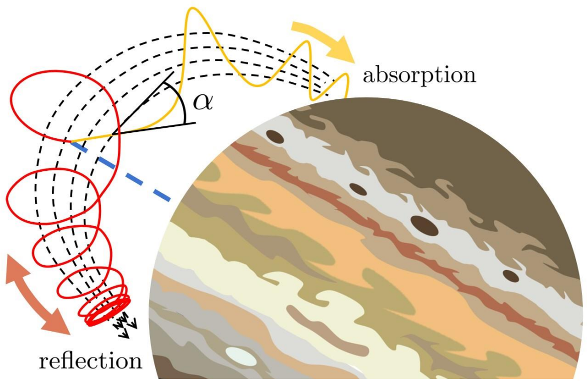
❑Boost ~ m_χ/m_ξ



Maximum rates when γ/Γ_D ~ distance

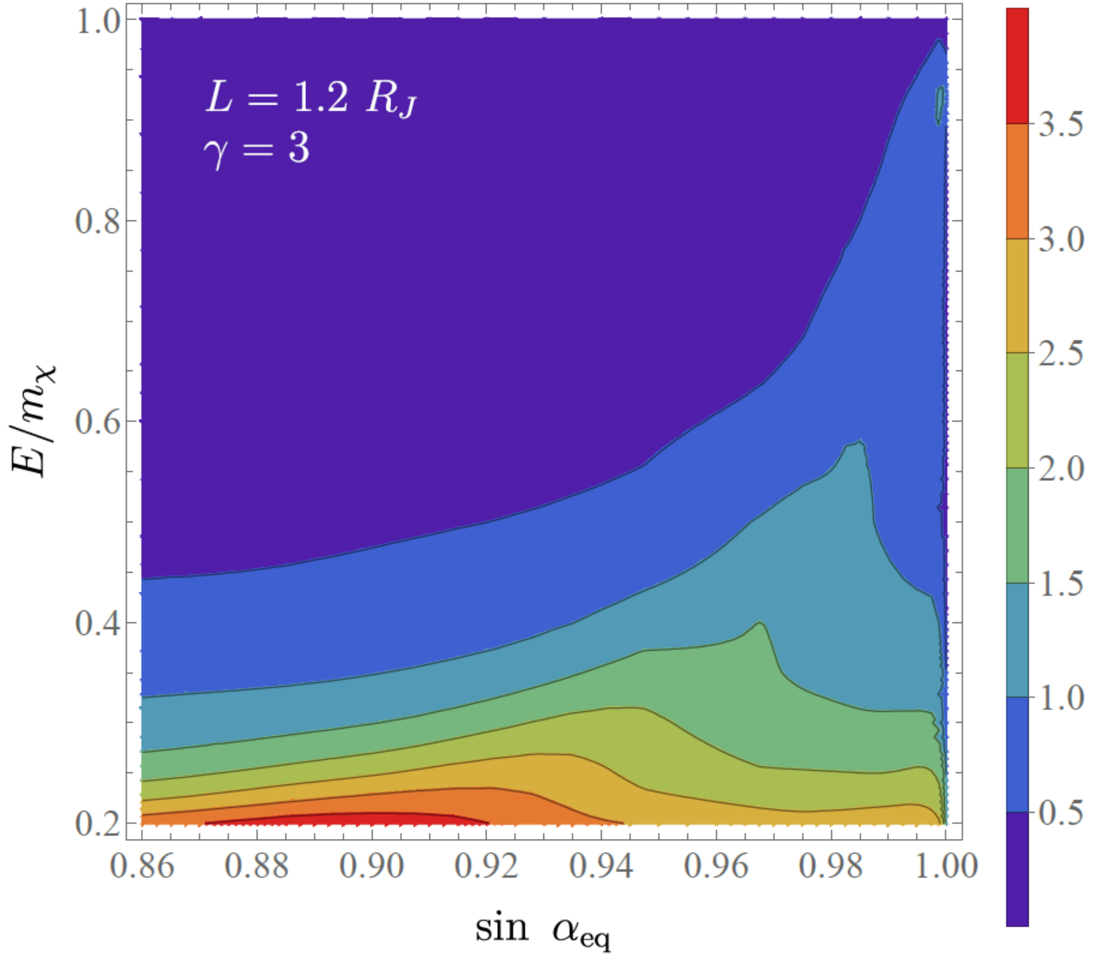
❑Lifetime

* The volume is large to compensate

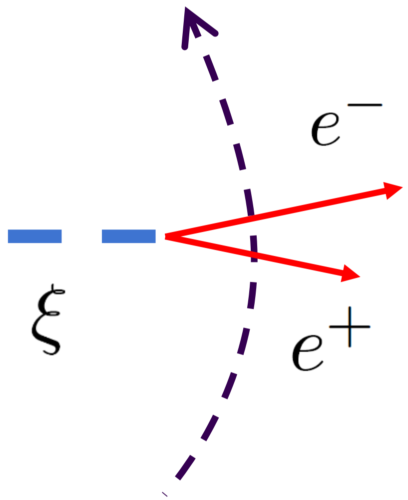


Source Term

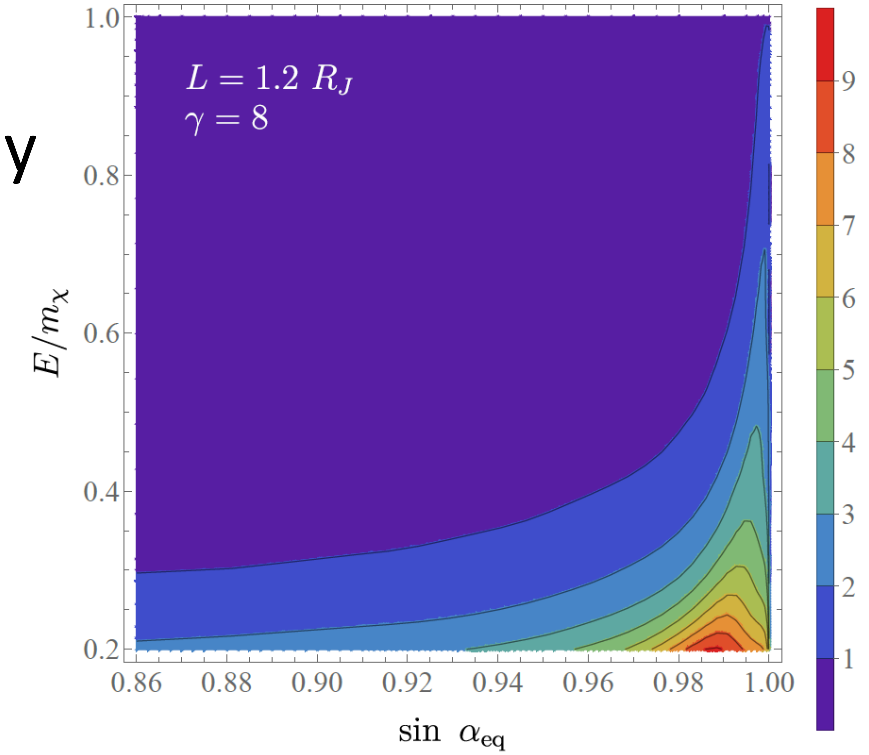
Injected electrons' phase space distribution



Dimensionless form for unit decay rate density

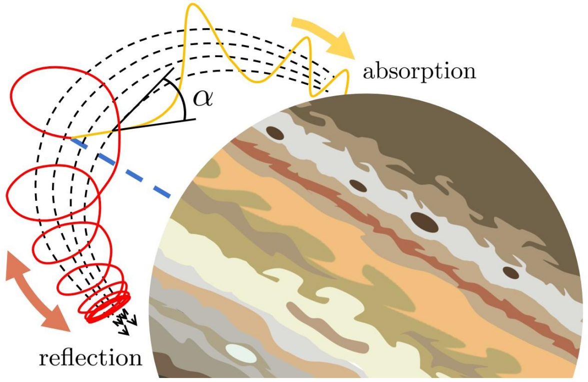


Tends to have high α_{eq}: boost $\gamma>1$

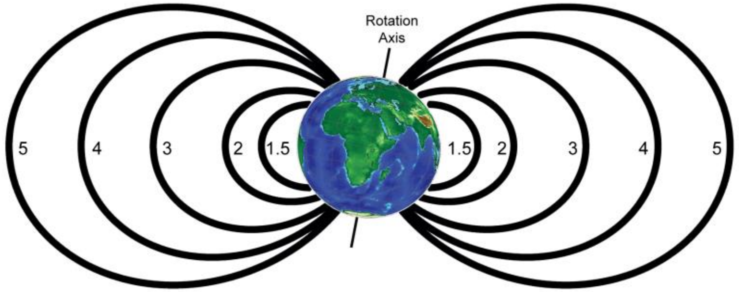


Scales as E^{-2} before integration

Phase Space Parameters



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

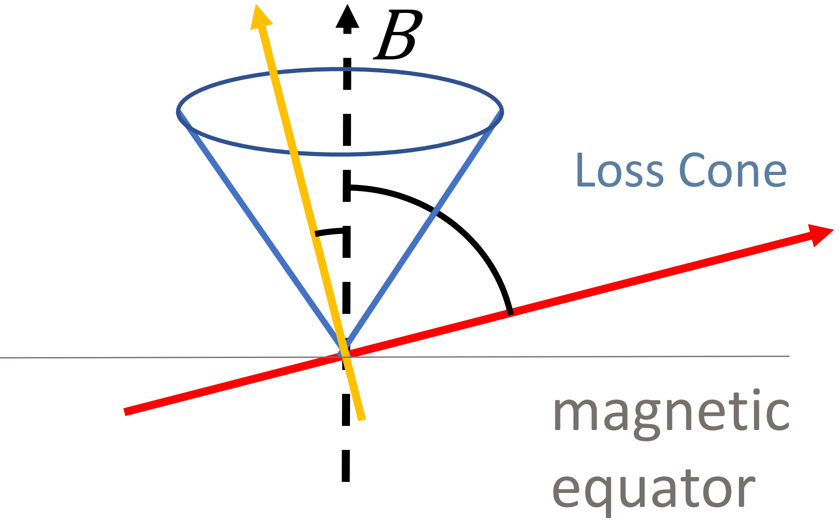


1) E: Kinetic energy

2) L: Mcilwain L-parameter

[C. E. McIlwain, 1961]

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

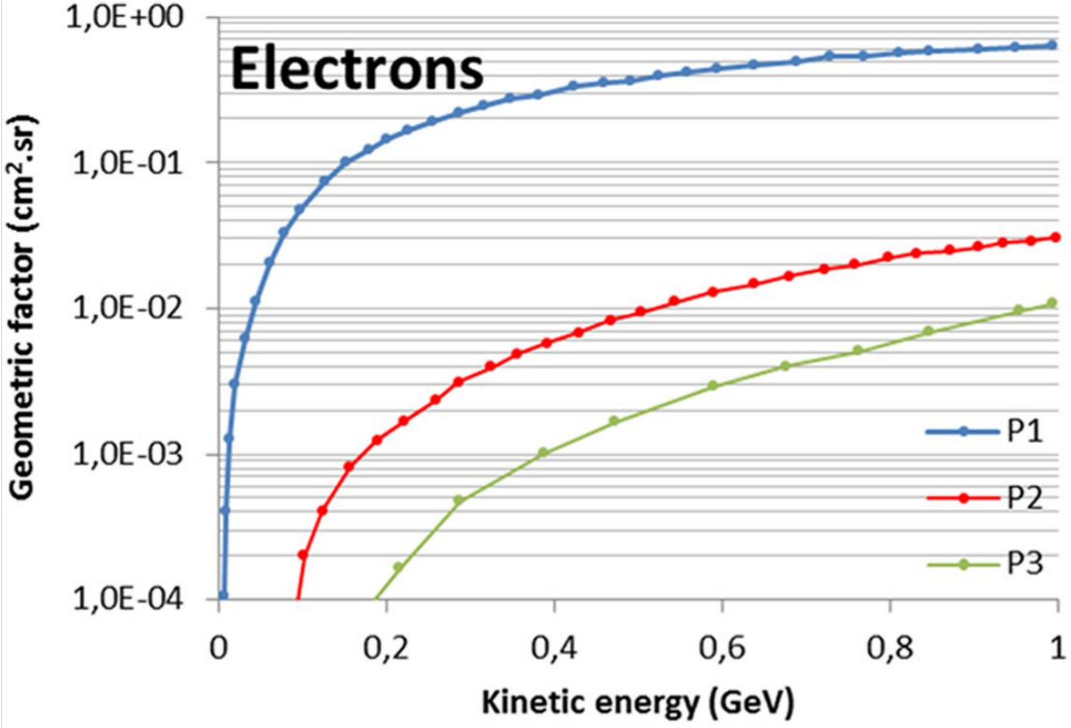


3) α_{eq}: Equatorial pitch angle

Inside the loss cone, the mirror points are below the atmosphere, no bouncing

Jupiter Mission Readouts

- ☐Galileo Probe EPI: "Calorimeters" [H. M. Fischer, E. Pehlke, G. Wibberenz, L. J. Lanzerotti, J. D. Mihalov, Science 272, 1996]
- ☐Juno RM: CCD cameras [H.N. Becker, D. Santos-Costa et al., Geophys. Res. Lett. 44, 2017]

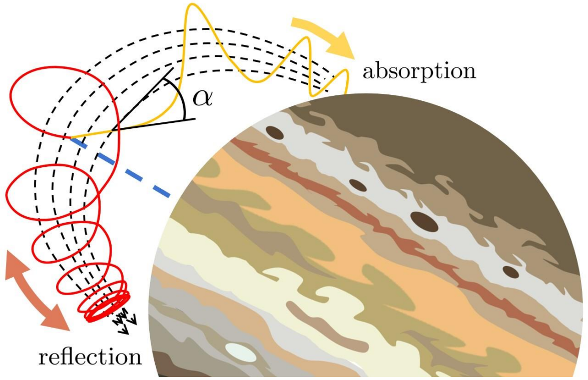


No precise spectroscopy: Higher energy → higher penetration rates

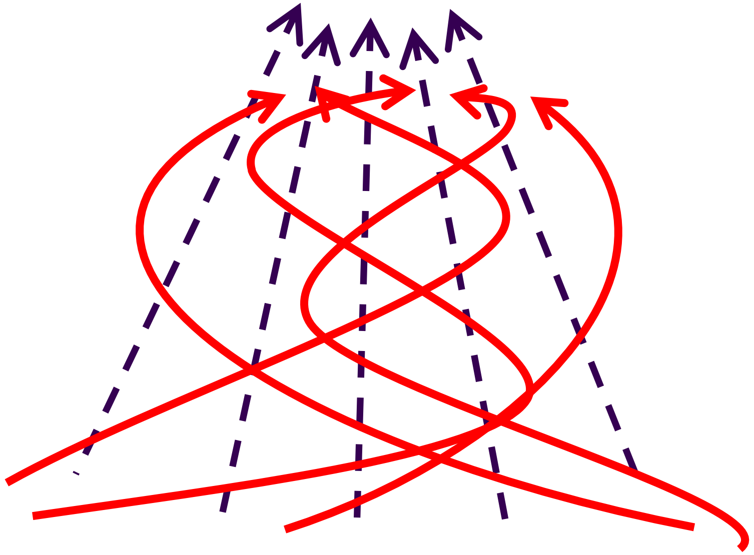
Q. Nenon, A. Sicard, P. Kollmann, H. B. Garrett, S. P. A. Sauer, C. Paranicas, 2018

Positron & electron become identical without a magnetic field

Spatial Distribution

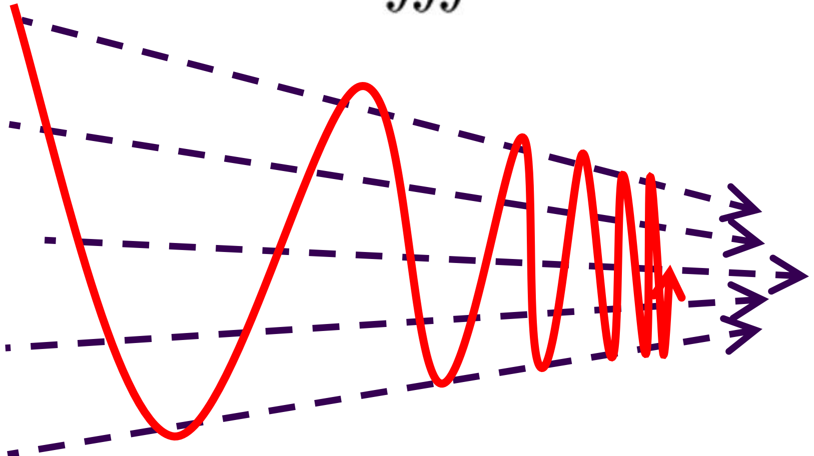


The (omnidirectional) electron flux is NOT the same along the same L-shell



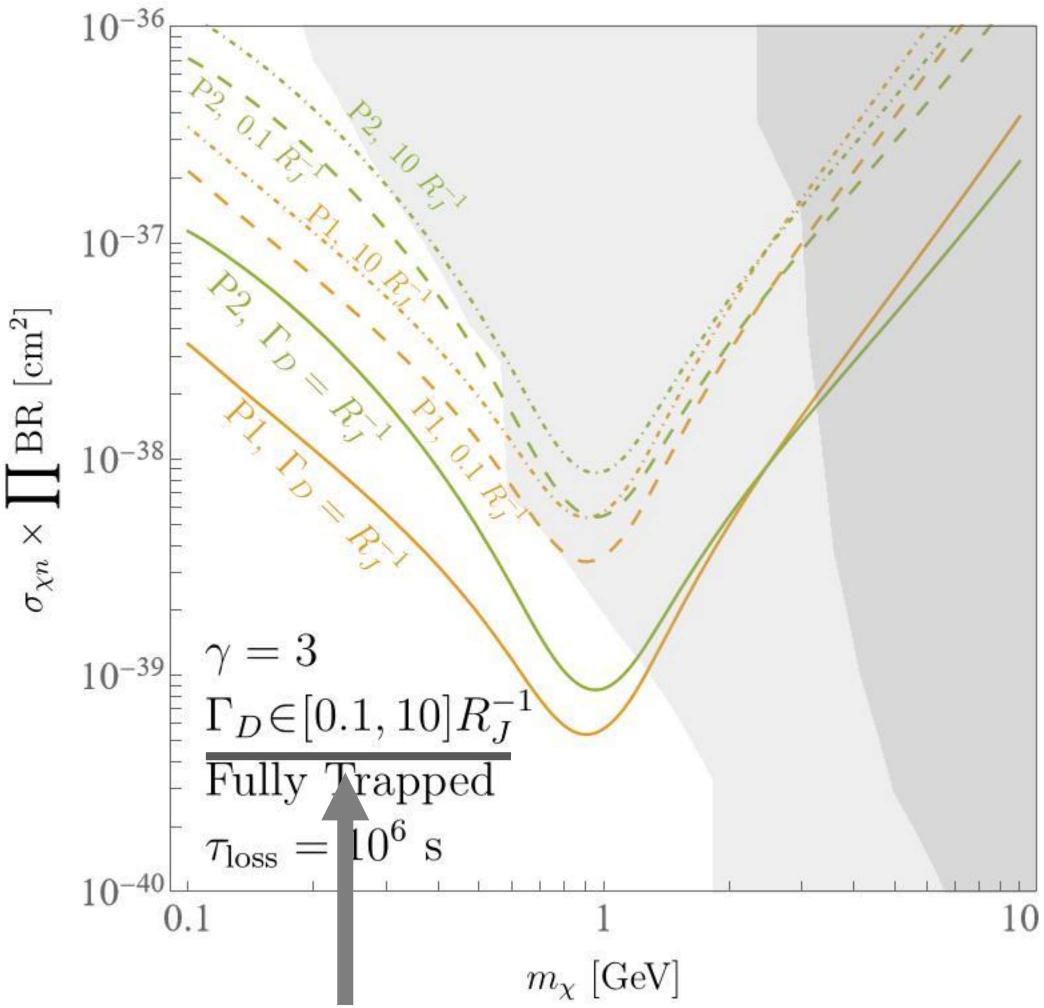
The tube narrows as the field goes stronger

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



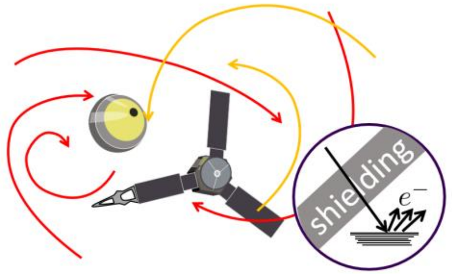
The coil gets denser when the field is strong

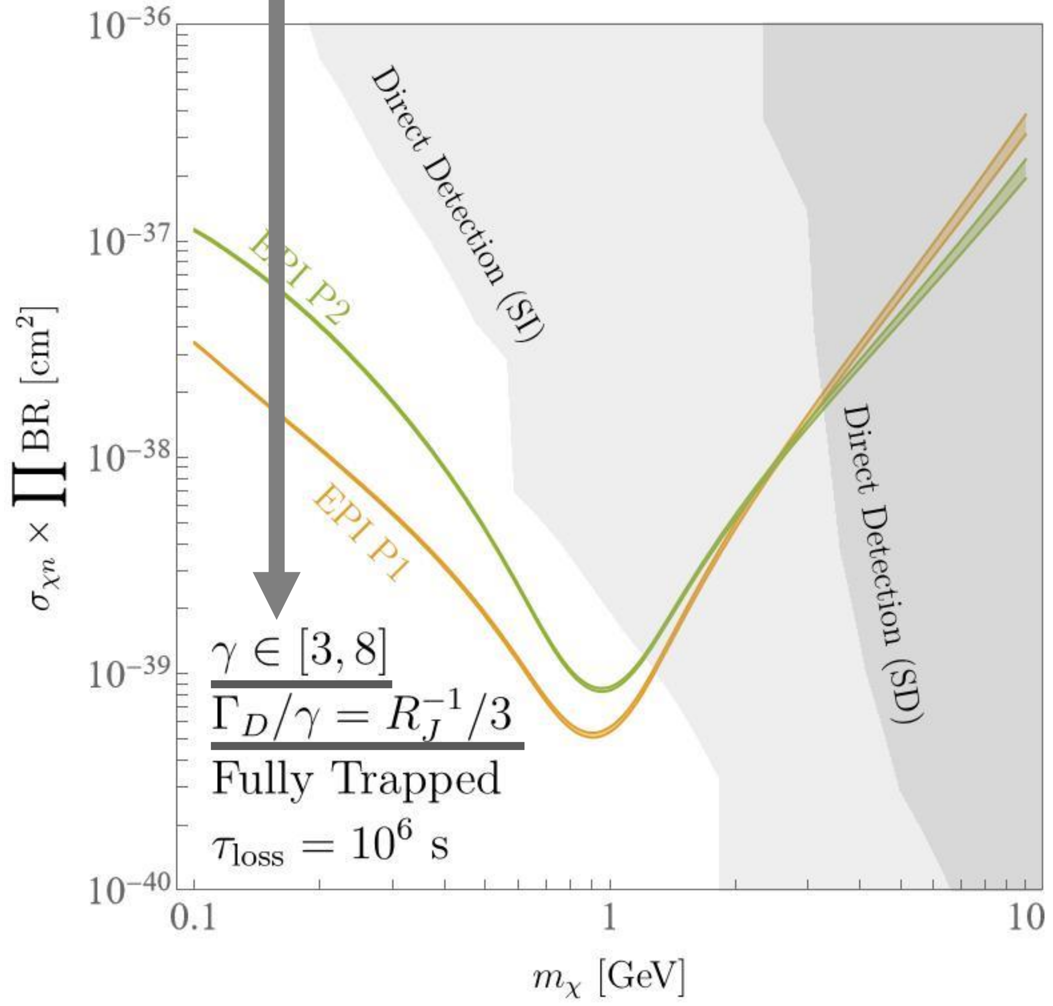
Speed ∝ $\cos^{-1}\alpha$



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

Insensitive to boost once the proper decay length is fixed



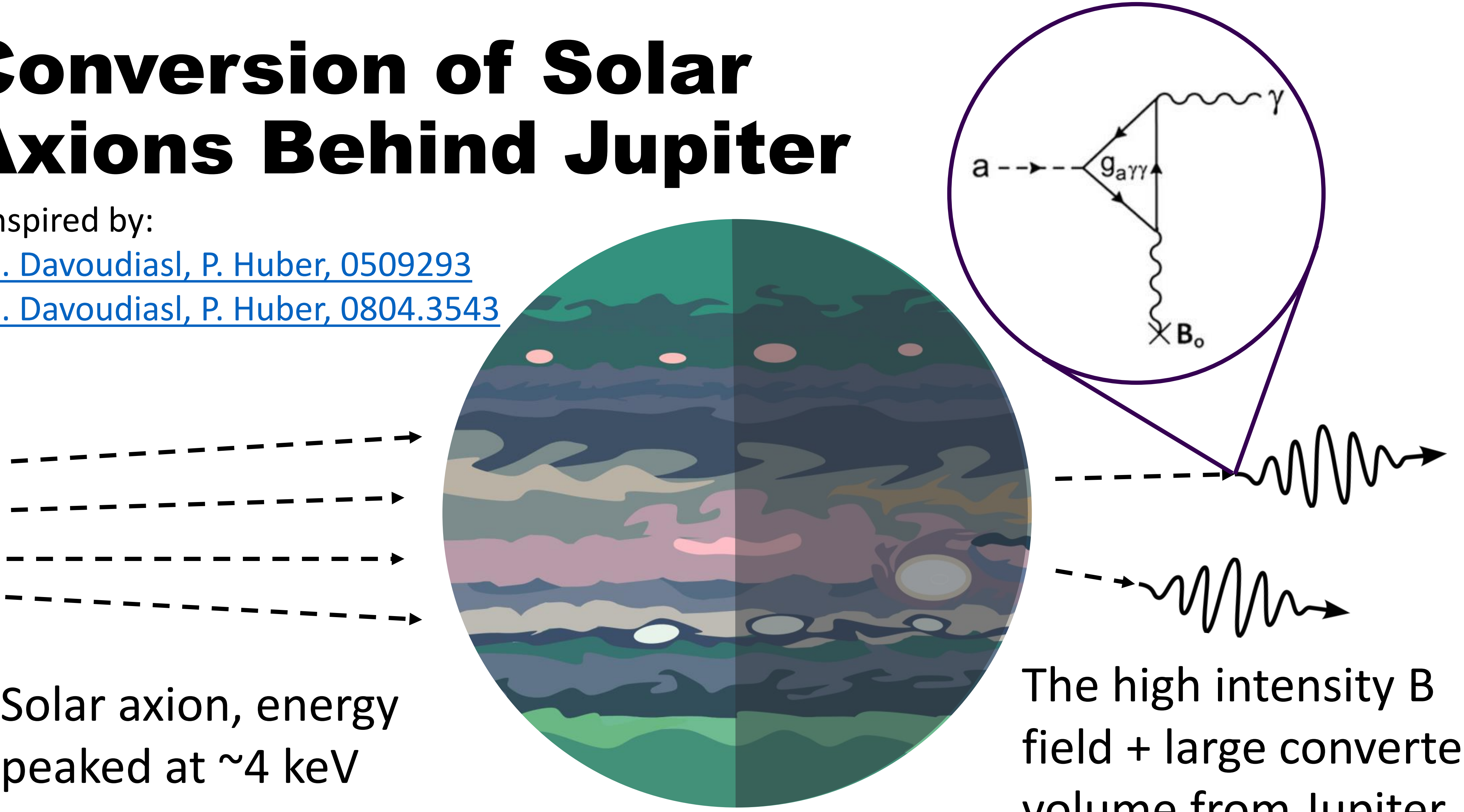


Conversion of Solar Axions Behind Jupiter

Inspired by:

[H. Davoudiasl, P. Huber, 0509293]

[H. Davoudiasl, P. Huber, 0804.3543]



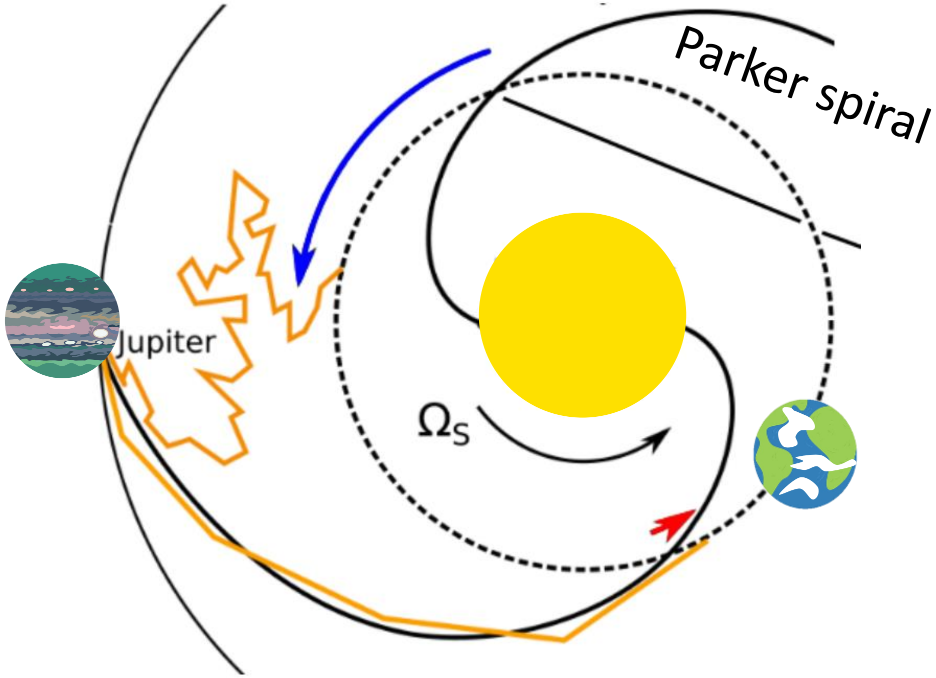
Solar axion, energy peaked at ~4 keV

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

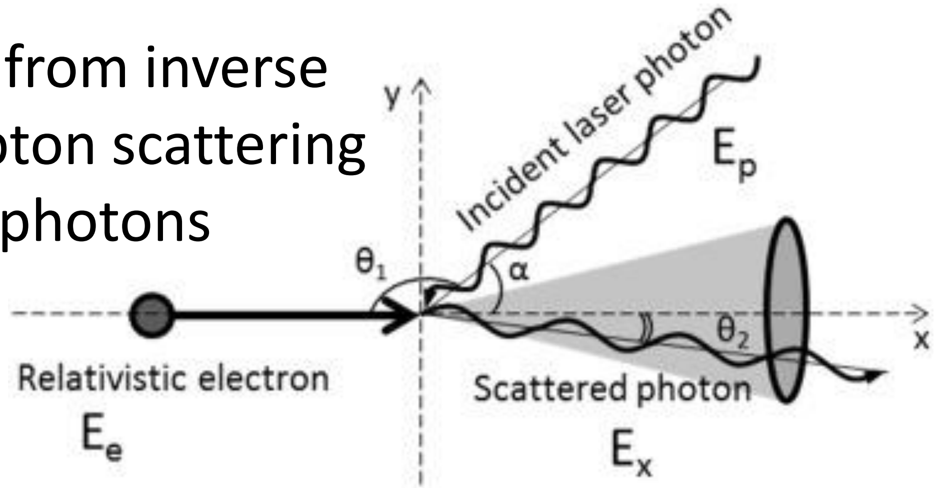


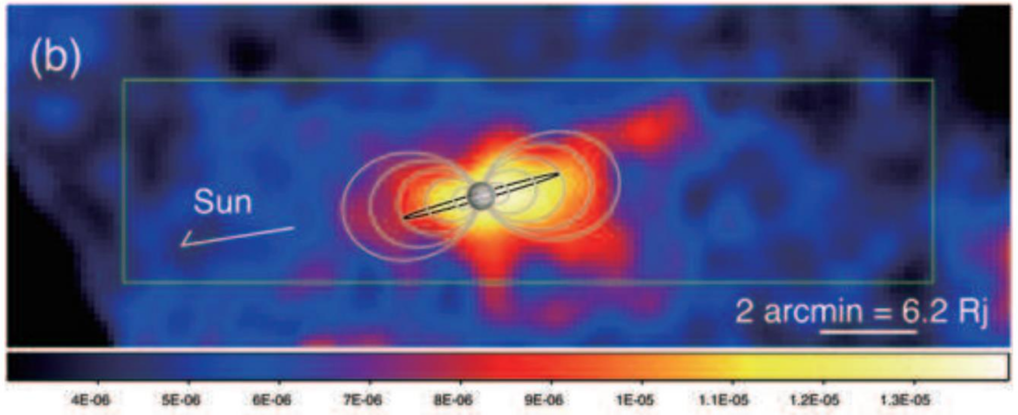
~13 month period of Jovian positrons, see e.g.

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