Dark Matter Drag on Saturn's Rings

26xx.xxxxx with:
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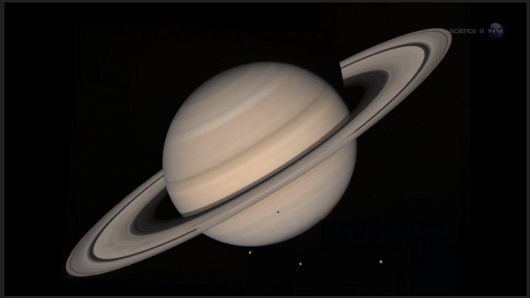
Zachary S.C. Picker

Light Dark World 2026

Overview

Saturn + Rings



'Doppler drag'

Coherent elastic scattering

Pheno

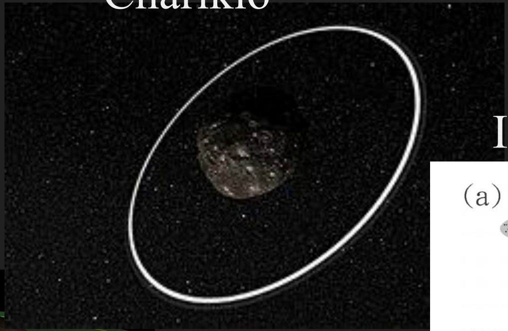
Observations?

Planetary Rings

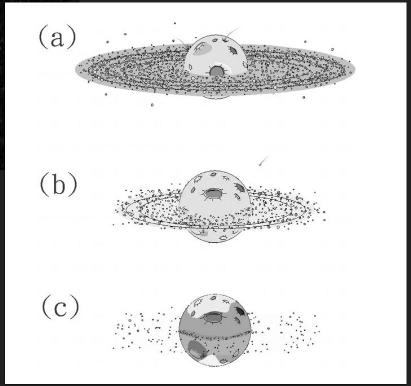
Planetary rings across the solar system

Neptune

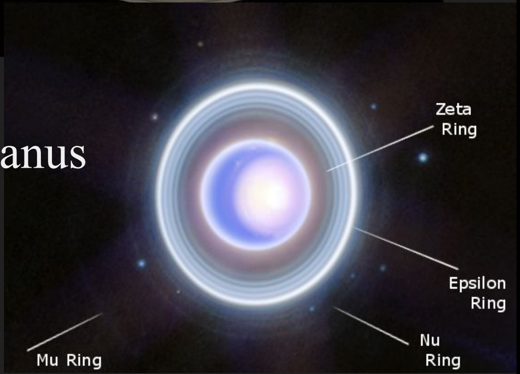
Chariklo

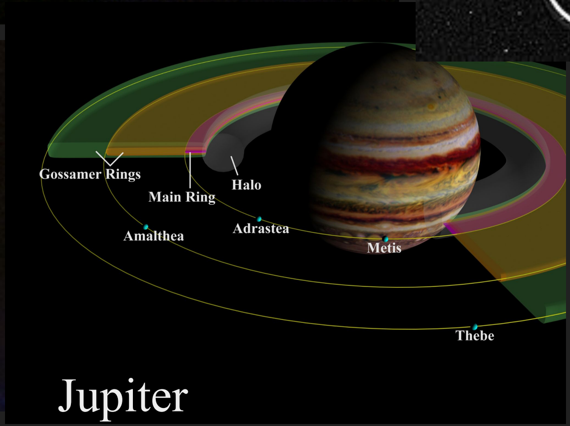


Iapetus



Uranus





Jupiter

Mars?
Pluto?
~~Earth?~~

Dusty rings and dense rings

Dusty rings:

- <100 μm particles
- Degrade quickly:
  - Radiation pressure
  - Plasma drag
  - Torque from planetary EM fields
  - Micrometeorites
- Must be constantly replenished
  - E.g., from volcanic moons or micrometeorite ejecta
- Not great for dark matter…

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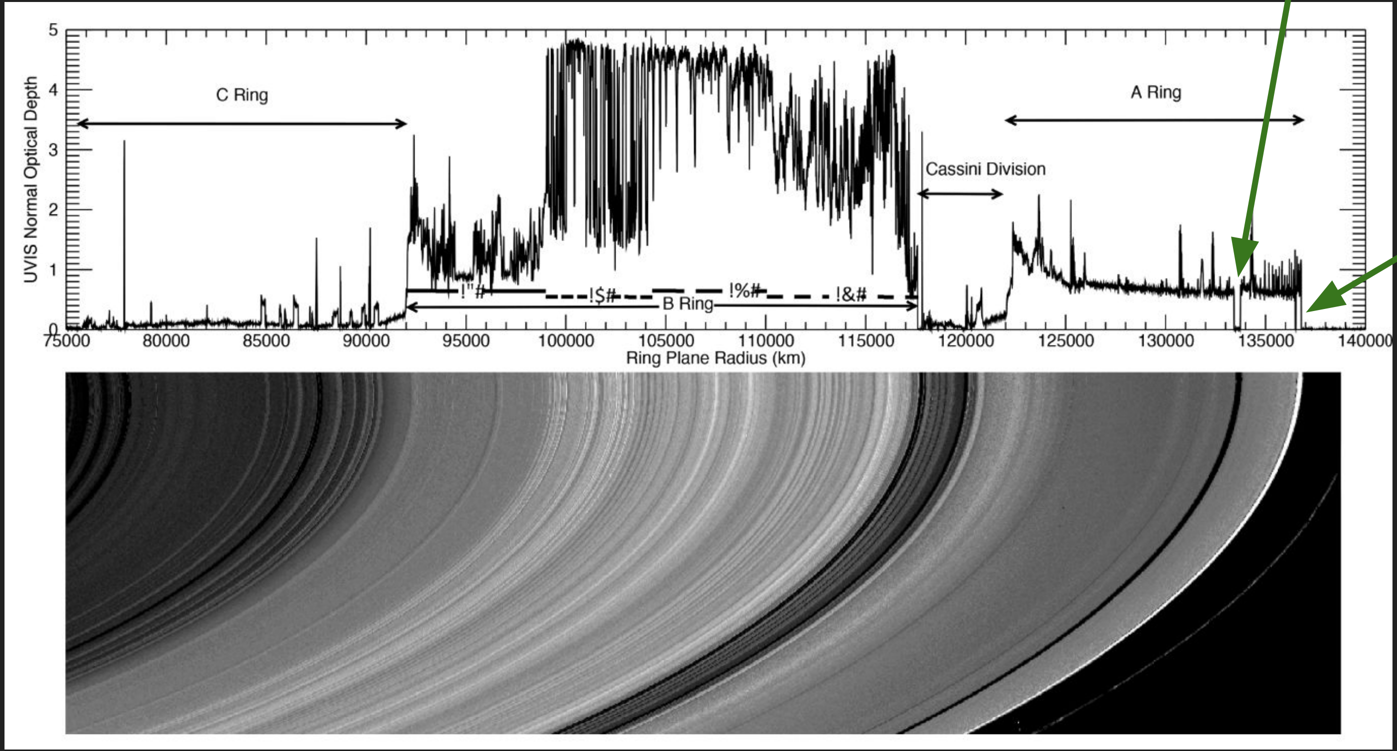
Dense rings:

- ~mm - 10 m particles
- Saturn and Uranus only

Saturn’s main rings

Keeler gap (Pan)

Encke gap (Daphnis)

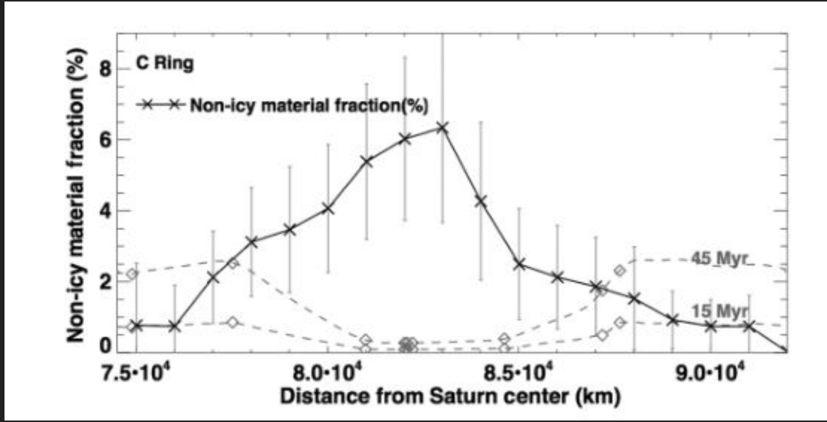


‘The Rings of Saturn,’ *Planetary Ring Systems* (Tiscareno+Murray)

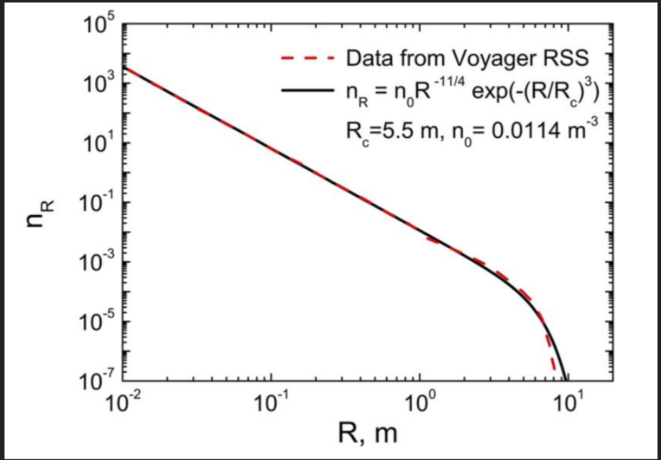
The composition of Saturn's main rings

- Basically all ice
- Thickness is ~radius of biggest particles
- Mass spectrum is from collisional boltzmann system
  - ~mm monomers
  - Aggregation+scattering+fragmentation
- Planetary oblateness keeps rings equatorial:

$$U = -\frac{GMm}{r}\left[1 - J_2\left(\frac{R}{r}\right)^2\left(\frac{3z^2}{2r^2} - \frac{1}{2}\right)\right] ,$$



Zhang et al (2017), Cassini 2cm
Brilliantov et al 2015

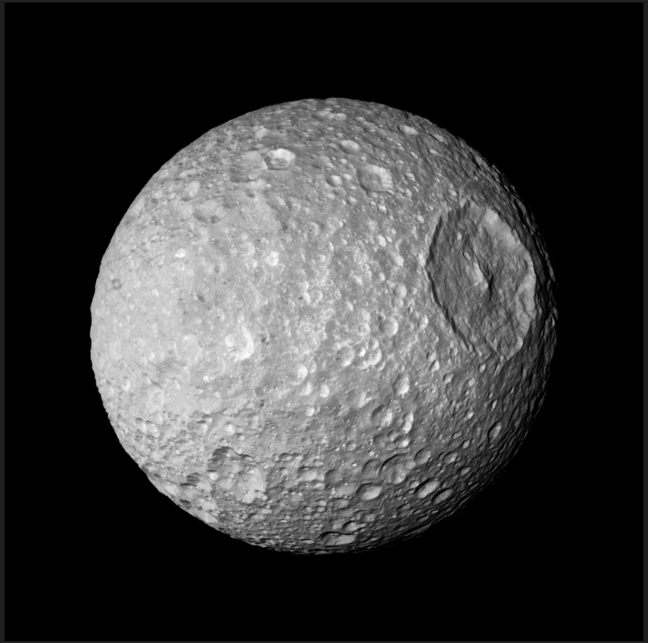


Formation scenarios:

Review: Crida et al (2025)

No complete consensus

- Remains of primordial disk
  - All gas giants have them
  - But, drag from gas, temperature of disk should affect composition (silicates, iron)
- Tidal disruption of satellite
  - Total mass ~ Mimas
  - ‘Young’ scenario: how do you ensure only ice?
- Tidal disruption of passing comet/centaur
  - Probably doesn’t work for young rings
- Moon-moon, moon-comet collisions

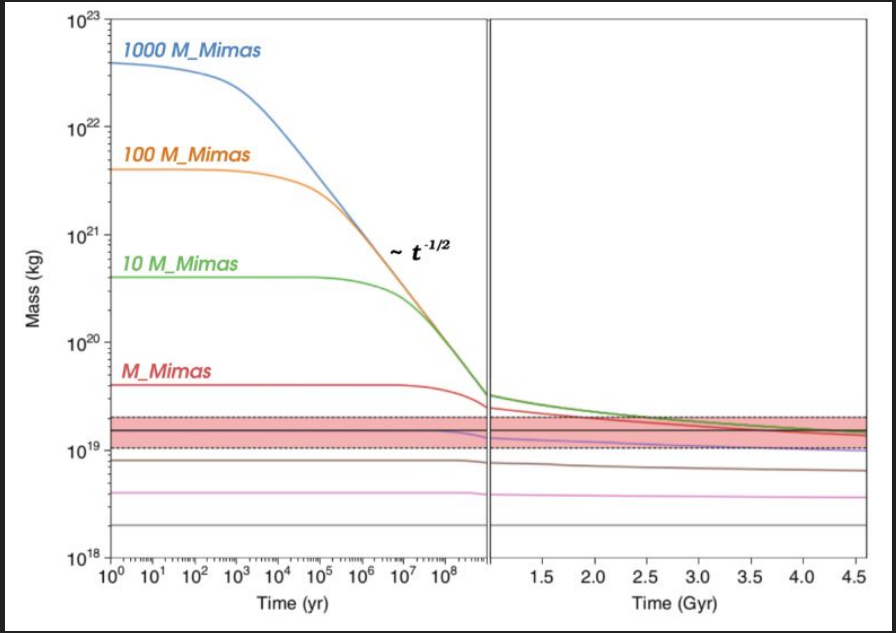


The age of Saturn’s Rings

Review: Crida et al (2025)

Still no complete consensus

- Exposure age: darkening from dust bombardment
  - 100-400 Myr
  - Heavy micrometeorite flux uncertainty, potentially ‘cleaned’ as nanograins fall inwards
- Dynamical age: viscous spreading of rings
  - Consistent up to ‘primordial’ ages (4.5 Gyr)
  - Including micrometeorite flux → 1.5 Gyr
- Stability of some small-scale structures (edges and gaps)
  - ~150 Myr



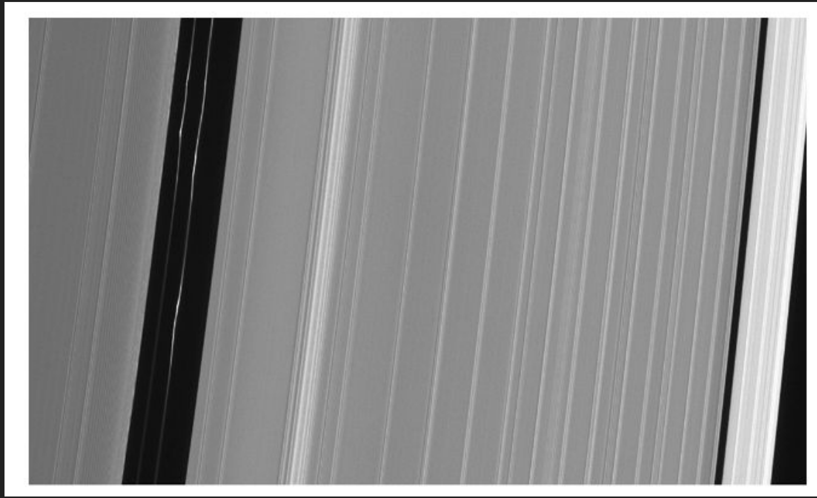
Crida et al 2019

Dynamics, (more) complications, and open questions

Overall: the detailed structure of the rings is *very* poorly understood!

- Microstructure:
  - Gravity wakes
  - ‘Straw’ from spiral density waves, from moons
- Shephard moons: existence… and not!
  - Cassini division outer edge is not guarded by anything
- Tidal resonances

Cuzzi et al (2010)



‘Doppler drag’

Keplerian orbits with external forces

Quick thought experiment: what happens to an object in a Keplerian orbit when a constant (small) external force is applied on it?

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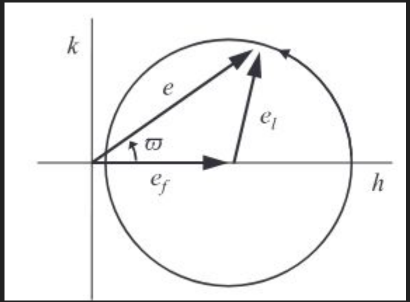
Answer:

- almost* nothing. It averages to zero over the orbit…
- If the planet is oblate, then precession → small ‘fixed eccentricity’
- Has been observed from solar radiation in Saturn’s dusty rings!



‘An introduction to planetary ring dynamics,’ *Planetary Ring Systems* (Tiscarno+Murray)

Realistic forces: radiation. Include ‘higher order’ effects:

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Radiation force, now
including Doppler effect:

$$F_\gamma = \frac{E_\gamma(\vec{v}_p)}{E_\gamma} \frac{L_\odot}{4\pi \ell_\bullet^2} \frac{\sigma}{c}$$

$$\frac{E_\gamma(\vec{v}_p)}{E_\gamma} = \sqrt{\frac{1-\beta}{1+\beta}}$$

$$\beta = \frac{v_p}{c} \cos\lambda_\bullet \ ,$$

$$\vec{F}_\gamma = F_\gamma(1,0,0)$$

$$\vec{v}_p = v_p(\cos\lambda_\bullet, \sin\lambda_\bullet, 0)$$

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Change in orbital energy:

$$\frac{\mathrm{d}E}{\mathrm{d}t} = \vec{F}\cdot\vec{v}_p .$$

Average over one orbit:

$$\left\langle\frac{\mathrm{d}E}{\mathrm{d}t}\right\rangle \equiv \frac{1}{2\pi}\int_0^{2\pi}\mathrm{d}\lambda_\bullet\frac{\mathrm{d}E}{\mathrm{d}t} \simeq -\frac{1}{2}\frac{v_p^2}{c}F_{\gamma,0} ,$$

$$F_{\gamma,0} = L_\odot\sigma/4\pi\ell_\bullet^2 c$$

Convert to change in semimajor axis:

$$\left\langle\frac{\mathrm{d}a}{\mathrm{d}t}\right\rangle = -\frac{a}{m}\frac{F_{\gamma,0}}{c} .$$

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Convert to change in semimajor axis:

$$\left\langle \frac{\mathrm{d}a}{\mathrm{d}t} \right\rangle = -\frac{a}{m} \frac{F_{\gamma,0}}{c} \; .$$

Solution: orbital decay

$$\frac{a_f}{a_i} = \exp\left(-\frac{t}{m} \frac{F_{\gamma,0}}{c} \right)$$

$$F_{\gamma,0} = L_\odot \sigma / 4\pi \ell_\bullet^2 c$$

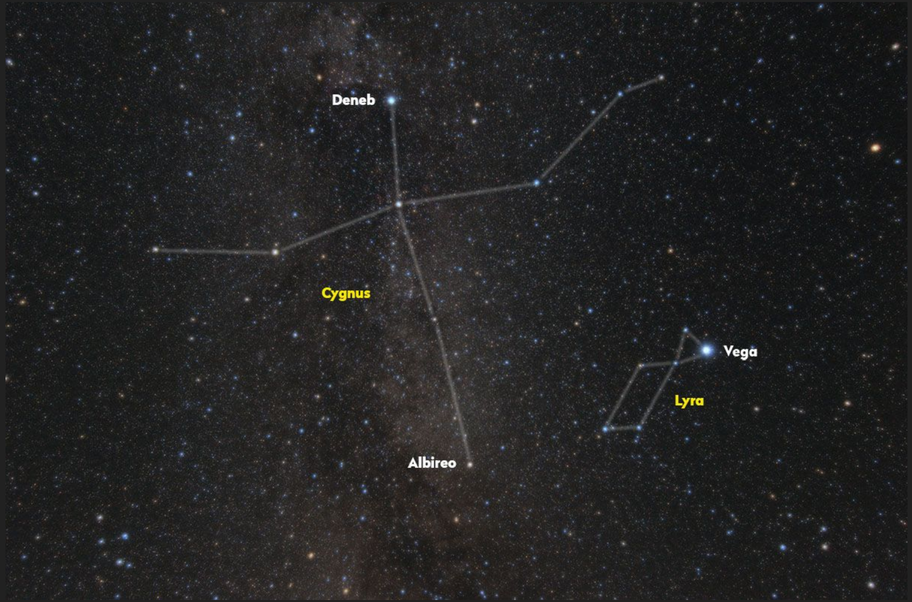
Realistic forces: flux of massive particles

Basically the same story, same result:

$$\vec{F}_\chi = n_\chi \sigma v_{\rm rel} \vec{q}$$
$$v_{\rm rel} = |\vec{v}_\chi - \vec{v}_p| \ ,$$

$$\left\langle \frac{{\rm d}E}{{\rm d}t} \right\rangle \simeq -\frac{1}{2}\frac{v_p^2}{v_\chi} F_{\chi,0}$$
$$\left\langle \frac{{\rm d}a}{{\rm d}t} \right\rangle \simeq -\frac{a}{m}\frac{F_{\chi,0}}{v_\chi}$$
$$\frac{a_f}{a_i} \simeq \exp\left(-\frac{t}{m}\frac{F_{\chi,0}}{v_\chi}\right)$$

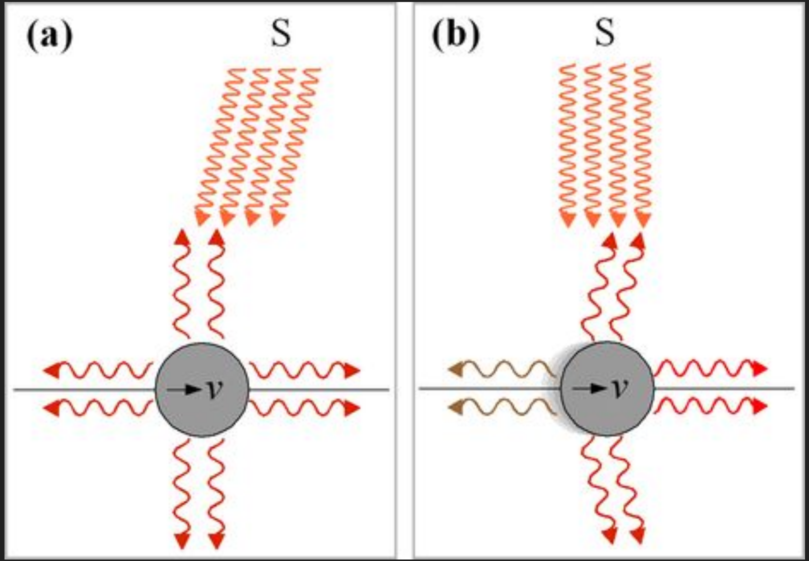
$$F_{\chi,0} \simeq \rho_\chi \sigma v_\chi^2$$



Is this just Poynting-Robertson drag??

(N.b.: I actually don't know…)

- Poynting-Robertson drag:
  - Photon is absorbed and re-emitted
  - Isotropic re-emission is in object's frame of reference
    - In planetary frame, no longer isotropic
    - Causes orbital decay
- Well-known effect which causes dust to spiral towards sun, planets
- Our 'doppler' drag is elastic collision, not sensitive to isotropic re-emission…



$$\left\langle \frac{\mathrm{d}a}{\mathrm{d}t} \right\rangle = -3 \frac{a}{m} \frac{F_{\gamma,0}}{c}$$

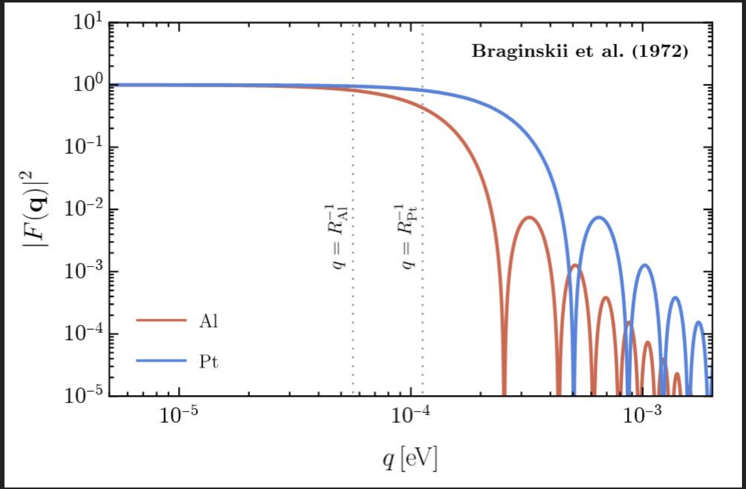
Coherent Enhancement

The familiar story (for DM): coherent elastic scattering

- If de Broglie wavelength is larger than target, cross-section is enhanced
  - Constructive interference of wave functions for each individual scattering
  - (Must be spin-independent scattering)
- Huge enhancement:

$$\frac{d\sigma_{\rm tot}}{d\Omega_\chi} = A^2\left(N_A + (N_A^2 - N_A)F(q)^2\right)\frac{d\sigma_{\chi N}}{d\Omega_\chi} \simeq A^2 N_A^2 F(q)^2 \frac{d\sigma_{\chi N}}{d\Omega_\chi},$$

- Makes it preferable to use heavy nuclei for direct detection experiments



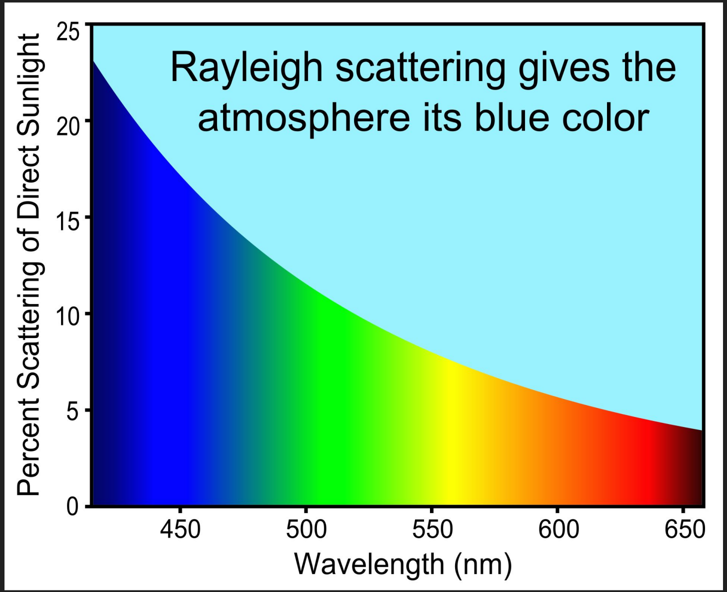
Matsumoto et al (2025)

The familiar story (for undergrads): Rayleigh scattering

Intensity of Rayleigh scattering:

$$I_s = I_0 \frac{1+\cos^2\theta}{2R^2}\left(\frac{2\pi}{\lambda}\right)^4\left(\frac{n^2-1}{n^2+2}\right)^2 r^6$$

$$r^6 \sim V^2 \sim N^2$$



The ‘critical’ size for targets

$$\frac{a_f}{a_i} = \exp\left(-\frac{t}{m}\frac{F_{\gamma,0}}{c}\right)$$

- Coherent enhancement is not unlimited
- ‘Geometric saturation’
  - Cross-section can only increase up to the actual size of the target
- Drag wants small mass, coherence wants big mass… up to saturation
- What is the *smallest* radius of sphere for which geometric saturation is reached?

$$s_c = \left(\frac{9}{16\pi}\frac{m_p^2}{\rho^2\sigma_{\chi N}F(q,s)^2}\right)^{1/4}$$

$$= 2.7\ \text{cm}\ F(q,s_c)^{-1/2}\left(\frac{\rho}{1\text{g cm}^{-3}}\right)^{-1/2}\left(\frac{\sigma_{\chi N}}{10^{-50}\text{cm}^2}\right)^{-1/4}$$

We shoudl look at ~1-10 cm scales

Specifying the dark matter

- 1-10 cm de Broglie wavelength gives dark matter mass:

$$m_\chi \lesssim 0.05 \text{ eV} \left(\frac{\rho}{1\text{g cm}^{-3}}\right)^{1/2} \left(\frac{\sigma_{\chi N}}{10^{-50}\text{cm}^2}\right)^{1/4}$$

- Too light to be fermionic
- For concreteness we choose a quadratically coupled scalar dark matter:

$$\mathcal{L} \supset \pm\chi^2 \bar{N} N / \Lambda_\chi$$

  - Should enforce Z_2 symmetry to avoid Yukawa coupling to nucleons
  - Also assume angle-independent scattering cross-section (for simplicity)

Pheno

The dark matter wind

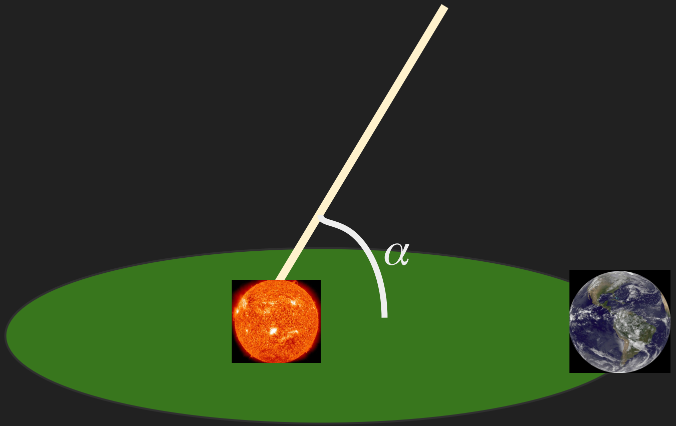
- Assume the Solar System has a circular trajectory through Milky Way
  - (not quite true: not closed, vertical oscillations)

$$\vec{w}_\odot(\lambda_{◎}) = w_\odot \begin{bmatrix} \sin \lambda_{◎} \\ \cos \lambda_{◎} \\ 0 \end{bmatrix}$$

- What is the angle the wind make with the ecliptic plane?

$$\sin \alpha_\chi = |0.097 \sin \lambda_{◎} - 0.86 \cos \lambda_{◎}|$$

- Maximum ~60º…very recently
  - (not ideal!)



Orbital decay for ring particles

Drag calculation with full geometry:

$$\vec{F}_\chi(\lambda_{◎}) = n_\chi \int \frac{\mathrm{d}\Omega}{4\pi} \frac{\mathrm{d}\lambda_\odot}{2\pi} \frac{\mathrm{d}w \; w^2 f(w)}{N} \mathrm{d}\Omega_\chi \frac{\mathrm{d}\sigma_{\mathrm{tot}}(\vec{q})}{\mathrm{d}\Omega_\chi} v_{\mathrm{rel}} \; \vec{q} \,,$$

$$\left\langle \frac{\mathrm{d}E}{\mathrm{d}t} \right\rangle = \frac{1}{2\pi} \int_0^{2\pi} \mathrm{d}\lambda_\bullet \; \vec{F}_\chi \cdot \vec{v}_p$$

$$\vec{v}_p = v_p R_\bullet \begin{bmatrix} \cos\lambda_\bullet \\ \sin\lambda_\bullet \\ 0 \end{bmatrix}$$

$$\frac{a_f}{a_i} = \exp\left(\frac{1}{\omega_{◎} m \; v_p^2} \int_{\omega_{◎} t_i}^{\omega_{◎} t_f} \mathrm{d}\lambda_{◎} \left\langle \frac{\mathrm{d}E}{\mathrm{d}t} \right\rangle \right)$$

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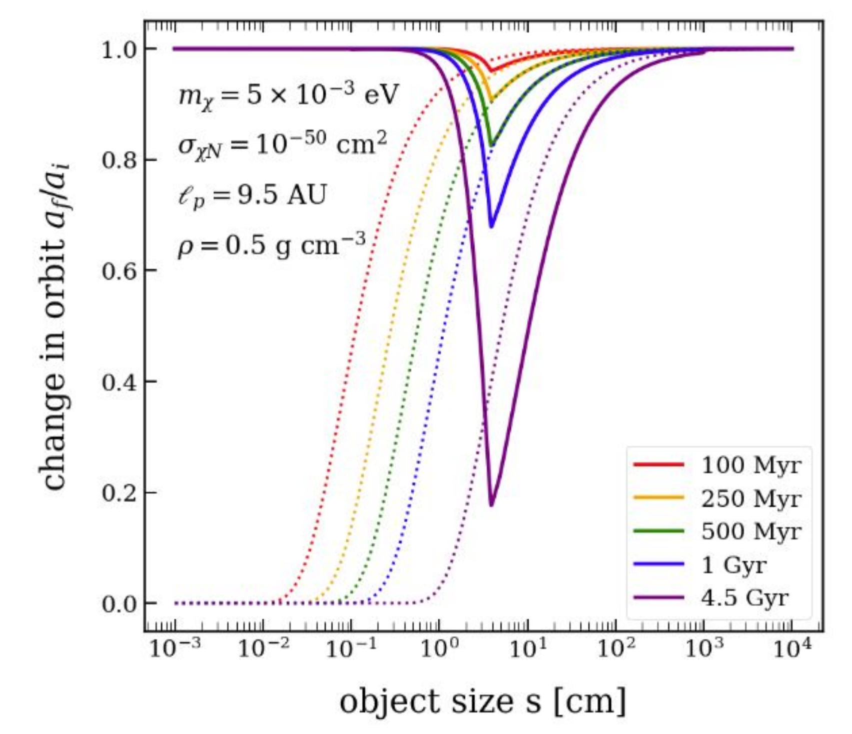
- Ratio of inner to outer edges of A ring is ~0.9
- Can have sizeable mass segregation in main rings

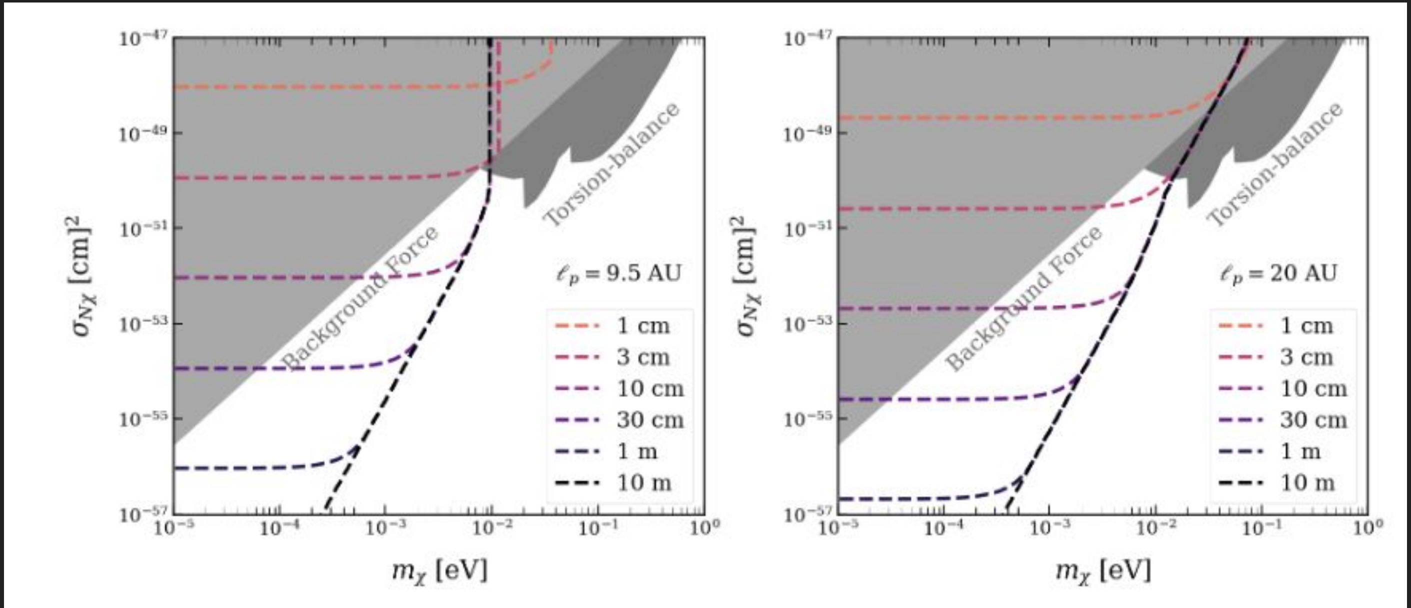


Where does this beat Solar radiation?

Critical distance from sun where DM effect beats Solar radiation:

$$\ell_c^2 = \frac{L_\odot}{4\pi c^2} \frac{1}{\rho_\chi v_\chi \beta \cos\alpha_\chi}$$
$$\rightarrow \ell_c \simeq \frac{7\mathrm{AU}}{\sqrt{\beta \cos\alpha_\chi}} \, .$$

Saturn Uranus

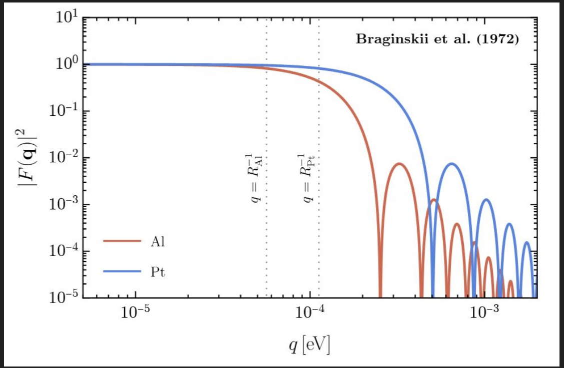


Background force: Van Tillburg (2024)
Torsion-balance: Matsumoto et al (2025)

Observations

Real complications:

- Rings are collisional systems
  - Somewhat helpful: allows us to smooth over the bumps in F(q)
  - Detailed balance means we always gain a particle when we lose one elsewhere
  - Makes it very difficult to model mass segregation evolution
- Plasma drag
  - Saturn's magnetic field accelerates ions (mainly oxygen), which collide with rings
  - Ions are accelerated at planetary spin rate: outside synchronous orbit, it causes orbits to spiral *outwards*
  - Heavy uncertainty on plasma density in vicinity of main rings…
  - ~approximately equal to Solar-only drag in the A ring

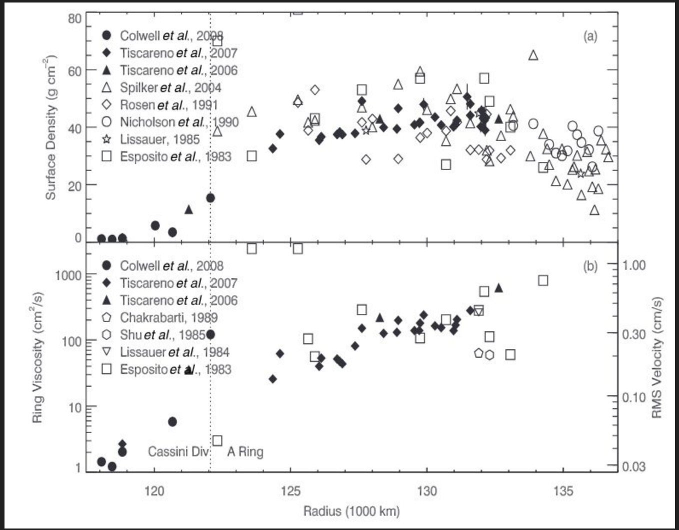


Mass segregation in Saturn's rings

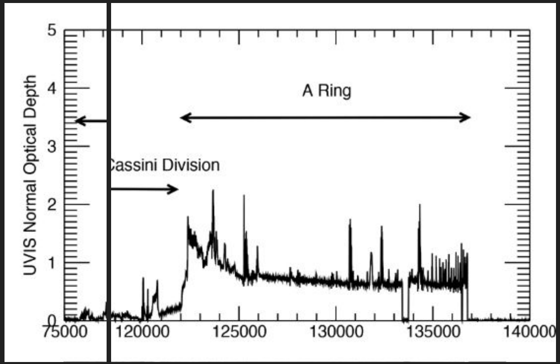
- Focus on outermost A ring, where particles truly deplete from the outermost edge
    - B and C rings are (possibly) replenished, and have very complicated microstructure
- Ideally, we would place constraints from the non-observation of mass segregation…

The real A ring

- However, mass segregation is not only observed, but currently unexplained
  - Surface density σ decreases
  - Optical depth τ increases
- Simple analysis: opacity $\kappa = \sigma/\tau = \frac{3}{4}\rho s$
  - s is particle size
  - s decreases towards inner edge of A ring
    - 10 cm - 50 cm



Colwell et al (2009)



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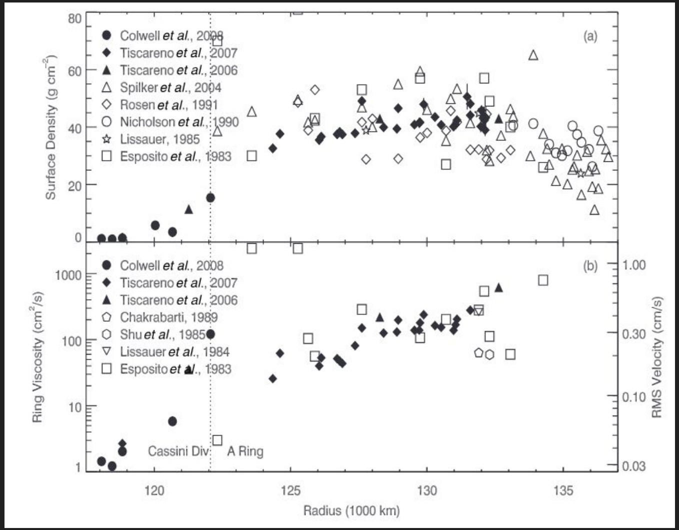
- Could this be dark matter??
  - Probably not



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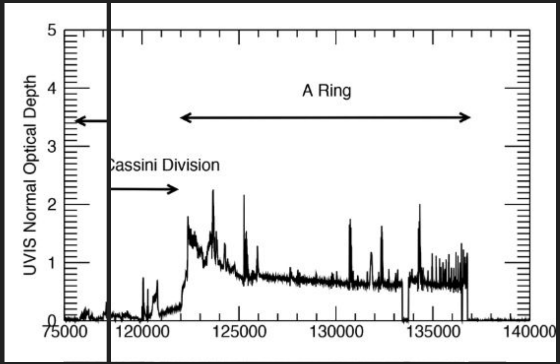

Conclusions

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- Planetary rings are very interesting and very complicated
- Fixed forces don’t affect orbits
  - Until you account for the Doppler effect or particle flux
  - Maybe this is already known as Poynting-Robertson drag??
- Coherent scattering is a powerful enhancement for 1-10 cm objects
- Orbital decay in Saturn’s A Ring from dark matter would cause mass segregation
  - Which we *actually* do observe
  - But which I don’t know if I’ll be able to model…
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Thanks!!

Propaganda: the Solar System as a dark matter detector

- Plethora of well-studied objects
  - Asteroids, kuiper belt, etc.
  - Planetary rings
  - Planetary surfaces
  - Moons
- Wide variance of object sizes
- Many objects have been undisturbed for Myr or Gyr
  - Good for dark matter constraints!
- Its fun
  - 2504.07232 (ZP)