KB, J. Kumar, L. Strigari, M.-Y. Wang (2017)

Sommerfeld-Enhanced J-Factors for Dwarf Spheroidal Galaxies

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OVERVIEW OF INDIRECT DETECTION

- Search for DM by detecting annihilation/decay into SM particles (e.g., photons)
- Focus on DM annihilation in dwarf spheroidal galaxies (DM-dominated, good S/N)
- Differential flux

$$\frac{d^2\Phi}{dE\,d\Omega} = \mathcal{J}(\Omega)\frac{1}{4\pi}\sum_f \frac{\langle\sigma v_{\rm rel}\rangle_f}{2m^2}\frac{dN_f}{dE}$$

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Particle Physics

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Astrophysics

$$\mathcal{J}(\Omega) = \int_{\rm los} \rho^2_{\rm DM}(r)$$

$$J = \int_{\Delta\Omega} \mathcal{J}(\Omega)\, d\Omega$$

- Separate astrophysics from particle physics

J-FACTORS FOR DWARF SPHEROIDAL GALAXIES

Fermi LAT, PRL ***115****, 231301 (2015)*
DES, ApJ ***808****, 95 (2015)*

	$\log_{10}[\, J \,/\, (\mathrm{GeV}^2\mathrm{cm}^{-5})\,]$
➤ Ursa Minor	18.8
➤ Draco	18.8
➤ Reticulum II	18.9
➤ Coma Berenices	19.0
➤ Segue 1	19.6

$\Delta\Omega = 2.4 \times 10^{-4}$

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A CLOSER LOOK

$$\frac{d^2\Phi}{dE\,d\Omega} = \mathcal{J}(\Omega)\frac{1}{4\pi}\sum_f \frac{\langle\sigma v_{\rm rel}\rangle_f}{2m^2}\frac{dN_f}{dE}$$

- Velocity-averaged annihilation cross section

$$\langle\sigma v_{\rm rel}\rangle = \int d^3v_1\, f(v_1)\int d^3v_2\, f(v_2)\sigma|\vec{v}_1 - \vec{v}_2|$$

- Trivial integral for s-wave, no velocity dependence
  → proceed as usual

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  ➞ proceed as usual
- If there is velocity dependence, factorization of astrophysics and particle physics does not hold!
- DM velocity is dependent on location within the halo — relate to DM density profile
- (This is not specific to dSphs or Sommerfeld enhancement)

PROPERLY INCORPORATE DM VELOCITY DISTRIBUTION

- Eddington formula for isotropic distribution

$$\epsilon = \frac{v^2}{2} + \Psi(r)$$

$$f(\epsilon) = \frac{1}{\sqrt{8}\pi^2} \int_{\epsilon}^{0} \frac{d^2 \rho_{\rm DM}}{d\Psi^2} \frac{d\Psi}{\sqrt{\epsilon - \Psi}}$$

- Assume NFW profile

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{\left(\frac{r}{r_s}\right)\left(1 + \frac{r}{r_s}\right)^2}$$

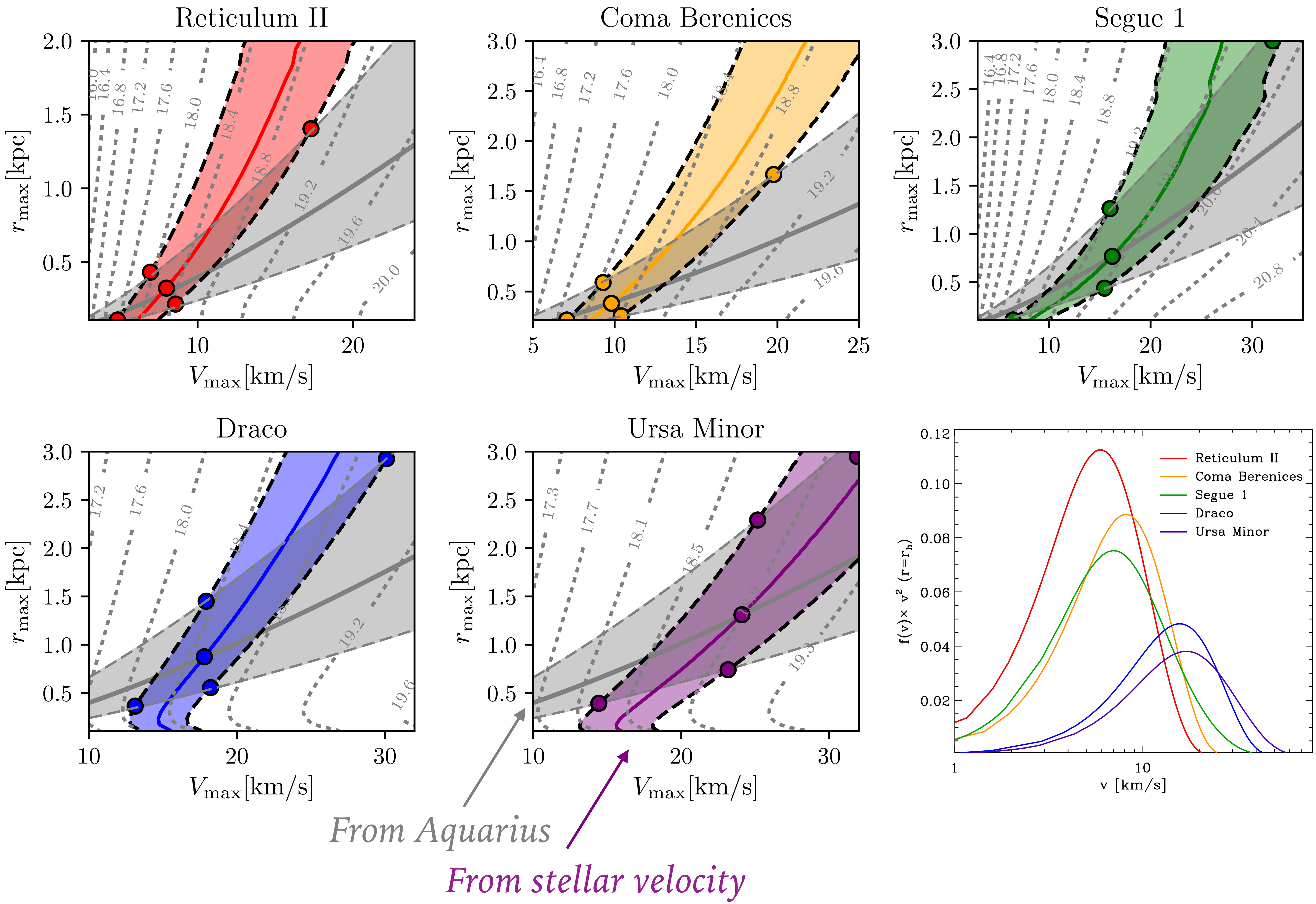
Depends on ρ_s and r_s
(or equivalently, V_{max} and r_{max})

- DM density

$$\rho_{\rm DM}(r) = 4\pi \int_0^{v_{\rm esc}} dv\, v^2 f(r, v)$$

DETERMINE NFW PROFILE PARAMETERS

- Constrain using average LOS stellar velocity distribution
  - Assume Plummer profile
  - Obtain stellar velocity distribution from Eddington formula
  - Match average velocity dispersion to observed value
- Constrain using (V_{max},r_{max}) relation from Aquarius simulation



Reticulum II
Coma Berenices
Segue 1
Draco
Ursa Minor
$r_{\rm max}$[kpc]
$V_{\rm max}$[km/s]
f(v)× v² (r=r_h)
v [km/s]
Reticulum II
Coma Berenices
Segue 1
Draco
Ursa Minor
From Aquarius
From stellar velocity

SOMMERFELD ENHANCEMENT

- Yukawa potential

$$V(r) = -\frac{\alpha_X}{r} e^{-m_\phi r}$$

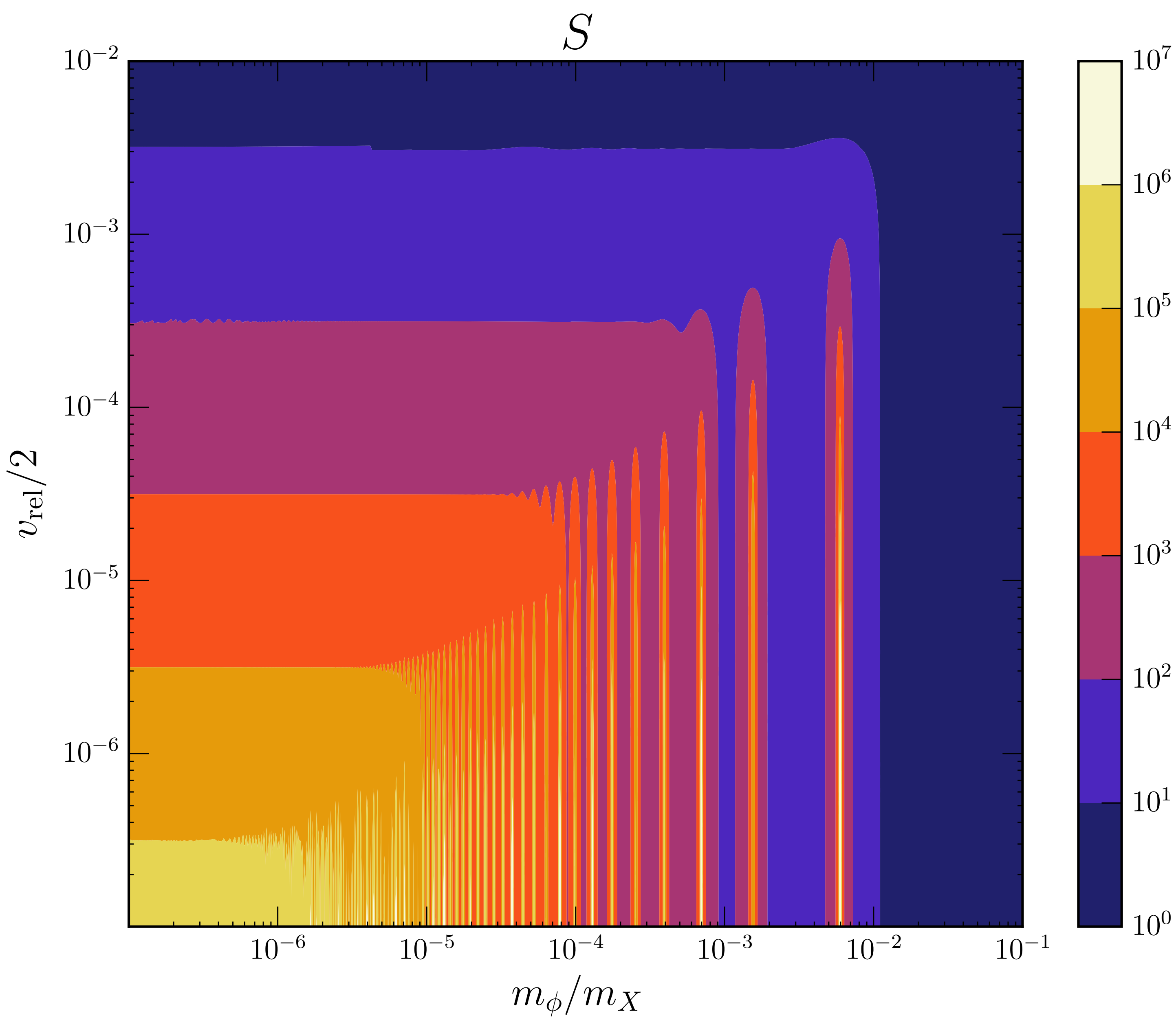
- Long-range force causes distortion in incoming wave function, particularly at low relative velocities

$$\sigma v_{\rm rel} = (\sigma v_{\rm rel})_0 \times S\left(\frac{v_{\rm rel}}{2}\right)$$

- Annihilation cross section enhanced by $S = |\psi(0)|^2$

- Rearrange:

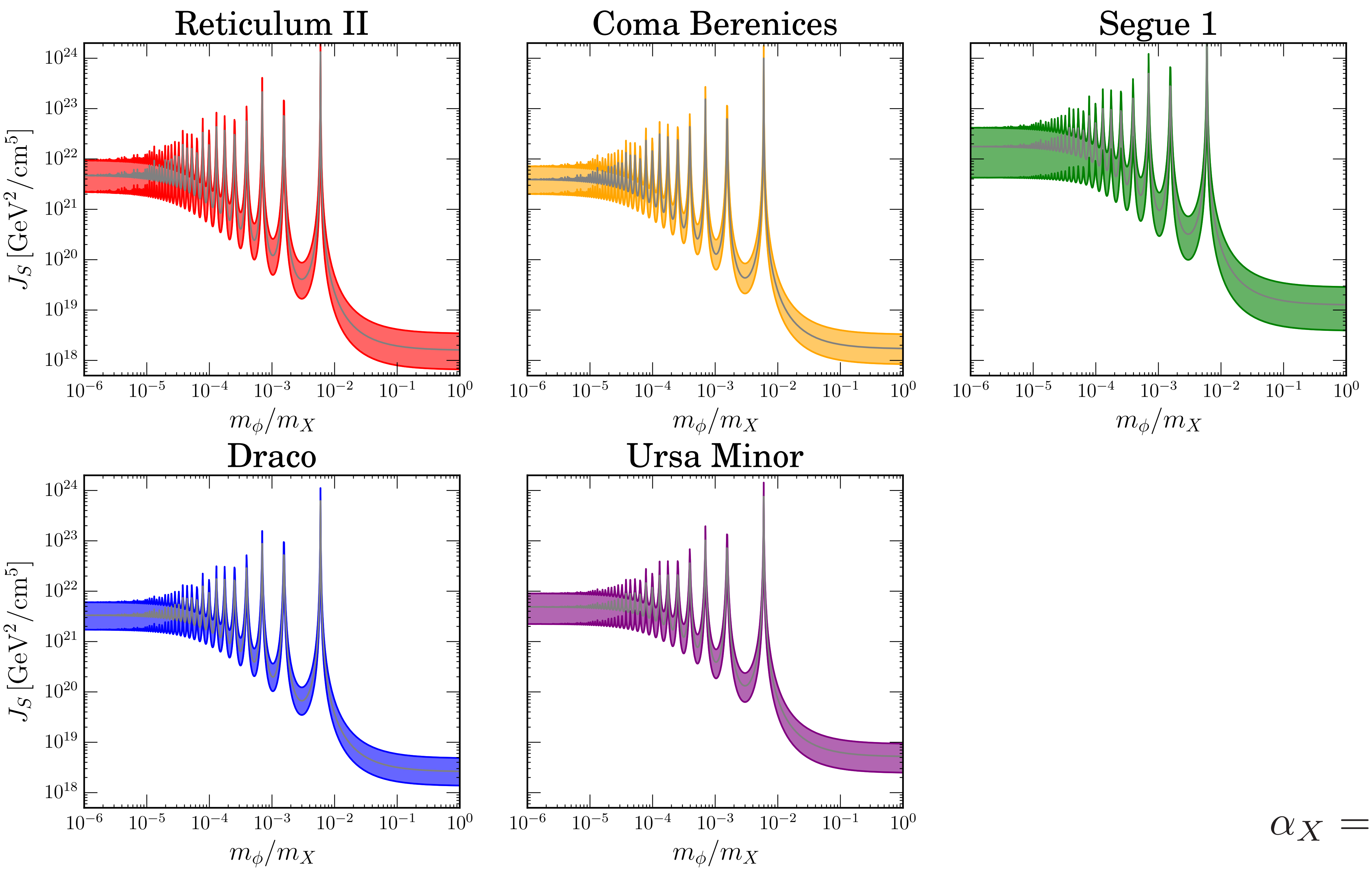
$$\frac{d^2\Phi}{dE\, d\Omega} = [\ldots] \times \frac{1}{4\pi} \sum_f \frac{(\sigma v_{\rm rel})_{0,f}}{2m^2} \frac{dN_f}{dE}$$



$\alpha_X = 10^{-2}$

SOMMERFELD-ENHANCED J-FACTORS

$$J_S = \int_{\Delta\Omega} \int_{\mathrm{los}} \int d^3v_1\, f(r(l,\Omega),\vec{v}_1) \times \int d^3v_2\, f(r(l,\Omega),\vec{v}_2) S(|\vec{v}_1 - \vec{v}_2|/2)$$



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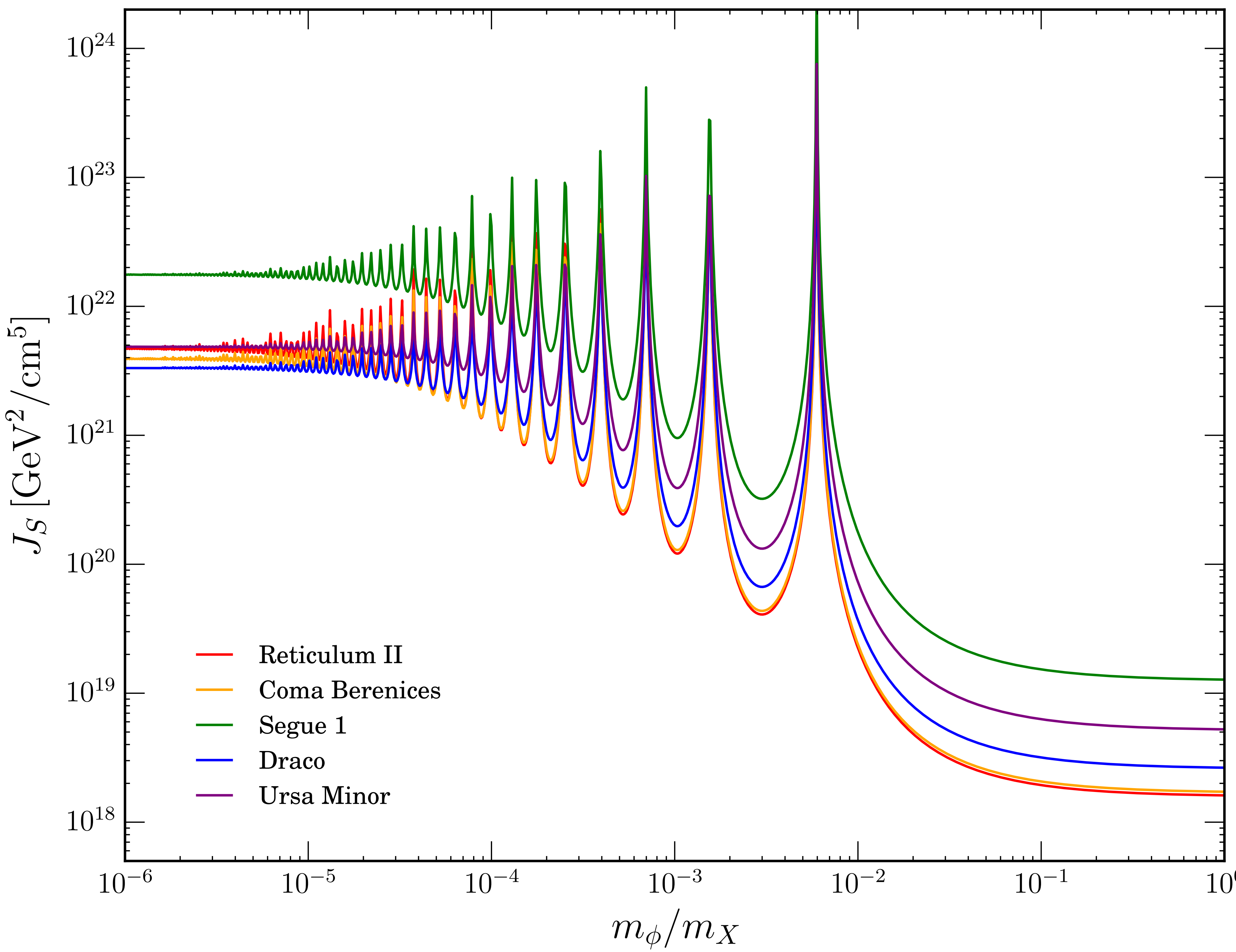
ORDER FLIP EXAMPLE #1



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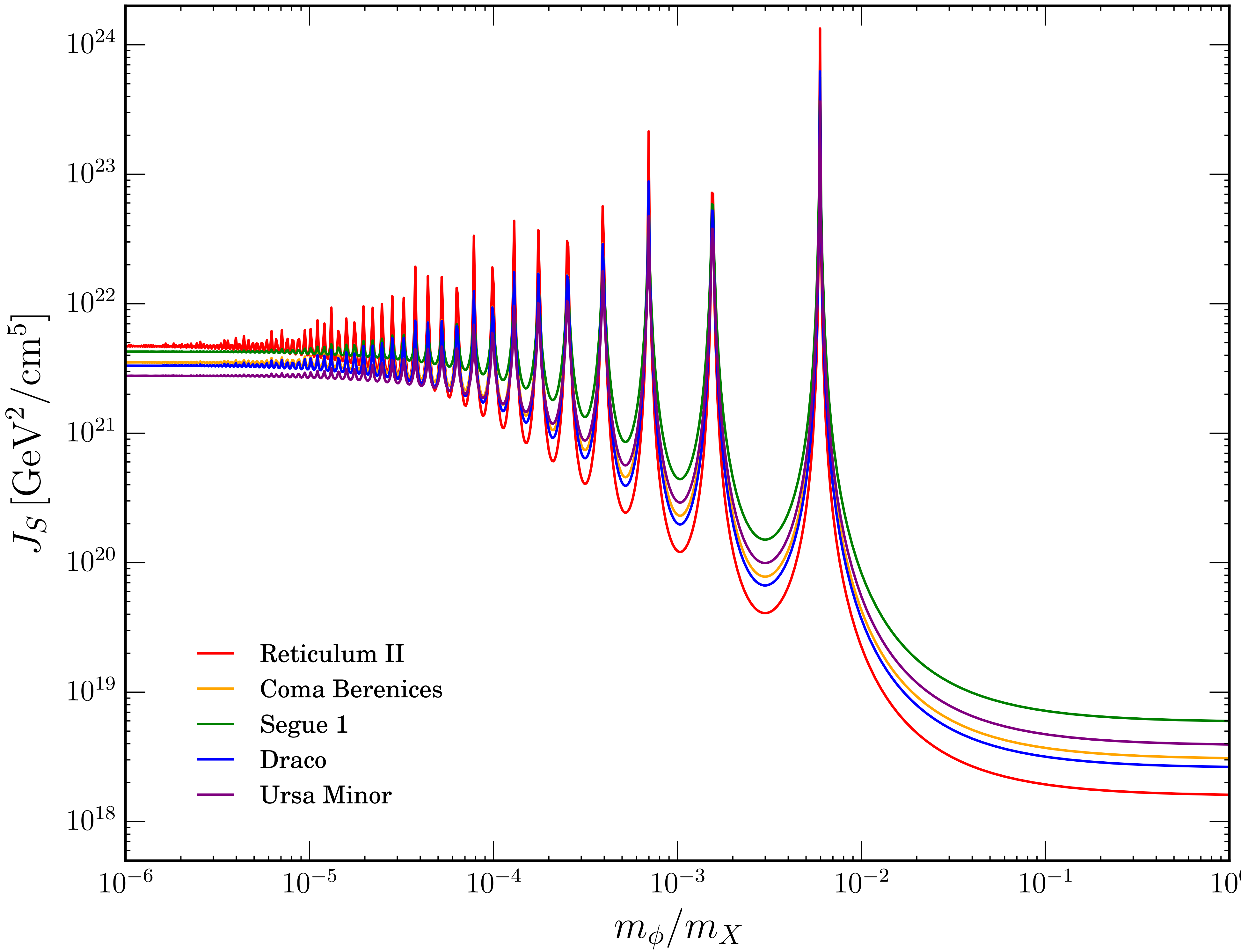
ORDER FLIP EXAMPLE #2



$\alpha_X = 10^{-2}$

SUMMARY

- **Large variations** in J-factors due to:
  - Astrophysics: Form of density profile (and velocity distribution)
  - Particle physics: Velocity dependence of annihilation cross section
- **Proper velocity averaging** may significantly impact limits (or derived quantities from a future detection) on particular models
- **Ordering** of dwarf spheroidal J_S-factors is different in s-wave limit vs. Coulomb limit for Sommerfeld enhancement
- **Beware naive consistency check**: Possible signal could still have a DM interpretation, even if no signal is observed in another system with larger “s-wave” J-factor