Dark matter annihilation in the Milky Way's dwarf spheroidal galaxies

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Outline

I) Dark matter (DM) and dwarf spheroidal galaxies

II) Reconstructing DM density profiles: the Jeans analysis

III) DM annihilation factors for the Milky Way's dwarf spheroidal galaxies

Conclusions and prospects

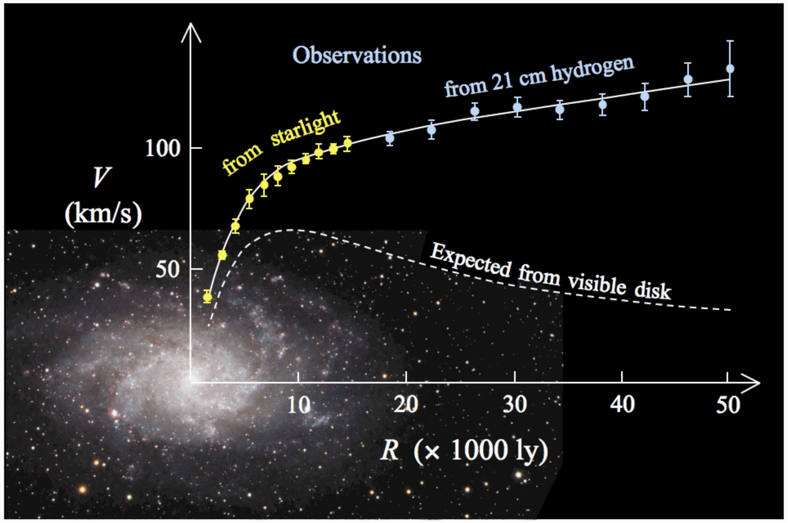
I) Evidences for dark matter

Many evidences for the existence of DM in the Universe:

- **Galactic scale:**

Orbital velocities of stars/gas in spiral galaxies: cannot be explained by visible matter.

→ Possible solution: existence of large DM halos surrounding the galaxies.

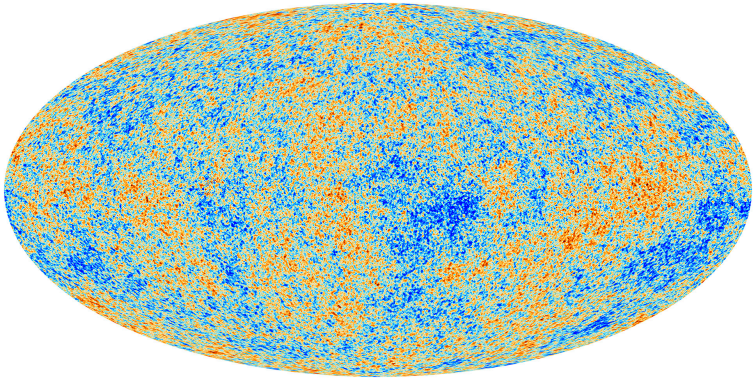


M33 galaxy – Corbelli & Salucci (2000)

- **Cosmological scale:**

Angular fluctuations of temperature in the cosmic microwave background: require large amounts of non-interacting matter.

→ ~85% of the matter in the Universe is dark matter.



Planck collaboration (2013)

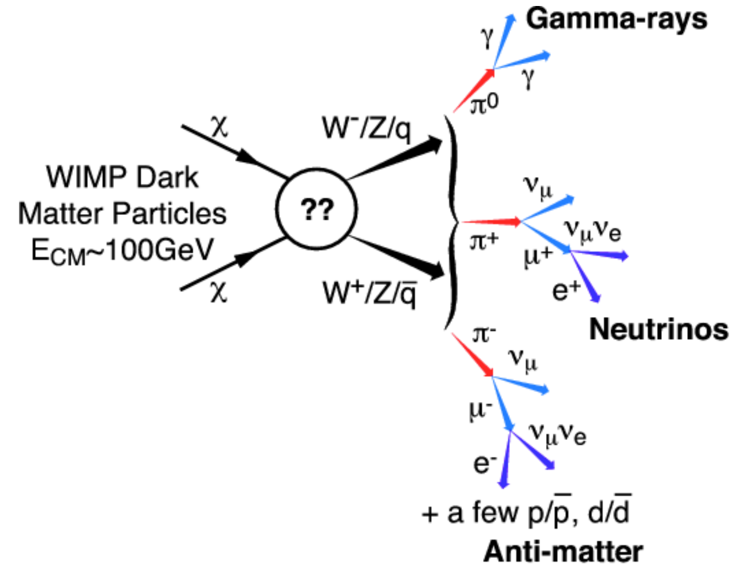
I) The WIMP hypothesis

What is dark matter made of?

- « Natural » candidate: the **WIMP** (Weakly Interacting Massive Particle)

- Massive particle sensitive to the weak interaction:
→ can explain the observed DM density in the Universe

- Predicted by particle physics theories beyond the Standard Model (e.g. SUSY, UEDs…).



- Annihilation of local WIMPs could be detected in γ-rays – the « golden » channel:
  - ~ No absorption during propagation;
  - Propagation in straight line.

I) Where to look for ?

Where to look for the γ-rays?

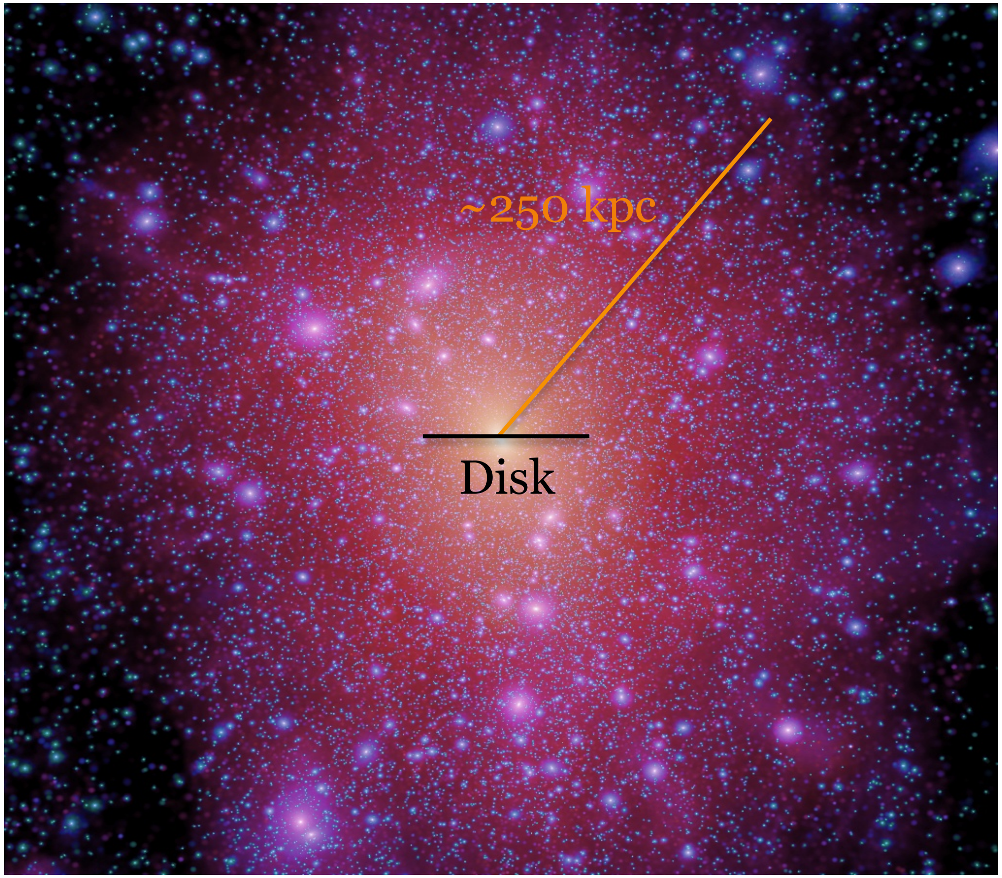
- Need **dense** and **close** dark matter regions: stronger annihilation signals

Best target: center of the Milky Way
 - Very high DM density,
 - Very close (~8 kpc),

→ But large astrophysical γ-ray emission.

Other choice: most massive « clumps » of dark matter with baryons

→ **Dwarf spheroidal galaxies**



Aquarius simulation – Springel et al. (2008)

I) Dwarf spheroidal galaxies

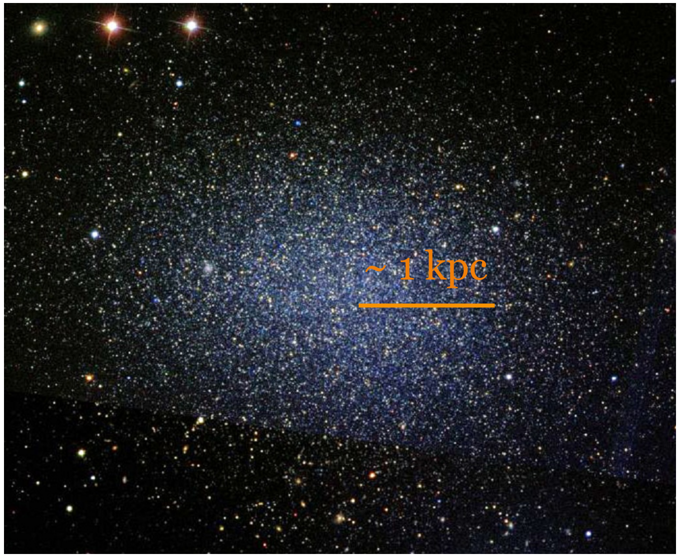
- Dwarf spheroidal galaxies (dSphs) are Milky Way satellites:

  - Highly **dark matter dominated**: *M/L > 10-1000 M⊙/L⊙*

  → Largest DM clumps in which baryonic matter collapsed.

  - ~30 were discovered, ranging from very bright (« classical ») to ultra-faint objects.
  - Free of astrophysical γ-ray emission.

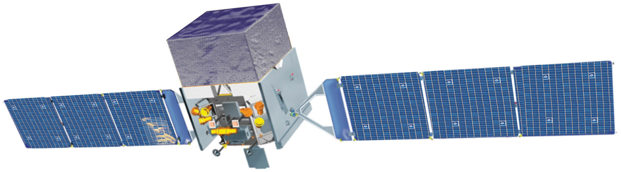
  → Among the best targets for searching γ-ray emission from dark matter annihilation.



Leo I dSph. Credit: WikiSky (SDSS)

$d \sim 250$ kpc; $M \sim 10^7 M_\odot$

- dSphs are primary targets of γ-ray observatories:
  - Fermi-LAT [20 MeV – 300 GeV; $\alpha_{res} = 0.5^\circ$ at ~1 GeV];
  - H.E.S.S., MAGIC, and VERITAS [30 GeV – 100 TeV; $\alpha_{res} = 0.1^\circ$ at ~100 GeV]

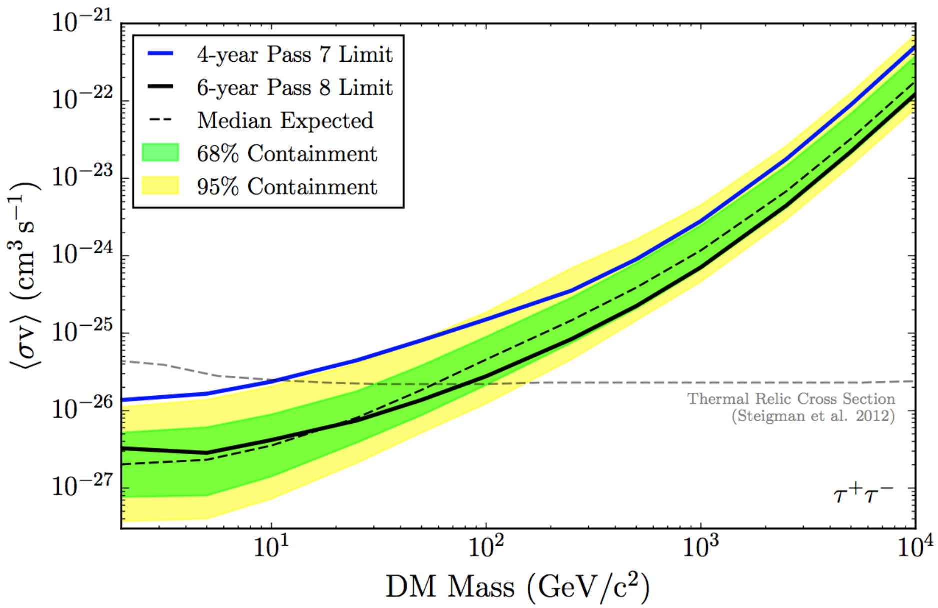


I) J-factors

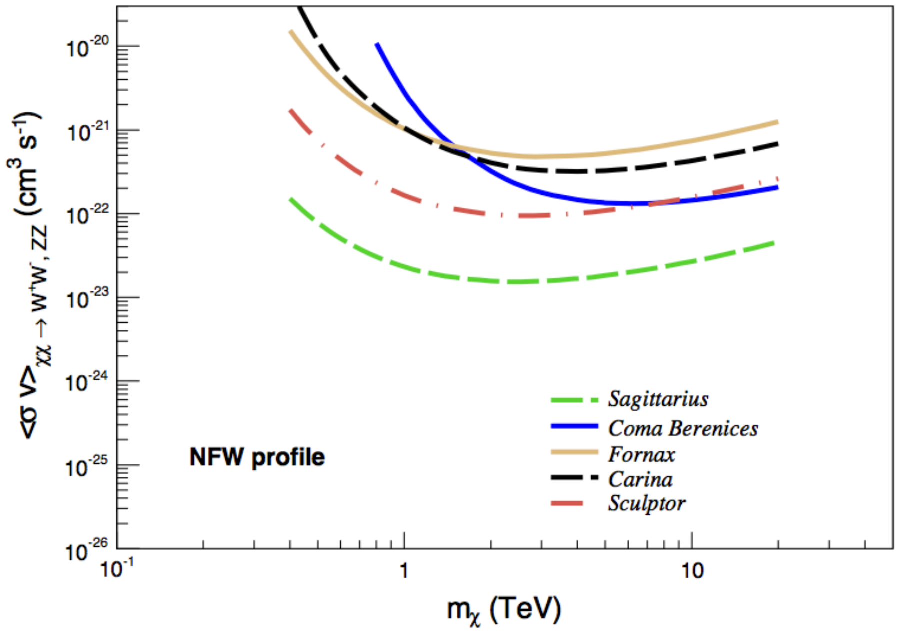
- Absence of γ-ray emission: constraints on DM properties.
- γ-ray differential flux coming from dark matter annihilation:

$$\frac{d\phi_\gamma}{dE} = \frac{1}{4\pi}\frac{dN_\gamma}{dE}\frac{<\sigma_{ann}v>}{2m_\chi^2}\underbrace{\int_0^{l_{max}}\int_0^{\Delta\Omega}\rho_{DM}^2\, d\Omega\, dl}_{\text{J-factor}}$$

J-factor



Fermi collaboration (2015)



H.E.S.S. collaboration (2014)

II) Jeans analysis (1)

- J-factor: requires the DM density profile

→ Use the stellar population of the dSph as tracer of its gravitational potential: **Jeans analysis**

Assumptions:
- *Spherical symmetry,*
- *Dynamical equilibrium,*
- *Collisionless,*
- *Negligible rotational support*

[Binney & Tremaine (1987)]

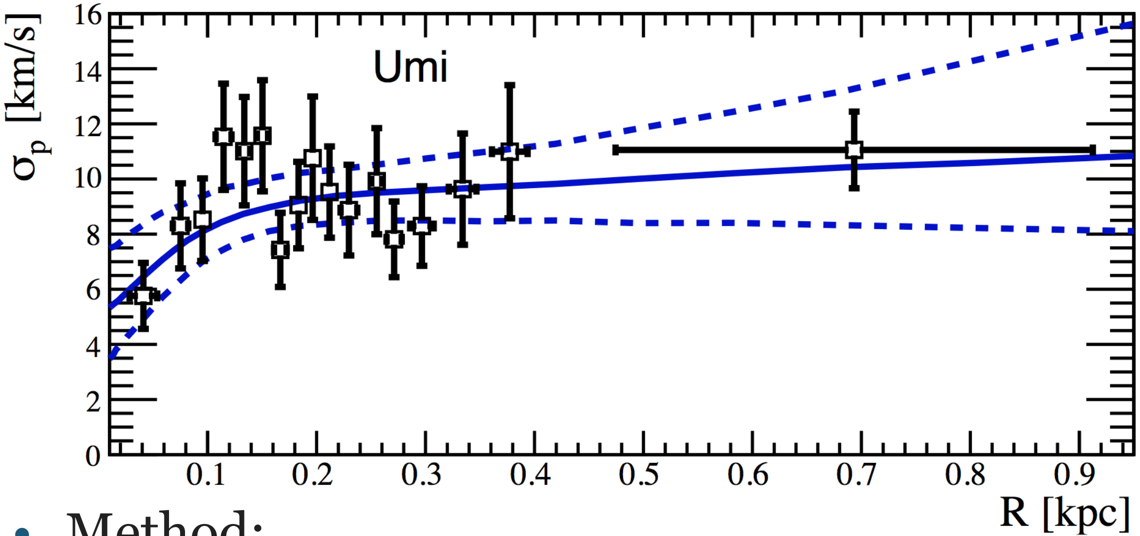
Spherical Jeans equation

$$\underbrace{\frac{1}{\nu}\frac{d}{dr}(\nu \bar{v_r^2}) + 2\frac{\beta_{\mathrm{ani}}(r)\bar{v_r^2}}{r}}_{\textbf{Stellar}} = \underbrace{-\frac{GM(r)}{r^2}}_{\textbf{DM}}$$

- From the solution, we can compute the stellar velocity dispersion along the line of sight: $\sigma_p(R)$

$$\sigma_p^2(R) = \frac{2}{I(R)}\int_R^\infty \left(1 - \beta_{\mathrm{ani}}(r)\frac{R^2}{r^2}\right)\frac{\nu(r)\,\bar{v_r^2}(r)\,r}{\sqrt{r^2 - R^2}}\mathrm{d}r$$

II) Jeans analysis (2)



Velocity dispersion profile of the « classical » dSph Ursa Minor.

- Method:
  - Assume parametric models for $\beta_{ani}(r)$ and $\rho_{DM}(r)$ [4 – 7 free parameters]
  - Compute $\sigma_p(R)$
  - Compare to the measured velocity dispersion [MCMC analysis - GreAT]
  - Compute J-factor from $\rho_{DM}(r)$ [CLUMPY package]

$\sigma_p(R)$ → $\beta_{ani}(r),\ \rho_{DM}(r)$ → *J-factor*

→ Development of a Jeans analysis module for the CLUMPY public code – new release soon (Bonnivard et al. in prep).

II) Jeans analysis: uncertainties (1)

- Is the J-factor reconstruction robust against the several ingredients of the Jeans analysis?

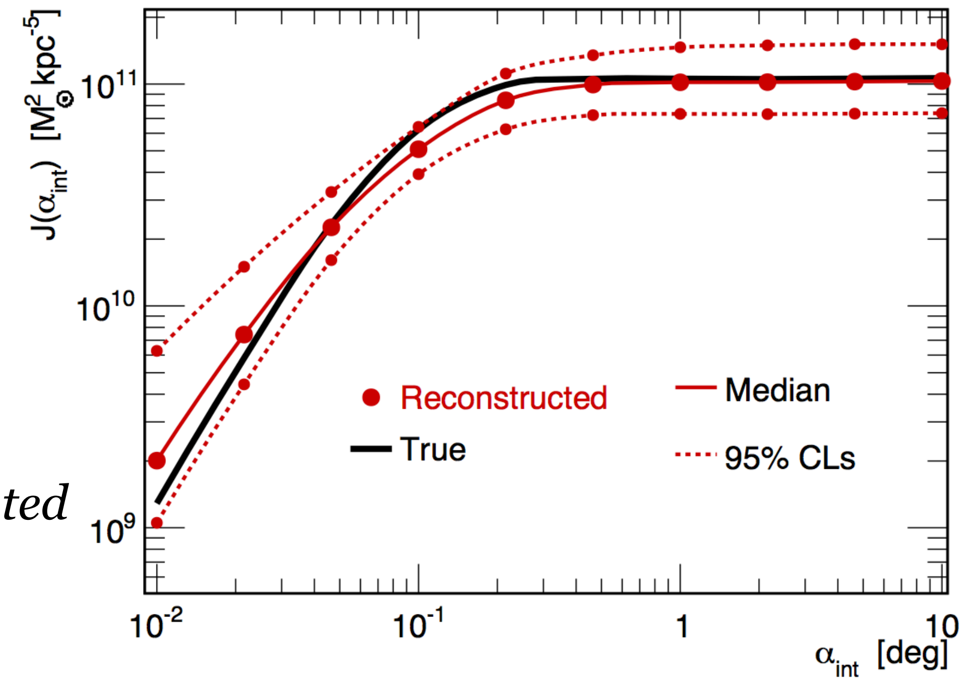
→ Use **simulated dSphs** for which the DM and anisotropy profiles are known.

  - ~100 mock dSphs used;
  - Covering large ranges of DM densities and anisotropy values;
  - Mimicking observationnal uncertainties.

- We find that:

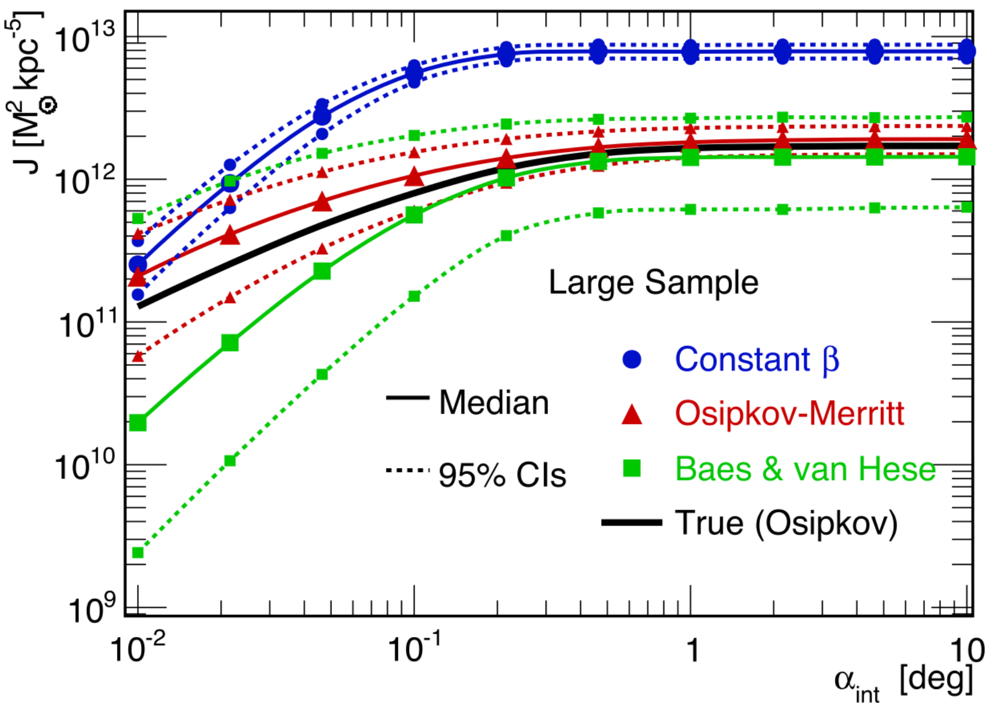
  - J-factors are generally robustly reconstructed

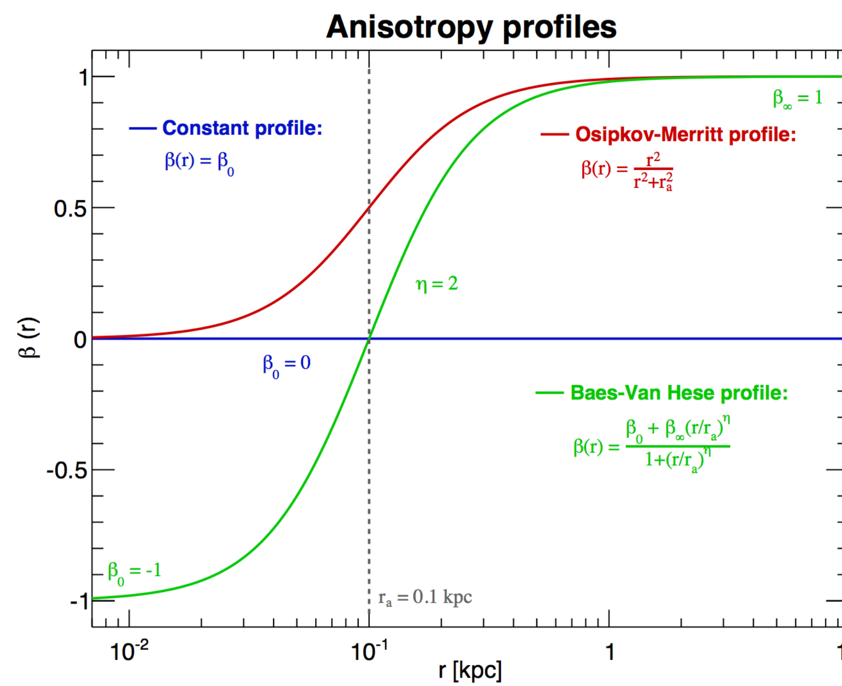
Simulated dSph



II) Jeans analysis: uncertainties (2)

- Several ingredients can **bias** the J-factor reconstruction:
  - Too specific anisotropy parametrizations,



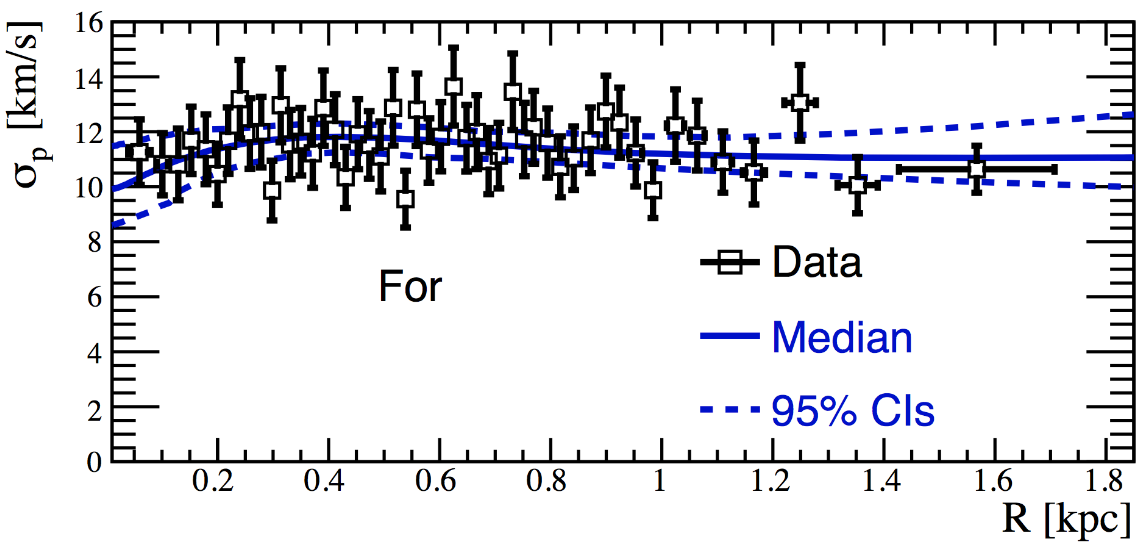


  - Fitting of the stellar projected number density,
  - Non-sphericity of the DM halo (triaxiality).

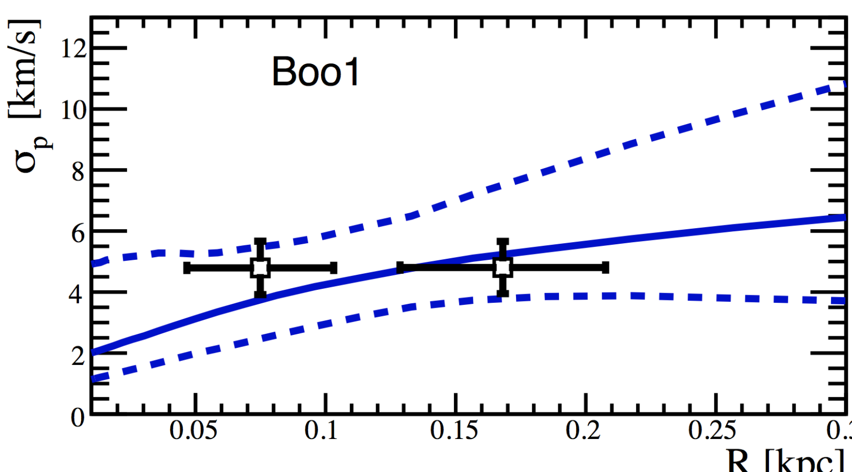
→ We proposed an « optimised » setup in Bonnivard et al. (MNRAS 2015).

III) Application to the real dSphs (1)

- We have applied our setup to real data: 8 « classical » and 13 « ultrafaint » dSphs (Bonnivard et al., submitted to MNRAS).



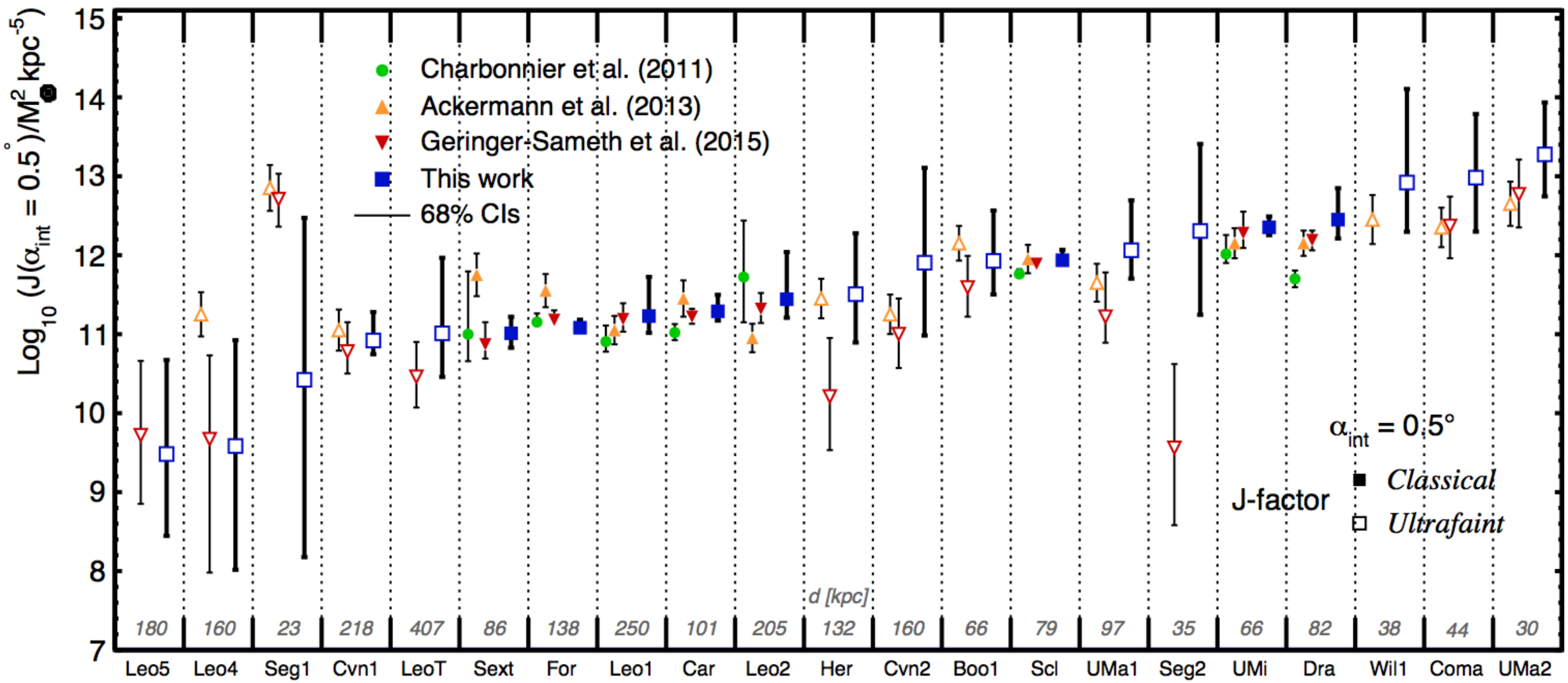
Velocity dispersion profile of the « classical » dSph Fornax.



Velocity dispersion profile of the « ultrafaint » dSph Bootes I.

III) Application to the real dSphs (2)

- J-factors and comparison to other works:

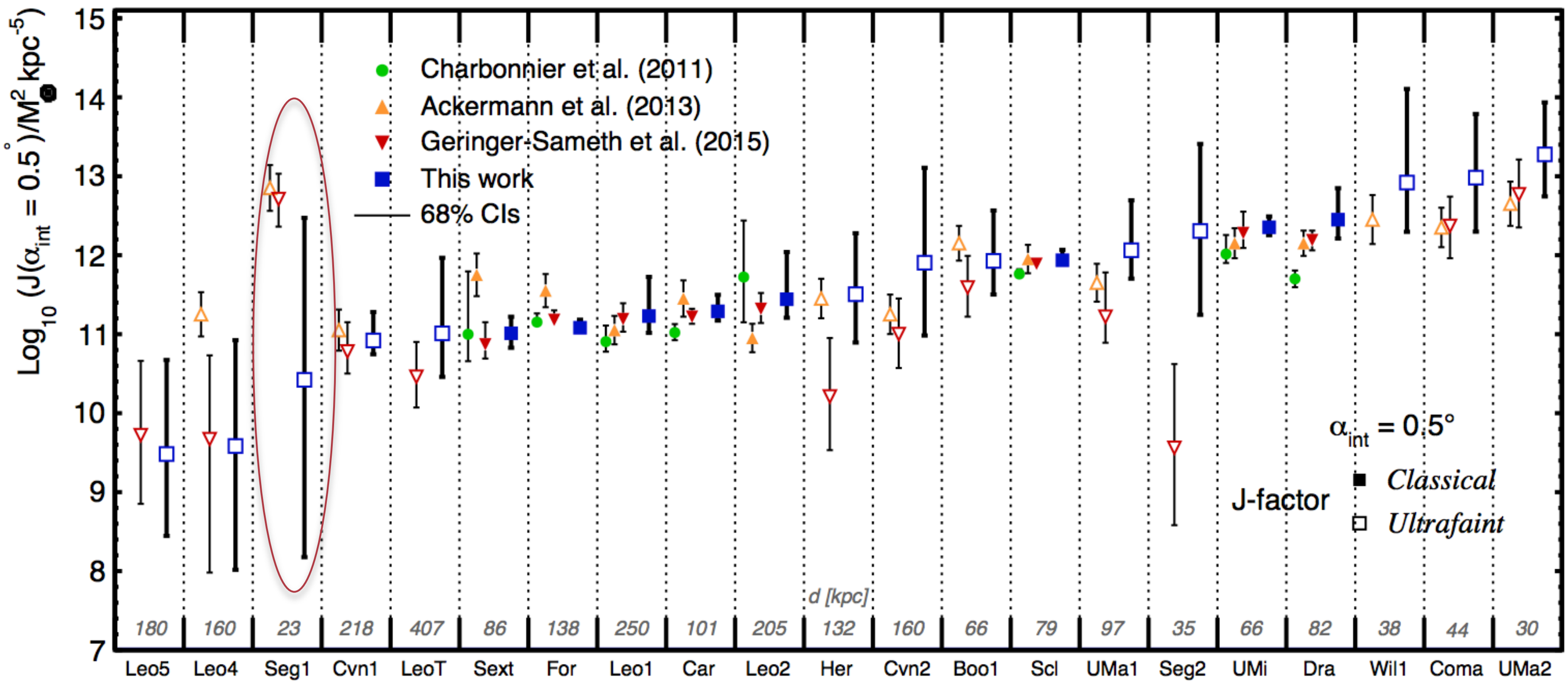


  - « Ultrafaint » dSphs are more uncertain,
  - Our setup gives larger uncertainties than in other analyses.

→ Consistant analysis of all the dSphs, with realistic uncertainties.

III) Application to the real dSphs (2)

- J-factors and comparison to other works:



  - « Ultrafaint » dSphs are more uncertain,
  - Our setup gives larger uncertainties than in other analyses.

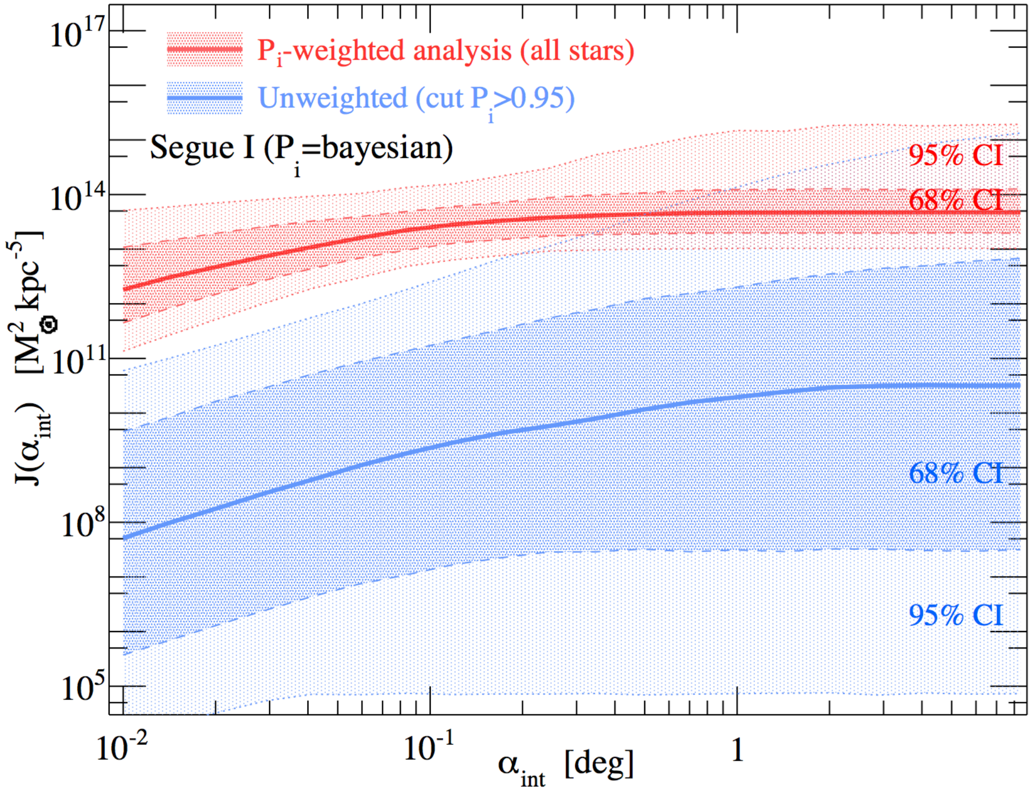
→ Consistant analysis of all the dSphs, with realistic uncertainties.

III) The Segue I case

- The ultrafaint **Segue I** is often promoted as the « best target » among the dSphs.

- However, its kinematic sample might be contaminated by Milky Way foreground stars.

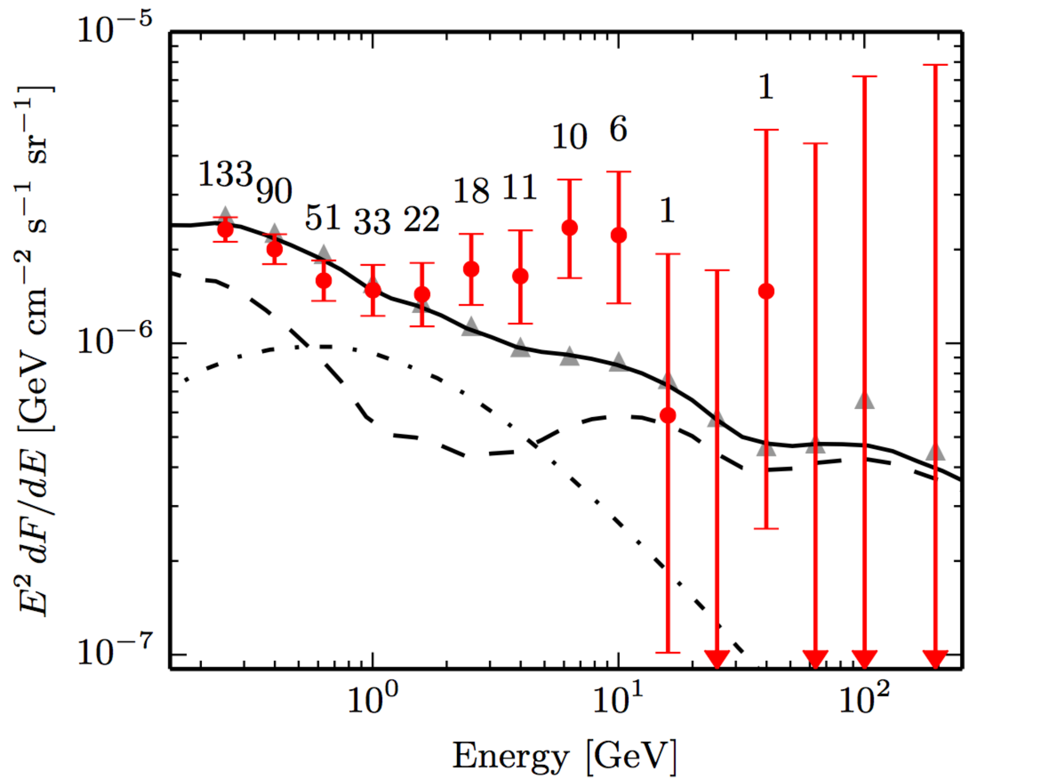
→ Our analysis is very sensitive to these ambiguous stars.



→ It appears as a very uncertain target! (Bonnivard, Maurin, Walker, in prep.)

III) Dark matter signal from Ret II?

- In March 2015, 9 new potential dSphs were discovered in the Southern Sky with the Dark Energy Survey (Koposov et al. & DES collaboration, 2015).
- Using publicly available Fermi-LAT data, Geringer-Sameth et al. found evidence for γ-ray emission from the closest object, **Reticulum II** [d ~ 32 kpc].
- Fermi-LAT collaboration found no excess using unreleased data sets (Fermi-LAT collaboration 2015).

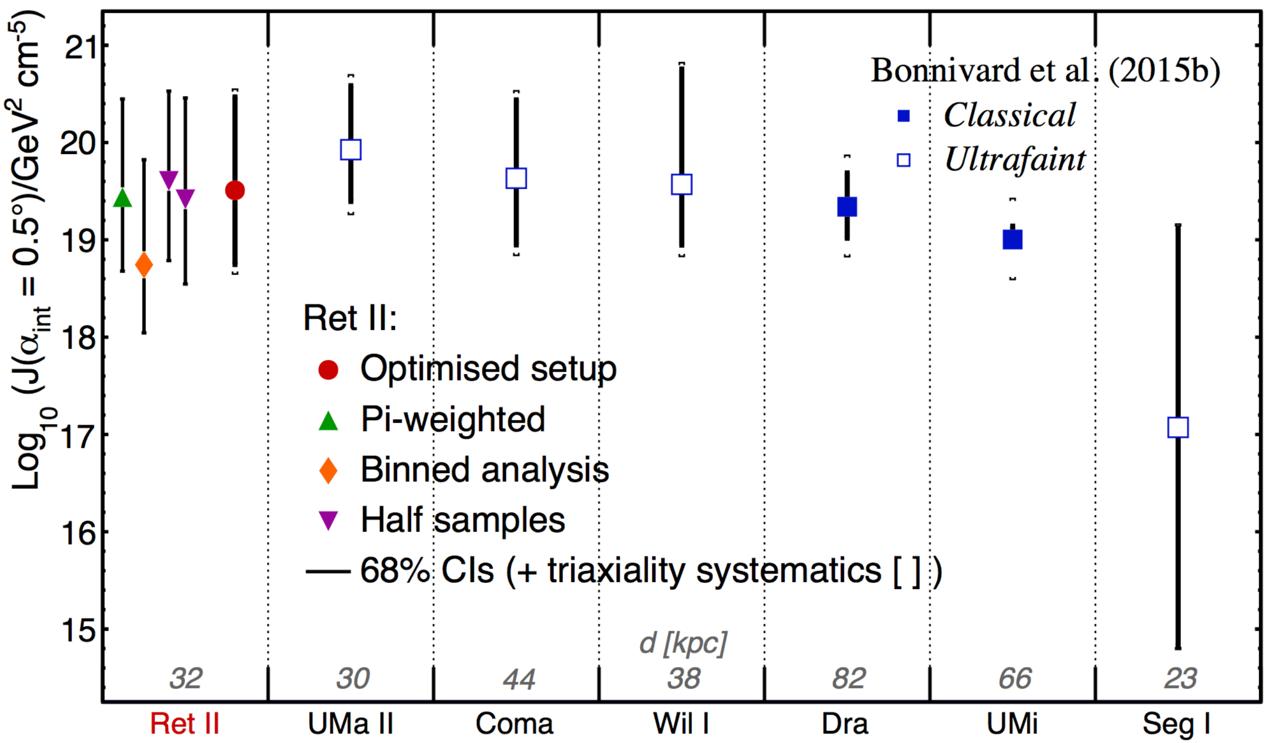


γ-ray flux toward Ret II (Geringer-Sameth et al. 2015 b)

III) J-factor of Reticulum II

- Stellar kinematic data from Ret II were obtained a few days later by Walker et al.

→ We used these data to publish the first estimation of Ret II's J-factor, using our optimised Jeans analysis (Bonnivard et al., submitted to ApJL):



We are associated to Geringer-Sameth's team for a paper on DM constraints from Ret II using this J-factor (in prep.).

Conclusions and prospects

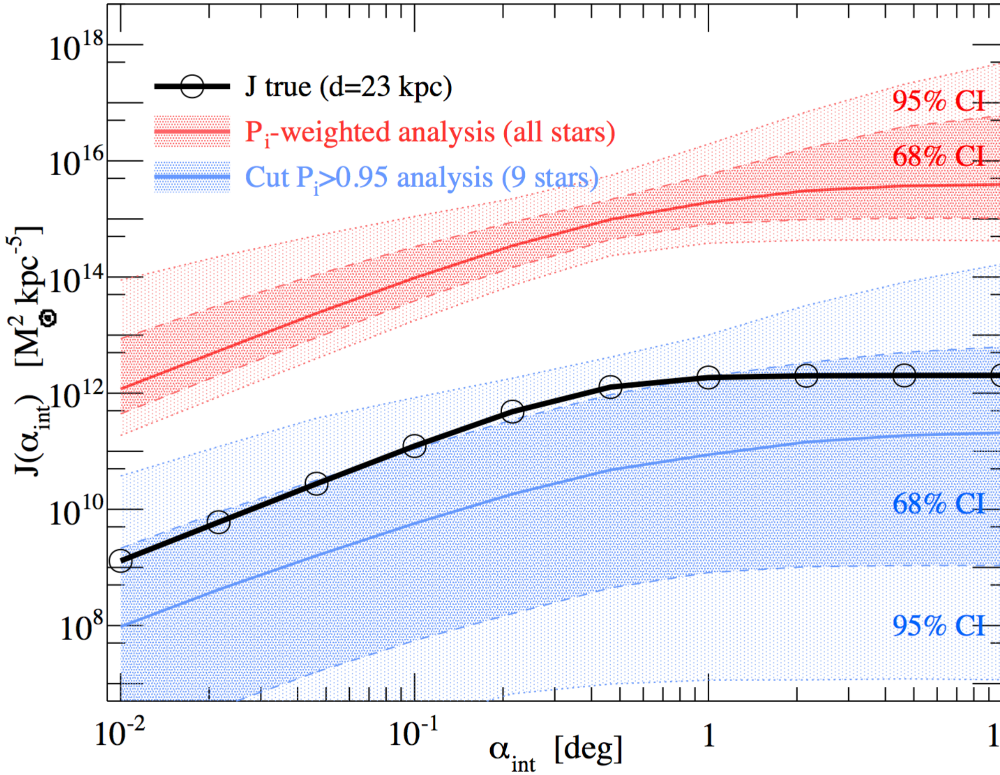
- **Context:**
  - Milky Way's dwarf spheroidal galaxies: among the best targets for searching γ-rays from DM annihilation.
  - J-factors needed for putting constraints on DM properties.
- **Results:**
  - Optimised Jeans analysis to mitigate several possible biases (Bonnivard et al., MNRAS 2015)
  - New Jeans analysis module added to the CLUMPY code (in prep.)
  - Annihilation and decay factors for 21 dSphs (Bonnivard et al., submitted to MNRAS)
  - Segue I highly uncertain due to contamination (in prep.)
  - First determination of J-factor for Reticulum II (Bonnivard et al., submitted to ApJL)
- **Prospects:**
  - Other channel for indirect detection of DM: charged antiparticles

→ AMS-02 data analysis of anti-deuterons

- The ultrafaint **Segue I** is often promoted as the « **best target** » among the dSphs.

- However, its kinematic sample might be contaminated by Milky Way foreground stars.

→ Our analysis is very sensitive to these ambiguous stars.



→ It appears as a very **uncertain target**! (Bonnivard, Maurin, Walker, in prep.)

Jeans analysis

$$\frac{1}{\nu}\frac{d}{dr}(\nu\bar{v_r^2}) + 2\frac{\beta_{\rm ani}(r)\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2}$$

Spherical Jeans equation

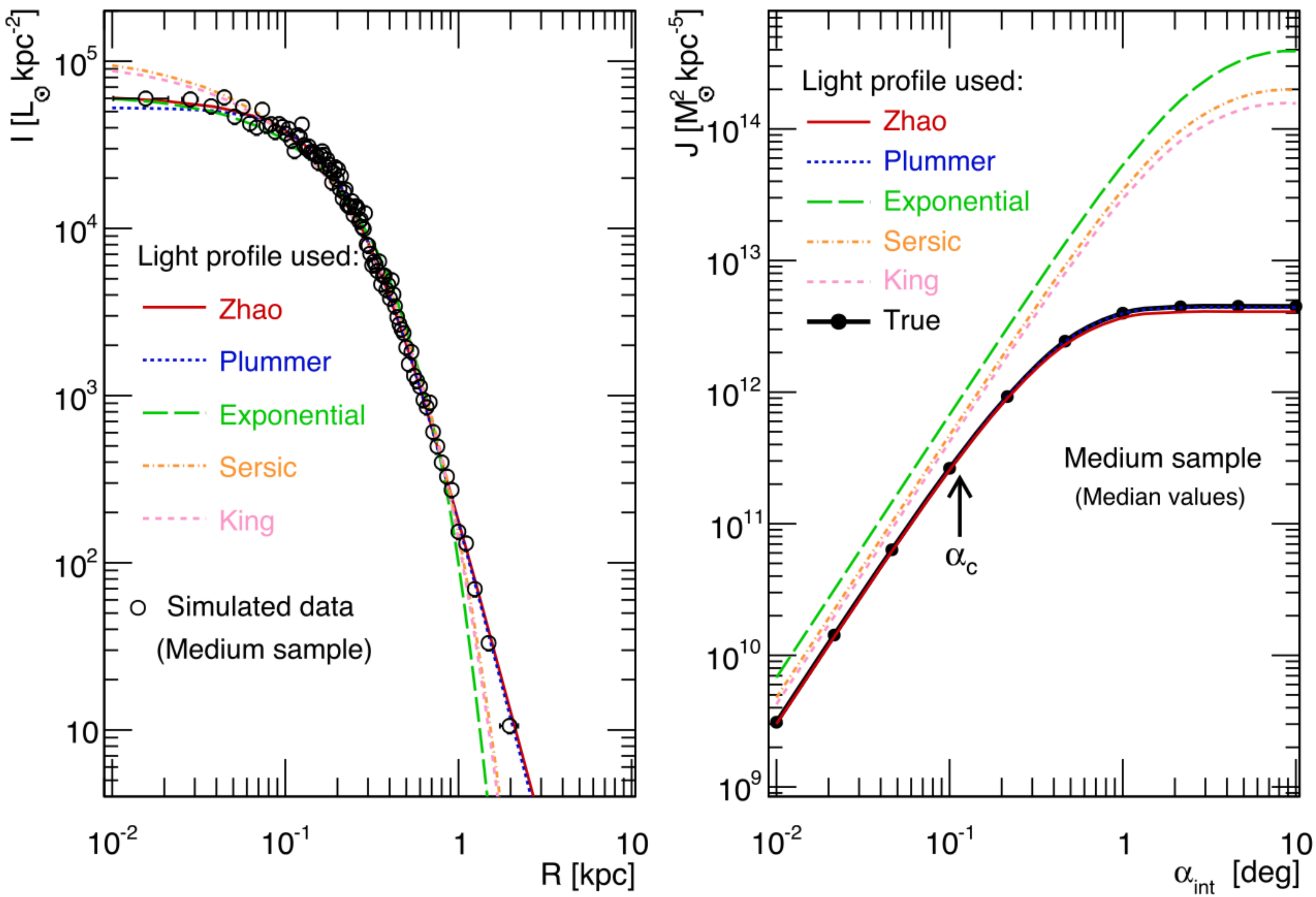
- Generic solution: $\nu(r)\bar{v_r^2}(r) = f(M, \beta_{\rm ani}, \nu, r)$

- However, the observables are: $\sigma_p(R)$ [velocity disp. along the l.o.s.],
  $I(R)$ [surface brightness]

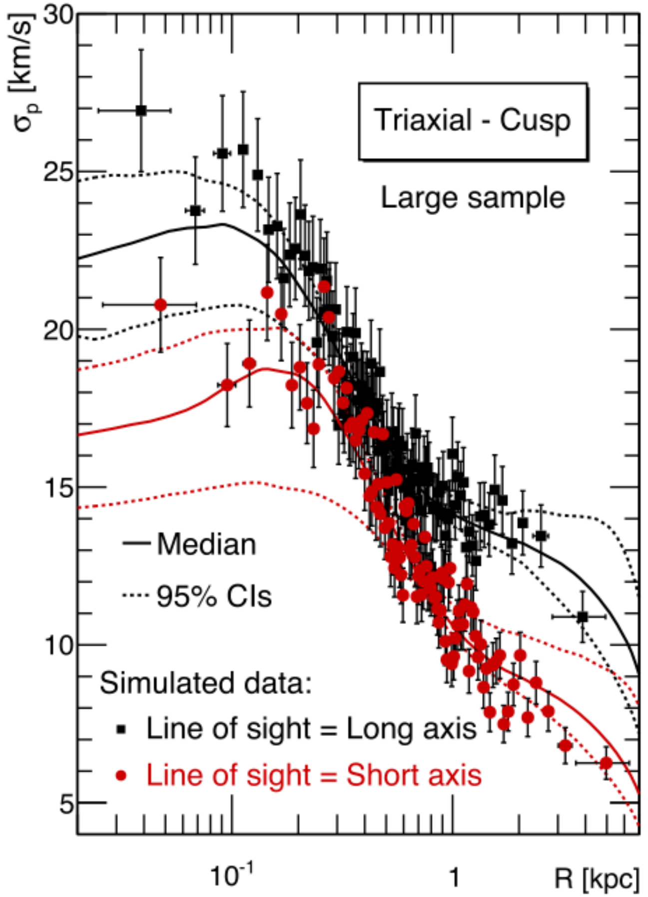
Line-of-sight projection

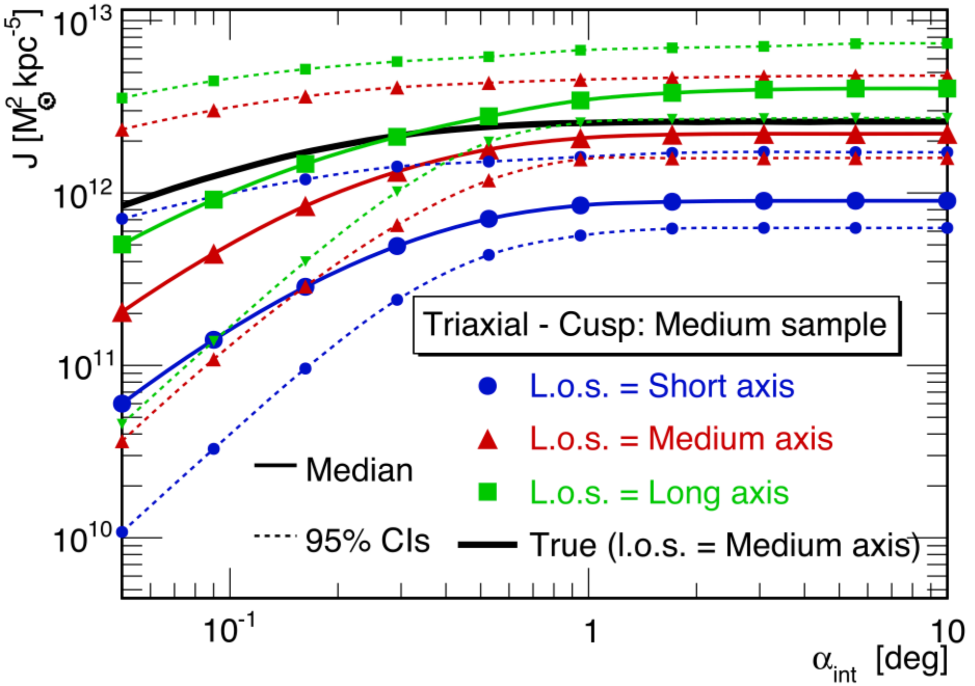
$$\sigma_p^2(R) = \frac{2}{I(R)}\int_R^\infty \left(1 - \beta_{\rm ani}(r)\frac{R^2}{r^2}\right)\frac{\nu(r)\,\bar{v_r^2}(r)\,r}{\sqrt{r^2 - R^2}}\mathrm{d}r$$

Light profile



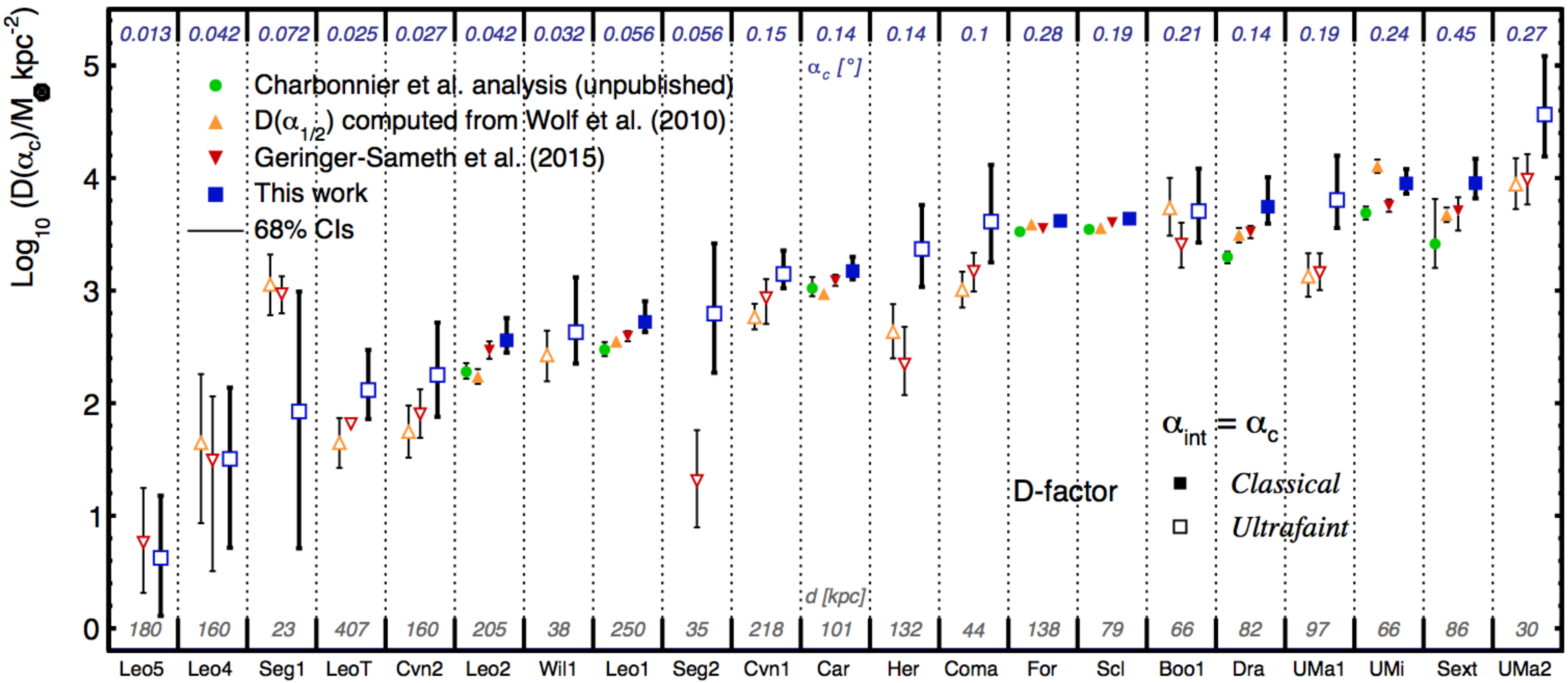
Triaxiality



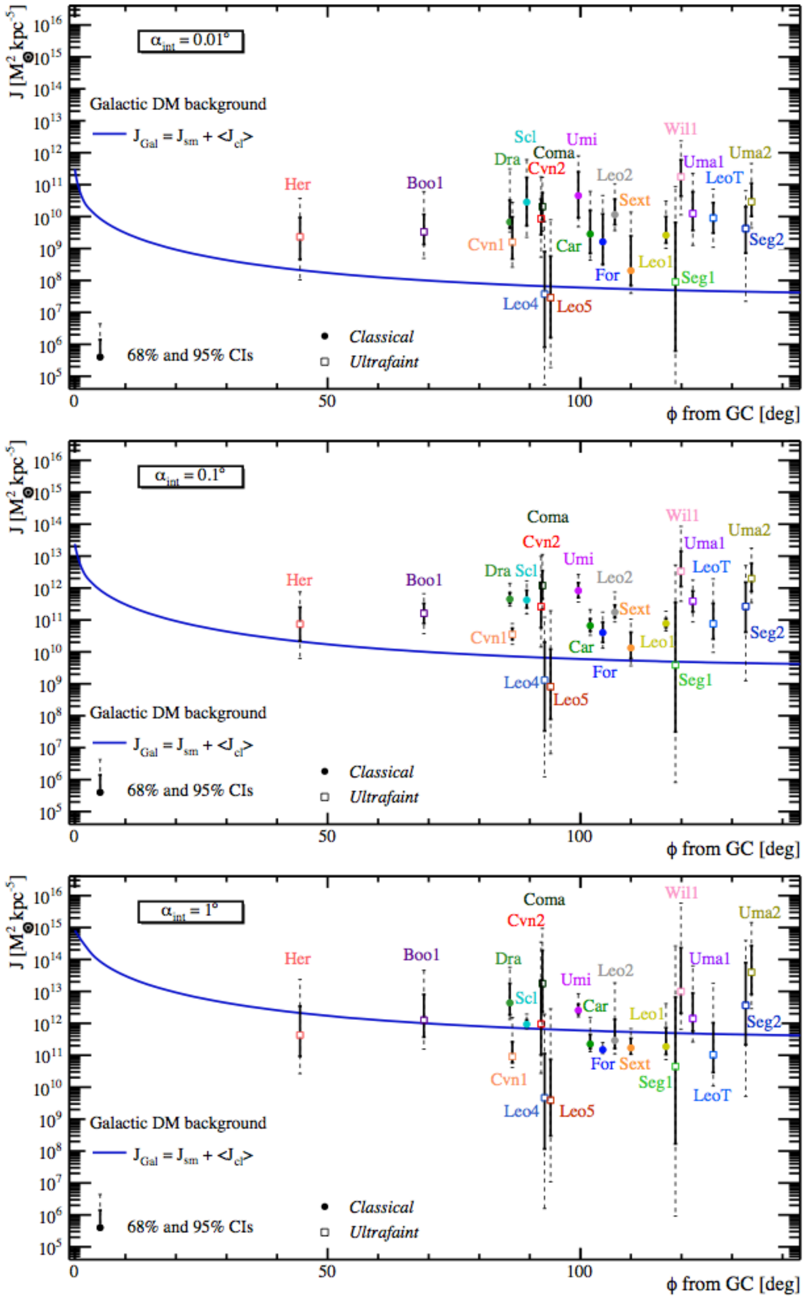


Decay

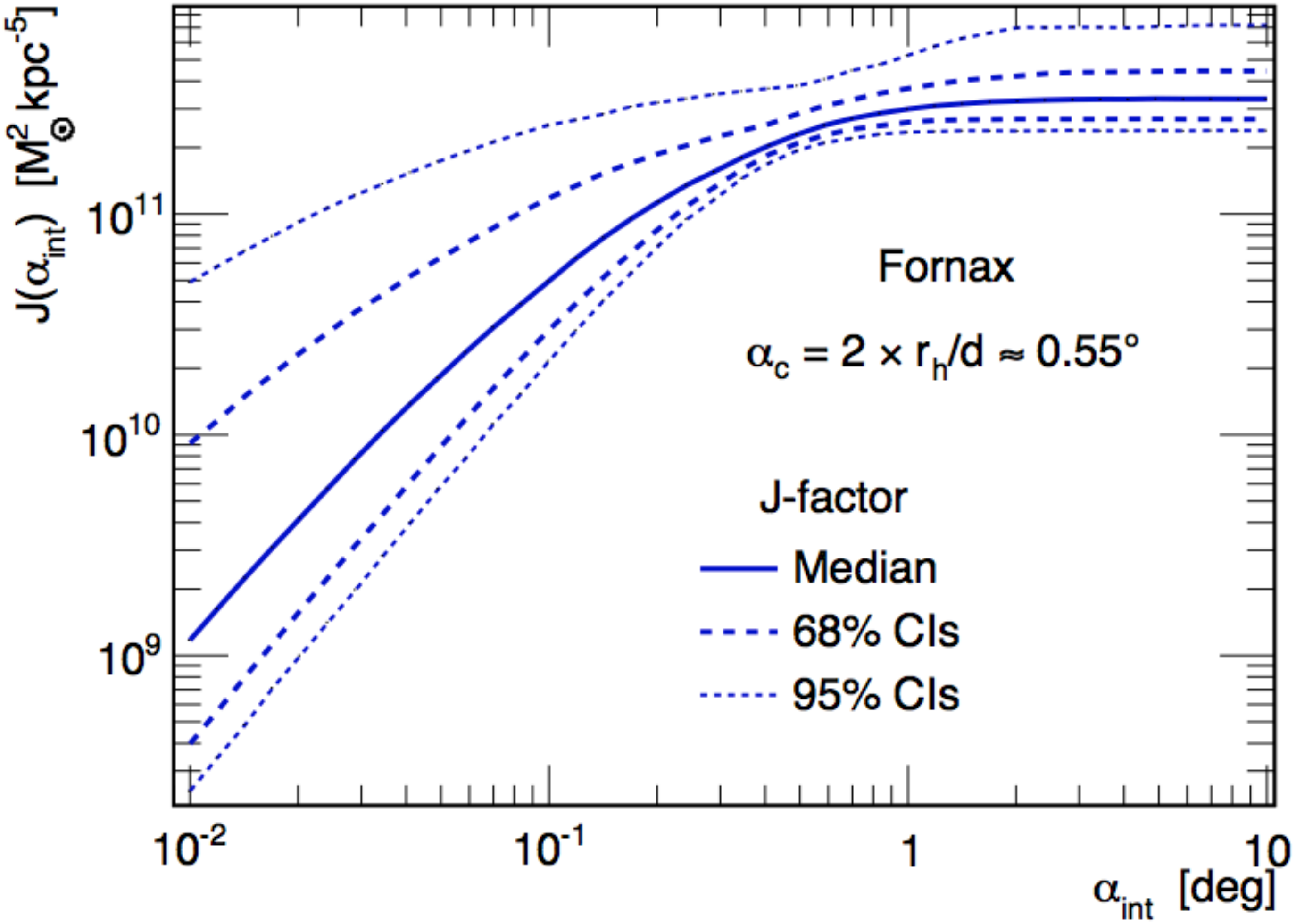
$$\frac{d\phi_\gamma}{dE} = \frac{1}{4\pi}\frac{dN_\gamma}{dE}\frac{1}{\tau}\int_0^{l_{max}}\int_0^{\Delta\Omega}\rho_{DM}\, d\Omega\, dl$$



J vs background

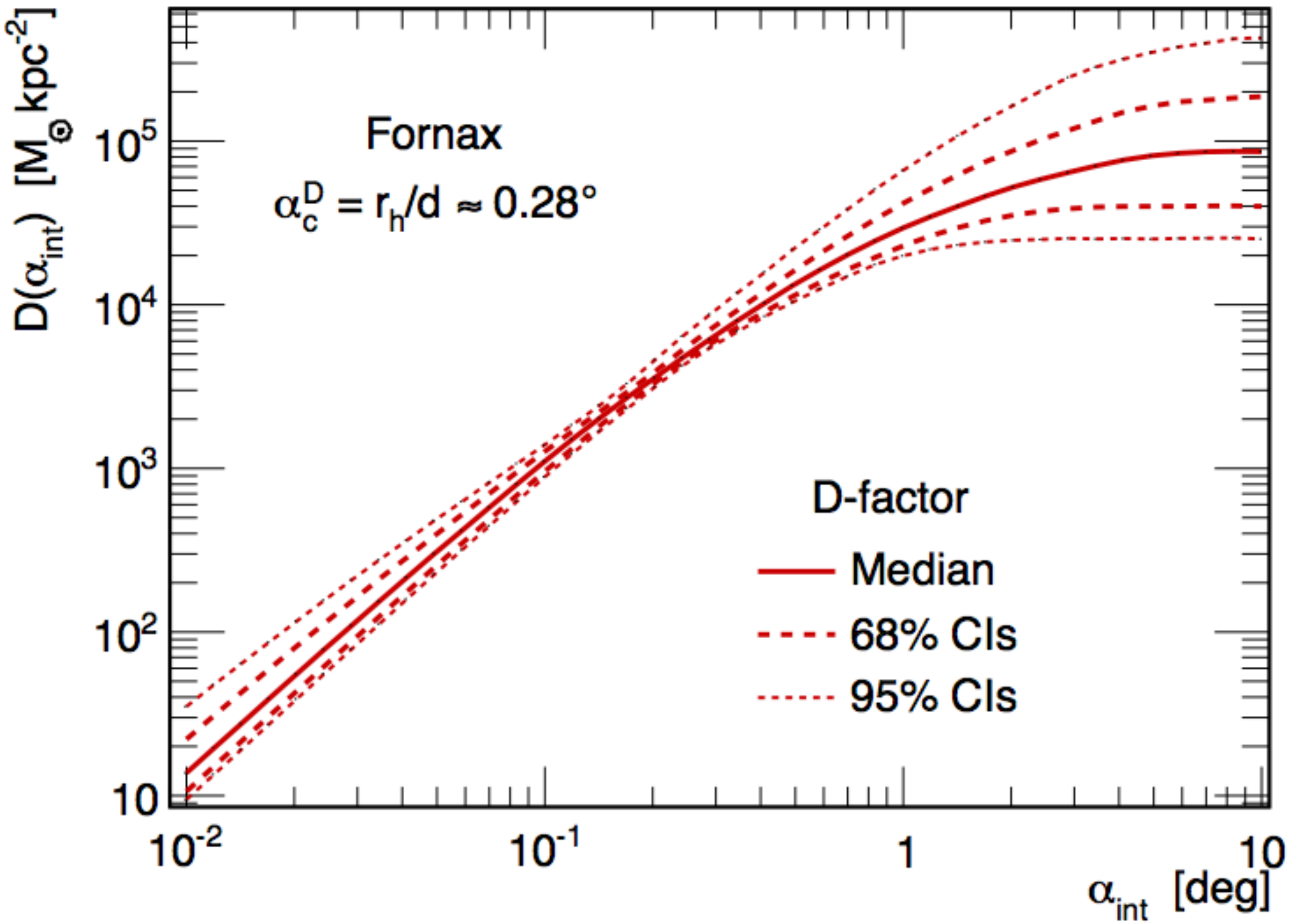


J-Fornax



$J(\alpha_{int})$ [$M_\odot^2$ kpc^{-5}]
10^{11}
10^{10}
10^{9}
10^{-2}
10^{-1}
1
10
α_{int} [deg]
Fornax
$\alpha_c = 2 \times r_h/d \approx 0.55°$
J-factor
Median
68% CIs
95% CIs

D-Fornax



Fornax
$\alpha_c^D = r_h/d \approx 0.28°$
D-factor
Median
68% CIs
95% CIs
$D(\alpha_{int})$ [$M_\odot$ kpc^{-2}]
α_{int} [deg]
10
10^2
10^3
10^4
10^5
10^{-2}
10^{-1}
1
10

Leo I