EFFECT OF BINARIES ON DARK MATTER ESTIMATES IN DWARF GALAXIES

Caveats to Dwarf Galaxy Indirect Detection Limits

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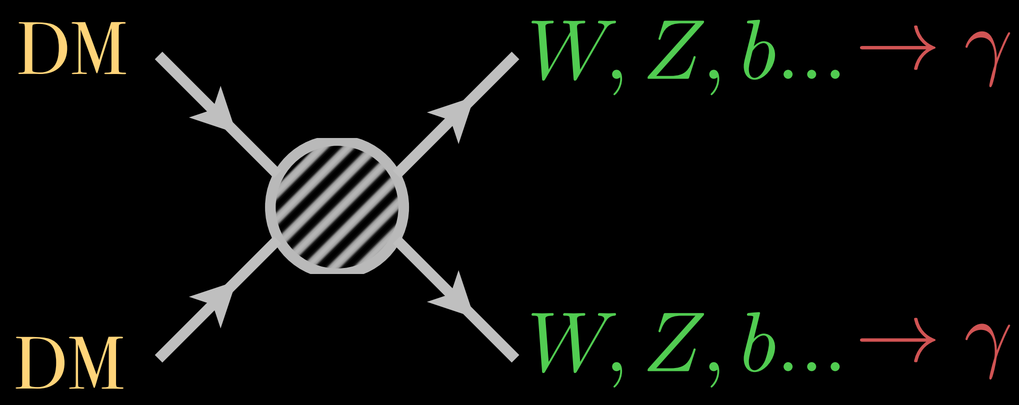
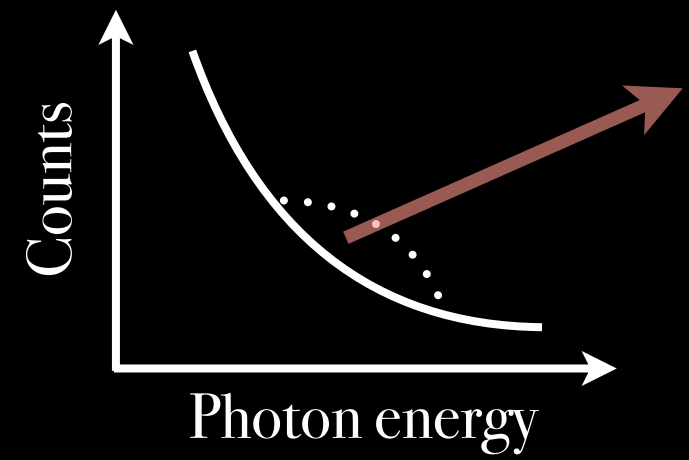
PRINCETON UNIVERSITY

Small Galaxies, Cosmic Questions
July 31, 2019

IN COLLABORATION WITH: LINA NECIB (CALTECH)

THERMAL WIMP DARK MATTER (DM)





enhanced emission from dark matter-rich regions

Weakly **I**nteracting **M**assive **P**article**s**
→ gamma rays

Indirect detection

Fermi Large Area Telescope (*Fermi*-LAT)

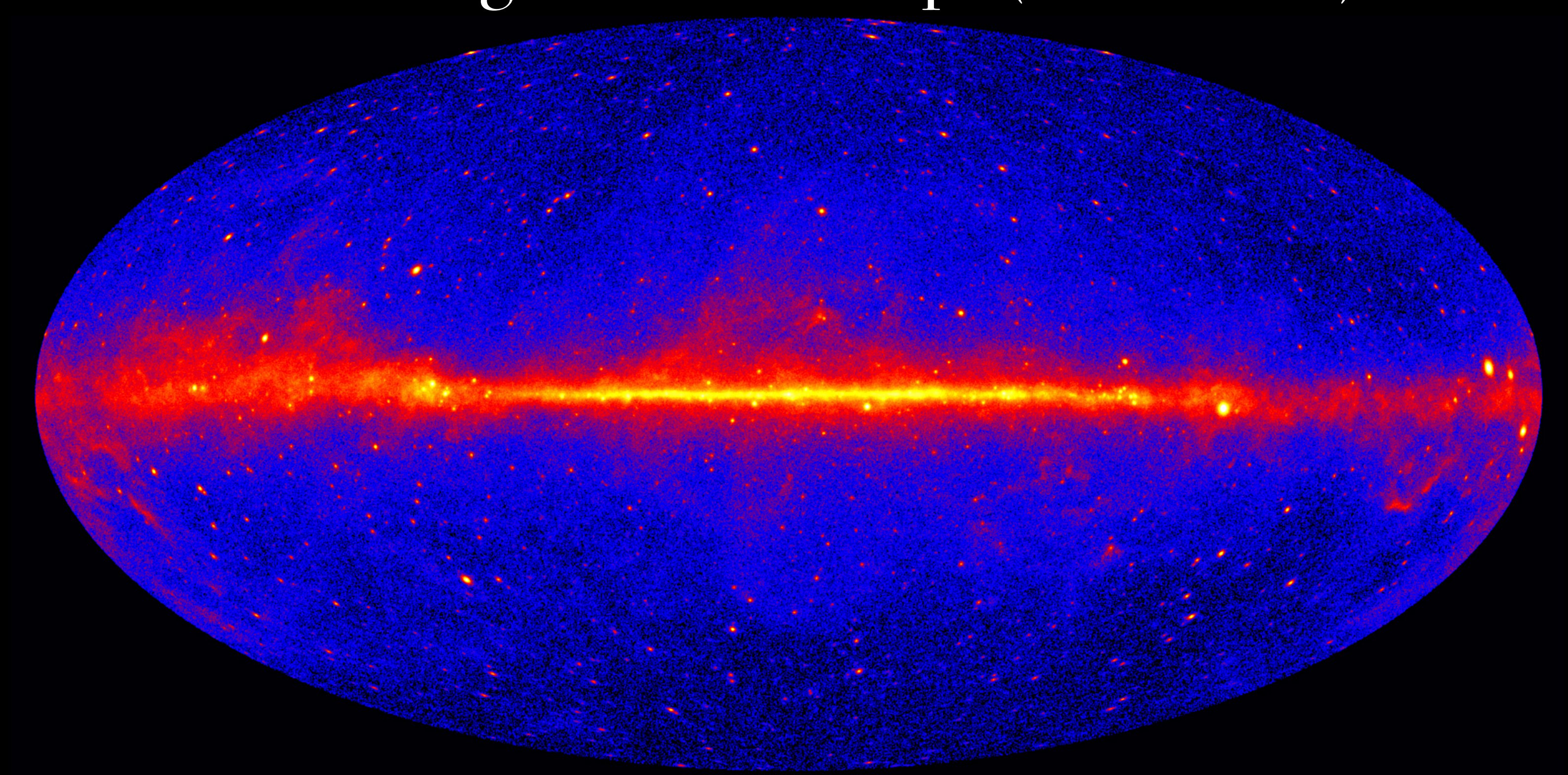
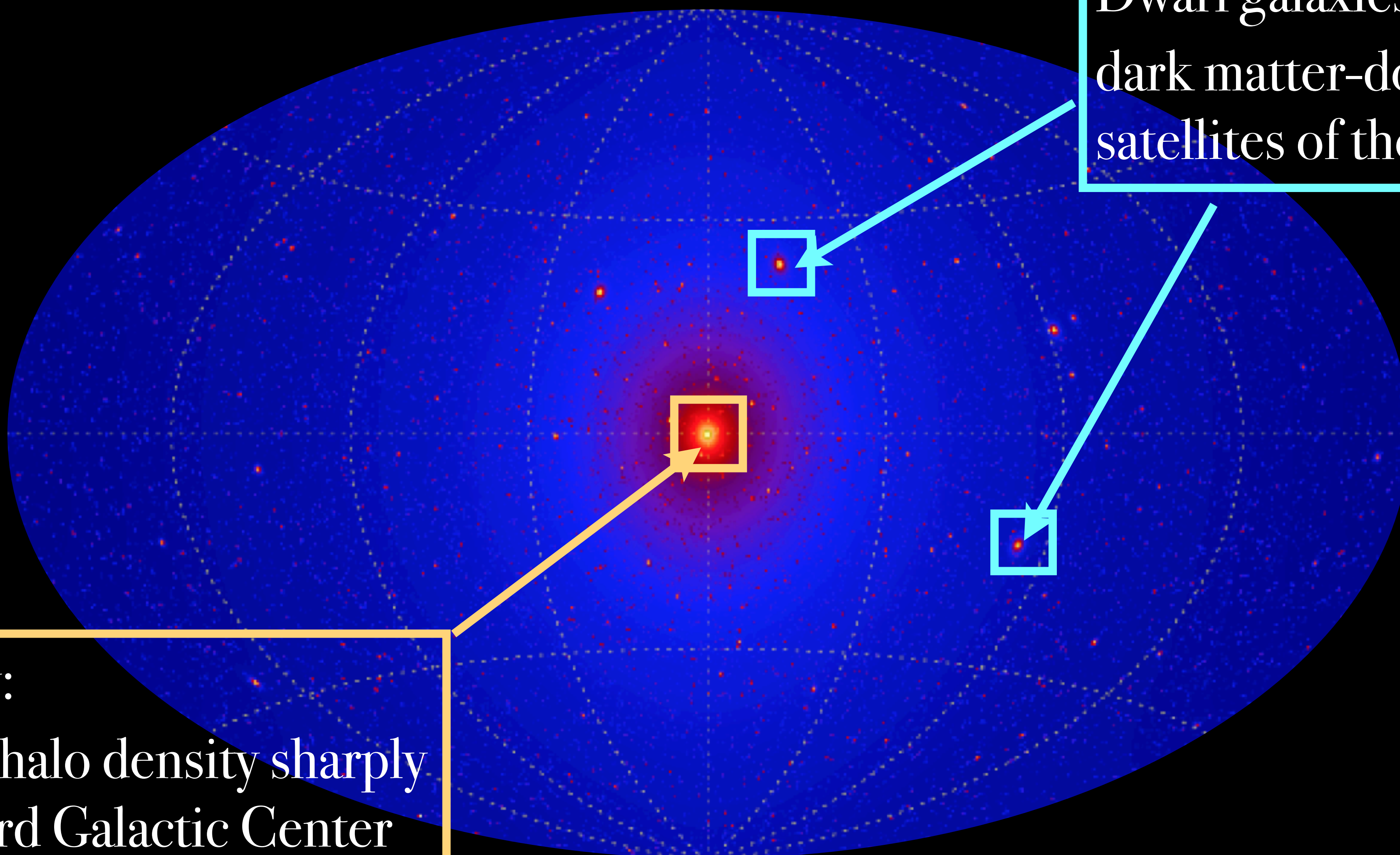


Image: NASA, DOE, *Fermi*-LAT collaboration

DARK MATTER ANNIHILATION IN THE SKY

$$\Phi_\gamma(\Delta\Omega) = \underbrace{\frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2m_{\rm DM}^2}\int_{E_{\rm min}}^{E_{\rm max}}\frac{{\rm d}N_\gamma}{{\rm d}E_\gamma}{\rm d}E_\gamma}_{\text{particle physics}} \times \underbrace{\int_{\Delta\Omega}\int_{\rm l.o.s.}\rho_{\rm DM}^2(\mathbf{r}){\rm d}l{\rm d}\Omega'}_{\text{astrophysics (J-factor)}}$$

Dwarf galaxies:
dark matter-dominated satellites of the main galaxy



Inner Galaxy:
Dark matter halo density sharply peaked toward Galactic Center

L. Pieri et al. [0908.0195]

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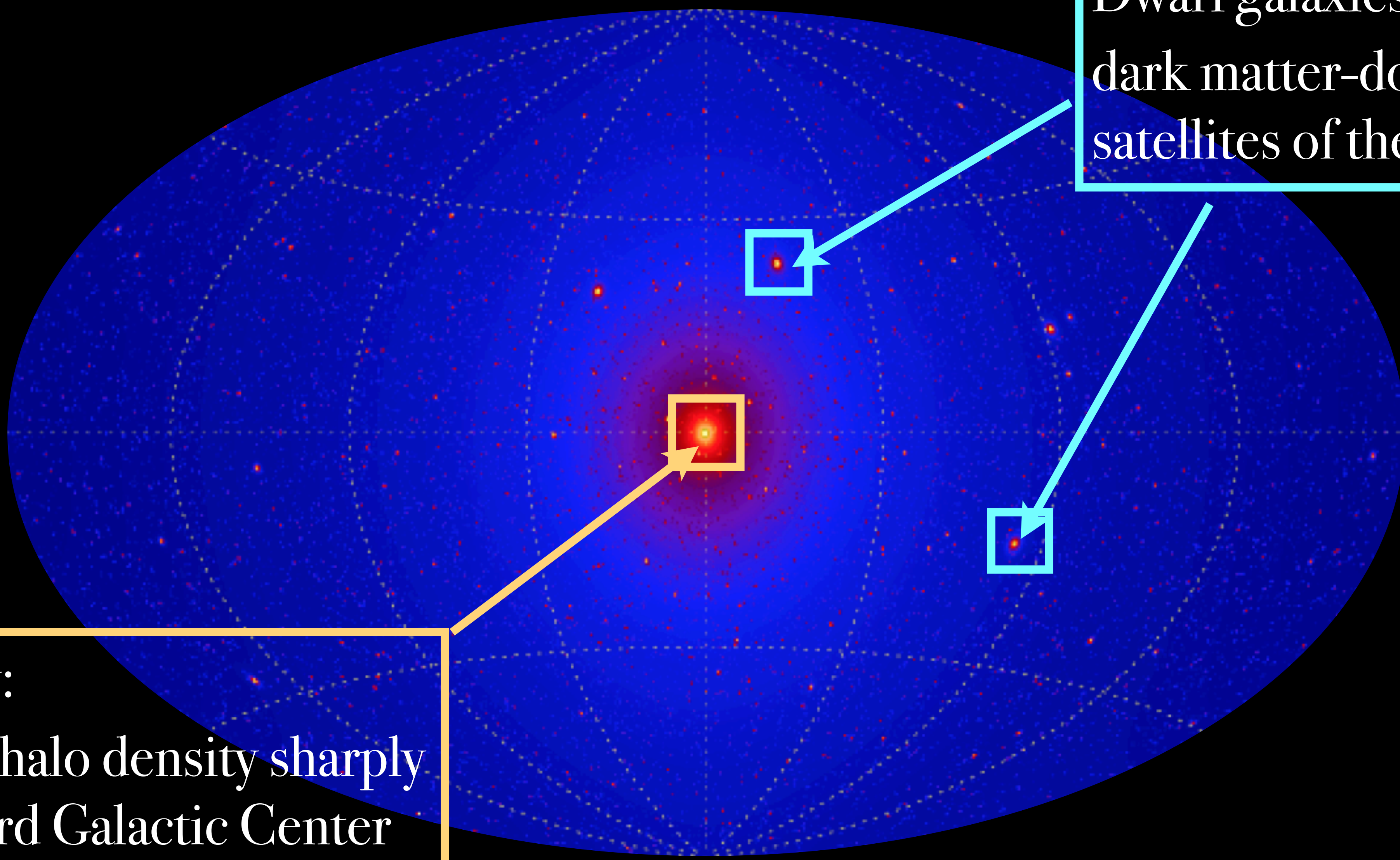

Dwarf galaxies:
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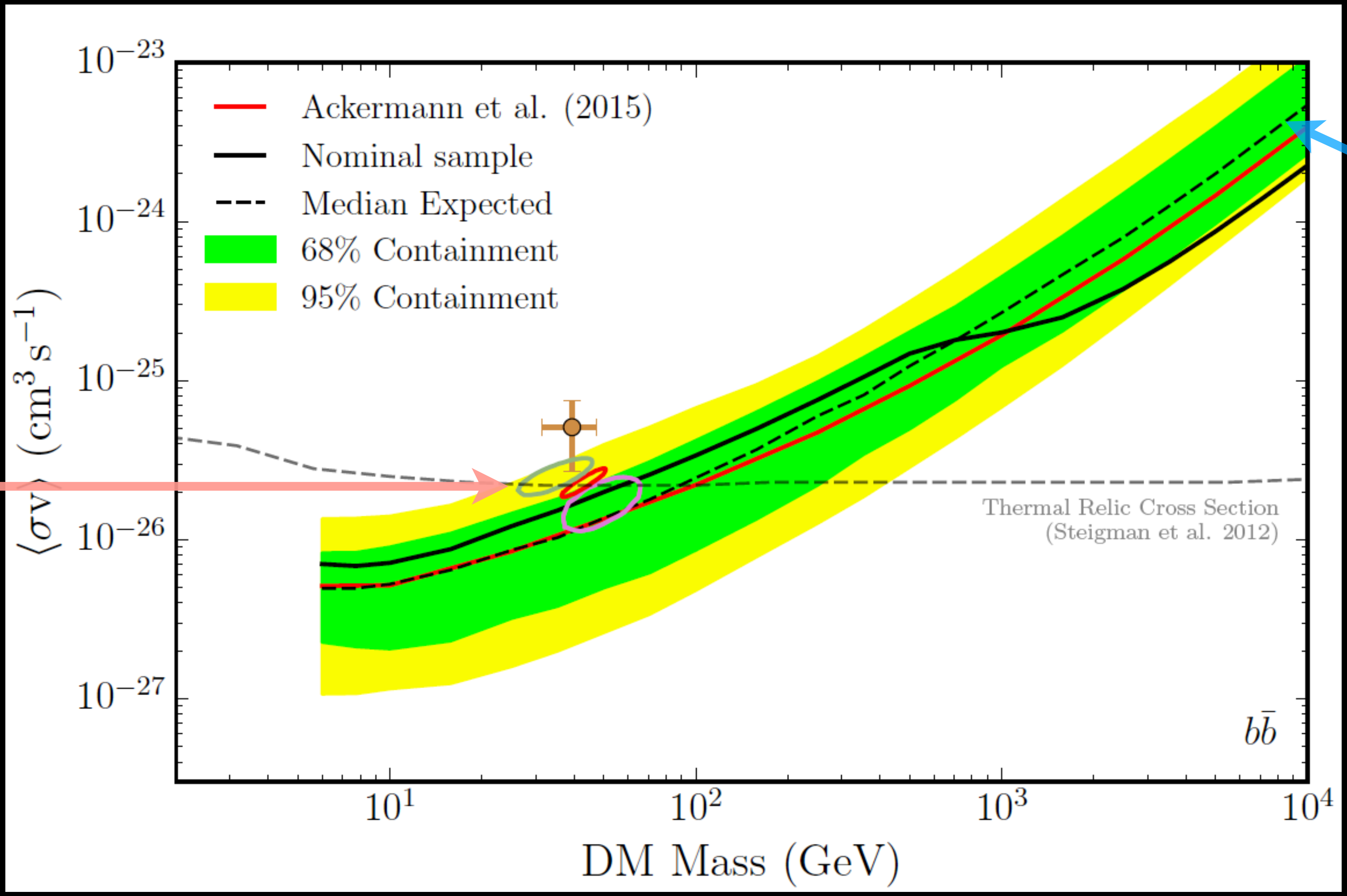
INDIRECT DETECTION BENCHMARK: DWARF GALAXIES

- Low astrophysical backgrounds (dust/gas) compared to other indirect detection targets
  → some of the most stringent and robust constraints



Galactic Center Excess (GCE), dark matter interpretation

Analyze blank regions of the sky (no systematics)

Fermi-LAT collaboration and DES collaboration [1611.03184]

DWARF GALAXY INDIRECT DETECTION CAVEATS

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Kinematically Confirmed Galaxies						
Boötes I*	358.08, 69.62	66	189	-6.3	18.2 ± 0.4	18.5
Boötes II	353.69, 68.87	42	46	-2.7	...	18.9
Boötes III	35.41, 75.35	47	...	-5.8	...	18.8
Canes Venatici I	74.31, 79.82	218	441	-8.6	17.4 ± 0.3	17.4
Canes Venatici II*	113.58, 82.70	160	52	-4.9	17.6 ± 0.4	17.7
Carina*	260.11, -22.22	105	205	-9.1	17.9 ± 0.1	18.1
Coma Berenices*	241.89, 83.61	44	60	-4.1	19.0 ± 0.4	18.8
Draco*	86.37, 34.72	76	184	-8.8	18.8 ± 0.1	18.3
Draco II	98.29, 42.88	24	16	-2.9	...	19.3
Fornax*	237.10, -65.65	147	594	-13.4	17.8 ± 0.1	17.8
Hercules*	28.73, 36.87	132	187	-6.6	16.9 ± 0.7	17.9
Horologium I	271.38, -54.74	87	61	-3.5	...	18.2
Hydra II	295.62, 30.46	134	66	-4.8	...	17.8
Leo I	225.99, 49.11	254	223	-12.0	17.8 ± 0.2	17.3
Leo II*	220.17, 67.23	233	164	-9.8	18.0 ± 0.2	17.4
Leo IV*	265.44, 56.51	154	147	-5.8	16.3 ± 1.4	17.7
Leo V	261.86, 58.54	178	95	-5.2	16.4 ± 0.9	17.6
Pisces II	79.21, -47.11	182	45	-5.0	...	17.6
Reticulum II	266.30, -49.74	32	35	-3.6	18.9 ± 0.6	19.1
Sculptor*	287.53, -83.16	86	233	-11.1	18.5 ± 0.1	18.2
Segue 1*	220.48, 50.43	23	21	-1.5	19.4 ± 0.3	19.4
Sextans*	243.50, 42.27	86	561	-9.3	17.5 ± 0.2	18.2
Triangulum II	140.90, -23.82	30	30	-1.8	...	19.1
Tucana II	328.04, -52.35	58	120	-3.9	...	18.6
Ursa Major I	159.43, 54.41	97	143	-5.5	17.9 ± 0.5	18.1
Ursa Major II*	152.46, 37.44	32	91	-4.2	19.4 ± 0.4	19.1
Ursa Minor*	104.97, 44.80	76	120	-8.8	18.9 ± 0.2	18.3
Willman 1*	158.58, 56.78	38	19	-2.7	...	18.9
Likely Galaxies						
Columba I	231.62, -28.88	182	101	-4.5	...	17.6
Eridanus II	249.78, -51.65	331	156	-7.4	...	17.1
Grus I	338.68, -58.25	120	60	-3.4	...	17.9
Grus II	351.14, -51.94	53	93	-3.9	...	18.7
Horologium II	262.48, -54.14	78	33	-2.6	...	18.3
Indus II	354.00, -37.40	214	181	-4.3	...	17.4
Pegasus III	69.85, -41.81	205	57	-4.1	...	17.5
Phoenix II	323.69, -59.74	96	33	-3.7	...	18.1
Pictor I	257.29, -40.64	126	44	-3.7	...	17.9
Reticulum III	273.88, -45.65	92	64	-3.3	...	18.2
Sagittarius II	18.94, -22.90	67	34	-5.2	...	18.4
Tucana III	315.38, -56.18	25	44	-2.4	...	19.3
Tucana IV	313.29, -55.29	48	128	-3.5	...	18.7
Ambiguous Systems						
Cetus II	156.47, -78.53	30	17	0.0	...	19.1
Eridanus III	274.95, -59.60	96	12	-2.4	...	18.1
Kim 2	347.16, -42.07	105	12	-1.5	...	18.1
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Fermi-LAT collaboration and DES collaboration [1611.03184]

DWARF GALAXY INDIRECT DETECTION CAVEATS

- Constraints rely on accurate J-factors

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Boötes III	35.41, 75.35	47	...	-5.8	...	18.8
Canes Venatici I	74.31, 79.82	218	441	-8.6	17.4 ± 0.3	17.4
Canes Venatici II*	113.58, 82.70	160	52	-4.9	17.6 ± 0.4	17.7
Carina*	260.11, -22.22	105	205	-9.1	17.9 ± 0.1	18.1
Coma Berenices*	241.89, 83.61	44	60	-4.1	19.0 ± 0.4	18.8
Draco*	86.37, 34.72	76	184	-8.8	18.8 ± 0.1	18.3
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Fermi-LAT collaboration and DES collaboration [1611.03184]

Use with caution:

"Galaxies for which Published Kinematics May Not Reliably Translate to Masses"

J. D. SImon [1901.05465]

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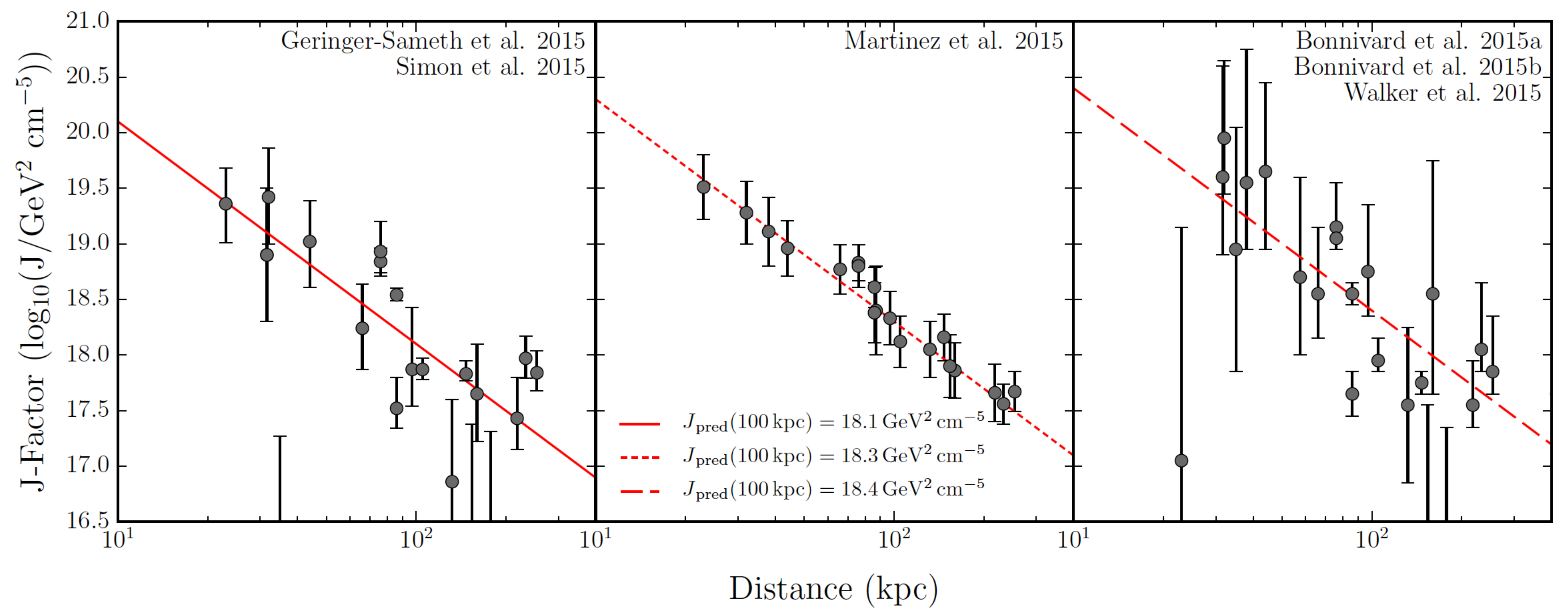

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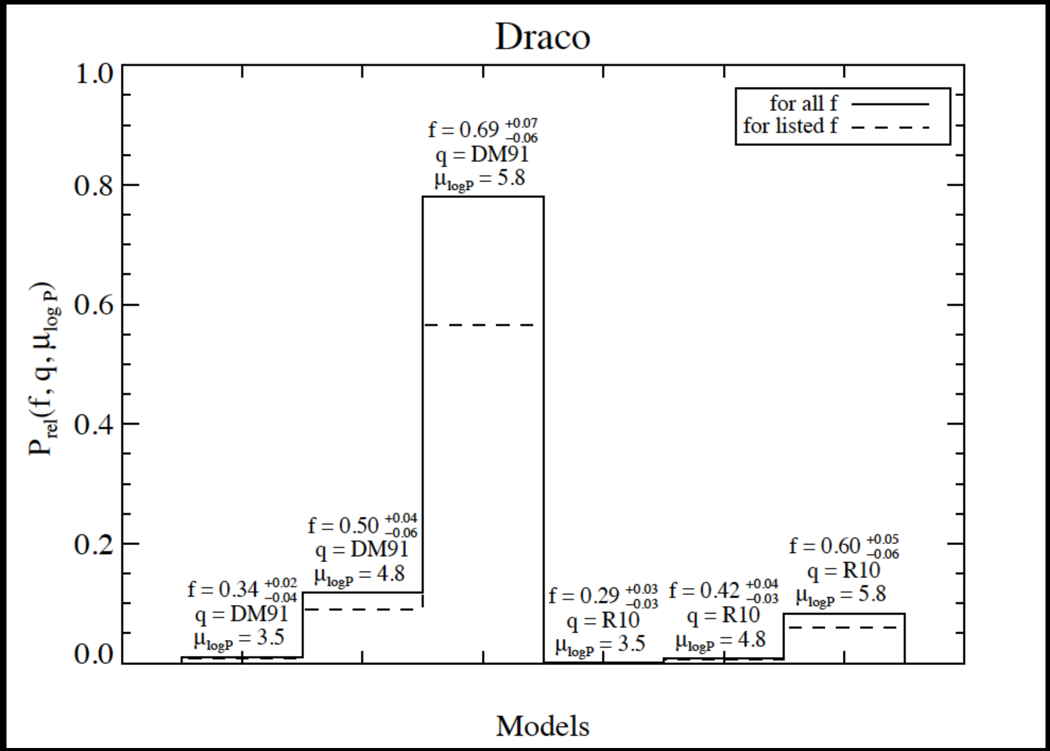

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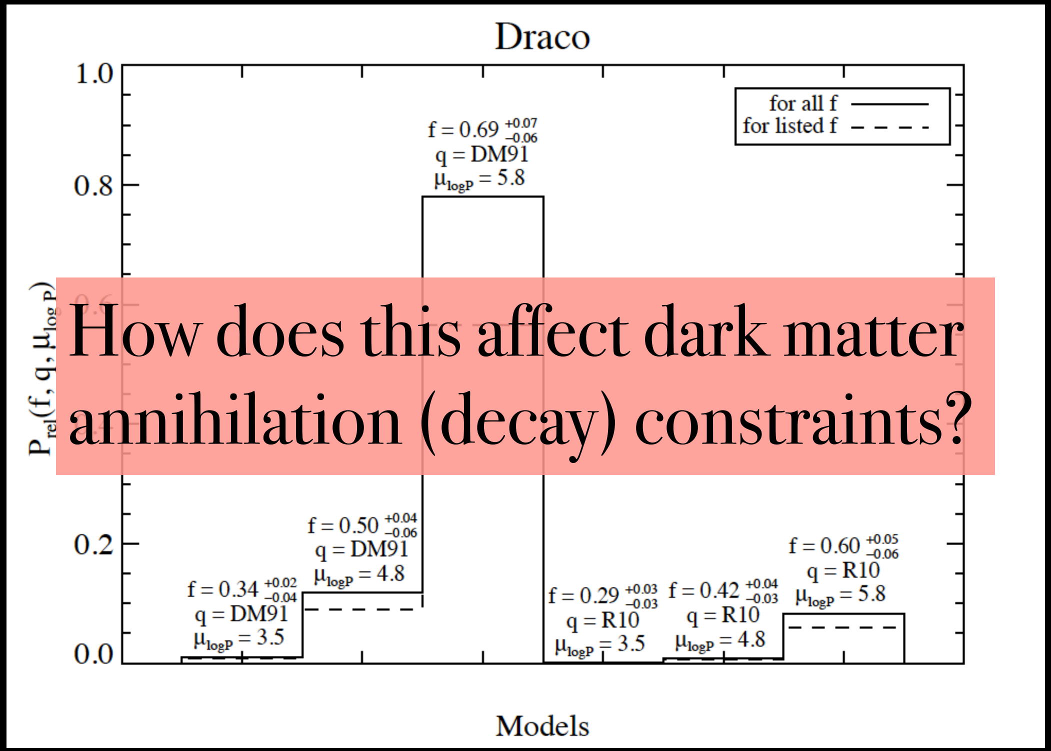

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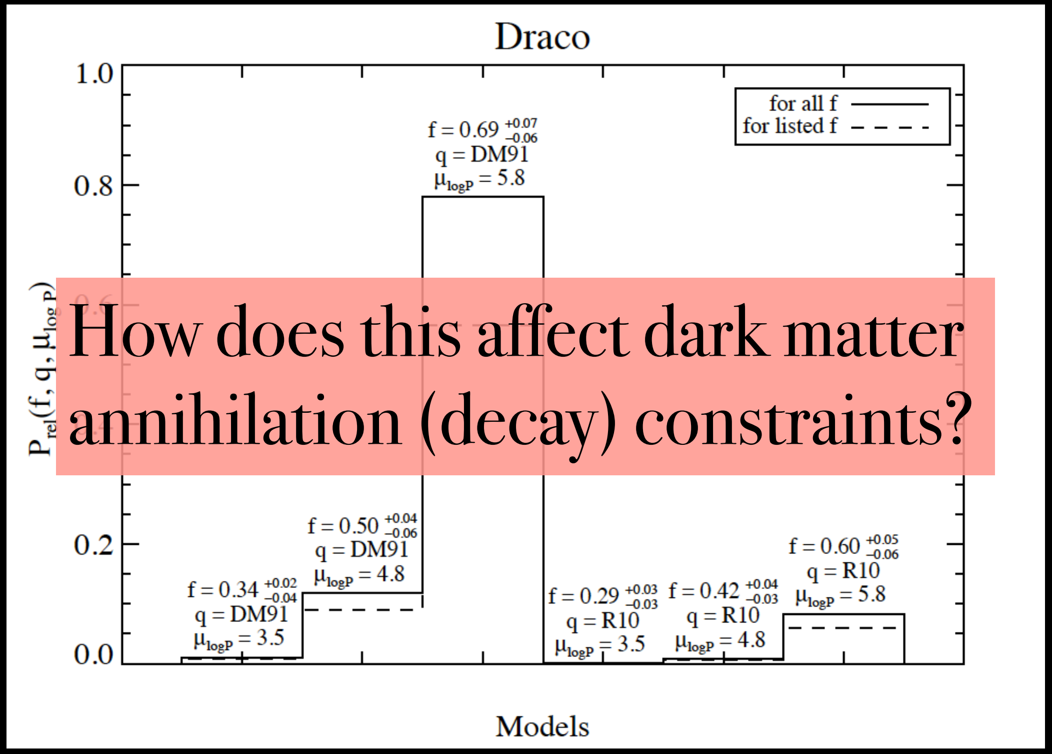

M. E. Spencer et al. [1811.06597]

Spherical Jeans equation

3d radial velocity dispersion, stellar density profile ⟷ Halo mass (DM density profile)

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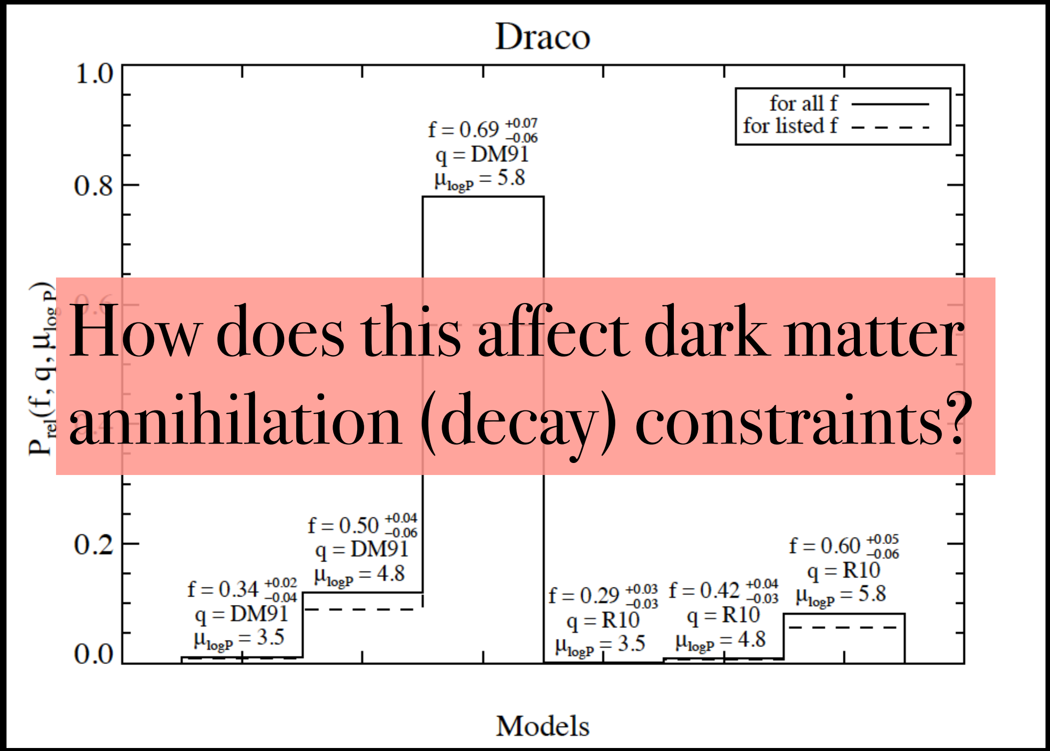

M. E. Spencer et al. [1811.06597]

In practice, observe line-of-sight projected quantities

Line-of-sight projected velocity dispersion, stellar density profile ⟷ Halo mass (DM density profile)

↓

J-factor ⟶ Constraint on DM annihilation
(+ particle physics)

$M-\beta$ $(\rho-\beta)$ degeneracy

J.I. Read and P. Steger [1701.04833]

OUTLINE OF METHODOLOGY

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The question

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In the cleanest scenario, what is the effect of binaries on dwarf galaxy J-factors?

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The (simulated) data

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Gaia Challenge spherical mocks:

- Plummer light profile
- Cusped DM profile
- No velocity anisotropy

Gaia Challenge http://astrowiki.ph.surrey.ac.uk/dokuwiki
M. G. Walker and J. Peñarrubia [1108.2404]

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Run through pipeline to get J-factors for Gaia Challenge

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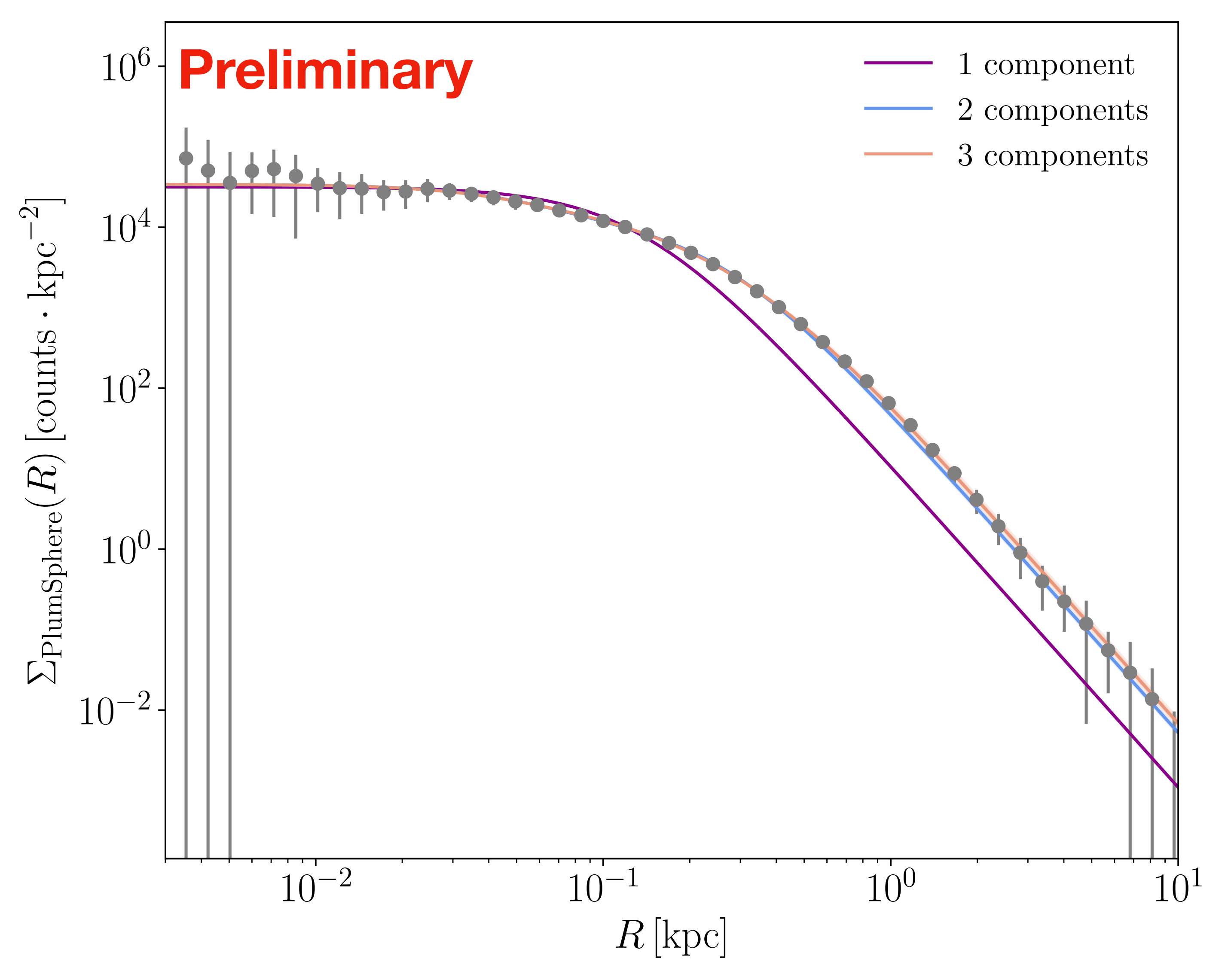
The method

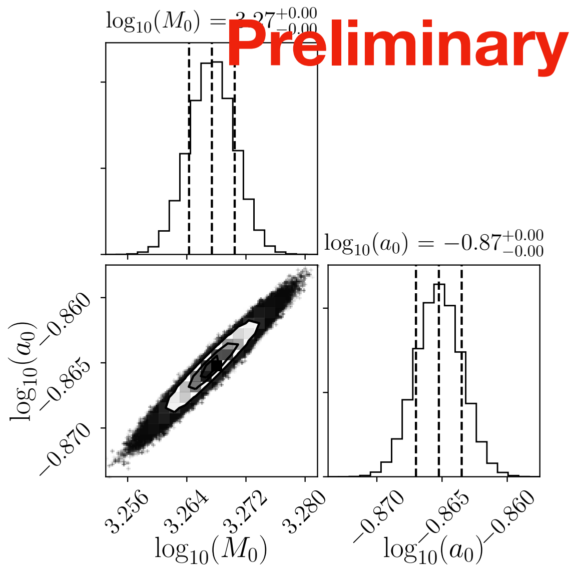
Run through pipeline to get J-factors for Gaia Challenge
→ Repeat analysis with injected binary motions

STEP 1: LIGHT PROFILE FIT

- Binned likelihood fit to stellar positions
- Fits tend to be well-constrained

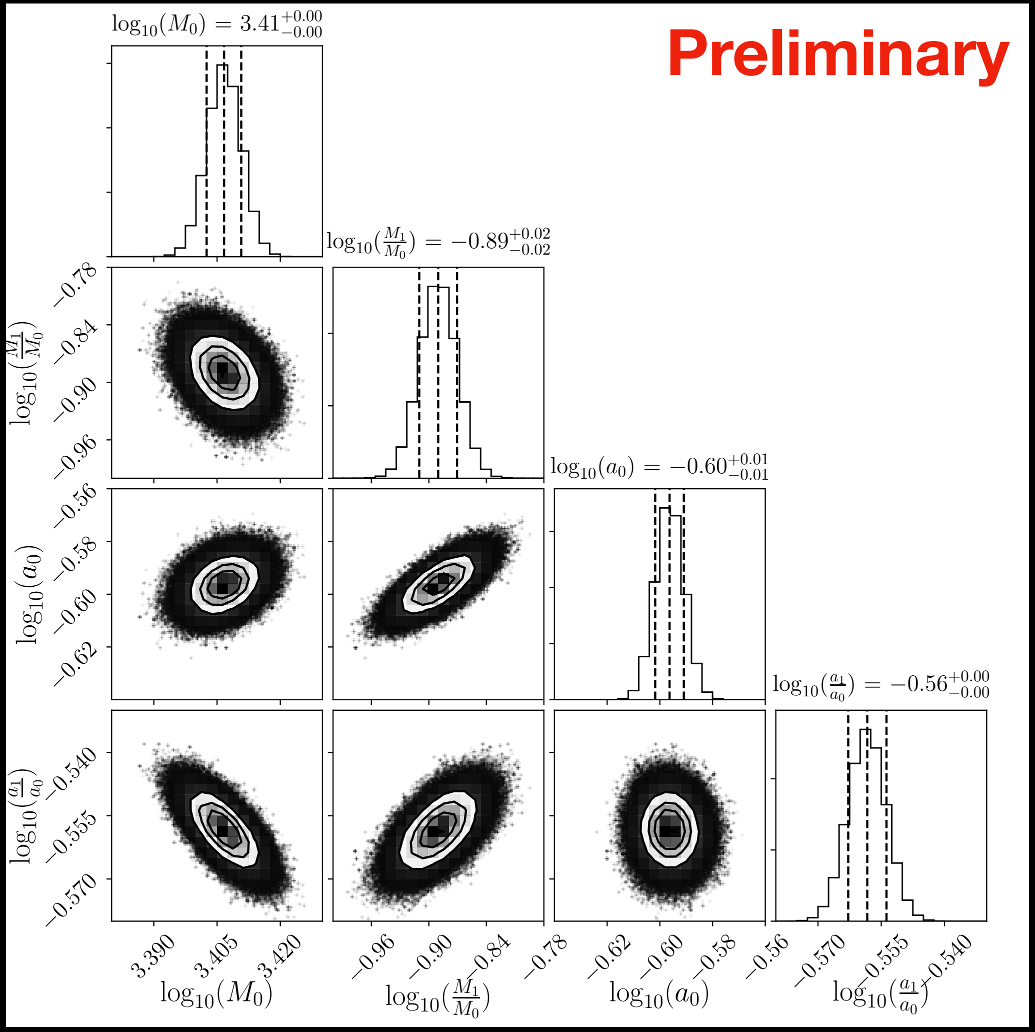
3000 tracers





1 Plummer component

2 Plummer components



STEP 1: LIGHT PROFILE FIT

- Binned likelihood fit to stellar positions
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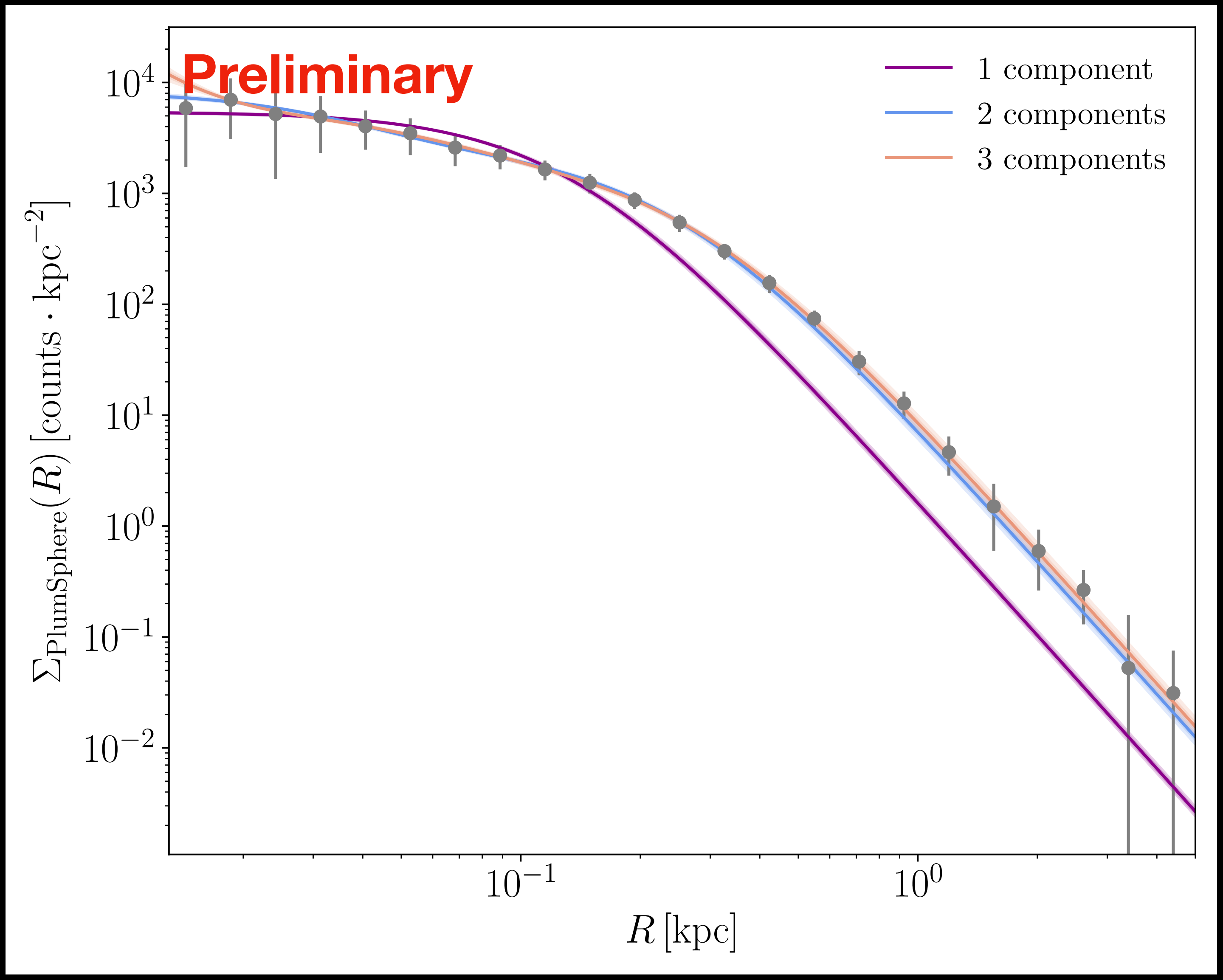
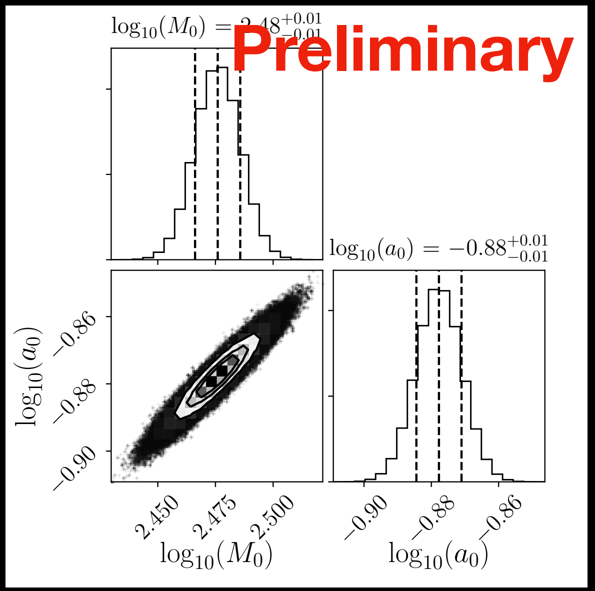
500 tracers





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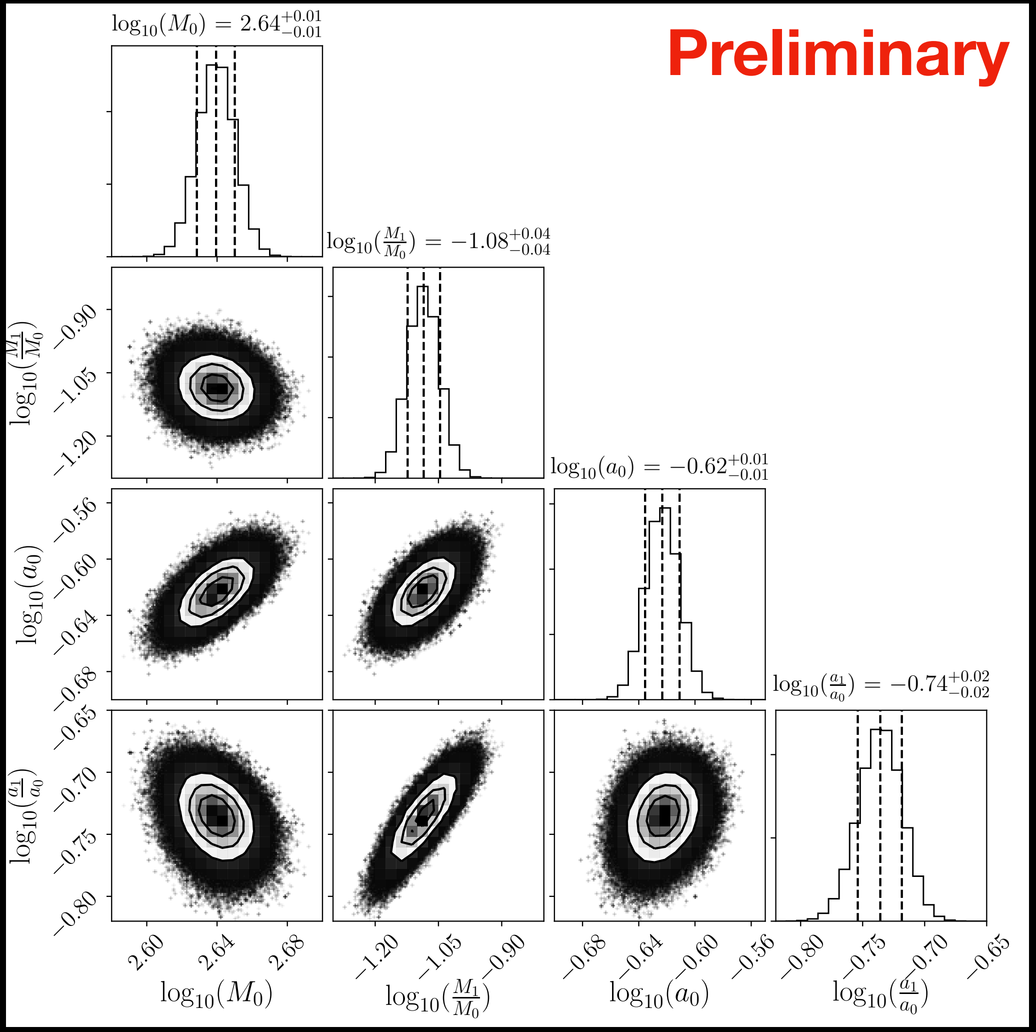

STEP 2: VELOCITY DISPERSION FIT

- Use Step 1 to constrain light profile parameters: float over middle 95% posterior parameter ranges from light profile fit
- Optimistically assume velocity error of 0.2 km/s
- Extract posterior distributions for DM parameters

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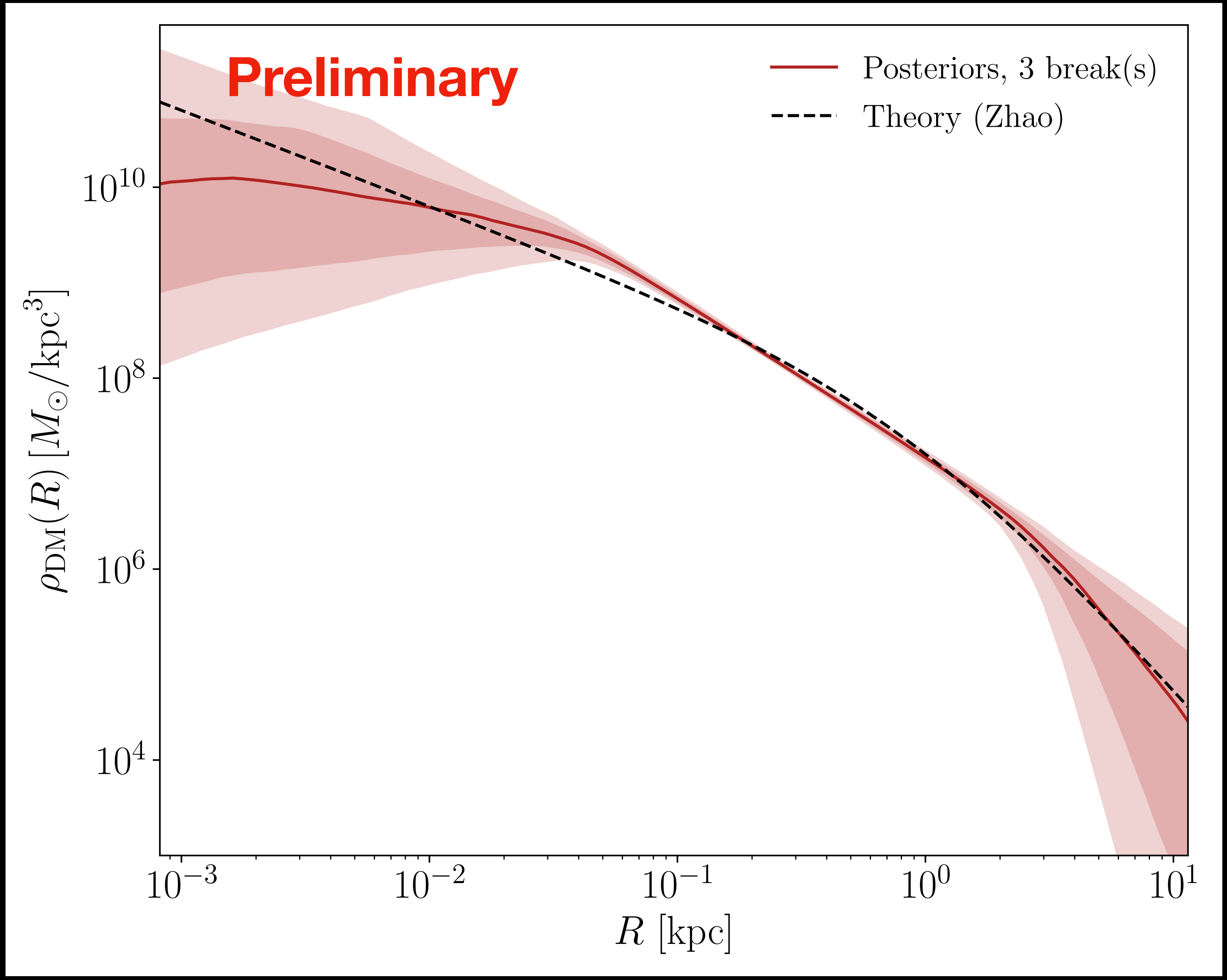

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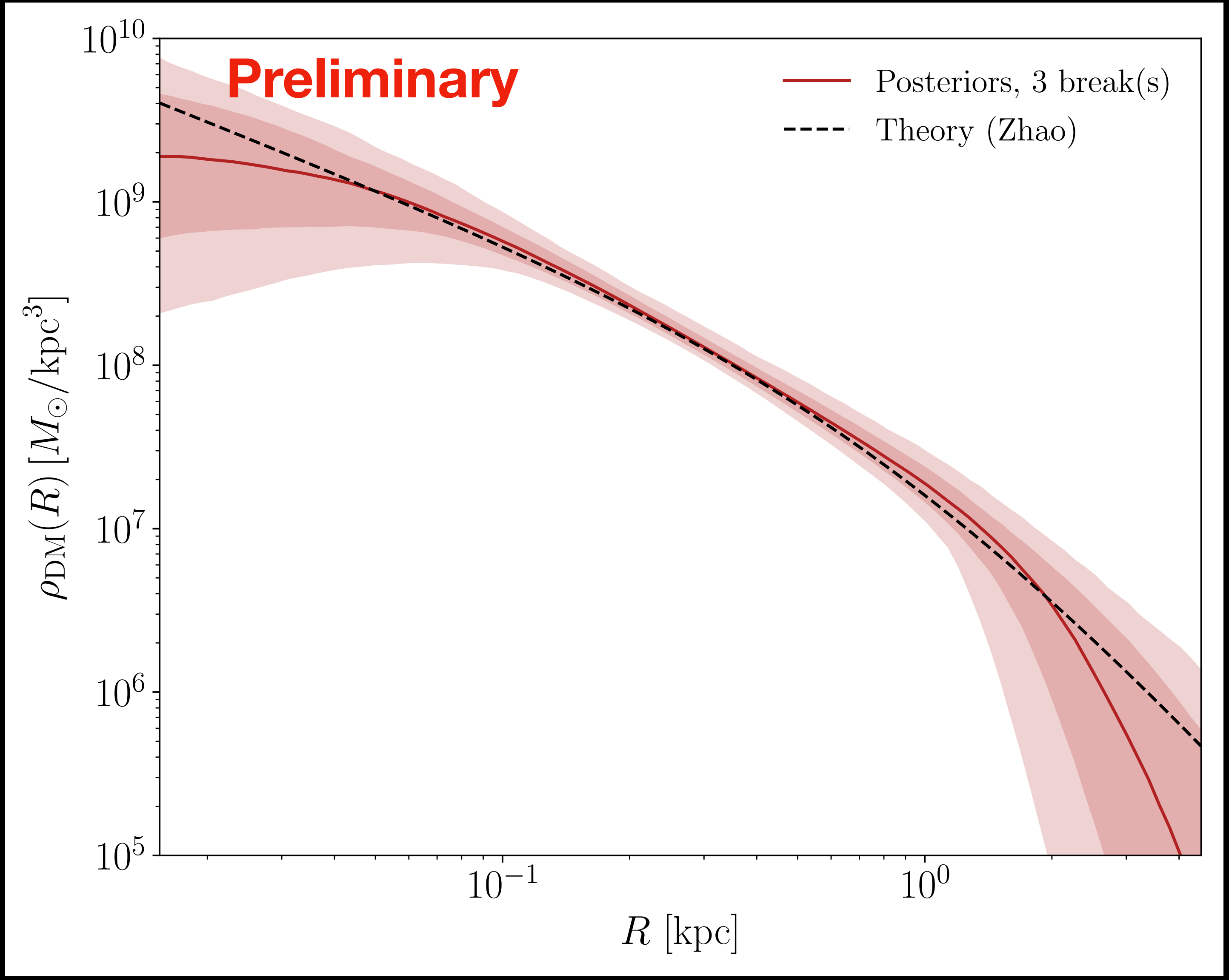
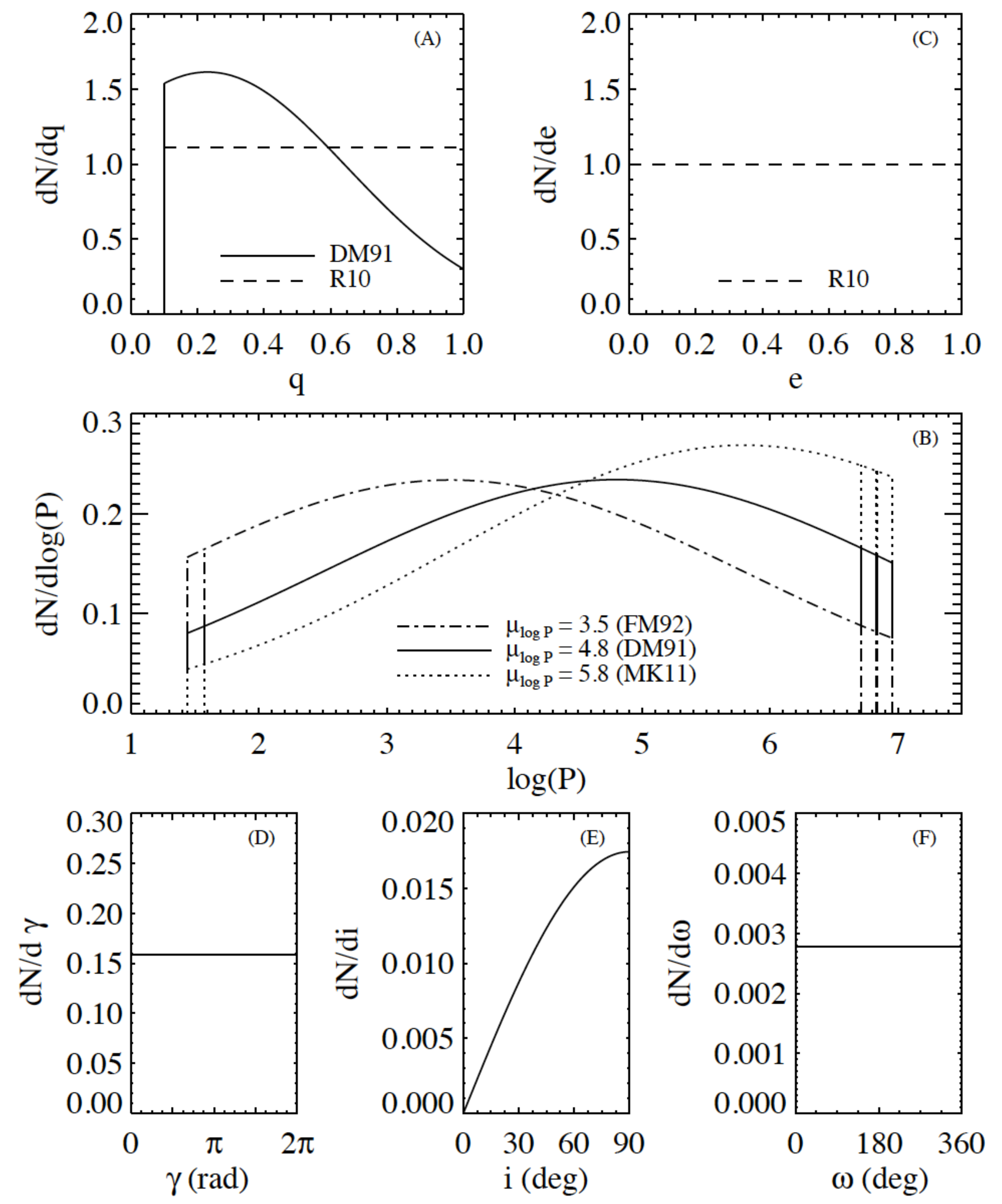


INJECTING BINARIES

M. E. Spencer et al. [1811.06597]

$$v_{r,orb} = \frac{q \sin i}{\sqrt{1-e^2}} \left(\frac{2\pi G m_1}{P(1+q)^2} \right)^{1/3} \big(\cos(\theta + \omega) + e \cos \omega \big). \quad (2)$$

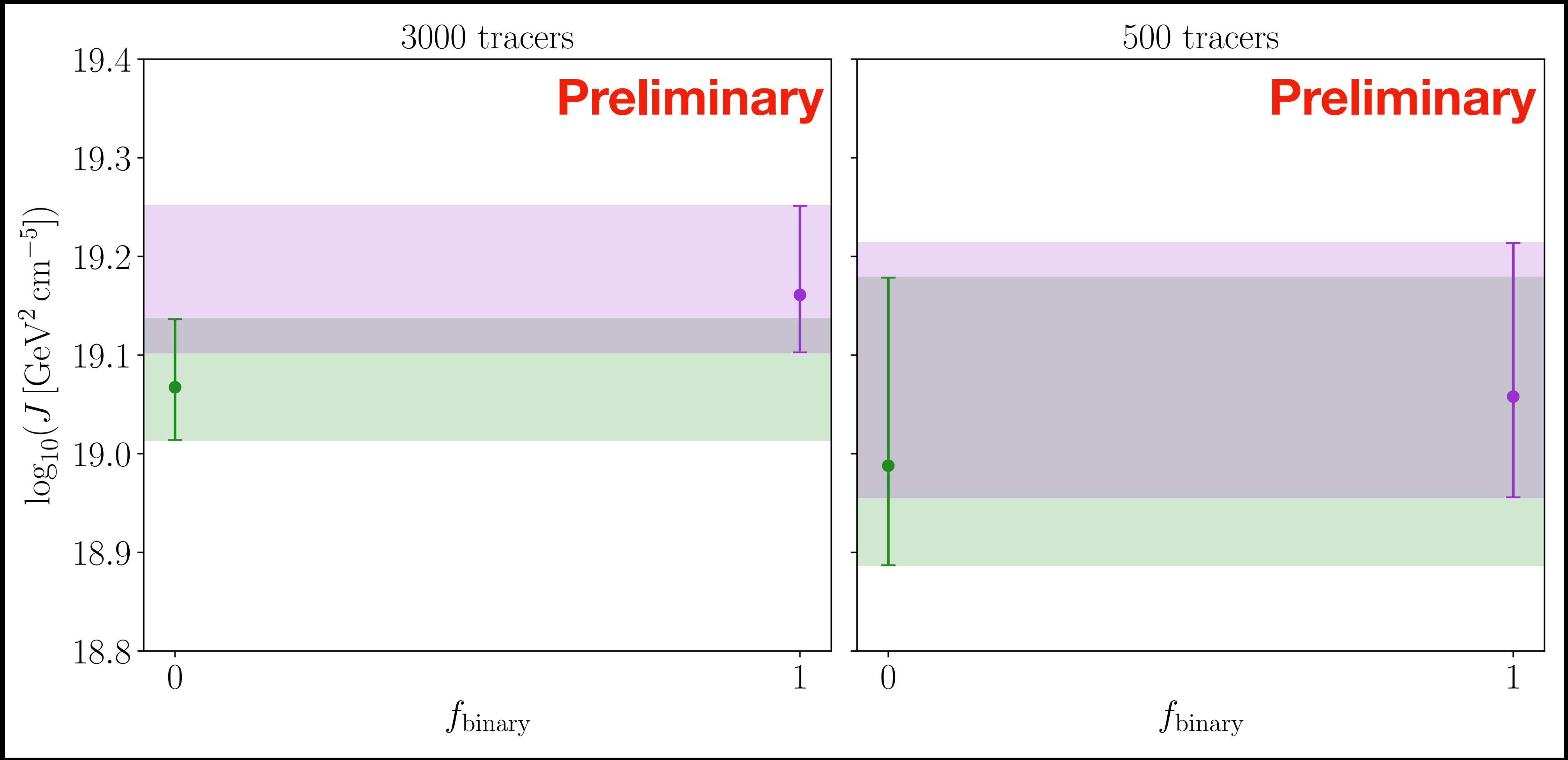


As a starting point:

Model and code for modeling binary motion from Spencer+ 2018

(If you have a favorite binary model we should try, please let us know!)

EFFECT OF UNMODELED BINARIES ON J-FACTORS



N_{tracers}	f_{binary}	$\log_{10}\left(M(<R_{1/2})/M_\odot\right)$	$\log_{10}\left(M(<R_{\mathrm{max}})/M_\odot\right)$	$\log_{10}\left(J/\left(\mathrm{GeV}^2\,\mathrm{cm}^{-5}\right)\right)$
3000	0	$7.32^{+0.02}_{-0.02}$	$9.14^{+0.25}_{-0.26}$	$19.07^{+0.07}_{-0.05}$
3000	1	$7.38^{+0.17}_{-0.19}$	$9.19^{+0.23}_{-0.20}$	$19.16^{+0.09}_{-0.06}$
500	0	$7.25^{+0.04}_{-0.05}$	$8.81^{+0.18}_{-0.17}$	$18.99^{+0.19}_{-0.10}$
500	1	$7.30^{+0.04}_{-0.04}$	$8.76^{+0.21}_{-0.18}$	$19.06^{+0.16}_{-0.10}$

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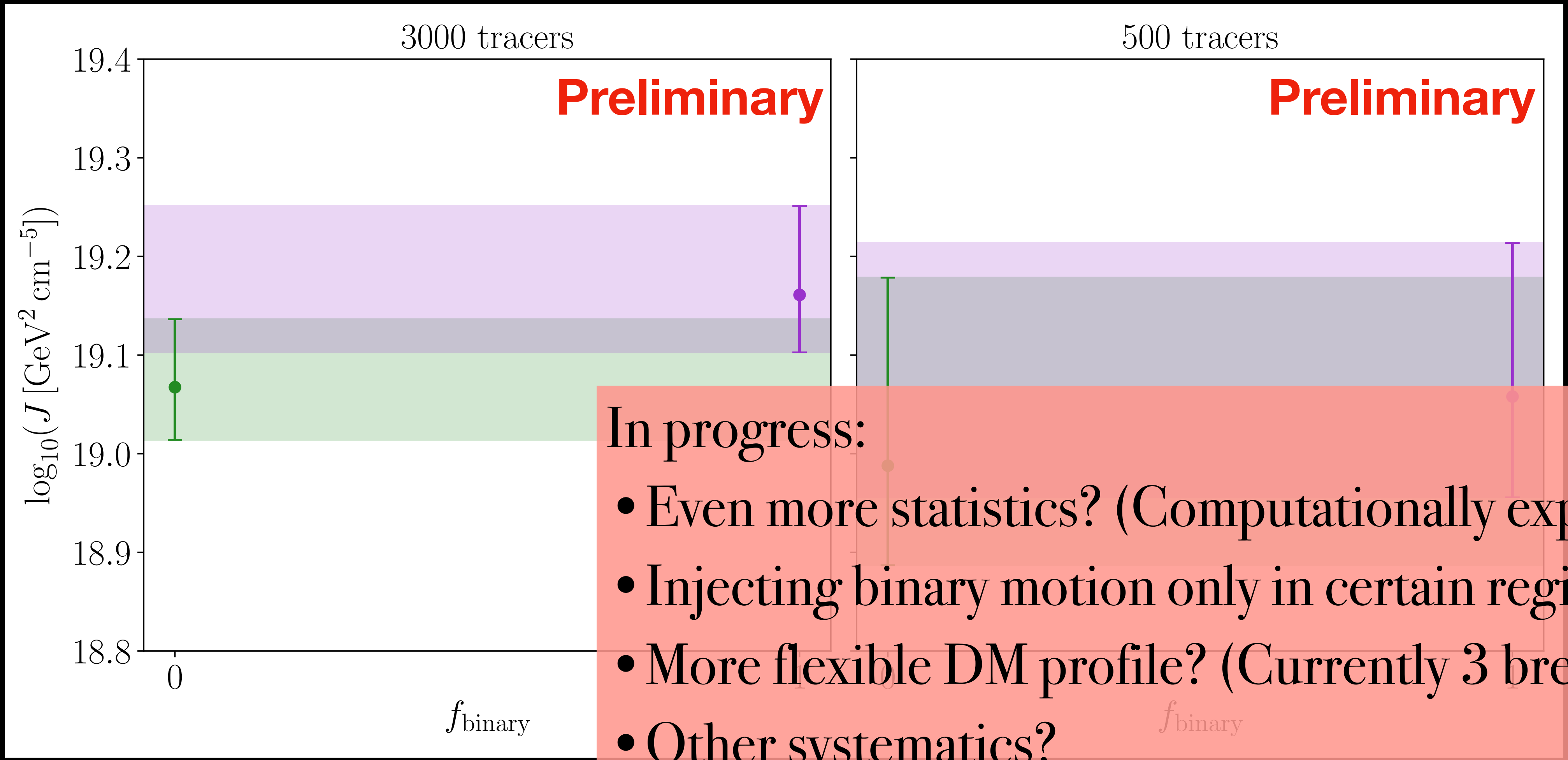

In progress:

- Even more statistics? (Computationally expensive)
- Injecting binary motion only in certain regions
- More flexible DM profile? (Currently 3 breaks)
- Other systematics?

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CONCLUSIONS & EXTENSIONS

- In very simple examples on mock data, the presence of unmodeled binaries can bias estimates of dwarf galaxy J-factors ⇒ bias dark matter constraints derived
- Effect of binaries becomes more drastic with increased statistics
  - With more stars measured and more accurate measurements, will this become a more measurable effect? J. D. Simon et al. [1903.04743]
  - With future multi-epoch binary measurements, could exclude confirmed binaries from analysis
- Statistical uncertainties in dwarf galaxy dark matter constraints need to be better understood and characterized
- Other important systematics: tidal disruption, deviations from equilibrium, non-sphericity, …

PAUL & DAISY SOROS FELLOWSHIPS FOR NEW AMERICANS
NSF

BACKUP SLIDES

INDIRECT DETECTION BENCHMARK: DWARF GALAXIES

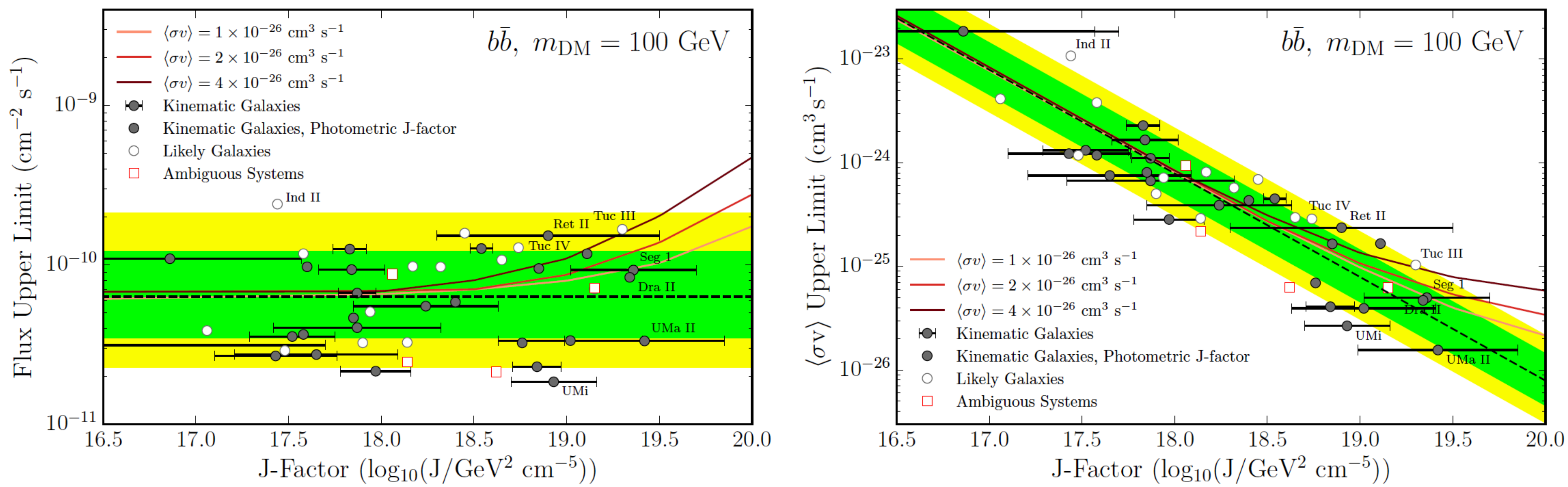

Figure 6. Upper limits on flux (*left*) and cross section (*right*) versus J-factor. The points represent J-factors for each target estimated either from spectroscopy (filled circles with error bars) or from the scaling relation discussed in Section 4 (filled circles). The green and yellow shaded regions are the 68% and 95% containment regions for the blank-sky expectations, respectively. For comparison, the three solid lines show the median expected upper limits for DM annihilation with the given cross section. No significant deviation from the background-only expectation is observed.

INFERRING DWARF GALAXY J-FACTORS

$$\frac{1}{\nu}\frac{\mathrm{d}}{\mathrm{d}r}(\nu\bar{v}_r^{\,2}) + 2\frac{\beta_{\mathrm{ani}}\bar{v}_r^{\,2}}{r} = -\frac{GM(r)}{r^2}$$

3d radial velocity dispersion

velocity anisotropy

$$M(r) \approx 4\pi\int_0^r \rho_{\mathrm{DM}}(r')\, r'^2 \mathrm{d}r'$$

INFERRING DWARF GALAXY J-FACTORS

Spherical Jeans equation

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- $\bar{v}_r^{\,2}$: 3d radial velocity dispersion
- β_{ani}: velocity anisotropy
- $M(r) \approx 4\pi\int_0^r \rho_{\mathrm{DM}}(r')\, r'^2 \mathrm{d}r'$

In practice, observe line-of-sight projected quantities

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

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- $\bar{v}_r^{\,2}$ → 3d radial velocity dispersion
- $\beta_{\rm ani}$ → velocity anisotropy
- $M(r)$ → $M(r) \approx 4\pi\int_0^r \rho_{\rm DM}(r')\, r'^2 \mathrm{d}r'$

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- $\sigma_p^2(R)$ → projected velocity dispersion
- $\Sigma(R)$ → 2d stellar density ("light profile")

FIDUCIAL SETUP

- Nested Plummer light profile

J.I. Read and P. Steger [1701.04833]

$$\nu(r) = \sum_{i=1}^{N_p} \frac{3M_i}{4\pi a_i^3} \times \left(1 + \frac{r^2}{a_i^2}\right)^{-5/2} \xleftrightarrow{\text{Abel transform}} \Sigma(R) = \sum_{i=1}^{N_p} \frac{M_i a_i^2}{\pi(a_i^2 + R^2)^2}$$

- Broken power law DM profile: analytic formula for enclosed DM mass

$$\rho(r) = \begin{cases} \rho_0 \left(\frac{r}{r_0}\right)^{-\gamma_0} & r < r_0 \\ \rho_0 \left(\frac{r}{r_j}\right)^{-\gamma_{j+1}} \prod_{n=1}^{j} \left(\frac{r_n}{r_{n-1}}\right)^{-\gamma_n} & r_j < r < r_{j+1} \end{cases}$$

DM profile can span cusped ↔ cored

- Gaia challenge spherical mocks:
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Analytic formulas for 2d/3d stellar density and enclosed DM mass profiles → more computationally tractable

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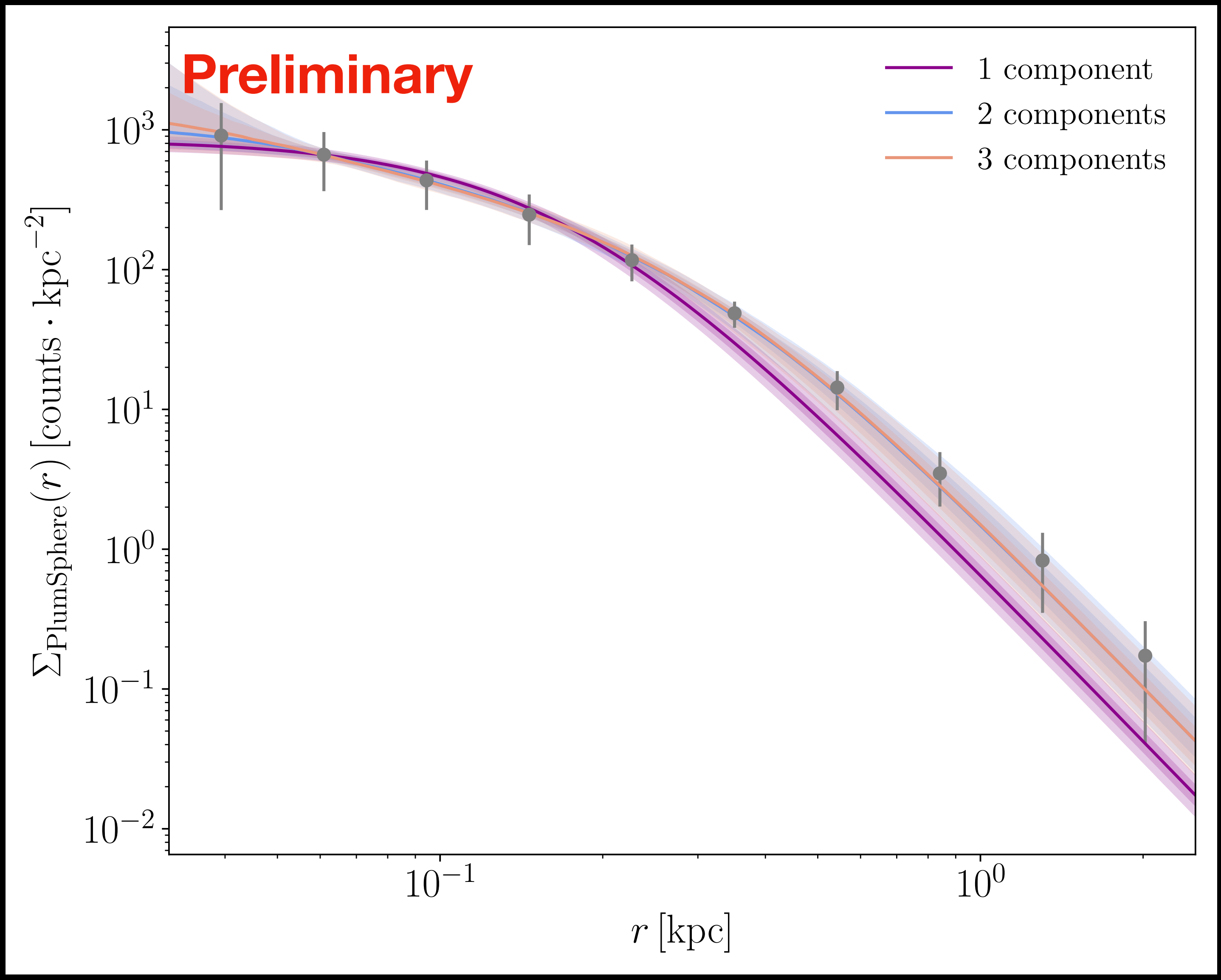
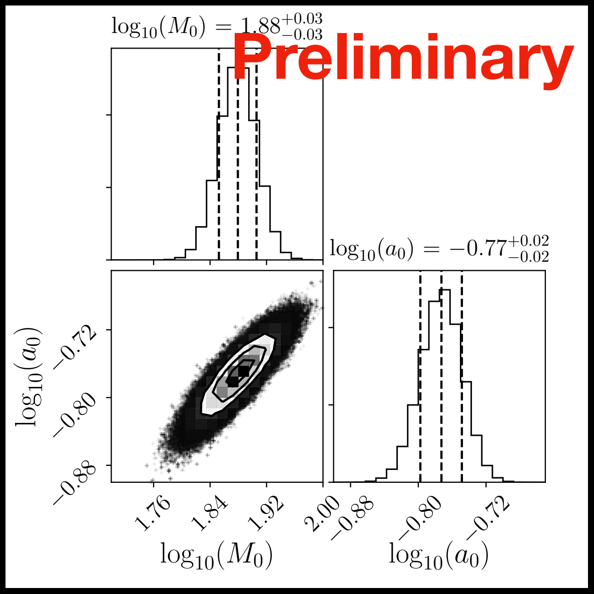
100 stars





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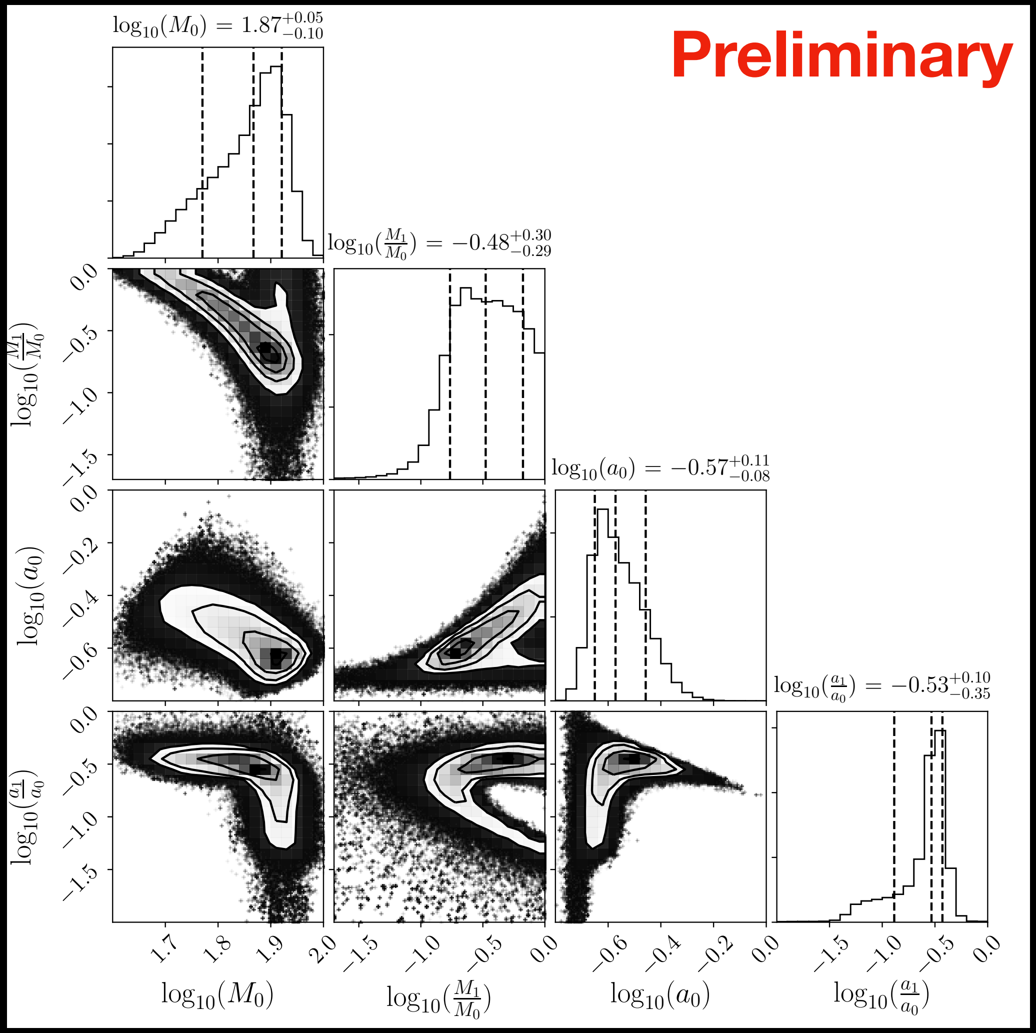
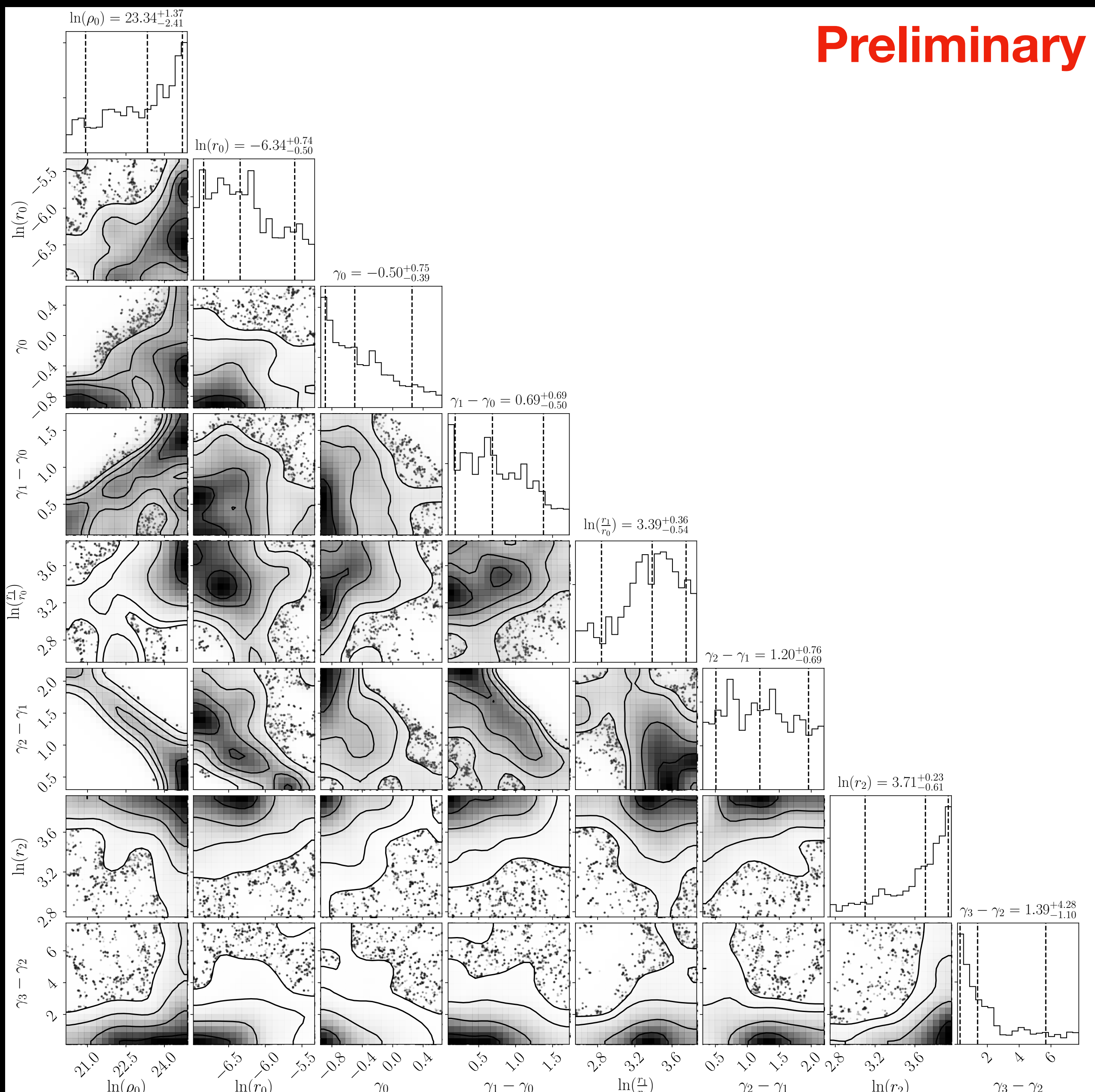
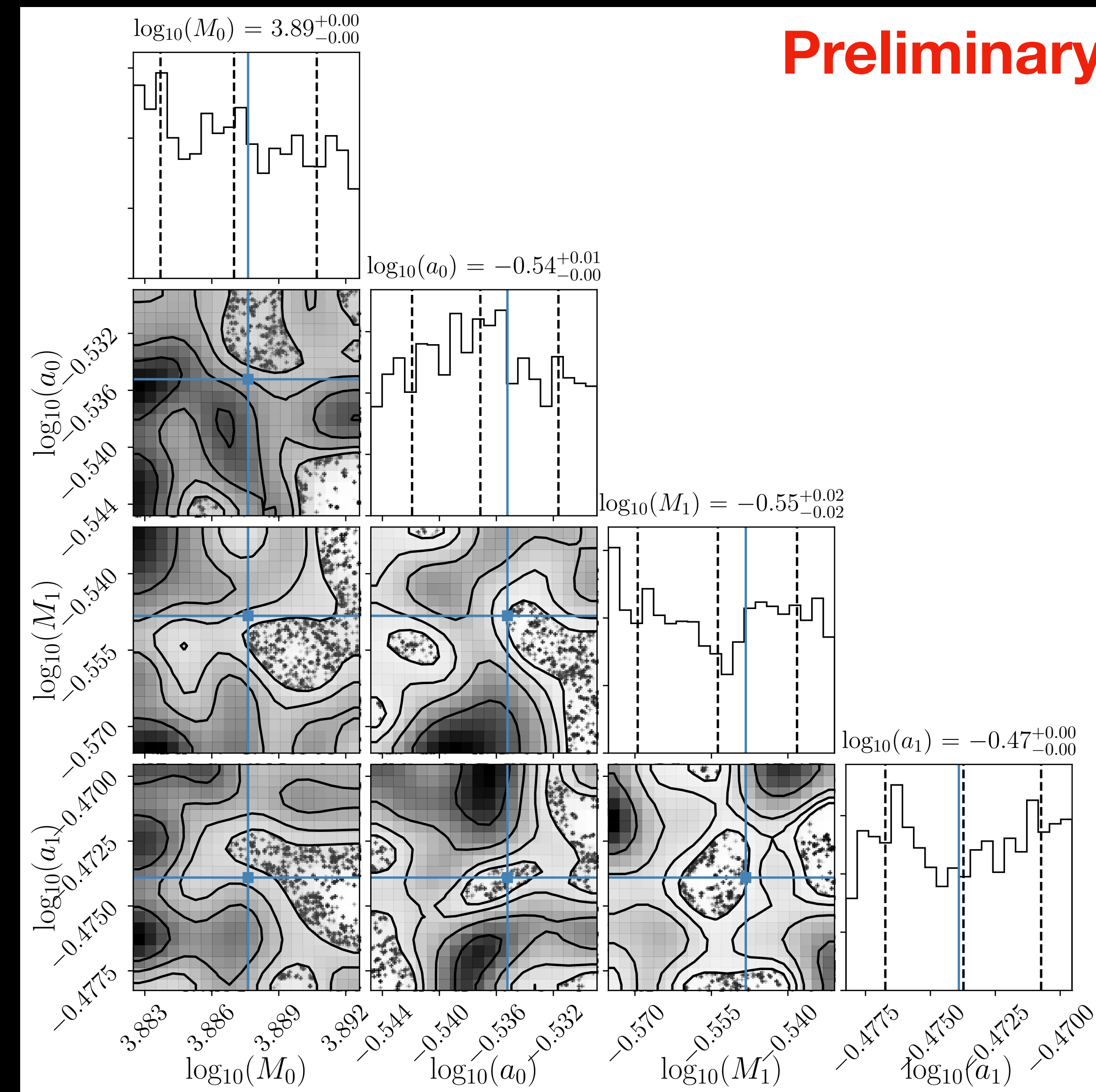
2 Plummer components



STEP 2: VELOCITY DISPERSION FIT

3000 stars





STEP 2: VELOCITY DISPERSION FIT

500 stars