Search for dark matter in 10 years of Fermi-LAT data with the DMcat pipeline

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On behalf of the Fermi-LAT Collaboration

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Fermi Gamma-ray Space Telescope

DMcat project

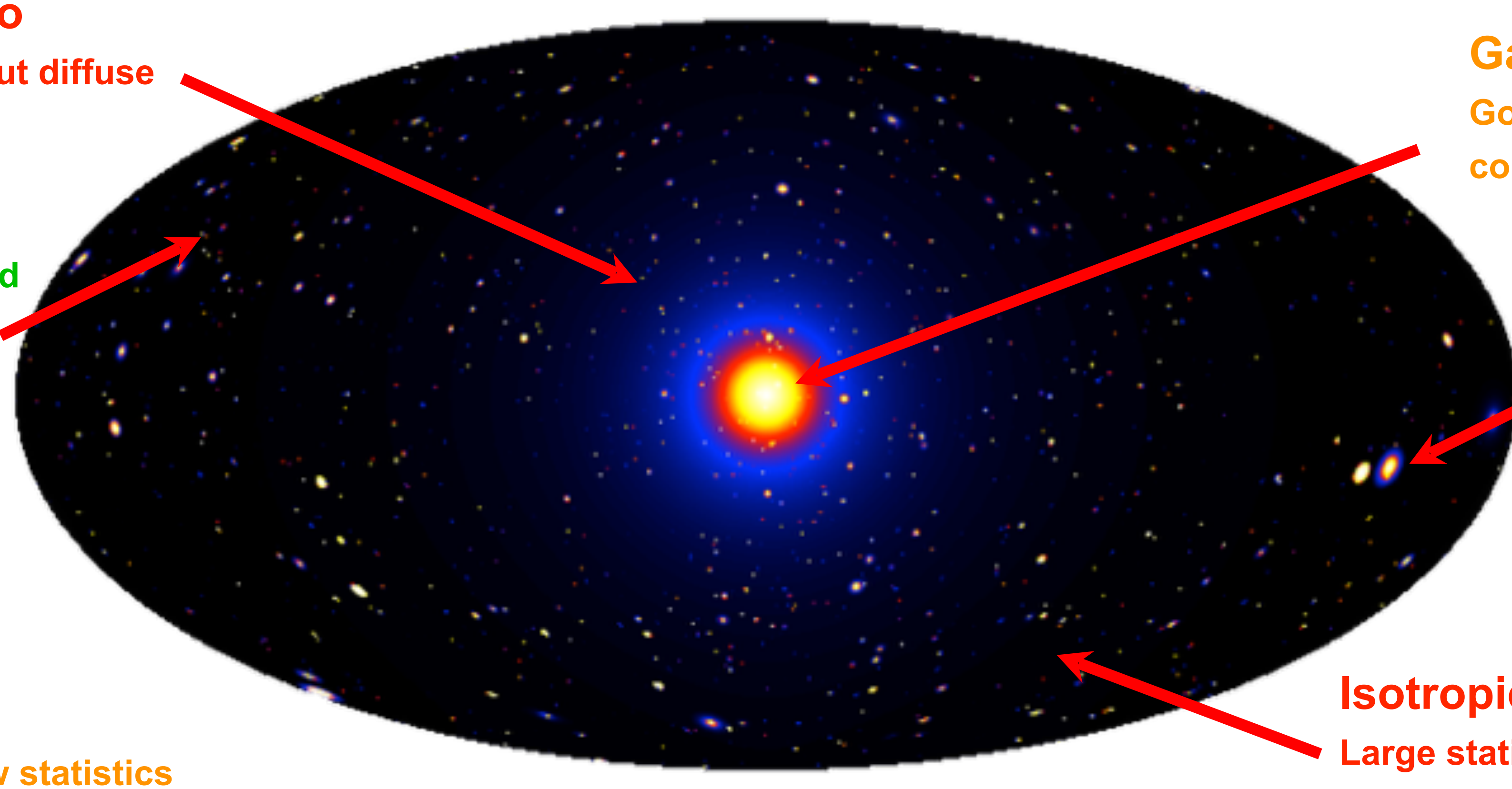
- **DMcat project**: perform a combined search for Dark Matter (DM) from multiple targets.
- We plan to release the results in a format that can be used by the community to perform their own DM searches.

Milky Way Halo
Large statistics, but diffuse background

Satellite galaxies
Low background and good source id, but low statistics

Unassociated sources

Galaxy Clusters
Low background, but low statistics



Galactic Center
Good statistics, but source confusion/diffuse background

Nearby Galaxies
Good statistics, diffuse background

Isotropic contributions
Large statistics, but astrophysics, Galactic diffuse background

Spectral Lines
Little or no astrophysical uncertainties, good source id, but low sensitivity because of expected small branching ratio

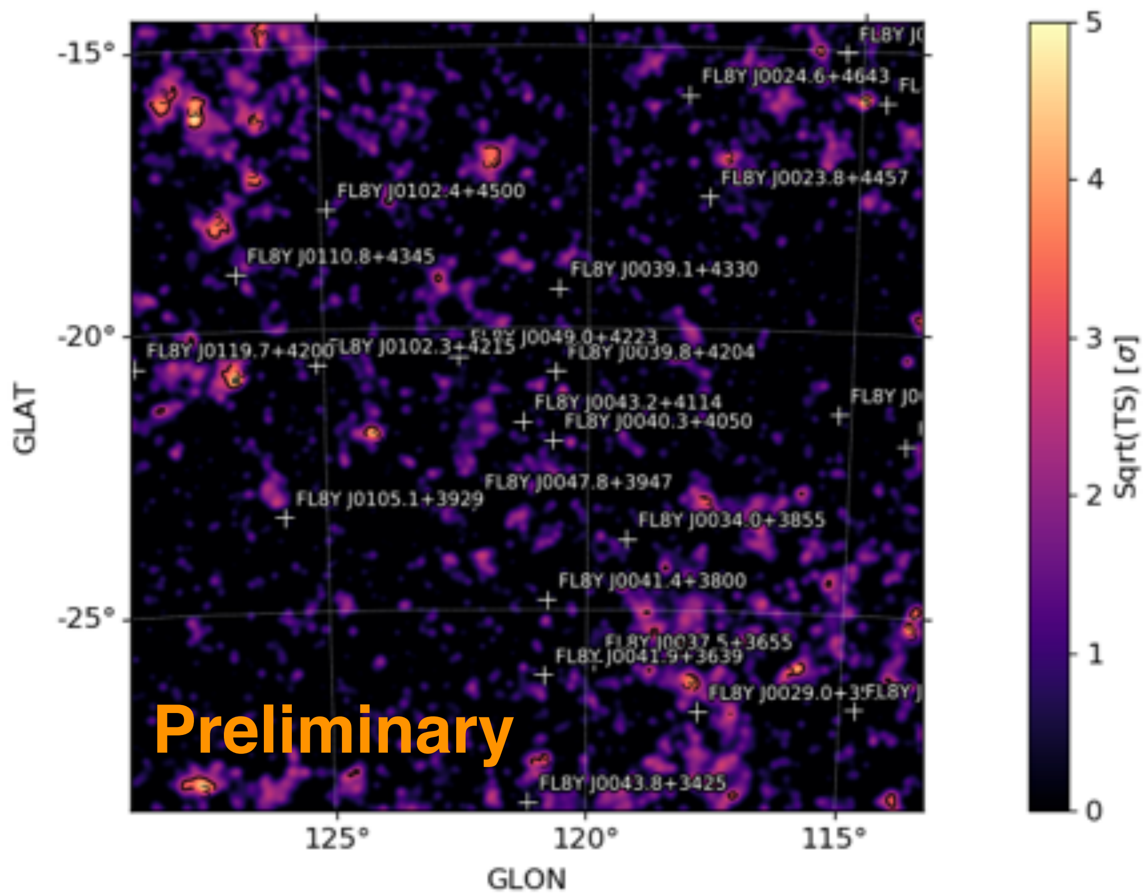
Targets already implemented

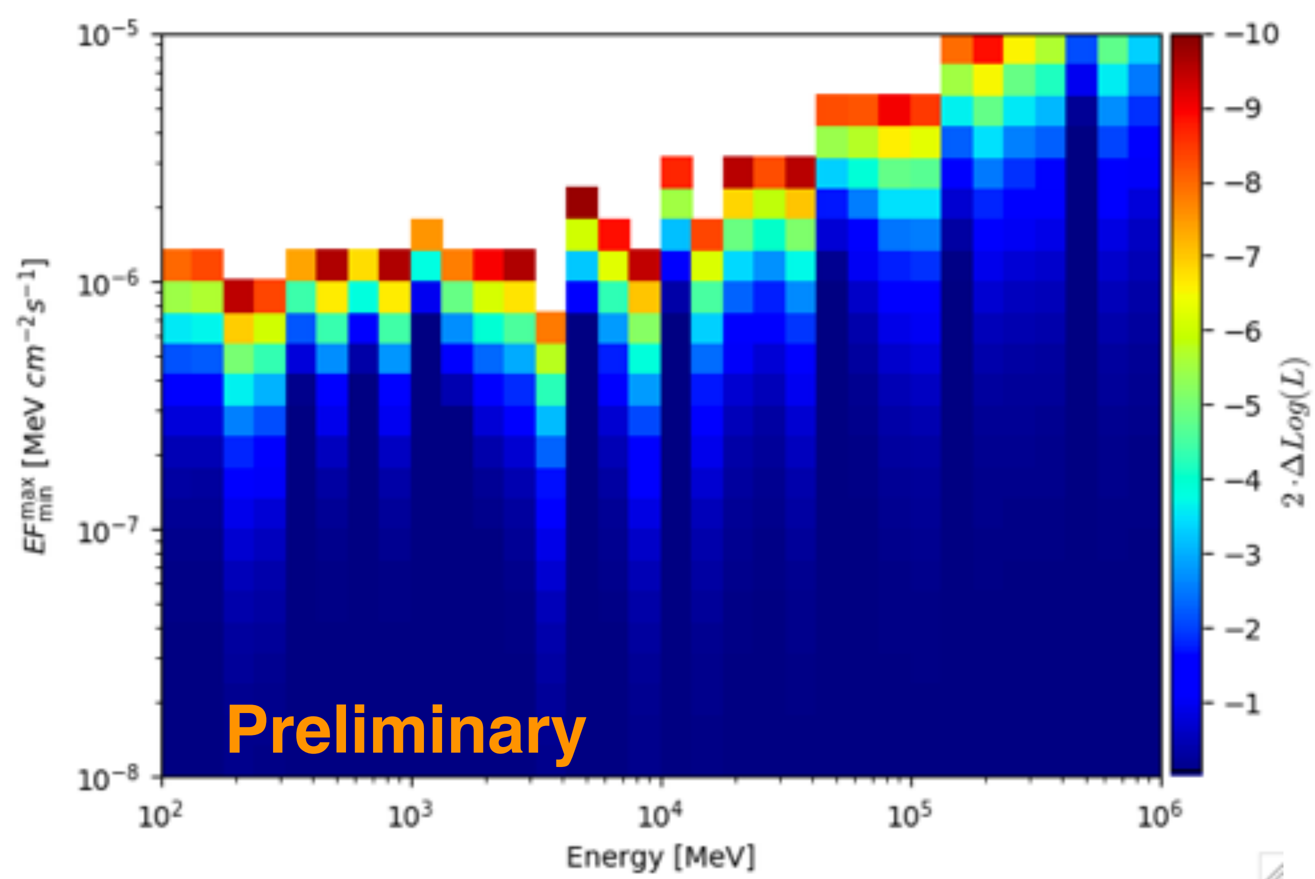
Targets will be considered in the future

Targets we will probably not consider

Analysis setup and pipeline (M31)

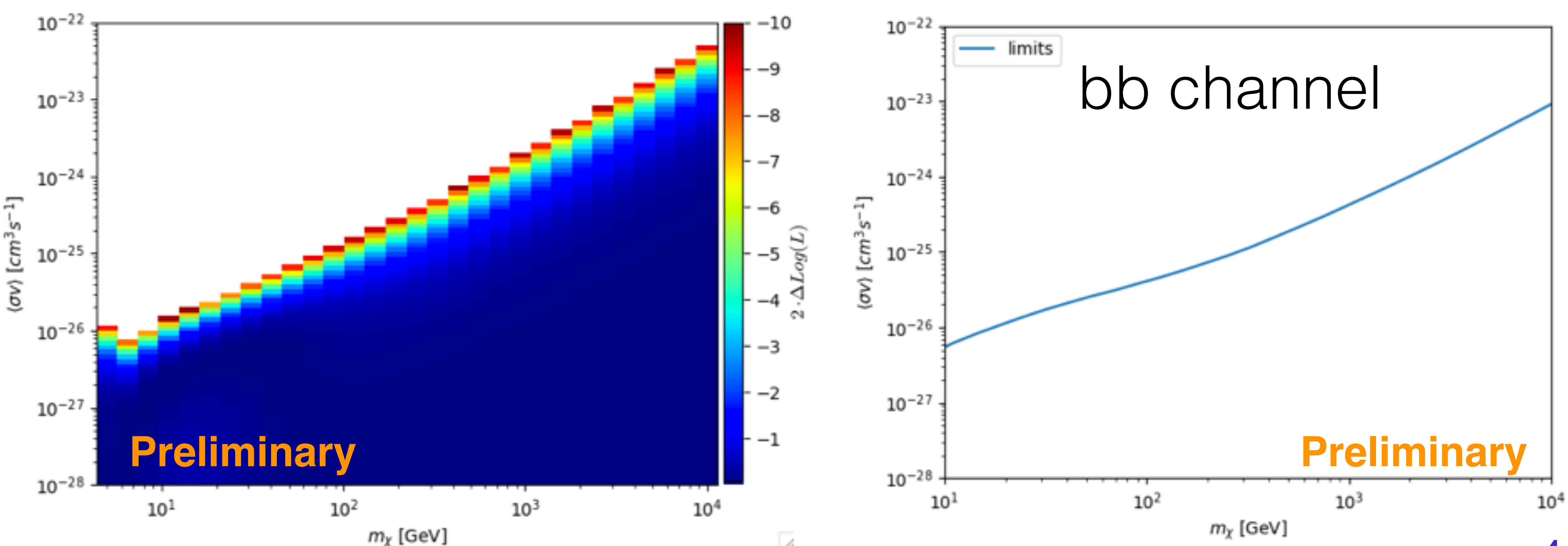
- Analysis setup: 115 months of LAT Pass 8 data, E=[0.1,1000] GeV, FL8Y source catalog.
- Analysis pipeline:
  - Fit to the roi.
  - Sources in the model are relocalized.
  - New sources with TS>25 are searched.
  - The SED of the target with DM template is calculated (castro plot).





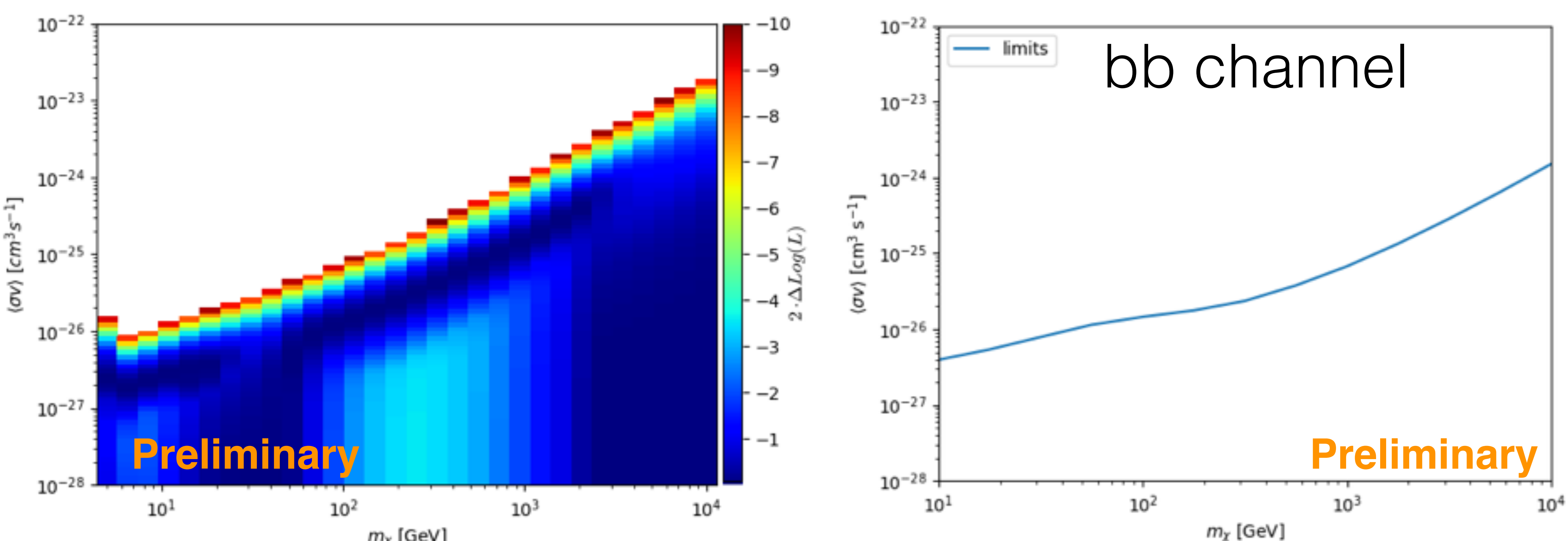
Castro plot in DM space (M31)

- The castro plot in SED space is converted into the castro plot in DM space (M_{DM},<σv>).
- This is performed with a particular value and prior for J and for a given DM channel.
- From the castro plot in DM space the limits for the cross section are calculated.



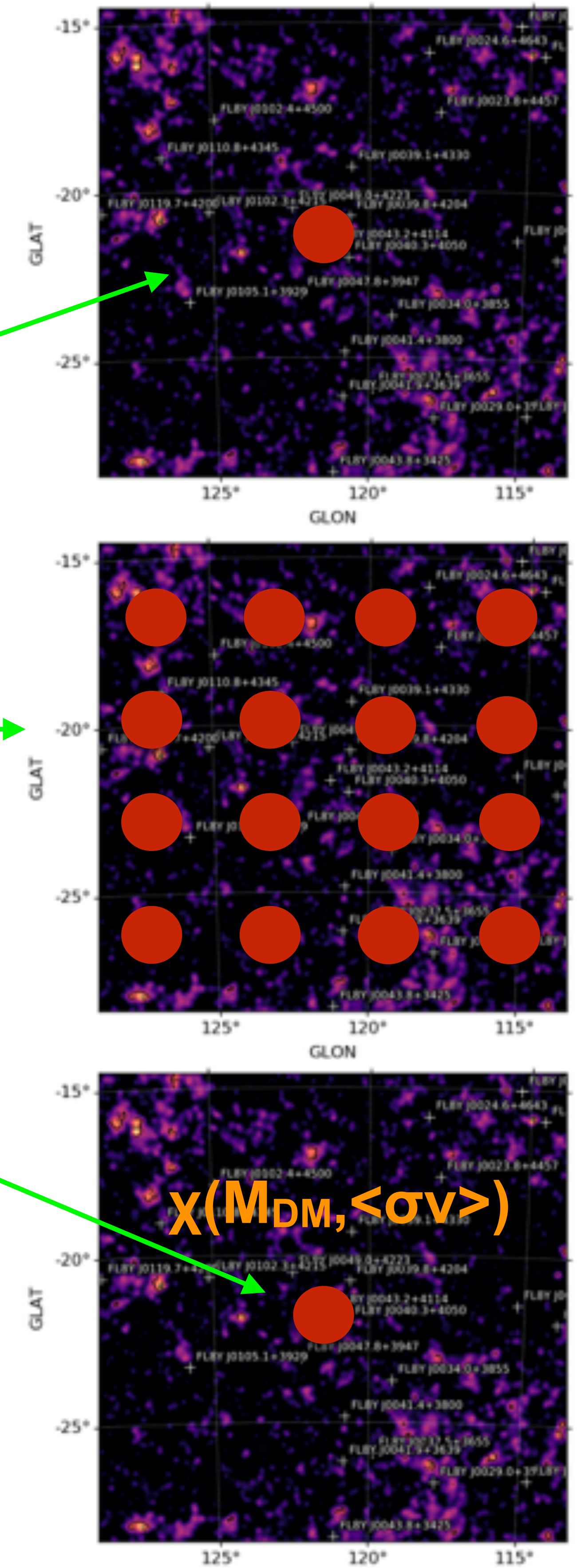
Stacking the limits for a list of targets

- The pipeline runs for each target.
- Then the likelihood profiles are stacked together to create the stacked castro plots.
- Finally, the stacked castro plots are converted into upper limits for <σv>.
- The example below is for the dSphs considered in our analysis.



Simulations

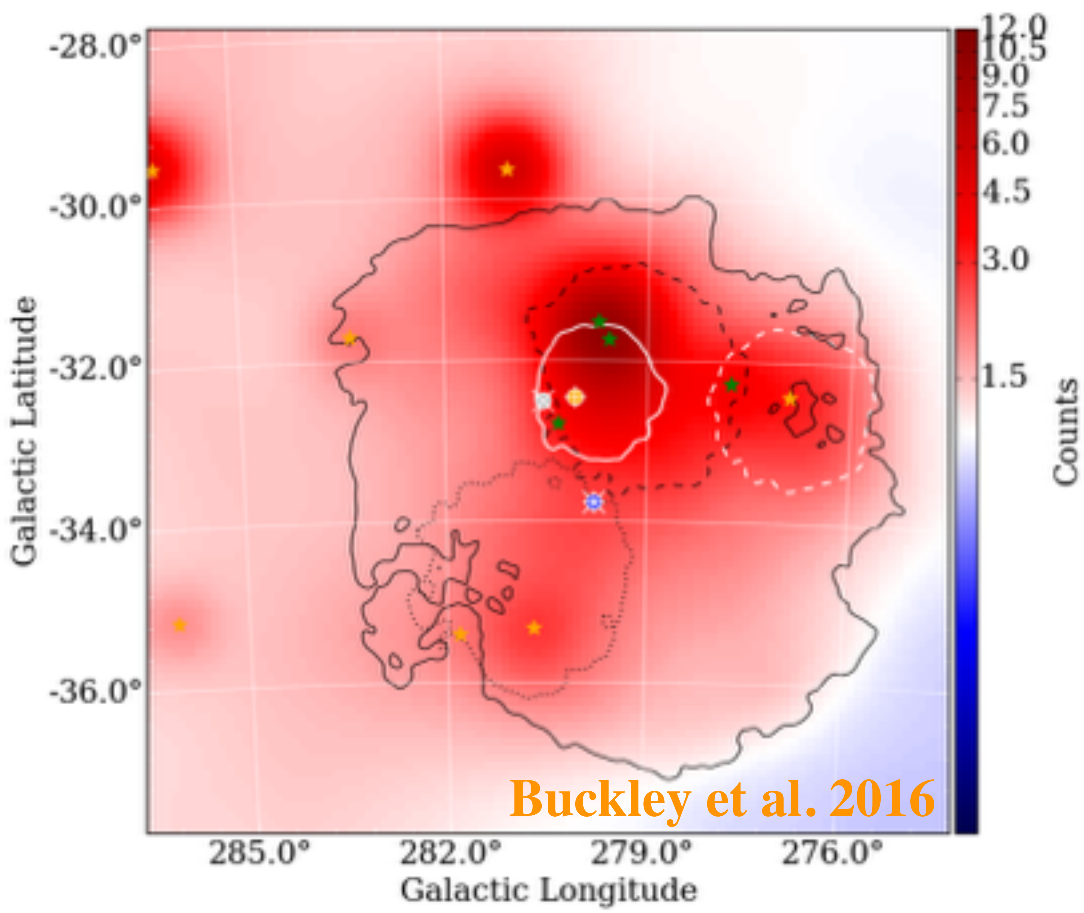
- It is also possible to perform simulations for the null signal or with an injected signal.
  - **sim_null**: no sources at the location of the targets
  - **sim_random**: searches for gamma-ray emission at different directions in the target ROIs.
  - **sim_injected**: signal of DM emission with a given M_{DM} and $<\sigma v>$.
- In the pipeline it is possible to chose different J profiles and priors to run the simulations with.

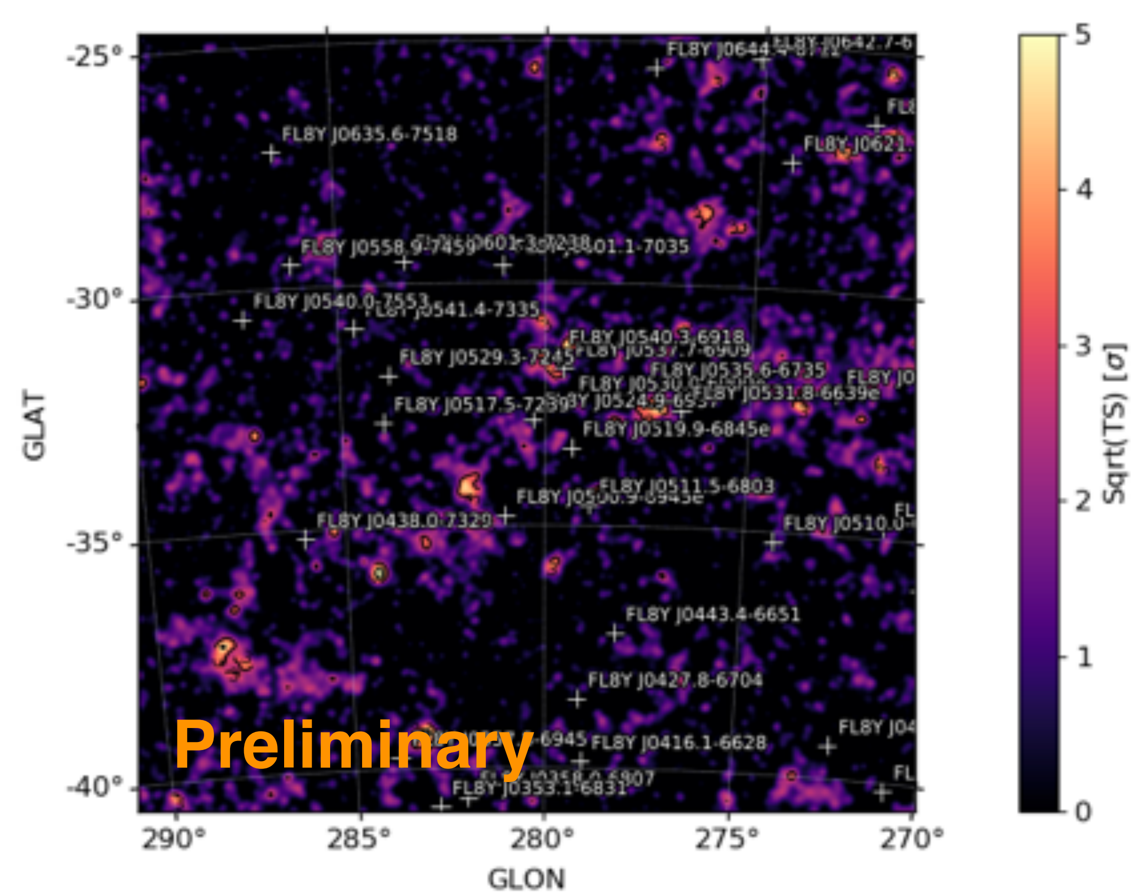


Large Magellanic cloud

- The LMC is at a distance of 50 kpc and has a DM mass of $\sim 10^{10}\,M_\odot$.
- The astrophysical background is calculated using the FL8Y model for LMC.
  - This includes four different templates.
- For the DM profile we used the same model as in Buckley et al. 2016 with $\sigma_{Log10(J)}$=0.20

Profile	α	β	γ	r_S (kpc)	ρ_0 ($M_\odot$/kpc^3)	J (GeV^2/cm^5)	M(8.7 kpc) ($M_\odot$)
nfw-mean	1	3	1	12.6	2.6×10^6	9.4×10^{19}	7.7×10^9

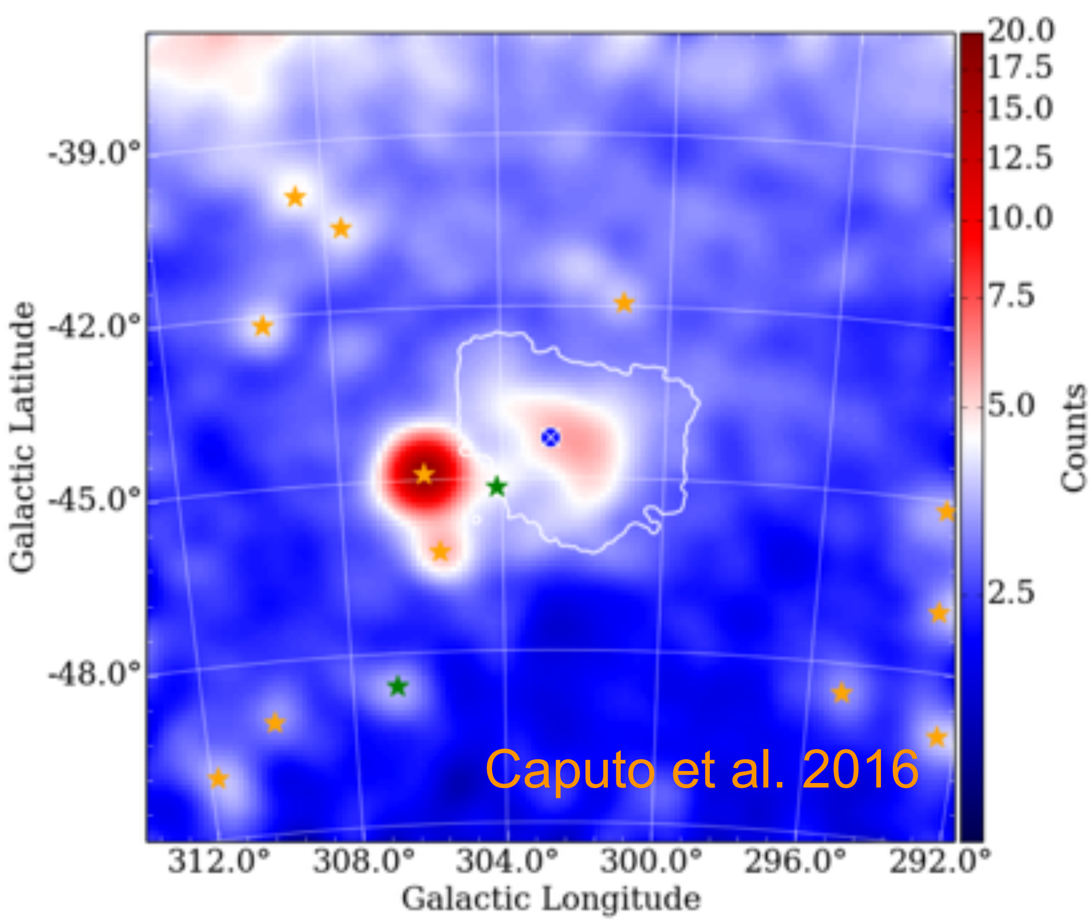


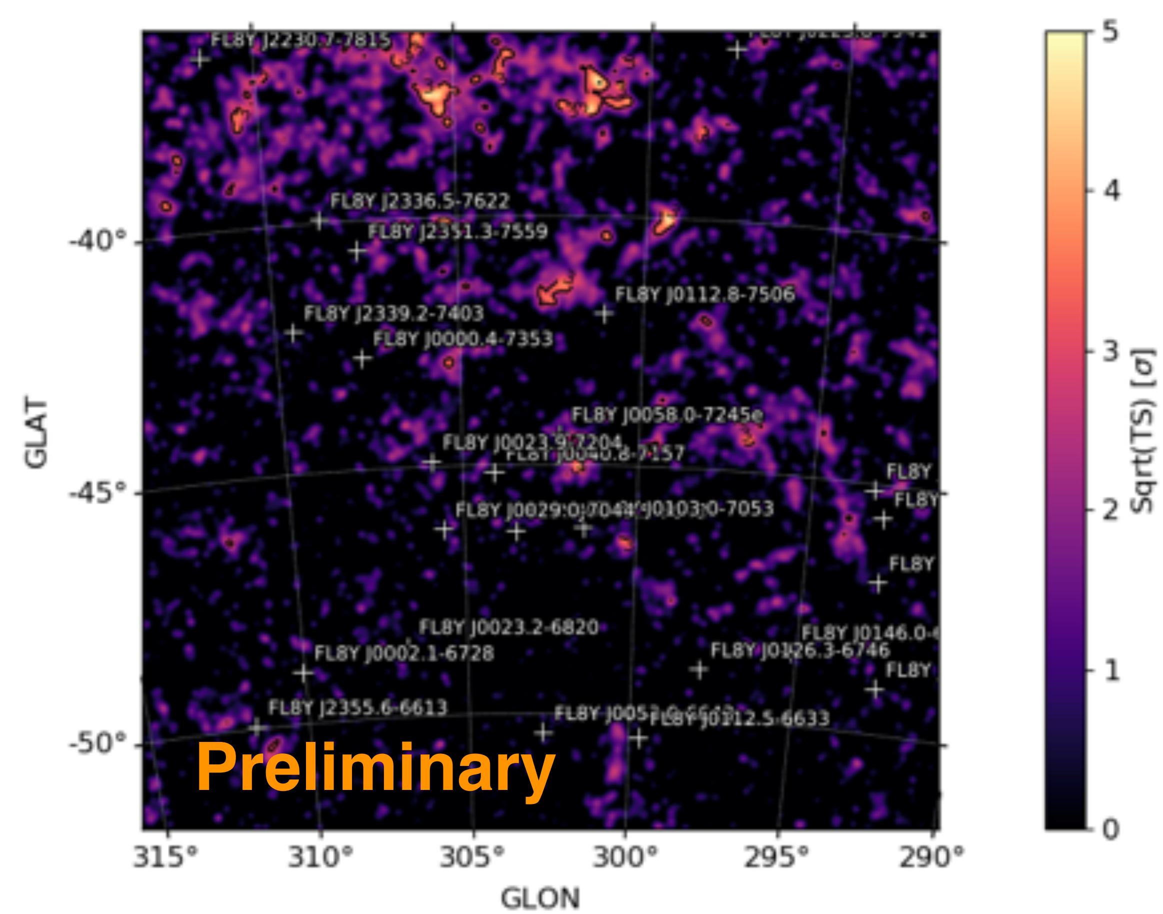


Small Magellanic cloud

- The SMC is the second-largest satellite galaxy of the Milky Way and is only 60 kpc away. The mass of DM that it contains is of ~10^{10} $M_\odot$.
- For the astrophysical background we am using the FL8Y SMC template.
- For the DM profile we used the same model as in Caputo et al. 2016 with $\sigma_{Log10(J)}$=0.20.

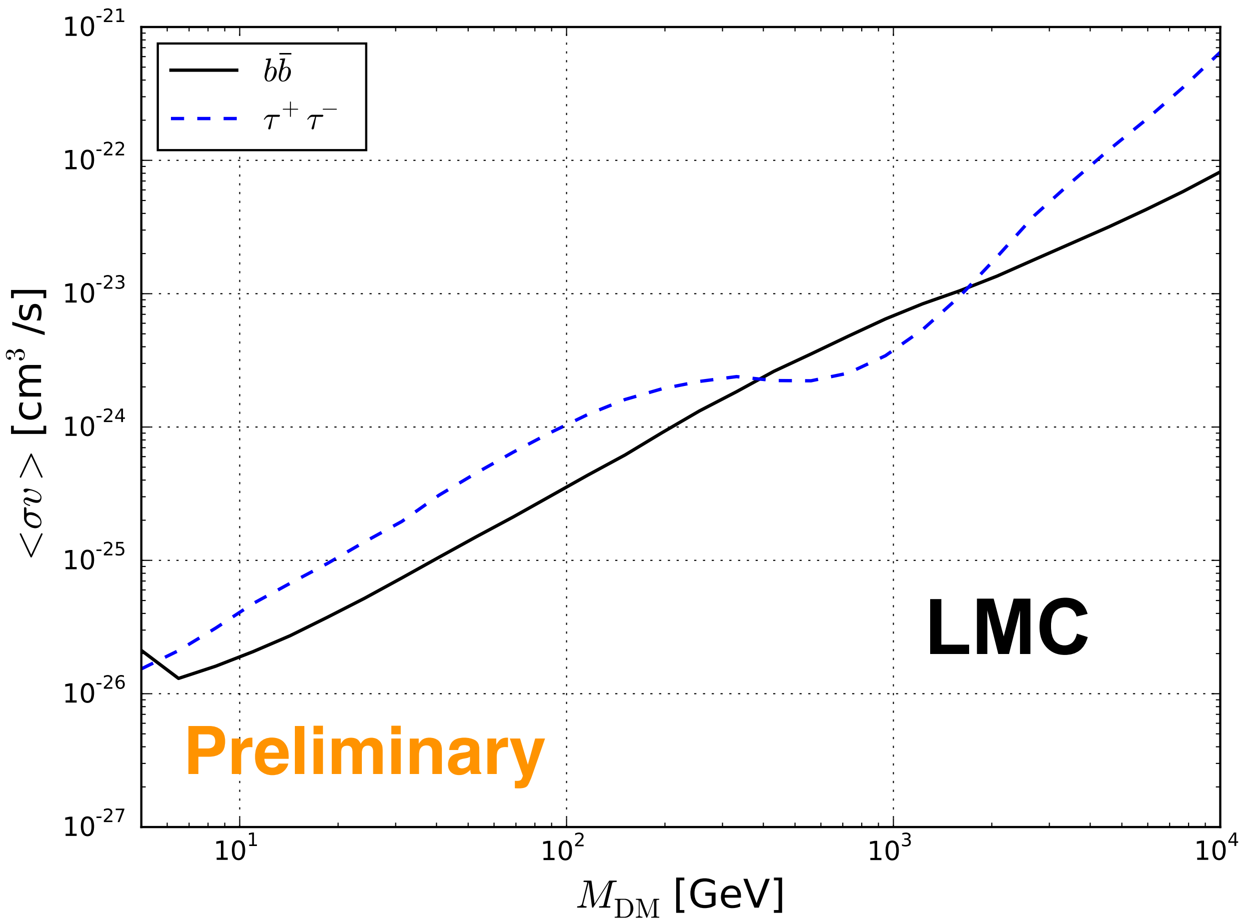
Profile	α	β	γ	r_S (kpc)	ρ_0 ($M_\odot$/kpc^3)	J (GeV^2/cm^5)
NFW	1	3	1	5.1	4.1×10^6	$1.13 \pm 0.01 \times 10^{19}$

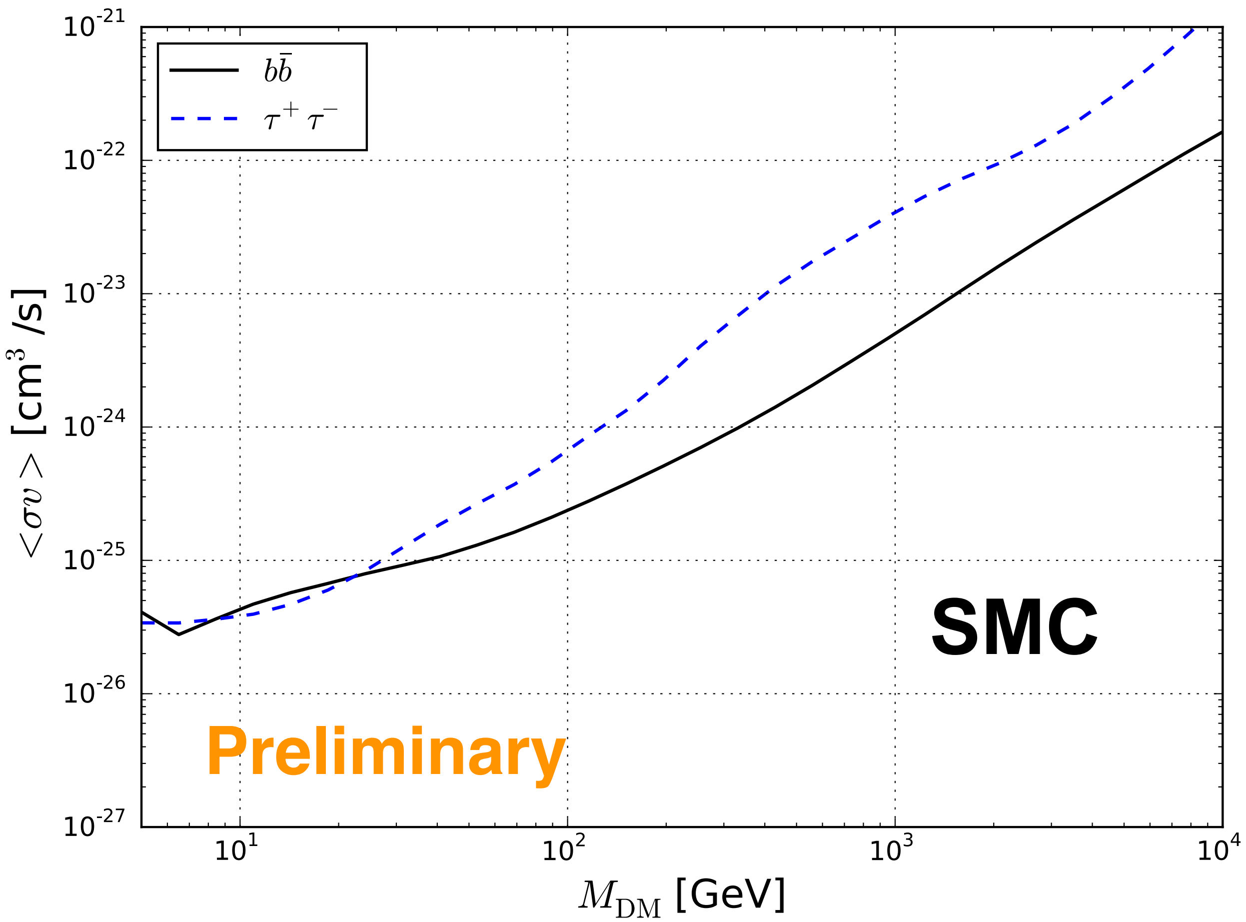




DM limits for LMC and SMC

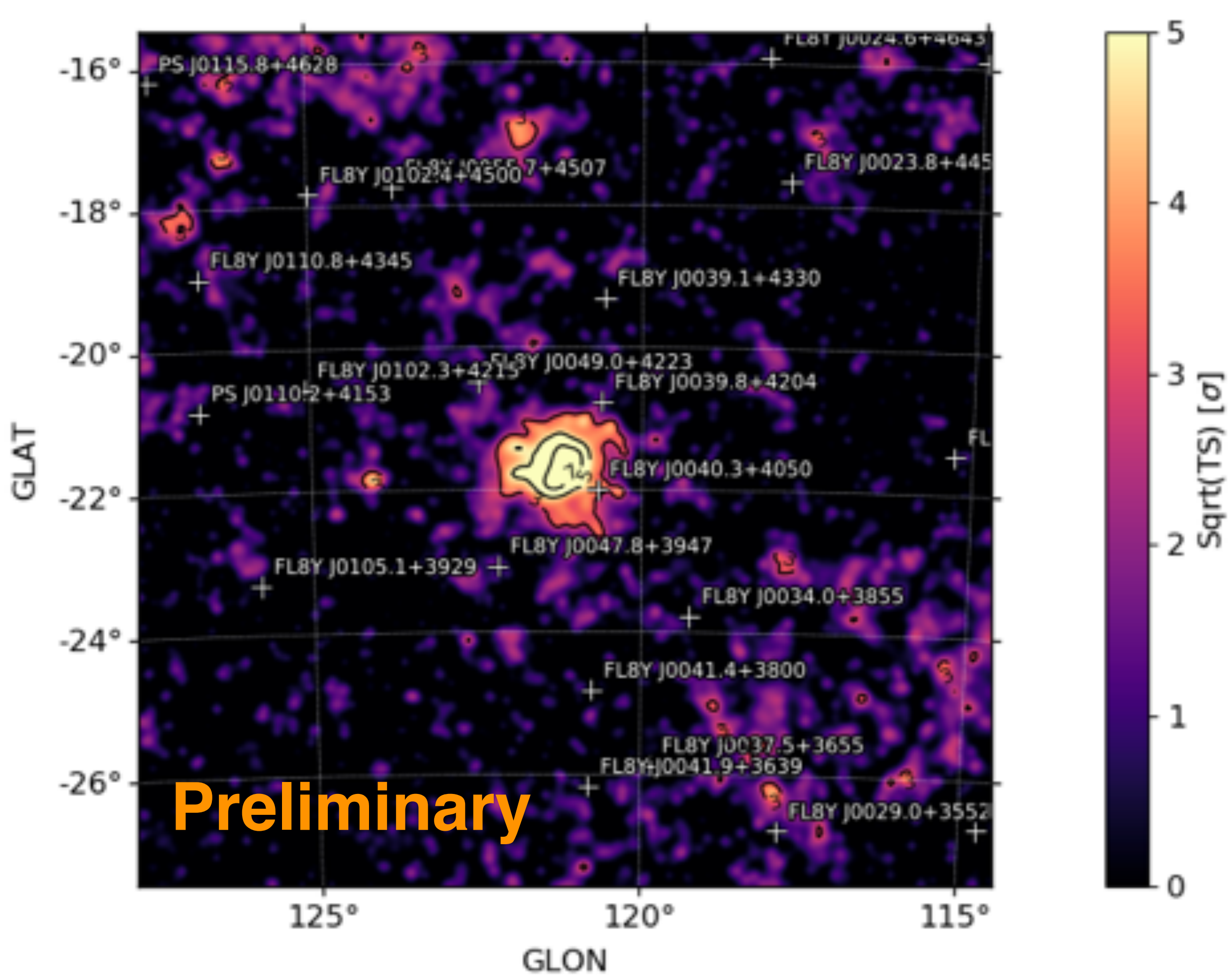
- We considered radial, map and point like DM spatial distributions.
- The limits are similar to one presented in Buckley et al. 2016 for the LMC and Caputo et al. 2016 for the SMC.
- TS for the presence of DM is **7 (0)** for LMC (SMC).

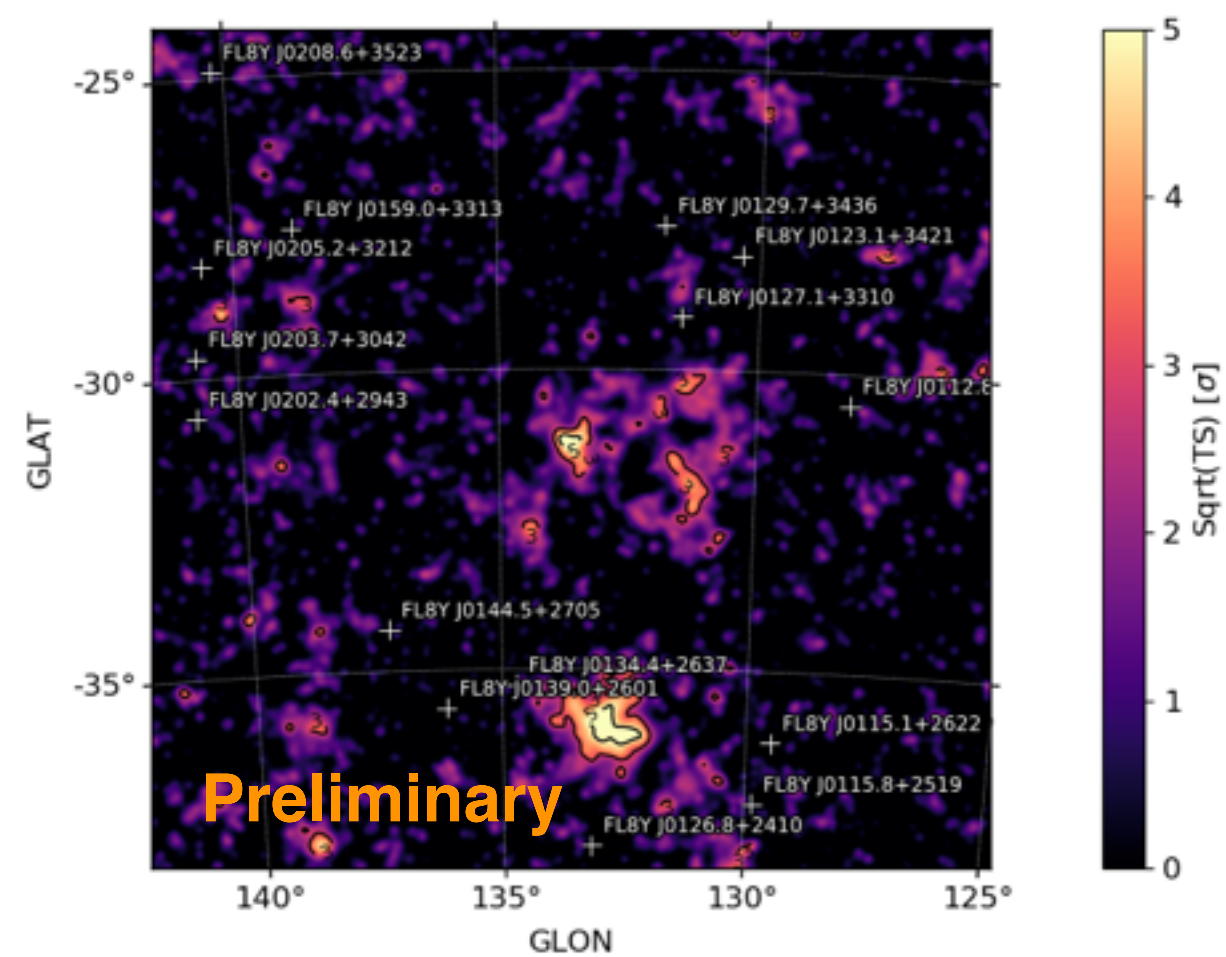




Andromeda and Triangulum Galaxies

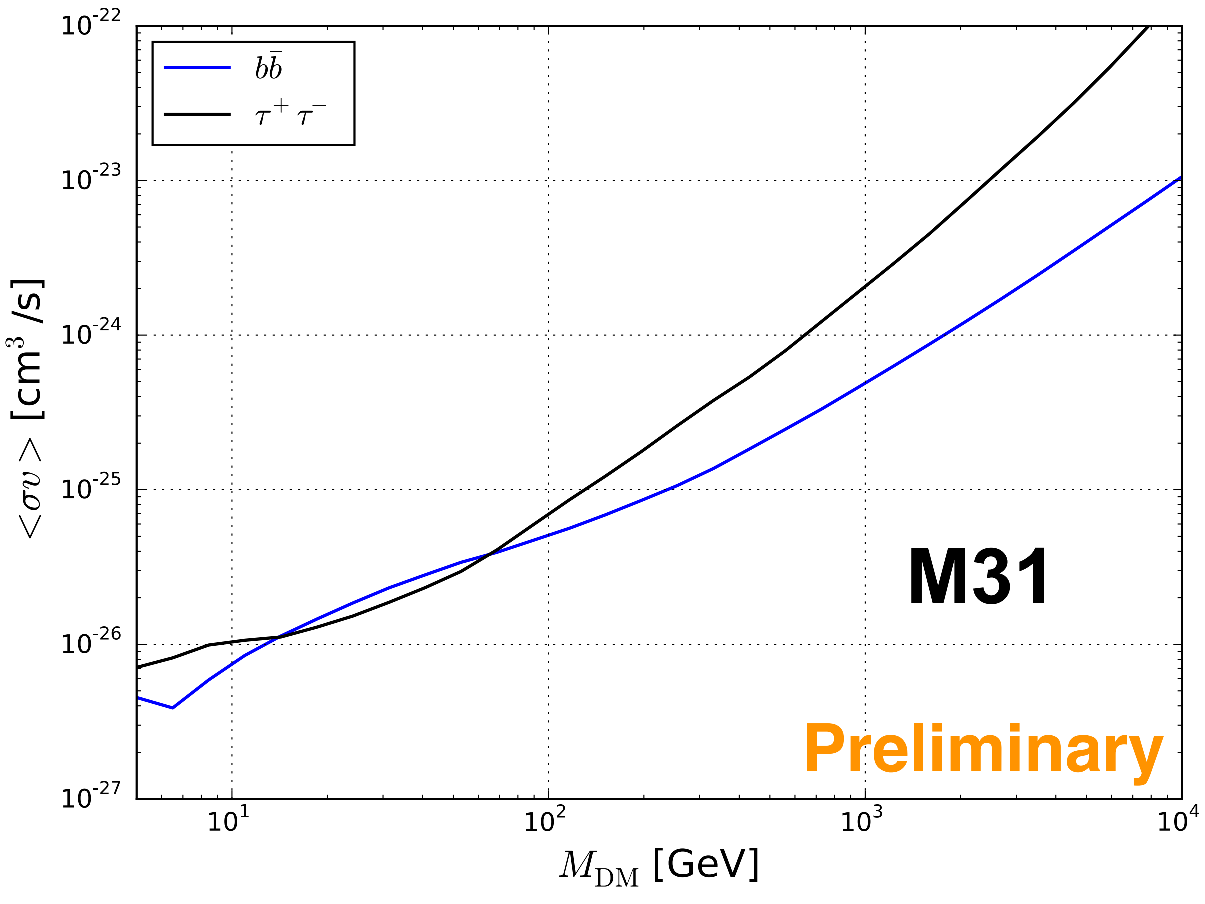
- M31 and M33 are among the closest galaxies with a DM mass of $\sim10^{12}$ and $\sim4\ 10^{11}\ M_{\odot}$.
- For the astrophysical background of the sources I am using an extended source for M31 0.30deg extended (TS_{ext}=16) and a point like source for M33.
- The DM profile is taken as the MED model in Albert et al. 2018 for M31 and Corbelli et al. 2014 and Fune et al. 2017 for M33, with $\sigma_{Log10(J)}$=0.20 for both.

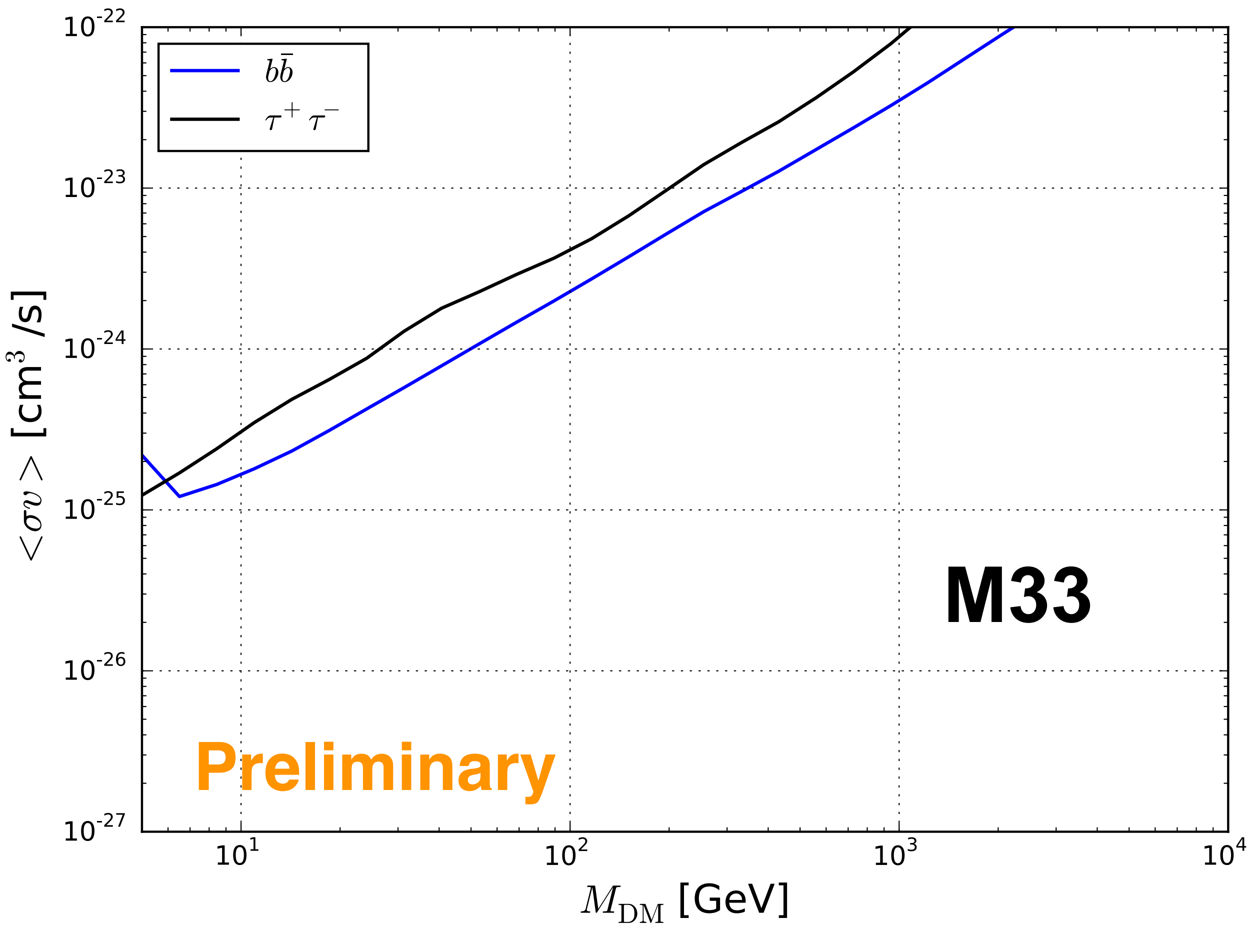




DM limits for M31 and M33

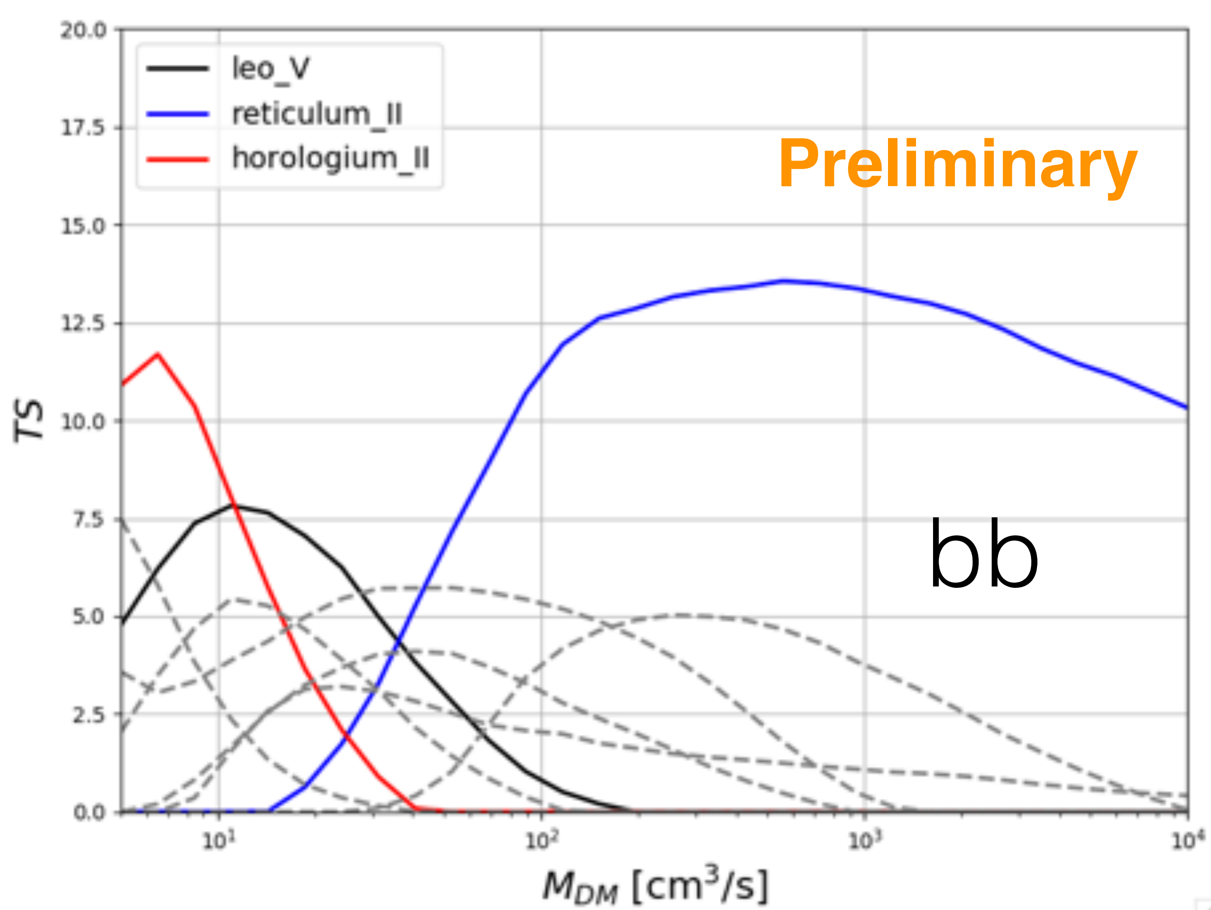
- We considered a map and point like spatial distribution for DM.
- We calculate the limits for annihilation and decay.
- The TS for the presence of DM is approximatively 0 for all channels and for annihilation and decay.

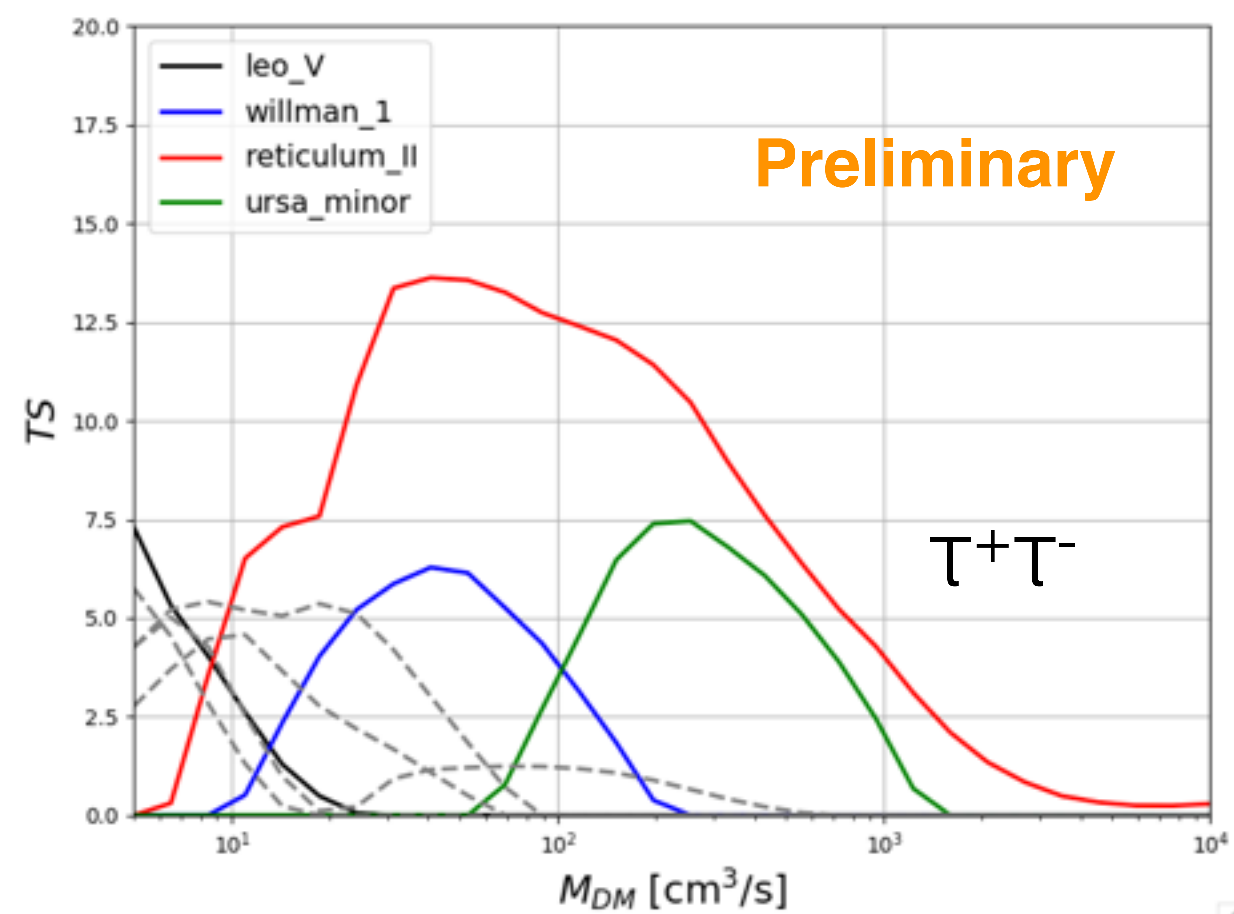




dSphs: target list

- We used a sample of 48 dSphs from Pace and Strigari 2018.
- For the dSphs without photometric measurement of the J factor we take the prediction from their photo-J scaling relationship.
- The dSphs with the highest TS are Reticulum II and Horologium II.

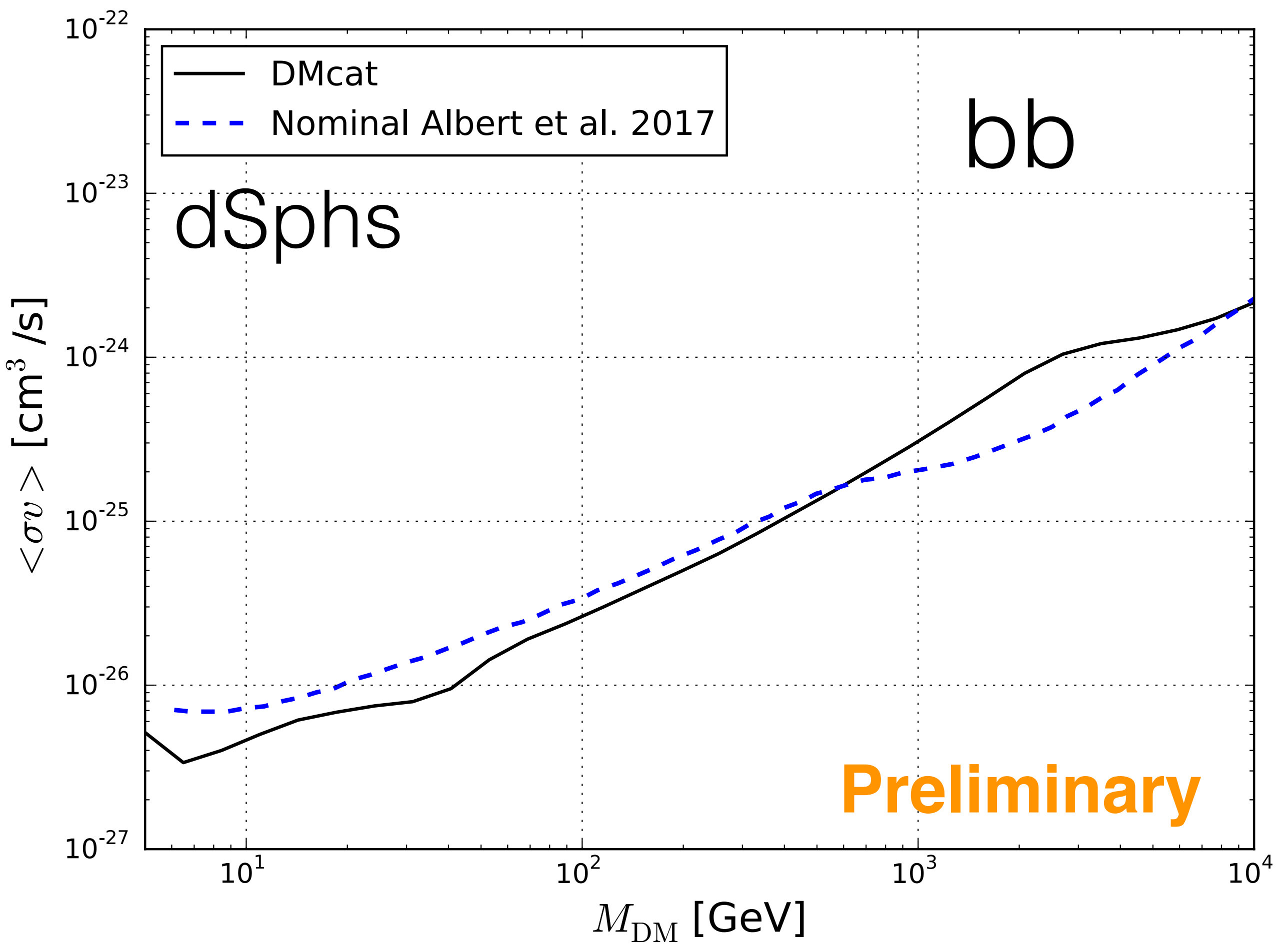


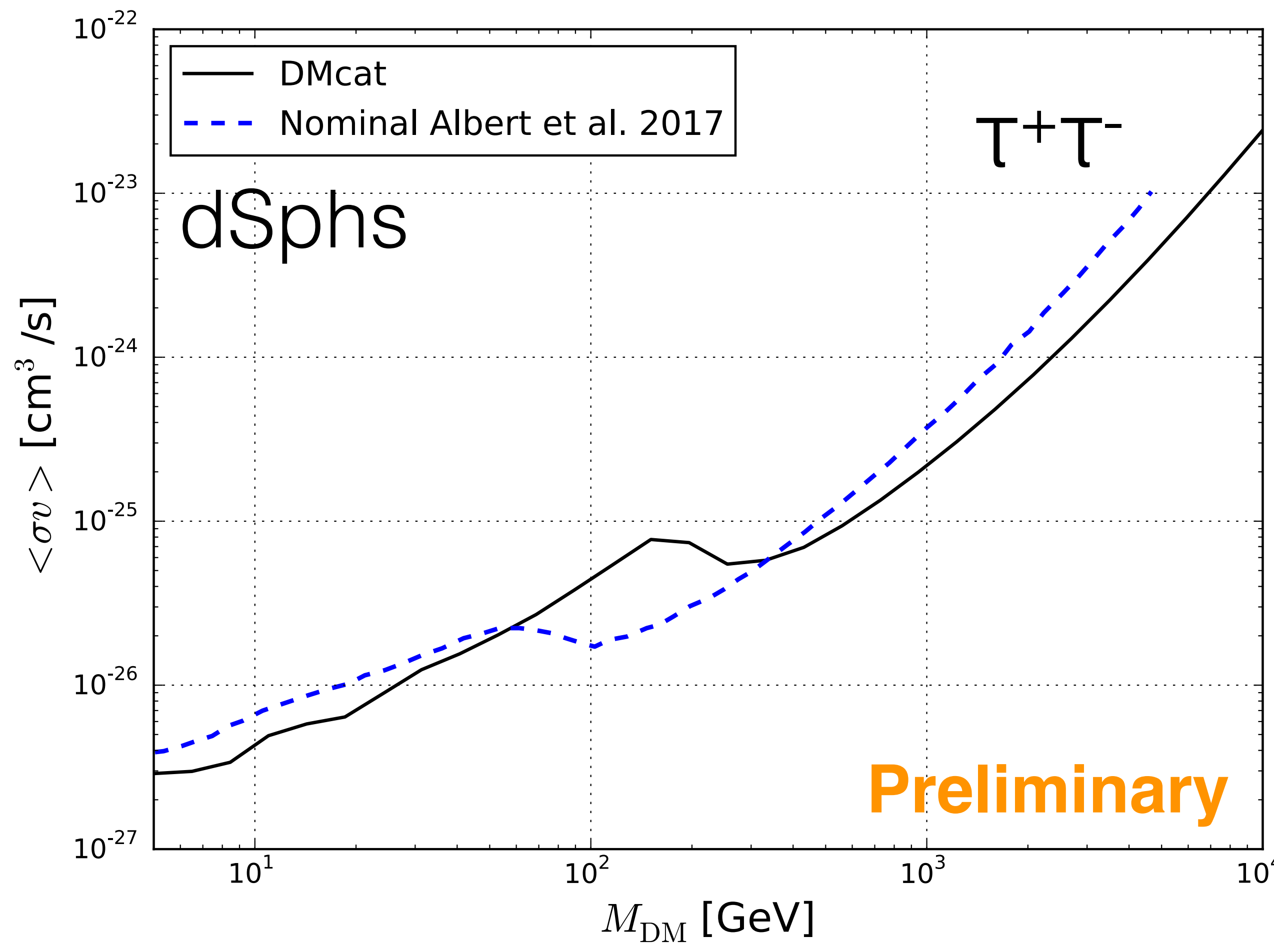


pace2018_all in (https://github.com/fermiPy/dmsky/blob/master/dmsky/data/rosters/roster.yaml)

DM limits for dSphs

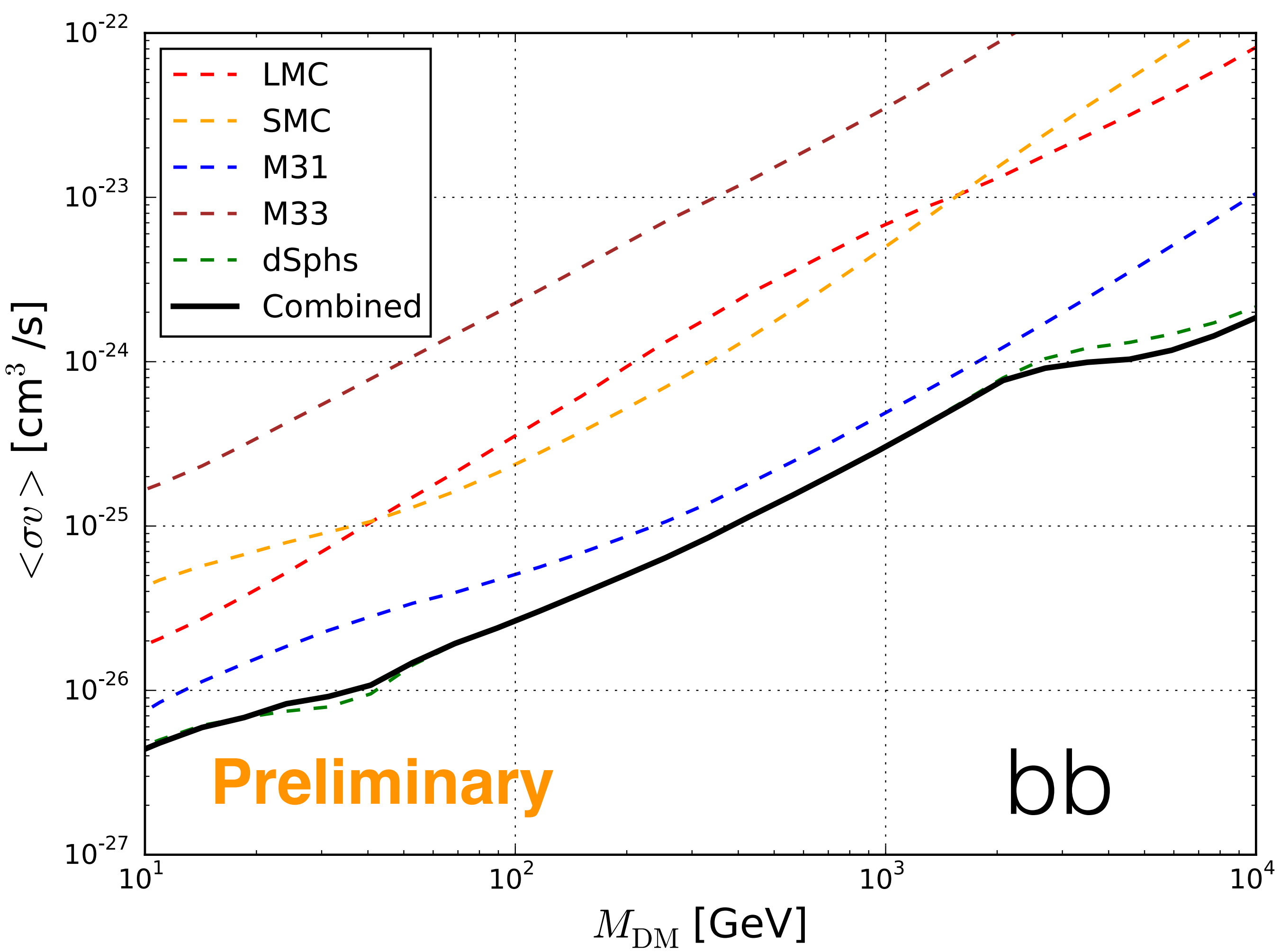
- The peak of TS for the stacking analysis is:
  - m_{DM}=100 GeV with **TS=7** for bb channel and
  - m_{DM}=60 GeV with **TS=10** for $\tau^+\tau^-$ channel
  - Limits are similar to the one derived in Albert et al. 2017.

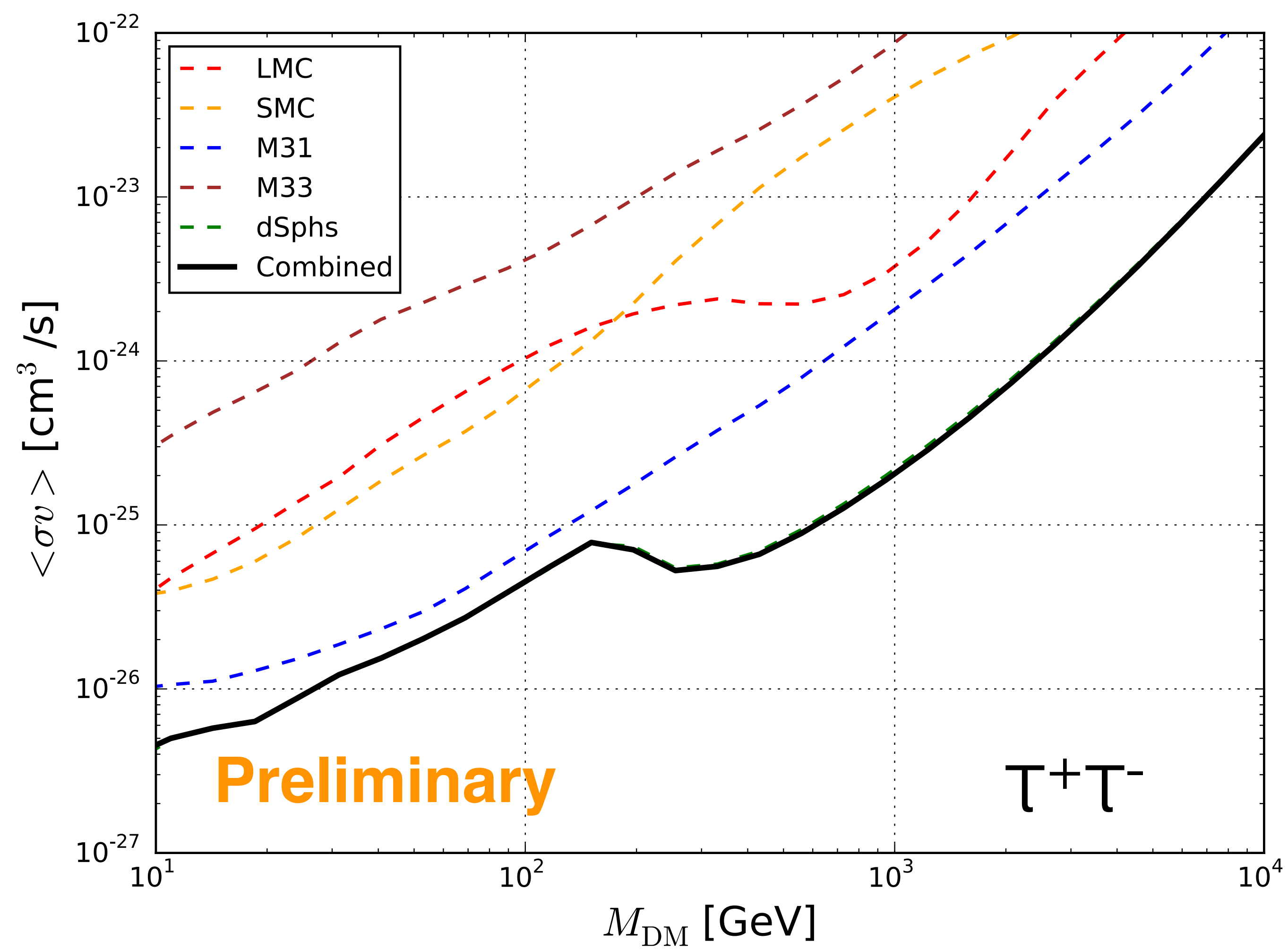




Combining the limits from the different targets

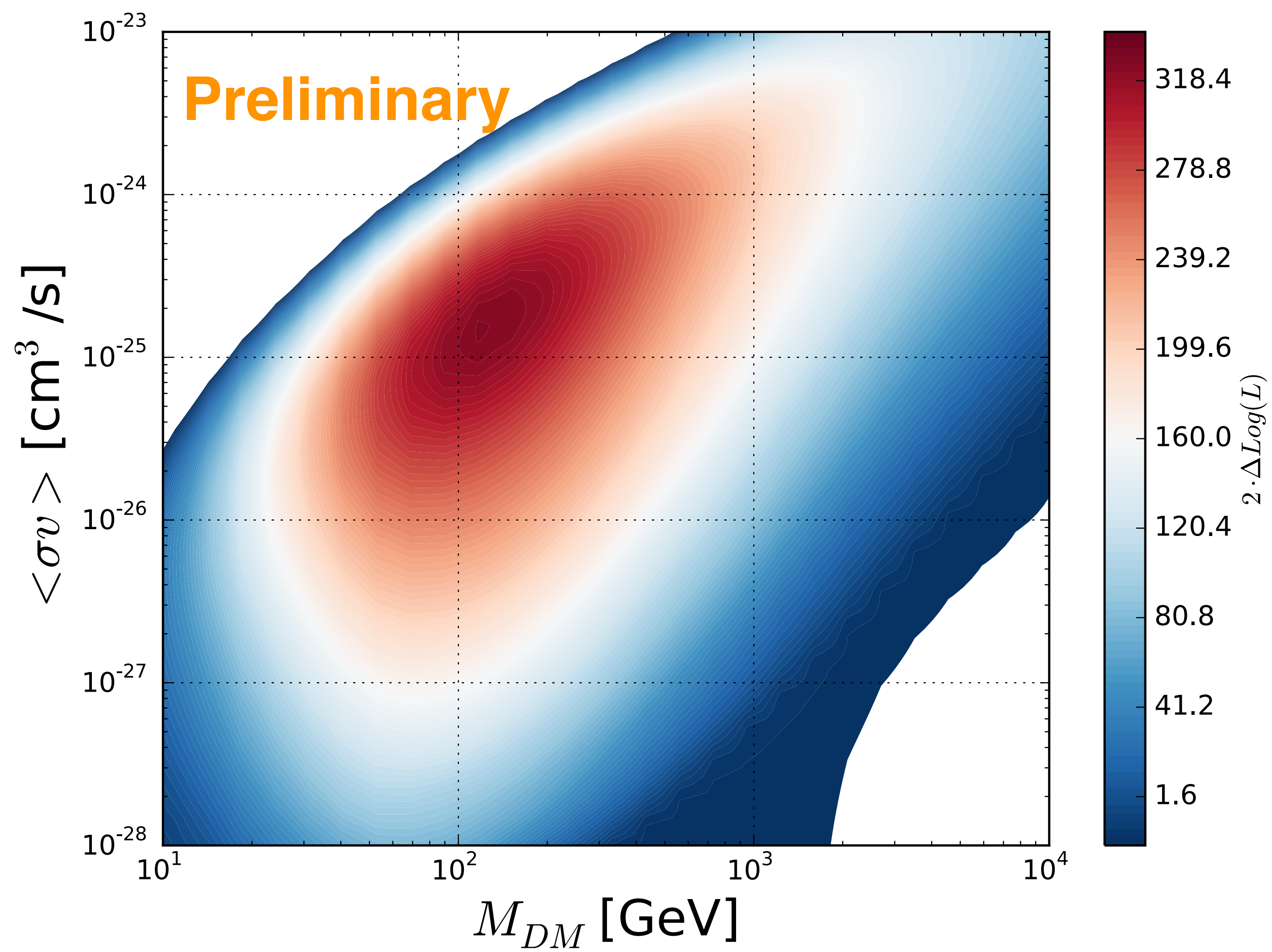
- We can now combine the results derived for the different targets.
- The peak of the TS is similar to the one of the dSphs.
- The limits are also mainly driven by dSphs.
- These results have been derived with a “MED” DM models.





Injected signal simulations

- We tested an injected signal with <σv>= 10^{-25} cm^2/s and M_{DM}=100 GeV.
  - The peak of the TS for the presence of DM is **320**.
  - **<σv>= (1.14±0.16) 10^{-25} for M_{DM}=100 GeV**.
- The result is perfectly compatible with the injected signal.



Conclusions

- We analyzed almost 10 years of Fermi-LAT data and performed a combined search for DM from LMC, SMC, M31, M33 and dSphs.
  - We do not find any significant emission from DM.
- Future steps of the analysis:
  - We will run the simulations with an injected signal compatible with the GC excess.
  - We will add to the target list clusters and the Galactic center.
- We plan to publish a paper with this analysis and we will include likelihood profiles for individual targets and for the combined search.
- This can be used by the community to test their particular DM models.

Backup slides

DMcat Pipeline Overview

- The DMcat pipeline implemented in the DMcat project is based on the dSphs pipeline written by Alex DW, Matt Wood and others.
- The package is based on the following softwares: *Pymodeler, Dmsky, Gammapy, Fermipy and Dmpipe*.
- Main changes are software-related, rather than physics-related.
  - Now uses *fermipy* for data analysis.
  - Also uses *fermipy* for storing and manipulating likelihood curves.
  - Simulate efficiency is vastly improved thanks to *fermipy.*
- Simulations are done against "baseline" model of ROI obtained by *fermipy* as part of fitting procedure.
- Random direction studies also performed inside the ROIs already fitted with *fermipy.*
  - Batch farm interface is changed, uses *fermipy/jobs* module.

More details about these tools in Eric's presentation later in this session!

Packages used by DMcat pipeline

- The package is based on the following softwares: Pymodeler, Dmsky, Gammapy, Fermipy and Dmpipe.
  - All of them are available on github.
  - **Pymodeler** (https://github.com/kadrlica/pymodeler) Infrastructure for creating parametrized models in python (https://pymodeler.readthedocs.io/en/latest/).
  - **DMsky**: created by Alex D-W for J-factor computation and book-keeping (https://github.com/kadrlica/dmsky, https://dmsky.readthedocs.io/en/latest/)
  - **Gammapy**: package for gamma-ray astronomy. It will be used for CTA (https://github.com/gammapy/gammapy).
  - **Fermipy**: Fermi-LAT Python Analysis Framework (https://github.com/fermiPy/fermipy, https://fermipy.readthedocs.io/en/latest/fermipy_jobs.html).
  - **DMpipe**: it contains analysis scripts for LAT DM Analysis (https://github.com/fermiPy/dmpipe, https://dmpipe.readthedocs.io/en/latest/).

dSphs: target list

- Alex D.W. used the sample presented in Page and Strigari 2018.
- For the dSph without photometric measurement of the J factor we take the prediction from their photo-J scaling relationship.
- The sample contains 48 dSphs.

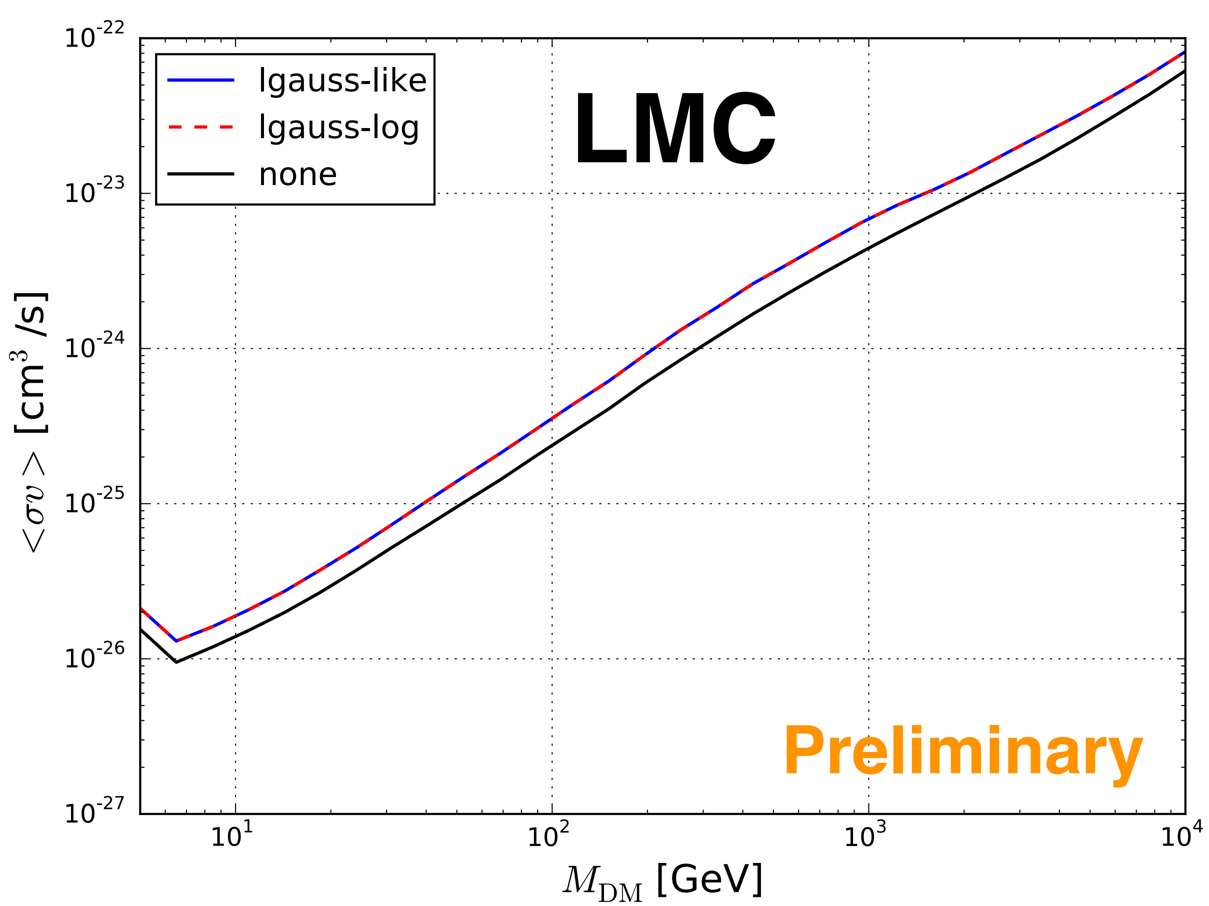
Galaxy	L_V $L_\odot$	$r_{1/2}$ pc	d kpc	J(0.5°) $\mathrm{GeV^2\,cm^{-5}}$	Citation
Cetus II	8.6e1	17	30	19.1	a
Cetus III	8.2e2	44	251	17.2	b
Columba I	4.1e3	98	183	17.3	c
Grus II	3.1e3	93	53	18.4	a
Horologium II	94e2	33	78	18.3	d
Indus II	4.5e3	181	214	16.9	a
Pictor II	1.6e3	46	45	18.7	e
Pictoris I	2.6e3	43	126	17.9	f
Phoenix II	26e3	33	95	18.3	f
Reticulum III	1.8e3	64	92	18.0	a
Sagittarius II	1.0e4	33	67	18.7	g
Tucana IV	2.1e3	98	48	18.4	a
Tucana V	3.7e2	9.3	55	19.0	a
Virgo I	1.2e2	30	91	17.9	b

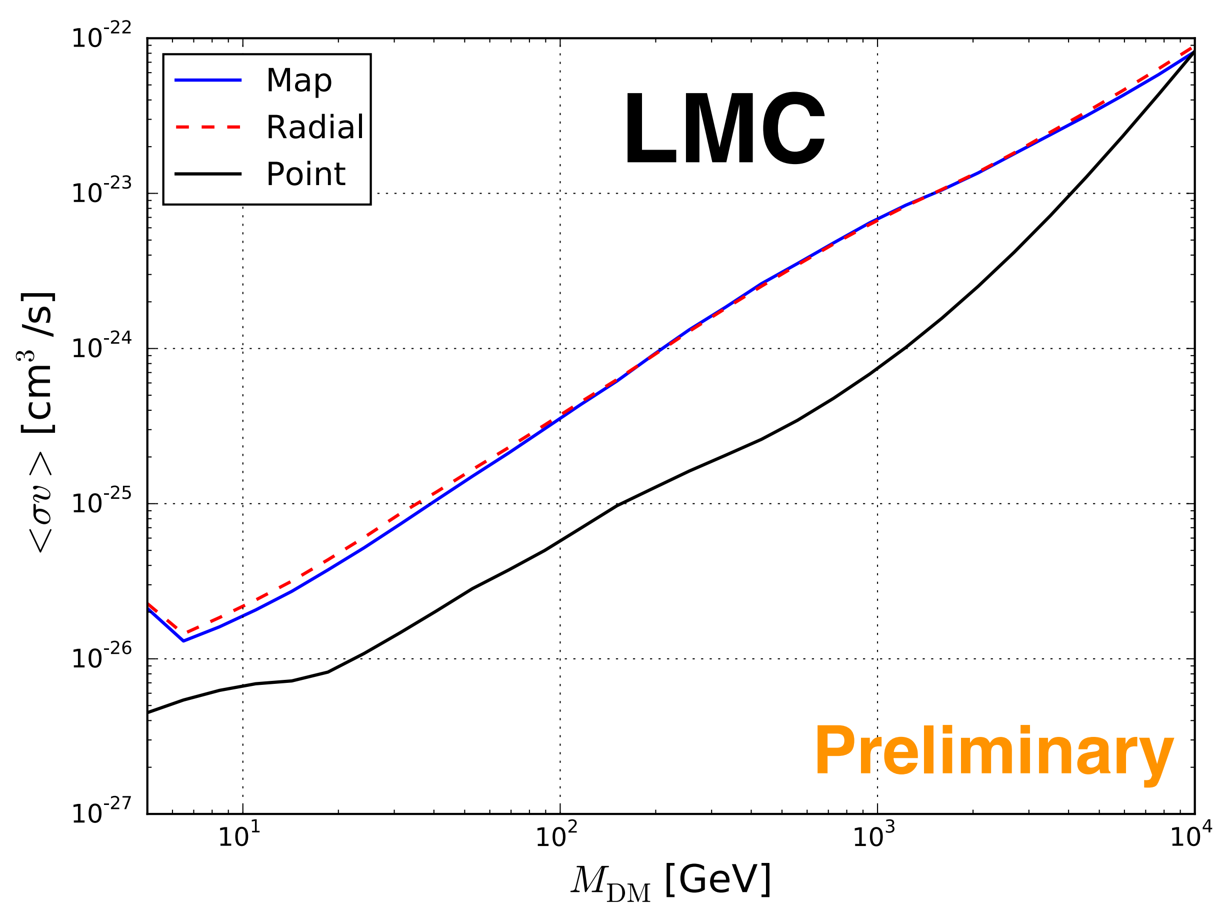
Galaxy	Distance kpc	$r_{1/2}$ pc	σ $\mathrm{km\,s^{-1}}$	N	M_V	α_c deg	J(0.1°) $\mathrm{GeV^2\,cm^{-5}}$
Canes Venatici I	210 ± 6(a)	424 ± 25(b)	$7.6^{+0.5}_{-0.4}$	209(c)	-8.6 ± 0.15	0.232	$17.16^{+0.19}_{-0.18}$
Carina	105.6 ± 5.4(d)	203 ± 22(e)	$6.4^{+0.2}_{-0.2}$	758(f)	-9.1 ± 0.4	0.221	$17.66^{+0.16}_{-0.15}$
Draco	76 ± 6(i)	182 ± 13(b)	$9.1^{+0.3}_{-0.3}$	476(j)	-8.75 ± 0.15	0.276	$18.35^{+0.14}_{-0.11}$
Fornax	147 ± 9(k)	609 ± 38(l)	$10.6^{+0.2}_{-0.2}$	2409(f)	-13.4 ± 0.3	0.476	$17.90^{+0.12}_{-0.14}$
Leo I	258.2 ± 9.5(m)	292 ± 26(n)	$9.0^{+0.4}_{-0.4}$	327(o)	-12.0 ± 0.3	0.13	$17.36^{+0.12}_{-0.11}$
Leo II	233 ± 15(p)	159 ± 14(q)	$7.4^{+0.4}_{-0.4}$	175(r)	-9.9 ± 0.3	0.078	$17.63^{+0.19}_{-0.17}$
Sculptor	83.9 ± 1.5(s)	230 ± 36(e)	$8.8^{+0.2}_{-0.2}$	1349(f)	-11.04 ± 0.5	0.314	$18.30^{+0.14}_{-0.14}$
Sextans	92.5 ± 2.2(t)	524 ± 23(u)	$7.1^{+0.3}_{-0.3}$	424(f)	-9.1 ± 0.1	0.659	$17.37^{+0.24}_{-0.24}$
Ursa Minor	76 ± 4(v)	201 ± 23(w)	$9.3^{+0.4}_{-0.4}$	311(x)	-8.8 ± 0.5	0.305	$18.76^{+0.16}_{-0.20}$
Aquarius II	107.9 ± 3.3(y)	123 ± 22(y)	$6.2^{+2.6}_{-1.7}$	9(y)	-4.36 ± 0.14	0.131	$18.00^{+0.63}_{-0.59}$
Bootes I	66 ± 3(z)	187 ± 20(b)	$4.9^{+0.7}_{-0.6}$	37(aa)	-6.3 ± 0.2	0.325	$17.76^{+0.29}_{-0.28}$
Canes Venatici II	160 ± 7(ab)	68 ± 8(ac)	$4.7^{+1.2}_{-1.0}$	25(c)	-4.6 ± 0.2	0.049	$17.52^{+0.42}_{-0.41}$
Carina II	37.4 ± 0.4(ad)	76 ± 8(ad)	$3.4^{+1.2}_{-0.8}$	14(ae)	-4.4 ± 0.1	0.234	$17.86^{+0.56}_{-0.55}$
Coma Berenices	42 ± 1.5(af)	57 ± 4(ag)	$4.7^{+0.9}_{-0.8}$	58(c)	-3.9 ± 0.6	0.157	$18.59^{+0.31}_{-0.32}$
Draco II*	20.0 ± 3.0(ah)	12 ± 5(ah)	$3.4^{+2.5}_{-1.9}$	9(ai)	-2.9 ± 0.8	0.071	$18.60^{+1.29}_{-1.65}$
Grus I*	120.2 ± 11.1(aj)	52 ± 25(aj)	$4.5^{+5.0}_{-2.8}$	5(ak)	-3.4 ± 0.3	0.05	$16.64^{+1.50}_{-1.68}$
Hercules	132 ± 6(al)	106 ± 13(am)	$3.9^{+1.3}_{-1.0}$	30(c)	-6.6 ± 0.3	0.092	$17.11^{+0.51}_{-0.51}$
Horologium I	87 ± 8(an)	32 ± 5(an)	$5.9^{+3.3}_{-1.8}$	5(ao)	-3.5 ± 0.3	0.047	$19.00^{+0.76}_{-0.63}$
Horologium I	79 ± 7(aj)	60 ± 35(aj)	$5.9^{+3.3}_{-1.8}$	5(ao)	-3.4 ± 0.1	0.079	$18.59^{+0.86}_{-0.78}$
Hydra II	151 ± 8(ap)	71 ± 11(aq)	< 6.82	13(ar)	-5.1 ± 0.3	0.054	< 17.51
Leo IV*	154 ± 5(as)	111 ± 36(at)	$3.4^{+2.0}_{-1.8}$	17(c)	-4.92 ± 0.2	0.083	$16.28^{+0.94}_{-1.18}$
Leo V*	173 ± 5(au)	30 ± 16(ac)	$4.9^{+3.0}_{-1.9}$	8(av)	-4.1 ± 0.4	0.02	$17.53^{+0.89}_{-0.96}$
Pegasus III*	215 ± 12(aw)	37 ± 14(aw)	$7.9^{+4.4}_{-3.1}$	7(aw)	-3.4 ± 0.4	0.02	$18.25^{+0.84}_{-0.99}$
Pisces II*	183 ± 15(ac)	48 ± 10(ac)	$4.8^{+3.3}_{-2.0}$	7(ar)	-4.1 ± 0.4	0.03	$17.15^{+0.95}_{-1.08}$
Reticulum II	32 ± 2(an)	34 ± 8(an)	$3.4^{+0.7}_{-0.6}$	25(ax)	-3.6 ± 0.1	0.121	$18.47^{+0.36}_{-0.34}$
Reticulum II	30 ± 2(aj)	32 ± 3(aj)	$3.4^{+0.7}_{-0.6}$	25(ax)	-2.7 ± 0.1	0.121	$18.55^{+0.35}_{-0.33}$
Segue 1	23 ± 2(ay)	21 ± 5(b)	$3.1^{+0.9}_{-0.8}$	62(az)	-1.5 ± 0.7	0.103	$18.85^{+0.55}_{-0.60}$
Segue 2	36.6 ± 2.45(ba)	33 ± 3(bb)	< 3.20	25(bc)	-2.6 ± 0.1	0.103	< 17.84
Triangulum II	30 ± 2(bd)	28 ± 8(bd)	< 6.36	13(be)	-1.8 ± 0.5	0.109	< 19.36
Tucana II	57.5 ± 5.3(aj)	162 ± 35(aj)	$7.3^{+2.6}_{-1.7}$	10(ak)	-3.8 ± 0.1	0.325	$18.42^{+0.57}_{-0.50}$
Tucana II	57.5 ± 5.3(an)	115 ± 32(an)	$7.3^{+2.6}_{-1.7}$	10(ak)	-3.9 ± 0.2	0.232	$18.64^{+0.60}_{-0.55}$
Tucana III	25 ± 2(bf)	43 ± 6(bf)	< 2.18	26(bg)	-2.4 ± 0.2	0.2	< 17.31
Ursa Major I	97.3 ± 5.85(bh)	200 ± 21(bi)	$7.3^{+1.2}_{-1.0}$	36(c)	-5.5 ± 0.3	0.236	$17.94^{+0.34}_{-0.32}$
Ursa Major II	34.7 ± 2.1(bj)	99 ± 7(ag)	$7.2^{+1.8}_{-1.4}$	19(c)	-4.2 ± 0.5	0.327	$18.99^{+0.45}_{-0.41}$
Willman 1	38 ± 7(bk)	18 ± 4(b)	$4.5^{+1.0}_{-0.8}$	40(bl)	-2.7 ± 0.7	0.056	$19.18^{+0.47}_{-0.44}$
Cetus	780 ± 40(bm)	497 ± 37(bn)	$8.2^{+0.8}_{-0.7}$	116(bo)	-10.1 ± 0.0	0.073	$16.20^{+0.21}_{-0.19}$
Eridanus II	366 ± 17(bp)	176 ± 14(bp)	$7.1^{+1.2}_{-0.9}$	28(bq)	-7.1 ± 0.3	0.055	$17.14^{+0.29}_{-0.26}$
Leo T	407 ± 38(br)	142 ± 36(b)	$7.9^{+2.0}_{-1.5}$	19(c)	-7.1 ± 0.0	0.04	$17.35^{+0.45}_{-0.42}$
And I	727 ± 17.5(bs)	699 ± 29(bt)	$10.9^{+2.3}_{-1.7}$	51(bu)	-11.2 ± 0.2	0.11	$16.68^{+0.37}_{-0.36}$
And III	723 ± 21(bs)	296 ± 33(bt)	$9.8^{+1.5}_{-1.3}$	62(bu)	-9.5 ± 0.3	0.047	$16.85^{+0.29}_{-0.27}$
And V	742 ± 21.5(bs)	294 ± 33(bt)	$11.0^{+1.2}_{-1.0}$	85(bu)	-9.3 ± 0.2	0.045	$17.11^{+0.23}_{-0.21}$
And VII	763 ± 35(bv)	717 ± 39(bn)	$13.3^{+1.0}_{-1.0}$	136(bu)	-12.2 ± 0.0	0.108	$16.89^{+0.17}_{-0.17}$
And XIV	793 ± 50(bs)	297 ± 53(bt)	$5.9^{+1.0}_{-0.9}$	48(bu)	-8.5 ± 0.35	0.043	$15.65^{+0.37}_{-0.38}$
And XVIII	1214 ± 41.5(bs)	260 ± 38(bt)	$10.5^{+2.8}_{-2.1}$	22(bu)	-9.2 ± 0.35	0.025	$16.70^{+0.46}_{-0.43}$

pace2018_all in (https://github.com/fermiPy/dmsky/blob/master/dmsky/data/rosters/roster.yaml)

Priors on J and DM spatial distribution

- You can use different shapes for the prior on J:
  - ‘none’: No priors, ’lgauss_log’: gaussian prior in log scale, ’lgauss_like’: simular to ‘lgauss_log’.
  - Regarding the spatial distribution you can choose among point-like, radial distribution and map template.





Null signal simulations