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Fermi
Gamma-ray Space Telescope

Constraining dark matter signal from a combined analysis of Milky Way satellites with the Fermi-LAT

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LABORATOIRE UNIVERS & PARTICULES MONTPELLIER

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Constraining Dark Matter Models from a Combined Analysis of Milky Way Satellites with the Fermi Large Area Telescope

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(The Fermi-LAT Collaboration)

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Satellite galaxies of the Milky Way are among the most promising targets for dark matter searches in gamma rays. We present a search for dark matter consisting of weakly interacting massive particles, applying a joint likelihood analysis to 10 satellite galaxies with 24 months of data of the Fermi Large Area Telescope. No dark matter signal is detected. Including the uncertainty in the dark matter distribution, robust upper limits are placed on dark matter annihilation cross sections. The 95% confidence level upper limits range from about 10^{-26} cm^3 s^{-1} at 5 GeV to about 5×10^{-23} cm^3 s^{-1} at 1 TeV, depending on the dark matter annihilation final state. For the first time, using gamma rays, we are able to rule out models with the most generic cross section ($\sim 3 \times 10^{-26}$ cm^3 s^{-1} for a purely s-wave cross section), without assuming additional boost factors.

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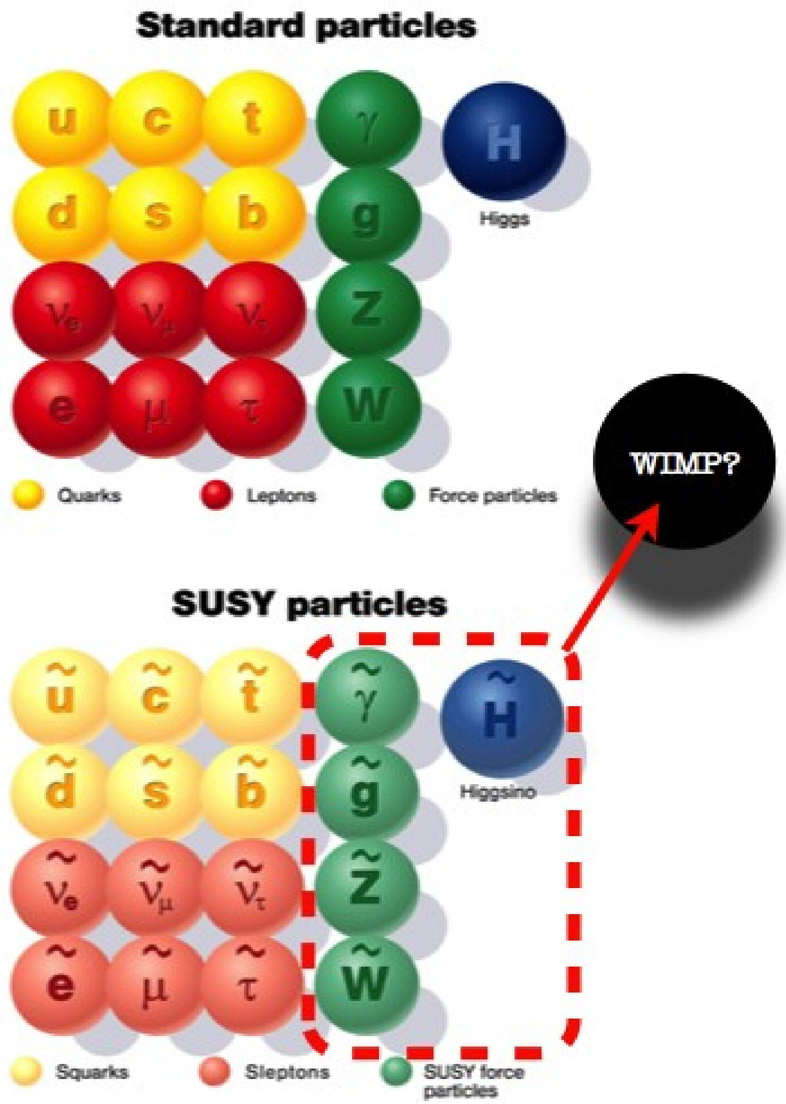
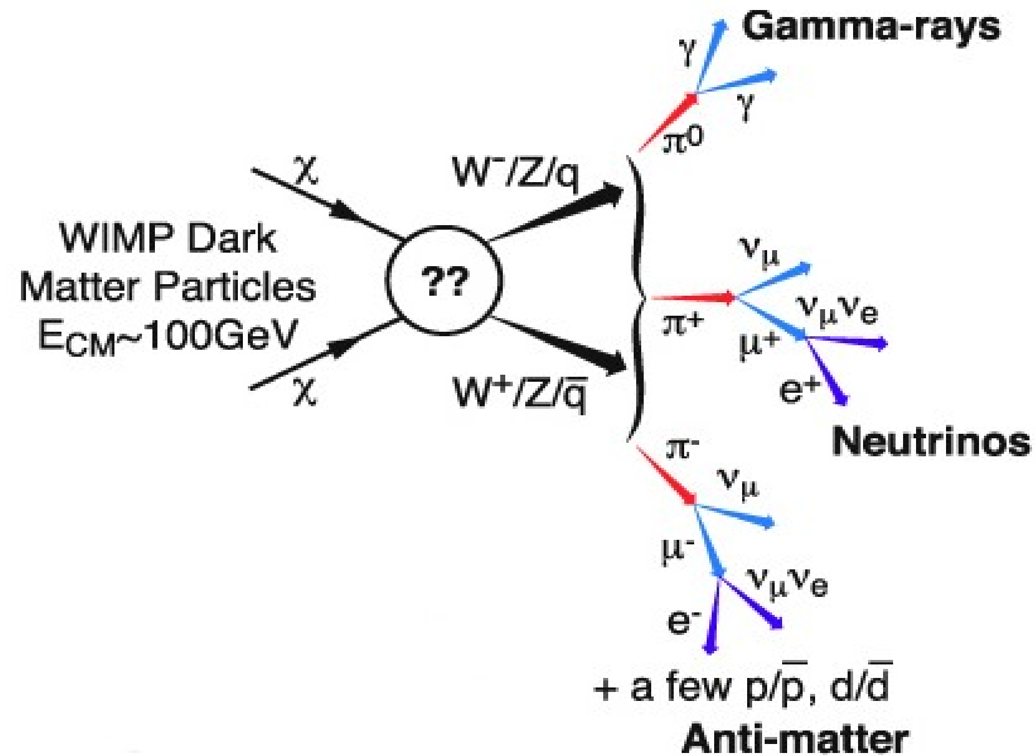
arxiv:1108.3546

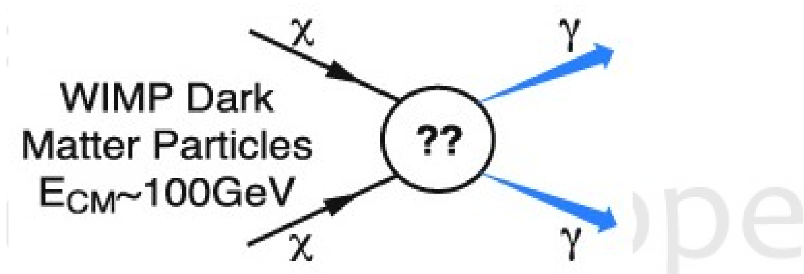
Outline

- Introduction to γ rays and dark matter
- Fermi-LAT
- Dark Matter in Dwarf Spheroidal Galaxies
- Likelihood analysis
- Data analysis
- Results

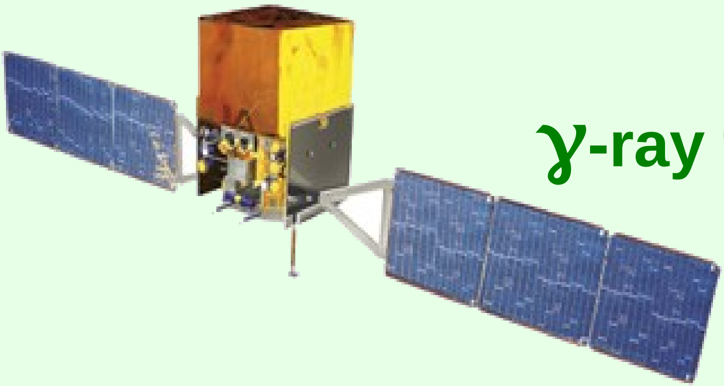
γ rays from Dark Matter





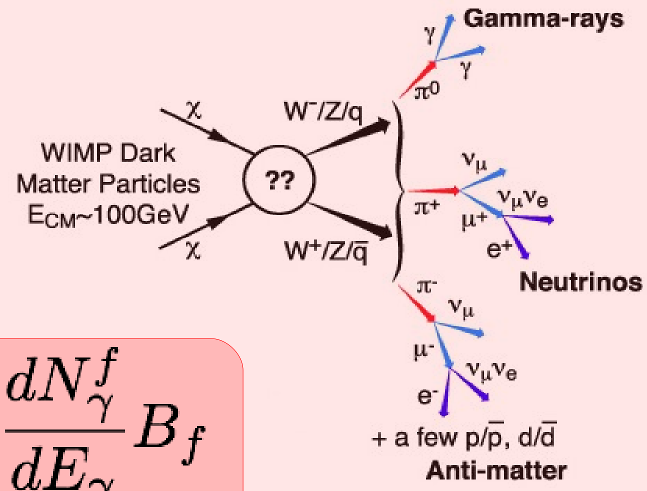


γ rays from Dark Matter



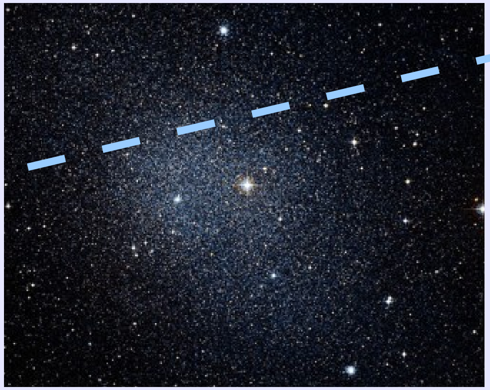
γ-ray flux

Particle physics



$$\Phi_{WIMP}(E_\gamma, \psi) = \frac{1}{4\pi} \frac{<\sigma_{ann} v>}{2\, m^2_{WIMP}} \sum_f \frac{dN^f_\gamma}{dE_\gamma} B_f$$

$$\times \int_{l.o.s.} dl(\psi) \rho^2(l(\psi))$$



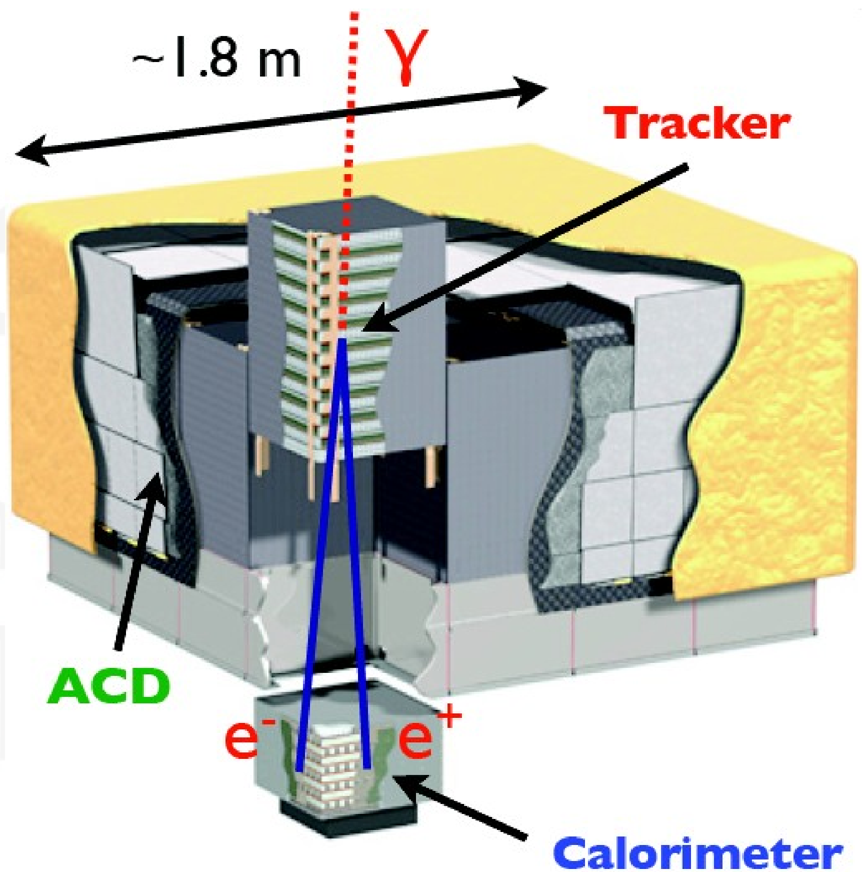
Dark Matter Distribution

“Astrophysical factor” or “J-factor”

The Fermi-LAT

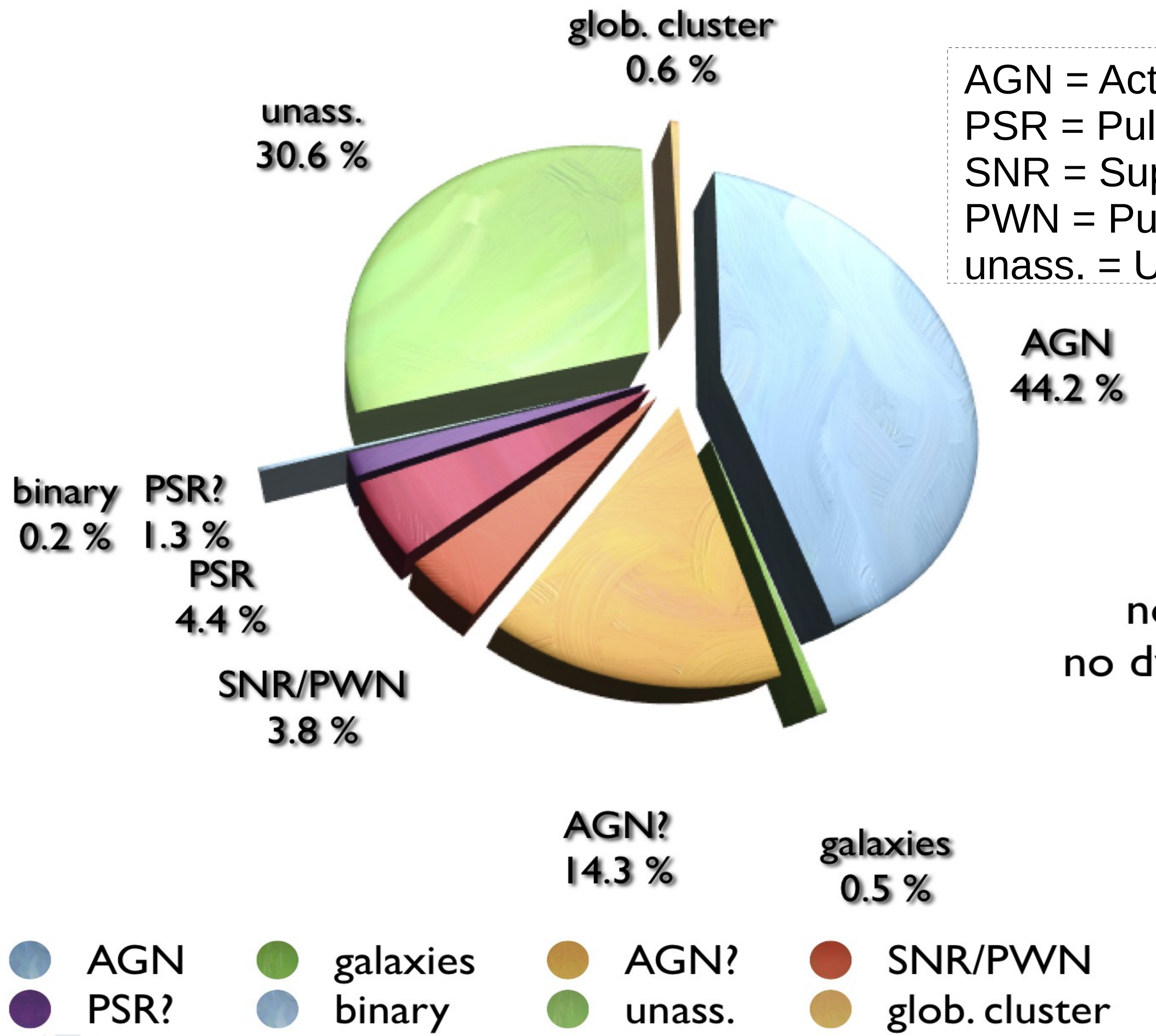
Fermi Large Area Telescope

- Launched Jun 11, 2008
- Pair-conversion telescope
- 20 MeV to > 300 GeV
- Observes all sky in ~2h
- Energy resolution < 10%
- Angular resolution < 3.5˚



The Fermi γ-ray sky

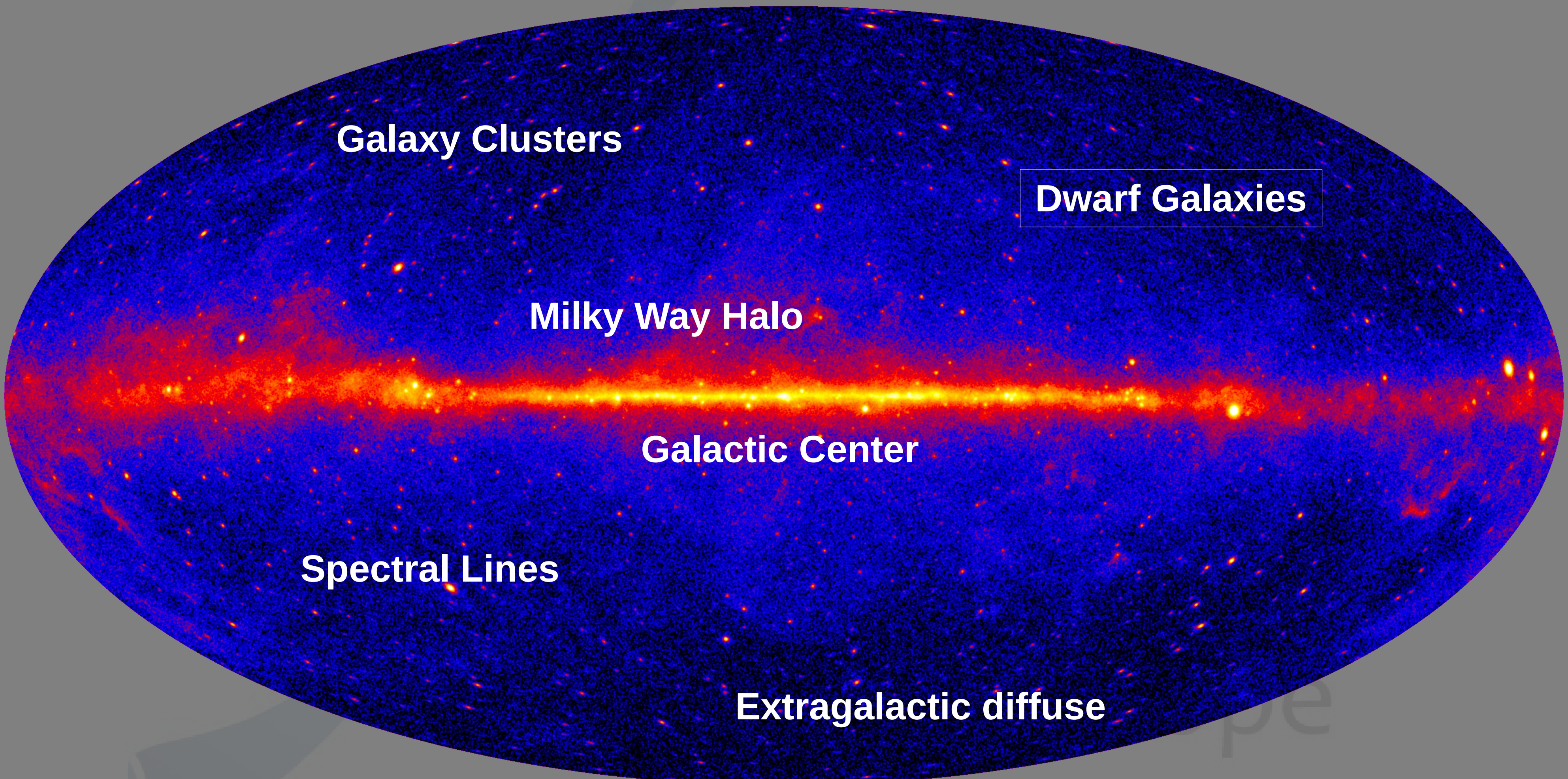
AGN = Active Galactic Nuclei
PSR = Pulsar
SNR = Supernova Remnant
PWN = Pulsar Wind Nebula
unass. = Unassociated sources



no gal. clusters
no dwarf spheroidals

Maja Llena Garde
on behalf of the Fermi-LAT collaboration

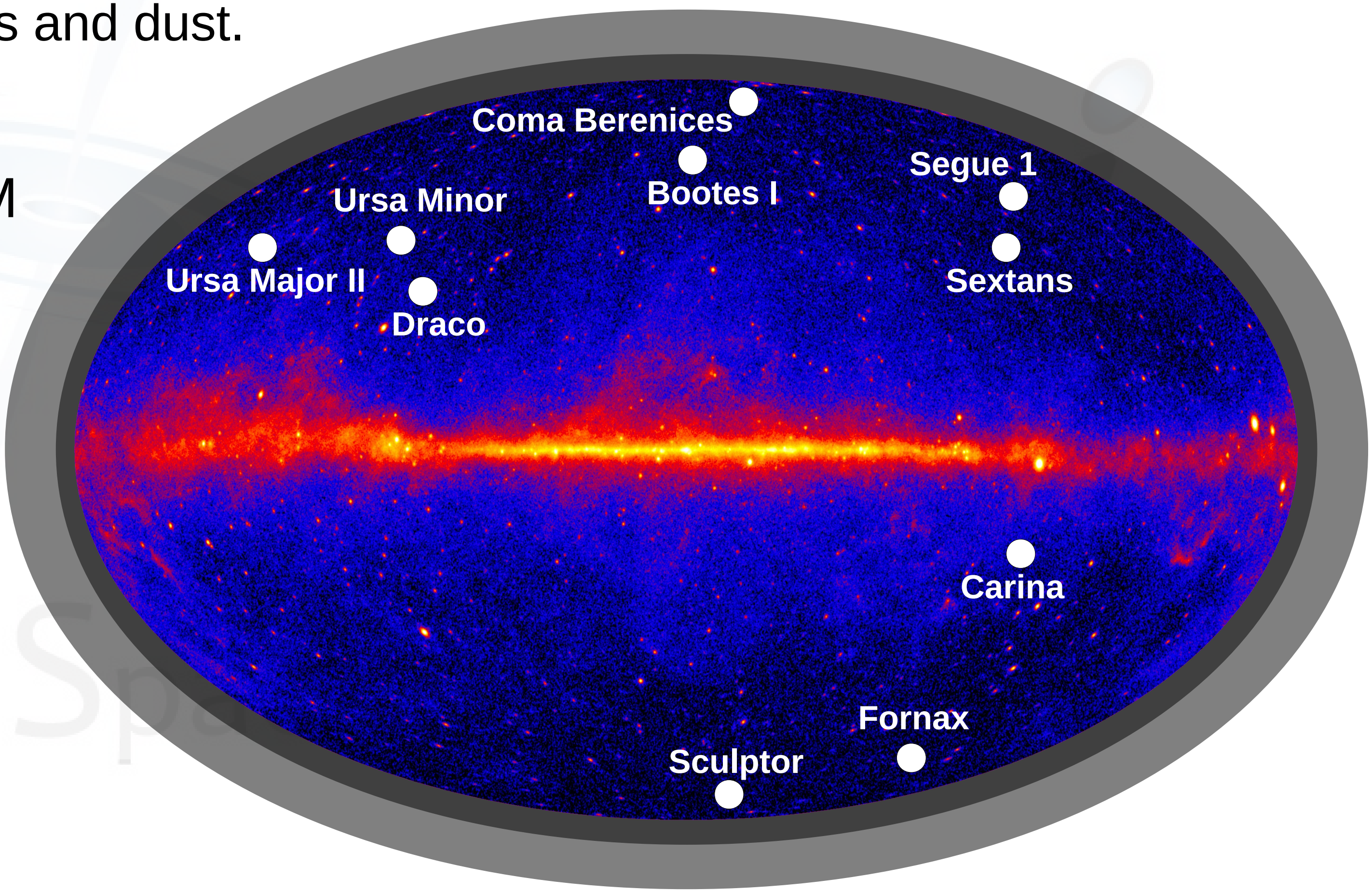
Where to look for Dark Matter



Dwarf spheroidal galaxies

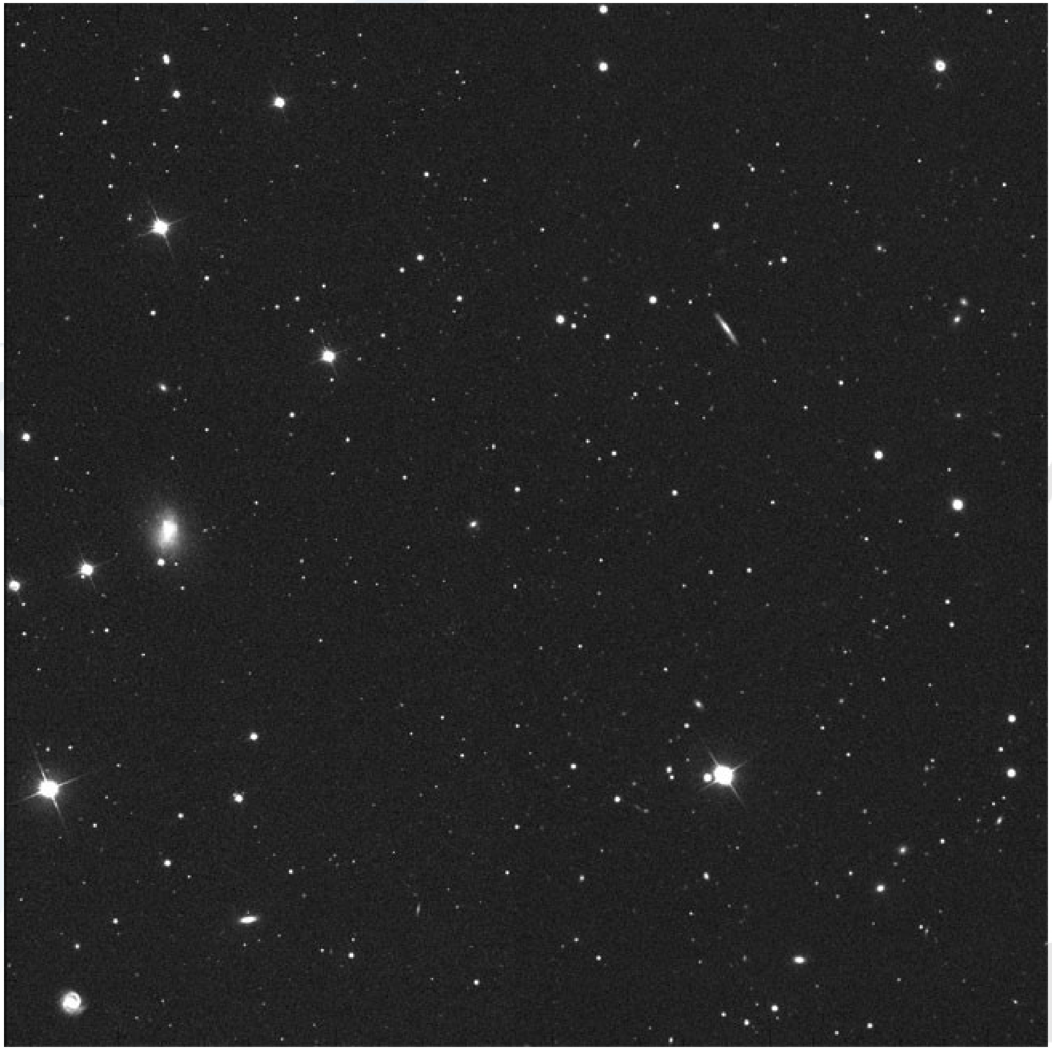
- ✔ dSphs are DM dominated systems (they have very high M/L ratios).
- ✔ Many dSphs are closer than 100 kpc to the Galactic Centre.
- ✔ Low background
    - Most dSphs are expected to be free from other astrophysical γ-ray sources.
    - Small content of gas and dust.

- ✗ Predicted flux from DM is very low.
- ✗ Dependence on DM distribution.
  But:
  fortunately good estimates from stellar velocity data



Very faint galaxies...

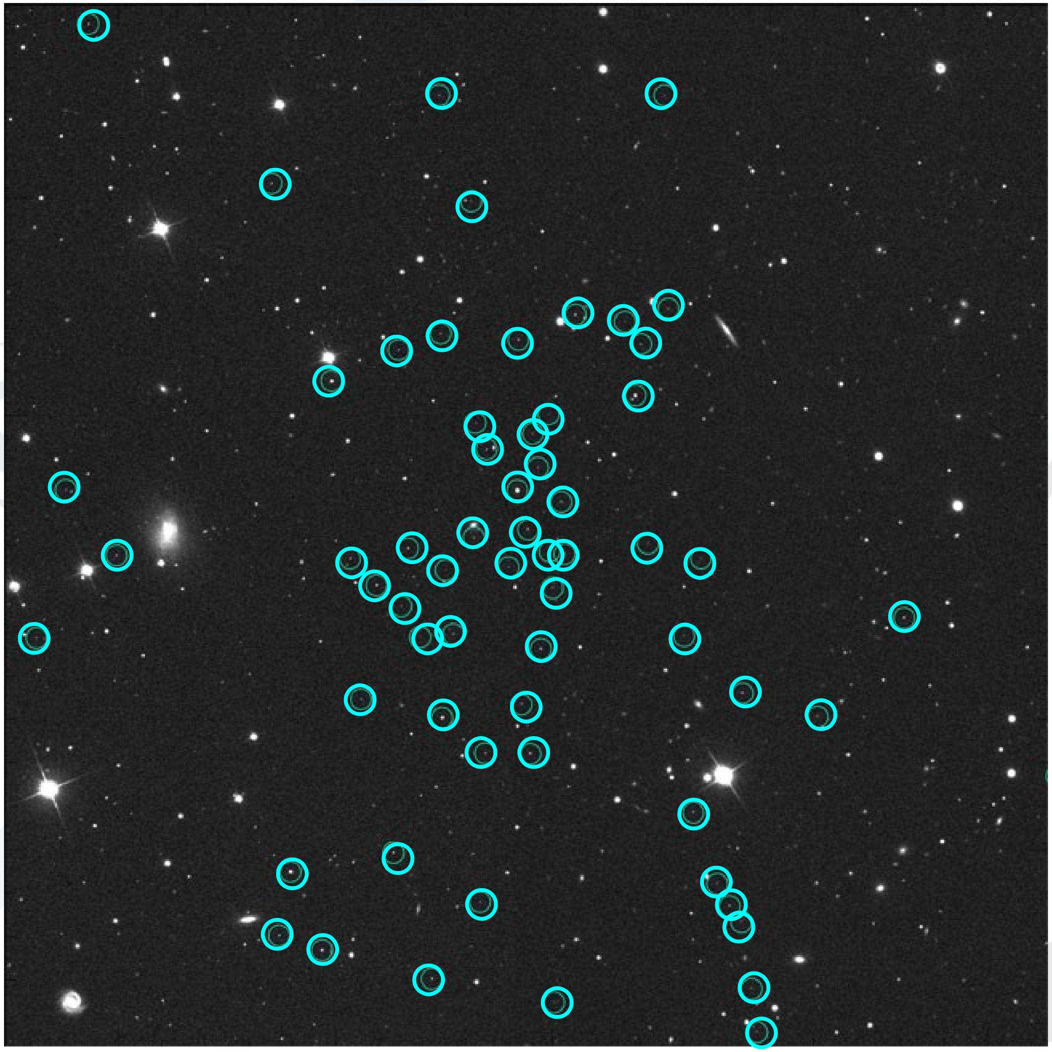
Segue 1



Credit: Marla Geha,
http://keckobservatory.org/news/found_heart_of_darkness/

Very faint galaxies...

Segue 1



Credit: Marla Geha,
http://keckobservatory.org/news/found_heart_of_darkness/

Analysis details

- 10 dSphs
- 24 month Pass 6 data
- Diffuse event class (only events with the highest gamma-like confidence)
- Region of interest: 10° radius centered on dSph location
- Energy range from 200MeV to 100GeV
- Standard cuts removing Earth albedo (zenith angle < 100°)
- Instrument response function: P6_V3_DIFFUSE
- Models:
    - dSphs modelled as DM point sources (DMFIT)
    - Galactic and Isotropic diffuse models recommended by the Fermi-LAT collaboration
    - Point-like sources from the 1FGL point source catalogue (A. A. Abdo et al 2010 ApJS 188 405) with some additions
- Binned Likelihood (using energy and spatial information)
- *Parameter of interest:* DM cross-section
  Nuisance parameters: J-factors, normalizations of the Diffuse Backgrounds, and the normalization of nearby sources (<5°)

Analysis method

- **Maximum likelihood fit to data**
  - **Fermi-LAT Science Tools**
- **Nuisance parameters**
  - **Diffuse Backgrounds, Point Sources *and* J factors**
  - **J factors from stellar velocity measurements, but we have the likelihood!**

TABLE I. Position, distance, and J factor (under assumption of a Navarro-Frenk-White profile) of each dSph. The 4th column shows the mode of the posterior distribution of $\log_{10} J$, and the 5th column indicates its 68% C.L. error. See the text for further details. The J factors correspond to the pair annihilation flux coming from a cone of solid angle $\Delta\Omega = 2.4 \times 10^{-4}$ sr. The final column indicates the reference for the kinematic data set used.

Name	l (degree)	b (degree)	d (kpc)	$\overline{\log_{10}(J)}$ ($\log_{10}[\mathrm{GeV}^2\,\mathrm{cm}^{-5}]$)	σ	Reference
Bootes I	358.08	69.62	60	17.7	0.34	[15]
Carina	260.11	−22.22	101	18.0	0.13	[16]
Coma Berenices	241.9	83.6	44	19.0	0.37	[17]
Draco	86.37	34.72	80	18.8	0.13	[16]
Fornax	237.1	−65.7	138	17.7	0.23	[16]
Sculptor	287.15	−83.16	80	18.4	0.13	[16]
Segue 1	220.48	50.42	23	19.6	0.53	[18]
Sextans	243.4	42.2	86	17.8	0.23	[16]
Ursa Major II	152.46	37.44	32	19.6	0.40	[17]
Ursa Minor	104.95	44.80	66	18.5	0.18	[16]

[15] S. E. Koposov *et al.*, Astrophys. J. **736**, 146 (2011).
[16] M. G. Walker *et al.*, Astrophys. J. **704**, 1274 (2009).
[17] J. D. Simon and M. Geha, Astrophys. J. **670**, 313 (2007).
[18] J. D. Simon *et al.*, Astrophys. J. **733**, 46 (2011).

Joint Likelihood

- Different targets but same model
- Target-independent parameters can be fitted jointly!
- Target-dependent parameters are treated as nuisance parameters

Individual parameters

$$L(D|\mathbf{pw},\{\mathbf{p}\}) = \prod_i L_i^{LAT}(D|\mathbf{pw},\mathbf{p}_i)$$

Common parameters

- Not to be confused with data stacking!

Joint Likelihood for the dSphs

- γ-ray spectrum is universal. J-factors individual.
- Joint likelihood (not data stacking) - add likelihood function of each dSph, keep σv as common parameter across all likelihood functions:

Individual parameters (J-factors, backgrounds, point sources)

$$L(D|\mathbf{pw},\{\mathbf{p}\}) = \prod_i L_i^{LAT}(D|\mathbf{pw},\mathbf{p}_i)$$

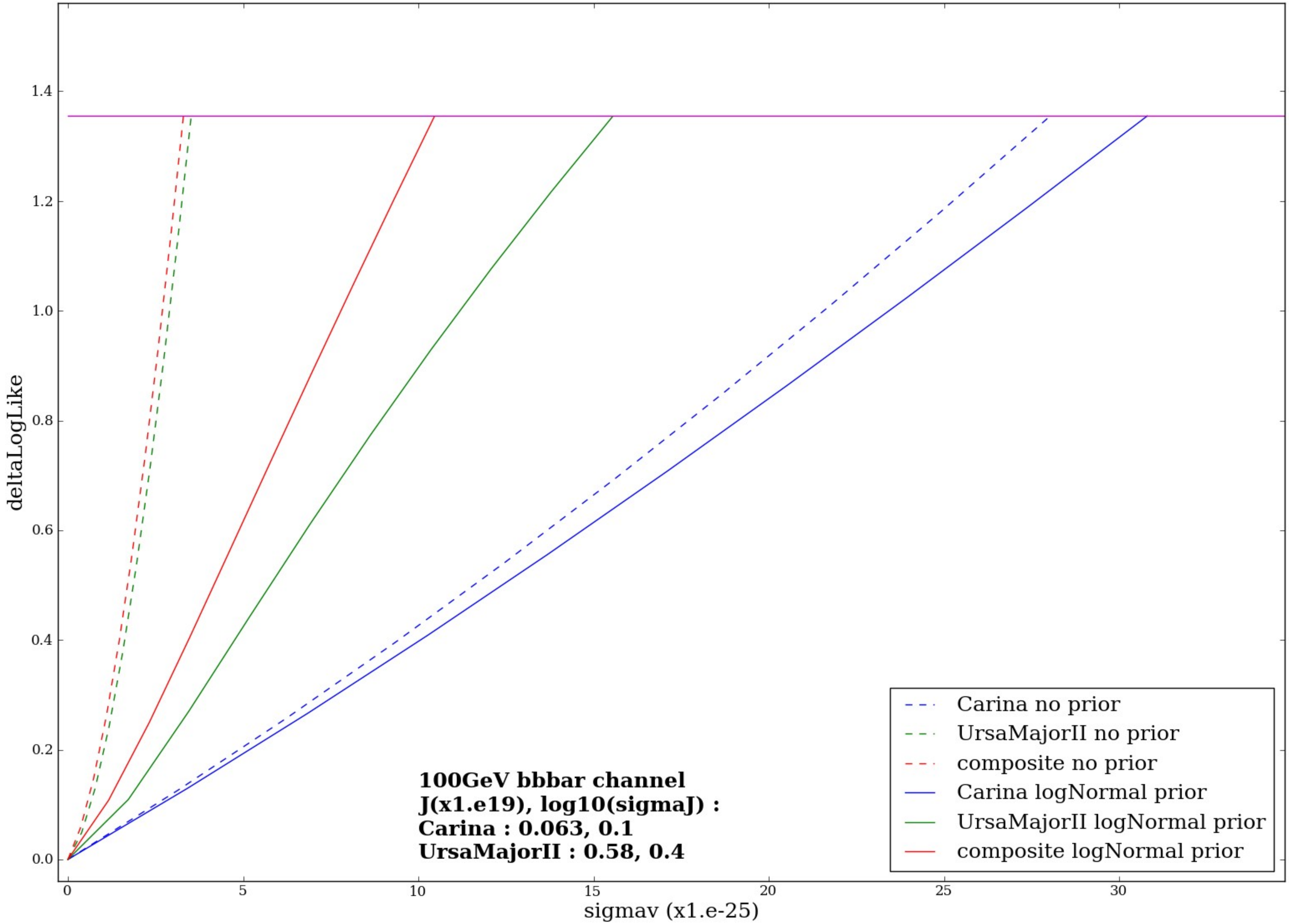
Common parameters, ie DM properties

Include the J-factor likelihood to include uncertainties

$$\times \frac{1}{\ln(10)\, J_i \sqrt{2\pi}\sigma_i} e^{-\left(\log_{10}(J_i) - \overline{\log_{10}(J_i)}\right)^2 / 2\sigma_i^2}$$

- J-factor statistical uncertainties included!
- The analysis can be individually optimized, and is more robust under background fluctuations and J-factor uncertainties.
- We have used *Composite2* in Fermi ScienceTools

Joint Likelihood example



J-factor tests

- We only include statistical uncertainties in our analysis.
- Examine systematic uncertainties in deriving the dwarf J-factors

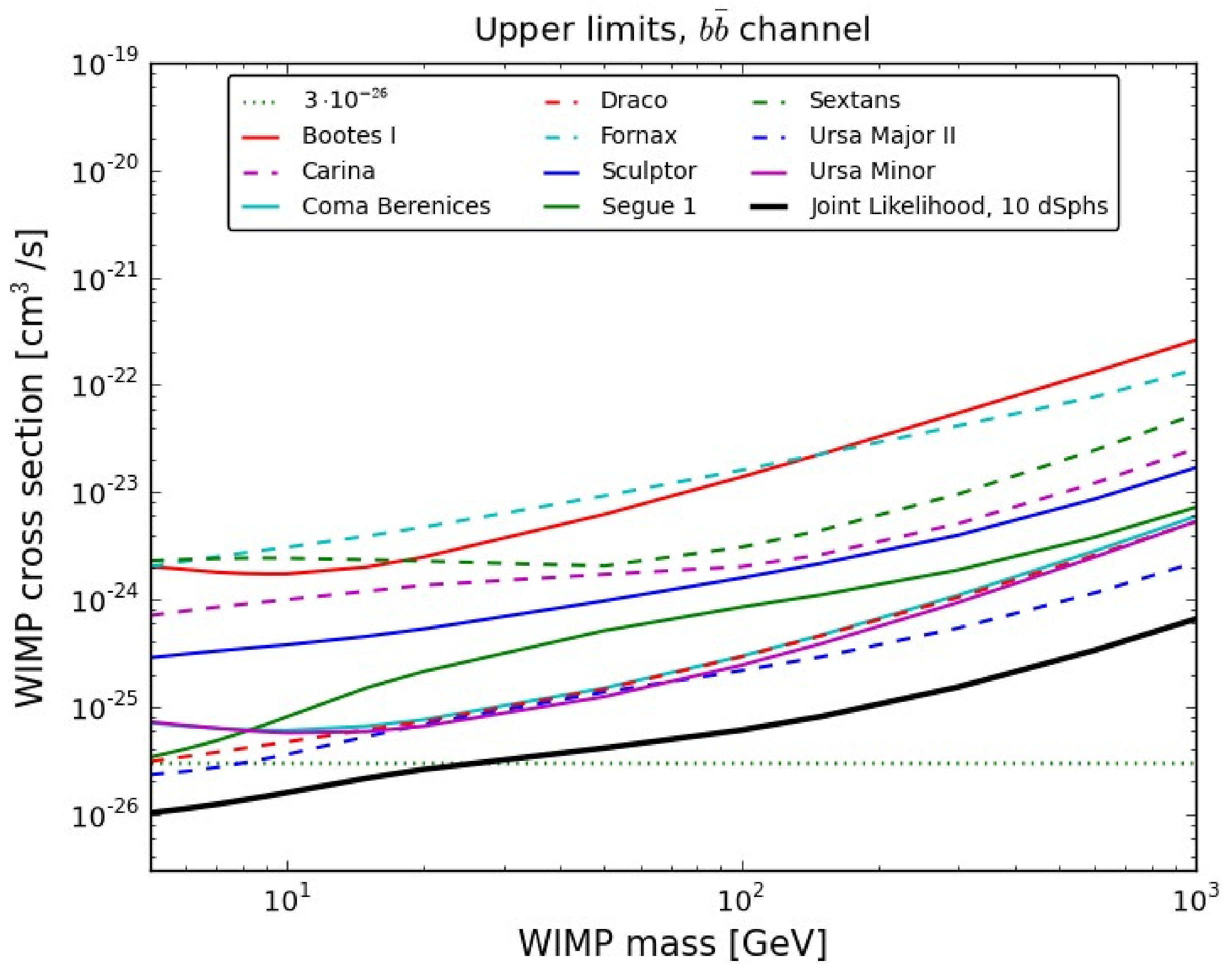
- Choice of profile:
  - J-factors integrated over a cone with radius 0.5 degrees
  - Comparable to or larger than the scale radii of the dwarfs
  - The choice of cored or cusped profile at small radii has little effect

- Change of stellar kinematic analysis:
  - J-factors determined using the methodology of Strigari et al. (2008) and Martinez et al. (2009)
  - Perform combined analysis of 6 conventional dwarfs with J-factors calculated independently by Chabonnier et al. (2011)
  - Combined results differ by < 25% for these 6 dwarfs and when incorporated into the full combined analysis of 10 dwarfs this becomes a ~ 10% effect

- Impact of ultra-faint dwarfs:
  - The dark matter distributions of Segue 1 and Ursa Major II are calculated from 66 and 20 stars, respectively
  - Removing both Segue 1 and Ursa Major II from combined analysis impacts the results by a factor of ~1.5

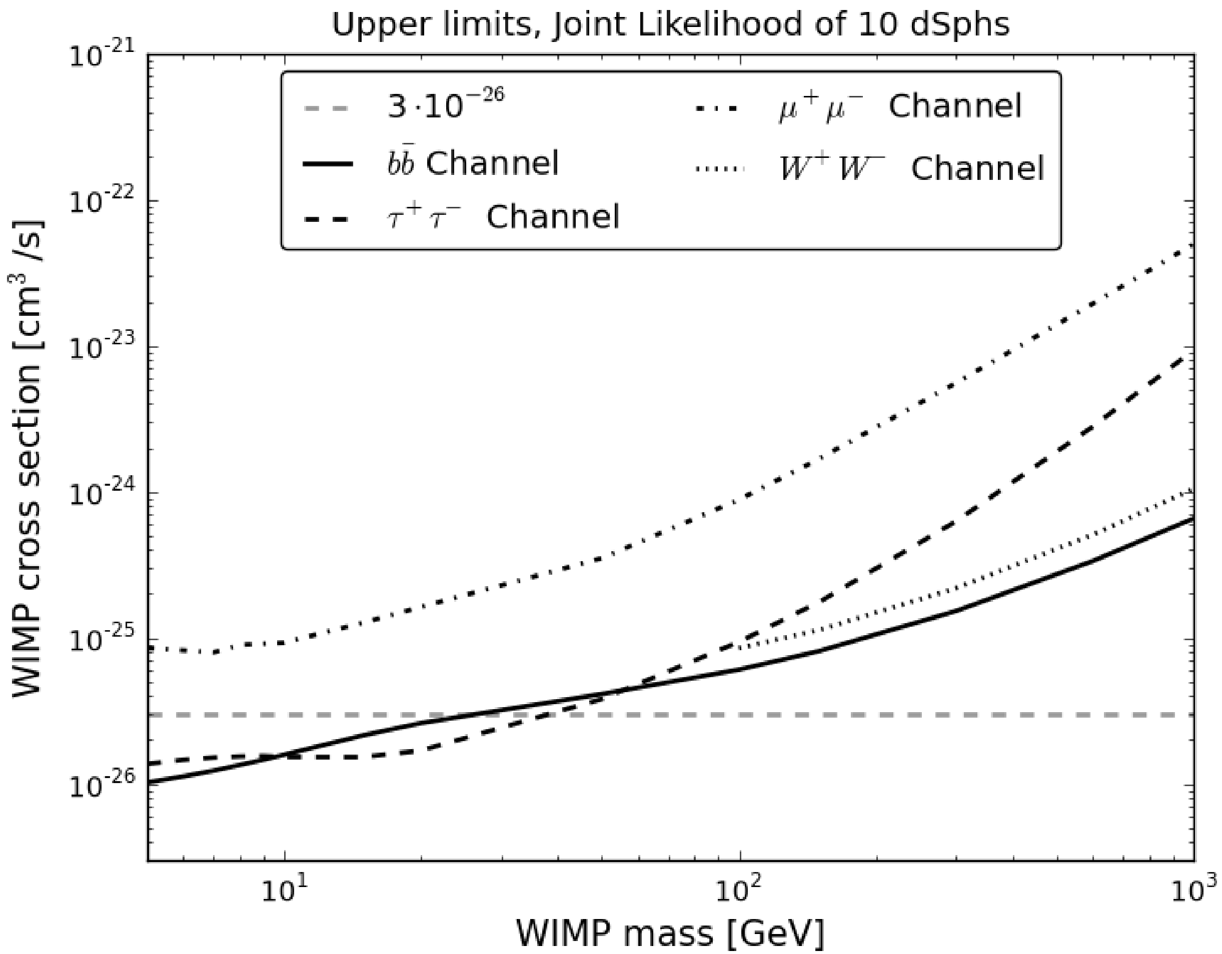
Upper Limits from dSphs

- 24 months of data
- 10 dSphs
- Model the dSphs as DM point sources.
- Model Galactic and isotropic backgrounds and near by point sources.
- J-factor uncertainties included!
- The joint likelihood limit start to constrain interesting parameter space.



Combined limits for 10 dSphs

- **4 annihilation channels**
- **Start to constrain very interesting parameter space at low WIMP masses.**



What the future may hold...

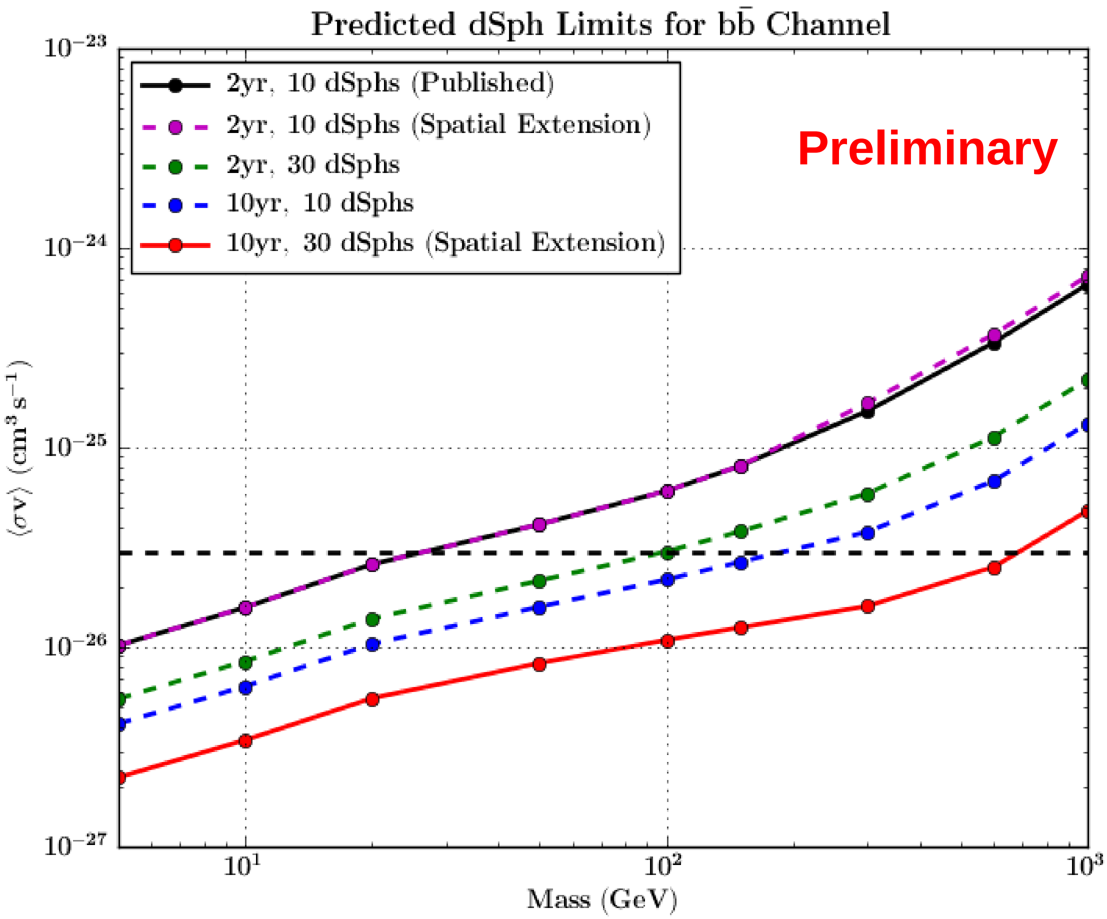
2yr, 10 dSphs - The published results from Ackermann et al. (2011)

10yr, 30 dSphs - The predicted limits using 10 years of data (5x increase) and 30 dSphs (3x increase). Additionally, the projected effects of spatial extension are included. These limits go roughly as 1/sqrt(15) at low mass (mass < 200 GeV) and 1/15 at high mass.

10yr, 10 dSphs - Predicted limits only assuming a 5x increase in data.

2yr, 30 dSphs - Predicted limits taking the current 2yr data sample but using 30 dSphs.

Spatial extension is expected to minimally change the limits.

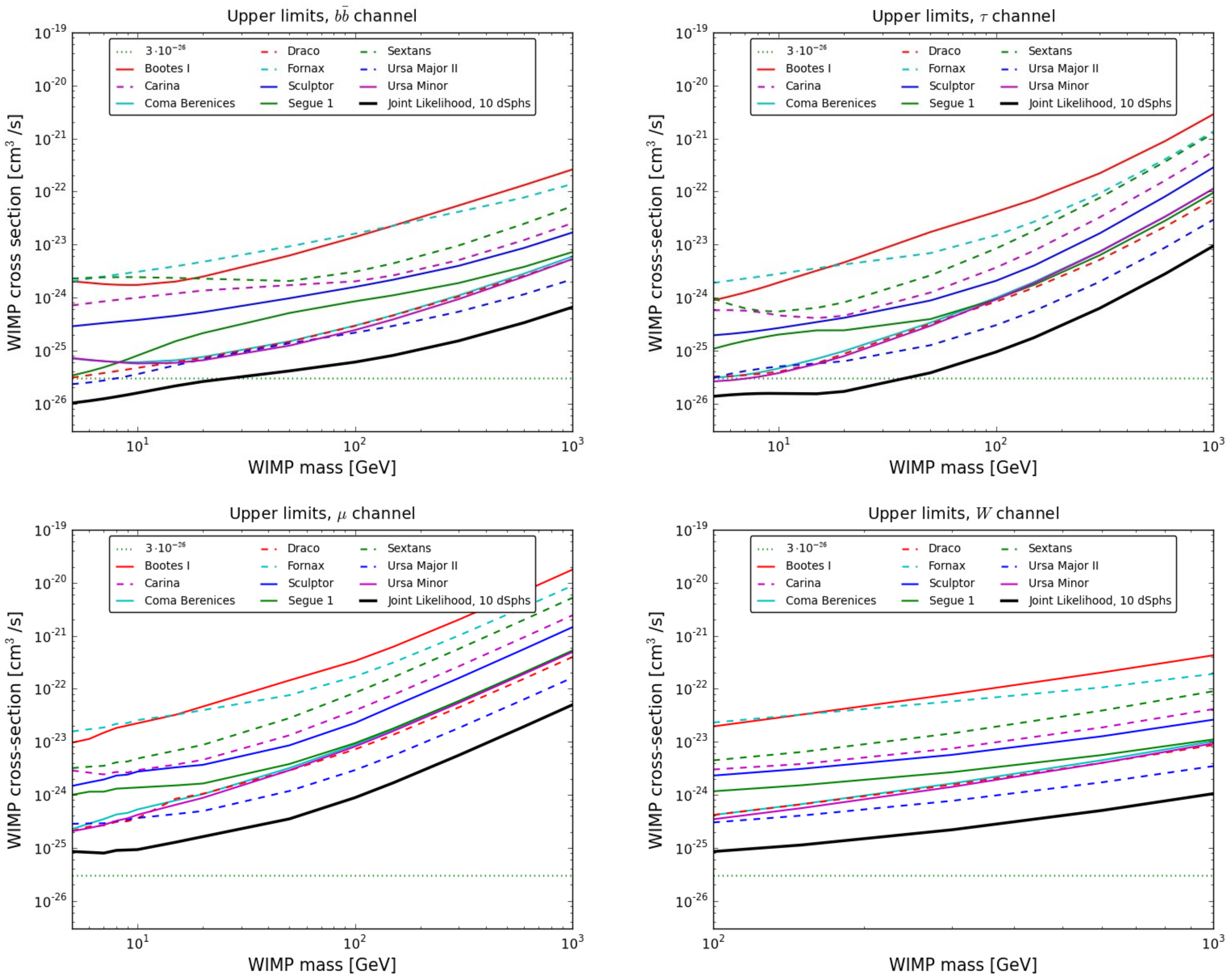


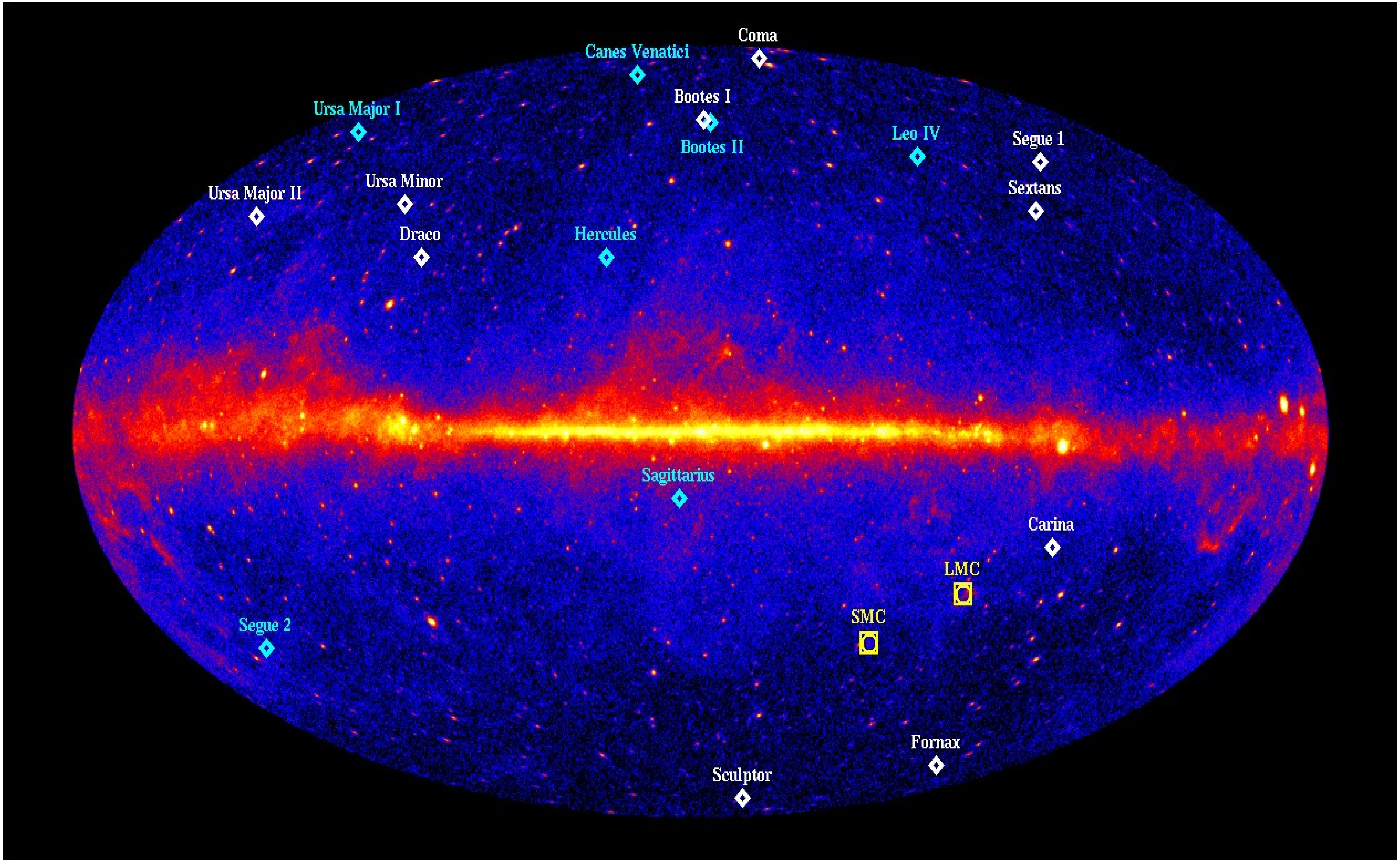
Summary

- Robust constraints, including J-factor uncertainties, on dark matter annihilation cross-sections from a joint likelihood analysis of 10 dSph galaxies for different annihilation channels.
- The limits start to cut into parameter space below the thermal WIMP cross-section for low masses!
- Various tests and cross-checks have been made to verify the method.

Back-up slides

Other channels

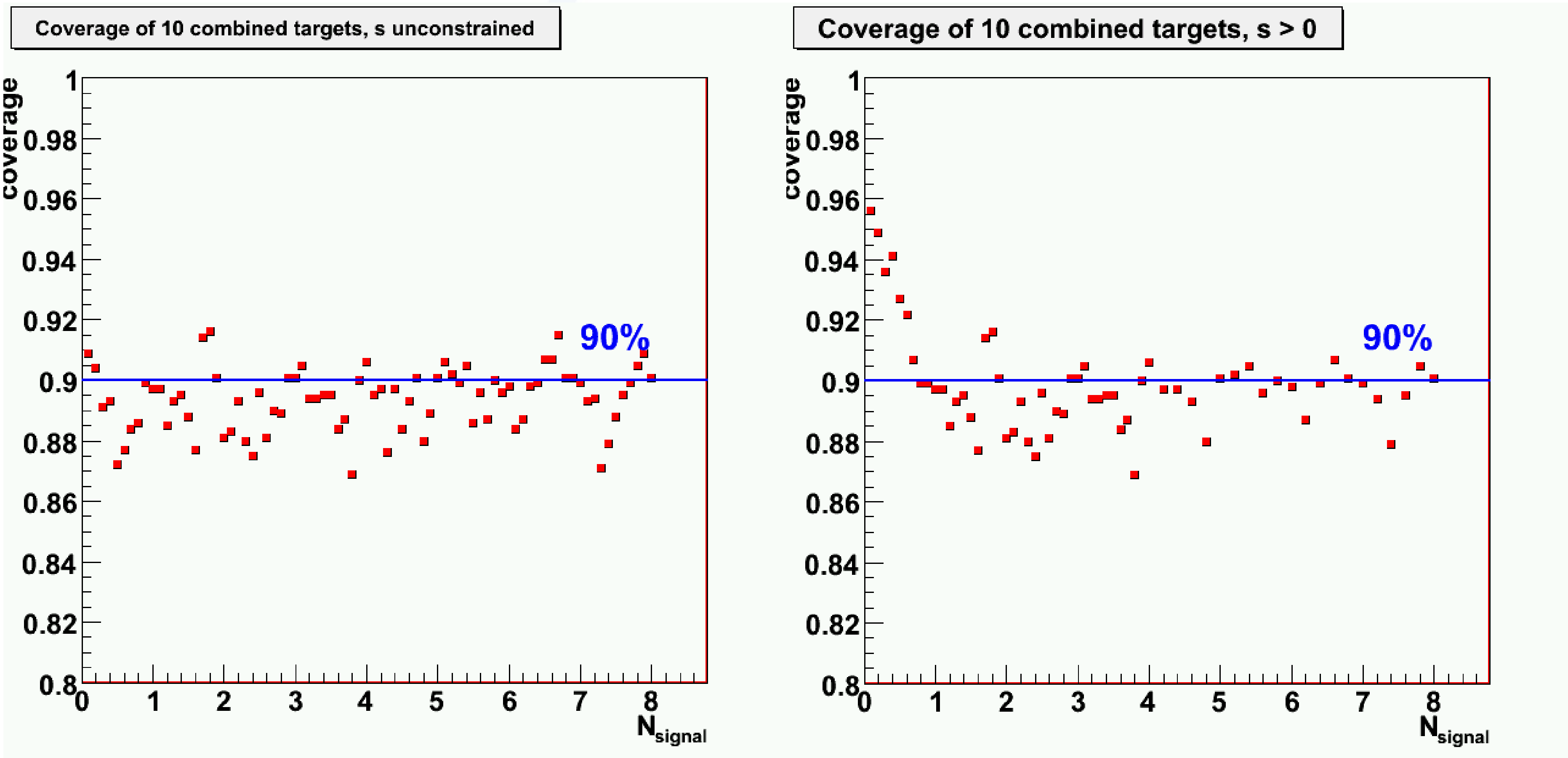




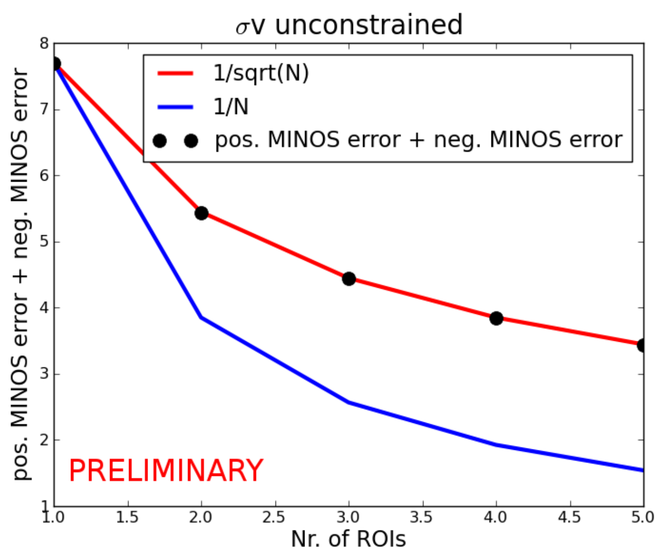
Coma
Canes Venatici
Bootes I
Ursa Major I
Bootes II
Leo IV
Segue 1
Ursa Minor
Ursa Major II
Sextans
Draco
Hercules
Sagittarius
Carina
LMC
SMC
Segue 2
Fornax
Sculptor

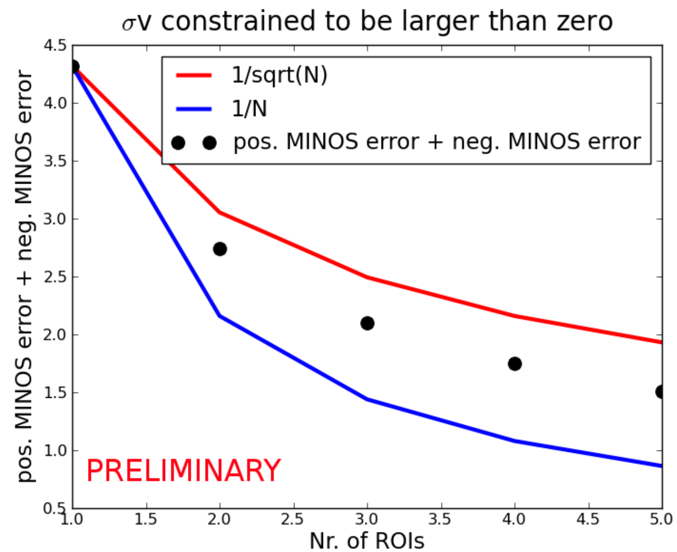
Coverage tests

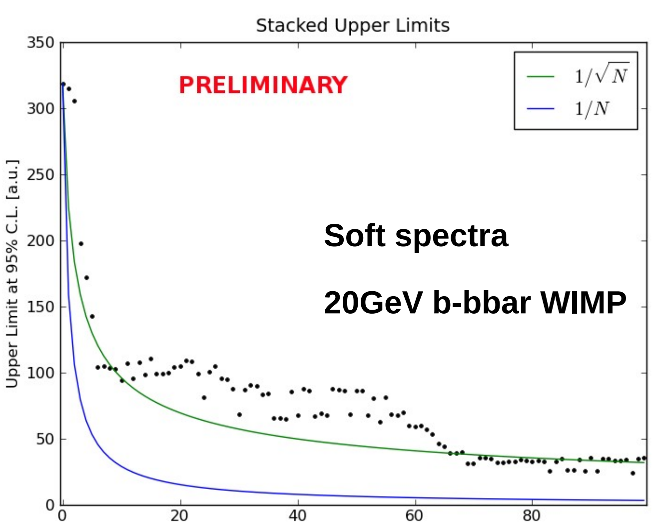
Coverage: the fraction of times the true value is contained in the confidence interval in a large number of repeated identical experiment.
Here we have tested the coverage on a toy model: Poisson with known background.

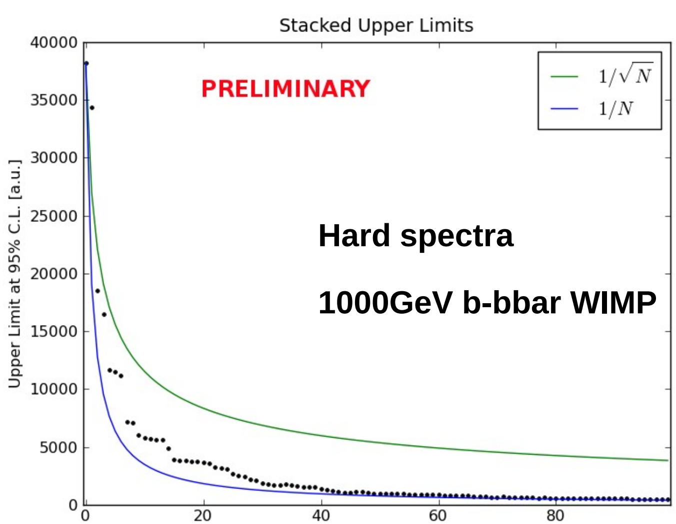


Behavior tests









The behavior is not always the same.

Depends on how the parameter is defined, and hardness of spectra.

Fig. by Alex Drlica-Wagner