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Bundesministerium für Bildung und Forschung

Exploring the population of Galactic very-high-energy γ-ray sources

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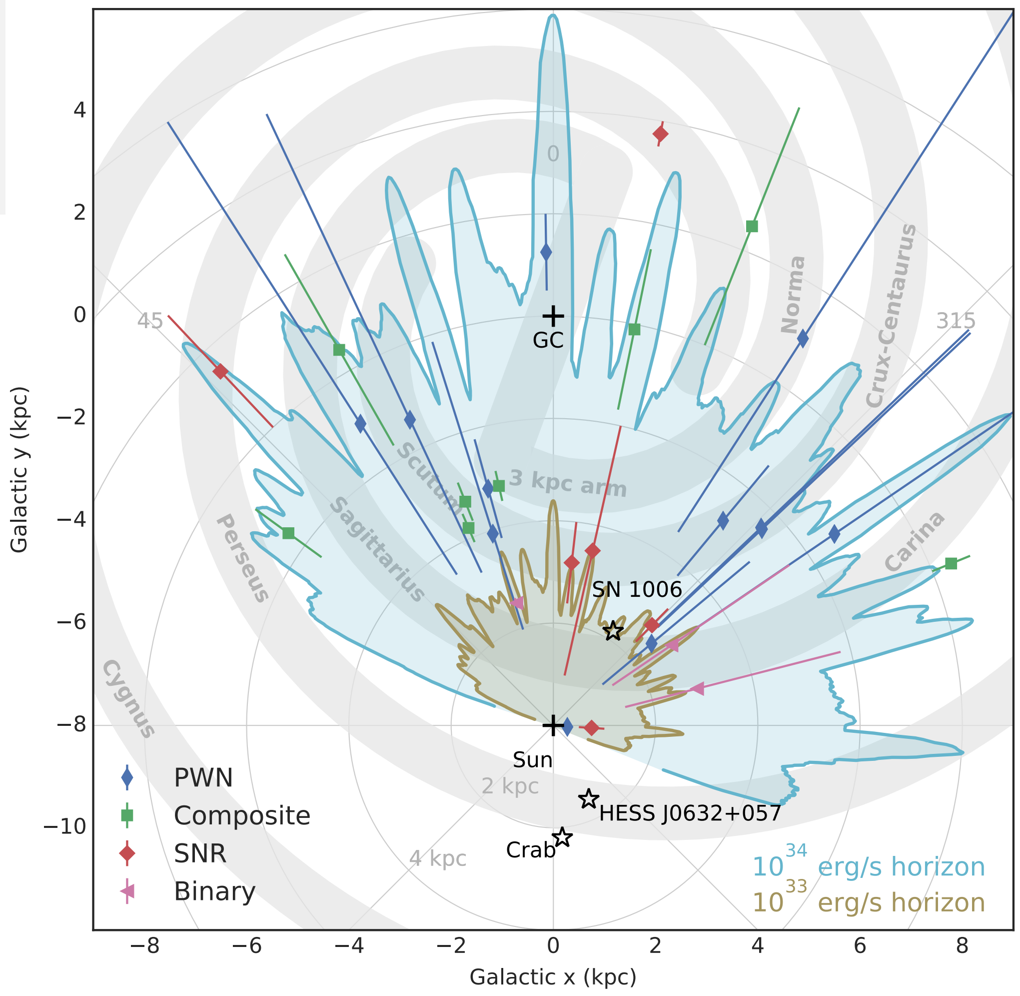
for the CTA Consortium

This work was conducted in the context of the CTA Consortium

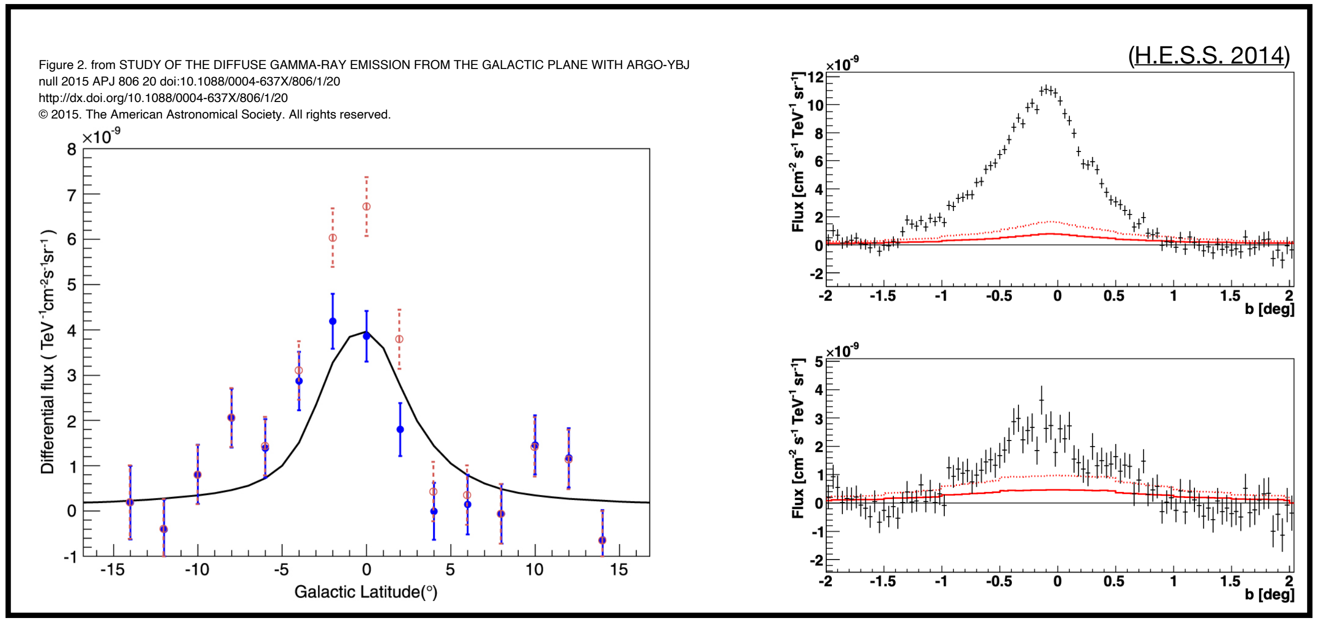
Introduction

- Nearly 150 Galactic VHE γ-ray sources have been detected
- These are only the tip of the iceberg
  - i.e. closest or most luminous ones
  - Small volume of the Milky Way has actually been probed at VHE
- Still, the hidden part of the population of VHE γ-ray sources has a significant impact on measurements
  - i.e. source confusion & unresolved sources in diffuse emission

Sensitivity range of the H.E.S.S. Galactic plane scan (H.E.S.S. Collaboration 2018)



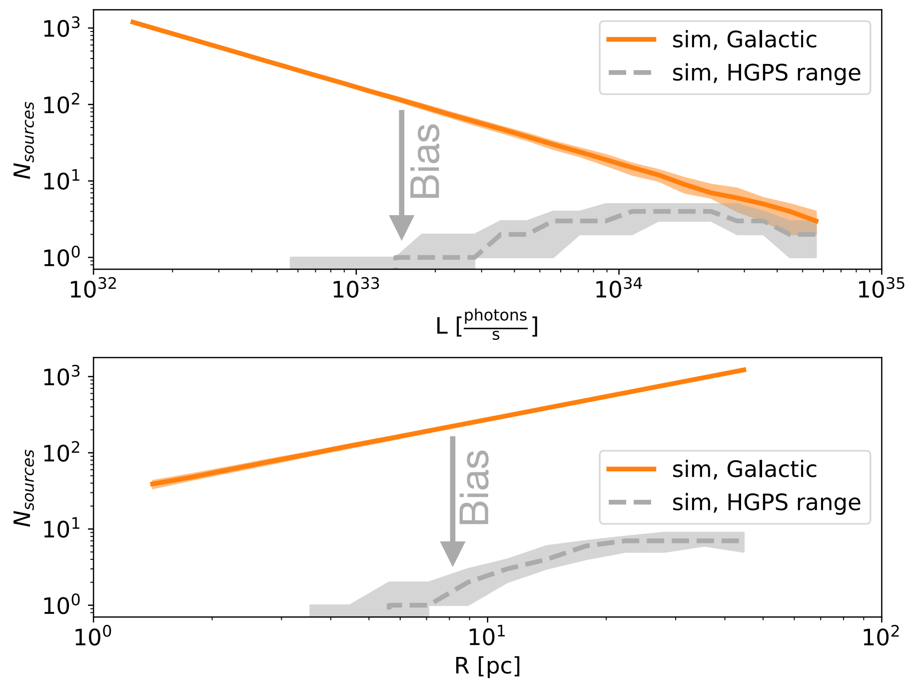
Diffuse emission at very-high energies



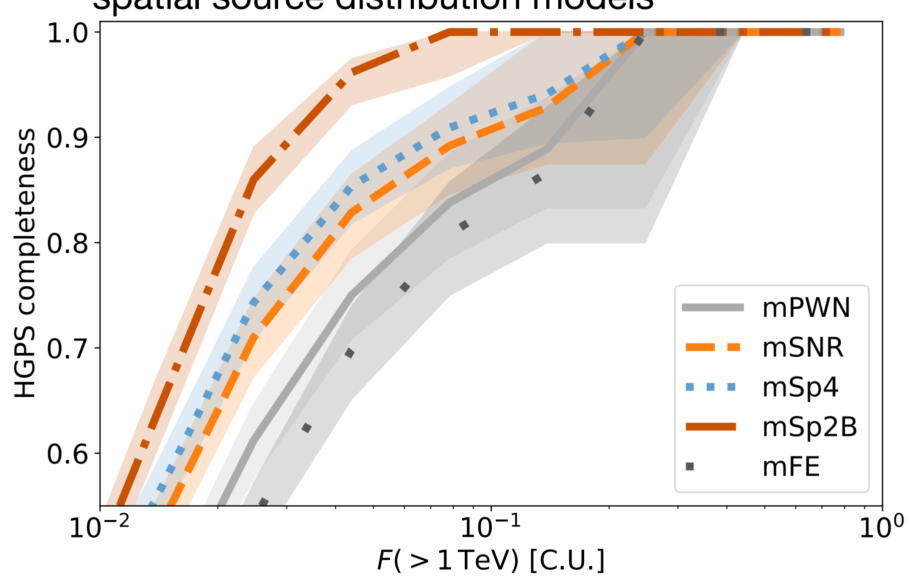
Introduction

- Sample of detected sources is not representative
- Strong observational bias
  - Dependence of the sensitivity on angular extent and position on the sky
- Range of completeness of a survey depends on properties of the population
  - e.g. size & spatial distribution of sources
  - HGPS completeness for pulsar-like distribution: 85% @ F>0.1 Crab

Comparison of the L & R distributions between the entire Galactic population and the sample in the HGPS sensitivity range (Steppa 2020)



HGPS completeness range for different spatial source distribution models



Introduction

- Goal:
  - Methodology for deriving population properties in the presence of strong observational biases
  - Modelling the entire Galactic population of VHE γ-ray sources

Details:

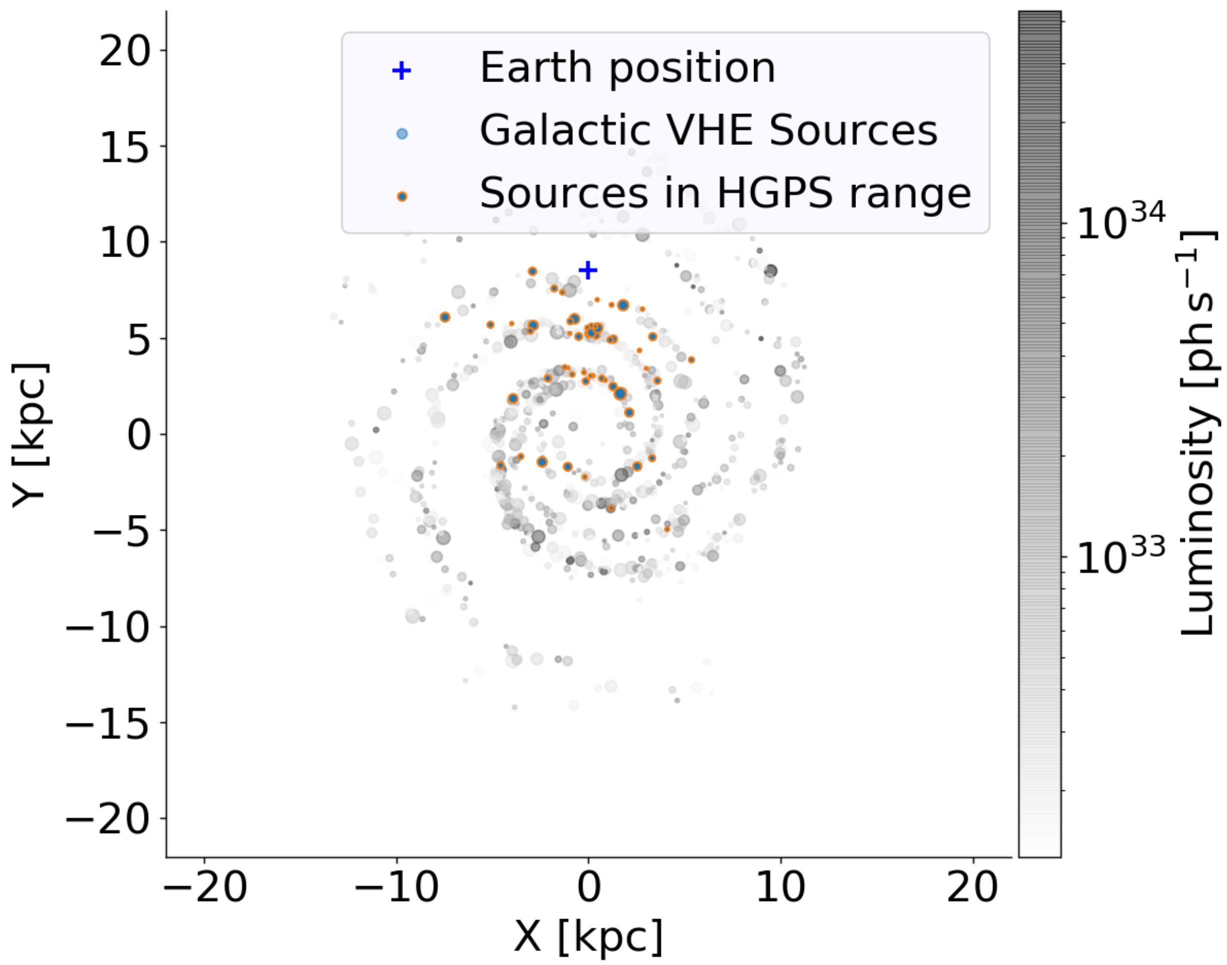
Constantin Steppa and Kathrin Egberts. Modelling the Galactic very-high-energy γ-ray source population. A&A, 643:A137, November 2020.

Approach to a model of the Galactic population

- Population synthesis
  - Simulations of Galactic source populations
  - Position, luminosity & size of each source is a random sample of modelled distribution functions
  - Calculation of observational quantities, i.e. flux, angular extent & position on the sky
  - Select sample of sources that fall into the sensitivity range of the instrument
  - Compare properties of the selected sample with catalogue sources
  - Adjust model parameters to achieve agreement

—> Accounting properly for the observational bias

Example of a synthetic source population with a source distribution following the spiral-arm structure of the Milky Way (Steppa 2020)

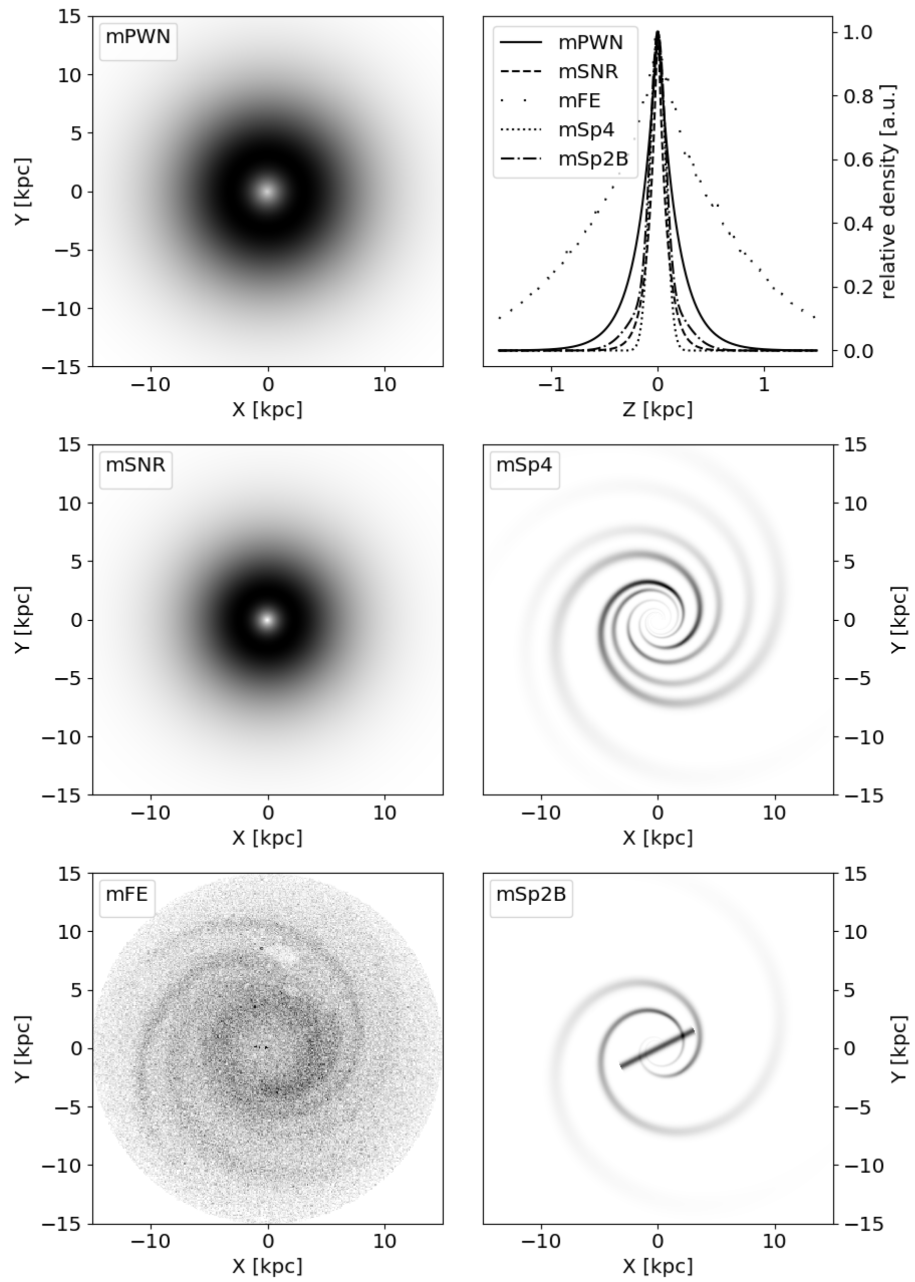


Model

- Sources are simulated as generic γ-ray emitters with radially symmetric shape
    - No distinct classes, spectrum or morphology
- Five distributions with fixed parameters were tested
    - Motivated by pulsars, supernova remnants, ISM, free electrons
- Bolometric luminosity above 1 TeV
    - power law with fixed boundaries & free index
- Radius
    - power law with fixed boundaries & free index
- All variables are assumed to be independent

—> 5 models (for different spatial distributions) with 2 free parameters (α_L, α_R)

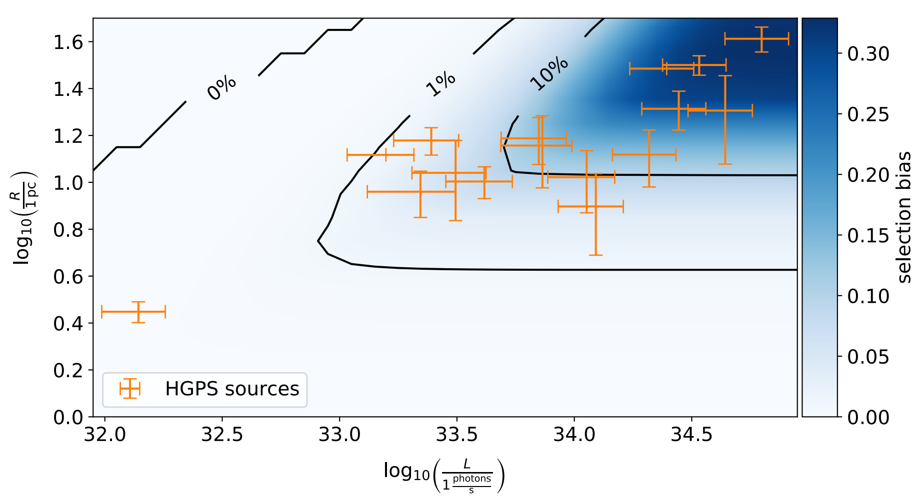
Tested spatial source distribution models



Parameter reconstruction with maximum likelihood estimation

- Reconstruction of global properties based on a biased subsample
- Using the HGPS catalogue with provided sensitivity map
- Derive expected distribution of sources within the HGPS sensitivity range in a 2D histogram over luminosity & radius via simulation
- Optimise model parameters to maximise the likelihood for the observed distribution

Selection bias & HGPS sample (Steppa 2020)



Likelihood estimation

- Sensitivity estimate

$$F_{min}(l, b, \sigma_{source}) = \begin{cases} F_{min,0}(l, b)\sqrt{\dfrac{\sigma_{source}^2 + \sigma_{PSF}^2}{\sigma_{PSF}^2}}, & \sigma_{source} \leq 1° \\ \infty, & \sigma_{source} > 1° \end{cases}$$

- Expected number of detected sources within field of view for given L & R

$$N_{det}(L, R) = N_{FoV}\, P(L, R) \int_0^\infty \mathrm{d}F \int_0^\infty \mathrm{d}\sigma \int_{V_{FoV}} \mathrm{d}\mathbf{x}\, P(\mathbf{x}) \cdot \mathscr{H}\left(F - F_{min}(l(\mathbf{x}), b(\mathbf{x}), \sigma)\right) \cdot \delta\left(F - \frac{L}{4\pi\, d^2(\mathbf{x})}\right) \cdot \delta\left(\sigma - \tan^{-1}\left(\frac{R}{d(\mathbf{x})}\right)\right)$$

- Expected number of sources in a 2D interval (L_{min}, L_{max}, R_{min}, R_{max})

$$N_{pred,i} = N_{FoV} \int_{L_{min,i}}^{L_{max,i}} \mathrm{d}L \int_{R_{min,i}}^{R_{max,i}} \mathrm{d}R\; P(L, R)\, C(L, R)$$

- Negative log-likelihood for parametric distribution function P(L,R | α_L, α_R)

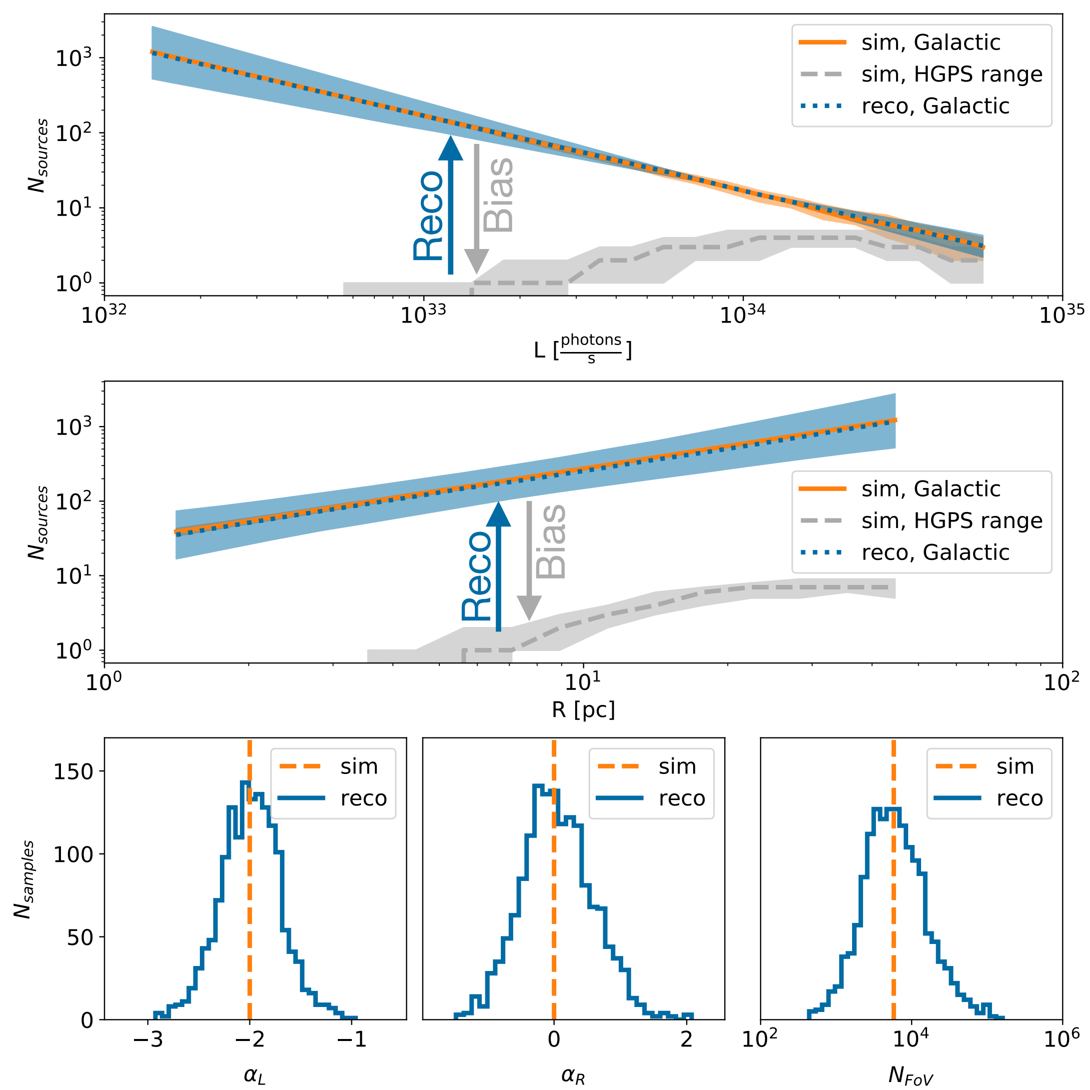
$$\mathscr{L} = -\sum_i \log\left(P_{N_{pred,i}}\left(N_{true,i}\right)\right)$$

Parameter reconstruction with maximum likelihood estimation

- Limited to extended sources with known distance —> 16*
- Validation of reconstruction method with simulations
    - i.e. unbiased parameter estimation from biased source sample
- Result:

Model	α_L	α_R
mSNR	-1.70	-1.19
mPWN	-1.81	-1.13
mFE	-1.94	-1.21
mSp4	-1.64	-1.17
mSp2B	-1.78	-1.62

Luminosity & radius distribution from hundreds of simulated populations with fixed model parameters, the corresponding source samples in the HGPS sensitivity range and the reconstructed distributions (Steppa 2020)

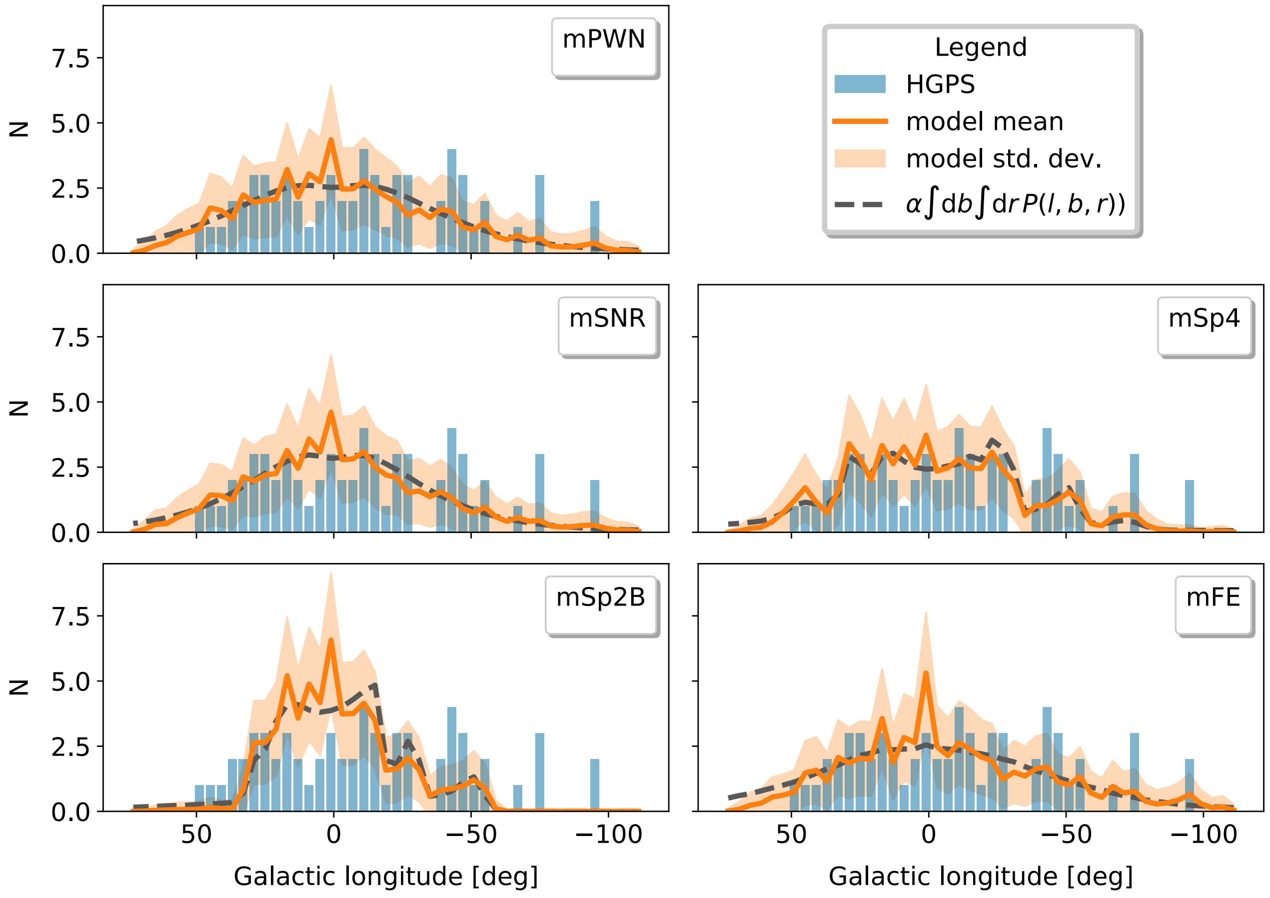


* sources that surpass the detection threshold according to the sensitivity estimate

Evaluation of the model

- Using population synthesis and sensitivity estimate to derive „detectable“ sources
- Comparison with HGPS sample
- Distribution over longitude
    - Match for almost all spatial distribution models

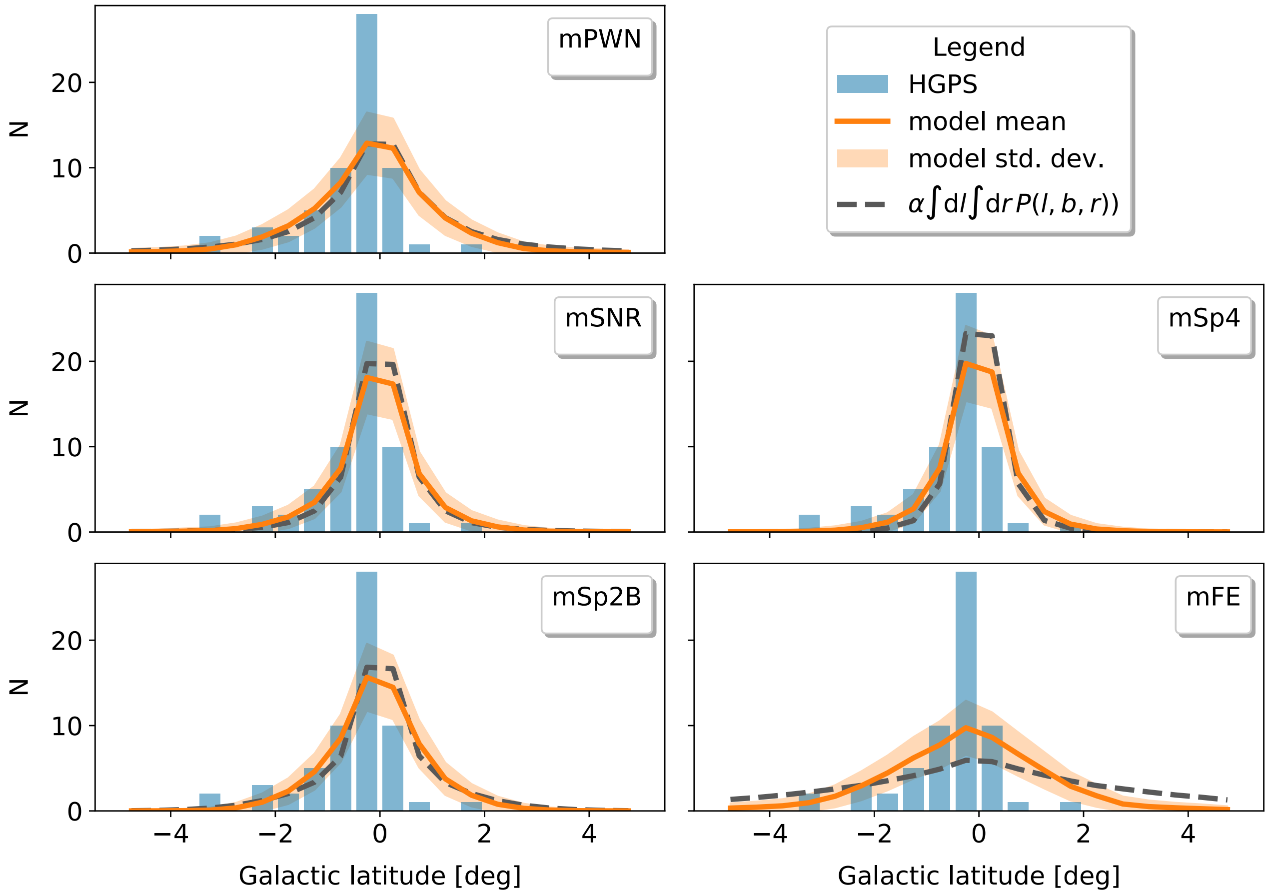
Comparison between the source distributions over longitude for the HGPS sample and simulated sources in the HGPS sensitivity range (Steppa 2020)



Evaluation of the model

- Using population synthesis and sensitivity estimate to derive „detectable“ sources
- Comparison with HGPS sample
- Distribution over latitude
  - Asymmetry in HGPS sample not reproduced
  - —> intrinsic feature of the source spatial distribution

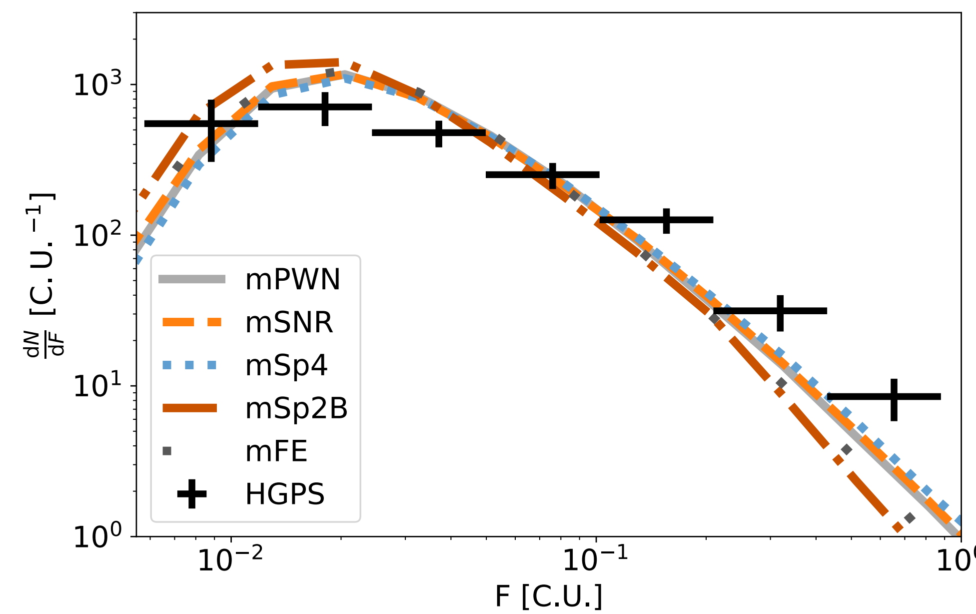
Comparison between the source distributions over latitude for the HGPS sample and simulated sources in the HGPS sensitivity range (Steppa 2020)



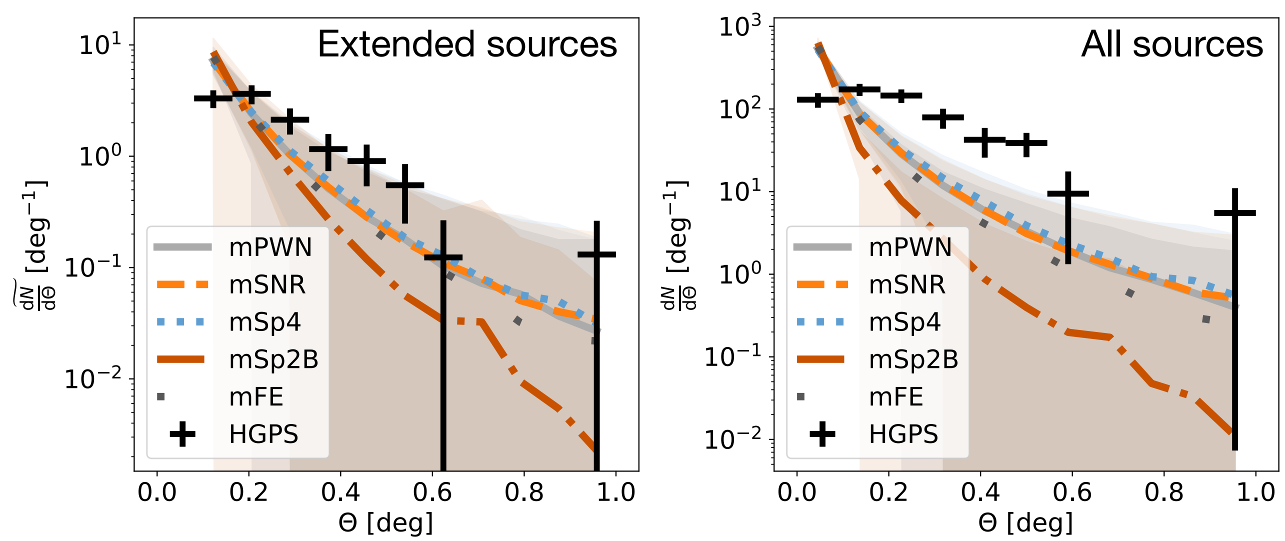
Evaluation of the model

- Using population synthesis and sensitivity estimate to derive „detectable“ sources
- Comparison with HGPS sample
- Distribution over flux & extent
    - Fair agreement, but no perfect match
    - Too few extended sources

Comparison between the source distributions over flux for the HGPS sample and simulated sources in the HGPS sensitivity range



Comparison between the source distributions over angular extent for the HGPS sample and simulated sources in the HGPS sensitivity range



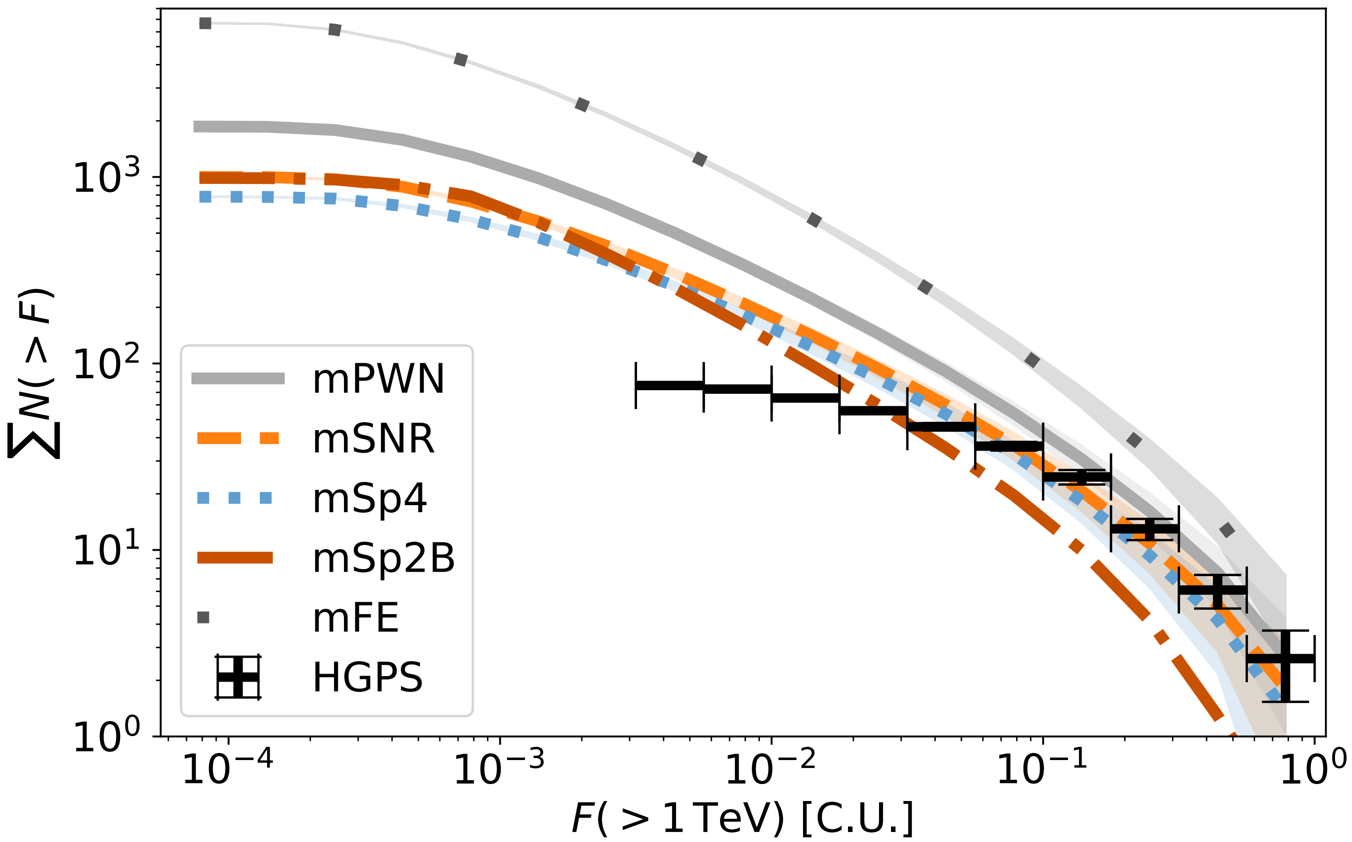
Application of the model

- Prediction of global properties of the population

Model	N	L [ph s^{-1}] Mean / Std	F [ph cm^{-2} s^{-1}] Median / QD
mSNR	1063^{+137}_{-126}	$(1.73 / 0.16) \cdot 10^{36}$	$(4.89 / 1.41) \cdot 10^{-10}$
mPWN	2004^{+259}_{-239}	$(2.47 / 0.18) \cdot 10^{36}$	$(7.74 / 1.86) \cdot 10^{-10}$
mFE	7038^{+912}_{-839}	$(6.32 / 0.26) \cdot 10^{36}$	$(1.54 / 0.16) \cdot 10^{-9}$
mSp4	831^{+107}_{-98}	$(1.59 / 0.17) \cdot 10^{36}$	$(3.38 / 0.70) \cdot 10^{-10}$
mSp2B	1081^{+140}_{-128}	$(1.44 / 0.14) \cdot 10^{36}$	$(1.96 / 0.20) \cdot 10^{-10}$

13%-32% of the flux in HGPS region attributed to as yet unresolved sources

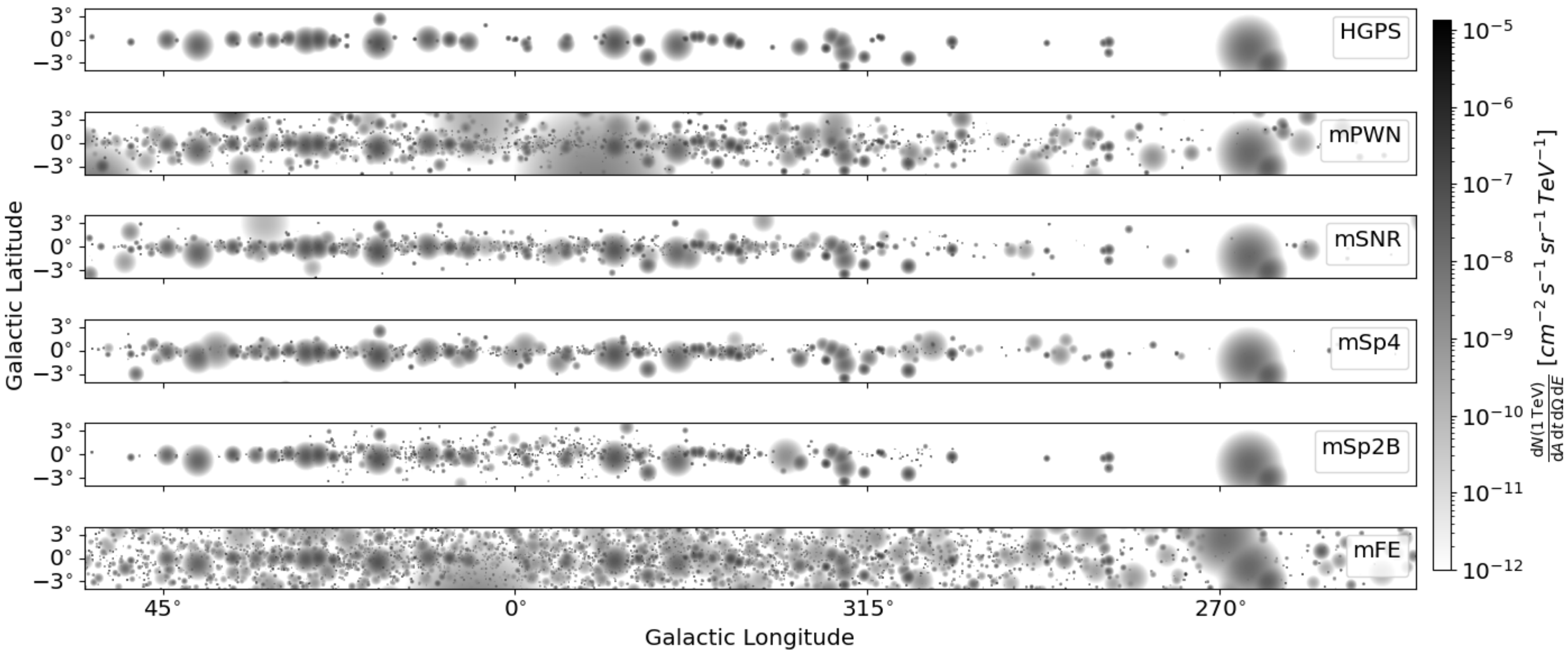
Comparison between the log(N)-log(S) distributions for the HGPS sample and simulated source populations (Steppa 2020)



Application of the model

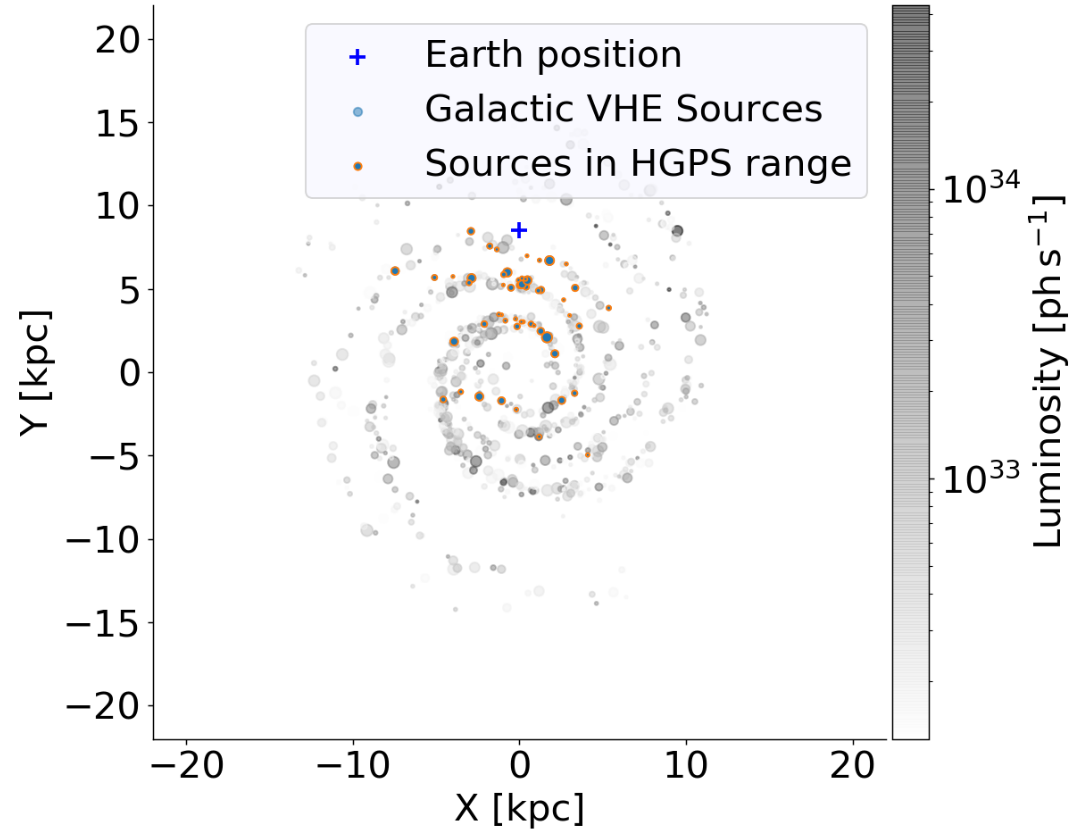
- Prediction of global properties of the population
- Generation of flux maps and templates of unresolved sources

Flux maps of synthetic source populations for different spatial distribution models including the HGPS sample (Steppa 2020)



Application of the model

- Prediction of global properties of the population
- Generation of flux maps and templates of unresolved sources
- Deployment of synthetic populations with discrete sources for cosmic-ray propagation code



Application of the model

- Prediction of global properties of the population
- Generation of flux maps and templates of unresolved sources
- Deployment of synthetic populations with discrete sources for cosmic-ray propagation code
- Assessment of the observed source sample and prospects of future instruments

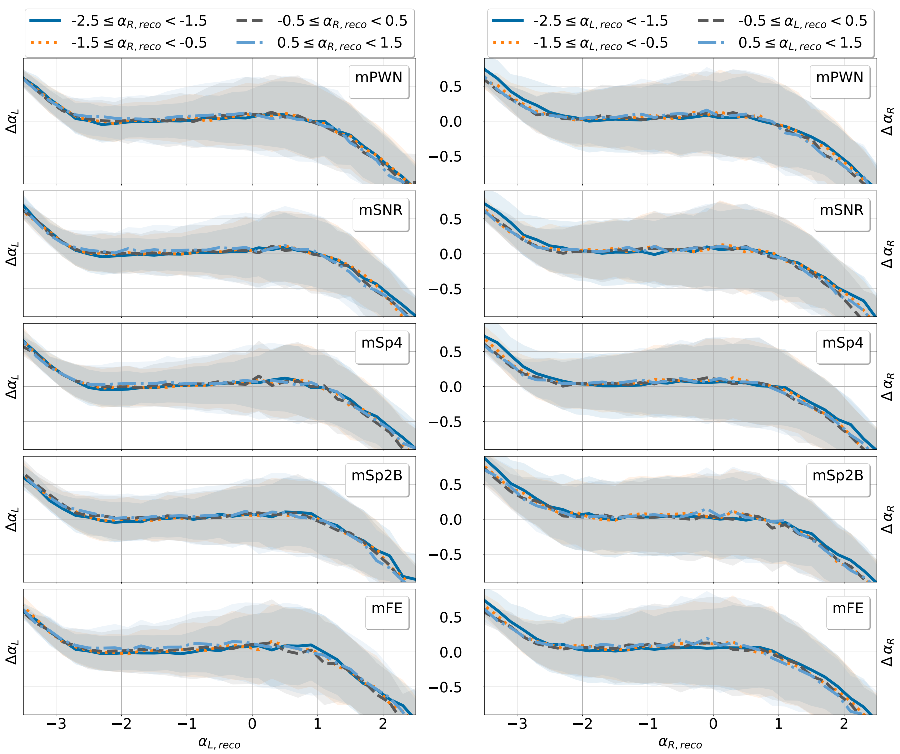
	HGPS	CTA*
Sample size	78	200 - 600
Source confusion	22%-24%	20%-25%

* CTA GPS with a homogeneous sensitivity of 2 mCrab in the inner Galactic region $|l| < 60°$, $|b| < 2°$ (The CTA Consortium 2019) and an angular resolution of 0.05° @ 1 TeV (prod3b-v2)

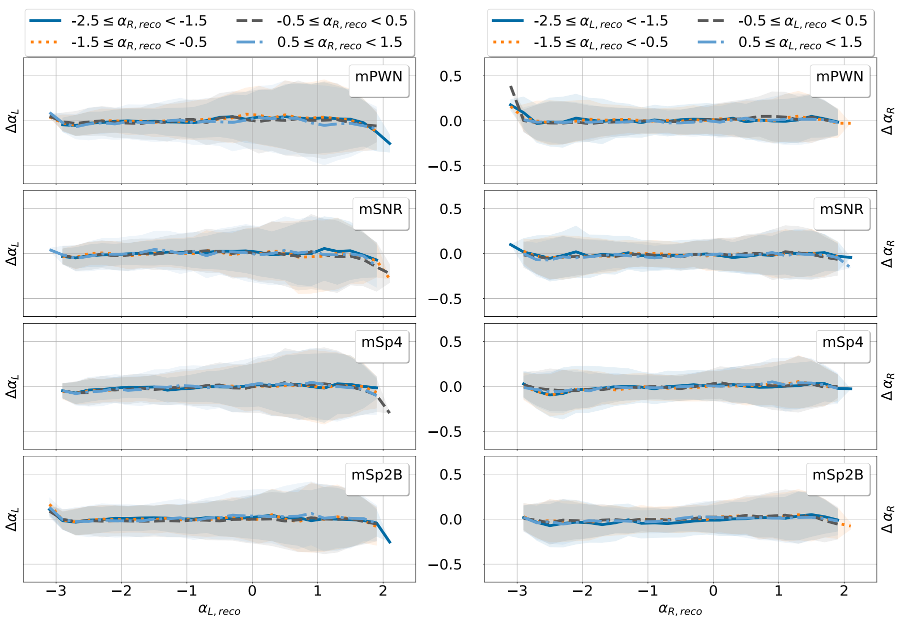
Improving the parameter reconstruction

- Increase the statistics by estimating L & R for sources with unknown distance & angular extent
- Analyse complex distribution of the sample with deep learning to infer global properties
- MC simulations show reduced reconstruction errors

Reconstruction errors with the MLE method for different spatial distribution



Reconstruction errors with the DL method for different spatial distribution



Conclusion

- A method to derive global properties of the population of Galactic very-high-energy γ-ray sources from a biased sample has been presented
- The models tested are comparable to observation
- Various applications are made possible by the population synthesis approach, including
  - Characterisation of the population of individual source classes
  - Generation of templates for unresolved sources
  - Study of instrumental effects, i.e. the impact of source confusion on the sensitivity of a Galactic survey