Recovering Population Properties of Gamma-Ray Sources in the Presence of Biased Data

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GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

Universität Potsdam

Connecting Observables to Reality

Only tiny fraction of gamma-ray sources detected

Yet: knowledge of entire population desirable to

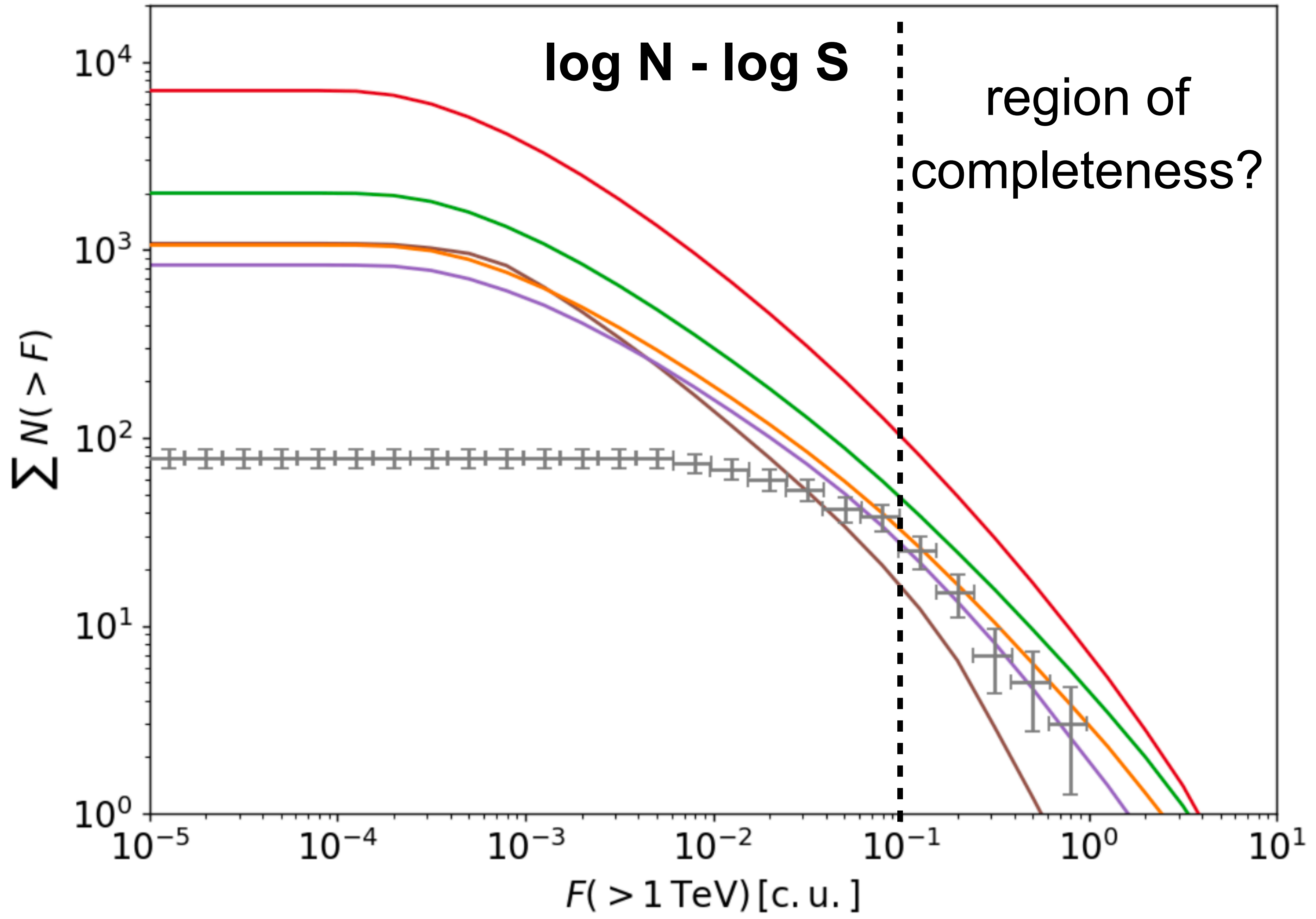
Derive Milky Way properties like energy output in cosmic rays & connection to locally observable cosmic-ray spectrum

Understand contribution of unresolved sources in diffuse emission

Detected sources are a highly biased sample

We only see the brightest and closest sources

Detection threshold effects



Usually not enough!

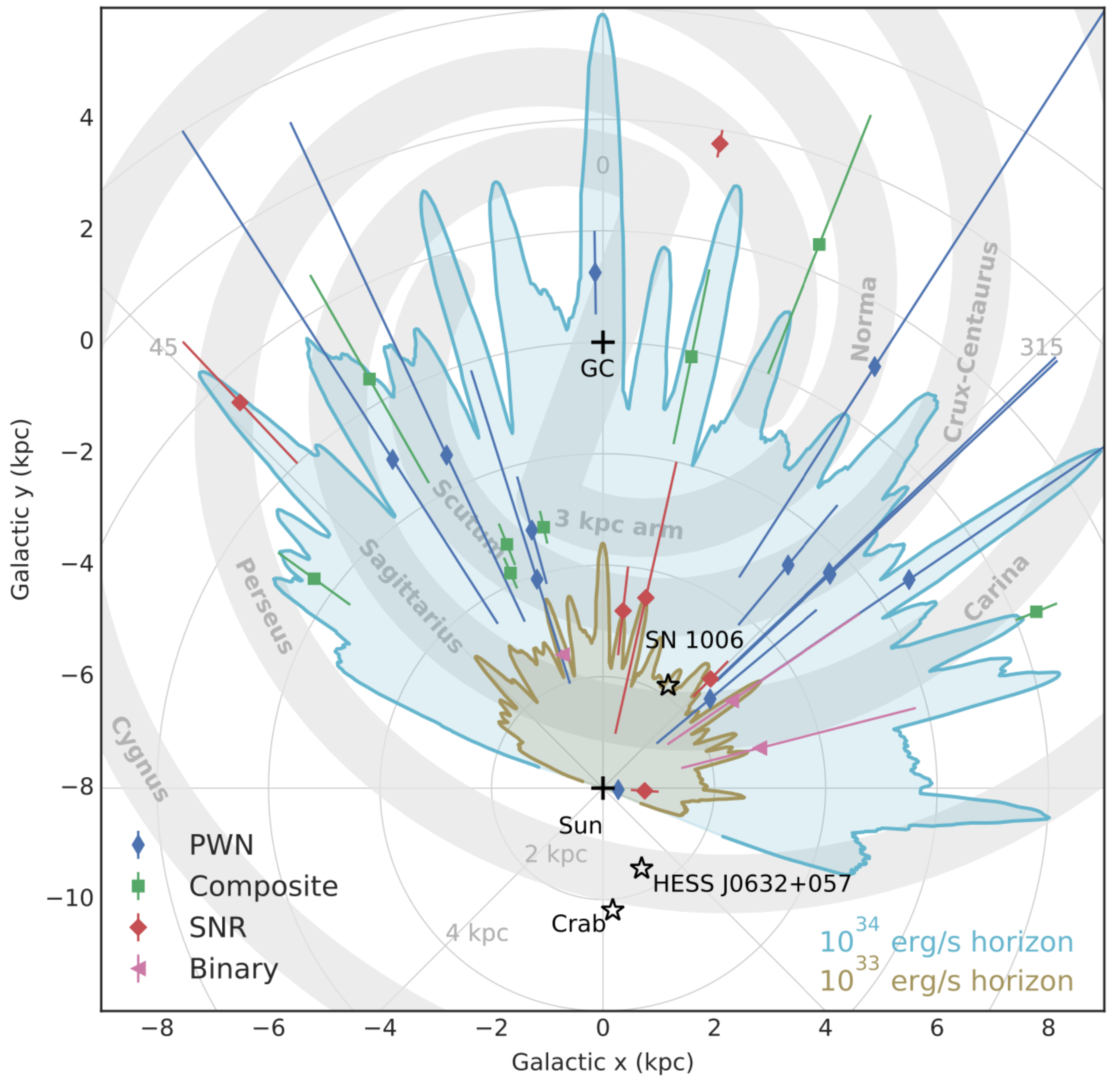
Also severely limits the data set

Detection threshold depends on instrument characteristics and analysis procedures (e.g. background estimation)

Example H.E.S.S. Galactic Plane Survey

Detection threshold function of longitude, latitude and source extension σ_{source}

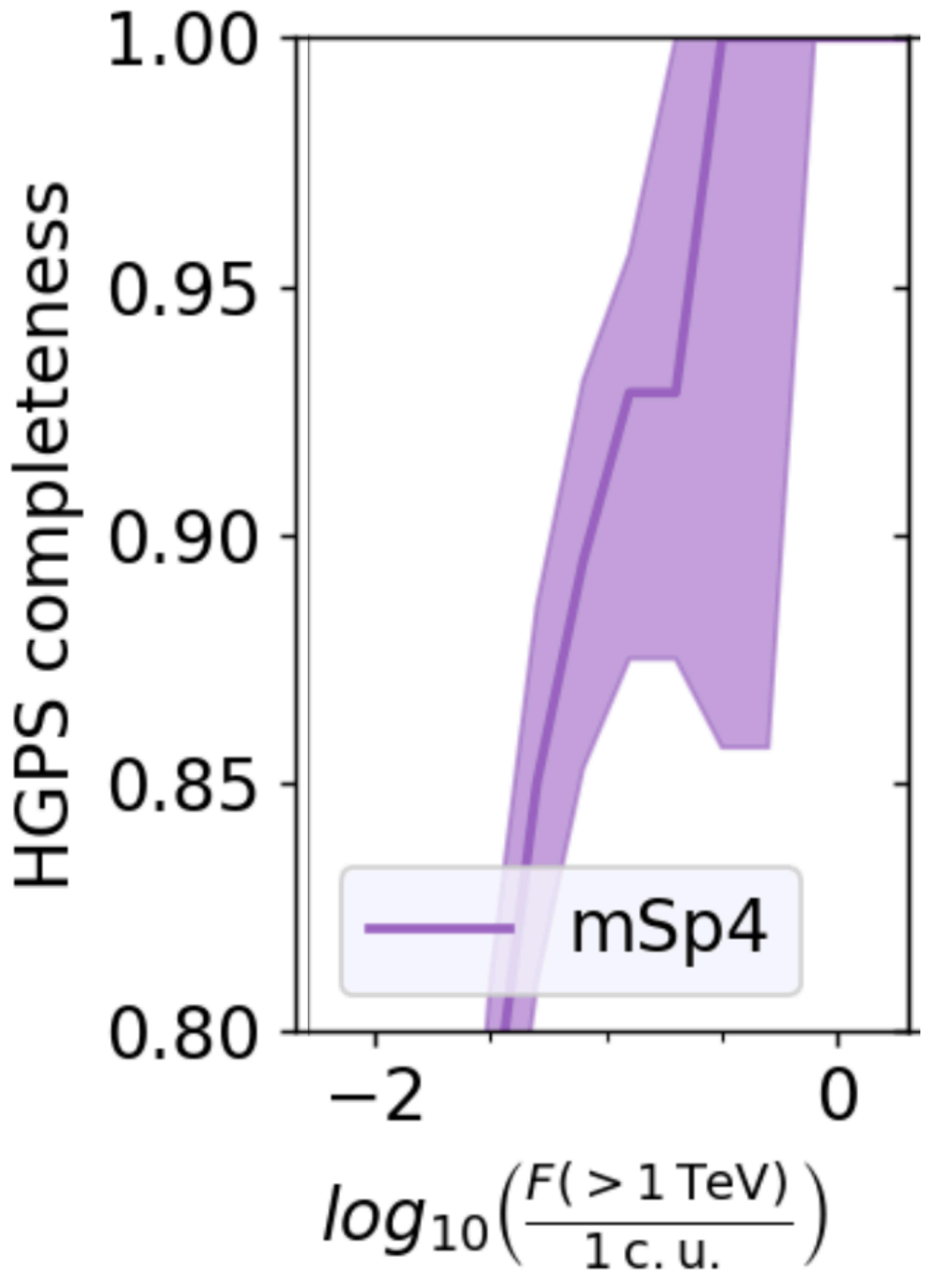
$$F_{min}(\sigma_{source}) = \begin{cases} F_{min,0}\sqrt{\frac{\sigma_{source}^2+\sigma_{PSF}^2}{\sigma_{PSF}^2}}, & \leq 1^\circ \\ \infty, & > 1^\circ \end{cases}$$



Other instruments, other effects:

Fermi-LAT - homogeneous exposure but larger background along the Galactic plane due to diffuse emission

Completeness Level

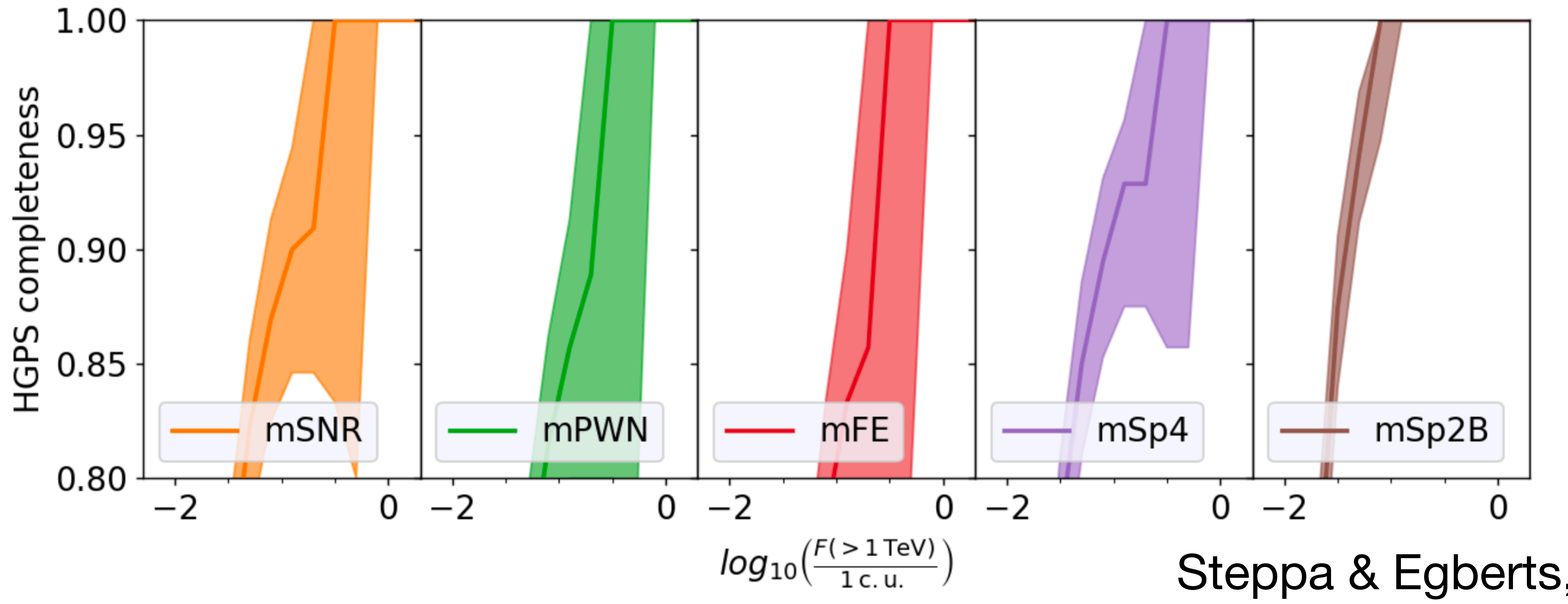


Based on simulated source populations and implementation of the HGPS detection threshold

Even extremely bright sources can be missed!

In the covered sky region, there is still a chance to miss sources as bright as the Crab (if extended enough)

Predictions depend crucially on the underlying model

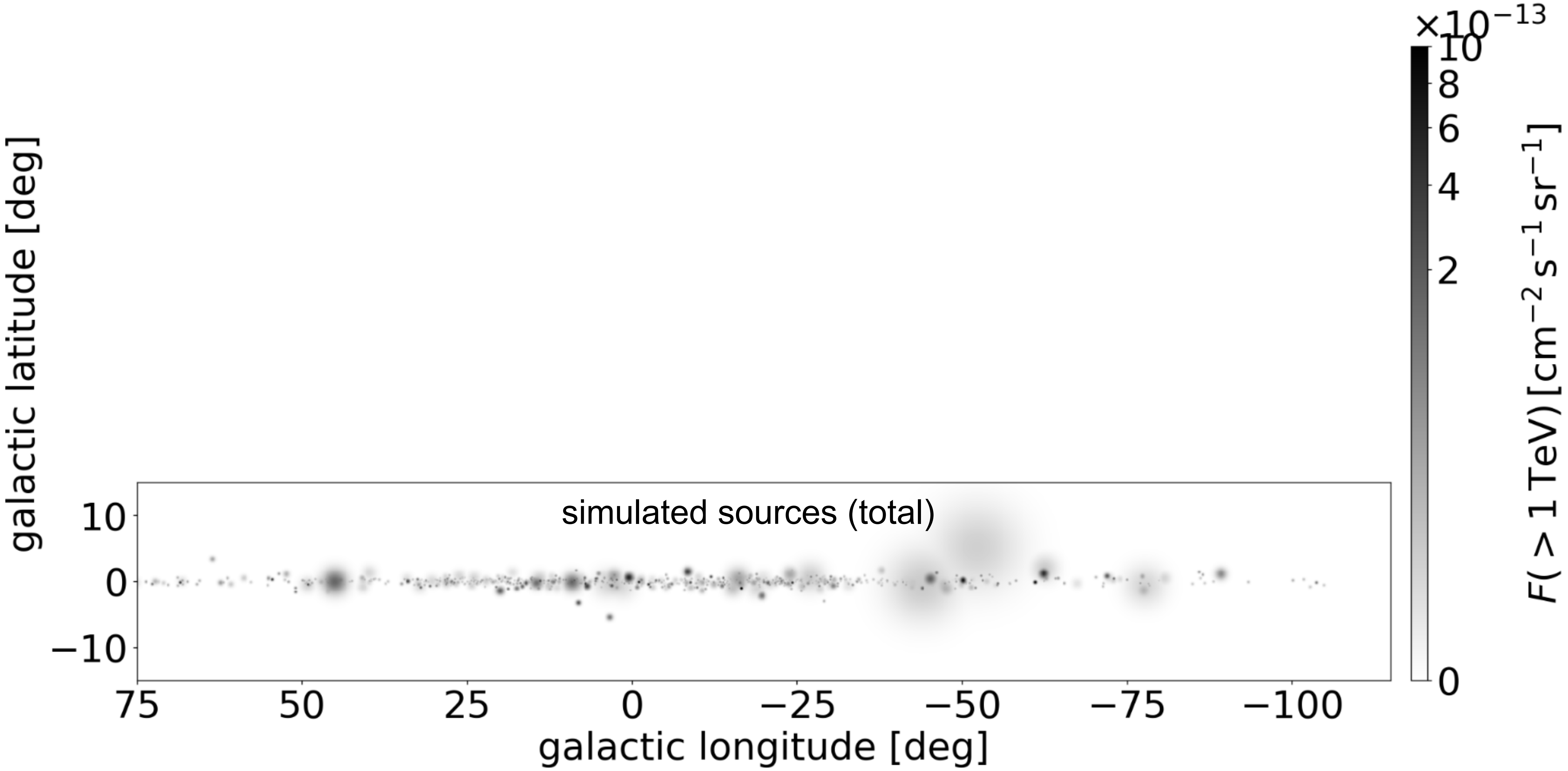


Steppa & Egberts, A&A 2020

different spatial models

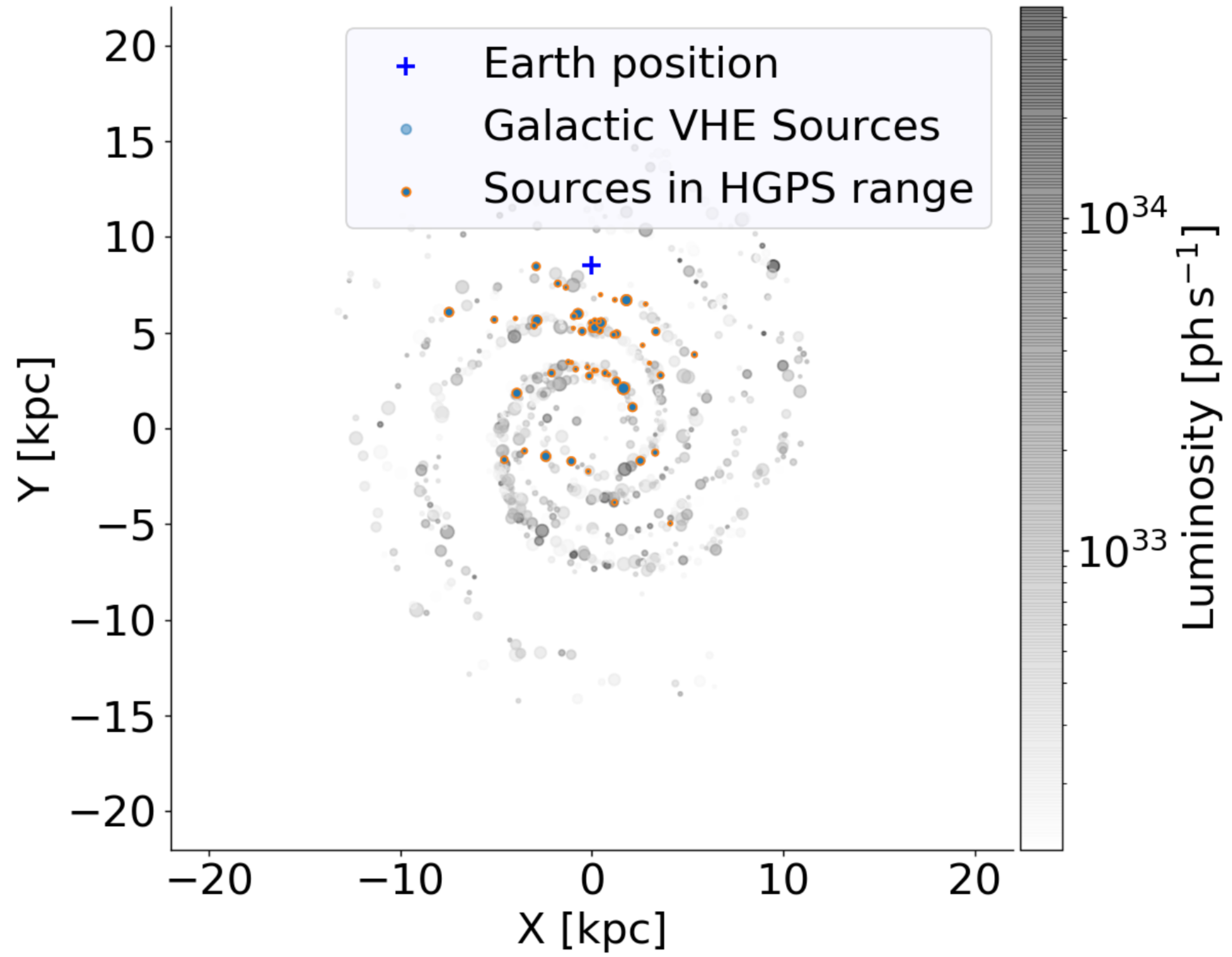
How to derive population properties with biased data?

Forward folding approach: Population synthesis



generic source model:

sources characterised by position, radius, luminosity



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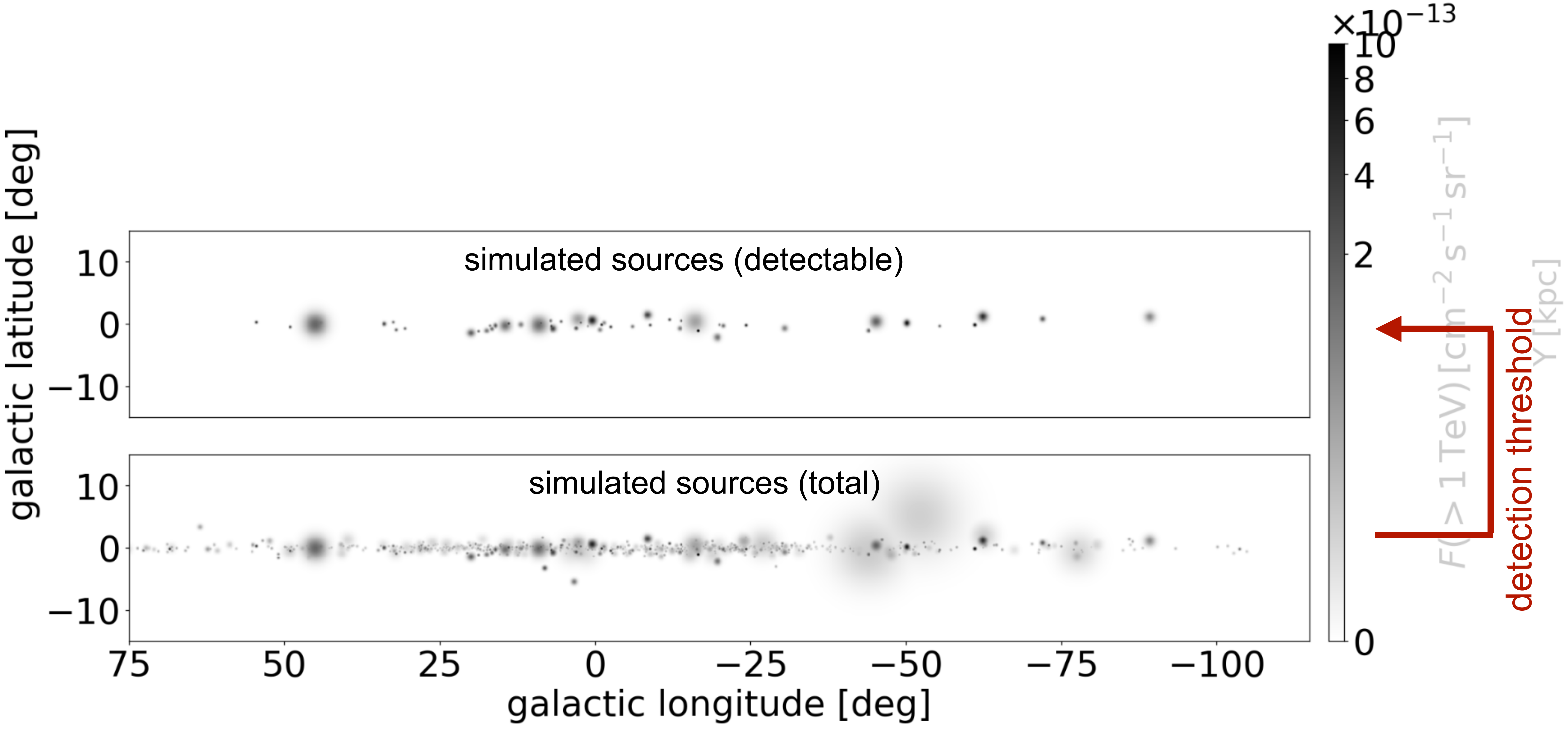

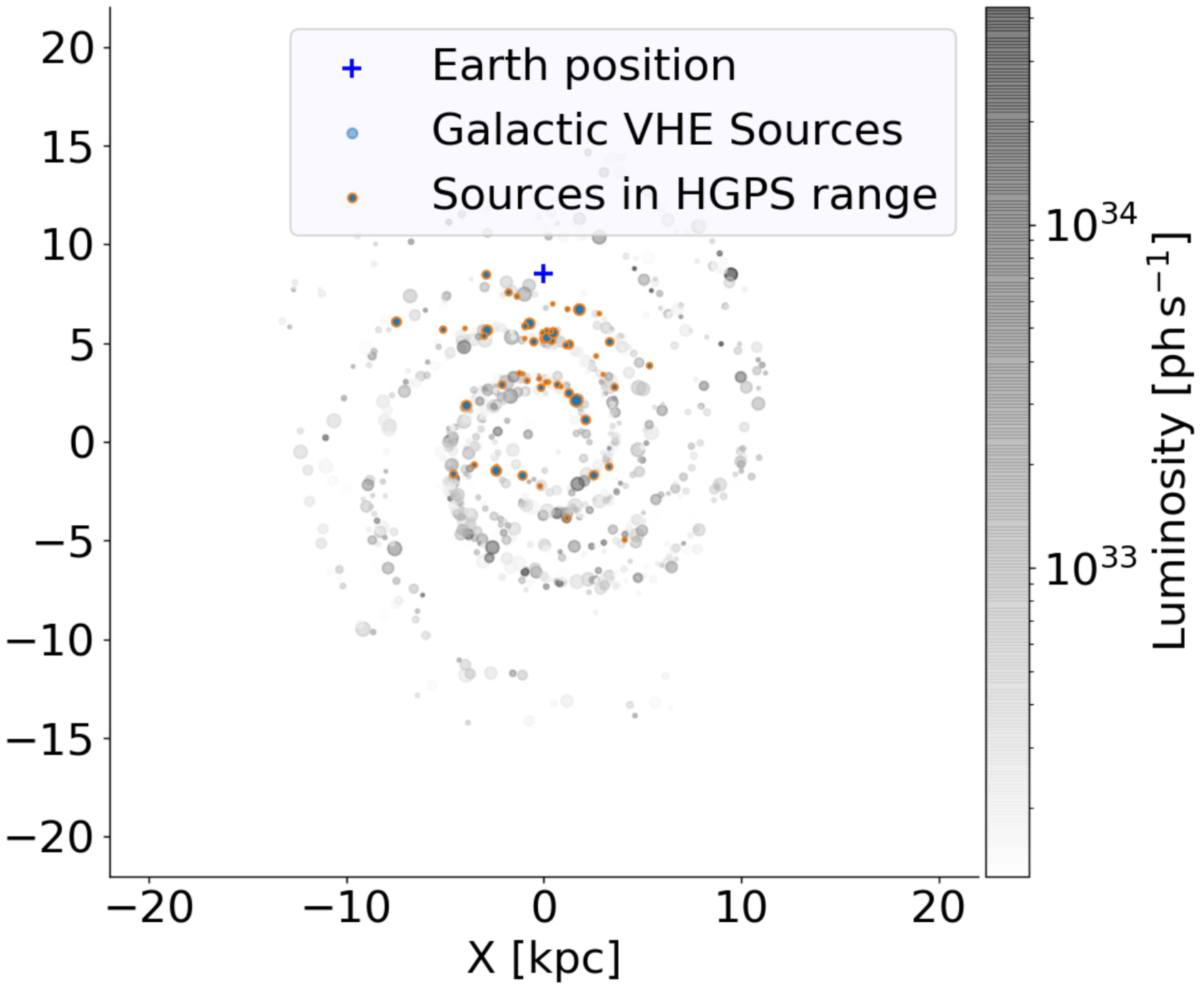

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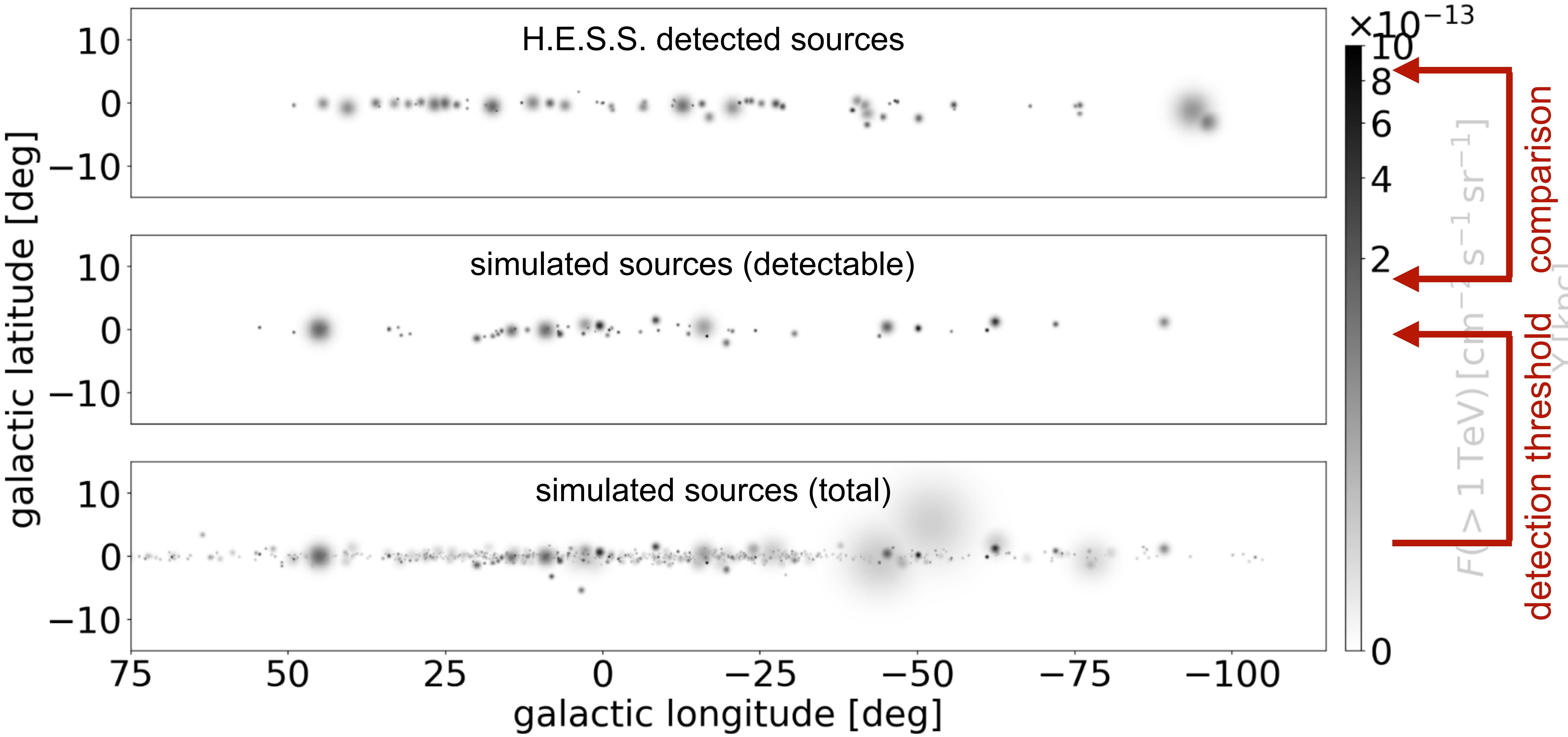

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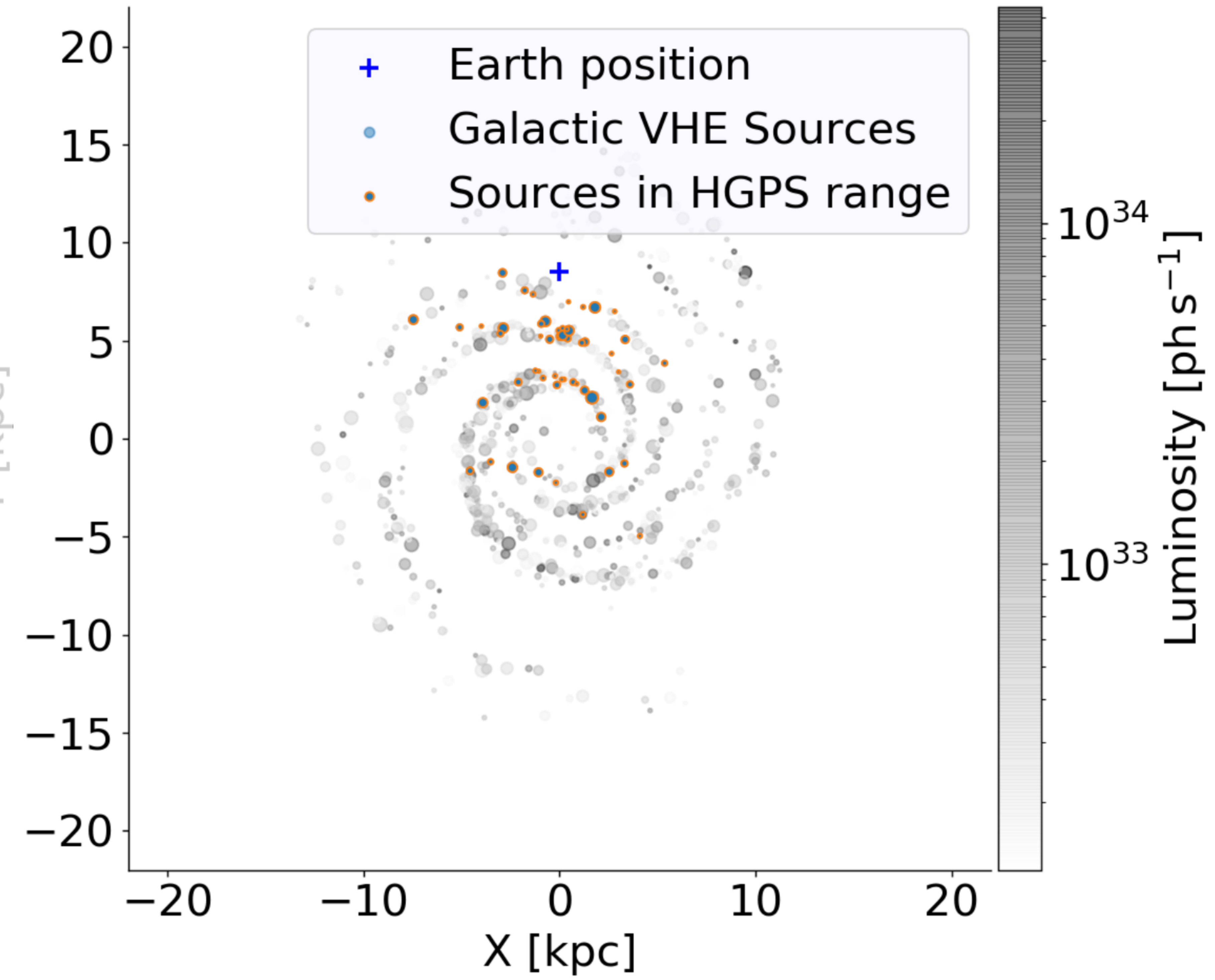


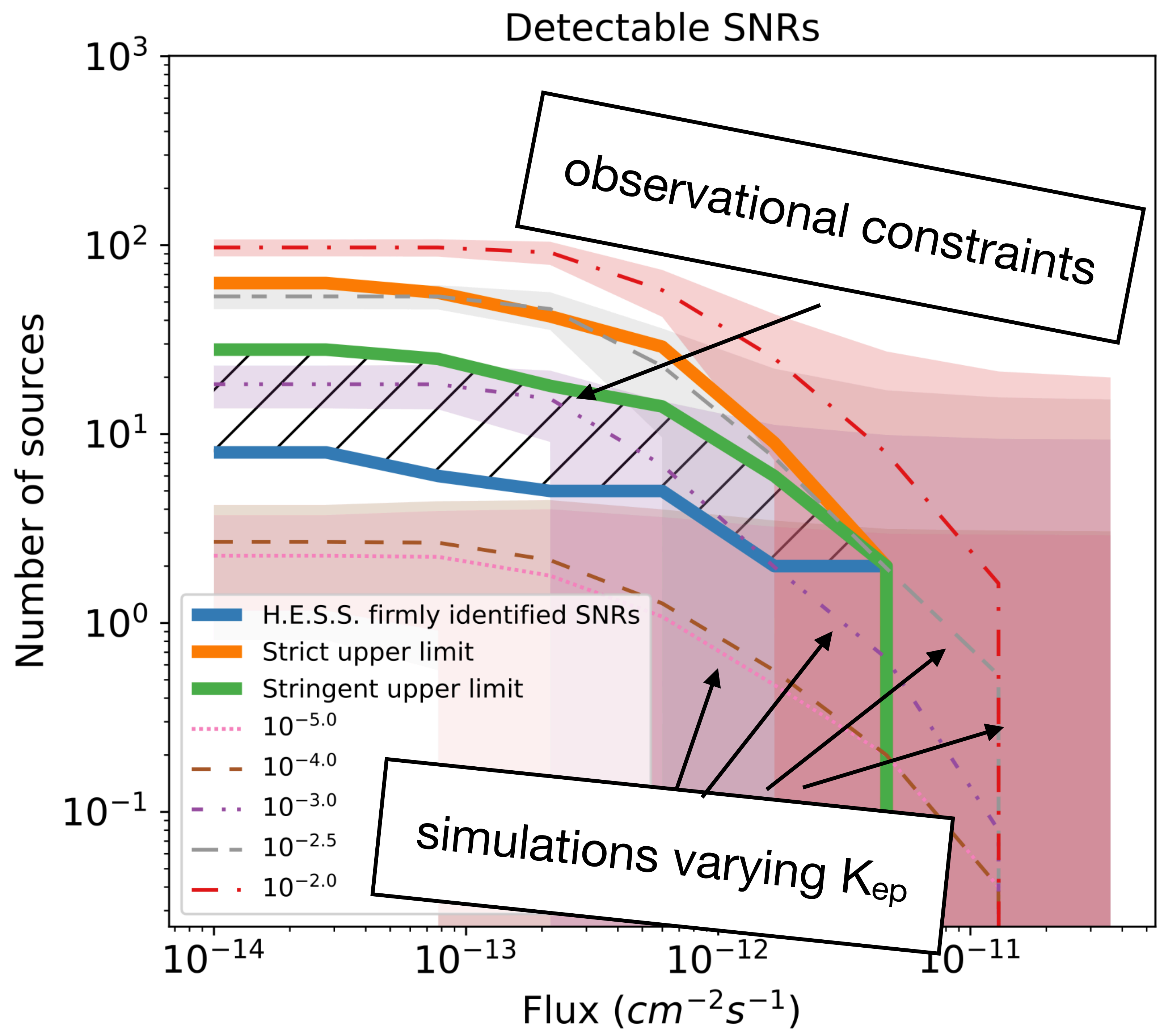
For simple models analytical optimisation possible,
more complex models require scan of the parameter space

Steppa & Egberts, A&A 2020

Example: SNRs

Inclusion of source physics allows systematic scan of the physical parameter space
- constraints of source physics

log N - log S



with additional constraint on maximum energy
Emax > 10 TeV in at least 4 sources

best agreement with observations: α = 4.2, $K_{ep} = 10^{-5}$, η= 9%,
with ~97% of realisations matching data

Batzofin, Cristofari, Egberts, Steppa, Meyer A&A 2024

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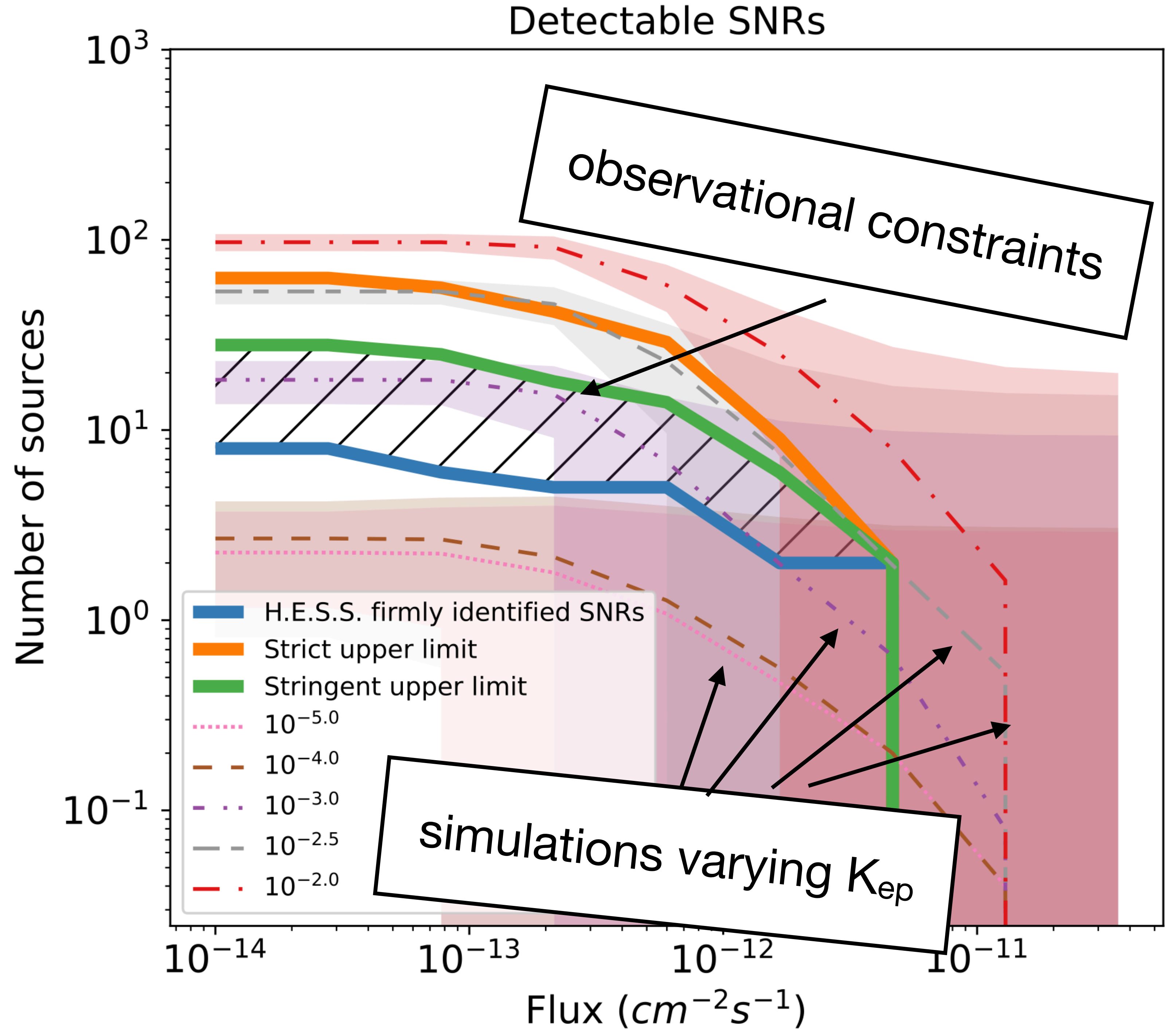

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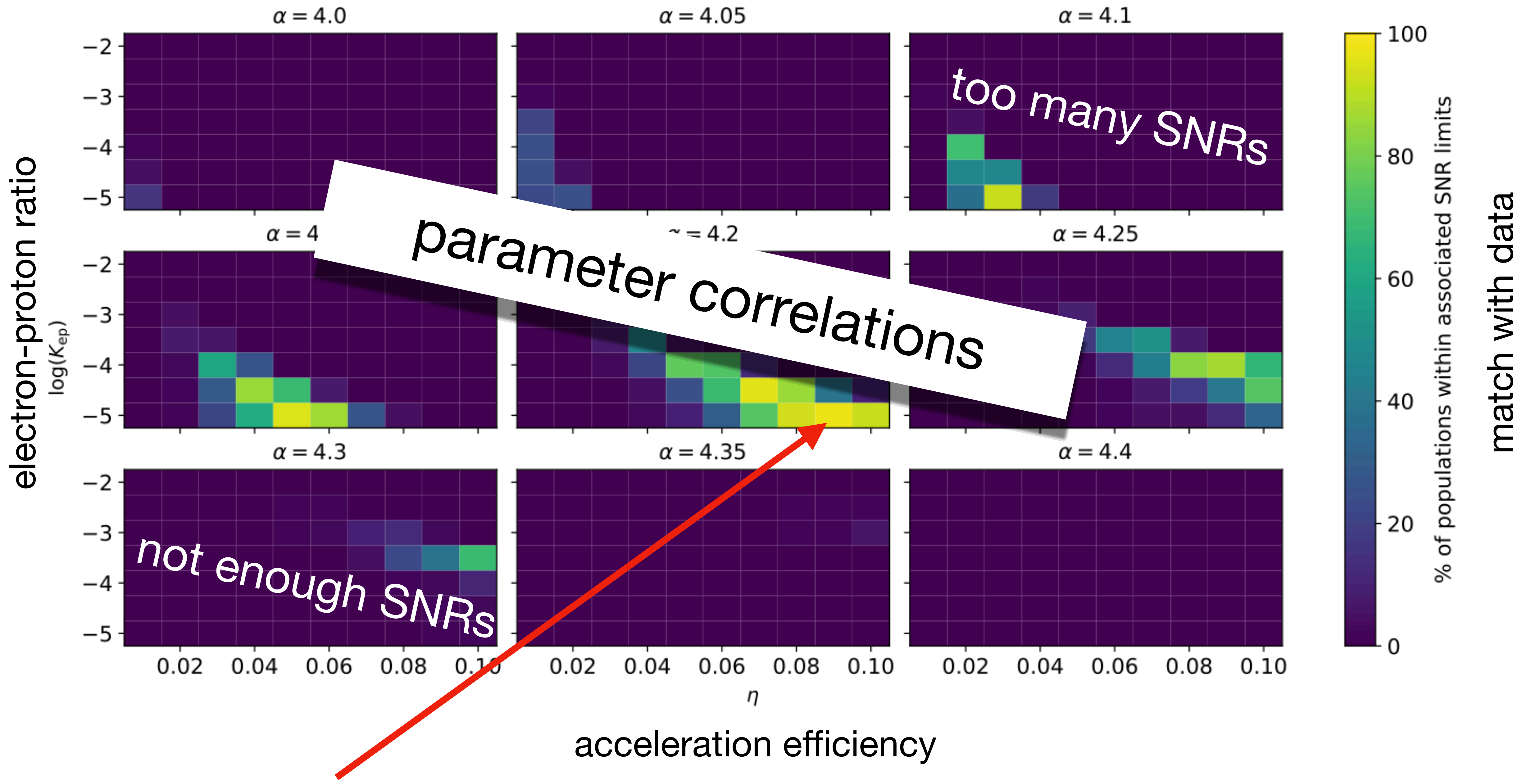

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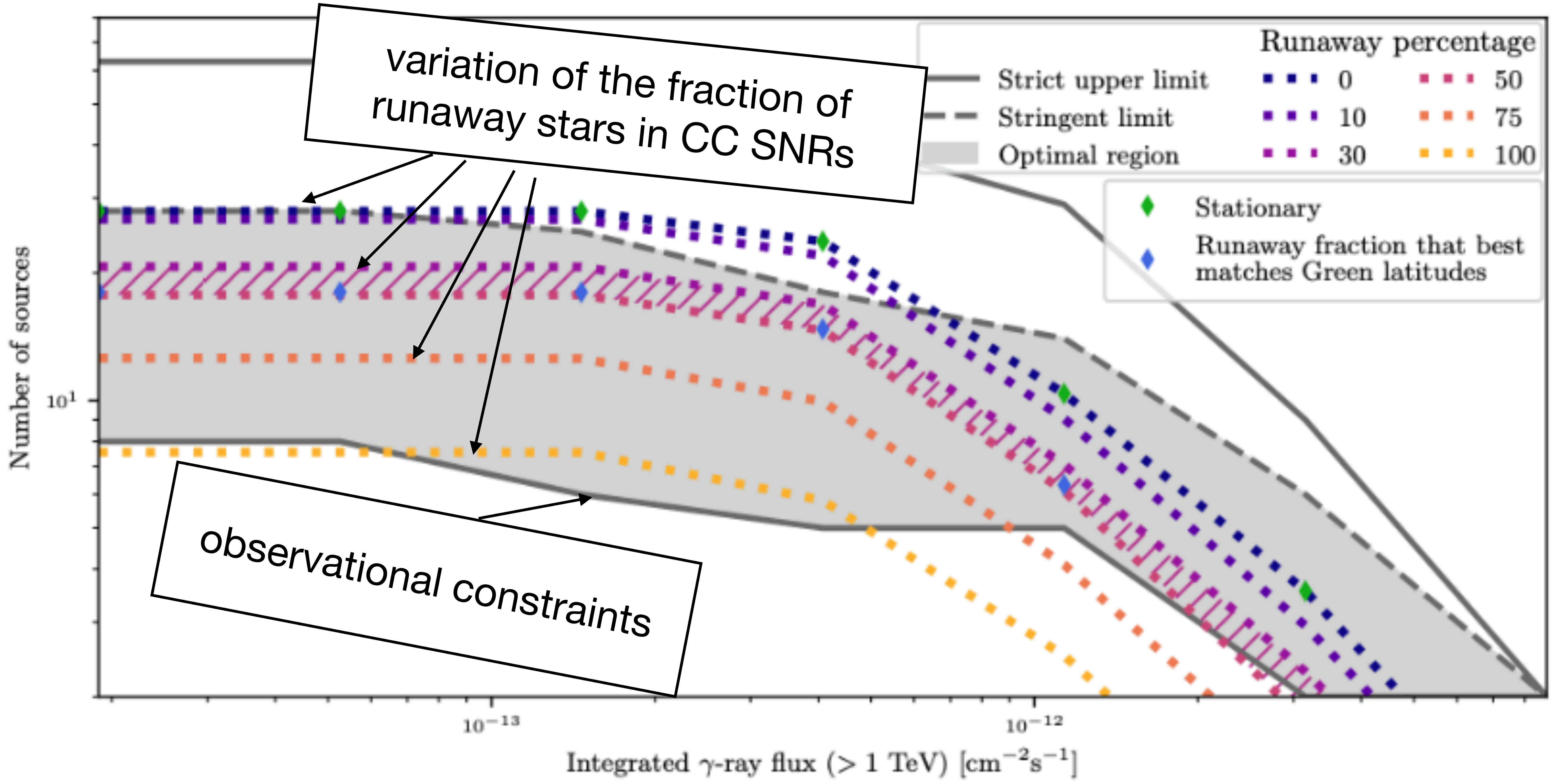
Impact of the spatial distribution

Inclusion of intrinsic velocities of supernova progenitors

Supernova Remnants



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Spatial distribution affects detectability and thus, optimal parameter combination

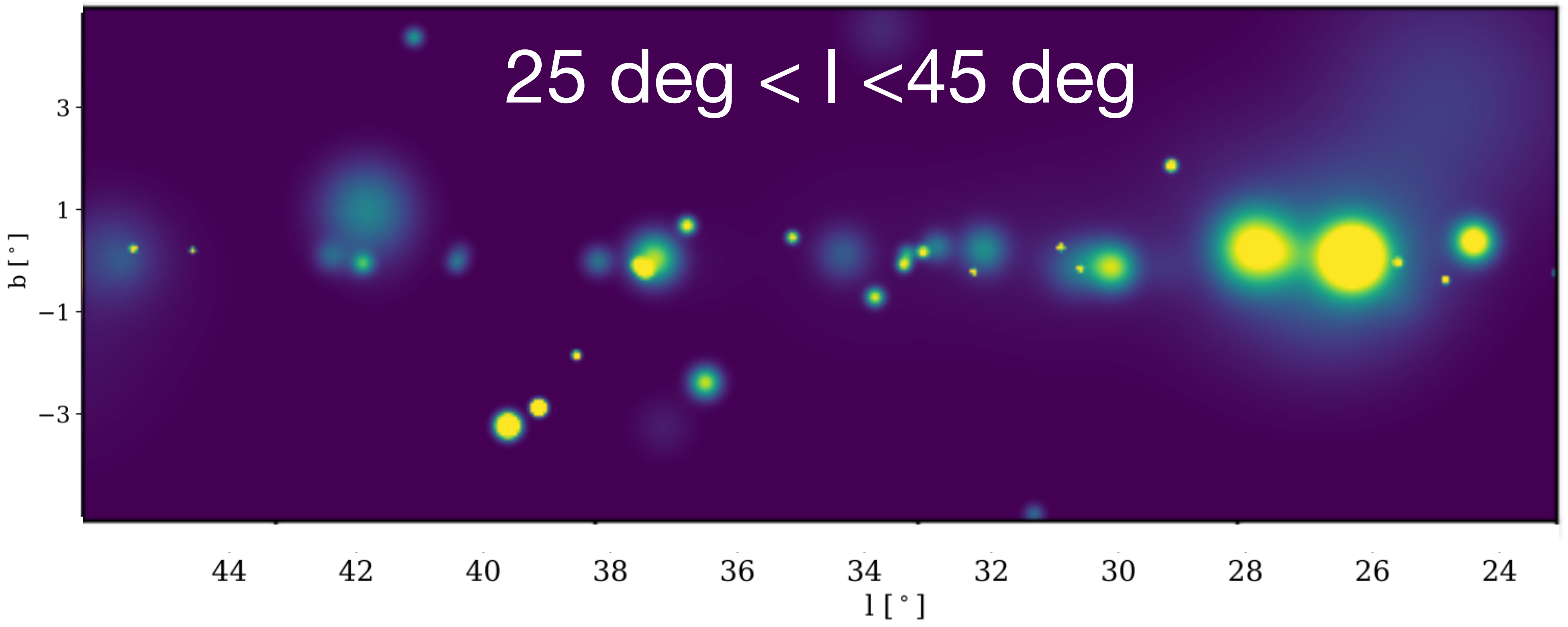
Double effect:

- SNRs leaving the region of observations
- SNRs moving to regions of smaller ISM density → lower luminosity

Another example of degeneracies

Where source counts fail

flux for angular resolution of 0.01 deg



Population model predicts
~200 detected sources for HAWC and
~300 for LHAASO-WCDA

Where source counts fail

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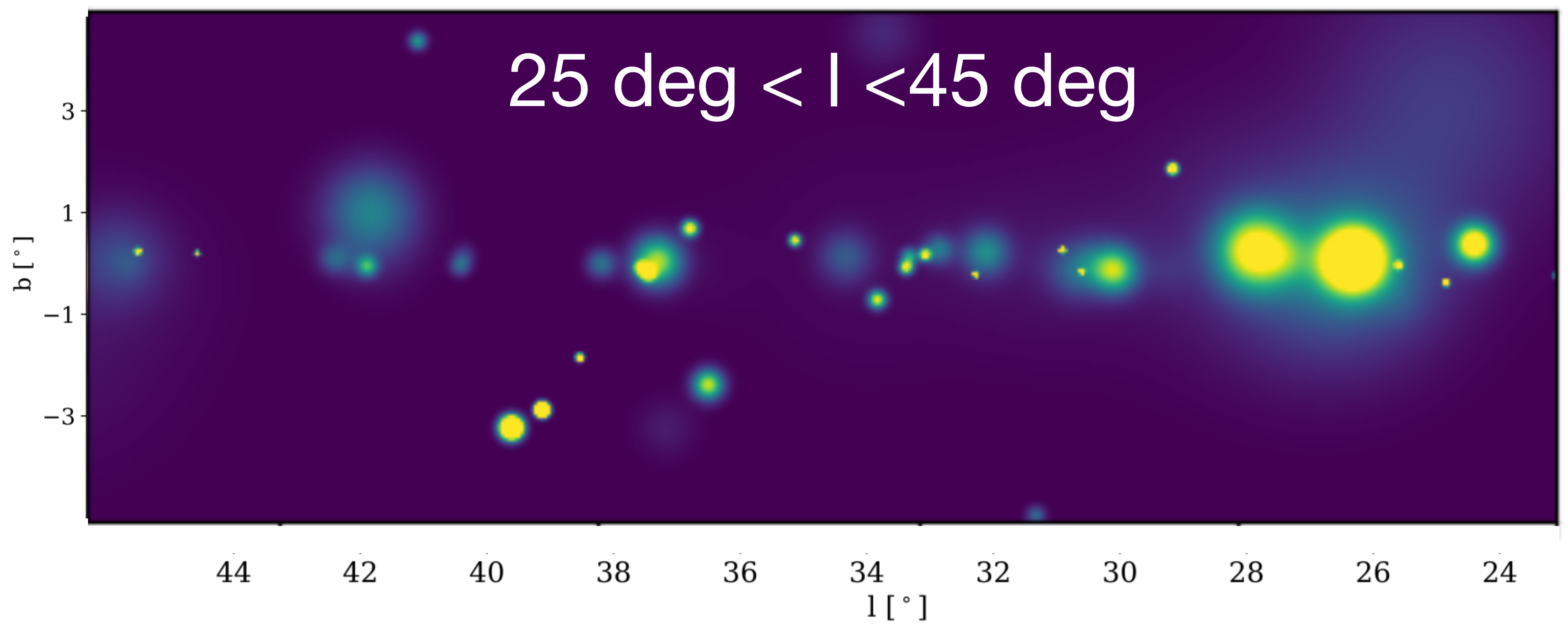
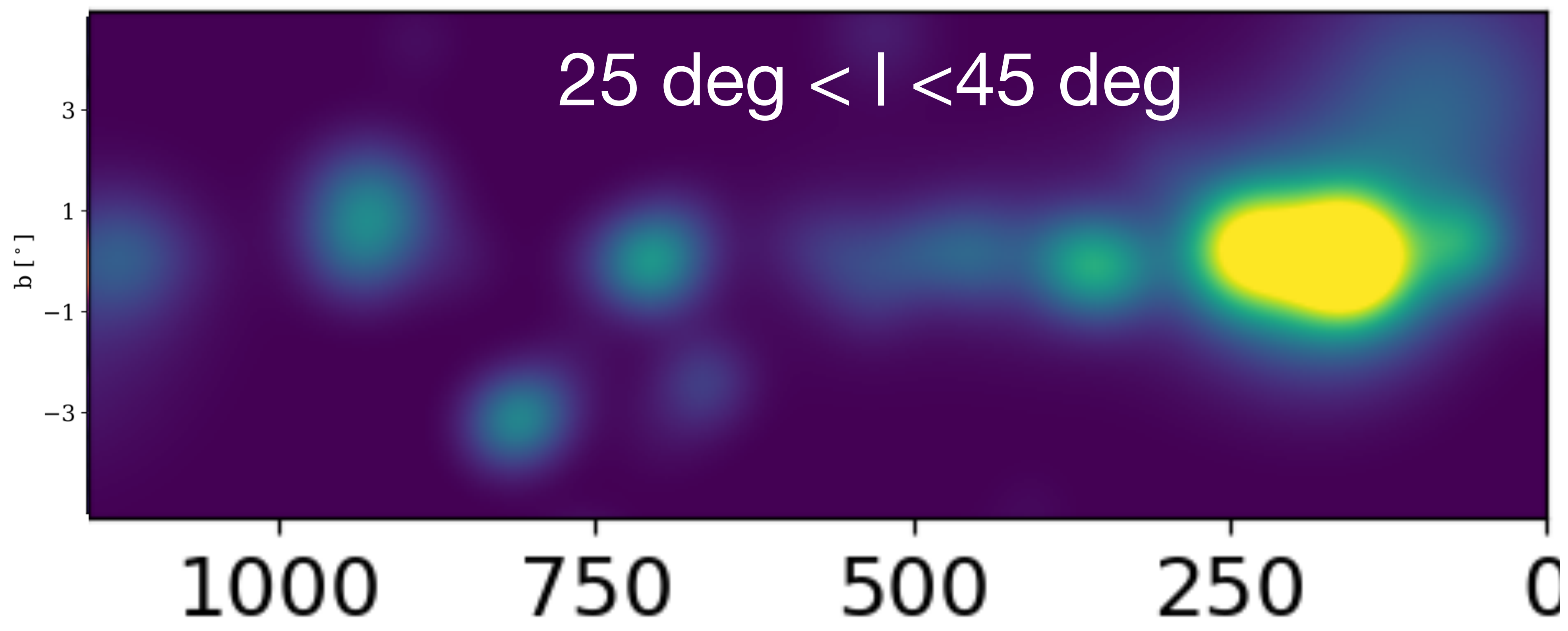


flux for angular resolution of 0.5 deg



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Angular resolution is crucial for source identification

Where source counts fail

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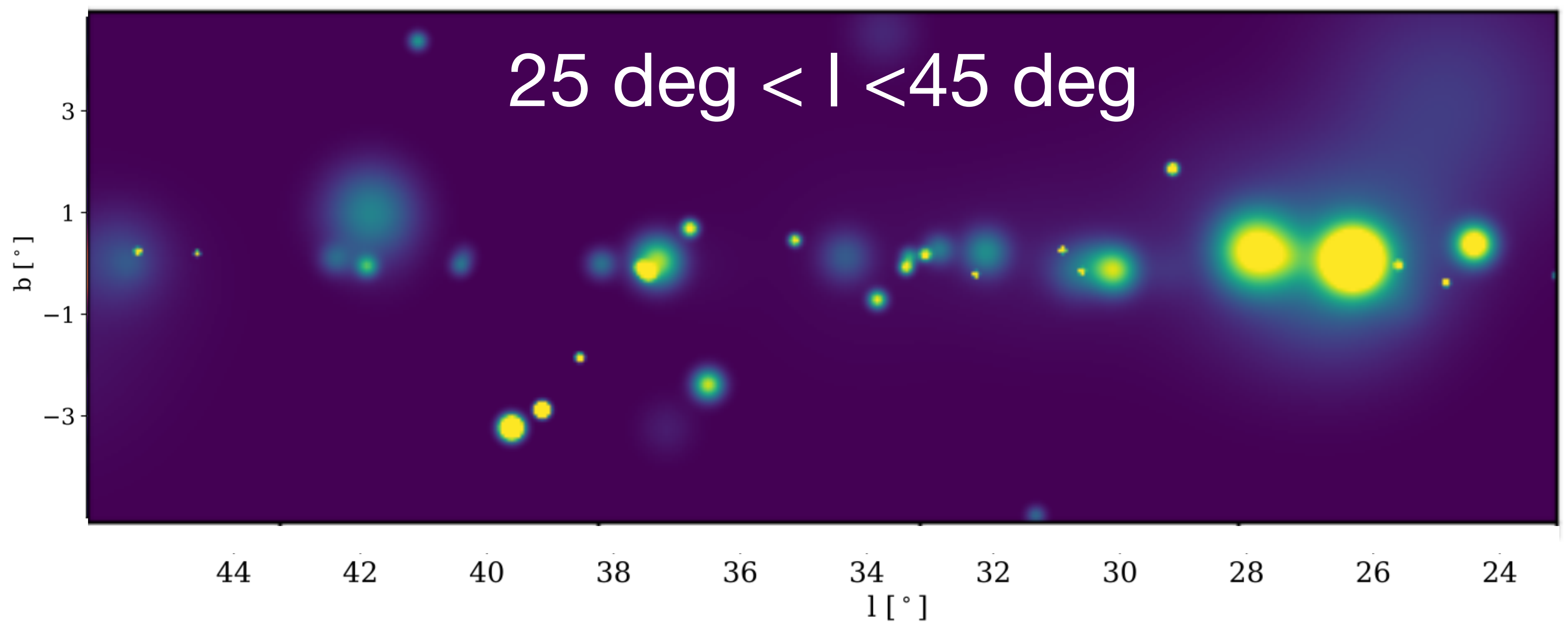

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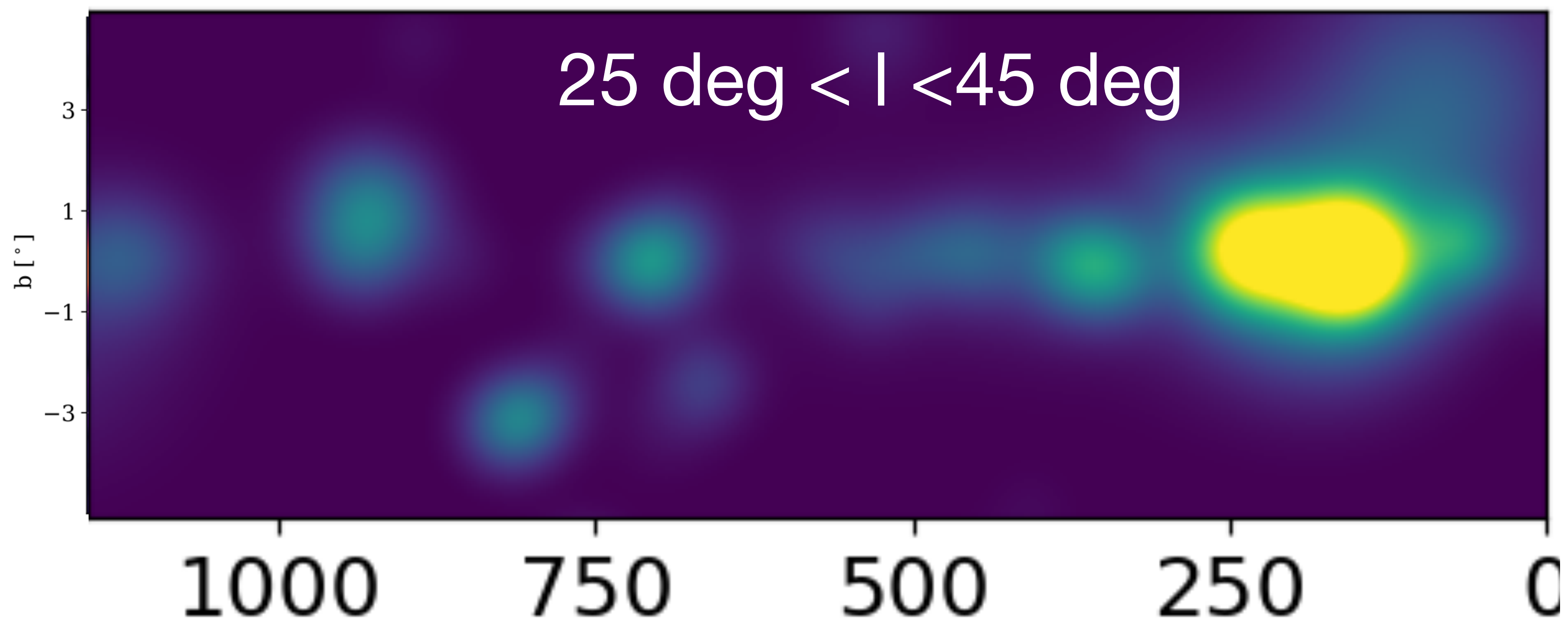

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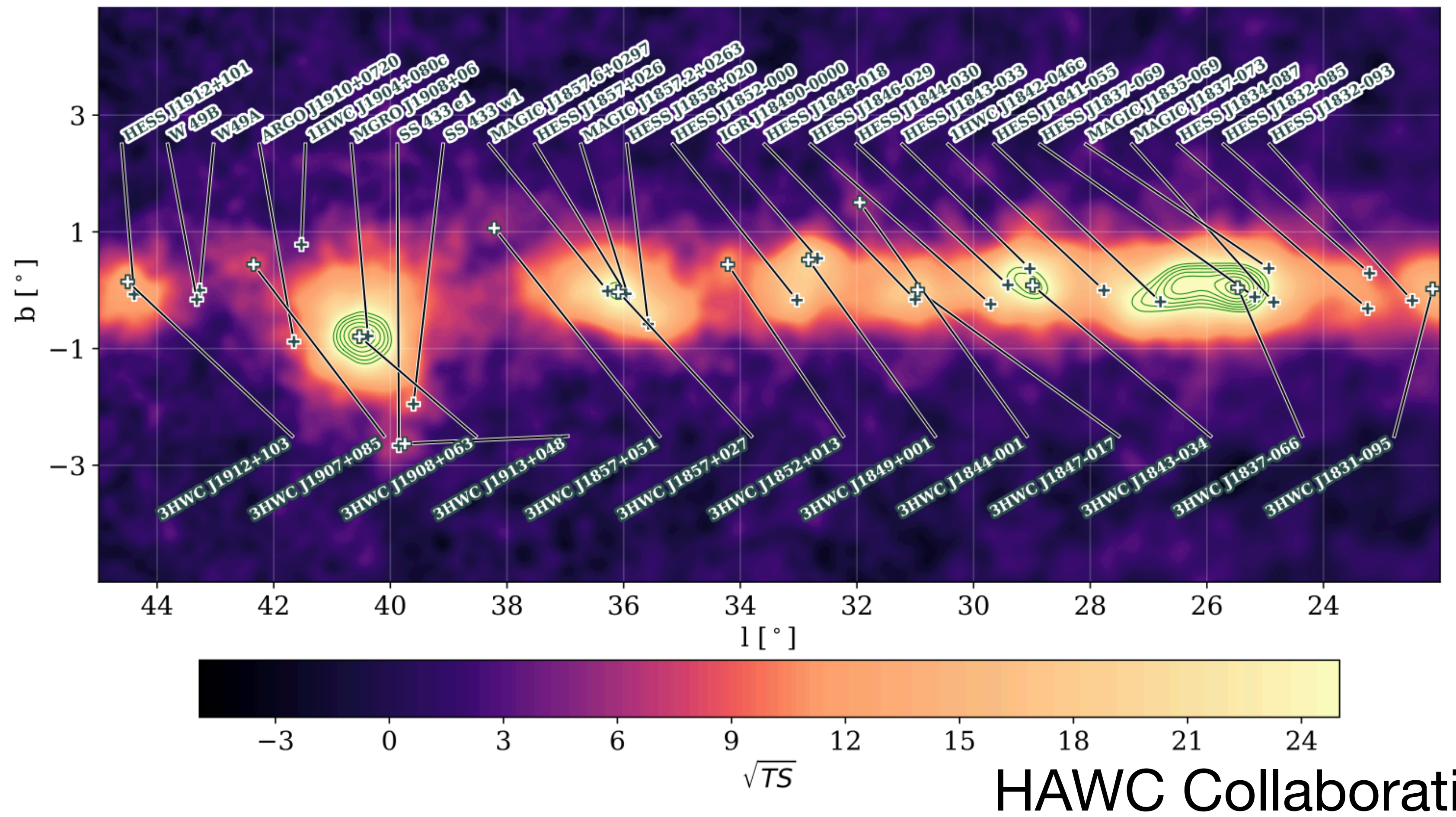
Angular resolution is crucial for source identification

Source confusion has to be taken into account!

to be compared to



HAWC Collaboration 2021

Conclusion

Details of the detection threshold are crucial when investigating source populations

Detection threshold complex function depending on background, field of view, observation direction

IACTs have particularly complex detection thresholds due to pointed observations,
but also feature best angular resolution → worth the effort!

Even with limited datasets we can place constraints on source populations
(source physics as well as spatial distributions)

Parameter space strongly correlated, preventing the identification of one optimal parameter combination

Source confusion calls for more sophisticated means of comparing


Thank you

Likelihood optimisation for generic sources

Calculated number of detectable sources:

realistic detection threshold as function of position and angular extent

assumed spatial distribution

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

assumed luminosity-radius function with free parameters for optimisation

binning in L, R allows precalculation of the integrals…

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

… and **optimisation** of the free parameters in a likelihood fit

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

SNR Modelling & Parameters

Shock velocity and radius are determined at the age of the SNR, taking into account the density of the ISM (empirical model closely matching the GALPROP gas distribution - Shibata et al. 2010)

Magnetic field amplification:

- initially from the growth of non-resonant streaming instabilities upstream of the shock (Bell et al. 2013)

- later resonant streaming instabilities (Morlino & Caprioli 2012)

Based on the shock and the magnetic field amplification we calculate the maximum energy of accelerated particles

- Determined by the growth of non-resonant streaming instabilities (Bell) (Bell et al. 2013)

- $f_{CR}(p) = A\left(\frac{p}{m_p c}\right)^{-\alpha}$ Differential spectrum of accelerated particles
- p is the momentum and α is the spectral index
- The normalisation (A) is found by requiring the CR pressure to be some fraction, η_{CR} of the ram pressure at the shock location.
- $\underbrace{\frac{1}{3}\int_{p_{min}}^{p_{max}} dp\, 4\pi p^2 f_{CR}(p) p v(p)}_{\text{Cosmic ray pressure}} = \underbrace{\eta_{CR}\rho v_{sh}^2}_{\text{Ram pressure}}$

Relative rates of supernovae: Thermonuclear 32%, Core collapse 68%, 3 supernovae per century