Universität Potsdam Mathematisch-Naturwissenschaftliche Fakultät

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H.E.S.S.

The population of Galactic supernova remnants in the TeV range

Rowan Batzofin[1], Pierre Cristofari[2], Kathrin Egberts[1], Constantin Steppa[1], and Dominique M.-A. Meyer[3]

[1] Universität Potsdam, Institut für Physik und Astronomie, Campus Golm, Haus 28, Karl-Liebknecht-Str. 24/25, 14476 Potsdam-Golm, Germany

[2] Observatoire de Paris, PSL Research University, 61 avenue de l'Observatoire, Paris, France

[3] Institute of Space Sciences (ICE, CSIC), Campus UAB, Carrer de Can Magrans s/n, 08193 Barcelona, Spain

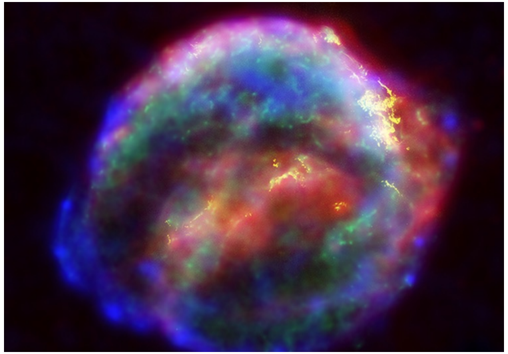


Image from NASA

Outline

- What are we looking for?
- SNR population model
- Properties of the SNR population investigated
- Results

What are we looking for?

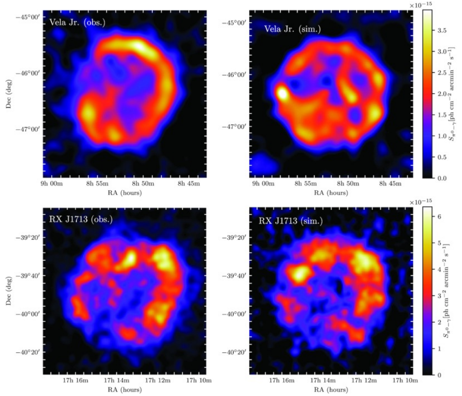
- SNRs produce gamma rays in the VHE (> 0.1 TeV) range but the details of this gamma-ray emission are not well understood.

- Questions to answer:
  - Can we describe the H.E.S.S. Galactic Plane Survey (HGPS) data?
  - What is the spectrum of accelerated particles?
  - What is the efficiency of particle acceleration?
  - Is the gamma-ray emission dominated by hadronic or leptonic origin?

What are we looking for?

Single SNR simulation

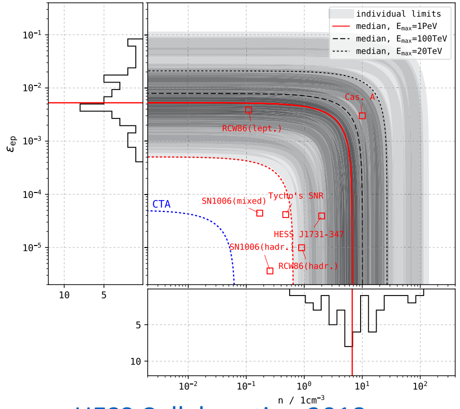
- Complicated modelling of the SNR
- Understanding the physical conditions and processes
- Only 1 SNR to compare to



[Pais et Pfrommer 2020]

Population simulation

- Simpler modelling of individual SNRs
- Reveal common properties of SNRs
- More SNRs for comparison



[HESS Collaboration 2018]

Gamma rays from SNRs

- Cosmic rays (CRs) are thought to be accelerated in SNR shocks
- The acceleration of CRs interacting with the interstellar medium can also produce gamma rays in the TeV range mainly via 2 mechanisms:

Hadronic

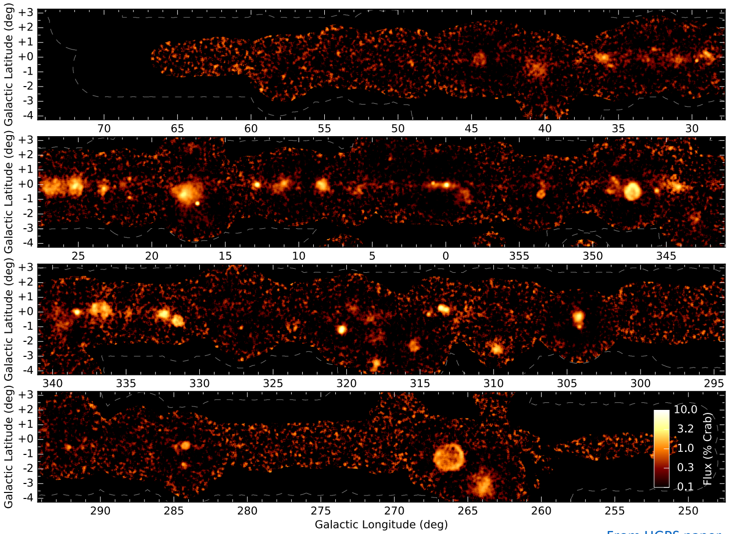
- Proton spectrum
- Pion decay

Leptonic

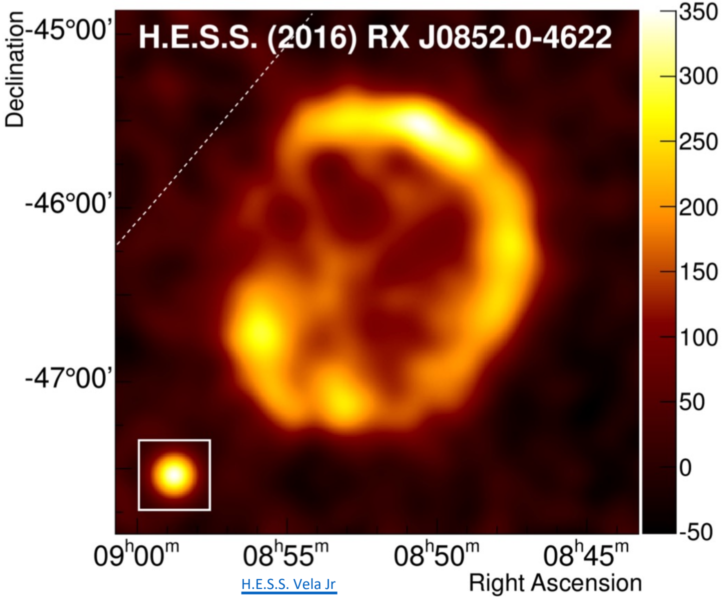
- Electron spectrum
- Inverse Compton

H.E.S.S. Galactic Plane Survey

- The High Energy Stereoscopic System (H.E.S.S.) performed a systematic survey of the Galactic plane (0.1 to 100 TeV)
- A total of 78 sources detected



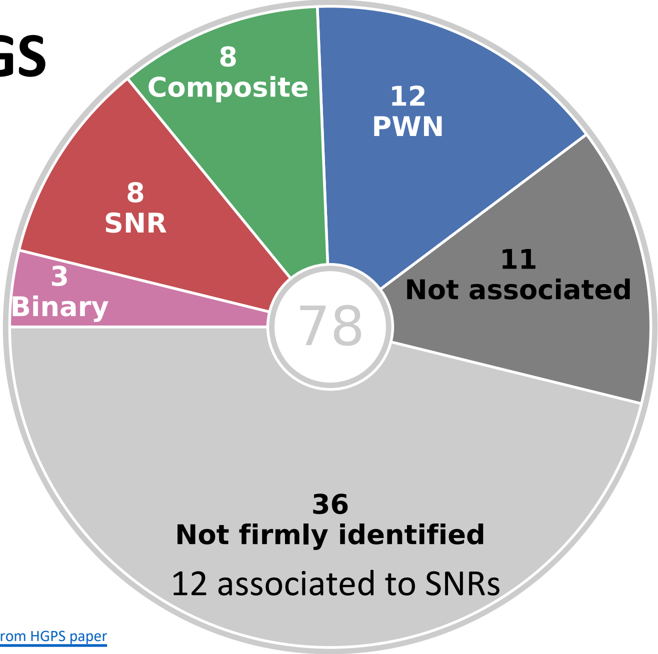
From HGPS paper



H.E.S.S. Vela Jr

HGPS data

HPGS



From HGPS paper

Comparison

- Lower limit of 8
- Strict upper limit of 63 (8 + 8 + 47)
- Stringent upper limit of 28 (8 + 8 + 12)

SNR population model ingredients

- Physics of the supernova remnant
  - Evolution of the radius and velocity of the shock
  - Magnetic field amplification
  - Maximum energy of accelerated particles

- Distribution of sources and matter
  - Types of SNRs
  - Where in the Milky way
  - Ejecta mass and explosion energy distribution

Properties of the SNR population investigated

- Spectral index, α (4.0 to 4.4)
- Electron proton ratio, Kep $(10^{-2}$ to $10^{-5})$
- Efficiency of gamma-ray production, η (1% to 10%)

Realisation of a single population

- Taking into account the HGPS sensitivity
- Gray shaded region is HGPS sensitivity for a source with luminosity, $L = 5{\times}10^{33}$ ph s^{-1}

Parameters:

α = 4.3

Kep = 10^{-3}

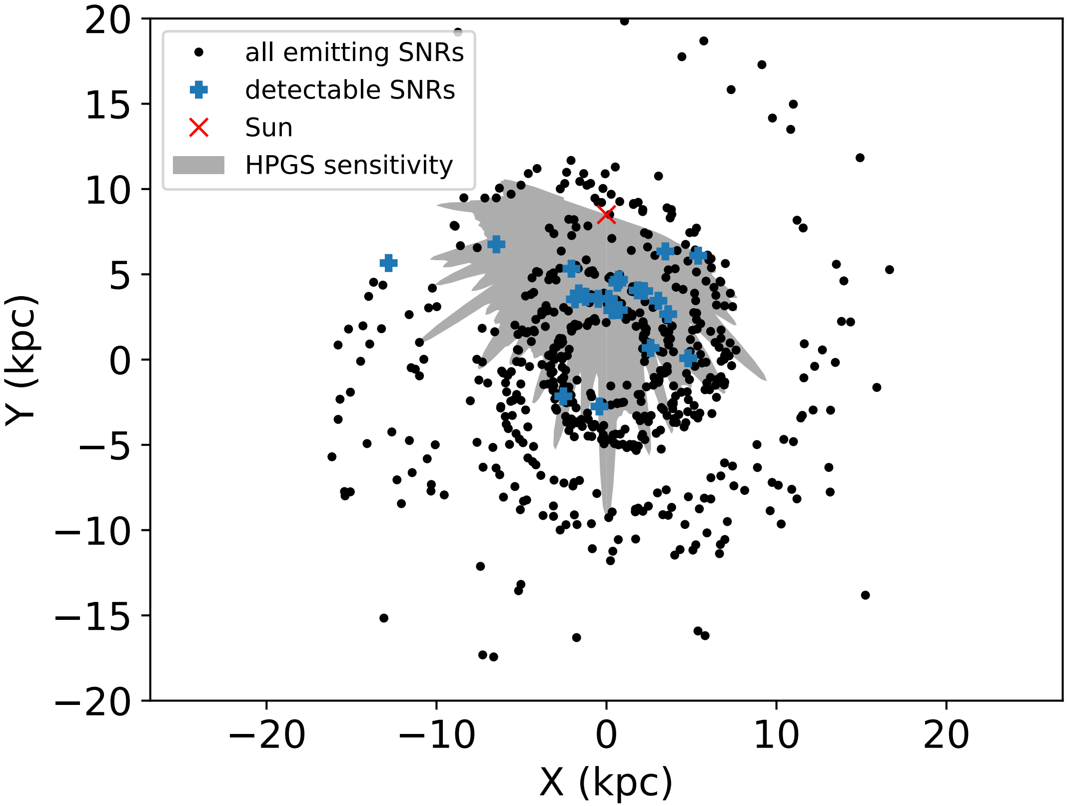
η = 0.07

ST = 20 kyr

Steiman-Cameron distribution

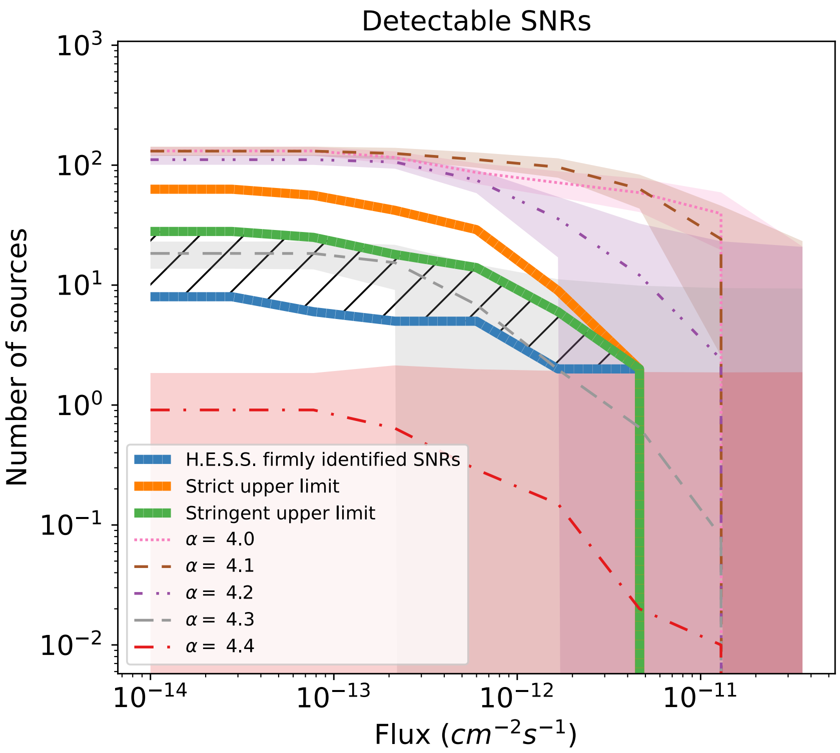
Shaded region:

$L = 5{\times}10^{33}$ ph s^{-1} (~$4{\times}10^{-11}$ TeV^{-1} cm^{-2} s^{-1} at 1 kpc)

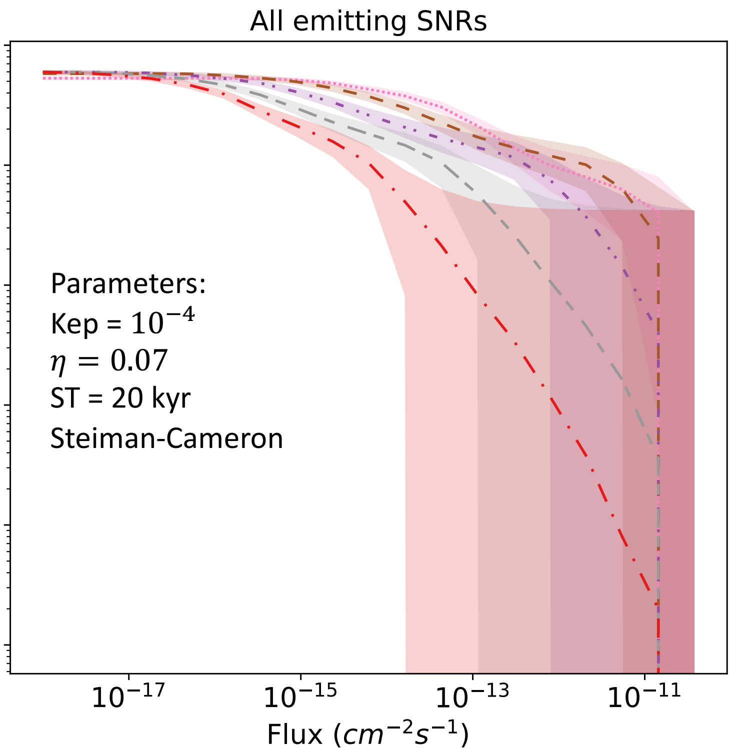


Results – Spectral Index

- Log-N log-S distributions
- Same no. of total SNRs
- Can't just draw a line at some flux to determine detectability
- Larger α means less detections



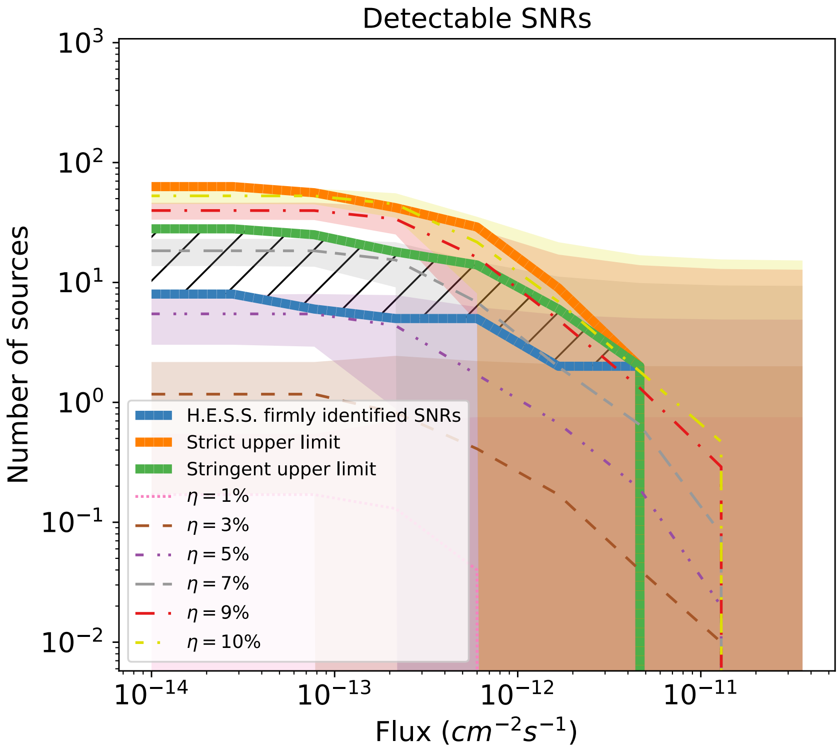
Cumulative distribution of the detectable SNRs averaged over 100 populations.



Cumulative distribution of all simulated SNRs averaged over 100 populations.

Results – Acceleration efficiency

- Illustrative parameter set remains the same
- 5% < η < 10% is within the strict limit
- Larger η means more detections



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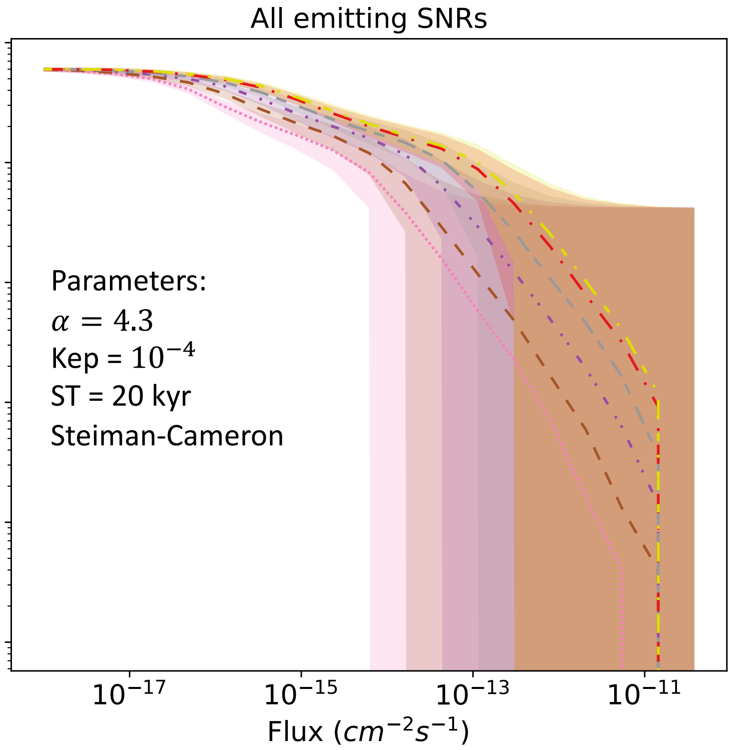
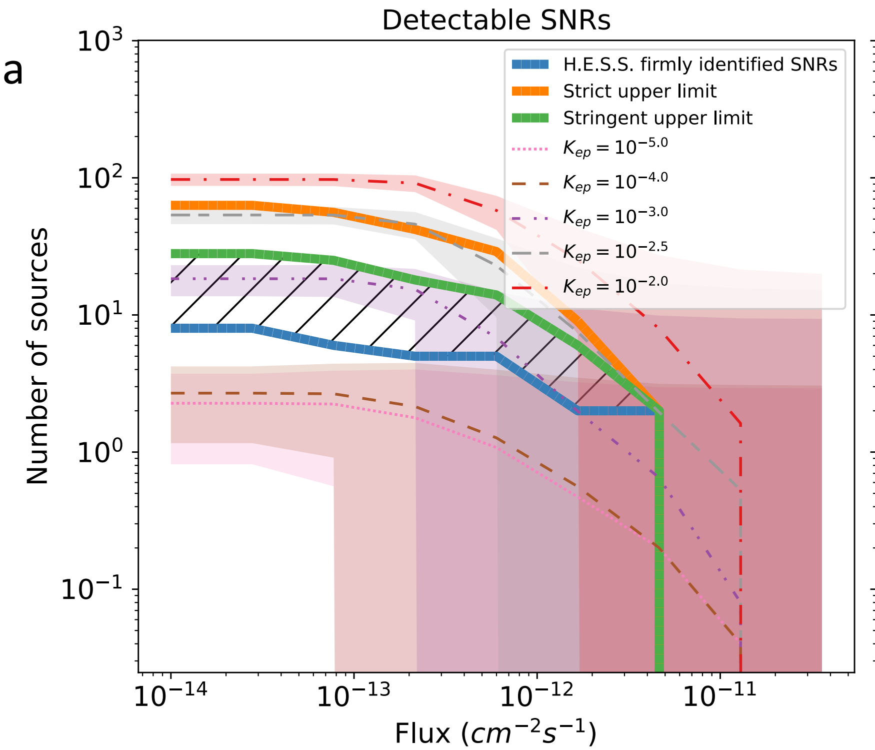


Cumulative distribution of all simulated SNRs averaged over 100 populations.

Results – Electron-proton ratio

- $K_{ep} = 10^{-2.5}$ is a possible but extremely unlikely case
- Larger K_{ep} means more detections



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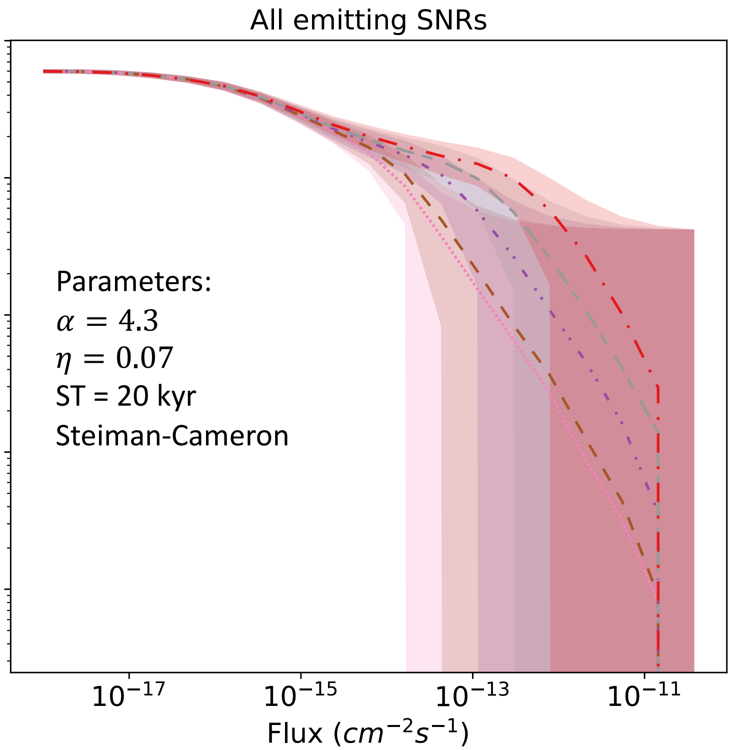


Cumulative distribution of all simulated SNRs averaged over 100 populations.

Systematic exploration of parameter space

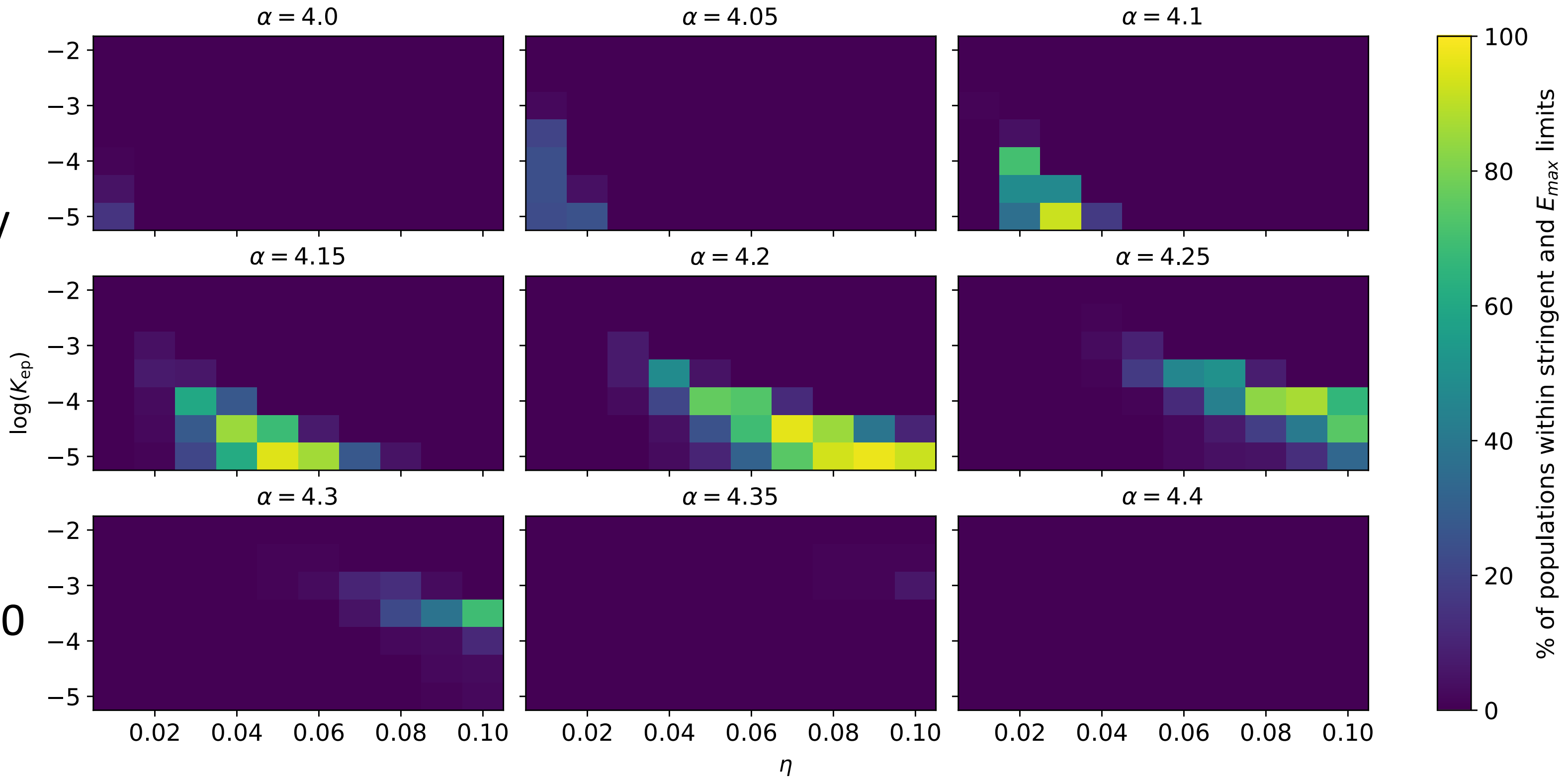
- It's clear that by changing only one parameter at a time that there should be other combinations that work.

- We explored a large parameter space changing α, η and $K_{ep.}$

- Need populations with:
  - > 8 SNRs (firm detections)
  - < 28 SNRs (associated)
- Additional E_{max} criterion
- 8 firmly detected SNRs
  - 4 $E_{max} > 10$ TeV
  - 2 $E_{max} \sim 10$ TeV
  - 2 $E_{max} < 10$ TeV

Results – Parameter exploration

- $\alpha < 4.1$ produces populations with too many detectable SNRS
- $\alpha > 4.3$ does not produce enough SNRs with Emax > 10 TeV



Best populations (>90% in agreement with HGPS)

- $K_{ep} \geq 10^{-4.5}$
- $4.1 \leq \alpha \leq 4.2$
- Hadronic ratio is not only dependant on K_{ep}
- SNRs dominated by emission from hadronic processes are typically younger and brighter than SNRs dominated by leptonic emission

Population Parameters			% compatible with HGPS	Hadronic Ratio	Mean No. detectable SNRs	Mean Had. Age (kyr)	Mean Lep. Age (kyr)	Mean Had. Dist. (kpc)	Mean Lep. Dist(kpc)
$\alpha = 4.2$	$K_{ep} = 10^{-5.0}$	$\eta = 0.09$	97	0.62	16.84	2.15	4.86	5.65	4.88
$\alpha = 4.2$	$K_{ep} = 10^{-4.5}$	$\eta = 0.07$	96	0.43	16.14	1.94	4.36	5.64	4.9
$\alpha = 4.15$	$K_{ep} = 10^{-5.0}$	$\eta = 0.05$	95	0.51	16.41	2.06	5.21	5.62	4.79
$\alpha = 4.2$	$K_{ep} = 10^{-5.0}$	$\eta = 0.08$	93	0.66	13.6	2	4.88	5.63	5.06
$\alpha = 4.1$	$K_{ep} = 10^{-5.0}$	$\eta = 0.03$	92	0.37	19.56	2.05	5.7	5.61	4.63
$\alpha = 4.2$	$K_{ep} = 10^{-5.0}$	$\eta = 0.1$	92	0.6	20.64	2.32	4.92	5.66	4.76

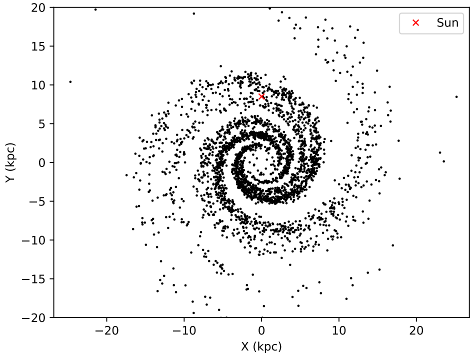
Summary

- Confronted SNR population model to HGPS, taking into account the multi-dimensional exposure for the first time.
- Explored a large parameter space but correlations prevent the identification of an optimal combination.
- Can exclude some parts off the parameter space:
  - $\alpha \lesssim 4.05$
  - $K_{ep} \gtrsim 10^{-2.5}$
  - $K_{ep} \sim 10^{-3}$ requires $\alpha \gtrsim 4.35$ and $\eta \lesssim 0.02$
- Realisations with $\gtrsim 90\%$ compatible:
  - $4.1 \lesssim \alpha \lesssim 4.2$
  - $10^{-5} \lesssim K_{ep} \lesssim 10^{-4.5}$
- Despite very low electron-proton ratios we still find many SNRs dominated by leptonic emission.
- The detectable SNRs are clearly a highly biased sample.
- Batzofin, et al. (2024), The population of Galactic supernova remnants in the TeV range, A&A, 687, A279, doi: 10.1051/0004-6361/202449779124

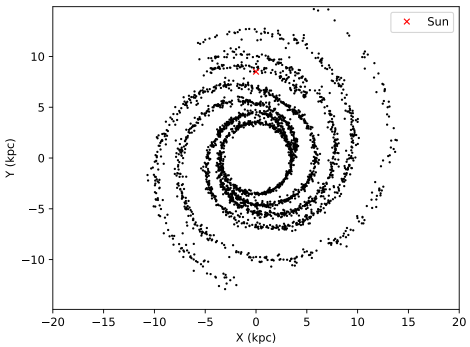
Backup slides

Source and matter distribution

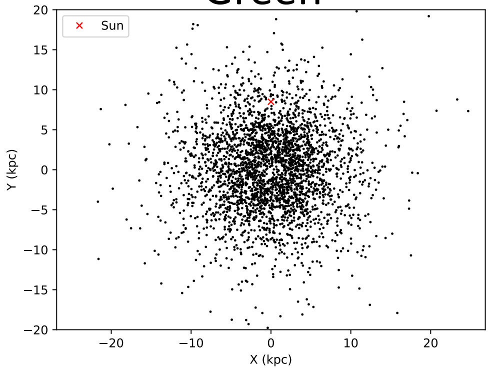
Steiman-Cameron



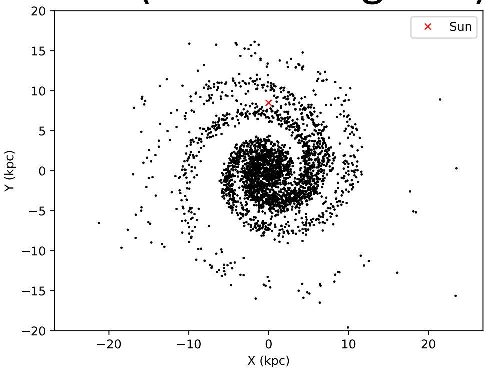
Reid



Green

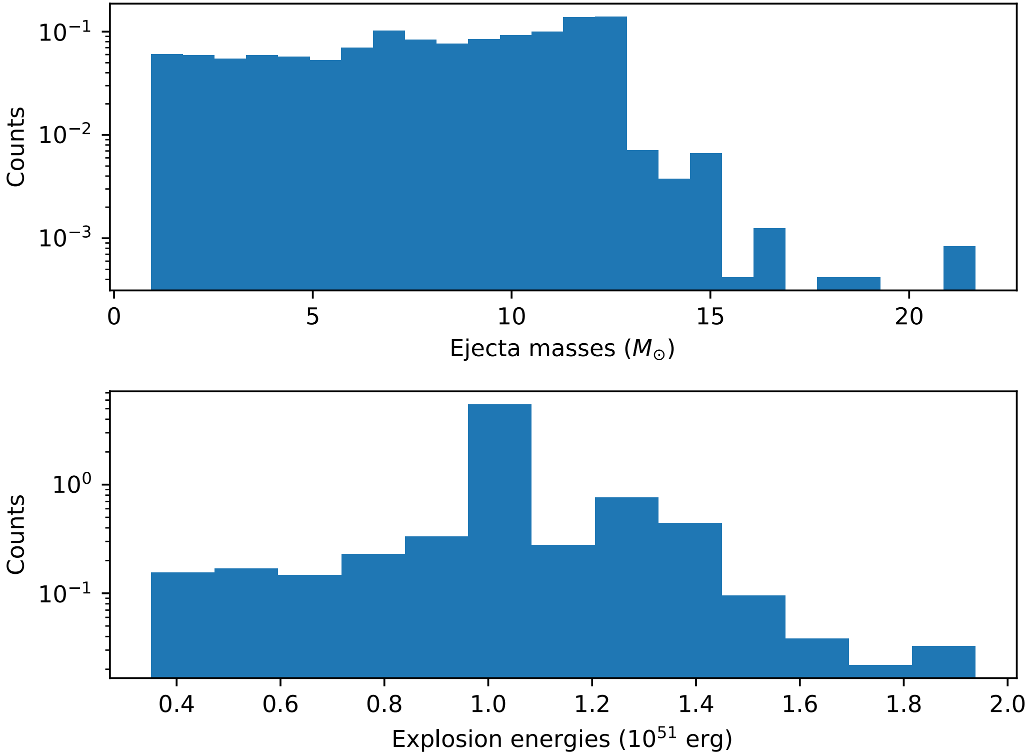


CAFG (Faucher-Giguere)



- Relative rates of supernovae:
  - Thermonuclear 32%
  - Core collapse 68%
- 3 supernovae per century
- Source distribution models
  - Steiman Cameron (ISM)
  - Reid (Massive stars)
  - Green (SNRs)
  - CAFG (Pulsars)
- Matter distribution follows an empirical model that closely matches the GALPROP code - Shibata et al. 2010

Distribution of masses and explosion energies of simulated SNRs



Distribution of mass and energy of explosion

Thermonuclear:

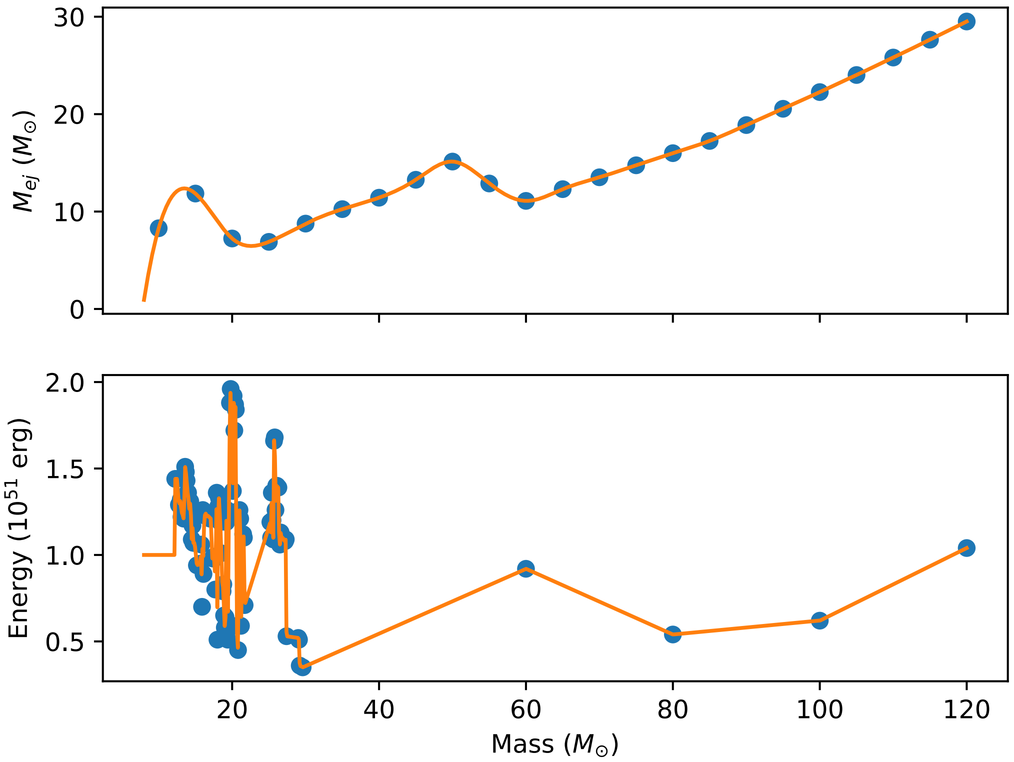
$M_{ej} = 1.4\ M_\odot$

$E_{SN} = 10^{51}$ erg

Core collapse:

Initial mass distribution $N \propto \int_8^{120\ M_\odot} M_\bigstar^{-2.3}\, dM_\bigstar$

E_{SN} interpolated from results obtained in Sukhbold et al. 2016



Supernova dynamics

- Place the SNR in the Milky way.
- Shock velocity and radius are determined at the age of the SNR, taking into account the density of the ISM.
- 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
  - Determined by Hillas estimation (Hillas)

Supernova dynamics

- $f_{CR}(p) = A\left(\frac{p}{m_p c}\right)^{-\alpha}$ 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.
- $\underbrace{\frac{1}{3}\int_{p_{min}}^{p_{max}} dp\, 4\pi p^2 f_{CR}(p) p v(p)}_{\text{Cosmic ray pressure}} = \eta_{CR} \underbrace{\rho v_{sh}^2}_{\text{Ram pressure}}$

SNR population model improvements

Expanding on the work done by Cristofari et al.:

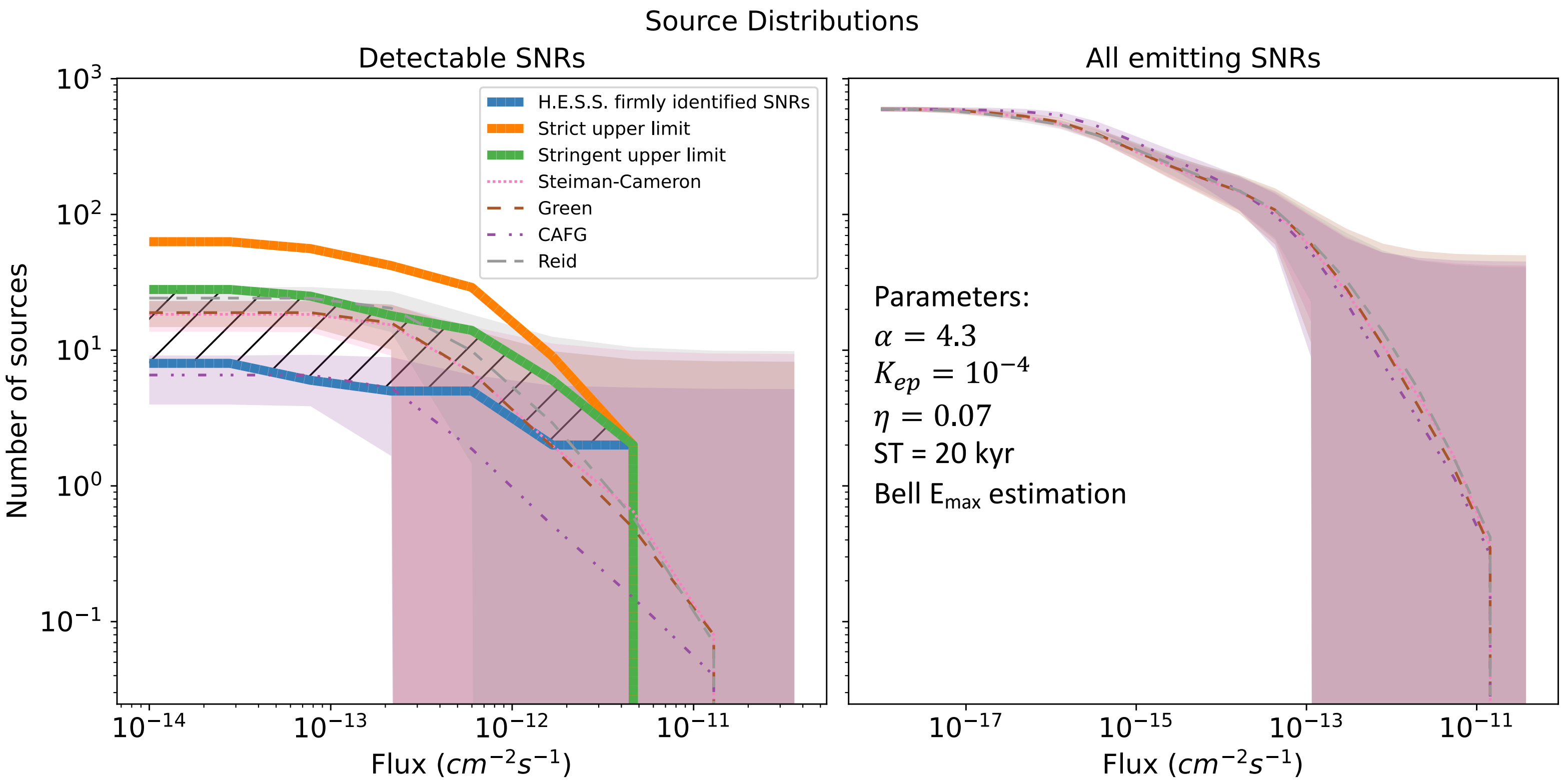
- Connection between ejecta masses and explosion energies
- Refined description of magnetic field amplification and corresponding maximum energy for protons and electrons
- Inclusion of diffusive shock reacceleration at SNR shocks
- Multiple prescriptions for the spatial distribution of SNRs in the Galaxy

Emission from reaccelerated CRs - Cristofari & Blasi (2019)

- Galactic CRs reaccelerated at the SNR shock
  - Assume spectrum is the same as local interstellar spectrum

- $f_0^{seed}(p) = \alpha \int_{p_0}^{p} \frac{dp'}{p'} \left(\frac{p'}{p}\right)^{\alpha} f_\infty(p')$
  - $f_\infty(p)$ is the distribution function at upstream infinity of the seeds to be reaccelerated.
  - $p_0 = 10^{-2}$ GeV

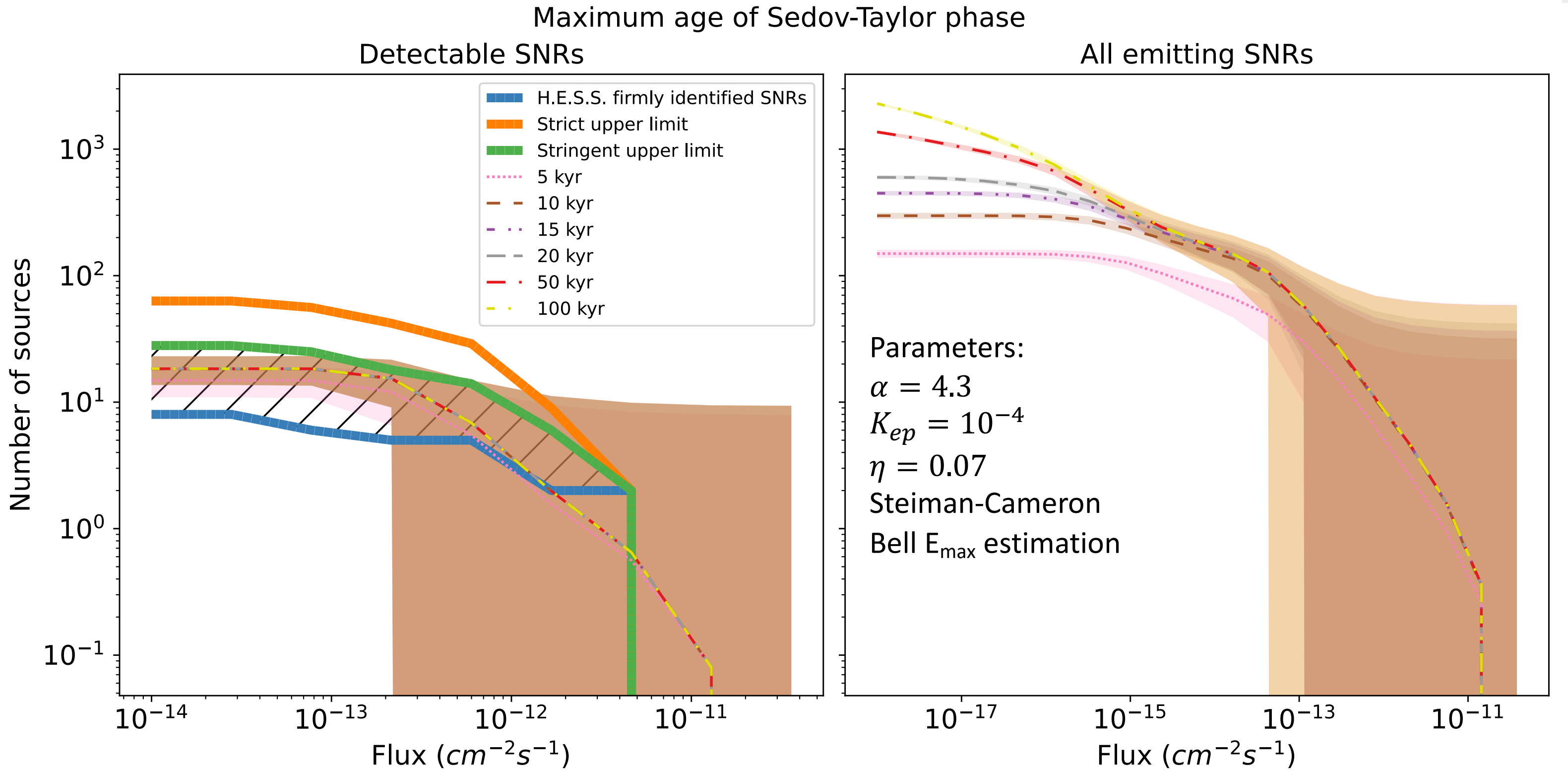
Results – Spatial distribution



Cumulative distribution of the detectable SNRs averaged over 100 populations.

Cumulative distribution of all simulated SNRs averaged over 100 populations.

Results – Maximum length of Sedov-Taylor phase

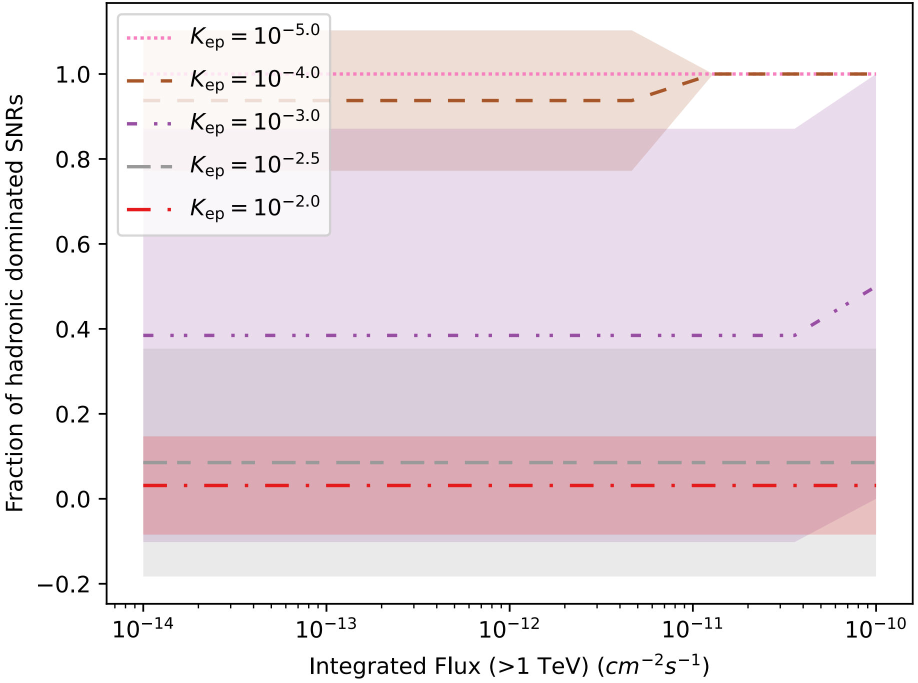


Cumulative distribution of the detectable SNRs averaged over 100 populations.

Cumulative distribution of all simulated SNRs averaged over 100 populations.

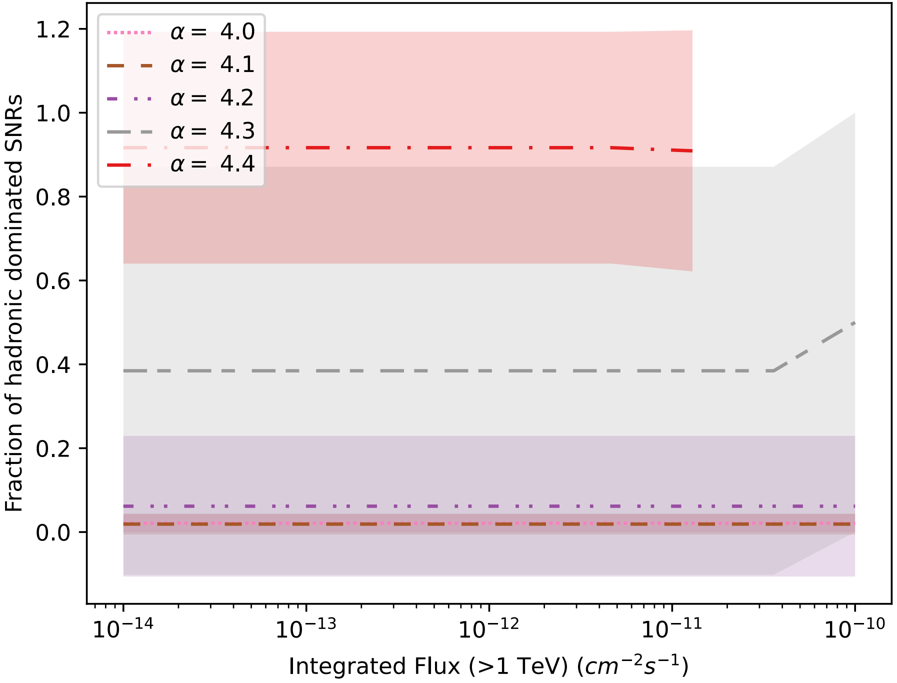
Ratio of detectable sources dominated by hadronic emission

- As the electron-proton fraction increases the hadronic fraction decreases
- Is this the only property that changes the hadronic ratio?

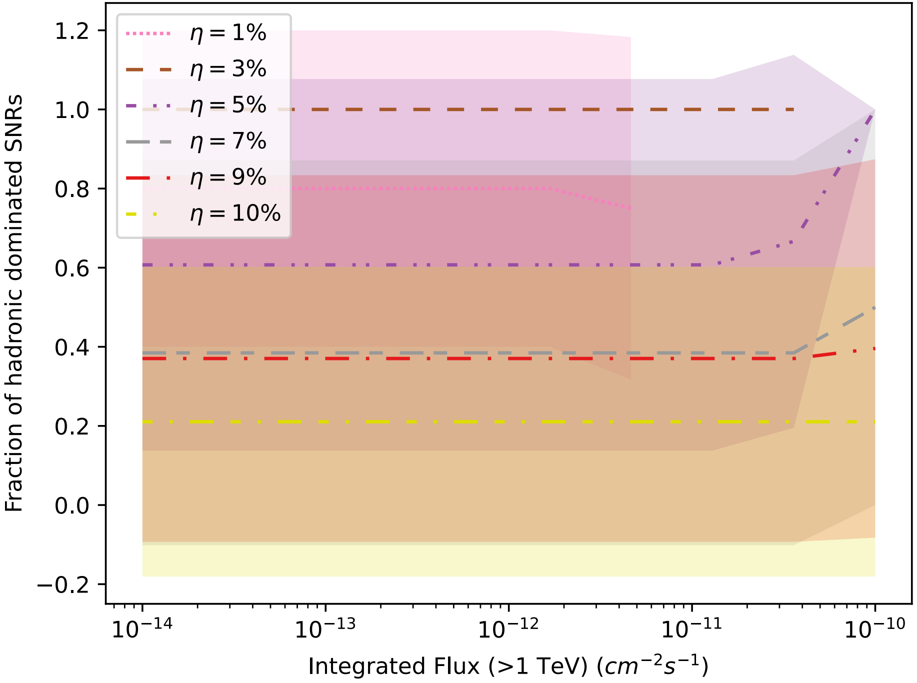


Cumulatively binned in integrated flux.

Ratio of detectable sources dominated by hadronic emission

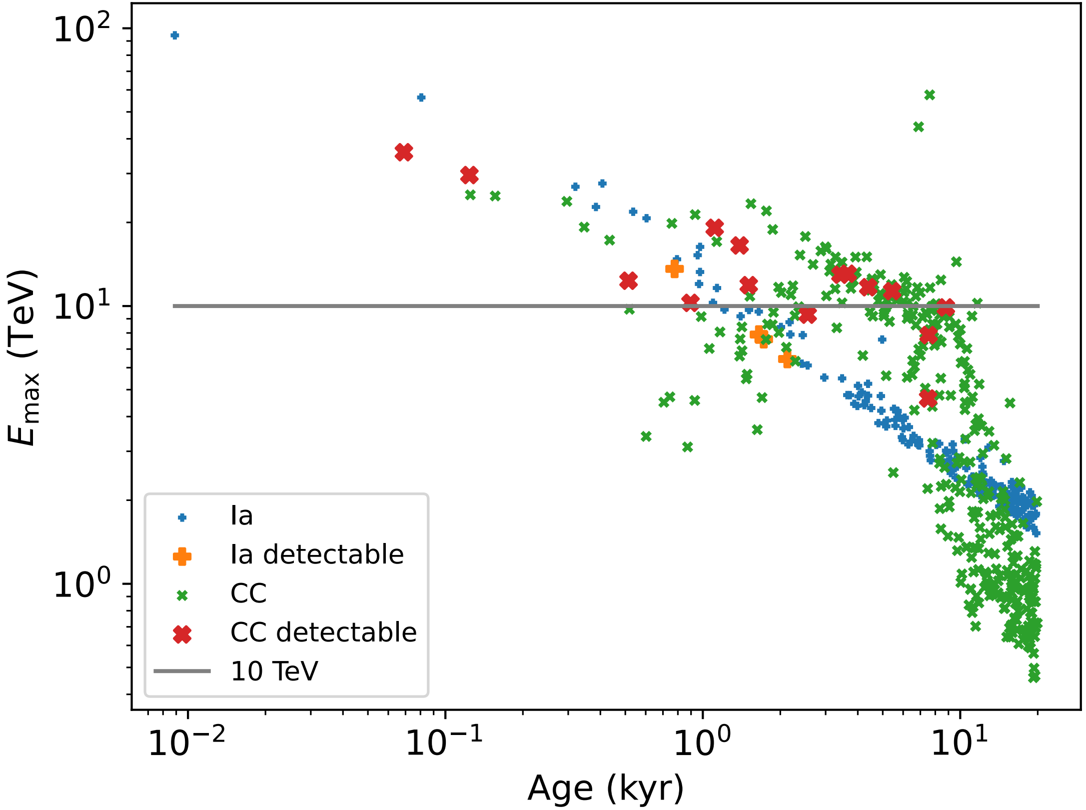


Cumulatively binned in integrated flux.



Cumulatively binned in integrated flux.

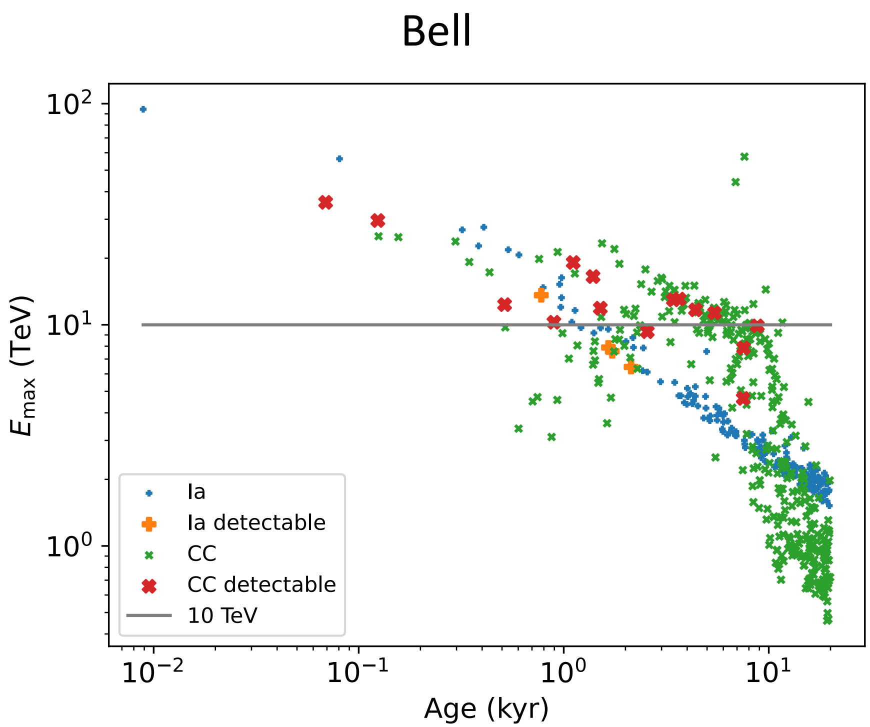
Additional E_{max} criterion

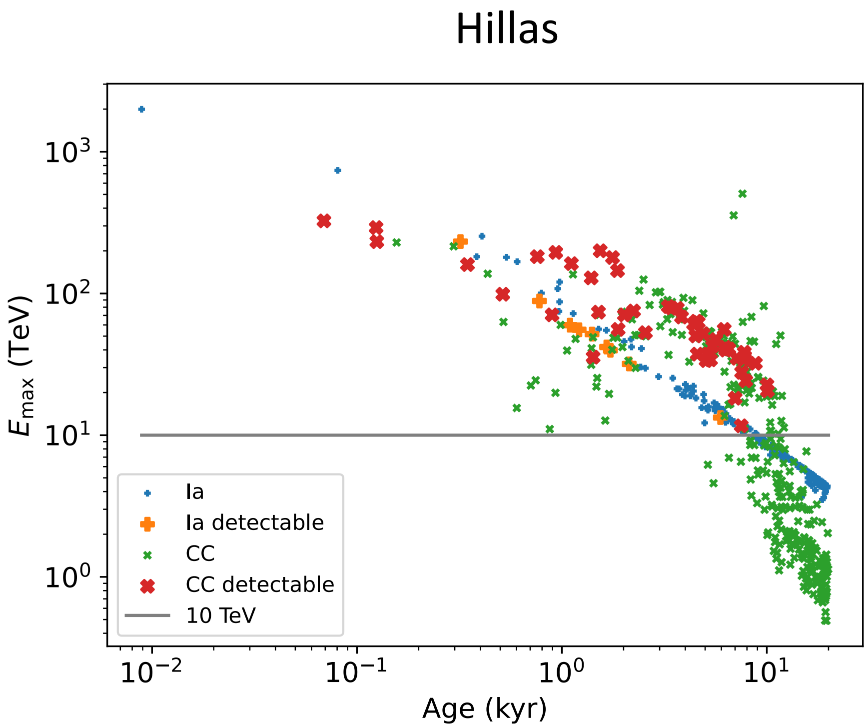


Parameters:
α = 4.2
Kep = 10^{-5}
$\eta = 0.09$
ST = 20 kyr
Steiman-Cameron

Maximum energy of particles

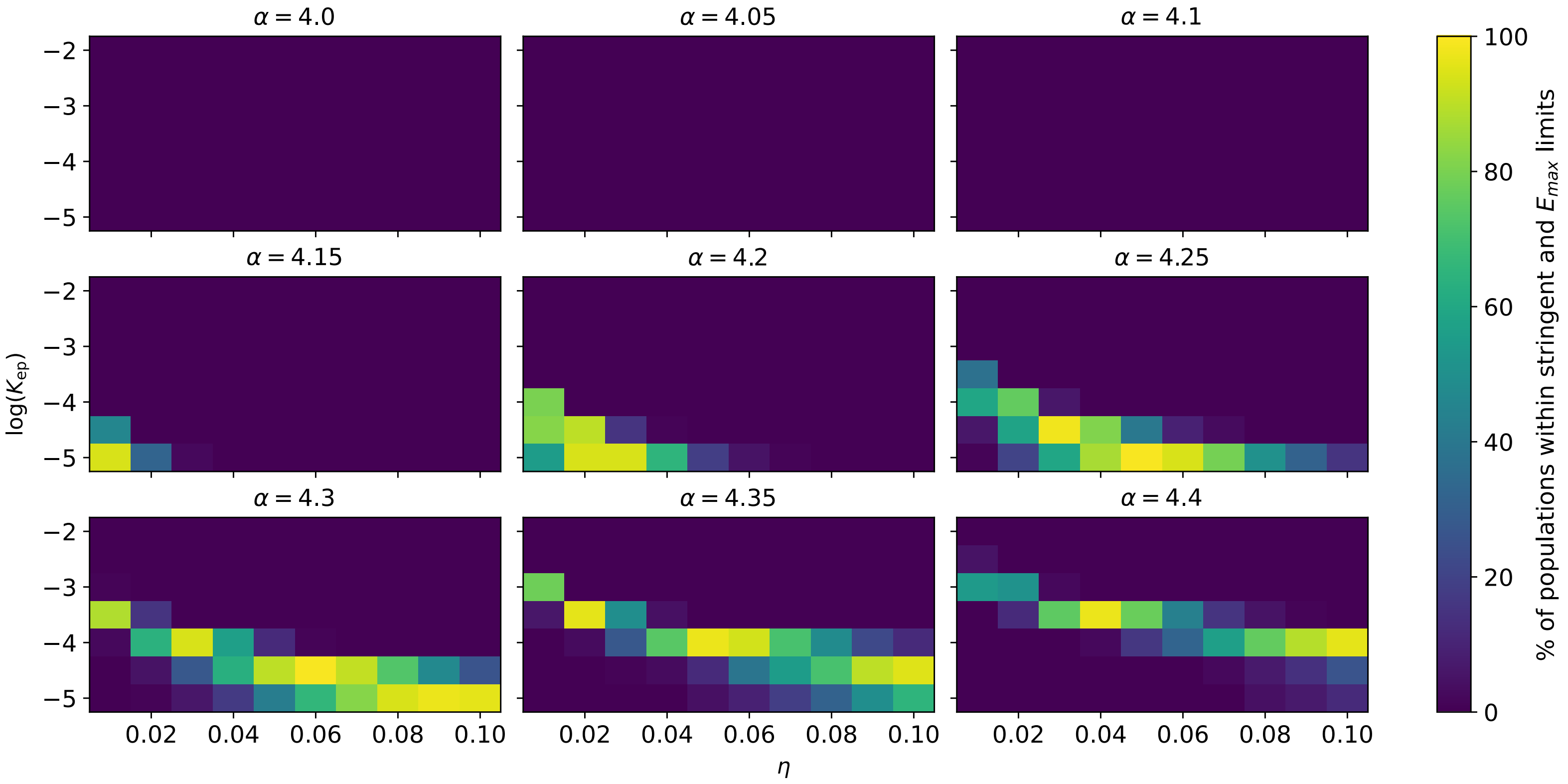
Parameters:
α = 4.2
Kep = 10^{-5}
$\eta = 0.09$
ST = 20 kyr
Steiman-Cameron





Results – Parameter exploration (Hillas)

- $\alpha < 4.15$ and $K_{ep} > 10^{-3}$ means too many detectable SNRs
- None of the populations within the stringent are excluded by the E_{max} limit



Radius and luminosity distributions