Mathematisch-Naturwissenschaftliche Fakultät

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H.E.S.S.

The population of Galactic supernova remnants in the TeV range

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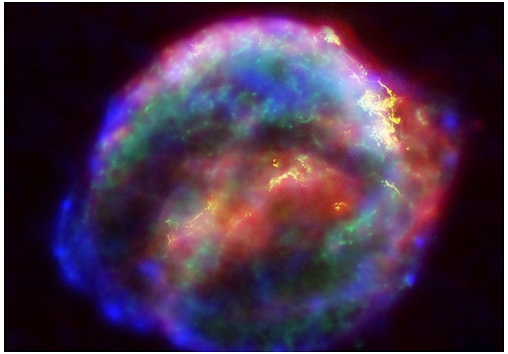


Image from NASA

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 (>1 TeV) range but the details of this gamma-ray emission is not well understood.

- Questions to answer:
  - Can we describe the 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?

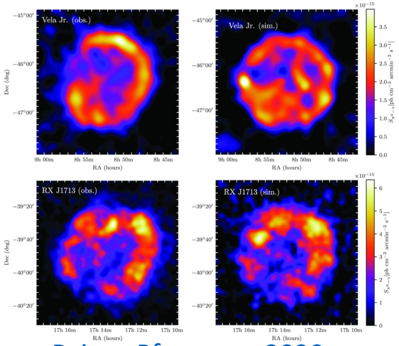
What are we looking for?

Single SNR simulation

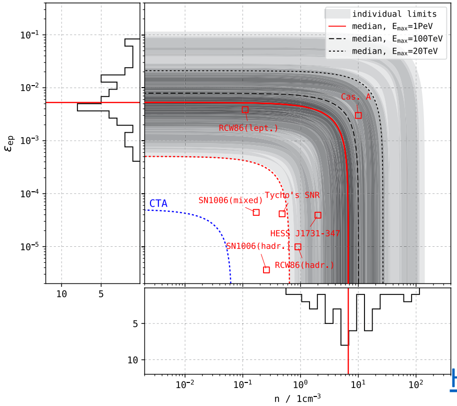
- Complicated modelling of the SNR
- Understanding the physical conditions and processes
- Only 1 SNR to compare to
- Focuses on extreme (brightest) cases

Population simulation

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



Pais et Pfrommer 2020

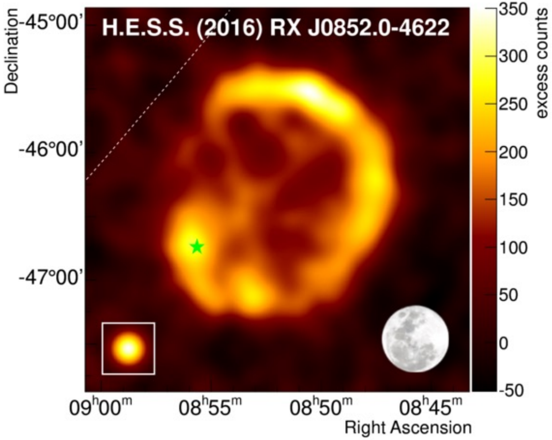


HESS Collaboration 2018

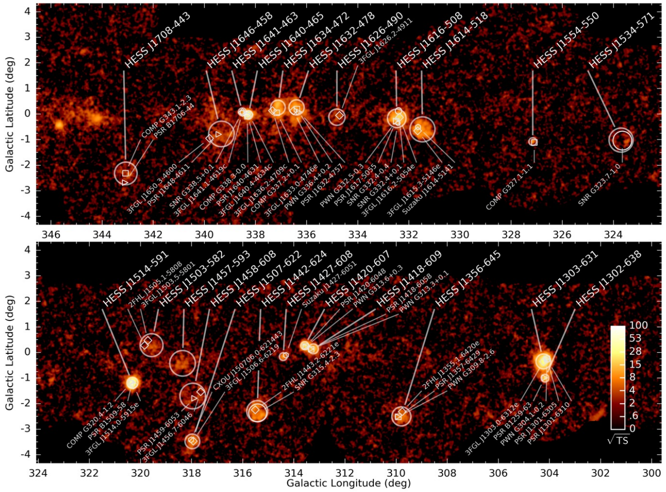
H.E.S.S. (High Energy Stereoscopic System)

H.E.S.S.

Vela Jr detected by H.E.S.S.

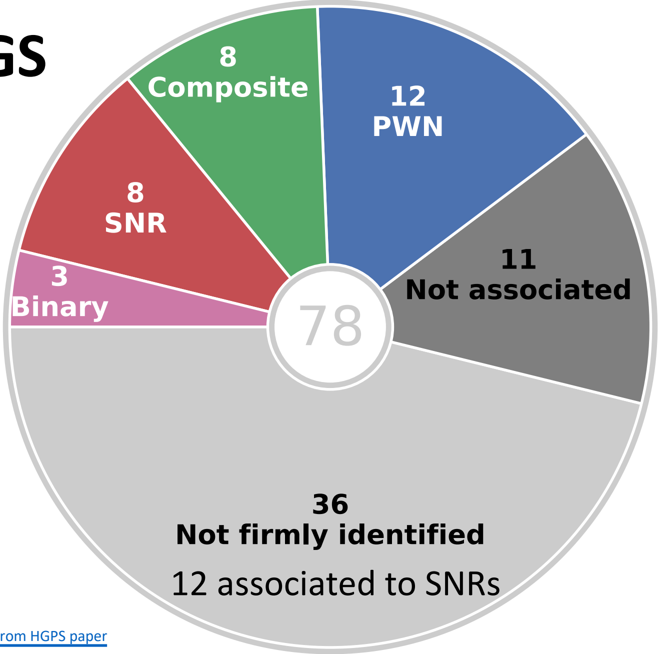


H.E.S.S. Galactic Plane Survey (HGPS)



HGPS (H.E.S.S. Galactic Plane Survey) 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

- 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

SNR population model

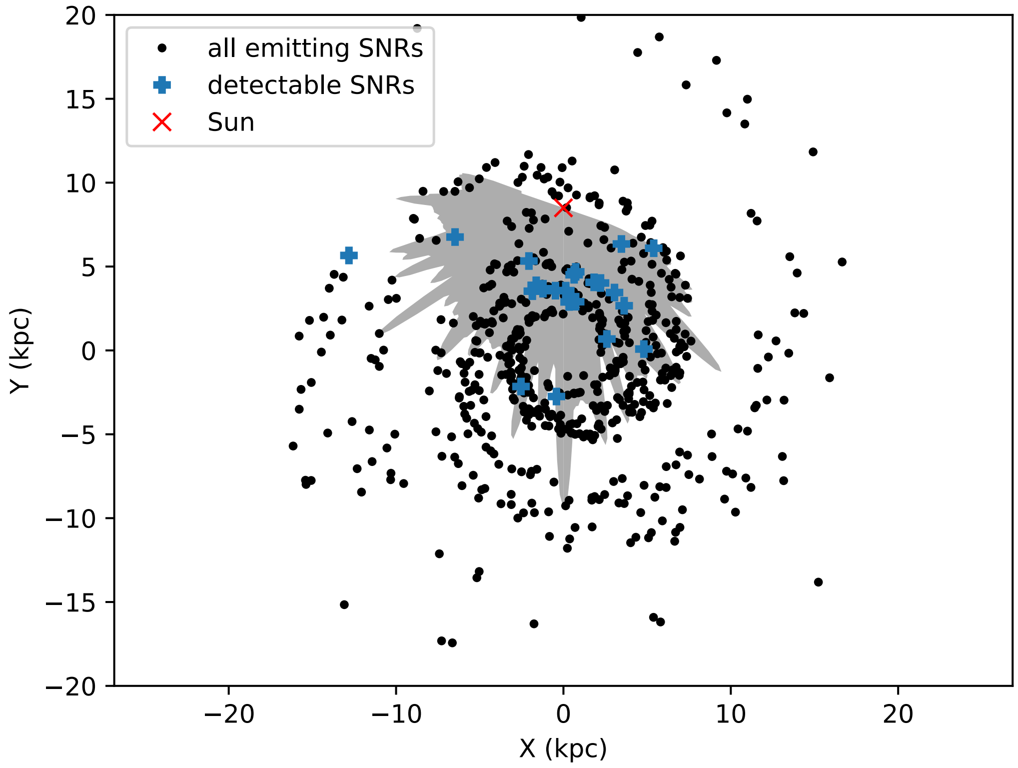
- Expanding on the work done by Cristofari et al.
  - Connection between ejecta masses and explosion energies
  - Refined description of magnetic field amplification and corresponding maximum energy for protons and electrons
  - Inclusion of diffusive shock reacceleration at SNR shocks
  - Multiple prescriptions for the spatial distribution of SNRs in the Galaxy

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%)
- Spatial distribution (Steiman-Cameron, Green, Reid, CAFG)
- Maximum duration of ST phase
- Maximum energy calculation

Realisation of a single population

- Taking into account the HGPS sensitivity
- Shaded region: $L = 5{\times}10^{33}$ ph s^{-1} ($\sim 4{\times}10^{-11}$ TeV^{-1} cm^{-2} s^{-1} at 1 kpc)



Parameters:

α = 4.3

Kep = 10^{-3}

η = 0.07

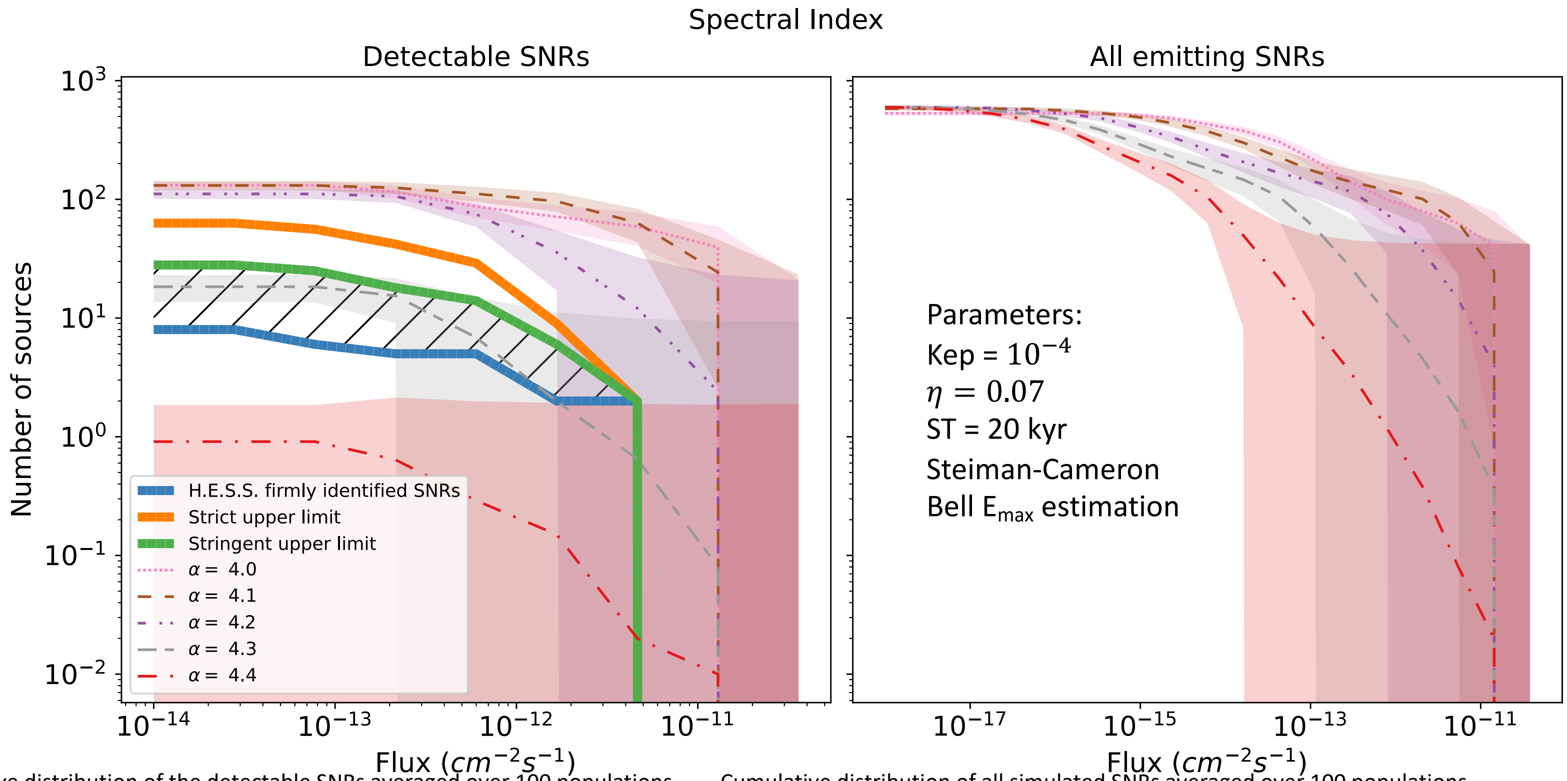
ST = 20 kyr

Steiman-Cameron distribution

Bell E_{max} estimation

Results – Spectral Index

- Log N log S
- Same no. of total SNRs
- Larger α means less detectable SNRs



Cumulative distribution of the detectable SNRs averaged over 100 populations. Cumulative distribution of all simulated SNRs averaged over 100 populations.

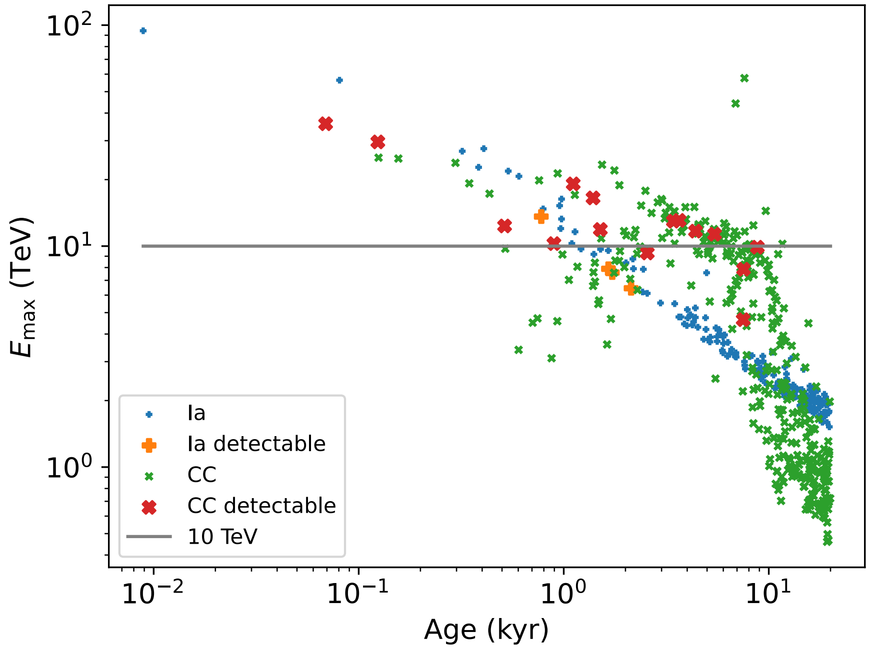
Systematic exploration of parameter space

- 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

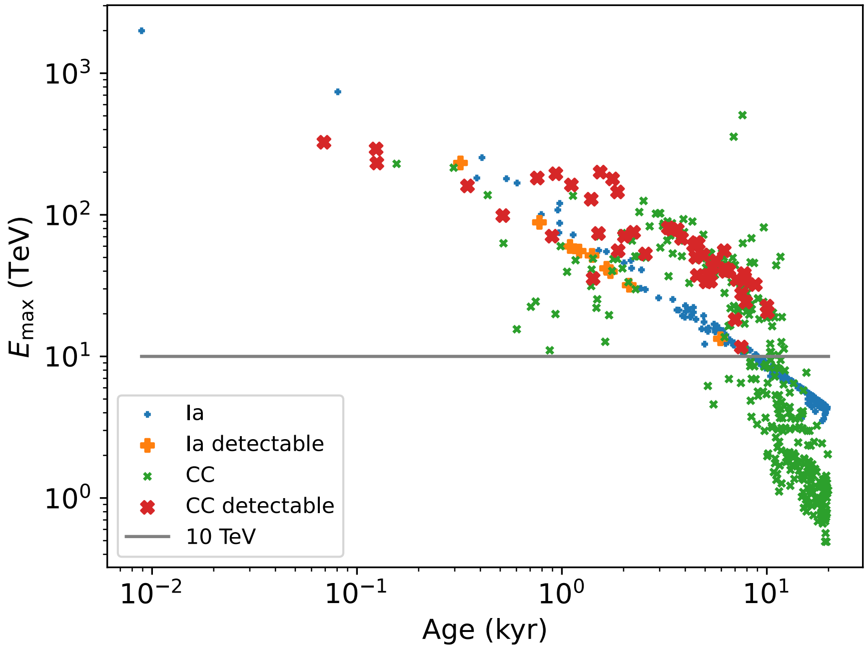
Maximum energy of particles

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

Bell



Hillas



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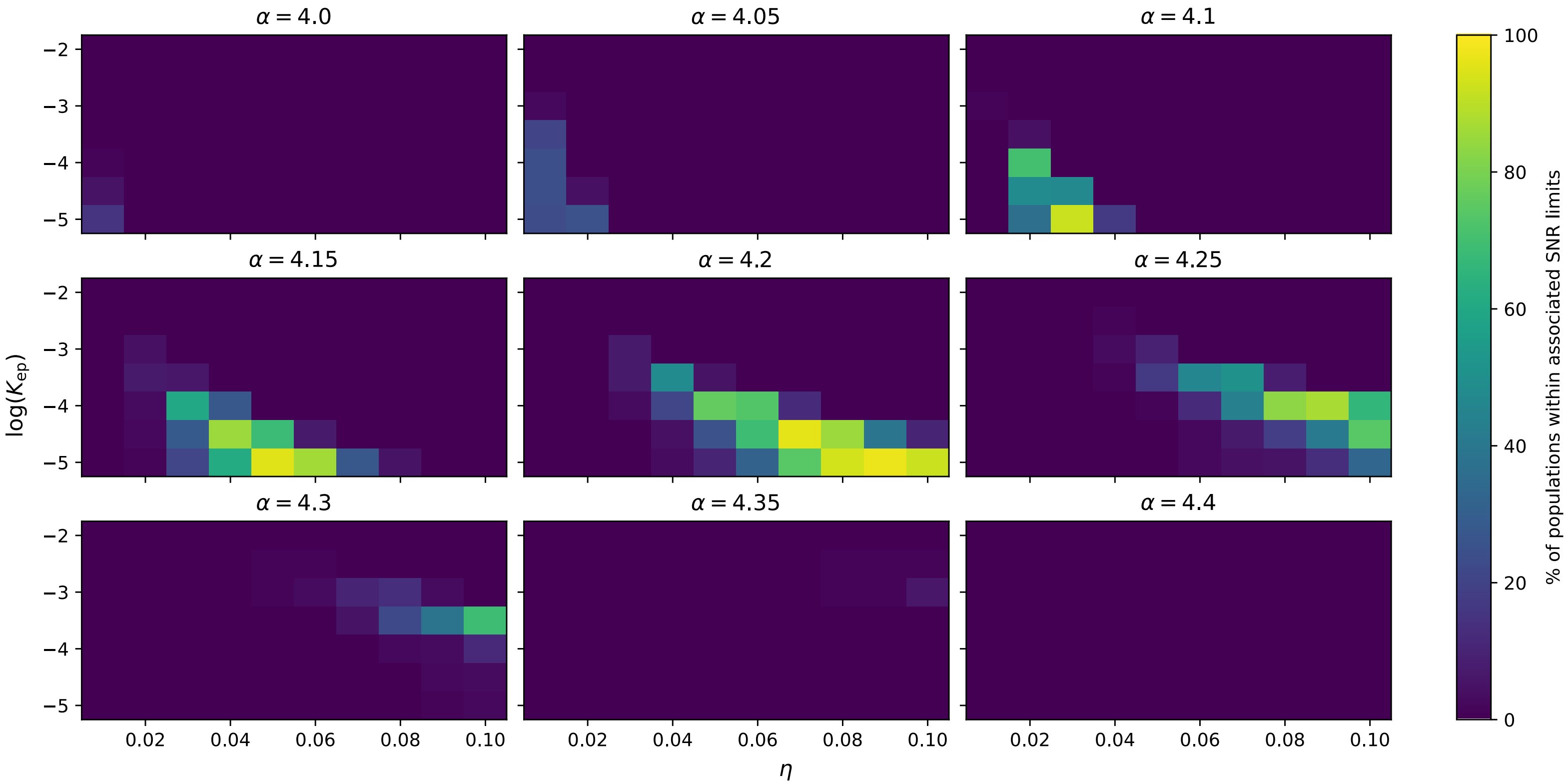
Results – Parameter exploration (Bell)



Best Populations (> 90% compatible)

Population Parameters			% of realisations 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

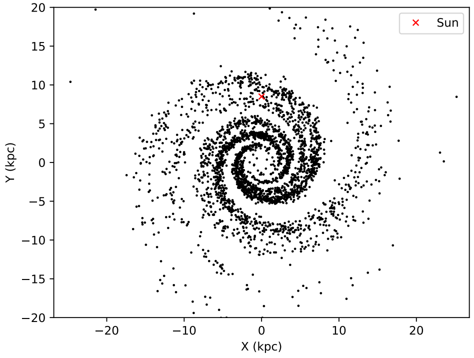
Summary

- Confronted SNR population model to HGPS, taking into account the multi-dimensional exposure.
- Explored a large parameter space but correlations prevent the identification of an optimal combination.
- Can exclude some parts off the 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 (with Emax set by the growth of non-resonant streaming instabilities):
  - $4.1 \lesssim \alpha \lesssim 4.2$
  - $10^{-5} \lesssim K_{ep} \lesssim 10^{-4.5}$
  - $0.03 \lesssim \eta \lesssim 0.1$
- Despite very low electron-proton ratios we still find many SNRs dominated by leptonic emission.
- It’s clear that when looking at individual SNRs you are not getting the full picture of the population.
- This work has been accepted for publication in A&A!

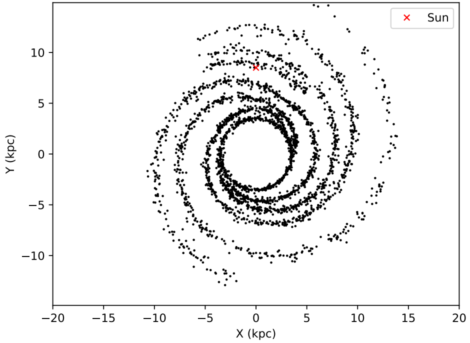
Backup slides

Source and matter distribution

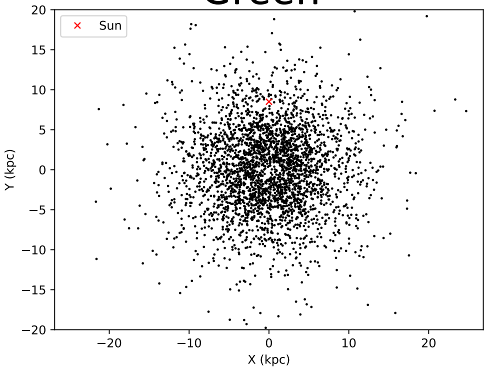
Steiman-Cameron



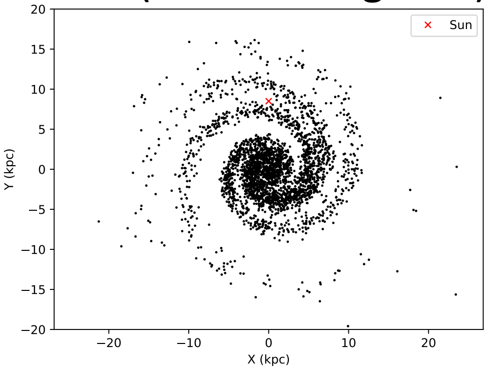
Reid



Green



CAFG (Faucher-Giguere)



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

- 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 mass and explosion energy

Thermonuclear:

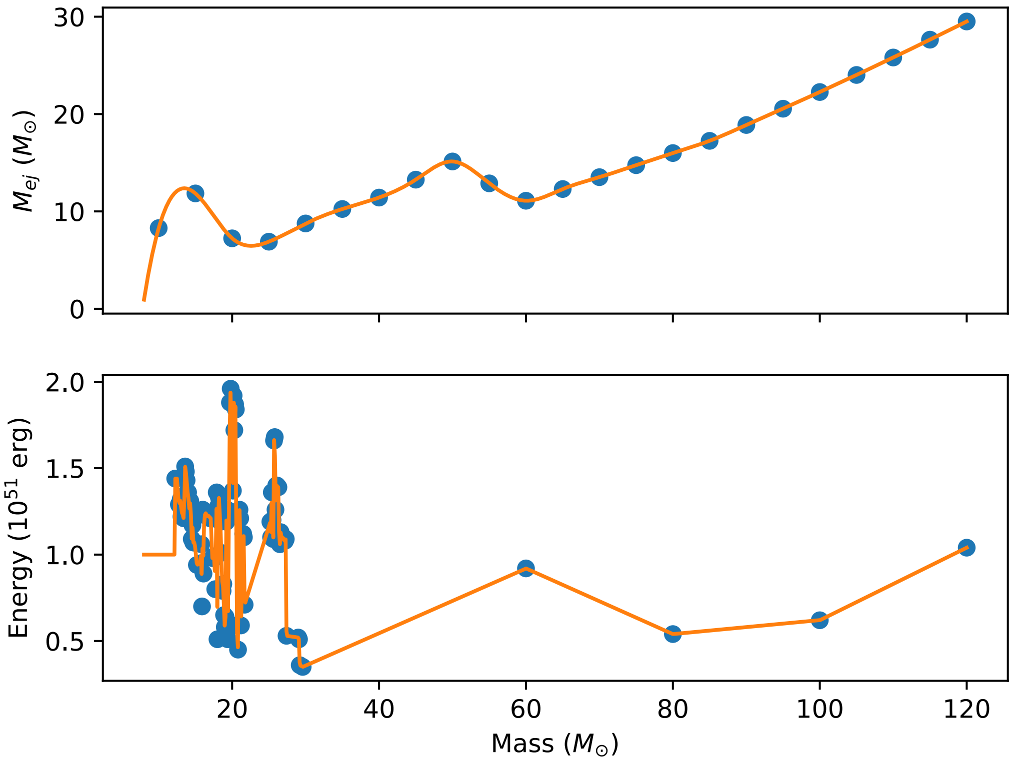
$M_{ej} = 1.4\ M_{\odot}$

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

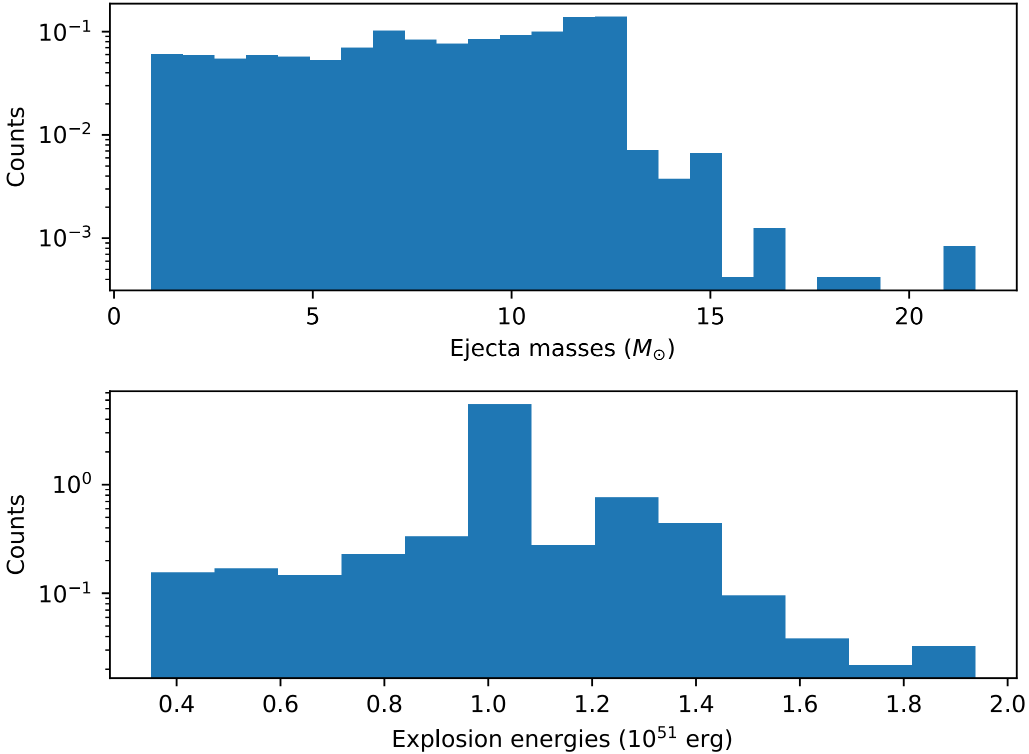
Core collapse:

Initial mass distribution $N \propto \int_{8}^{120\ M_{\odot}} M_{\star}^{-2.3} dM_{\star}$

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



Distribution of masses and explosion energies of simulated SNRs



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

Supernova dynamics

- Gamma rays from proton spectrum via proton-proton collision and Pion Decay.

- Gamma rays from electron spectrum via inverse Compton assuming an electron proton ratio (K_{ep}).

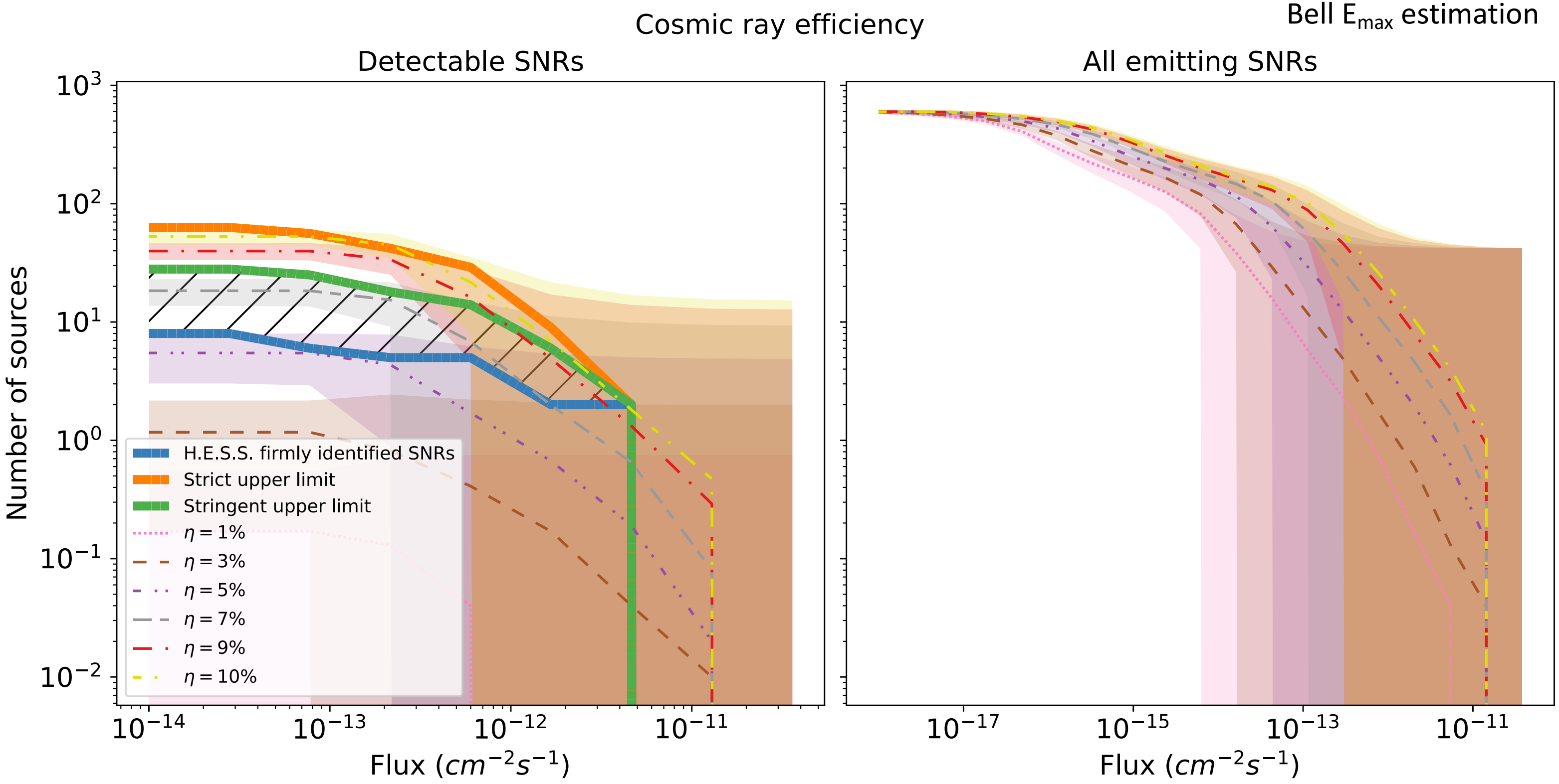
Emission from reaccelerated CRs - Cristofari & Blasi (2019)

- 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 – Cosmic Ray Efficiency

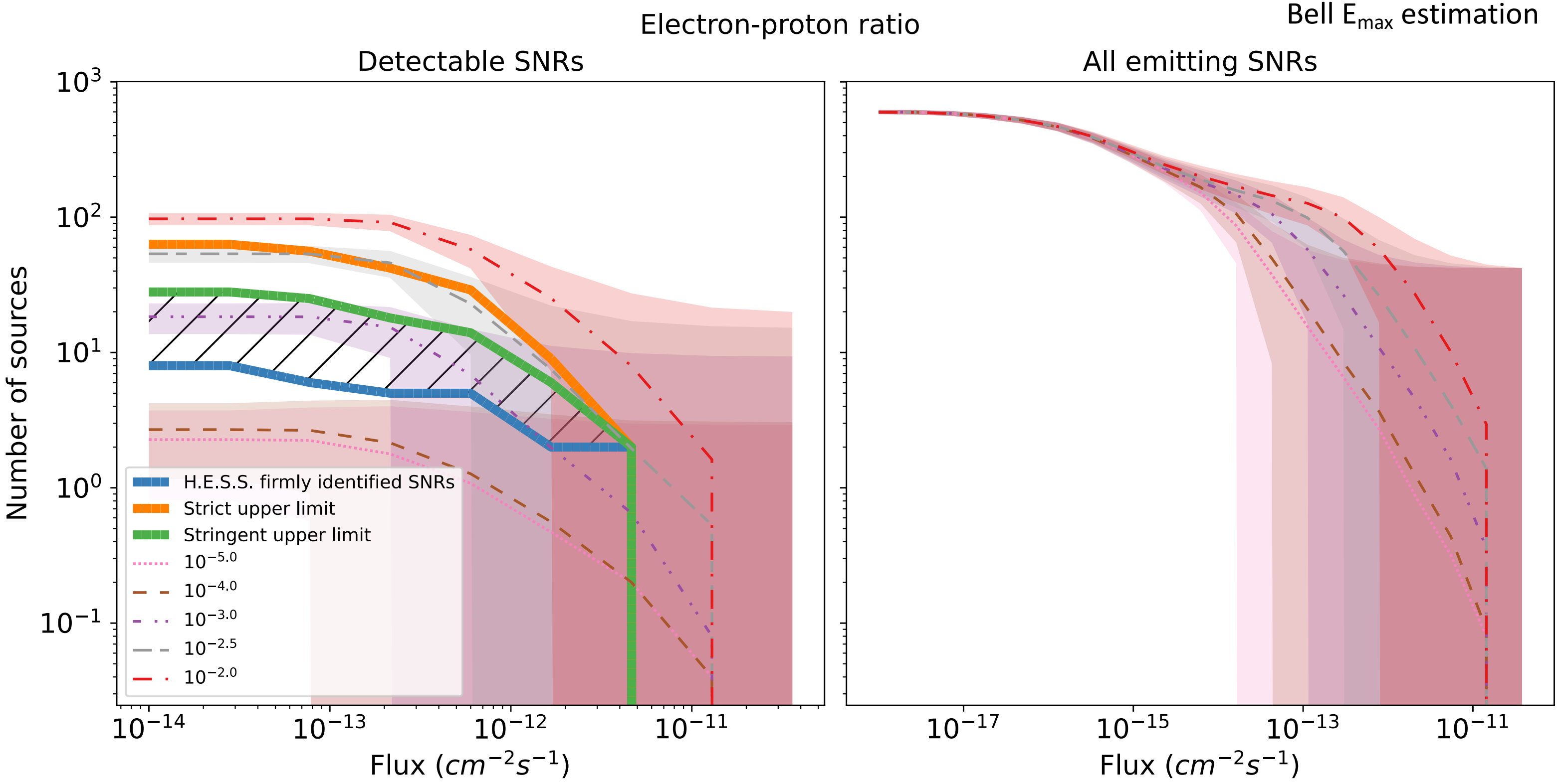
Parameters:
$\alpha = 4.3$
Kep = 10^{-4}
ST = 20 kyr
Steiman-Cameron
Bell E_{max} estimation



Cumulative distribution of the detectable SNRs averaged over 100 populations. Cumulative distribution of all simulated SNRs averaged over 100 populations.

Results – Electron-proton ratio

Parameters:
$\alpha = 4.3$
$\eta = 0.07$
ST = 20 kyr
Steiman-Cameron
Bell E_{max} estimation



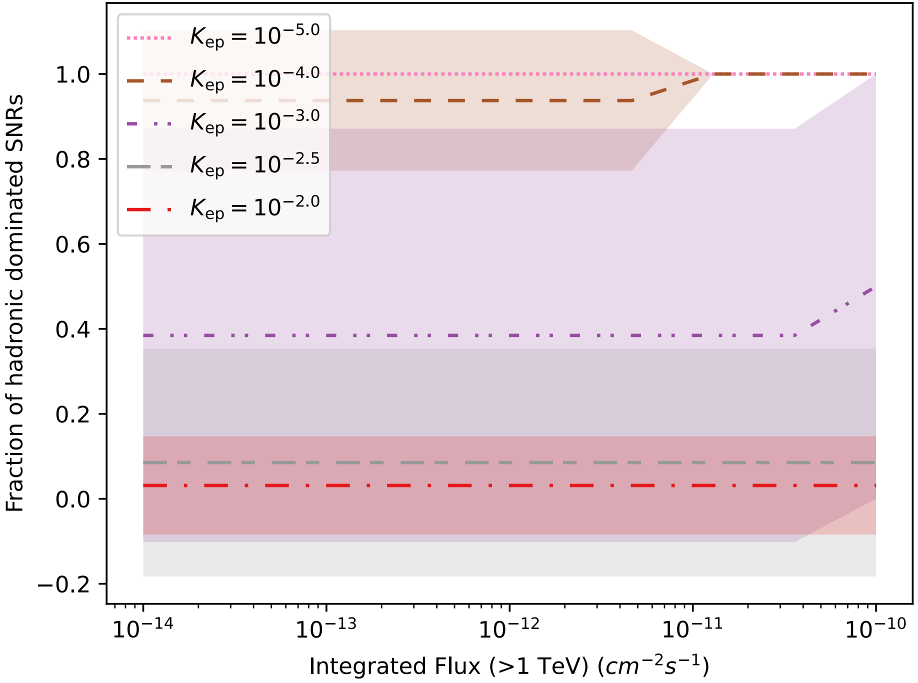
Cumulative distribution of the detectable SNRs averaged over 100 populations.

Cumulative distribution of all simulated SNRs averaged over 100 populations.

Ratio of detectable sources dominated by hadronic emission

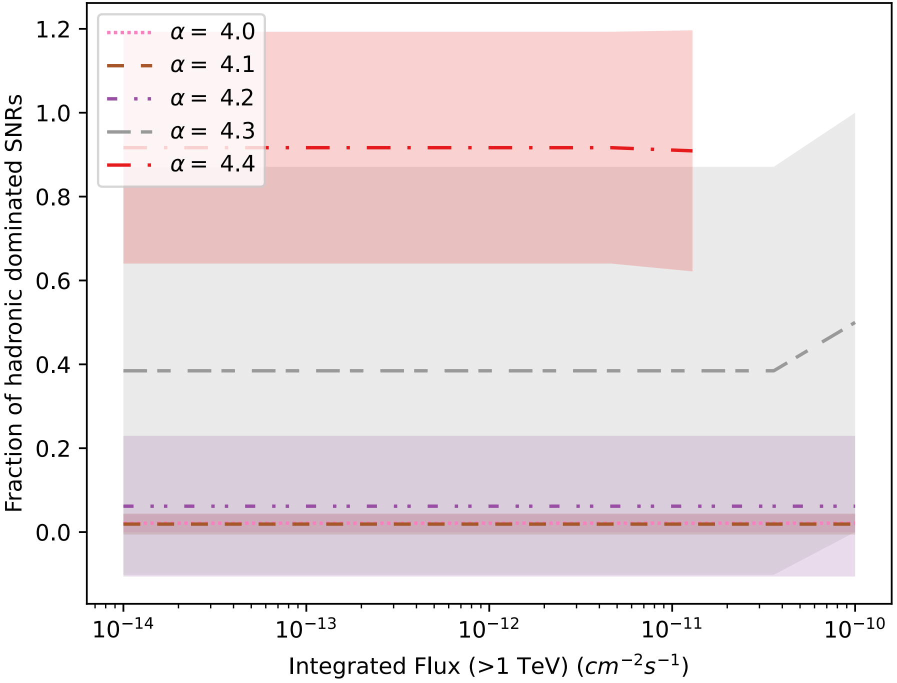
- As the electron-proton fraction increases the hadronic fraction decreases

- Is this the only property that changes the hadronic ratio?

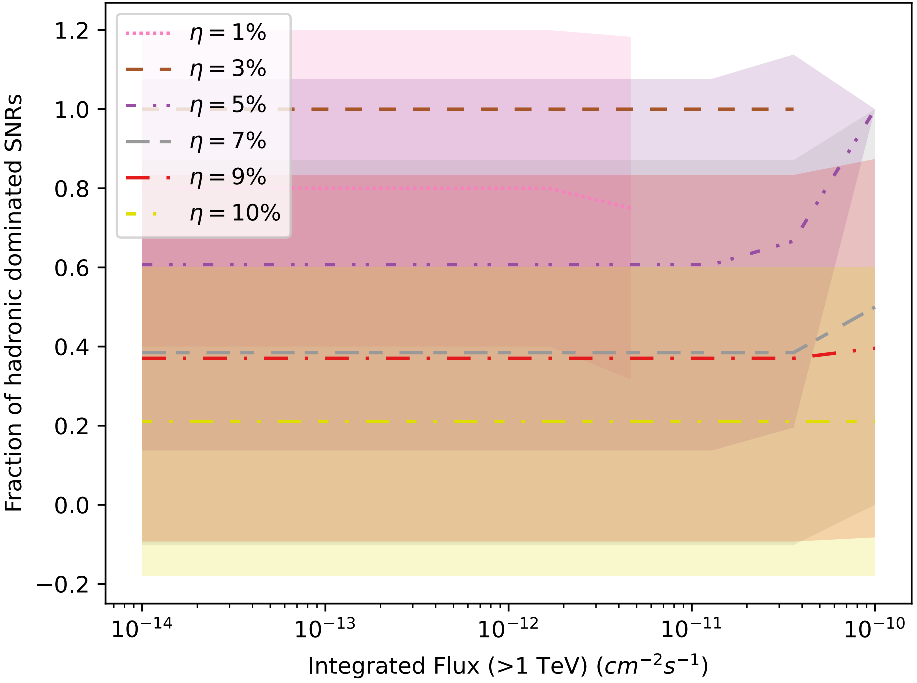


Cumulatively binned in integrated flux.

Ratio of detectable sources dominated by hadronic emission



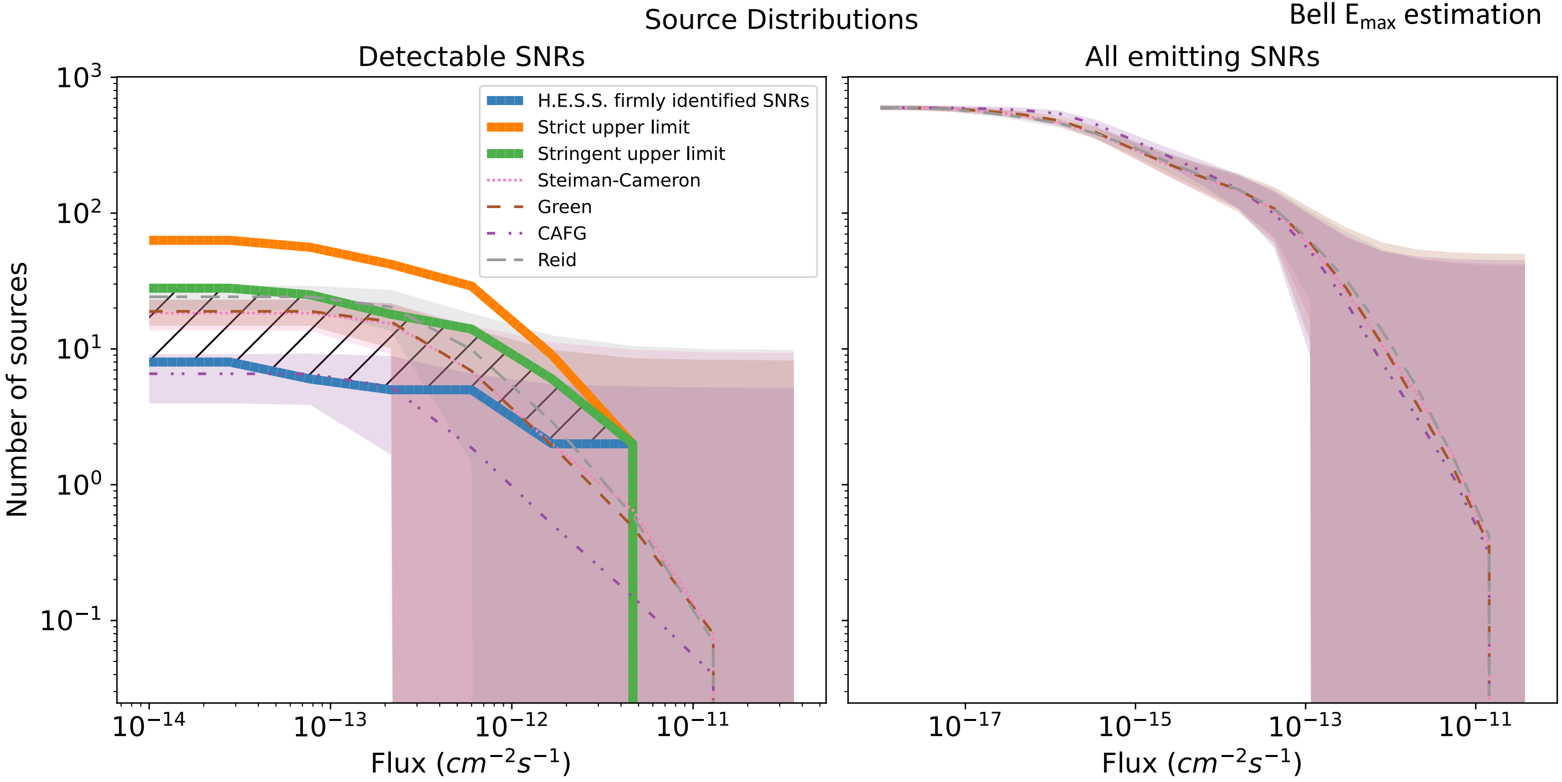
Cumulatively binned in integrated flux.



Cumulatively binned in integrated flux.

Results – Spatial distribution

Parameters:
$\alpha = 4.3$
$K_{ep} = 10^{-4}$
$\eta = 0.07$
ST = 20 kyr
Bell E_{max} estimation

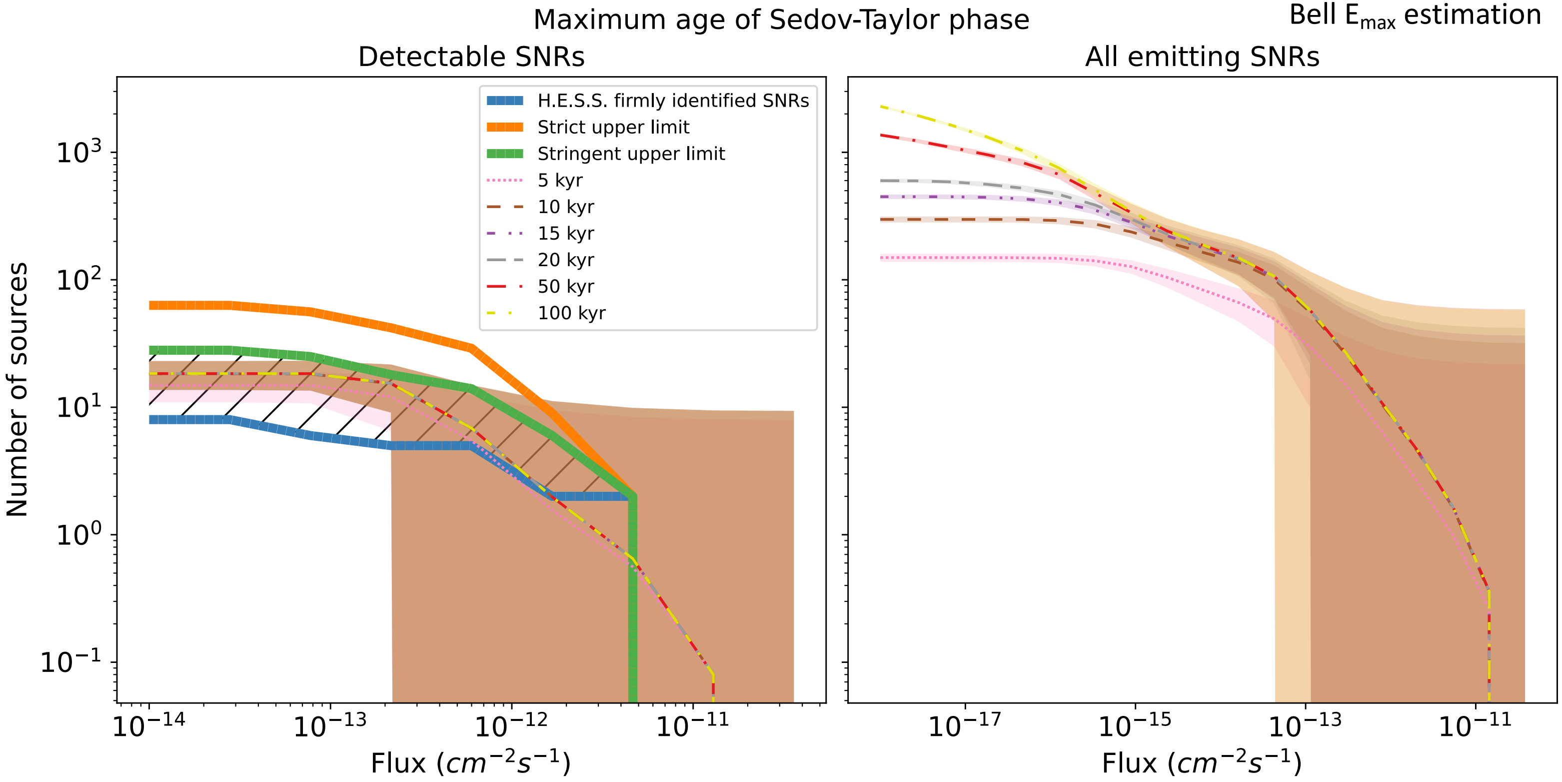


Cumulative distribution of the detectable SNRs averaged over 100 populations.

Cumulative distribution of all simulated SNRs averaged over 100 populations.

Results – Maximum length of Sedov-Taylor phase

Parameters:
$\alpha = 4.3$
$K_{ep} = 10^{-4}$
$\eta = 0.07$
Steiman-Cameron
Bell E_{max} estimation



Cumulative distribution of the detectable SNRs averaged over 100 populations.
Cumulative distribution of all simulated SNRs averaged over 100 populations.

Results – Parameter exploration (Hillas)