SNRs as PeVatron candidates for CTA

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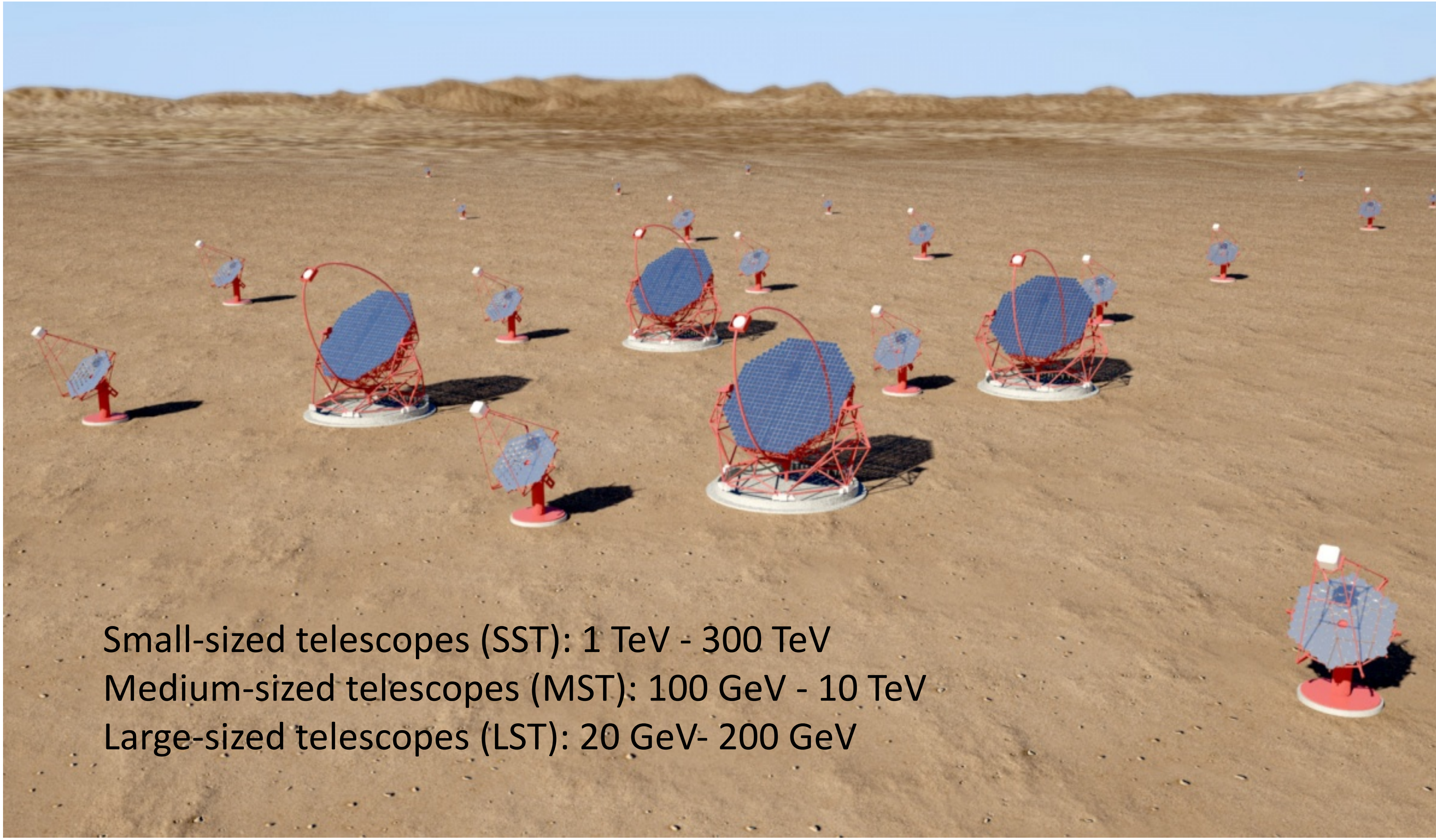
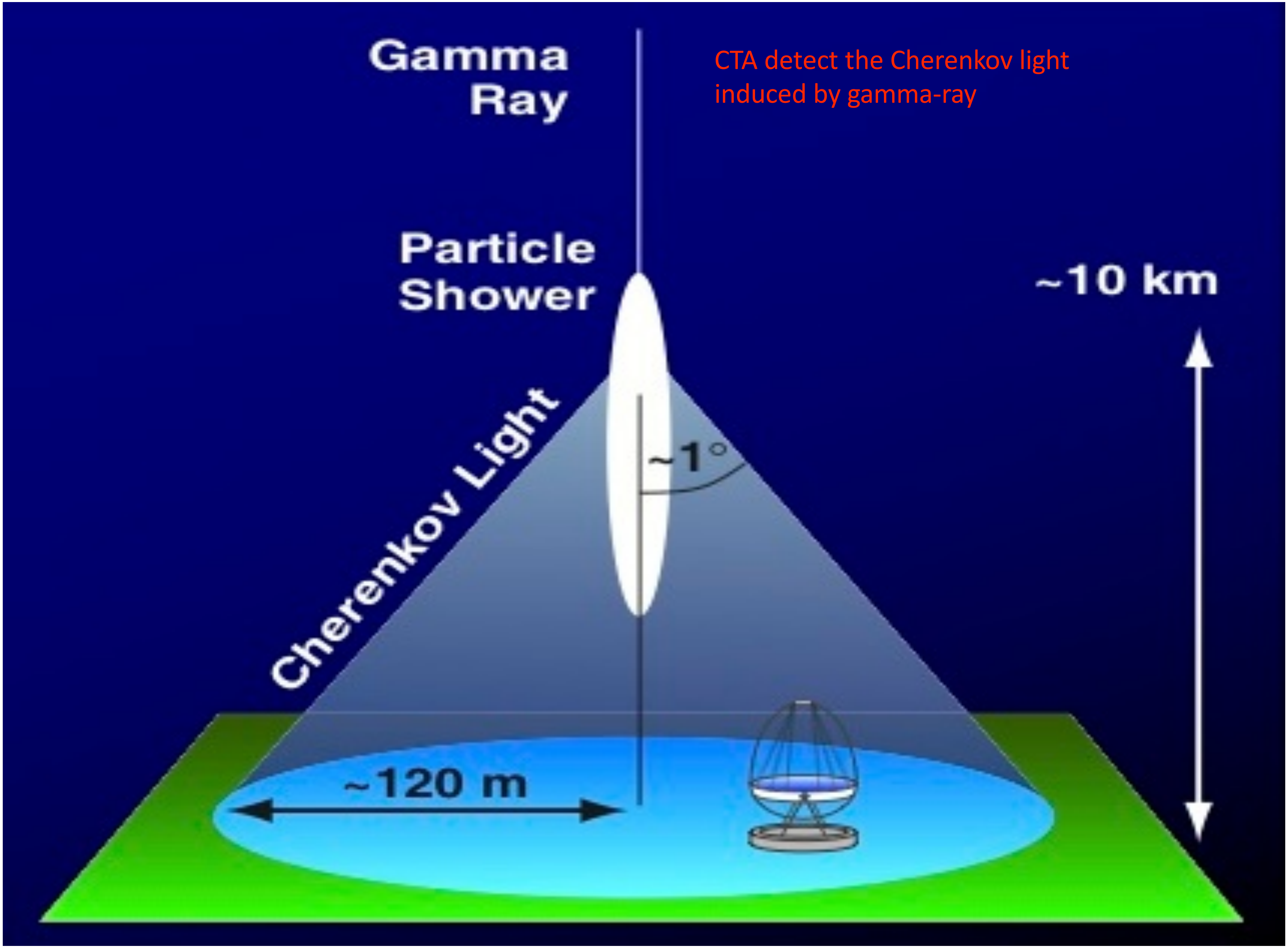
- Cherenkov Telescope Array
- Supernova Remnants as PeVatron candidates
- Naima and model fitting
- Main results
- Summary

Cherenkov Telescope Array (CTA)



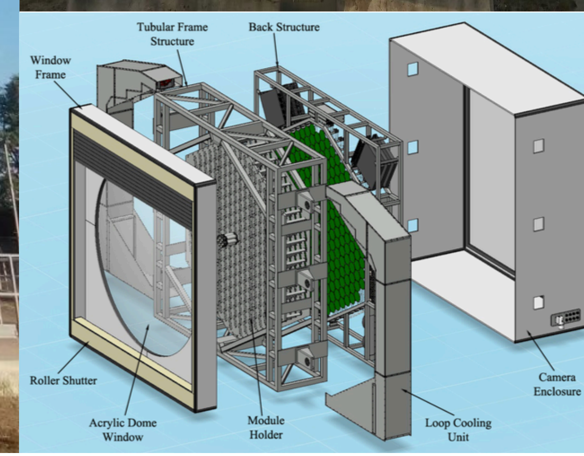
North site: La Palma (Spain)

South site: Paranal (Chile)

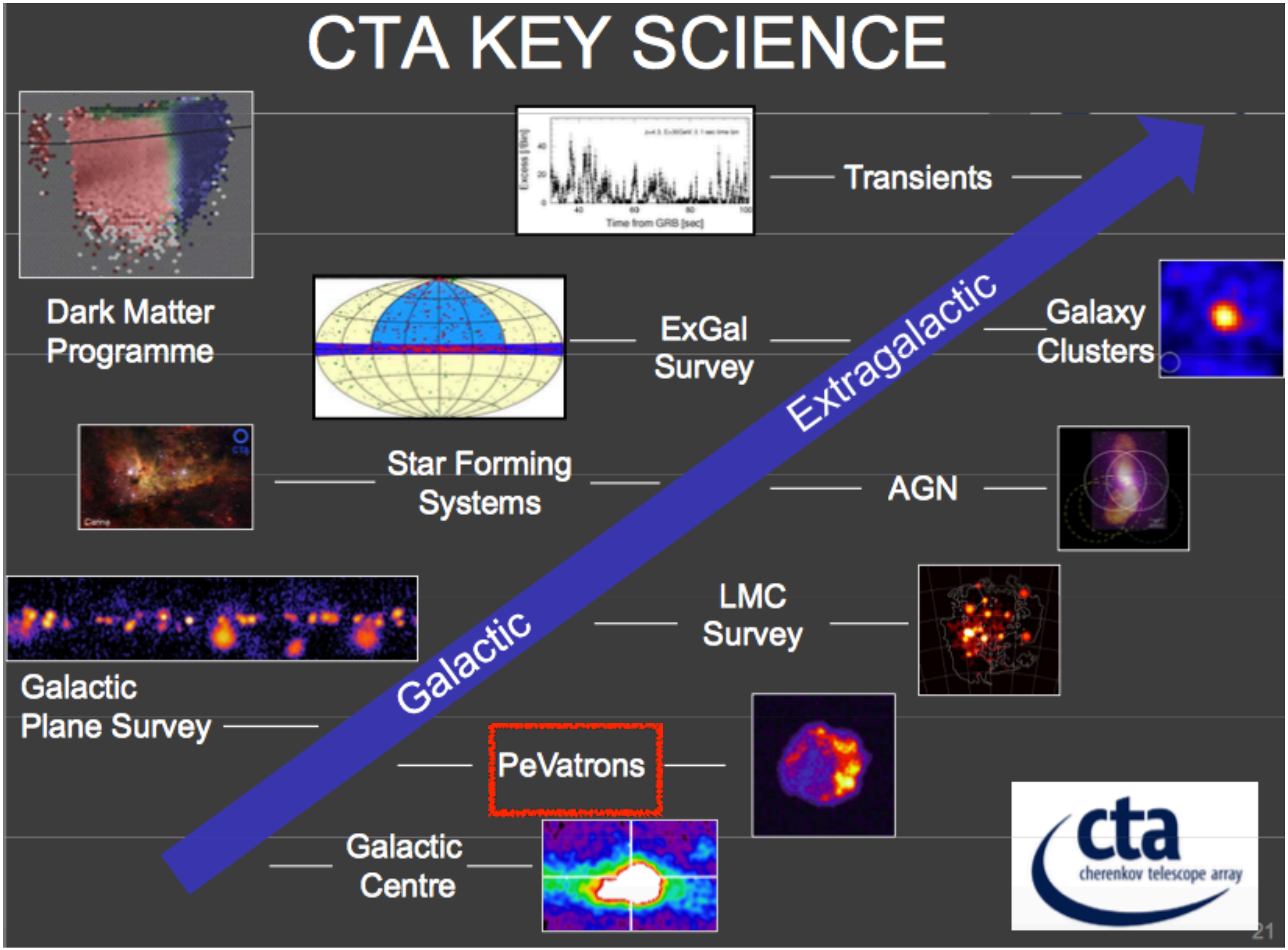

Gamma
Ray
CTA detect the Cherenkov light
induced by gamma-ray
Particle
Shower
~10 km
Cherenkov Light
~1°
~120 m


LST, 2017-11, La Palma, Spain


MST, 2018-09, DESY, Germany


Window Frame
Tubular Frame Structure
Back Structure
Roller Shutter
Acrylic Dome Window
Module Holder
Loop Cooling Unit
Camera Enclosure

CTA: Cosmic-rays PeVatron as a Key Science Project (KSP)



from Rene Ong (2015)

Cosmic-Rays accelerated up to 1 PeV

- PeVatrons: astrophysical object accelerated particles above 1 PeV (10^15eV).
- The energy of spectrum of Cosmic-Rays (CRs) extends until few PeV where it steepens originating the ‘knee’.
- Theoretical prediction and measurements of CR indicate that the CR should be accelerated up to 1 PeV in our Galaxy.

Supernova Remnants (SNRs) as promising Galactic PeVatron candidates

- The detection of SNRs with spectrum up to 100 TeV imply that they are one kinds of PeVatron candidates, because ~100 TeV photons are produced by ~ PeV protons. (observation)
- SNRs are able to satisfy the cosmic-ray energy requirement by converting the kinetic energy into accelerated particle. (theory)
- SNRs (and Pulsar Wind Nebulae) are the majority of Galactic poululation.

Proton-proton collision induces pion decay

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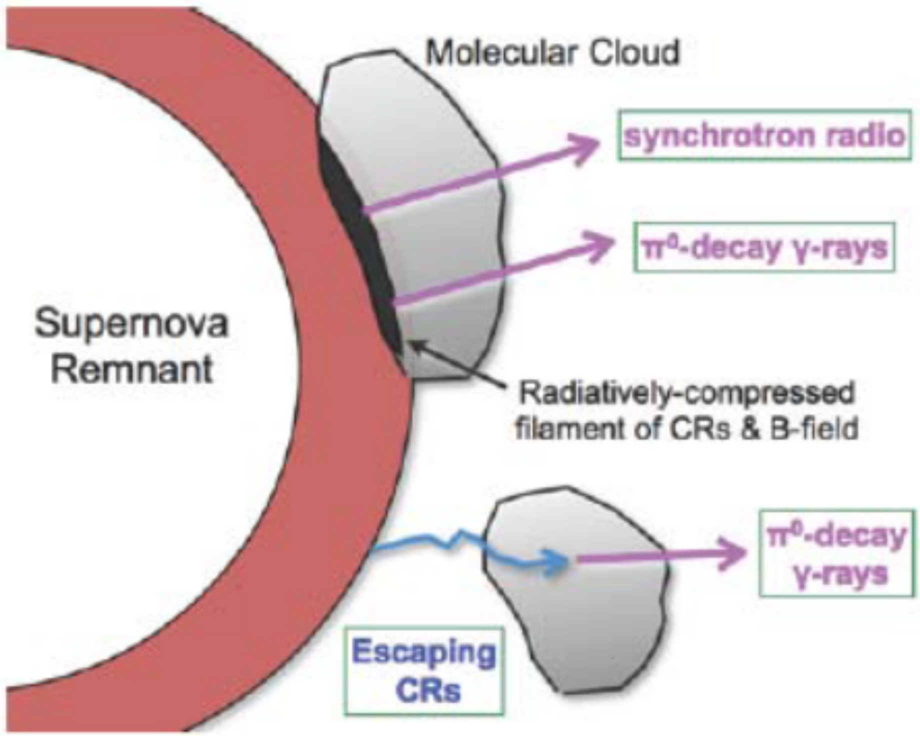


For accelerated protons, hadronic interactions with ambient matter produce neutral pion, decaying into two γ-ray photons

$$\pi^0 \rightarrow \gamma_1 + \gamma_2,$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu,$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \rightarrow e^- + \bar{\nu}_e + \nu_\mu + \bar{\nu}_\mu.$$

DC-1 data, Prod3b IRF and ctools

- Data Challenge one (DC-1): **simulated** data enable the CTA Consortium Science Working Group to derive science benchmarks for the CTA KSP.

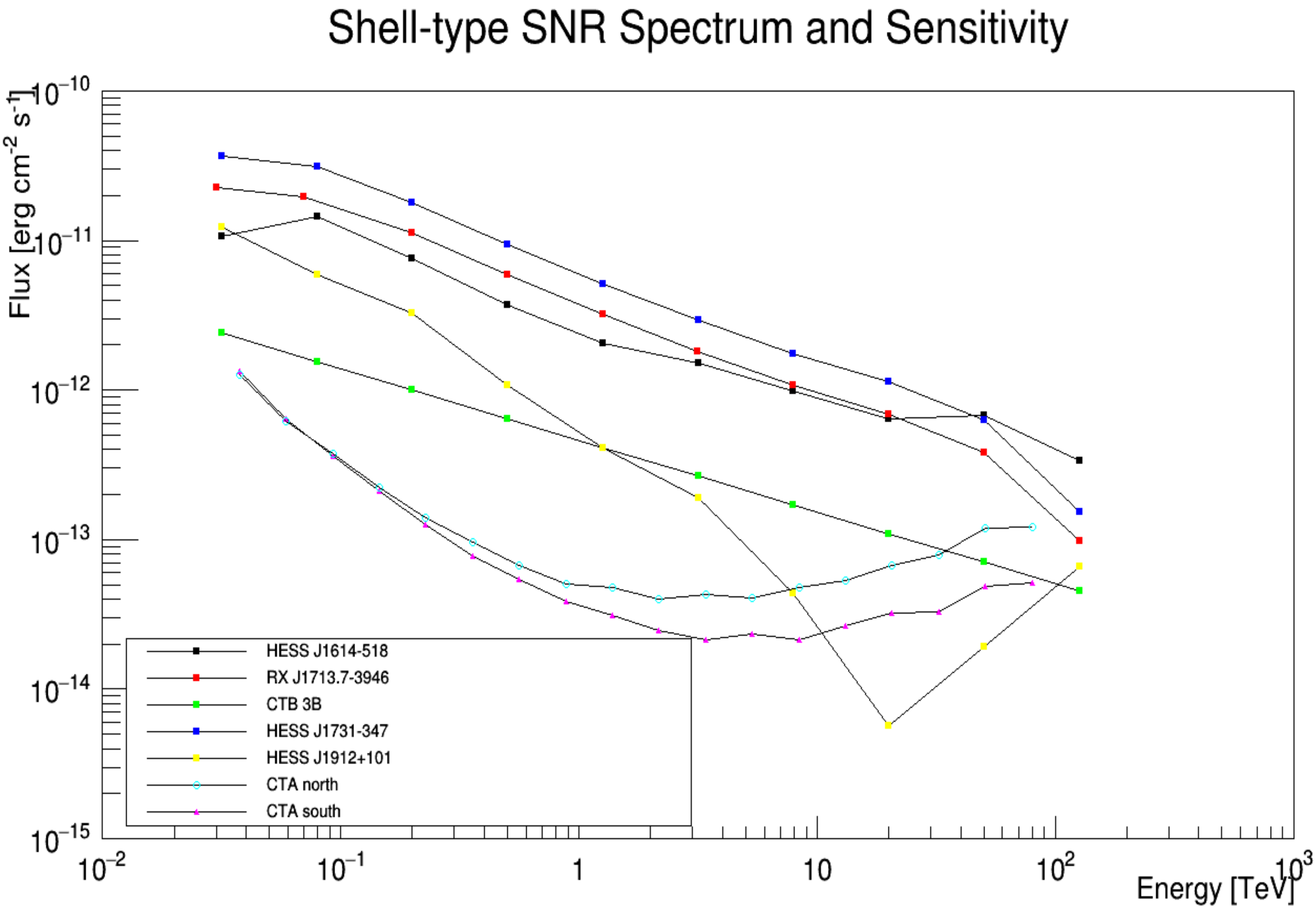
- DC-1 includes Galactic Plane Scan (GPS) as one of the key science projects. We use GPS data to analysis SNRs.

- Prod3b Instrumental Response Functions (IRFs): the performance values are derived from Monte Carlo simulation of CTA instrument based on the CORSIKA air shower code.

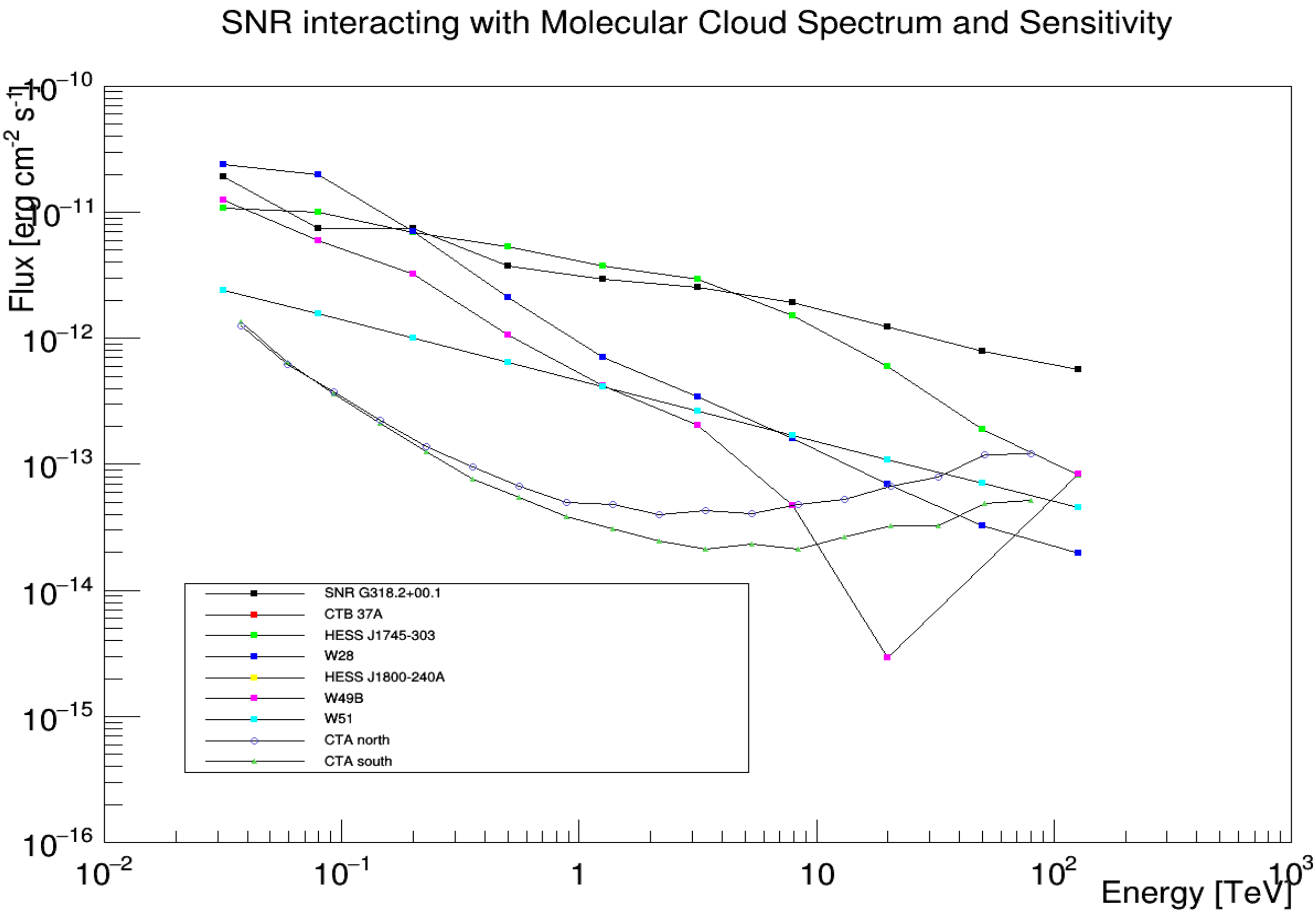
- Ctools: a soft package developed for scientific analysis of CTA data. We run ctools pipeline to judge whether SNRs from TeVCat are considered in DC-1 GPS, and to draw the spectrums.

Low Galactic latitude from TeVCat

SNR name	Galactic Longitude	Galactic Latitude	Type
HESS J1534−571	323.65	-0.92	Shell
HESS J1614+516	331.52	-0.58	Shell
RX J1713.7−3946	347.34	-0.47	Shell
CTB 37B	348.65	0.38	Shell
HESS J1731−347	347.34	-0.47	Shell
HESS J1912+101	44.39	-0.07	Shell
0FGL J1954.4+2838	65.30	0.38	Shell
SNR G318.2+00.1	318.36	-0.43	SNR/Molec. Cloud
CTB 37A	348.39	0.11	SNR/Molec. Cloud
SNR G349.7+00.2	349.72	0.17	SNR/Molec. Cloud
HESS J1745−303	358.71	-0.64	SNR/Molec. Cloud
HESS J1800−240C	5.71	-0.06	SNR/Molec. Cloud
HESS J1800−240B	5.90	-0.37	SNR/Molec. Cloud
W 28	6.66	-0.27	SNR/Molec. Cloud
HESS J1800−240A	6.14	-0.63	SNR/Molec. Cloud
W 49B	43.32	-0.16	SNR/Molec. Cloud
SNR G015.4+00.1	15.41	0.16	Composite SNR



Shell-type SNR Spectrum and Sensitivity
Flux [erg cm^-2 s^-1]
10^-10
10^-11
10^-12
10^-13
10^-14
10^-15
10^-2
10^-1
1
10
10^2
10^3
Energy [TeV]
HESS J1614-518
RX J1713.7-3946
CTB 3B
HESS J1731-347
HESS J1912+101
CTA north
CTA south



SNR interacting with Molecular Cloud Spectrum and Sensitivity
Flux [erg cm^{-2} s^{-1}]
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
Energy [TeV]
SNR G318.2+00.1
CTB 37A
HESS J1745-303
W28
HESS J1800-240A
W49B
W51
CTA north
CTA south

Naima python package

Given that the MCMC procedure will sample the areas of the distribution with maximum value of the objective function, it is useful to define the objective function as the log-likelihood disregarding constant factors:

$$\ln \mathcal{L} \propto \sum_{i=1}^{N} \frac{(S(\vec{p}; E_i) - F_i)^2}{\sigma_i^2}.$$

The $\ln \mathcal{L}$ function in this assumption can be related to the χ^2 parameter as $\chi^2 = -2 \ln \mathcal{L}$, so that maximization of the log-likelihood is equivalent to a minimization of χ^2.

class `naima.models.`**`Synchrotron`**(*particle_distribution*, *B=<Quantity 3.24e-06 G>*, ***kwargs*) [source]

Synchrotron emission from an electron population.

This class uses the approximation of the synchrotron emissivity in a random magnetic field of Aharonian, Kelner, and Prosekin 2010, PhysRev D 82, 3002 (arXiv:1006.1045).

Parameters: **particle_distribution** : function

Particle distribution function, taking electron energies as a `Quantity` array or float, and returning the particle energy density in units of number of electrons per unit energy as a `Quantity` array or float.

B : `Quantity` float instance, optional

Isotropic magnetic field strength. Default: equipartition with CMB (3.24e-6 G)

class `naima.models.`**`PionDecay`**(*particle_distribution*, *nh=<Quantity 1. 1 / cm3>*, *nuclear_enhancement=True*, ***kwargs*) [source]

Pion decay gamma-ray emission from a proton population.

Compute gamma-ray spectrum arising from the interaction of a relativistic proton distribution with stationary target protons using the parametrization of Kafexhiu et al. (2014).

If you use this class in your research, please consult and cite Kafexhiu, E., Aharonian, F., Taylor, A.M., & Vila, G.S. 2014, Physical Review D, 90, 123014.

Parameters: **particle_distribution** : function

Particle distribution function, taking proton energies as a `Quantity` array or float, and returning the particle energy density in units of number of protons per unit energy as a `Quantity` array or float.

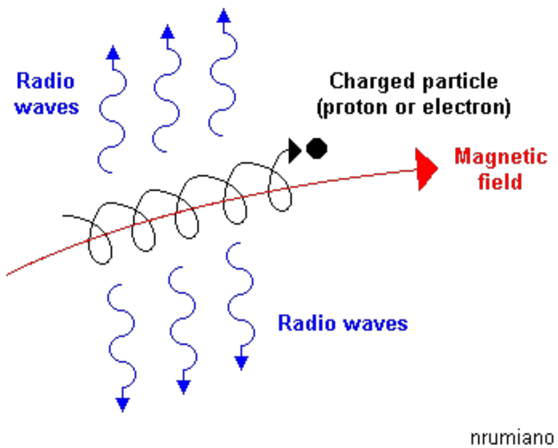
nh : `Quantity`

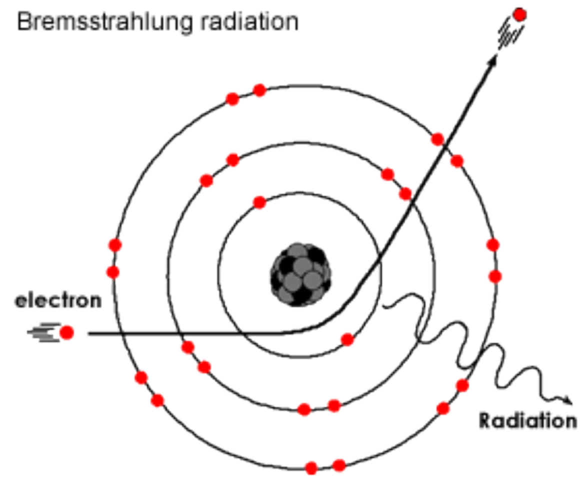
Number density of the target protons. Default is $1 \mathrm{cm}^{-3}$.

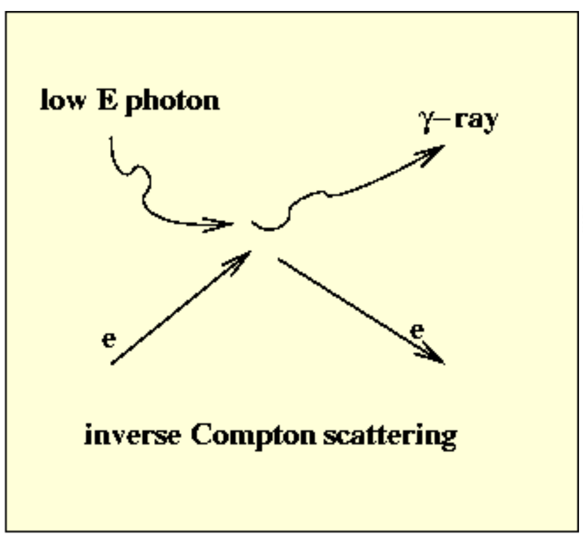
Radiation mechanism for SNRs

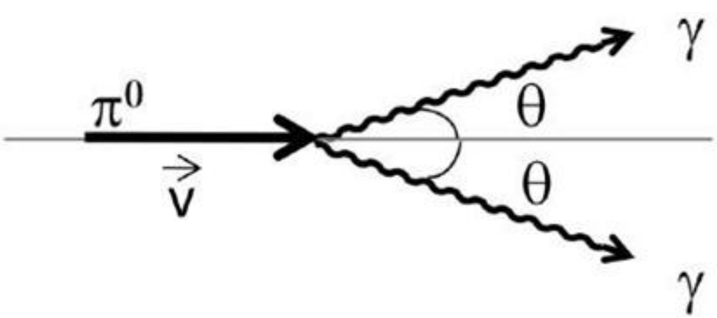
Four main non-thermal radiative mechanisms for producing γ-ray

Synchrotron







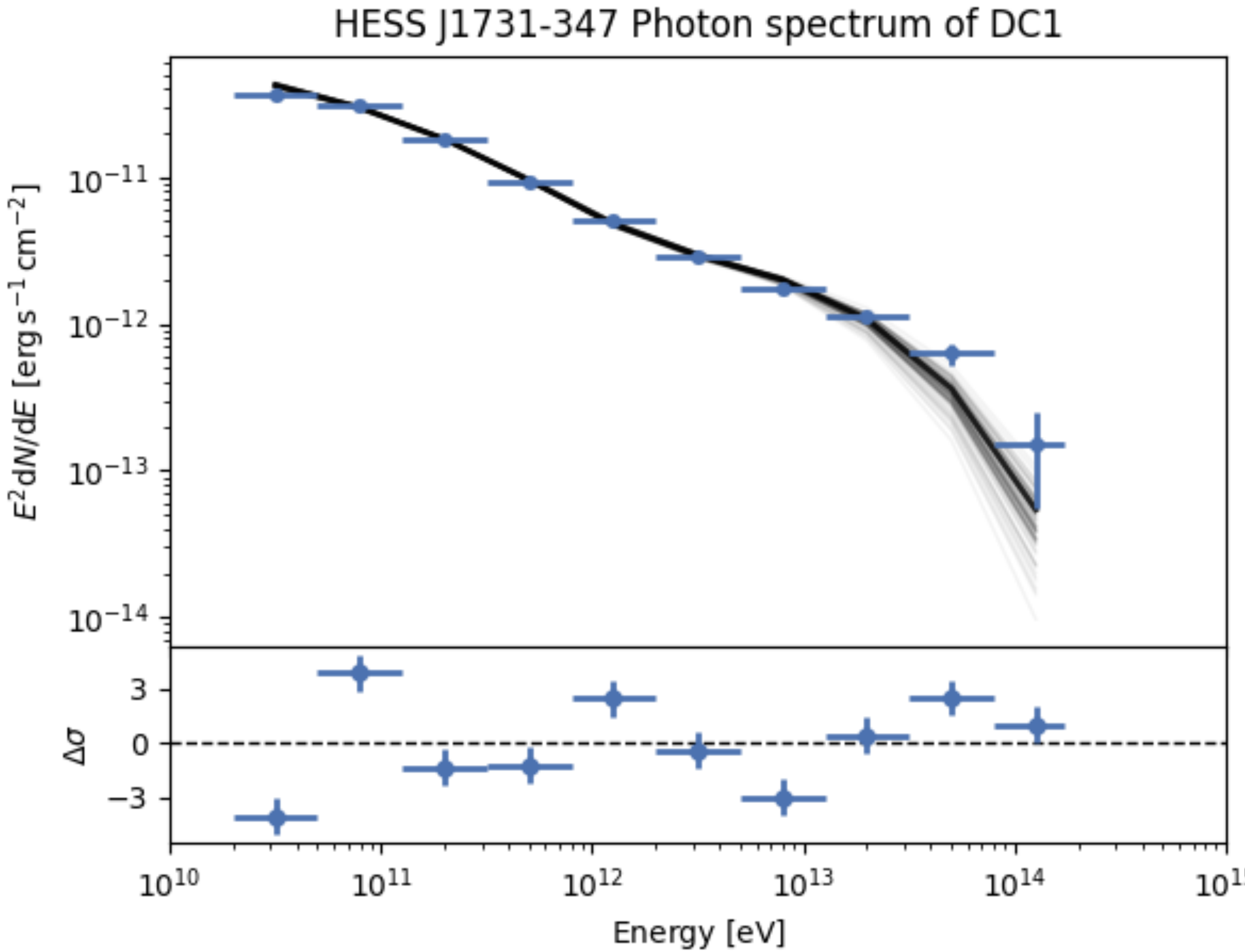


pion-decay

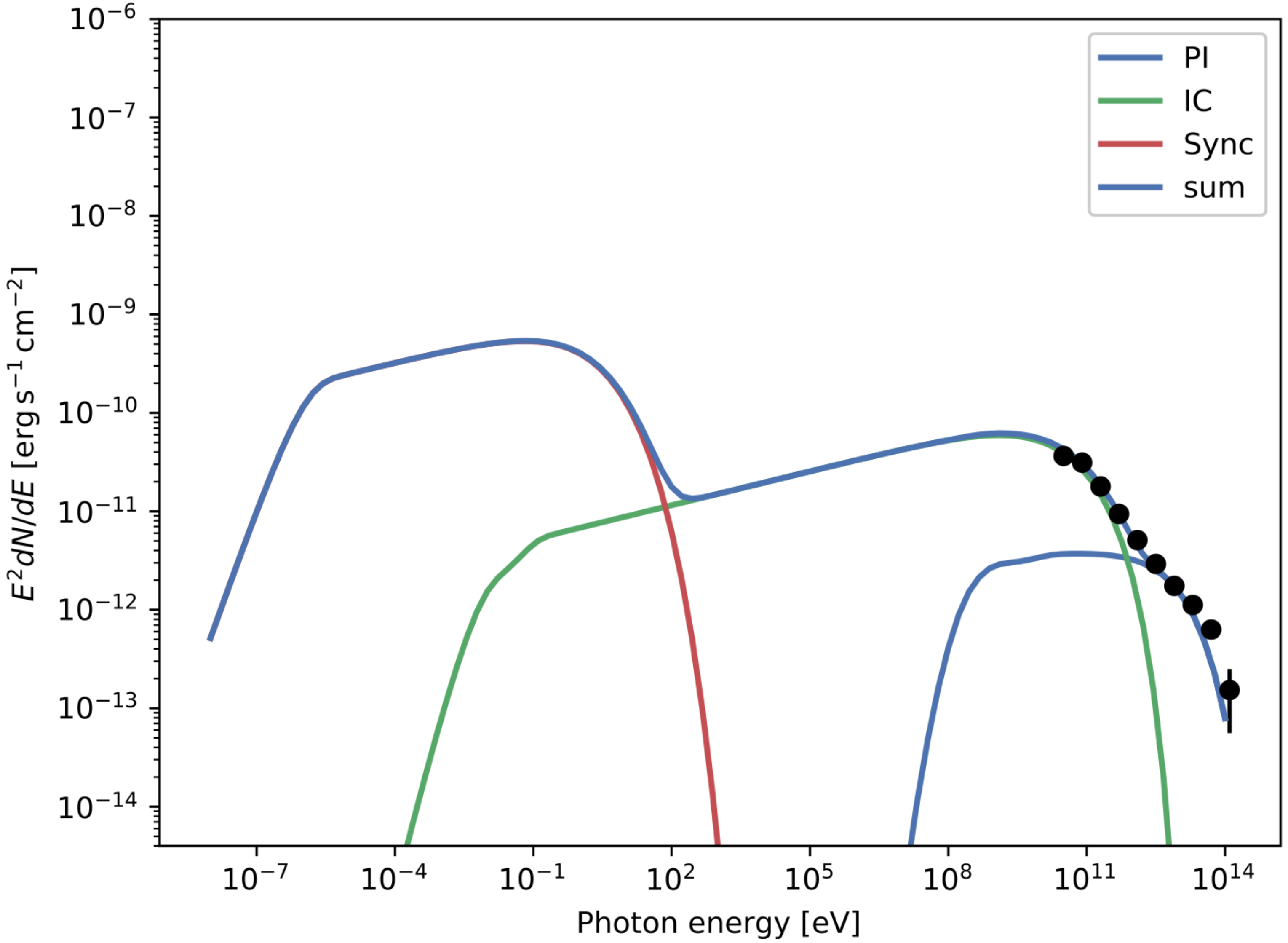
SNR name	K	$A_p[log_{10}\mathrm{GeV}^{-1}]$	α_e	α_p	$E_{cut}(e)[log_{10}\mathrm{GeV}]$	$E_{cut}(p)[log_{10}\mathrm{GeV}]$	$B[\mu\mathrm{G}]$	$N_H\,[\mathrm{cm}^{-3}]$
RX J1713.7−3946	0.19	52.09	2.78	1.1	4.7	2.9	26.67	0.006
HESS J1614−518	0.28	52.35	2.94	1.33	5.39	2.74	17.6	0.0161
HESS J1731−347	0.296	53.19	2.77	2.04	3.16	5.14	15.4	0.008
SNR G318.2+00.1	0.276	51.94	2.57	1.97	3.08	5.54	15.4	0.058

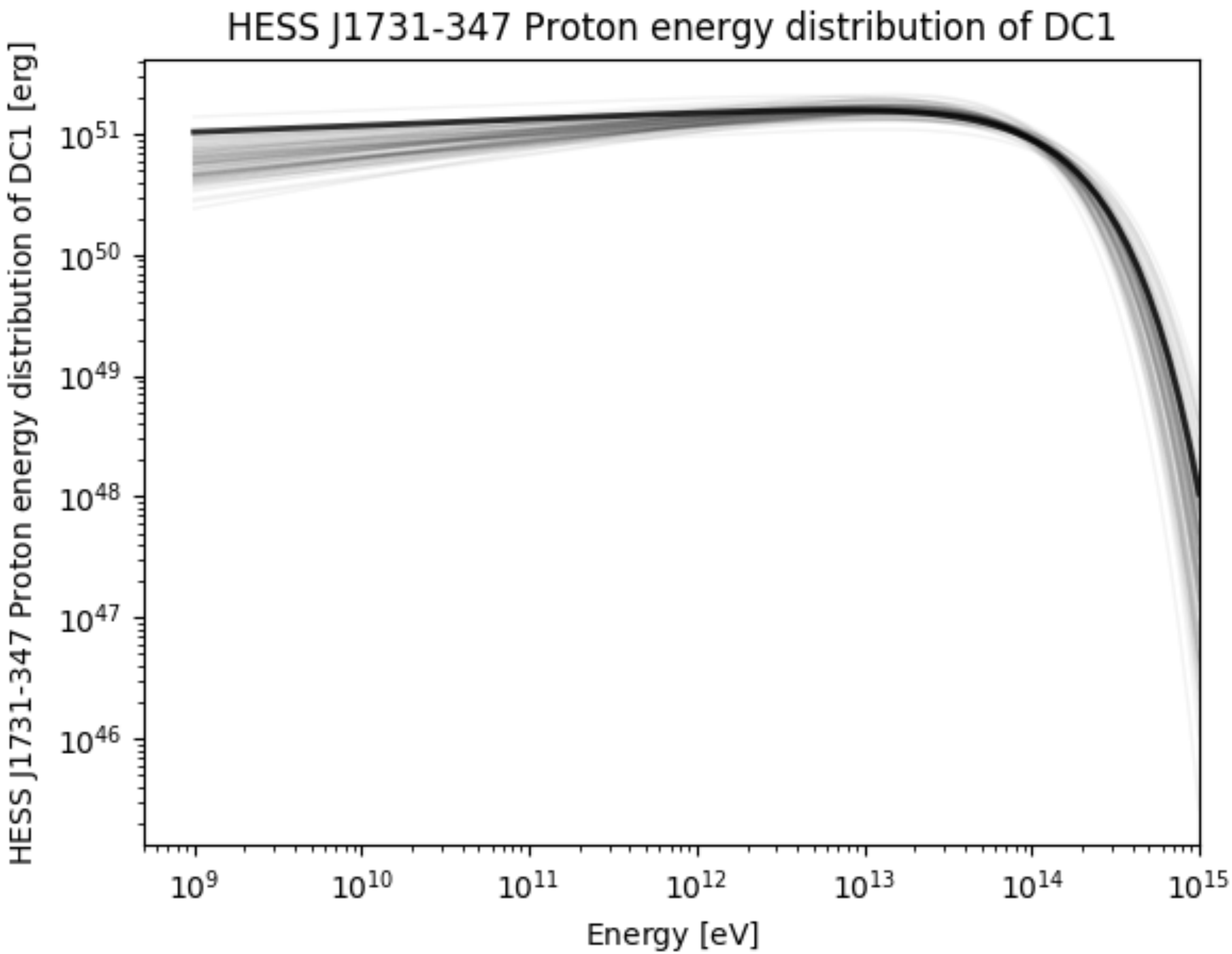
Electron and proton follow exponential cutoff power-law

$$f(E) = A(E/E_0)^{-\alpha} exp(-(E/E_{cutoff})^{\beta}),$$


HESS J1731-347 Photon spectrum of DC1
$E^2 dN/dE$ [erg s^{-1} cm^{-2}]
10^{-11}
10^{-12}
10^{-13}
10^{-14}
$\Delta\sigma$
3
0
−3
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
10^{15}
Energy [eV]

HESS J1731-347 Spectral Energy Distribution





HESS J1731-347 Proton energy distribution of DC1
HESS J1731-347 Proton energy distribution of DC1 [erg]
10^51
10^50
10^49
10^48
10^47
10^46
10^9
10^10
10^11
10^12
10^13
10^14
10^15
Energy [eV]

Summary

- Proton cut-off energy values as PeVatron indicators.
- Distinguish pion-decay or inverse Compton process dominate SNRs radiation.
- I do not consider the energy dispersion.
- Reset the XML model definition file to smooth residuals maps.