Credit Spitzer Cocoon Legacy

HAWC PeVatrons

KM3NeT Town Hall Meeting 2022, Catania Sabrina Casanova, IFJ-PAN, Krakow

Searching for the Galactic PeVatrons

- 90% protons, 9% helium, 1% electrons
- Almost featureless spectrum
- CRs up to the knee are believed to have a Galactic origin
- Galactic accelerators have to inject particles up to at least to the knee at PeV
- The knee for protons at about 400-500 TeV (ARGO Collaboration 2015)

. Cronin, T. Gaisser, S. Swordy, Sci. Amer. 276 (1997) 44.

Several features in the CR spectrum $s_{\alpha\alpha}$ in the GCR spectrum: contributions by two or \mathbb{R}^n

Lipari & Vernetto 2019

 $E(G_{\alpha}V)$

Direct Messangers of PeVatrons

$$
CRs + gas \rightarrow \pi_0 \rightarrow \gamma \gamma \ (\sim 0.1 \, PeV)
$$

$$
CRs + gas \rightarrow \pi^- \pi^+ \rightarrow v
$$

PeVatrons emits multi-TeV to hundred TeV γ -rays and vs

- γ detected in hundreds TeVatrons and few PeVatrons
- degeneracy leptonic-hadronic
- $\gamma\gamma$ absorption within and outside sources
- v difficult to detect even with 1 km^2
- v unique identification of hadronic processes
- v no absorption no spectral deformation

Neutrino flux from $γ$ **flux** <u>dx control dans de l'observe de</u>
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 $\Phi_\gamma \propto E^{-\Gamma}$

$$
\Phi_\nu[E] = Z_\nu[\Gamma] \cdot \Phi_\gamma[E]
$$

- Neutrino flux roughly the same k rc \log hly the sa \log
- Neutrino flux shifted to lower \parallel energies .
۷ cl lifted to lower l
Ow
- for a -2 spectrum shown in the dotted and solid lines corresponds to the dotted and solid lines corresponds to \sim r_{C} and r_{C} is the approximation Z shown in Fig. 3 for where the dotted, dashed and solid lines corresponds to ν = νµ, ν^µ and (ν^µ + νµ),
	- Best range : 10-100 TeV $r = \frac{P}{2}$ $r = \frac{P}{2}$ Best funge. To 100 fer

Lipari 2006, Villante&Vissani, Kappes2007,... the cutoff cutoff cannot be too sharp connected the spectral features of the spectrum are discussed in the paradisc the spectrum are discussed in the paradisc of the spectrum are discussed in the paradisc of the paradisc s $\mathbb{Z}_{\mathbb{P}}$ was $\mathbb{Z}_{\mathbb{P}}$ is sufficiently smooth, we can extract $\mathbb{P}_{\mathbb{P}}$ is sufficiently smooth. parametrized primary proton spectra was studied. One sees that our calculation predicts ∝ 10% larger predicts ∝ 10% larger calculation predicts ∝ 10% larger calculation predicts ∝ 10% larger calculation predicts ∿ 10% lar σ , σ married σ flooding that the calculation of σ

Minimum detectable flux in v and γ

Ambrogi+2018

High-Altitude Water Cherenkov Gamma-Ray Observatory

Pico de Orizaba Puebla, Mexico (19°N)

5m tall, 7.3 m diameter ~200,000 L of water

4 PMTs facing upwards collect **Cherenkov light produced by secondary particles**

 $-4,100$ m.a.s.

Energy range: \sim 100 GeV - 100TeV

Field of view: 45° from zenith

Observing time: >95% of the time

Angular resolution: $~10.1$ ° - 1°

Site: Sierra Negra, Mexico, 19°N, 4,100 m altitude.

 $22,000 \text{ m}^2$

• Inaugurated March 2015.

 $300 \times$

Tex for scale

Instantaneous FOV 2sr. Daily 8sr (66% of the sky).

HAWC Water Cherenkov Detectors

• The WCDs are filled with 200,000 I of purified water. The particles from the shower induce **Cherenkov** light in **water,** detected by the 4 PMTs.

3900 tanker truck trips needed ⁹

Detection Technique

shower front

- The particle detectors are tanks full of water. Particles from the shower pass through the water and induce Cherenkov light detected by PMTs.
- High altitude means closer to the shower maximum

The reconstruction of the events Involves determining:

Direction of the Event

Likelihood of an event to be g

Size of the Event

Direction reconstruction

The concentration of secondary particles is highest along the trajectory of the original primary particle, termed the air shower core.

Determining the position of the core on the ground is key to reconstructing the direction

At first order, we fit a plane to the relative timing of each PMT

Sub-nanosecond precision is needed

 4.0

Gamma-Hadron Separation

- Main background is hadronic CR, e.g. 400 γ /day from the Crab vs 15k CR/s.
- Gamma/hadron can be discriminated based on the event footprint on the detector: gamma-ray showers are more compact, cosmic rays showers tend to "break apart"
- Showers appear quite different particularly above several TeV..

Montecarlo Shower Simulation

Energy deposited away from the core

Pass 5 reconstruction

Better Angular Resolution - doesn't degrade at high zenith angles

Wider FOV - Previous 45^o now 60^o

Pass 4

Pass 5

HAWC Pass 5 – 2090 days maps

Sources above 56 TeV

Point source map

8382818079787776757473727170696867666564636261605958575655545352515049484746454443424140393837363534333231302928272625242322212019181716151413121110987

More than half unidentified and mostly extended

Sources above 100 TeV

Point source map

0.5 degree extended map

More than half unidentified and mostly extended

Sources above 177 TeV

Point source map

0.5 degree extended map

More than half unidentified and mostly extended

GC PeVatron

 10^{-10}

HAWC View of the Galactic Centre Ridge

- $6\,\sigma$ detection in Pass 5
- HAWC and HESS fluxes compatible
- **No spectral cutoff**
- Maximum γ energy detected in HAWC
- 1 sigma: 69.57 TeV
- 2 sigma: 50.17 TeV
- 3 sigma: 34.24 TeV

The Galaxy above 100 TeV: Spectra

FIG. 2. The same as Figure 1, but for *E >*ˆ 100 TeV. The symbol convention is identical to Figure 1. Source name RA (*^o*) Dec (*^o*) Extension *>* F (10¹⁴ ^p*TS >* nearest 2HWC Distance to ^p*TS >* 56 Text (or) ph contract (or) ph co ¹) 56 TeV source 2HWC source() 100 TeV eHWC J0534+220 83.61 *±* 0.02 22.00 *±* 0.03 PS 1.2 *±* 0.2 12.0 J0534+220 0.02 4.44 eHWC J1809-193 272.46 *[±]* 0.13 -19.34 *[±]* 0.14 0.34 *[±]* 0.13 2.4+0*.*⁶ 0*.*⁵ 6.97 J1809-190 0.30 4.82 eHWC J1825-134 276.40 *±* 0.06 -13.37 *±* 0.06 0.36 *±* 0.05 4.6 *±* 0.5 14.5 J1825-134 0.07 7.33 eHWC J1839-057 279.77 *±* 0.12 -5.71 *±* 0.10 0.34 *±* 0.08 1.5 *±* 0.3 7.03 J1837-065 0.96 3.06 eHWC J1842-035 280.72 *±* 0.15 -3.51 *±* 0.11 0.39 *±* 0.09 1.5 *±* 0.3 6.63 J1844-032 0.44 2.70 eHWC J1850+001 282.59 *[±]* 0.21 0.14 *[±]* 0.12 0.37 *[±]* 0.16 1.1+0*.*³ 0.20 3.31 J2849-0.20 3.31 J2849-0.20 3.31 J2849-0.20 3.31 J2849-0.20 3.31 J2849-0.20 3.31 J2849-0.20 3.31 J284 eHWC J1907+063 286.91 *±* 0.10 6.32 *±* 0.09 0.52 *±* 0.09 2.8 *±* 0.4 10.4 J1908+063 0.16 7.30 eHWC J2019+368 304.95 *[±]* 0.07 36.78 *[±]* 0.04 0.20 *[±]* 0.05 1.6+0*.*³ 0.2 10.2 J2019-3.2 J eHWC J2030+412 307.74 *±* 0.09 41.23 *±* 0.07 0.18 *±* 0.06 0.9 *±* 0.2 6.43 J2031+415 0.34 3.07 $\frac{2}{10}$ ₁₀−13 Emission. A Hemission. A Hemission. A Baument for a simulation. A simulation. A simulation $\begin{bmatrix} 10 & -10 & -10 \\ -10 & -10 & -10 \end{bmatrix}$ $\begin{bmatrix} 10 & -10 & -10 \\ -10 & -10 & 0 \end{bmatrix}$ $\frac{1}{\sqrt{1-\frac{1$ Crab Nebula uncertainties are statistical only. The point spread function of $\ddot{}$ $\frac{1}{100}$ $\frac{1}{100}$ $\frac{1}{101}$ $\frac{1}{102}$ Energy (TeV)

HAWC Collaboration+20

The Galaxy above 56 TeV

gr (TABLE I. Sources exhibiting *E >*ˆ 56 TeV emission. A Gaussian morphology is assumed for a simultaneous fit to the source location and E $>$ 56 TeV (0.5 degree extended source assumed) for *F* and *F* above F and F and F above F

Visibility of bright HAWC PeV candidates

Galactic longitude (deg)

HAWC J1908+063 following values: αγ to neglect the exponential terms in Equations (18) and (19).

The first component is attributed to model to model the molecular component is a
The molecular clouds surrounded to more substituted to molecular clouds surrounded to molecular component is a $\begin{bmatrix} 1 & 1 & 1 \\ 1 & 1 & 1 \end{bmatrix}$ remains the second is likely leptonic in $\begin{bmatrix} 0 \\ 1 \end{bmatrix}$ H ignt ascension (°) $\overline{1}$

using a 2D scheme of the estimated energy (*E*ˆ) and the fraction $\sigma = 10^{-13}$ σ \sim (2019). \times 10 16 (1eV cn $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ is a quarter decade in $\begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$ $\frac{1}{2}$ between $\frac{1}{2}$ given above, kv and ky and ky $\frac{1}{2}$ $\sim 7.5 \times 10^{-13}$ (TeV cm² s)⁻¹. Now that the expected neutrino flux has been computed, we

float separately in the fit. THAWC > 220 IEV. LF \ldots \ldots \ldots \ldots HAWC > 220 TeV, LHAASO 440 TeV

HAWC J1908+06 as neutrino source?

Some HAWC PeV candidates are promising neutrino sources

Neutrinos seen in coincidence with a PeVatron candidate would unambiguously indicate hadronic origin

J1908+06 one of best p-values in IceCube point source searches, although still consistent with background-only hypothesis

eHWC J1842-035 **eHWC J1842-035**eHWC J1842-035 Altitude Water Cherenkov

Maximum measured

Fermi - Argo -HAWC-LHAASO cocoon

hnological

Fermi detected hard and extended emission from Cygnus X, between OB2 and Gamma Cygni SNR

HAWC significance map

HAWC Coll, NatAstr 2021

Cocoon Spectrum and morphology <u>Cocoon Spectrum and morphology</u>

Unique SFR seen from GeV to PeV energies

Spectral break with respect to Fermi datapoints are the 1*σ* statistical errors. At low TeV energy, HAWC data agree with the 1*σ* statistical errors. At low TeV energy, HAWC data agree with the 1*σ* statistical errors. At

CR density > 10 TeV higher than local CR in the whole region modelling of the region. (The leptonic modelling results are provided in Extended Data Fig. 1). **b**, Cosmic ray energy density profile calculated for four

 Γ was the profile would suggest a continues injection. The chistant profile would suggest a recent burst event happened less than 0.1 Myr **constant profile (signature of the burst infection)**, respectively, calculated by assuming a spherical extension, calculated by a spherical extension of the burst infection, α 1/r profile would suggest a continous injection. A constant profile would suggest a recent

10000 CygOB2 would be required for CRs Galactic population

Highest energy photon

- l **1.42±0.13 PeV from the Cygnus region**
- l **Chance probility due to cosmic ray background 0.028%.**

eHWC J1825-134

HAWC J1825-134

\overline{C} Cell April 2024 HAWC Coll ApJL 2021

Above 177 TeV

BDS20 PSR Bubble

H II region [MML2017] 99

 $0°00$

 \mathbf{b} [$^{\circ}$]

34

 π_0

 π ⁰

 $\frac{1e23}{1.0}$

 0.9

HAWC 1825-134 and LHAASO J1825-136 above 200 TeV

SNR G106.3+2.7: Galactic PeVatron ?

HAWC Collaboration, ApJL 2020

- $62.0 \cdot$ 61.5 12229+61147 MGRO 12228461 HAWG 2227+610 $61.0 -$ **VER** 2227+608 $60.5 -$ 338 337 336 335 Right Ascension [°] 0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 $1e21$ N_{H_2} [cm⁻²]
- SNR G106.3+2.7 is a 10kyr comet-shaped radio source at 0.8 kpc
- PSR J2229+6114, seen in radio, X-rays, and gamma rays
- Boomerang Nebula is contained in the remnant
- VERITAS source (energy range 900 GeV 16 TeV)
- HAWC emission pointlike, morphology compatible with VERITAS source and coincident with a region of high gas density

G106.3+2.7 : a Galactic PeVatron?

Gamma PL : 2.29, Lower limit on gamma Ecut = 120 TeV

Proton PL : 2.35, Lower limit on proton Ecut = 800 TeV,

 $Wp = 10^{48}$ (n/50)⁻¹ erg

HAWC J2227+ 610 (Boomerang region)

HAWC detection of microquasars

Microquasars as gamma-ray sources: SS433 Lobes

SS 433 is a Galactic micro-quasar observed in radio-X-rays.

- SS433 is a binary system formed by a Supergiant 30 solar masses star and a compact object, either a neutron star or a black hole
- Two jets, the most powerful known in the Galaxy, extend perpendicular to the line of sight and terminate in W50 nebula and produce western and eastern X-ray lobes
- SS433 jet : 10³⁹⁻⁴⁰ erg/s
- SS433 jet speed roughly c/4
- Baryon loaded

• Particle acceleration is believed to occur at the lobes where strong radiation is expected to be emitted at GeV and TeV energies

Origin of the emission (e1)

- IC scattering off CMB photons, scattering off optical and infrared suppressed electron field acceleration and TeV \sim 100 μ are produced via IC scattering of the same eacceleration
- Electrons of at least 130 TeV required in a magnetic field of 16microGauss
	- $\overline{}$ $\overline{}$ **∂** Hadronic emission assume I 0% conversion of jet energy into protons and 0.05 cm-3

	—— $\alpha E^{0} \exp(\frac{1}{\pi})$, *dE* $E_{\rm max}$ density

The closest known microquasar : **V4641 Sagitarii**

• One of the fastest superluminal jets in the Milky Way galaxy – Implies jet point toward us –
but radio jet is very small Newly discovered Tea micro- quasar One of the fastest superluminal but radio jet is very small

 Ω 7 σ in Pose F Medien F High zenith angle for HAWC 9.7σ in Pass 5 Median E~25 TeV

- -45 o d 5 star 5 – 45o off zenith
	- Extent appears <0.25o

• Median E~25 TeV Highest energy measured 180 TeV

Diffuse g**-rays at hundred TeVs 1.7 (GeV** \boldsymbol{p} and \boldsymbol{p} and \boldsymbol{p} gamma-ray/neutrino observation in the southern hemi-

- tractional s
تاریخچه The fractional source contribution to the diffuse component is estimated to be 13%.
- apart from known sources. PeV electrons cannot easily explain such emission • All events above 398 TeV observed more than 0.5 deg
- f_0 200 T_o $/$ 1 out of 10 events are detected within $4[°]$ from the centre of the Cygnus cocoon If these 4 events are simply excluded,
the chasmed flux at the the observed hux at the
highest energy agrees with the model prediction. • Above 398 TeV 4 out of 10 the observed flux at the

Conclusions and outlook

- Both target analysis and discoveries in blind survey searches brought recently new insights in the search for the Galactic PeVatrons
- We have **not yet** pinned down the origin of PeV particles but we now know that the Galaxy is rich in multi-TeV up to PeV gamma-ray sources
- Both hadronic and leptonic mechanisms possible in most cases
- Gamma-ray sources such as microquasars might be suffering from absorption
- Neutrino observatories have the potential to pin down the most extreme Galactic accelerators. The flux of the brightest gamma-ray sources known is close to the minimum detectable flux by Km3Net but it seems that there are some possibilities.

First Suspects : Young SNRs

Theoretically: efficient CR acceleration mechanism **RXJ1713-3946 HESS Collaboration+16**Energetically: energy budget – 10^{51} erg – to sustain the Gal CR population 14 $\frac{1}{12}$ \vert_{10} $-39°20$ 10^{-6} **HESS data** 10^{-10} $40¹$ fit model (2007) Dec (J2000) **Excess** \exists ux (cm $^{-2}$ s $^{-1}$ TeV $^{-1}$) 10^{-11} 10^{-12} 10^{-13} $-40°00'$ 10^{-14} 10^{-15} 10^{-16} $20'$ **68% PSF** $17h10m$ $16m$ $14m$ $12m$ RA (12000) Young (~1.5 kyr) and nearby (~1 kpc) SNR 10 Energy (TeV) First, and brightest resolved TeV shell 10 years of H.E.S.S. data. (> 27000 y's) Spectrum up to \sim 50 TeV: cuts off \sim 12 TeV

Spectra of young SNRs

- Cutoffs in the spectra of famous young SNRs at few TeVs. Particle acceleration proceeds up to 100 TeV. No indication of particle acceleration proceeding up to the knee
- SNRs thought to act as PeVatrons only during the early phases. Small chance to detect SNRs when they are PeVatrons. Maybe PeVatron gamma-ray signatures from nearby clouds illuminated by runaway CRs

Hadronic or leptonic ?

Both hadronic and leptonic can explain the GeV to TeV emission

The content in accelerated hadrons in unknown because of the uncertainty in the estimate of the gas density and of the B-field

of the c.r. target (gas or radiation field). The c.r. target (gas or radiation field). The radiation of the ra tion value is a well known conservation in the source is a well known conservation of the source is a well known conservation of the source is a well with the source is a well with the source is a well with the source is a nuclei in the c.r. parent population, and the nature \mathbf{r}_i ating weakly decaying particles (mostly π[±], and trum, the relative importance of protons and heavy nuclei in the contract population, and the nature population, and the nature μ **and a function of the slope areas as an** ϵ $\sqrt{2}$ 0.2 0.4 0.4 eutríno **Cliny Craw Neutrino flux from** g **fluxes**

$$
\pi^+ \to \mu^+ + \nu_\mu
$$
\n
$$
\nu_\mu / \nu_e \simeq 2
$$
\nA flux of roughly 10^1-11 can be detected-dangerously close to the brightest gamma-ray sources known
\nSome gam ray sources might suffer internal and external absorption
\nBest range 10-100 TeV

1980

$$
\{\nu_e,\overline{\nu}_e,\nu_\mu,\overline{\nu}_\mu,\nu_\tau,\overline{\nu}_\tau\} \simeq \{1+\epsilon,1-\epsilon,2,2,0,0\}
$$

$$
\{\nu_e + \overline{\nu}_e, \nu_\mu + \overline{\nu}_\mu, \nu_\tau + \overline{\nu}_\tau\} = \{1, 1, 1\}
$$
Linear 2006

A flux of roughly 10^-11 can be detected-dangerously close to the brightest gamma-ray sources known Some gam ray sources might suffer internal and external absorption Best range 10-100 TeV $\frac{\nu_{\mu}/\nu_{e}}{\simeq 2}$ attested-dangerously close to the brightest gamma-ray sources known come gam ray sources injeht suffer ∇_{μ}
 ∇_{μ} best range 10-100 TeV

Lipari 2006 tipari 2006
تارىخىلى ئىللىنىڭ ئارىسى ئىللىنىڭ ئارىسى ئىللىنىڭ ئارىسى ئىللىنىڭ ئارىسى ئىللىنىڭ ئارىسى ئىللىنىڭ ئارىسى ئىللى

 $\begin{array}{c} \hline \hline 1.25 \end{array}$ $\begin{array}{c|c|c|c|c} \hline \multicolumn{2}{c|}{\textbf{1.25}} & \multicolumn{2}{c|}{\textbf{Before ν Oscillations}} \\\hline \end{array}$ 1.25 $t_{1.00}$ $\mathsf{Equation}\left\{ \mathsf{Equation}\right\}$ $Sum[\nu]$ Feynman scaling for inclusive 1 Feynman scalın
2 feynman scalın ρ _o = Kcr E- α -> ρ nu \simeq Knu E- α $\sum_{\alpha=1}^{\infty}$ and $\sum_{\alpha=1}^{\infty}$ and φcr ≃ Kcr E−α -> φnu ≃ Knu E−α φ cr \simeq Kcr E-a -> φ nu \simeq Knu E-a
if interaction aperav independent if interaction energy independent \hat{a} if interaction ene if interaction energy independent ϵ pendent in an energy dependent interaction probability. If CR cutoff -> gradual steepening for $E > 0.01$ $E³$ and $E⁶⁰$ If CR cutoff -> gradual steepening for $E > 0.01$ Ecutoff[®] If CR cutoff -> gradual steepening for $E > 0.01$ Ecutoff $\frac{1}{\sqrt{\nu}}$ Flux roughly the same $\sum_{0.25}$ That todging the same ϵ cutoff energy in gamma ϵ ^{0.25} $\nu_{\rm e}$ Cutoff energy about 0.5 Cutoff energy in gamma 3 s_{sc} be denoted to be determinated by \mathbb{R} $\overline{\overline{\overline{\nu}}_{\mathbf{e}}}$ controled by the relative intervalse importance of $\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0$ $\frac{0.00}{2.0}$ 2.2 2.6 2.8 3.0 2.4 Slope α 49

For our calculations we use recent parameterisations of the pion and secondary particle \mathbf{p} to derive the relations in the relationship between \mathbf{p} $N_{\rm eff}$ counterpart (NCP): The lack of any good counterpart at other wavelengths supports supp trina filly fram π filly ac production. LS 5039 and PSR B1259−63. In general, these objects are treated as leptonic (inverse Compton) accelerators but in the case of LS 5039 also a hadronic interpretation of the v-ray emission of the \sim **Mautrino fluv fram γ-fluvec** exist [4]. $\overline{}$ (NCP): The lack of any good counterpart at other wavelengths supports supp **100 / 20 11076 1** mean at **Neutrino flux from** g **fluxes**

interpretations Kannes 121 \mathbf{r} shows a sky map of all currently known \mathbf{r} exp [−]E^p Kappes+2007 \mathcal{L}

 α α β β β γ β γ β γ β shows as example the neutrino spectrum of the neutrino spectrum of

$$
\frac{\mathrm{d} N_p}{\mathrm{d} E_p} = k_p \, \bigg(\frac{E_p}{1 \, \textrm{TeV}} \bigg)^{-\alpha} \exp \bigg(\frac{E_p}{\epsilon_p} \bigg)
$$

 $k_\nu \approx (0.71 - 0.16 \alpha)\, k_\gamma$

 $\mathbf u$ assumption has to be assumption for a source-by-source-basis on a source-by-source-by-source-basis. The most of $\mathbf u$ $\alpha - 0.1$ and $\alpha - 1$, $\alpha - 1$ $\frac{u_1v_\nu}{\Omega} = \int dE_\nu A^{\text{eff}}_{\nu} \frac{u_1v_\nu}{\Omega}$ $\mathrm{d}t$ denoting $\mathrm{d}E_{\nu}$ $\text{d}N_{\nu}$ from the H.E.S. catalogue with range of $\text{d}N_{\nu}$ $\frac{dt}{dt} = \int dL \nu \Delta \nu \frac{dE}{dE}$ $\frac{\mathrm{d}N_{\nu}}{\mathrm{d}t} = \int \mathrm{d}E_{\nu} A_{\nu}^{\text{eff}}$ $\mathrm{d}N_\nu$ $\mathrm{d}E_\nu$

n **sensitivity and** g **sensitivity**

Ambrogi,Celli, Aharonian2018

