Spectral features of PeVatrons (and detection prospects)

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Multimessenger High Energy Astrophysics in the Era of LHAASO
"La Sapienza" University of Rome
28th July 2020

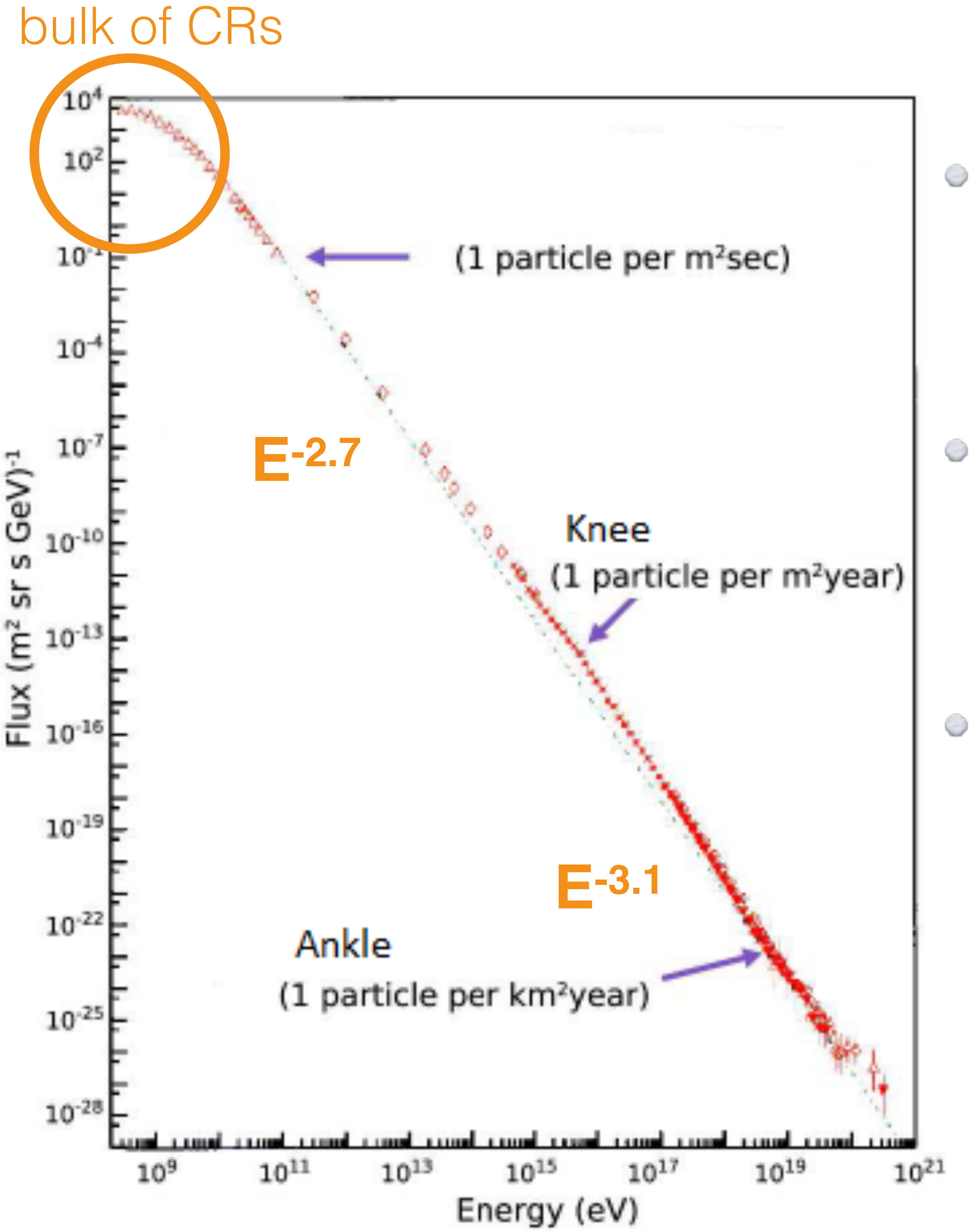
OUTLINE

i) The **multi-messenger** framework for exploring **PeV cosmic accelerators**: cosmic rays, photons and neutrinos;

ii) Secondary production in **pp collisions** and spectral signatures of PeVatrons;

iii) **Sensitivity studies** for the next-generation instruments: **LHAASO, CTA & KM3NeT**.

The local CR spectrum



- **Energy density**
  - which are the CR sources?
  - how can we identify them?

$\longrightarrow$ **γ and ν astronomy**

- **Spectral shape**
  - which acceleration mechanism?
  - what are the effects of the CR propagation?
- **Other observables**
  - Chemical composition
  - Isotropy

Focus on the energy range up to the knee (~3 PeV)

$\longrightarrow$ **PeVatrons**

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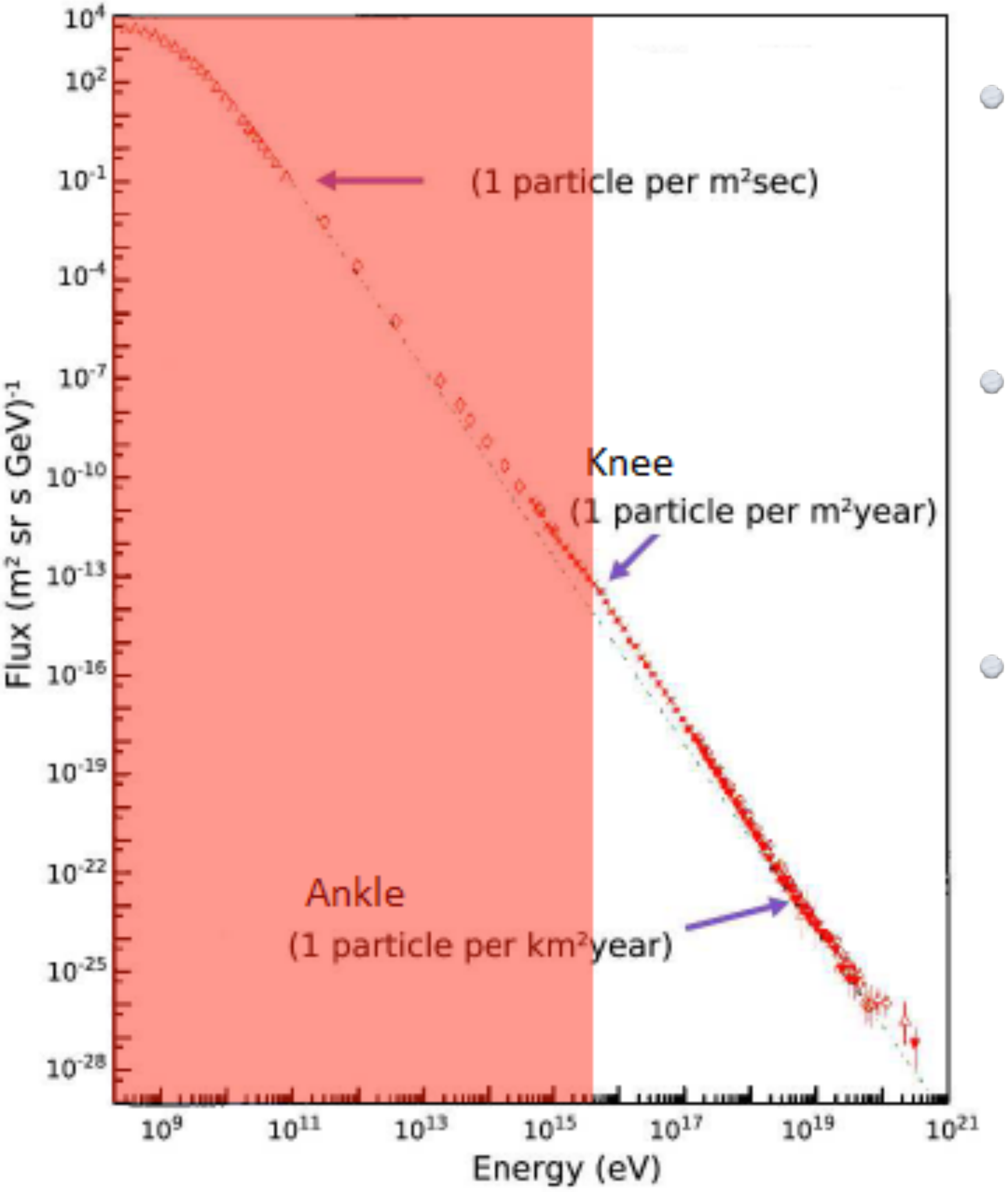

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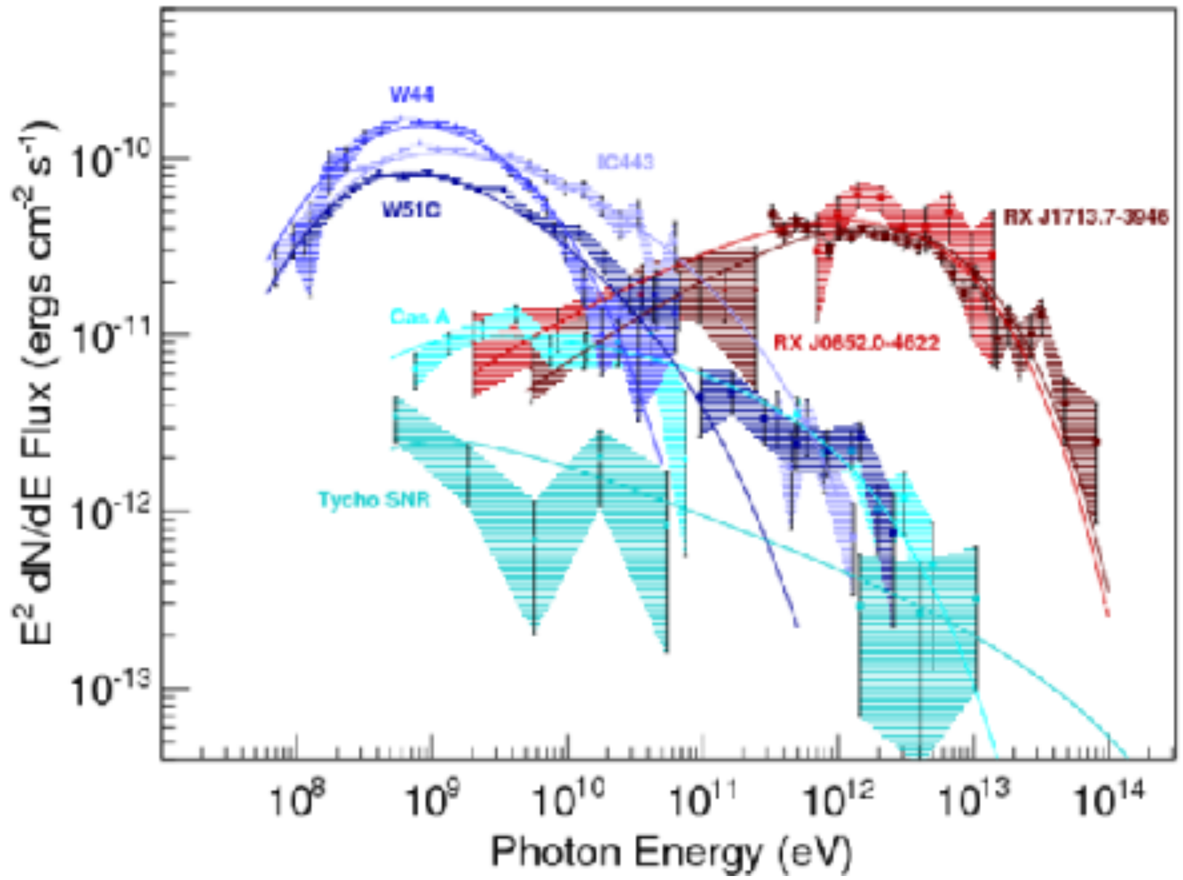
Candidate CR sources



Funk, Ann. Rev. Nucl. Part. Sci. 65 (2015) 245

Supernova remnants (SNRs)

i) enough power to sustain the local CR flux

ii) **shocks** as acceleration sites

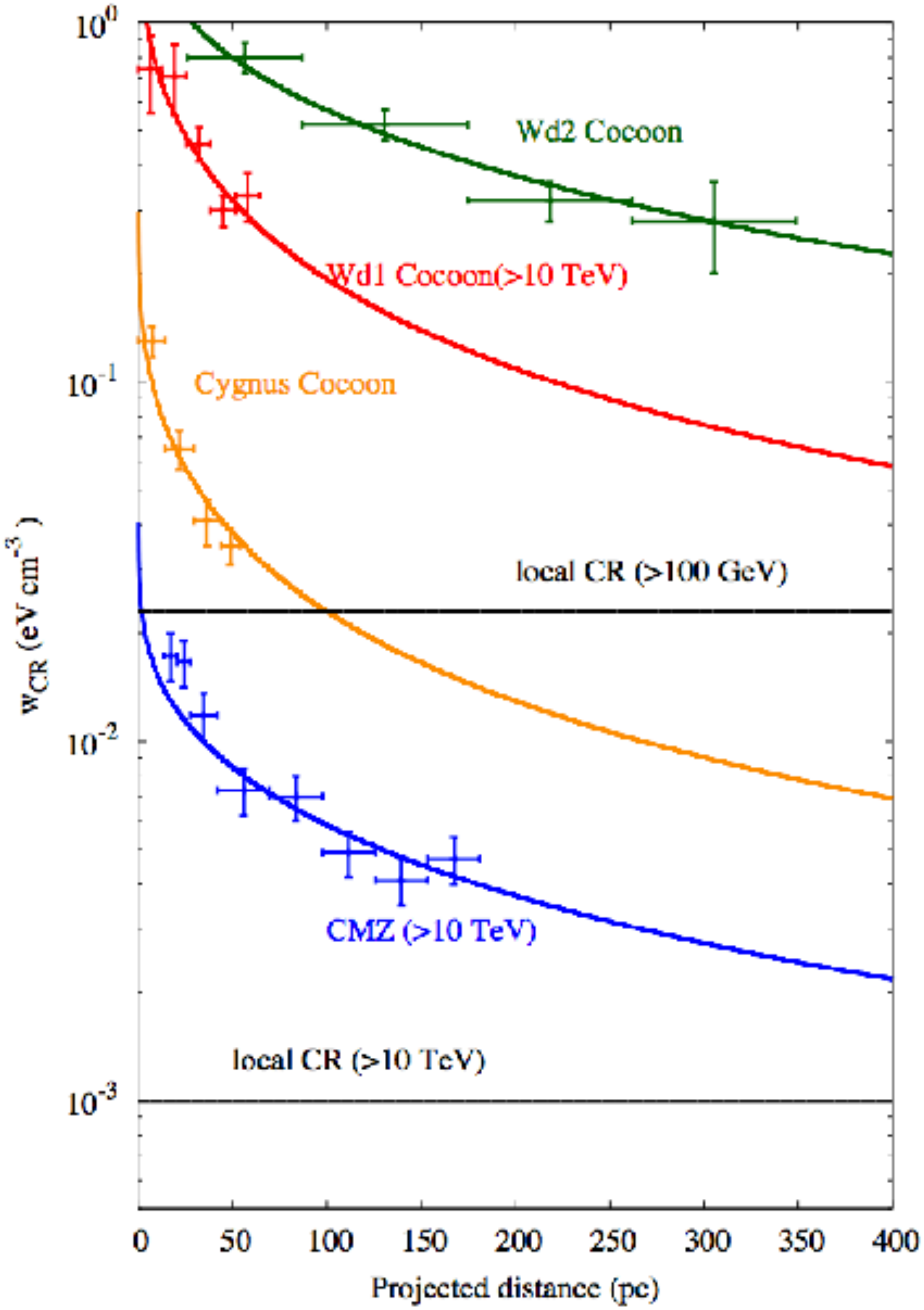
iii) maximum energy (Hillas criterion)

$$E_{max} \simeq \underset{\text{shock speed}}{v_s}\,\underset{\text{radius}}{R}\,\underset{\text{magnetic field}}{B}$$

$$E_{\rm max} \simeq 1 \underbrace{\left(\frac{v_s}{10^3\,{\rm km/s}}\right)}_{3} \underbrace{\left(\frac{R_s}{\rm pc}\right)}_{3} \underbrace{\left(\frac{B}{\mu{\rm G}}\right)}_{10} {\rm TeV}$$

$$\boxed{E_{max} \simeq 100\,{\rm TeV}}$$

Candidate CR sources



Aharonian et al., Nature Astr 3 (2019) 561

Massive stellar cluster

i) enough power to sustain the local CR flux
ii) **winds** as acceleration sites
iii) maximum energy (Hillas criterion)

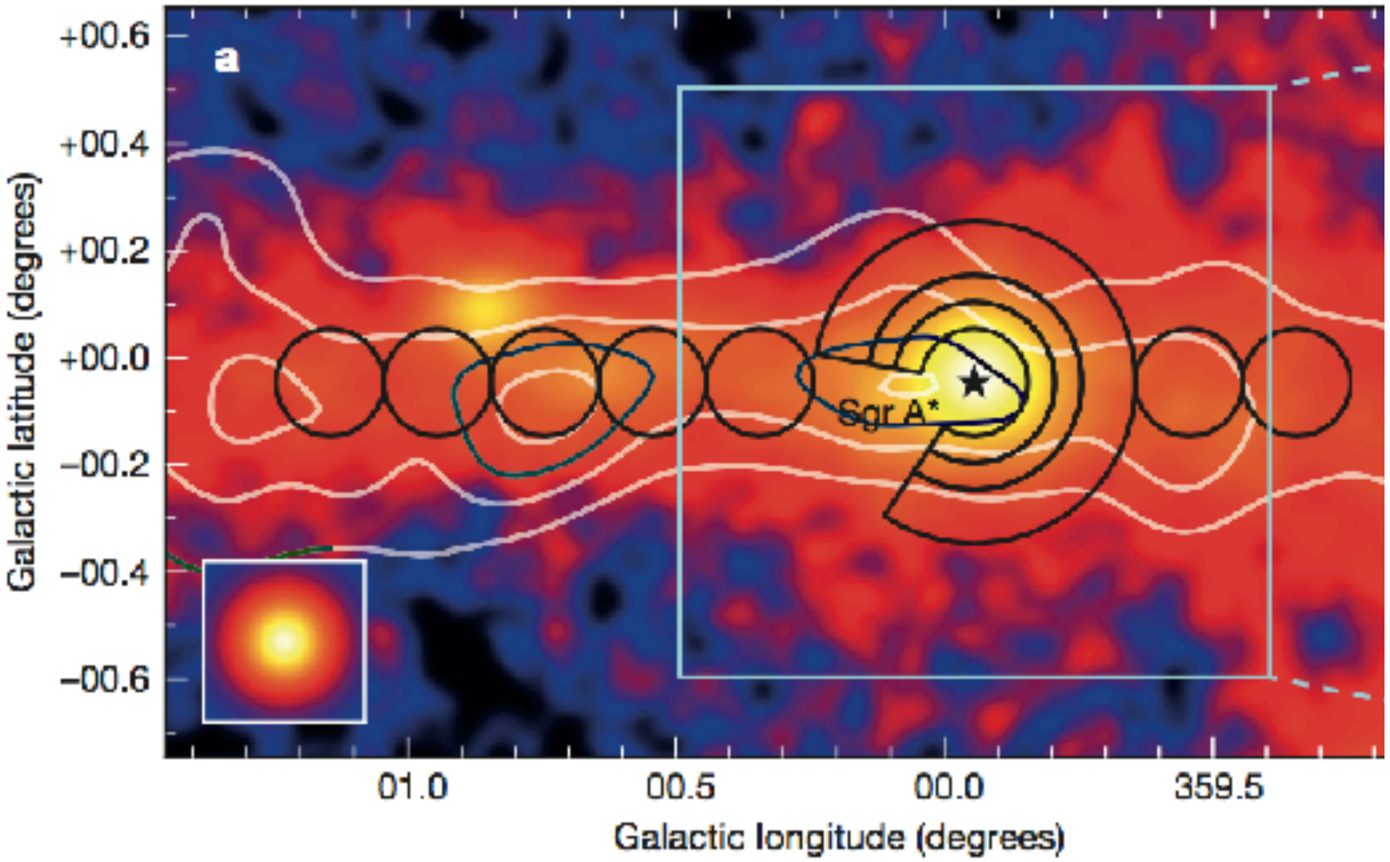
$$E_{max} \simeq v_s R B$$

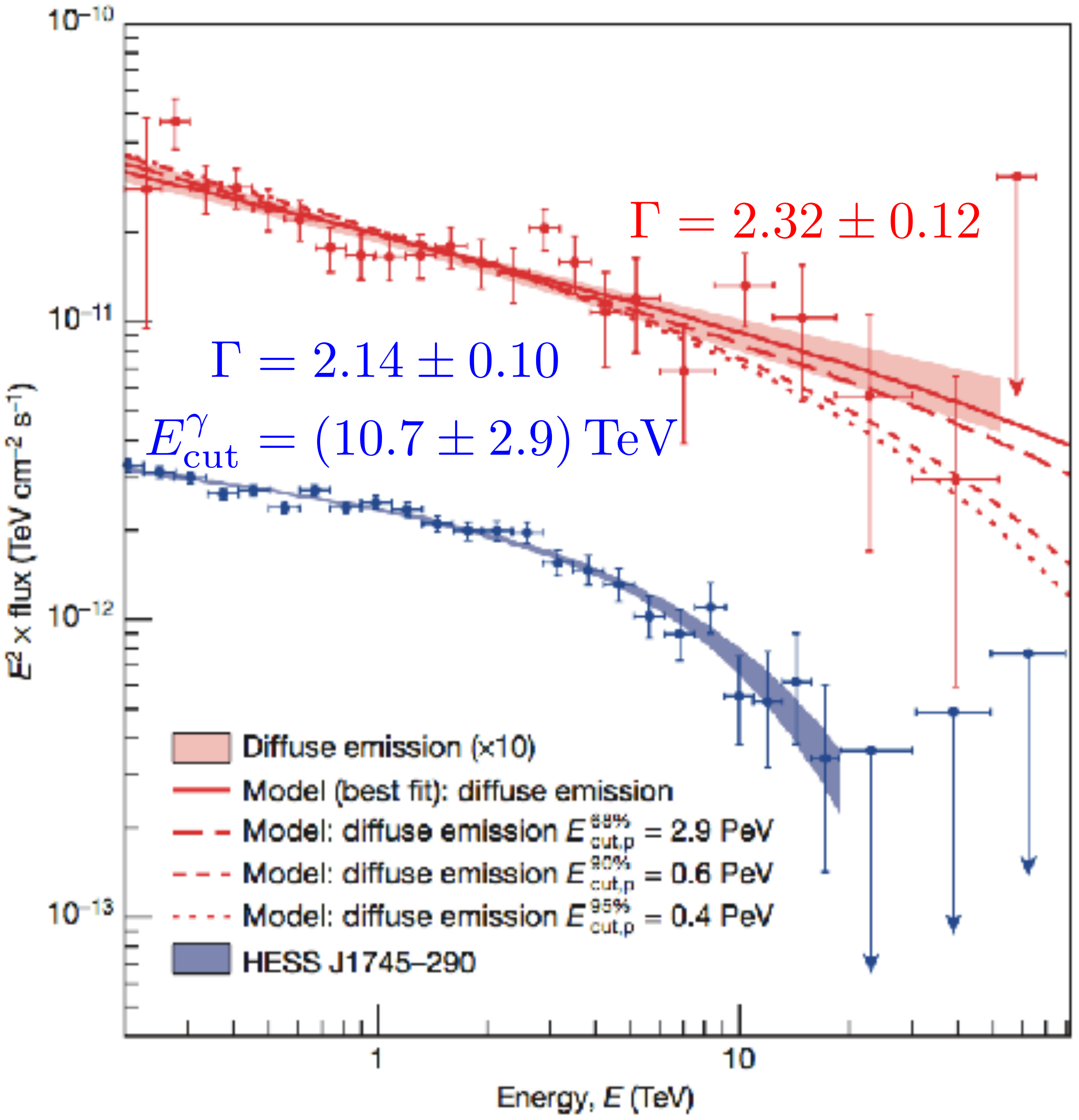
wind speed **radius** **magnetic field**

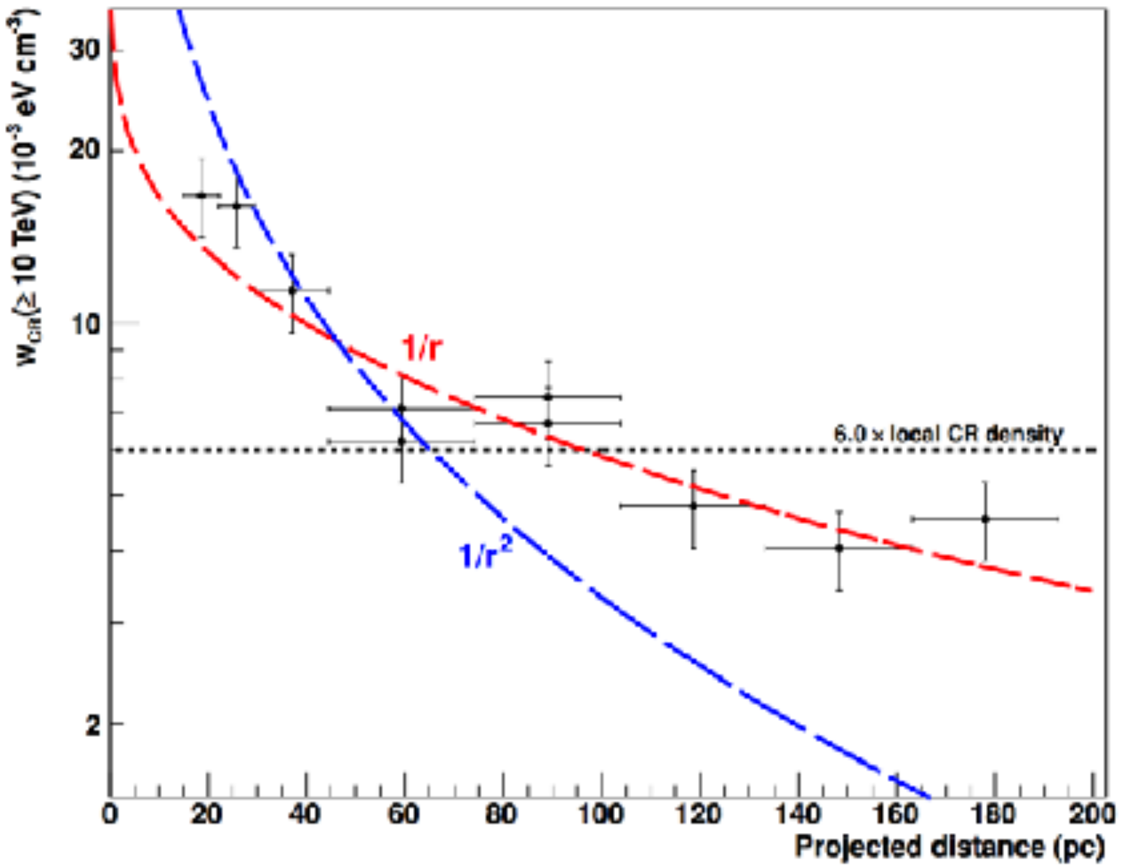
$$E_{\rm max} \simeq 1 \underbrace{\left(\frac{v_s}{10^3\,{\rm km/s}}\right)}_{\mathbf{3}} \underbrace{\left(\frac{R_s}{\rm pc}\right)}_{\mathbf{50}} \underbrace{\left(\frac{B}{\mu{\rm G}}\right)}_{\mathbf{10}} \,{\rm TeV}$$

$$\boxed{E_{\rm max} \simeq 1.5\,{\rm PeV}}$$

A proton PeVatron in the Galactic Center?



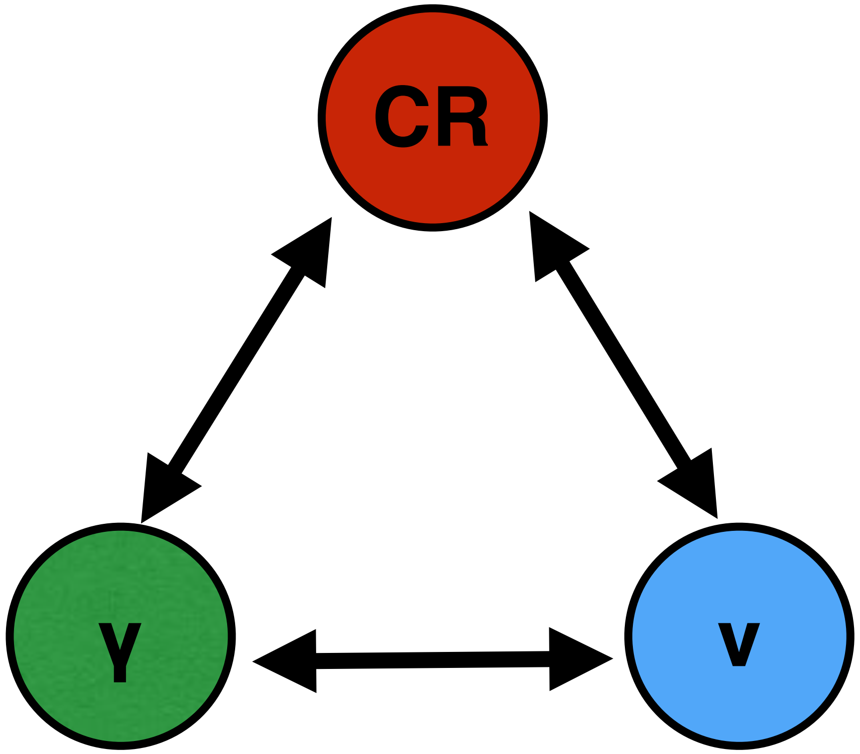




Aharonian et al. (HESS Coll.), Nature 531 (2016) 476

The search for CR sources

Photons and **neutrinos**
as messengers of
cosmic-ray accelerators



- **leptonic production** is realized at **CR-electron** collisions with matter (bremsstrahlung) and/or radiation fields (inverse Compton) and/or magnetic fields (synchrotron);

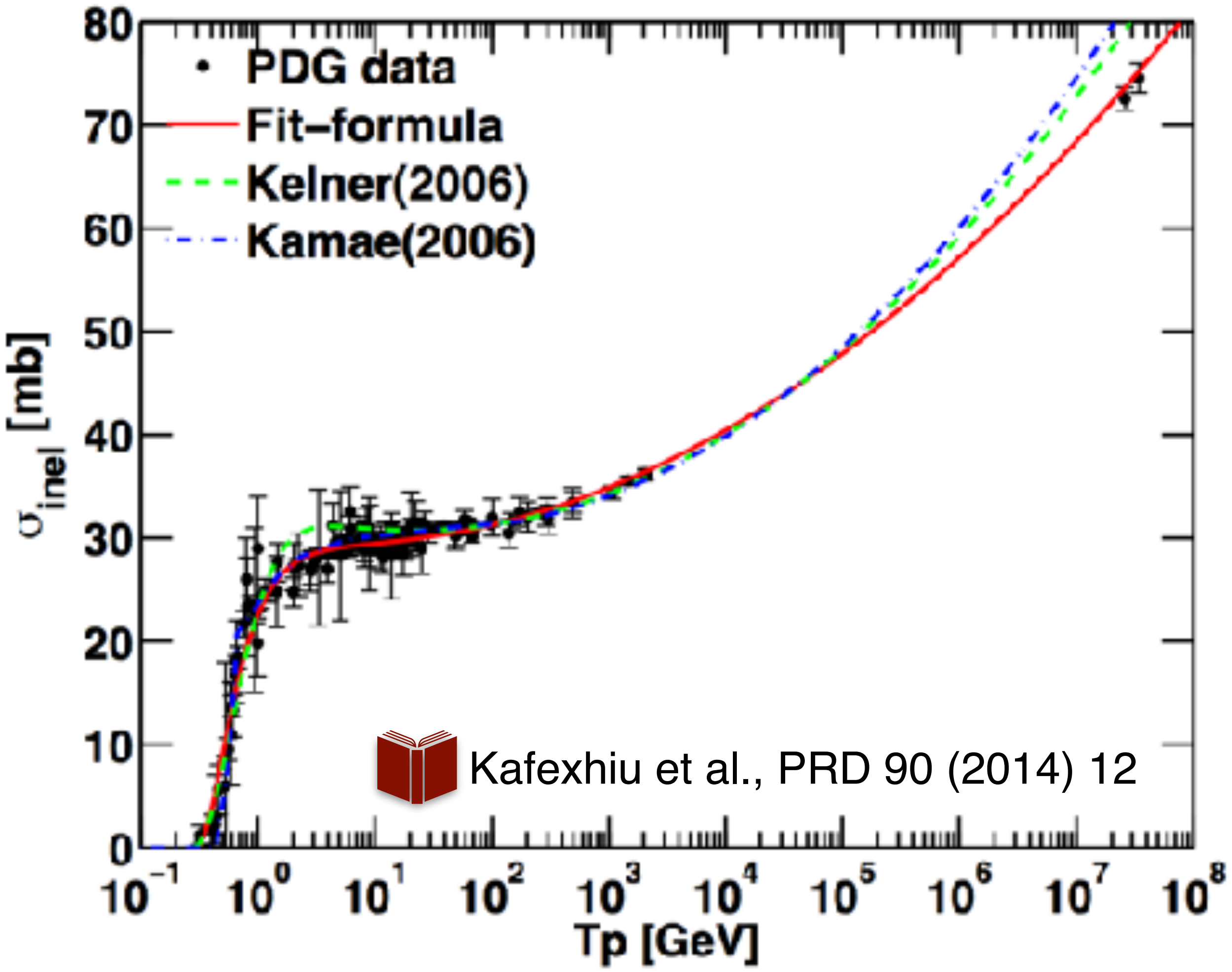
- **hadronic production** is realized at **CR-proton** collisions with matter (“pp”) and/or radiation fields (“pγ”), mostly via meson production.

Proton-proton collisions

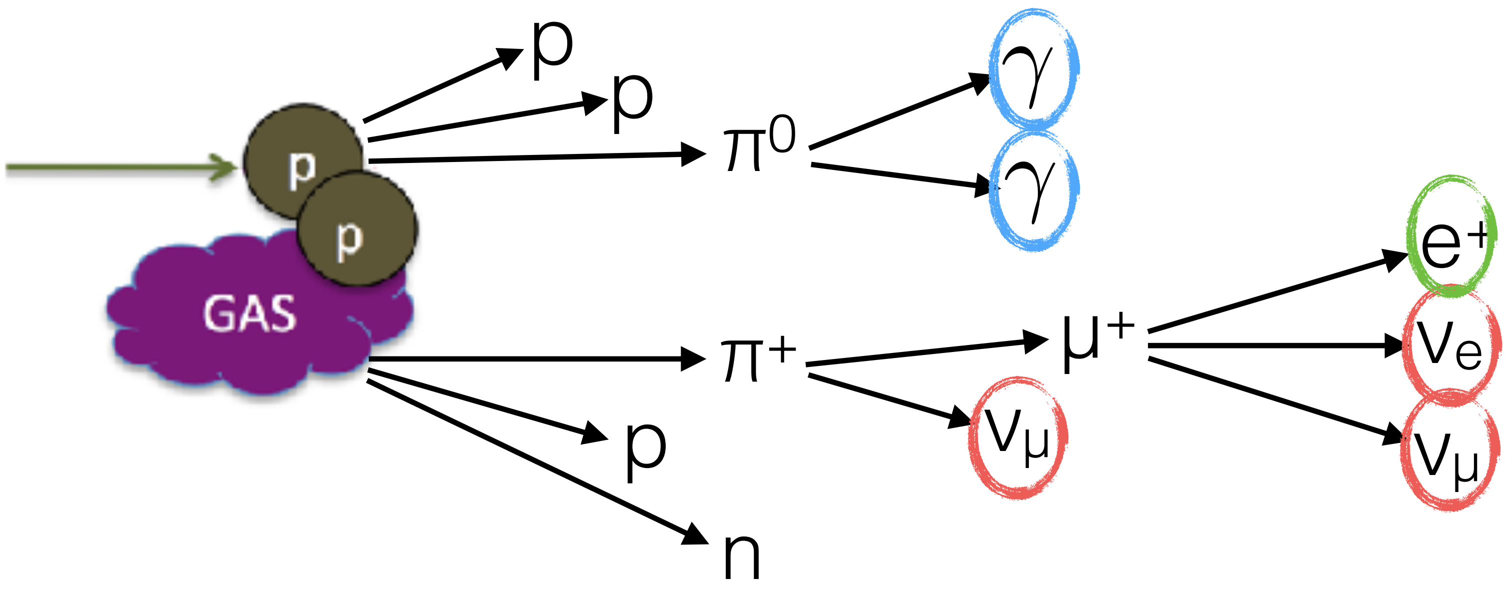
$$\boxed{p + p \longrightarrow N\pi + X}$$

accelerated proton

target gas



Kafexhiu et al., PRD 90 (2014) 12



$$\boxed{E_\gamma \simeq E_{\rm p}/10}$$

$$\boxed{E_\nu \simeq E_{\rm e} \simeq E_{\rm p}/20}$$

From protons to secondaries

Secondaries produced from spectrum of accelerated protons **J_p (E_p)** **uniformly propagating** within a target of **density n**:

$$\boxed{\epsilon_{\rm i}(E_{\rm i}) = cn \int_{E_i}^{\infty} \sigma_{\rm inel}(E_{\rm p}) J_{\rm p}(E_{\rm p}) F_{\rm i}\left(\frac{E_{\rm i}}{E_{\rm p}}, E_{\rm p}\right) \frac{dE_{\rm p}}{E_{\rm p}}}$$

Kelner, Aharonian & Bugayov, PRD 74 (2006) 3

- Hp 1: Proton spectrum is

$$J_{\rm p}(E_{\rm p}) = K_{\rm p} E_{\rm p}^{-\alpha_{\rm p}} \exp\left[-\left(\frac{E_{\rm p}}{E_{0,\rm p}}\right)^{\beta_{\rm p}}\right]$$

- Hp 2: Secondary electrons cooled in surrounding B field:

$$J_{\rm e}(E_{\rm e}) = \frac{\tau_{\rm sy}(E_{\rm e})}{E_{\rm e}} \int_{E_{\rm e}}^{\infty} \epsilon_{\rm e}(E) dE$$

Synchrotron radiation from secondary electrons

$$\tau_{\rm sy}(E_{\rm e}) = \frac{6\pi m_e^2 c^3}{\sigma_{\rm T} E_{\rm e} \beta_e^2 B_0^2} \simeq 1.3\times 10^4 \left(\frac{E_{\rm e}}{\rm GeV}\right)^{-1} \left(\frac{B_0}{1~\rm mG}\right)^{-2}~\rm yr$$

Warning: Cooling assumption is valid as long as $T_0 > \tau_{\rm sy}(E_{\rm e})$

$$\boxed{\epsilon_{\rm sy}(E) = \frac{\sqrt{3}}{2\pi} \frac{e^3 B_0}{m_{\rm e} c^2} \frac{1}{\hbar E} \int_0^\infty J_{\rm e}(E_{\rm e}) R\left(\frac{E}{E_{\rm c}(E_{\rm e})}\right) dE_{\rm e}}$$

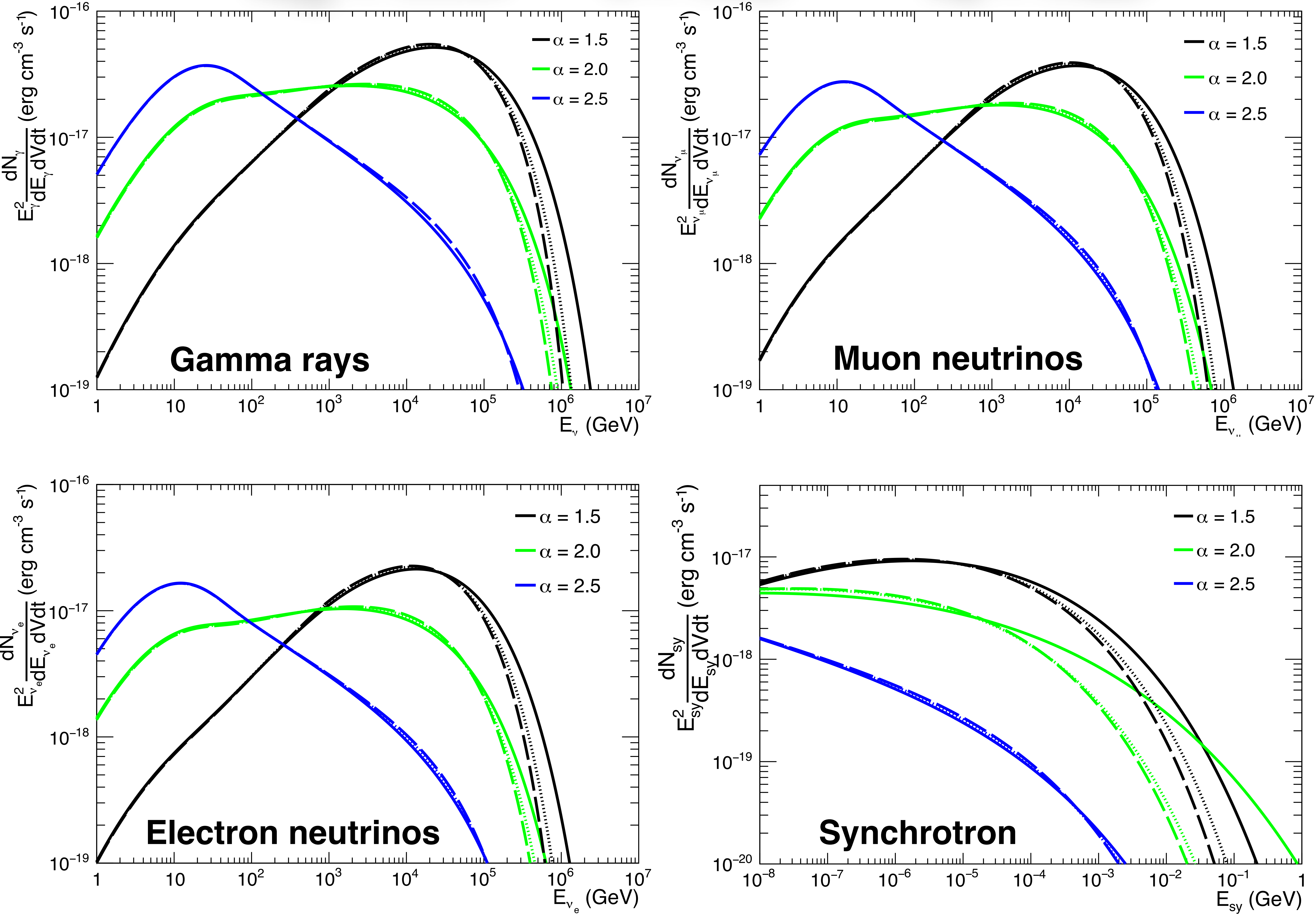
$$E_{\rm c} = 1.5\hbar e B_0 \frac{E_{\rm e}^2}{m_{\rm e}^3 c^5} \simeq 0.04 \left(\frac{B_0}{\rm mG}\right) \left(\frac{E_{\rm e}}{\rm TeV}\right)^2~\rm keV$$

$$R(x) = \frac{\alpha}{3\gamma_e^2}\left(1 + \frac{1}{x^{2/3}}\right) e^{-2x^{2/3}}$$

Derishev & Aharonian, ApJ 887 (2019) 181

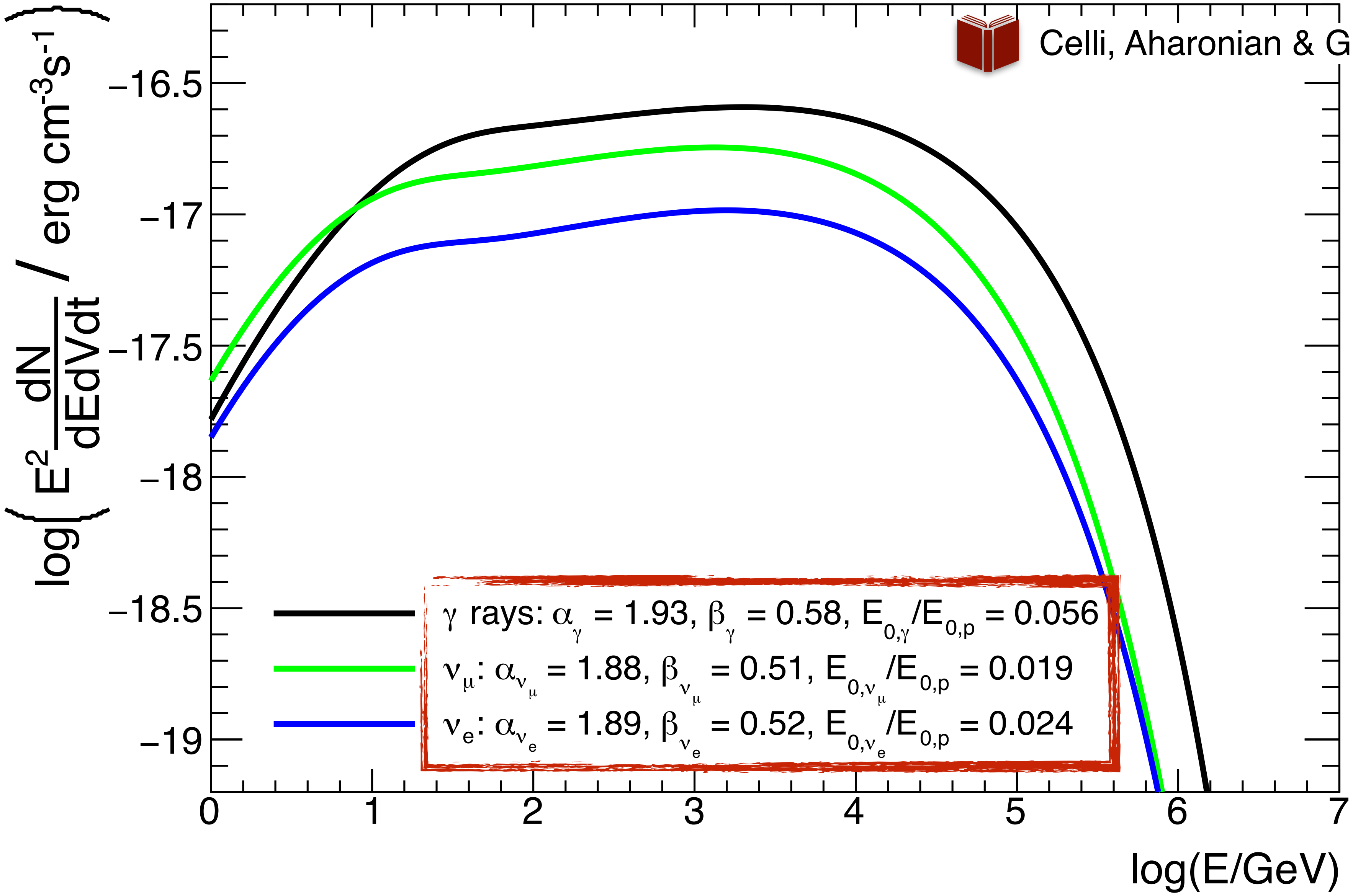
$$x = 9E/(8E_{\rm c})$$

$E_{0,\mathrm{p}} = 1\,\mathrm{PeV} \qquad n = 1\,\mathrm{cm}^{-3} \qquad B_0 = 1\,\mathrm{m}G$



A closer look to gamma rays and neutrinos

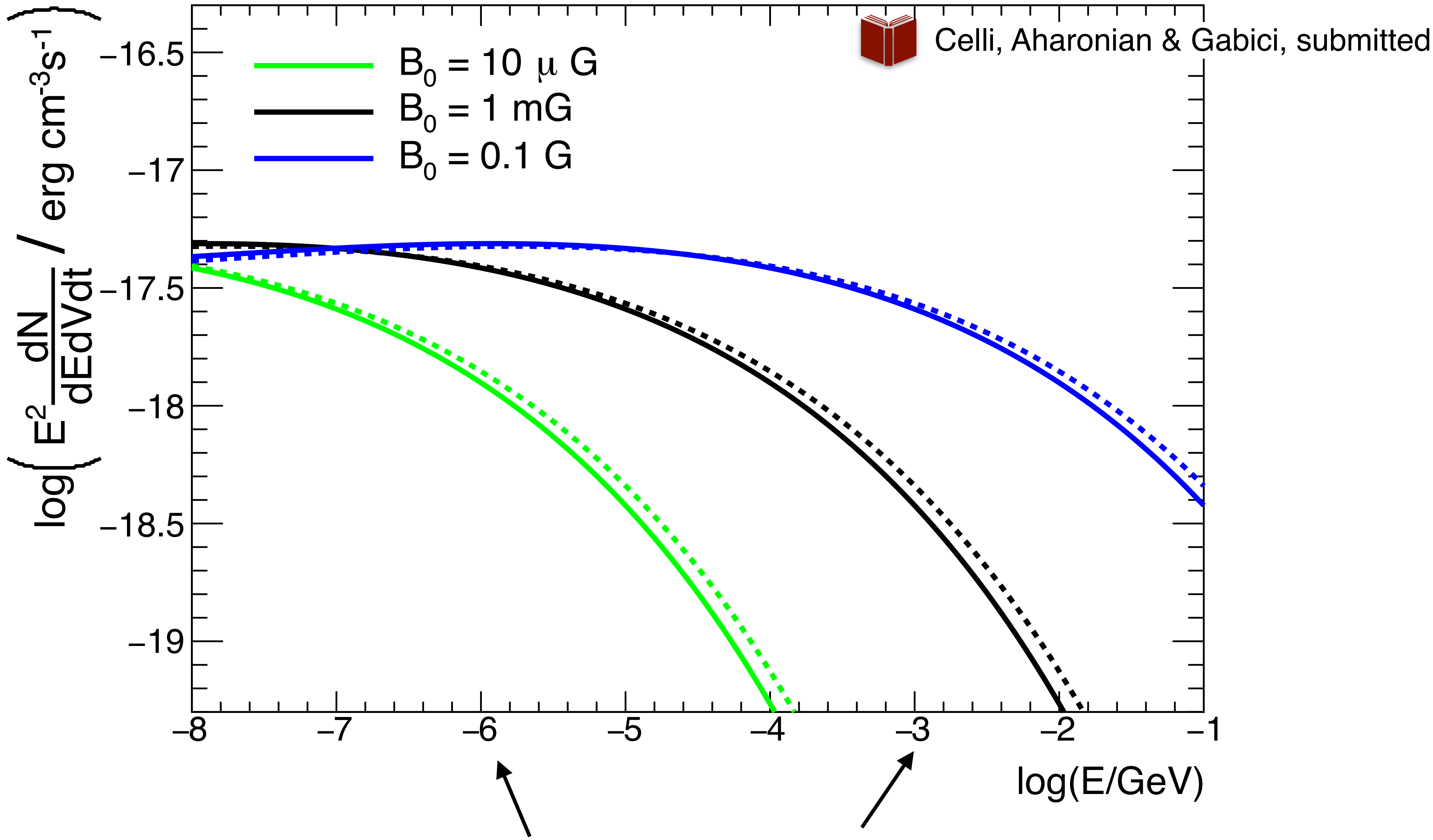
$$\alpha_{\mathrm{p}} = 2,\ \beta_{\mathrm{p}} = 1,\ E_{0,\mathrm{p}} = 1\,\mathrm{PeV}$$



Celli, Aharonian & Gabici, submitted

A closer look to synchrotron radiation

$$\alpha_{\rm p} = 2,\ \beta_{\rm p} = 1,\ E_{0,\rm p} = 1\,{\rm PeV},\ B_0 = 1\,{\rm m}G$$

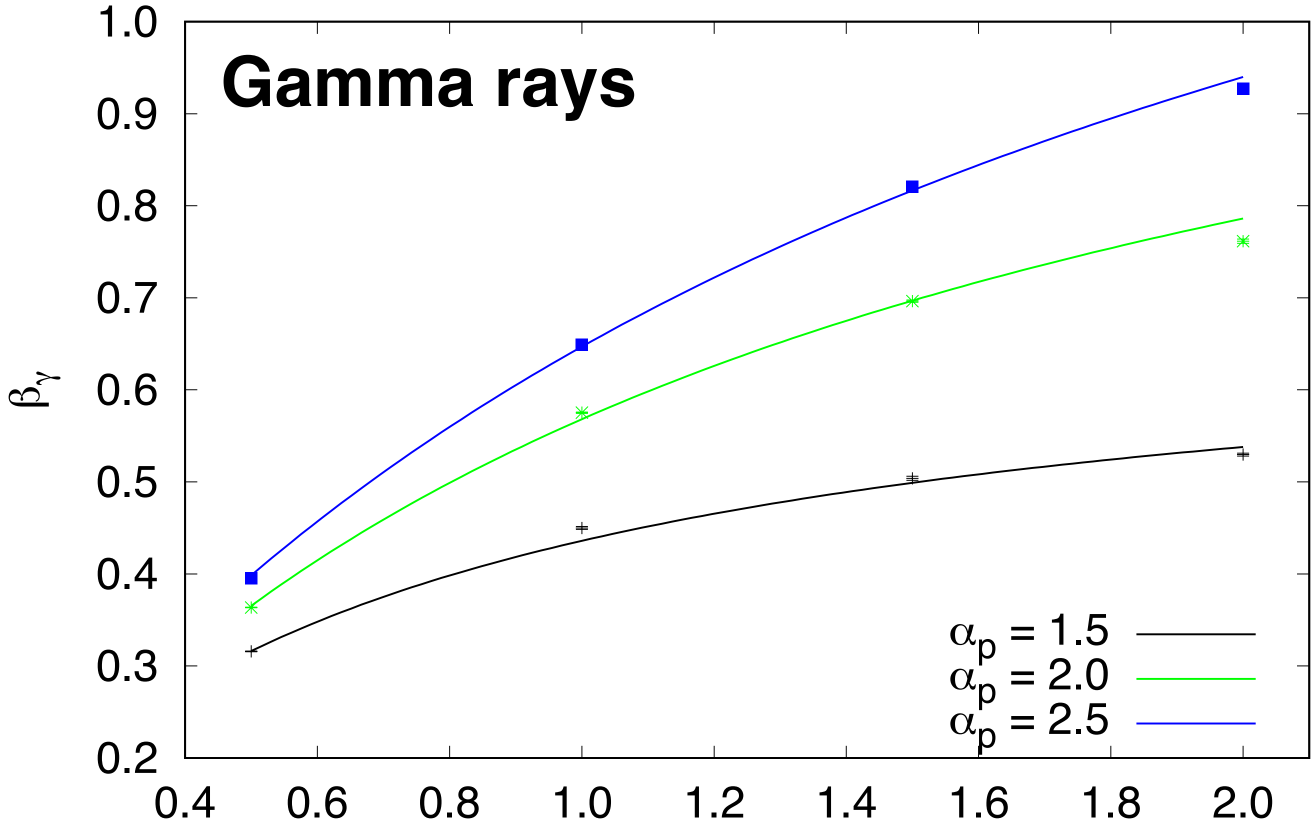


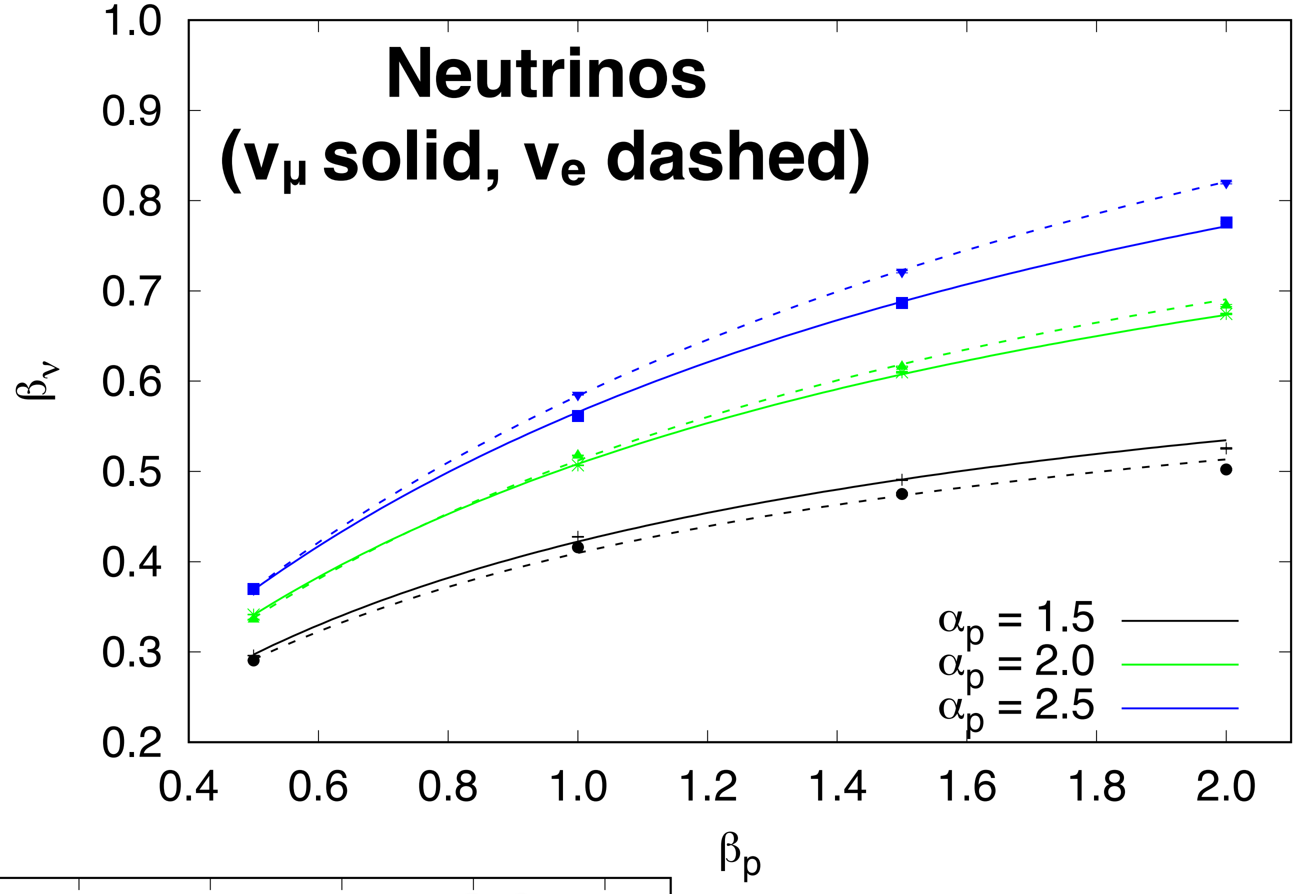
Celli, Aharonian & Gabici, submitted

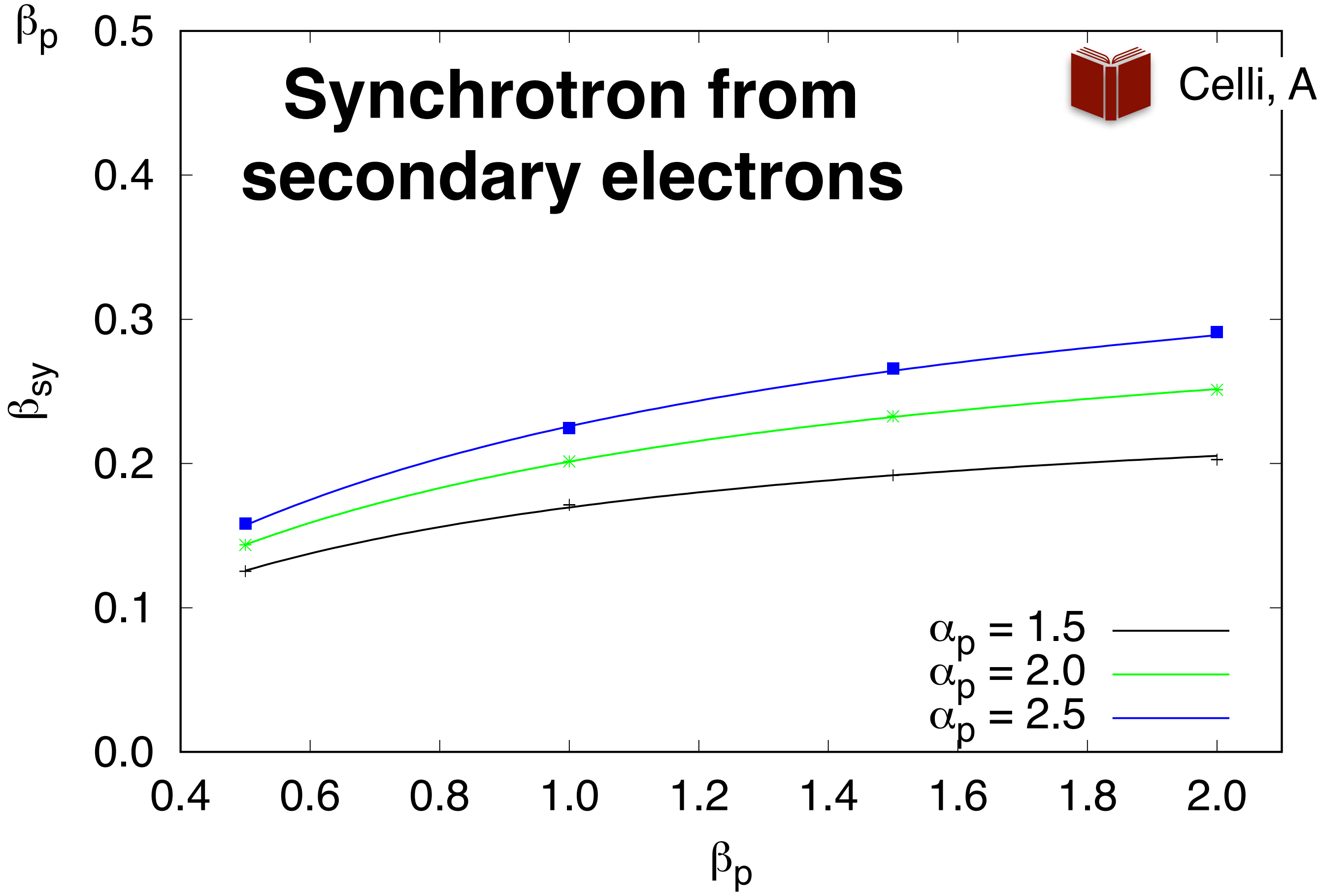
keV

MeV

Parametrizing the cut-off shape





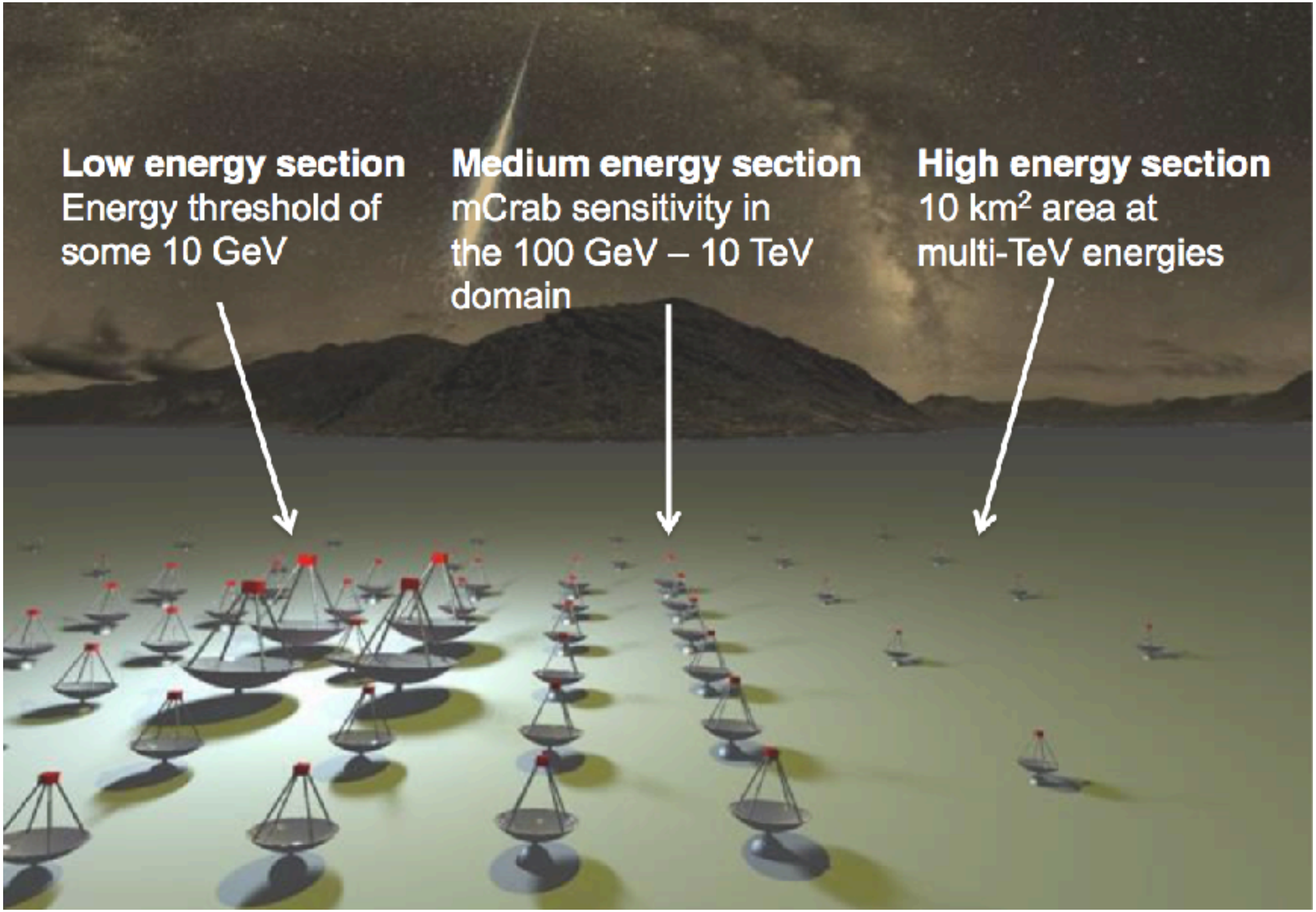


📕 Celli, Aharonian & Gabici, submitted

$E_{0,\mathrm{p}} = 1\,\mathrm{PeV}$

SENSITIVITY STUDIES FOR THE NEXT GENERATION INSTRUMENTS

The Cherenkov Telescope Array

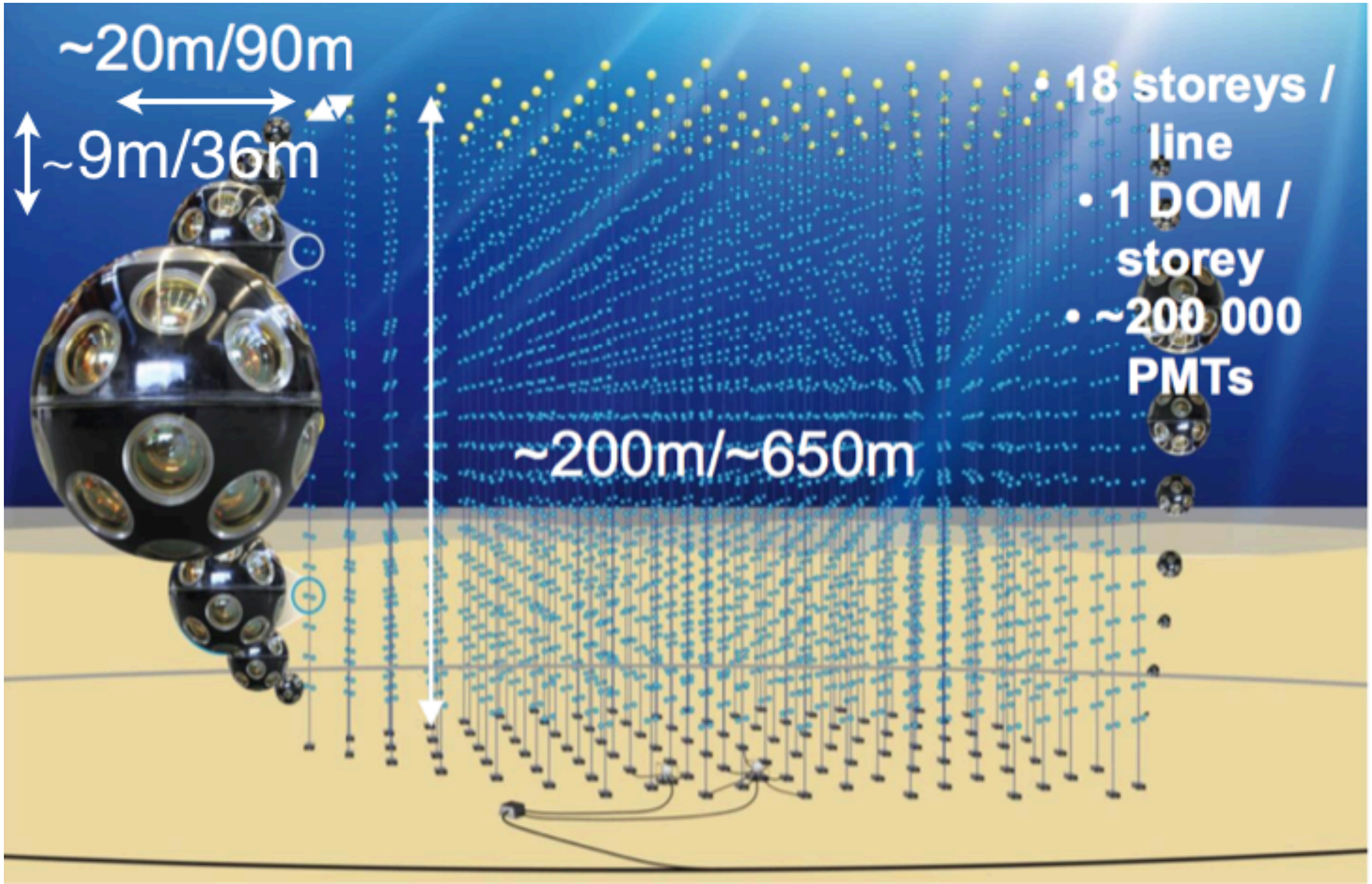


Low energy section
Energy threshold of
some 10 GeV

Medium energy section
mCrab sensitivity in
the 100 GeV – 10 TeV
domain

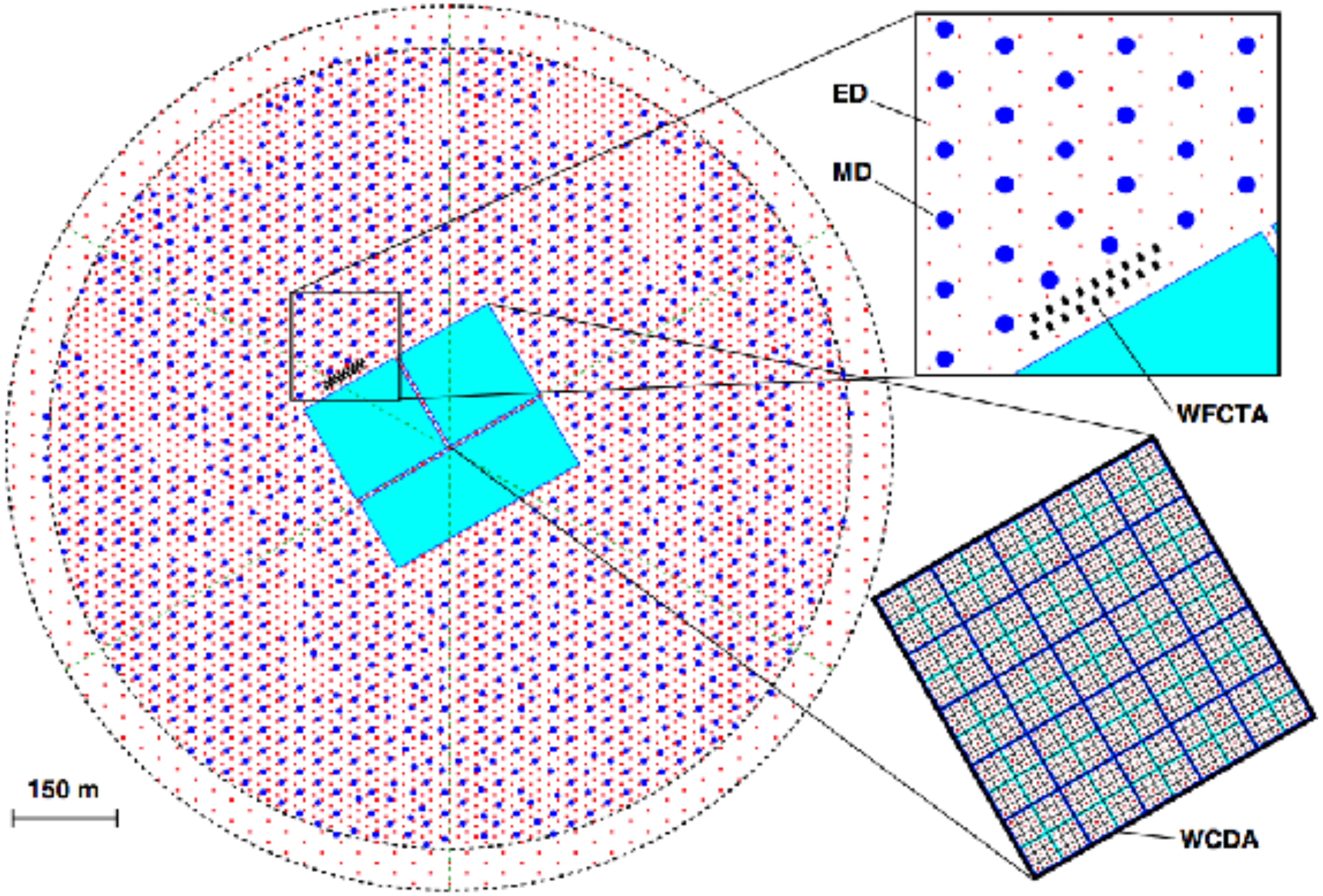
High energy section
10 km^2 area at
multi-TeV energies

KM3NeT



- **ARCA**, multi-km^3 array offshore Italy, mostly dedicated to astronomical studies (sources & diffuse flux);
- **ORCA**, 115 strings deployed offshore France, devoted to studies of neutrino properties (mass ordering, exotic, etc.).

LHAASO



- A 1 km^2 array (**KM2A**) for electromagnetic particle detectors (EDs);
- An overlapping 1 km^2 array of water Cherenkov for muon detection (MDs);
- A surface water Cherenkov detector (**WCDA**);
- Wide-field-of-view air Cherenkov telescopes (**WFCTA**).

The following discussion is based on the LHAASO simulations performed in the past years

Cui et al., Astropart. 54 (2014) 86-92

LHAASO white paper, arXiv:1905.02773 (2019)

How to define instrument sensitivity?

SENSITIVITY = minimum detectable flux

1. **Common approach** for gamma-ray and neutrino astronomy;
2. **Differential sensitivities** allow for direct comparison of performances among different instruments and for spectroscopic analyses of source fluxes;
3. **Instrument response function** requirements:
   i) angular+energy resolution;
   ii) effective area;
   iii) background rate.

Ambrogi, Celli & Aharonian, Astropart. 100 (2018) 69

Sensitivity studies

In each energy bin, these conditions have to be satisfied:

- Minimum **number of signal events**, $N_s^{\min}$;
- Minimum **significance** in bkg rejection, $\sigma_{\min} = N_s/\sqrt{N_b}$;
- Minimum **signal excess** over background uncertainty level, $N_\mathrm{s}/N_\mathrm{b} > X$;

LHAASO/CTA	**KM3NeT**
$N_s^{\min} \geq 10$	$N_s^{\min} \geq 1$
$\sigma_{\min} \geq 5$	$\sigma_{\min} \geq 3$
$N_s/N_b \geq 0.05$	$N_s/N_b \geq 0.75$

The energy bin is driven by the instrument with the largest energy resolution (here KM3NeT): $\sigma(\ln E) = 0.3$

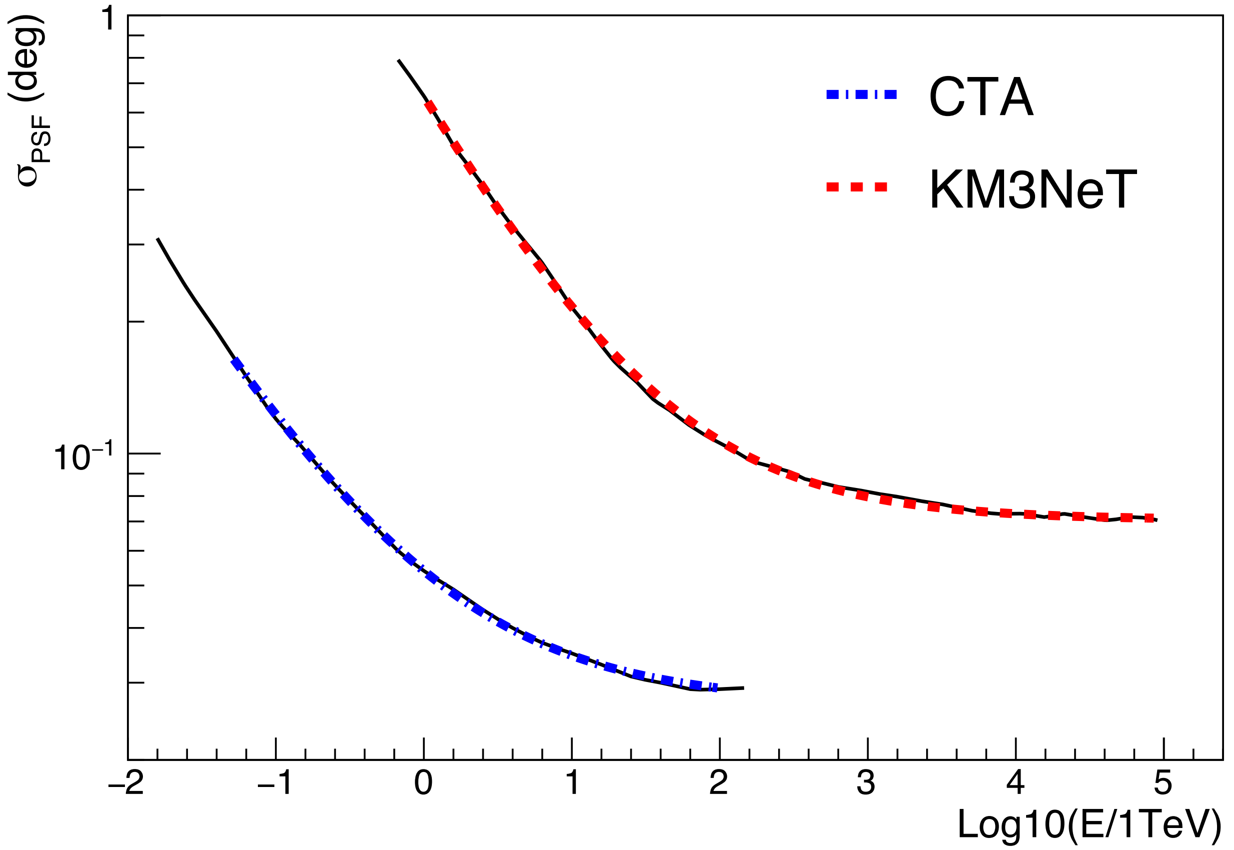
→ 3 bins per log decade

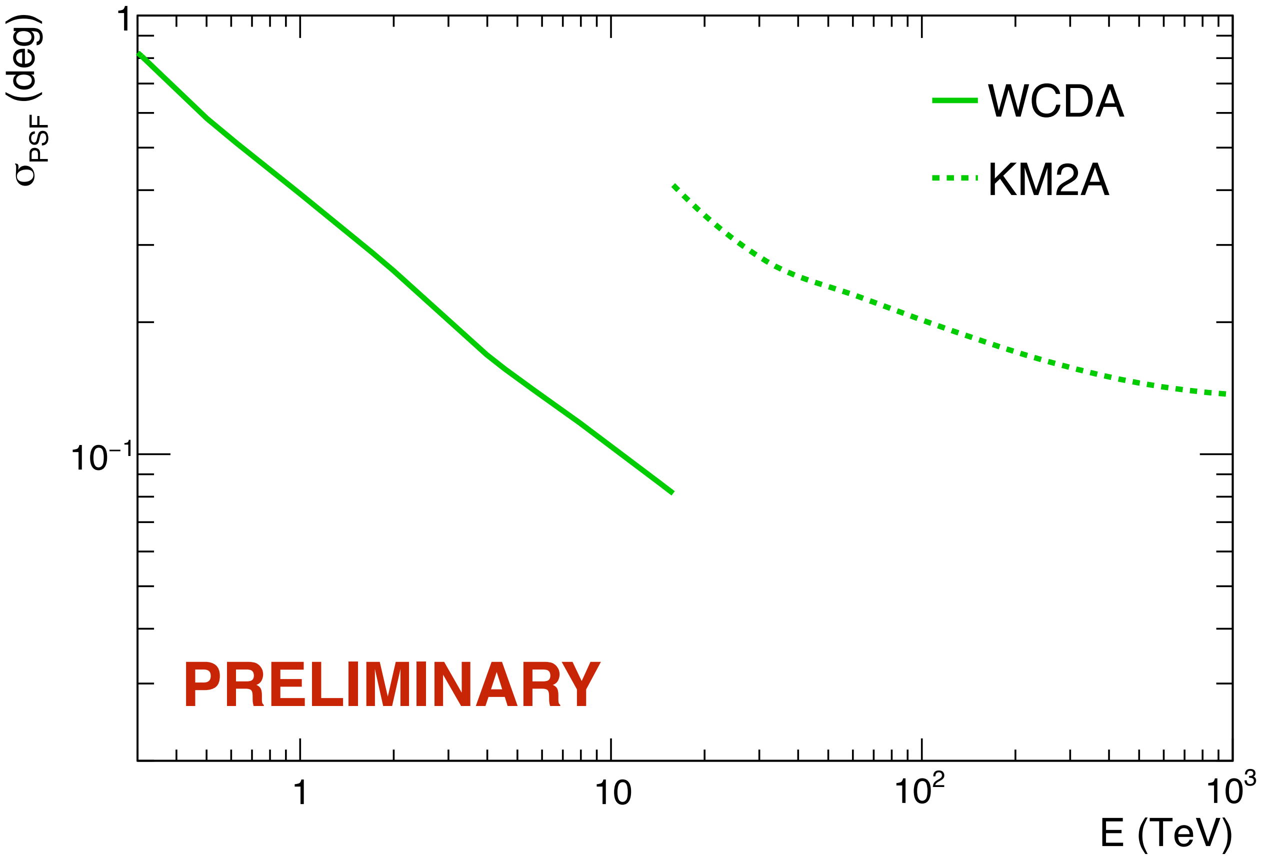
Next generation instrument performances

CTA South Array:
4 LSTs (23 m, FoV=4.5°),
24 MSTs (12m, FoV=7°),
72 SSTs (4m, FoV=9.5°)

KM3NeT Phase 3
(6 building blocks)
upgoing tracks

LHAASO
WCDA+KM2A





Ambrogi, Celli & Aharonian, Astropart. 100 (2018) 69

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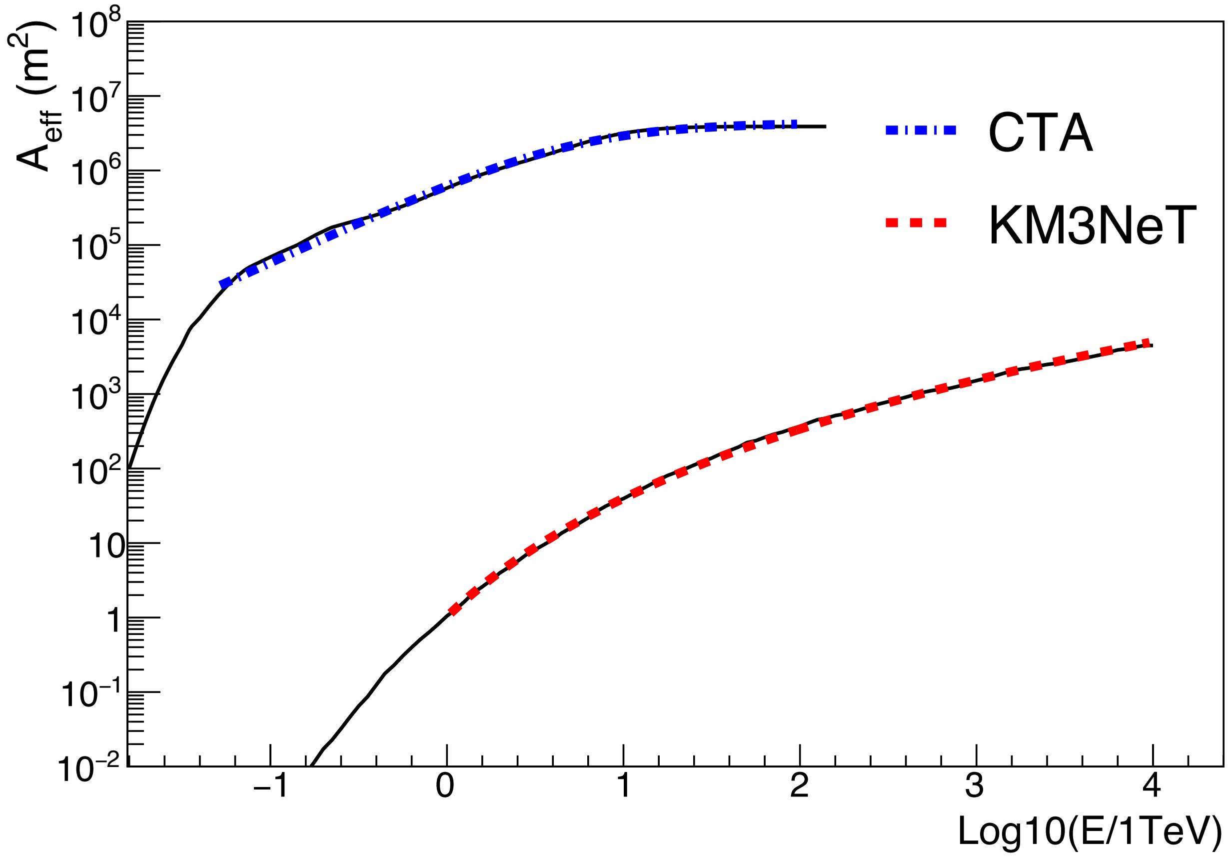
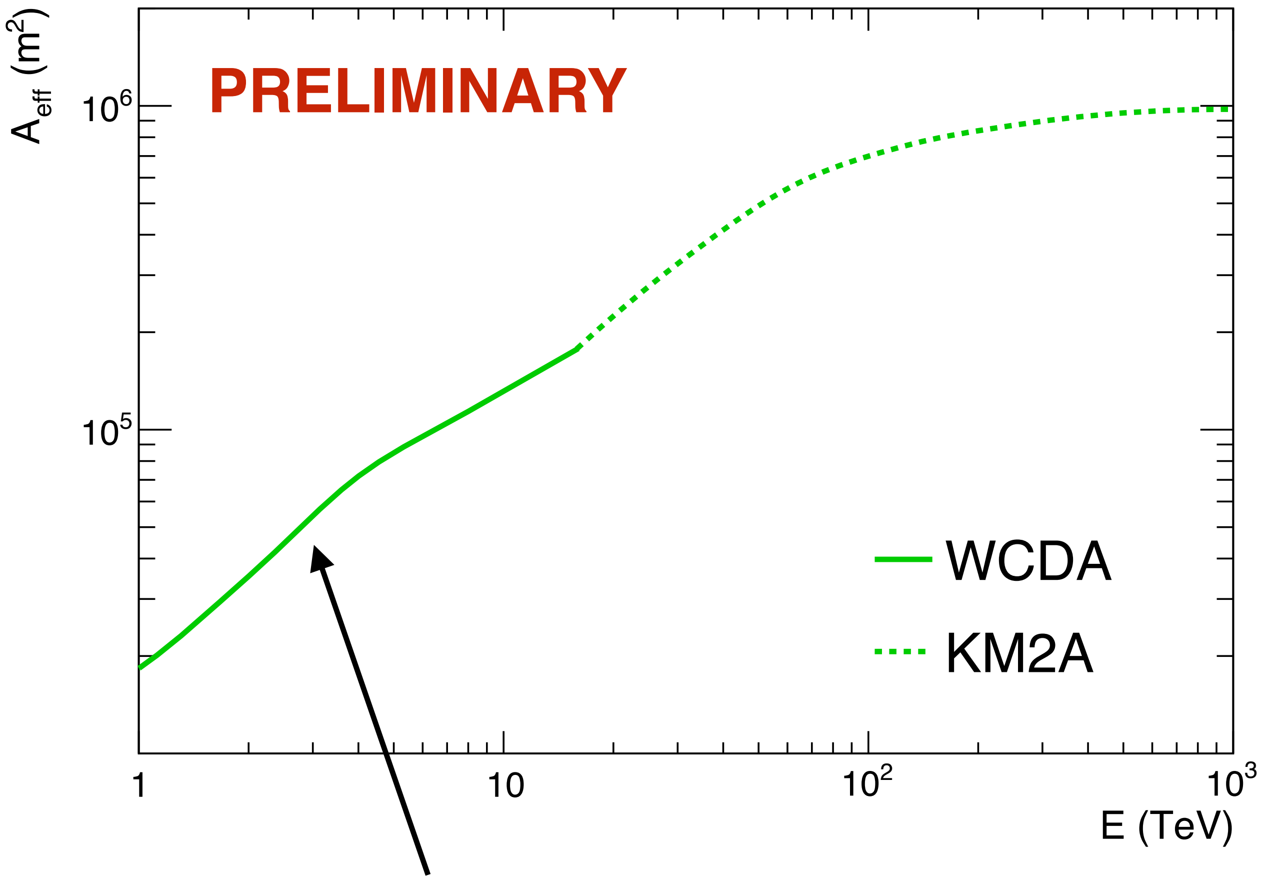


Ambrogi, Celli & Aharonian, Astropart. 100 (2018) 69



zenith averaged between 0 and 60 deg

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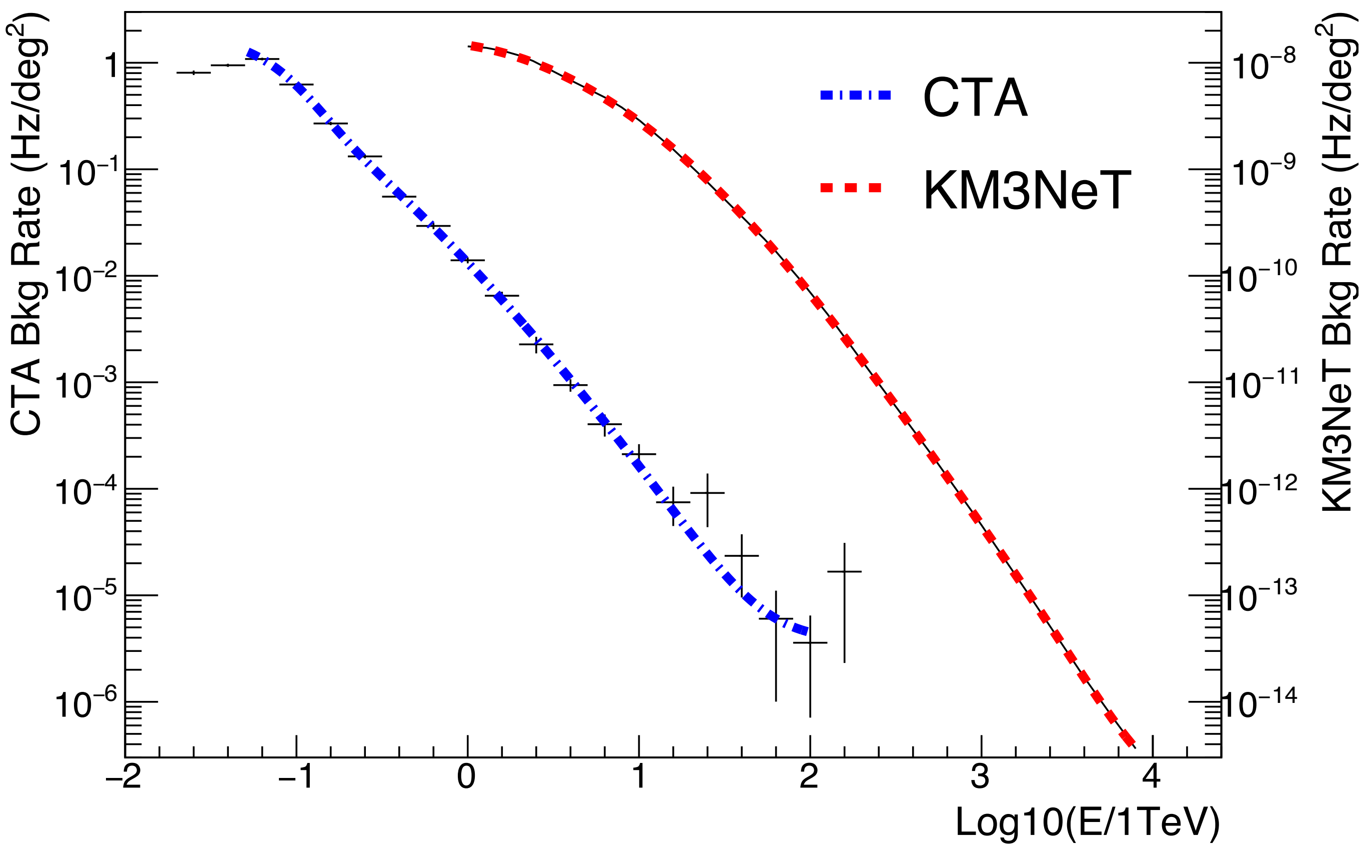

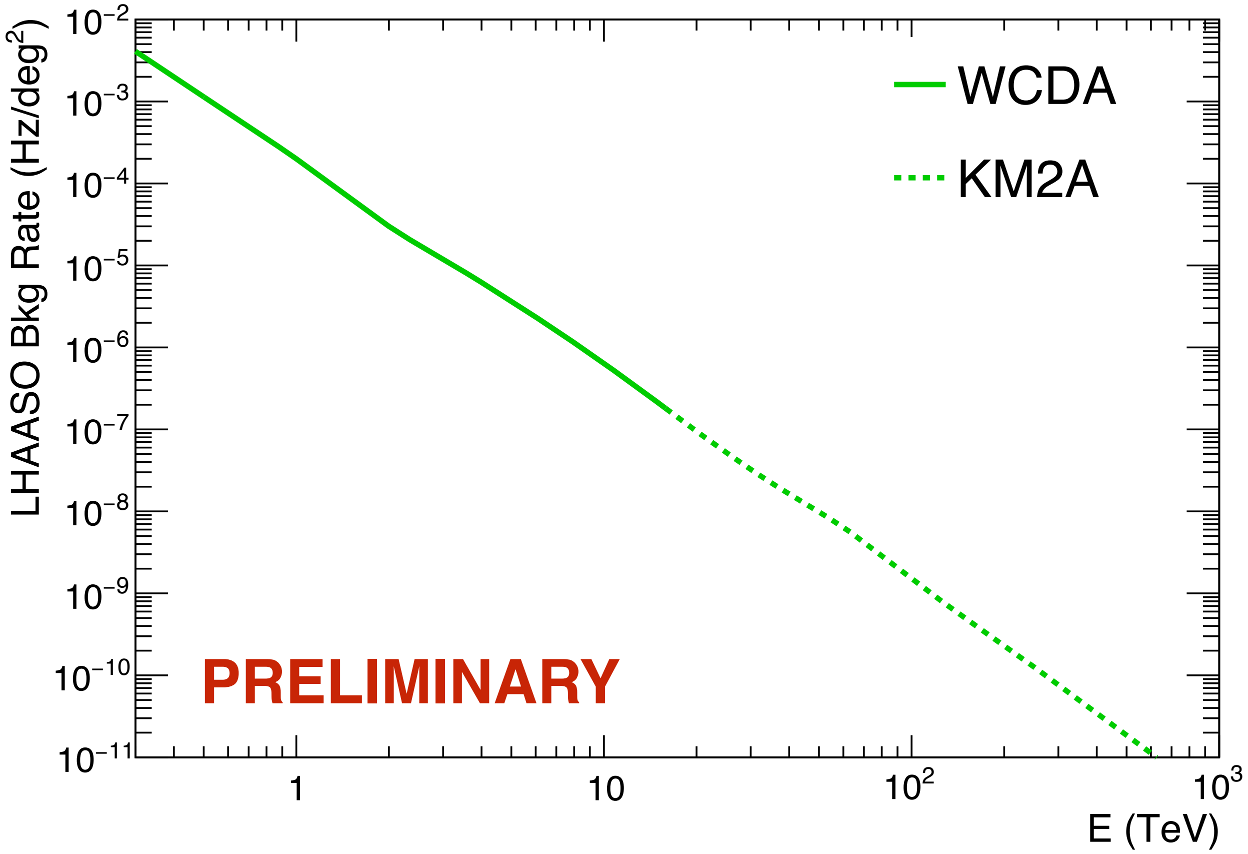

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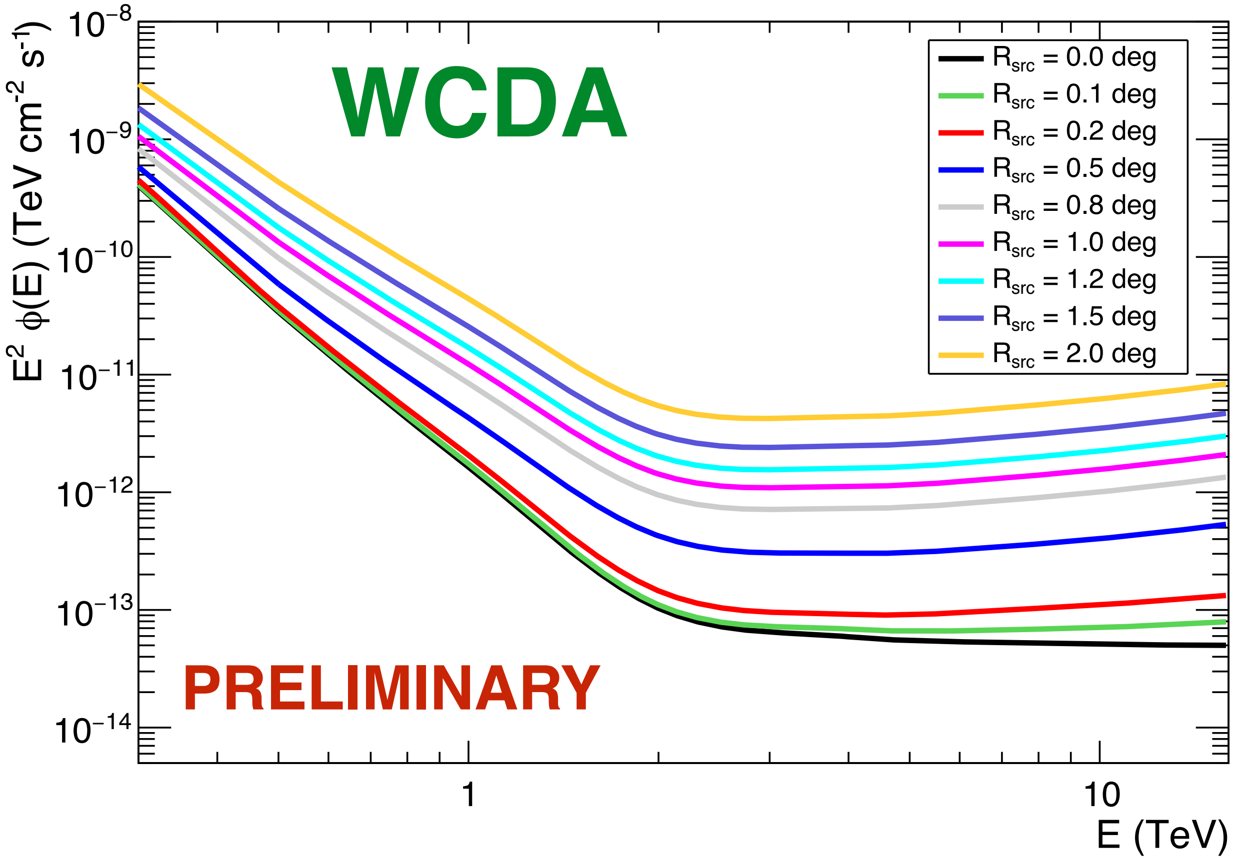
Extended sources

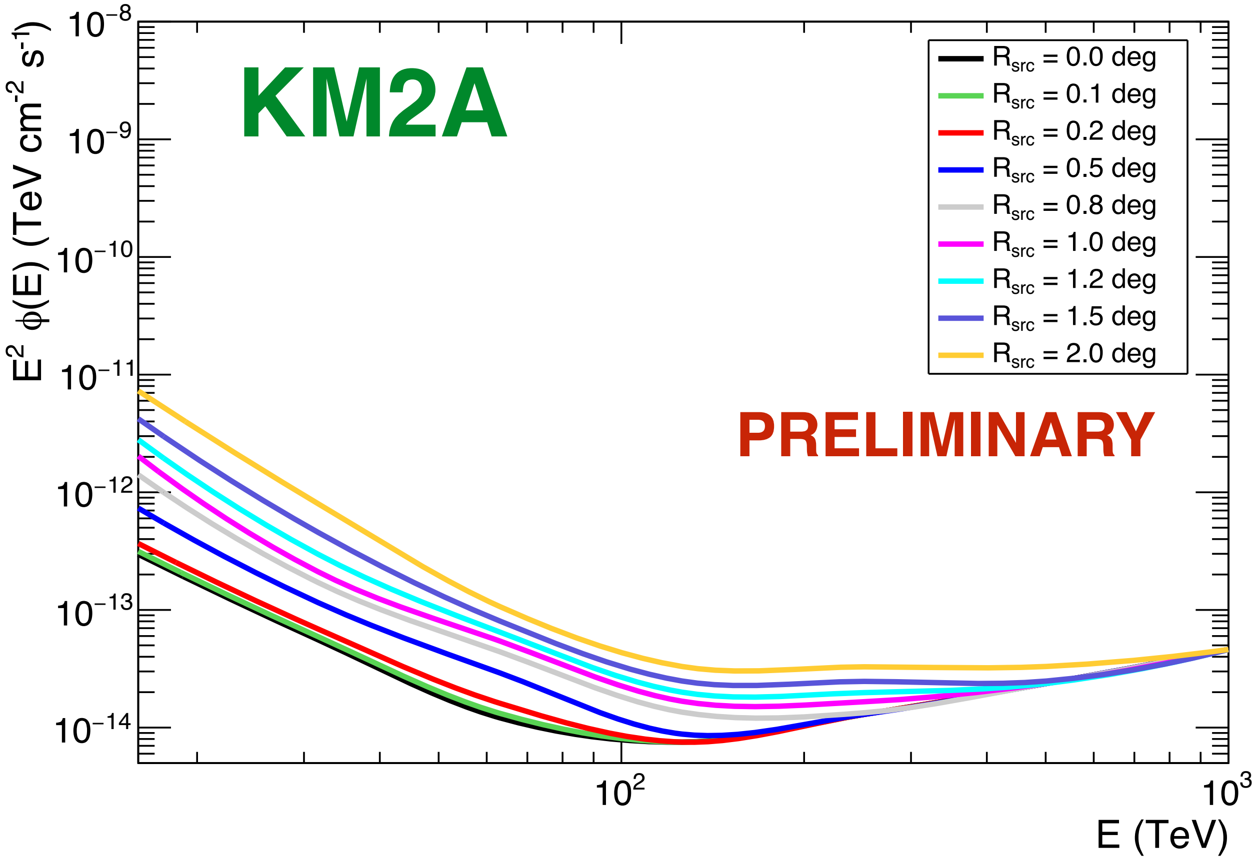
The bkg is very sensitive to the source extension, as

$$N_b \propto R_{\mathrm{ROI}}^2$$

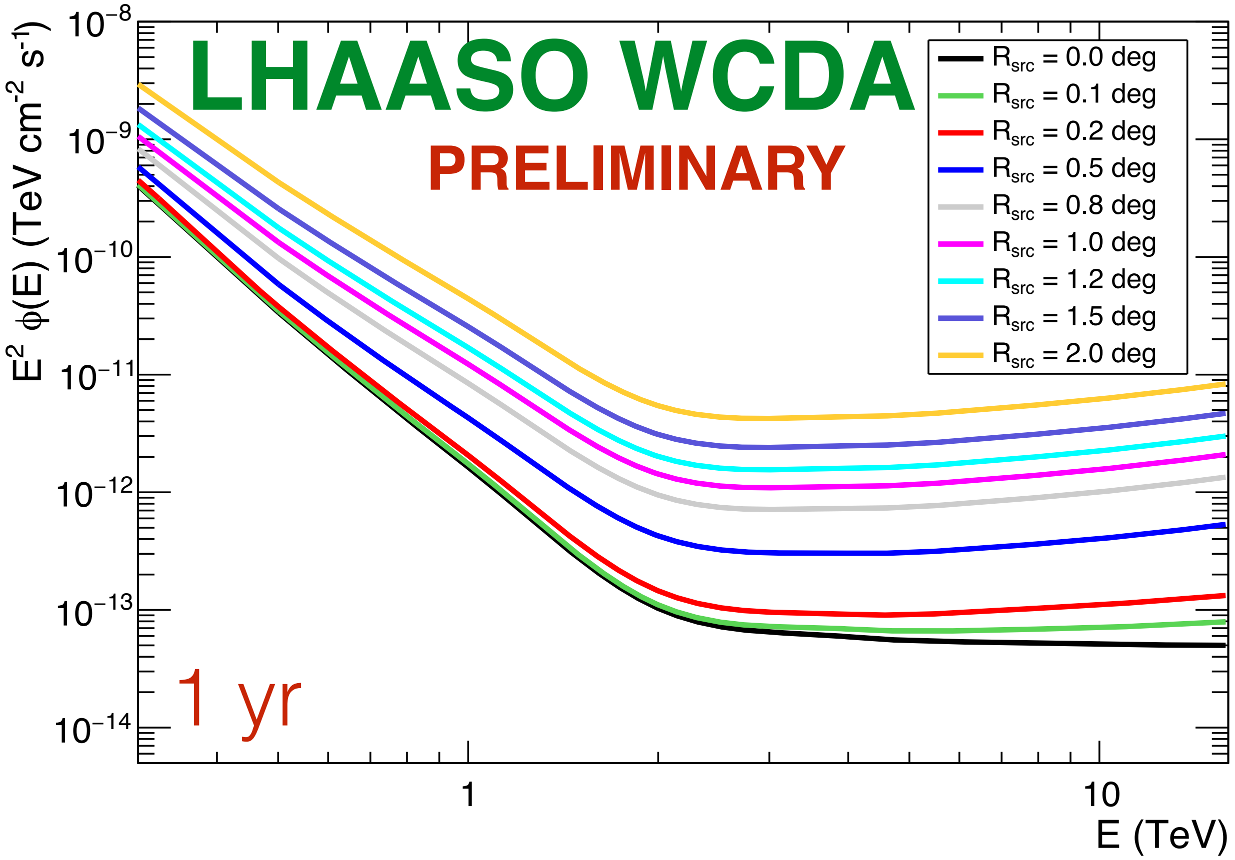
$$R_{\mathrm{ROI}} = \sqrt{\sigma_{\mathrm{PSF}}^2 + R_{\mathrm{src}}^2}$$

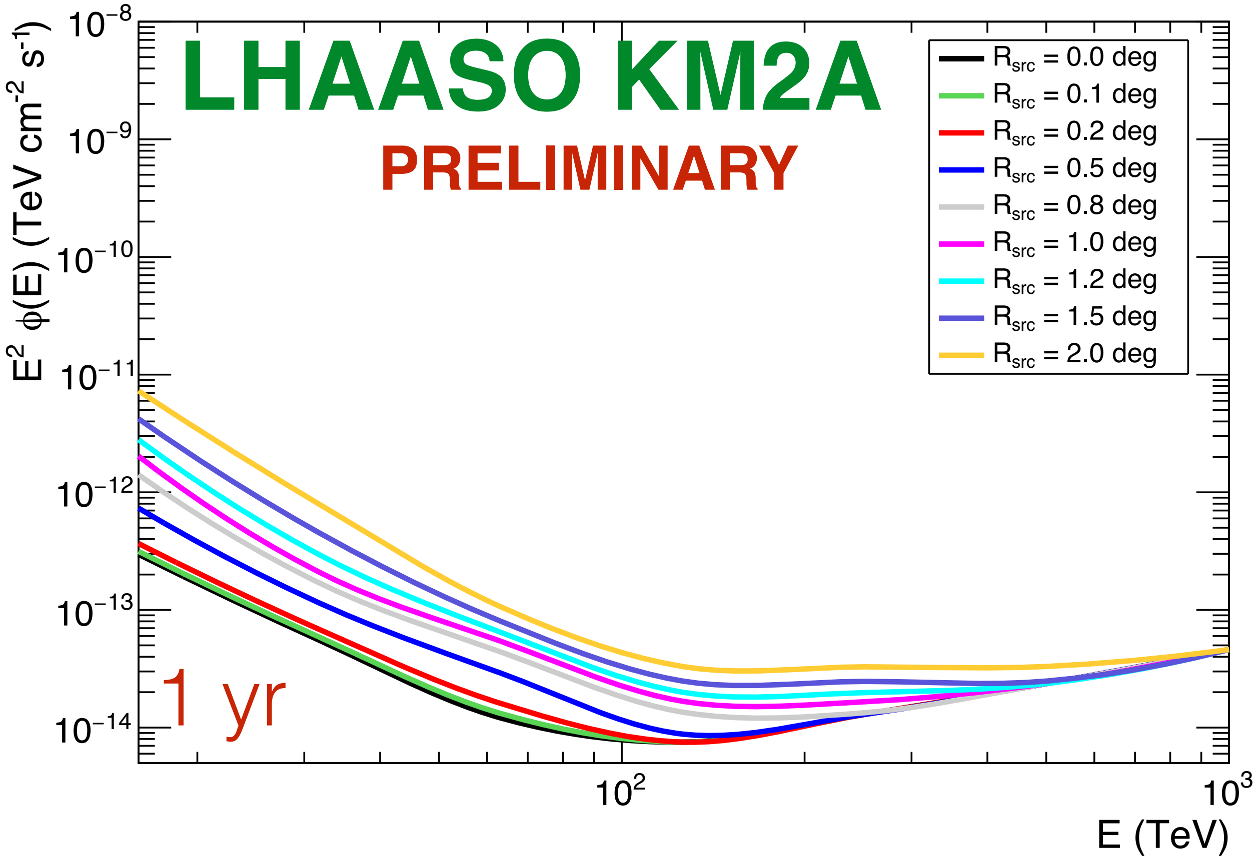
LHAASO 1 yr

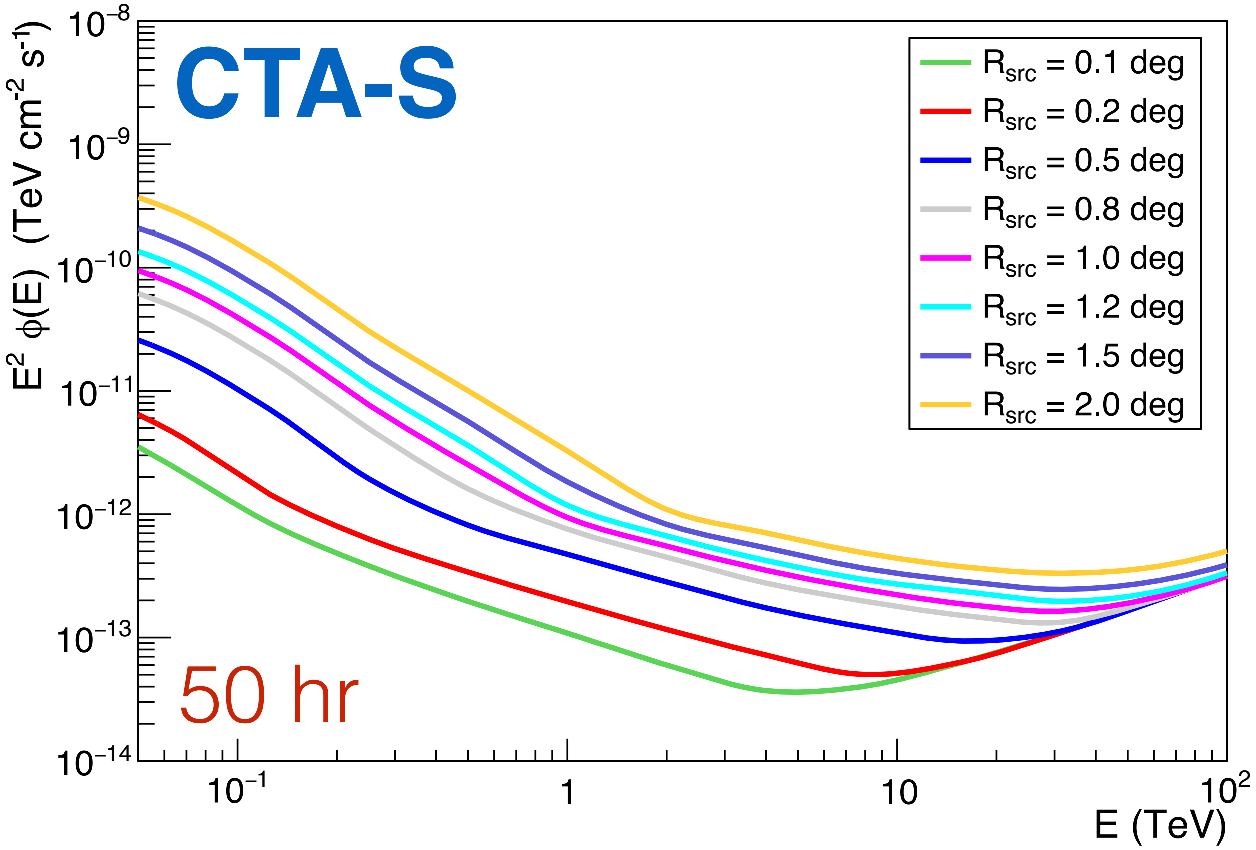


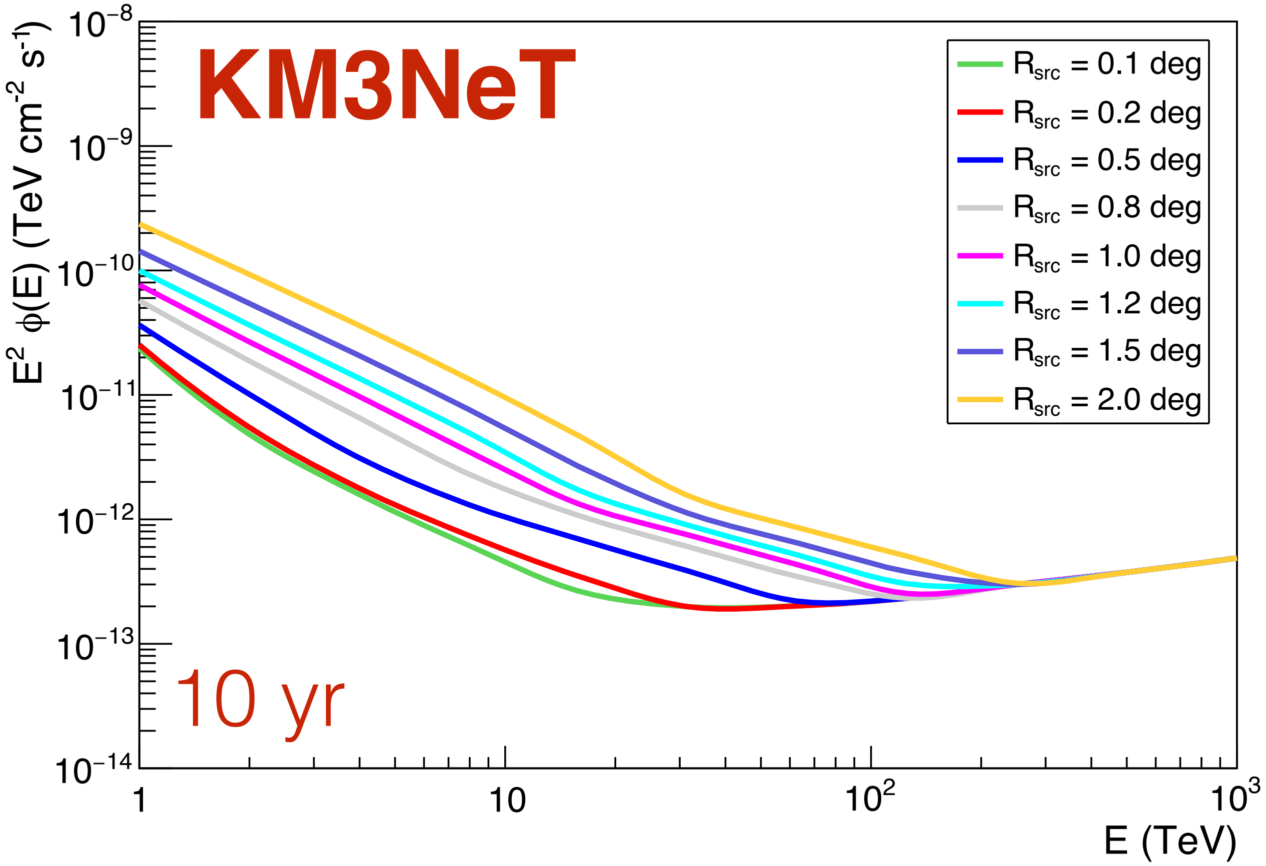


LHAASO / CTA / KM3NeT









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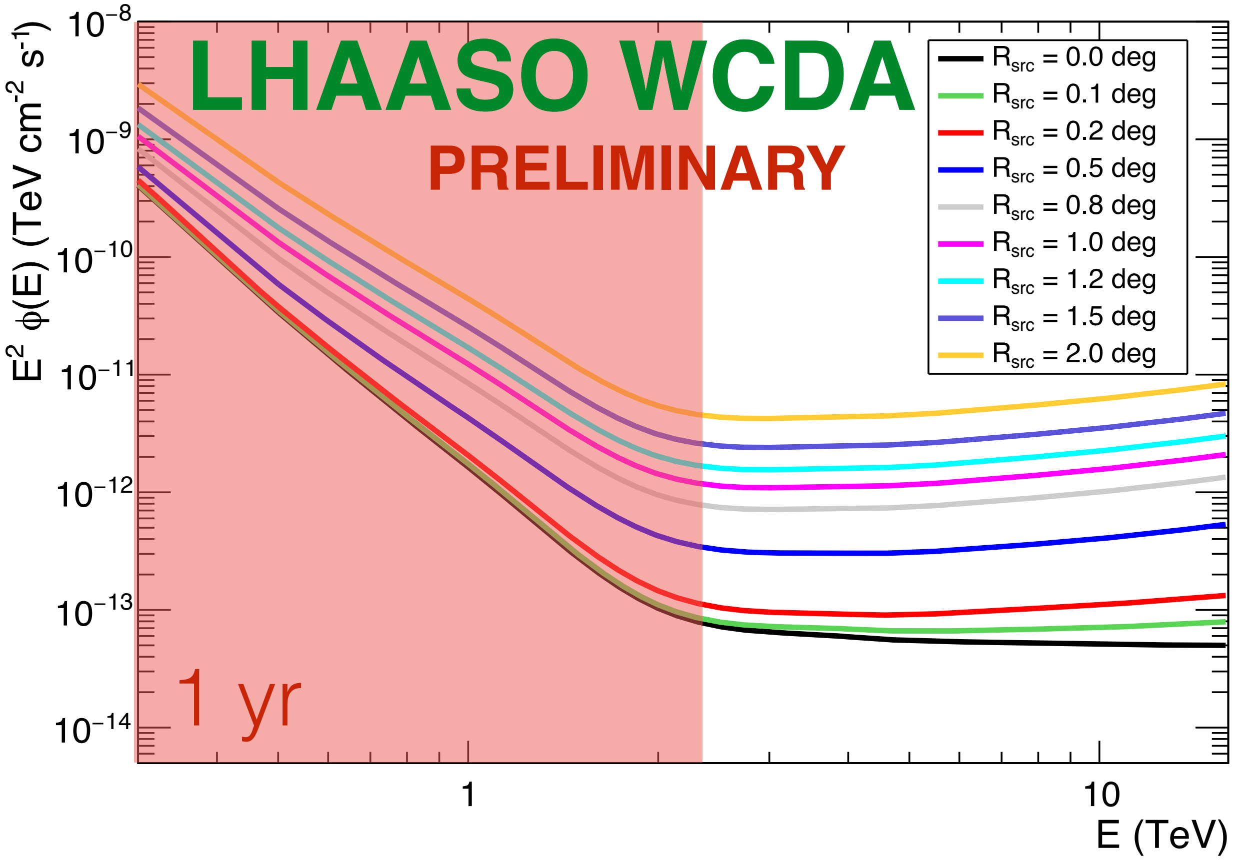
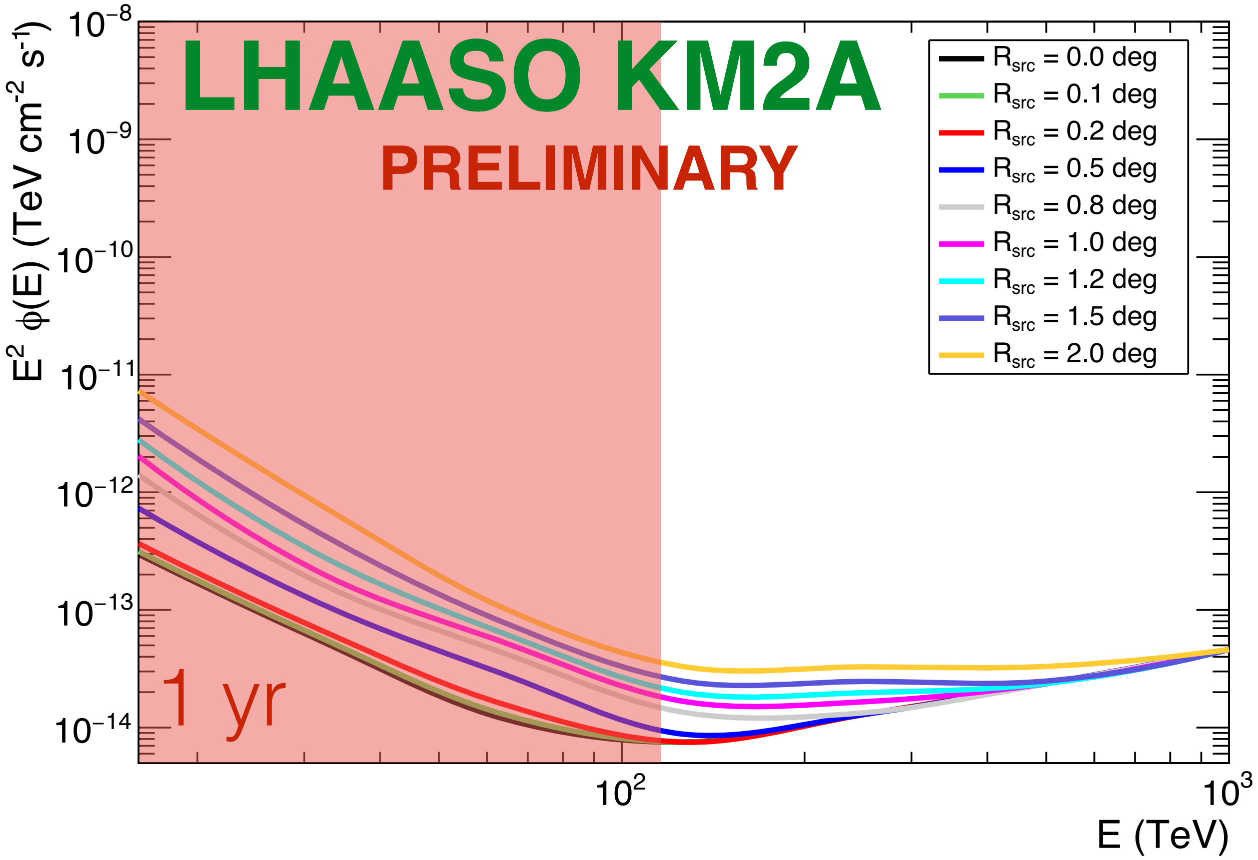
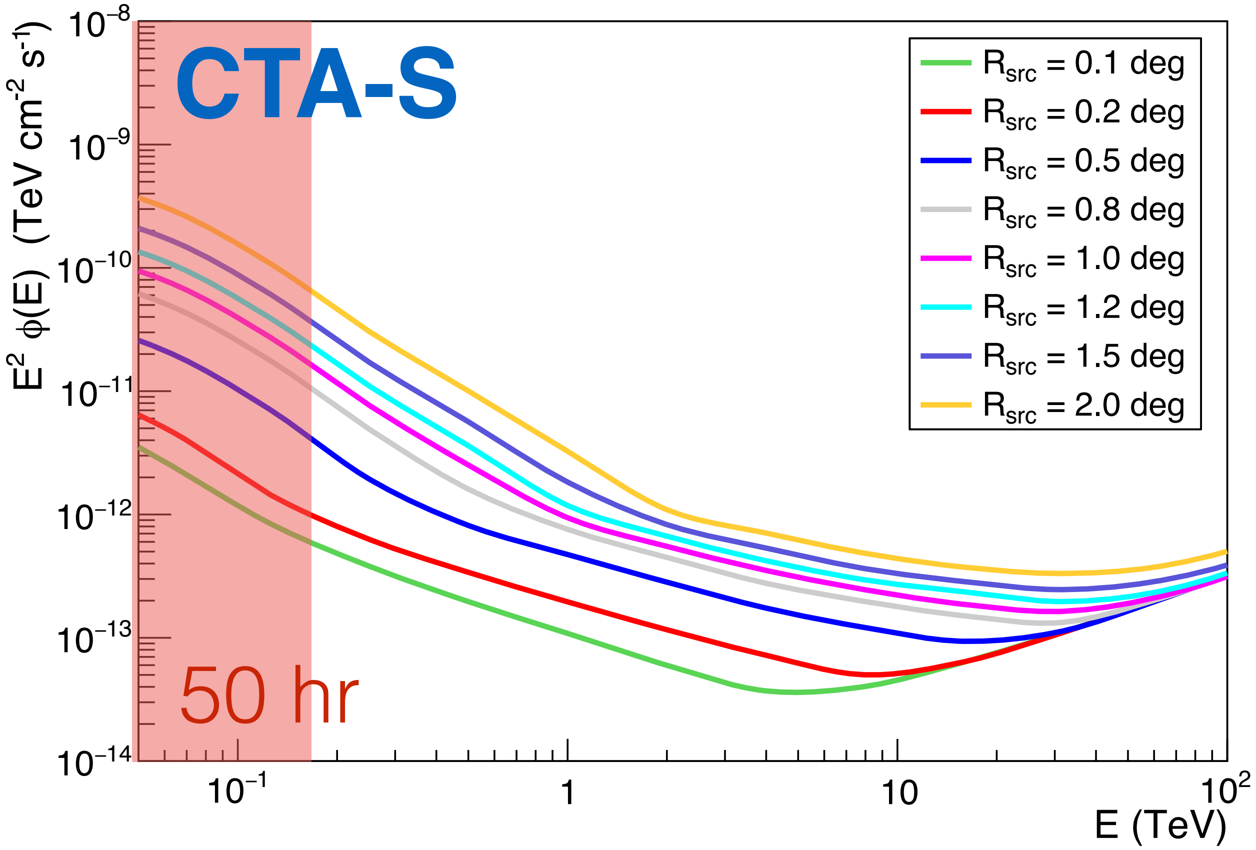
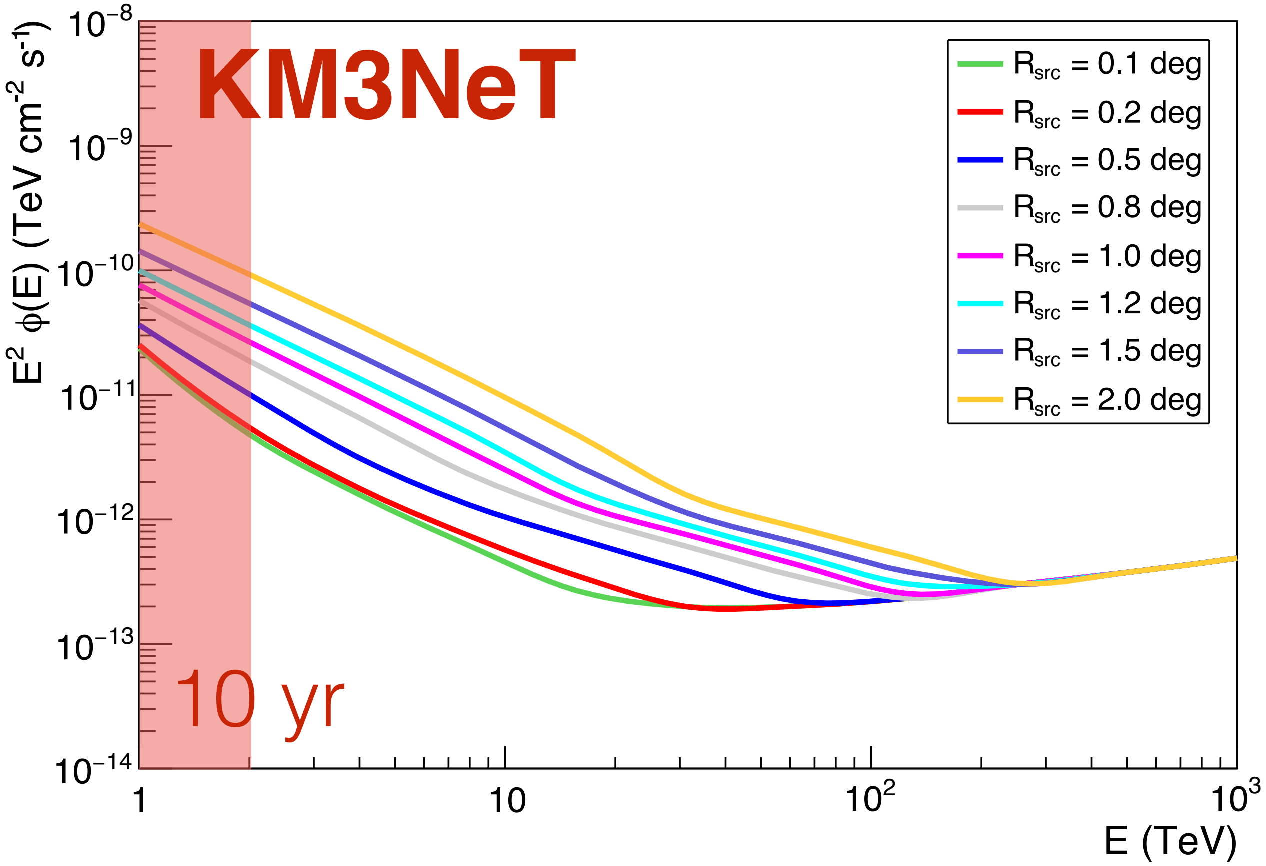
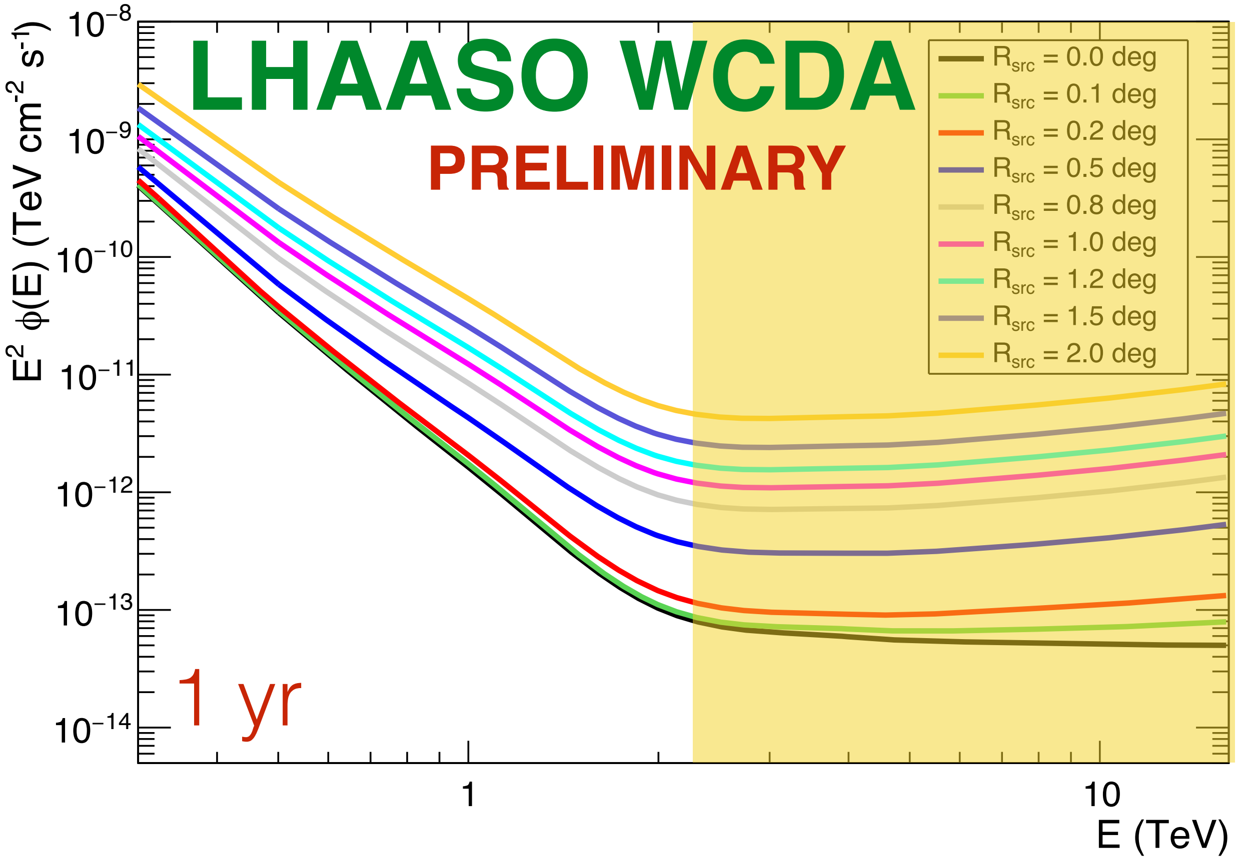


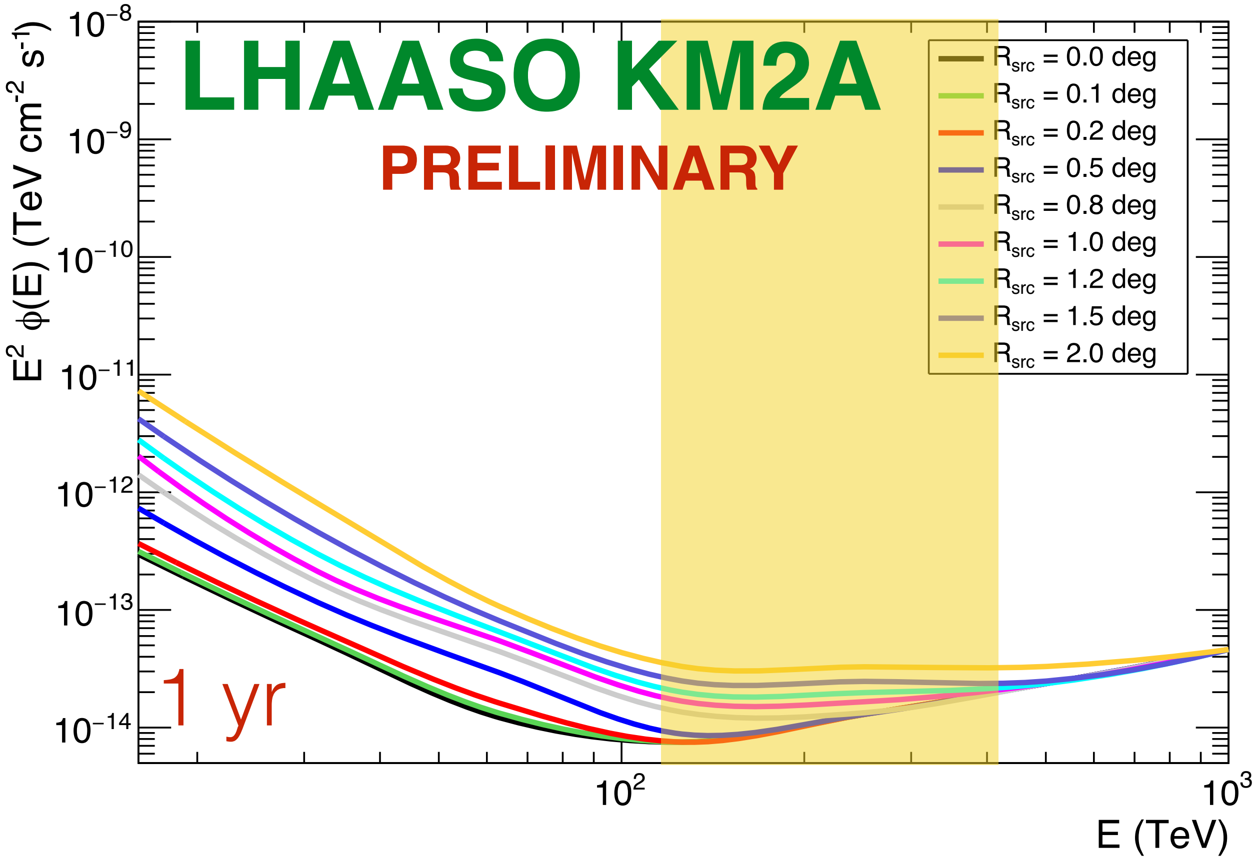


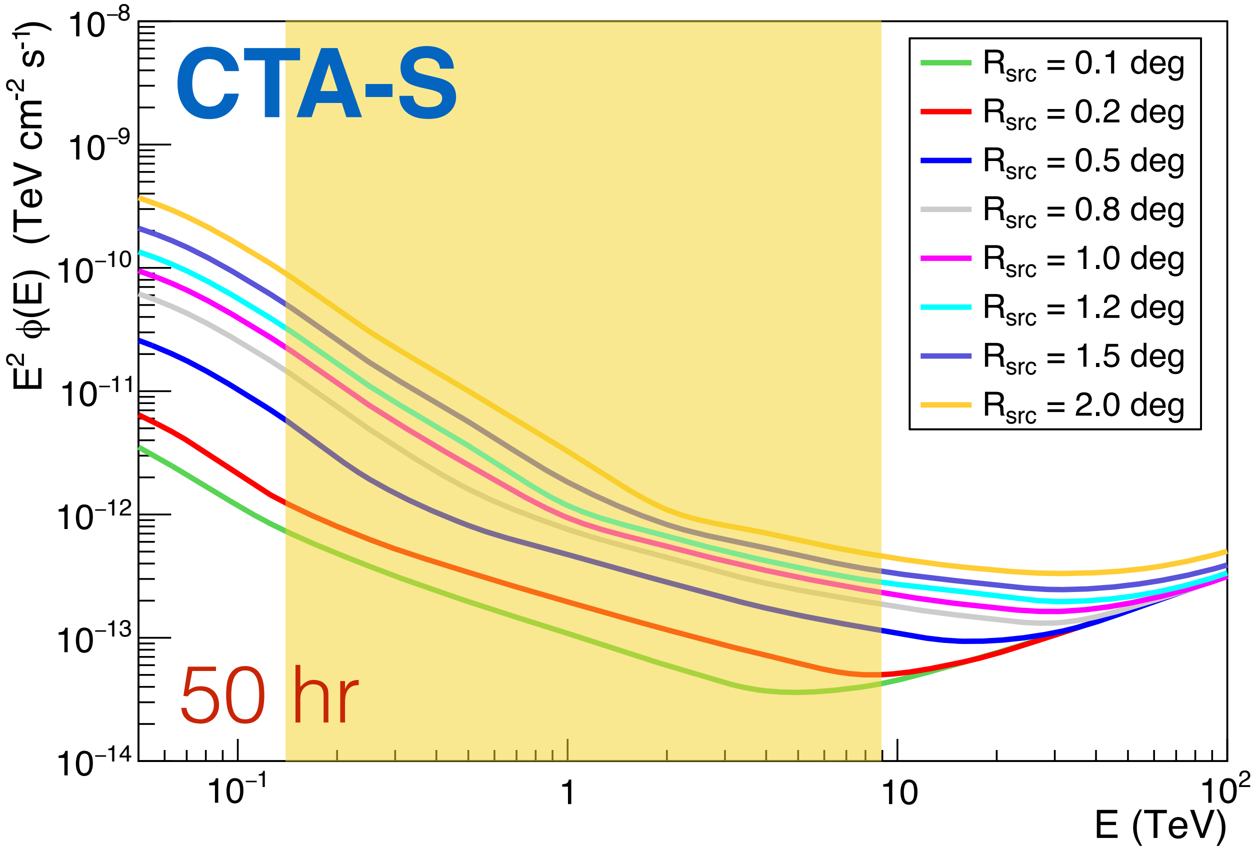


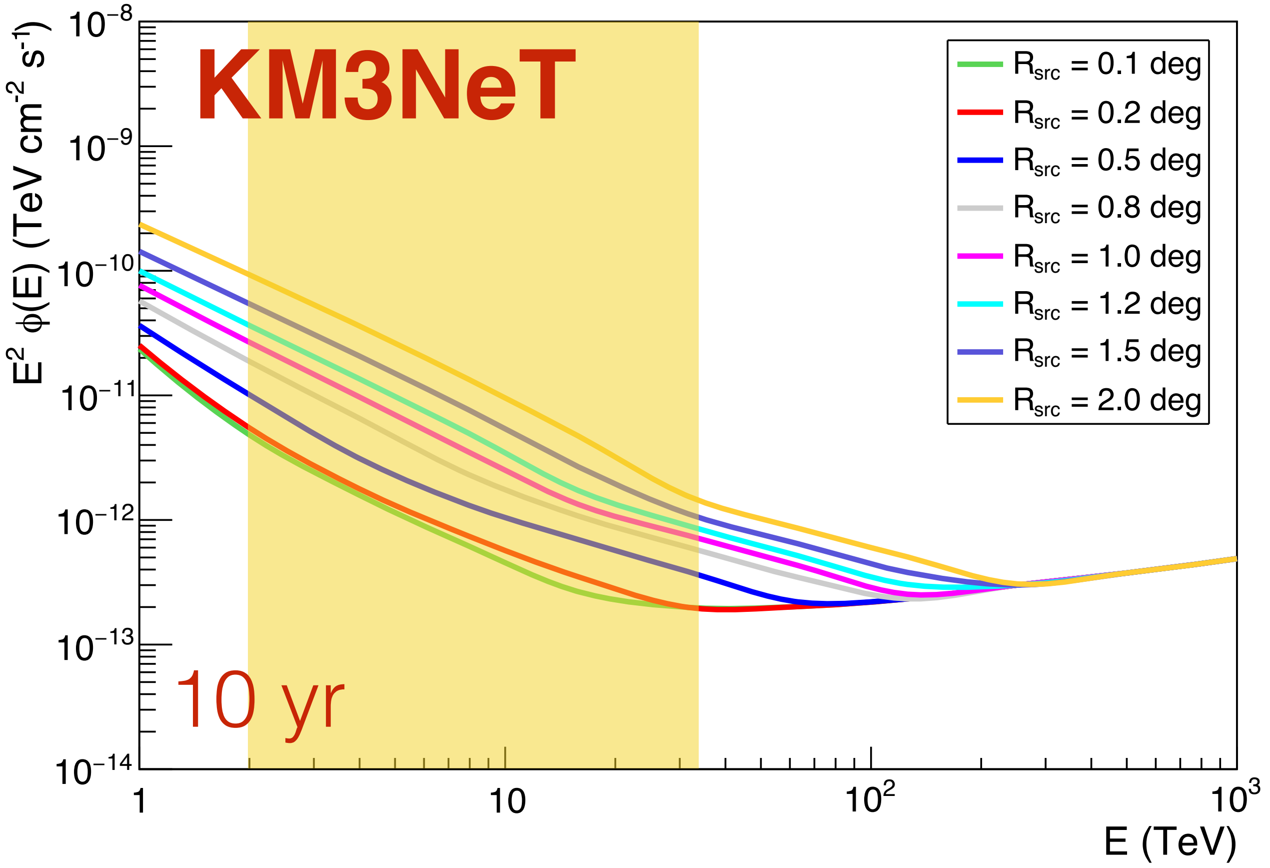


LHAASO / CTA / KM3NeT

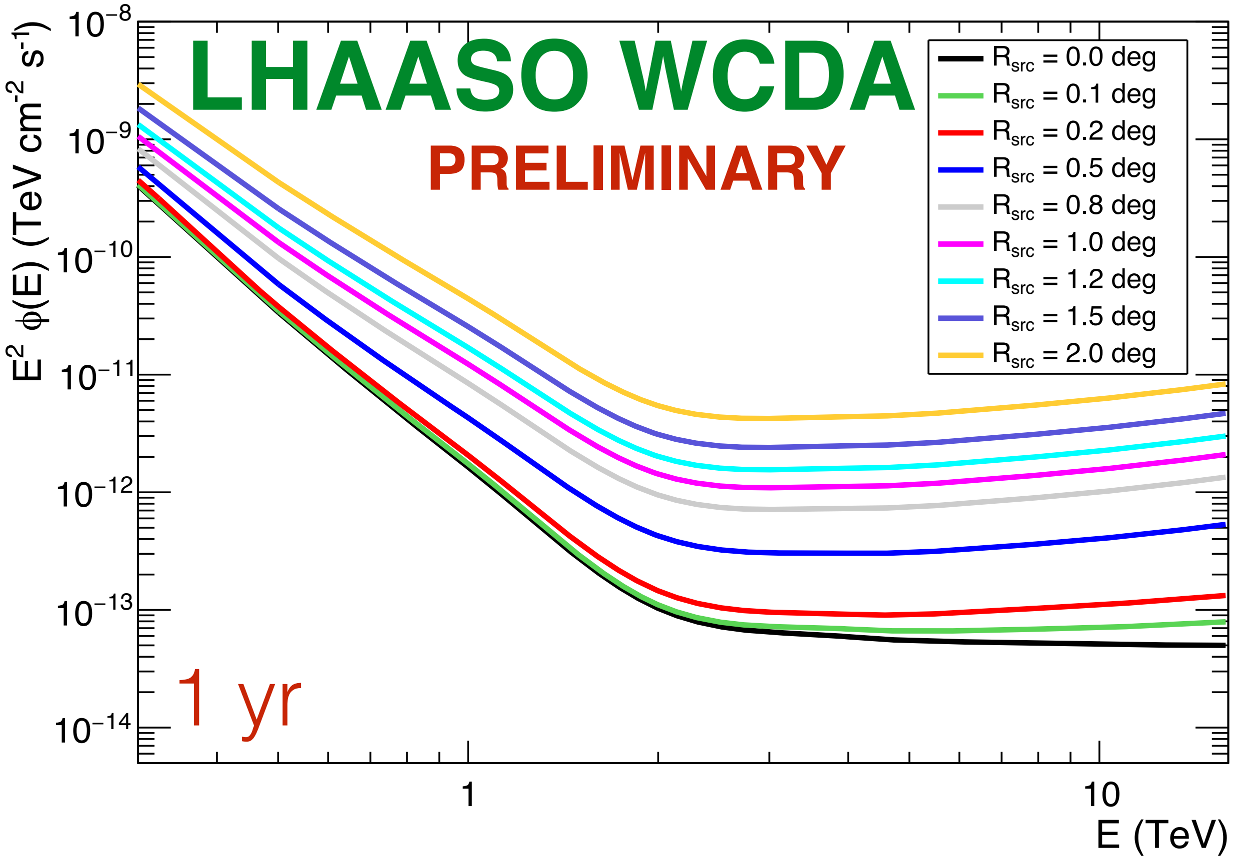


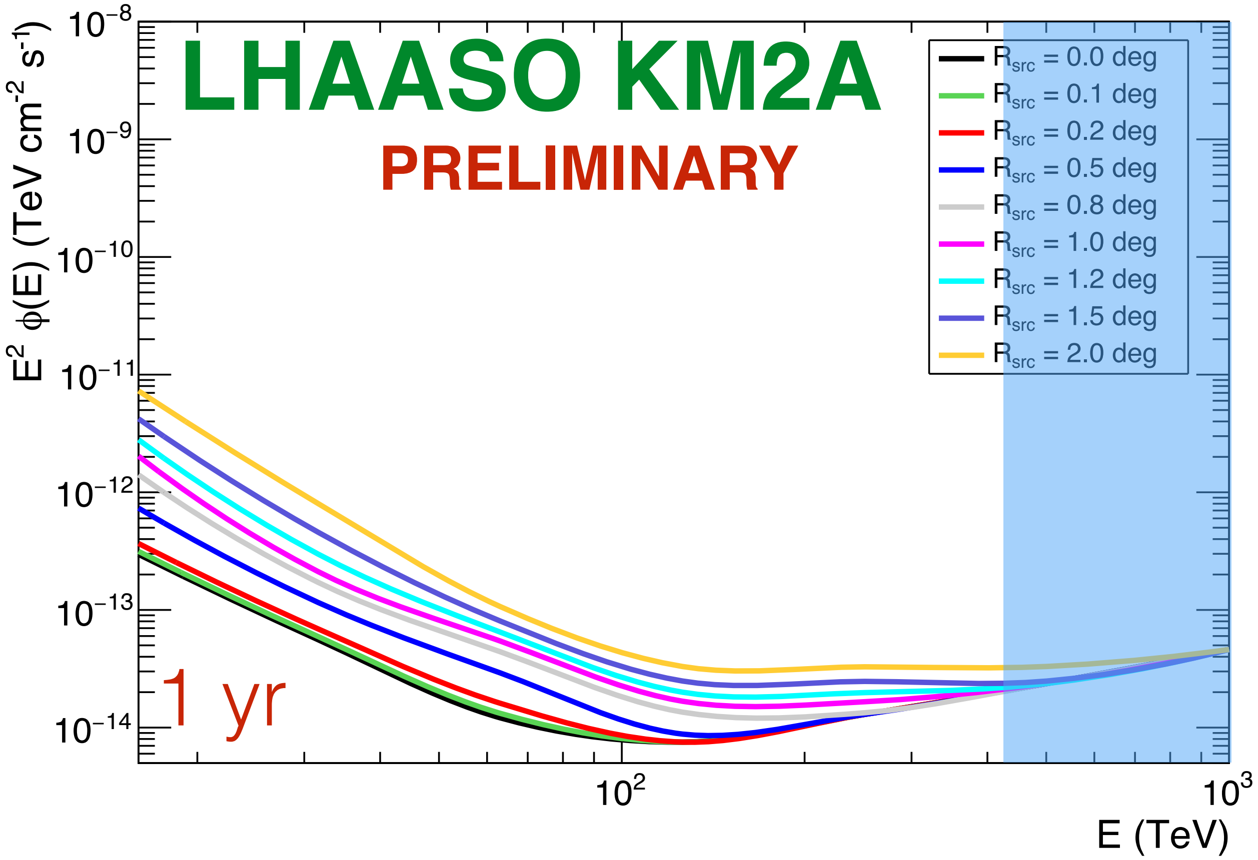


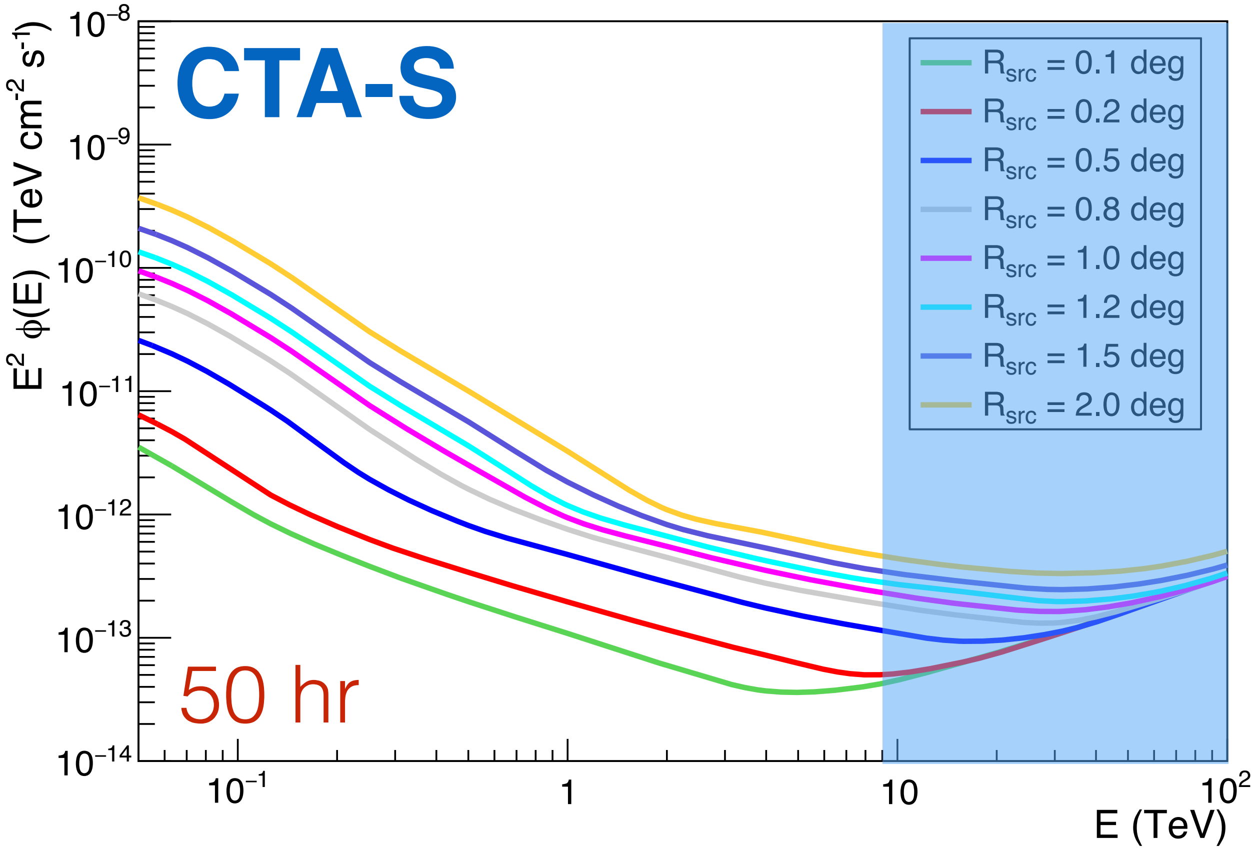


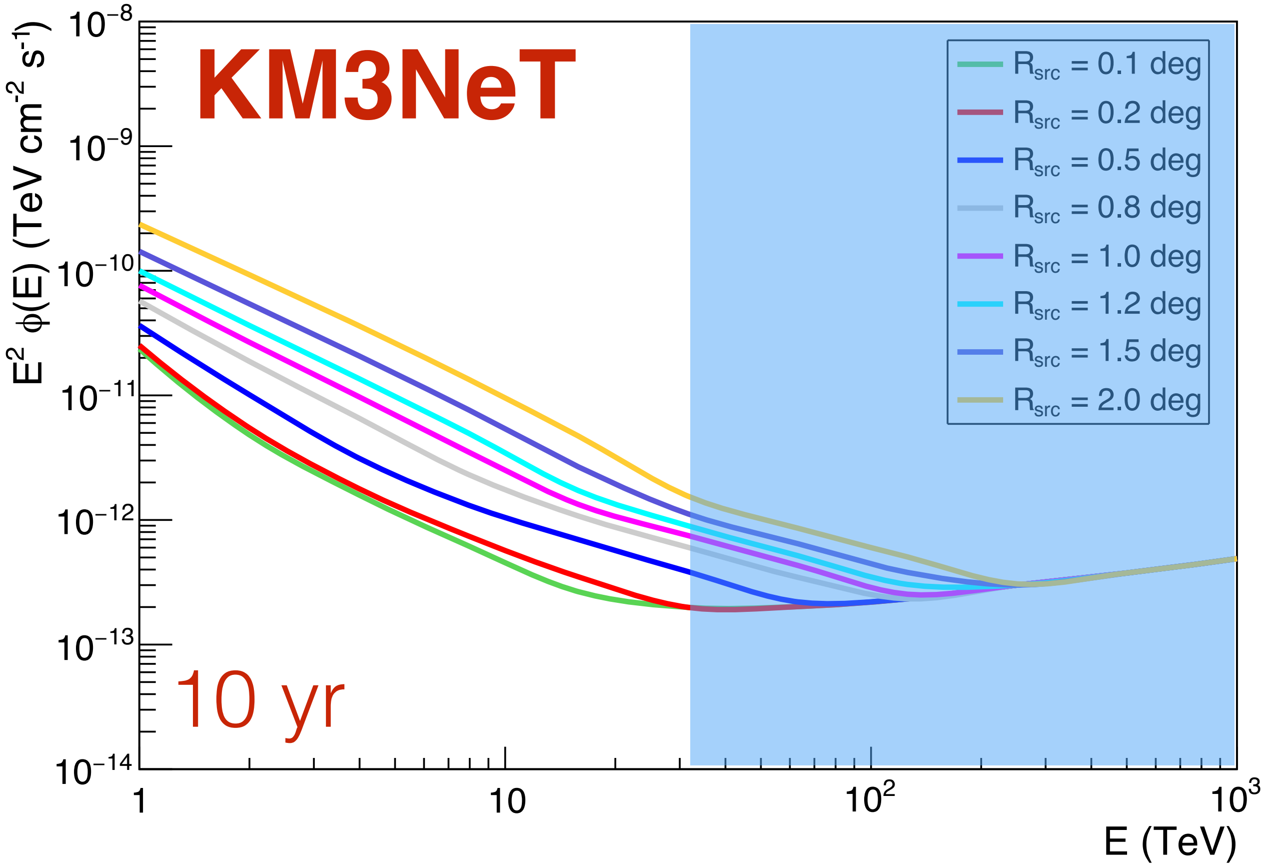


LHAASO / CTA / KM3NeT









Conclusions

- Search strategy for **PeVatrons** in a multi-messenger and multi-wavelength framework;

- Key discriminator for hadronic sources will be detection of
  - 100 TeV gamma rays,
  - high energy neutrinos,
  - synchrotron X rays from secondary electrons

  —> interest in e.g. **massive clouds** illuminated by a nearby accelerator;

- Expected **synergies** between next generation instruments (LHAASO, CTA & KM3NeT);

- LHAASO will allow **deep observations** of sources beyond few tens of TeV —> several application to Galactic astrophysics (source halos, SNRs, etc.)