On the origin of the complex energy-dependent structure of HESS J1702-420

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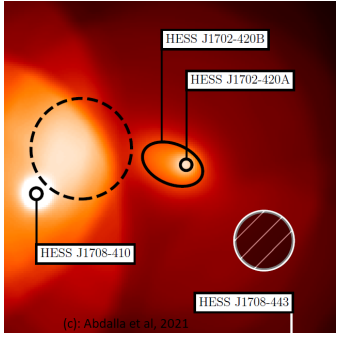
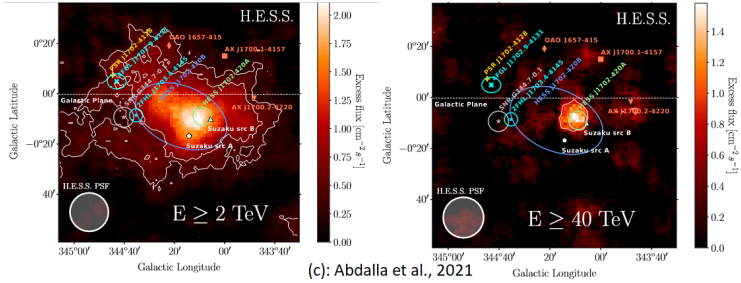


HESS J1702-420: Introduction



(c): Abdalla et al., 2021

- Discovered in 2006 during the first HESS galactic plane survey

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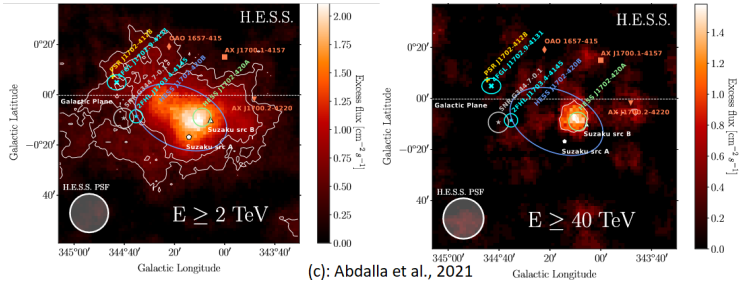

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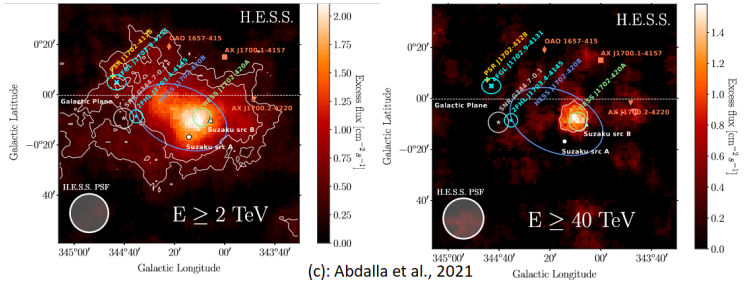

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- Size changes from $\sim 0.3^\circ$ below 5 TeV to point-like above 30-40 TeV

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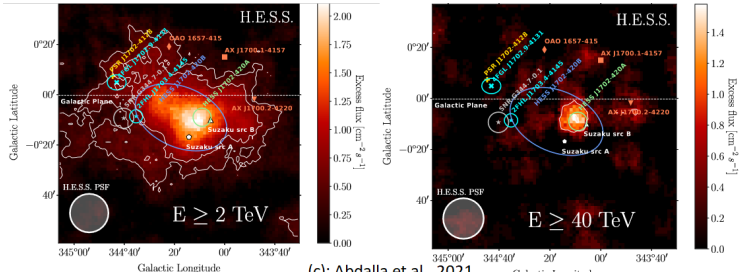

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- Size changes from $\sim 0.3^\circ$ below 5 TeV to point-like above 30-40 TeV
- Morphology: point-like HESS J1702-420A + diffuse HESS J1702-420B

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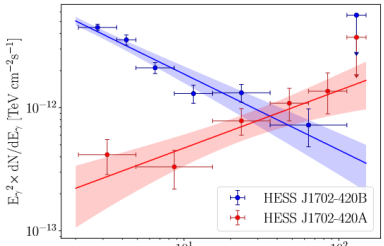

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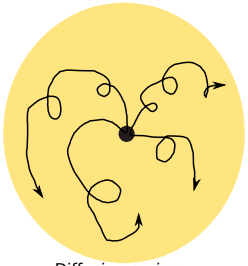
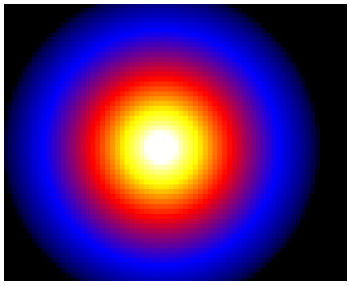
- Spectra: powerlaw with no cut-off indications up to 100 TeV
- HESS J1702-420A: $\Gamma = 1.53 \pm 0.19_{stat} \pm 0.20_{syst}$
- HESS J1702-420B: $\Gamma = 2.62 \pm 0.10_{stat} \pm 0.20_{syst}$
- Motivation: Describe simultaneously and self-consistently spectral/spatial behaviour of both (A+B) sources.

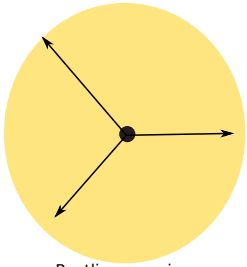
Energy dependent diffusion


Diffusive regime

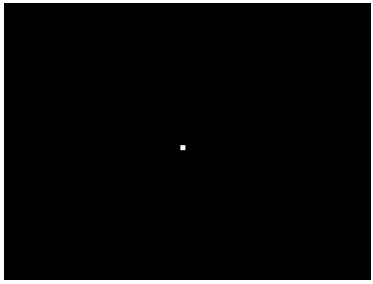


- An accelerator of VHE protons at the center of HI cloud. Observed photons – π^0 decay.
- Propagation of protons is described with energy dependent diffusion $D(E) = D_0(E/1TeV)^{i_d}$
- "Low" energies: diffusive propagation; protons are entangled and randomized in momenta space $\Rightarrow$ "Extended" source

Energy dependent diffusion



Rectlinear regime



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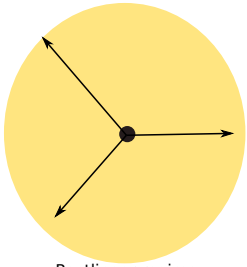
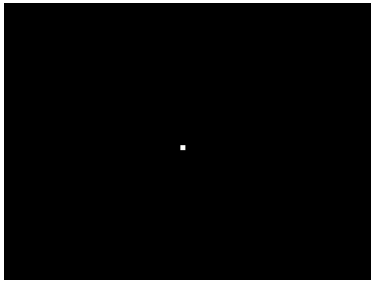
Energy dependent diffusion



Rectlinear regime



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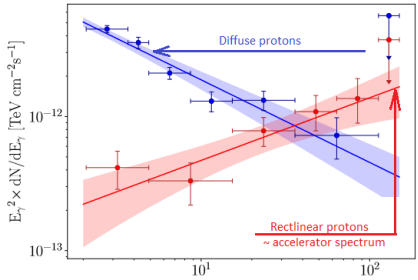
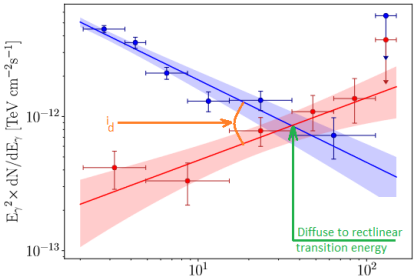
- Propagation of protons is described with energy dependent diffusion $D(E) = D_0(E/1TeV)^{i_d}$
- "High" energies: rectlinear propagation of protons $\Rightarrow$ "point-like" source
- Transition criteria: diffusion time longer than free-fly time: $r^2/D \gg r/c$

Back of the envelope estimations





- An accelerator energetics and spectrum: point-like source spectrum (+density; +cloud size)

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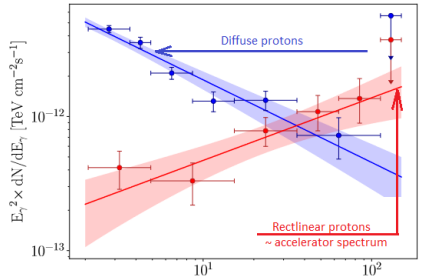

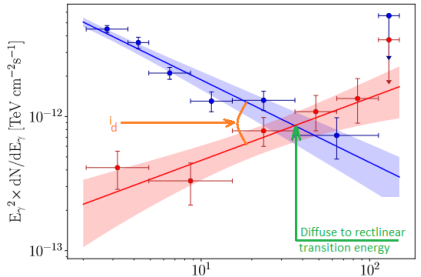

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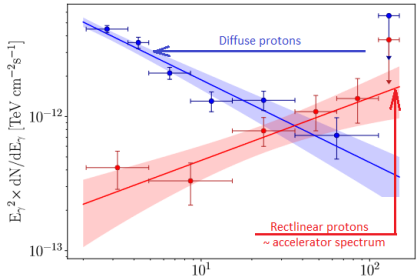
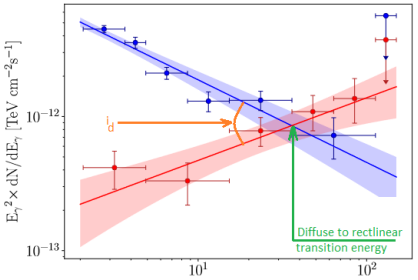
$$dN/dE \propto Q_{100}(E_p/1TeV)^{i_p}; i_p \sim 1.5$$

$$F_{ph} = \frac{\kappa L_p}{4\pi D^2}\frac{t_{esc}}{t_{pp}} \simeq 10^{-12}\frac{Q_{100}n_0}{10^{40}\text{erg/s cm}^{-3}}\frac{\kappa}{1/6}\frac{R}{20\text{pc}}\left(\frac{D}{3.5\text{kpc}}\right)^{-2}\text{erg/s/cm}^2$$

Back of the envelope estimations





- Diffusion coefficient index: difference of diffuse and point-like sources spectral indexes:

$$i_d \sim 1$$

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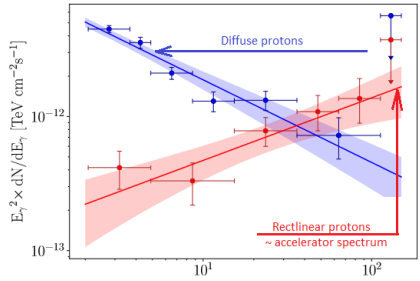
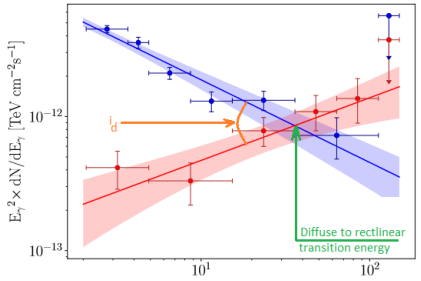




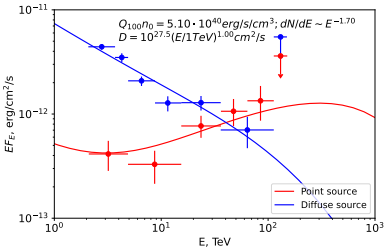
- Diffusion coefficient index: difference of diffuse and point-like sources spectral indexes:

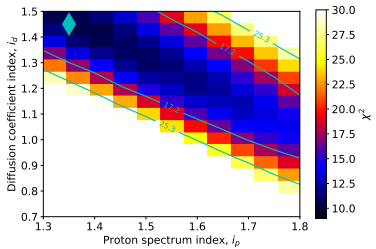
$$i_d \sim 1$$

- Diffusion coefficient normalisation: transition energy:

$$D_0 \lesssim \frac{Rc\beta}{(E_c/1TeV)^{i_d}} \sim 6 \cdot 10^{26} \frac{R}{20pc} \left(\frac{E_c}{30TeV} \right)^{-i_d} \frac{\beta}{0.01} \, cm^2/s$$

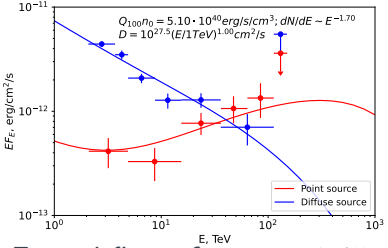
Proper modelling

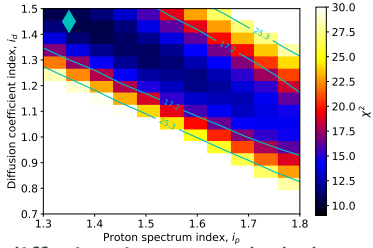




- Relativistic diffusion distribution function for protons describing evolution in space and momenta space: analytical expression from Prosekin et al. 2015
- Photon emission processes – naima (v.0.9.1, Zabalza et al, 2015)
- Secondary electrons production – aafragpy (v.1.12, Koldobskiy et al., 2021)

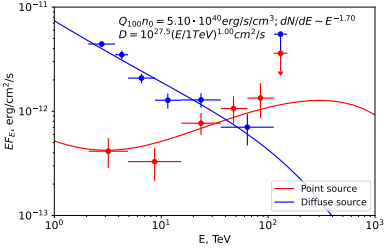
Proper modelling: spectra and energetics

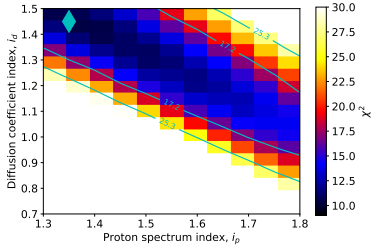




- Formal fit prefers $i_d \sim 1.45$, but Bohm-like diffusion is not excluded
- $D_0 \approx 10^{26.2}$ cm^2/s at 1 TeV, by a factor of 100 faster then Bohm for $B_0 = 10\,\mu$G

Proper modelling: spectra and energetics





- For Bohm-like diffusion $Q_{100}n_0 \sim 5 \cdot 10^{40}$ erg/s/cm^3. Comparable to Crab energetics for $n_0 \sim 100$ cm^{-3}

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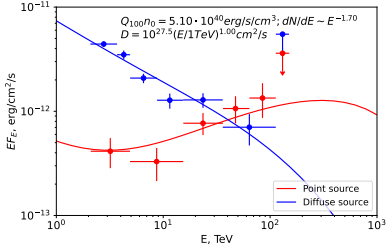
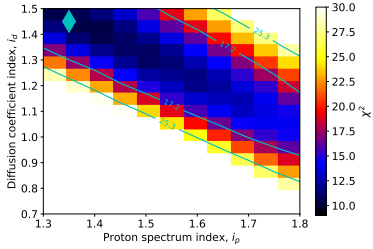
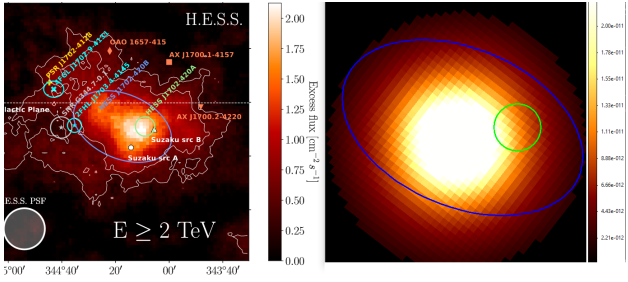




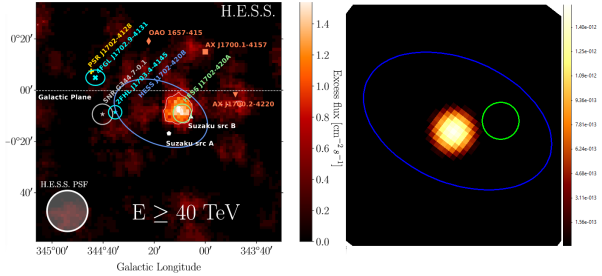
- For Bohm-like diffusion $Q_{100}n_0 \sim 5 \cdot 10^{40}$ erg/s/cm^3. Comparable to Crab energetics for $n_0 \sim 100$ cm^{-3}
- Energetics could be further decreased, if the accelerator/cloud are located closer and/or are denser. $Q_{100} \sim D$. Abdalla et al., 2021: nearby dense (200-700 cm^{-3}) clouds at ~ 0.3 kpc...

Proper modelling: sky maps



- The model well describes the energy-dependent changes of HESS J1702-420 morphology

Proper modelling: sky maps



- The data demonstrates offset of the point-like source from the the center of diffuse source.

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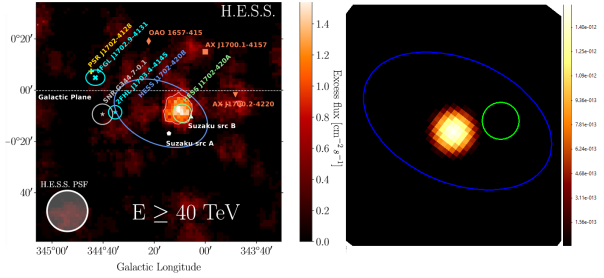
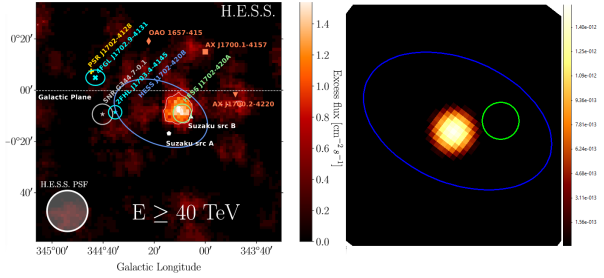


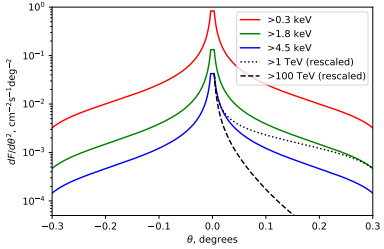
- The data demonstrates offset of the point-like source from the the center of diffuse source.
- Misaligned proton accelerator? Space-dependent diffusion coefficient?

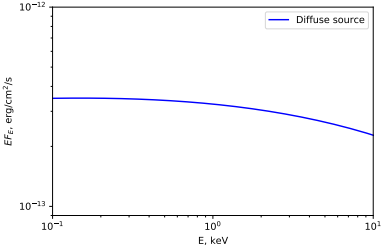
Proper modelling: sky maps



- Strongly misaligned accelerator (PeVatron) could illuminate nearby cloud which will show soft spectrum. The hard-spectrum accelerator remains invisible or visible just at highest energies.

Proper modelling: secondaries emission





- Secondary electrons: synchrotron emission in the keV band?

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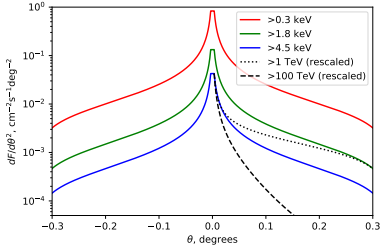

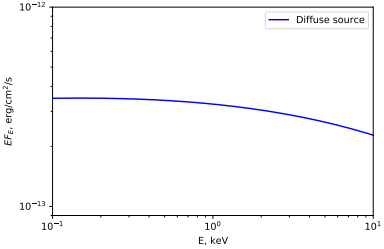

- Secondary electrons: synchrotron emission in the keV band?
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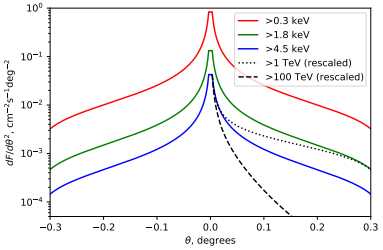
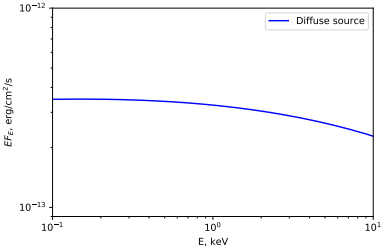
Proper modelling: secondaries emission





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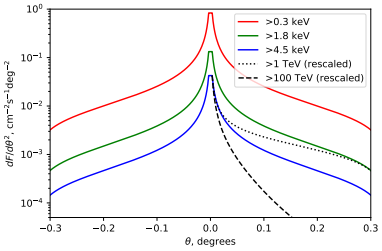

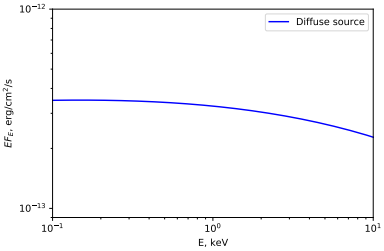

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- Hard-spectrum ($\Gamma \sim -2$), diffuse ($\sim 0.05^\circ$-radius) X-ray source, detectable by XMM-Newton/eROSITA
- Non-detection – non-continuous injection of protons ($t < t_{sync} \sim 1000$ yr)

Conclusions

- Energy-dependent diffusion allows to explain energy-dependent morphology of VHE sources.
- HESS J1702-420 can be modelled as a proton accelerator embedded into HI cloud + energy-dependent diffusion + π^0-decay emission
- The data is well described with Bohm-like diffusion (~ 100 times faster for $B = 10\,\mu$G). The required energetics of the accelerator is comparable to Crab for the medium density $n_0 \sim 100\,cm^{-3}$
- The energetics can be decreased if HI cloud is located at $D < 3.5$ kpc. Several such clouds were reported in Abdalla et al., 2021
- Strongly misaligned accelerator (PeVatron) could illuminate nearby cloud which will show soft spectrum. The hard-spectrum accelerator remains invisible or visible just at highest energies.
- Secondaries can produce detectable X-ray emission. Non-detection would indicate non-continious injection of protons at $t < t_{sync} \sim 1000$ yr

¡Gracias por las atenciones!