Probing the Intergalactic Magnetic Fields by means of high energy pair halos around extreme blazars

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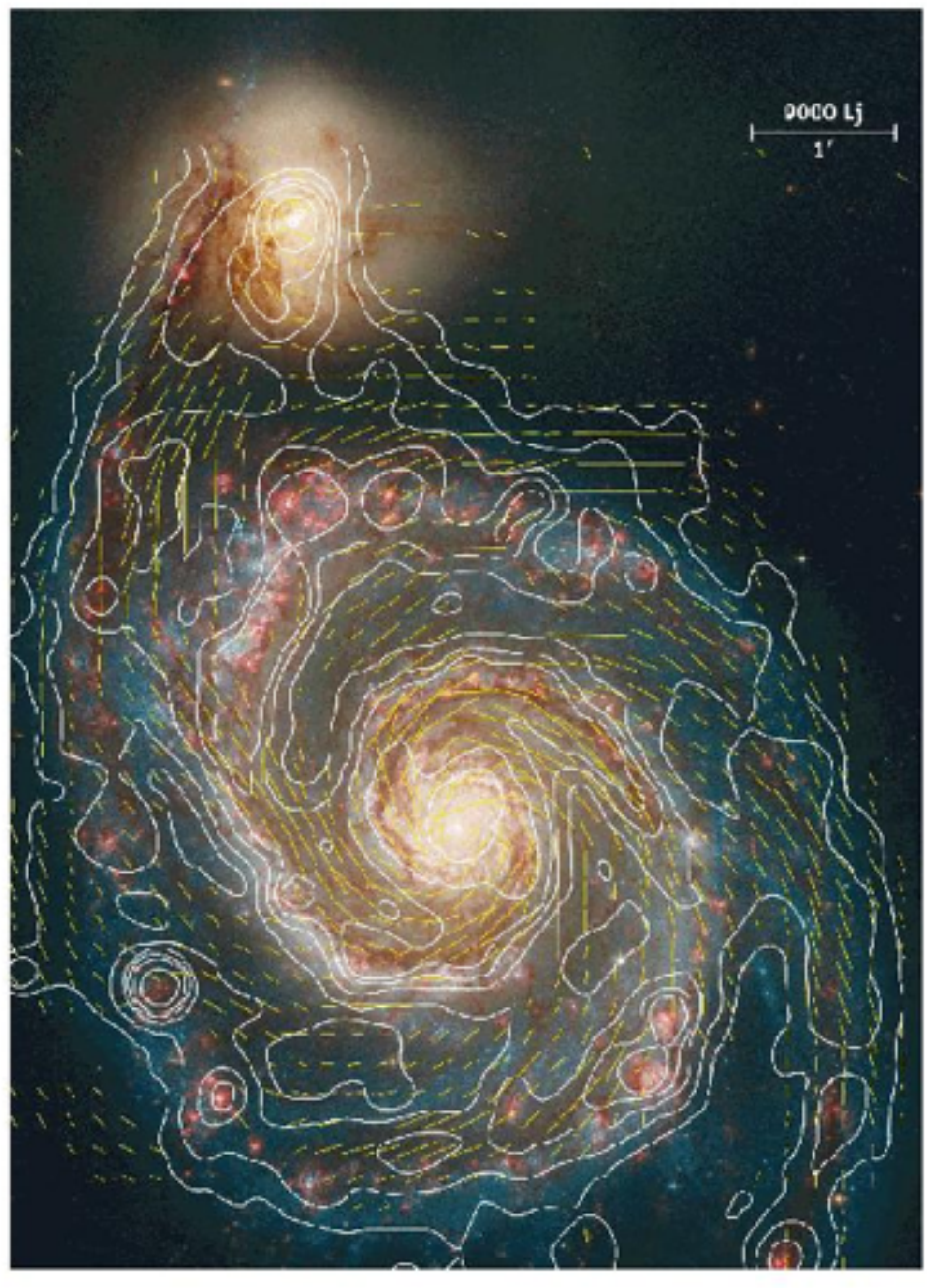
Summary

- Magnetic fields in galaxies and how to measure them
- Constraints of Inter Galactic Magnetic Fields (IGMF) with gamma ray observations of Active Galactic Nuclei (AGN)
- Search for extended gamma ray emission around TeV AGN with MAGIC telescopes
- Upper limits on halo emission
- Conclusions

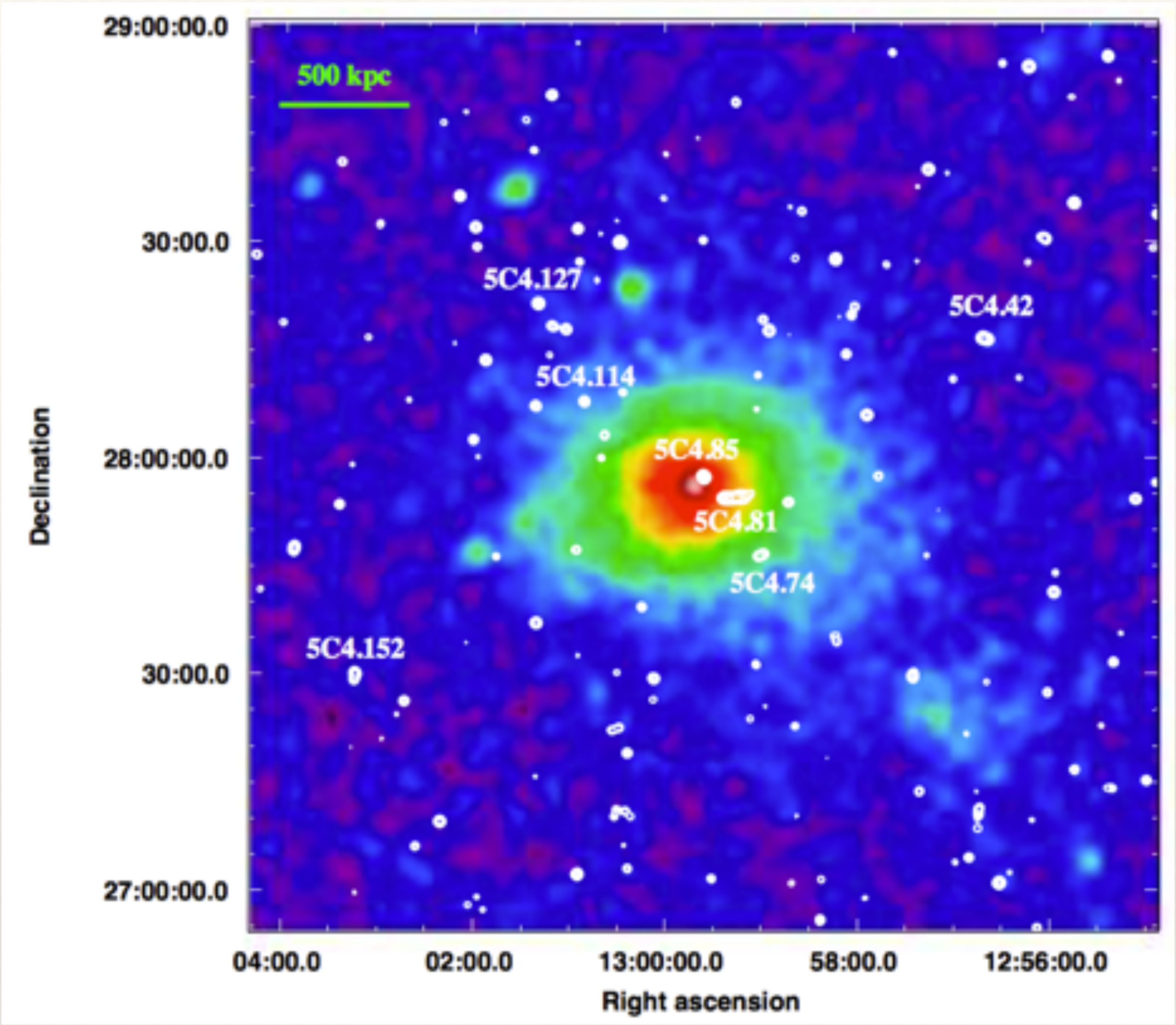
Magnetic fields in galaxies and how to measure them

Magnetic fields in galaxies

2.8 kpc



M51



Coma cluster

500 kpc

B≃15 μG

B≃2 μG

What is the origin of these magnetic fields?

Magnetic fields in galaxies and clusters of galaxies

- galactic dynamo:

$$\frac{\partial \overline{\mathbf{B}}}{\partial t} = \nabla \times \left(\mathbf{U} \times \overline{\mathbf{B}}\right) + \nabla \times \left(\langle \delta \mathbf{V} \times \delta \mathbf{B} \rangle\right)$$

$$B_0 \simeq 10^{-14}\ G$$

- adiabatic compression:

$$B_{prim,0} = B_{gal} \left(\frac{\rho_{cosmic}}{\rho_{gal}}\right)^{2/3}$$

$$B_{prim,0} \simeq 10^{-10}\ G$$

- Both hypothesizes assume a pre-existing magnetic field!

On the nature of the seed fields

- The nature of the seed fields is largely unknown. From theoretical point of view two main hypothesis on their origin:
  - *the astrophysical origin*
  - *the cosmological origin*

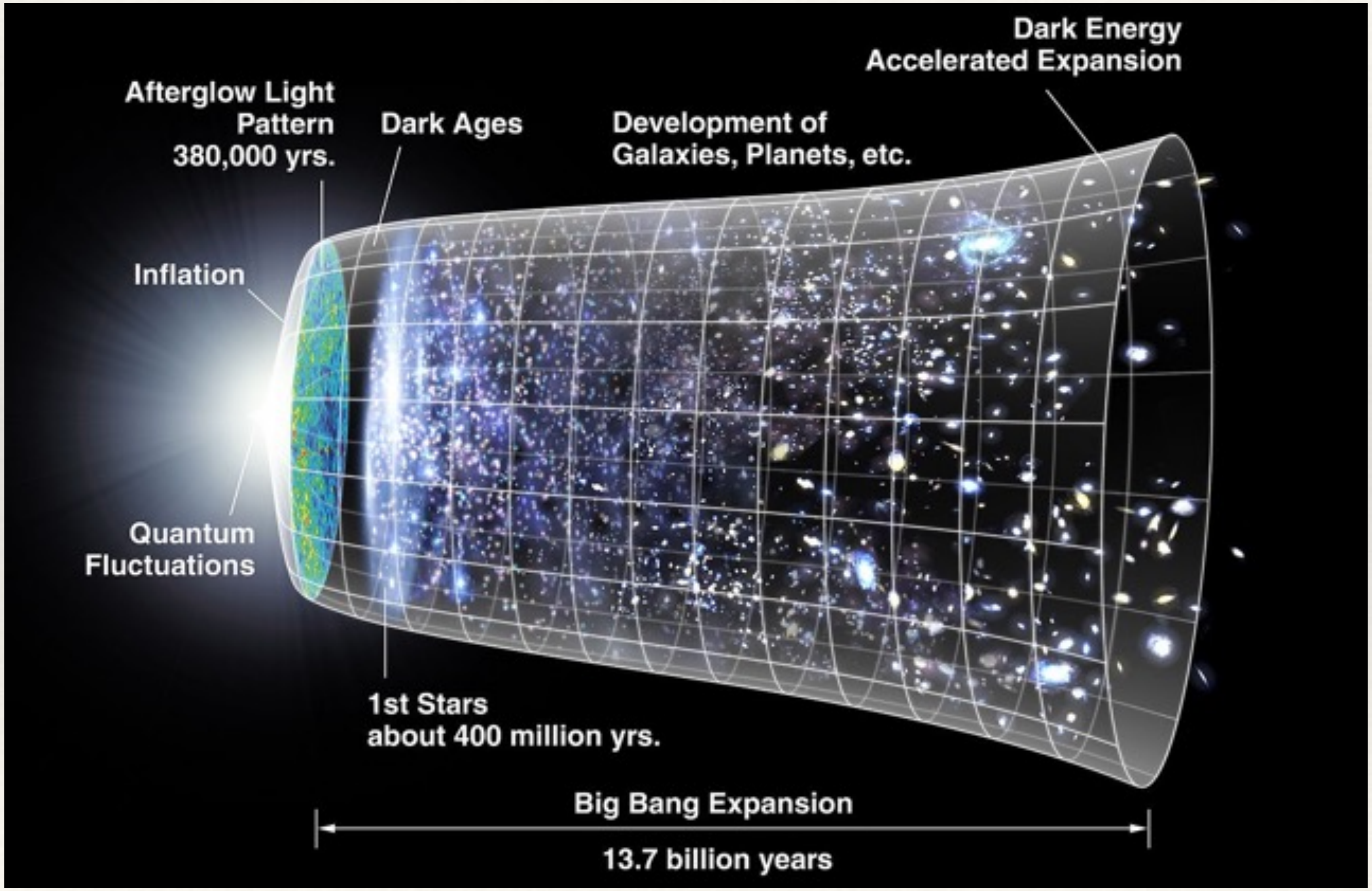
Observationally we need the measurements of the magnetic fields in the Intergalactic medium

The Astrophysical origin

- Basic idea: difference in mobility between electrons and protons.
    - seeds from Radiation-Era Vorticity
    - Biermann battery effect
    - Magnetic field produced by the stars
    - Active Galactic Nuclei

The Cosmological Origin

- Four main transition phases:



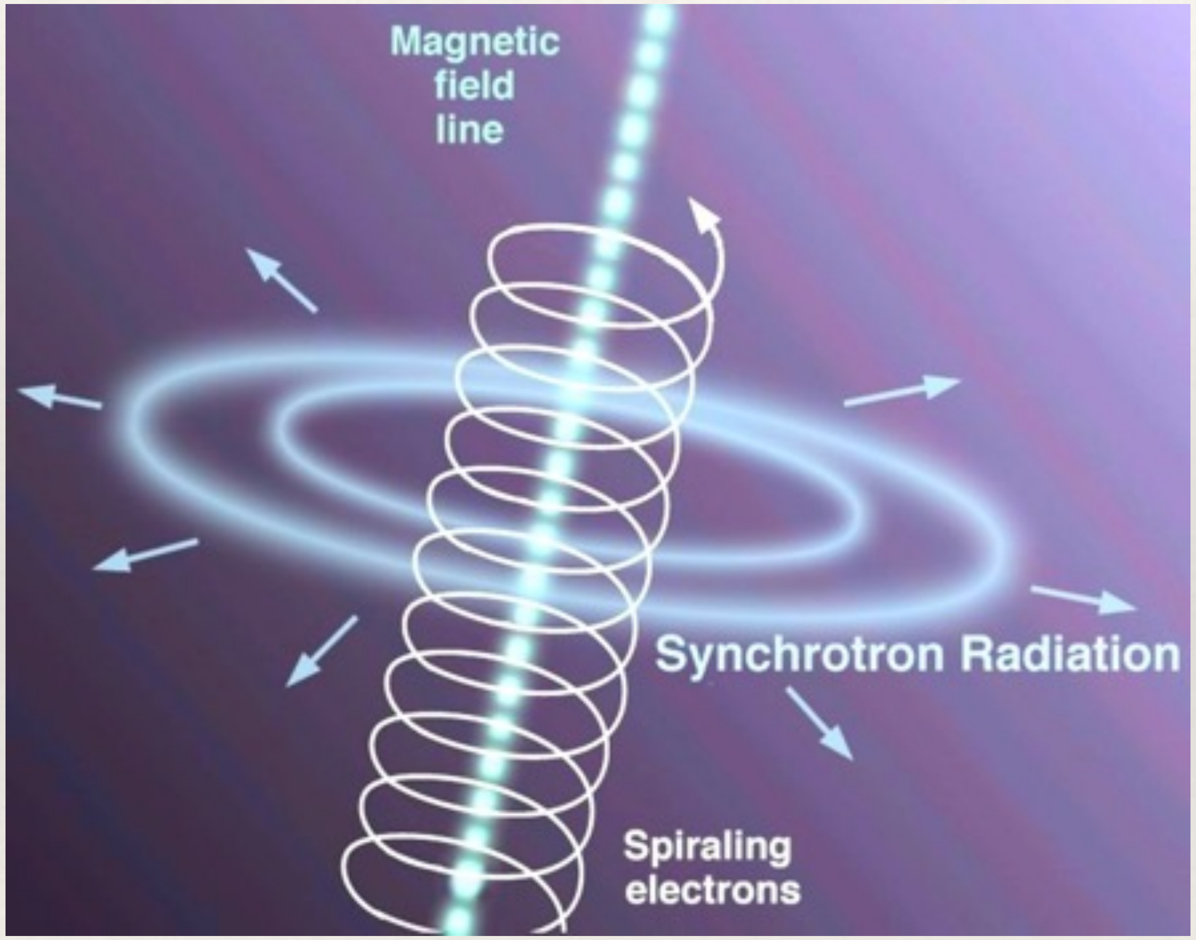
1. inflation
2. electroweak
3. QCD
4. recombination

The tools to measure magnetic fields

- Standard tools to measure magnetic fields:
  - Synchrotron emission
  - Faraday rotation
  - Zeeman splitting

Synchrotron emission

- It is the emission of relativistic electrons gyrating in a magnetic field



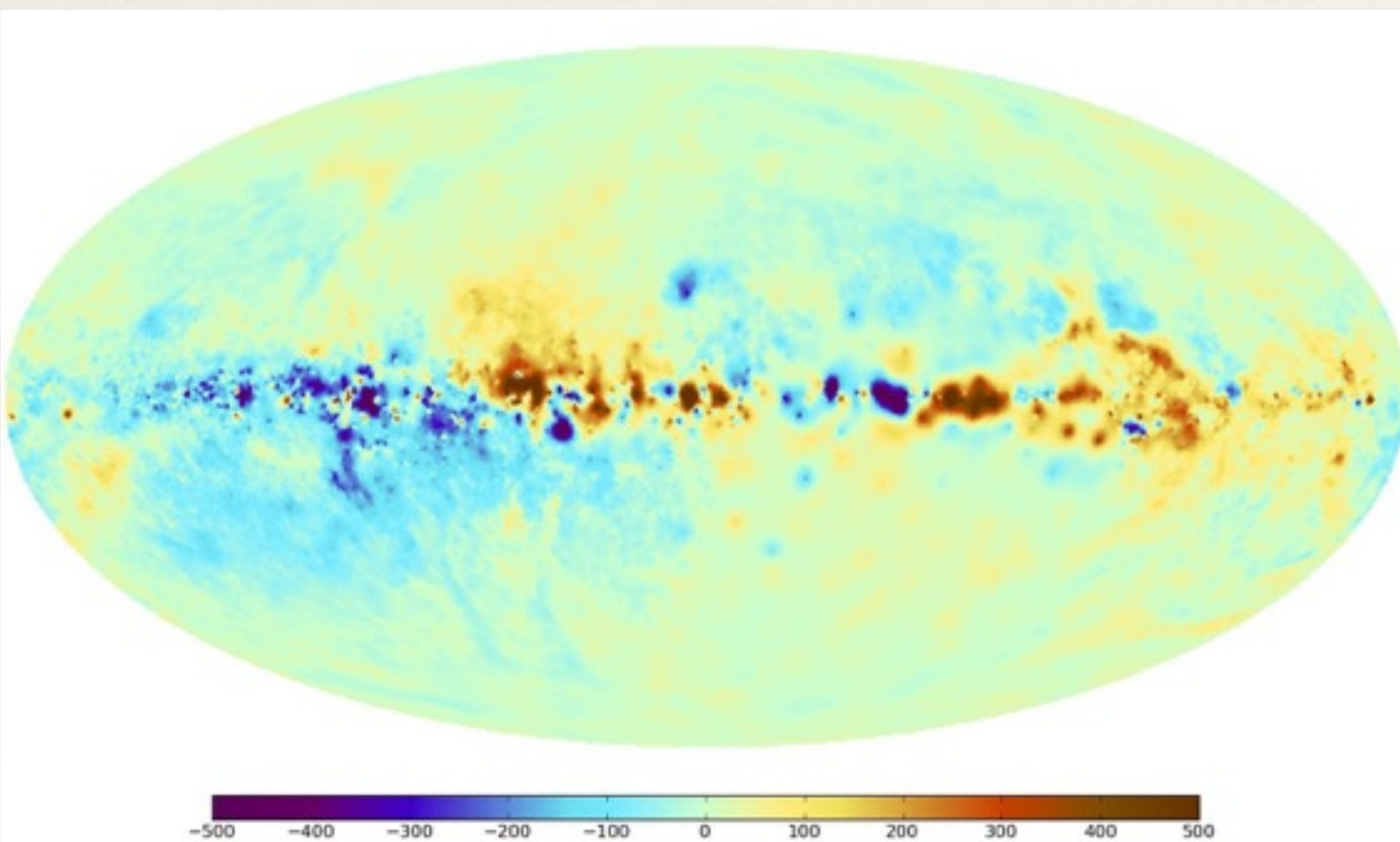
$$j_\nu \propto n_e \, \nu^{(1-\gamma)/2} B_\perp^{(1+\gamma)/2}$$

- Assuming equipartition between energy particle and magnetic field we can estimate B

- The degree of polarization is an indicator of the field's directionality

Faraday Rotation

- When polarized emission propagates in a region with ionized gas and magnetic field, it undergoes Faraday rotation



Oppermann et al. 2015

$$\phi_{FR} = \frac{e^3 \lambda^2}{2\pi m_e^2 c^4} \int_0^{l_s} n_e(l)\, B_\parallel dl$$

Assuming an electron distribution we can constrain B

Zeeman Splitting

- The electronic energy levels of an atom are independent of its angular momentum vector. The presence of a magnetic field removes this degeneracy

$$\frac{\Delta\nu}{\nu} = 1.4g\left(\frac{B}{\mu G}\right)\left(\frac{Hz}{\nu}\right)$$

$$\frac{\Delta\nu}{\nu} = 10^{-9}g\left(\frac{B}{\mu G}\right)$$

21 cm line for neutral hydrogen

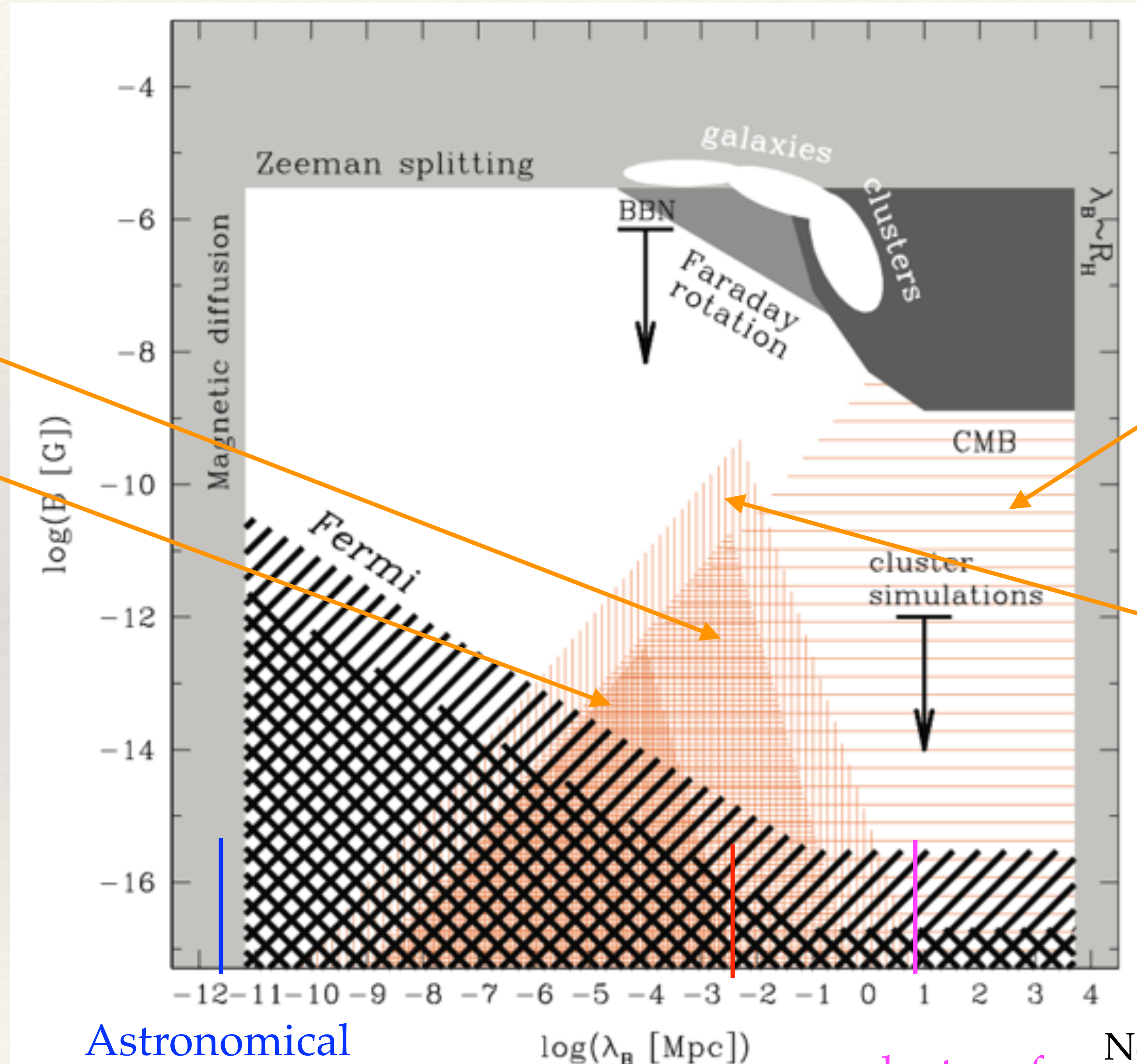
$$\frac{\Delta\nu}{\nu} = 6\times10^{-7}\left(\frac{T}{100K}\right)^{1/2}$$

Doppler broadening

Extremely difficult to observe

The Inter Galactic Magnetic Field

- The IGMF is characterized by the field strength B and the correlation length λ_B



QCD

electroweak

inflation

recombination

B (intensity)

λ_B (correlation length)

Astronomical Unit

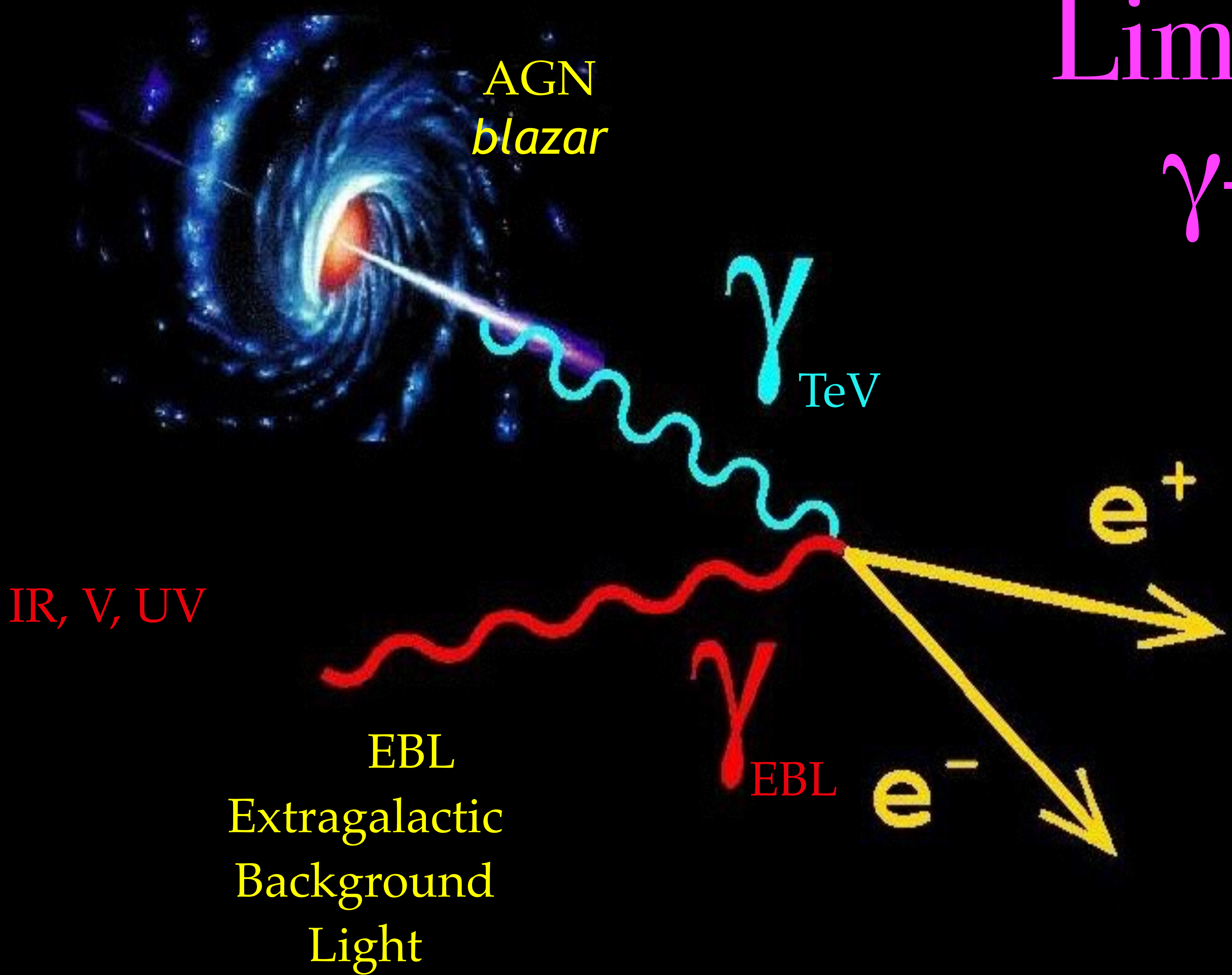
galaxies

cluster of galaxies

Neronov & Vovk, 2010

Constraints of IGMF with γ-ray observations of AGN

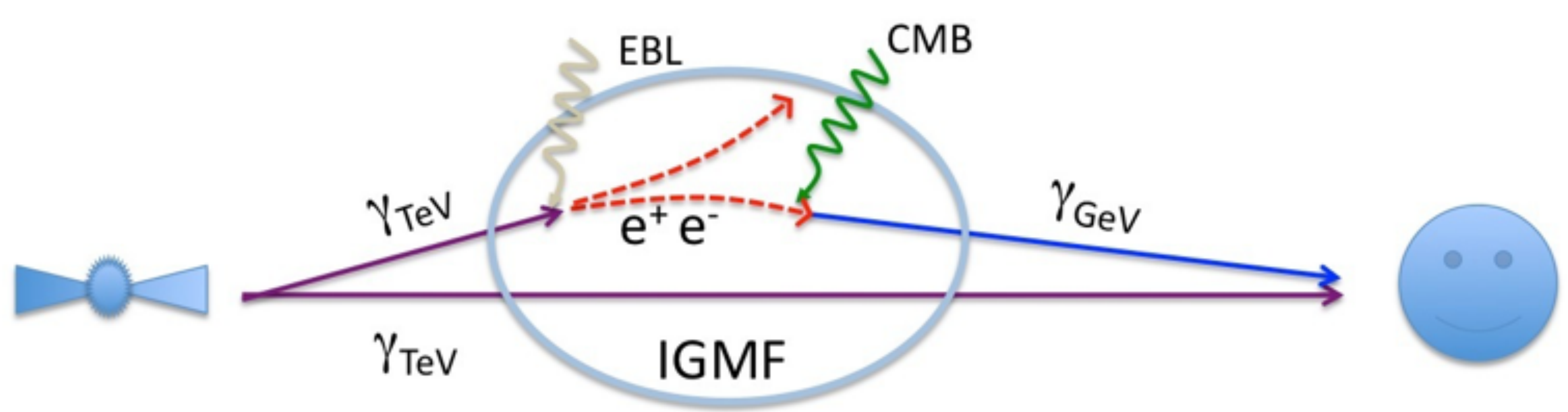
Limits on IGMF with γ-ray telescopes



Limits on IGMF with γ-ray telescopes

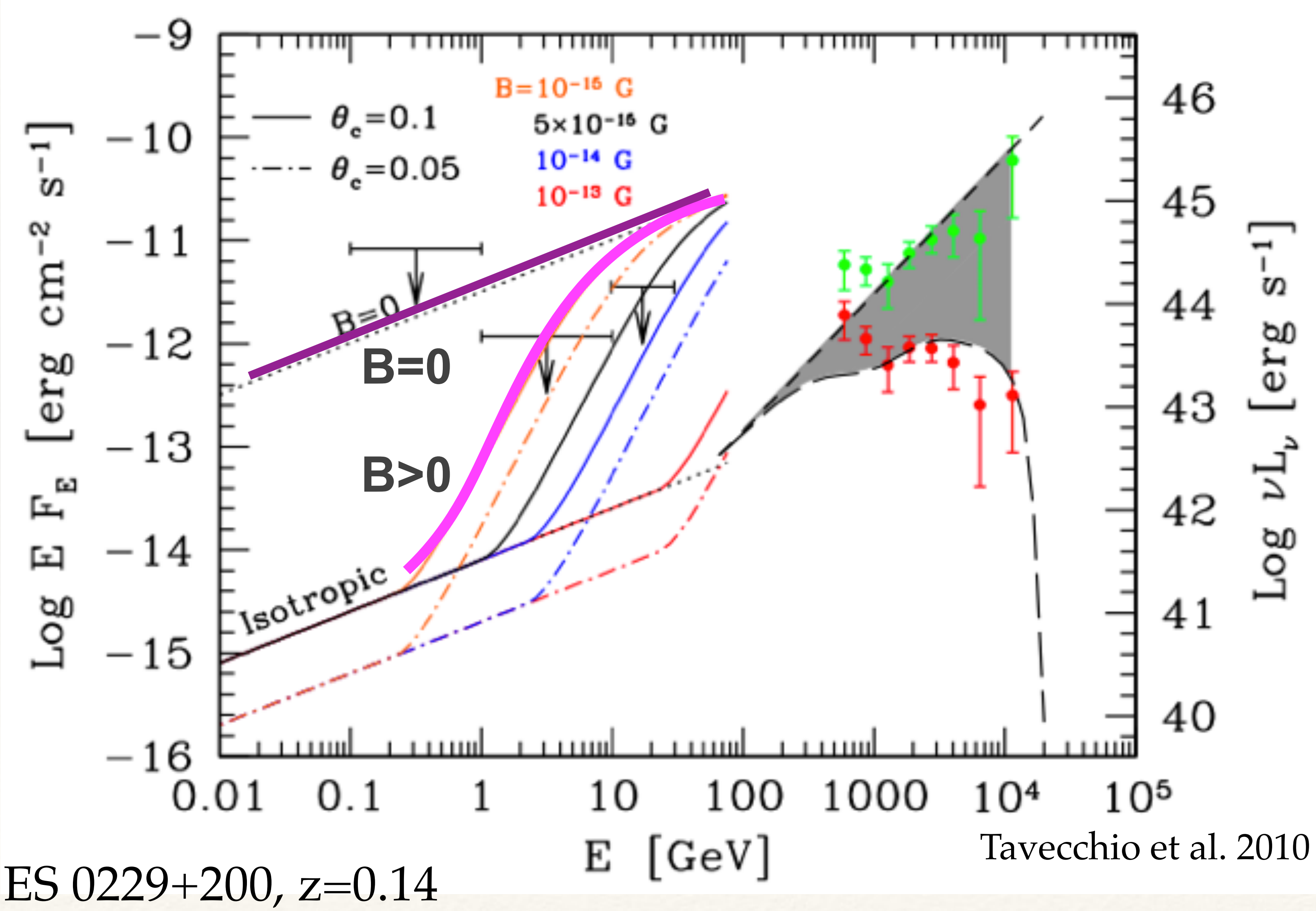
- Physical process: reprocessing of TeV photons in the GeV band
- Measurable effects:
  - spectral features
  - extended emission

$$E_\gamma \simeq 70 \left[\frac{E'_{\gamma 0}}{10\ TeV} \right]^2 GeV$$



Spectral features

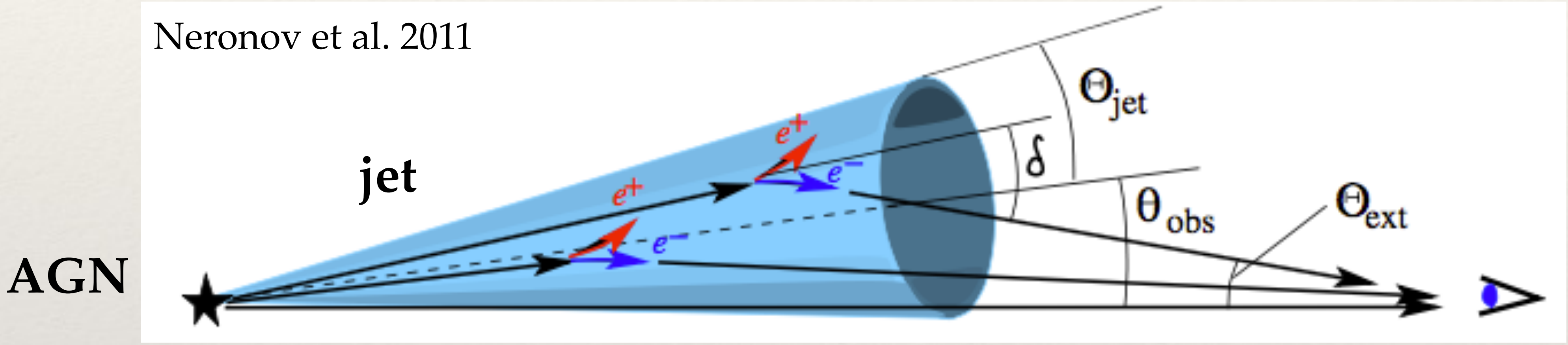
- Measuring the amount of absorbed flux of a TeV blazar we can predict the the amount of cascade emission. Its suppression depends on the IGMF strength



1ES 0229+200, z=0.14

Extended emission

- Observable effect: extended emission around the point source. The angular extension grows with increasing IGMF.



- Two regimes:
  - $\lambda_B \gg D_e$

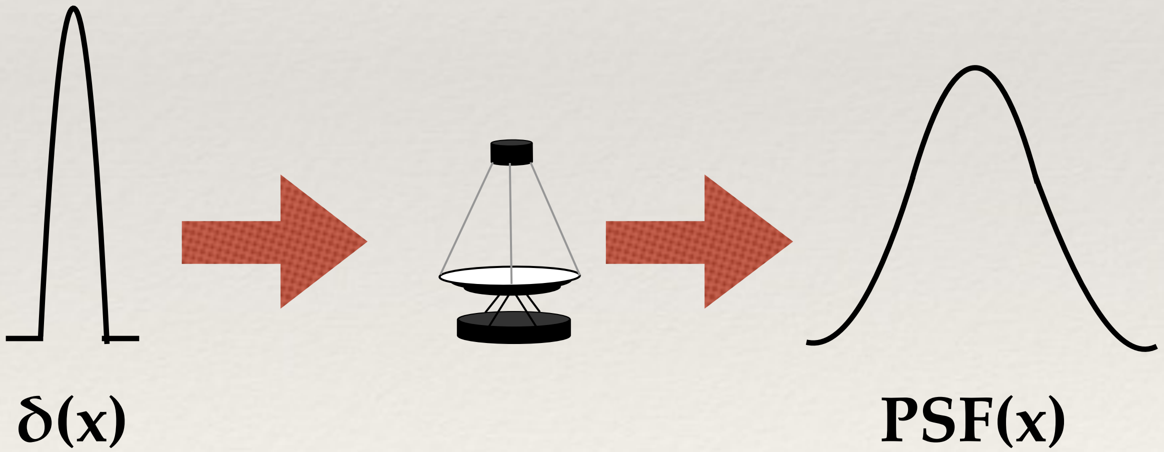
$$\Theta_{ext} \simeq 0.5° (1+z)^{-2} \left[\frac{\tau}{10}\right]^{-1} \left[\frac{E_\gamma}{0.1\ TeV}\right]^{-1} \left[\frac{B_0}{10^{-14}\ G}\right]$$

  - $\lambda_B \ll D_e$

$$\Theta_{ext} \simeq 0.07° (1+z)^{-1/2} \left[\frac{\tau}{10}\right]^{-1} \left[\frac{E_\gamma}{0.1\ TeV}\right]^{-3/4} \left[\frac{B_0}{10^{-14}\ G}\right] \left[\frac{\lambda_{B0}}{1\ kpc}\right]^{1/2}$$

Our project to search for extended γ-ray emission

- Through the study of the emission profiles of several TeV AGN we looked for halo emission around 100 GeV.
- We used the VHE data of MAGIC telescopes to derive an analytical description of the Point Spread Function (PSF)
- Four steps have been considered:
    - the background
    - model of PSF
    - stability of the PSF
    - comparison of PSF with profiles of AGN



Search for extended γ-ray emission around TeV AGN with MAGIC telescopes

Imaging Air Cherenkov Telescopes

IACT

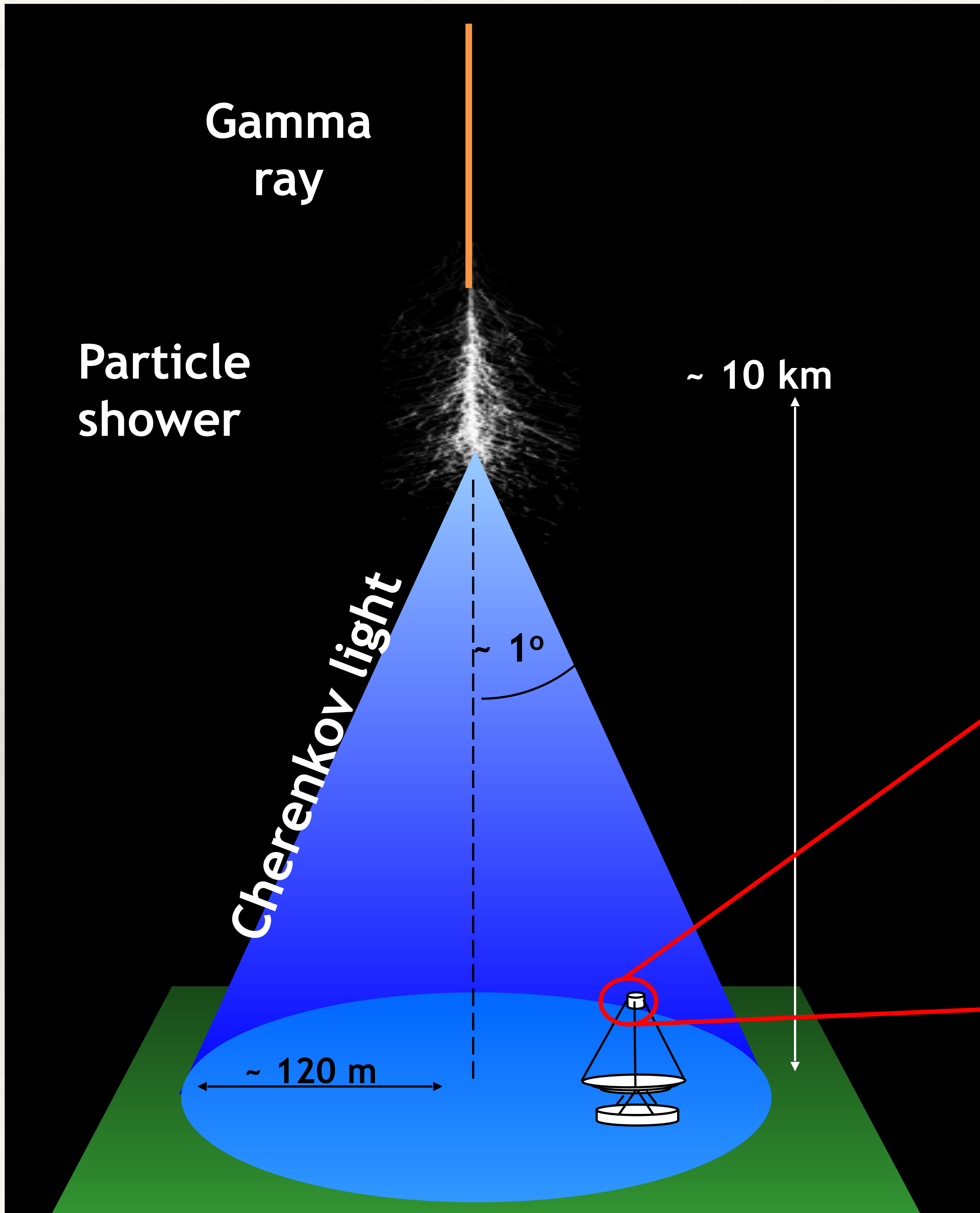
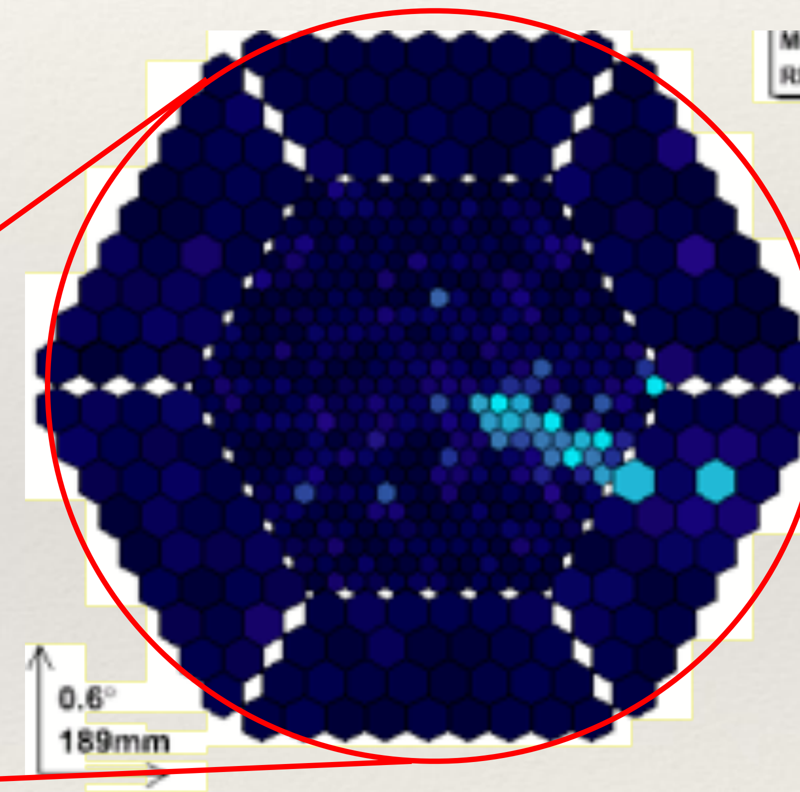


Image of Cherenkov flash on the camera



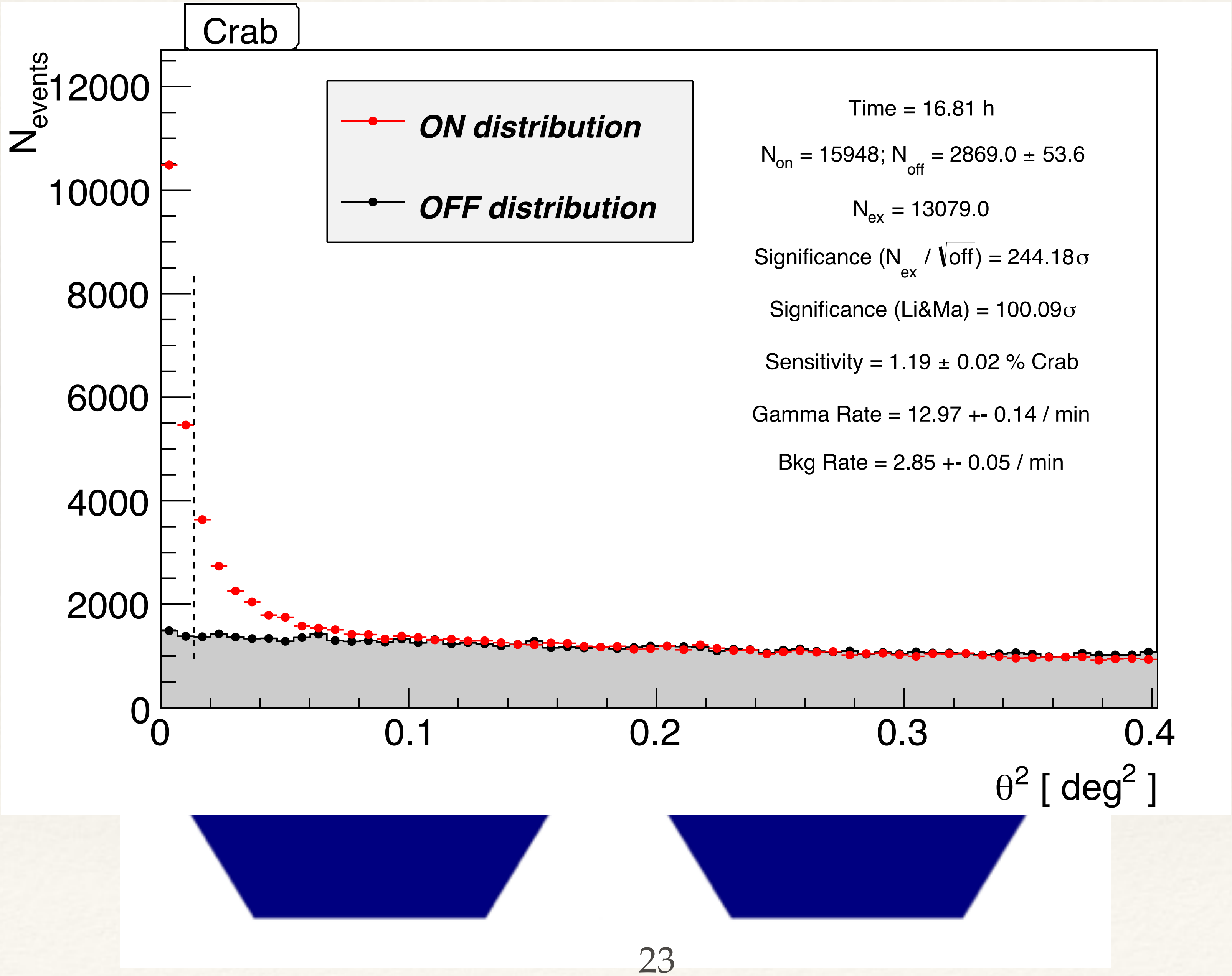
- gamma/hadron discrimination
- reconstruction of the energy and direction of the primary photon

The MAGIC telescopes

- Energy threshold ~50 GeV
- FOV 3.5°
- Energy Resolution ~16% (E>300 GeV)
- *Angular Resolution ~0.06° (E>300 GeV)*
- Sensitivity (5 σ in 50 hours) ~0.8% Crab Nebula flux (> 250 GeV)

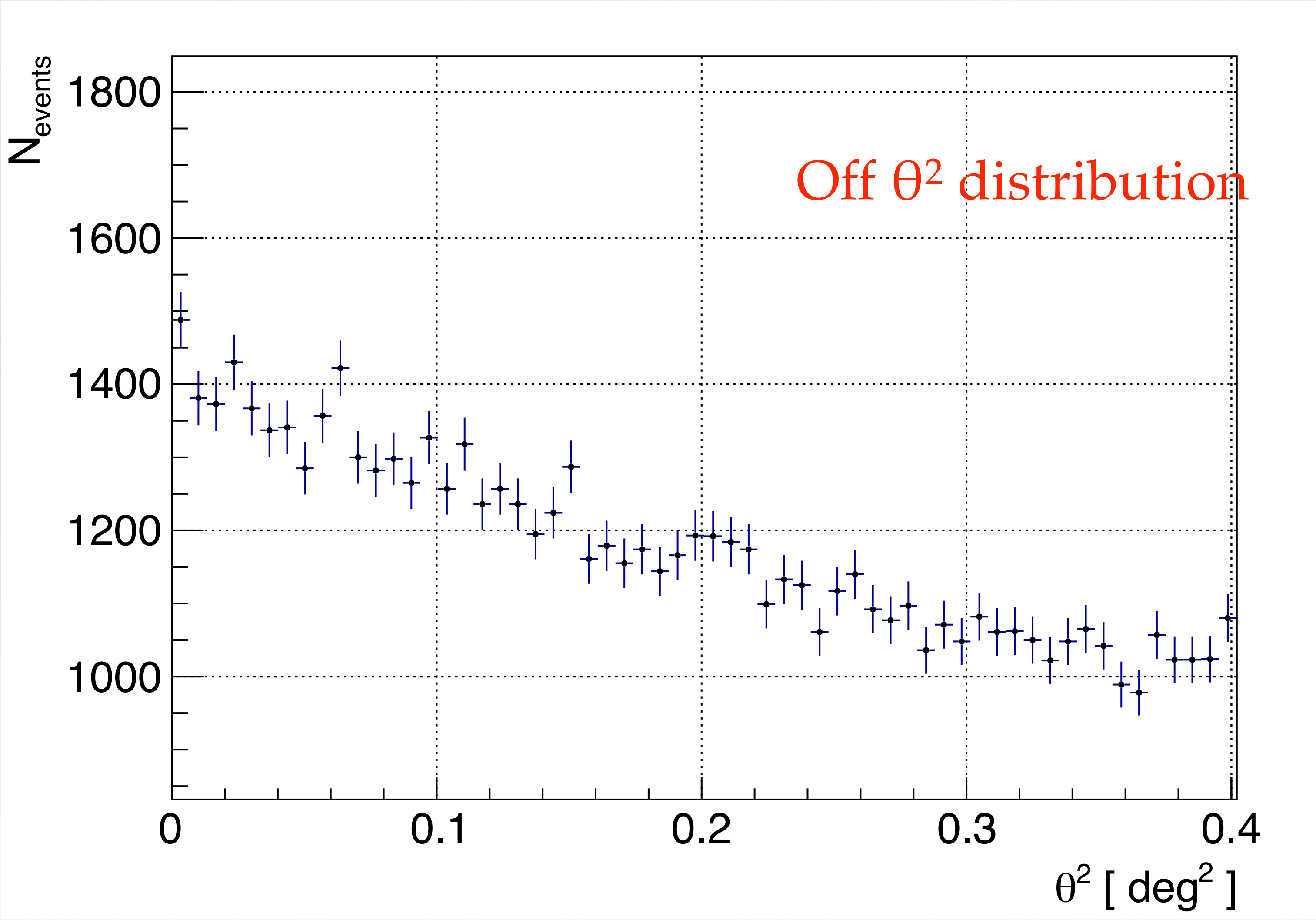
γ-ray direction reconstruction

- θ: angular distance between real and reconstructed position of the source
- Distribution after selection of gamma-like events



Study of MAGIC PSF

- For the proper characterization of the PSF the acceptance on the camera must be evaluated. The key point is the **off-axis response.**



the shape of the background is not flat, correction for the camera acceptance

Fit of MAGIC PSF

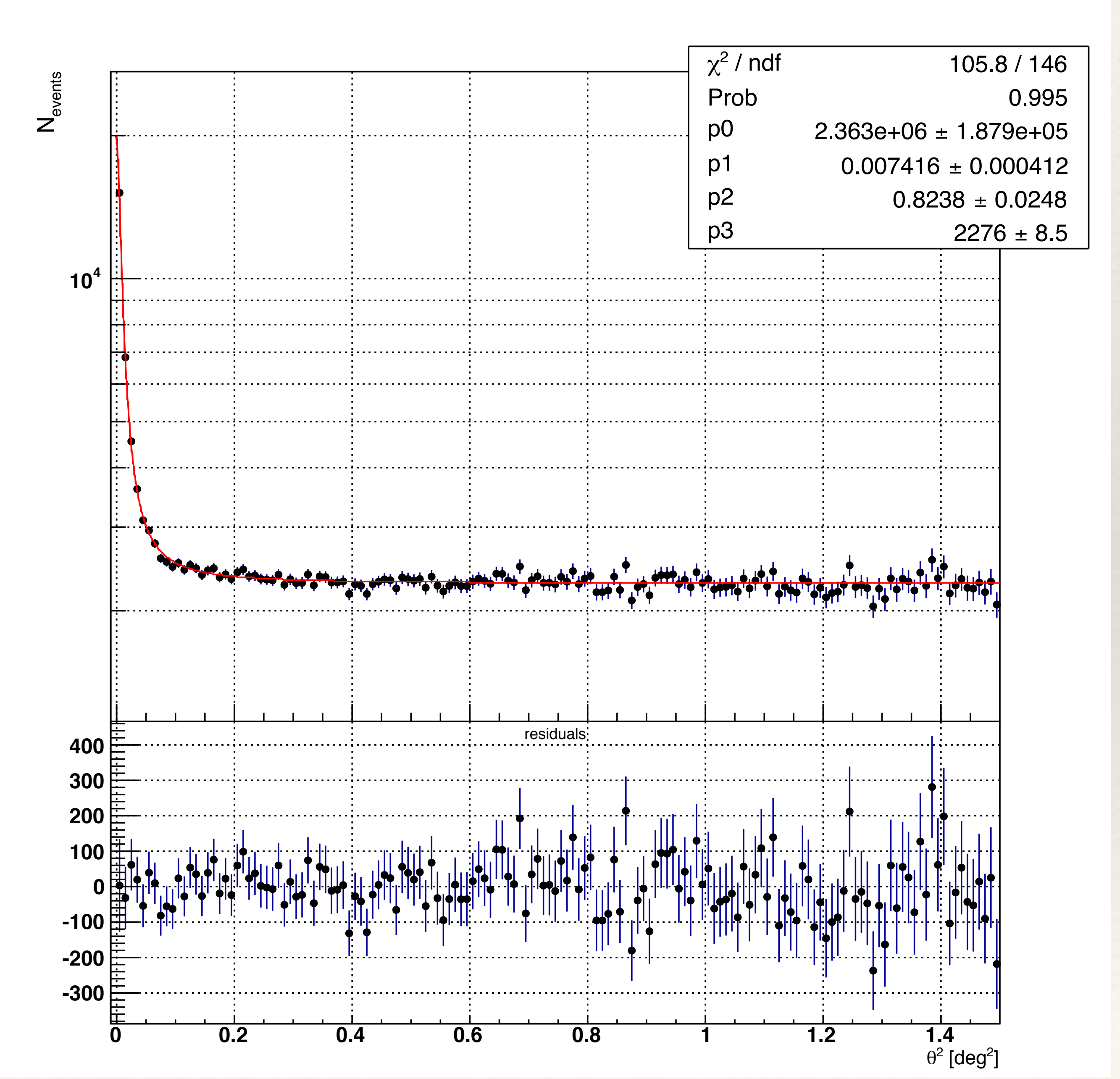
- We used the King function to fit the MAGIC PSF

$$f(\theta^2) = p0 * p1 * \left[1 + \left(\frac{\theta^2}{p1}\right)^2\right]^{-p2} + p3$$

King function

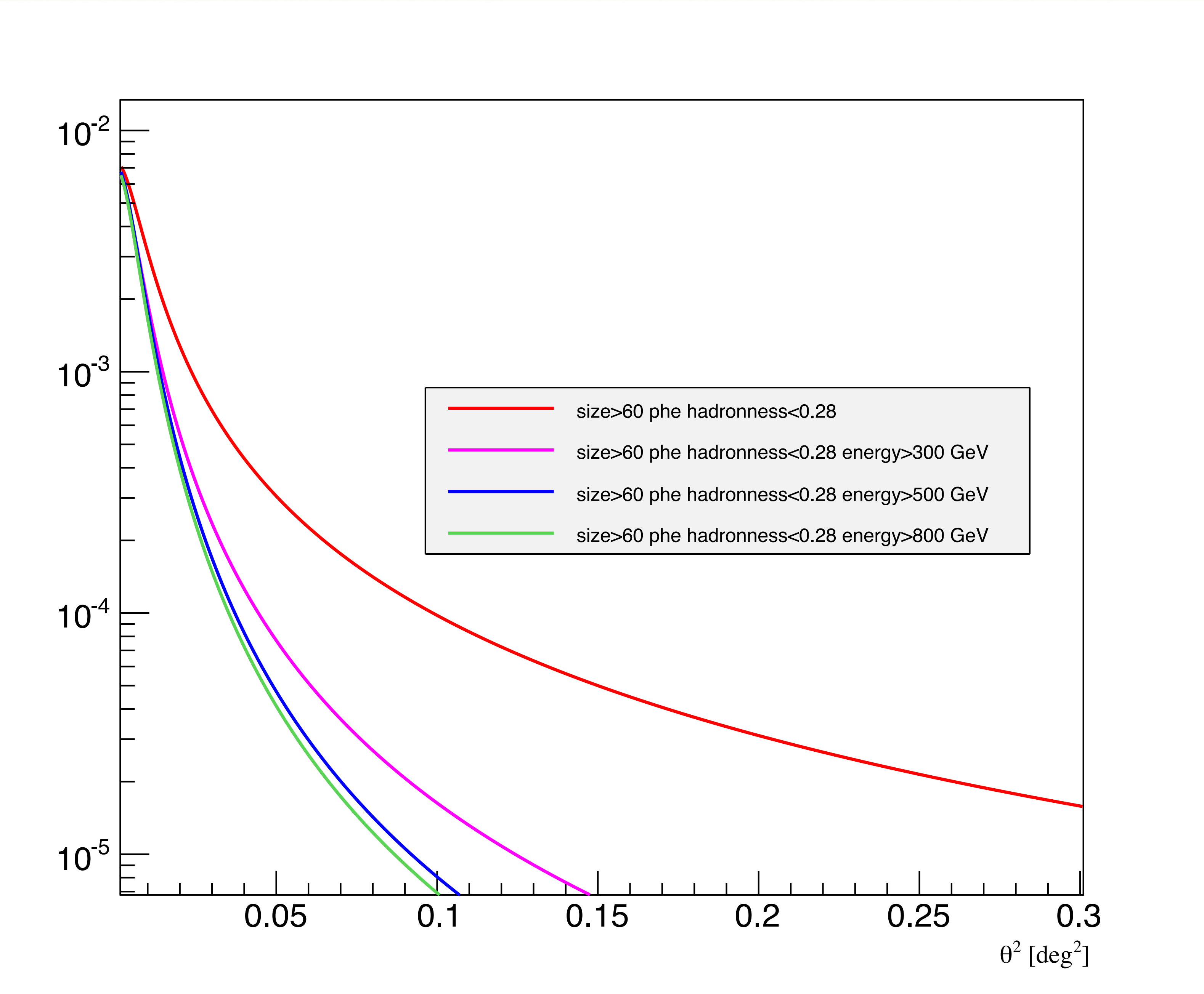
corrected background

This function is able to describe the data also at high values of θ^2



The dependence on energy

- We studied the behavior of the PSF adding an energy cut



Increasing the energy cut the King function becomes narrower

Search for extended γ-ray emission around TeV AGN

- We compared the PSF with the emission profiles of five AGN:
  - Markarian 421 (10 hours, z=0.03)
  - 1ES 1011+496 (11 hours, z=0.212)
  - PKS 1424+240 (28 hours, z≥0.6)
  - RX J1136.5+6737 (33 hours, z=0.13)
  - 1ES 0229+200 (40 hours, z=0.14)

Comparison of the PSF with AGN

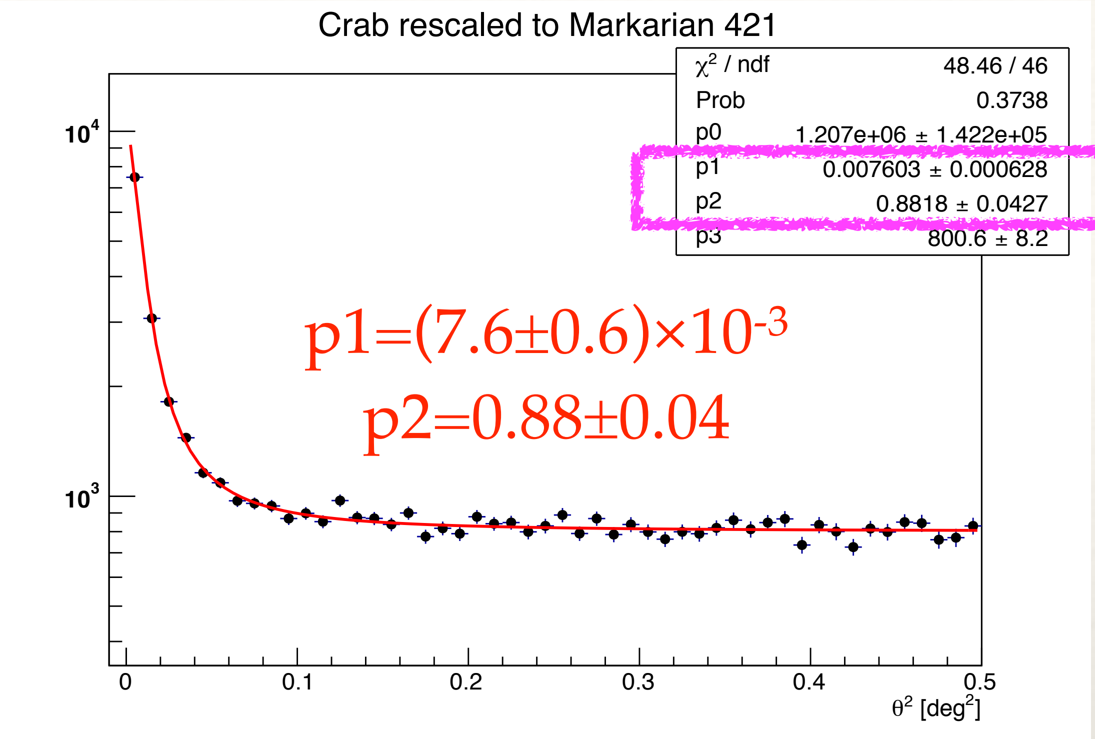
PSF model: $f(\theta^2) = p0 * p1 * \left[1 + \left(\frac{\theta^2}{p1}\right)^2\right]^{-p2} + p3$

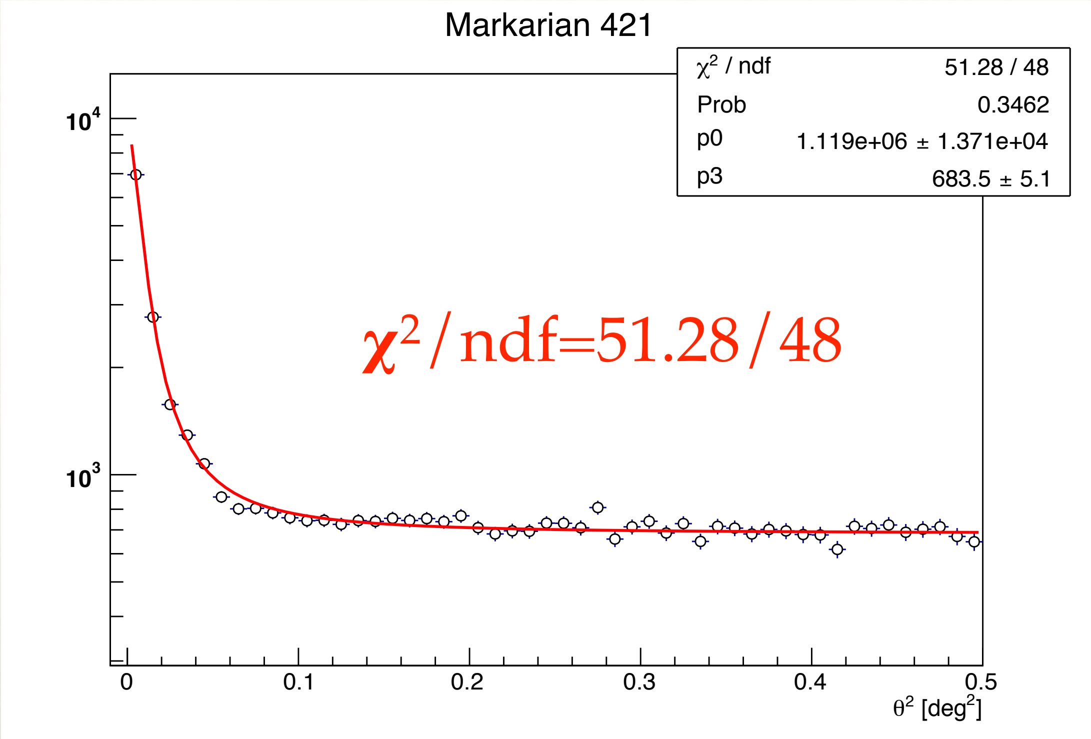
two independent methods

- **Method 1**:
  - Crab: fit with 4 free parameters
  - AGN: p1 and p2 fixed to Crab
- **Method 2**:
  - Crab: fit with 4 free parameters
  - AGN: fit with 4 free parameters
  - confidence contours on p1 and p2 for both Crab and AGN

Markarian 421

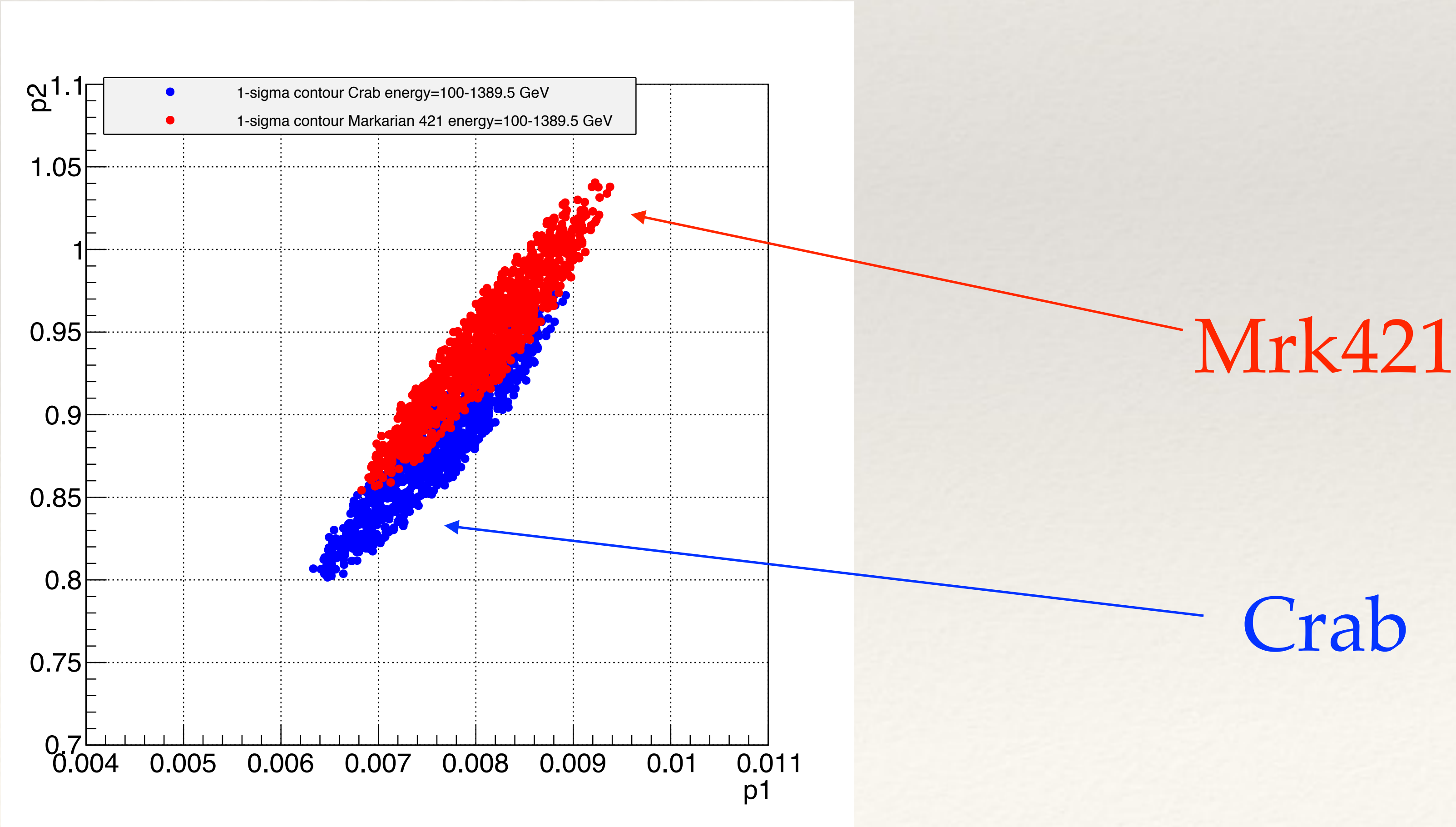
Method 1:





Method 2:

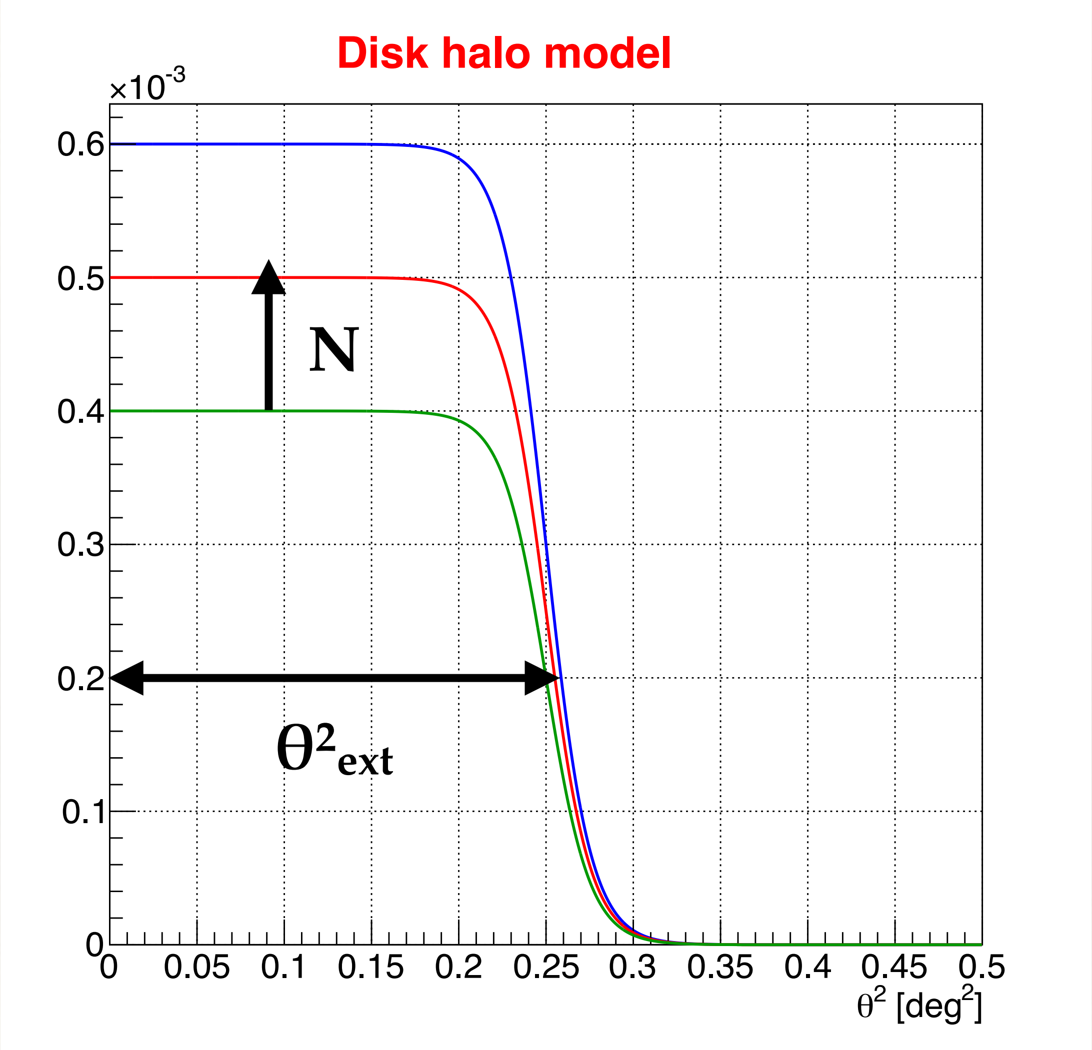
1σ contour plots

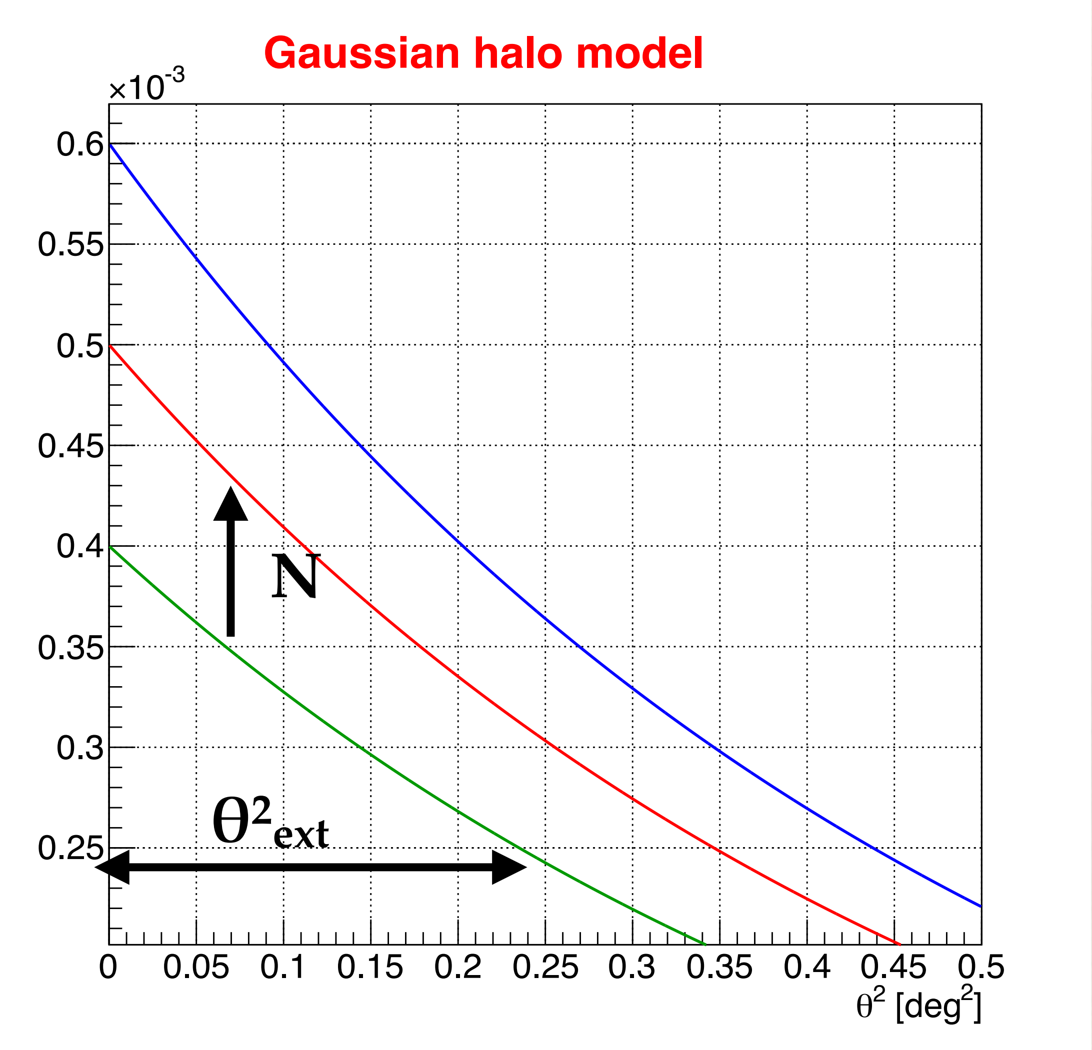


Upper limits on halo emission

Upper limits on halo

- We added a halo model to the PSF to compute upper limits





$$halo_{disk}(N, \theta^2_{ext}; \theta^2) = \frac{N}{1 + e^{k*(\theta^2 - \theta^2_{ext})}}$$

$$halo_{gaus}(N, \theta^2_{ext}; \theta^2) = N\ e^{-\frac{\theta^2}{2\theta^2_{ext}}}$$

Upper limits on halo

- The total model is:

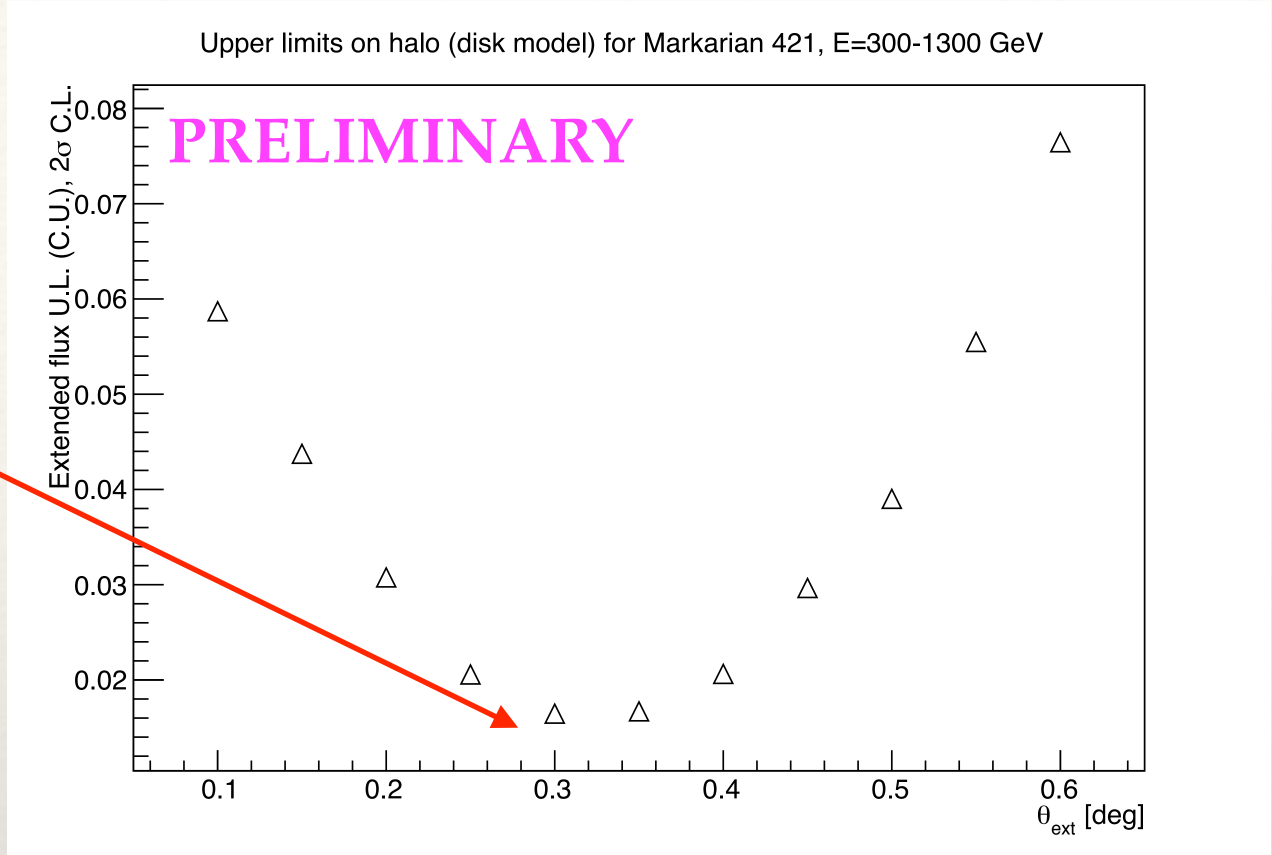
$$f(\theta^2) = halo(N, \theta^2_{ext}; \theta^2) + p0 * p1 * \left[1 + \left(\frac{\theta^2}{p1}\right)^2\right]^{-p2} + p3$$

- For a given halo extension (θ^2_{ext}) we increased the normalization (N) until we got a worsening of the fit correspondent to 2σ level

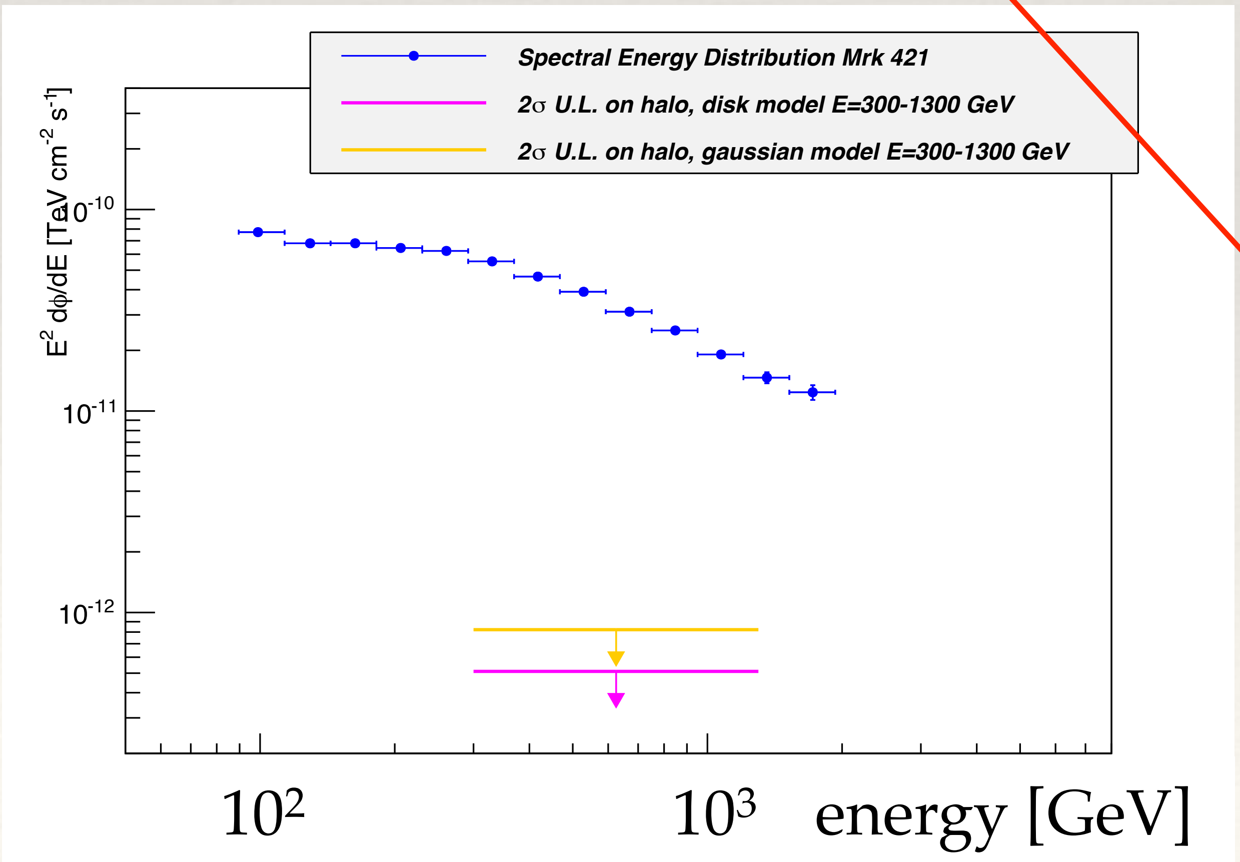
$$U.L.\ (2\sigma source\ units) = \frac{\int_0^\infty halo(N, \theta^2_{ext}; \theta^2) d\theta^2}{\int_0^\infty p0 * p1 * \left[1 + \left(\frac{\theta^2}{p1}\right)^2\right]^{-p2} d\theta^2}$$

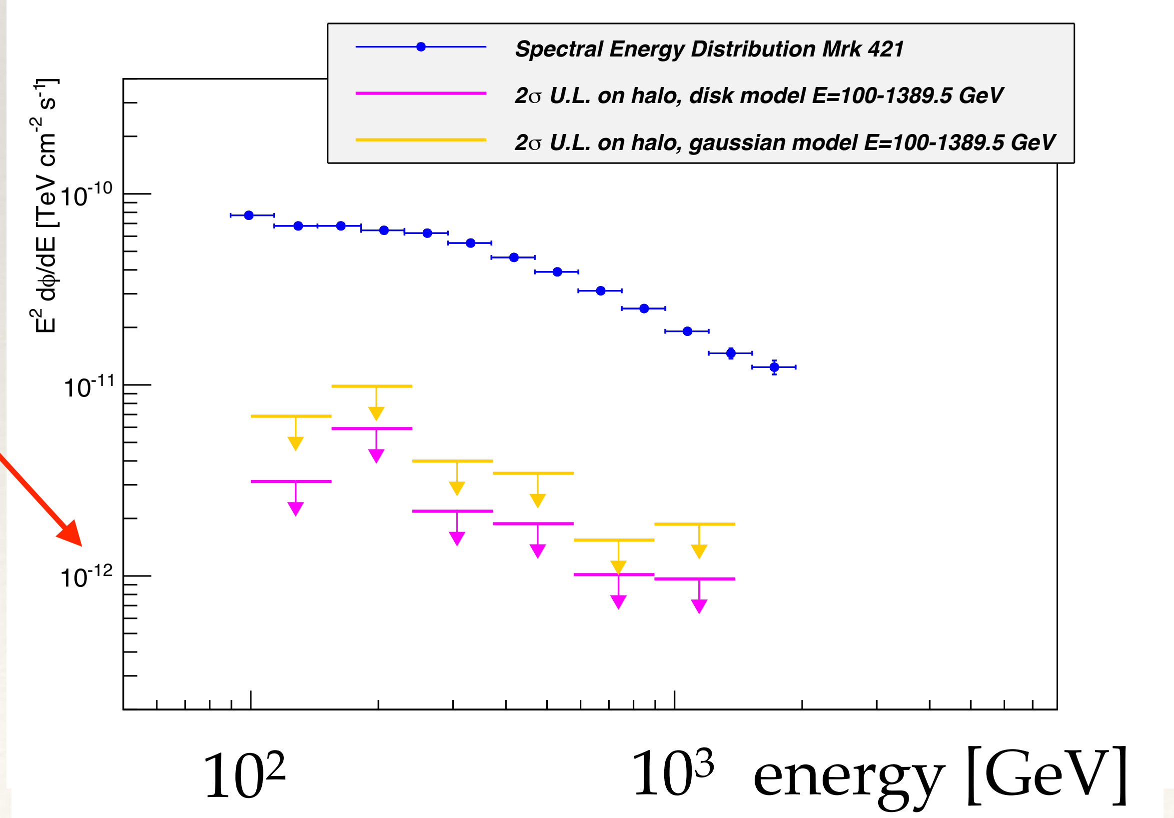
Markarian 421

Most stringent upper limit for θ_{ext}=0.3°. **U.L. (C.U.)=1.6%**



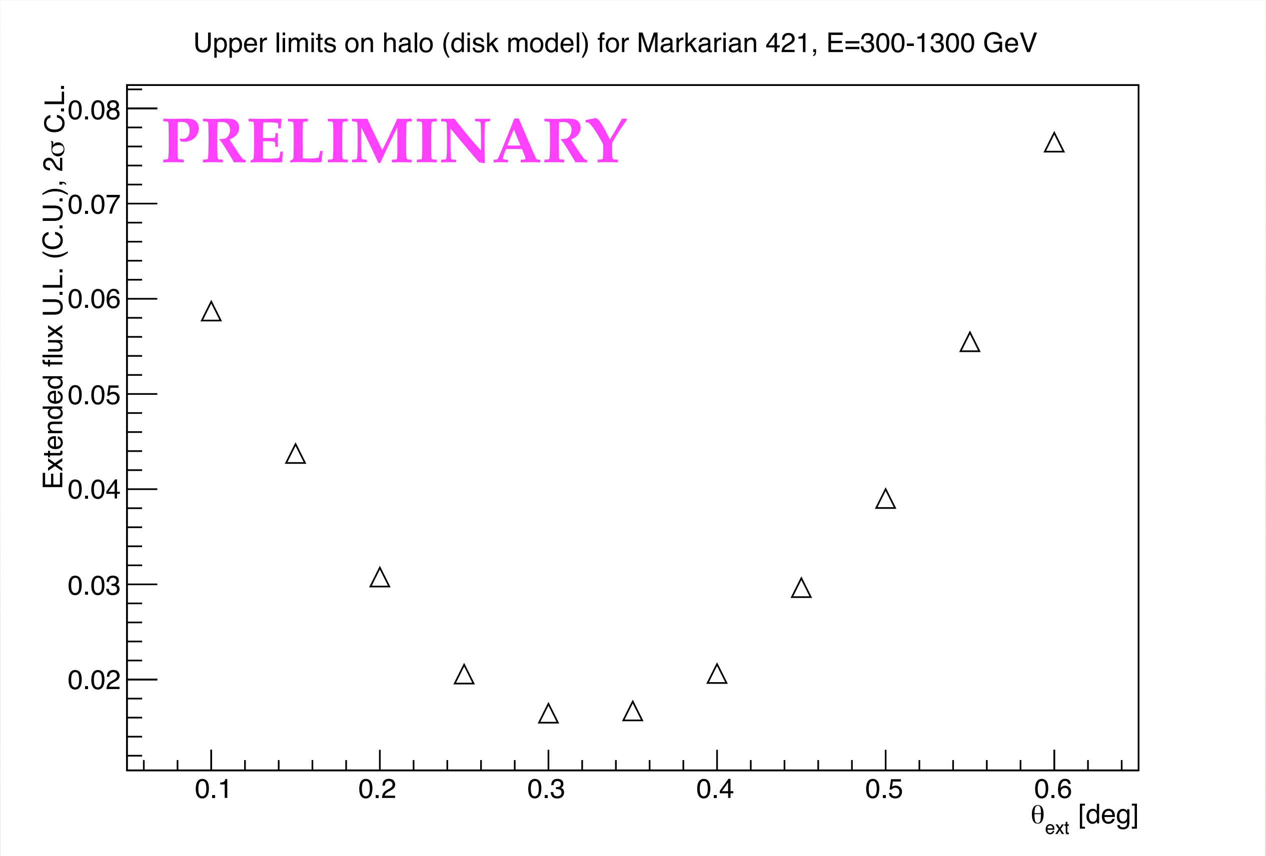
Upper limits performed in 6 energy bins in the range 100-1389.5 GeV



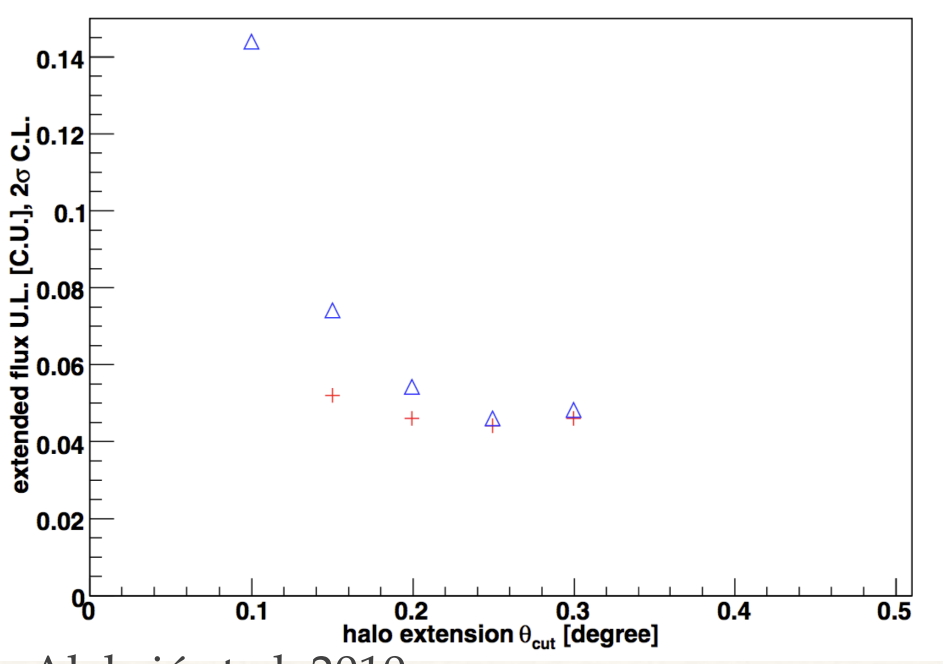


Markarian 421

- Our procedure provided an upper limit which is more than 3 times better than previous measurement



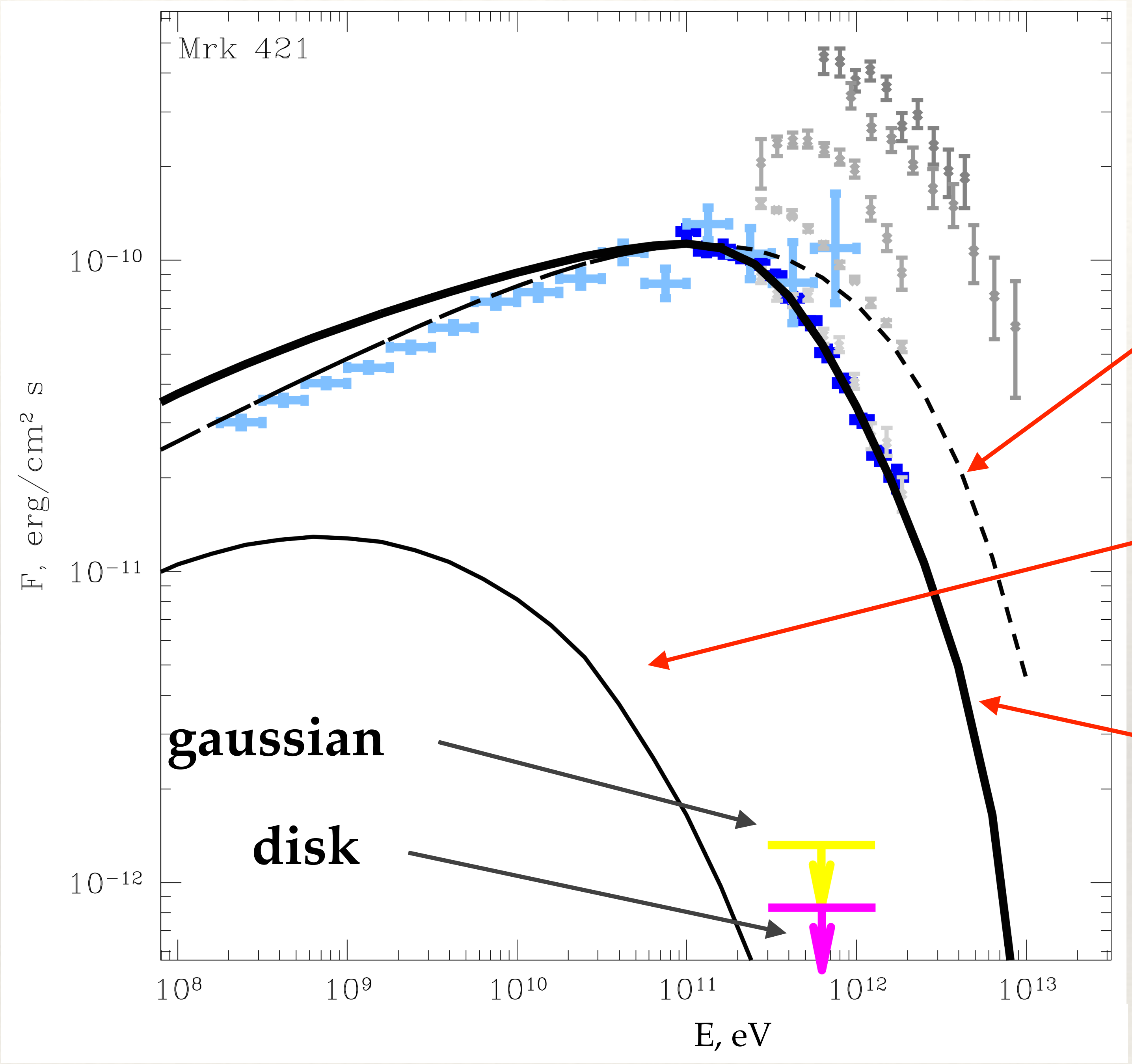
Most stringent upper limit for θ_{ext}=0.3°. **U.L. (C.U.)=1.6%**



Most stringent upper limit for θ_{ext}=0.25°. **U.L.(C.U.)=5%**

Aleksić et al. 2010

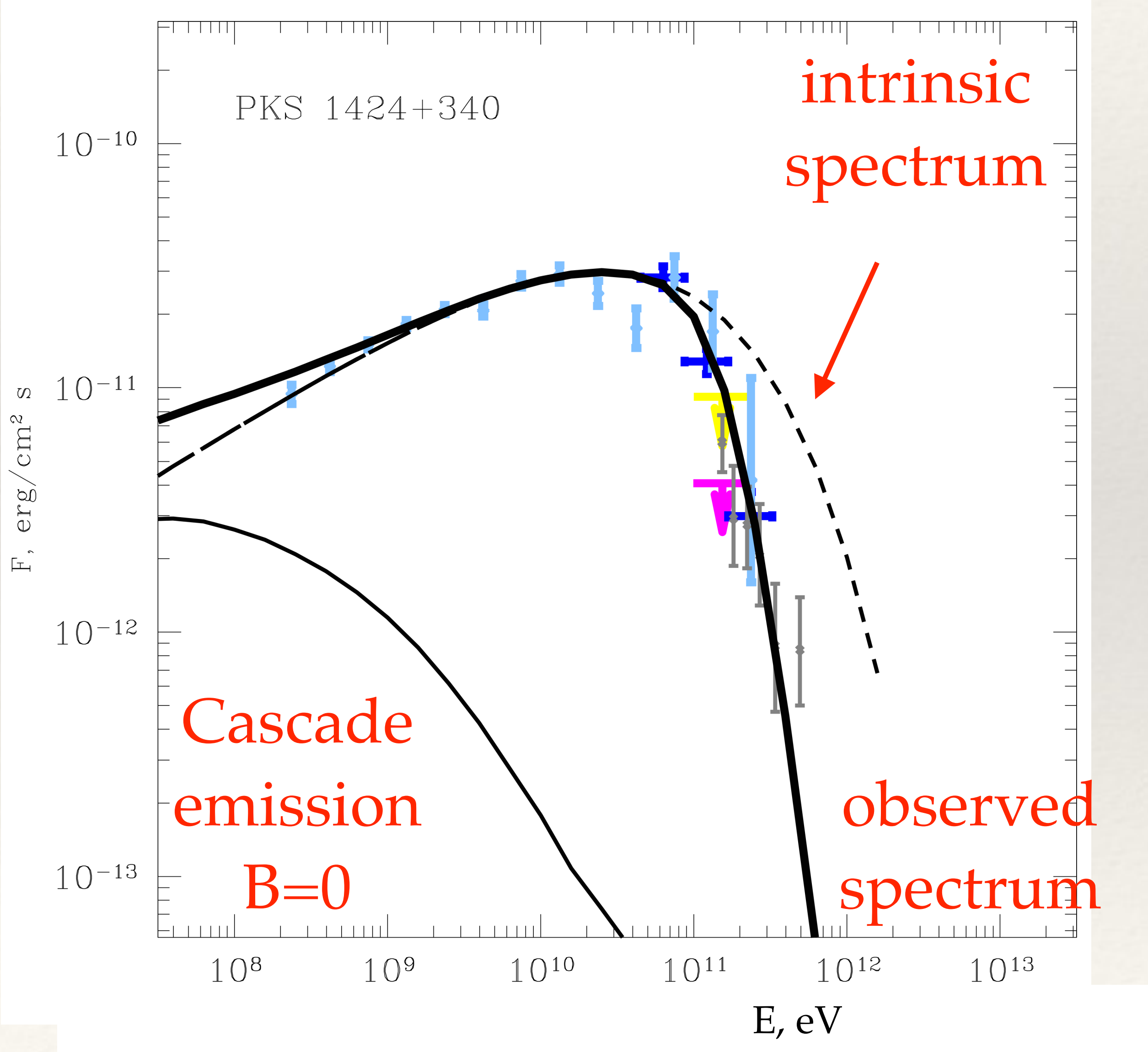
Markarian 421: spectral emission of cascade

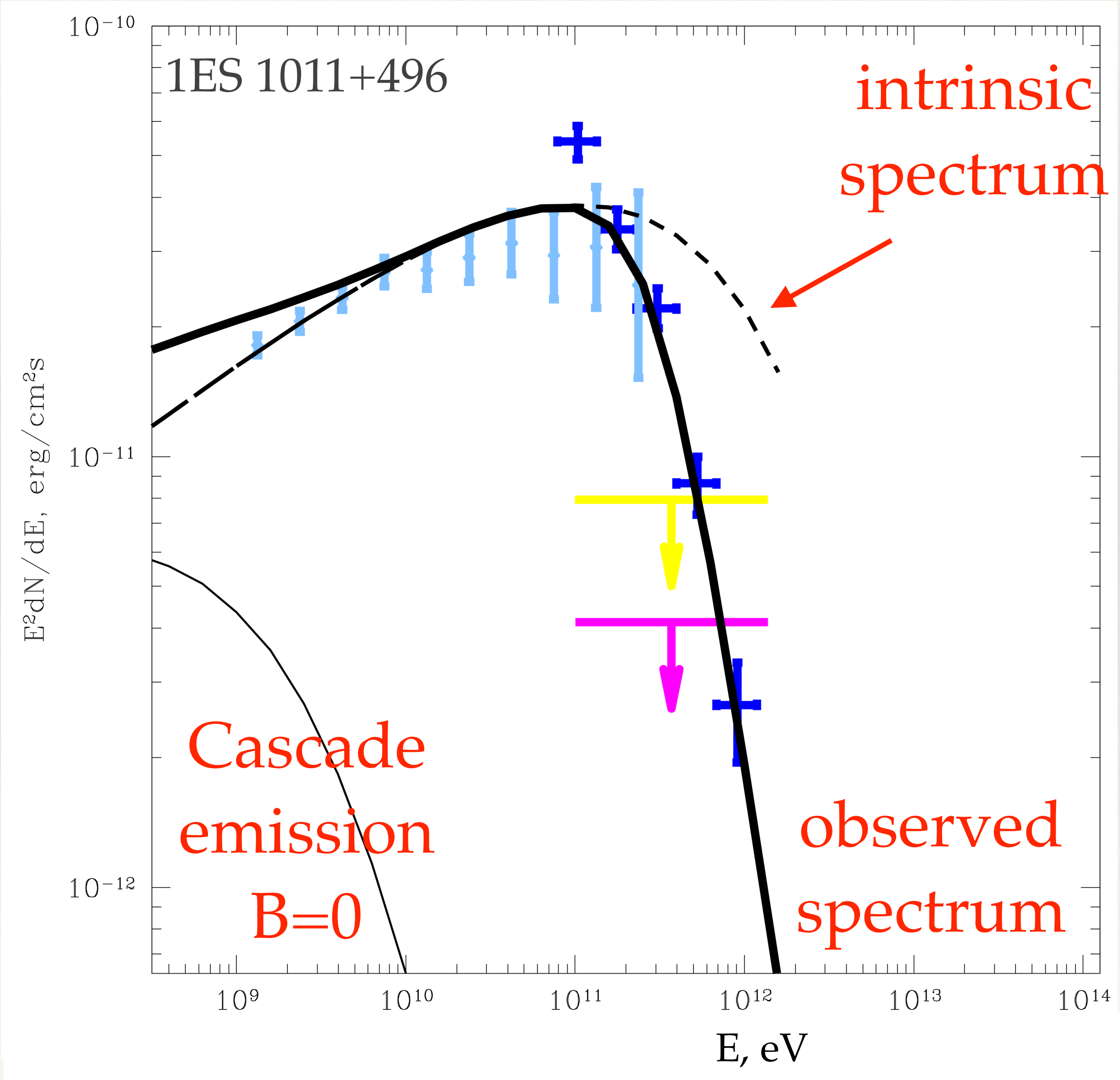


- **Due to the vicinity of the source and the cut-off in the intrinsic spectrum the contribution of the cascade emission to the total spectrum is too low**

PKS 1424+240 & 1ES 1011+496

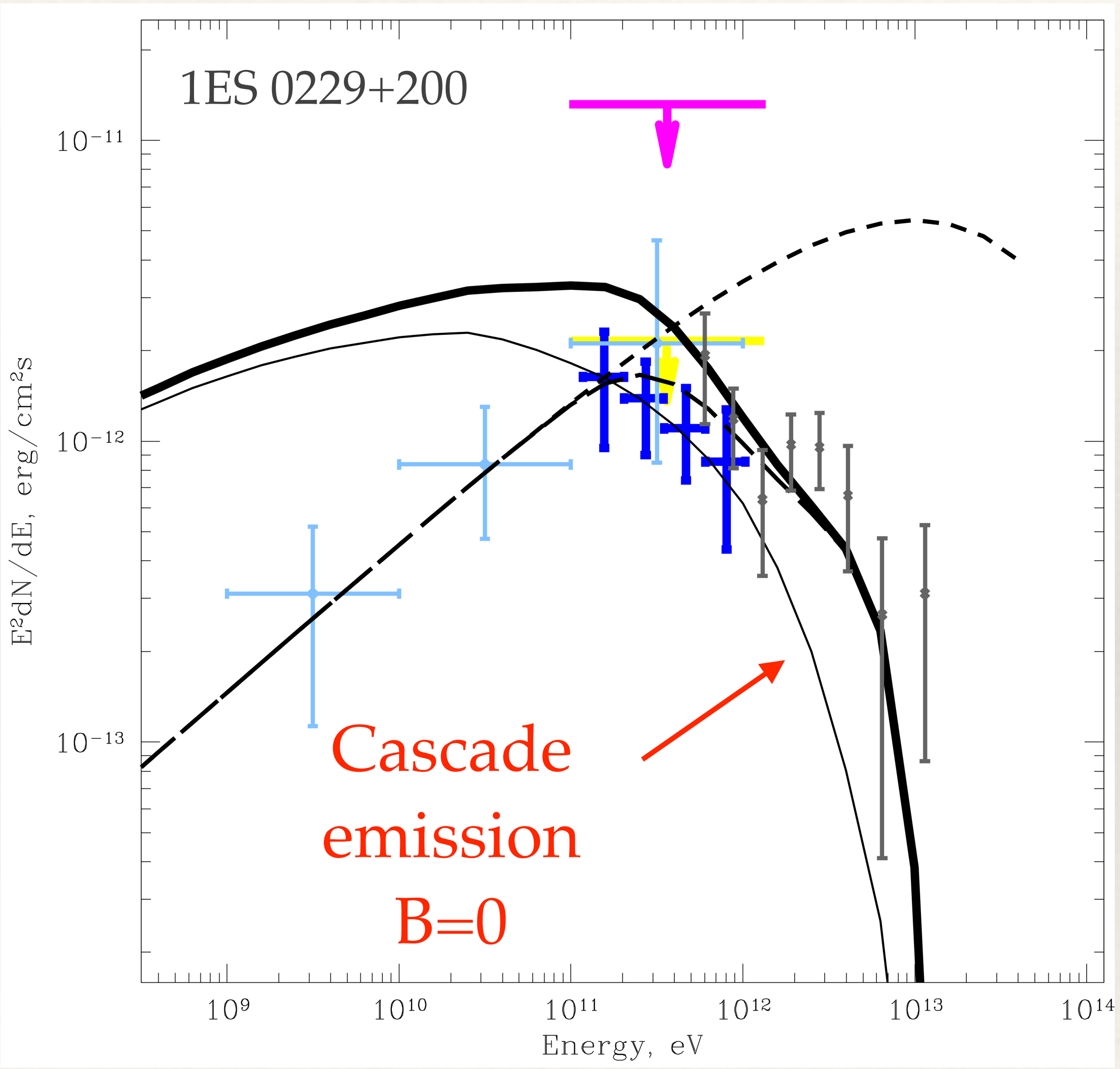
- Also for these sources the contribution of cascade emission is too low. **To be able to constrain the IGMF we need sources with hard intrinsic spectra.**

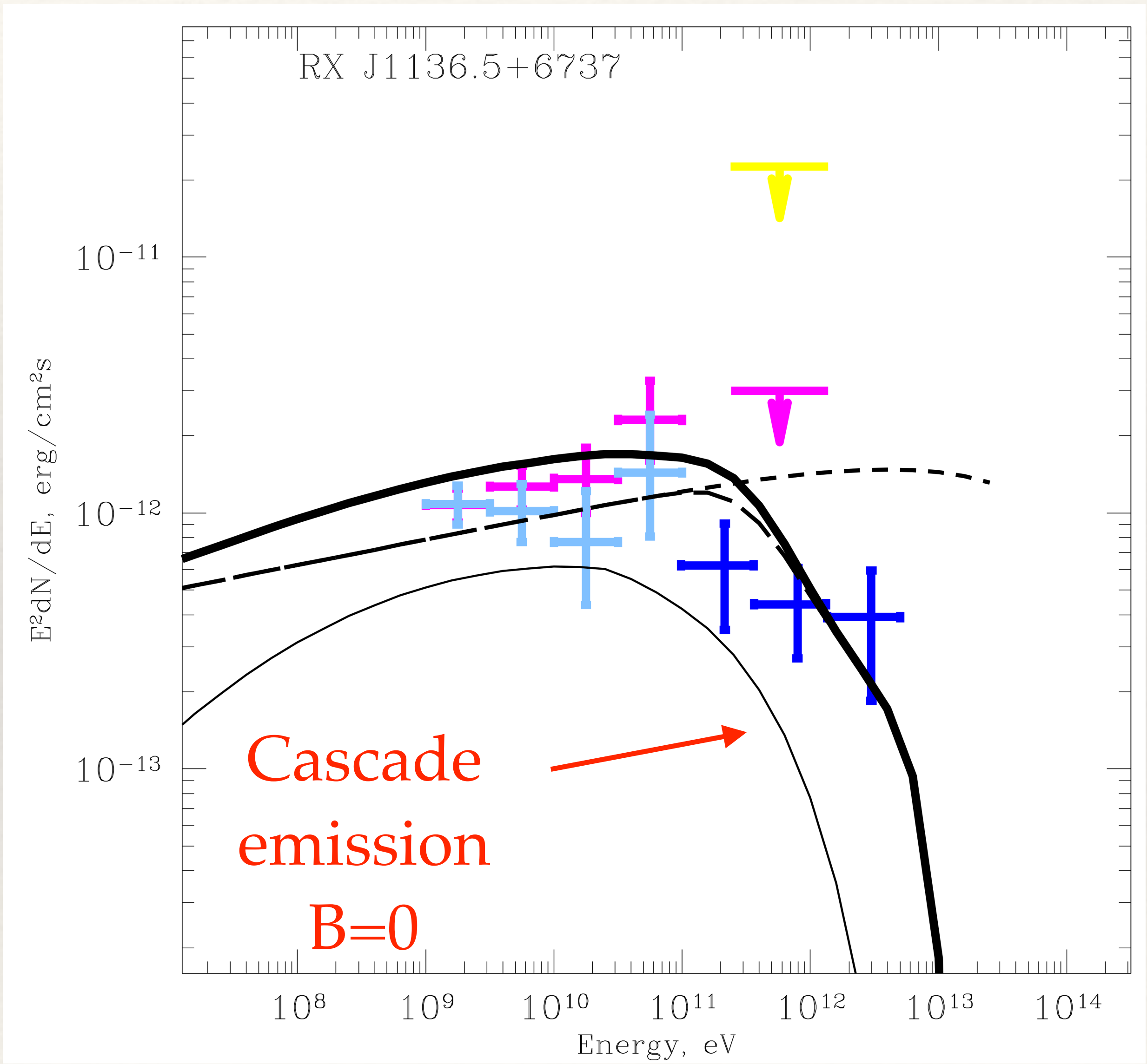




1ES 0229+200 & RX J1136.5+6737

- These sources have intrinsic spectral index less than 1.8

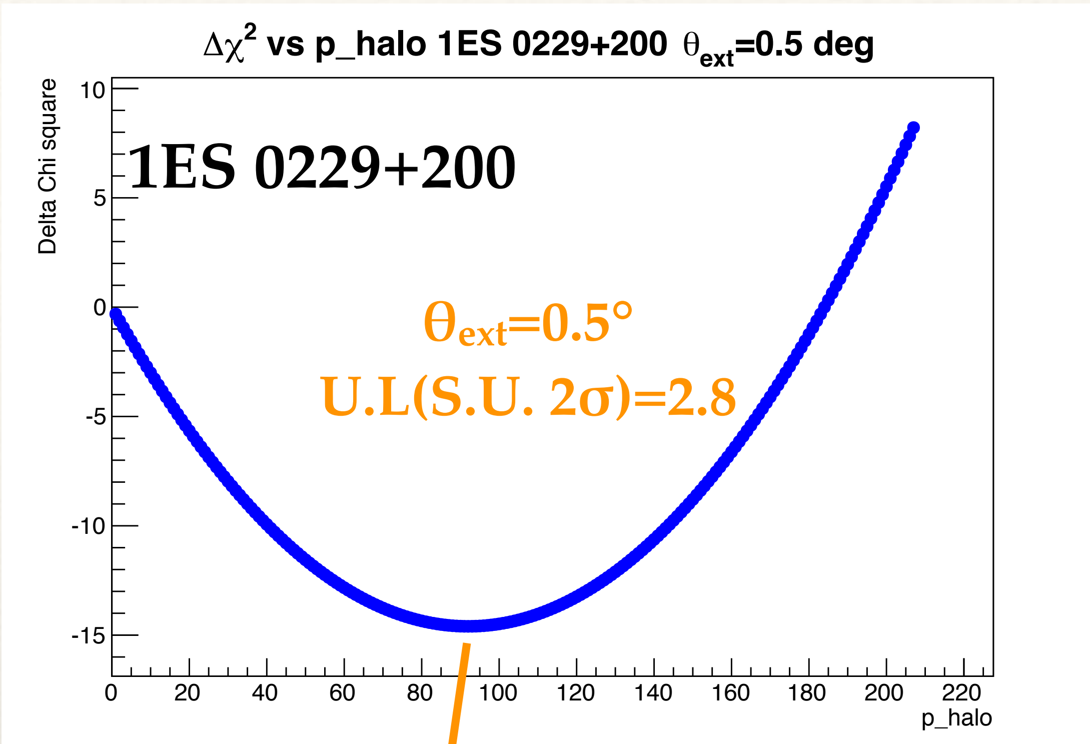




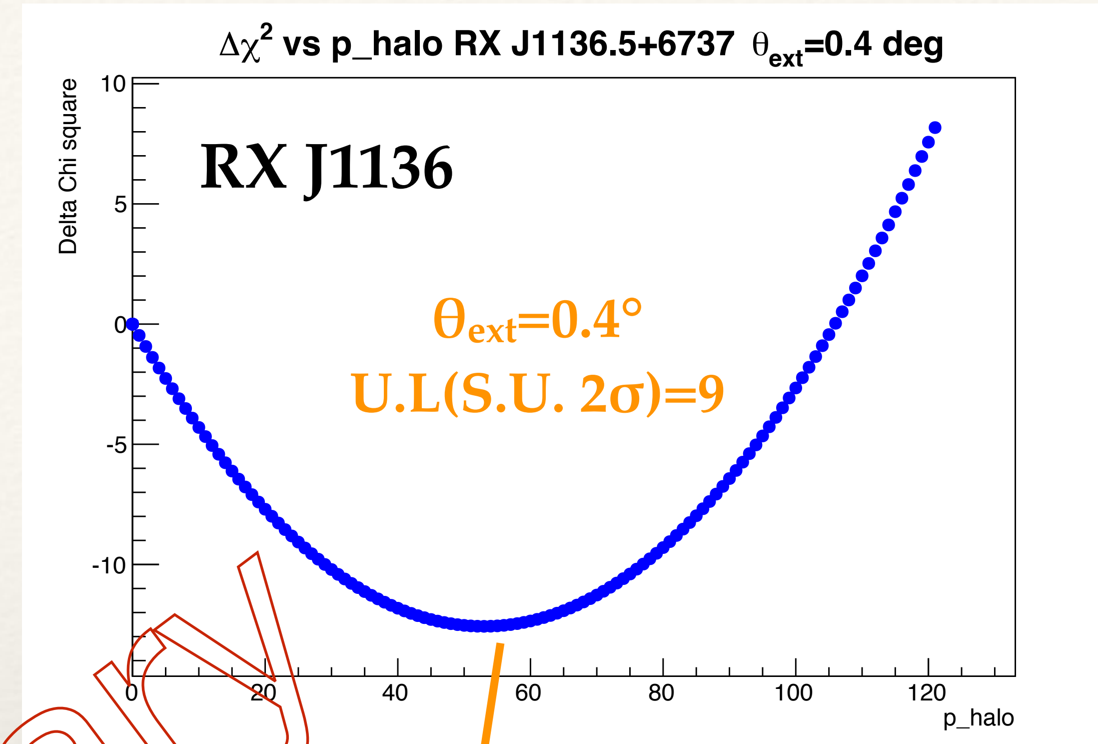
In these cases our upper limits are above the source level…

1ES 0229+200 & RX J1136.5+6737

$\Delta\chi^2$

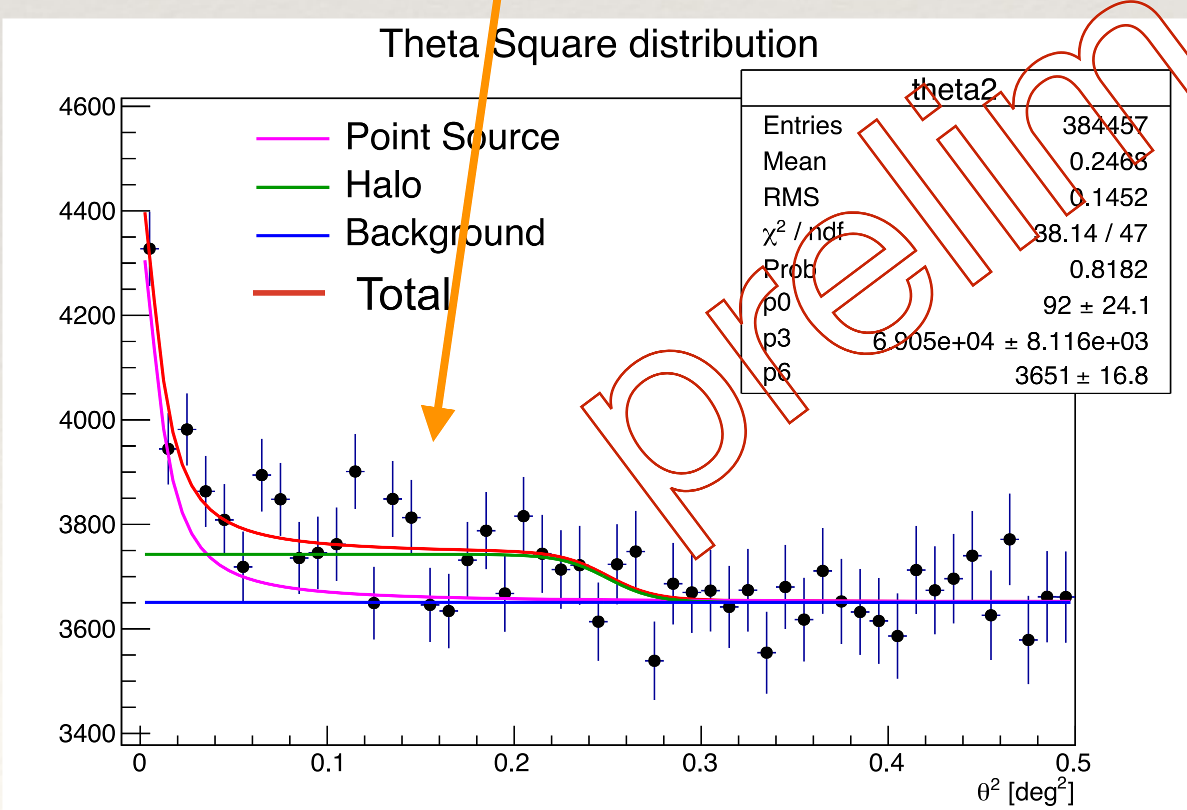


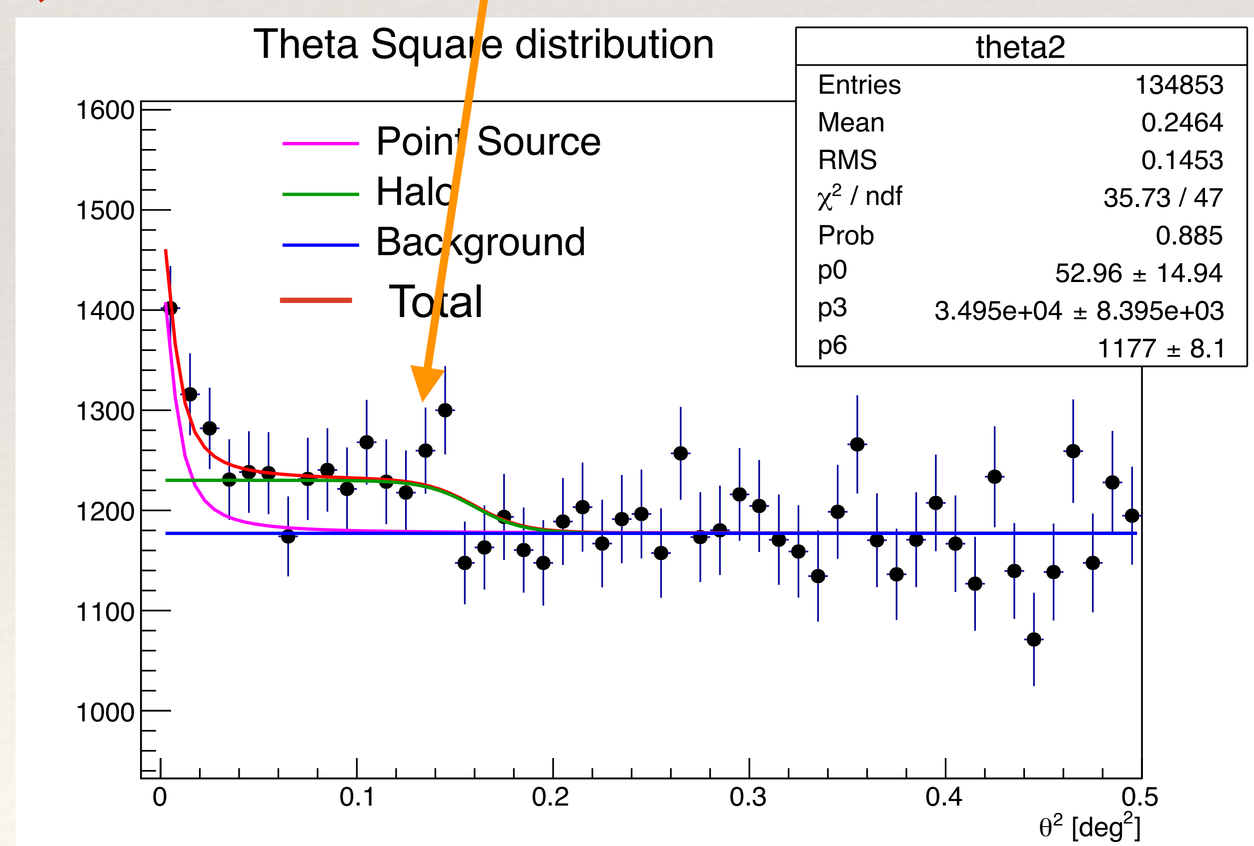
$\Delta\chi^2$



Halo intensity →

Halo intensity →





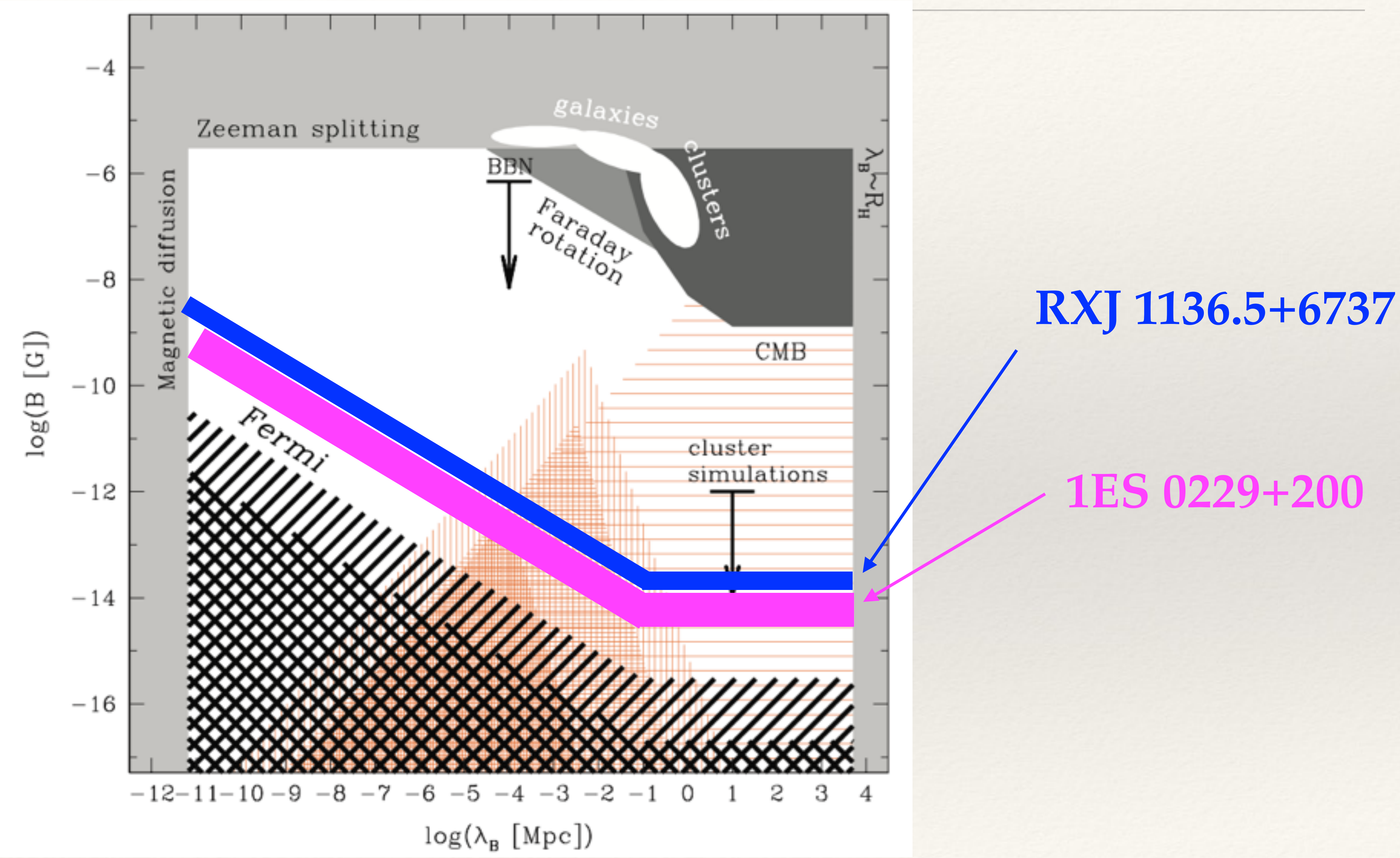
IGMF from 1ES 0229+200 and RX J1136.5+6737

- Assuming that the shape of the θ^2 distributions are due to the presence of extended emission we estimate the IGMF strength

$$\Theta_{ext} \simeq 0.5^{\circ}(1+z)^{-2}\left[\frac{\tau}{10}\right]^{-1}\left[\frac{E_{\gamma}}{0.1\ TeV}\right]^{-1}\left[\frac{B_0}{10^{-14}\ G}\right]$$

1ES 0229+200	RX J1136.6+6737
θ_{ext}=0.3°-0.55° (2σ level)	θ_{ext}=0.35°-0.45° (2σ level)
$E_{\gamma}\simeq$100 GeV	$E_{\gamma}\simeq$200 GeV
z=0.14	z=0.13
$\tau\simeq$10	$\tau\simeq$15
$B\simeq(0.5\text{-}1.3)\times10^{-14}$ G	$B\simeq(3.2\text{-}4.2)\times10^{-14}$ G

IGMF from 1ES 0229+200 and RX J1136.5+6737



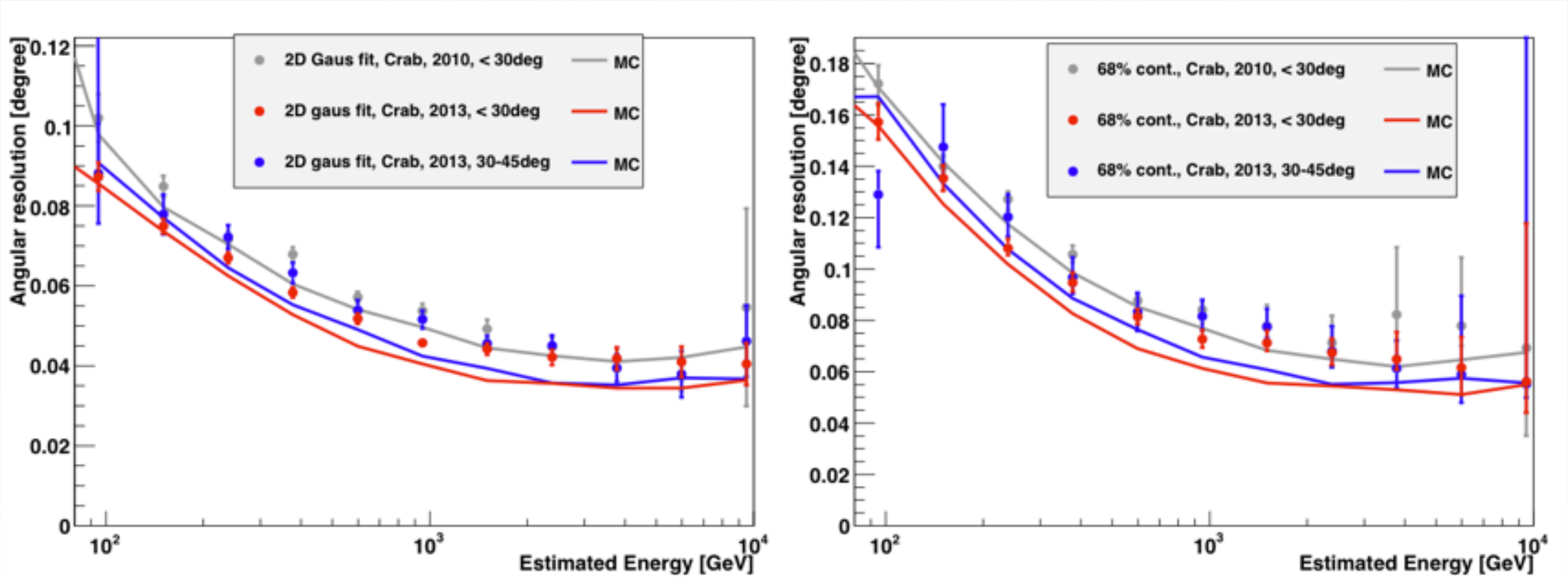
Conclusions

- We studied the emission profiles of several AGN in order to look for extended emission in VHE domain.
- We characterized the MAGIC PSF and gave a good analytical description (the King function).
- We computed upper limits on halo emission for two different halo models, improving previous published values on Markarian 421.
- The emission profiles of 1ES 0229+200 and RX J1136.5+6737 are compatible with the presence of extended emissions. The implied strengths of IGMF of the order of 10^{-14} G
  - Results needs to be confirmed with higher statistics with MAGIC.
- Expected improvements with CTA due to better sensitivity and angular resolution

Back up

Angular resolution

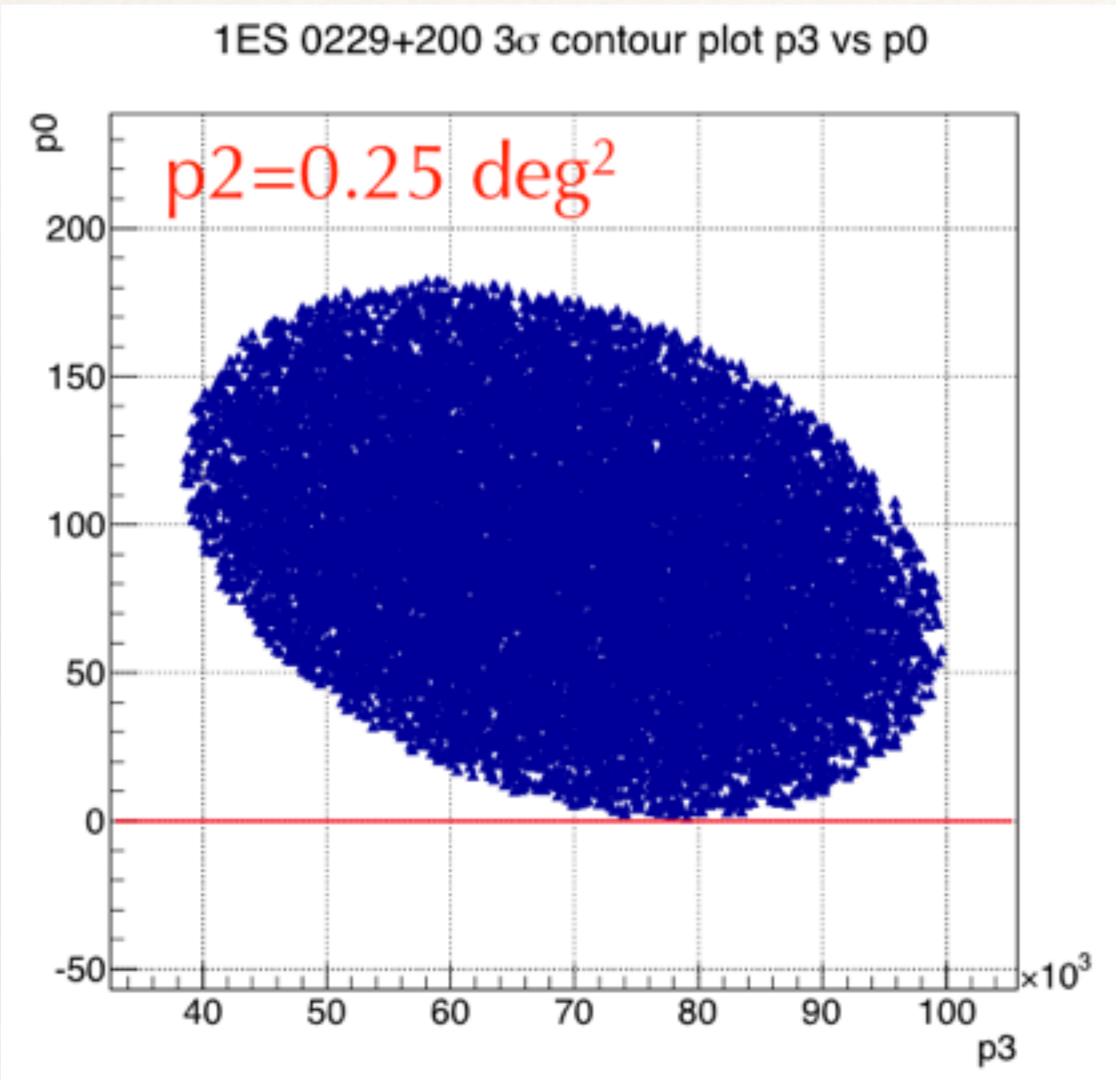
- Two techniques:
    1. fit of the distribution of the γ-ray excesses with a 2 dimensional Gaussian
    2. angular region that contains 68% of the excesses

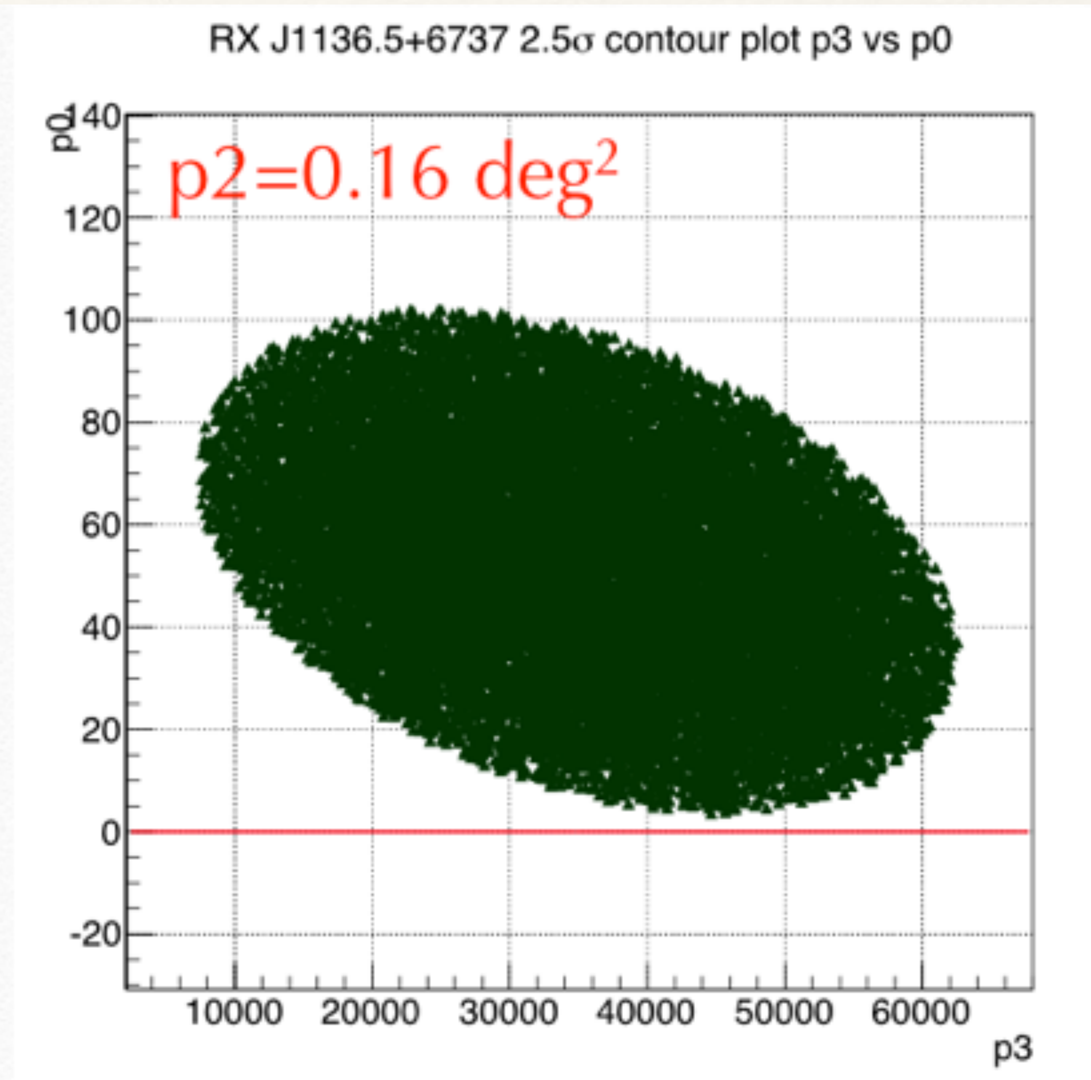


Aleksić et al. 2014

1ES 0229+200 & RX J1136.5+6737

- Significance of the model:





$$f(\theta^2) = halo(p0, p1, p2; \theta^2) + p3 * p4 * \left[1 + \left(\frac{\theta^2}{p4}\right)^2\right]^{-p5} + p6$$