



Very deep observation of the Perseus Cluster with MAGIC

Search of diffuse gamma-ray emission induced by the Cosmic-Ray population

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Cluster of galaxies

Clusters are the largest gravitationally bound systems in the Universe

- Mass: $10^{14} - 10^{15} M_{\odot}$
- Radius: few Mpc

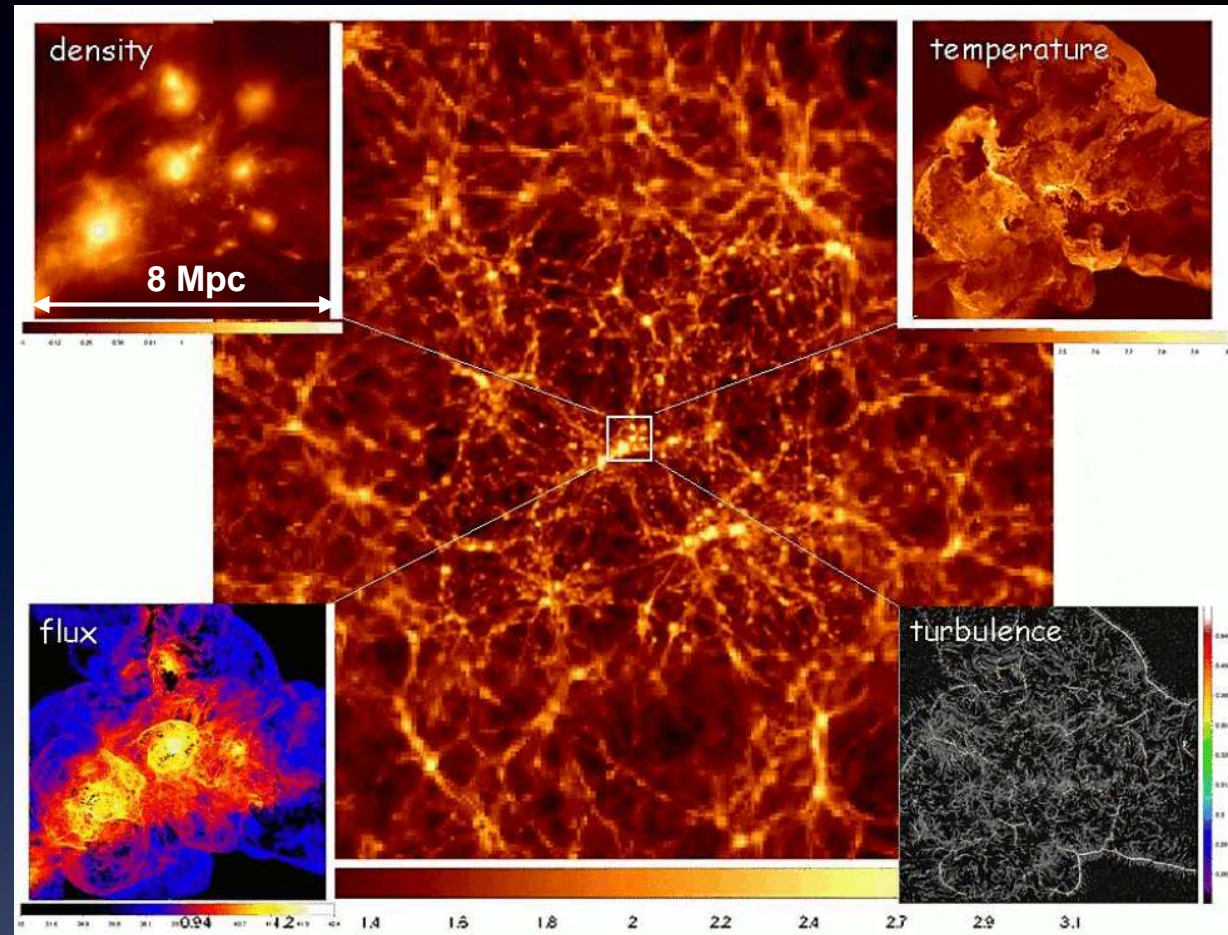
Mass composition:

- Dark Matter: $\sim 80\%$
- Intra-Cluster Matter: 15%
- Galaxies: 5%

Formation:

- Mergers and accretions of smaller systems
- Driven by gravitational forces (Dark Matter)
- Actively evolving objects (on-going formation)
- Dissipate energy in large-scale shocks (CR acceleration)

Matter density from a cosmological simulation of a piece of Universe



(from Vazza et al. 2010)

Non-thermal emissions

- Observed in radio:

- Synchrotron emission from CR electrons:
- Central Halo and Relic

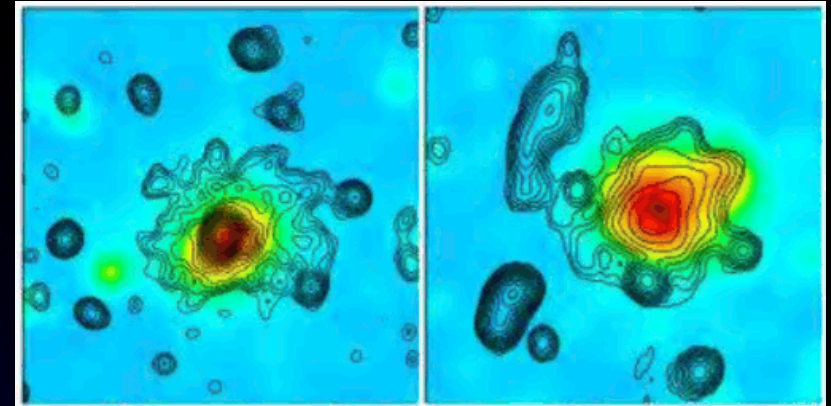
- Expected in gamma rays:

$$\text{CR}_p + \text{ICM}_p \rightarrow \pi^0 \rightarrow \gamma + \gamma$$

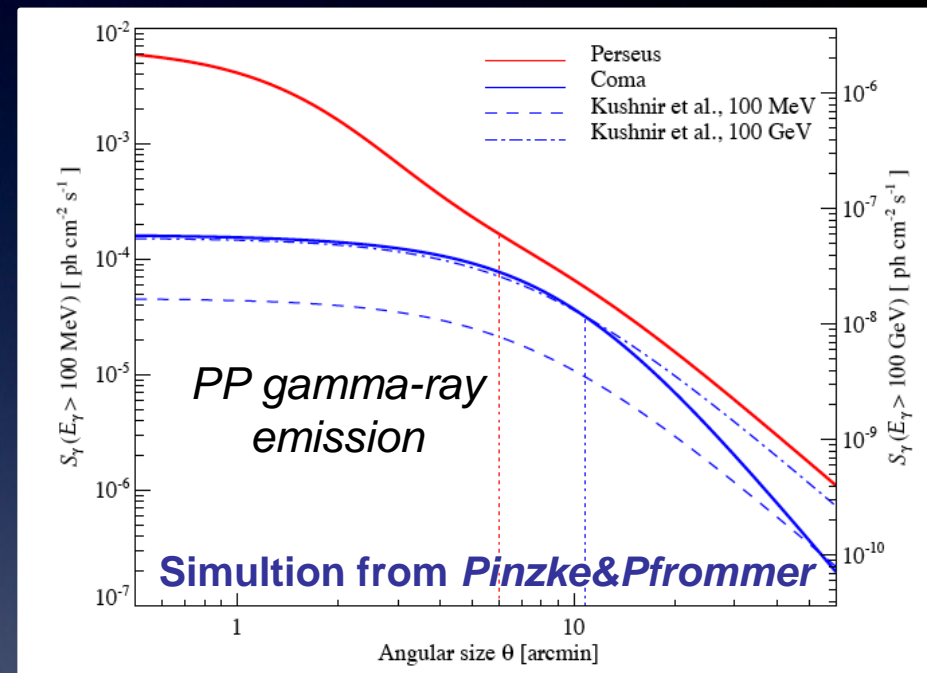
From Hydrodynamical simulations:

- CR spectrum: $P^{-\alpha}$ with $\alpha \sim 2.2$
- CR spatial distribution: variable
- VHE γ -ray spectrum: $E^{-\alpha}$ ($\alpha \sim 2.2$)
- VHE γ -ray spatial distribution: $\delta_{\text{CR}} \times \delta_{\text{ICM}}$

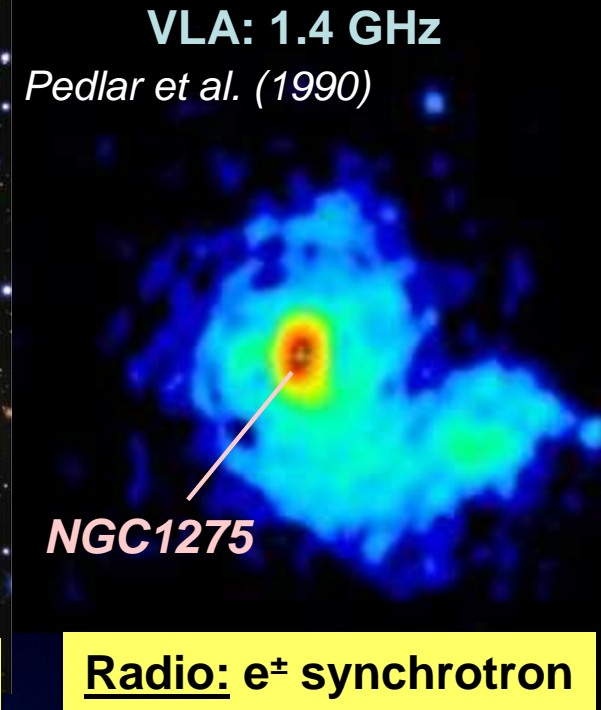
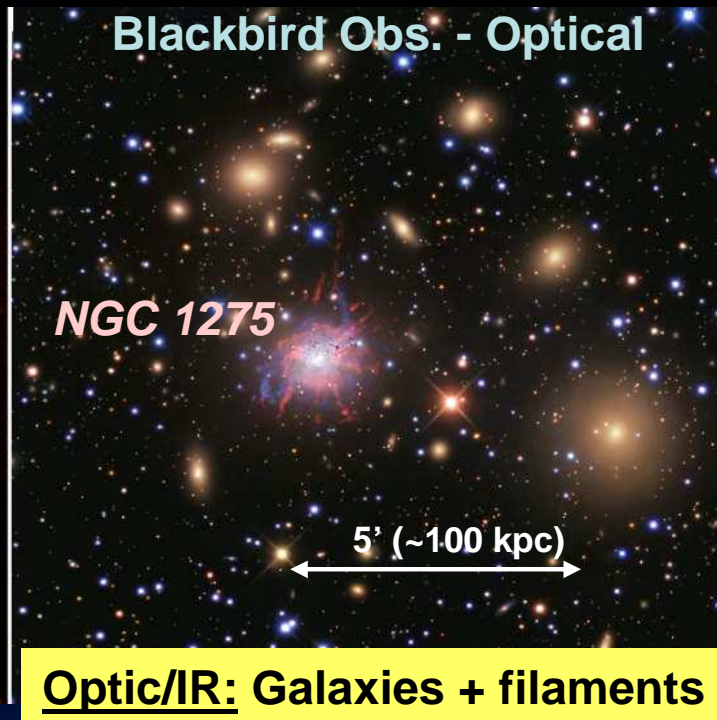
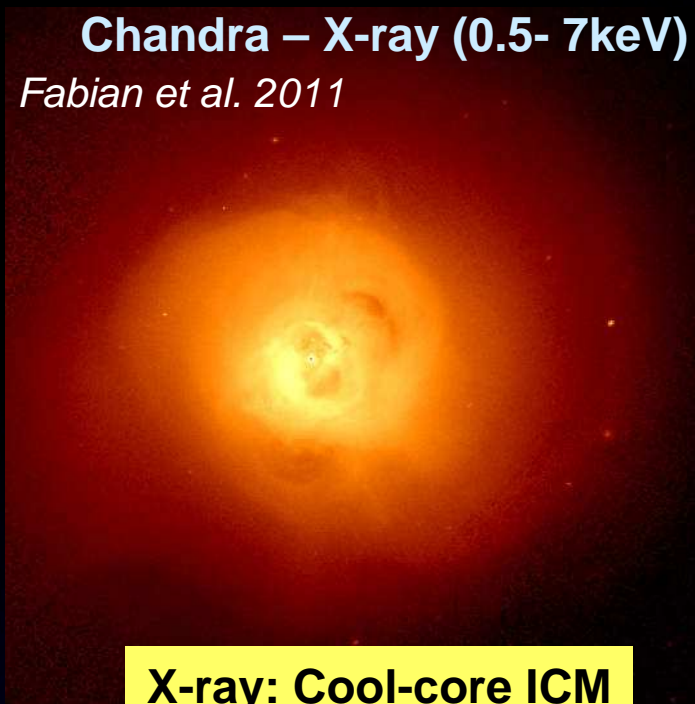
DM annihilation/decay
(see J. Palacio talk, Monday)



Color: Thermal/X-ray
Contour: Synchrotron/ Radio



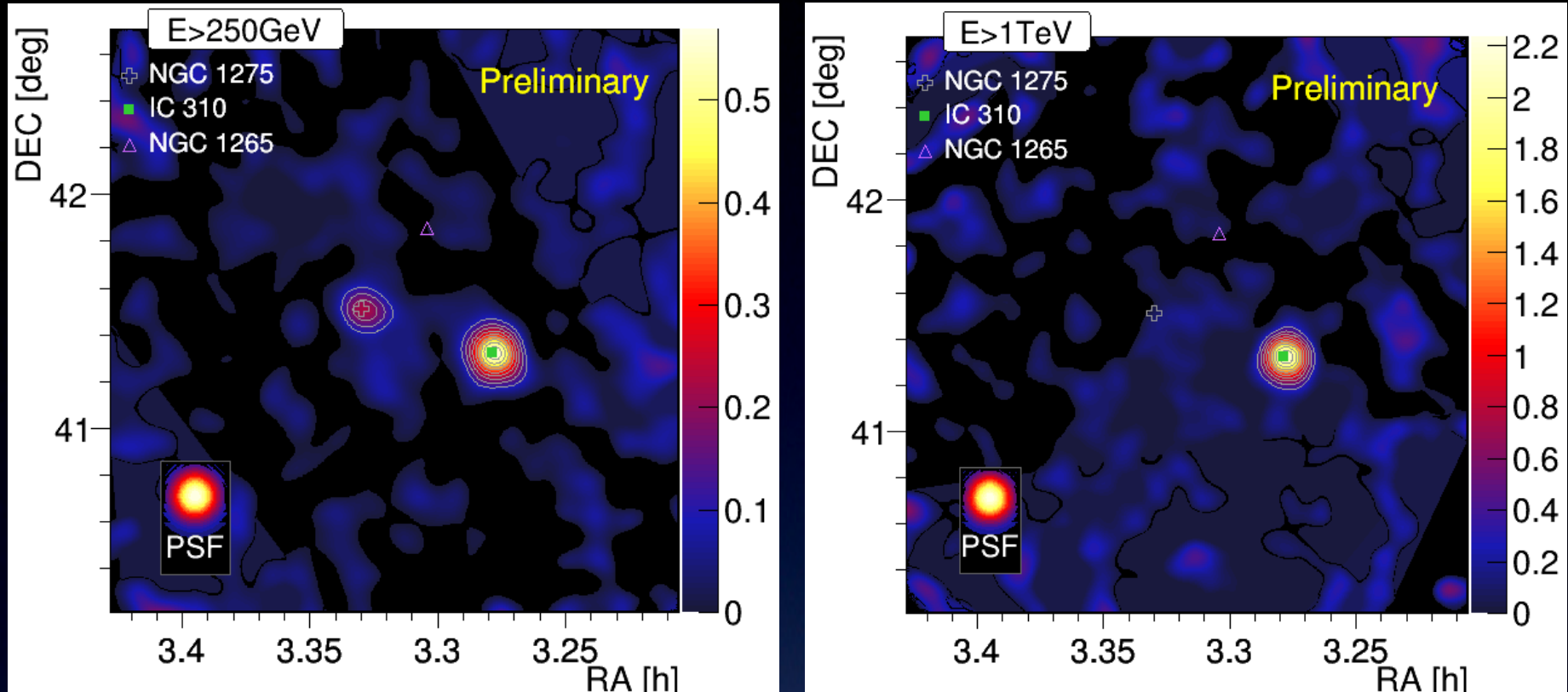
The Perseus cluster (Abell 426)



- Nearby ($z=0.018$) cool core cluster (relaxed cluster)
- Brightest X-ray cluster in the sky
- Dominant central radio galaxy: NGC 1275
- Non-thermal emission: bright radio mini-halo
- **Best target to search for CR-ICM-interaction emission**

Observation with MAGIC

253 hours of stereo data from 2009 to 2014



Color: *Relative flux (excess/background ratio)*

Contours: *Significance (from 4σ in step of 2σ)*

Detection of two AGNs (point-like sources)

- NGC 1275: Central radio galaxy
- IC 310: Peculiar radio galaxy (See D. Glawion talk)

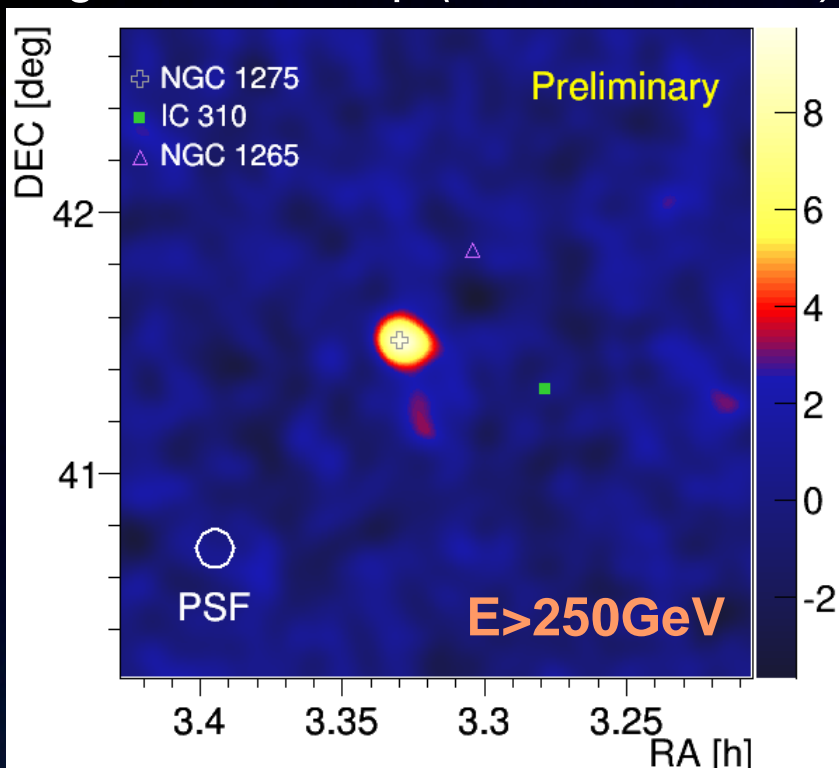
Search for diffuse emission at 250 GeV

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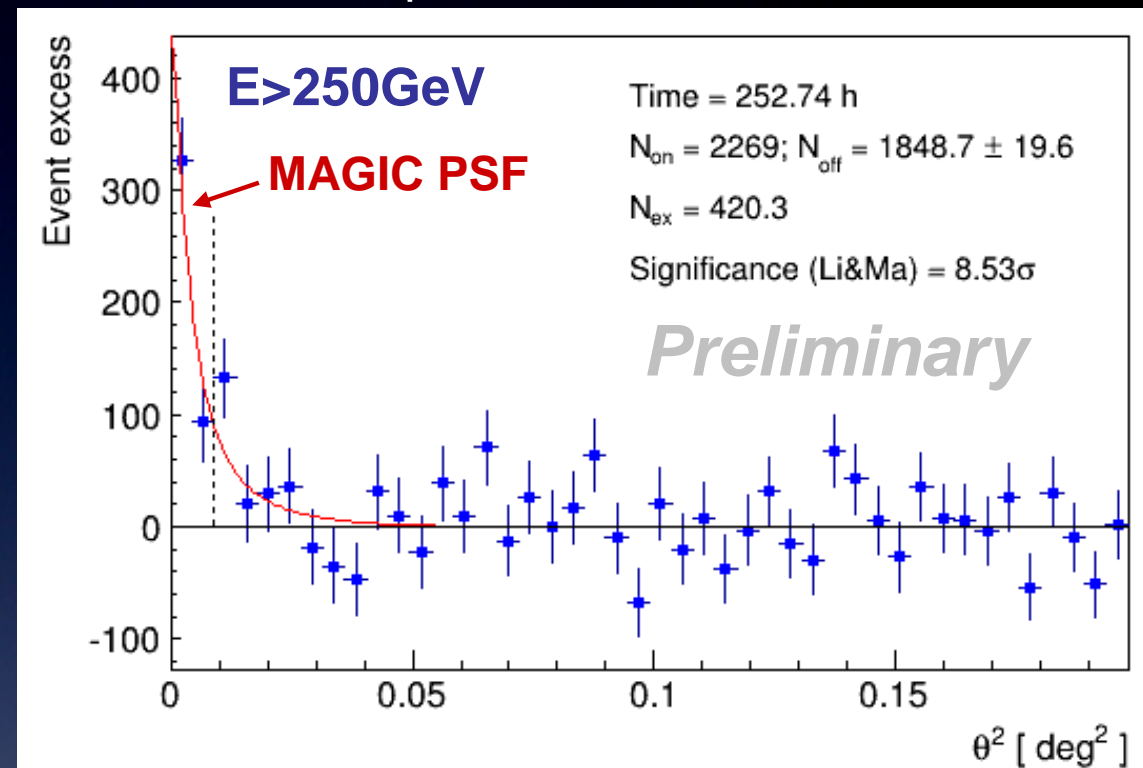
γ -ray bright AGNs can outshine CR-induced signal

- Background estimated from region without source
- IC 310 emission included in background model of the map

Significance map (*IC310 excluded*)



Distribution of squared distance from NGC 1275



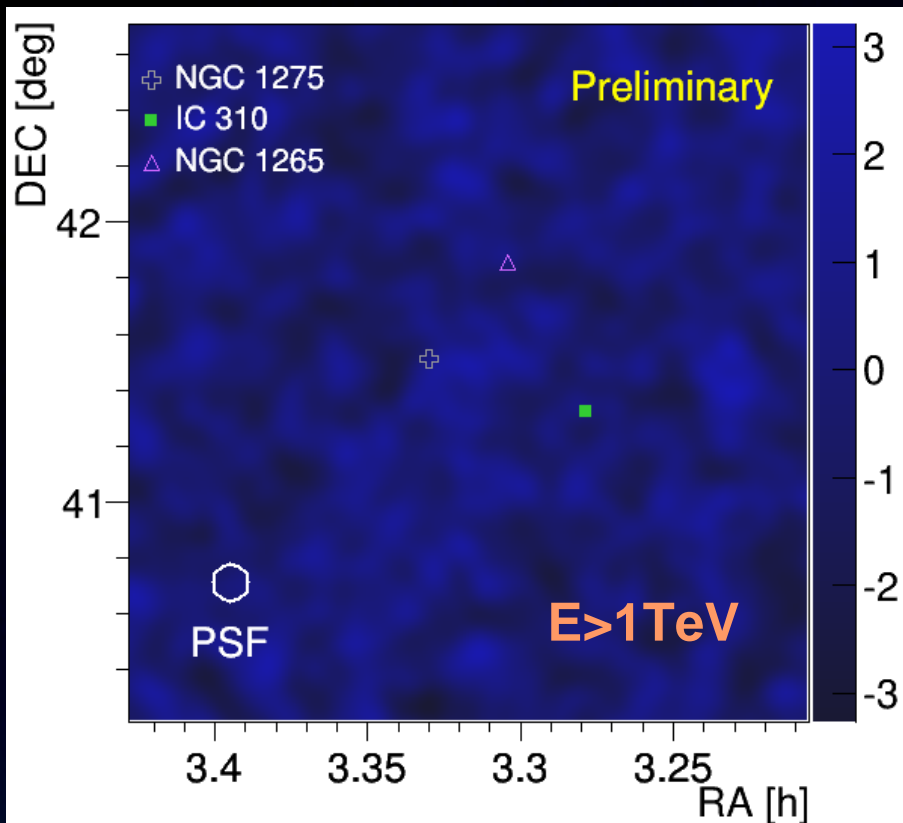
- Central excess in good agreement with point-like source (AGN)
- No sign of large-scale-structure emission

Search for central emission at 1 TeV

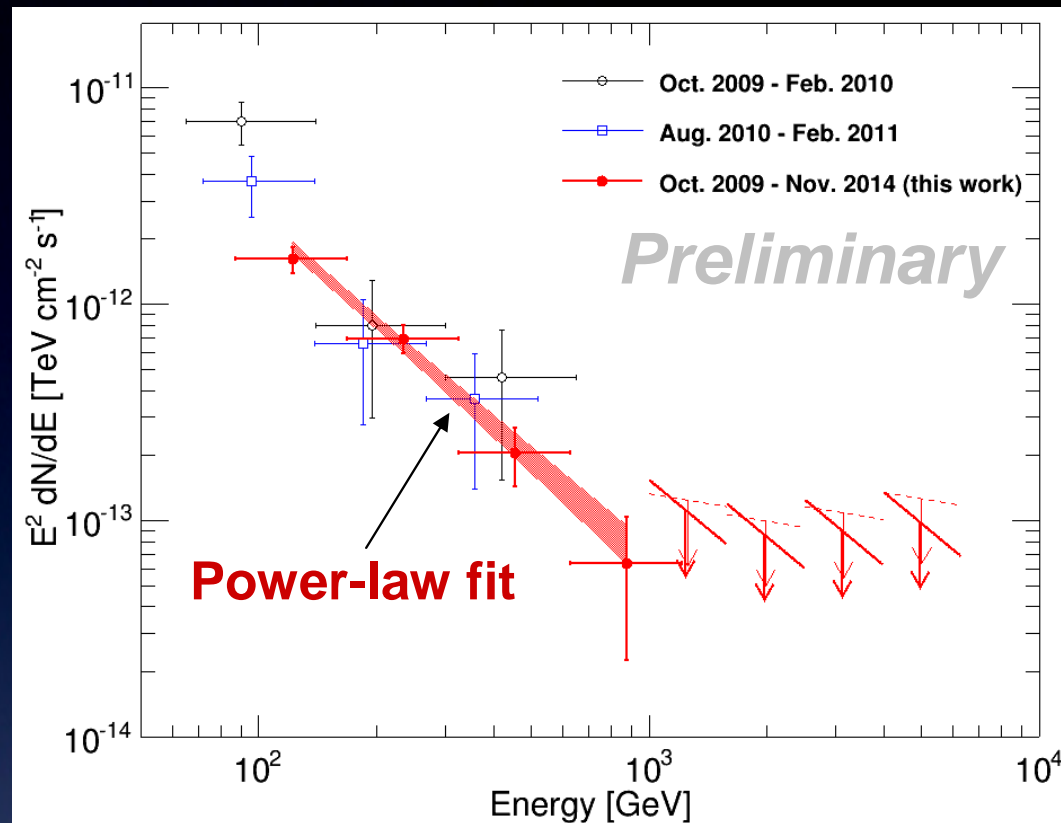
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IC 310 emission included in background model of the map

Significance map (*IC310 excluded*)



Spectral Energy Distribution of NGC 1275

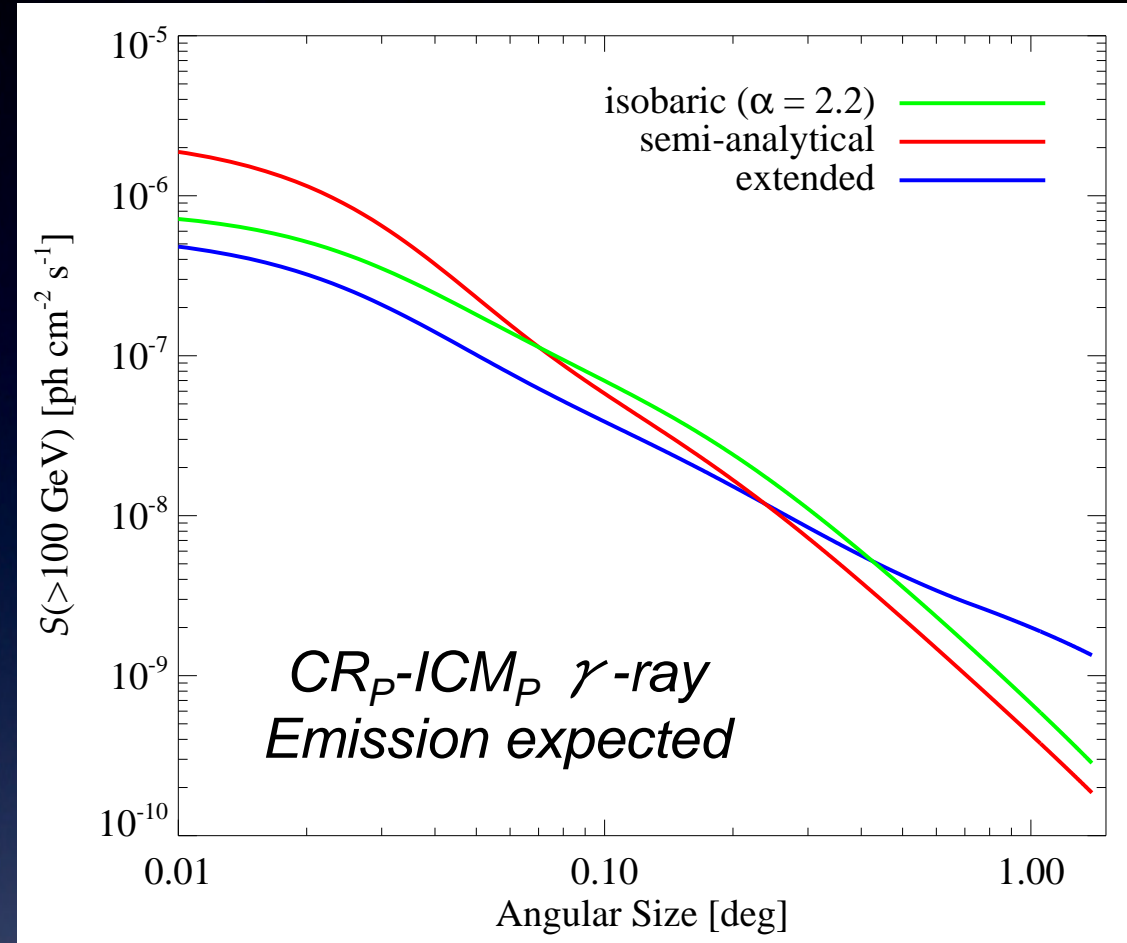


- NGC 1275 spectrum: $E^{-\Gamma}$ with $\Gamma = 3.6 \pm 0.2_{(\text{stat})} \pm 0.2_{(\text{syst})}$
- No significant excess above ~1 TeV
- No hint of large-scale-structure emission

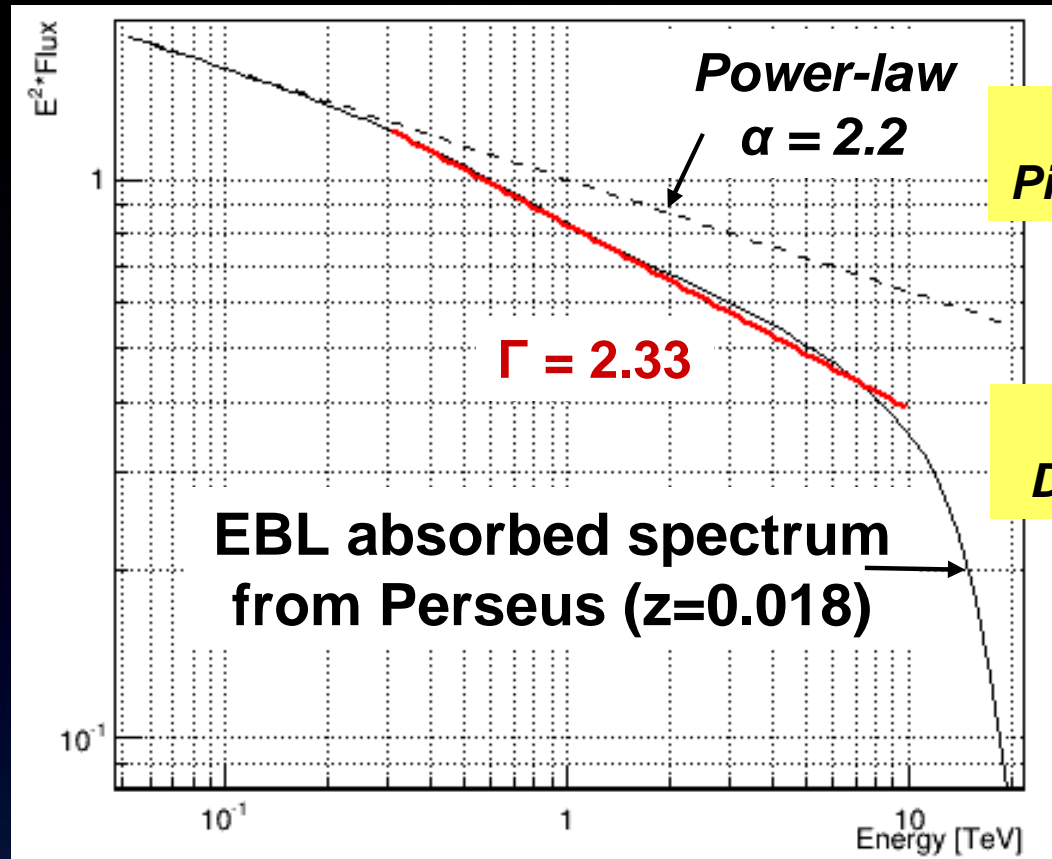
Search of CR-induced gamma-rays

We consider 3 spatial templates:

- **Isobaric:**
CR pressure = Thermal pressure
~39% of signal within 0.15°
(Pfrommer & Ensslin 2004)
- **Semi-analytical**
from hydrodynamical
simulations of clusters
~55% of signal within 0.15°
(Pinzke & Pfrommer 2010)
- **Extended**
Assuming CR propagation
out of the Cluster core
~22% of signal within 0.15°
(Zandanel et al. 2014)



Expected CR-induced spectrum



Intrinsic spectrum:
Pinzke & Pfrommer 2010

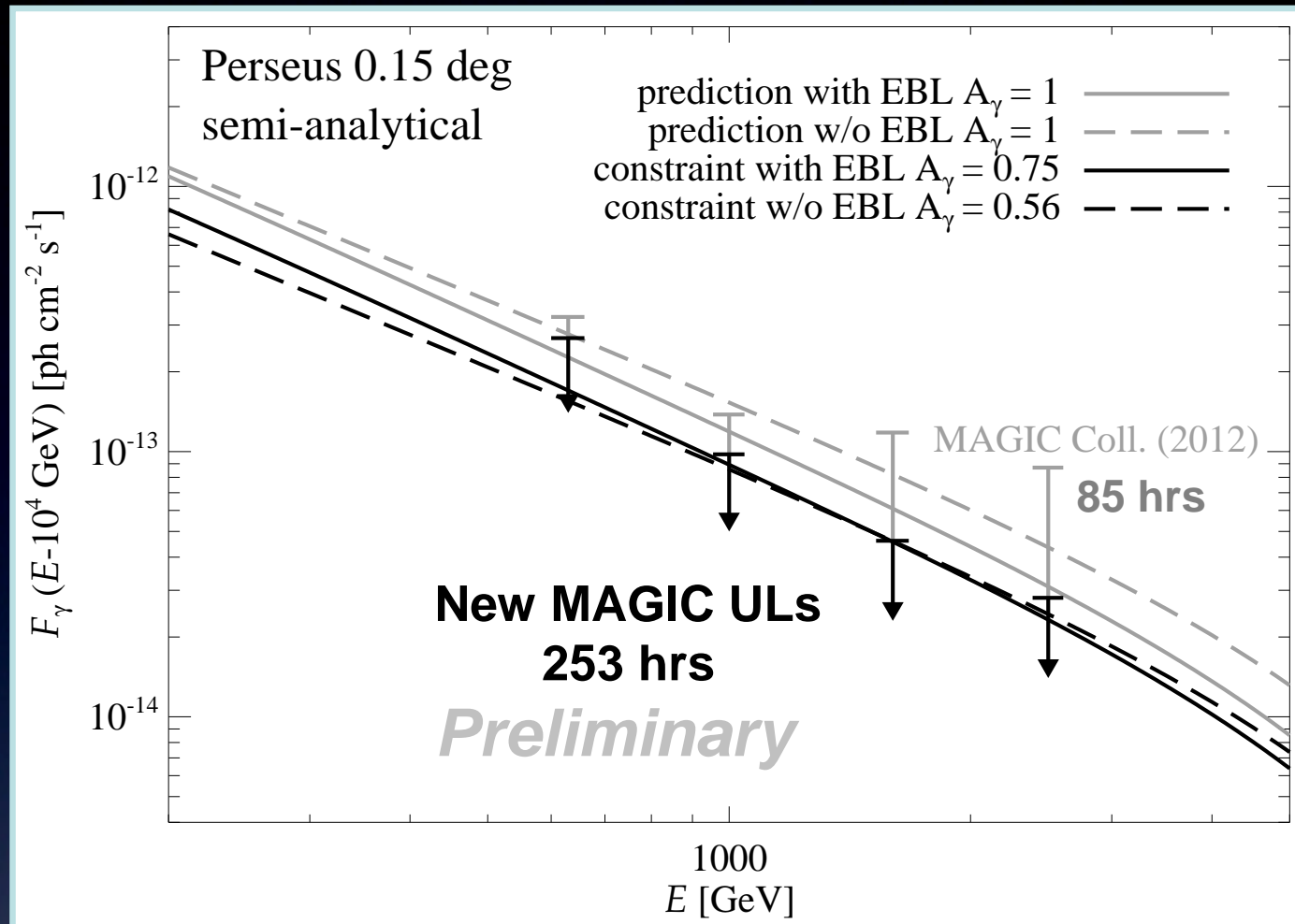
EBL model:
Dominguez et al. 2011

- Intrinsic spectrum: "universal" power-law $P^{-\alpha}$ with $\alpha=2.2$
 - **EBL absorption cannot be neglected above 1TeV !!!**
- Effect on PL emission on E range 0.3-10 TeV:

- Differential flux at 1TeV: -17%
- Spectral index: +0.13

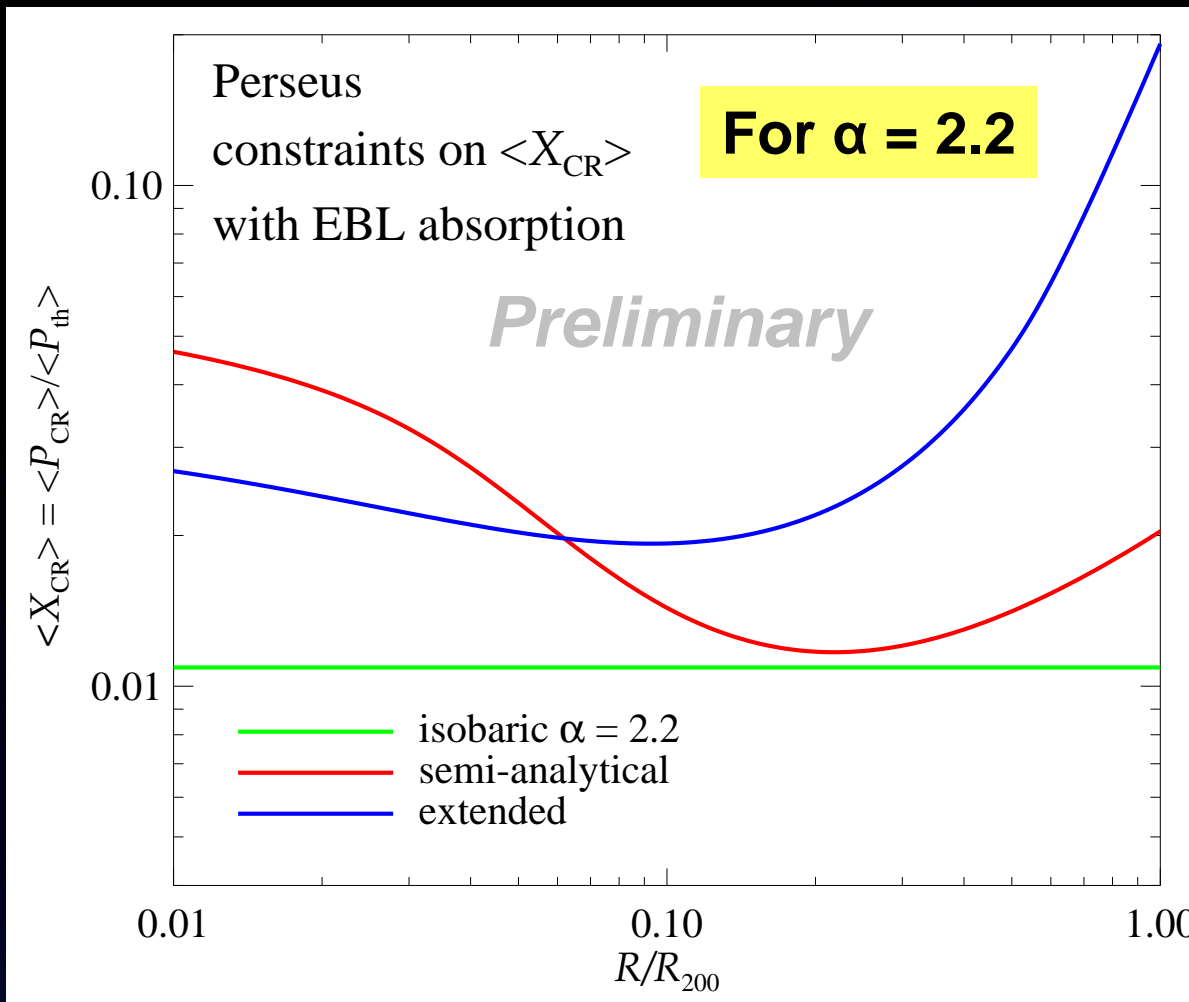
Flux upper limit vs Expected signal

- **MAGIC upper limits above a given energy depend on CR model**
- **Example:** *Semi-analytical model of Pinzke & Pfrommer (2010)*



CR-proton acceleration efficiency < 37% (without EBL: <28%)

CR-to-thermal pressure ratio $\langle X_{CR} \rangle$

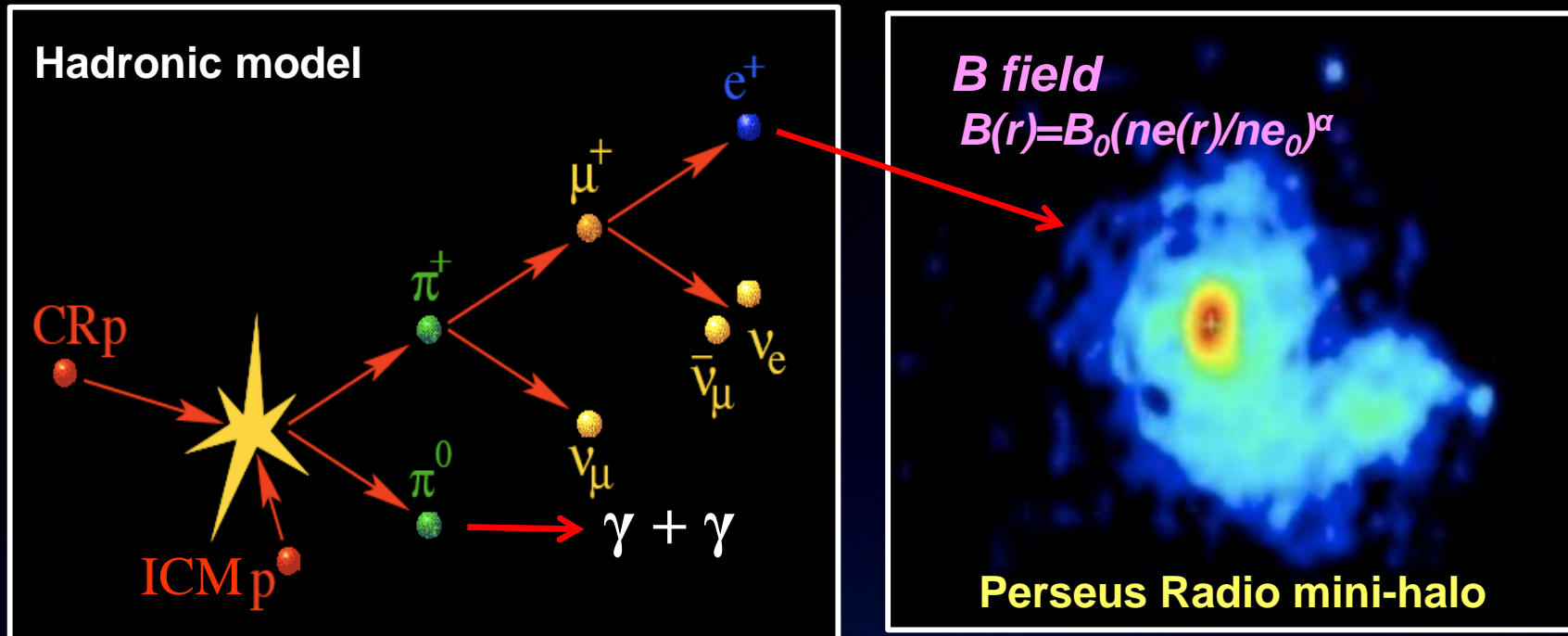


Constraints with the **isobaric model** ($X_{CR} = \text{constant}$) for different spectral index α

α	$\langle X_{CR, \max} \rangle [\%]$	$\langle X_{CR, \max}^{EBL} \rangle [\%]$
2.1	0.50	0.68
2.2	0.81	1.09
2.3	1.74	2.34
2.5	11.39	15.21

Semi-analytical & isobaric ($\alpha < 2.3$) models: CR pressure negligible ($< \sim 2\%$)
Extended & isobaric ($\alpha = 2.5$) models: CR pressure can be up to 15-20%

Hadronic model of radio mini-halo



Hadronic model:

Mini-halo coming from Synchrotron emission of secondary e^\pm induced by CR-ICM hadronic interactions

- Direct connection between diffuse radio and γ -ray emission
- MAGIC ULs imply a minimum B-field at the cluster center
- Minimum γ -ray emission for large B fields ($B \gg B_{\text{CMB}}$)
- Under the assumption of a hard CR spectrum ($\alpha < \sim 2.1$), the hadronic model could be ruled out with MAGIC.

Summary

- Galaxy clusters should contain large CR population accelerated at structure formation shocks
- Diffuse γ -ray emission is expected from CR-ICM interaction. **Best candidate: Perseus cluster**
- Very deep observation of Perseus (>250h) with MAGIC
 - **Two γ -ray bright AGNs discovered**
 - **No sign of any diffuse/CR-induced signal**
 - **Constraining flux Upper Limits at TeV energies**
 - CR-to-thermal pressure < 1-2%
 - Semi-analytical model: CR acceleration < 37%
 - On-going constraints on the cluster magnetic field assuming the hadronic model of radio mini-halo