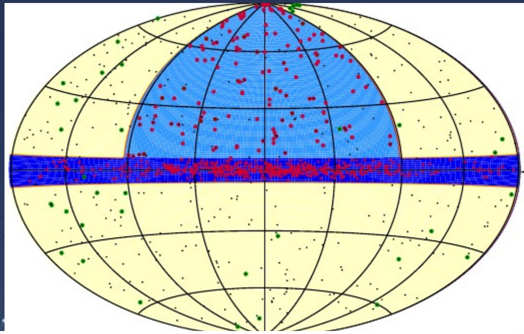
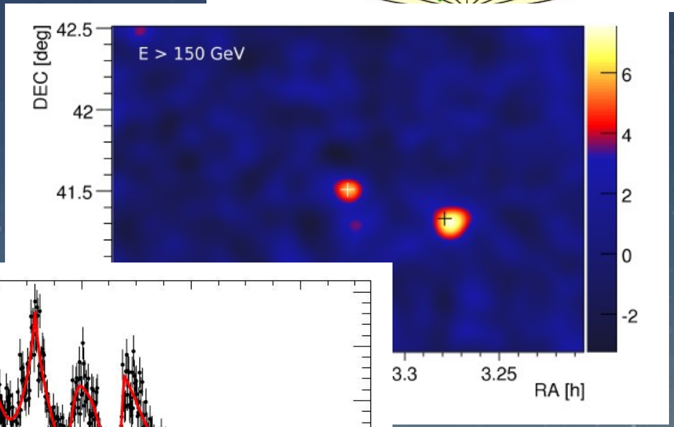
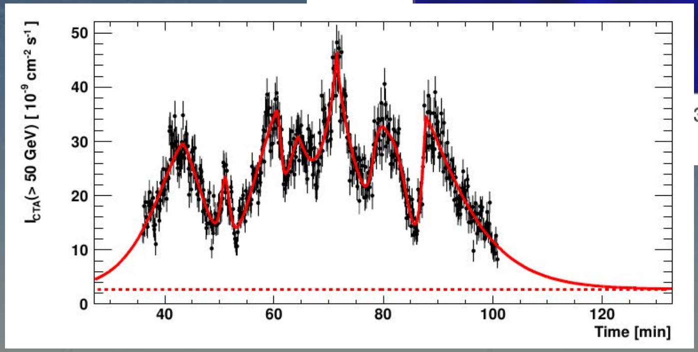
Extragalactic Science with CTA







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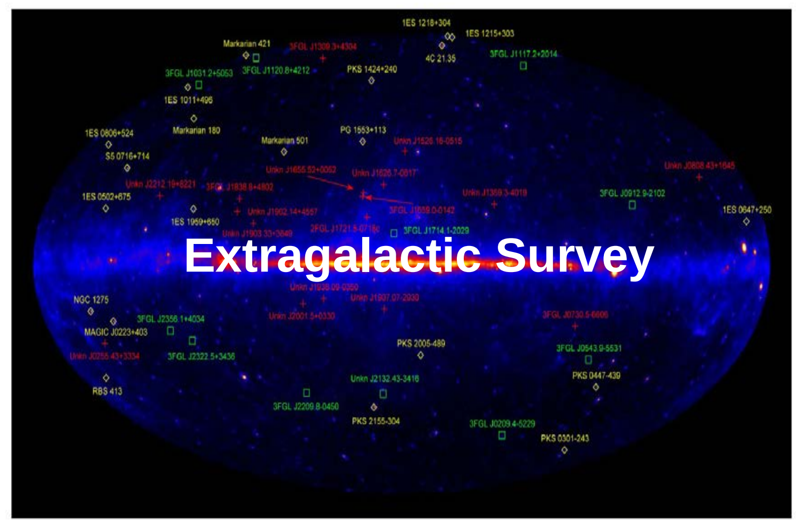
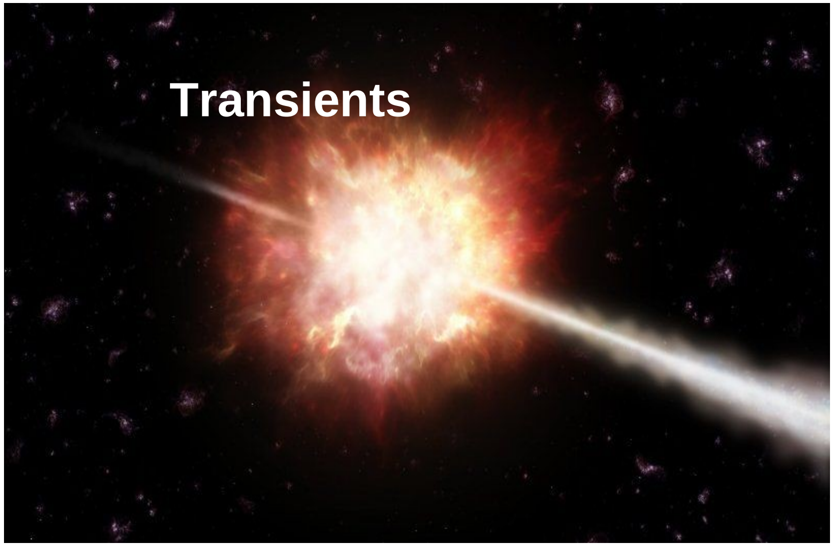
The Future of Research on Cosmic Rays
26-29 August - La Palma - Canary Islands

Extragalactic Science Prospects

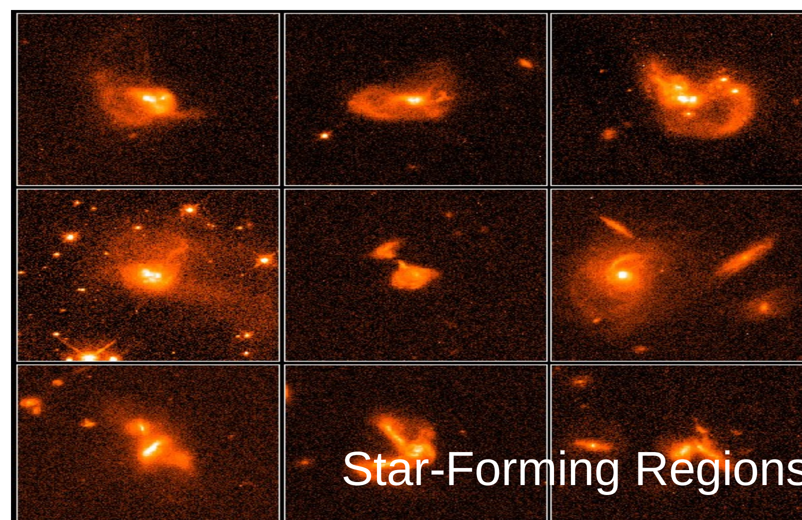
Extragalactic science topics covered today.



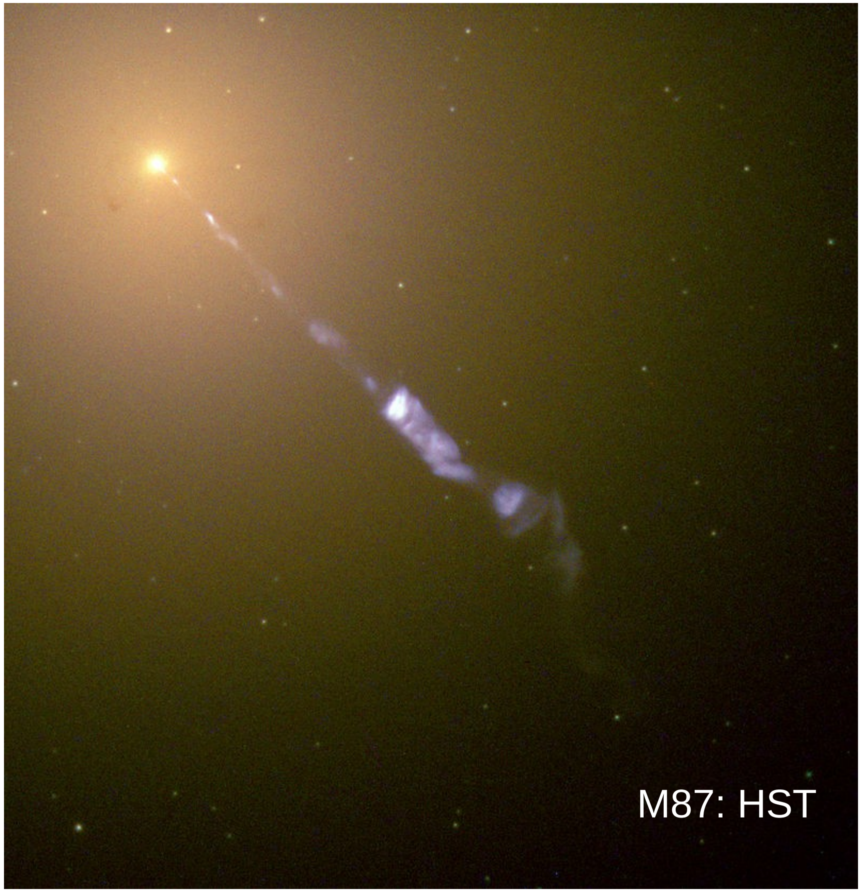
Extragalactic Science Prospects



Other extragalactic science topics not covered today.



Active Galactic Nuclei



Studies of AGN allow us to contribute to 3 key science goals of CTA.

- Probing extreme environments
  - Understanding the physical processes within the AGN
- Understanding the origin and role of cosmic rays
  - Revealing the identity of the γ-ray emitting particles within the AGN
- Exploring frontiers in physics
  - Searching for Lorentz invariance violation & axion-like particles and constraining the extragalactic background light & intergalactic magnetic fields

Active Galactic Nuclei: Strategy

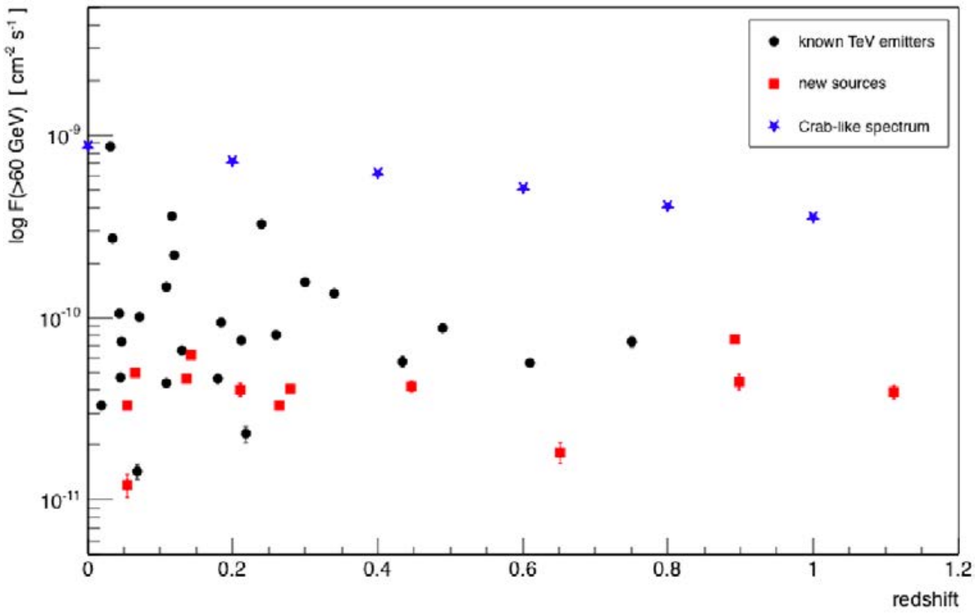
3 key components

- Long term flux monitoring
  - List of select archetypal VHE bright AGN (different classes and redshift)
  - 30 minutes each week for each target when visible
  - Lightcurves & time resolved spectra over a 10 year baseline
- Flare monitoring
  - External triggers from other instruments (threshold TBD)
  - Internal triggers from regular (~fortnightly) snapshots with CTA subarrays for a large sample of AGN (different AGN classes and redshift)
- High-quality spectra
  - Systematic coverage of VHE spectra across a large redshift range and across a variety of AGN type

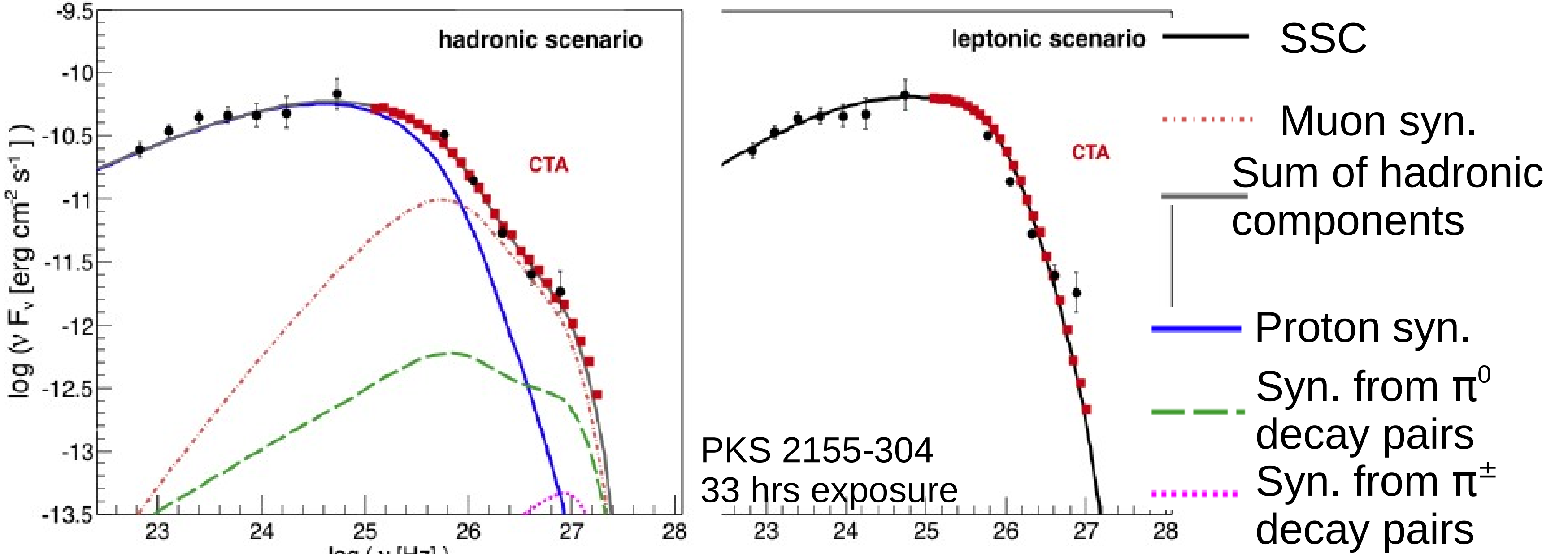
AGN: High-quality spectra Strategy

- A large number of CTA's extragalactic science goals require high temporally-resolved spectra with excellent energy resolution
- Construct list of targets (both known **and** potential VHE emitters) by extrapolating from 2nd Fermi Hard catalog (*E*>50 GeV) and applying modern EBL absorption models.
- Require broad redshift coverage (0.009 < z < 1.11)
- Require homogeneous coverage across AGN classes

Simulations: D. Mazin & A. Zech



AGN: High-quality spectra
Particle identification



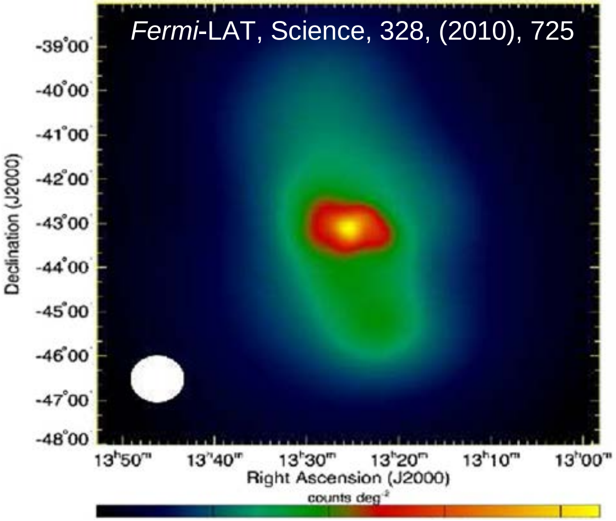
Cerruti,Zech & Boisson, 2015, MNRAS, 448, 0910

A. Zech & M. Cerruti for CTA, 33rd ICRC

- Current instruments lack the energy resolution/sensitivity to differentiate between hadronic and leptonic models
- Improvements afforded by CTA will allow us to identify emission from both leptonic and hadronic particles

AGN: Deep exposures (100h) of radio galaxies

- Cen A and M87 are both proposed for deep observations
  - Extract high-quality spectra
  - Search for extended emission
- M87: given its smaller extension, will be covered by one deep (100h) exposure
- Cen A: due to extension, 3 pointings are required (limited by FoV of LSTs).
  - ~50h per pointing
  - Allows us to cover southern radio lobe, as well as the kpc jets.



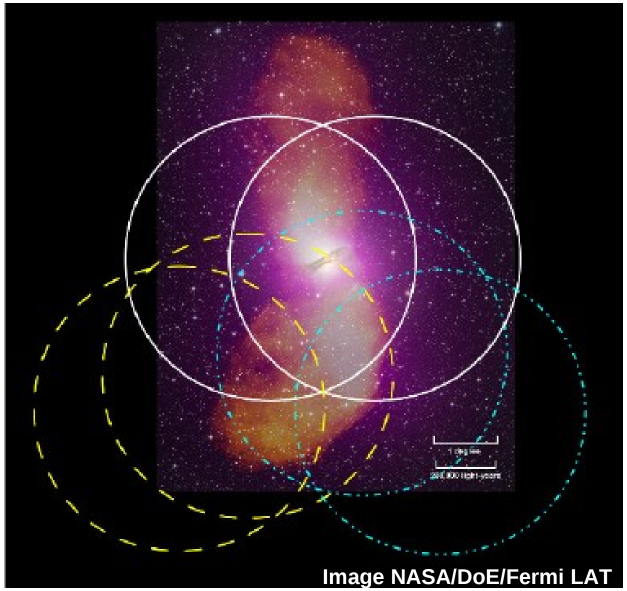
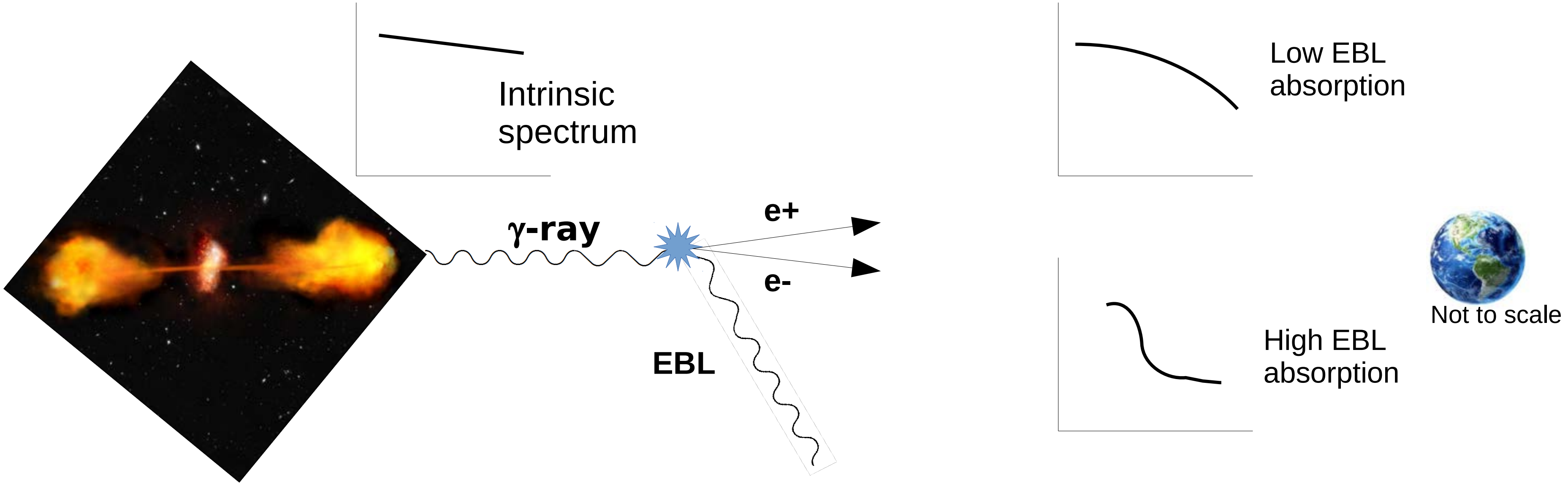


Image NASA/DoE/Fermi LAT
Capella et al.

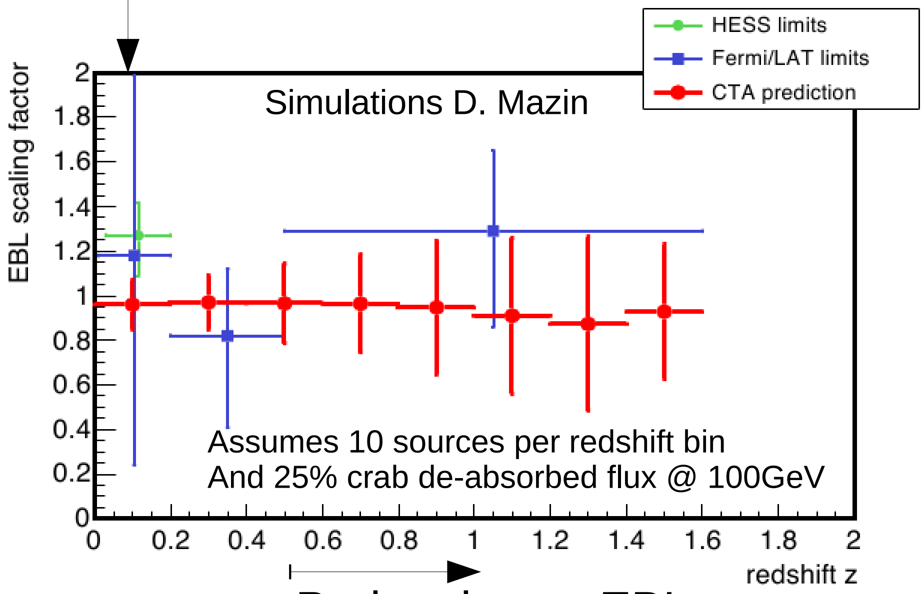
AGN: Extragalactic background light



- γ-rays interact with EBL photons to produce $e^{\pm}$ pair, attenuating the observed γ-ray spectrum
  - Severity of effect is redshift, EBL strength and γ-ray energy dependent
- Use this process to investigate the strength of the EBL

AGN: Extragalactic background light Potential

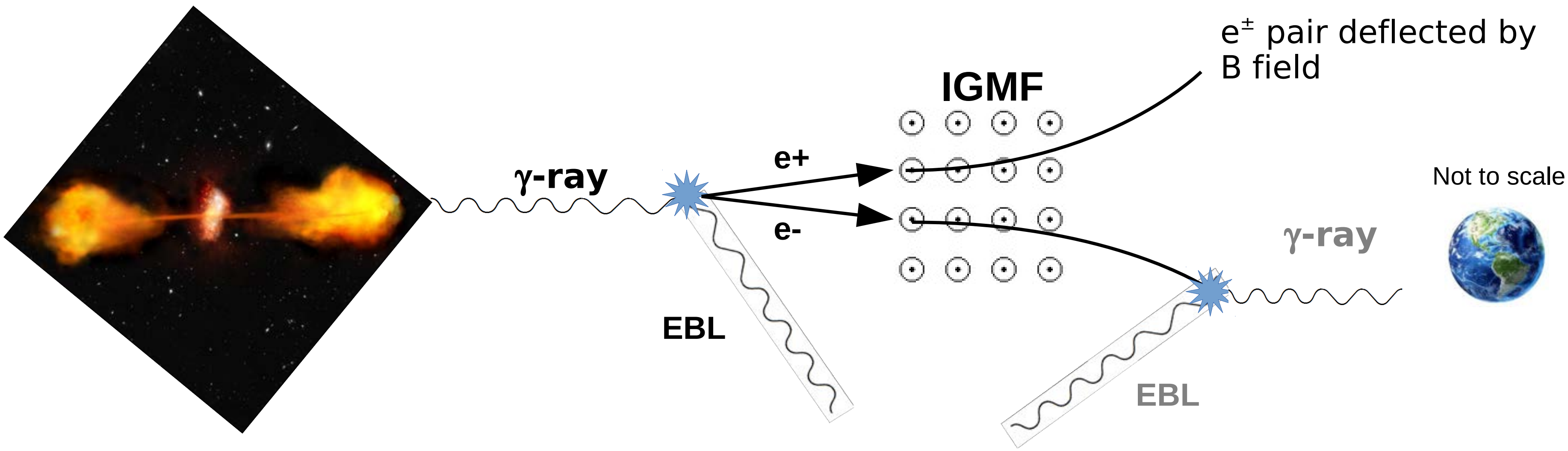
Primarily probe mid-IR EBL



Probe shorter EBL wavelengths (optical and UV)

- CTA's ability to simultaneously observe the GeV and TeV components of an AGN's flux allows us to disentangle intrinsic physical processes from external absorption features
- CTA will observe AGN across a large range of redshift. Targets taken from:
  - High-quality spectra program
  - Flare monitoring program (for large z)
- CTA's EBL-related goals include:
  - Measuring the far-IR to mid-UV EBL spectrum at z~0 with a 20-30% uncertainty
  - Characterise the evolution of the EBL up to a redshift of z~1 (allows to probe galaxy evolution and Hubble's constant eg Biteau & Williams, 2015)

AGN: Inter-Galactic Magnetic Field



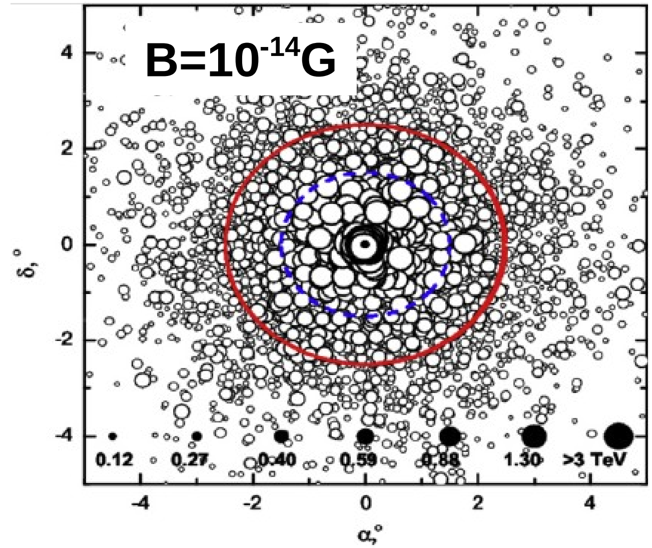
- γ-rays interact with EBL photons to produce e± pair, which then interact with the IGMF before interacting with EBL photons through inverse compton to produce a γ-ray again
- Use this process to investigate the strength of the IGMF
  - Time-resolved spectra
  - Imaging analysis

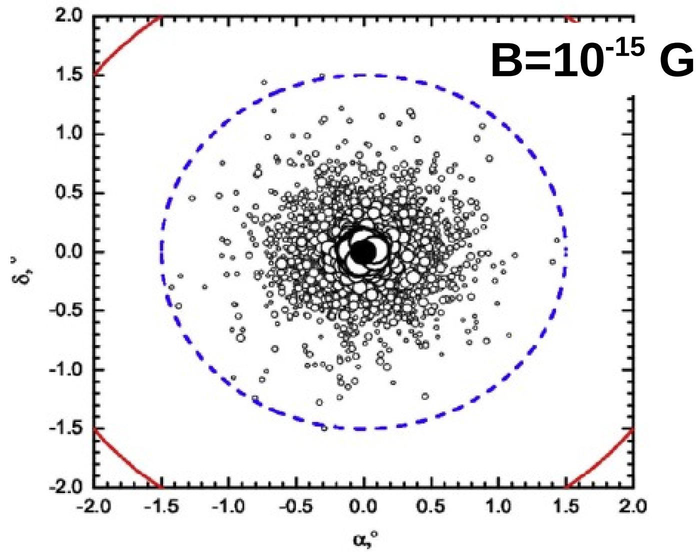
AGN: IGMF
Imaging strategy

- If B>10^{-16}G, the size of the deflection angle of the $e^{\pm}$ pairs allows us to search for an extended γ-ray 'halo' emission around the AGN.

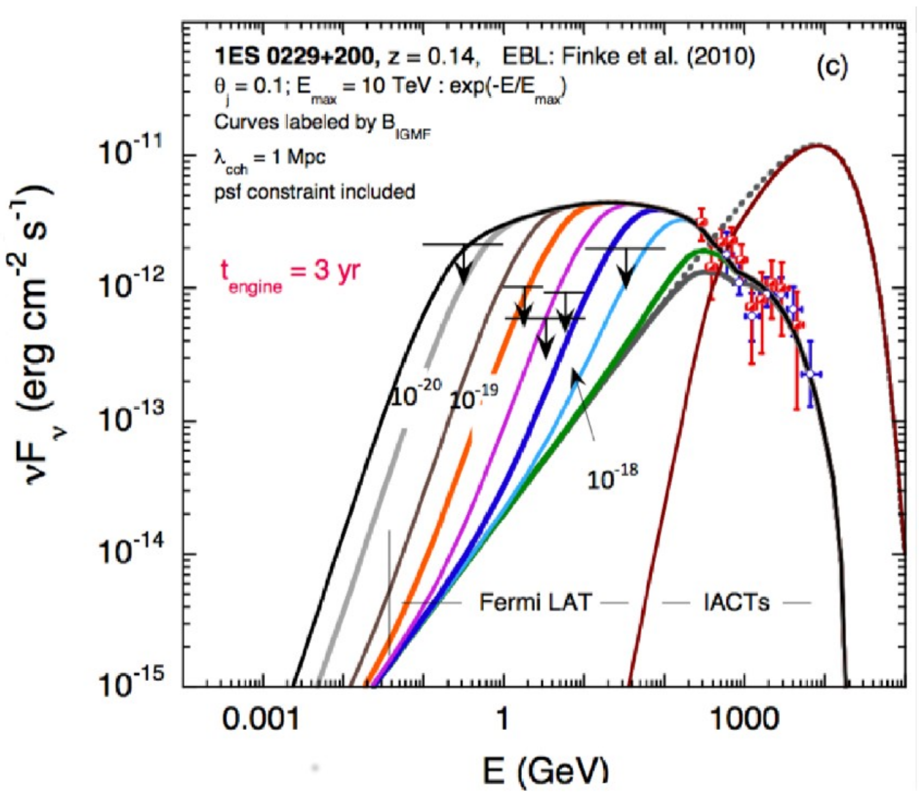
- CTA's angular resolution, combined with CTA's large field of view and sensitivity, will give us unprecedented ability to search for this emission.

Elyiv, Neronov & Semikoz, 2009, Phys.ReV.D, 80, 2





AGN: IGMF
Time-resolved spectra strategy



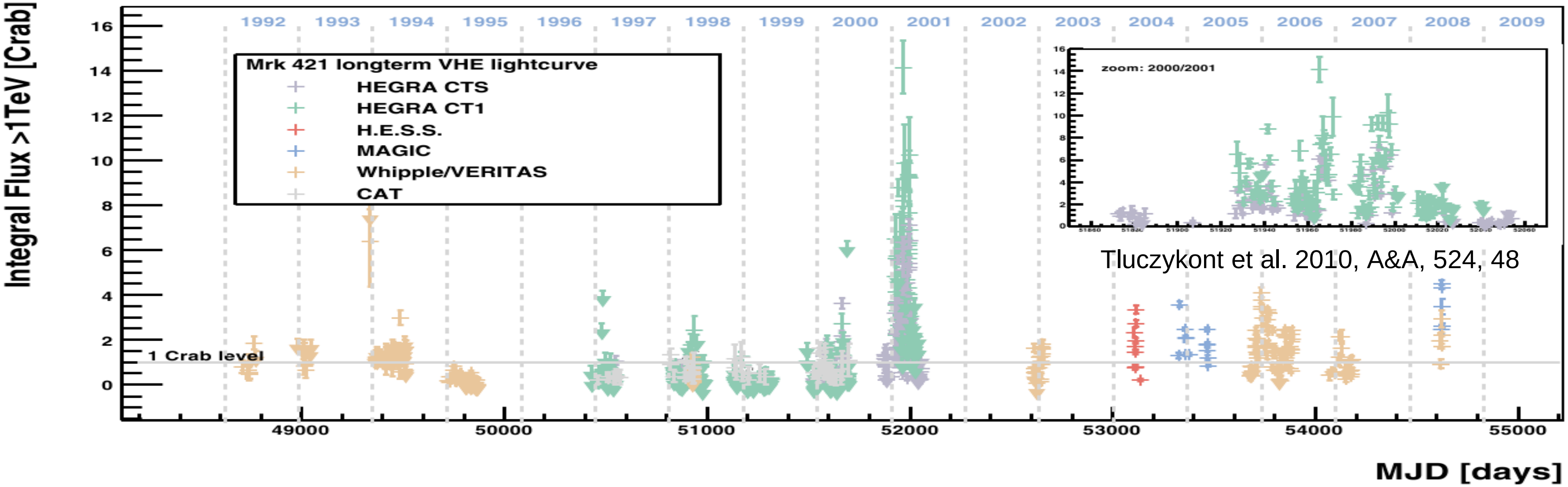
Dermer, Cavadini & Razzaque, 2011, ApJ, 733,L21

- For $B<10^{-16}$G: utilise the temporal properties of the magnetically driven cascade by searching for delayed signals at lower γ-ray energies.
- CTA's sensitivity allows us to disentangle temporally-dependent spectral components from constant ones.

AGN: Long term monitoring Motivation

- Long term monitoring allows us to study:
  - γ-ray properties in quiescence
  - Probability of flaring states
  - (Quasi-)periodic oscillations
  - Disk-jet connection

- Observing known VHE emitters irrespective of activity state allows for an unbiased duty-cycle.



Tluczykont et al. 2010, A&A, 524, 48

AGN:Long term monitoring Strategy

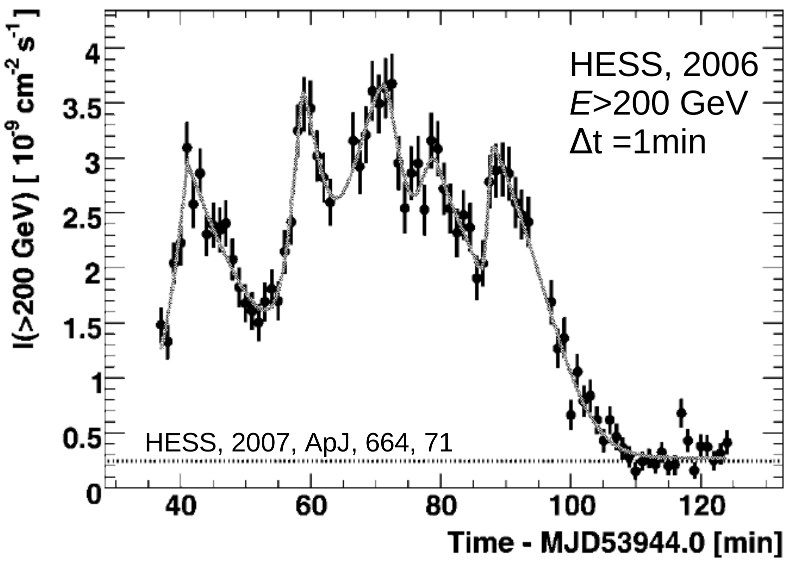
- Target prominent VHE sources across AGN class spectrum
  - ~30 minutes observation each week source is visible
  - Utilise full array
  - 7σ detection of all sources, sufficient for spectral measurements
  - For bright sources, will be able to extract spectra on shorter timescales

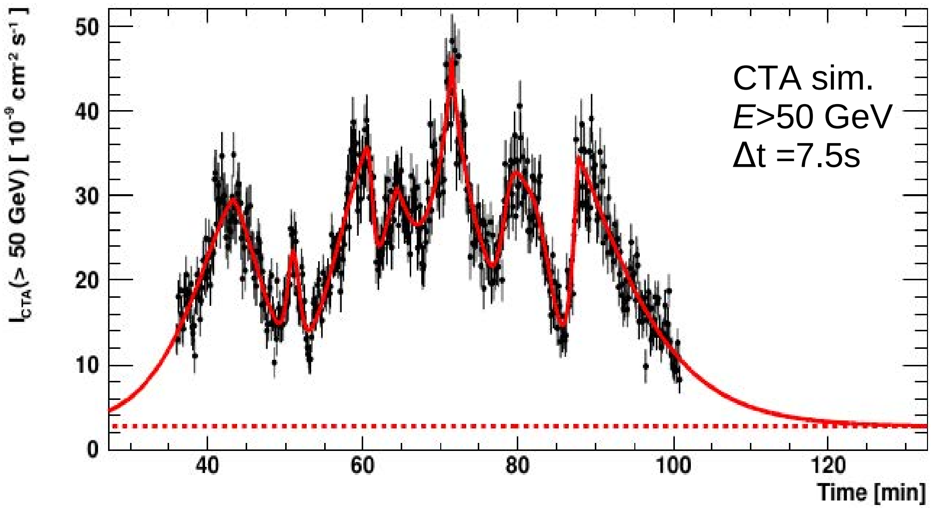
- UHBL
  - 1ES0229+200, 1ES1426+426 & 1ES1101-232
- HBL
  - Mrk 421, Mrk 501 & PKS 2155-304
- IBL
  - 1ES1011+496, 3C66A & W Comae
- LBL
  - AP Lib, BL Lacertae
- FSRQ
  - PKS 1510-089 & PKS 1222+216
- Radio Galaxies
  - M87 & NGC1275

AGN:Flare monitoring Strategy

- 2 complimentary approaches to catching flares
  - External triggers from eg. *Fermi-LAT,* HAWC, LHASSO or future instruments eg *VSOM*, *ASTROGAM, ATHENA*, LSST, SKA, GAMMA400
  - Internal triggers from CTA subarray snapshots of ~80 AGN (both known **and** potential VHE emitters).
- Snapshot program will use subarrays of CTA to take short exposure of ~80 AGN at ~20% crab flux sensitivity
  - Both known **and** potential VHE emitters
  - FSRQs through to UHBLs, *Fermi*-LAT detected radio galaxies & NLSy1s
- ~20 sources per week per site, ~1 hr per night total per site
  - Assuming flaring probability of ~1%, based on current duty cycle knowledge, expect around 20 flares per year per site

AGN:Flare monitoring Expected Results



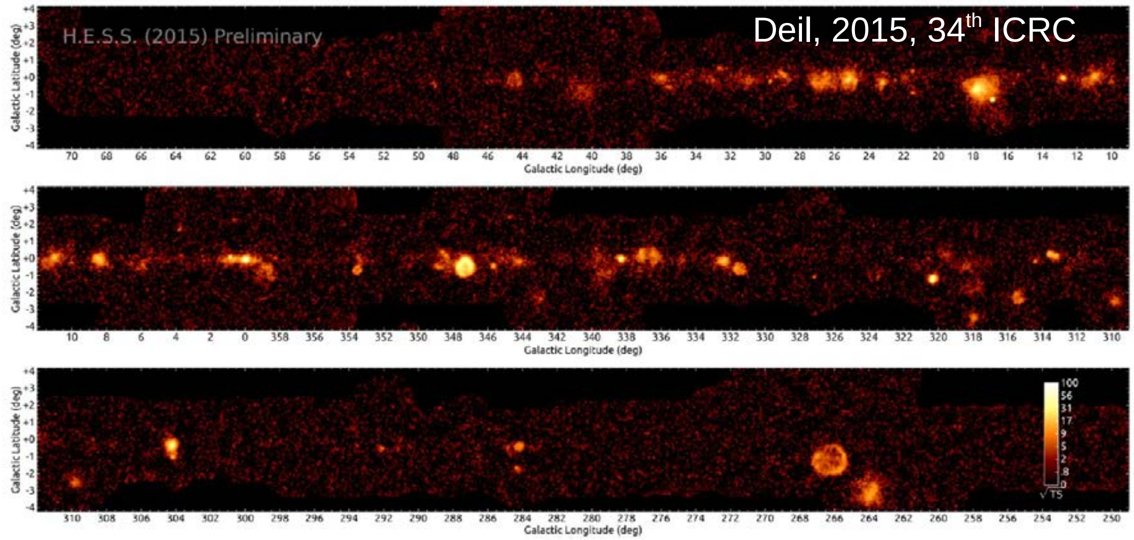


- Consider PKS 2155's 2006 flare
  - Power-law extrapolation of the HESS power spectrum, assuming red-noise at high frequencies
- Large effective area and energy range allows binning on timescales of ~7s!
- Allows for smaller variability timescales to be observed.
- Allows for better definition of flare rise and fall timescales.

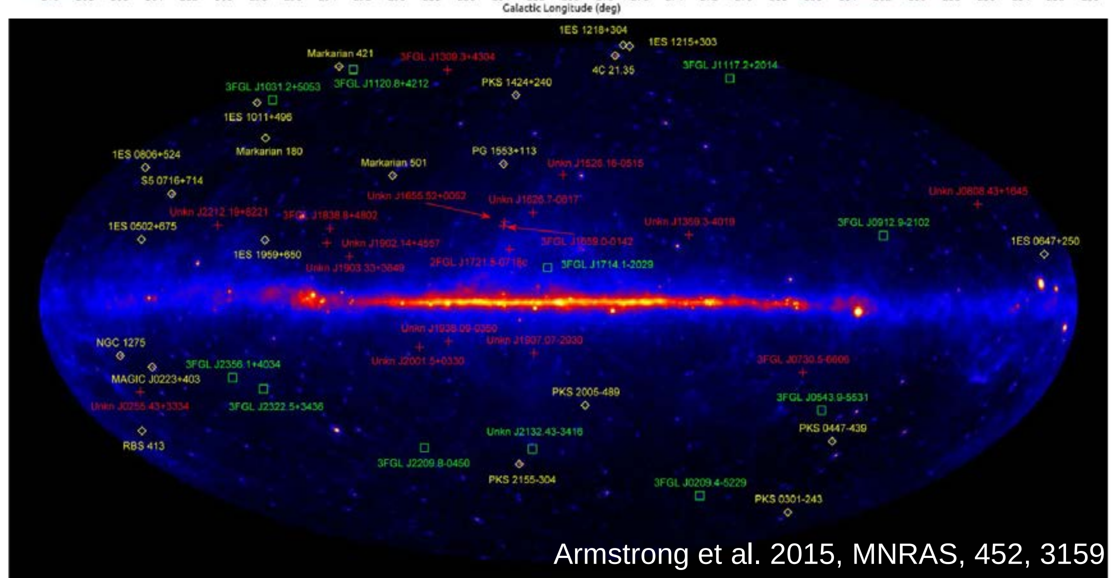
CTA's sensitivity allows for unprecedented temporal resolution

Extragalactic survey

- Previous surveys of the γ-ray sky have yielded valuable insights.
- A 'blind' extragalactic survey is a powerful tool.
  - Unbiased catalog of VHE sources
  - Discovery of new source types
  - Discovery of dark sources with no astrophysical counterpart
  - Serendipitous discovery of transients
  - Measure the diffuse emission (E>500 GeV)

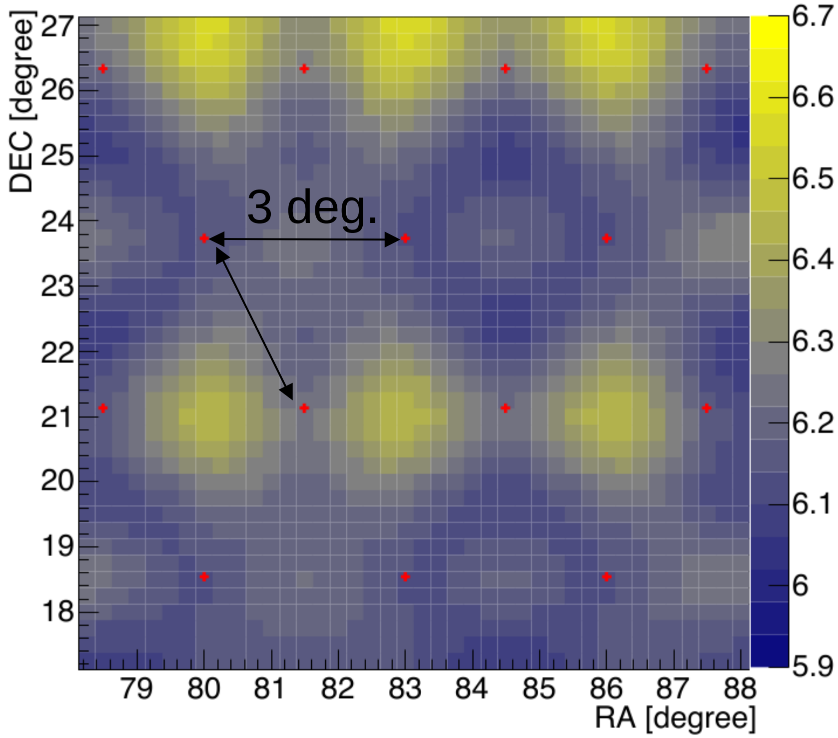


Deil, 2015, 34th ICRC



Armstrong et al. 2015, MNRAS, 452, 3159

Extragalactic survey: Strategy

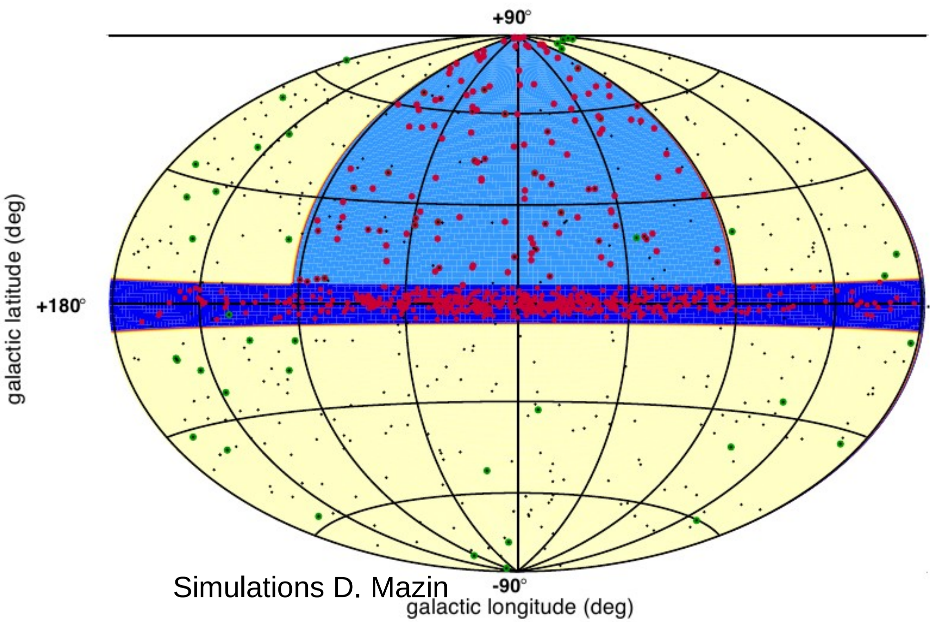


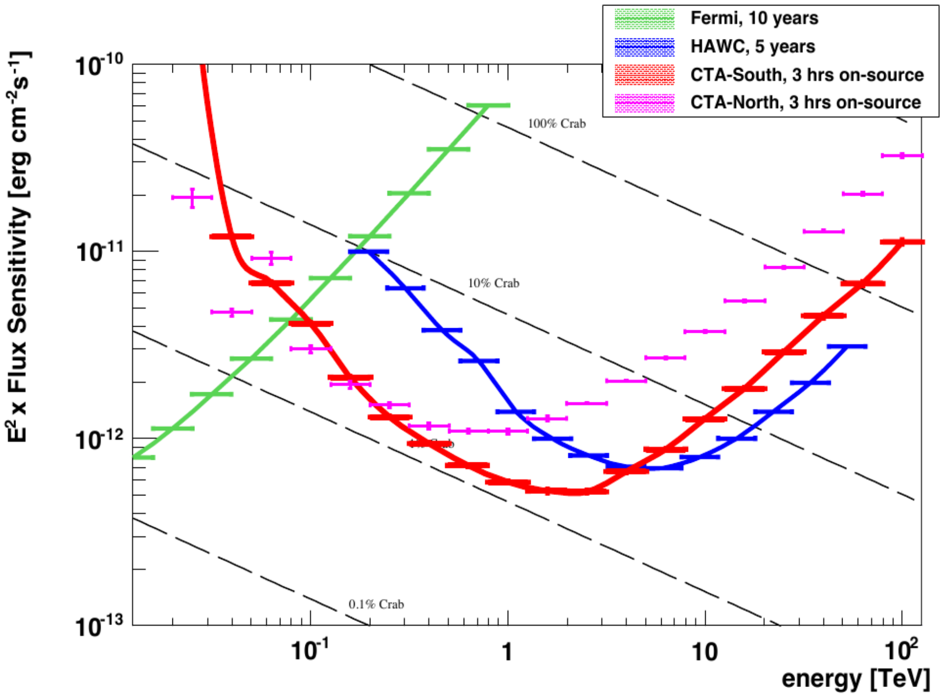
IRF		Time per pointing (h)	Integral sensitivity $S \pm \Delta S$
South	2a-noLST	0.55	5.9 ± 0.5
North	2NN	1.25	6.6 ± 0.6

- CTA will conduct a blind survey of 25%(10,000 deg^2) of the extragalactic sky
  - 1000h taken over ~3 yrs
  - Observe each FoV with several pointings (3 deg separation)
  - Uniform exposure ~6mCrab
- Divergent pointing?
  - Assuming FoV~200 deg^2
    - Factor 2 degradation in angular/energy resolution
    - Factor 1.5 gain in sensitivity
    - Beneficial for transients.

Extragalactic survey: Expected results

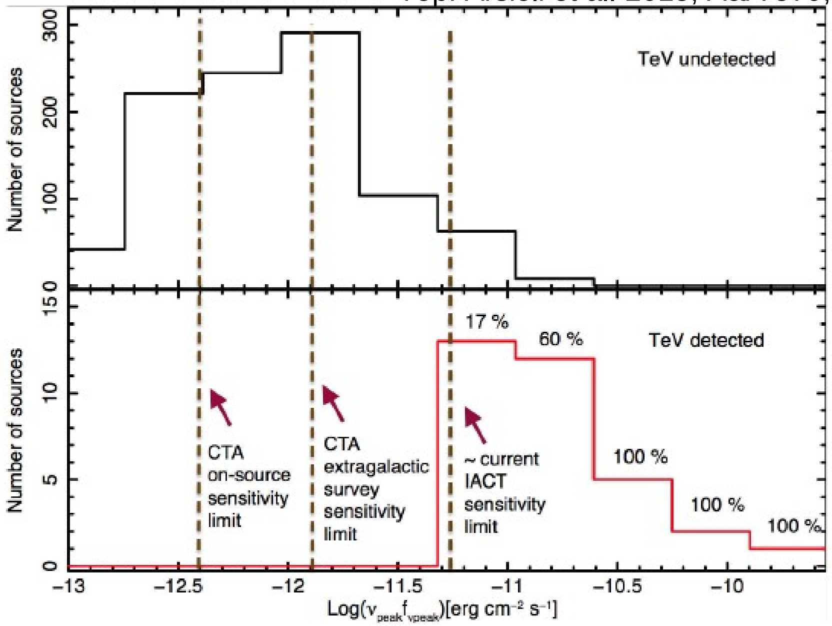
- At worse: expect 30-40 detections based upon 1FHL spectra
- At best: expect up to ~150 detections based on AllWISE catalog with IR/X-ray cuts
- In general: first unbiased view of $0.1 < E_\gamma < 10$ TeV extragalactic sky



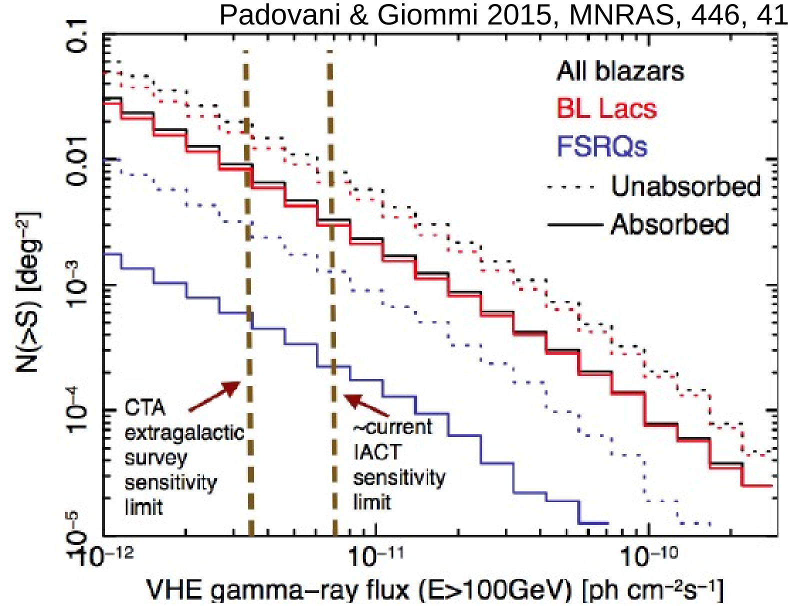


Extragalactic survey: Discovery Potential

Top: Arsioli et al. 2015, A&A 579, A34

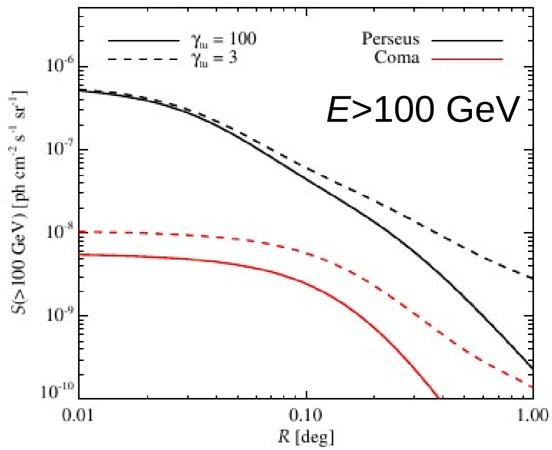


Padovani & Giommi 2015, MNRAS, 446, 41

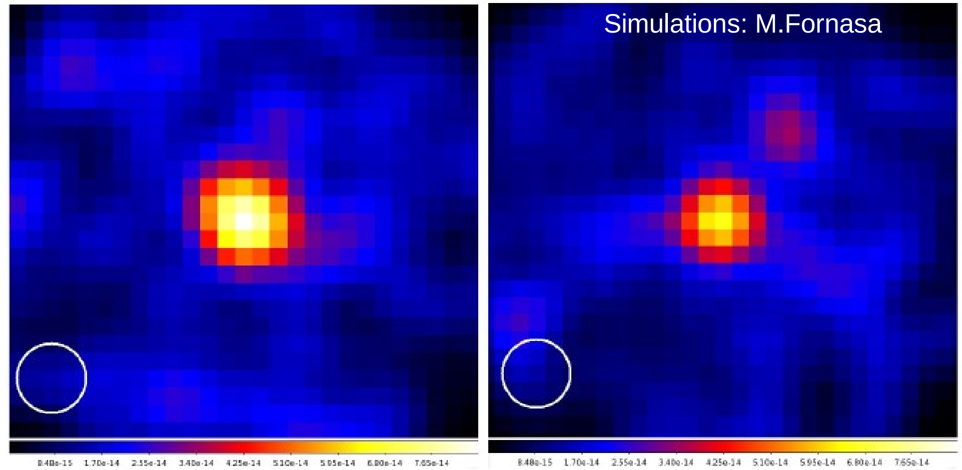


- Unbiased survey allows us to measure the luminosity function of blazars (the so-called log N – log S distribution).
  - Fundamental to understanding the main physics drivers of the γ-ray emission and how they evolve with time
  - Crucial to determining the total γ-ray diffuse background

Galaxy Clusters



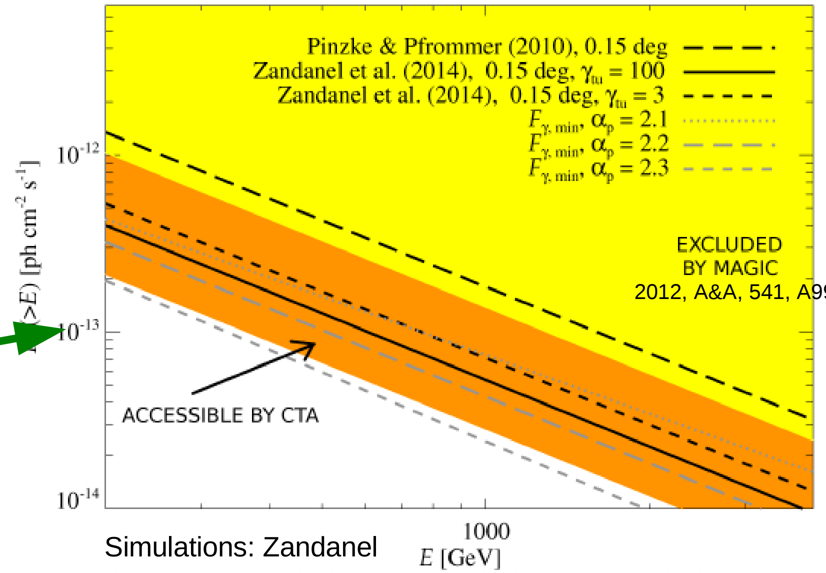
Zandanel et al. 2014, MNRAS, 438, 124

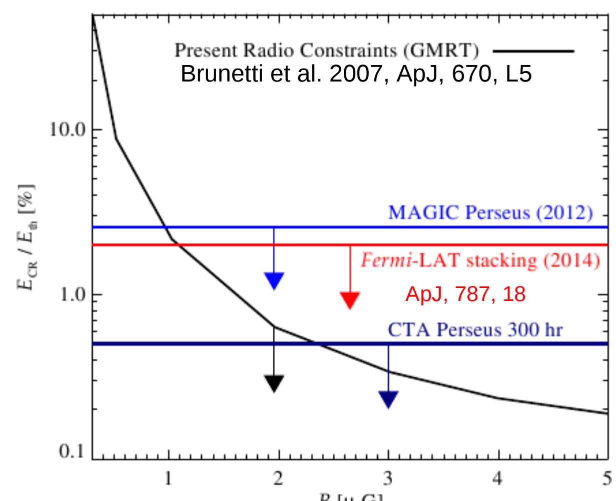


- CR protons accelerated and contained within cluster during its lifetime → do not expect properties to change significantly between different clusters with similiar masses.
- Deep (~300h) observation of the Perseus cluster
  - Target selection based on distance, mass & size of the cluster, in conjunction with the strength of its diffuse radio emission and the results of hydrodynamical simulations
- Additionally, we get deep exposures of NGC 1275 and IC310

Galaxy Clusters: Expected Results

- Expect a factor of 5 improvement on current flux limits of diffuse VHE emission from clusters
- If no diffuse emission is observed, we can
  - Constrain a hadronic origin for the radio halo
  - Constrain the CR/thermal ratio for a range of B-fields
- If diffuse emission is observed, we will perform spatial and spectral studies to investigate CR propagation.





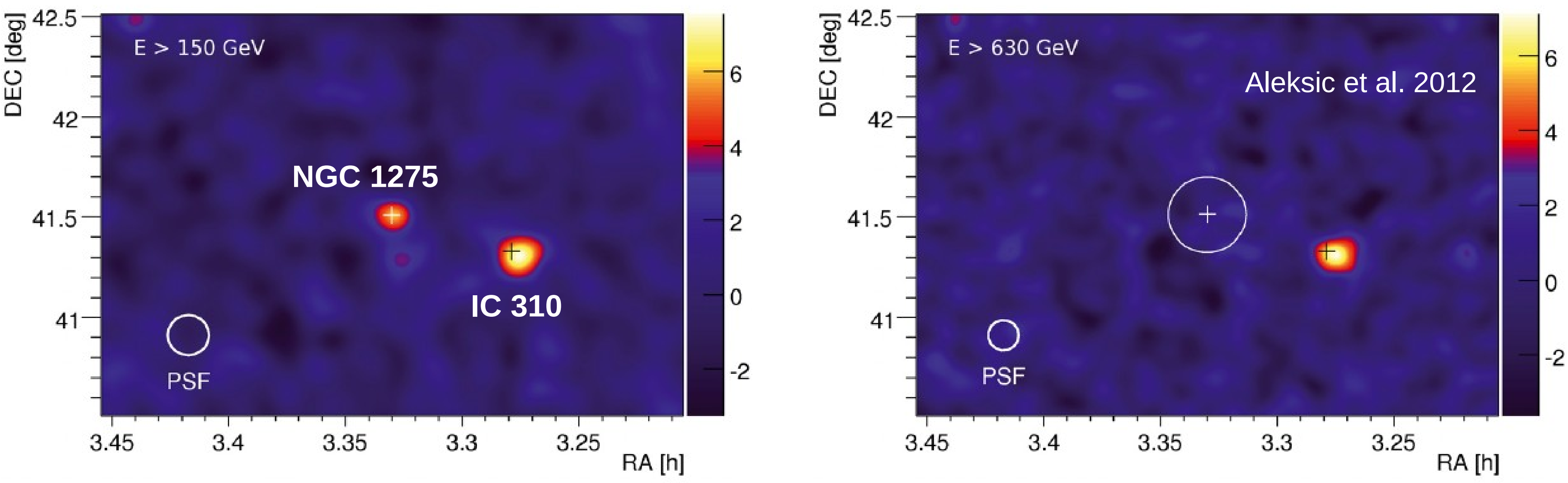
Summary

- Observations in the early phase of operation will be used to 'fine tune' CTA's extragalactic observing program
- The improvement in telescope performance afforded by CTA will:
  - Give us an unparalleled view of AGN with unprecedented spectral and temporal resolution
  - Allow us to perform a survey of the extragalactic sky with unprecedented sensitivity in the ~100GeV to ~10 TeV energy range
  - Observe/constrain cosmic ray induced diffuse emission in galaxy clusters
- Flare alerts to the community, combined with MWL and MM coverage will strengthen the science return of CTA's extragalactic observing program
- Since CTA will cover observing program which require large amounts of observing time, there is still plenty of AGN science to be done as a guest observer!

Back-up

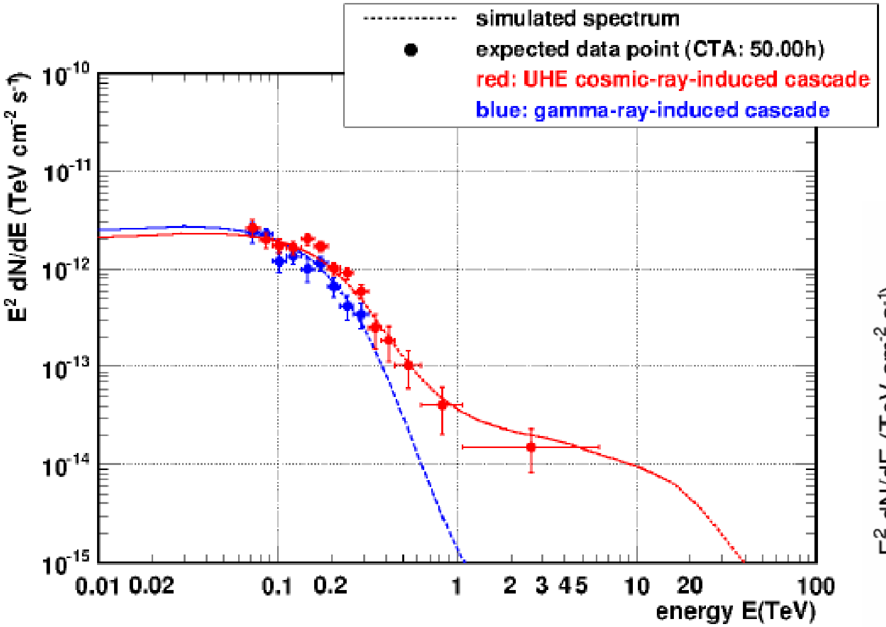
Galaxy Clusters: Perseus cluster AGN sources

- IC310 is 0.6 degrees from Perseus cluster center thus is spatially removed from where we expect the diffuse emission
- NGC1275 is at the center. However:
  - Its point like
  - Spectrally-soft (index of -4)
  - Large amount of flux variability

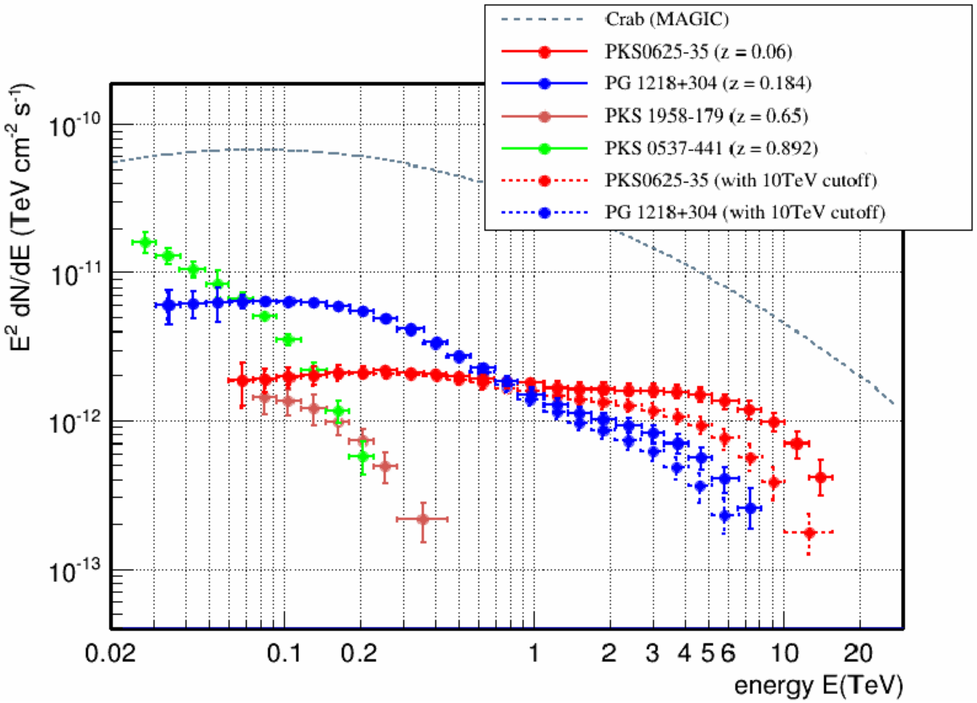


AGN: High-quality spectra other signatures?

- UHECR signature?



- Cut-offs in the spectrum?



AGN:Flare monitoring Motivation

- Sampling VHE fluxes below the light-crossing timescale of the SMBH affords valuable insights into the inner workings of AGN.
- To date, observations of a few extreme flare events have:
  - Highlighted the severe limitations of standard emission models (eg. HESS observations of PKS 2155-304)
  - Suggested more sophisticated models (eg. MAGIC observations of IC310)
  - Suggested multi-zone emission models (eg. *Fermi-LAT* observations of PKS 1510-089)
- Beyond understanding the intrinsic properties of AGN, flares are needed to study the EBL and IGMF at redshift > 0.5

AGN: Extragalactic background light

Mazin et al. 2013, APh, 43, 241