Large-Scale Intergalactic Magnetic Fields Constraints with the Cherenkov Telescope Array

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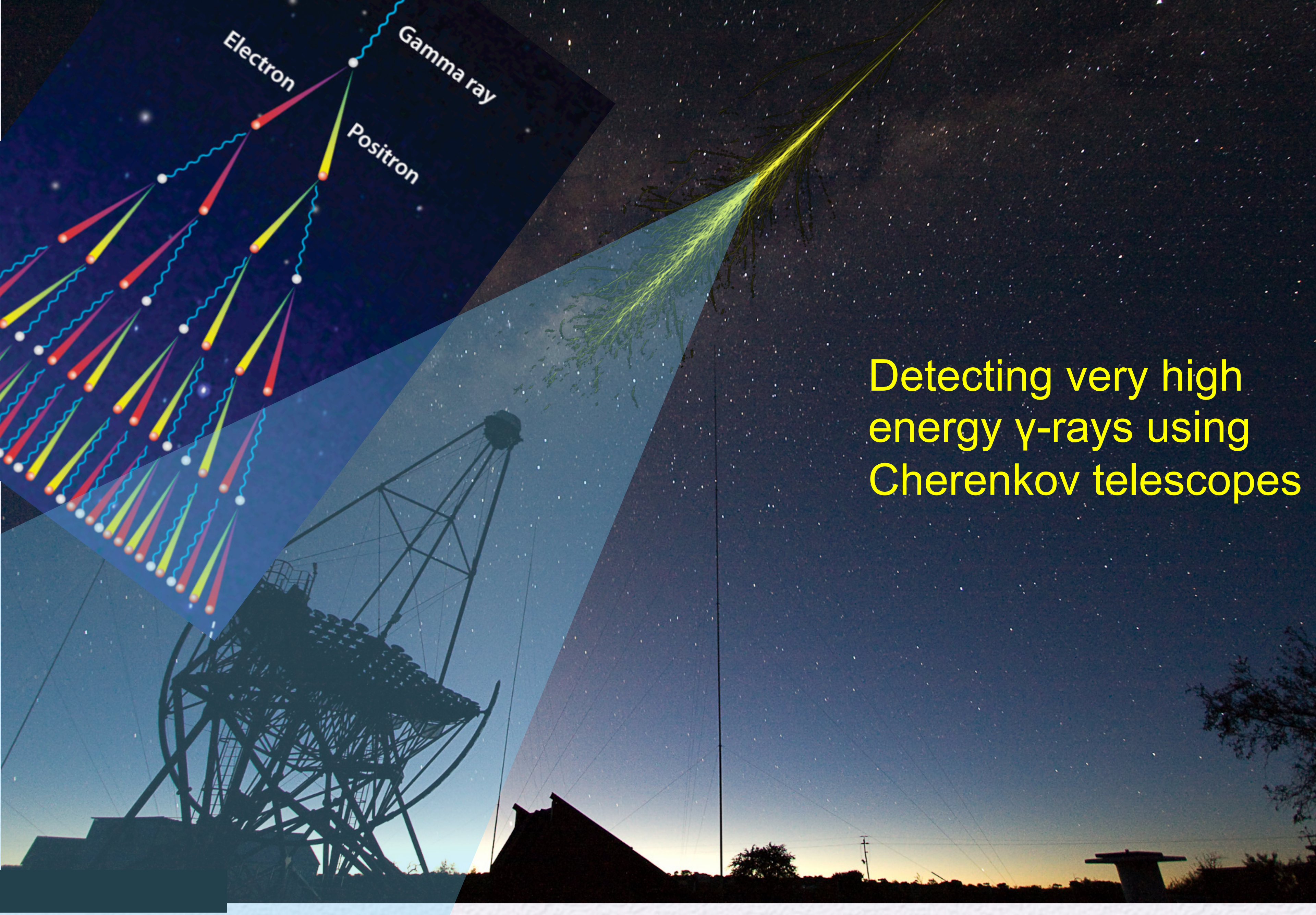
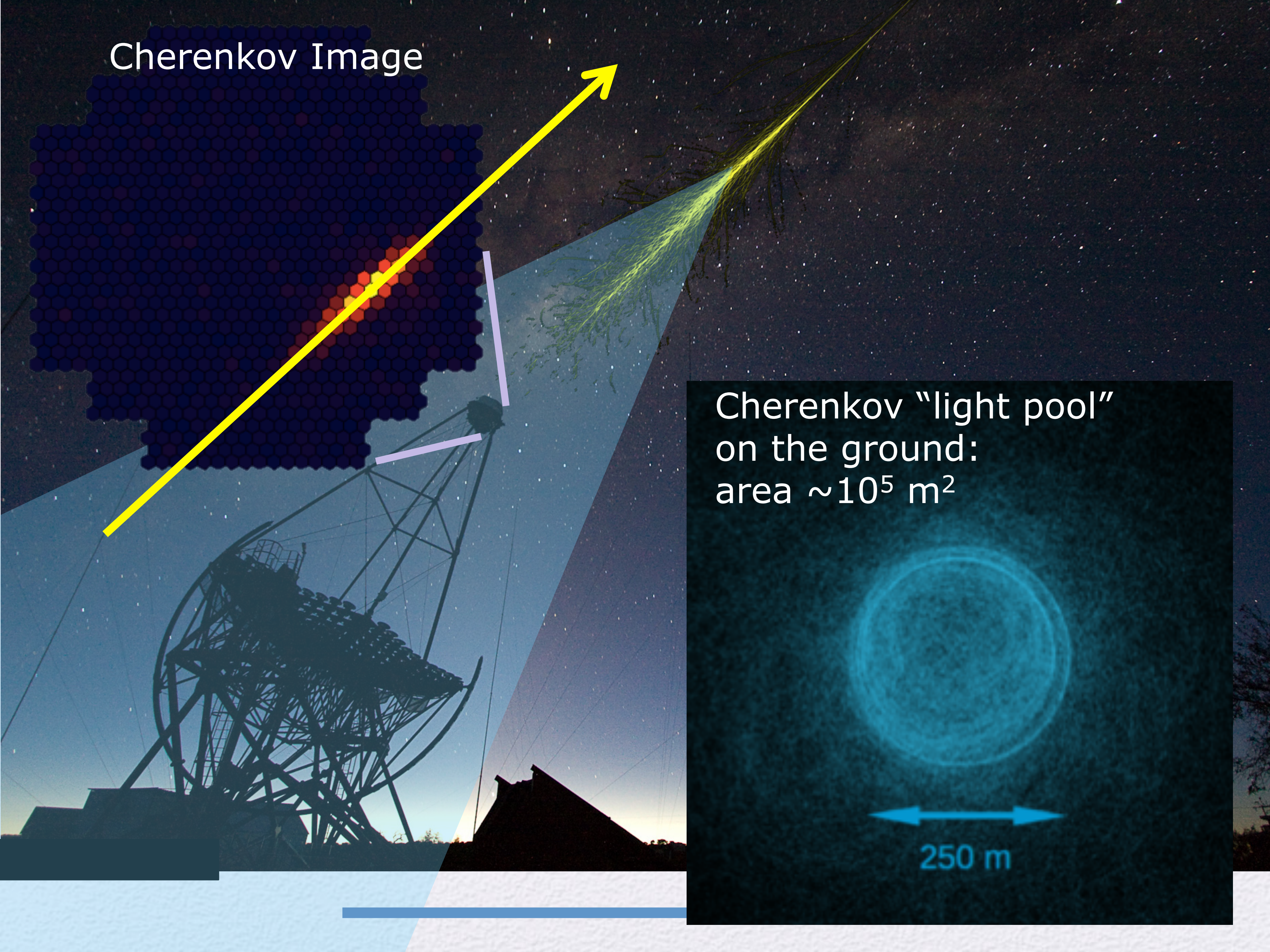
Magnetic Fields in the Universe VI conference

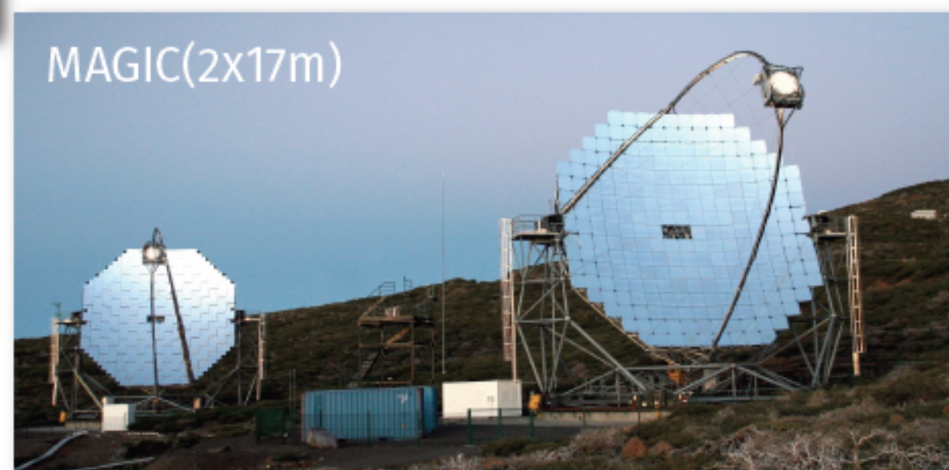


Detecting very high energy γ-rays using Cherenkov telescopes

slide from E. de Gouveia Dal Pino


Cherenkov Image
Cherenkov "light pool"
on the ground:
area ~10^5 m^2
250 m

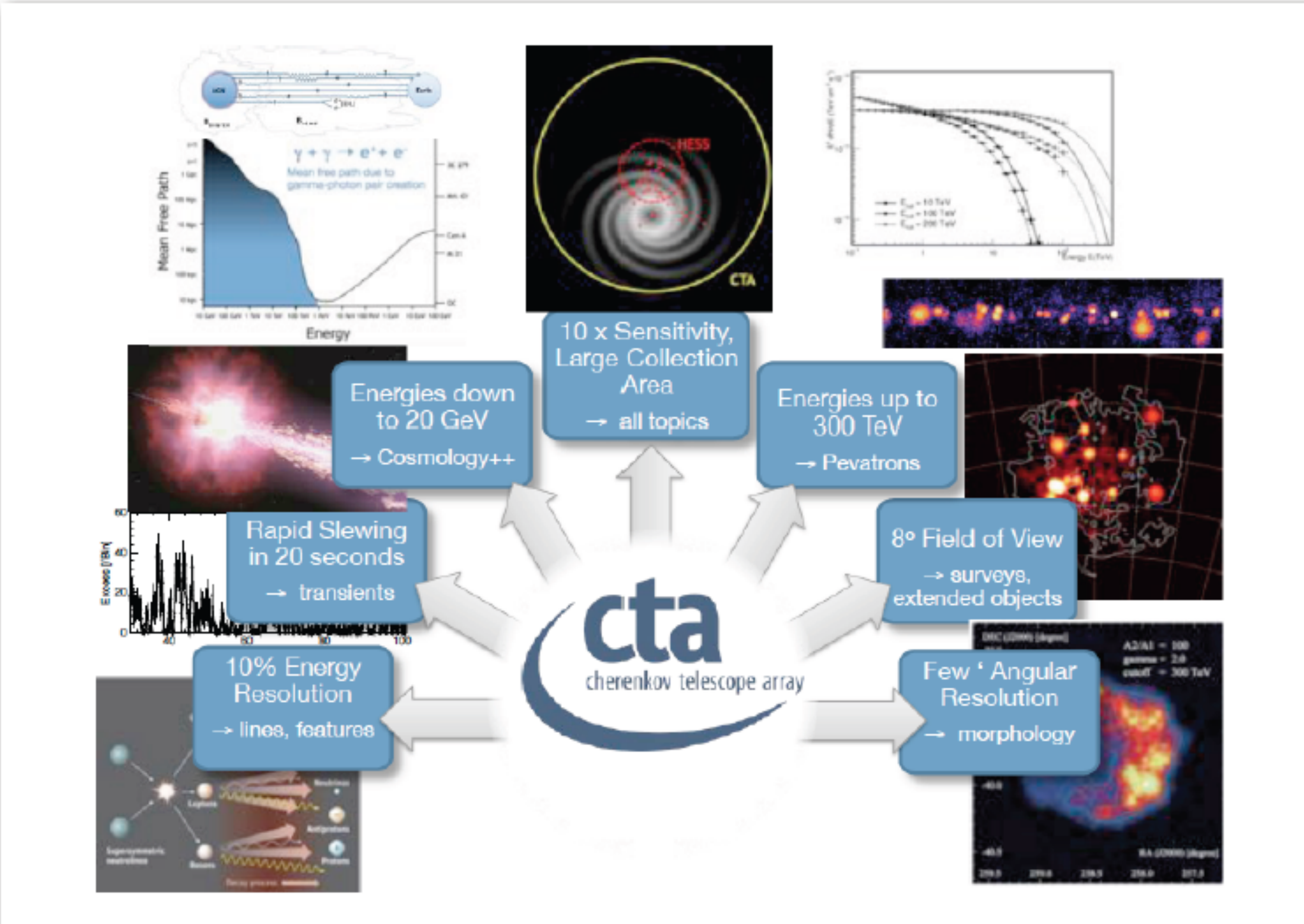
The current IACT status



- CTA ➔ next generation imaging atmospheric Cherenkov telescope

Where to find us

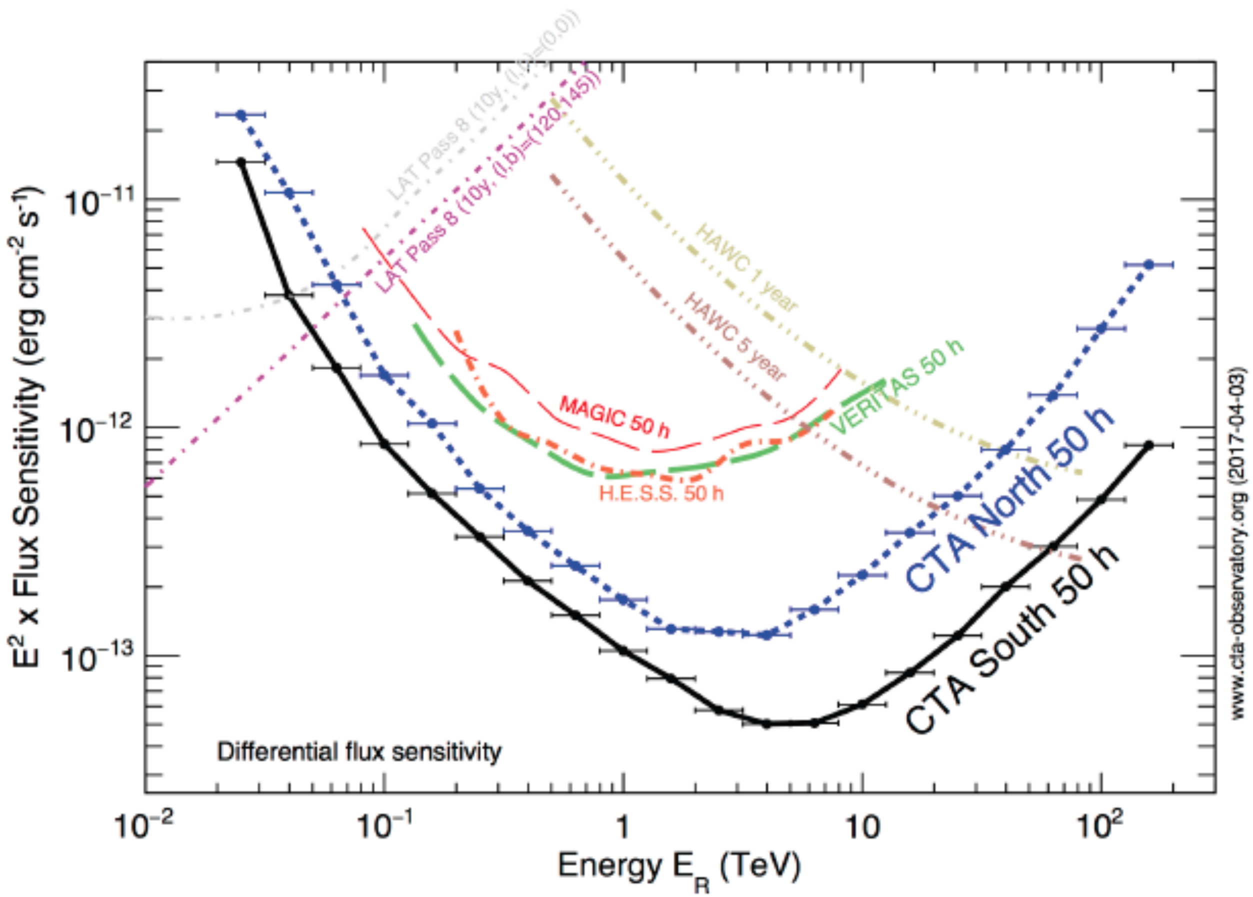
CTA Science



Credits: W. Hofmann, MG 2015

CTA Performance

Differential Sensitivity



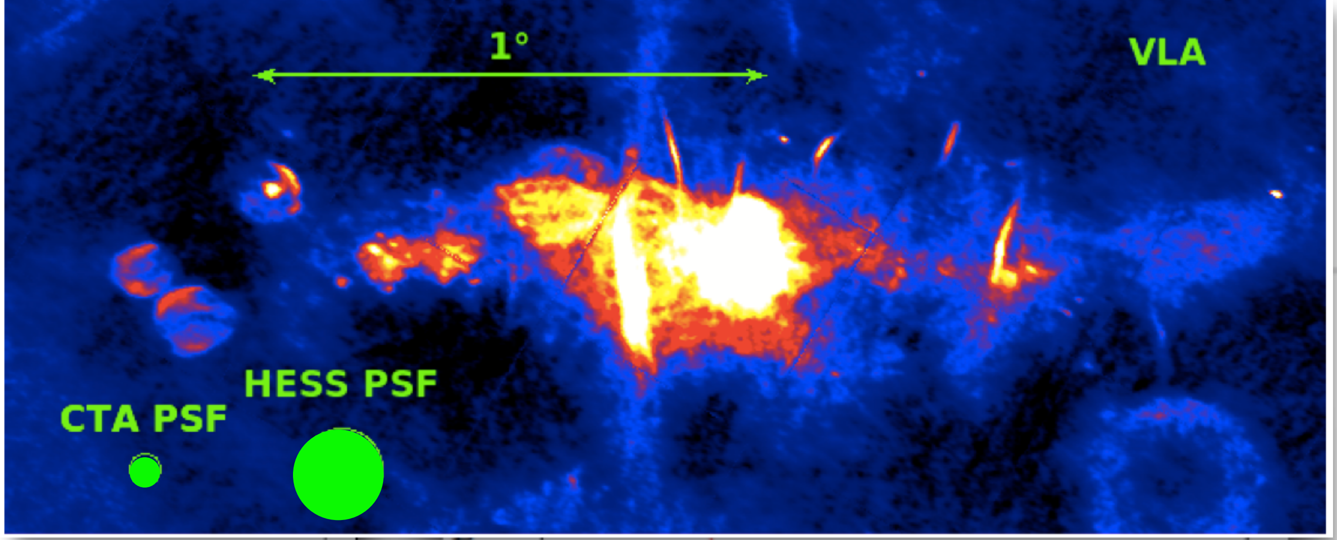
A factor of **5-10 improvement** in sensitivity in the domain of **about 100 GeV to some 10 TeV.**

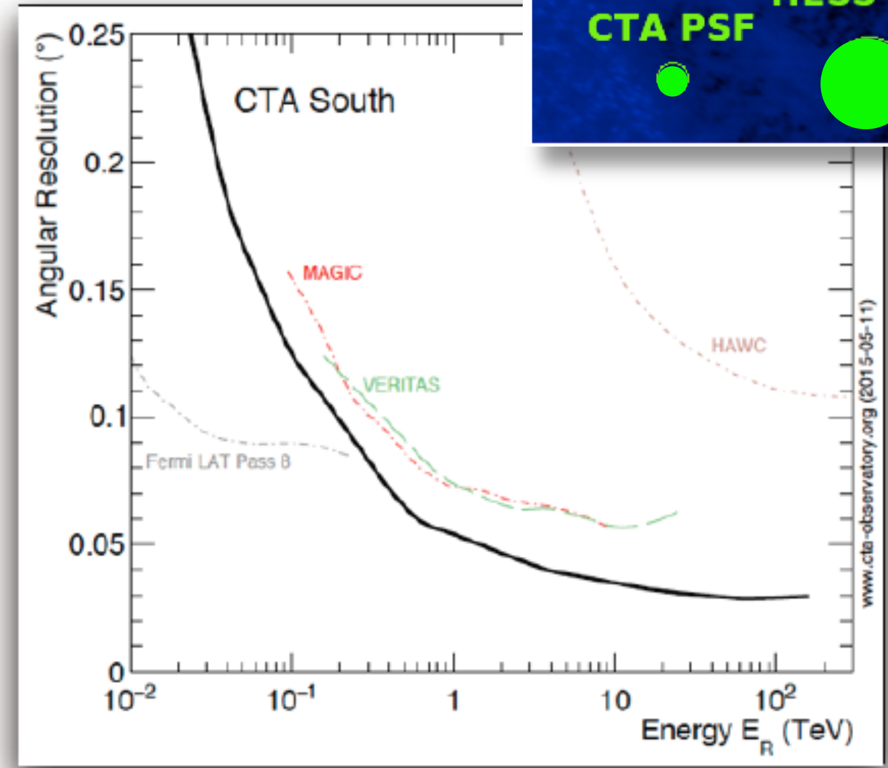
Extension of the accessible energy range from **well below 100 GeV to above 100 TeV.**

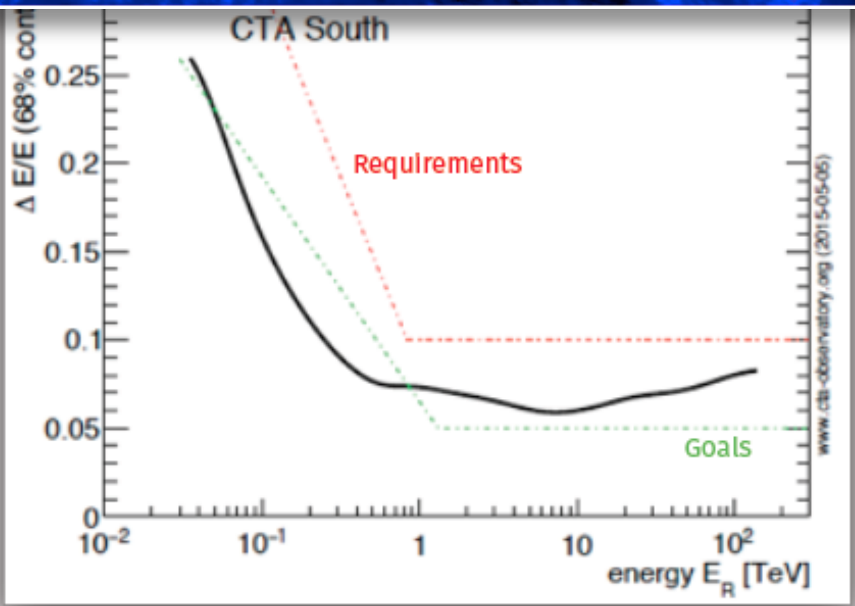
Credits: The CTA Consortium

CTA Perform

Angular Res





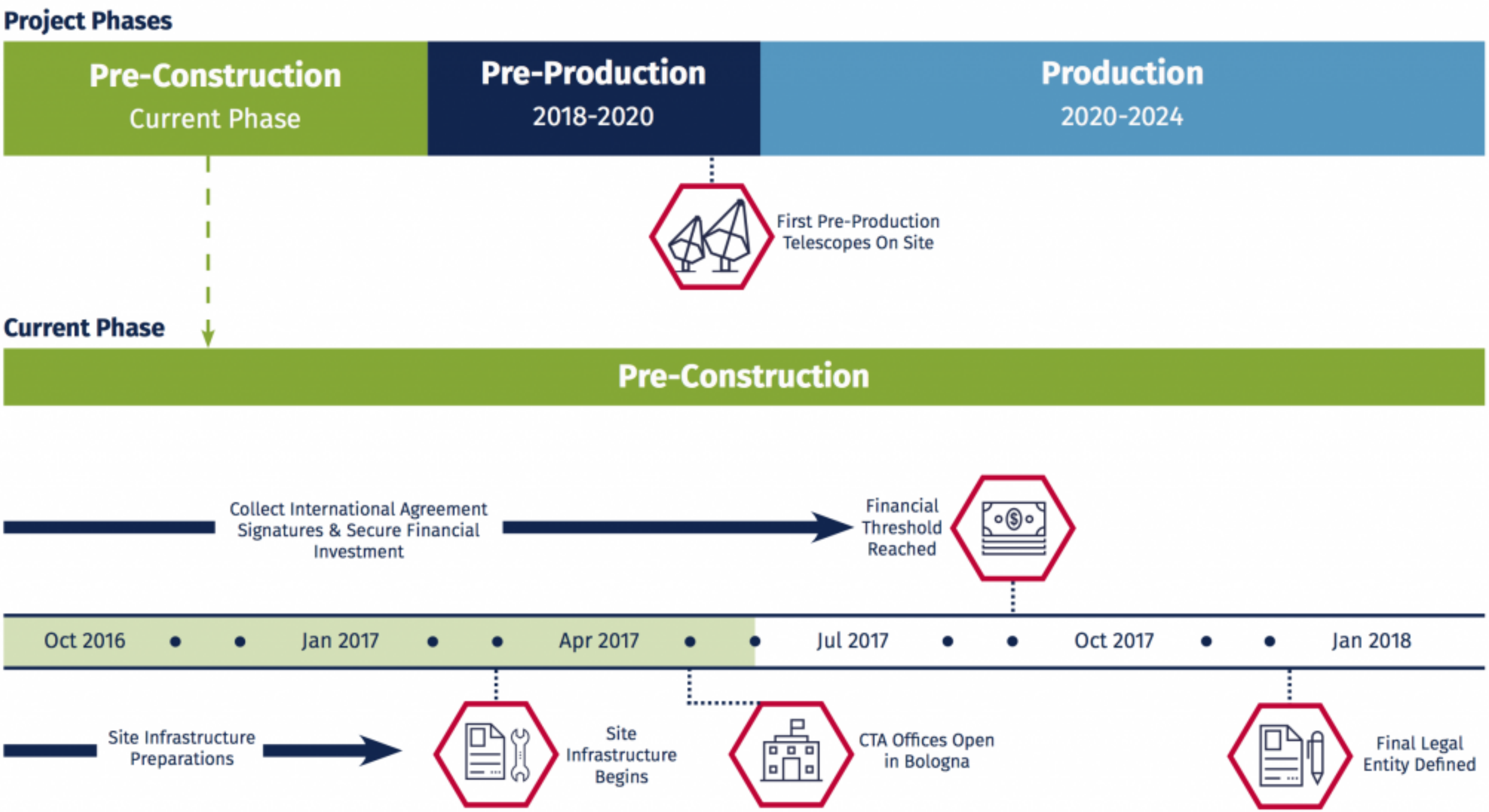


Further improvements of shower reconstruction algorithms and optimization of event selection can improve the IRFs.

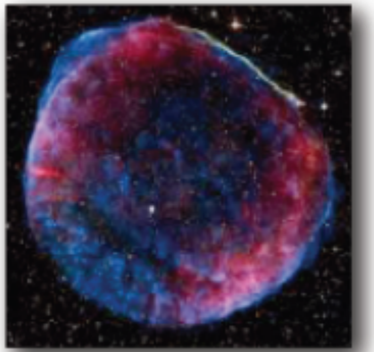
You can download the Instrument response functions at the following URL:
https://www.cta-observatory.org/science/cta-performance/

Credits: The CTA Consortium

CTA Timeline

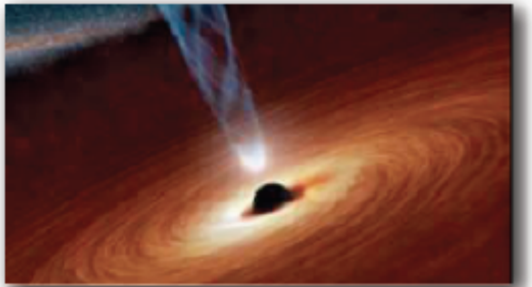


CTA Main Scientific Themes



Cosmic Particle Acceleration

- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?



Probing Extreme Environments

- Processes close to neutron stars and black holes
- Processes in relativistic jets, winds and explosions
- Exploring cosmic voids

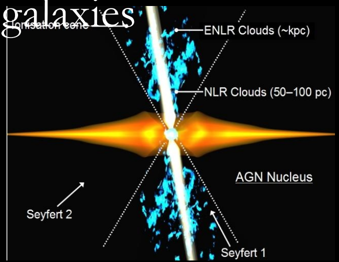
Physics frontiers – beyond the Standard Model

- What is the nature of Dark Matter? How is it distributed?
- Is the speed of light a constant for high-energy photons?
- Do axion-like particles exist?

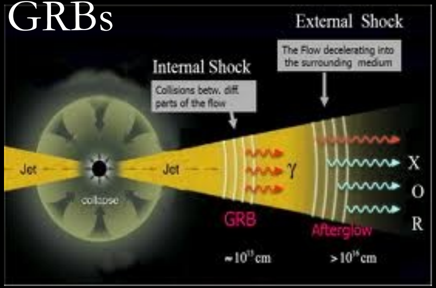
Adapted from J. Knödlseder.
More information on Astroparticle Physics, Vol. 43, 1-356 (2013) & CTA Contributions to the 2015 ICRC Conference [arXiv:1508.05894]

CTA Extragalactic Targets

other galaxies

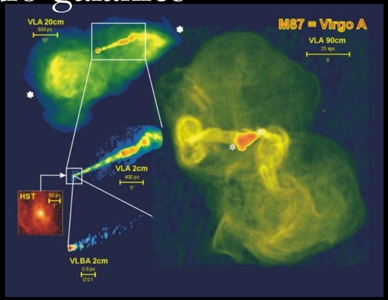


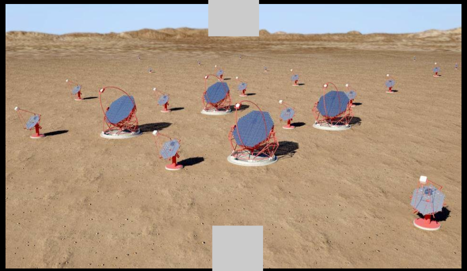
GRBs



blazars

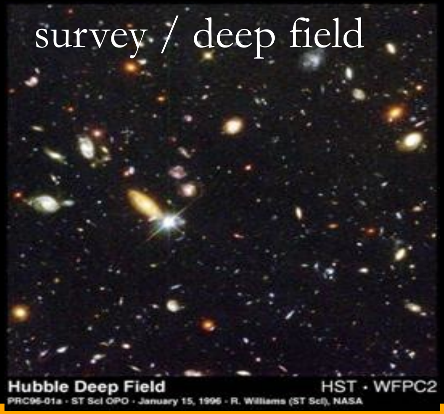
radio galaxies





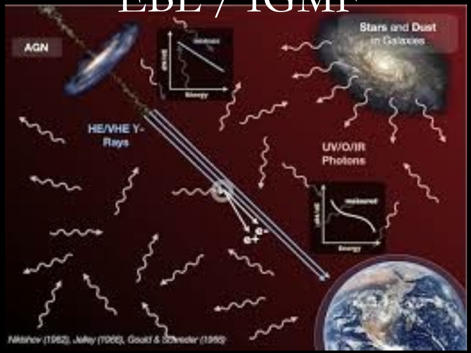
star forming regions

survey / deep field



galaxy clusters

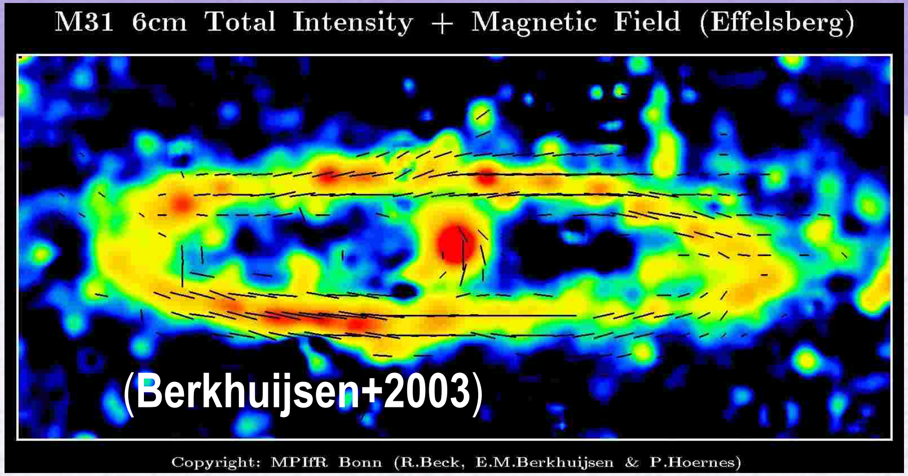
EBL / IGMF



Slide from D. Mazin

Origin of Cosmic Magnetic Fields

- Magnetic fields are observed on large scales
  - Galaxies, galaxy clusters
  - Order of 1 – 10 μG

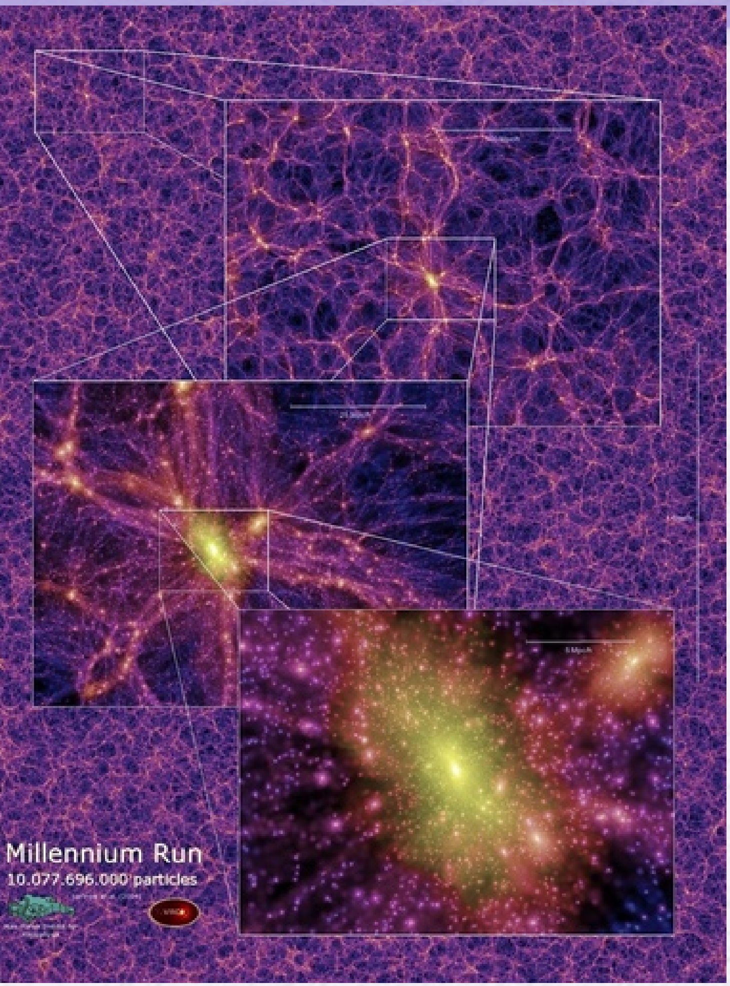


- Created from much weaker initial seed fields, via amplification by turbulent dynamo processes
- Origin of seed fields is unknown (Widrow 2002)
- 2 model classes for generating seed fields

✓ Cosmological: seed fields are produced in the primordial Universe
  - Inflation, decoupling, phase transitions (Grasso & Rubinstein 2001)

✓ Astrophysical: plasma motions from baryonic processes (SF, SN, BH, jets) in galaxies (Ryu+2012)

Magnetic Fields in InterGalactic Medium



- Intergalactic Magnetic Field (IGMF) =
  - ✓ MF in low-density intergalactic space
  - ✓ Not related to gravitational collapse
  - ✓ Coherent on scales larger than known structures in the cosmos
- IGMF distribution is crucial in understanding the origin of cosmic MF
- Challenging to directly observe diffuse magnetic fields in the IGM
- This talk ➔ how IGMF can be constrained using γ-ray obs

Upper Limit on IGMF: Standard Constraints

$B_{IG} < 10^{-8}$ G $B_{IG} < 10^{-9}$ G

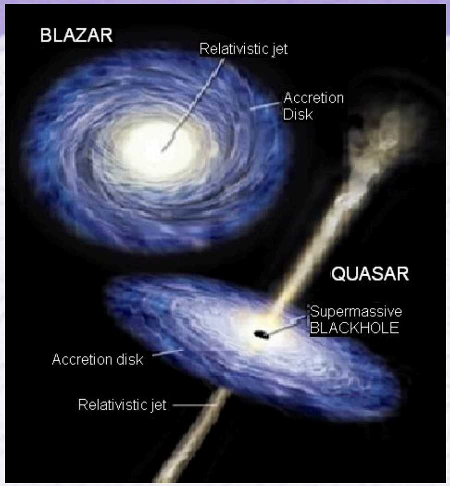
1) Big Bang nucleosynthesis:
   - a strong primordial magnetic field would change the expansion rate, & abundance of the primordial elements

2) CMBR anisotropy, angular power spectrum:
   - Magnetic field present at decoupling induces unequal expansion in different directions and distort the CMBR, not observed
   - over the 10Mpc-scale (Durrer+1998, Ade+2015)

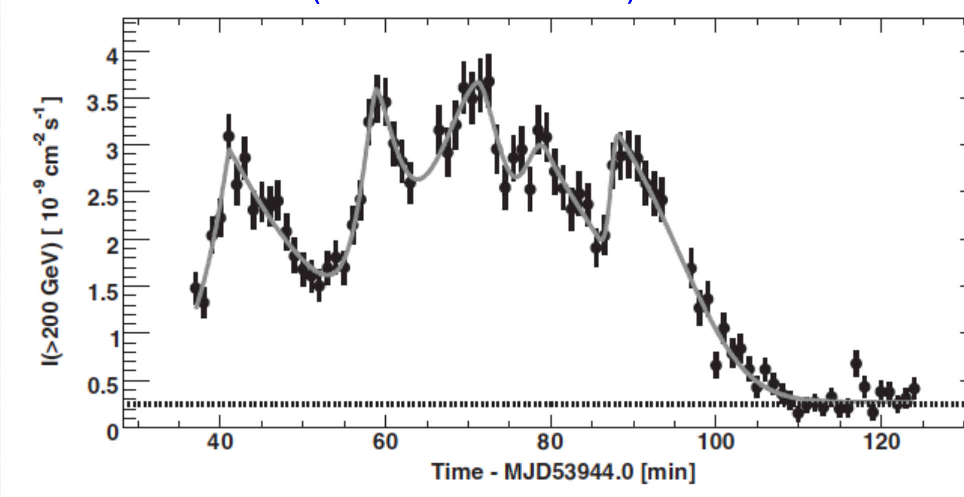
3) Faraday rotation measures of polarized radio emission from AGN/quasars
   - Variance of the rotation measures should increase with z, which is not detected
   - Upper limit deduced (Kronberg 1994, Pshirkov+2016)

Novel Technique to Measure IGMF: VHE Emission from Blazars

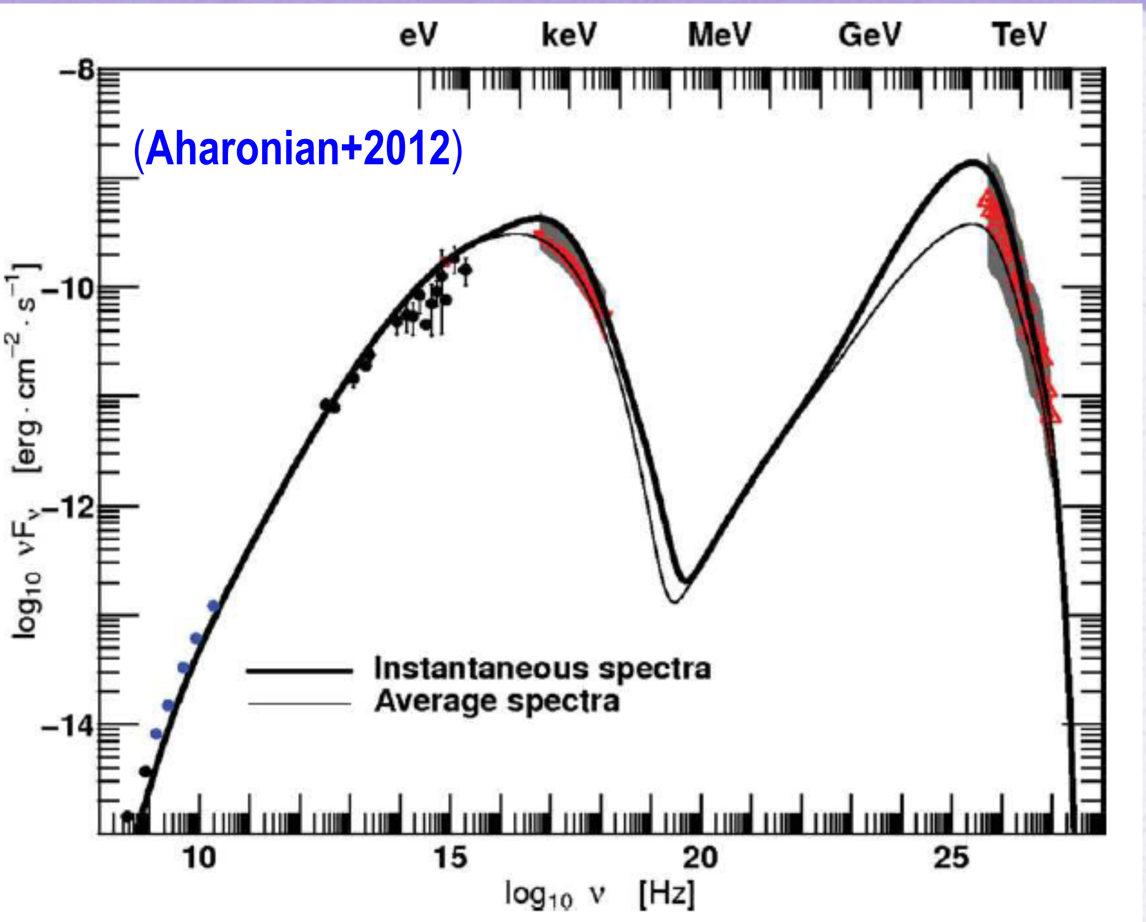
- IGMF's strength and filling factor can be constrained using very-high-energy γ-ray emission from distant AGN
- Blazar
  - AGN with jet pointed toward our line of sight
  - Rapid variability



(Aharonian+2007)

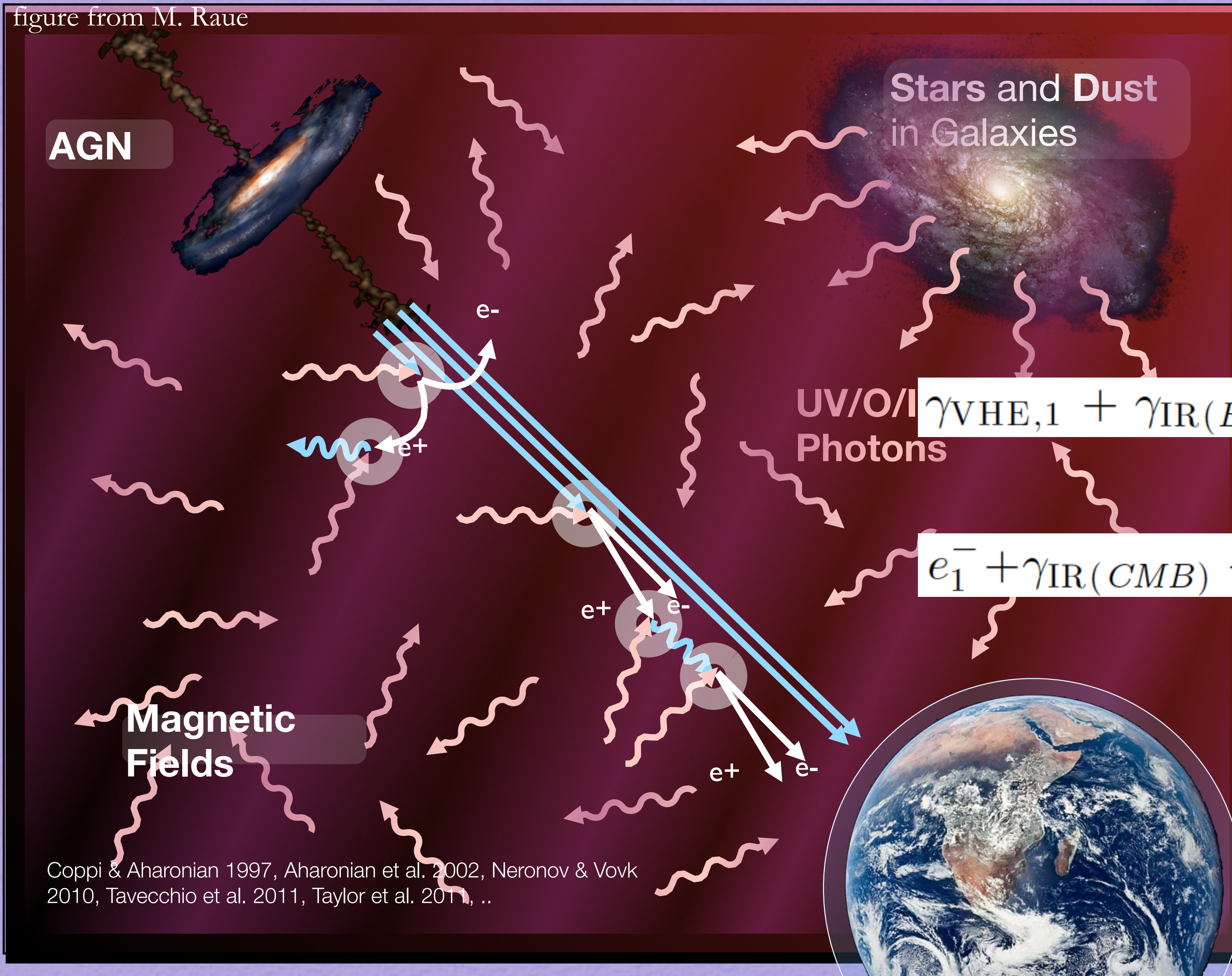


Blazar SED and Emission Origin



- Blazar TeV γ-ray emission comes from jet base, due to:
  - Relativistic electrons upscattering (IC) softer ambient photons to TeV
  - Relativistic protons:
    - Direct synchrotron radiation at VHE
    - Creation of secondary pions, which decay into TeV photons

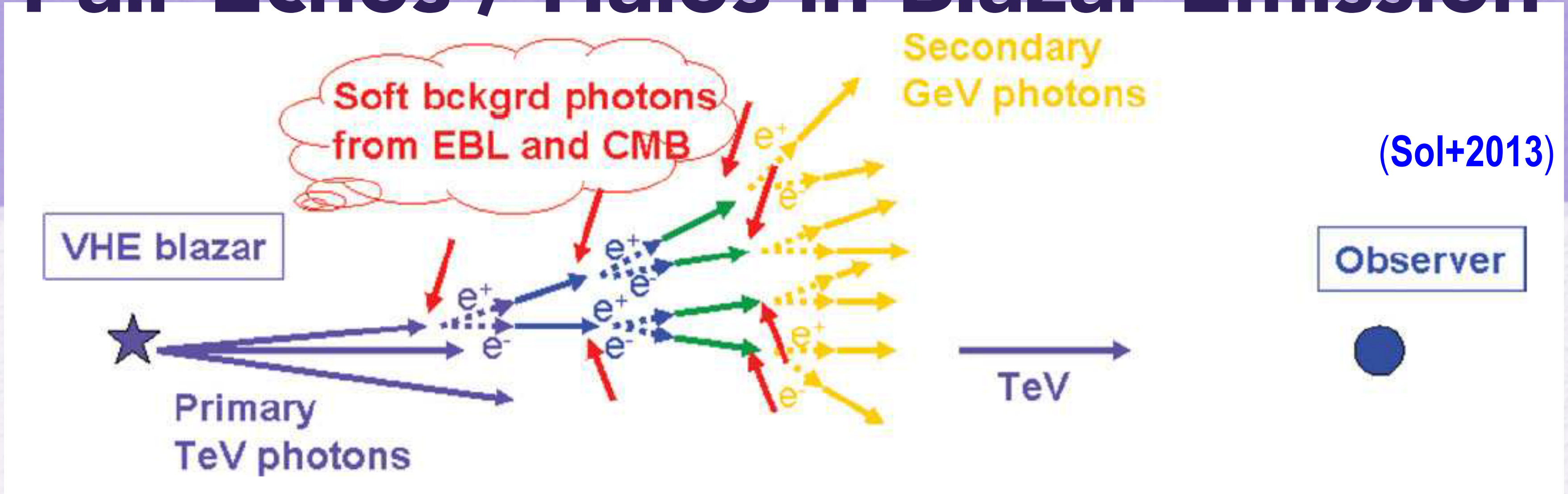
Interaction of Blazar VHE Photons with EBL & IGMF



$$\gamma_{\mathrm{VHE},1} + \gamma_{\mathrm{IR}(EBL)} \rightarrow e_1^+ e_1^-$$

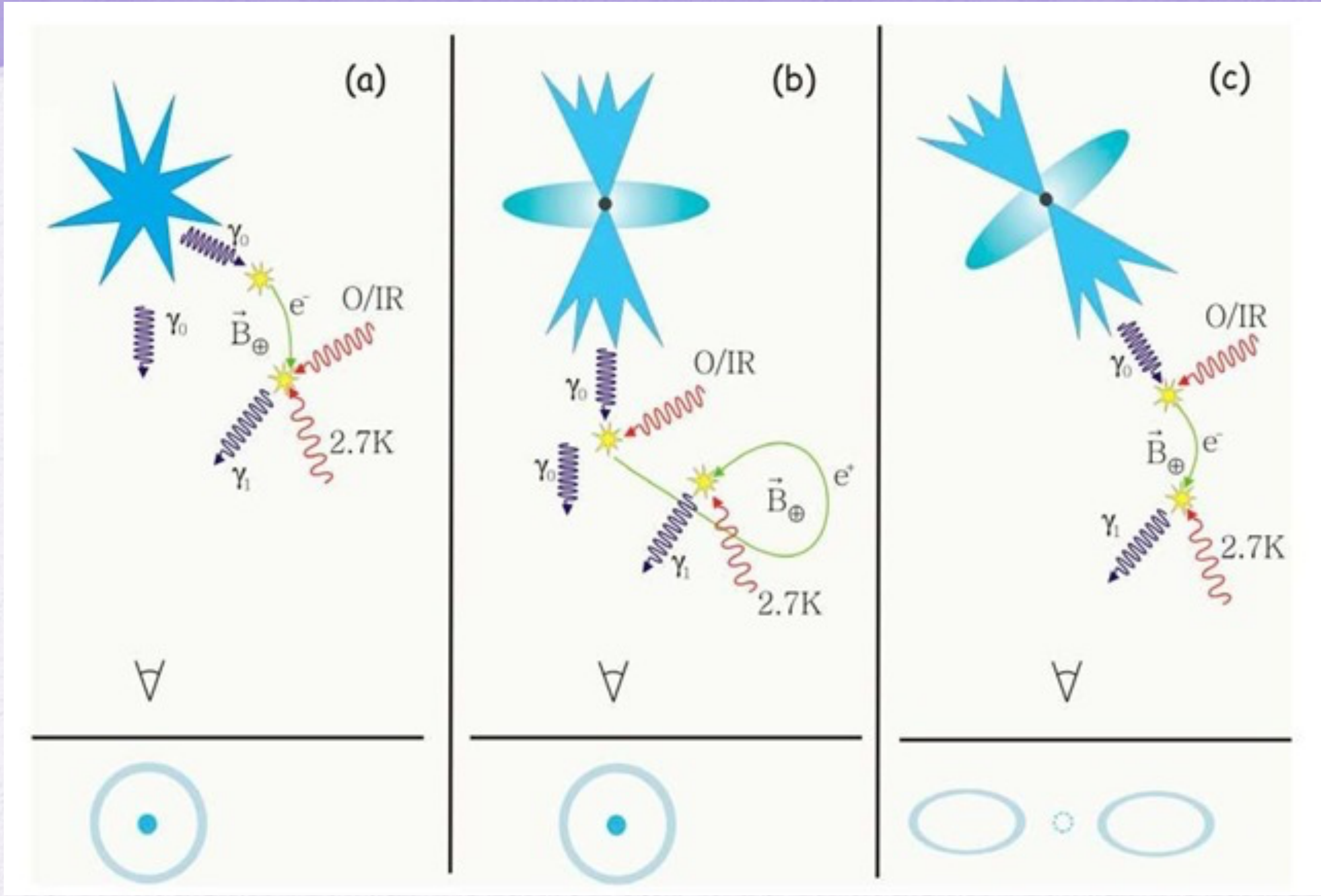
$$e_1^- + \gamma_{\mathrm{IR}(CMB)} \rightarrow \gamma_{\mathrm{VHE},2} + e_2^-$$

Pair Echos / Halos in Blazar Emission



- VHE primary TeV photons from distant blazars + EBL ➔ $e^{-}e^{+}$ pair ➔ IC scattering off CMB photons ➔ γ-ray = Secondary GeV components
- Electromagnetic cascades are deflected by IGMF, & secondary appears
  - **Pair Echo:** emission with time delay relative to the primary
  - **Pair Halo:** spatially-extended emission around primary TeV signal
- Can be detected with γ-ray telescopes (Fermi-LAT, HESS, CTA)

Expected Pair Halo schematic for 3 different sources: Isotropic Source, Blazar, Misaligned Blazar



Current Attempts of GeV Halo / Echo Detection

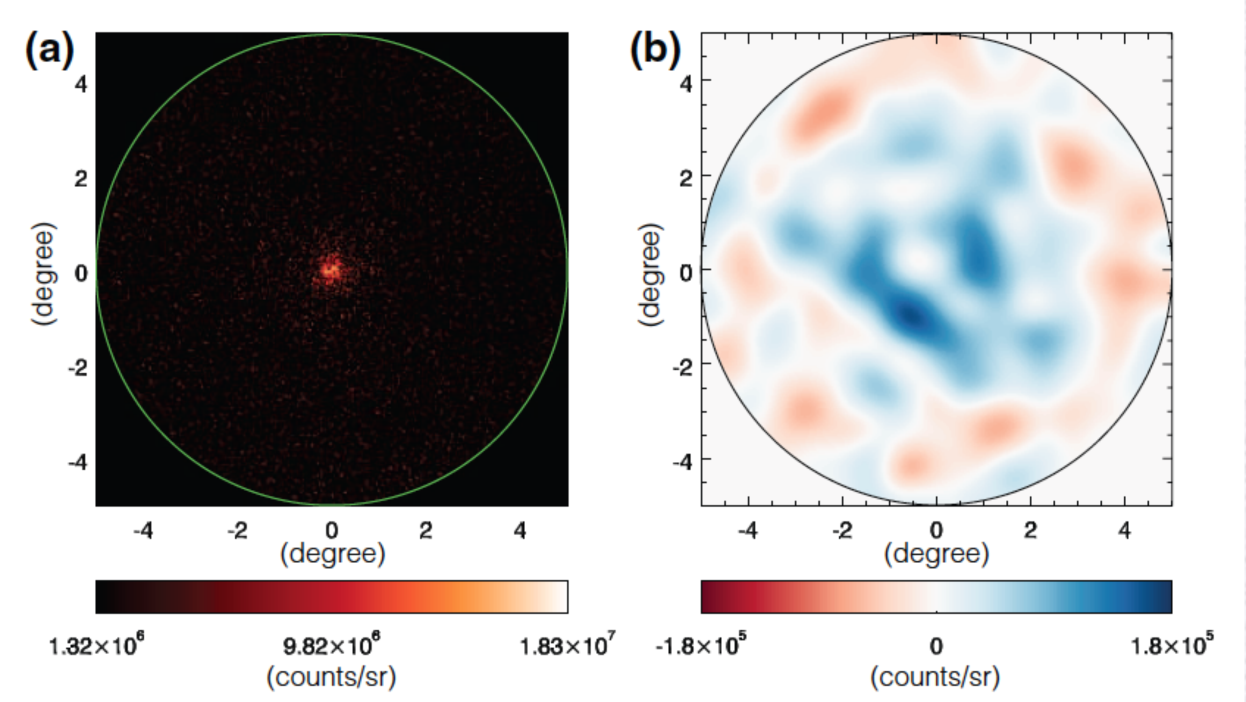
- 2 strategies:
  - ✓ Imaging analysis searches for extended pair halos around blazars, which are expected for $B>10^{-16}$ G
  - ✓ Time-resolved spectral analysis of pair echoes, for $B<10^{-16}$ G

- First hint for the existence of pair halos (Chen, Buckley & Ferrer 2015, PRL)
  - ✧ Stacked Fermi-LAT data of 24 $z<0.5$ blazars

$$B_{\rm IGMF} \sim 10^{-17} - 10^{-15}\,{\rm G}$$

statistical analysis

Bayes factor of $\log_{10} B_{10} > 2$



Lower Limit on IGMF from Echo Non-Detection

- Numerical studies
  - ✓ Model cascade development with Monte Carlo simulations
  - ✓ Compute simulated pair halo / echo
  - ✓ Compare with observations, e.g. Fermi data on blazars, & derive constraints

Neronov & Vovk 2010 $B \geq 3 \times 10^{-16}$ **gauss** ; **Taylor et al. 2011; Dolag et al. 2011**

- Non-detection of secondary components provide lower limits on B
  - ❖ Suppression of GeV flux is due to the deflection of e+e– pairs by IGMF
- Assume: coherence length > 1 Mpc for the IGMF, & persistent TeV emission over long timescales
  - ➢ If dimming of the cascade emission is due to spatial extension $B_{IG} > 10^{-17}$ G
  - ➢ If it is due to time delay $B_{IG} > 10^{-15}$ G
- If blazars emit γ-rays+cosmic rays ➔ secondary cascade photons can dominate the observed spectrum ➔ both upper & lower limits

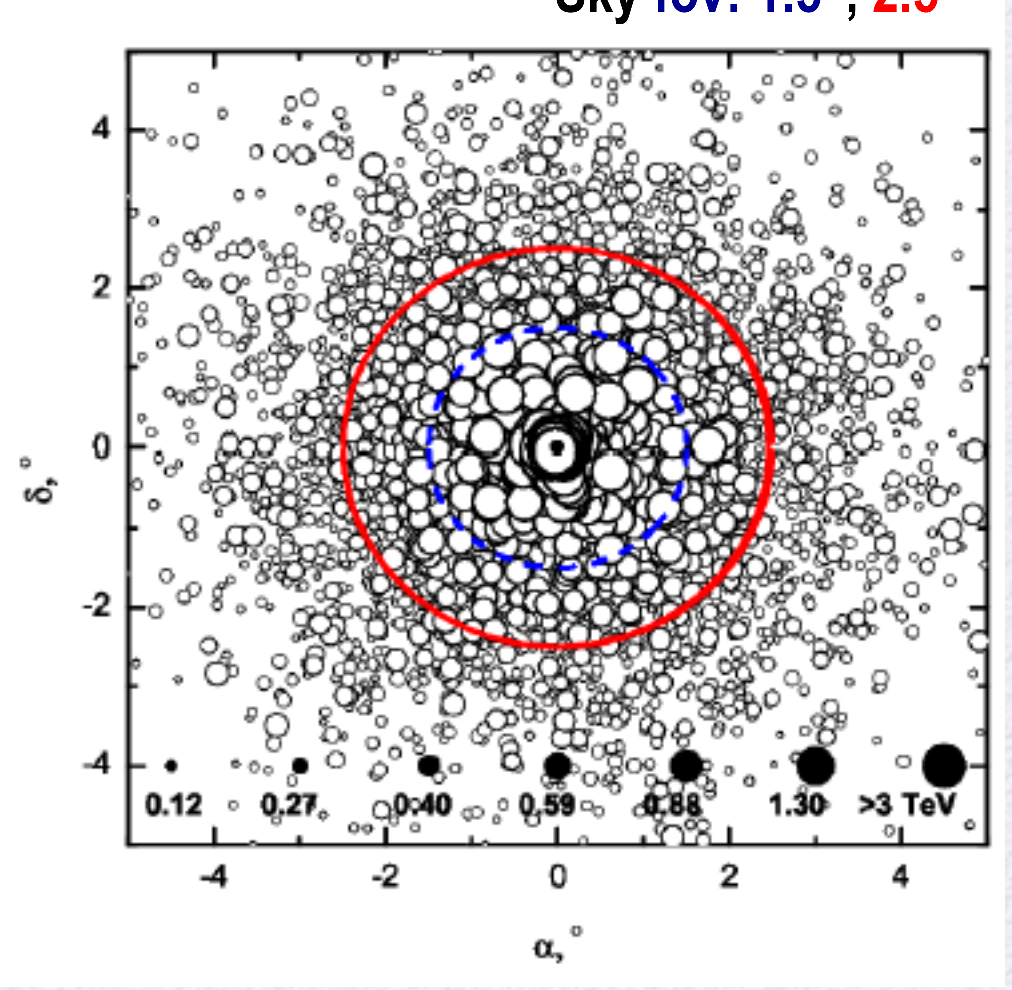
$$10^{-17} < B_{IG} < 3 \times 10^{-14} \text{ G}$$

Expected Geometry of a Pair Halo from Blazar

(Elyiv, Neronov & Semikoz 2009)

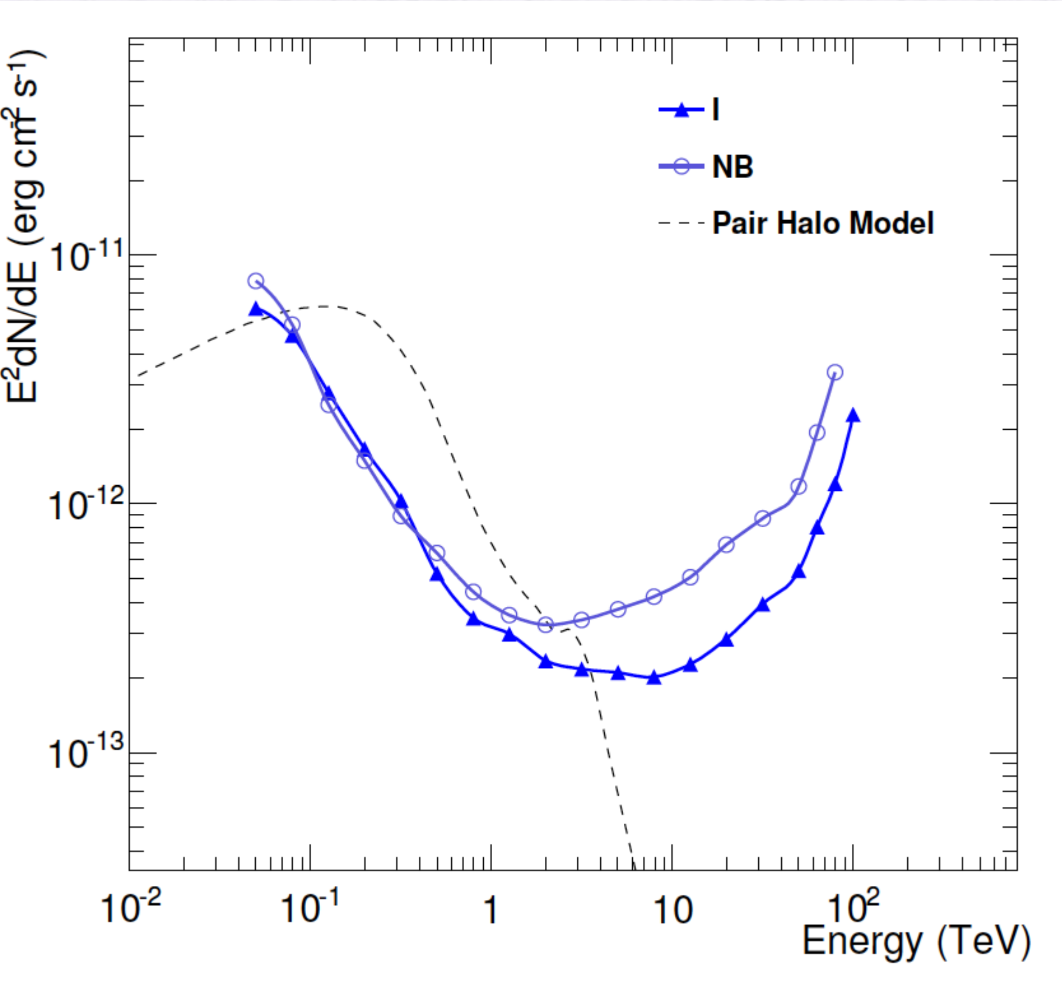
- Arrival directions of primary & secondary γ-rays (open black circles, sizes proportional to the photon energies), where:
  - Distance of blazar = *120 Mpc*
  - $B_{IGM}=10^{-14}$ G
  - Blazar intrinsic γ-ray spectrum is described as a power law with an exponential cut-off

Sky fov: 1.5°, 2.5°



Expected Pair Halo Flux for CTA Sensitivity

(Sol et al. 2013, Astroparticle Physics)



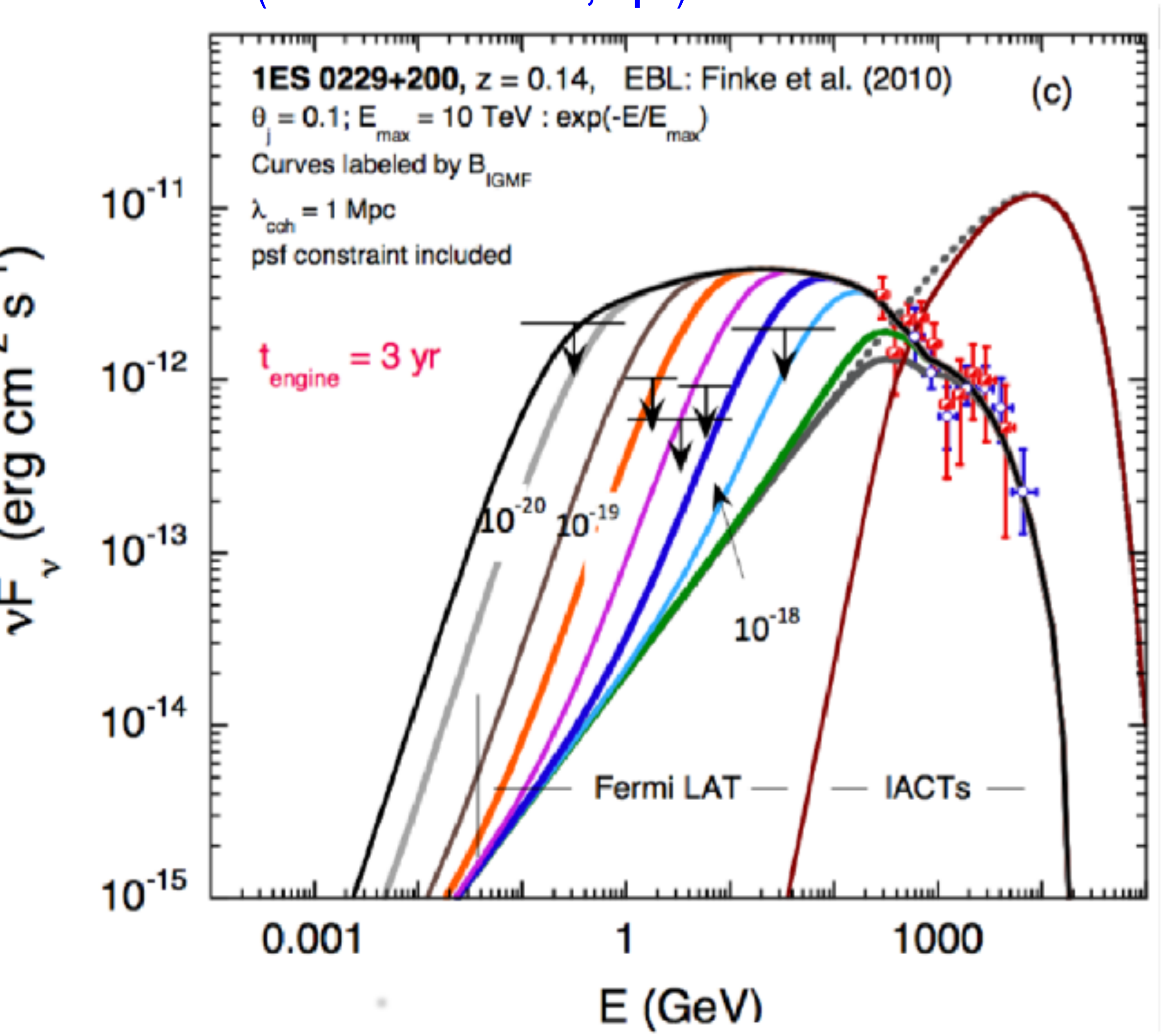
- Pair halo emission (dashed)
  - ❖ Using theoretical model: differential angular distribution of a pair halo at *z=0.129, E>100 GeV*

Eungwanichayapant & Aharonian (2009)

- Assume an observation time of 50h
- CTA sensitivity curves
  - ✓ South site: "I"
  - ✓ North site: "NB"

Cascade Radiation Spectrum for a Pair Echo

(Dermer et al. 2011, ApJ)

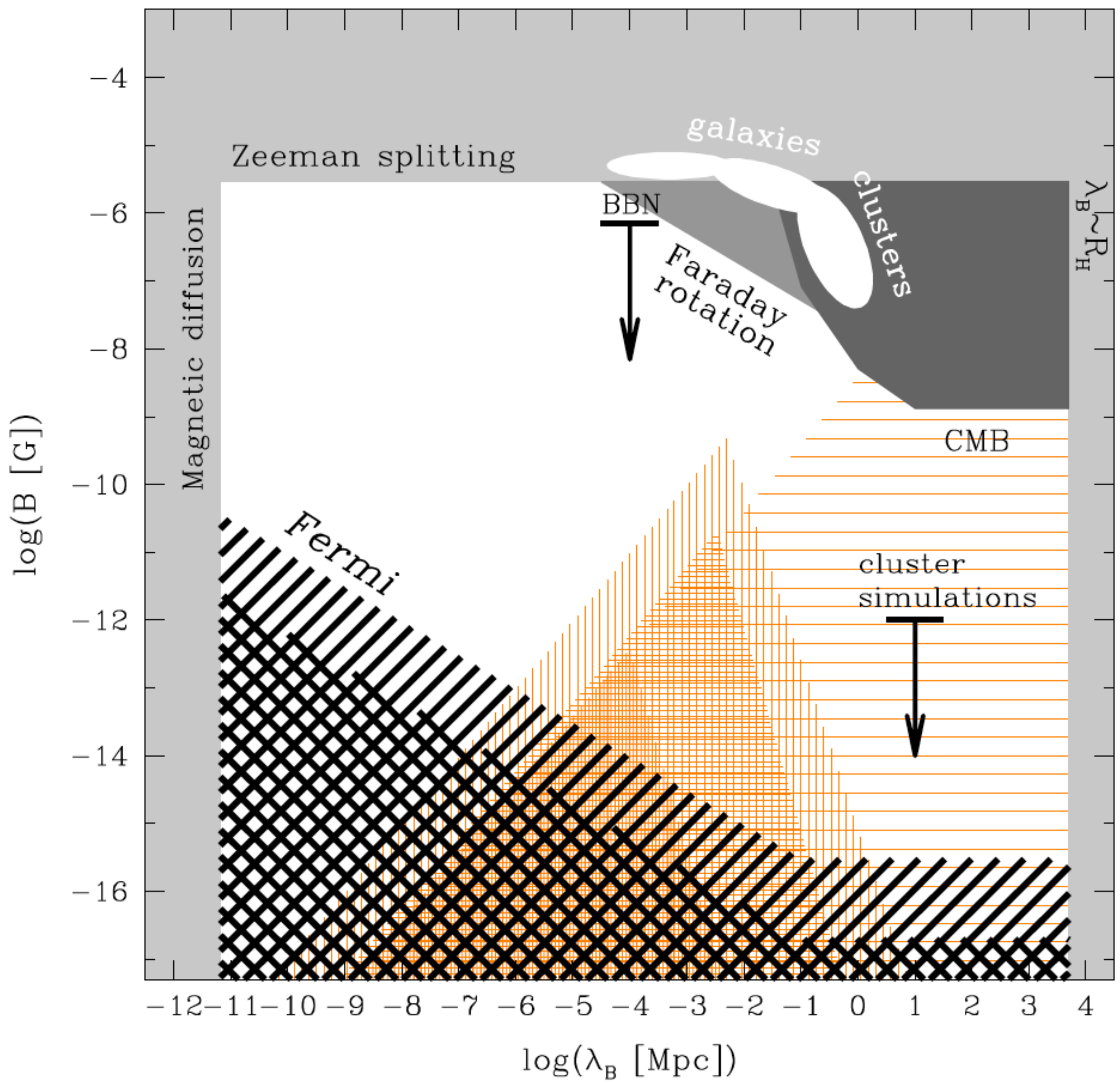


- Pair echo model applied to observations of the blazar 1ES 0229+200
- Cascade spectra assume persistent TeV emission for different values of the magnetic field strength and coherence length
- $B > 10^{-18}$ G

Obs Bounds on IGMF Strength & Coherence Length

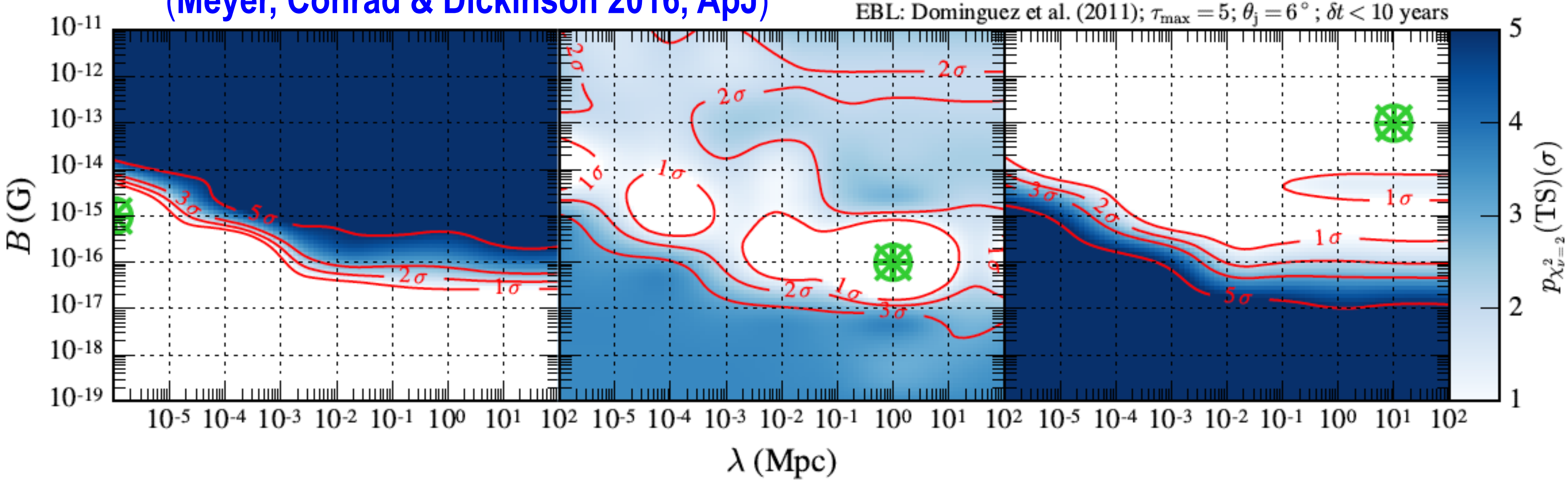
(Neronov & Vovk 2010, Science)

- Black hatched region: analysis from blazar pair-halo non-detection
- Orange hatched regions: cosmological origin
- White ellipses: range measured in galaxies & galaxy clusters



Constraints on IGMF Strength & Coherence Length

(Meyer, Conrad & Dickinson 2016, ApJ)



- Expected results of searches for pair echos with CTA
- Using a combined likelihood analysis of simulated CTA spectra of 4 blazars (with hard spectra in the TeV band) using the (non-)observation of a pair echo
  - Only cascade photons that arrive within the 80% containment radius, & a time delay of less than 10 years are included

Summary

- Observational signatures of extremely tiny magnetic fields permeating the cosmos on the largest scales in the IGM
  - Can shed light on the origin of seed fields

- Current results of the GeV and TeV γ-ray astronomy all conclude to the existence of a non-zero IGMF $10^{-17} < B_{IG} < 3 \times 10^{-14}$ G
  - Mostly based on the non-detection of expected secondary γ-rays

- Future studies need to take into account possible additional effects in the intergalactic space
  - ✓ Energy losses other than Inverse-Compton scattering

- Positive detection of Pair Halo or Pair Echo
  - Needed with detail data on cascade signatures
  - CTA with improved sensitivity is expected to observe these