Science prospects for extragalactic gamma-ray astronomy

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Outline

Why VHE gamma-ray astronomy ?

I- Active VHE emitters: compact sources

Active Galactic Nuclei (AGN): populations and physics

Search for Gamma-Ray Bursts (GRB) and other types of transients at VHE

II- Active VHE emitters: diffuse sources

Search for Dark Matter (DM) in dwarf galaxies and clusters

Search for cosmological and large-scale shocks

III- Passive VHE emitters: diffuse VHE sources revealed by cosmic rays

Extragalactic cosmic rays (CR): galaxies, starbursts, clusters of galaxies, intracluster medium …

IV- The diffuse VHE background (ie: I + II + III + ?)

V- Studying the lines of sight with AGN and GRB, beacons of ɣ-rays:

Extragalactic Background Light (EBL), InterGalactic Magnetic Field (IGMF), axion-like particles (ALP), Lorentz invariance violation (LIV)

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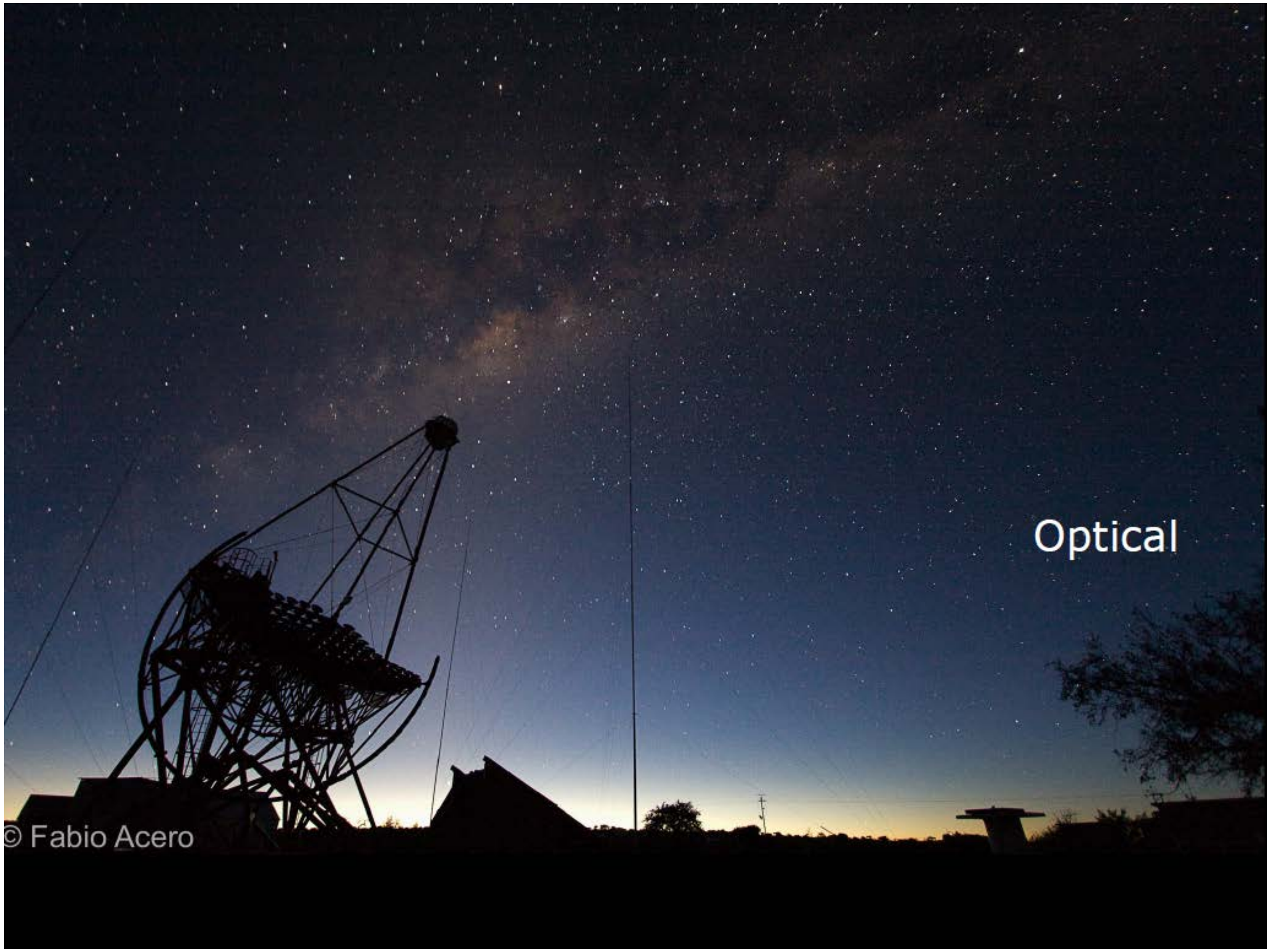
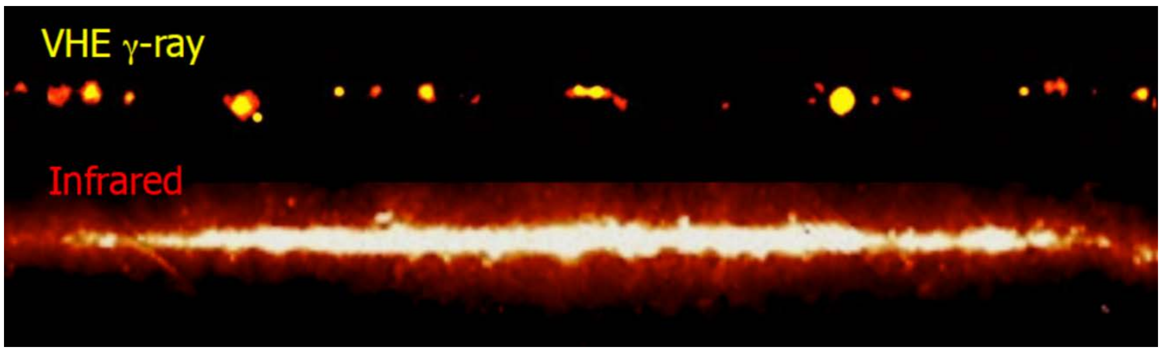
The night sky



The night sky with its VHE appearance

VHE astronomy of near future ~ **a (few) thousand** of sources
versus billions of sources of
radio, IR, optical, X-ray astronomy

Is VHE the 'poor' cousin of Astrophysics ? Not really



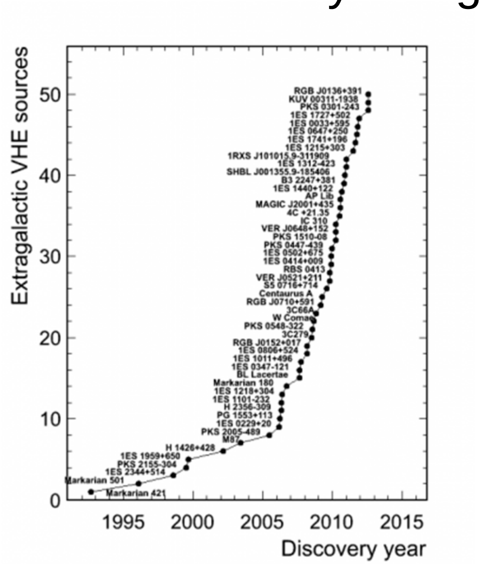
VHE astronomy = shapes the **energy skeleton of the universe**

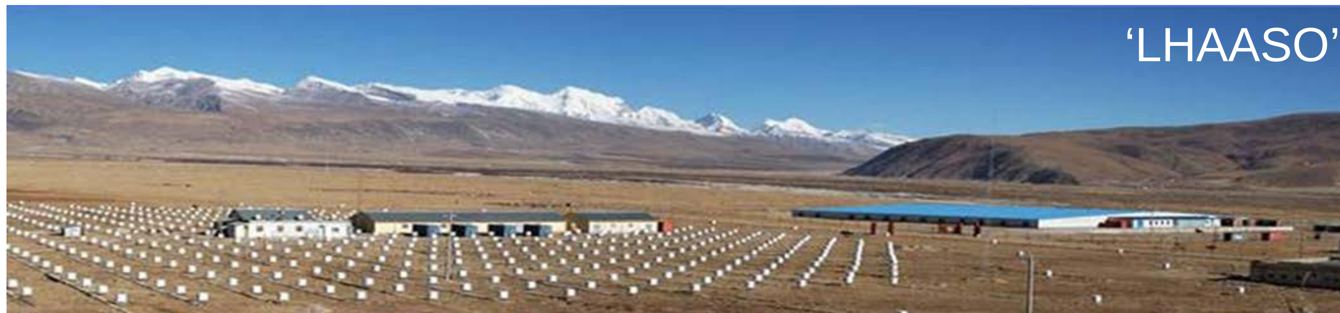
Sparse but **structuring vision of the cosmos**

The **turbulent and transient** universe, **extreme** phenomena, **energy cycle** and transfer, **probe** of space-time

Interesting times for VHE γ-ray astronomy !

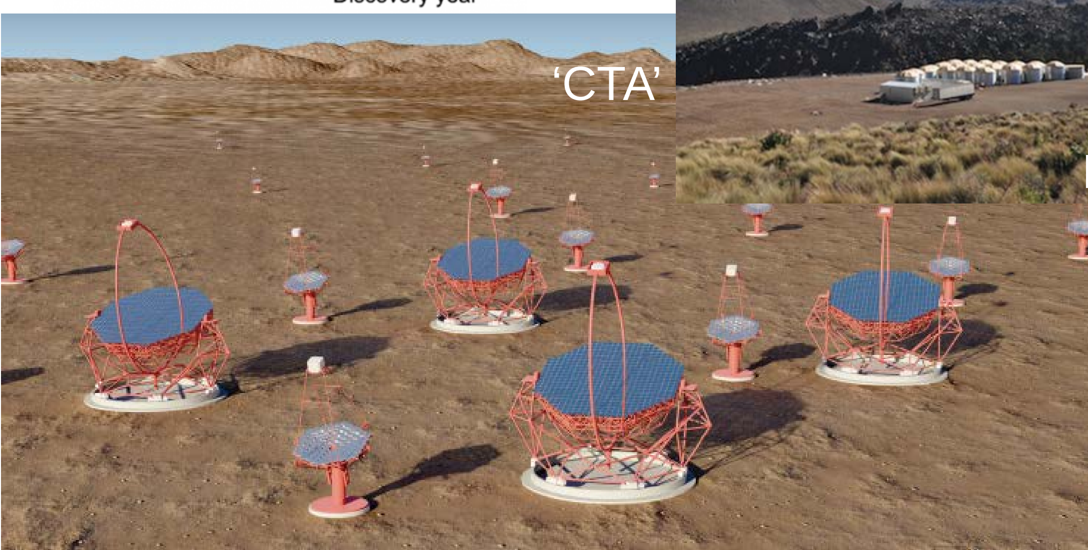
- A vast area of research recently opened
- A new generation of instruments with enhanced performances
- A variety of highly complementary instruments, with promising synergies





Left: The MACE telescope design. **Right:** Civil work at Hanle: MACE foundation and control room.

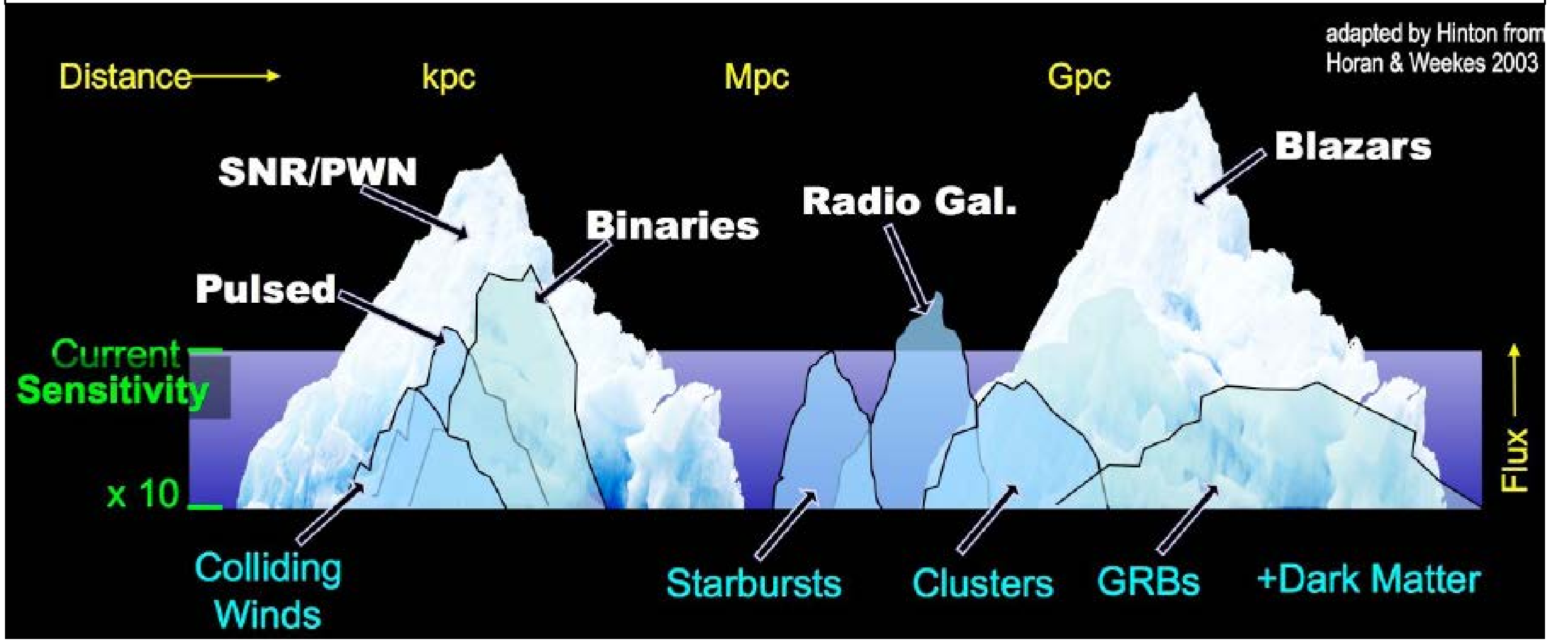
Views of the ongoing installation of MACE near Hyderabad, Andra Pradesh, South India.



$\neq$ FoV, $\neq$ duty cycle, $\neq$ E, $\neq$ σ, $\neq$ PSF…

Significant jumps in sensitivity and performances should provide:

* Thousand(s) of confirmed VHE sources
* TeV discoveries of new types of sources, especially in extragalactic science



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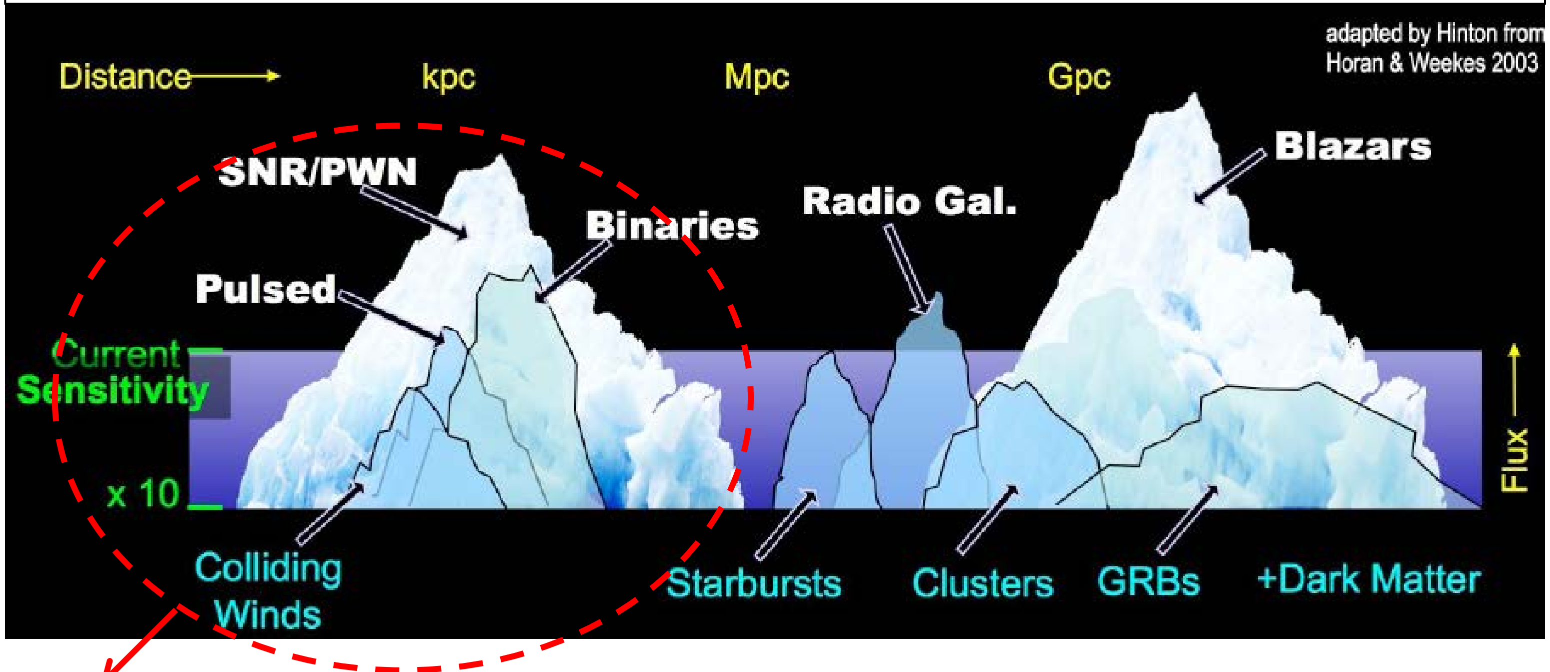

Search and study « galactic objects » in external galaxies
→ Magellanic clouds, dwarf galaxies, M31 (Andromeda), …

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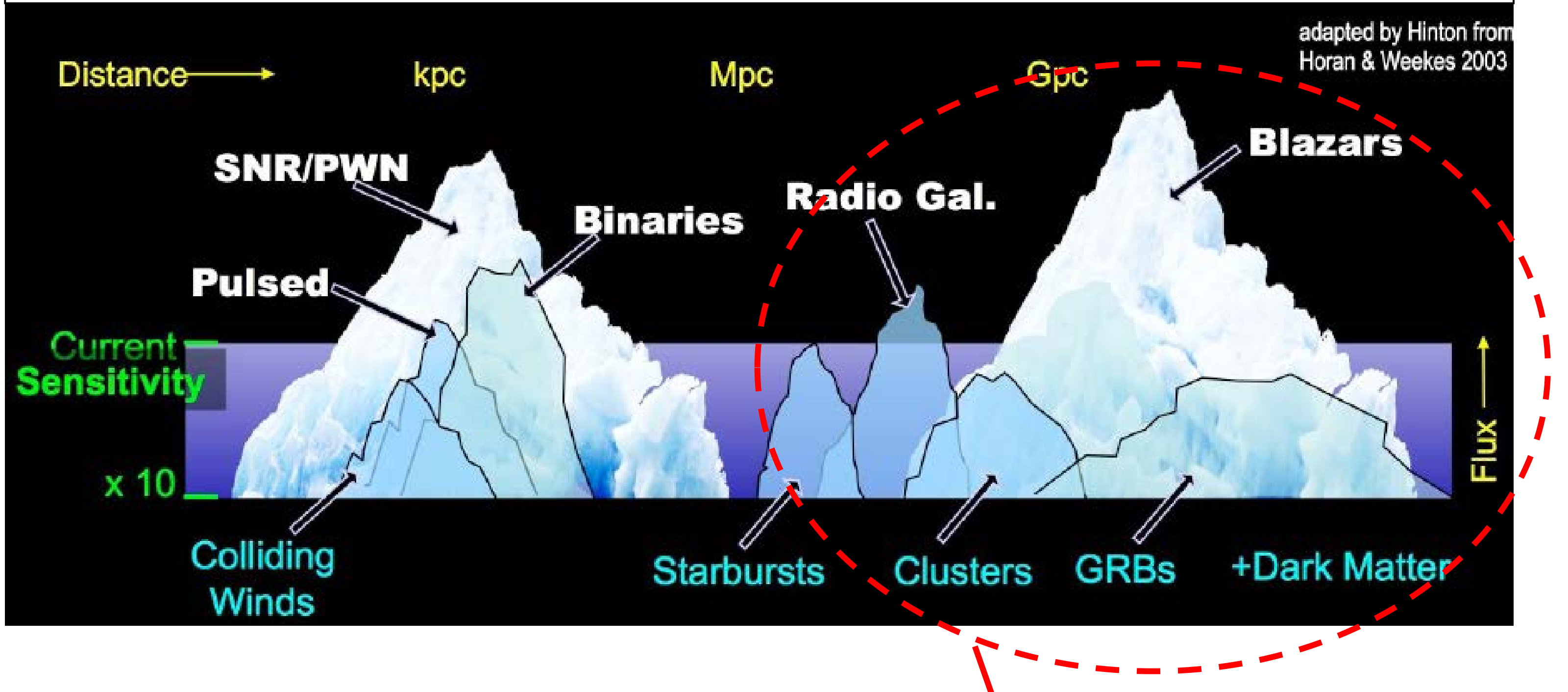

Discover the extragalactic space, still poorly known at VHE

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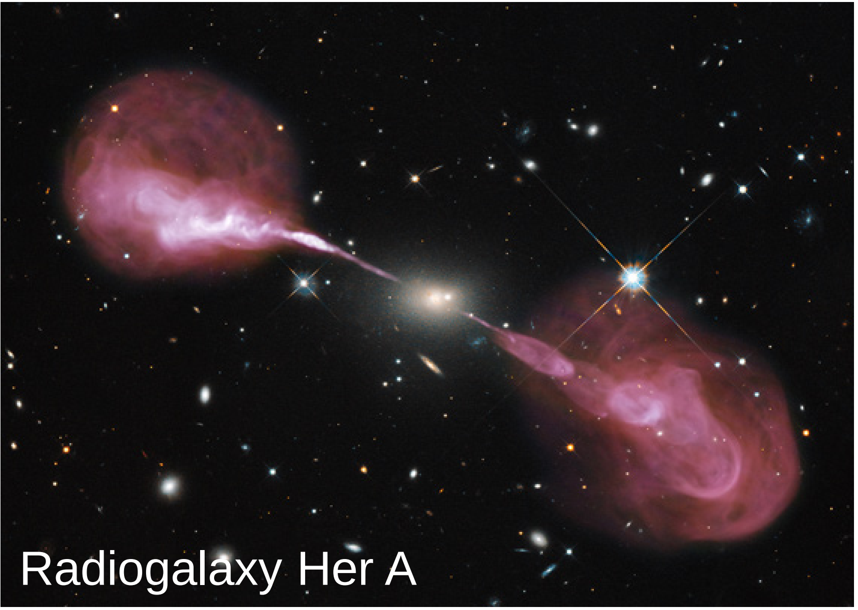
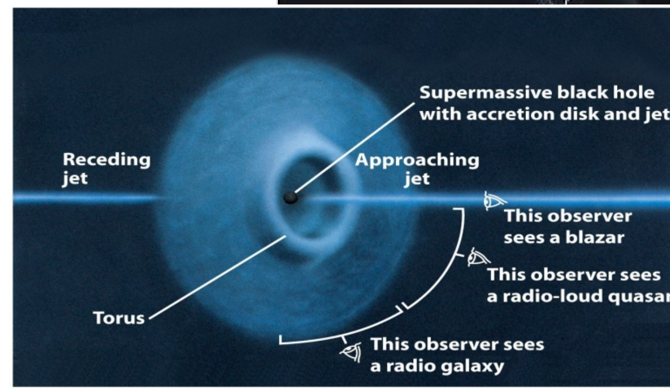
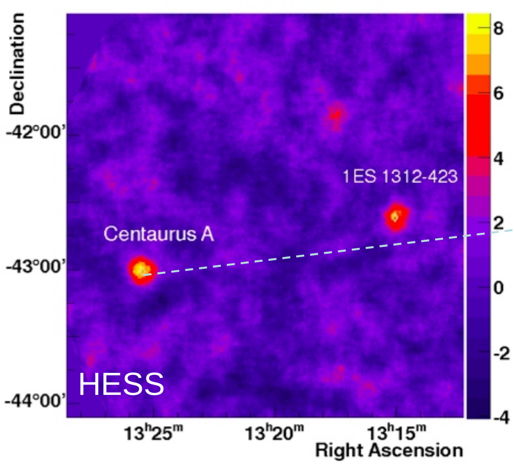


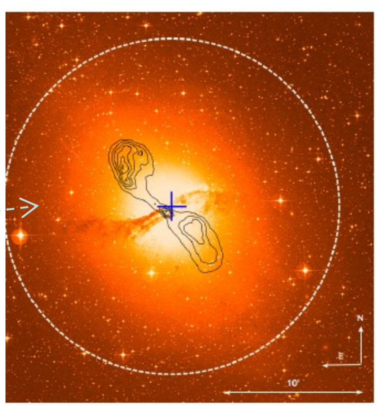
Active Galactic Nuclei

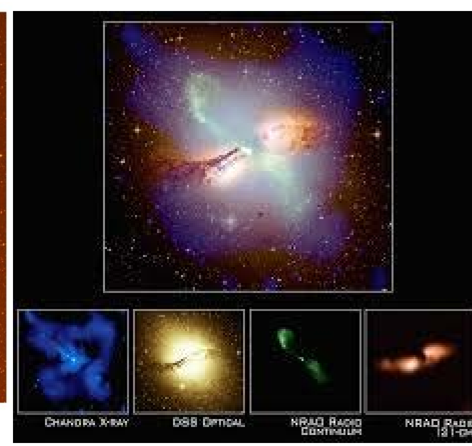


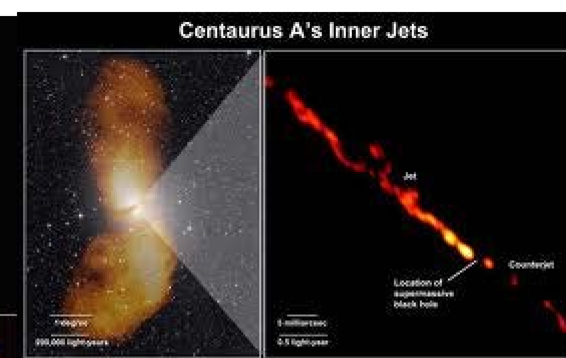
~ 55 AGN confirmed at VHE at the moment, mostly blazars

The nearby radiogalaxy Cen A in VHE and MWL: which VHE emission zone?





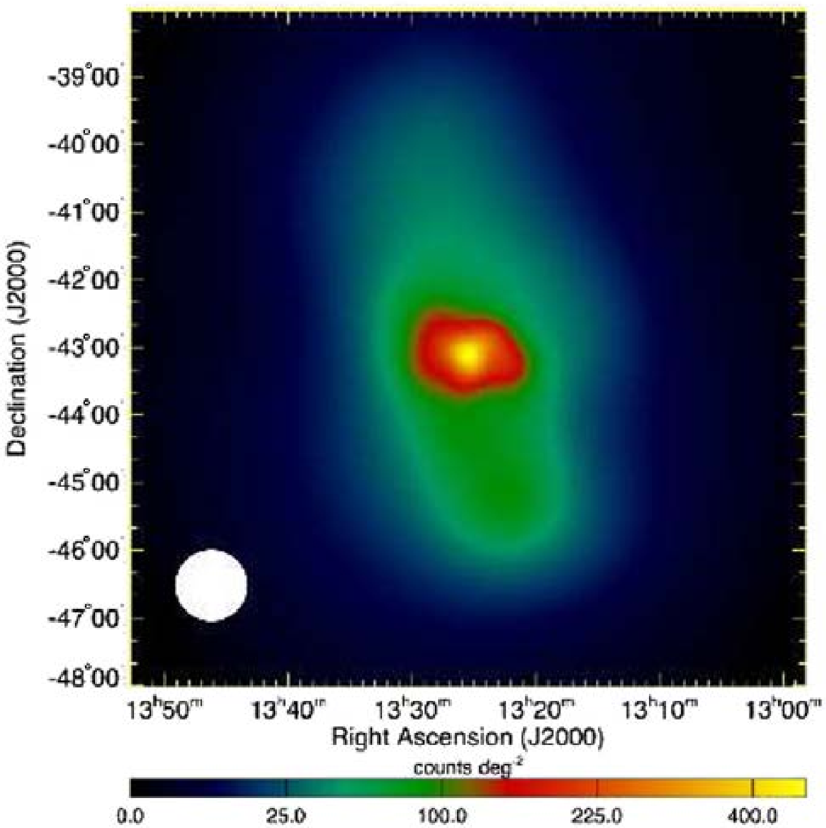




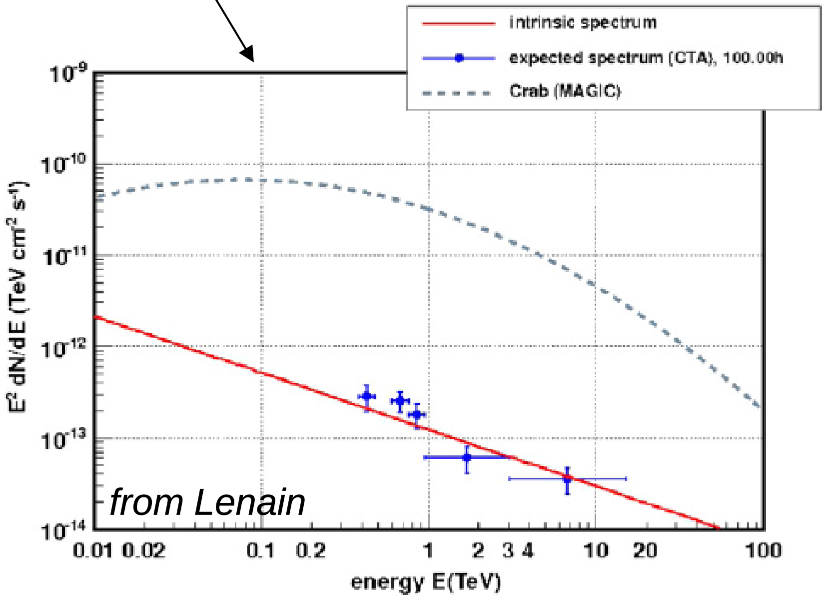
Active Galactic Nuclei

Search for extended VHE emission

Diffuse gamma-ray emission of Cen A as seen by Fermi



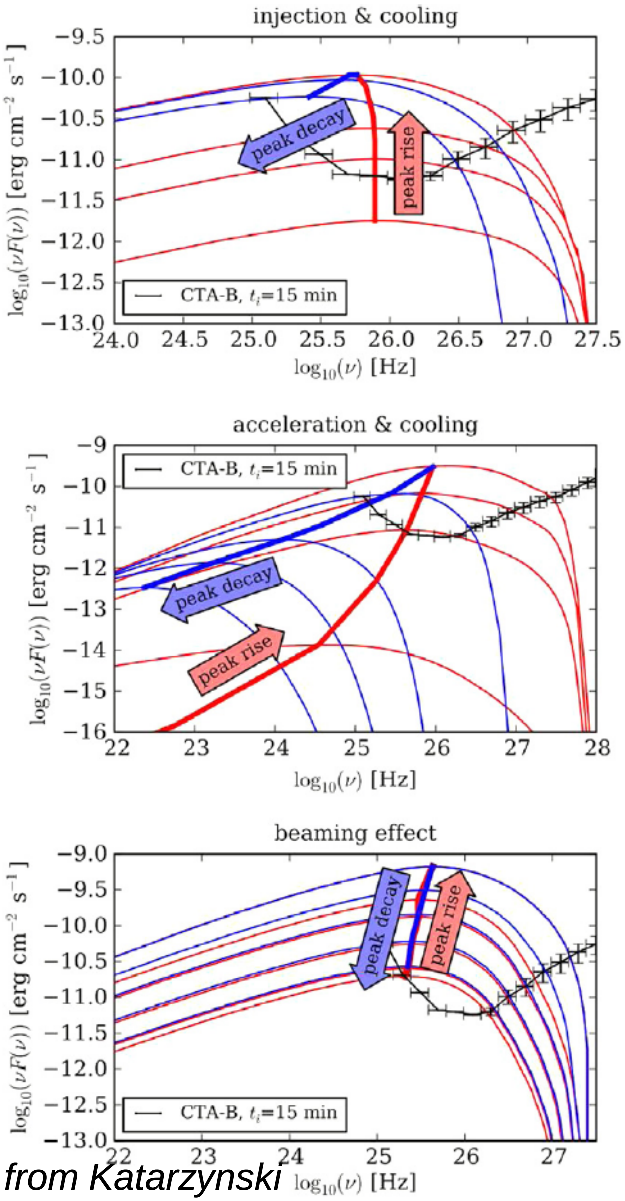
A halo of 0.2° with a flux of 50% of the total low state flux of M87 would be detectable with CTA. Here the CTA generated spectrum for array I and 100 hours.



(Sol et al, 2013)

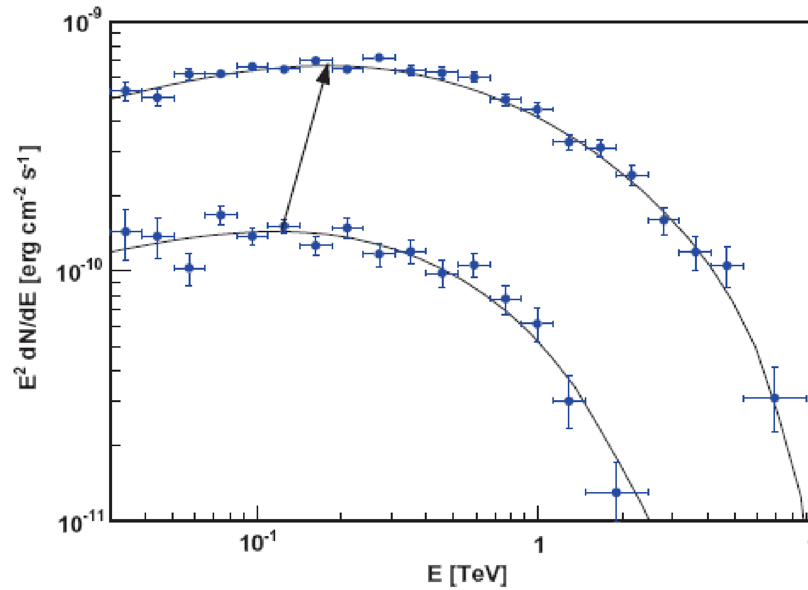
Active Galactic Nuclei

Emission processes: leptonic scenarios?



from Katarzynski

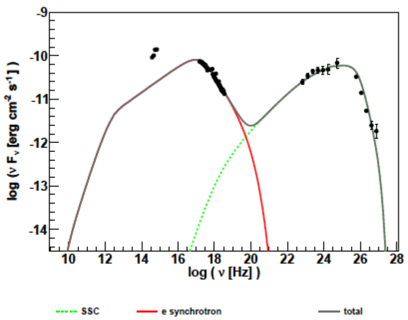
Alerts from wide FoV & MWL instruments
→ CTA observation of AGN flares: High quality monitoring of the evolution of the IC peaks should firmly constrain SSC scenarios.

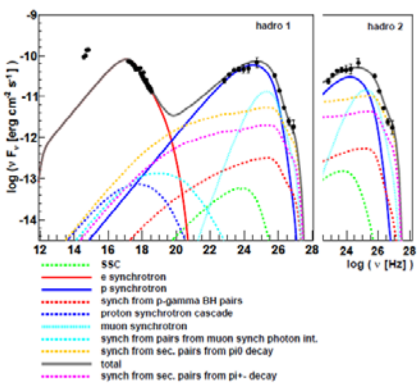


(Sol, Zech, et al, 2013)

Active Galactic Nuclei

Emission processes: hadronic components?





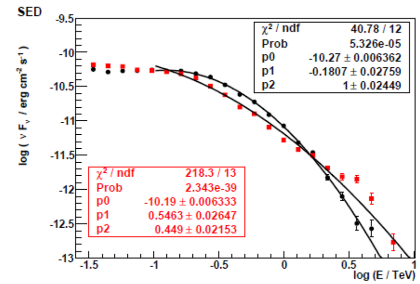
(Zech, Cerruti, 2013)

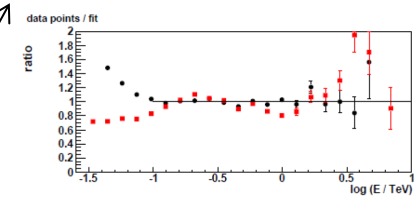
Leptonic or
hadronic scenarios??

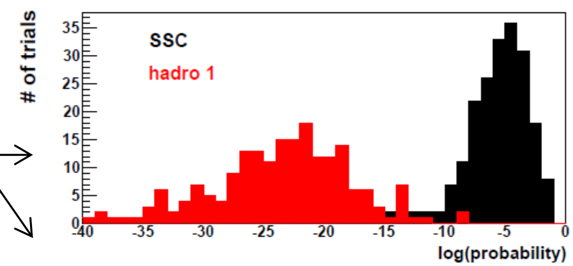
Searching for signatures of hadronic components in SED at VVHE.

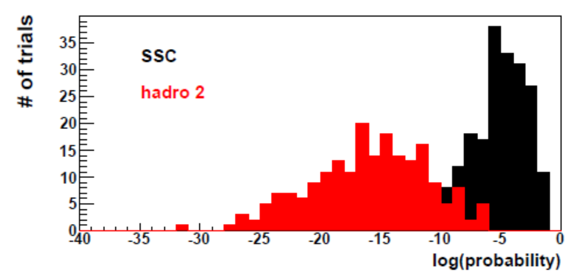
Simple logparabolic fits to the VHE spectrum show how hadronic solutions appear statistically different from leptonic SSC scenario.

Here the case of PKS2155-304 in 2008.



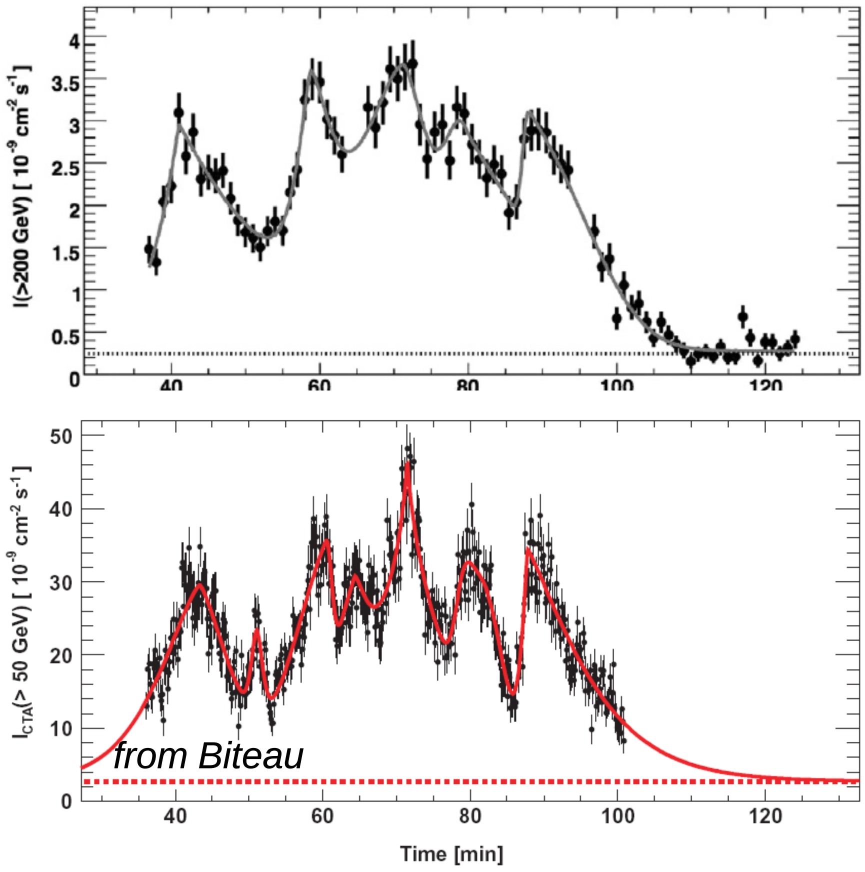






Active Galactic Nuclei

Variability on all timescales, from years down to the shortest ones during flares



The first big flare of PKS 2155-304 in 2006. Variability on a few min, seen by HESS

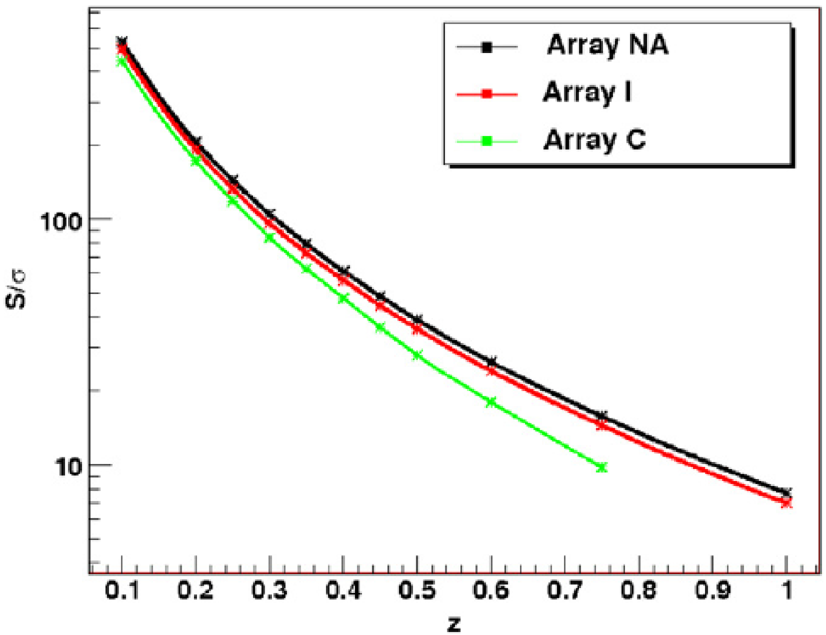
The same big flare as CTA could have seen it. Variability on a few seconds scale.

Strong constrains on geometry, dynamics, emission processes …

Analyze the evolution at all timescales to connect the events of microphysics to fluid mechanics

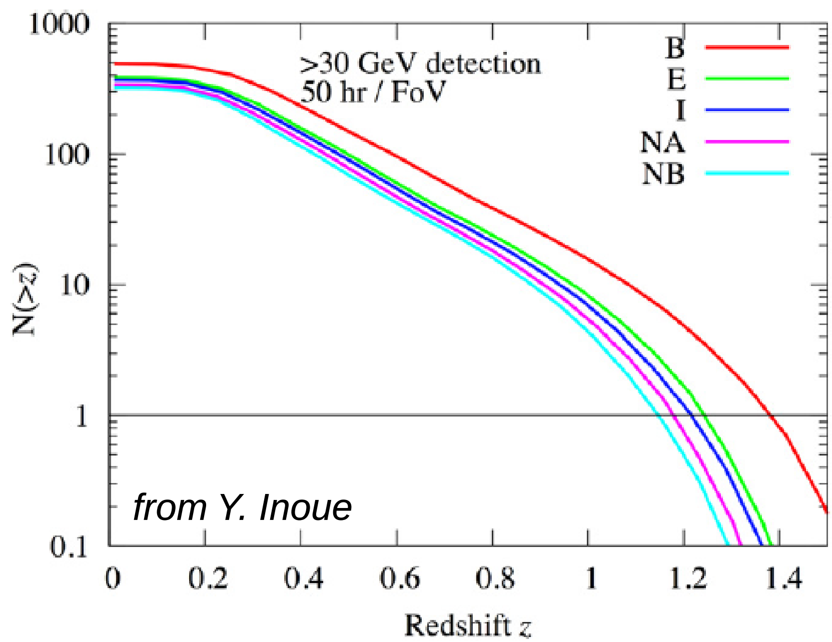
Active Galactic Nuclei with CTA

Populations



Very significant detection of AGN flares up to z ~1 and above

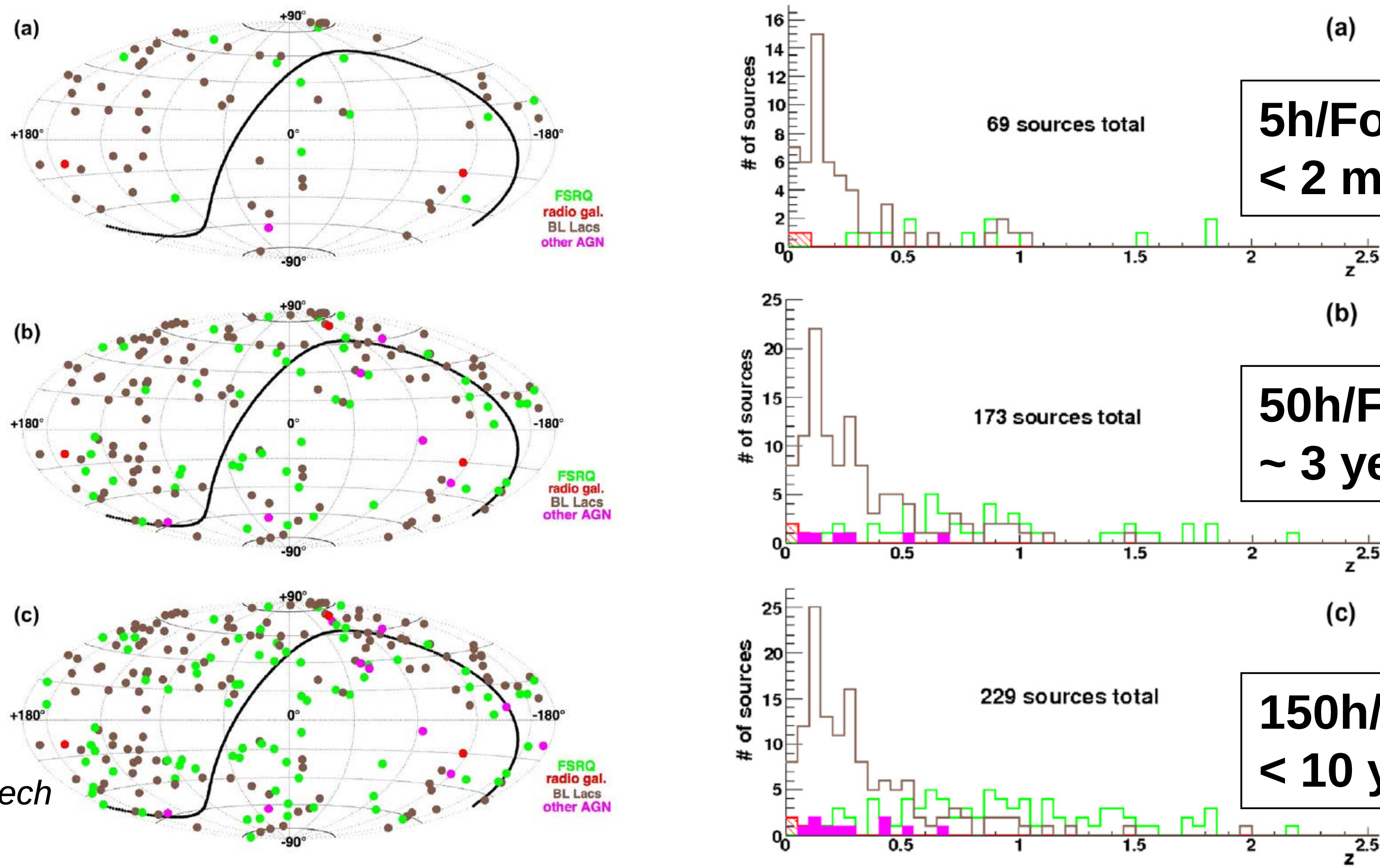
Cumulative z distribution of blazars above 30 GeV. From standard blazar sequence (lower limits) and a realistic blazar luminosity function:
* **370 blazars** potentially reachable with 50h per FoV for an all-sky survey
* **20 blazars at z > 1**



from Y. Inoue

Active Galactic Nuclei with CTA

Extrapolation from Fermi



5h/FoV
< 2 months

50h/FoV
~ 3 years

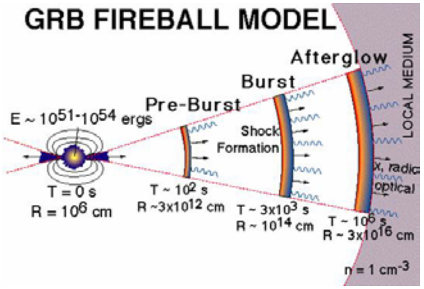
150h/FoV
< 10 years

from Zech

Results from HAWC should help to anticipate the probability of AGN discoveries by a blind CTA extragalactic survey.

Assuming 20° zenith angle over the whole sky (array B).

Gamma-ray bursts (GRB)



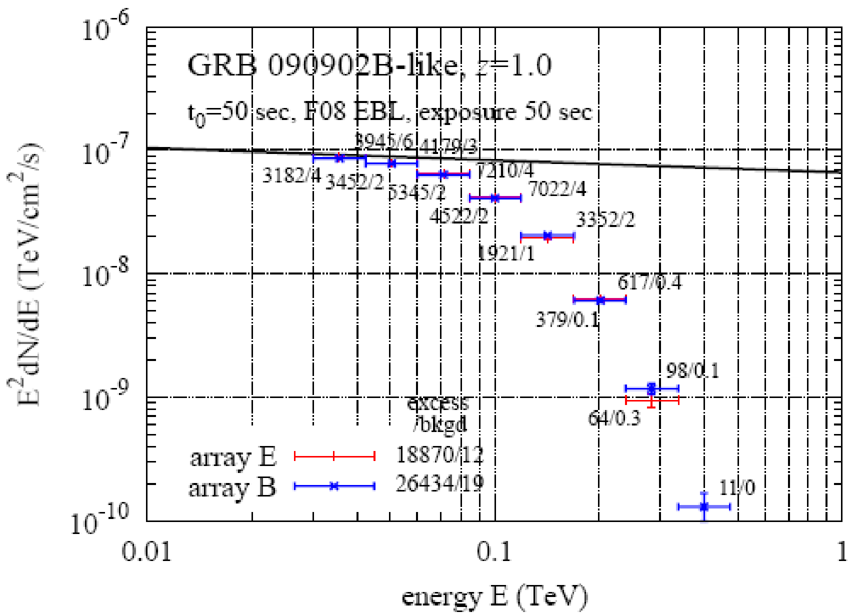
- Most energetic cataclysms known in cosmos: 10^{52} -10^{54} erg in 0.01-1000 seconds, mostly in MeV range
- Long GRB > 2 s (core collapse of massive stars) and short GRB < 2 s (coalescence of binaries ?)
- Prompt emission and afterglow, standard fireball model, many alternatives and open questions

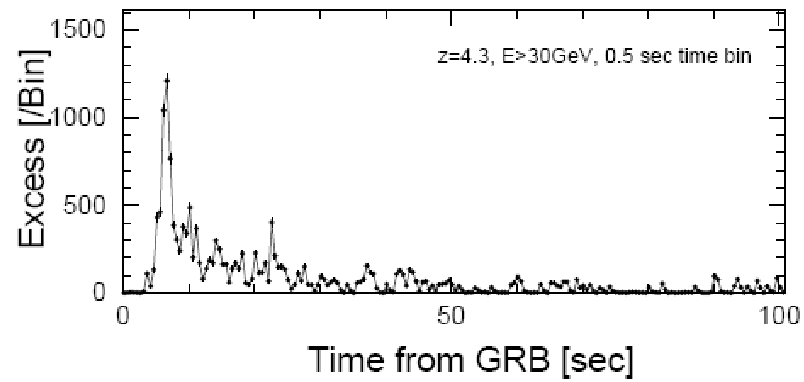
Gathering spectra and lightcurves at multi-GeV with high photon statistics with CTA due to:

- low energy threshold at a few 10 GeV
- large effective area (10^4 x Fermi at 30 GeV) and sensitivity
- rapid slewing capabilities (180° rotation in azimuth in 20 seconds)

→ Expected detection rate of a few GRB per year,
with 100s to 1000s VHE photons per burst

Gamma-ray bursts: simulated CTA spectra and light curves





Typical CTA light curve from z ~ 4.3
Array E, EBL Razzaque et al, 2010

Typical spectrum from z ~ 1,
for CTA arrays E and B,
50 s of observing time.
Intrinsic spectrum extrapolated from Fermi,
EBL from Franscheschini et al, 2008

(Inoue et al, 2013)

Prospects:

- constrain or even determine the bulk Lorentz factor, a key-parameter for GRB (for instance if detection of HE cutoff due to pair opacity)
- constrain the emission process (e^-, p^+ ?) for prompt GRB and early afterglows, and search for UHECR and ν signatures
- discover new GRB …

The transient universe: Targets of Opportunity

- Alert network between the various infrastructures

Searching for TeV counterparts of any astroparticle detector event
(or even of photonic events at lower energies)

- Electromagnetic counterpart of gravitational waves (GW)

During the lifetime of new generation VHE detectors, GW detectors should detect GW events !

[Advanced Virgo and LIGO & others (2015), LISA (2015++), Einstein telescope]

Electromagnetic signal is expected from GW transients

→ could identify the GW sources, confirm the detection, better constrain modeling, allow to compare different distance estimates, etc …

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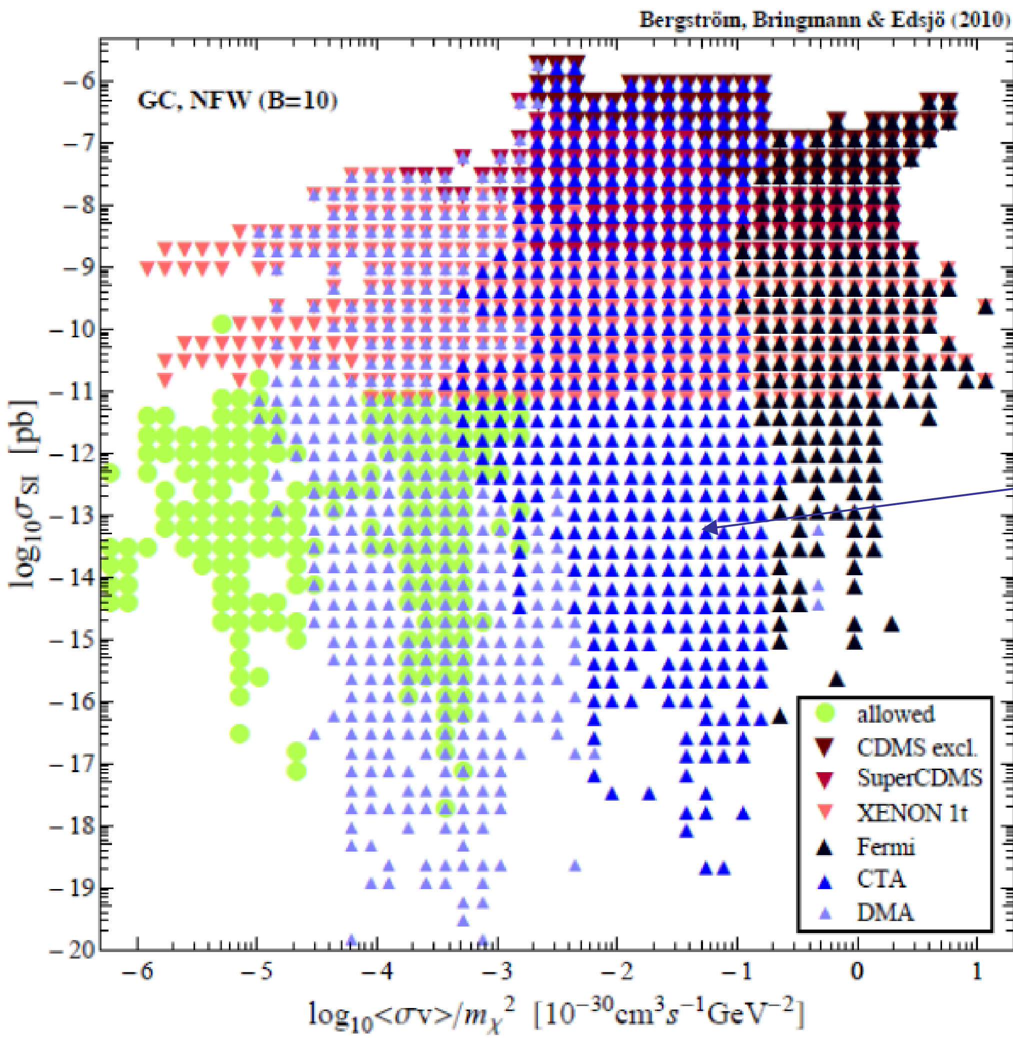
Search for Dark Matter

Detection or *identification* by spectral lines



(Bergstrom et al, 2011)

CTA ← **Fermi** ←

Large number of « possible » supersymmetric models.

Parameter space explored by the different detectors

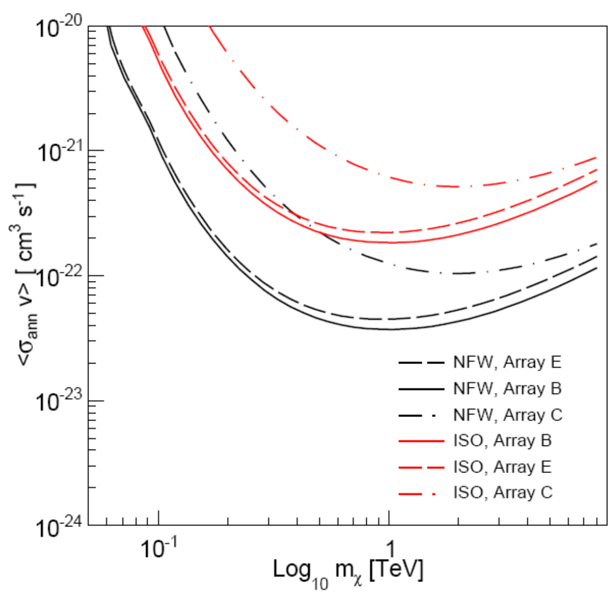
CTA domain of search in the plane σ_{SI} - $< \sigma\, v > / m_\chi^2$
(spin-independent cross-section on p, velocity, annihilation cross-section, neutralino mass)

Domain of indirect DM detection

Cosmic DM annihilation:
→neutrinos, charged CR, MWL photons from secondary e^- and prompt γ-rays

Search for DM in nearby dwarf satellite galaxies

- In CDM scenario, DM halos exist around all galaxies
- Dwarfs: most DM-dominated systems, many (> 23) at distance < 100 kpc, low gamma-ray background (no star formation, no gas) → Ursa minor, Sculptor, Draco, Willman 1, Segue 1, Sagittarius …
- Various models for halos and DM description, many unknown parameters



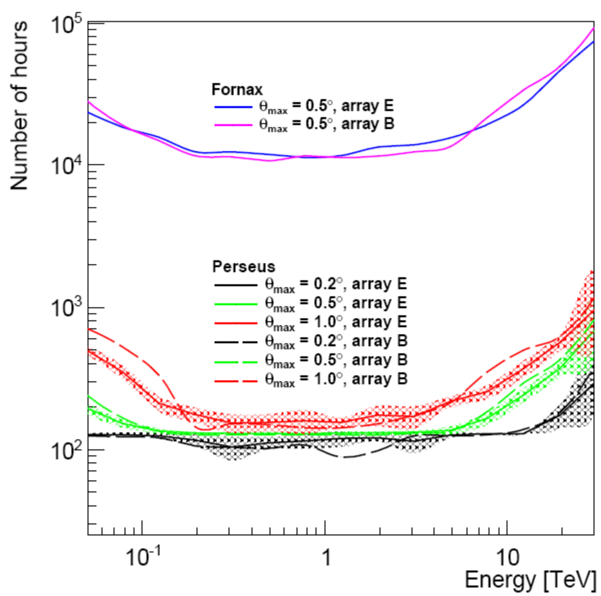
95% C.L. sensitivity towards Sculptor, 100 h with CTA
(Doro et al, 2013)

A higher chance of DM detection than current IACT due to:
- high sensitivity,
- large spectral range,
- large field of view,
- better angular resolution,
- better spectral resolution

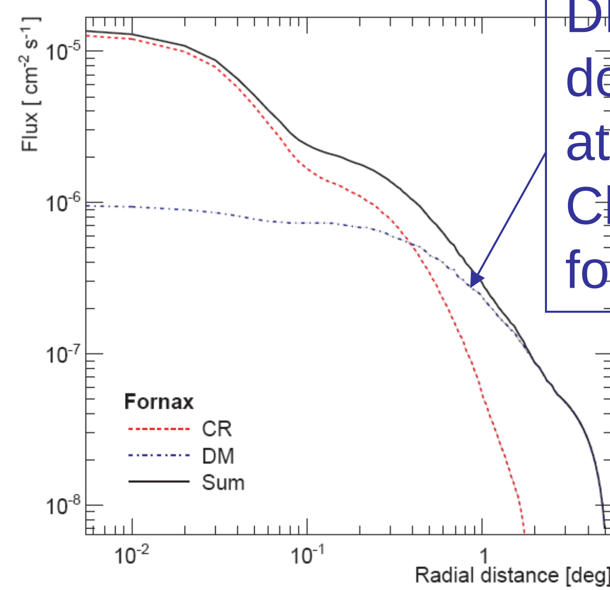
Identification by spectral features might determine the mass of the WIMP and its annihilation cross-section.

Search for DM in clusters of galaxies

- DM in clusters provides up to 80% of the mass → good targets for DM indirect detection
- Existence of substructures can boost the flux by 100-1000
- But other sources of VHE emission: AGN, galaxies, CR …



Observing time required to detect VHE at 5σ from CR in Perseus and Fornax



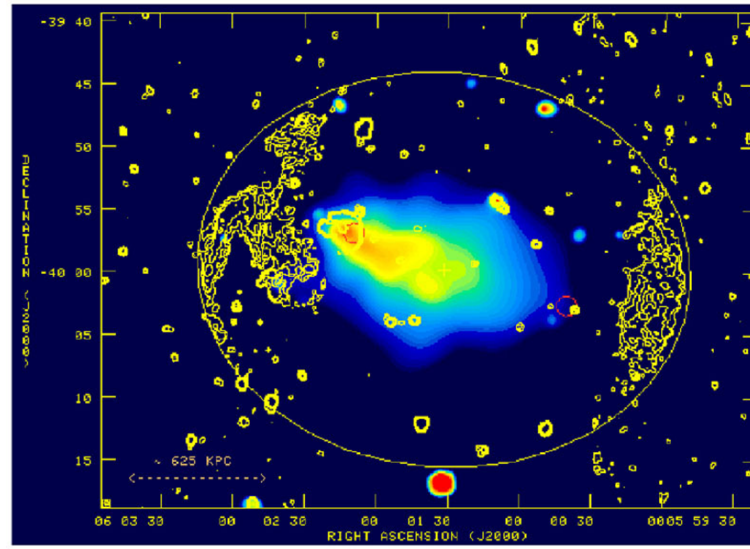
DM might dominates at > 0.4° Challenge for CTA.

Flux above 1 GeV of the gamma-rays expected from CR and DM in Fornax *(Doro et al, 2013)*

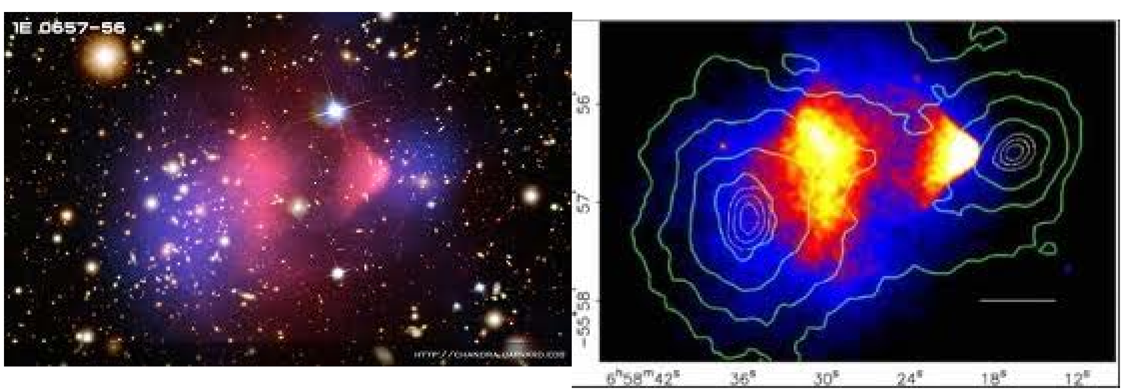
Large-scale and cosmological shocks

Large scale extragalactic structures:
- accretion shocks, i n the cluster oeriphery
- shocks and turbulence induced by major events of mergers of clusters of galaxies,
- shocks due to AGN activity (feedback)

→ Accelerate particles
→ Can trigger star formation
→ Amplify magnetic fields
→ Induce supernovae & smaller scale shocks, with particle acceleration…



Abell 3376: central X-rays emission + radio relics of shocks?



Bullet cluster, collision of two huge galaxy clusters

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Extragalactic cosmic rays (CR): galaxies, starbursts, clusters

- CR evolution: after acceleration *(= active emittors)*, escape from acceleration zone, diffusion and confinement for a while in the vicinity of accelerator, then full diffusion and mixing in the background → reveal *passive emittors*
- CR and γ-ray astronomy: a direct connection due to hadronic interaction of CR protons with ambient medium (interstellar, intergalactic, intracluster media), $\pi^0 \rightarrow \gamma\gamma$

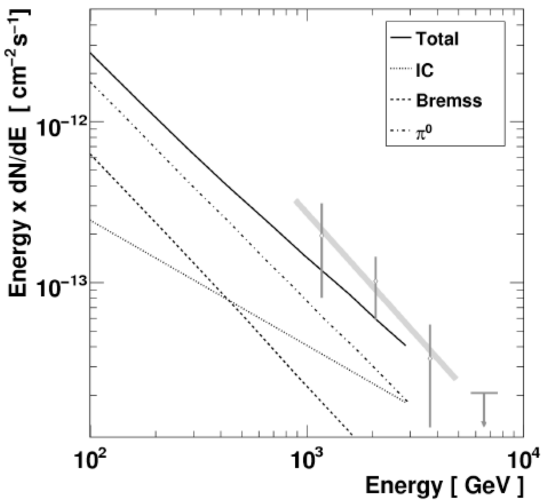
- Detection by Fermi of nearby galaxies + 2 starbursts NGC 253 and M82 seen at TeV energies

→ studies of CR acceleration, transport and confinement in external galaxies

- In group or cluster of galaxies: CR confined in large intracluster medium (Mpc-scale) for times > Hubble time

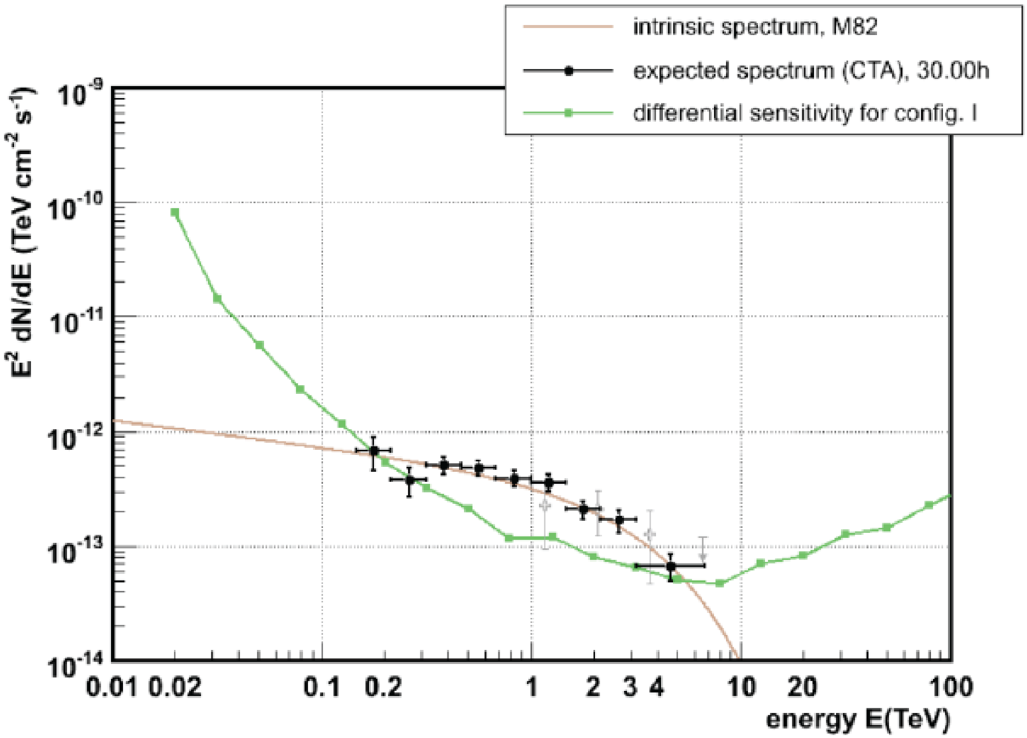
→ VHE emission expected from pp interaction in IGM

The starburst galaxy M 82



VHE discovery by VERITAS
(Acciari et al, 2009)

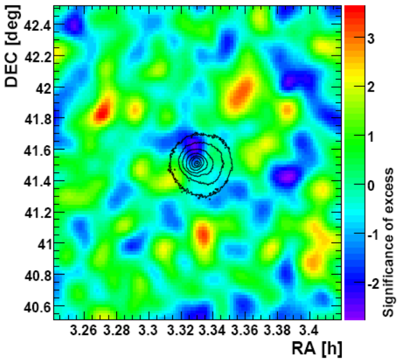
Simulated CTA spectrum for array I, 30h
(Acero et al, 2013)



CTA will detect cutoff
if present at TeV energies
→ Maximum energy of CR

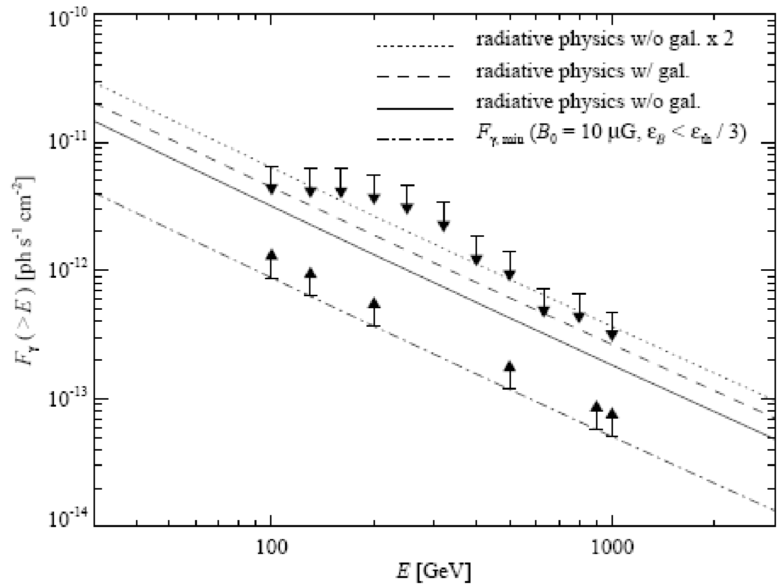
Extrapolated from VERITAS data
+ model by de Cea del Pozo et al, 2009

Clusters, IGM, cosmological shocks



Perseus cluster

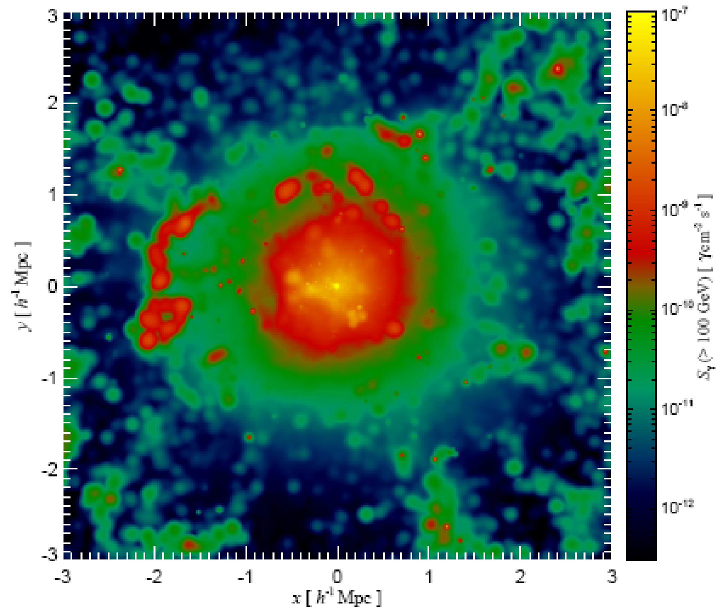
- VHE emission is expected from the intracluster medium (accretion and merger shocks, winds, turbulence, relativistic outflows and feedbacks from AGN …)

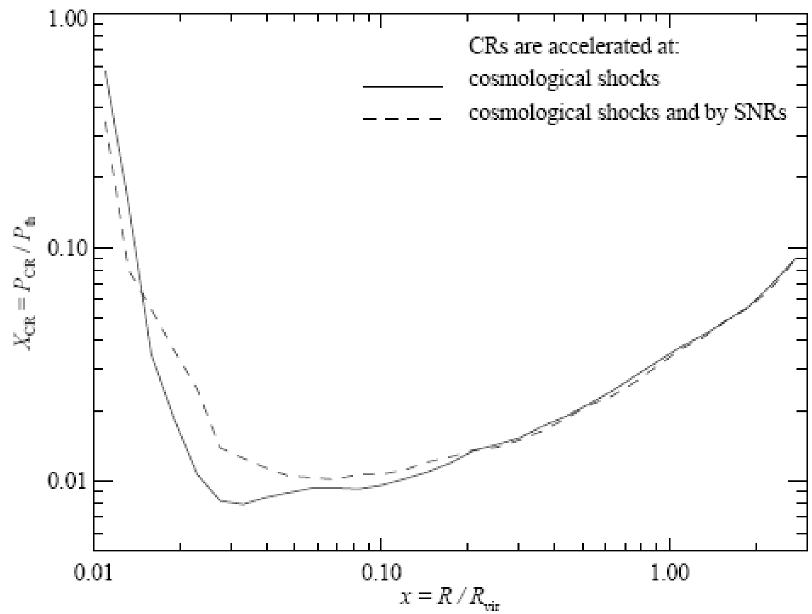


(Aleksic et al, 2010 MAGIC)

Extragalactic cosmic rays: clusters of galaxies

CTA has the potential to reach detection, or will put strong constraints on the models of clusters and intracluster medium (acceleration efficiency, magnetic field, CR fluxes, CR to thermal pressure ratio …)





Simulated VHE emission for a cluster of twice the mass of Perseus

(Aleksic et al, 2010)

Outline

Why VHE gamma-ray astronomy ?

I- Active VHE emitters: compact sources

Active Galactic Nuclei (AGN): populations and physics

Search for Gamma-Ray Bursts (GRB) and other types of transients at VHE

II- Active VHE emitters: diffuse sources

Search for Dark Matter (DM) in dwarf galaxies and clusters

Search for cosmological and large-scale shocks

III- Passive VHE emitters: diffuse VHE sources revealed by cosmic rays

Extragalactic cosmic rays (CR): galaxies, starbursts, clusters of galaxies, intracluster medium …

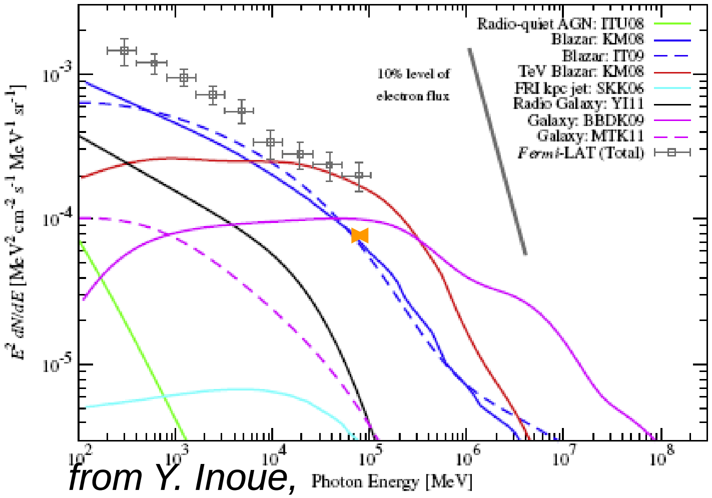
IV- The diffuse VHE background (ie: I + II + III **+ ?**)

V- Studying the lines of sight with AGN and GRB, beacons of ɣ-rays:
Extragalactic Background Light (EBL), InterGalactic Magnetic Field (IGMF), axion-like particles (ALP), Lorentz invariance violation (LIV)

The diffuse VHE background

Origin of the extragalactic gamma-ray background (EGRB)?
Contribution from unresolved sources as AGN,
+ galaxies, starbursts, diffuse IGM, pair halos, DM ?

Detection by Fermi below 100 GeV:
~ 70% of EGRB possibly explained by known populations
→ 30% may be new populations, or systematic uncertainties in measurement (foregrounds …)
→ Set an **upper limit** on the EGRB above 100 GeV (considering cascades on low-frequency backgrounds), below the Fermi data points !



from Y. Inoue, 2013

Studying the EGRB
to solve such inconsistency.
New physics ? New populations ?

Search for turnover above 100 GeV
due to EBL absorption

Real challenge

Outline

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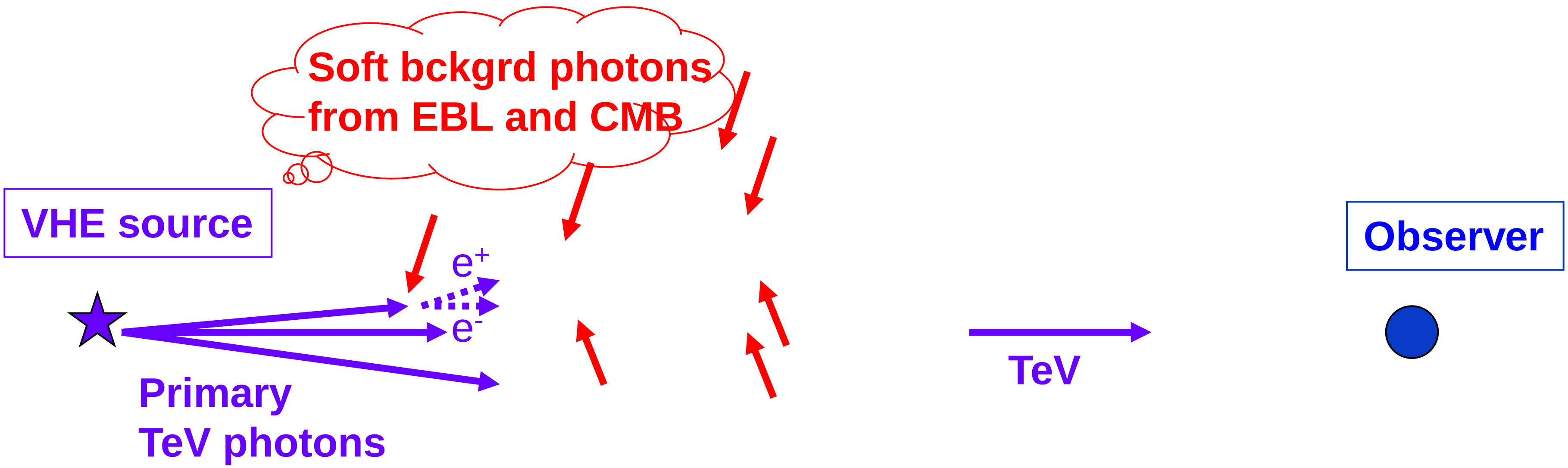
TeV gamma-ray signal from high-z sources

TeV gamma-ray signal from high-z sources

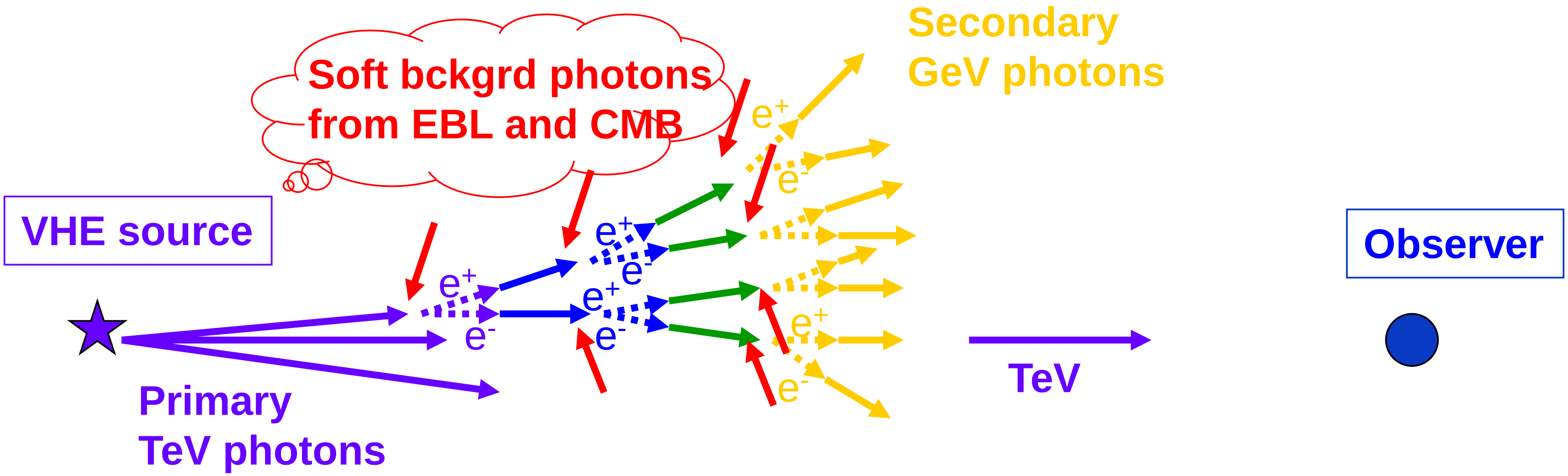


Cascades of e^+ e^- pair creation
and Inverse-Compton emission

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

$$e^-_1 + \gamma_{IR\ (CMB)} \rightarrow \gamma_{VHE,2} + e^-_2$$

TeV gamma-ray signal from high-z sources

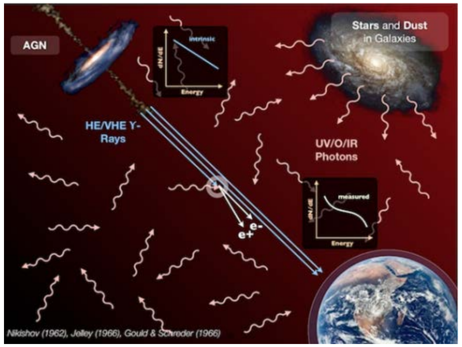


Cascades of $e^+ e^-$ pair creation
and Inverse-Compton emission

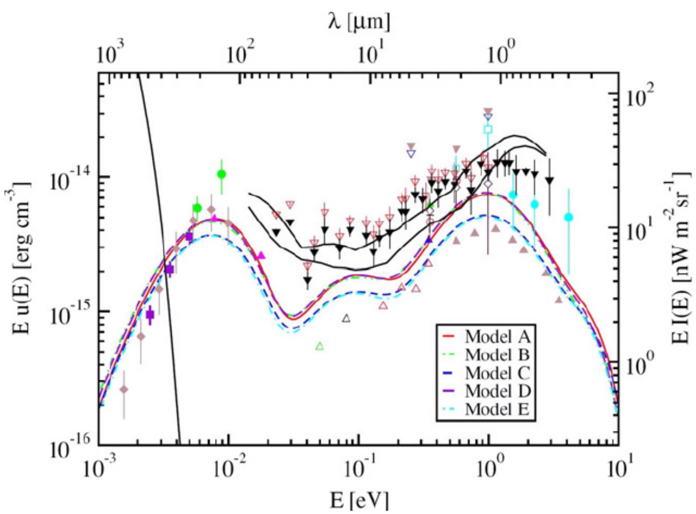
$$\gamma_{VHE,1} + \gamma_{IR\,(EBL)} \rightarrow e^+ + e^-$$

$$e^-_1 + \gamma_{IR\,(CMB)} \rightarrow \gamma_{VHE,2} + e^-_2$$

Probing the EBL



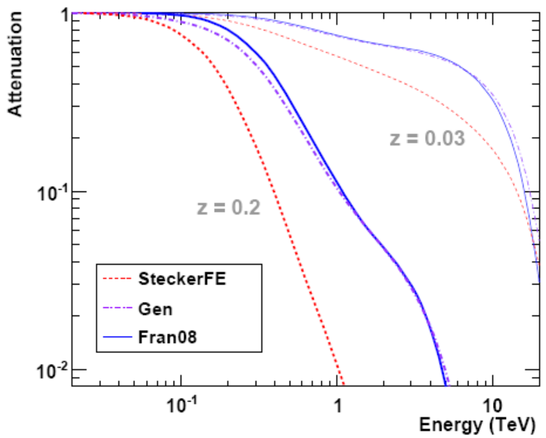
EBL = light from normal stars in whole history of universe, dust, AGN, pop III stars?, DM?, … pervading the IGM



(Finke et al, 2010)

→ Absorption of TeV photons by pair creation when $E_{VHE}.E_{EBL} > (m_e c^2)^2$

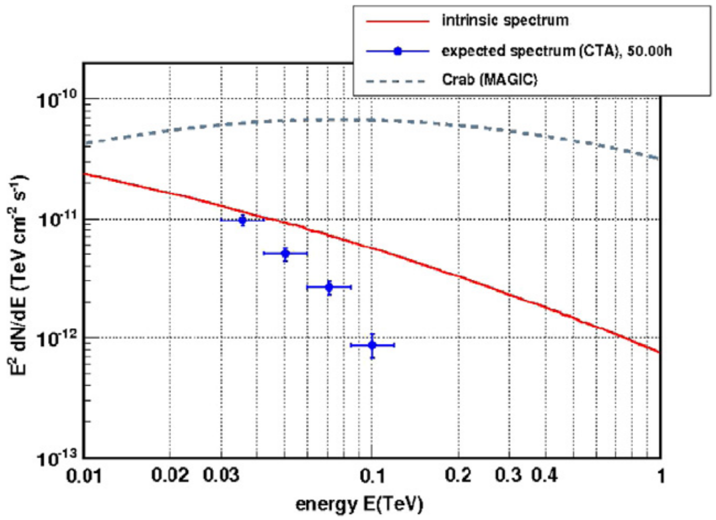
→ Imprint of EBL on observed spectra of high redshift sources

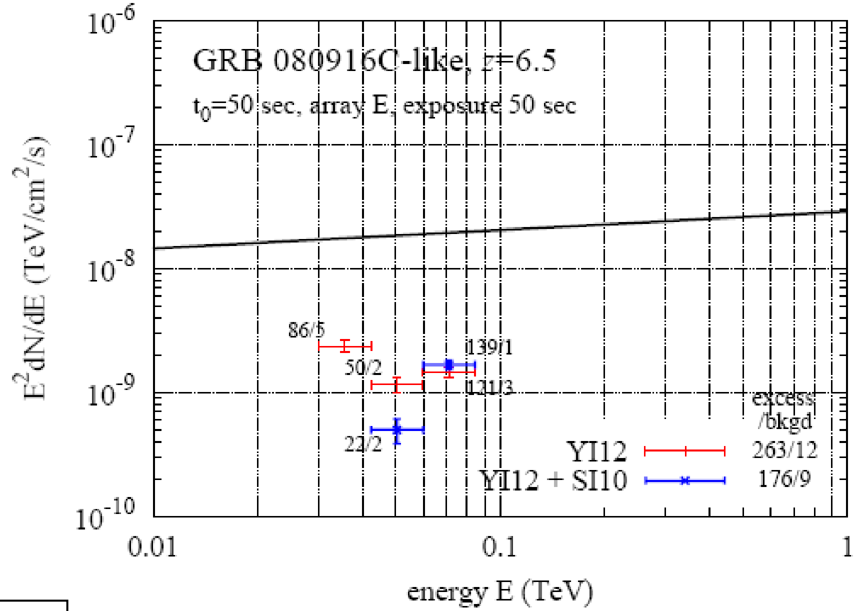


Attenuation factor as a function of energy for various EBL models, shown for 2 redshifts

(Raue, Mazin, 2010)

Probing the EBL





Simulated spectrum from extrapolation of a Fermi blazar at z = 1.839
CTA array B, 50h at 13.6 σ, zenith angle 20°
EBL from Franceschini et al, 2008

Simulated GRB spectra from z ~ 6.5 for 2 EBL models
GRB can probe the EBL at very high z, beyond the z ~ 2 of blazars

(Sol et al, 2013)

(Inoue et al, 2013)

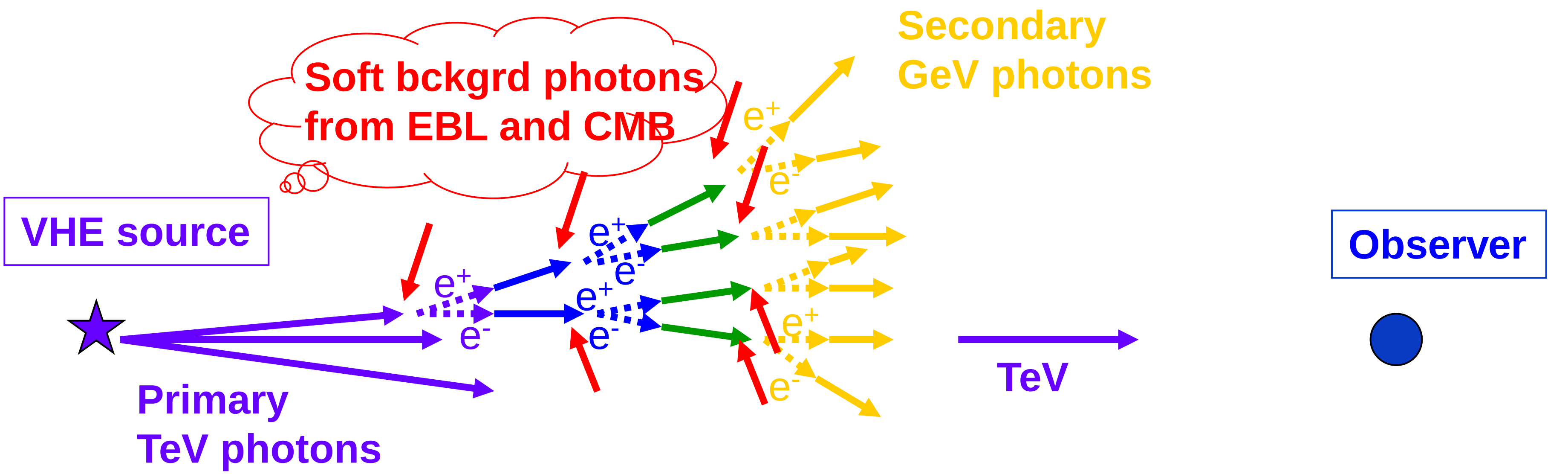
Probing the EBL

Disentangling intrinsic effects versus EBL effects:

- low energy GeV part of spectra, less affected by EBL, reflects intrinsic properties → extrapolate to TeV (require large spectral range)
- study of large sample of 100s sources at various z (require high sensitivity)
- study variability: VHE cut-offs due to EBL should be constant, while those due to intrinsic variable flux are expected to evolve (require high sensitivity)

- provide strong upper limits on the EBL, and possibly impose its lowest value deduced from galaxy counts
- constrain star formation rate
- probe some aspects of the epoch of reionization
- provide a new and independent cosmic distance estimate, of cosmological interest, once EBL is fully determined
- finding evidence of some inconsistency in the whole picture might reveal new physics

Probing the InterGalactic Magnetic Field



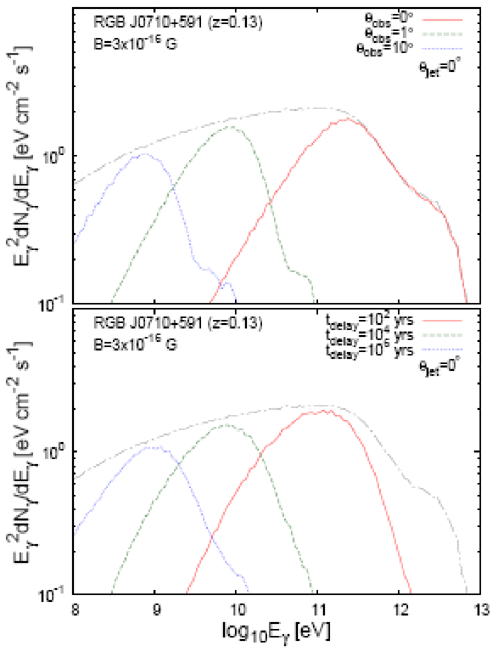
Cascades → secondary GeV flux,
dependent of the IGMF properties

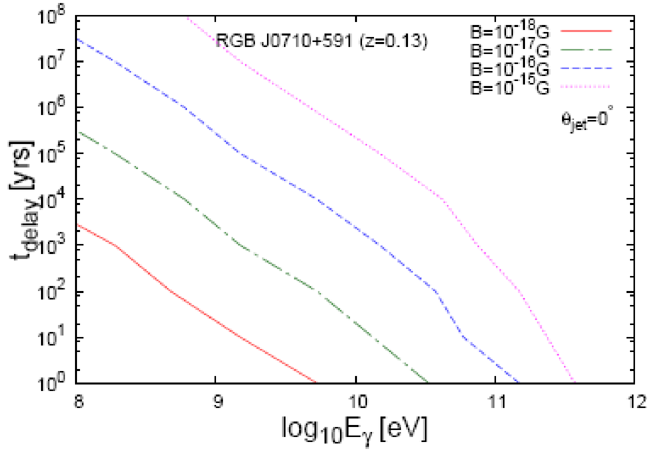
- Extended GeV emission around primary TeV signal
- Delay of secondary GeV emission

Lack of detection
so far provided first
non-zero lower limits
on the IGMF !

Origin of the magnetic
field in the universe …

Simulations of pair echoes





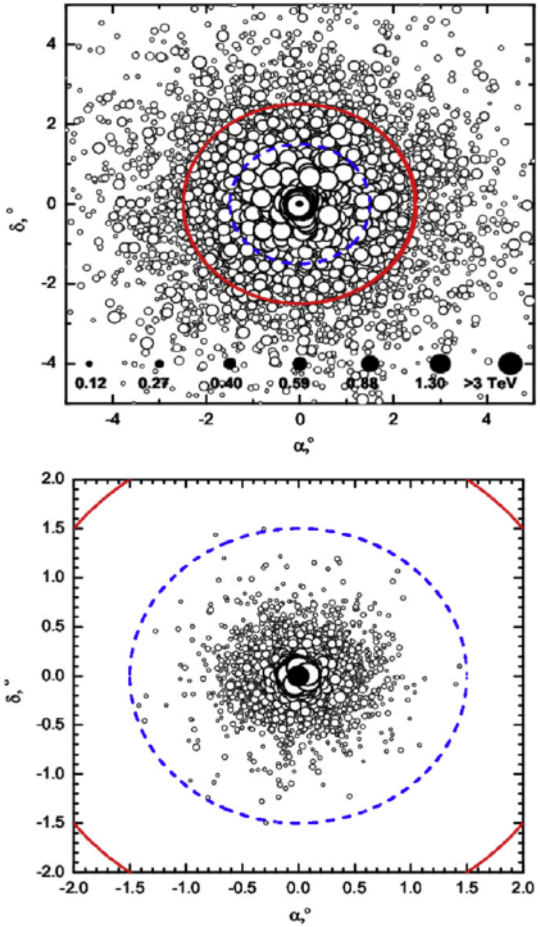
Arriving energy fluxes after injection of 100 TeV photons from z = 0.13
Top : for different viewing angles
Bottom : for different delay times

Corresponding mean time delay for different values of the IGMF

(from Taylor et al, 2011)

Searching for echoes: requires long term monitoring of variable AGN over large GeV-TeV spectral range

Probing the InterGalactic Magnetic Field



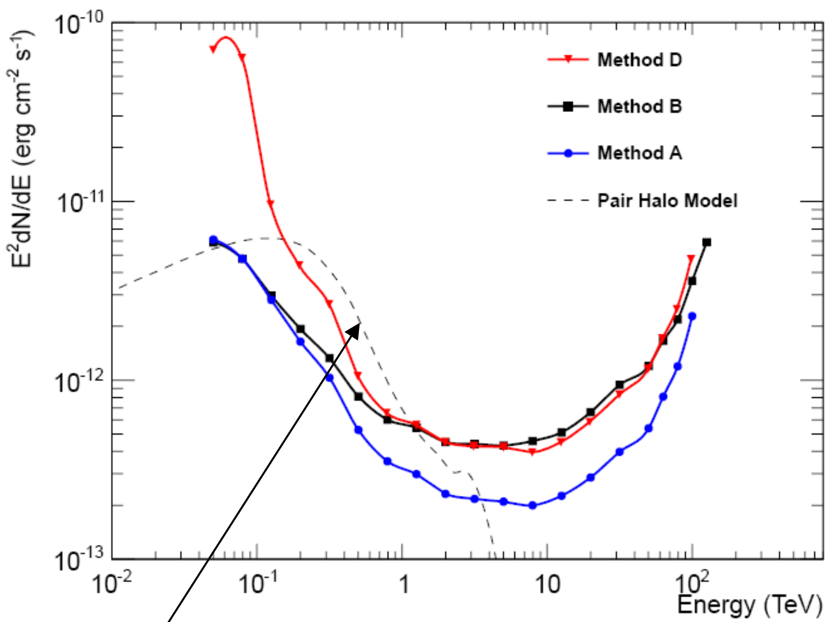
Formation of pair halo:

Arrival direction of primary and secondary gamma-rays from a source at 120 Mpc.
IGMF = 10^{-14} G (upper panel)
IGMF = 10^{-15} G (lower panel)

Red circle: field of 2.5°
Blue circle: field of 1.5°
→ well fit into the CTA FoV

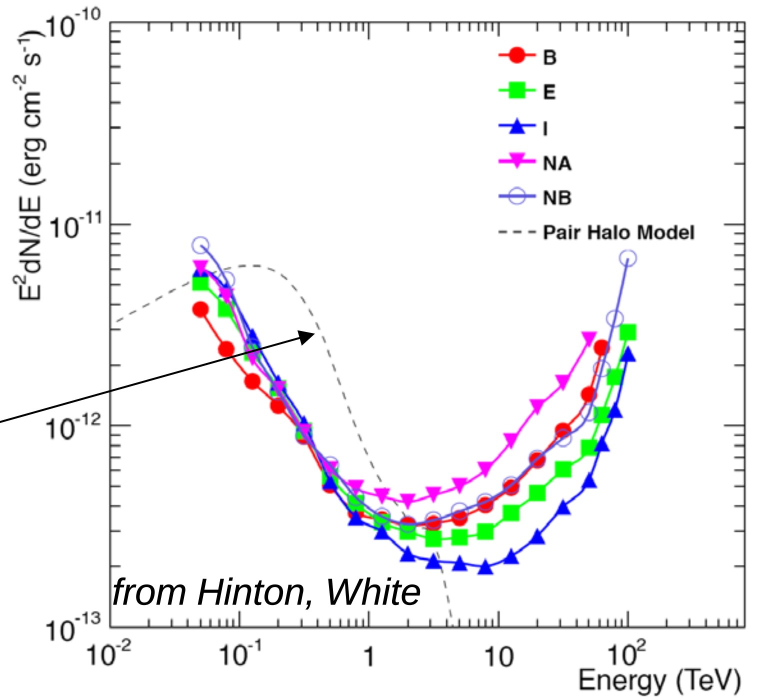
(Elyiv et al, 2009)

Flux sensitivity for pair halo detection



for 3 different analysis methods to search for the extension (configuration I for CTA array)

for 5 different CTA array configuration, 50 hours, 20° zenith angle (method A)



Differential angular distribution of a pair halo at z = 0.129 (1ES1426+482) and $E_\gamma > 100$ GeV [theoretical model from Eungwanichayapant, Aharonian, 2009; intermediate IGMF, mono-energetic primary at 100 TeV, 10^{45} erg/s]

Implication of detecting a B_{IGMF}

- Provides new information on the early universe: Generation of an IGMF during inflation or post inflation?

- Or pure astrophysical origin of the IGMF, through magnetized outflows and dynamo?

- Completes the dynamo description for the origin of cosmic magnetic fields.

- Provides magnetic seed fields for any dynamo amplification process

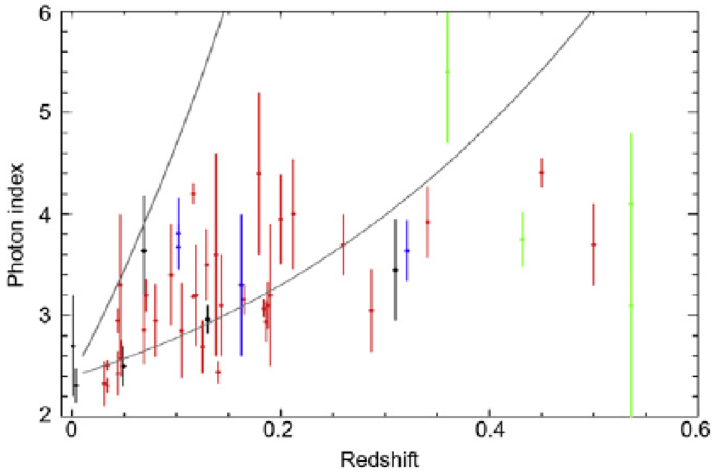
- Appears as an alternative to some dynamo scenarios, especially useful to explain young magnetized structures, with little time for dynamo growth
(ex: magnetic bridge in Coma supercluster)

New physics: search for axion-like particles ?

Axions, hypothetical low mass particles: candidates for DM, convert into photons in presence of non-zero IGMF. Such « axion-photon » mixing effect can distort the VHE spectra of high-z sources.

Their existence (if any) should modify our current interpretation of VHE extragalactic observations, and could provide interesting explanation in case of growing inconsistency with the standard views.

One example:



Increasing statistics with CTA will clarify the trend of **observed photon index versus redshift z**.

Should be an increasing function of z following standard view, due to EBL. Possibly detected for Fermi data but not yet firmly detected at VHE, possibly hidden by various observational biases.

New physics: search for Lorentz Invariance Violation ?

- Quantum gravity models → possibility of energy dependence of the speed of light in vacuum (~ space-time distorsion) → velocity dispersion for massless particles at $E \sim E_{Planck}$:

$$c^2p^2 = E^2 \left(1 \pm \xi_1 (E/E_P) \pm \xi_2^2 (E/E_P)^2 \pm \dots\right)$$

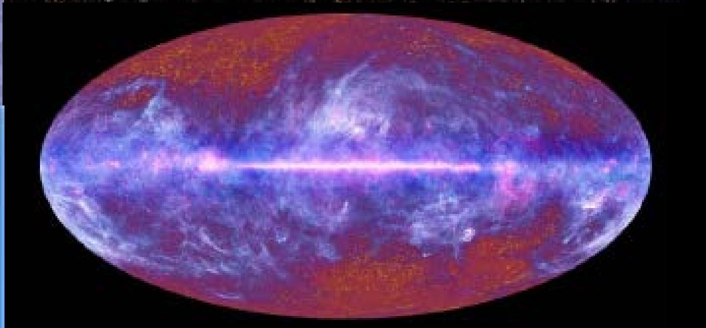
- Induced time delay between 2 photons with a difference in energy of ΔE

$$\Delta t \sim (\Delta E / \xi_\alpha E_P)^\alpha (L/c), \text{ where L is the distance of propagation}$$

- Fermi with a GRB and HESS with a blazar: best constrain the linear and quadratic term with no time delay detection so far

- Requires a large spectral range and a large sample of variable sources, AGN and GRB, at various z to disentangle intrinsic and propagation effects

- Beautiful programmes & synergies
- Large FoV experiments provide samples of sources & monitoring
- High-sensitivity instruments perform in-depth analysis
- Global alert network
- « HAWC & LHAASO » - south ?
- Gold nuggets ?



Active Galactic Nuclei with CTA

Extrapolation from Fermi

Number of detectable Fermi AGN with redshift for different array configurations (50 h of maximum exposure time). AGN with unknown type are classified as "other AGN".

Array	FSRQs	BL Lacs	other AGN	SBGs	RGs	Seyferts	Total
B	46	117	19	3	6	1	192
C	17	84	17	3	6	1	128
E	32	111	18	3	6	1	171
NA	33	109	18	3	6	1	170
NB	27	103	17	3	6	1	157

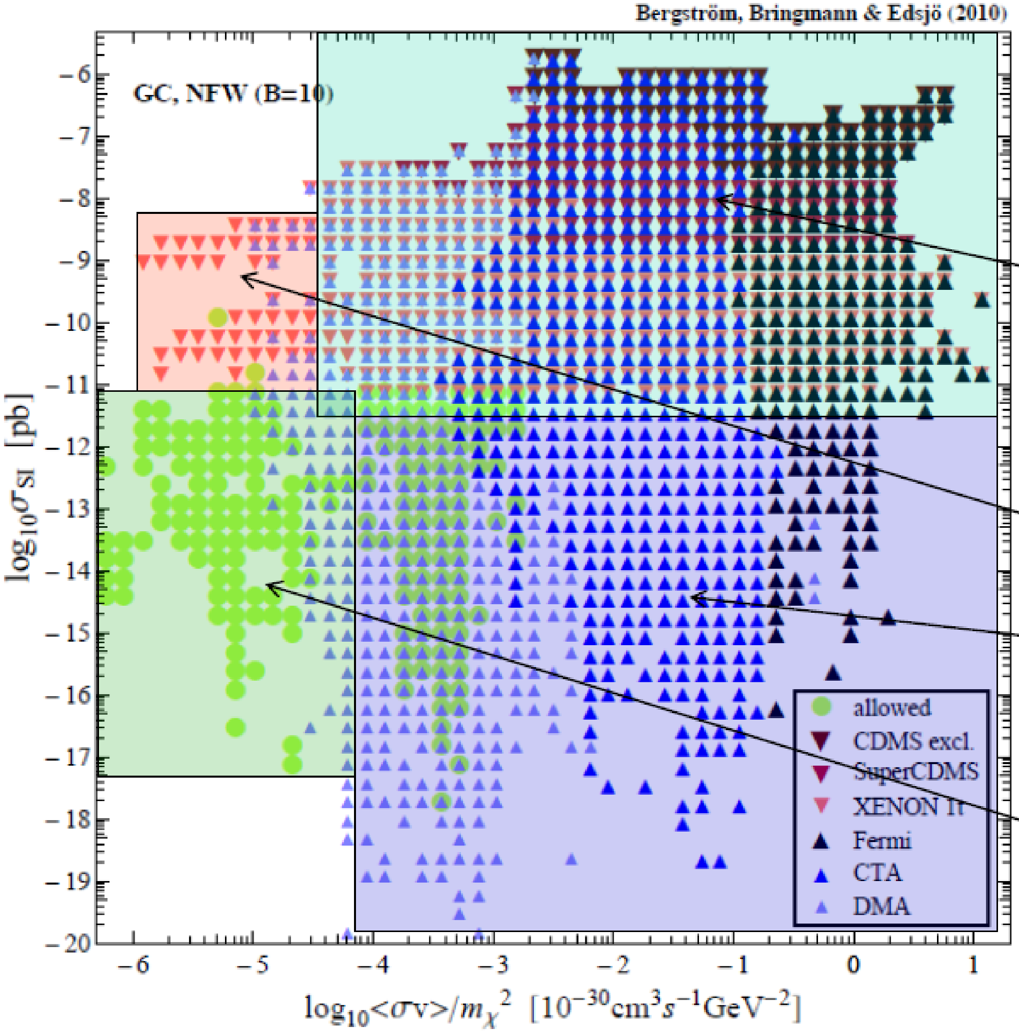
Estimates from another independent extrapolation from Fermi, leading to similar numbers (various arrays).

Blind extragalactic surveys

Results from HAWC should help to anticipate better the probability of discoveries by a blind CTA extragalactic survey.

All FoV of targeted extragalactic sources should provide about 100 serendipitous discoveries of blazars in ~10 years of CTA observations.

Explorer l'espace des paramètres grâce aux différents détecteurs



Détection directe et indirecte

Détection directe seulement

Détection indirecte seulement

Domaine très difficile d'accès

CTA **Fermi**

(Bergstrom et al, astro-ph, 23 février 2011)

GRB: simulated CTA data

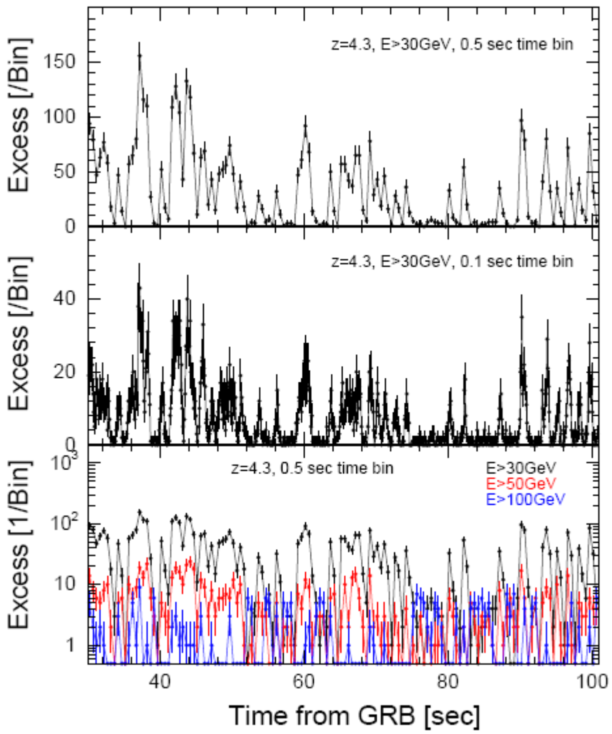
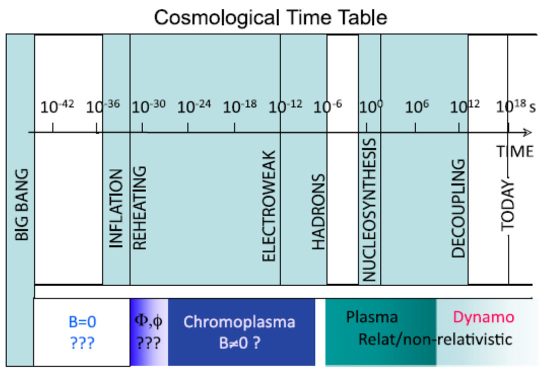


Figure 12: Simulated light curves of GRB 080916C at $z = 4.3$ for CTA array E. The EBL model of [223] was assumed. Top: Light curve for $E > 30$ GeV from $t_0 = 0$ sec, with 0.5 sec time binning. Upper middle: Same as top panel, but plotted from $t_0 = 30$ sec. Lower middle: Same as upper middle panel, but with 0.1 sec time binning. Bottom: Light curves from $t_0 = 30$sec with 0.5 sec time binning, for $E > 30$ GeV, $E > 50$ GeV and $E > 100$ GeV, from top to bottom.

Generation of an IGMF: 1°) primordial universe



If B= 0 at the beginning, need to find a time/place where flux freezing is not valid to start the magnetic field …
(Widrow et al, 2012)

During inflation : Quantum fluctuations can produce large scale phenomena from microphysical processes. Low-conductivity permits increase of magnetic flux. Electromagnetic quantum fluctuations amplified during inflation could appear now as static IGMF, electric fields being screened later on during the highly conducting plasma epoch
(Grasso, Rubinstein, 2001;
Kandus et al, 2011)

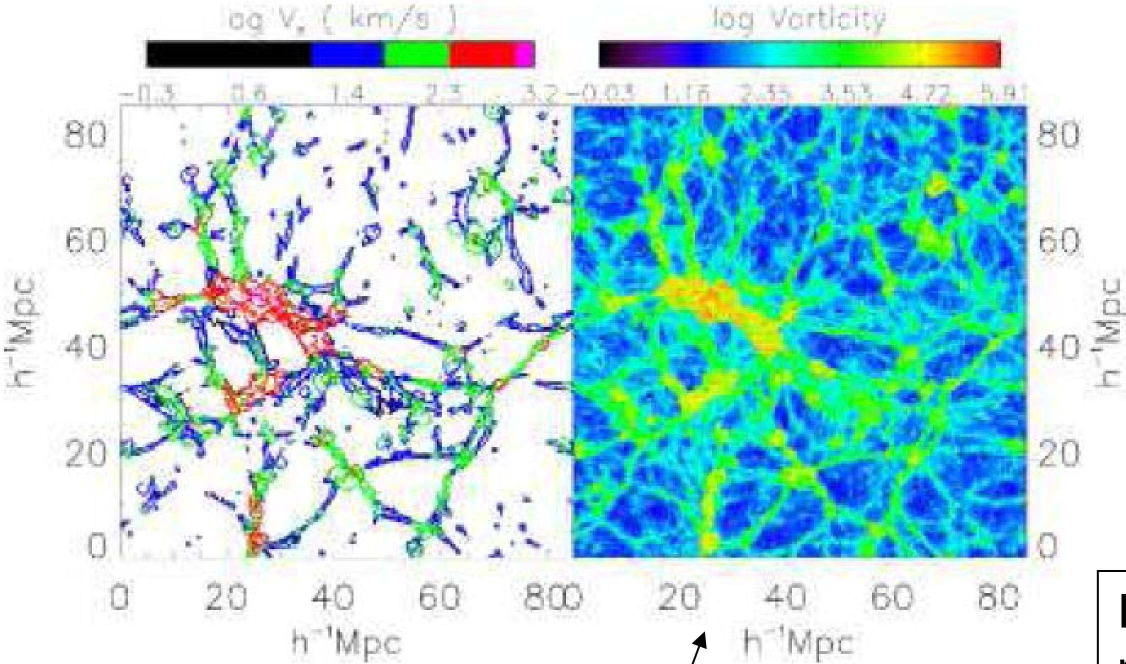
Post inflation : Decoupling transitions of fundamental forces (changes in nature of particles and fields + release of free energy → electric currents → generation of magnetic fields). Quark-hadron phase transition, electroweak phase transition [1st order transition; bubbles and shock fronts …]

(Grasso, Rubinstein, 2001)

Generation of an IGMF: 2°) magnetized outflows and dynamo

- Difficulties of primordial B scenarios:
  - B from inflation are very weak,
  - B from phase transition tend to have very small scales

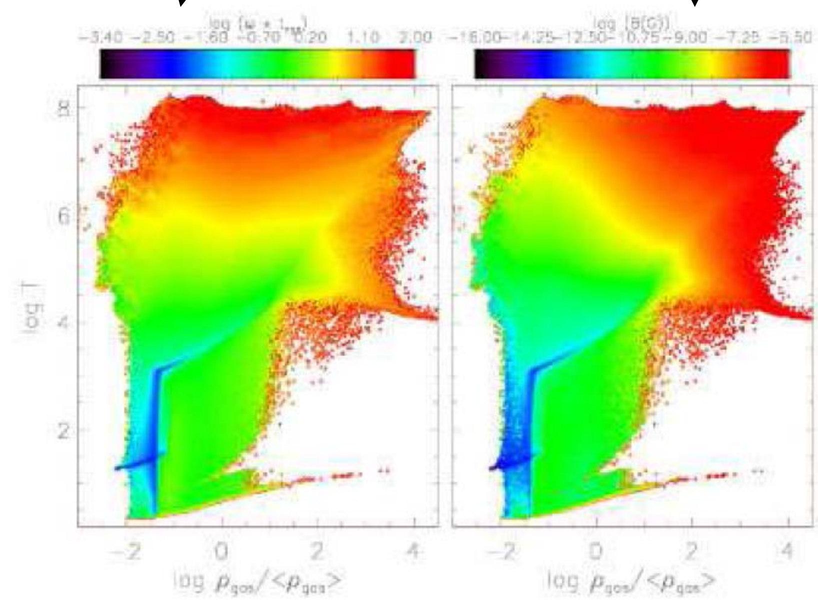
  → too weak or too small to serve as seed fields for galactic magnetic fields ? *(Kandus et al, 2011; Widrow et al, 2012)*
- Astrophysical origin of IGMF: later formation by **ejection of magnetized plasmas into intergalactic space**, from galaxies, AGN, starbursts, Pop III stars, large scale shocks … *(Kronberg, 1994; Widrow et al, 2012; Ryu et al, 2012; Lilly, 2012).*
- **Seed fields amplified by turbulent flows** during the formation of large scale structure of the universe, magnetic helicity and inverse cascade process *(Ryu et al, 2011; Widrow et al, 2012)*



Shocks and vorticity in a 2D slice of universe ($85h^{-1}$ Mpc x $85h^{-1}$ Mpc)

(from Ryu et al, 2012)

In the density-temperature plane, at z = 0, vorticity and strength of the IGMF



Detecting very low IGMF

Pair halos

- Electromagnetic cascades from VHE gamma-rays of AGN absorbed by e^+e^- pair production on the intergalactic background radiation fields.

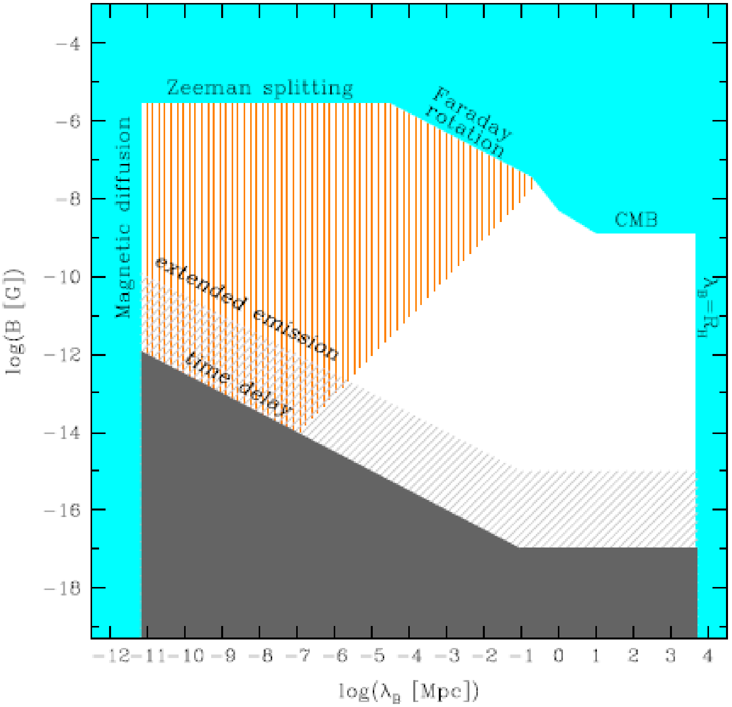
  Extended halos (> 1 Mpc) are formed when velocities of pairs are isotropized by the ambient IGMF

  (Aharonian et al, 1994)

Pair echoes

- Delay in arrival times of gamma-rays from remote variable sources such as gamma-ray bursts and flaring AGN: VHE photons interact with CMB and extragalactic background light (EBL) → production of e^+e^- pairs which Inverse-Compton scatter CMB photons and produce secondary VHE photons. IGMF deflect the pairs and delay the secondary gamma-ray pulse → should be able to detect B_{IG} down to 10^{-24} G *(Plaga, 1994)*

Typical current constraints on the IGMF *(including lower limits from γ-ray data):*



(From Taylor et al, 2011)

However, deep search for extended VHE halo by ACT for specific sources: obtained only upper limits up to now *(Aharonian et al, 2001, Aleksic et al, 2010, Fallon, 2010 …)*

Multi-lambda lightcurves difficult to interpret in term of precise time delays. Long term variability poorly constrained. Interpretation still somewhat model-dependent (ex: plasma-beam instability, *Broderick, et al, 2012)*

Positive detection of the cascade process would open new paths to characterize the IGMF and backgrounds

Search for …

- High energy tau neutrinos

Neutrinos above TeV can come from microquasars, AGN, GRB, compact sources, interactions of UHECR, DM, topological defects and cosmic strings … and contribute to CR

Tau neutrinos might be more easy to detect → pointing telescope towards the Earth or a mountain nearby (to reduce hadronic background)

Very difficult to reach for present IACT. Still difficult for CTA, but **can be done during bad weather !!** → *almost no cost*

cf Doro et al, 2012)