Physics with CTA: Particle Acceleration and Nonthermal Astrophysics

- “Few-source astronomy”
- Main promise: Cosmic Structure formation/evolution
- Starburst Galaxies, Galaxy Mergers
- Galaxy Clusters
- Black Hole Emitters
- Cosmic Ray Physics in Galaxy (left-overs from present instruments and GLAST)
- Multi-Wave-Length aspects and limitations

1) "Few-source astronomy" (ROSAT ~ 10^6 sources)

Up to CTA probably ~ 100 VHE sources

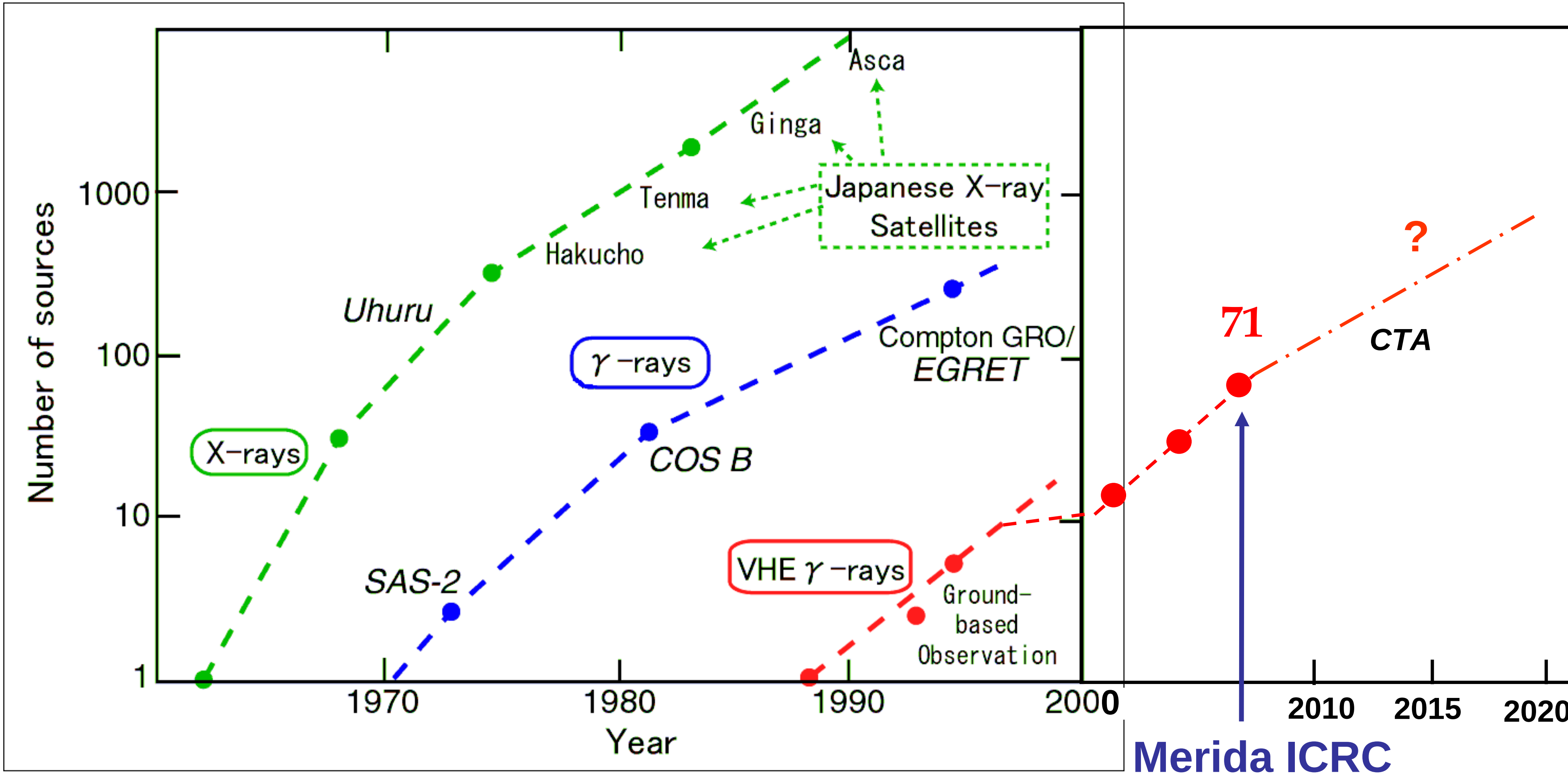
CTA hopefully increases source number
⇨ 1000 sources (in Galaxy confusion-limited)

Nevertheless: Population studies will not be the most promising program part of CTA (VHE sources not uniquely characterized by a few parameters like a star). *Pulsar Wind Nebulae* perhaps most promising type of sources in this regard, but rather well studied already.

Most important: a) Multi-Wave-Length (MWL) studies

b) Theoretical studies of these *complex systems*

``Kifune Plot''



Adapted from J. Hinton (2007)

Expect present/extended generation of ground-based telescope systems to essentially solve Cosmic Ray (CR) origin to the knee, also with help of *GLAST*

Probable exception are gamma-ray energies above 100 TeV.

⇨ Galactic CR physics to good part "finished" before CTA

2) Future field: Nonthermal part of Cosmic Structure Formation/Evolution

Baryonic aspect mainly given by:

a) (Proto)galaxy - (Proto)galaxy interactions to form the present large galaxies and their halos

b) Mergers of sub-clusters to form the observable rich clusters of galaxies

c) Interactions of supermassive Black Holes (AGNs) with their environment

2a) Starburst Galaxies, Galaxy Mergers

- **Upon formation (z = 2-3) galaxies probably go through an initial phase of massive star formation (starburst)**
- **In addition, large galaxies presumably form by mergers of galaxies**

⇨ Large elliptical and lenticular galaxies in clusters

⇨ Formation of galactic bulges followed by accretion of gas and/or dwarf galaxies ⇨ present gas-rich field galaxies

- **Also present-day massive galaxies interact with other galaxies**

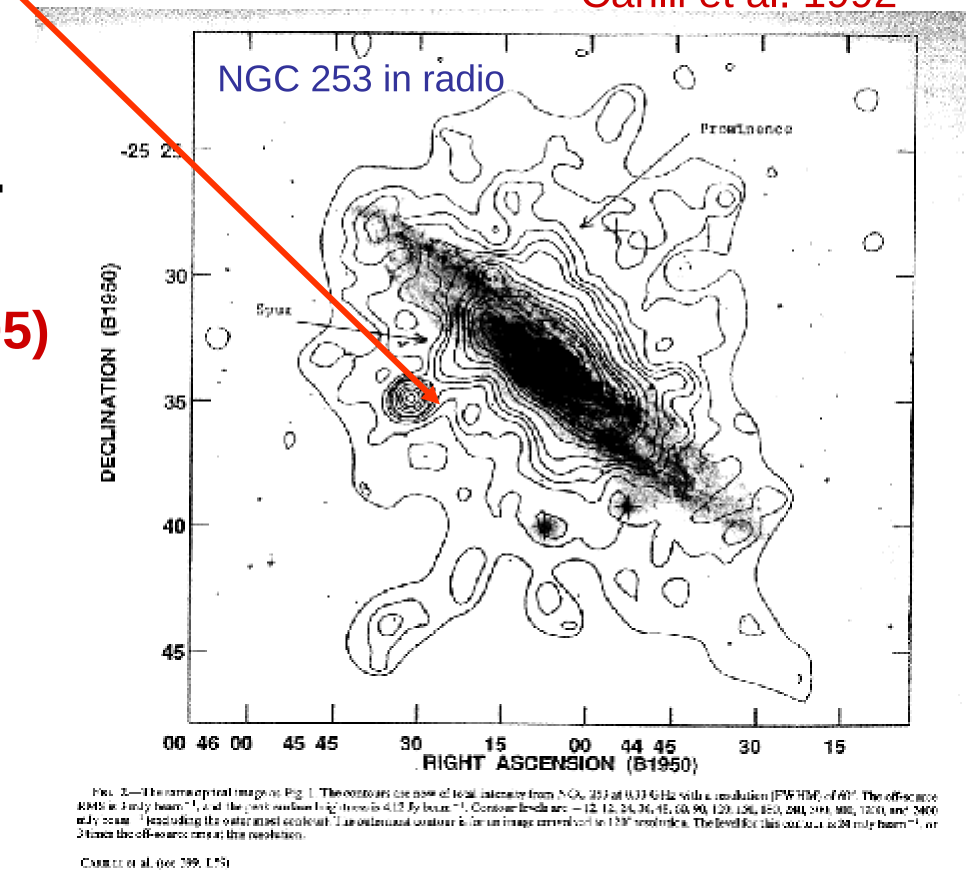
⇨ Present (z << 1) starbursts and Galaxy-Galaxy mergers

⇨ Conclude from them about cumulative effects from the past

Example 1: Starburst galaxy NGC 253 (d = 2.5-3.5 Mpc)

SN rate = 0.03 / yr in very small ~ 10^8 solar mass central volume of scale size 100 pc ⇨ Galactic wind ∝ 900 km/sec (Zirakashvili &V, 2006). Expect very high hadronic γ-luminosity

Carilli et al. 1992



NGC 253 not detected by H.E.S.S., but UL close to estimates (Aharonian et al., 2005; Domingo-Santamaria & Torres, 2005)

Detection still with H.E.S.S. I or II ?

M82 in Northern Hemisphere ?

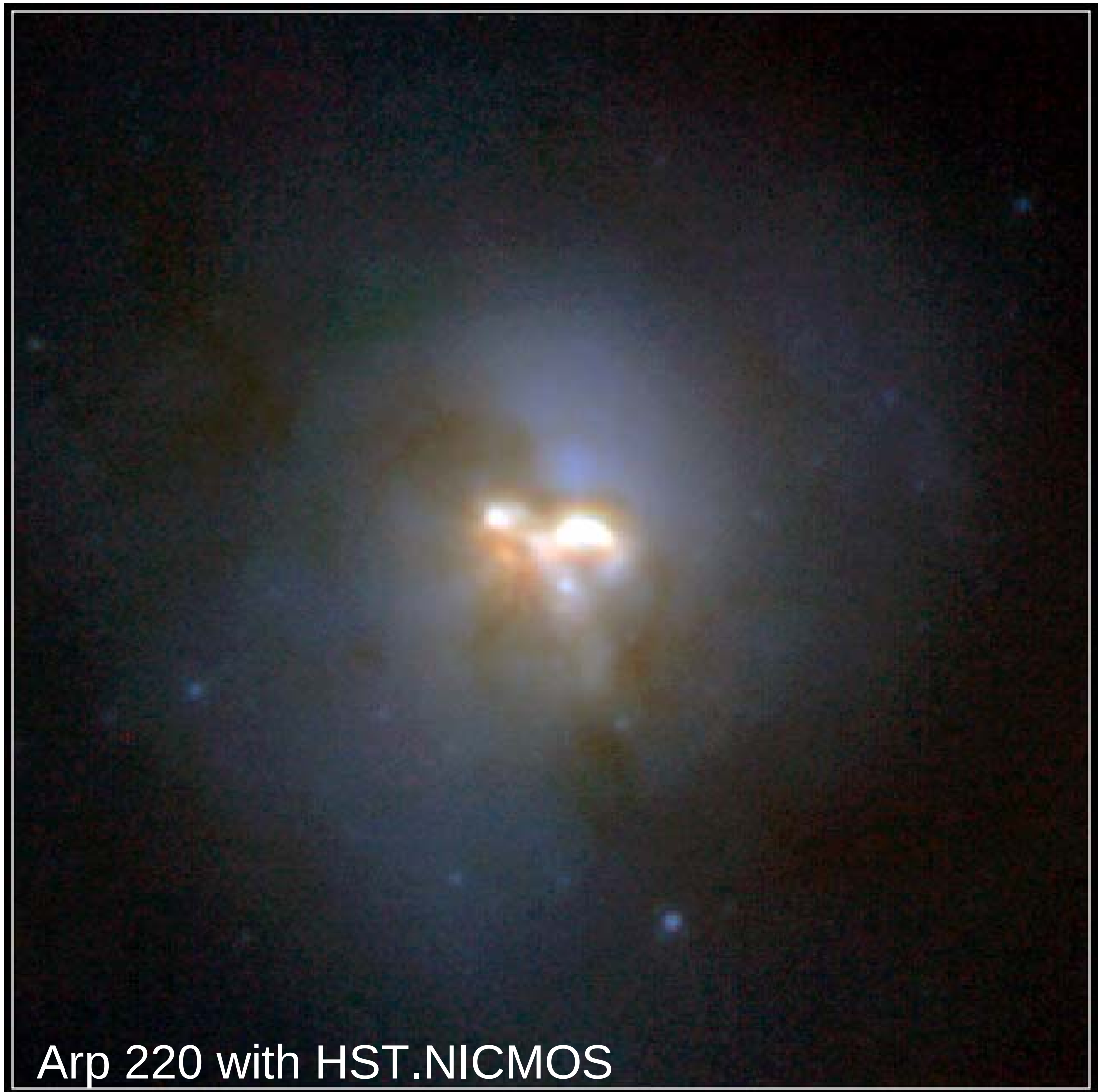
⇨ Rich field for CTA

Example 2:
Merging Spiral Galaxy Pair Arp 220 (d = 70-80 Mpc) = ULIRG (Ultra-Luminous Infrared Galaxy)

Large Supernova rate: 0.5 - 4 SNe/year (20 – 200 times Milky Way)

Brightest object in the local Universe: Rad'n field ~ 10^5 eV/cm^3

H.E.S.S. upper limit at 1 TeV, 14 hr live: $E^2 \times F(E) \propto 2$ mCrab, ~ consistent with Torres (2004, revised) and with Bernlöhr (2006, priv. comm.)



⇨ **At an energy flux level of**
E^2 x F(E) = 2 mCrab (1 TeV)

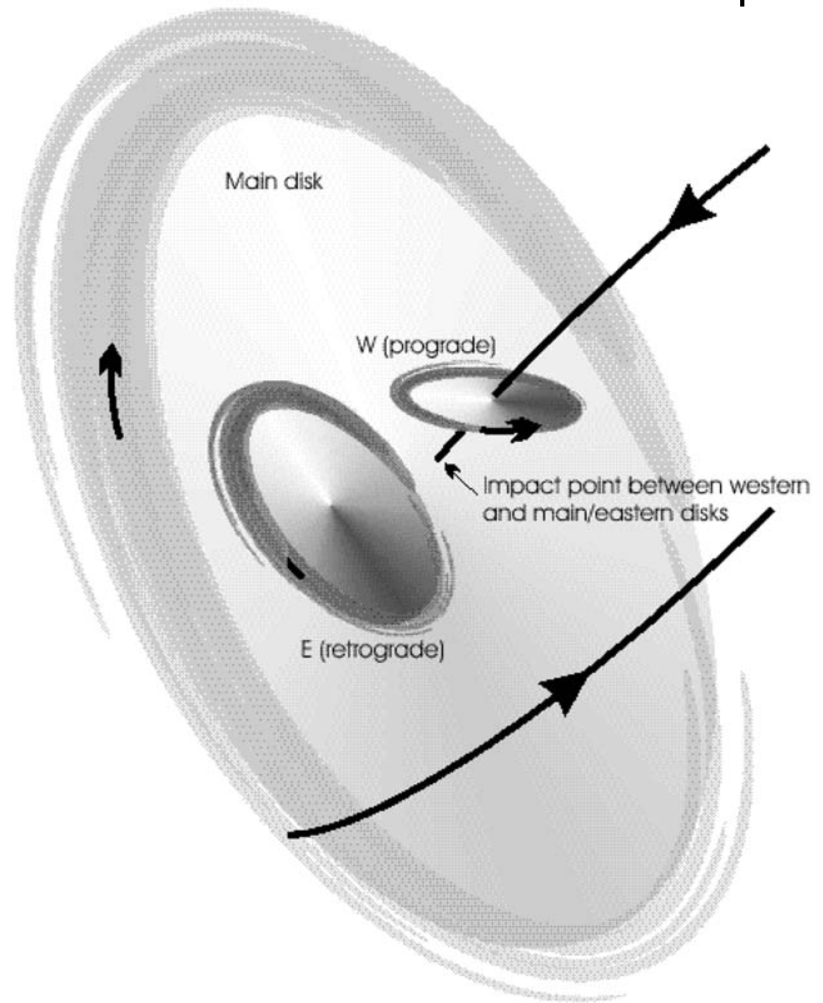
measurable with a
***CTA* of sensitivity**
6 x H.E.S.S.
in ~ 17 hr (integral)

In 50 hr ⇨ 5σ - spectrum, for
300 GeV < E < 5 to 10 TeV

Consequence:

Arp 220 detectable?
Similar objects as well ?

Schematic of Arp 220



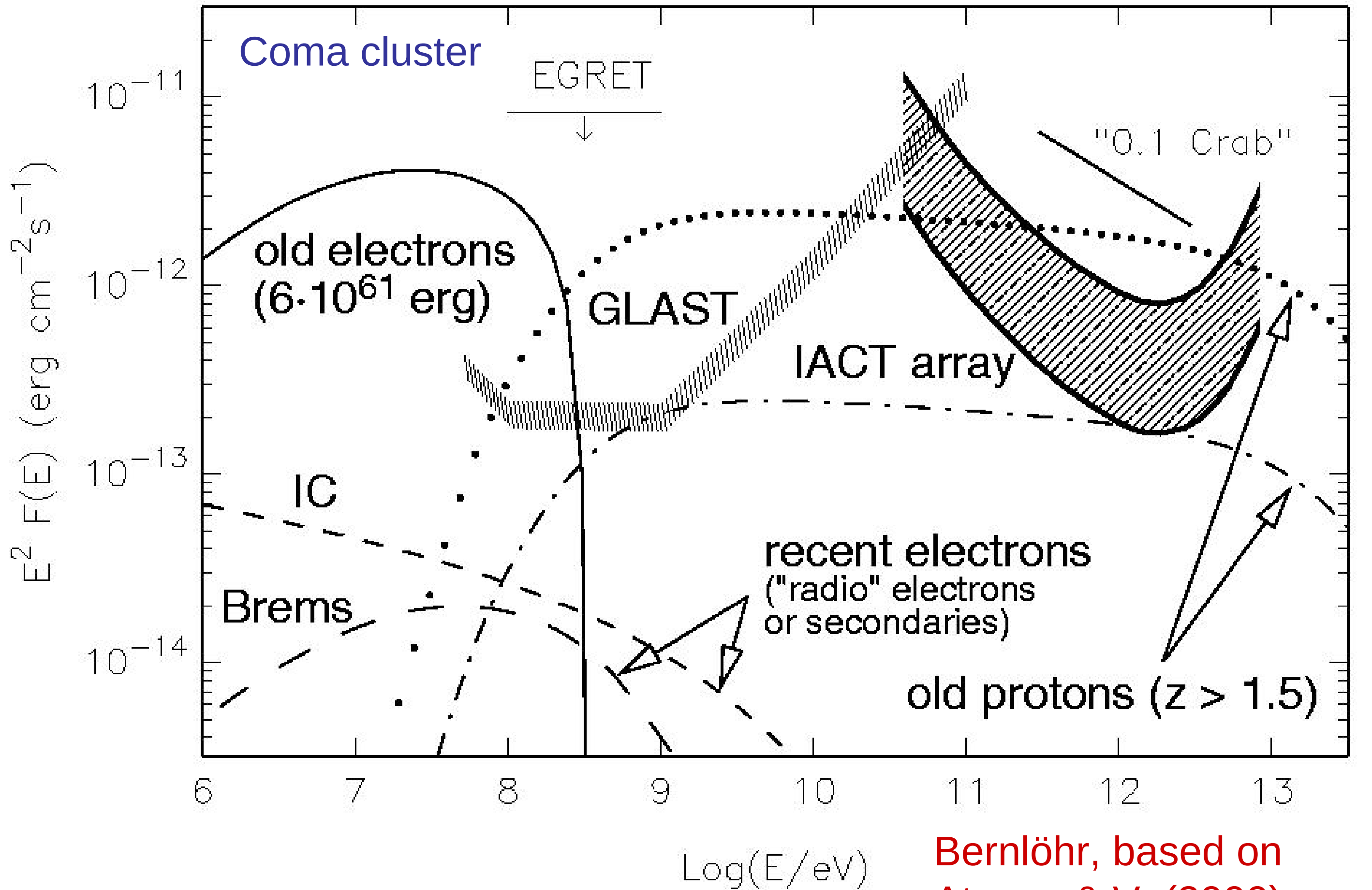
Mundell et al. (2001)

2b) Cumulative detection of these galaxy mergers (⇨ "Cosmological CRs") in Galaxy Clusters,

assuming that energetic particles within energy range of CTA (E_{proton} < few PeV) can not escape ?

Result:

marginal for *H.E.S.S.*-type instrument, but reasonable for *CTA*



Bernlöhr, based on Atoyan & V. (2000)

Still 2b) Mergers of sub-clusters to form the observable rich clusters of galaxies

Baghi et al. (2006)

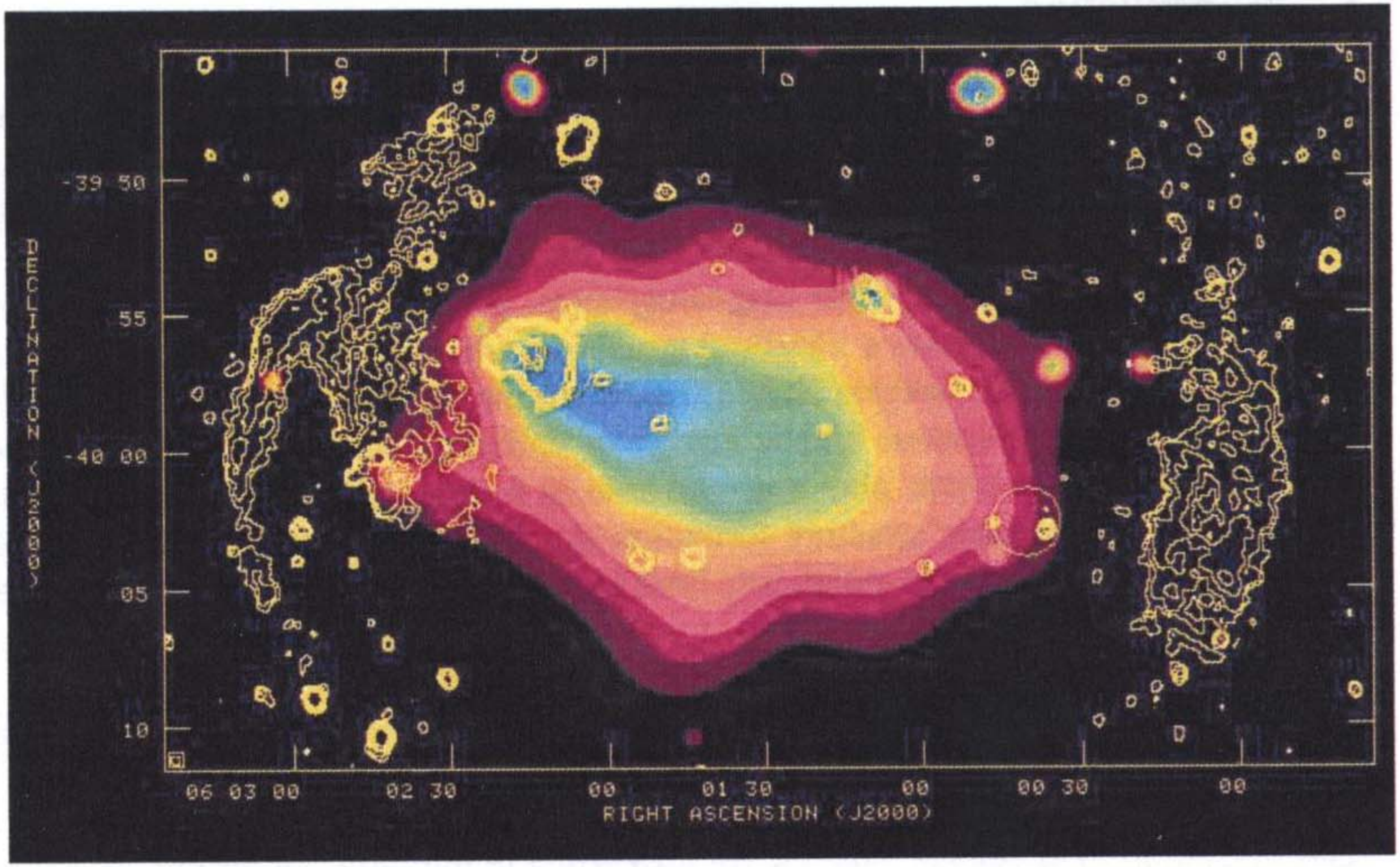


Figure 1. The ROSAT PSPC broad band X-ray image of A3376 cluster. Circles locate the two brightest clusters galaxies - brightest cD galaxy on lower right, second brightest (radio galaxy MRC 0600-399) near X-ray peak - and their sub-clusters [4, 5]. Contours depict deep (35 μJy rms noise) VLA 1.4 GHz radio image at a resolution of 20 seconds of arc.

Internal energy gain from gravitational heating in this form of cluster formation is about 10 times higher than from internal evolution effects (galaxy-galaxy mergers)

However, much of this is quasi-adiabatic heating in weak shocks, not leading to much particle acceleration. Strong shocks only in accretion of cold gas (about 10 percent of total accretion) (Blasi et al. 2007)

⇨ ***Internal evolution and accretion effects probably comparable in production of non-thermal energy***

Distinction through spatial distribution:

⇨ ***Accretion-produced nonthermal particles in outer parts***

⇨ ***Gamma rays from internal evolution in inner region***

Important: **Low Mach number accretion shock-generated population should have soft spectrum and therefore dominate at low energies. Presumably *GLAST* will detect this accretion population in GeV range.**

At same time, clusters of galaxies directly related to starburst and merger galaxies, because internal cluster evolution consists in starbursts and merger products ("early type galaxies")

Caveat: ***Until now no direct nonthermal particle acceleration observed from accretion shock phenomena, even though they often involve very strong shocks (i.e. accreting neutron stars and stellar Black Holes)***

2c) Interactions of supermassive Black Holes (AGNs) with their environment

A) Blazar-type AGNs, as observed at VHE by imaging Cherenkov telescopes show probably show particle acceleration in the relativistic jets near central BH as result of interior interactions in the jet. They might be due to leptonic jets or due to proton jets. Required energy dissipation small because of Doppler boosting (exception: M87 in nearby Virgo cluster)

Active field of research. Also used to constrain the diffuse extragalactic background light (EBL) through interpretation of gamma-gamma absorption features. This will surely continue with *GLAST* and *CTA.*

B) Hot Spots from large-scale jet termination shocks (Presumably accretion-driven hadronic jet, removing disk angular momentum)

Main dissipation (Hot Spot) of jet energy (~ 20 % of entire accretion energy) at termination shock of jet (For FR class II radio galaxies, like M 87, at great distance from galaxy ~ tens of kpc):

Quasi-steady, strong shock, very extended (many kpc) ⇨ high maximum particle energies in diffusive shock acceleration.

Long suspected sources of the UHECRs (Biermann,1991 ff.)

Potentially: correlation of detected UHECR sources with AGNs (Auger Collaboration, 2007)

These AGNs might be visible also at VHE in gamma rays, through a proton – photon cascade.
Best at low energies (Extragalactic absorption)

In general no Doppler boosting expected:
Low intensities

3) Cosmic Ray Physics in Galaxy

(left-overs from present VHE instruments/GLAST)

***GLAST* only a Super-*EGRET* with a rather feeble connection of its sources to VHE sources? (Obvious exception: E_γ >> 1 GeV, where main synergy with present Cherenkov telescopes. But statistics modest at these energies)**

⇨ GLAST- energy synergies mainly expected for VHE sources without in-between cutoffs, like Supernova Remnants.

Rest of localized Galactic Cosmic Ray tracers (e.g. Molecular Clouds) might only be incompletely detected by *GLAST*

⇨ Profitable tasks for *CTA* in Galactic CR physics

Other *CTA* task should concern gamma rays around 100 TeV and beyond:

Better not leave it to *HAWK* - type instruments

4) Multi-Wave-Length aspects

Essential "ingredient" of *CTA* physics,
together with theory

Decisive future instruments will be:

- ***LOFAR*** **(later *SKA*) at low radio frequencies**
  (IR-O-UV-soft X-rays mostly thermally dominated)
- ***ALMA*** **in the submm-range (e.g. mass distribution)**
- **Future hard X-ray observatories, like *NEXT***
  (for synchroton emission from secondary electrons)

5) Reservations and Conclusions

- **Probably not all topics, presently considered important, can be dealt with preferentially**

  ⇨ **Example: Population studies limited value ?**

  ⇨ **Example: GRBs in VHE range? Difficult for instruments with small FoV. Design drivers for *CTA* ? Leave this rather to *HAWK* – type detectors**

- **Astrophysical perspectives of *CTA* excellent**

- **Major perspectives seen in Extragalactic Physics of Cosmic Structure Formation and Evolution, that means, in Observational Cosmology**

END