Future Projects in Very High Energy γ-ray Astrophysics

J. Cortina IFAE

International Meeting on Fundamental Physics
Benasque 2009

THANKS FOR THE INVITATION!

Outline

- VHE: the breakthrough.
- Physics motivation for new instruments.
- The next years.
- The Cherenkov Telescope Array.
- CTA Spain.

VHE: The Breakthrough

The pioneers

- **Very High Energy (VHE) range = above 10 GeV.**
- The American **Whipple** telescope pioneered the Imaging Atmospheric Cherenkov Technique (1969-1989).

TeV γ-rays
from the Crab Nebula
Whipple Telescope :1989

2009= 20th Anniversary of VHE Astronomy!

- The youngest branch of Astrophysics!
- ... is becoming of age these days...

The past 20 years: lower in energy, deeper in sensitivity

- Followed HEGRA (Germany/Spain), CAT (France) and CANGAROO (Japan/Australia) telescopes (1990-2000): **about 10 sources in the first 10 years**.
- Around 1998 four major collaborations started a race to build new generation instruments: HESS, MAGIC, VERITAS and CANGAROO.
- The European collaborations **HESS and MAGIC** took the lead.
- The sensitivity of HESS is 10 times better than HEGRA, the threshold of MAGIC is 5 times lower than Whipple.
- As of now, ten years later, these two collaborations have discovered about **70 new sources** and published >100 papers, out of them, **6 papers in Science and 3 in Nature**.

H.E.S.S.

High Energy Stereoscopic System

- Array of 4 x 12 meter (100 sqm) Cherenkov Telescopes
- Located at the Khomas Highland Namibia (Southern Hemisphere)
- Fully operational since 2003
- Analysis E_th about 150 GeV and Crab-like detection in about 30 seconds
- Lots of discoveries and high impact results

The MAGIC Collaboration

Major Atmospheric Gamma-Ray Imaging Cherenkov Telescope:

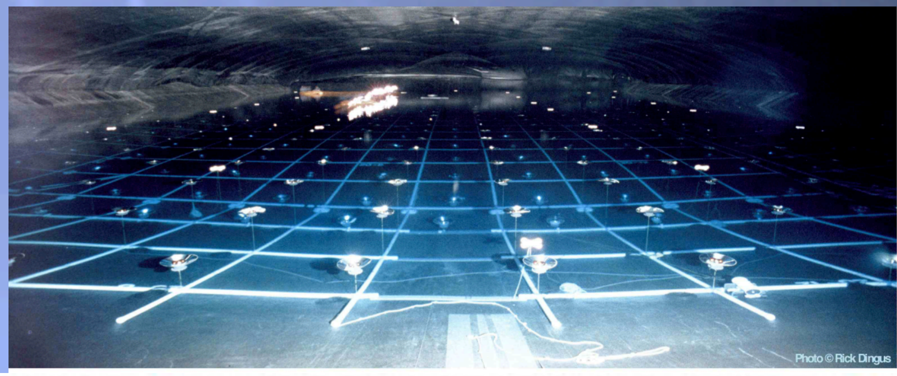
International collaboration of over 20 institutions from more than 10 countries (~140 collaborators)

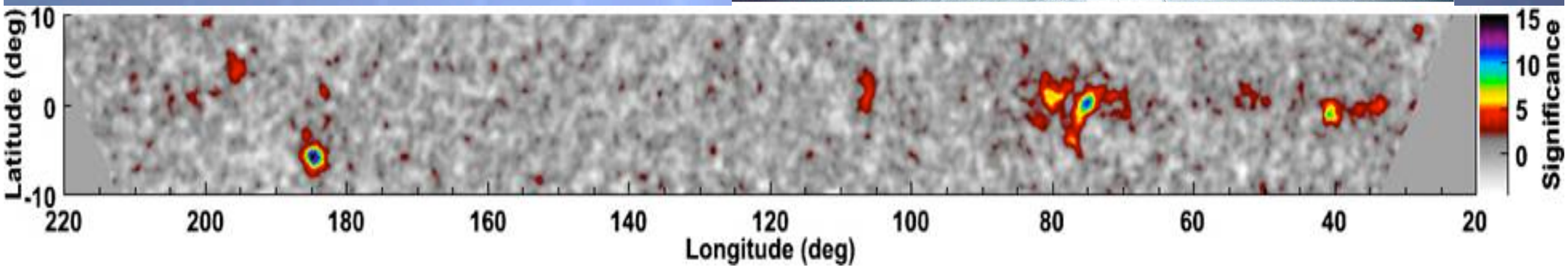
VERITAS

4x 12m telescopes in operation in Arizona: first-light celebration April 2007. First new results coming.

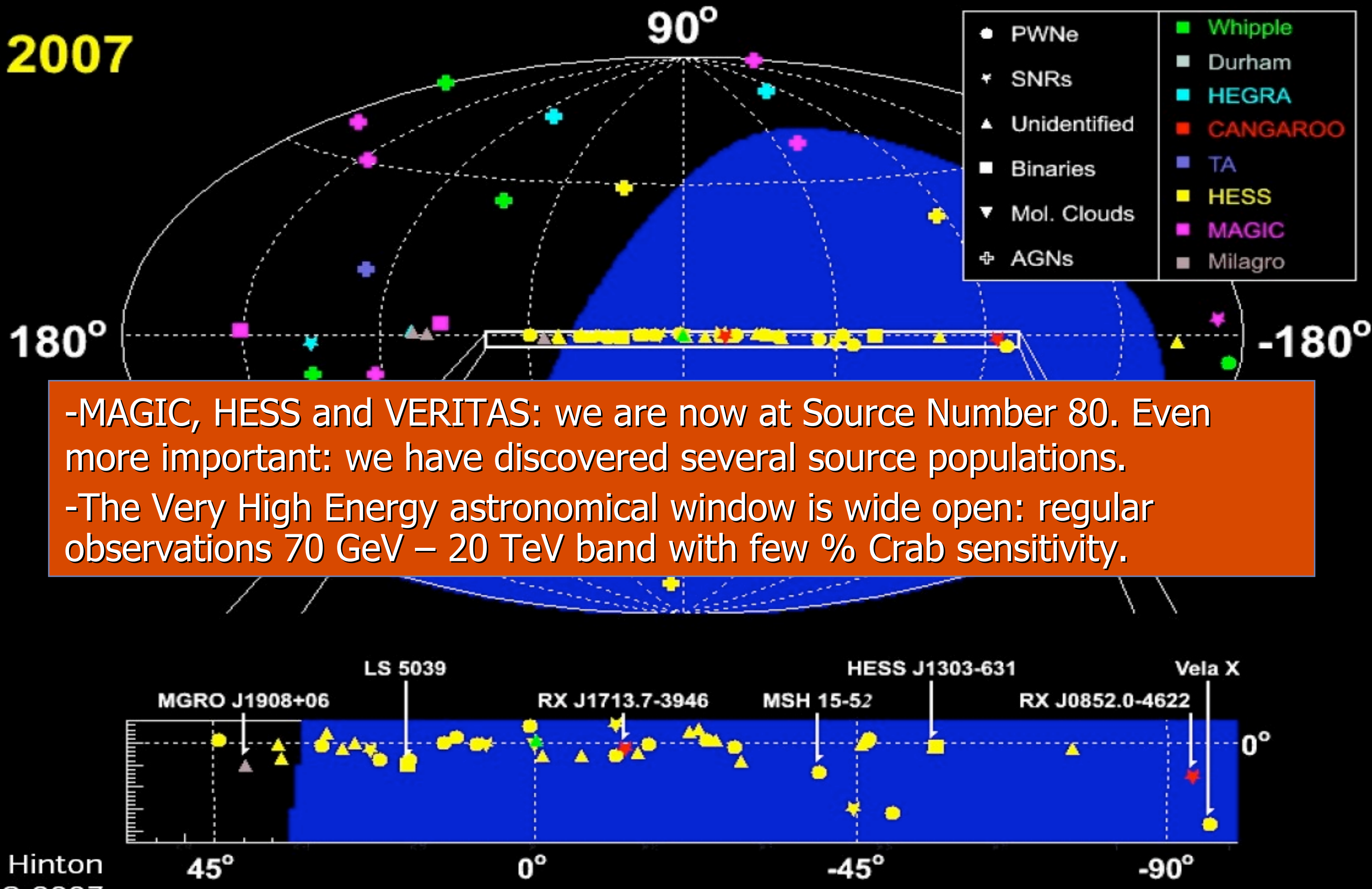
MILAGRO

- 60 × 80 × 8 m3 water Cherenkov pool instrumented with 2 layers of photomultipliers + outrigger huts.
- located in the Northern hemisphere, Los Alamos,
- Fascinating results: discovery of extended unidentified sources at energies >1 TeV.





New window to the universe



-MAGIC, HESS and VERITAS: we are now at Source Number 80. Even more important: we have discovered several source populations.

-The Very High Energy astronomical window is wide open: regular observations 70 GeV – 20 TeV band with few % Crab sensitivity.

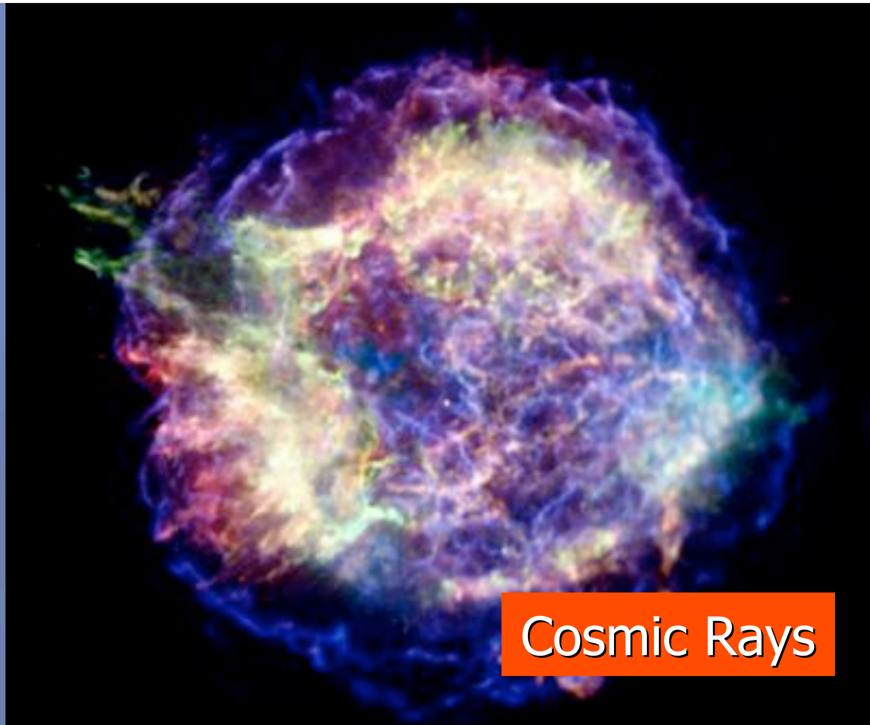
Jim Hinton
ICRC 2007

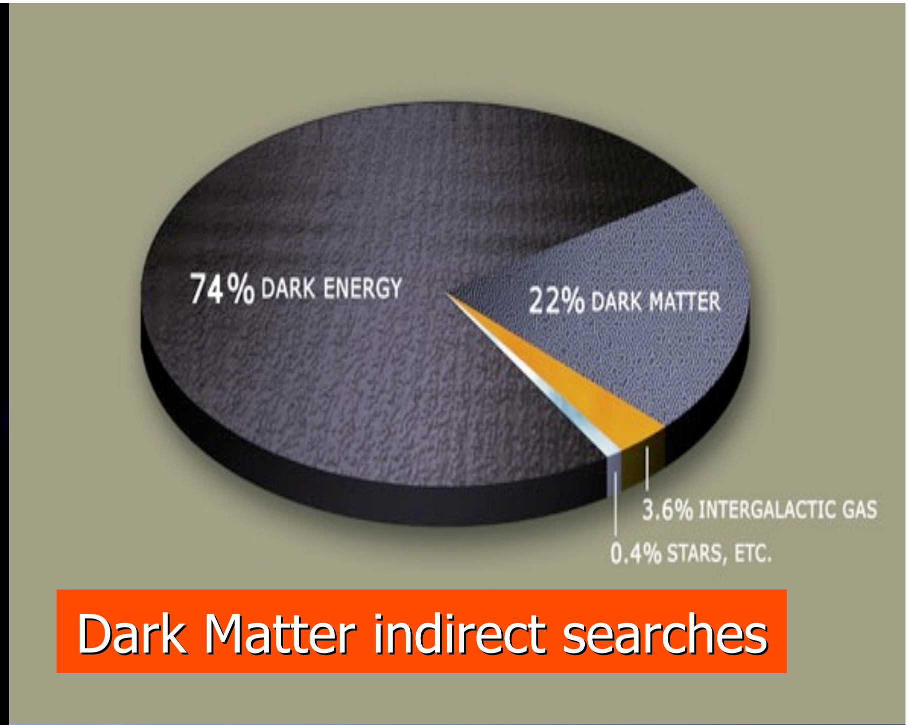
VHE: Physics drivers

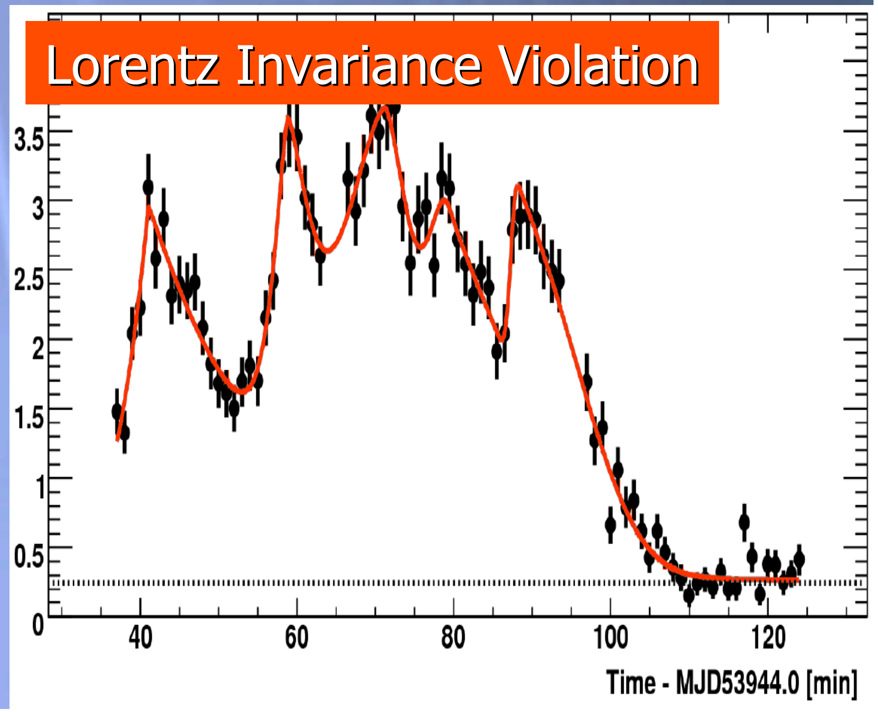
Disclaimer:
Telescopes are multi-purpose!

- Like most of the astronomical telescopes in the world, Cherenkov telescopes are not built with a single purpose in mind.
- Physics drivers range from the study of compact objects (black holes o neutron stars) to astronomical jets, collision winds, dark matter searches or more fundamental Physics.

Only some highlights







Highlights:

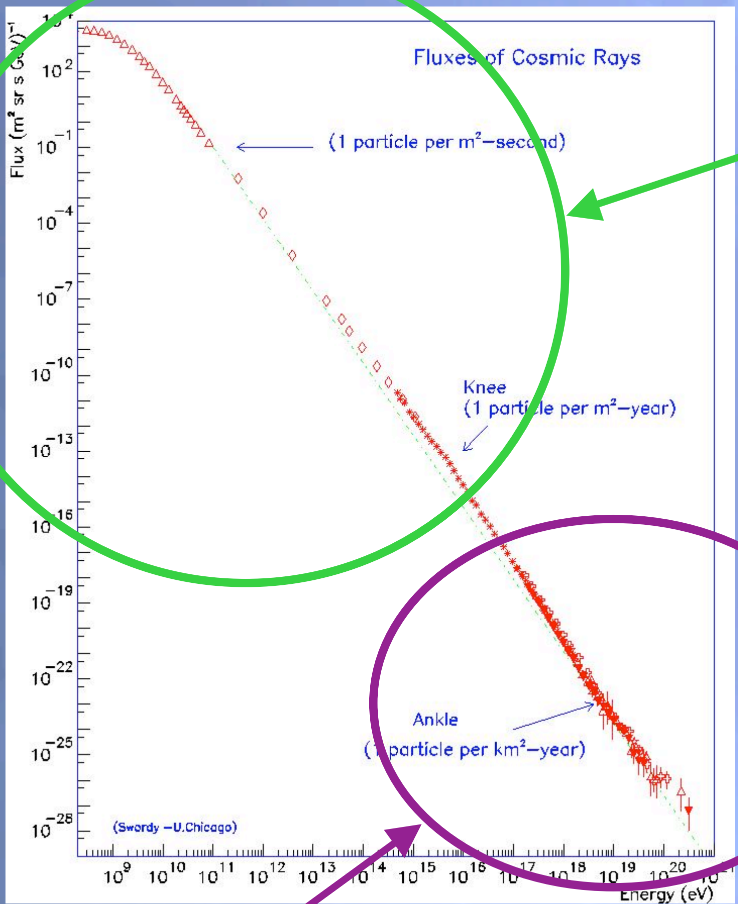
- Cosmic Rays.
- Dark matter.
- Extragalactic Background Light.
- Lorentz Invariance Violation.

Cosmic rays

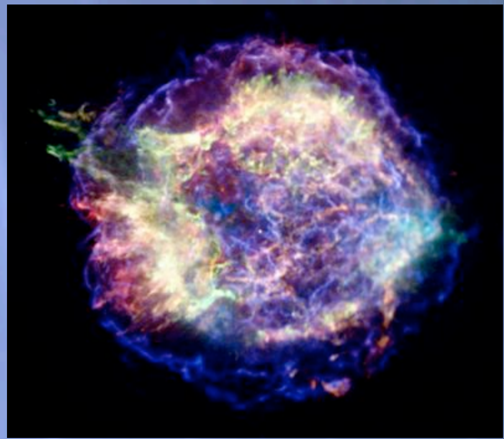
- Cosmic rays: protons, electrons, their antiparticles, ionized nuclei, constantly hitting our planet.
- They pervade the Universe, their spectrum extends from 1 GeV to 10 EeV.
- Only in our galaxy they represent a significant fraction of the total energy density:
  - 0.2 eV/cm^3 in magnetic fields.
  - 0.6 eV/cm^3 in stellar photons.
  - 1 eV/cm^3 in cosmic rays.
- They were discovered in 1911 by Victor Hess… we are in 2009…

It is about time that we find out their origin!

Cosmic rays: SNRs



- At energies below 10^{16} eV (the "Knee"), the cosmic rays are most probably galactic.
- The best candidates for galactic acceleration are SuperNova Remnants (SNR) = the left-overs of supernova explosions, which become efficient particle accelerators after 1000-10000 years.



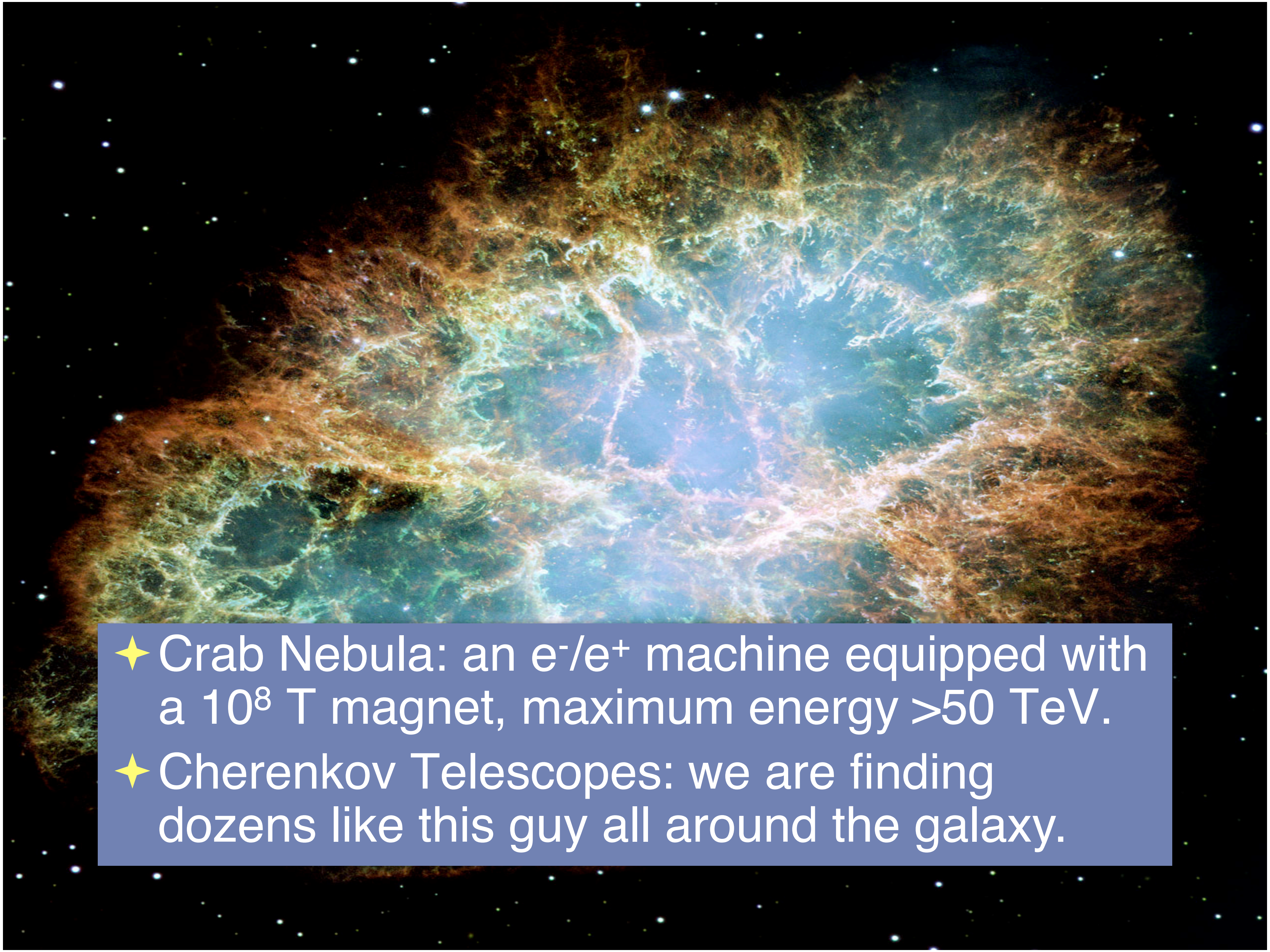
Extragalactic origin: wait for Massimo's talk

Cosmic rays: SNR??

- The argument is based on **energetics**: take the energy density in CRs which we measure at the Earth and compare with the E of a SN multiplied by the rate of SN explosions… they kind of match…

IN REALITY:

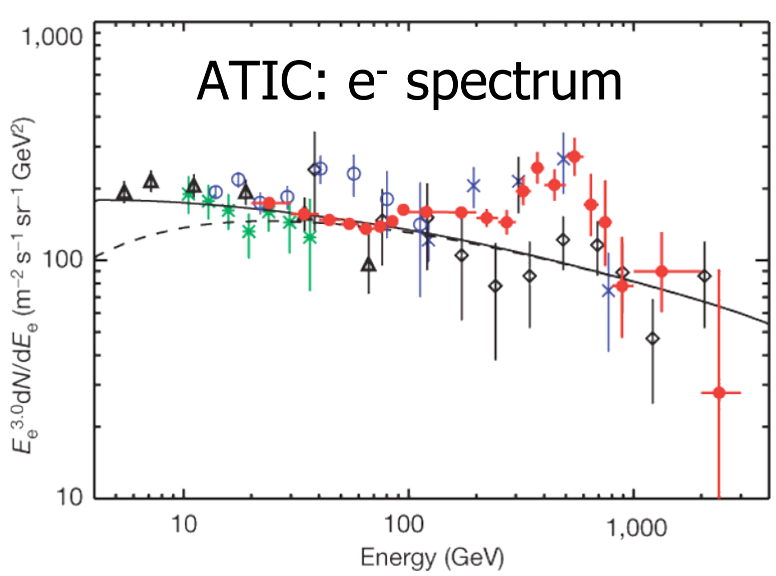
- We don't know if the **CR density is the same all over the galaxy**. We only measure CR at the Earth. As we will see, probably it is not!
- After production, **CR diffuse randomly in our galaxy**, so when we detect them at the Earth, we don't know where they come from.
- We know that **other galactic objects generate CRs**: pulsars, pulsar winds, microquasars… and dark matter??

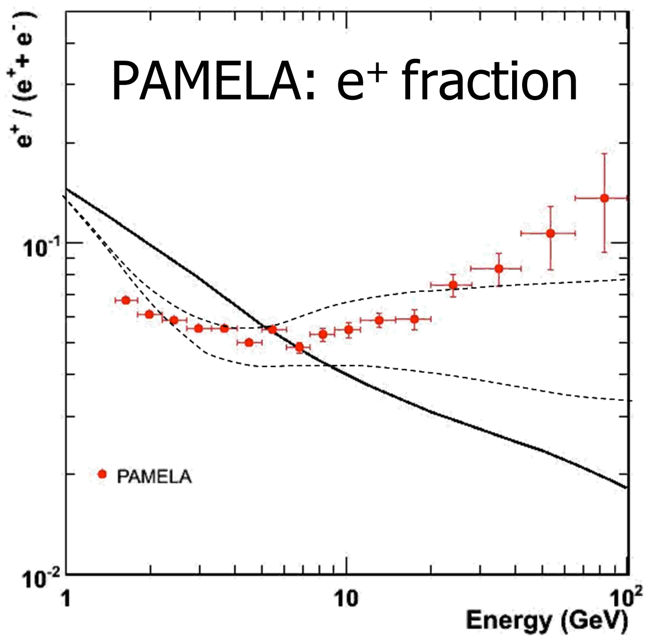


- Crab Nebula: an e^-/e^+ machine equipped with a 10^8 T magnet, maximum energy >50 TeV.
- Cherenkov Telescopes: we are finding dozens like this guy all around the galaxy.

Cosmic electrons & positrons

- PAMELA & ATIC: the cosmic electron and positron spectra show features at 10 GeV - 1 TeV energies.
- Nearby Crab's?? Dark matter annihilation?? [don´t miss tomorrow's talk]

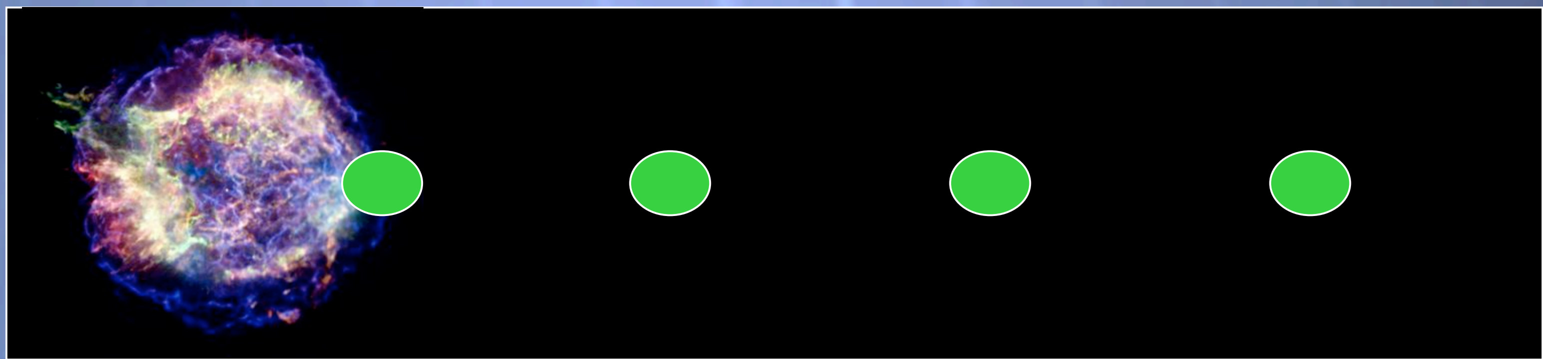




CRs & Cherenkov Telescopes

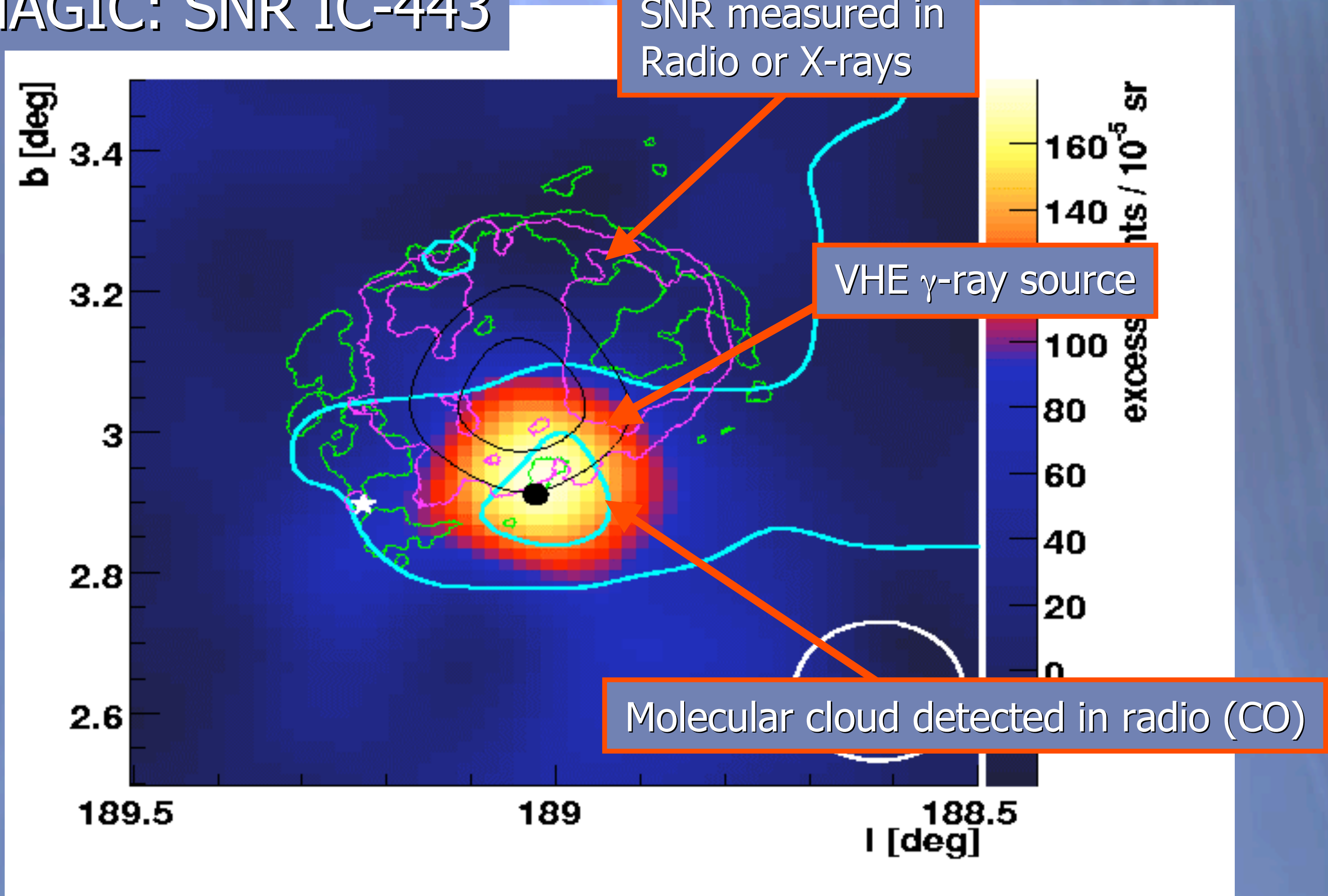
- Cherenkov telescopes detect γ-rays and γ-rays are produced by CRs when they hit interstellar matter.

- Interstellar matter clusters in molecular clouds.
- Molecular clouds are characterized with radiotelescopes.
- Clouds act as **probes** of the **local CR density around the galaxy**:



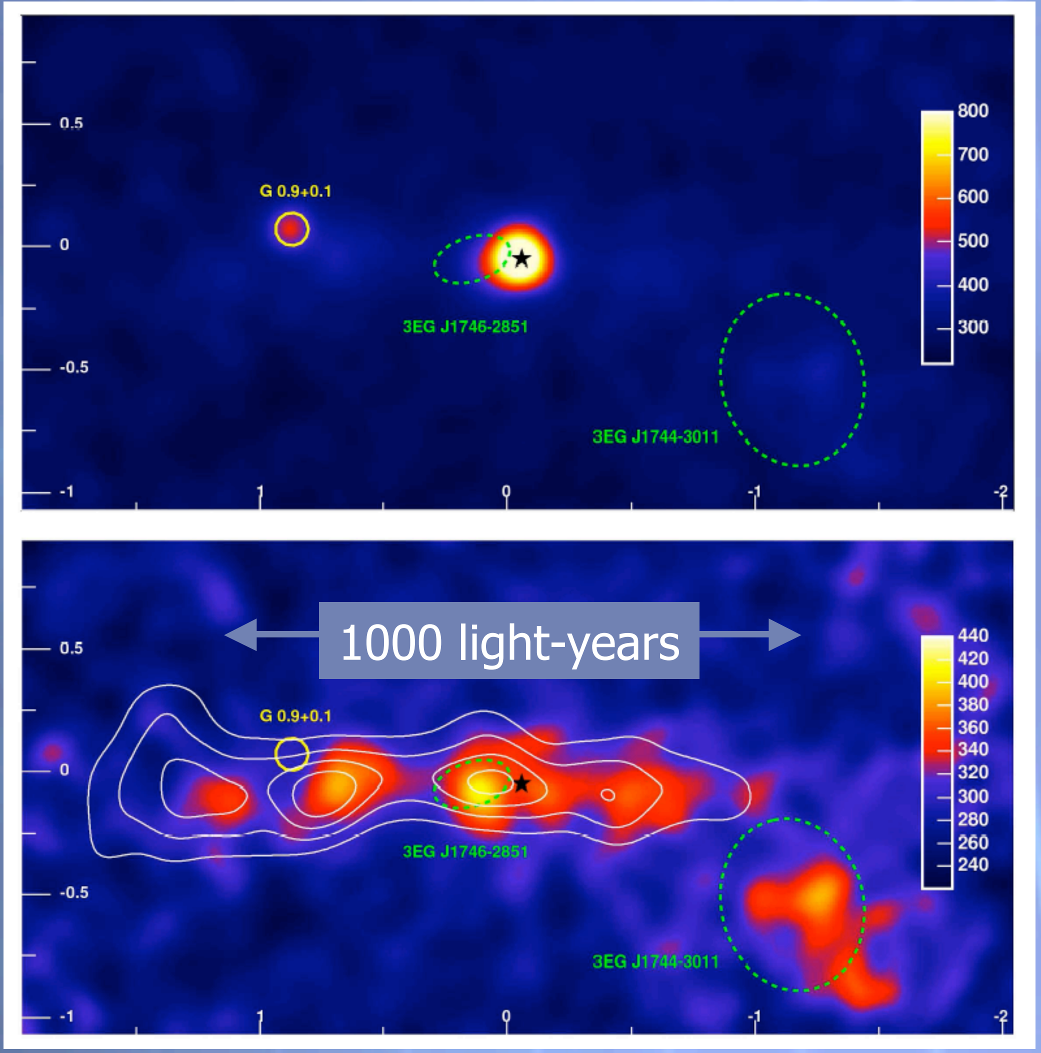
Probing with telescopes....

MAGIC: SNR IC-443



The Galactic Ridge

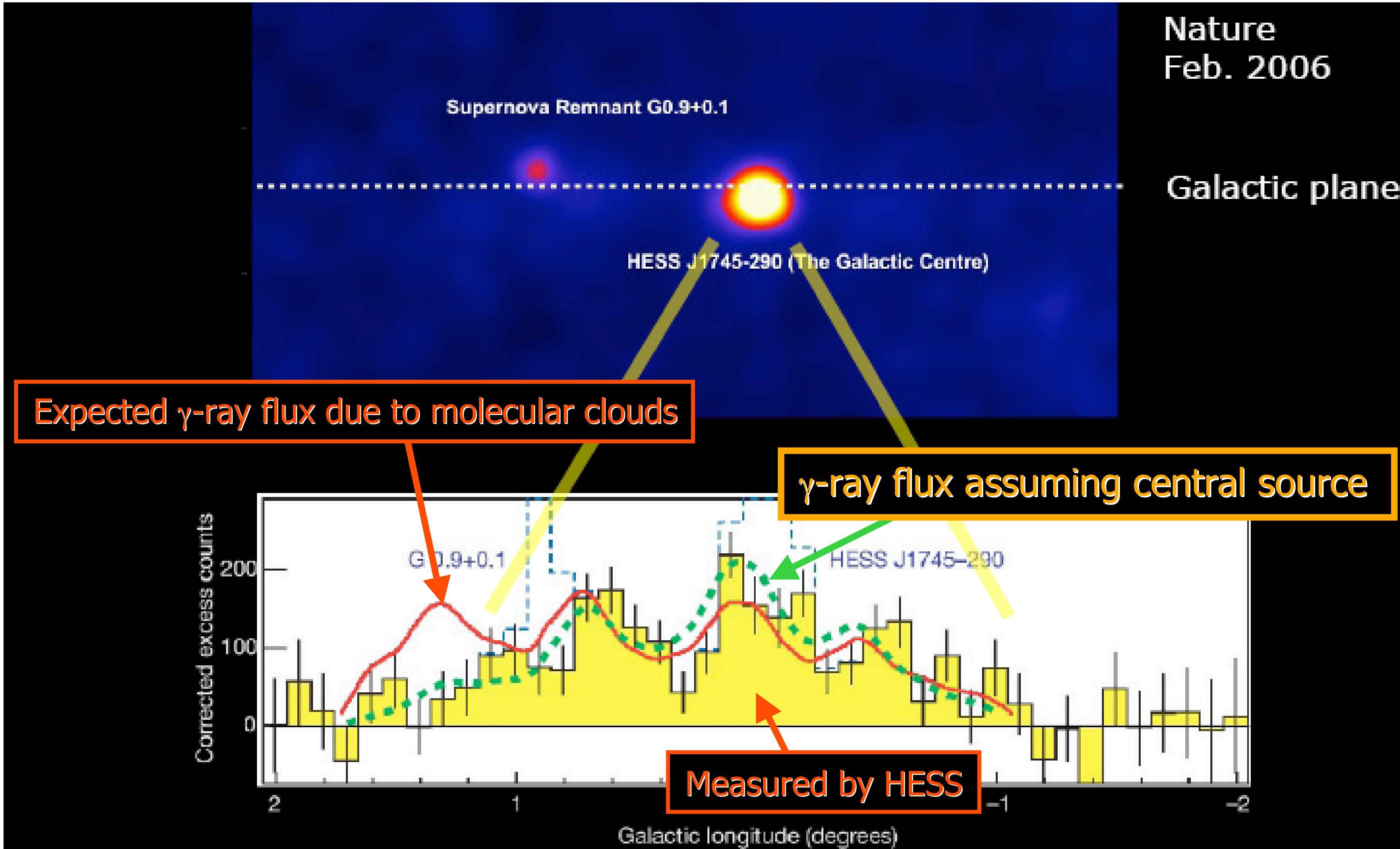
HESS



Galactic Centre gamma-ray count map

Same map after subtraction of two dominant point sources => Clear correlation with molecular gas traced by its CS emission

Nature
Feb. 2006



- Disagreement points to CR source in the center of our galaxy.
- Maybe SNR which was active thousands of years ago??

Highlights:

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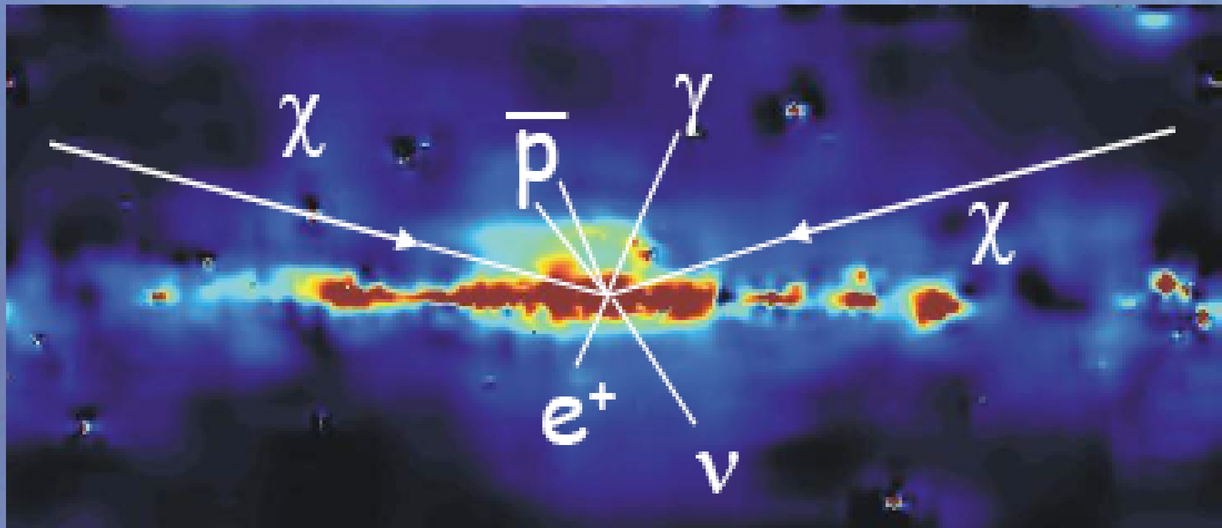
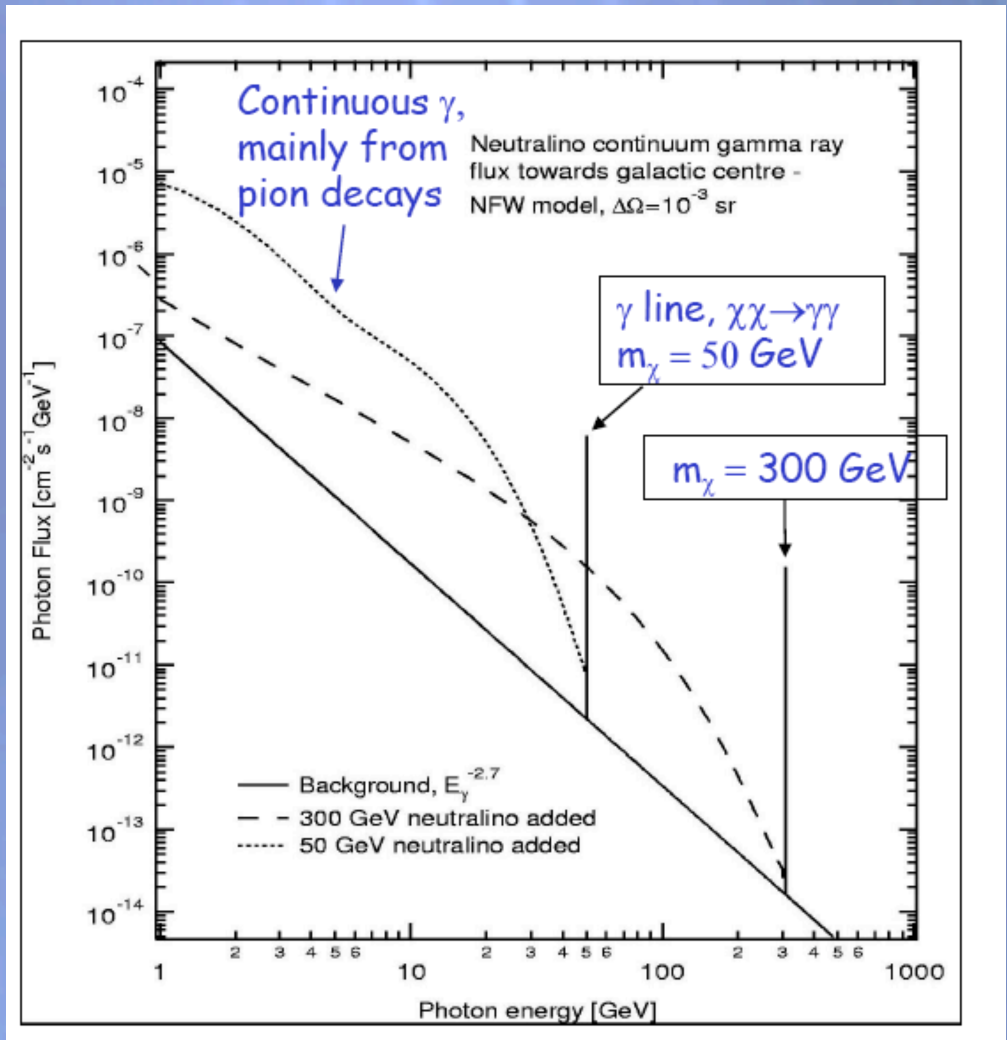
- Dark matter.
- Extragalactic Background Light.
- Lorentz Invariance Violation.

SUSY dark matter searches

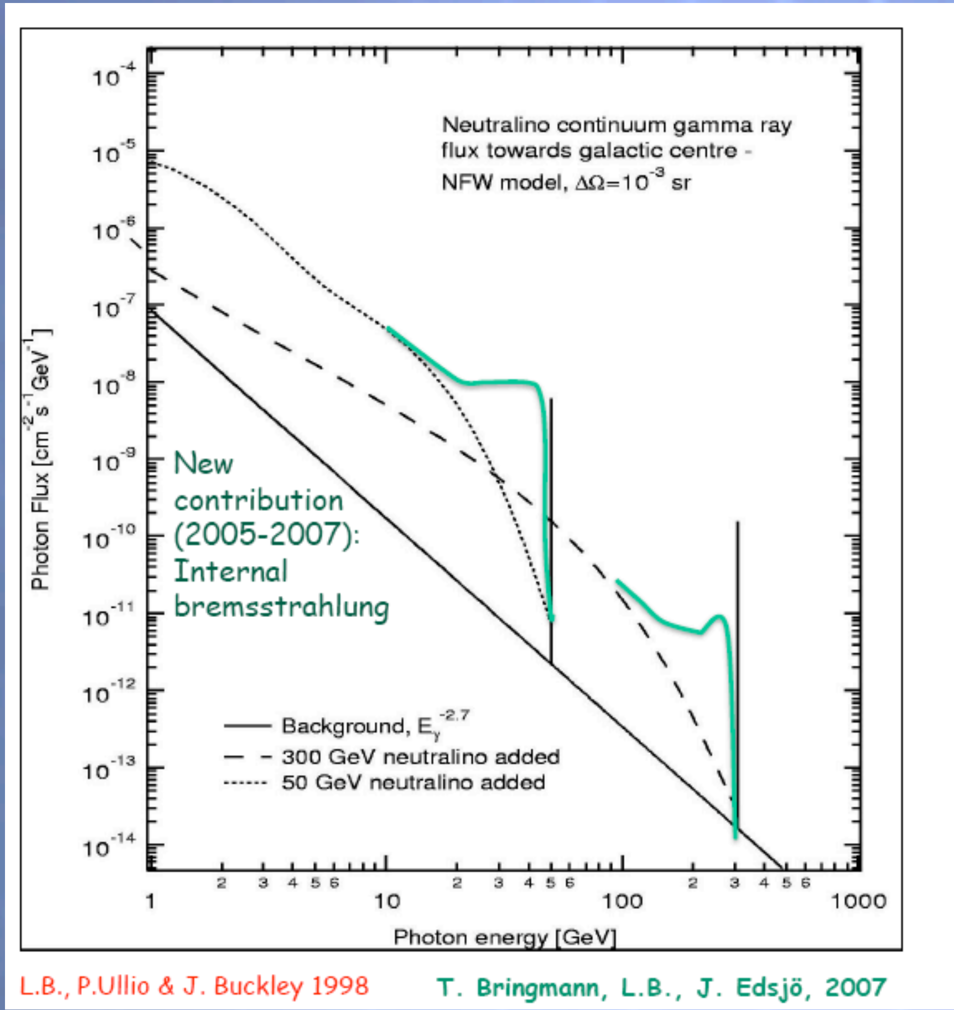


- Indirect detection: WIMP annihilation in extraterrestrial objects.
- Very much like detecting cosmic rays, but we probe regions where we expect clustering of WIMPs, i.e. high ρ_{DM}^2

Galactic Center γ-ray spectrum from neutralino annihilation

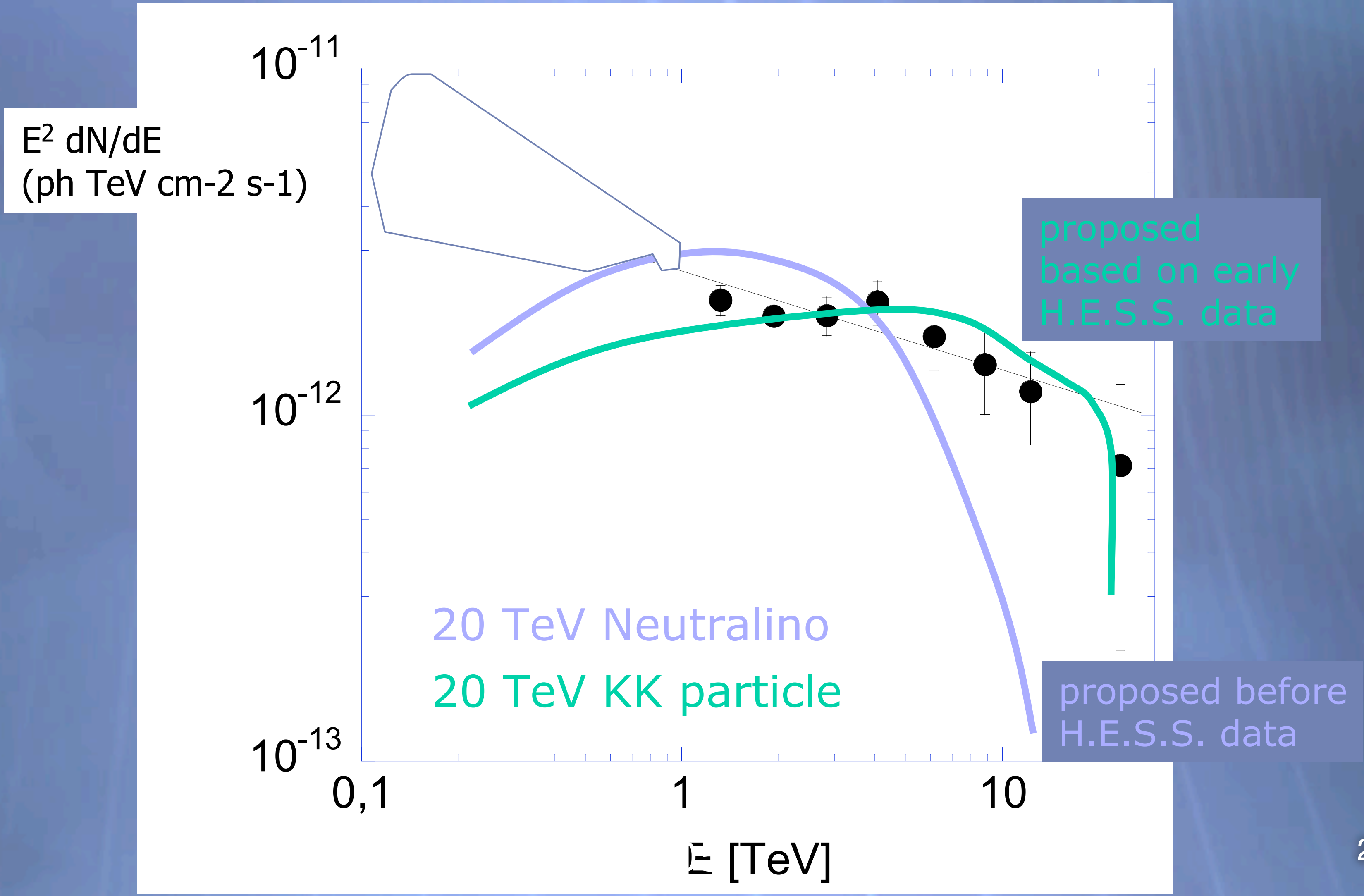


Internal Bremsstrahlung contribution

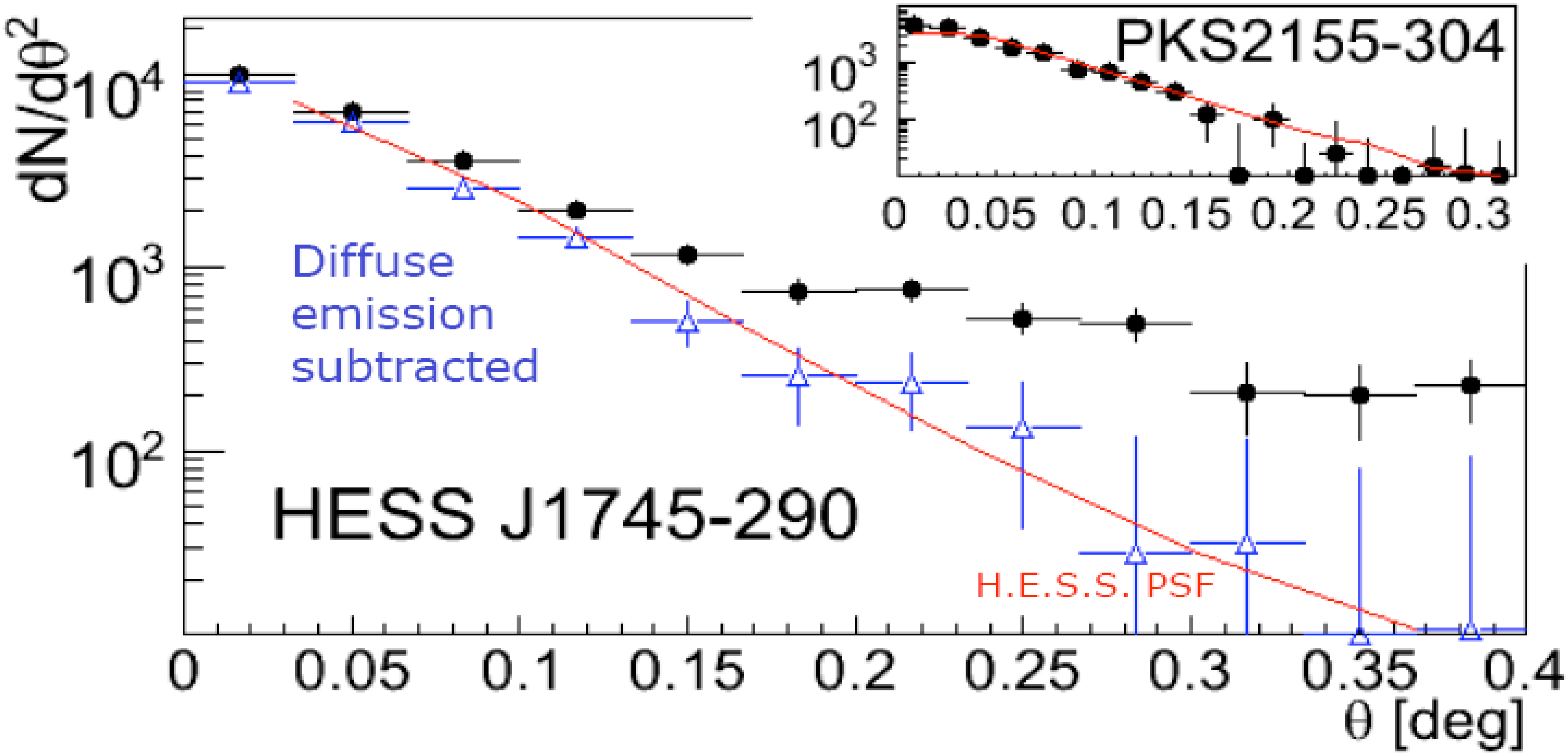


- Flux of line jumped by several orders of magnitude due to effect of Internal Bremsstrahlung previously ignored.
- Model predictions <u>are</u> uncertain!

Do Galactic Center γ-rays come from dark matter?



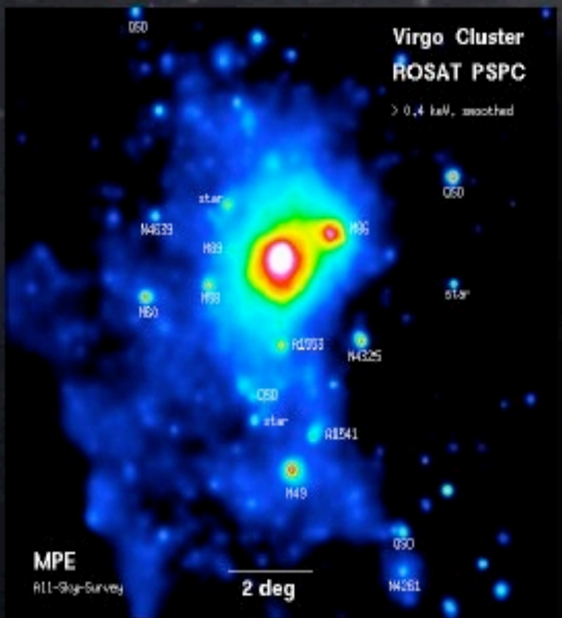
Do Galactic Center γ-rays come from dark matter?



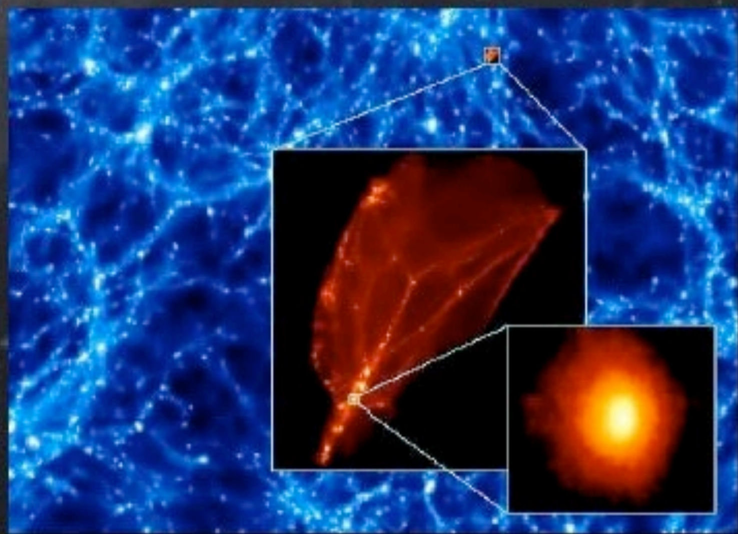
Dark matter: other targets?

Andromeda Galaxy

Dwarf Galaxies



Virgo Galaxy Cluster (X-ray)



Galactic Minihalos

J.Buckley

Other DM targets

- MAGIC, VERITAS, HESS: setting limits to dwarf spheroidals = galaxies with abnormally high Mass/Light ratio, pointing to very high content of DM.
- Limits set already to Draco, Ursa Minor & Willman-I
- Will observe more high M/L objects from all-sky optical surveys (SDSS, Pan-STARRS, DES)
- Will observe *Fermi* “dark sources” (no counterpart at other wavelengths) with hard spectra.
- Need significant increase in sensitivity to come close to model predictions!

Cherenkov telescopes play a unique role in identifying DM

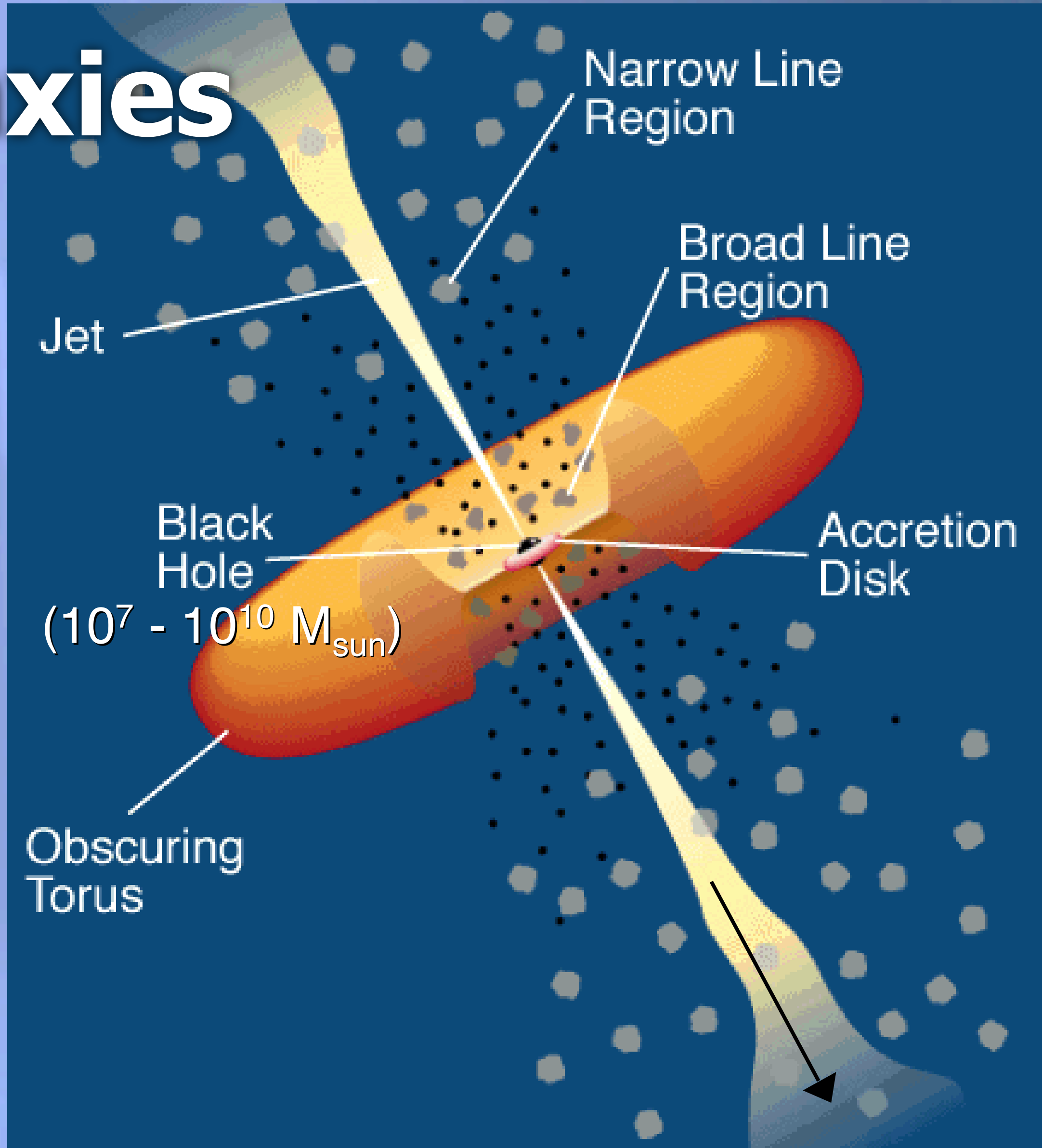
- Accelerators may find candidate particles, but they cannot prove that these particles are the DM.
- Direct searches only probe the local DM.
- Other indirect searches:
  - ν telescopes far from needed sensitivity [I hope Juanjo convinces you of the contrary].
  - Charged particles do not point back to source.
  - Space-born γ-ray telescopes may not reach high enough energy to identify features of DM spectra.

Highlights:

- ✦Cosmic Rays.
- ✦Dark matter.
- ✦Extragalactic Background Light.
- ✦Lorentz Invariance Violation.

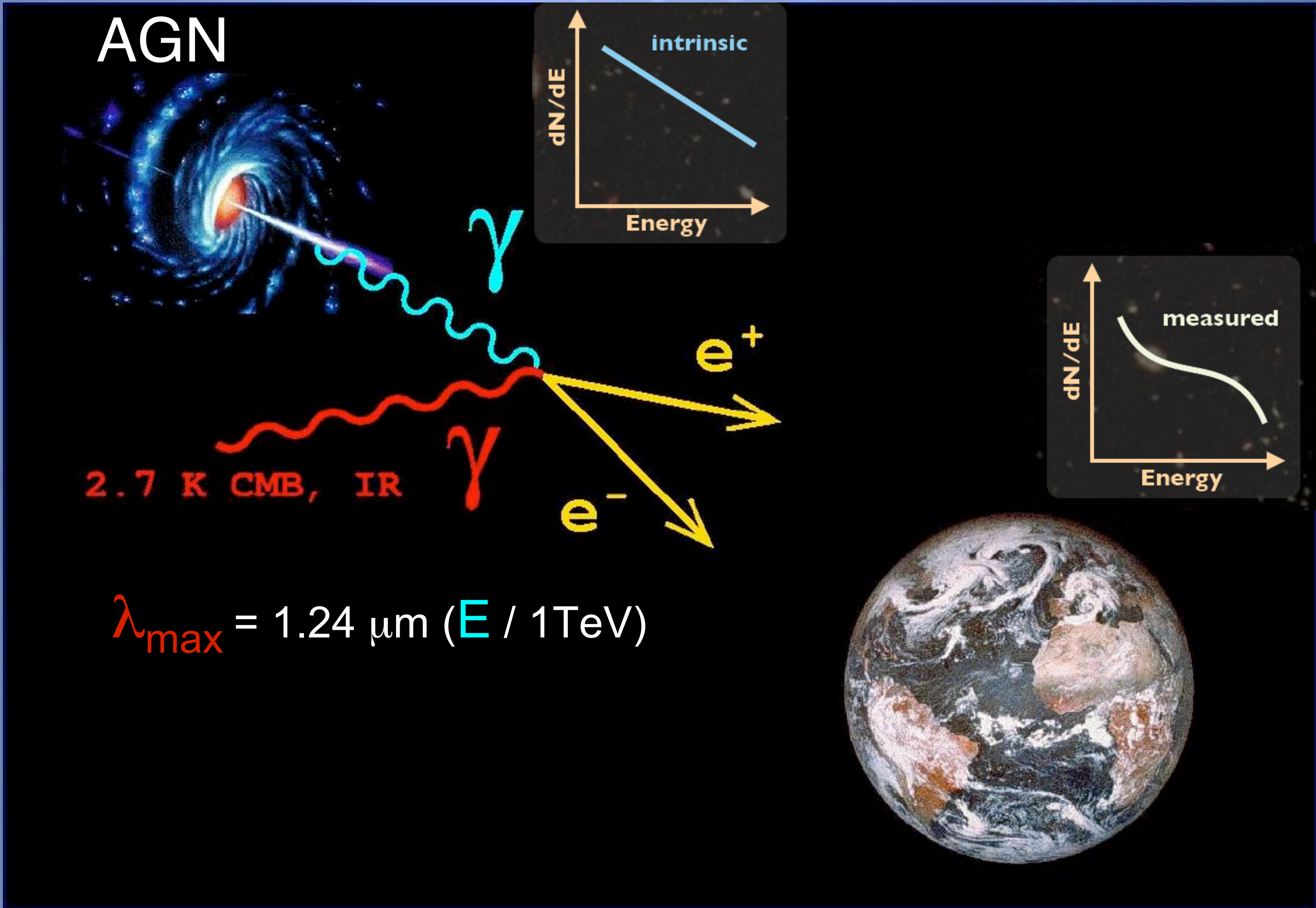
Active Galaxies

- Radiation from nucleus dominates
- AGN = Active Galactic Nucleus



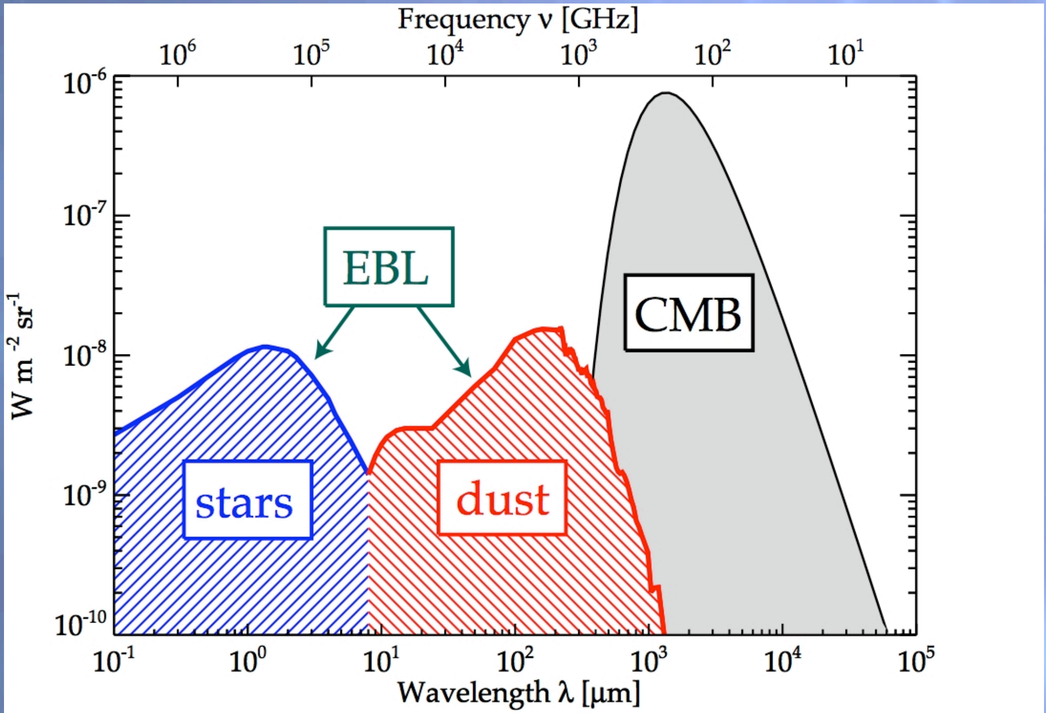
✓ VHE γ-rays

Attenuation of γ-rays in the Extragalactic Background Light



$\lambda_{max} = 1.24\ \mu m\ (E\ /\ 1TeV)$

Spectral energy distribution of Extragalactic Background Light



Redshifted star light

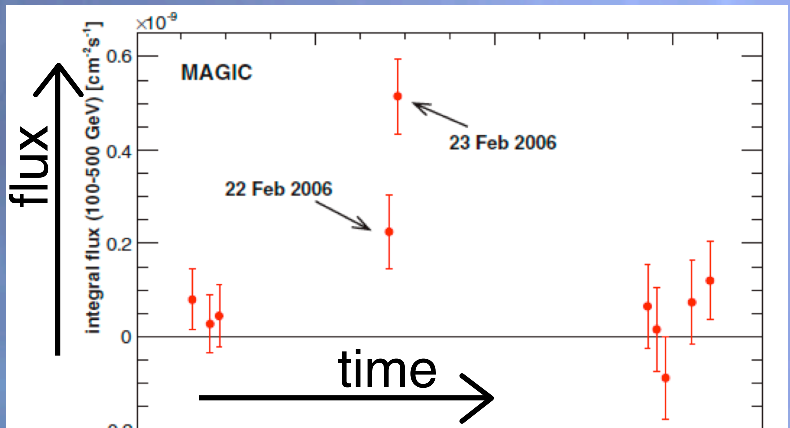
Redshifted dust emission

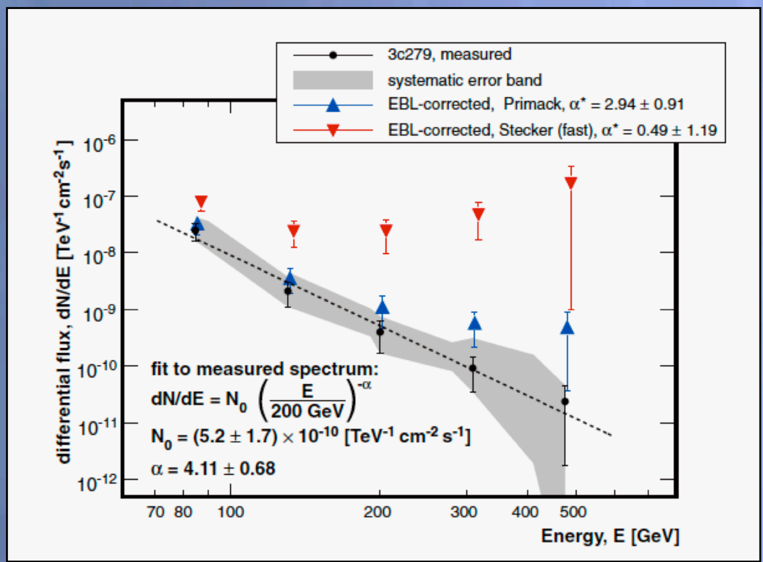
- An imprint of the history of the Universe (star formation and galaxy evolution)
- Direct measurements challenging (zodiacal light foreground)

⇒ Large uncertainties

3C 279 (z = 0.536): the most distant VHE γ-ray source

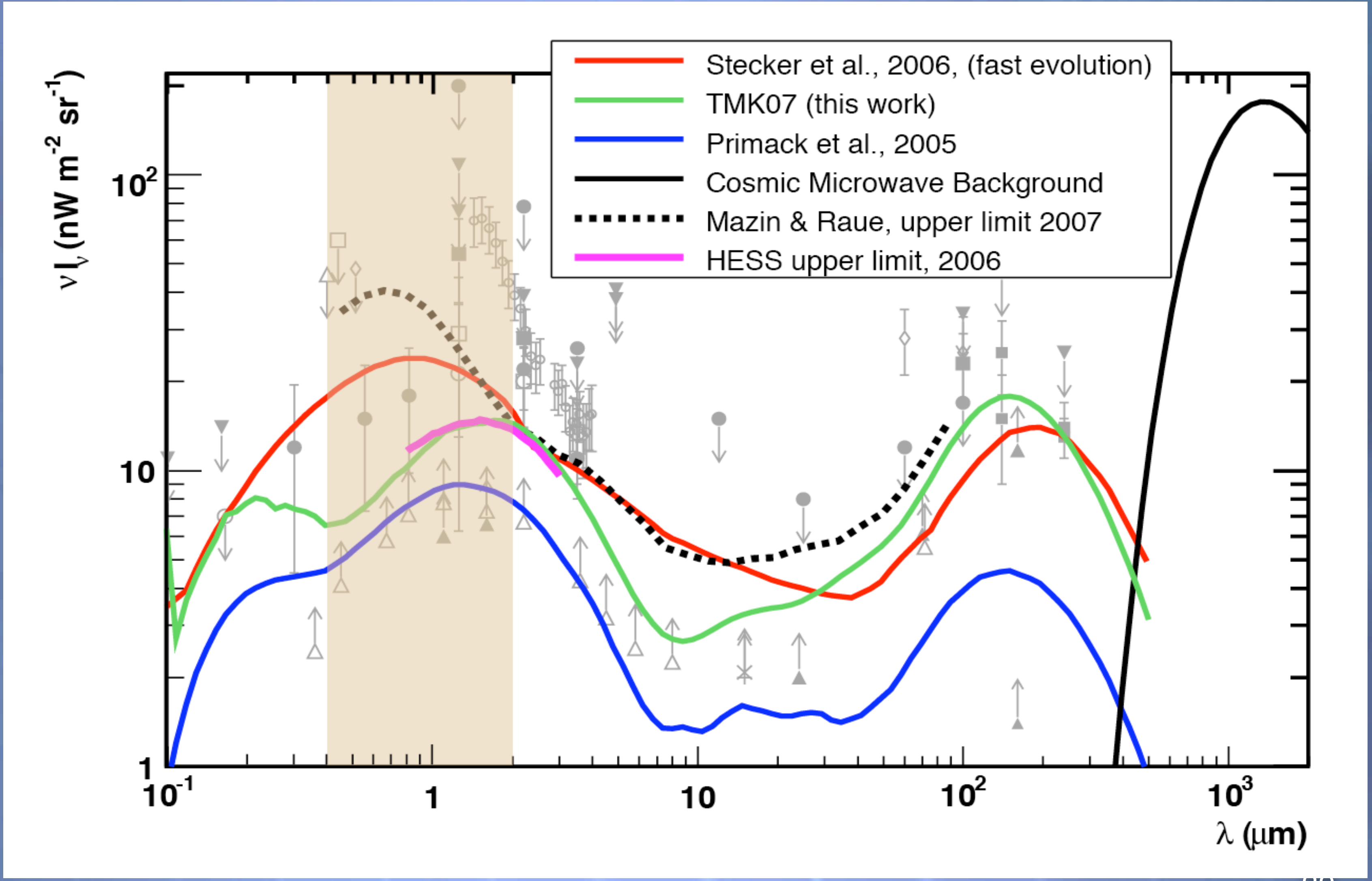
Science 320 (2008)



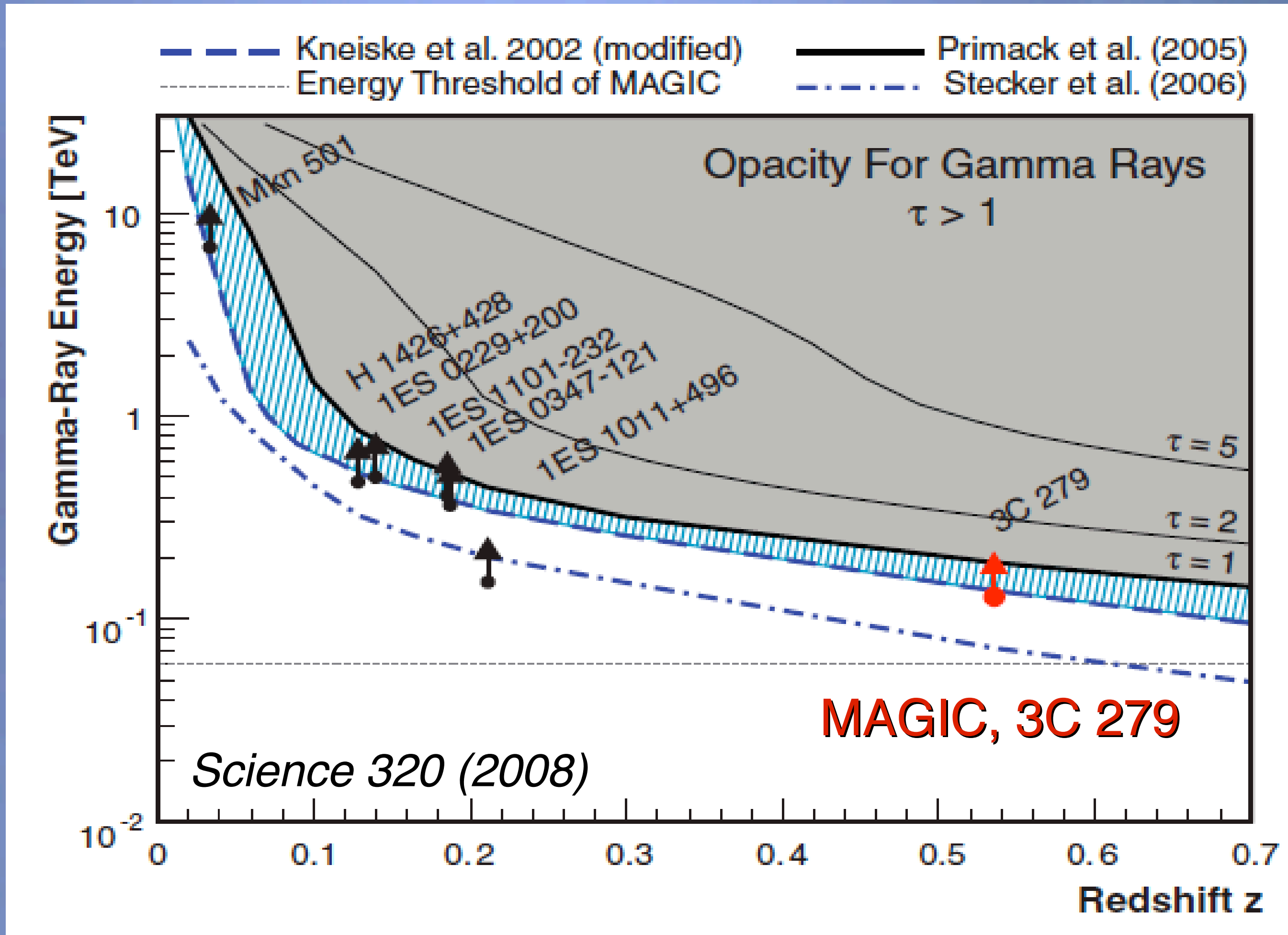


- MAGIC detects a clear signal from 3C 279 in February 2006
- First VHE quasar
- Measurements constrain EBL models under *safe* assumptions about the intrinsic spectrum

EBL constraints



γ-ray horizon



- Only narrow band left between lower limits (from galaxy counts) and IACT constraints

Highlights:

- Cosmic Rays.
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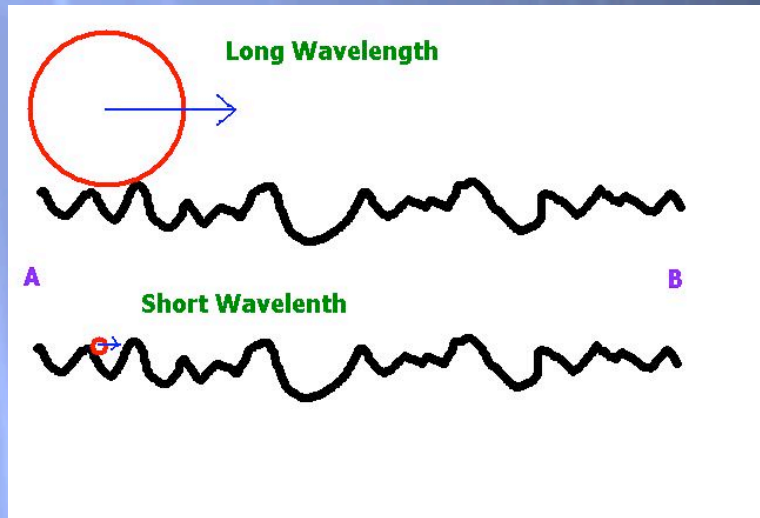
- Lorentz Invariance Violation.

Lorentz Invariance Violation

• Space-time at large distances is “smooth” but, if Gravity is a quantum theory, at very short distances it might show a very complex (“foamy”) structure due to Quantum fluctuations.

• A consequence of these fluctuations is the fact that the speed of light in vacuum becomes energy dependent.



• The energy scale at which gravity is expected to behave as a quantum theory is the Planck Mass

$$E_{QG} = O(M_P) = O(10^{19})\ \text{GeV}$$

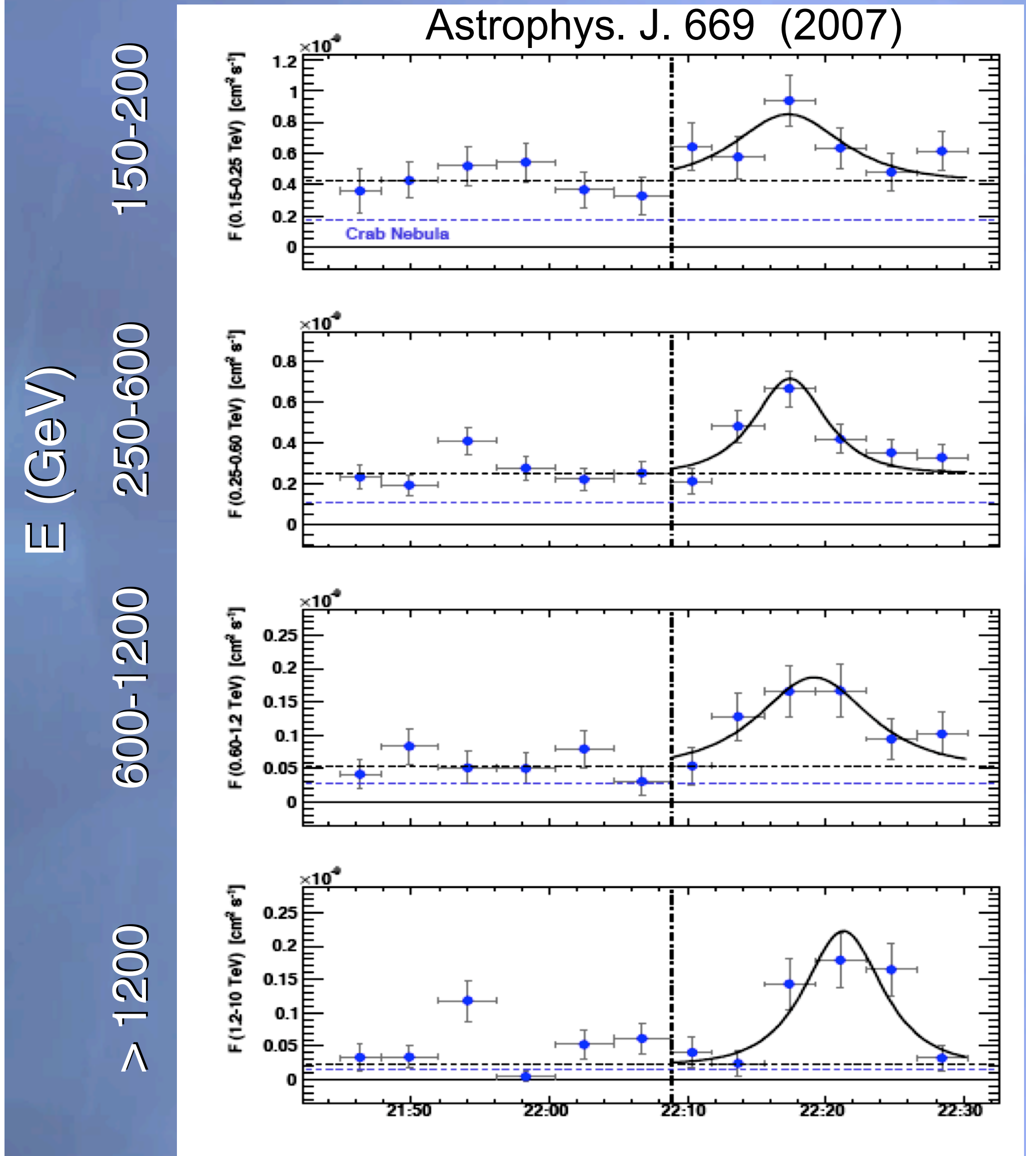
AGNs and Lorentz invariance

- From a purely phenomenological point of view, the effect can be studied with a **perturbative expansion**.(Amelino-Camelia, Nature 1998).
- The arrival delay of γ-rays emitted simultaneously from a distant source should be proportional to the path L to the source and the difference of the power *n* of their energies:

$$\Delta t \sim \frac{E^n - E_0^n}{E_{QG}^n}\frac{L}{c}$$

- The expected delay is very small and to make it measurable one needs to observe VHE γ-rays coming from sources at cosmological distances.

MAGIC observations of the AGN Mrk 501



- z = 0.034 (L≈100 Mpc)
- Hint (2.5 σ) of energy-dependent delay of fast flare

MAGIC: Mrk 501

Linear

$$\tau_l = (0.030 \pm 0.012) \ \text{s/GeV}$$

Quadratic

$$\tau_q = (3.71 \pm 2.57) \times 10^{-6} \ \text{s/GeV}^2$$

If delay is astrophysical, the delay due to QG must be smaller:
We can set limits to M_{QG} (95% C.L.):

$$M_{QG1} > 0.26 \times 10^{18} \ \text{GeV}$$

> 6 times better than previous limits

$$M_{QG2} > 0.27 \times 10^{11} \ \text{GeV}$$

> 4 times better than previous limits

If the <u>delay is due to QG (!!)</u> and not to astrophysical effect:

$$M_{QG1} = (0.47^{+0.31}_{-0.13}) \times 10^{18} \ \text{GeV}$$

$$M_{QG2} = (0.61^{+0.49}_{-0.14}) \times 10^{11} \ \text{GeV}$$

Phys.Lett B 668 (2008)

How to do better?

We need to measure delay for many objects. Which are best?

Rapidly variable objects: pulsars show sub-ms structure but are too close (kpc), AGN show min-scale and GRB ms-scale variations. Such variations can only be measured with telescopes,

Especially for n=2, essential to look at the highest possible energies: Cherenkov telescopes

$$\Delta t \sim \frac{E^n - E_0^n}{E_{QG}^n} \frac{L}{c}$$

We want to look for very far objects: AGNs (3c279 at z=0.5) or GRB

Fermi (<100 GeV) and Cherenkov telescopes (>10 GeV) to cover broad range of distances and time variations.

The next years

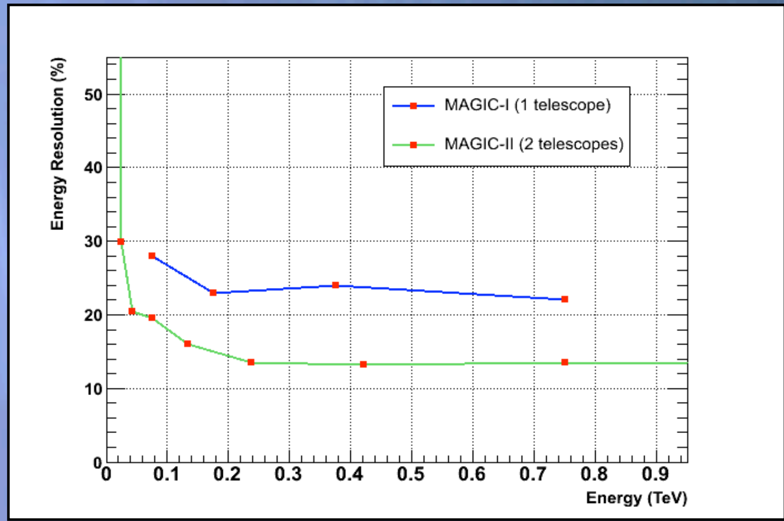
HESS-II

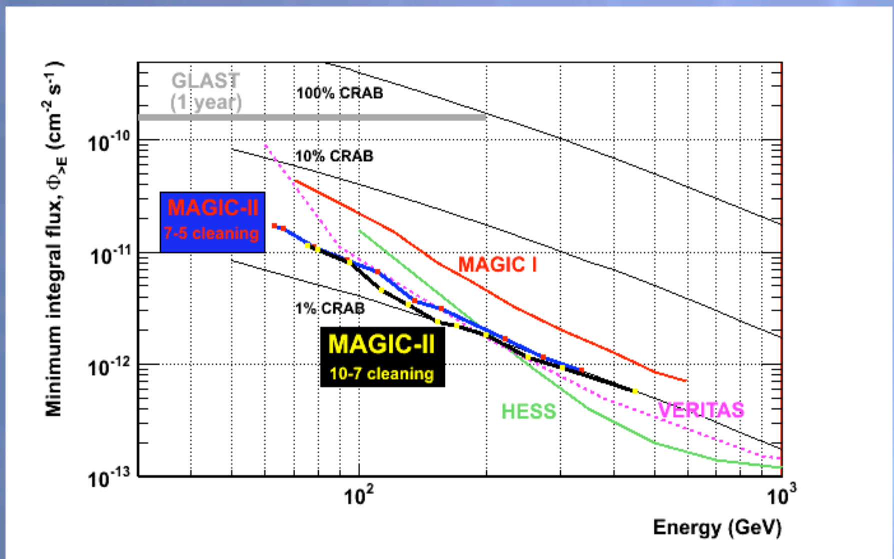
- New 28m telescope.
- Stand-alone: no stereo at the lowest energies.
- 2048 pixel camera.
- Lower energy threshold 40-50 GeV.
- First runs expected in 2010

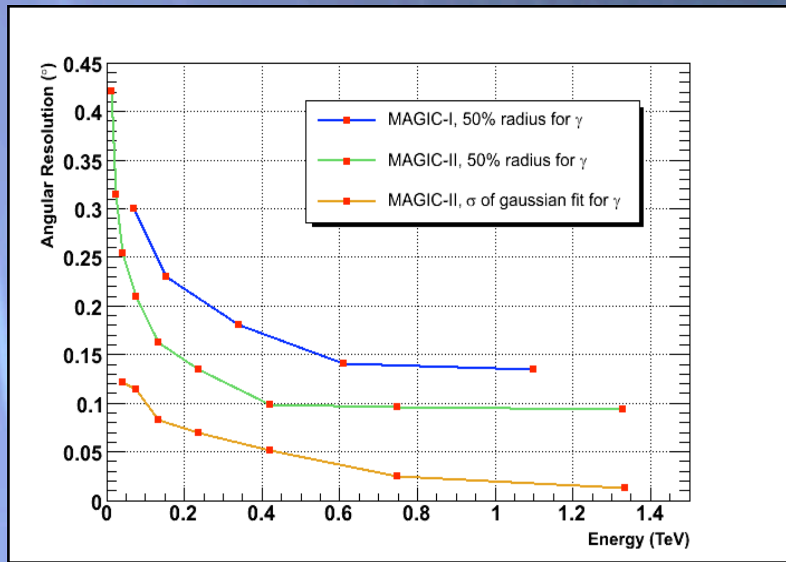

MAGIC Phase II
Extension to a stereoscopic system

Improved Shower reconstruction

- Energy resolution
  - ~25% ➔ 15-20%
- Angular resolution
  - Substantial improvement
- Overall sensitivity will be improved by a factor of 2-3

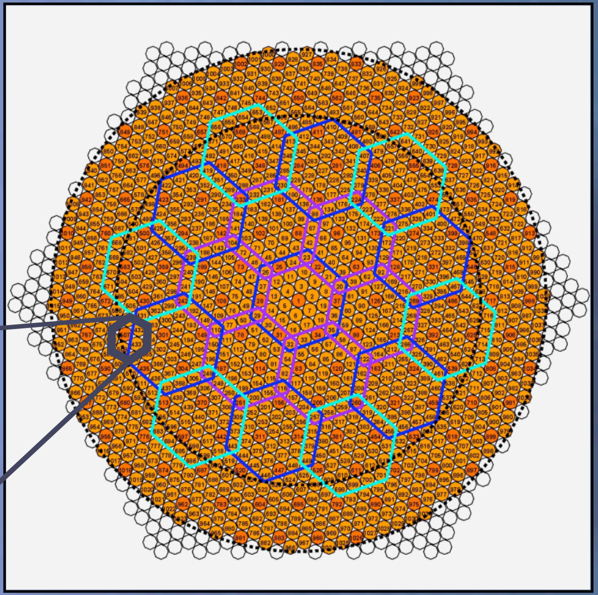


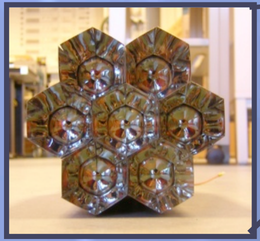


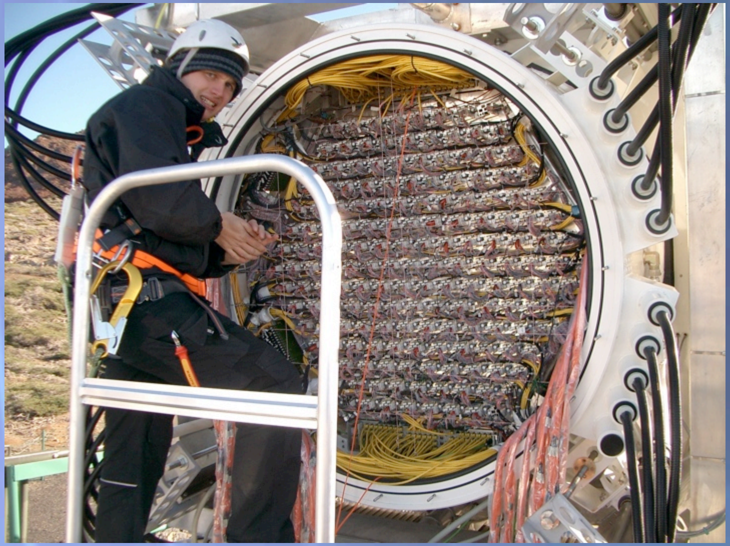


Camera is installed

- Design Criteria
  - High photodetection efficiency
  - 500MHz Band Width for the entire signal chain
- Modular Design
  - Cluster of 7 pixels
  - Easy replacements
  - <u>Upgrade to HPD and SiPM clusters</u>
- Field of view
  - 1039 x 0.1 degree pixels
  - Round configuration
  - Total FOV = 3.5^{o} (similar to M-I)

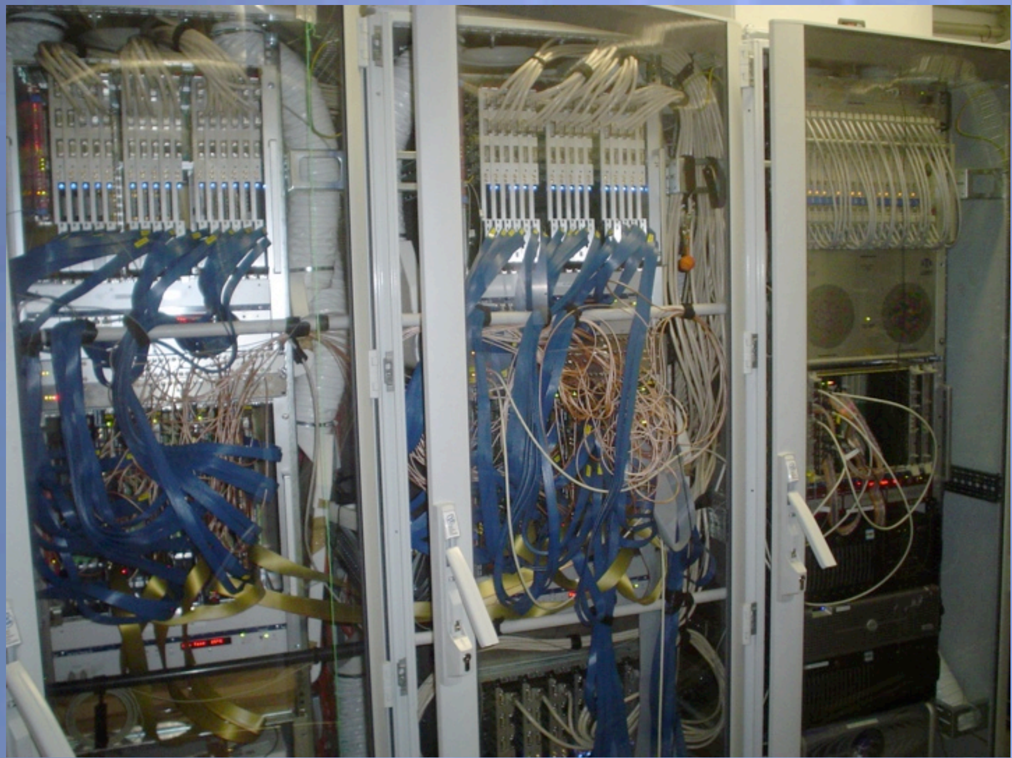




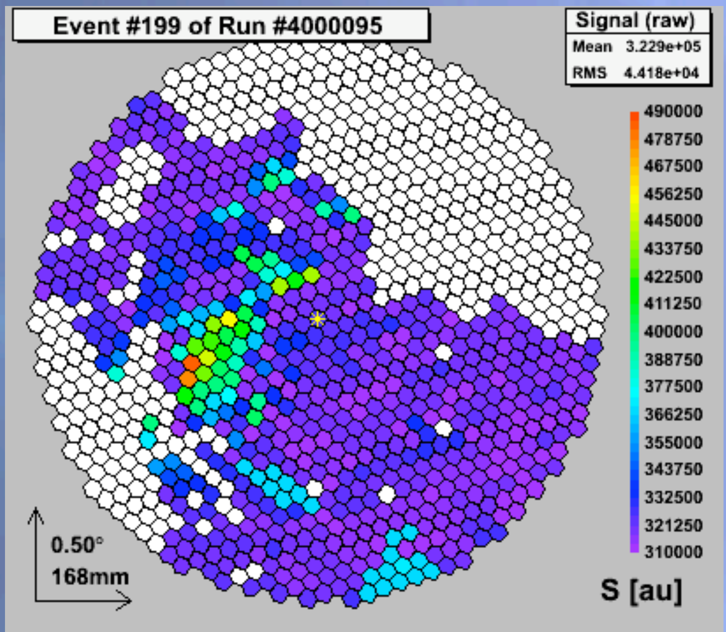


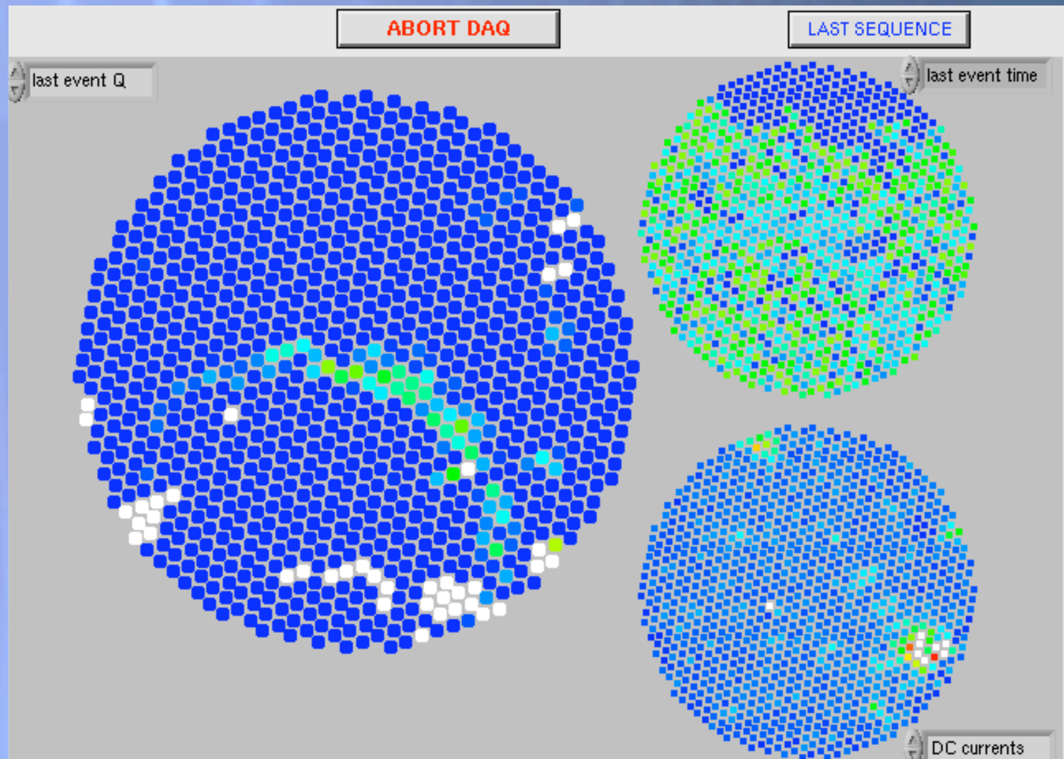
Readout is installed

- IFAE and INFN-Pisa have built the readout of MAGIC-II.
- This will the fastest readout in a Cherenkov telescope: 2-4 GHz sampling, based on the Domino Ring Sampler chip.
- Under commisioning.



First shower images & Muon rings





December 2008
First events with a partially equipped camera
No pedestal subtraction

January 2008
Muon Rings and DC currents

Last upgrades to MAGIC

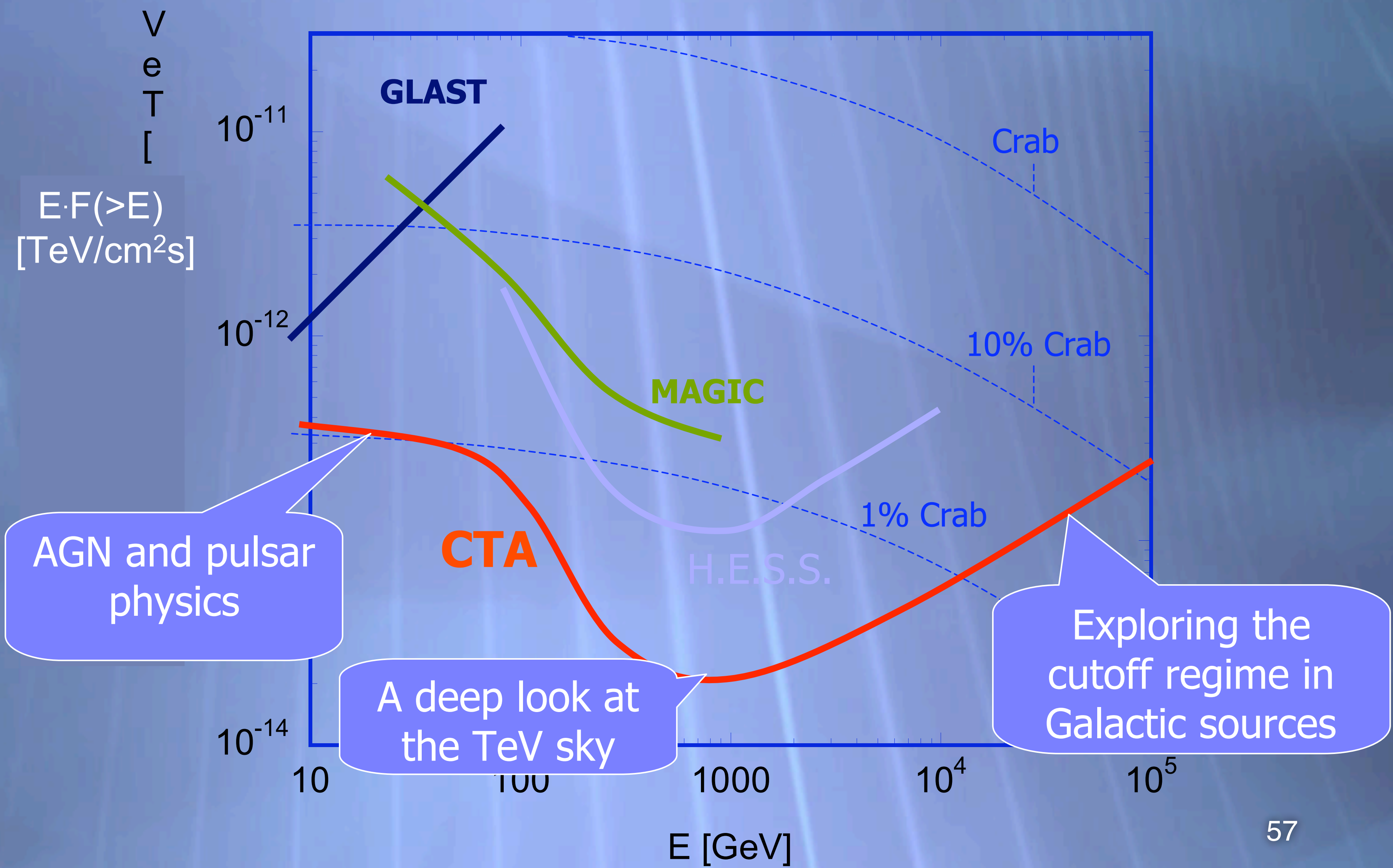
- The MAGIC collaboration has decided not to build any more telescopes.
- We are only planning:
  - Test 60 HPDs in the camera of MAGIC-II.
  - Replace the camera of MAGIC-I with a 1039 pixel camera clone of MAGIC-II.
  - Install the corresponding readout: collaboration of INFN-Pisa, IFAE and UCM.

Cherenkov Telescope Array

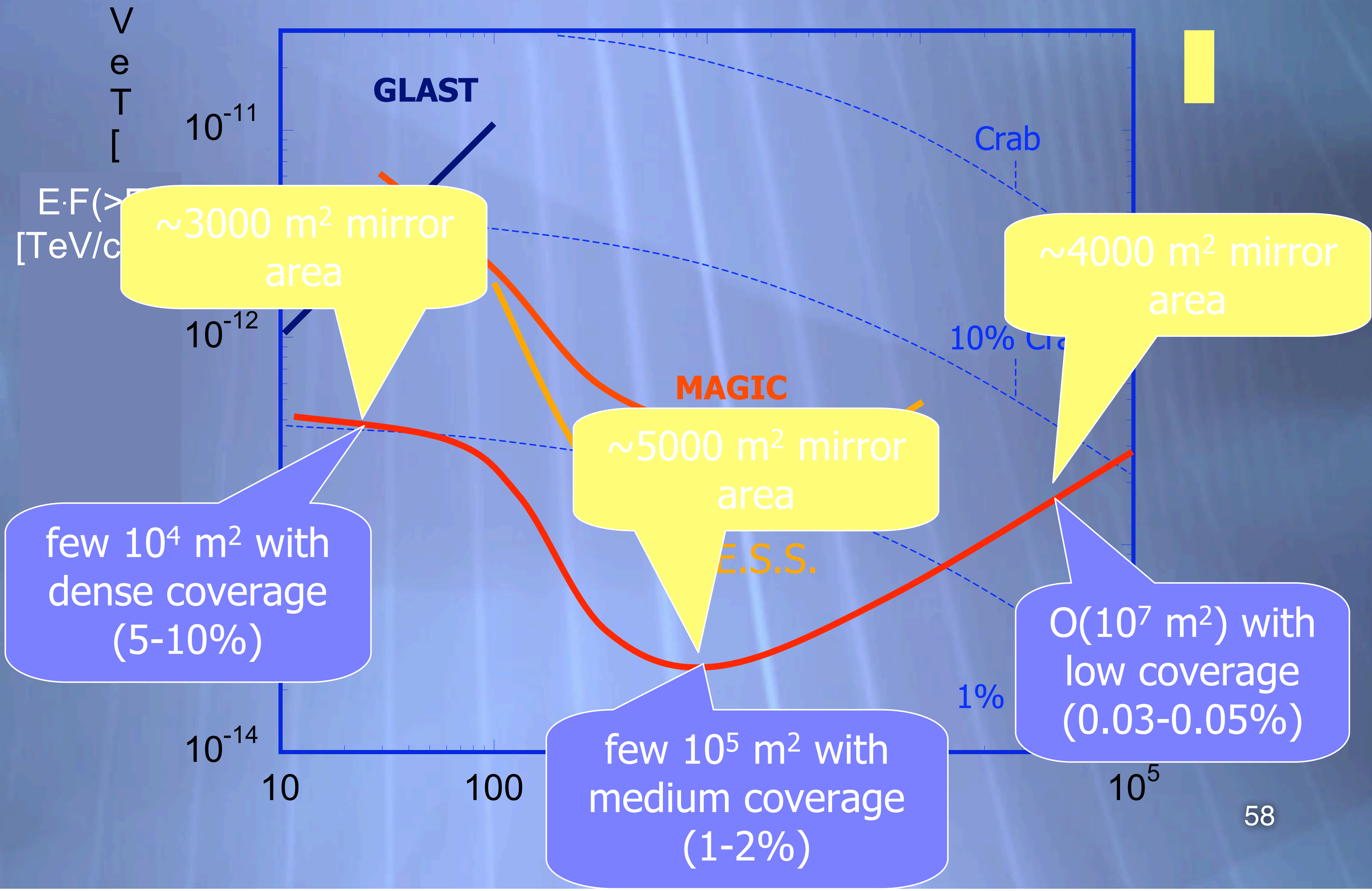
The Cherenkov Telescope Array (CTA) facility

- Aims at exploring the sky in the 10 GeV to 100 TeV energy range
- Combines guaranteed science with significant discovery potential
- Is a cornerstone towards a multi-messenger exploration of the nonthermal universe

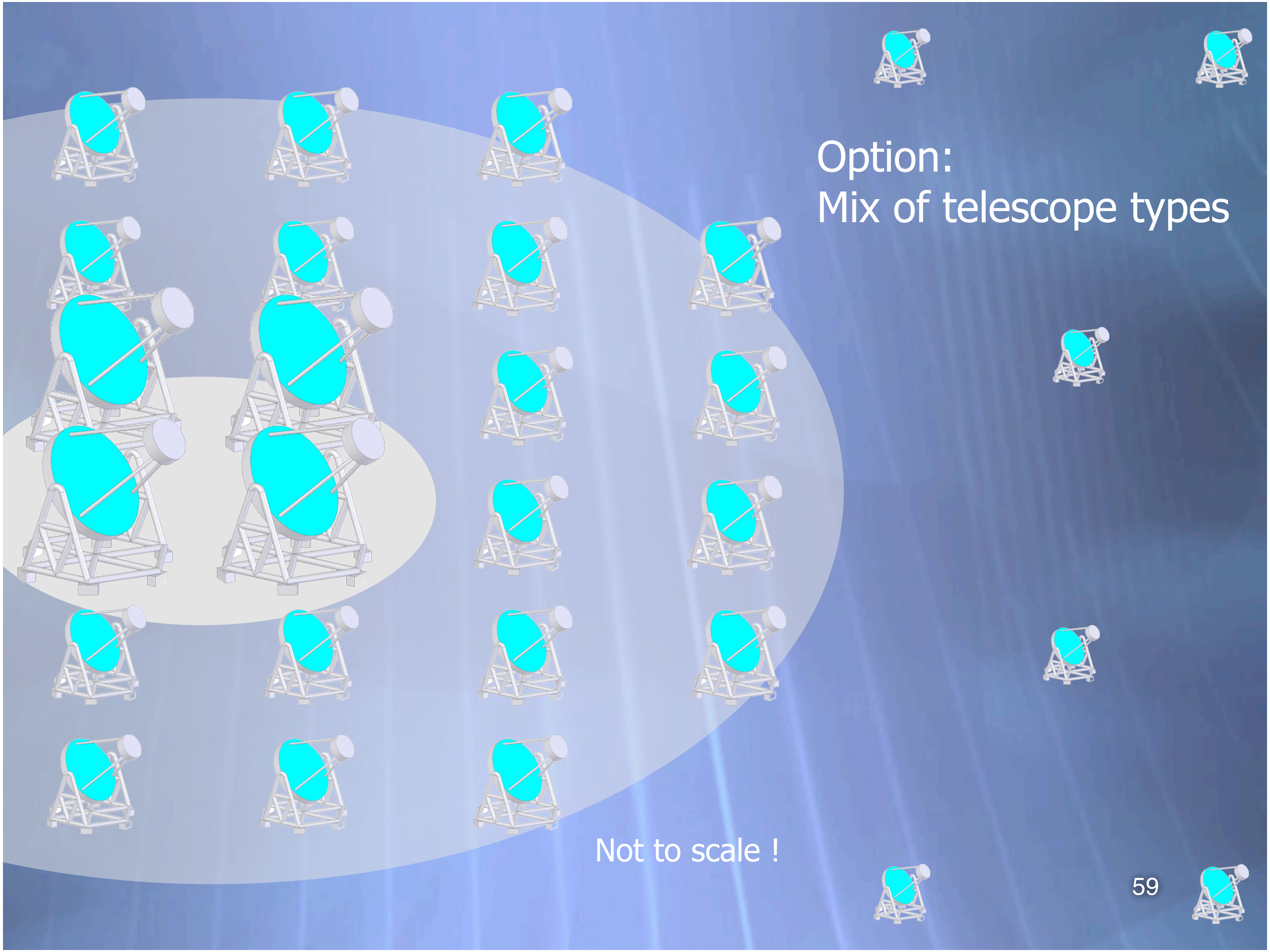
Sensitivity goal



How to achieve it

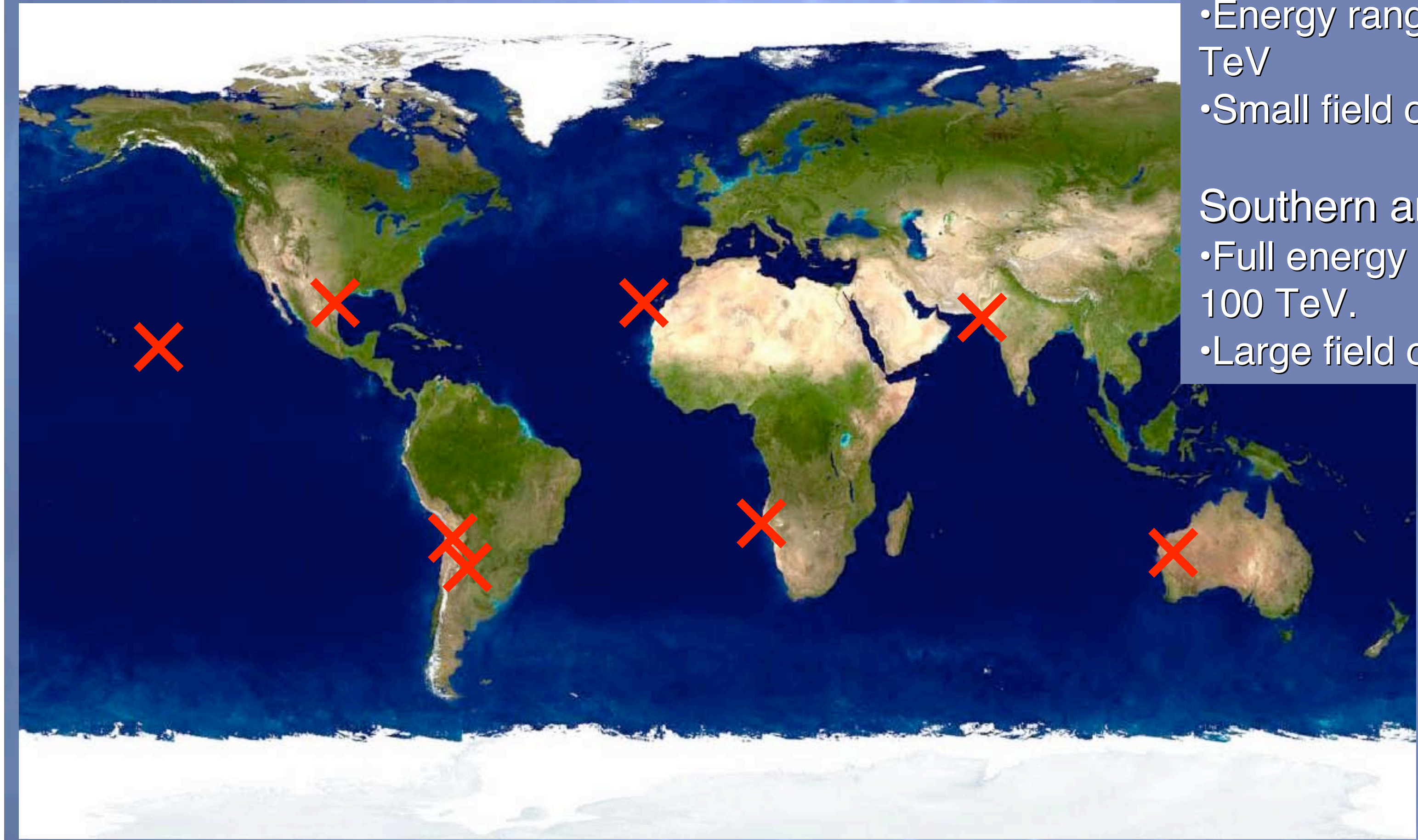


Option:
Mix of telescope types



Full sky coverage

One observatory with two sites operated by one consortium



Northern array (50 M€):
- Energy range 10 GeV – 1 TeV
- Small field of view

Southern array (100 M€):
- Full energy range 10 GeV – 100 TeV.
- Large field of view

CTA Consortium

Armenia	Yerevan
Czech Republic	Prague
Germany	HU Berlin, Bochum, DESY, Dortmund, Erlangen, Hamburg, MPI Heidelberg, U. Heidelberg, MPI Munich, Tübingen, Würzburg
Finland	Turku
France	Annecy, Grenoble, Montpellier, LLR Palaiseau, APC Paris, Obs. Paris-Meudon, U. Paris VI-VII, CEA Saclay, Toulouse
Italy	INFN Padova, Pavia, Pisa, Trieste, Rome, Siena, INAF Rome, Brera, Bologna, Padova, Palermo, Torino, ...
Ireland	DIAS Dublin, ...
Namibia	U. Namibia
Poland	Cracow, NCAC Warsaw, U. Warsaw, Lodz
Spain	IFAE, IEEC, UAB, UB Barcelona, UCM Madrid
South Africa	Northwest-Univ.
Switzerland	ETH Zurich, U. Zurich, Geneva, PSI
UK	Leeds, Durham, ...
more interested	**Argentina, Denmark, Japan, Netherlands, Russia, US (AGIS)**

CTA milestones

- ApPEC review in July 2003
  - Recommendation: join European efforts in VHE astronomy
- CTA Design Study kick-off meeting: Barcelona (UB group) January 24-25 2008:
  - Definition of Work packages
- ASPERA: CTA is one of the "7 Magnificent" experiments in Astroparticle Physics.
- October 2008: CTA among AstroNet priorities for the future of European astronomy
- December 2008: CTA in ESFRI (scientific infrastructure) roadmap.

Next Stages

- Next general meeting (Cracow, May): approve MoU for design study, elect Spokesman.
- Design study (until 2010)
  - Final Array layout
  - Telescope implementation choices and details
  - List of final few candidates sites
  - Proposal for organization, governance, operation
- Prototyping phase (2011-2012)
  - Construction of large size and medium size telescope prototypes.
- Construction phase (2013-2015):
  - Full arrays at southern and northern hemispheres.

Design study and prototyping

- Current telescopes not cost-optimized or reliable enough: cost would exceed target cost (100 M€) by factor 1.5 to 2.
- Wider field of view.
- Improved photosensors: HPDs or Geiger-mode APDs.
- Improved signal recording electronics.
- Larger dishes for reasonable price.
- Atmospheric monitoring and calibration integration
- Data handling and observatory concept

CTA in Spain

Established community

- Pioneer: Victoria Fonseca (UCM) in HEGRA.
- Currently 7 Spanish groups in MAGIC: UCM, IFAE, UAB, IEEC, UB, IAC, IAA.
- Significant contribution to MAGIC construction (~33%), one of the leading countries in operation, scientific exploitation and organization.
- After MAGIC-II, community is free to start with new technical developments.

Already strongly represented in CTA

- Atmospheric monitoring and Calibration
  - Manel Martínez: convener of the working package
  - Work already ongoing: LIDAR.
- Design optimization using MC
- Design of readout electronics
- Definition of physics case:
  - Diego Torres (IECC Barcelona): convener of working package.

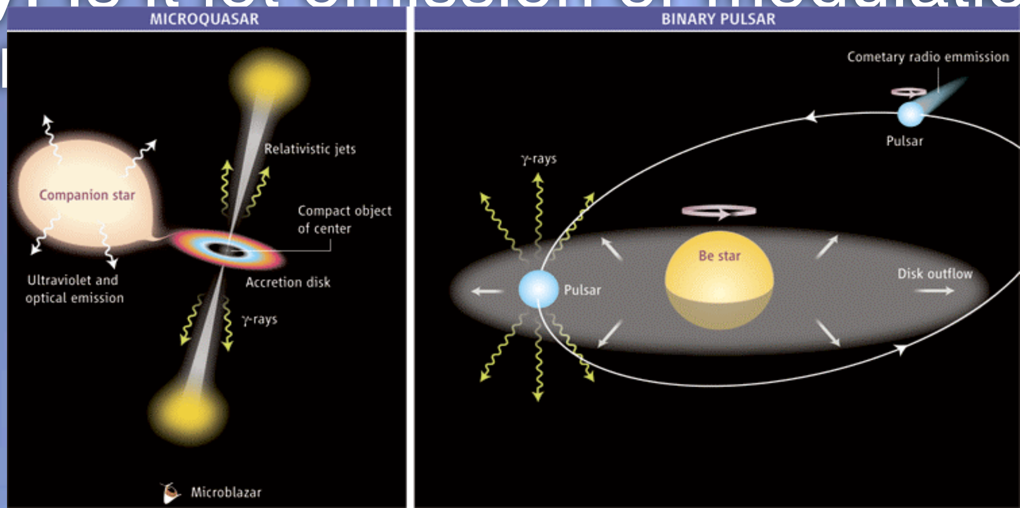
But this is not enough

- The MAGIC groups in CTA are by now very familiar with low energies and feel passion for low thresholds.
- The MAGIC groups (MPI, Italy, ETH) want to build a prototype of large telescope focused on low threshold (10-30 GeV).
- Spain has a solid expertise in photodetection (MAGIC-I camera) and readout electronics (MAGIC-II readout).
- A consortium of Spanish groups have coordinated to build a camera for the large telescope prototype: IFAE, UCM, UAB and CIEMAT (with individual contributions of UB and U.Murcia). UB will join in the next application.

backup

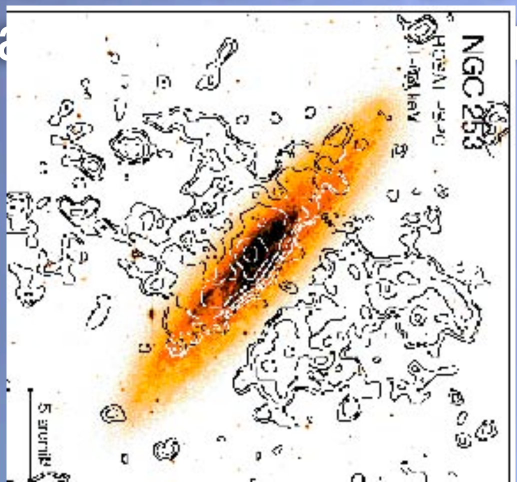
Galactic sources: γ-ray binaries

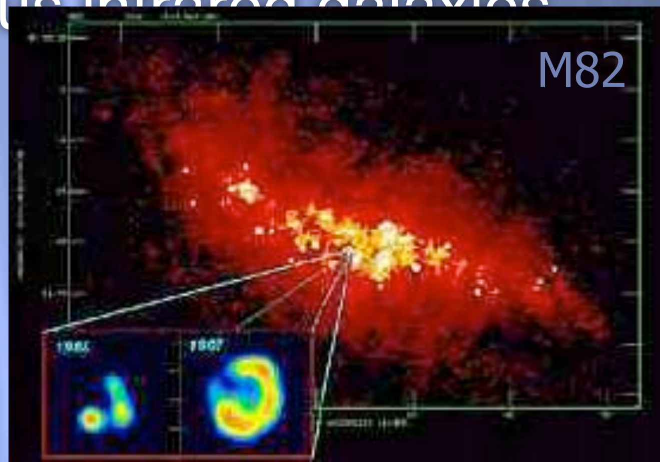
- CTA: must pin down physical model for each binary. Is it jet emission or modulation of pulsa



Extragalactic: starforming regions

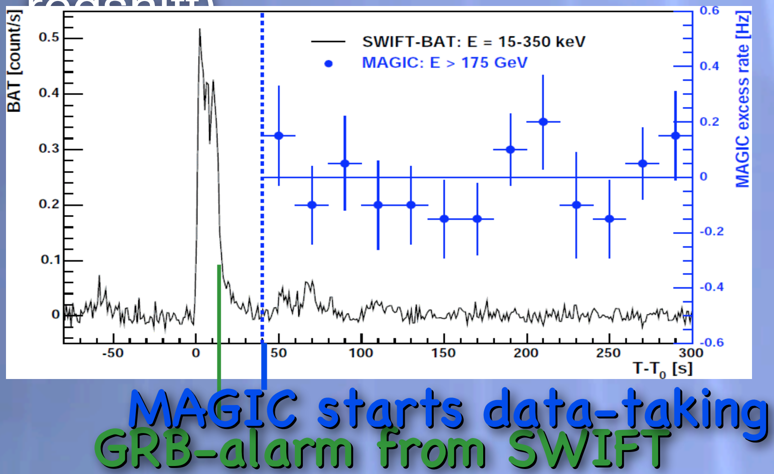
- Detailed modeling (e.g. Domingo-Santamaria & Torres) for objects such as NGC253 and M82 shows that CTA should see a good number of st[illegible] minou[illegible]

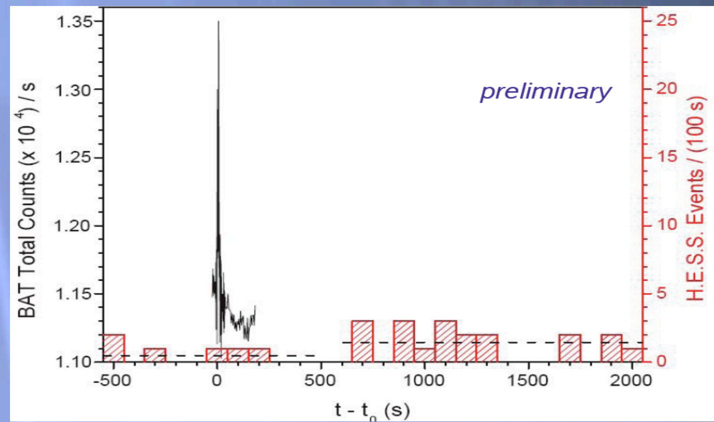




Extragalactic: GRBs

- No detection at VHE yet, even observing only tens of seconds after GRB peak in X-rays (MAGIC). Latest: serendipitious observation during prompt emission by HESS (but unknown redshift)

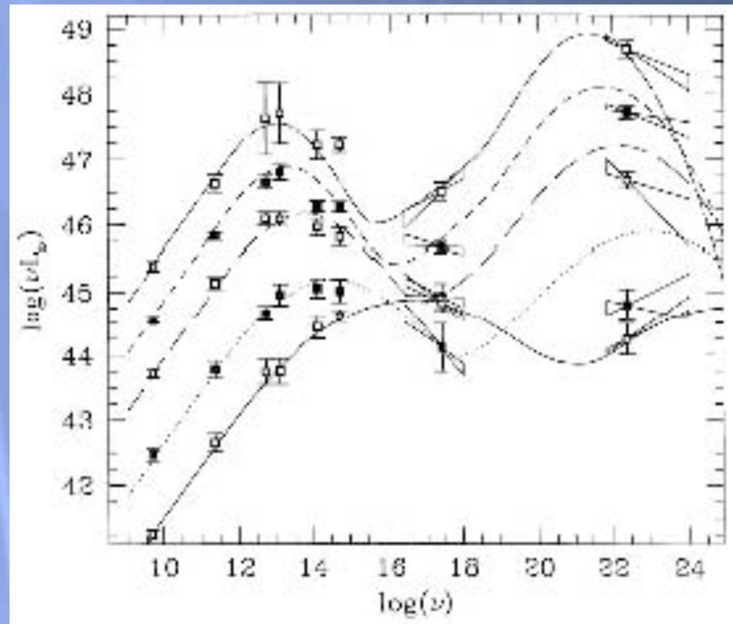




- We know from EGRET that there are photons at tens of GeV so it's only a matter of reducing the threshold.
- Advantage of CTA over GLAST: huge number of photons

Extragalactic: blazars

- The so-called "blazar sequence" is our current model to describe the spectral energy distribution of blazars.
- Needs a still larger population to cover all parameter space.
- We are also finding counter-examples to blazar sequence: changes in TeV that



Extragalactic: blazars

In general CTA well in demand for blazar studies:

- Need broader energy coverage to discriminate between leptonic and hadronic models.
- Need higher sensitivity to detect quiescent emission.
- Need higher energy coverage to establish high energy cutoffs.
- Need larger sample to study jet duty cycle.

European Strategy Forum
on Research Infrastructures

ESFRI

EUROPEAN ROADMAP FOR RESEARCH INFRASTRUCTURES

Report 2006

Baseline given in ESFRI LoI

6. Maturity of proposal (including possible timetable)
The performance and scientific potential of arrays of Cherenkov telescopes has been studied in significant detail; what remains to be decided is the exact layout of the telescope array. Ample experience exists in constructing and operating telescopes of the 10-12 m class (H.E.S.S., VERITAS). Telescopes of the 17 m class and 28 m class are operating (MAGIC) or under construction (H.E.S.S. II) and will serve as prototypes. Photon detectors with improved quantum efficiency are under advanced development and testing and will be available when the array is constructed. After a phase of detailed design (2006-2008), implementation could start in 2009/10, with full operation in 2012, allowing significant overlap with the GLAST satellite instrument to be launched in 2007, which covers the energy range below some 10 GeV and which serves as an all-sky monitor, triggering pointed observations at higher energies.
7. Budgetary information (preparation, construction and operation costs)
Depending on the exact number and size of the telescopes to be deployed, about 100 M€ are required for a southern site which will cover a wide energy range from some 10 GeV to 100 TeV for observations of our Galaxy at high resolution. A complementary site in the northern hemisphere would focus on extragalactic and cosmological objects, with instrumentation optimized for low energies (10 GeV-1 TeV), at a cost of about 50 M€. The stations would be constructed and operated by a single consortium. Total operating and maintenance costs are currently estimated to 3 to 5 M€ per year, including local staff. Up to 10 M€ are needed for site exploration, detailed design and industrial prototypes.

FP7 design study application

- Submitted application: May 2, 2007.
- Duration: 2008-2010.
- Budget: 5 M€.
- Participation of 34 institutes from 15 countries, mainly European.
- Spanish participation: IFAE, UB-ICC, UAB, UCM, ICE, IAC, IAA.
- Spain is leading two Work Packages (Physics planning – D. Torres, and Atmospheric Monitoring+Calibration – M. Martínez)

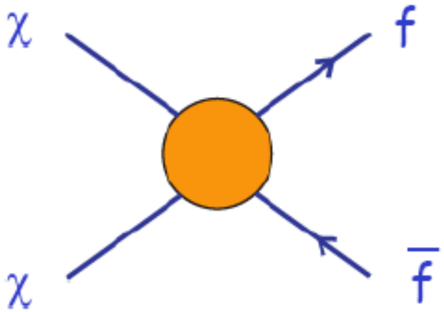
Prospects in Spain

- We have applied for an “Acción Complementaria” to fund the CTA activity in Spain.
- We are considering to organize the next CTA general meeting in Barcelona.

My personal view:

- Current two WPs in FP7 application are not enough. Spain is one of the three leading countries in MAGIC, we should keep a leading role in CTA. We should take responsability for a relevant technical contribution.
- The CTA collaboration is still building up. There is room for more partners in Spain.

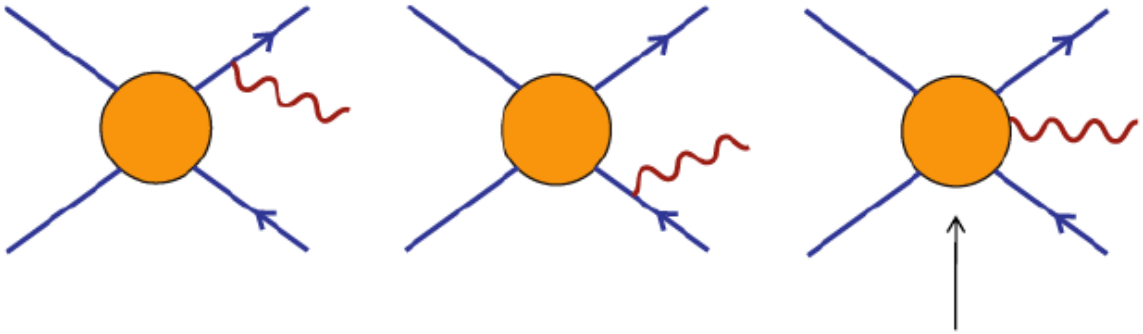
How to avoid helicity suppression for Majorana particles



$\sim m_f$ for Majorana particles in limit $v/c \to 0$

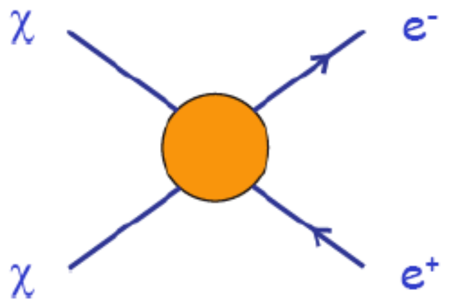
"Final state radiation"

"Internal bremsstrahlung", IB



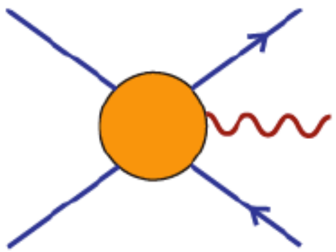
$\sim m_f$ $\sim m_f$ No m_f suppression!

Example, annihilation into electrons and positrons:



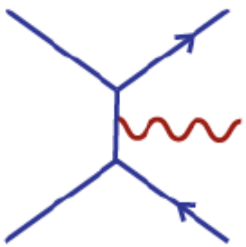
Annihilation rate $\sigma v \sim 3 \cdot 10^{-26}$ cm^{-3}s^{-1} at freeze-out, due to non-suppressed p-wave in early universe, $(v/c)^2 \sim 0.3 \Rightarrow$ WMAP relic density constraint fulfilled, $\Omega_{CDM}h^2 = 0.1$

Annihilation rate in the halo today
$\sigma v \sim 10^{-25}\,(m_e/m_\chi)^2$ cm^{3}s^{-1} $\sim 10^{-37}$ cm^{3}s^{-1} for slow-moving χ of mass 500 GeV. Impossible to detect!



First order QED "correction":
$(\sigma v)_{QED}/(\sigma v) \sim (\alpha/\pi)\,(m_\chi/m_e)^2 \sim 10^9 \Rightarrow 10^{-28}$ cm^{3}s^{-1}

t-channel selectron exchange



The "typical" QED correction of a per cent is here a factor of a billion instead! May give detectable rates!

(L.B. 1989)

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