γ-rays and neutrinos

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EPS HEP 2007

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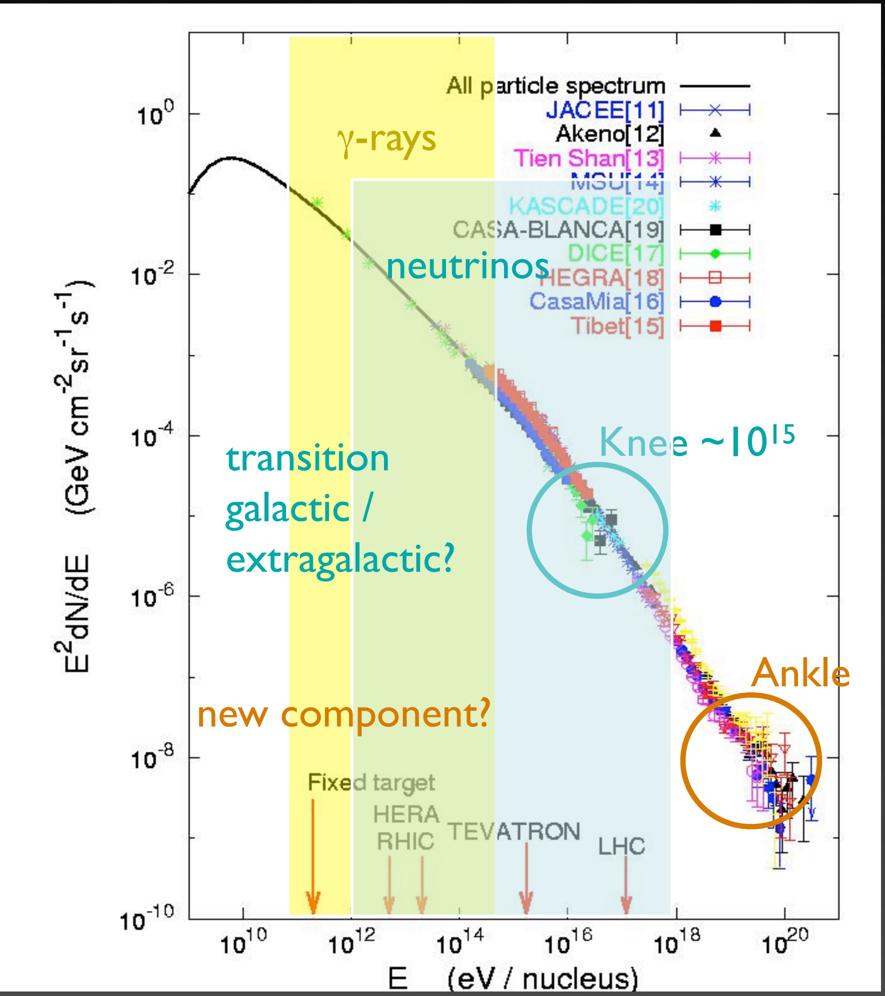
Manchester, England

Understanding cosmic rays



Other unsolved questions:

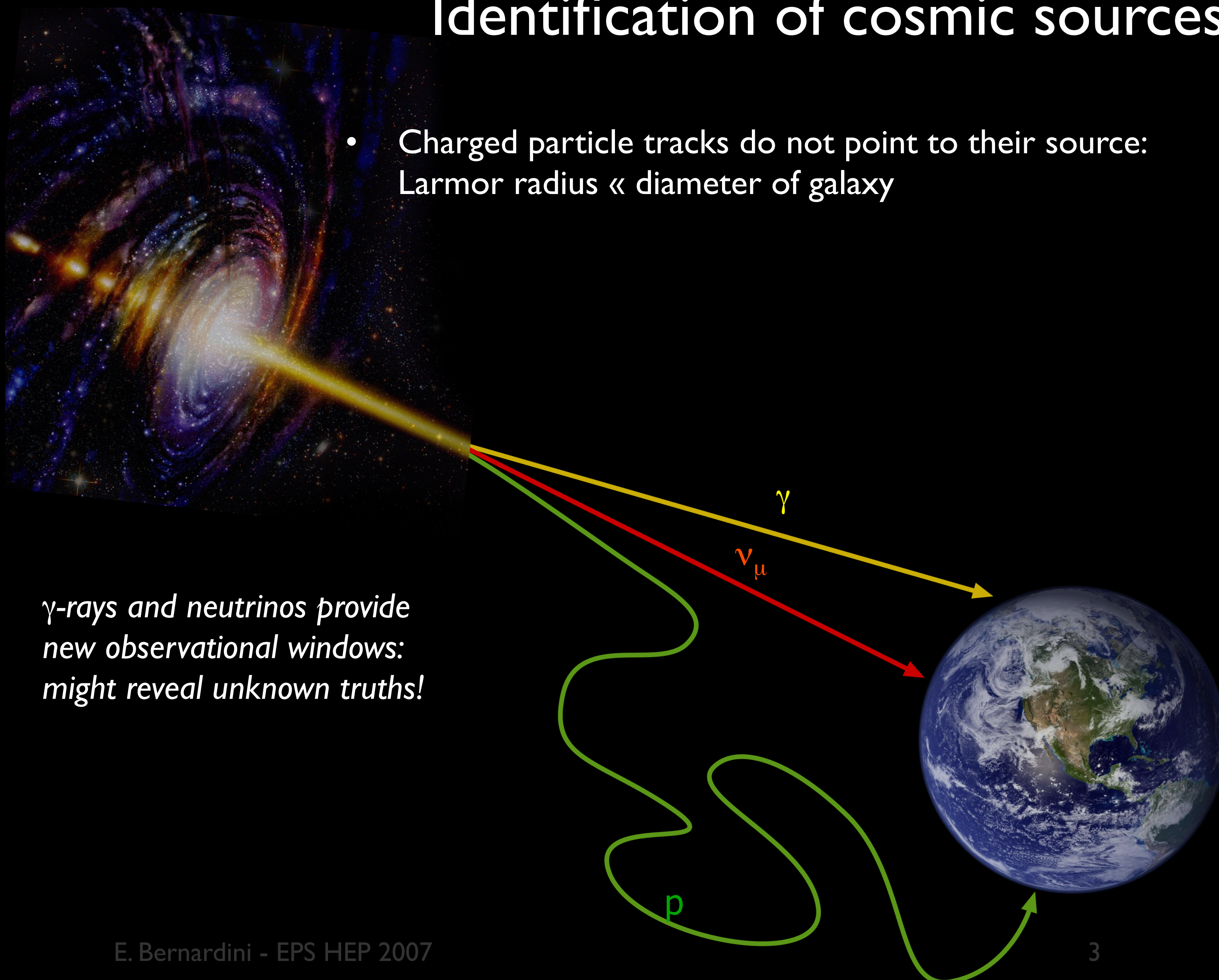
- Which and where are the sources?
- How do they work?

- Power Laws favor shock-front acceleration (reflection by magnetic mirrors)
- Need large magnetic fields and huge objects

- How do cosmic rays reach us?

Identification of cosmic sources

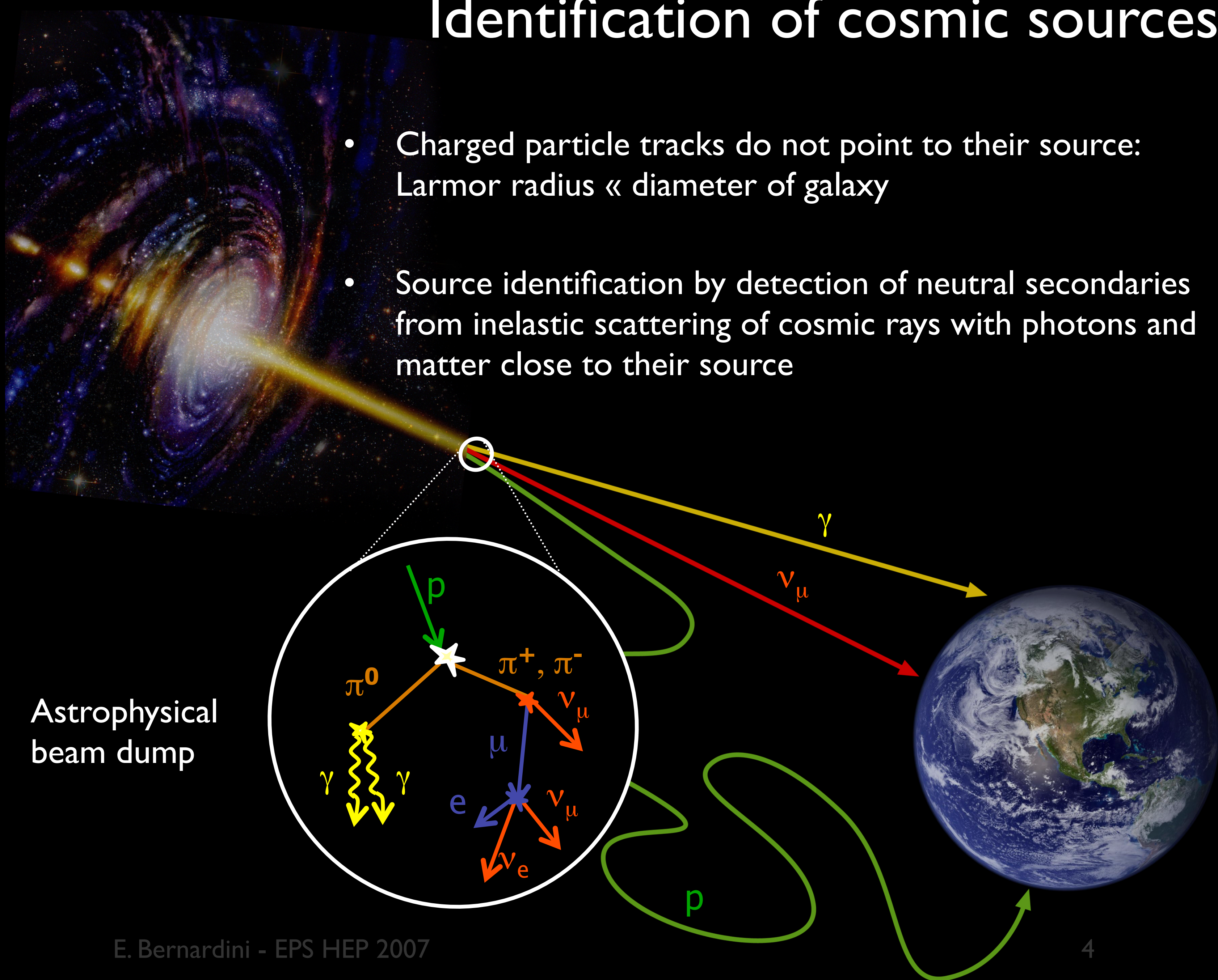
- Charged particle tracks do not point to their source: Larmor radius « diameter of galaxy



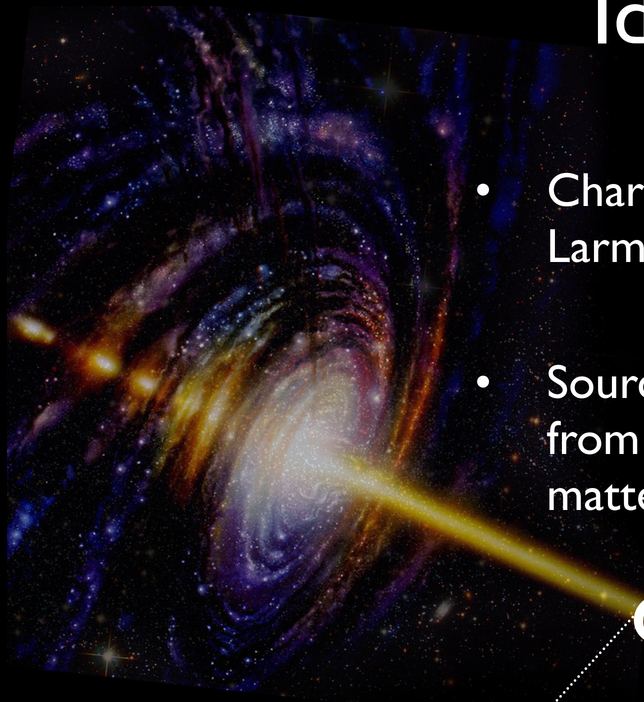
γ-rays and neutrinos provide new observational windows: might reveal unknown truths!

Identification of cosmic sources

- Charged particle tracks do not point to their source: Larmor radius « diameter of galaxy
- Source identification by detection of neutral secondaries from inelastic scattering of cosmic rays with photons and matter close to their source



Identification of cosmic sources



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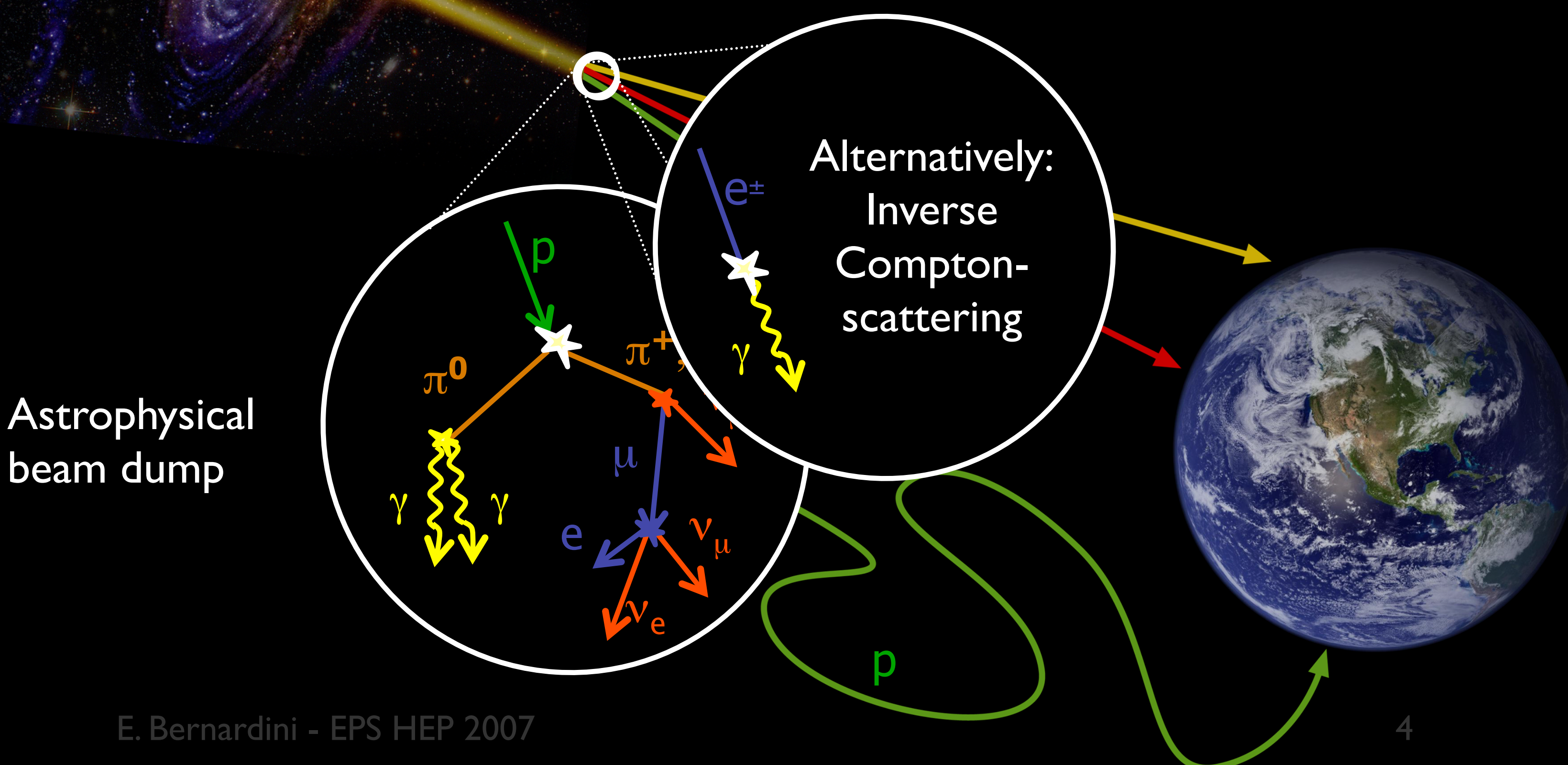


Candidate cosmic accelerators

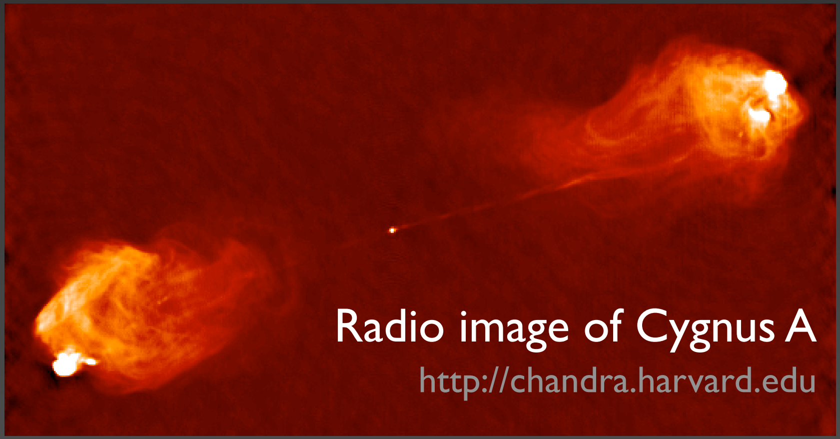
Source classes show clear evidence of non-thermal emission

Galactic Sources:

- Supernova Remnants, Pulsars, Supernova Wind Nebulae, binary systems, small mass black holes (e.g. Microquasars) …
- Lower luminosities are enough to give detectable fluxes

Extragalactic Sources:

- Active Galactic Nuclei (AGN), Gamma Ray Burst (GRB) …
- Higher luminosities required but are massive objects with highly variable engines



Results on γ-rays

γ-ray experimental techniques

1 MeV — 1 GeV — 1 TeV — 1 PeV — 1 EeV

Satellite
Direct
E.g. EGRET, GLAST

Air Cherenkov telescopes
Air-shower
E.g. Whipple, HEGRA, H.E.S.S., MAGIC, CANGAROO, VERITAS

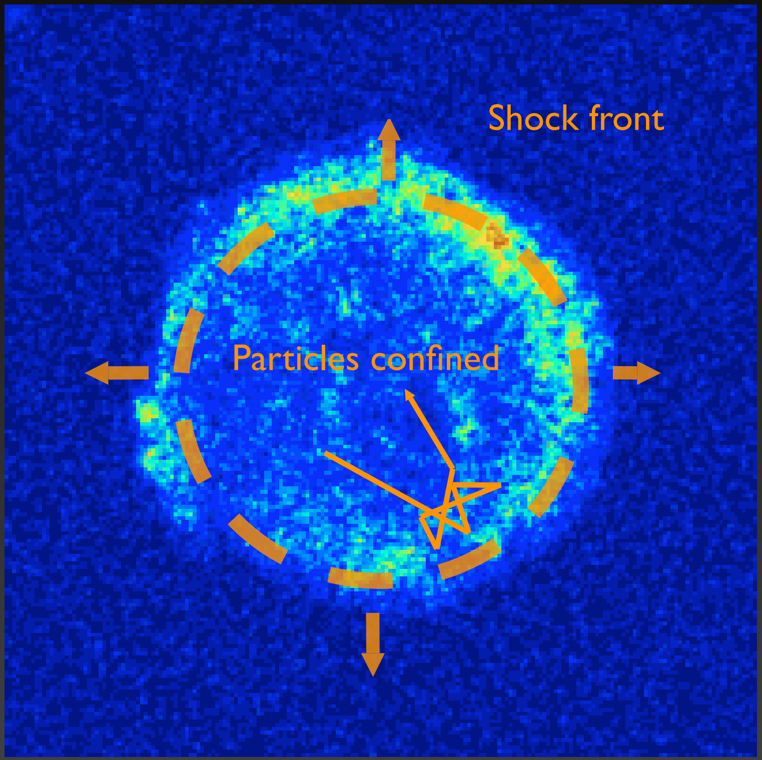
Water Cherenkov Detector
Air-shower
MILAGRO

Extensive Air-shower Arrays
Air-shower
E.g. Tibet, ARGO

At this conference:

- GLAST and the future of high energy γ-ray Astrophysics, A. Morselli
- Very high energy γ-ray Astronomy with HESS, J. Hinton
- Status and results of the MAGIC telescope, R. Firpo

SNR: sources of galactic cosmic rays?



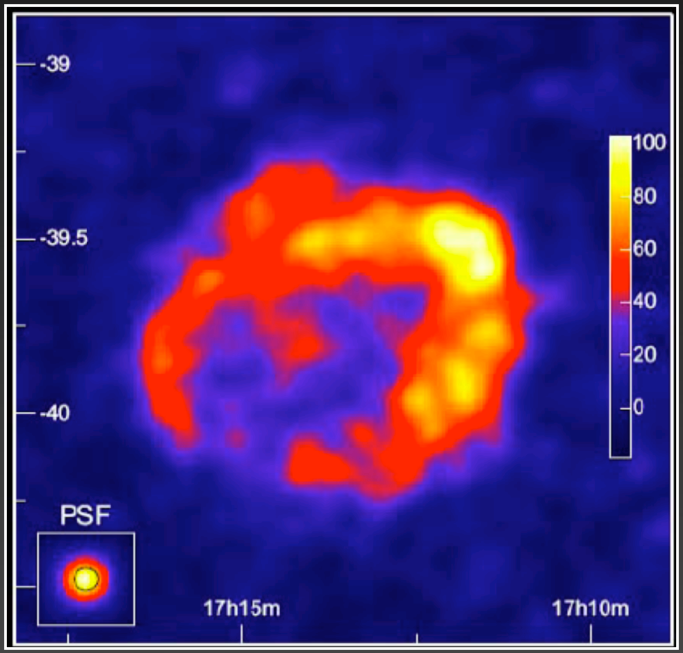
X-ray views of Tyco's SNR
http://science.nasa.gov

- Elastic collisions of particles at the shock front (Fermi acceleration) $dN/dE \sim E^{-\alpha}$; $\alpha \sim 2.1$

- Galactic CR budget:
  - 1 SNR / (30 - 70) yr
  - 10^{51} erg each
  - 5 - 10 % efficiency into CR would be sufficient
    Ginzburg & Syrovatskii 1964

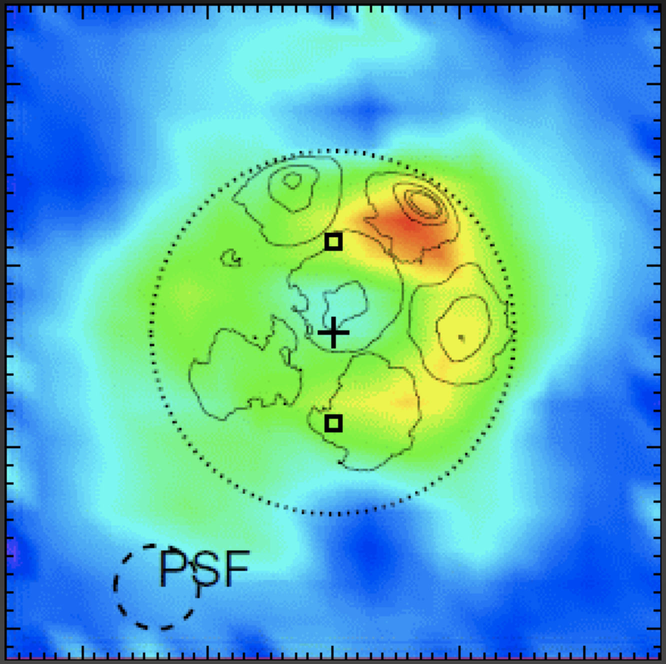
Extended galactic objects: SNRs

- Proof of emission of TeV γ-rays from the shell of SNRs
- Unambiguous evidence of particle acceleration (up to ~ 100 TeV)
- Hadronic or leptonic?
- If hadronic, neutrinos may be detected by cub-kilometer-scale neutrino telescopes A. Kappes et al. astro-ph/0606286, Vissani Astrop. P. 26, 310 (2006)



RX J1713.7-3946 (Ø = 1.3°)

F. Aharonian et al. astro-ph/0611813

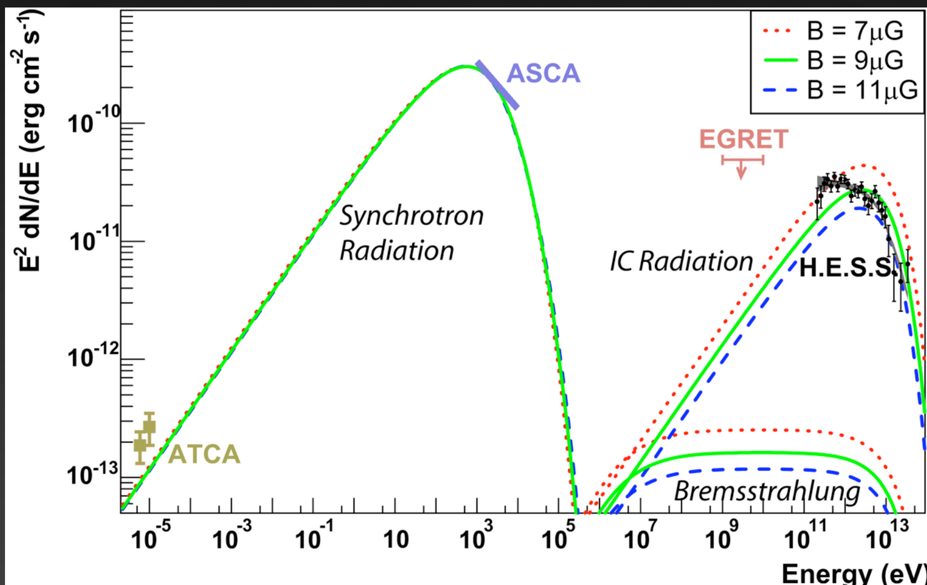


RX J0852.0-4622 (Ø = 2.0°)

Enomoto et.al, astro-ph/0608422

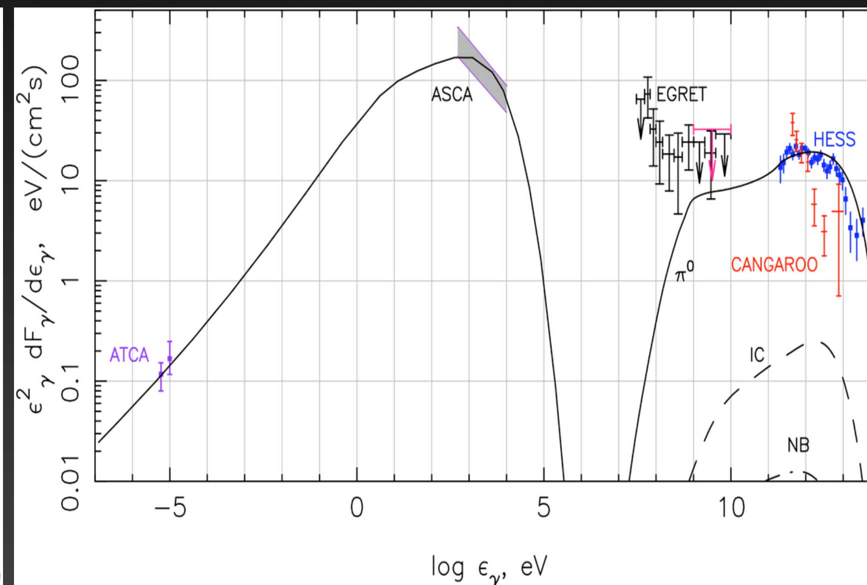
RX J1713-3946: hadronic vs leptonic

- Several non-constrained parameters (e.g. magnetic field, age)
- Hadronic scenario favored?
- Is *O*(10 %) of the energy transferred to cosmic rays?



RX J1713.7-3946 SED: leptonic model

F. Aharonian et al. A&A 449, 2006

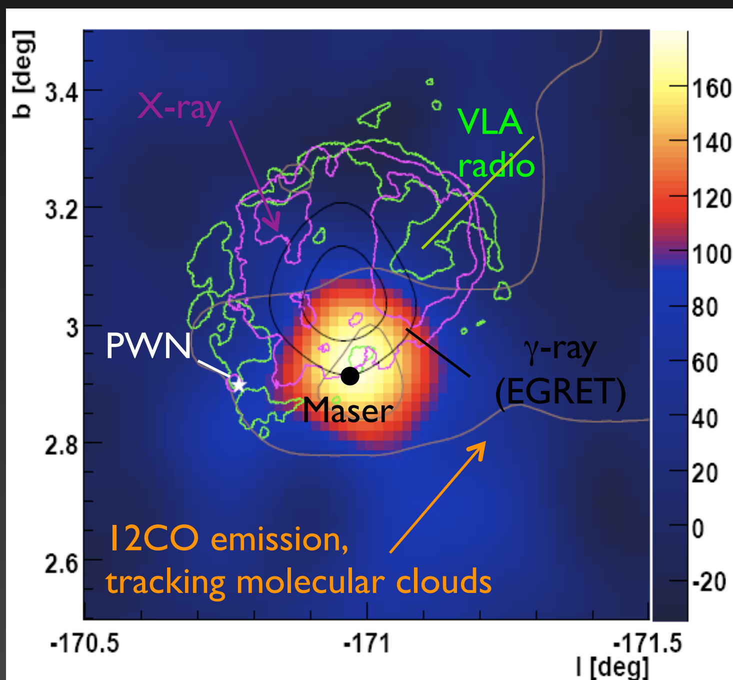


RX J1713.7-3946 SED: hadronic model

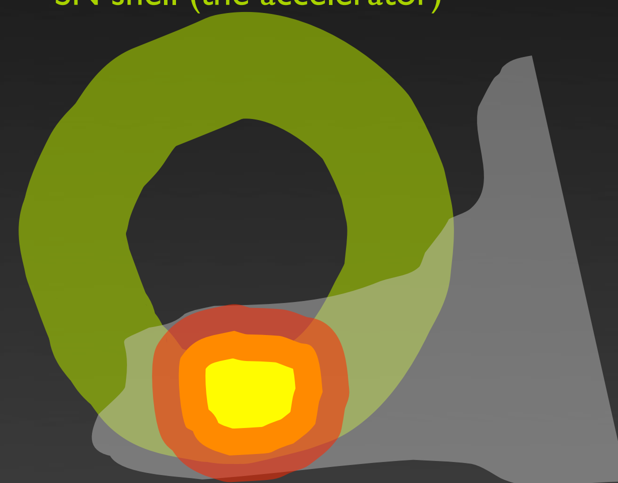
Berezkho & Völk astro-ph/0602177

SNRs: looking for hadronic smoking guns

- Look for clouds nearby potential accelerators F.A. Aharonian, Space Science Rev 99, 187 (2001)
- Expected neutrino flux is roughly the same order as γ-ray flux



VHE γ-rays from IC 443
J. Albert et al. arXiv:0705.3119



Cosmic beam dump
Adapted from M.L. Costantini & F. Vissani astro-ph/0508152

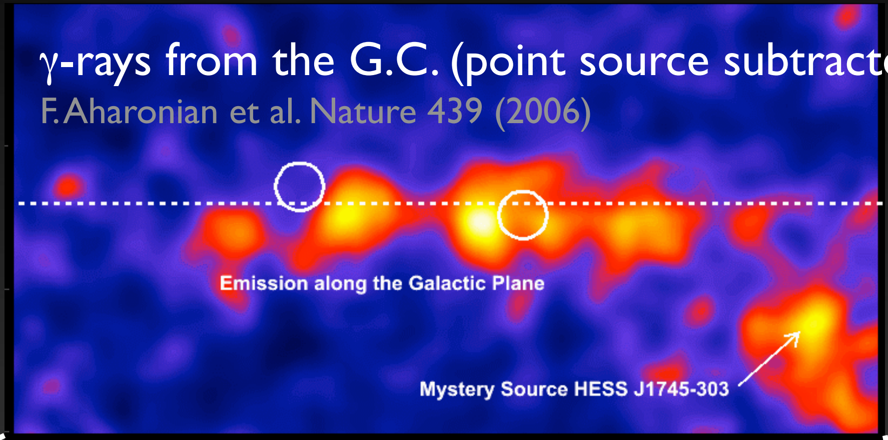
γ-ray emission from the Galactic Centre

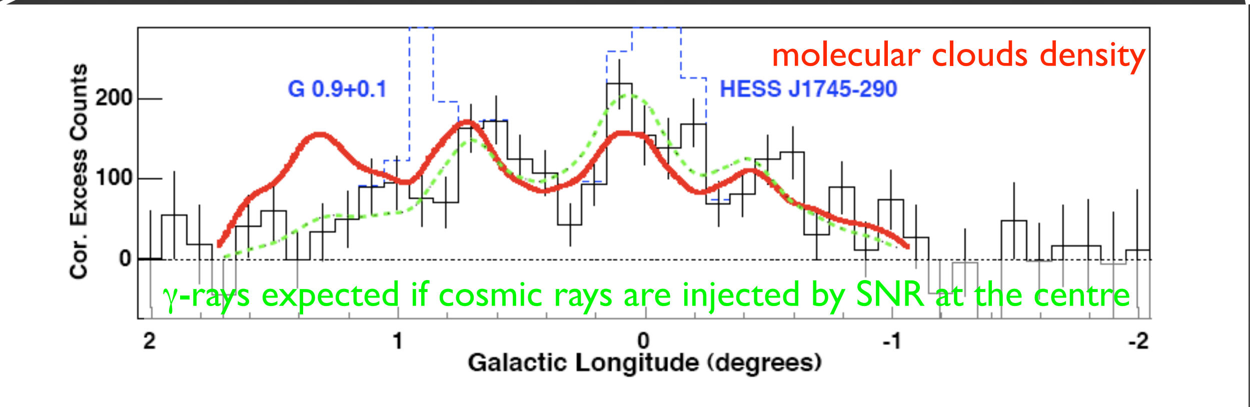
Looking for hadronic smoking guns:

1. Search for γ-ray emission by inefficient electron accelerators
2. Look for γ-ray emission correlated with clouds nearby potential accelerators

At this conference:

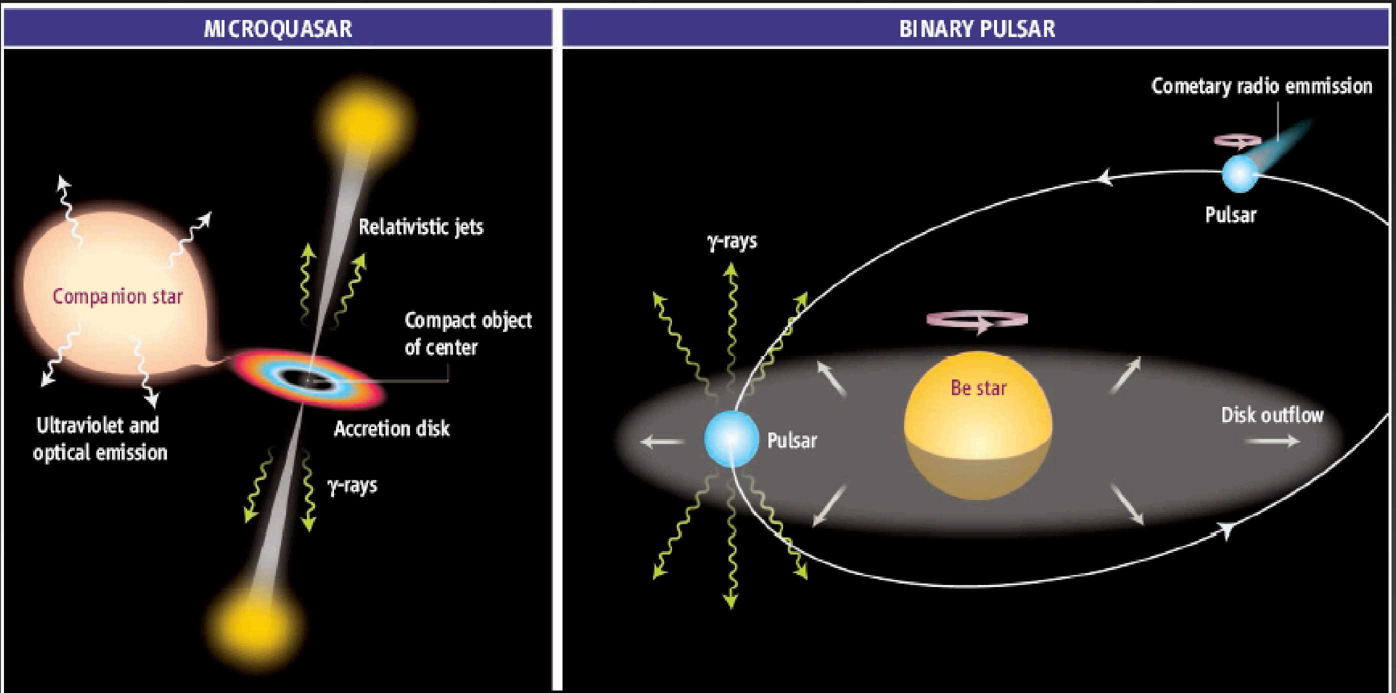
– Localizing the HESS galactic centre point source, I. Baun





Binary systems

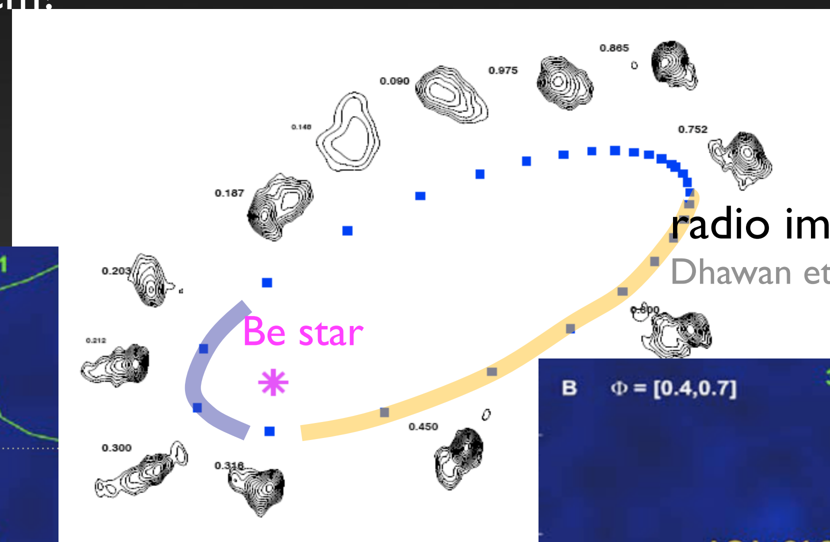
- The interaction between a compact object and its companion star creates a complicated system that includes many shocks
- Cosmic rays accelerated can then interact with matter (stellar wind or accretion disk)



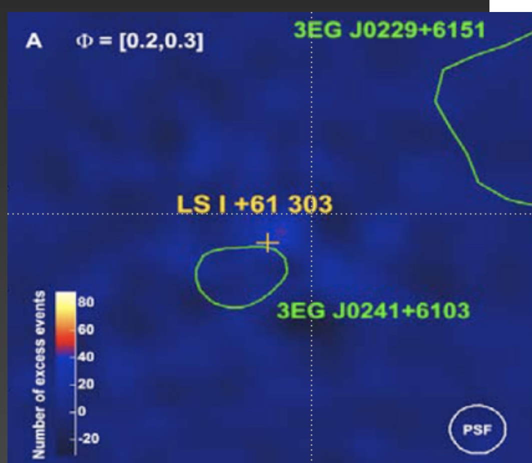
Micro-quasar versus binary pulsar models Mirabel (2006)

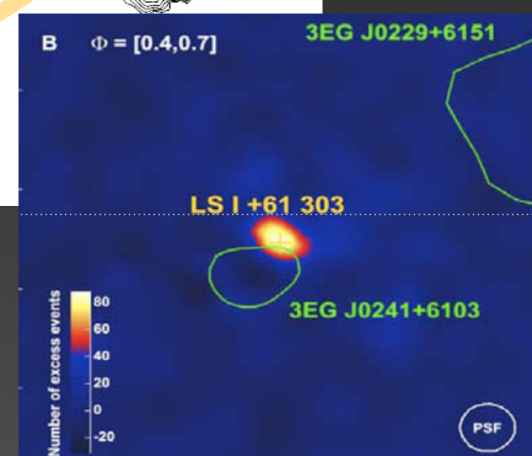
Compact galactic objects: binary systems

- If accelerated close to the system electrons loose energy by radiative losses and are not efficiently accelerated
- Look for evidence of γ-ray emission close to the system (e.g. periodicity, LS 5039, LS I +61 303 ?)
- Nature of the system?



radio imaging
Dhawan et al. (2006)





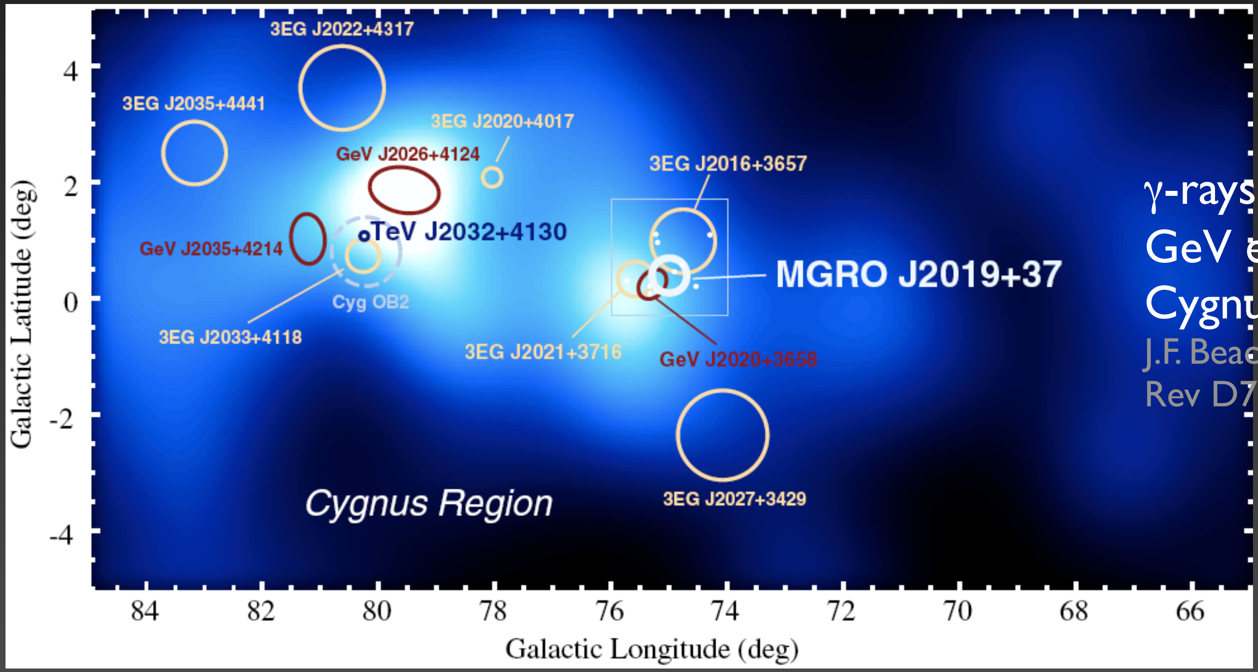
γ-rays from LSI +61 303
J. Albert et al. Science 312 (2006)

Extended galactic objects: the Cygnus region

- A site of intense on-going star formation
- Diffuse and point-like GeV emission, one un-identified TeV source and several hot-spots, possibly associated with GeV sources
- Brightest source might be detectable in neutrinos with IceCube

At this conference:

- TeV gamma-rays and neutrinos from photodissociation of cosmic-ray nuclei in Cygnus OB2, S. Palomares-Ruiz



γ-rays sources and diffuse GeV emission from the Cygnus region

J.F. Beacom, M.D. Kistler Phys. Rev D75, 083001 (2007)

Extragalactic sources of γ-rays: AGNs

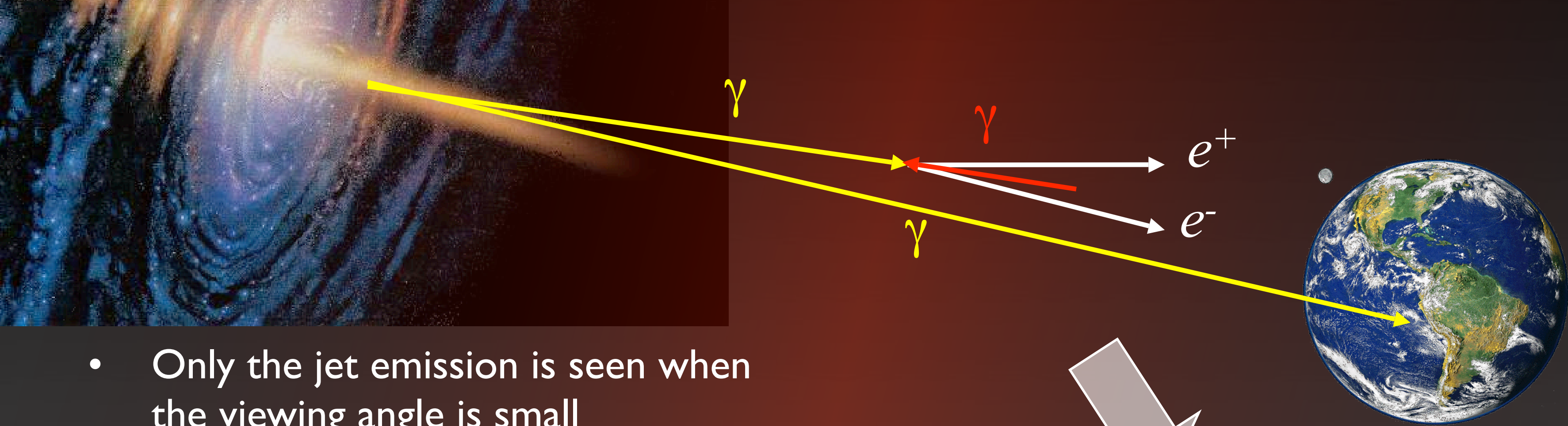
Source	z	
M87	0.004	day-scale variability F. Aharonian et al. Science 314 (2006)
Mrk 421	0.031	
Mrk 501	0.034	minute-scale variability J. Albert et al. arXiv:astro-ph/0702008
1ES 2344+514	0.044	
Mrk 180	0.045	
1ES 1959+650	0.047	
PKS 548-322	0.069	
BL Lacertae	0.069	new class (LBL) J. Albert et al. arXiv:astro-ph/0703084
PKS 2005-489	0.071	
PKS 2155-304	0.116	minute-scale variability F. Aharonian et al. arXiv:0706.0797
H 1426+428	0.129	
1ES 0229+200	0.139	
H 2356-309	0.165	
1ES 1218+304	0.182	
1ES 1101-232	0.186	constrain EBL F. Aharonian et al. Nature 440 (2006)
1ES 0347-121	0.188	
1ES 1011+496	0.212	
PG 1553+113	>0.25	
3C279	0.538	the most distant object J. Albert et al. 30th ICRC (PRELIMINARY)

- Active galactic nuclei (AGN) are powerful superluminal systems consisting of:
  - a central engine (black hole)
  - an accretion disk
  - Jets
- All AGN are believed to have the same structure, and differences are due to the viewing angle.

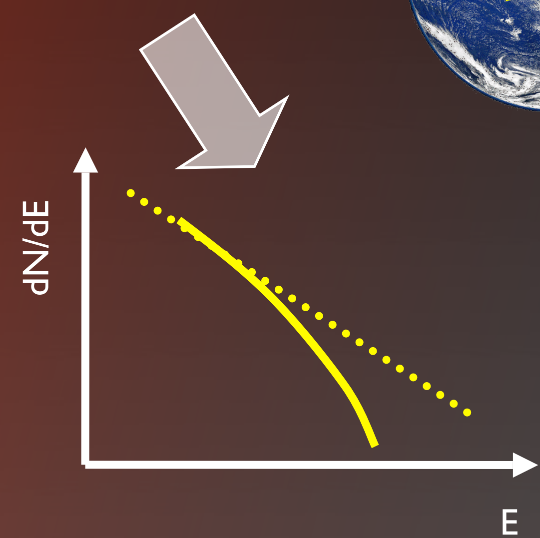
Active Galactic Nuclei (AGN) observed (to date) at TeV energies

AGNs and extragalactic background light

Absorption in (infrared) extragalactic background light (EBL):
$\gamma(\text{TeV}) + \gamma(\text{EBL}) \rightarrow e^+e^-$

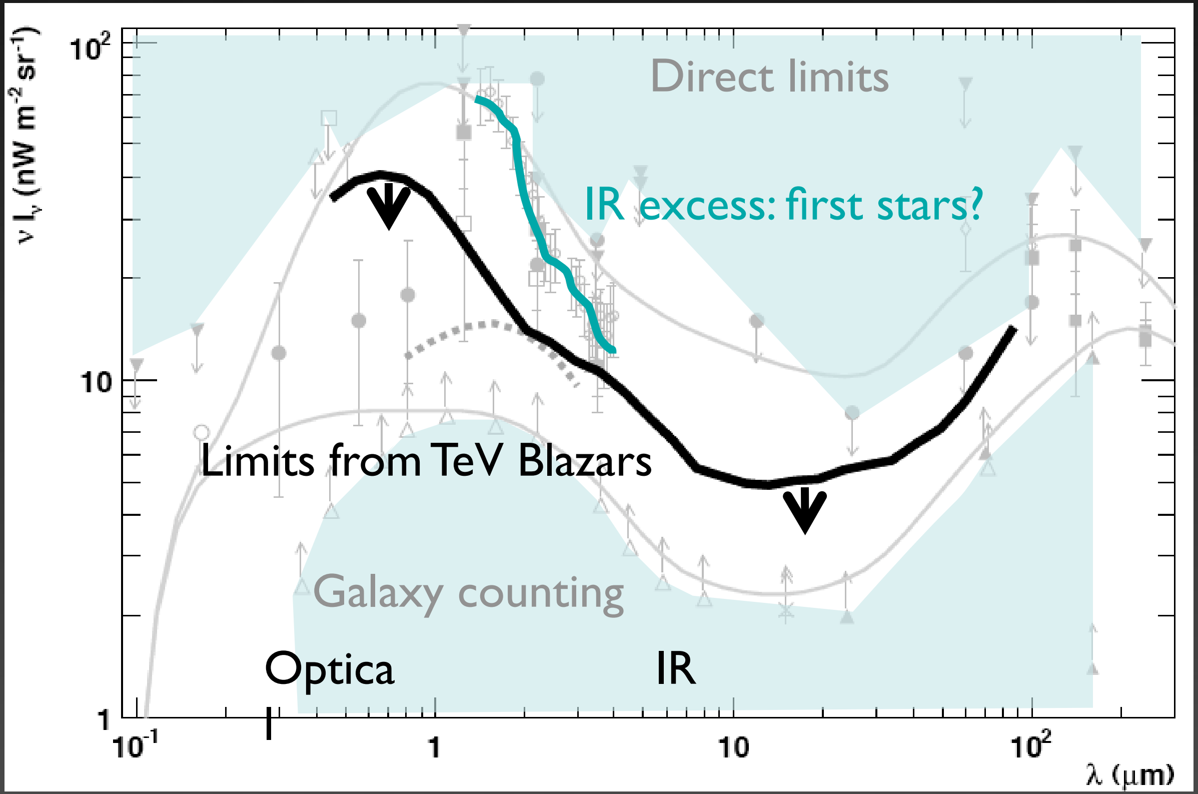


- Only the jet emission is seen when the viewing angle is small
- The luminosity of the jet depends on the Lorentz factors of the plasma in the jets
- Values as high as 10 have been observed



Measuring the extragal. backg. light (EBL)

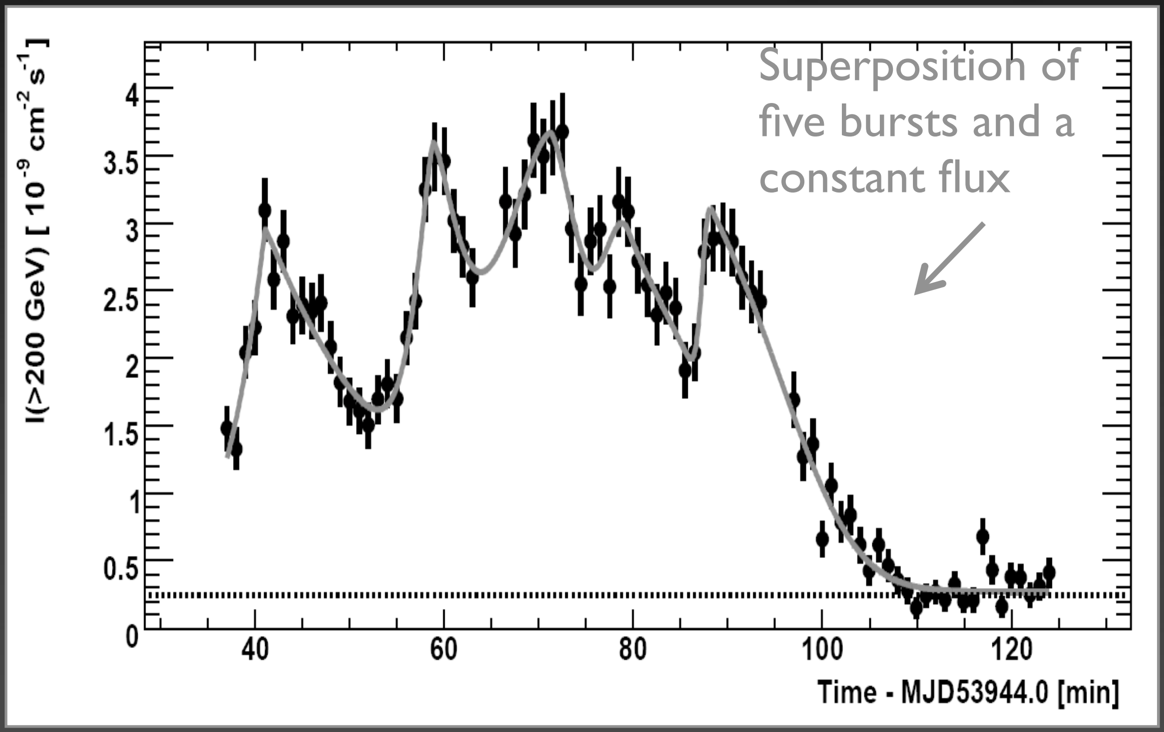
- EBL contains information on star and galaxy formation (Cosmology)
- Assumption:
  - intrinsic spectrum of blazars ($dN/dE \sim E^{-\gamma}$) can't be harder than γ = 1.5



Compilation on limits on EBL
D. Mazin, M. Rue, astro-ph/0701694

BL Lac variability

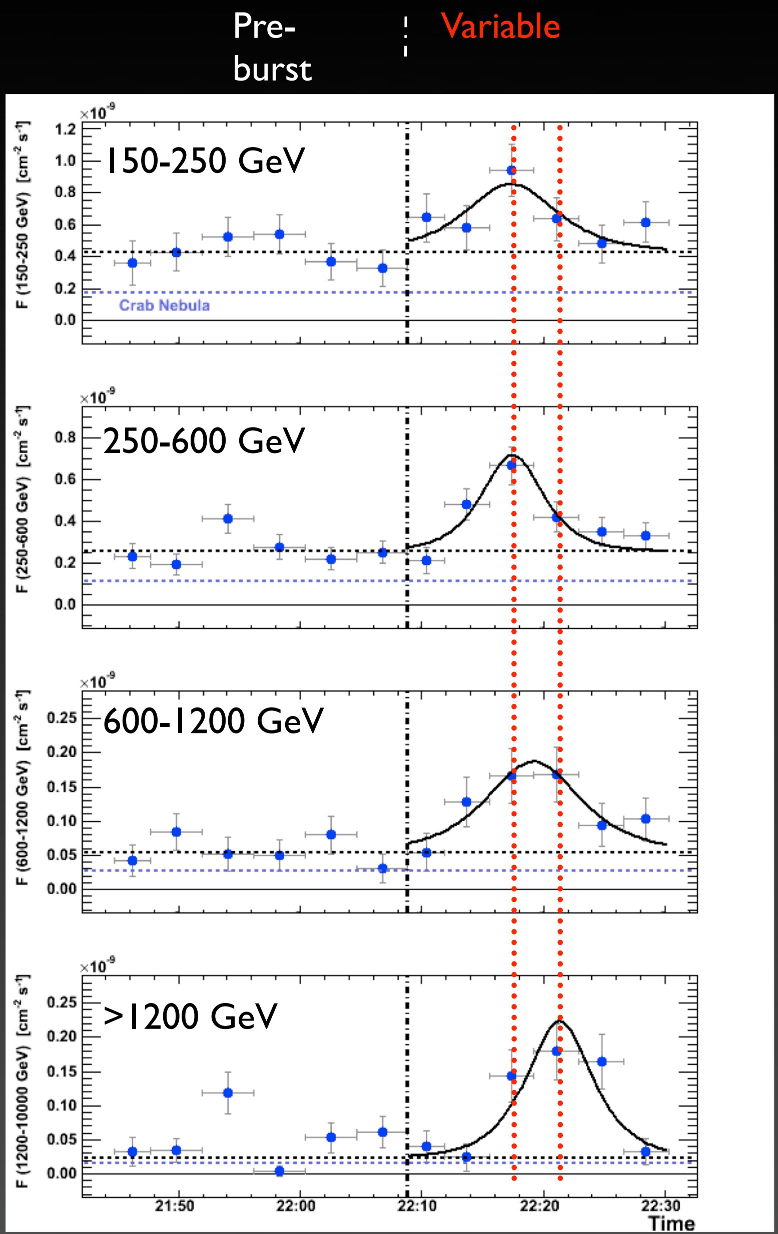
- Minute-scale variability:
  - extreme jet / blob emission with Γ-factor > *O*(10) OR not related to the black hole
- Challenge for hadronic models:
  - In pγ interactions high energies are needed and this takes long time …



PKS 2155-304

F. Aharonian et al. arXiv:0706.0797

BL Lac: time-lag

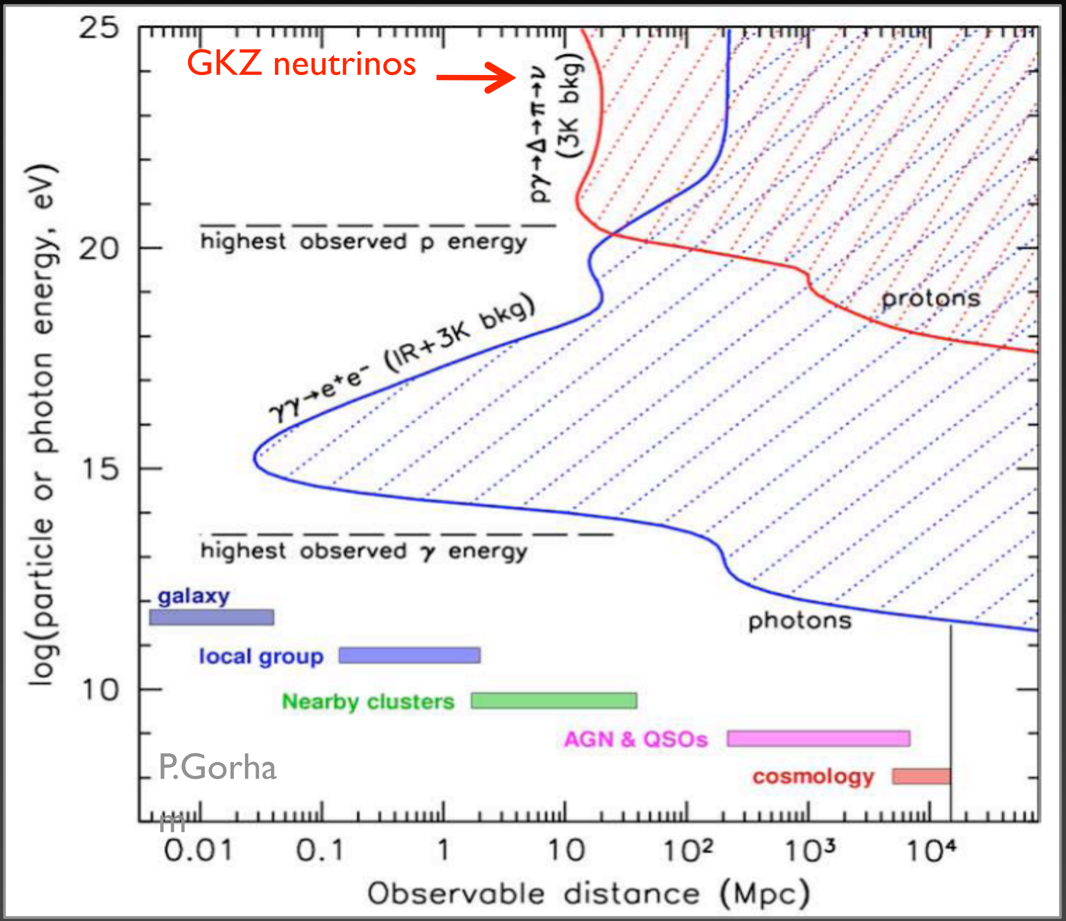


- Leptonic models cannot give arbitrary high energy
- Observation of E > tens TeV may favor hadronic models

Mrk 501 burst in July 2005:
Indication of a ~ 4 min delay between the peaks at I(<0.25 TeV) and I(>1.2 TeV)
progressive acceleration of electrons?
J. Albert et al. arXiv:astro-ph/0702008

Results on cosmic neutrinos

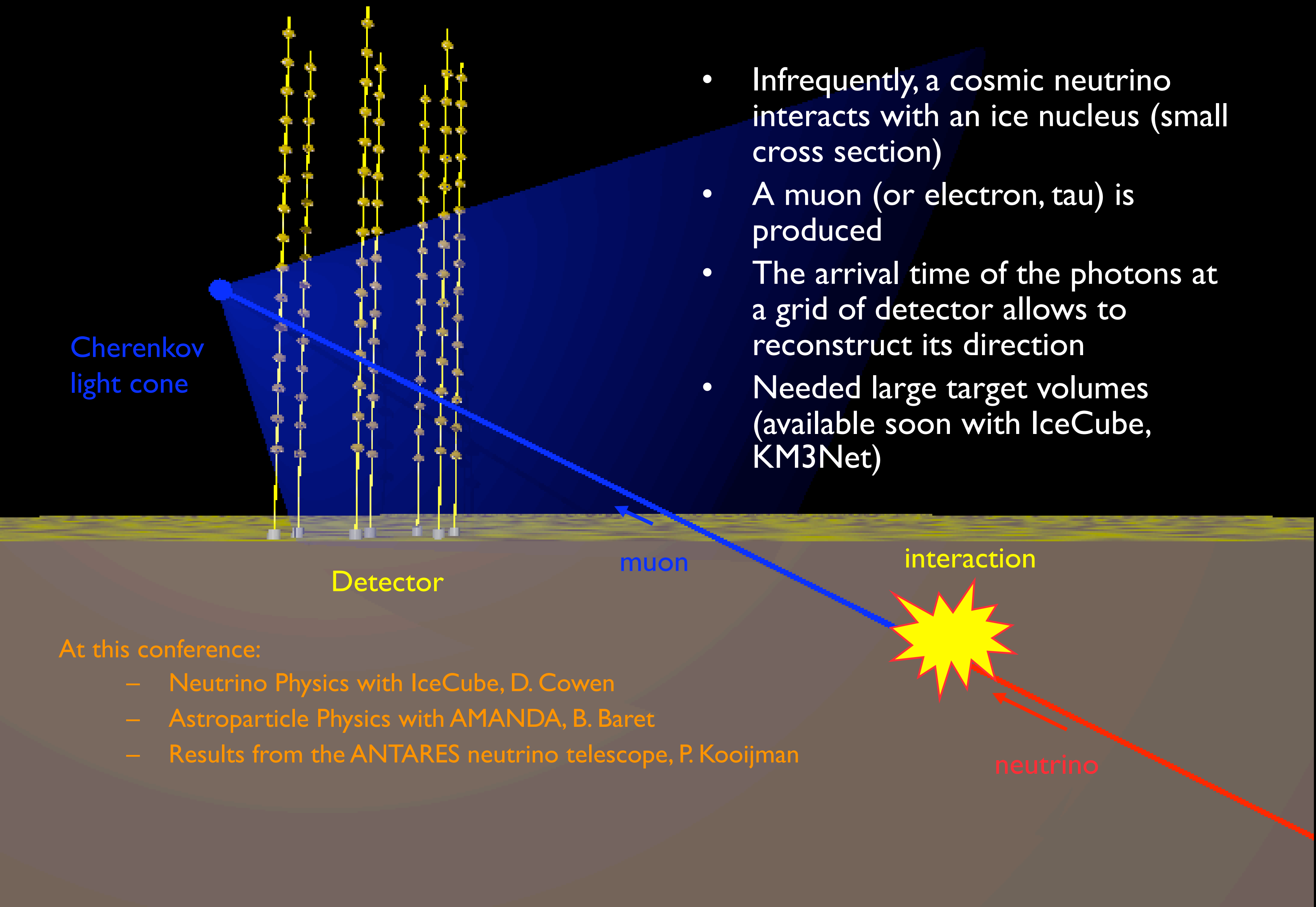
Cut-off energy and γ-ray/neutrino horizon



- While protons and photons interact, neutrinos survive
- Guaranteed neutrino source from interaction of cosmic rays of highest energies (GKZ) with microwave background

Neutrino telescopes

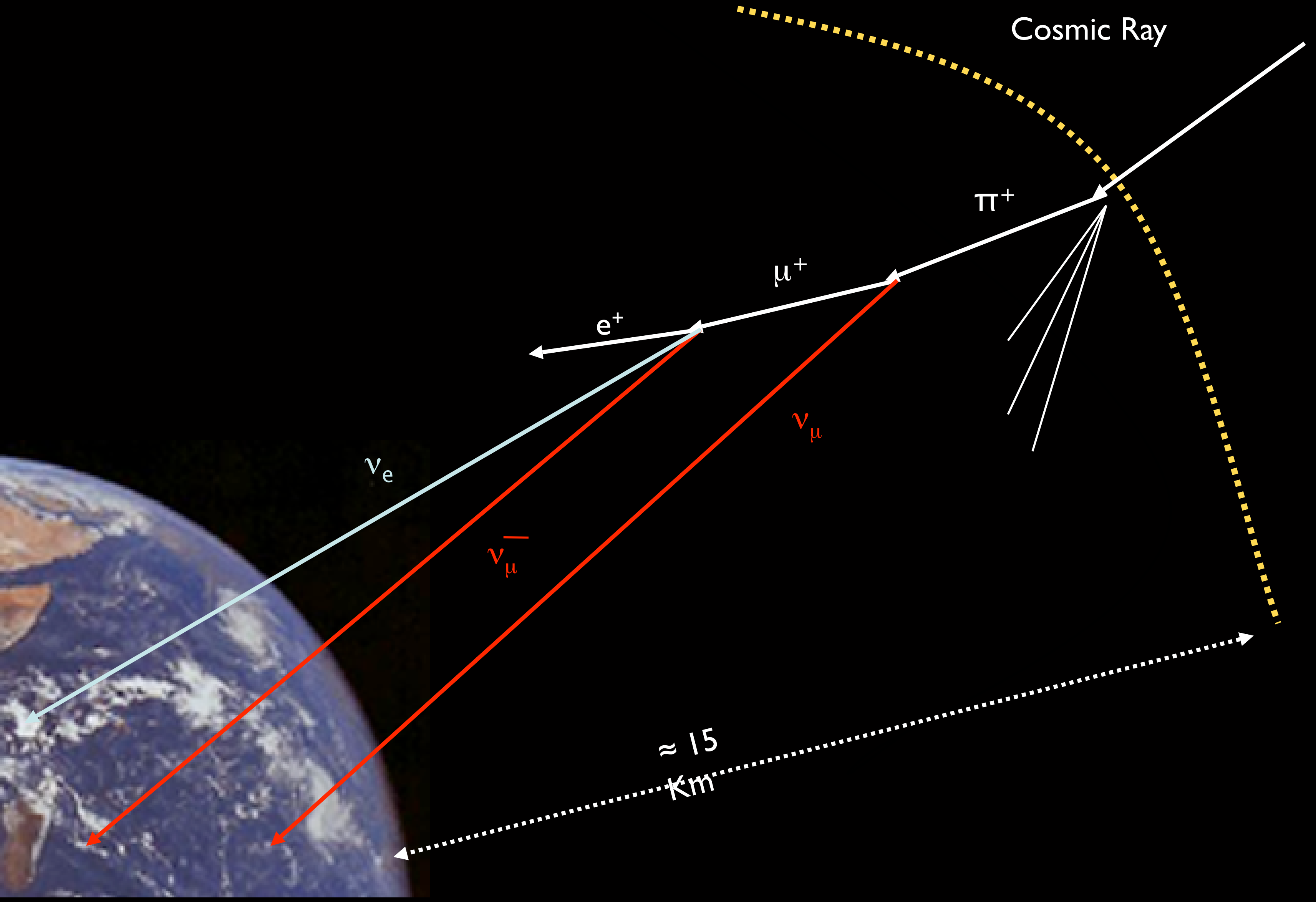
- Infrequently, a cosmic neutrino interacts with an ice nucleus (small cross section)
- A muon (or electron, tau) is produced
- The arrival time of the photons at a grid of detector allows to reconstruct its direction
- Needed large target volumes (available soon with IceCube, KM3Net)



At this conference:

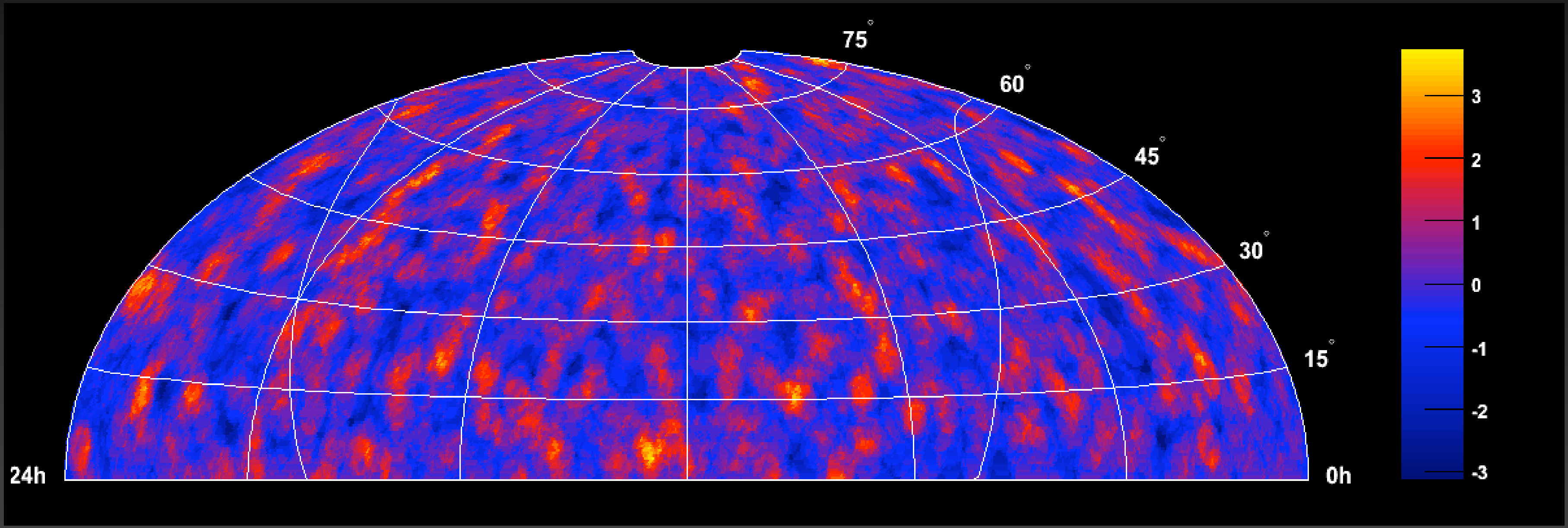
- Neutrino Physics with IceCube, D. Cowen
- Astroparticle Physics with AMANDA, B. Baret
- Results from the ANTARES neutrino telescope, P. Kooijman

Challenge: atmospheric neutrino background



State of the art in the search for cosmic neutrinos: point-like searches

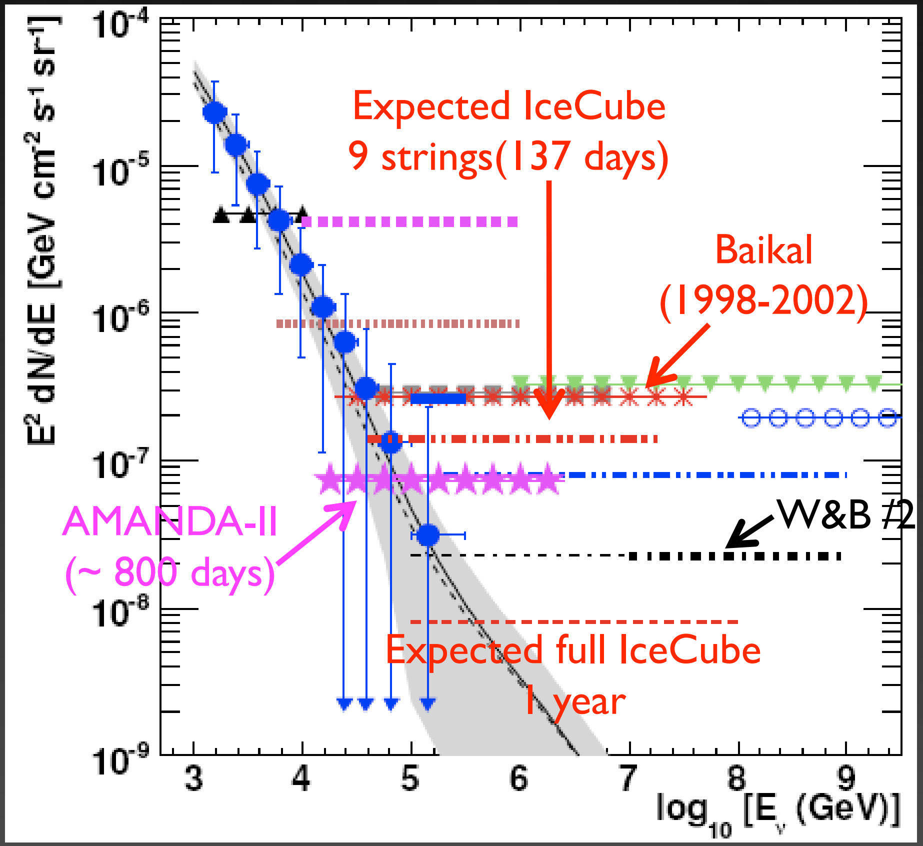
- Largest sample: 4282 events
- No hint of point sources (time-integrated, or neutrino-flares or correlations with states of high e.m. emission)

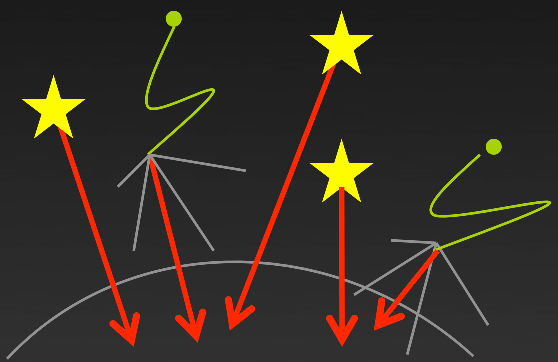


Neutrino significance map (5 years of AMANDA data)
A. Achterberg et al. Phys. Rev. D 75, 102001 (2007)

State of the art in the search for cosmic neutrinos: diffuse searches

- Many un-resolved sources may be detected as an overall excess



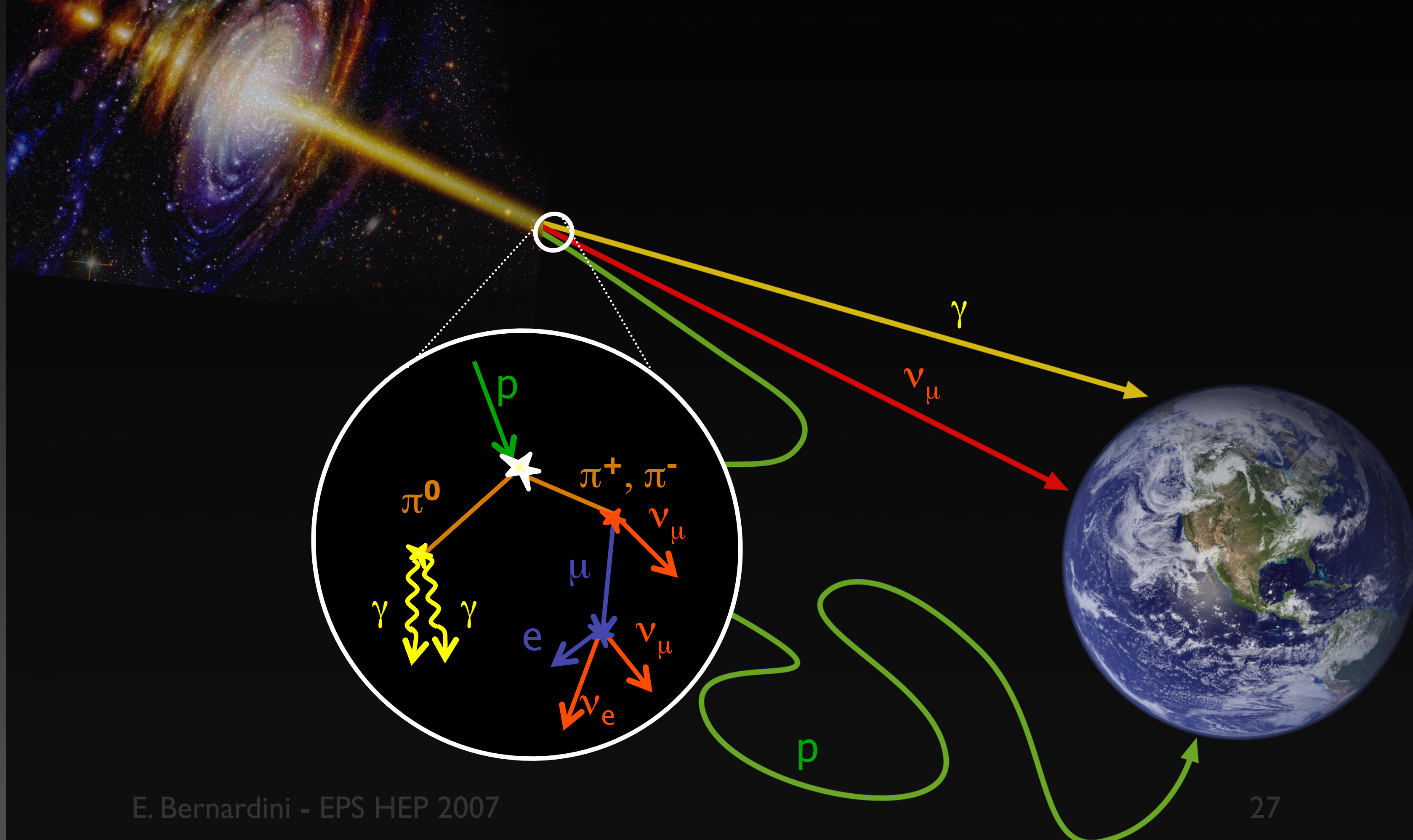


Upper limit on the diffuse muon neutrino flux

A. Achterberg, et al. arXiv:0705.1315

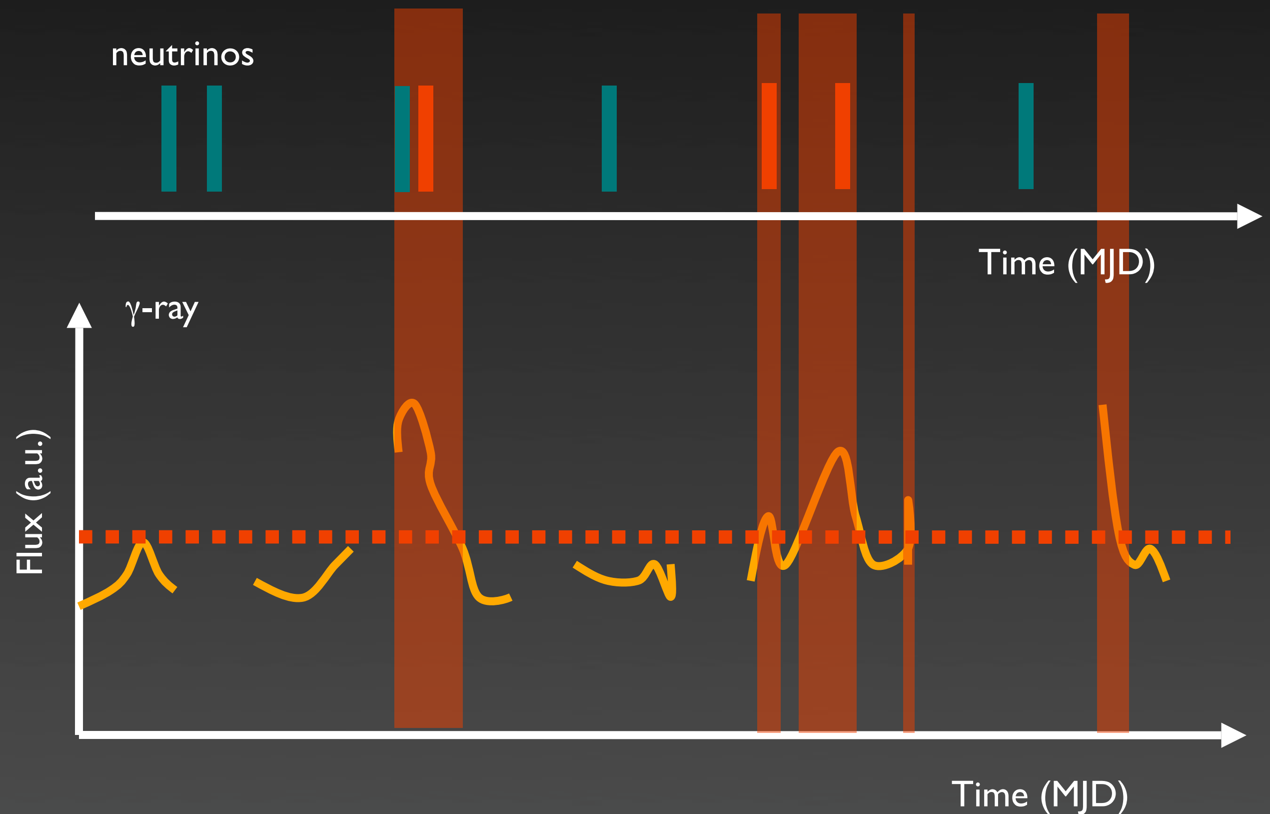
Multi-messenger approaches

- Enhance the discovery chance by optimizing search strategies to increase signal-to-noise and reduce trials
- For objects with evidence of time-variability



Multi-messenger approaches

- Enhance the discovery chance by optimizing search strategies to increase signal-to-noise and reduce trials
- For objects with evidence of time-variability
- Problem: very limited γ-ray coverage!



Neutrino triggered Target Of Opportunity

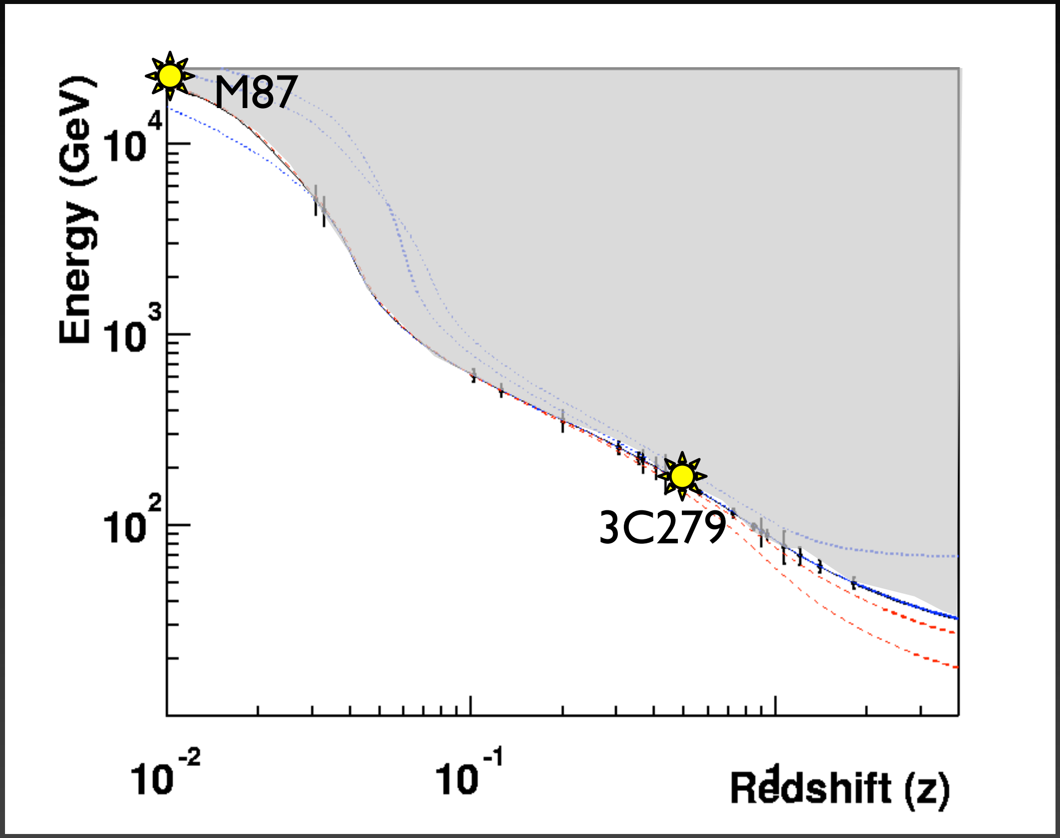
- Increase availability of (quasi-)simultaneous data with NToO:
  - Enhance the discovery chance
  - Understand the phenomenology of sources
- Feasibility study in 2006: two months coordinated observations AMANDA-MAGIC (test)

In conclusion

- Astro-particle Physics is in a very good shape!
- γ-ray Astrophysics is an established field
  - Only (very) limited selection of results and experiments shown here!
  - Extended developments (sensitivity, energy range, sky coverage …) promise further advancement
- Experimental situation is rapidly improving in the neutrino field
  - Necessary instrumented volumes are being available now
  - Multi-messenger approach (combining different observational windows) can increase the discovery chance
  - Coordination with γ-ray telescopes being explored

Some extra …

Absorption in extragal. backg. light (EBL)



γ-ray horizon versus redshift

O. Blanch, M. Martinez Astrop. Phys. 23, 598 (2005)

Astrophysical neutrinos

- Astrophysical neutrinos can be produced by two processes:
  - Nucleon interactions:

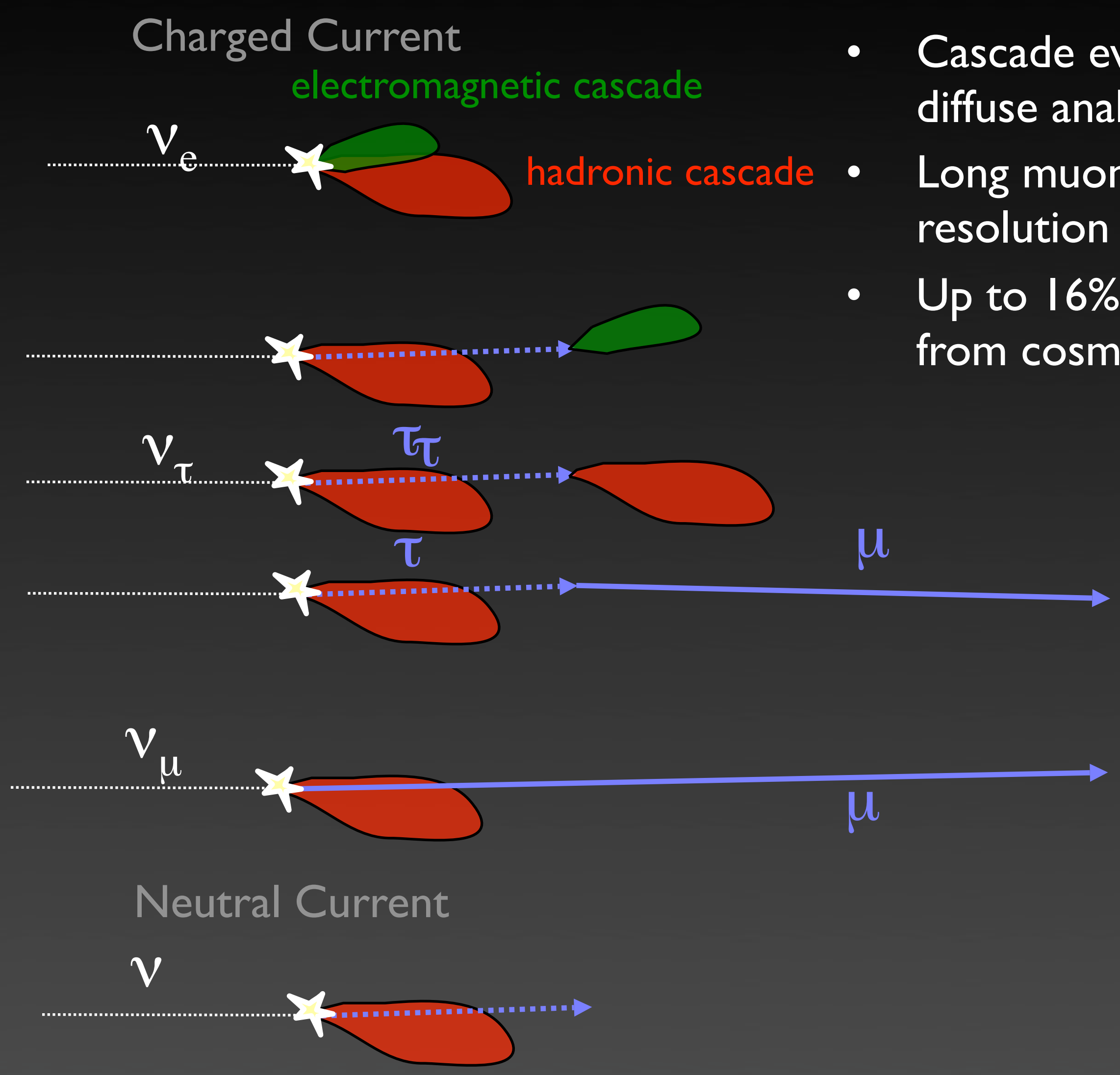
    $$pp \rightarrow pp(np,nn) + n_1\pi^{\pm} + n_2\pi^0 + n_3K^{\pm} + n_4K^0 + \ldots$$
  - Photonuclear interaction of very high energy protons (cross section smaller of a factor 100, but contribute where photon density is higher than matter density):

    $$p\gamma \rightarrow p(n) + n_1\pi^{\pm} + n_2\pi^0 + \ldots$$

- For a power law of cosmic rays at the source, the energy spectrum of neutrinos is expected to be the same

- If all mesons and muons decay the flavor ratio at the source would be $\nu_e : \nu_\mu : \nu_\tau = 1 : 2 : 0$ and oscillate to a ratio 1 : 1 : 1 at the earth
- If the magnetic fields at the source are very high, muons lose energy before decay and flavor ratio at the source could be ~ 0 : 1 : 0 and that at arrival will change e.g. T. Kashti astro-ph/0507599

Neutrino interactions and detection channels



- Cascade events energy resolution diffuse analysis
- Long muon track angular resolution
- Up to 16% contribution to signal from cosmic point sources

2006 NToO test run

Coincidence Time window: predefined

N_{obs} / N_{bck}	# γ-ray flares	σ
3 / 1	?	1.4
3 / 1	2	4.0
3 / 1	3	5.1

A toy numerical example of significance increase

Assumed a probability to detect a γ-ray flare of 1%

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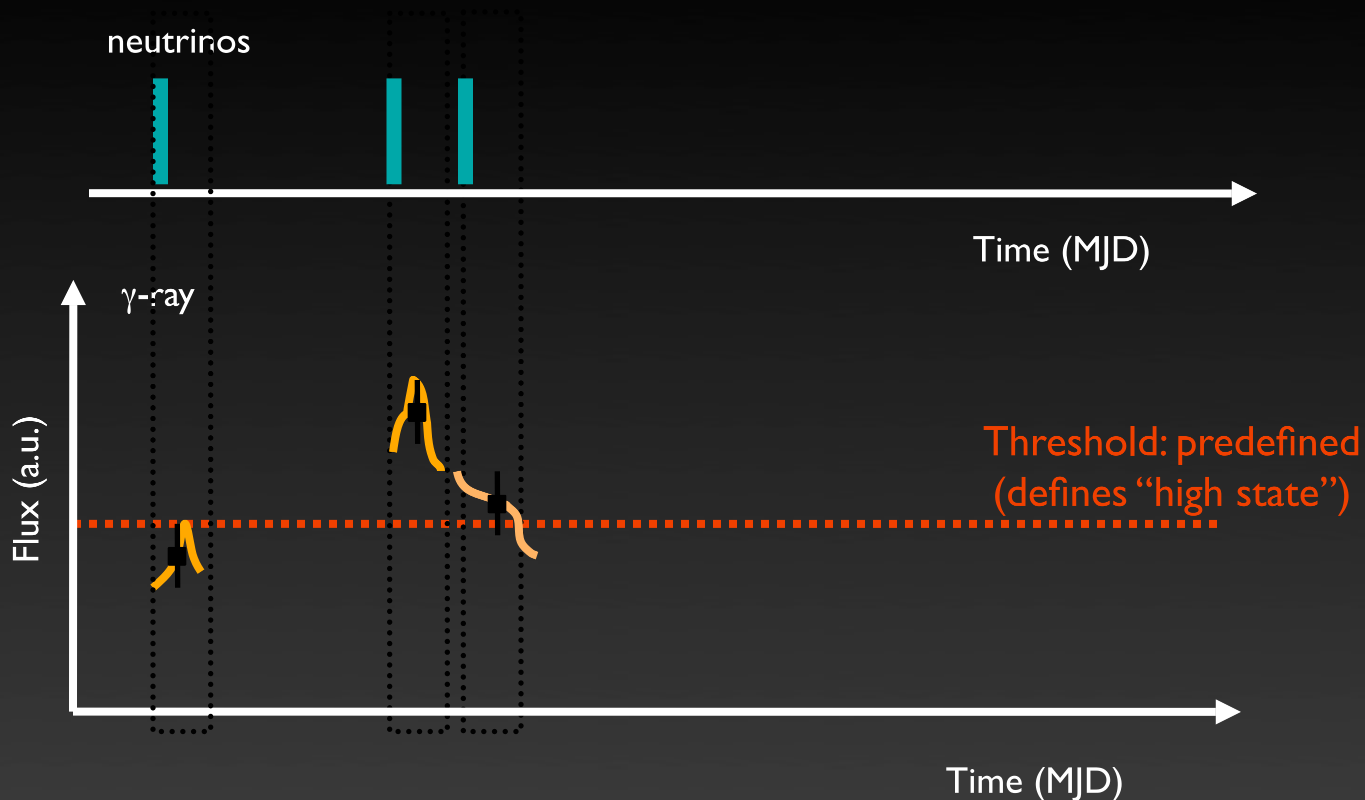

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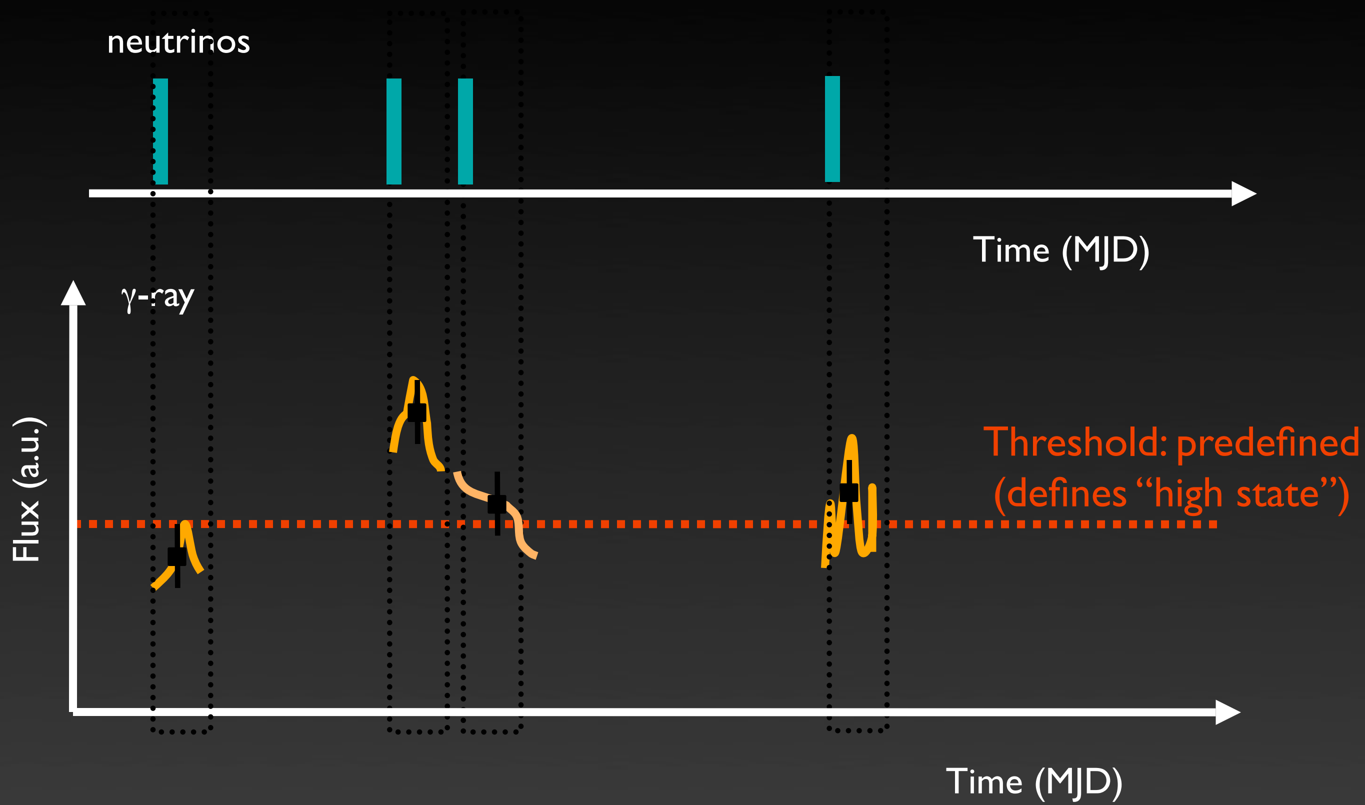

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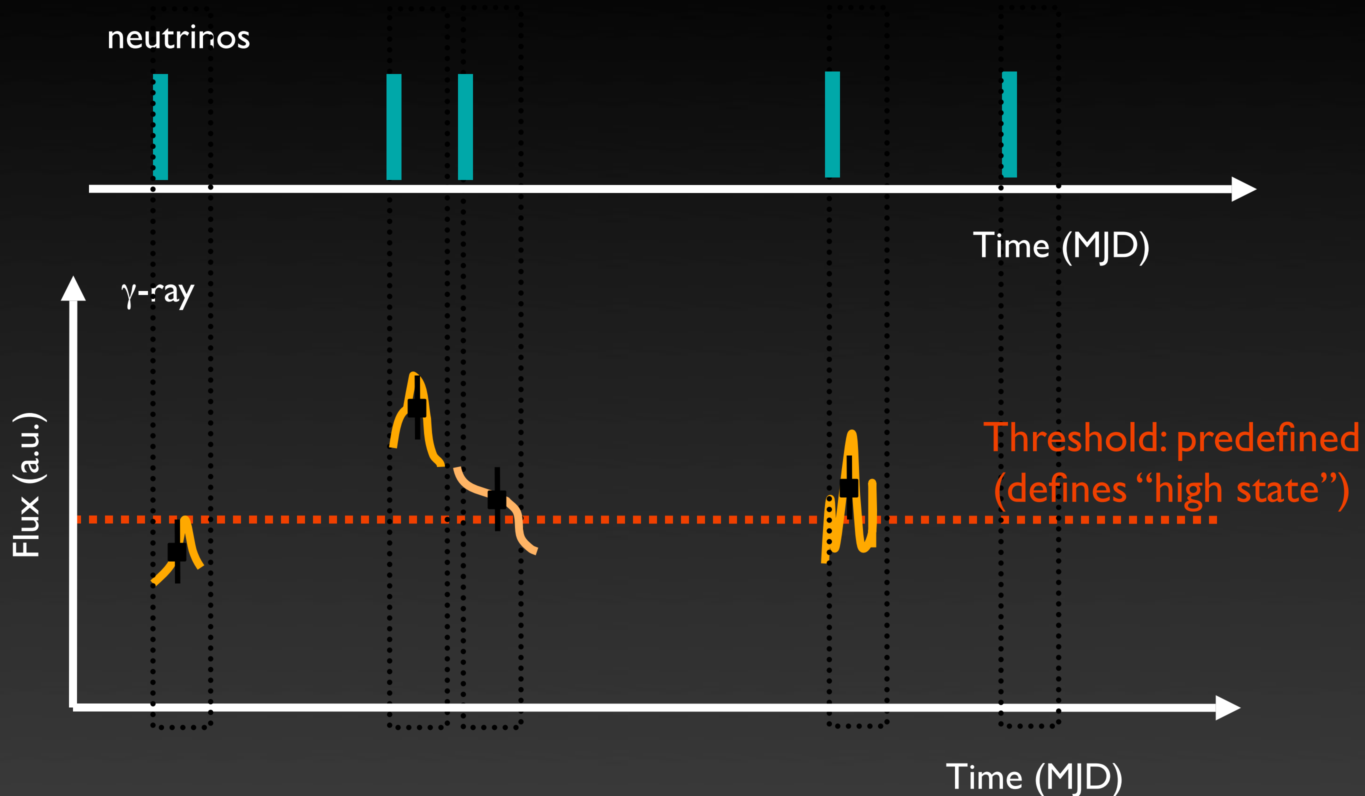

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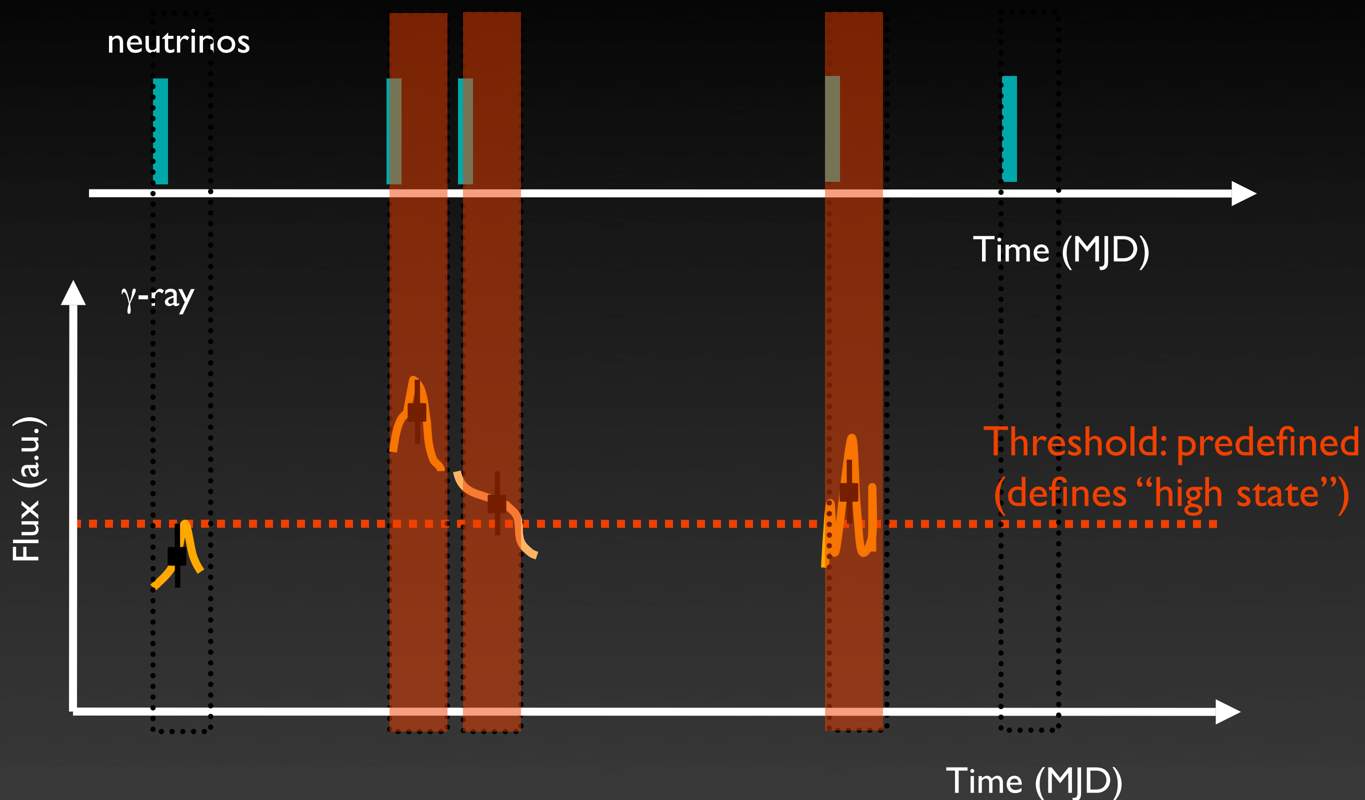

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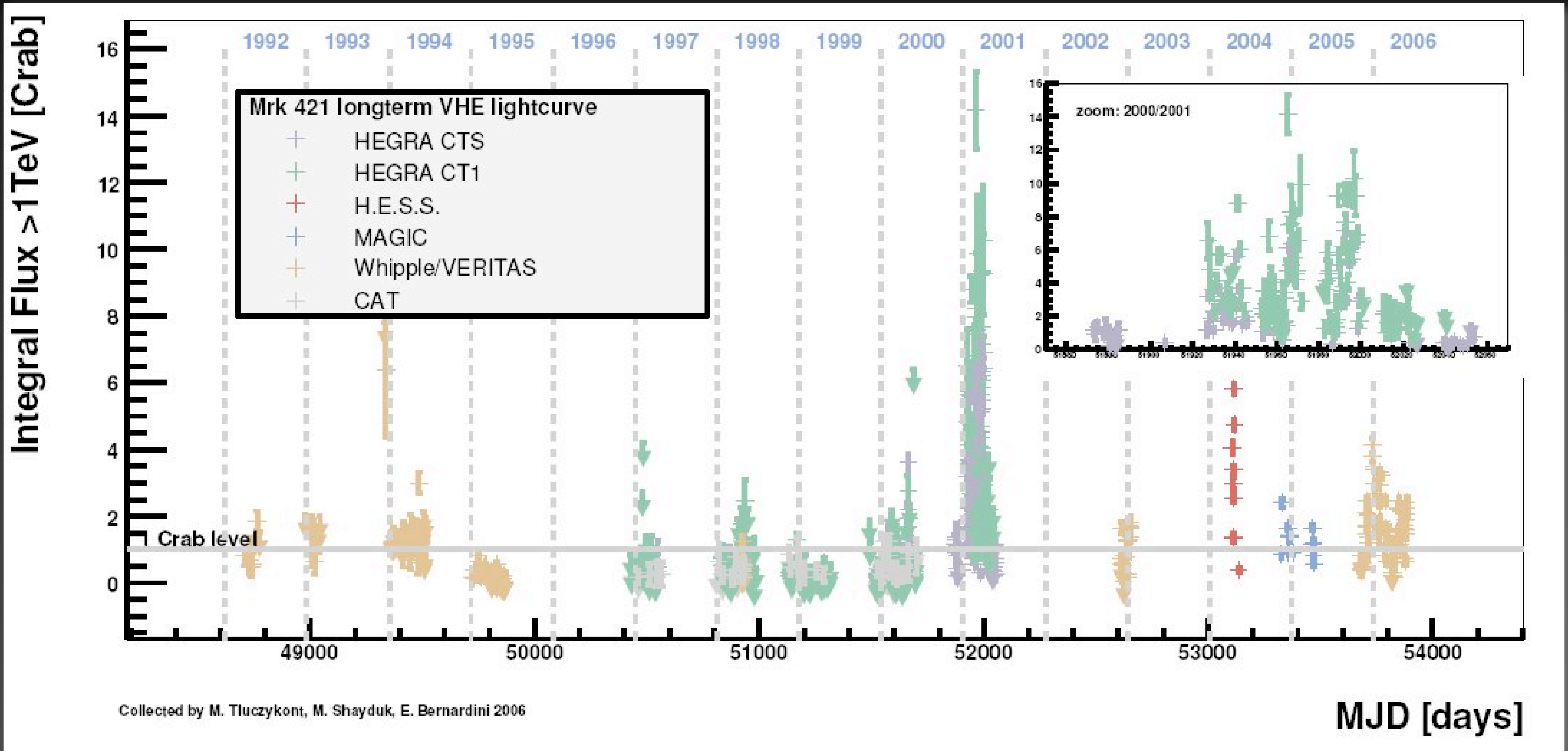
A toy numerical example of significance increase

Assumed a probability to detect a γ-ray flare of 1%

Estimating the frequency of AGN high states

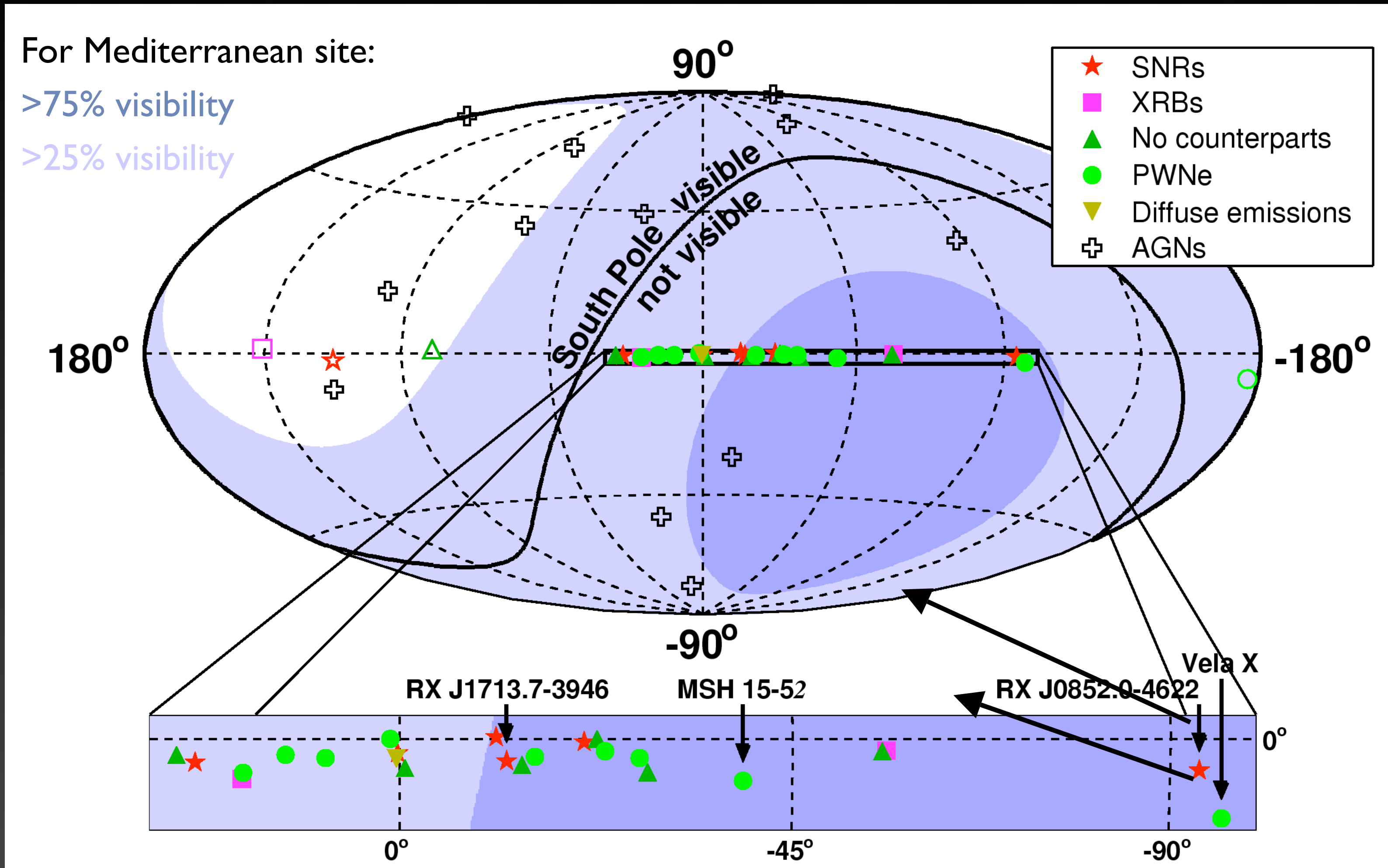
- Use un-biased data (see MAGIC and Whipple monitoring programs)
- Look at archived data:



Combined light curve for Markarian 421 (archived data) 15 years, more than 1500 hours

see also M. Tlucyzont et al. @ TeV II

Sky Coverage of Neutrino Telescopes



Sky visibility to up-going neutrinos (E < *O*(100 TeV)) and map of TeV γ-ray sources

A. Kappes et al. astro-ph/0607286