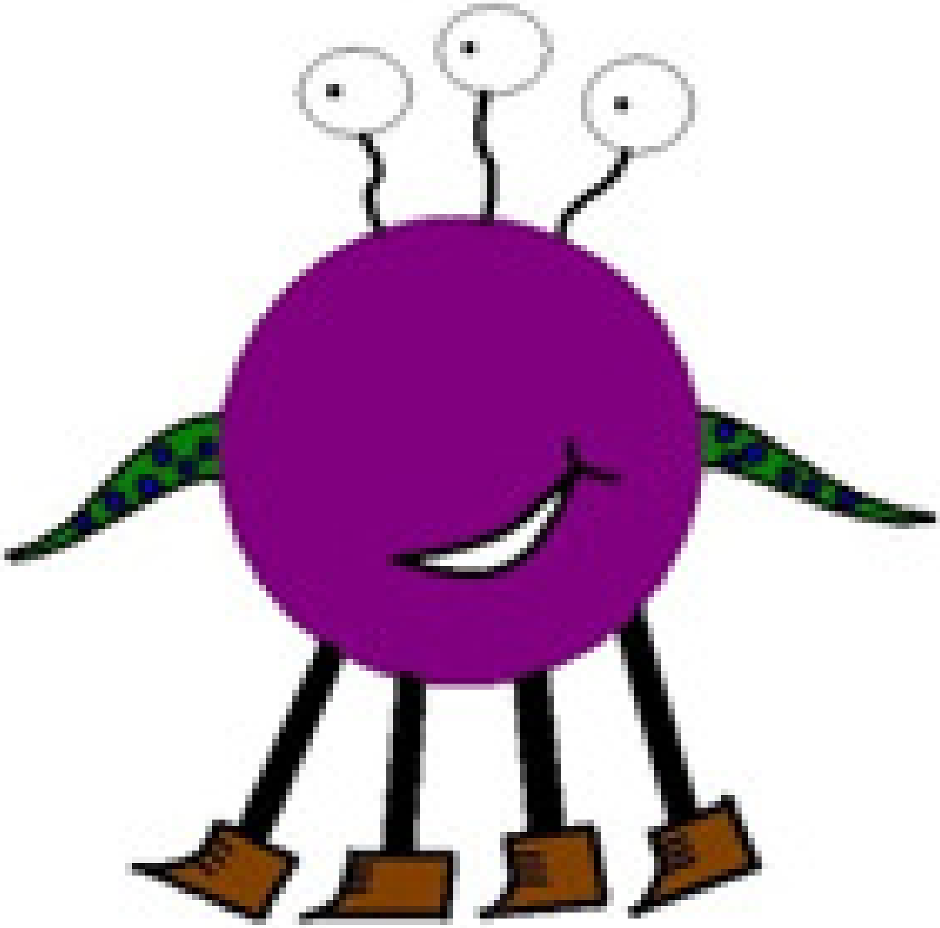
Exotic Physics in High Energy Cosmic Rays

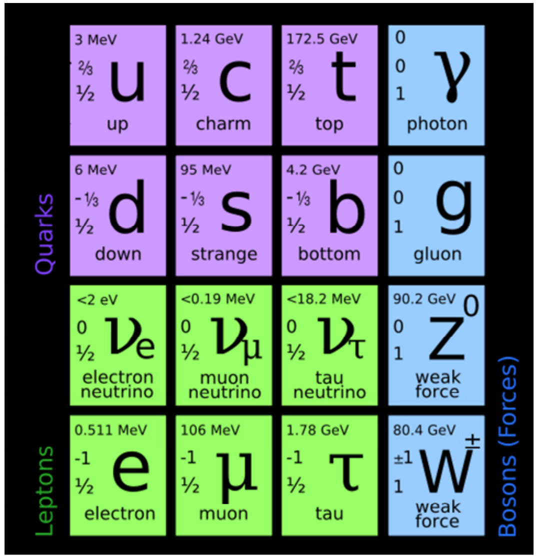
Bernardo Tomé
7th NWAP09, S. Tomé

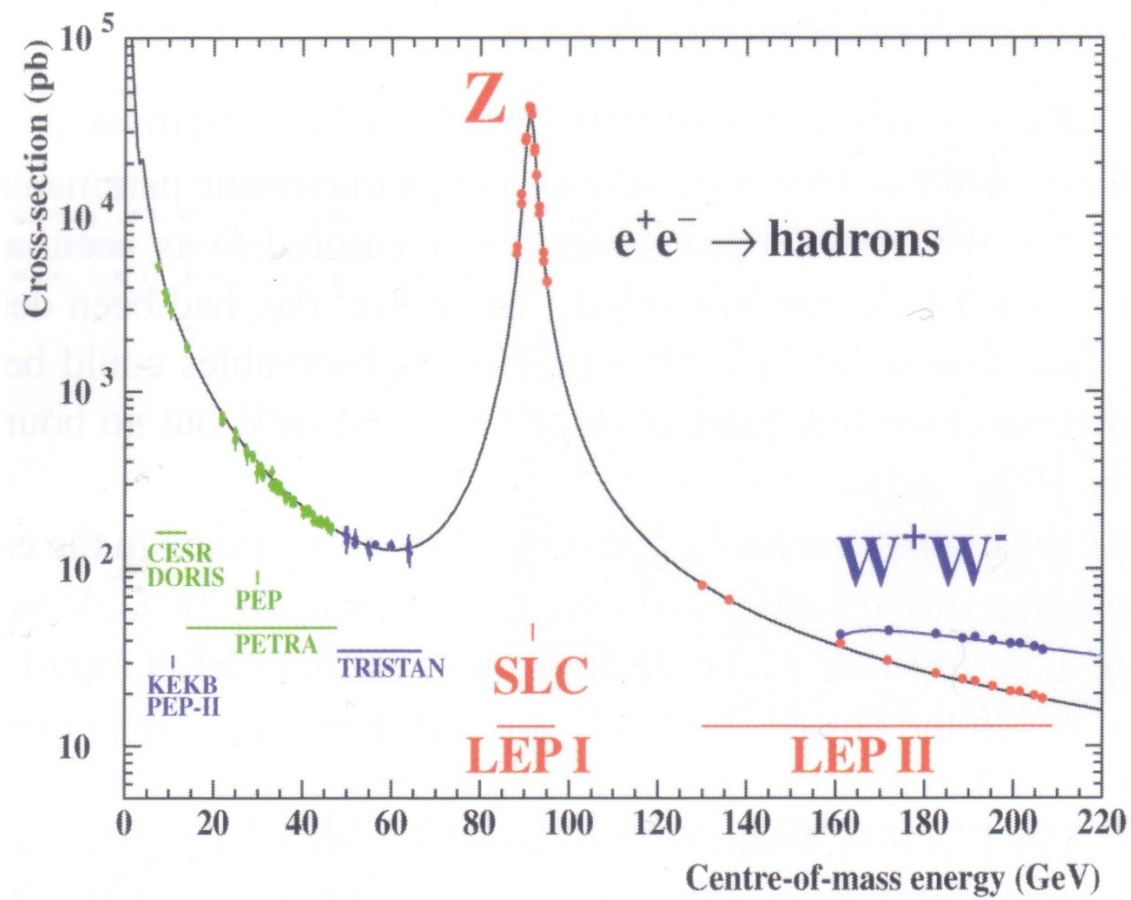


This talk is largely inspired in several talks presented at the 1st Pierre Auger Workshop on Exotic Physics in Cosmic Rays held at Lisboa last July.

Acknowledgements to M.C.Espírito Santo, I.Albuquerque, Washington Jr., D. Schuster

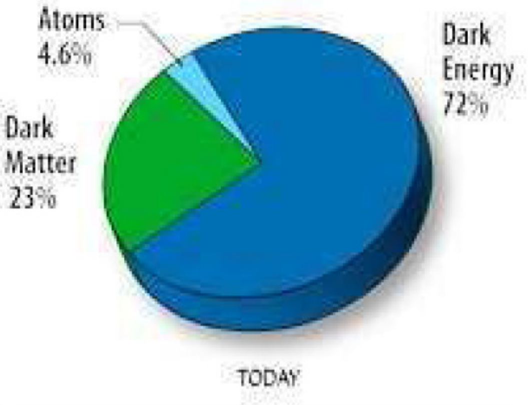
The success of the SM…



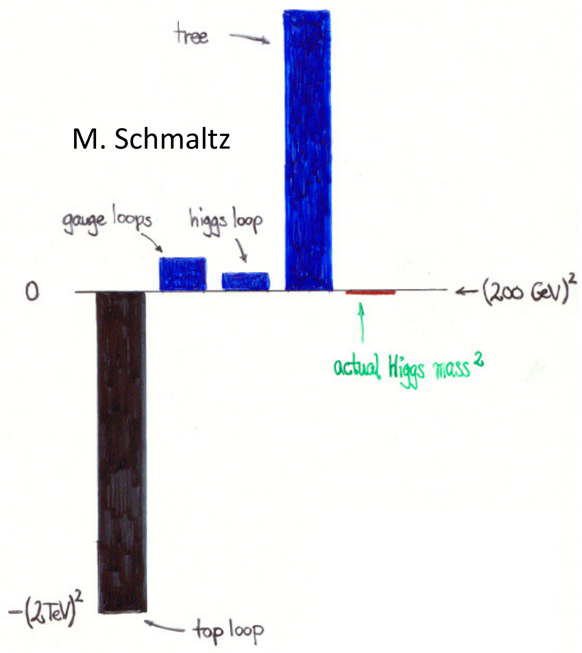


The need for New Physics !

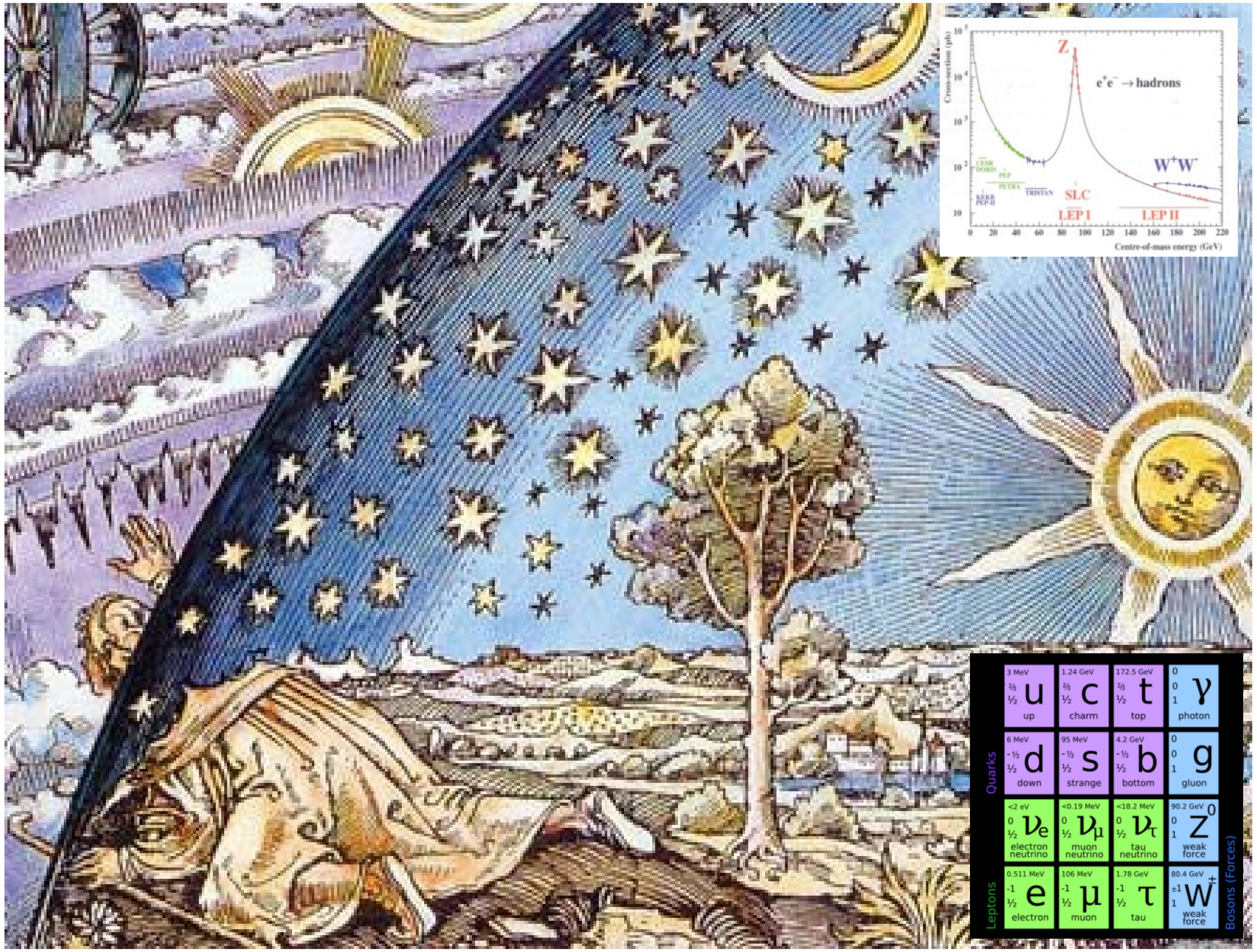
95% of the Universe not explained by SM of particle physics



Fine tuning the Higgs mass : YUCK !!!



M. Schmaltz



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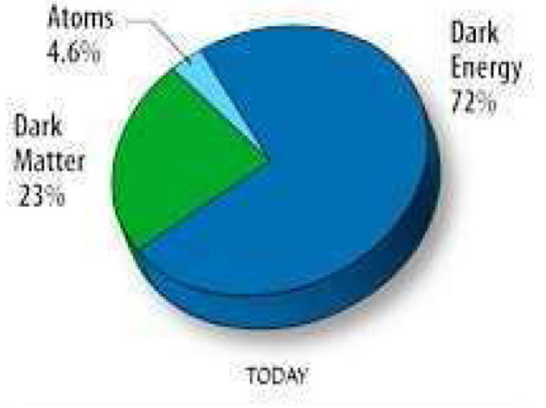

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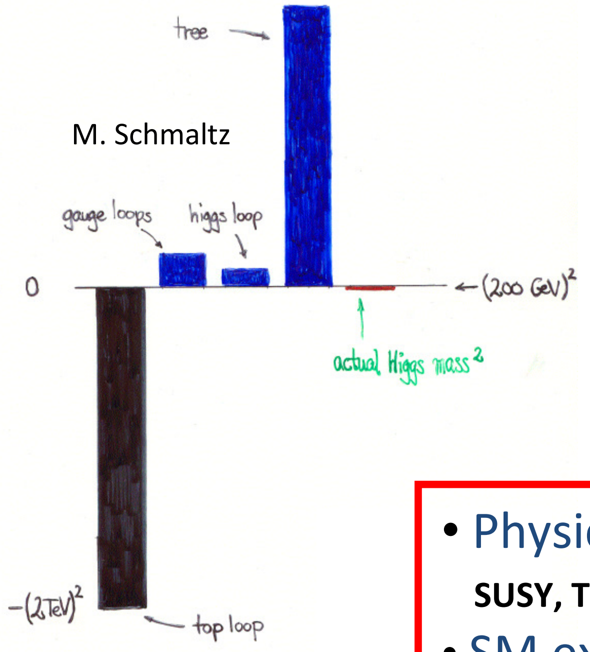
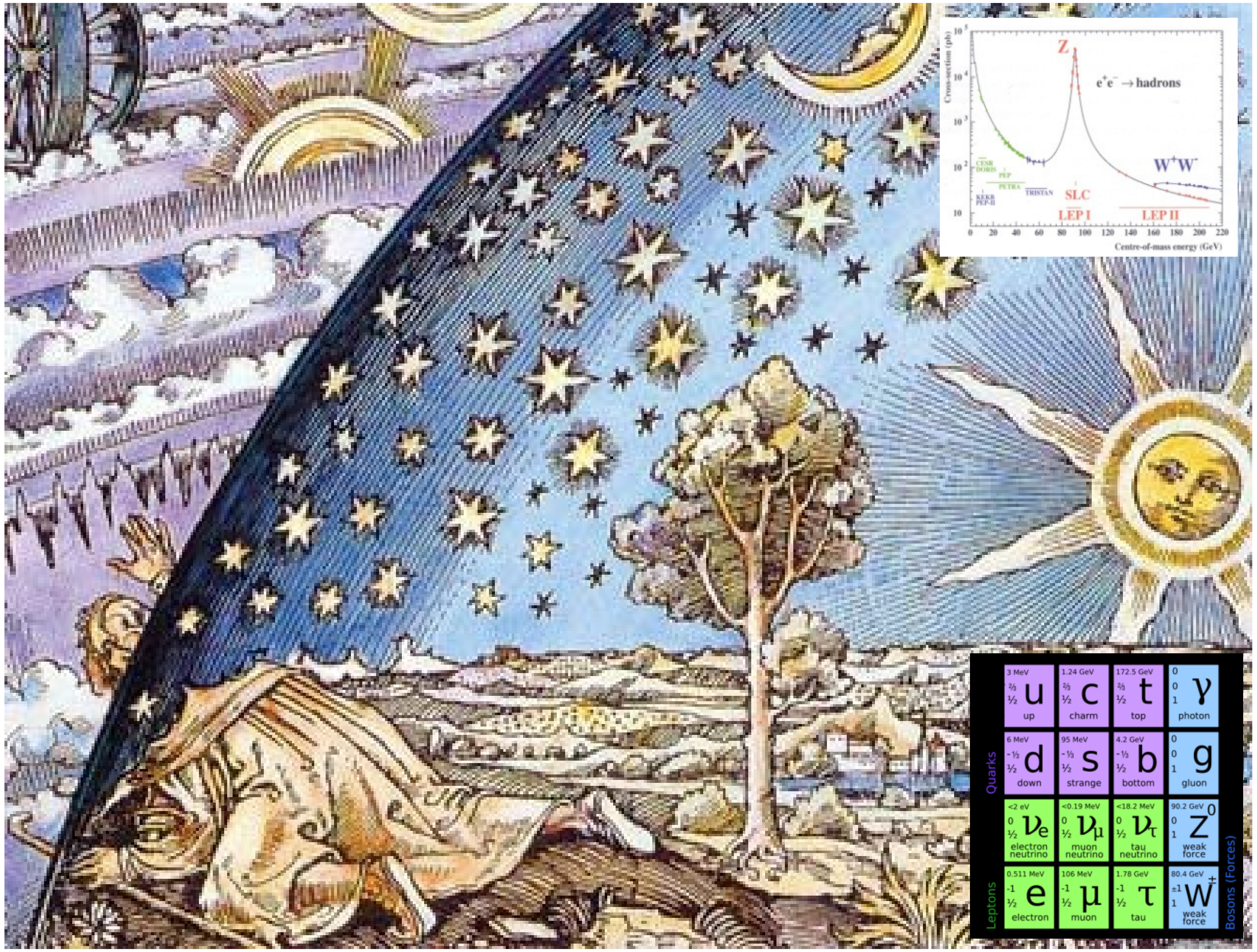
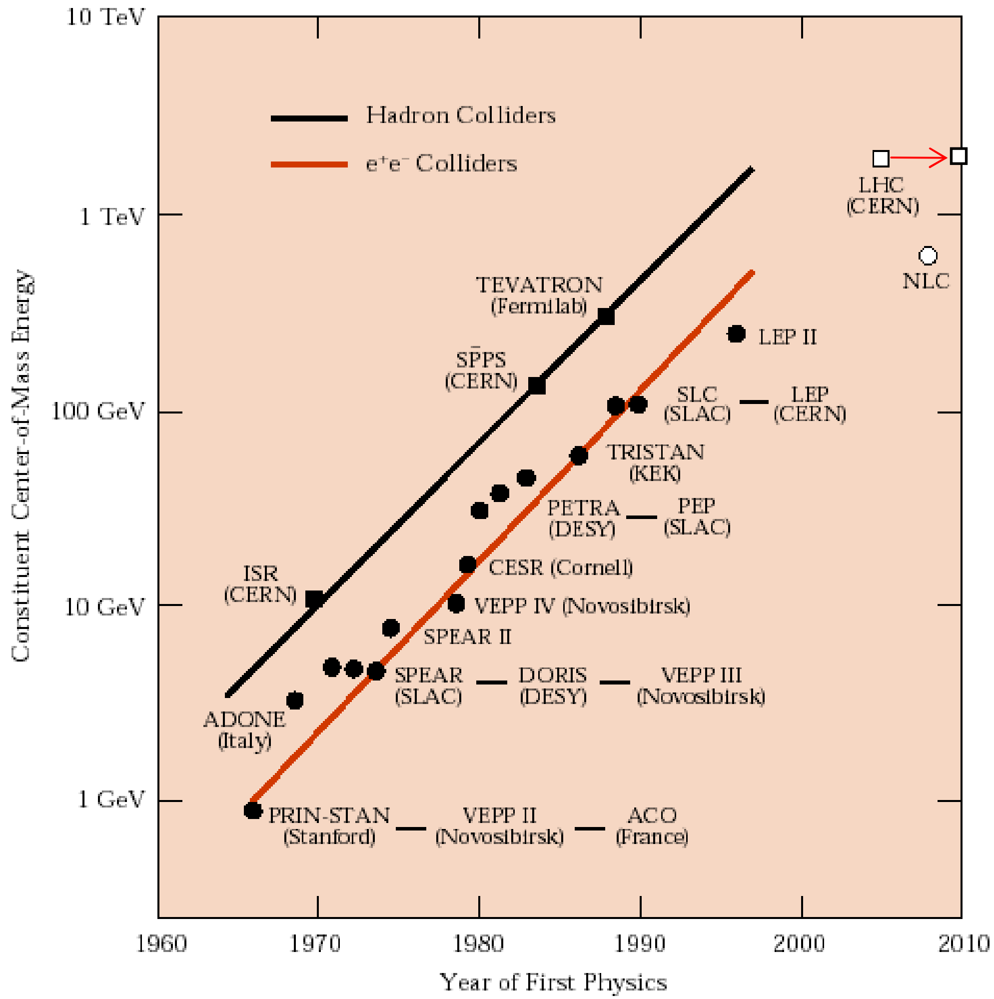




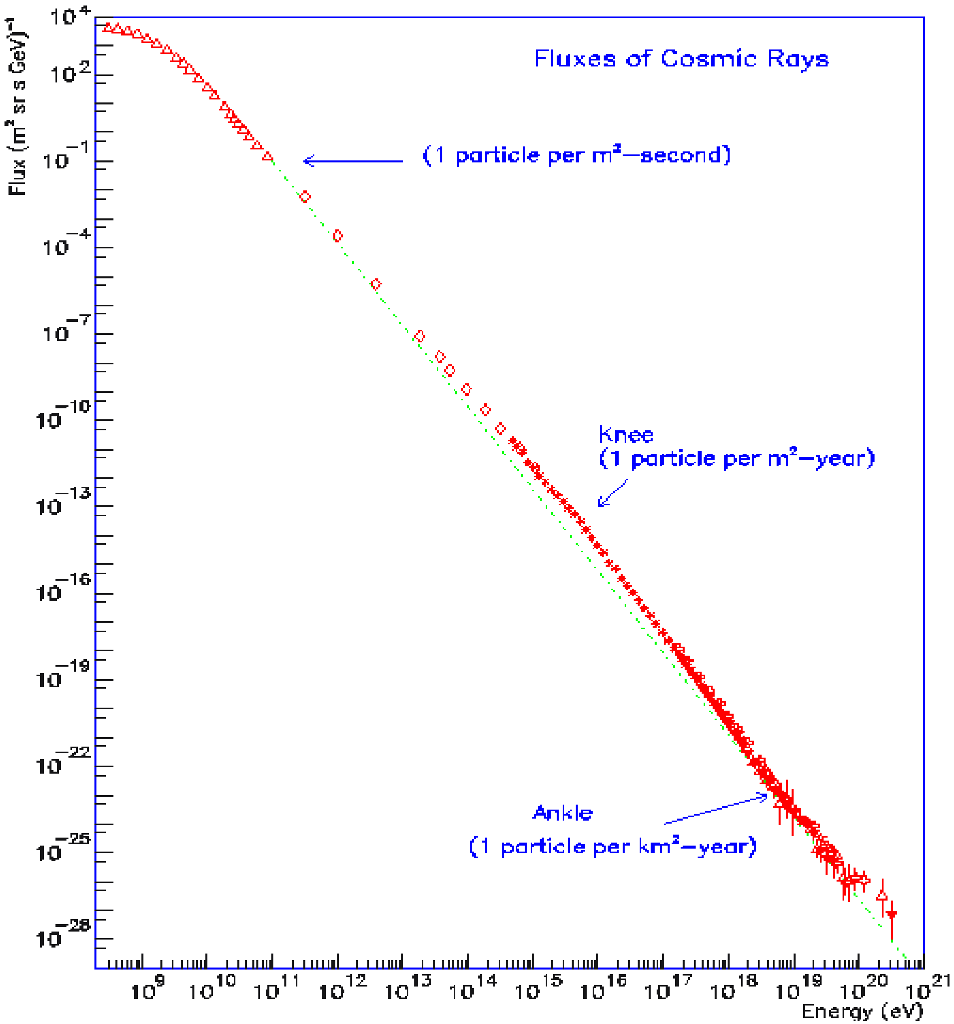
- Physics beyond the SM is expected at the EW scale O(10^2 GeV):

  SUSY, Technicolor, Large Extra Dimensions, Little Higgs, …
- SM extensions offer DM candidates

The quest for higher energies…



The Cosmic Ray beam at Earth



Ultra High Energy Cosmic Rays (UHECR) probe energies far beyond the reach of man made accelerators

UHECR vs LHC

UHECR	LHC
Fixed target	Collider
E ~ 10^{19} - 10^{20} eV	E ~ 10^{13} eV
sqrt(s) ~ 100 – 400 TeV	sqrt(s) ~ 10 TeV
Low fluxes	High luminosities
Initial beam not well defined (p/Fe/?)	Known beam composition
Much poorer detection capabilities	Powerful detectors

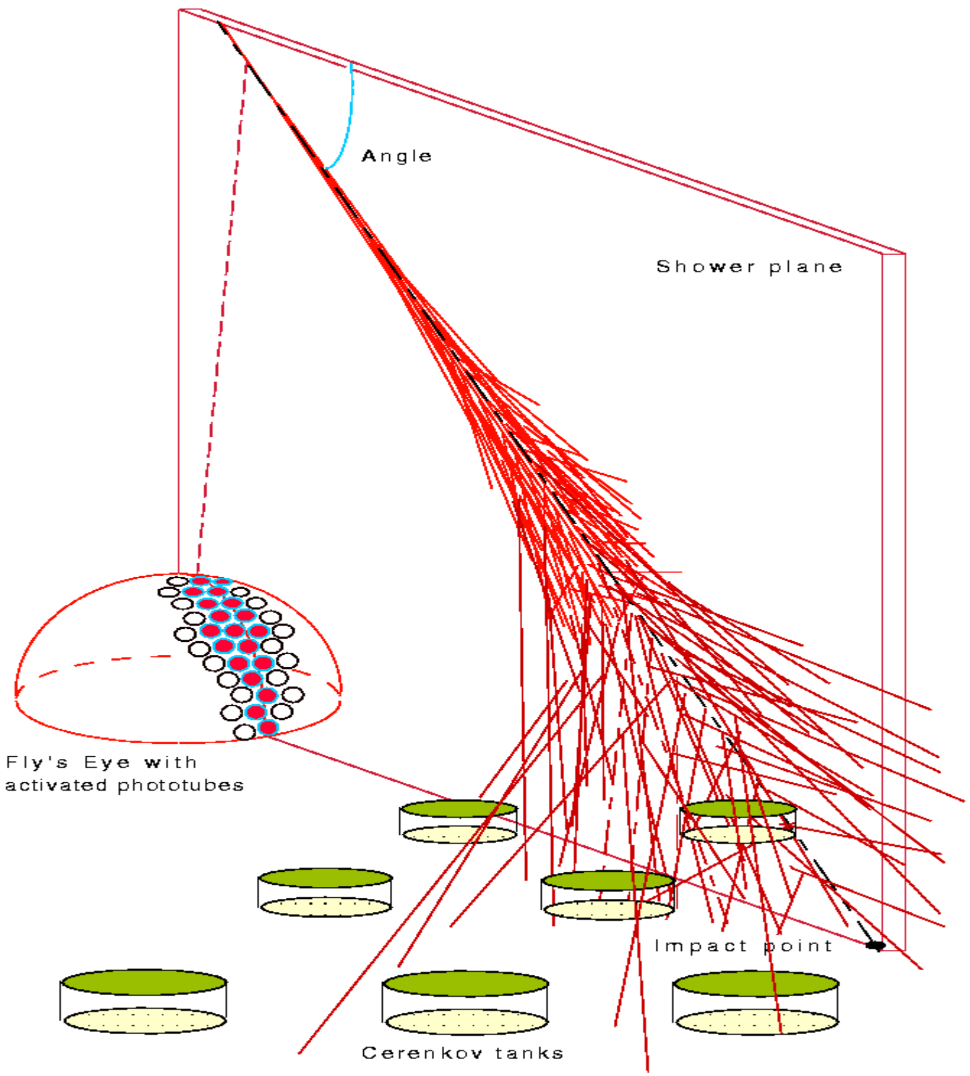
UHECR detectors can complement searches at man made accelerators

Exotics in UHECR

- Very large CM energies $O(10^2$ TeV$)$:
  - production of new heavy particles
- Huge beam energies/boost ($\gamma \sim 10^{11}$) :
  - Violation of fundamental physics laws ?
- Physics in extreme conditions:
  - look for signatures predicted by new theories/models but be prepared for the unexpected.

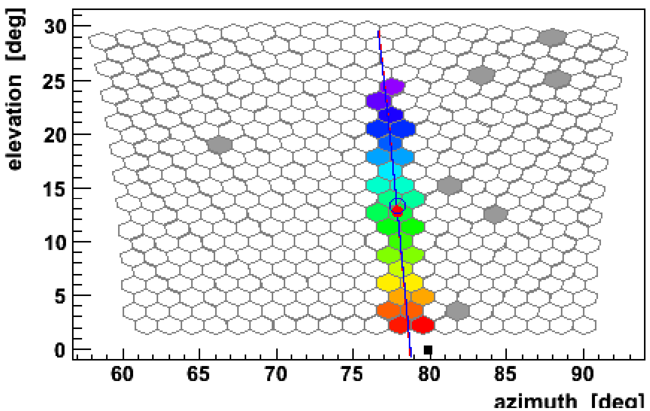
Measurement of UHE Cosmic Rays

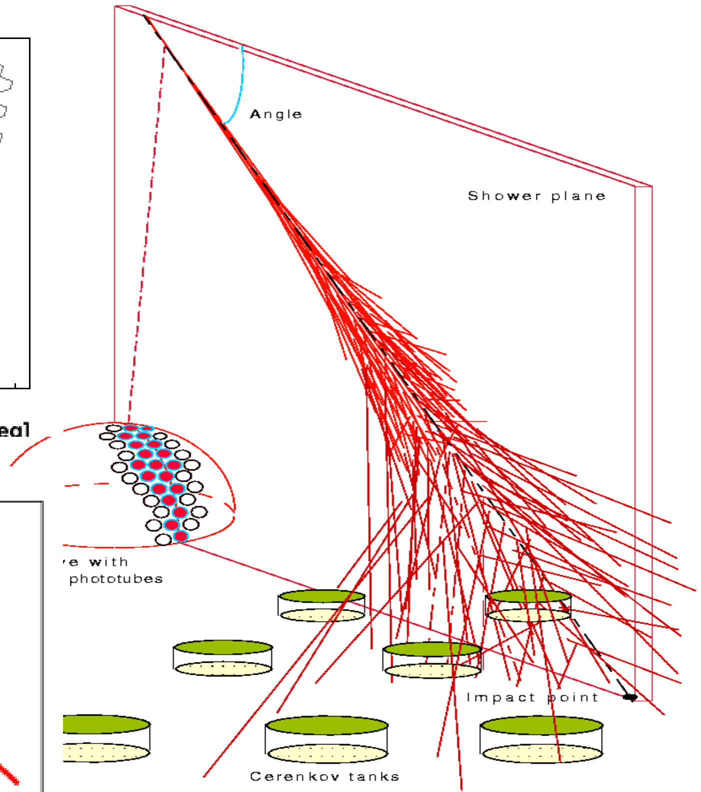
Extensive Air Showers

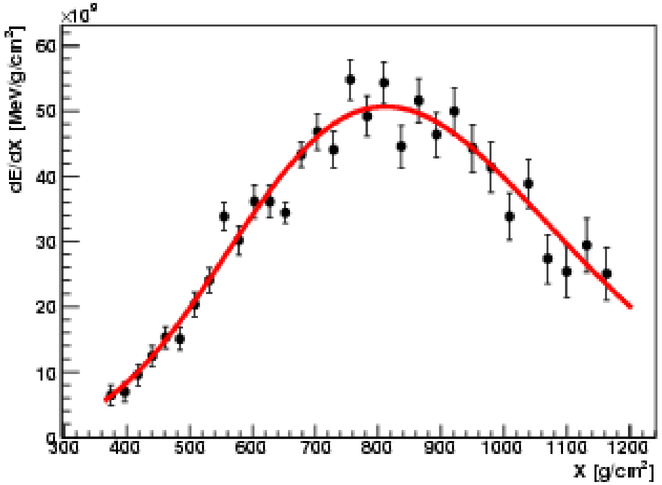


Measurement of UHECR

FD – Detection of Fluorescence from air N_2 molecules isotropic emmission along the shower







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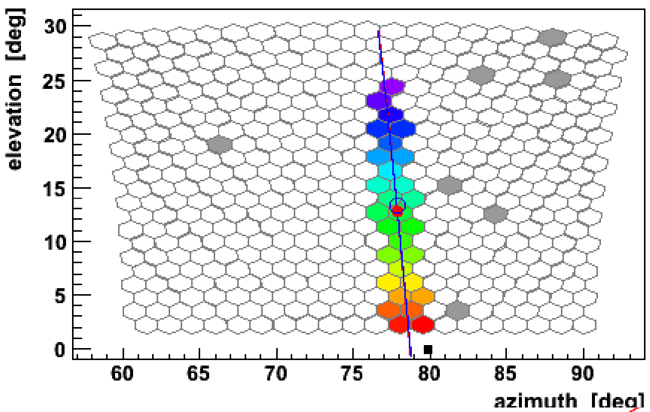
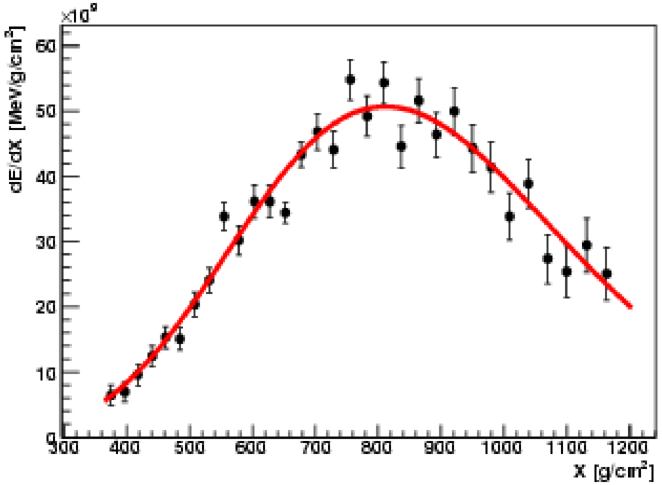
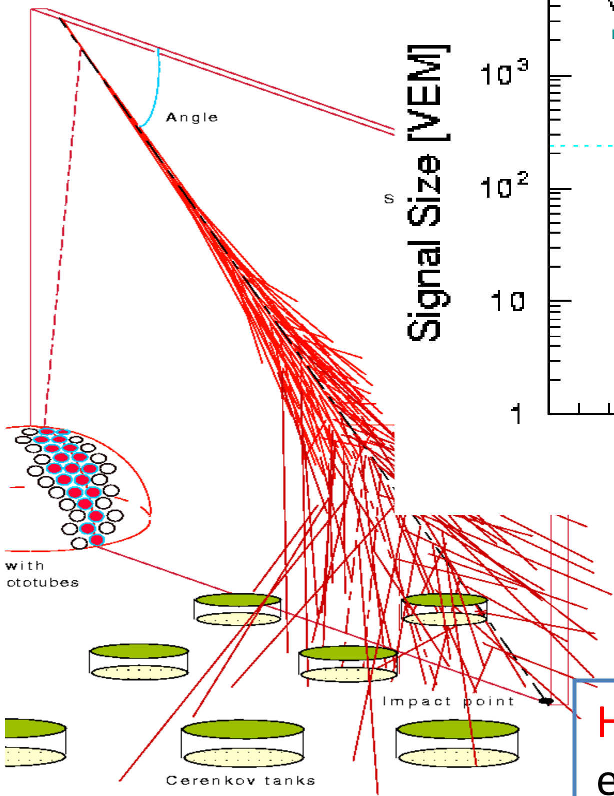
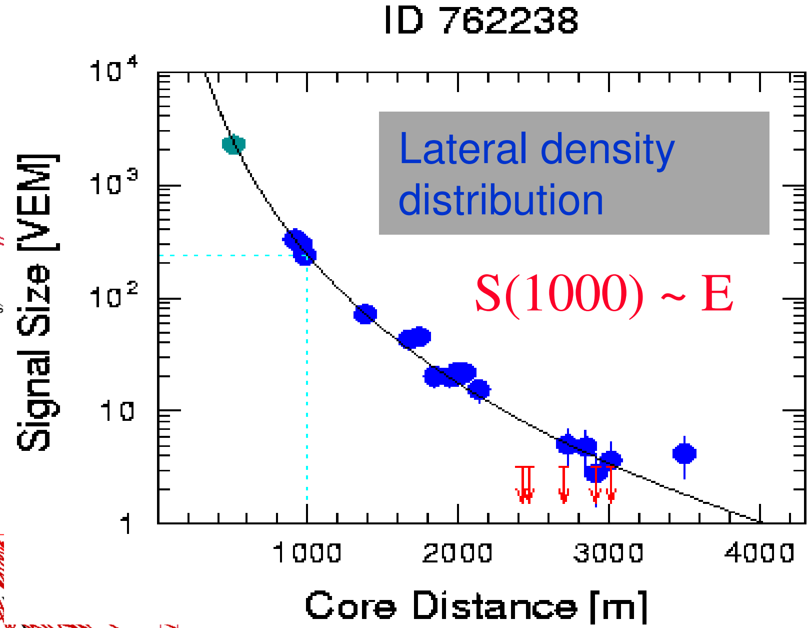






SD-Direct detection of shower particles



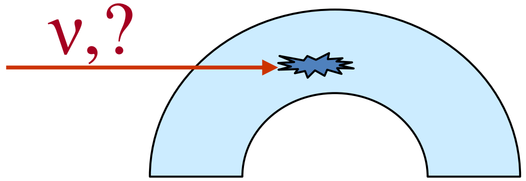
Hybrid Events - SD energy estimator calibrated by calorimetric measurement from Fluorescence Detector.

Physics Driven exotic targets

Identify specific exotic particles or interactions based on predictions in literature or searches by other experiments, or our own clever ideas.

- $\sigma_{em} < \sigma_{new} << \sigma_{had}$

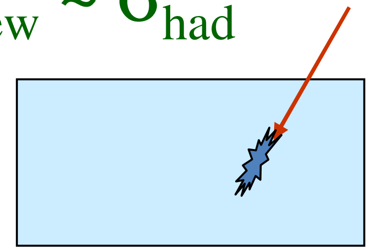
ν,?



Mini-BH, l*,LQ, χ^0, …

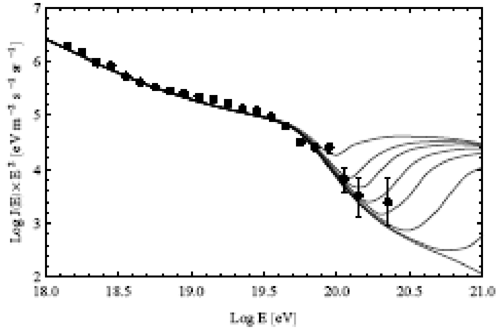
- $\sigma_{new} \sim \sigma_{had}$

p, ?



Z', squarks,strangelets, Q-balls, Exotic massive hadronic particles, …

- Lorentz invariance violation



Stecker and Scully

A modified GZK?

- Signatures
  - modified profiles/double-bang
  - Deep penetrating showers
  - Shower speed
  - Gamma showers, Muon contents
  - ????

Topological searches ???

(M. Pimenta)

Exotic particle searches at UHECR

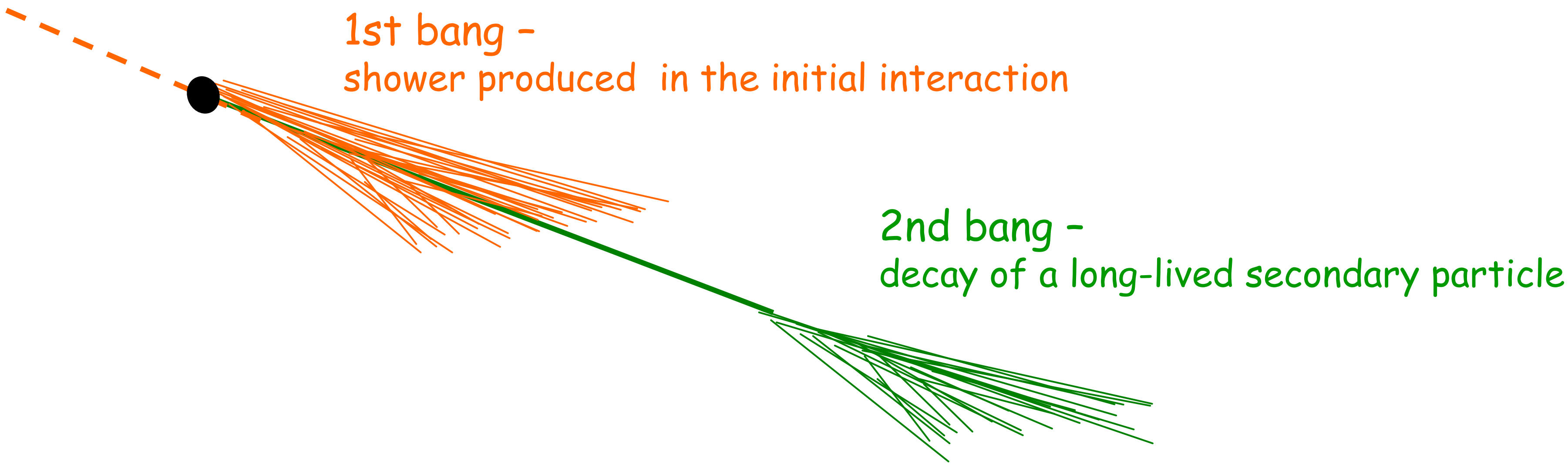
Candidate Particle	Properties	Observables
Magnetic Monopole	Mass of about 10^9 GeV, created in SU(4)xSU(2)xSU(2) symmetry breaking, catalyzes proton and electron decay	Strong electromagnetic component in the form of large amounts of Cherenkov radiation (~8500x more than a muon), shallow Xmax
Strangelet	Theorized ground state of QCD, bags of roughly equal proportions of up, down and strange quarks, mass of 10^4 10^8 GeV	Interacting primarily hadronically, narrow Gaisser-Hillas with shallow Xmax
Micro-Black Hole	The amount of Hawking radiation produced by a black hole is inversely proportional to its mass, so a burst of hadrons and photons would be expected from an MBH	Since secondary MBH's from neutrino-nucleon interaction is most likely looking for hadronic bursts with very high zenith angle (>75 degrees) is most promising
Q-ball	Created by Bose-Einstein condensation of a SUSY strangelet in which the fermionic quarks become bosons and then relax to a single wavefunction	Proton decay catalysis from electrically neutral Q-balls creating largely electromagnetic, deeply penetrating showers
Other Exotic Heavy	Generic, high mass, low rigidity particle, possibly a relic particle or dark matter candidate	Without saying anything else about the properties of the particle, the most telling observable would be its velocity being less than c
Other Strange Profiles	Short lived secondaries being produced from an initial interaction (taus), rapidly decaying exotic in the atmosphere, other strange or unexpected behavior	Double Bangs, Bumpy showers, FD-SD mismatches, unusually strong signal in a single SD with low or no other signal

(D. Schuster)

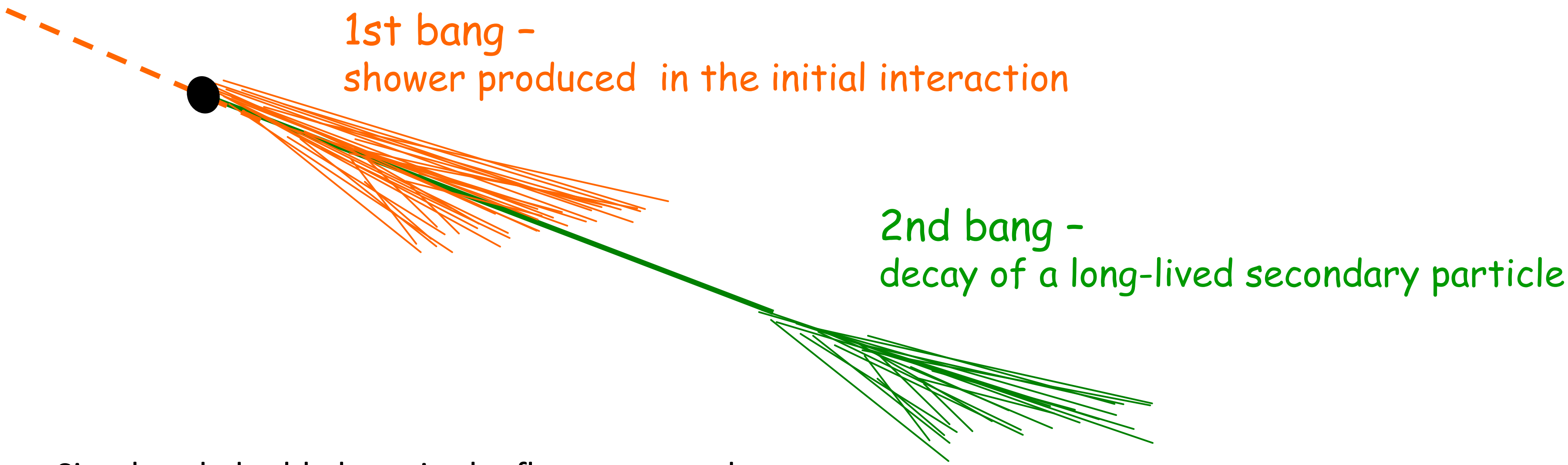
Signatures:

Modified shower profile, depth of shower max, shower speed, muon content, Cherenkov radiation, …

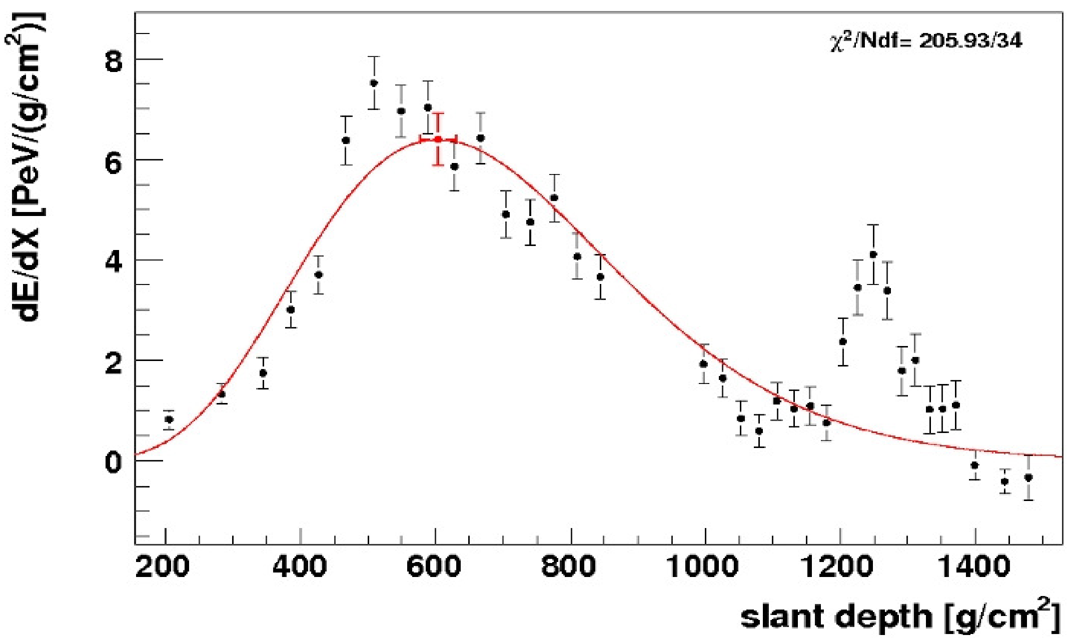
The double bang signature



The double bang signature



Simulated double bang in the fluorescence detector

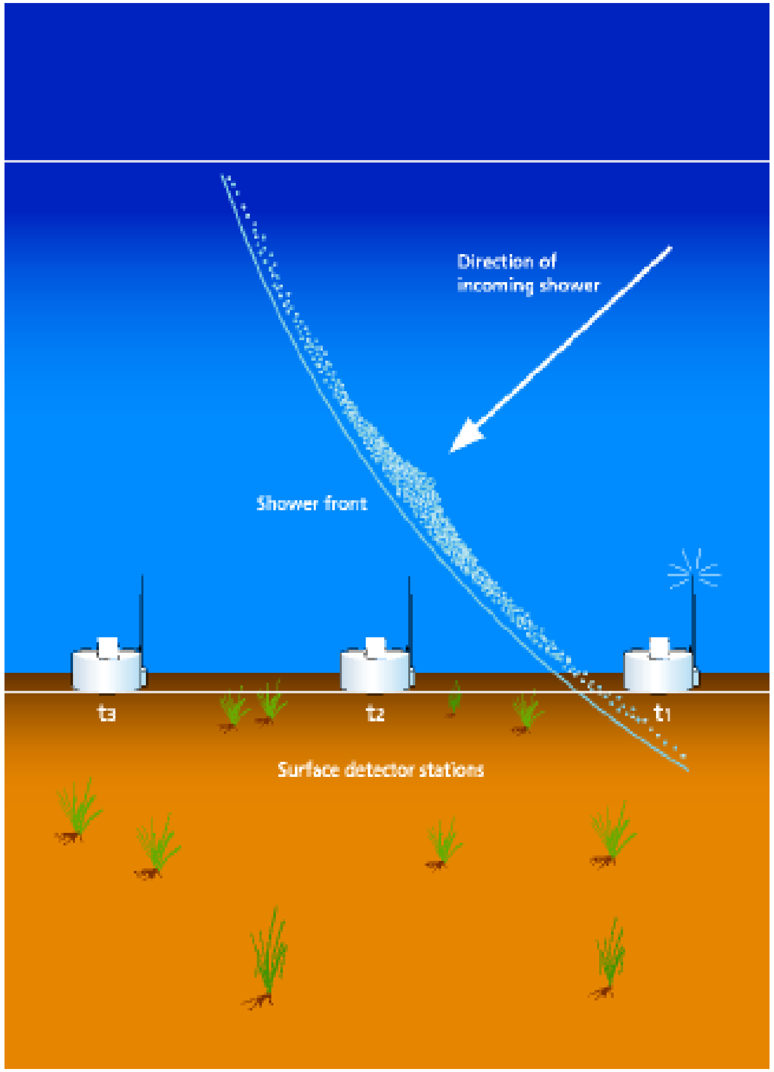


Clear double bang, but…

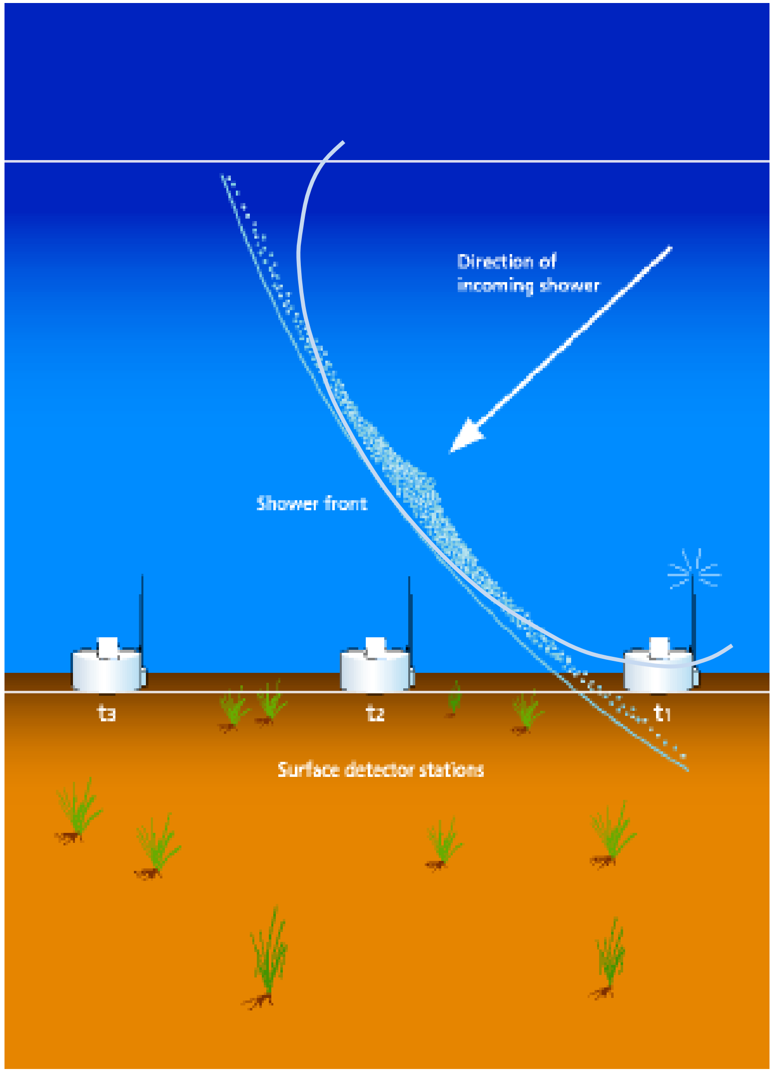
Signature might be less distinctive (e.g. only a distortion of the shower shape)

Atmospheric conditions (clouds,…) may give rise to bumpy showers

Double shells in the surface detectors



Double shells in the surface detectors



- Correlated peaks in different stations of one same event
- Analyze rare signal structures and measure the degree of correlation

Exotics in UHECR

- TeV black holes
- UHECRONs
- Lorentz invariance violation

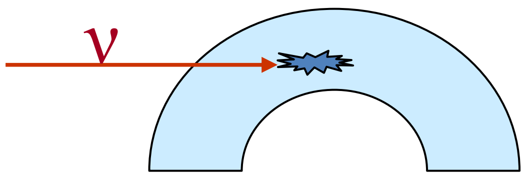
TeV Black Holes in UHECR interactions

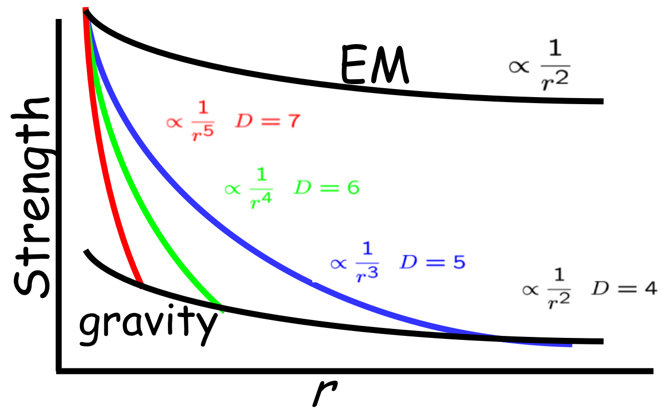
- Planck scale at O(TeV) in scenarios with large extra dimensions

- Gravity gets stronger at shorter distances

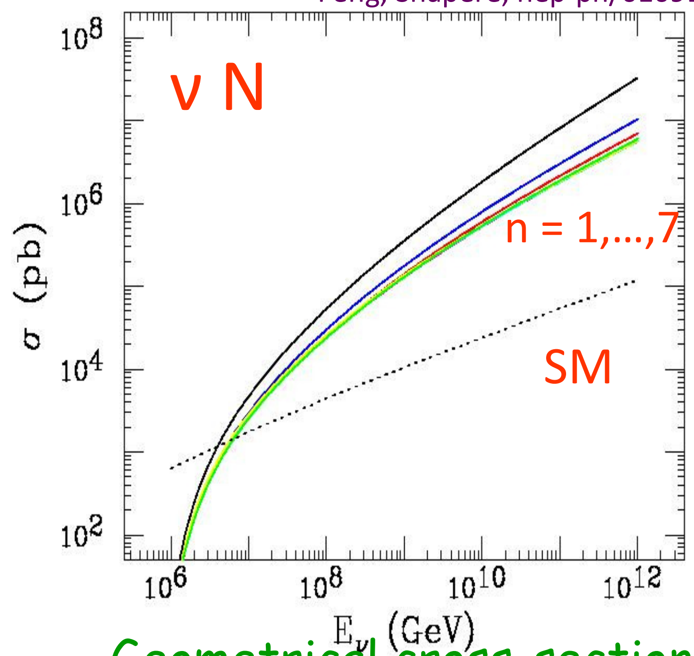
- Black holes can be produced in collisions with sqrt(s) > TeV

- Mini BH production in UHECR : ν + N -> BH





Feng, Shapere, hep-ph/0109106

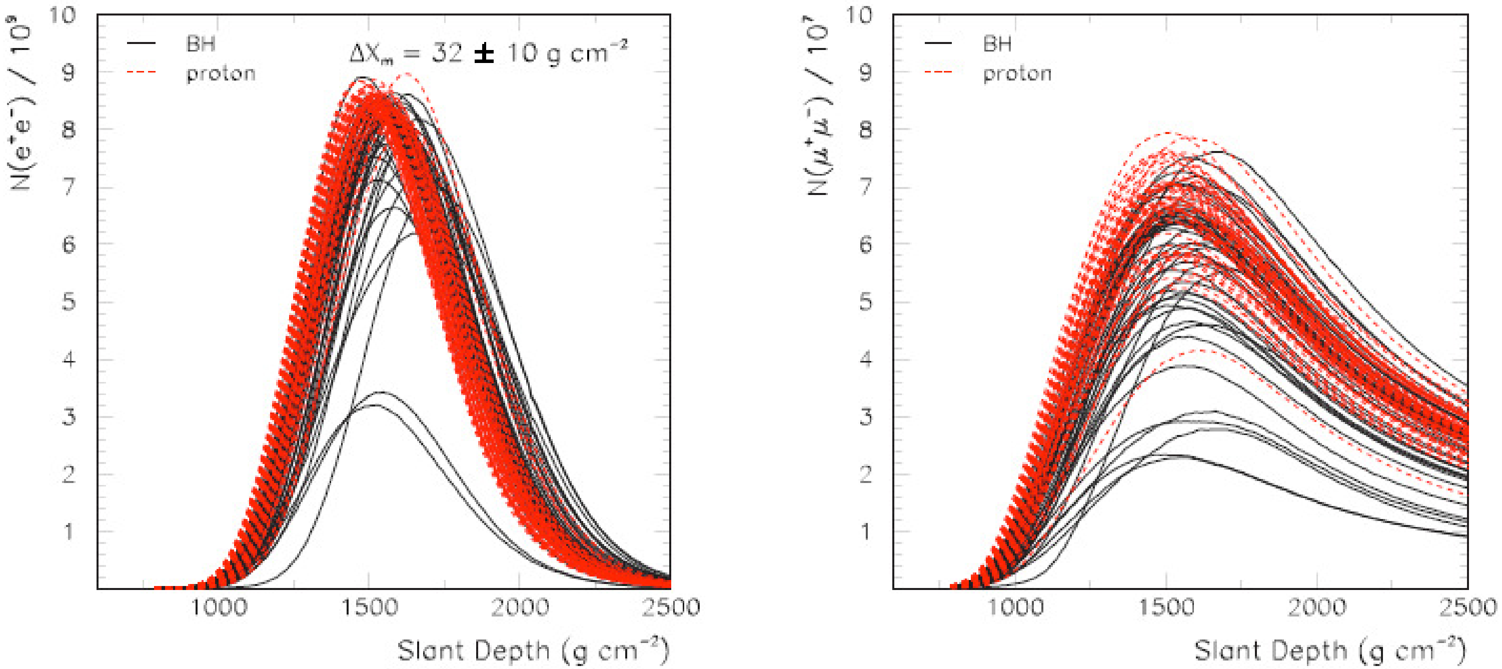


Geometrical cross-sections

$\sigma \sim \pi r_s^2$

Mini BH detection

- Main features of BH showers are independent of details of BH formation and evolution (Ahn & Cavaglia - PRD 73 - 2006)

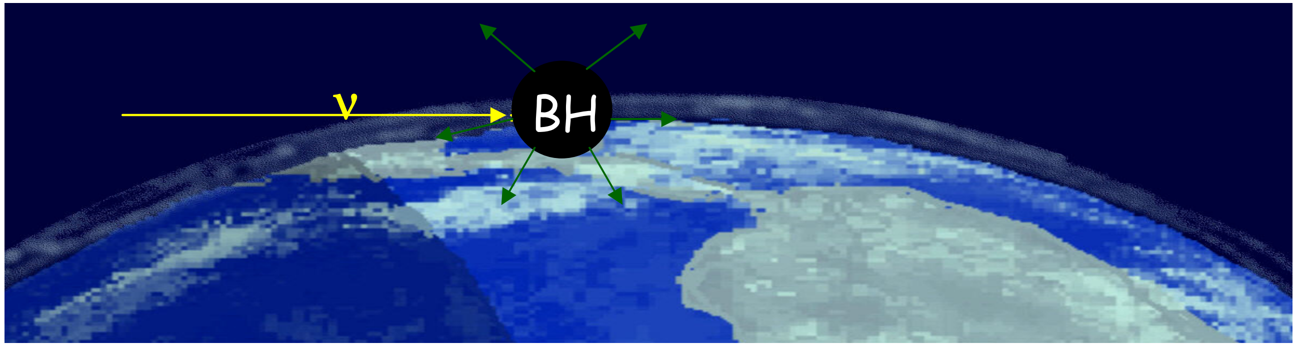


- Hadronic showers with large fluctuations; not so different from proton showers

- Experimentally tough…

Mini BH detection: the double bang scenario

V. Cardoso, M.C. Espirito Santo, M. Paulos, M. Pimenta, B. Tomé
Astroparticle Physics 22 (2005)



- Horizontal showers starting deep in the atmosphere
- 1st bang : Mini BH production + instantaneous democratic decay
- 2nd bang : decay of energetic taus ($L_{int} >> L_{dec}$)
- Distinctive signature ! But a narrow window for the detection of the second bang (tau energy vs tau decay length)

Next generation space-borne telescopes should take it into consideration

Observation prospects

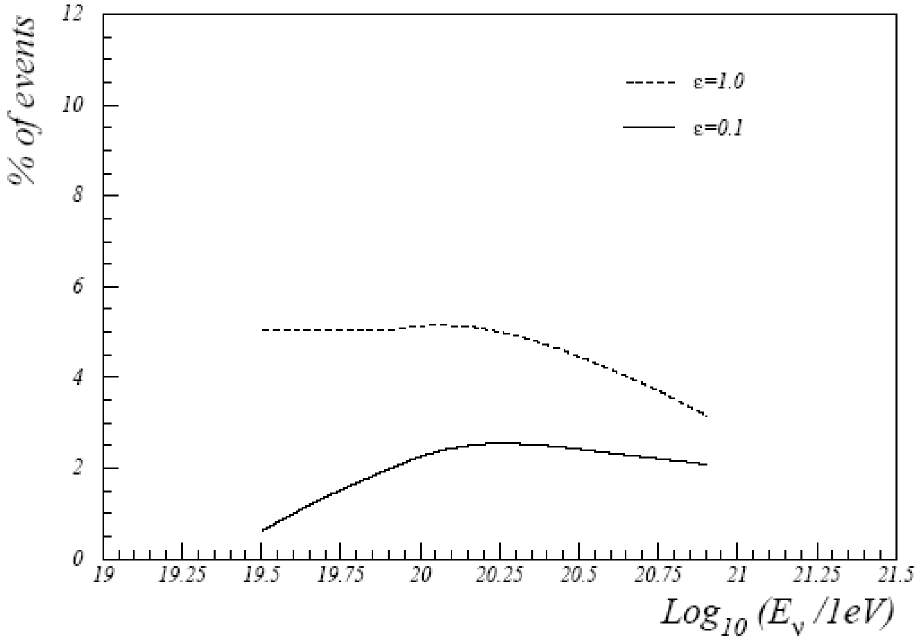
EUSO taken as case study

Order of magnitude computation with simple model

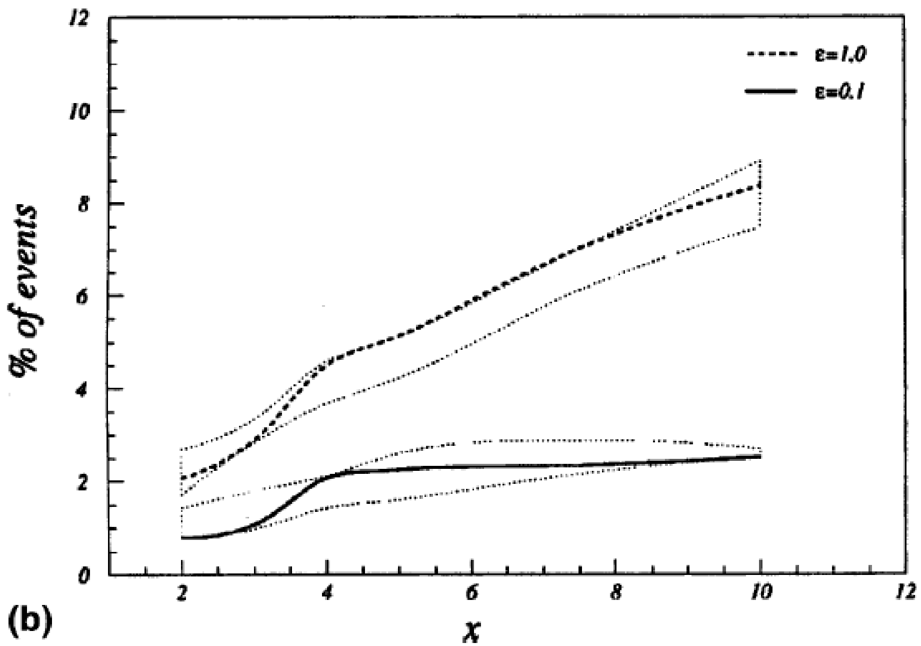
GIL + fluo model (Kakimoto) + LOWTRAN for atm

First bang randomly distributed horizontaly, and verticaly according to density profile

Chances of seeing the 2nd bang once the 1st one is detected



(b)



A few % of the events give double bangs in EUSO

UHECRONs

Chung, Farrar and Kolb Phys. Rev. D 57 (1998)

- Exotic massive stable neutral hadrons
- Increased threshold energy for pion production -> sources beyond

GZK distances

- Candidates:

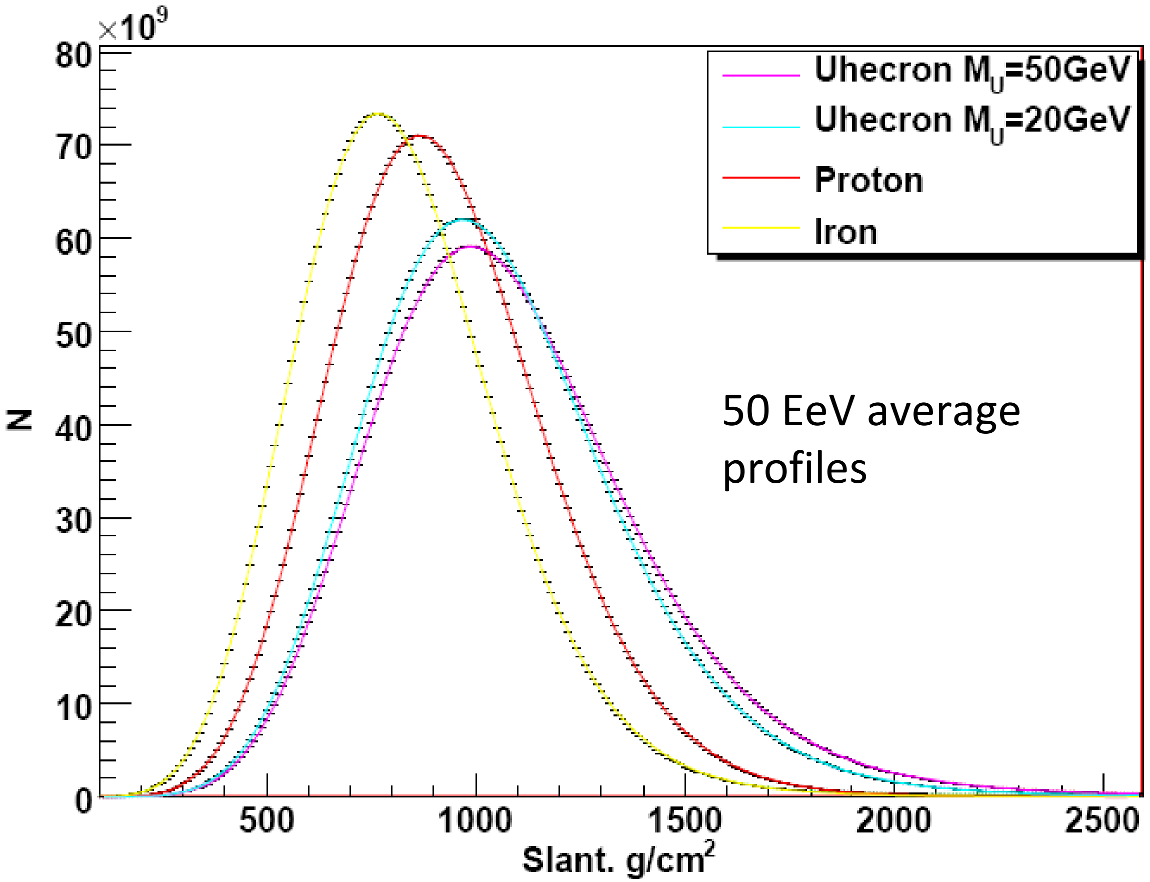
  Gluino-gluon color singlet in SUSY models in which the gluino is the LSP (S.Raby)

  Strongly interacting WIMPless dark matter (J. Feng)

UHECRON detection

Washington Carvalho Jr. & Ivone Albuquerque, to be published in PRD

Main distinctive signature is the longitudinal profile of EAS



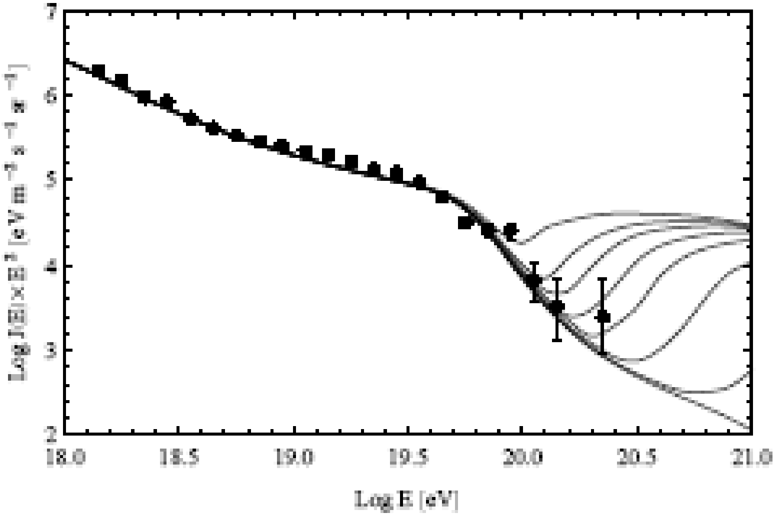
- Slower shower development
- Deep maximum
- Surface detector information will improve UHECRON discrimination (different μ/e.m. ratio !!)

UHECRON with M< 50 GeV can be detected and discriminated against p, Fe

Lorentz invariance violation

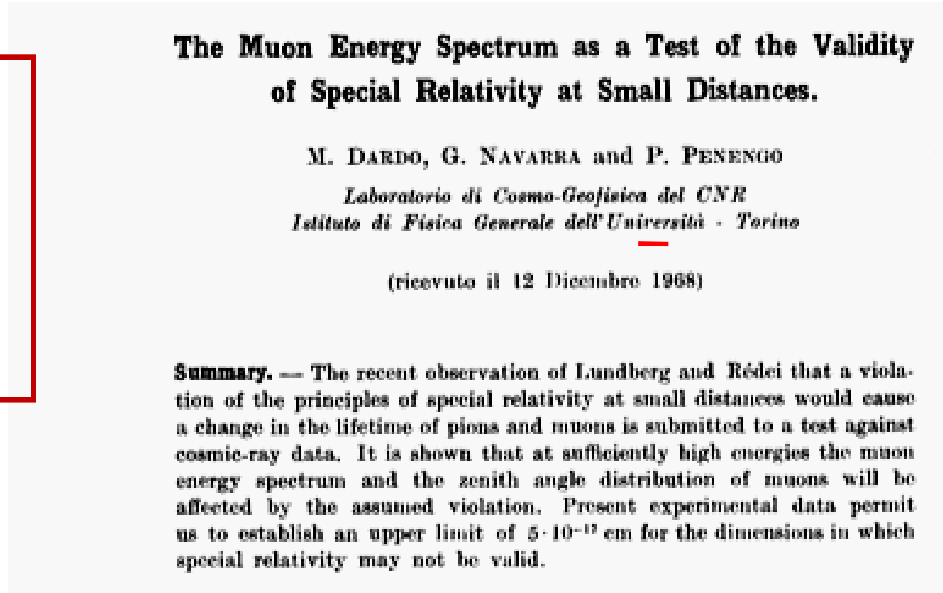
- Photoproduction $\gamma p \rightarrow \pi\, p$ at $\gamma \sim 10^{11}$
- Different propagation through the CMB ?
- Modified GZK cutoff

Stecker and Scully



- In certain conditions no π^0 decay above given threshold energy
- Modified shower development (shower shape, muon content)

New physics observed in standard UHECR collisions !



The Muon Energy Spectrum as a Test of the Validity of Special Relativity at Small Distances.

M. Dardo, G. Navarra and P. Penengo

Laboratorio di Cosmo-Geofisica del CNR
Istituto di Fisica Generale dell'Università - Torino

(ricevuto il 12 Dicembre 1968)

Summary. — The recent observation of Lundberg and Rédei that a violation of the principles of special relativity at small distances would cause a change in the lifetime of pions and muons is submitted to a test against cosmic-ray data. It is shown that at sufficiently high energies the muon energy spectrum and the zenith angle distribution of muons will be affected by the assumed violation. Present experimental data permit us to establish an upper limit of $5\cdot10^{-17}$ cm for the dimensions in which special relativity may not be valid.

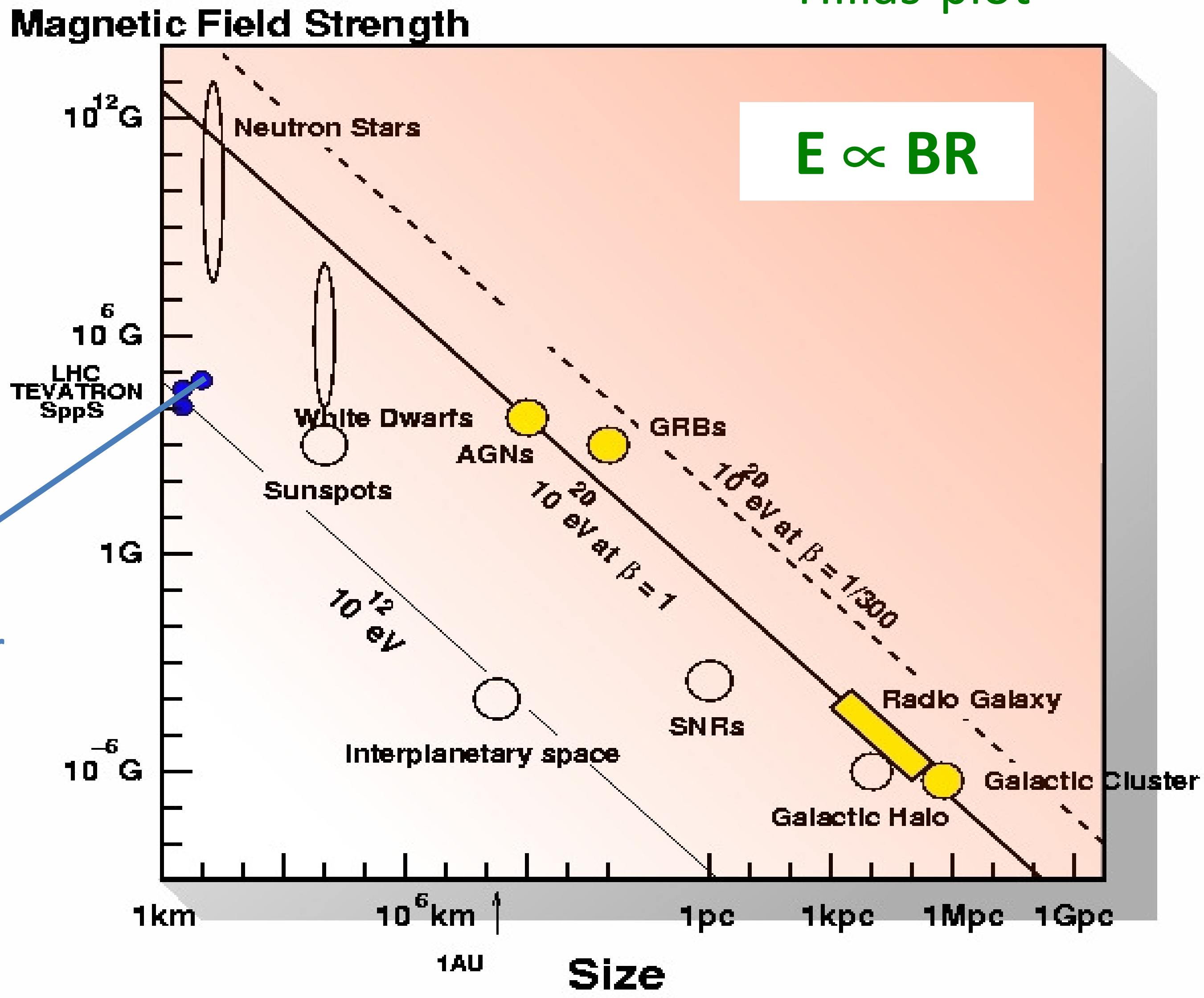
Summary

- UHECR telescopes probe energies far beyond man made accelerators
- Exotic physics is probably hiding in the bulk of the cosmic ray events
- Be prepared for the unexpected !

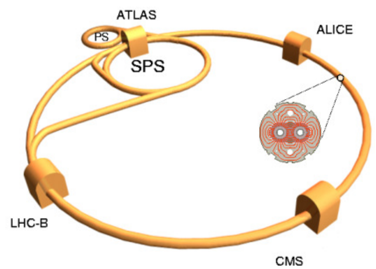
BACKUP

Cosmic accelerators

Hillas-plot



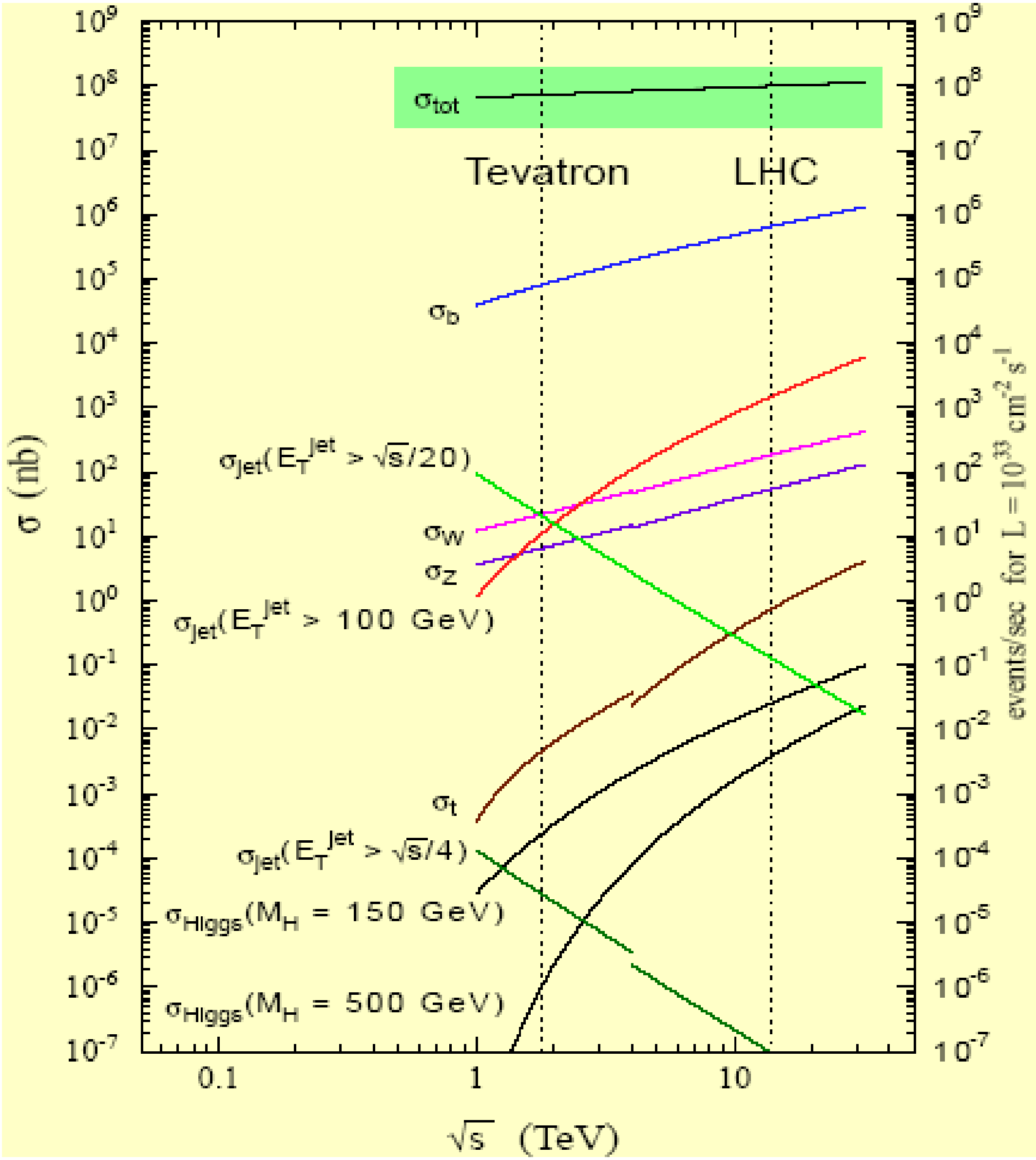
Large Hadron Collider



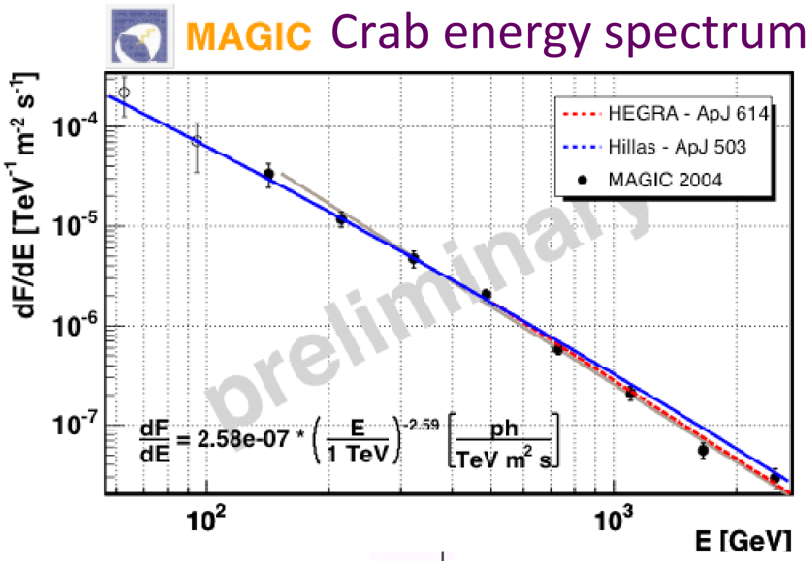
R ~ 10 km, B ~ 10 T

E ~ 10 TeV

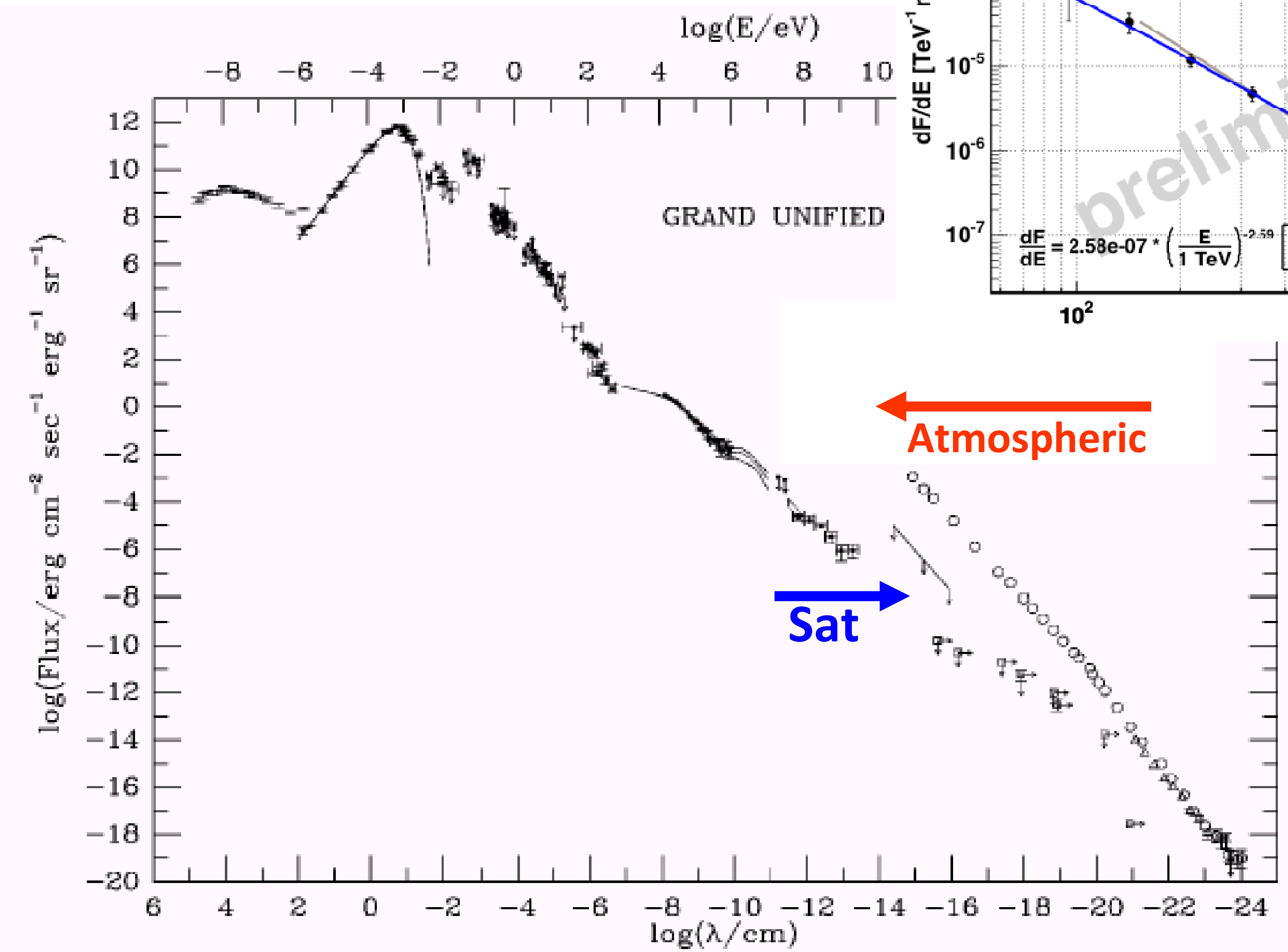
pp SM background



γ beams



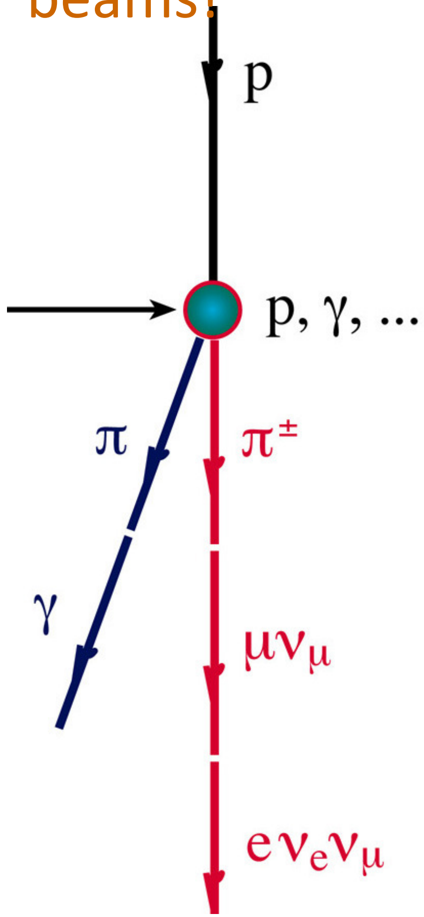
MAGIC Crab energy spectrum
dF/dE [TeV^{-1} m^{-2} s^{-1}]
HEGRA - ApJ 614
Hillas - ApJ 503
MAGIC 2004
preliminary
$\frac{dF}{dE} = 2.58e-07 * \left(\frac{E}{1\ TeV}\right)^{-2.59} \left[\frac{ph}{TeV\ m^2\ s}\right]$
E [GeV]

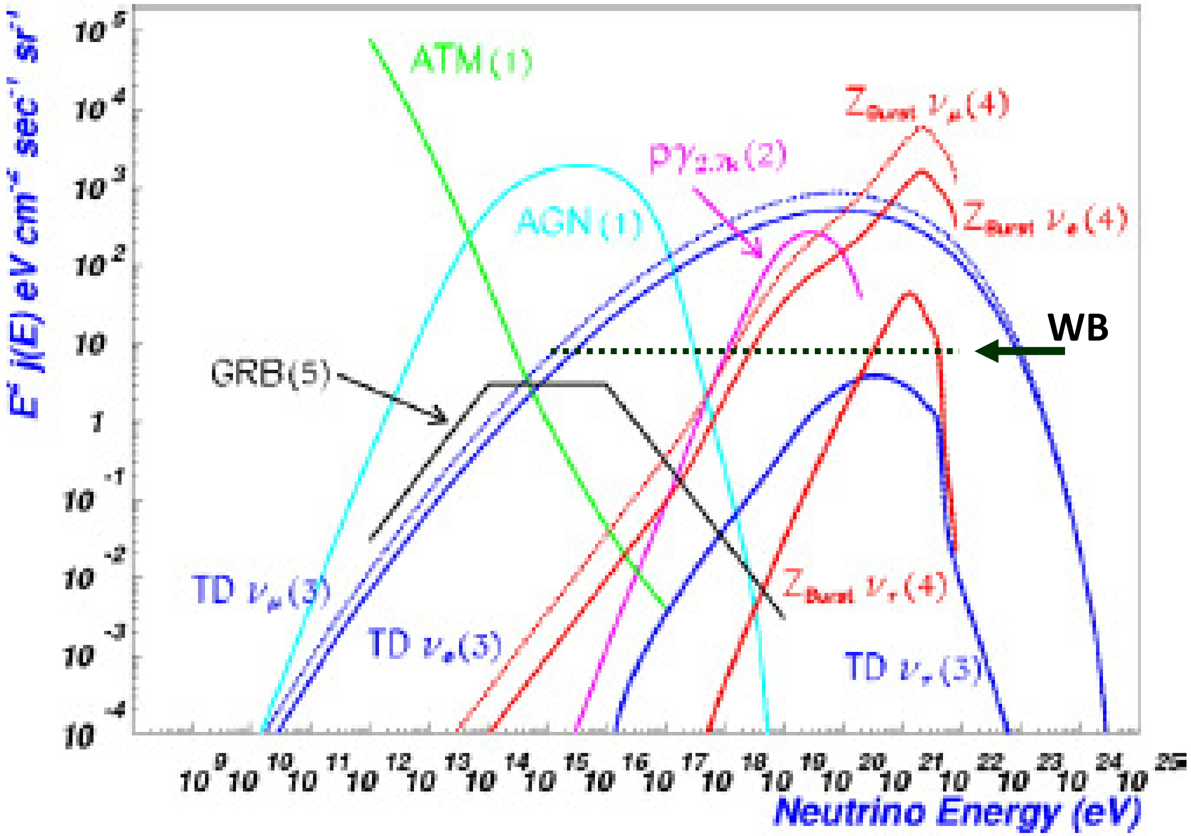


log(E/eV)
GRAND UNIFIED
log(Flux/erg cm^{-2} sec^{-1} erg^{-1} sr^{-1})
log(λ/cm)
Atmospheric
Sat

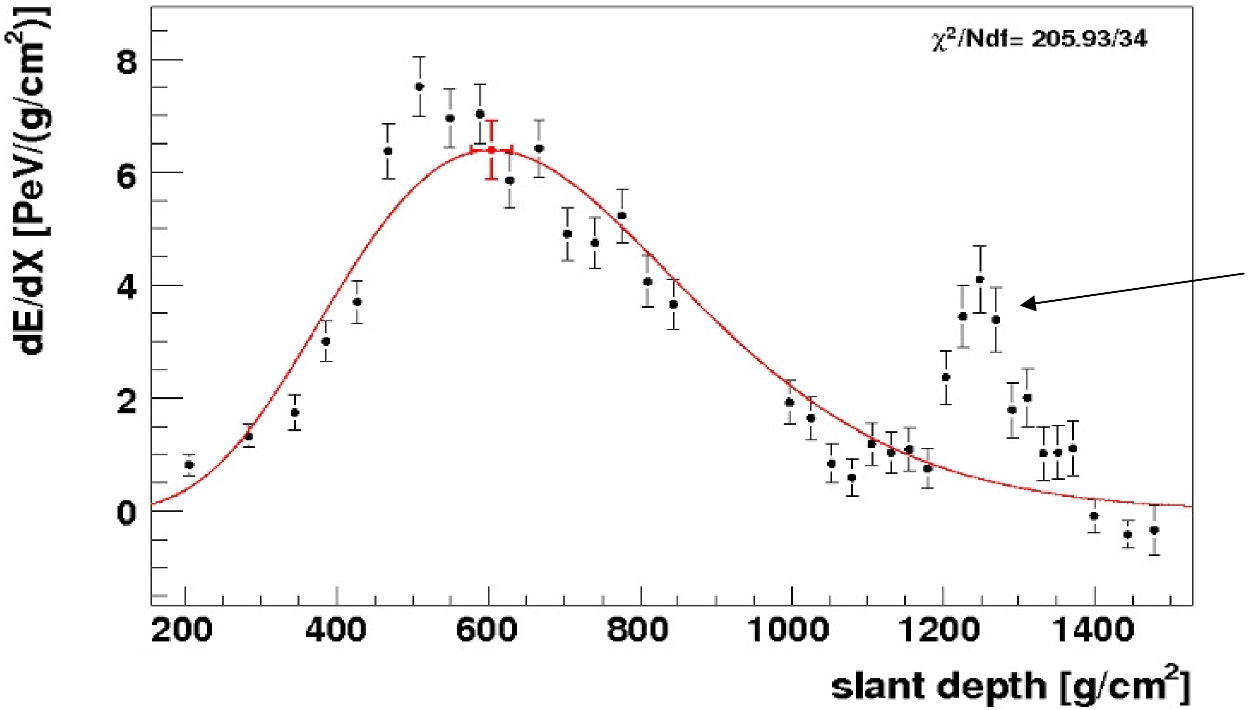
ν beams

secondary
γ and ν
beams!





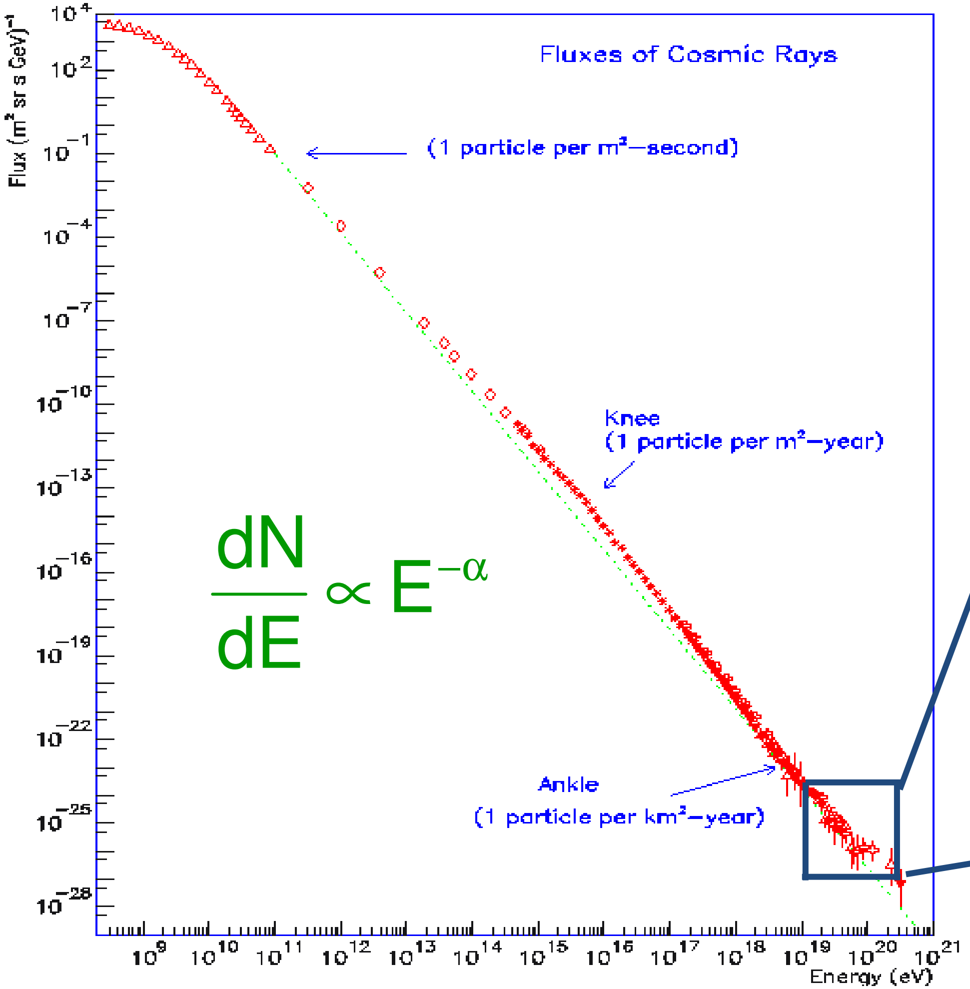
BUT no measurements
above $E > 10^6$ GeV !



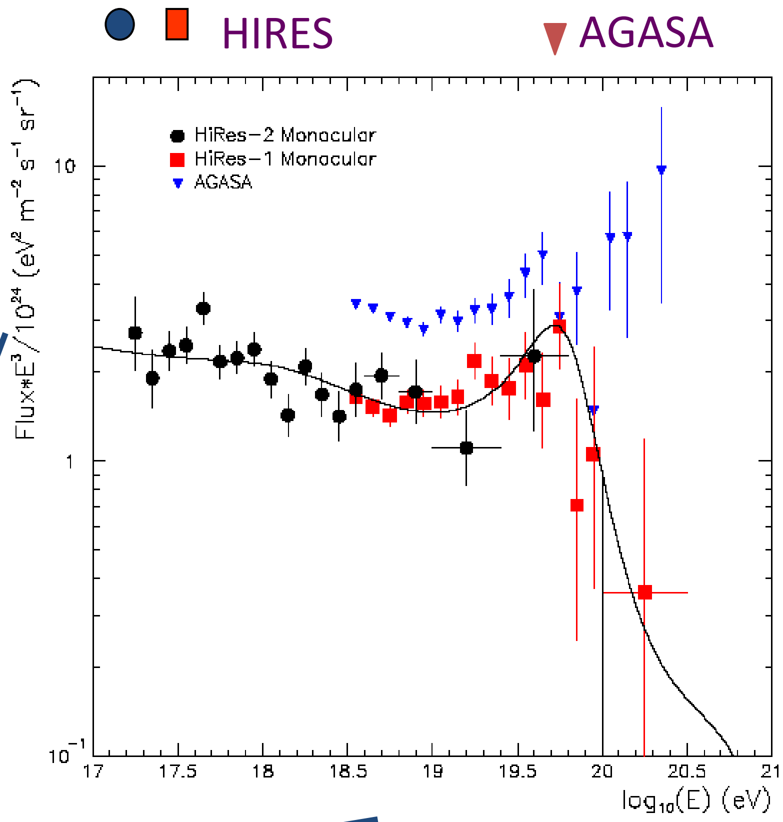
This analysis not sensitive to something like a double bang (profile caused by poor atmospheric conditions)

There are two ways of doing an exotic search, one focuses on finding strange things (like double bangs) that defy the typical profile. The other looks for things that are similar to typical profiles, but slightly differ. This analysis is sensitive to the latter and may help answer the questions: "how sensitive is our detector to exotic things?" and "how much room is in our data for exotic things?"

Charged (p/nucleus) beams



$$\frac{dN}{dE} \propto E^{-\alpha}$$



~2001

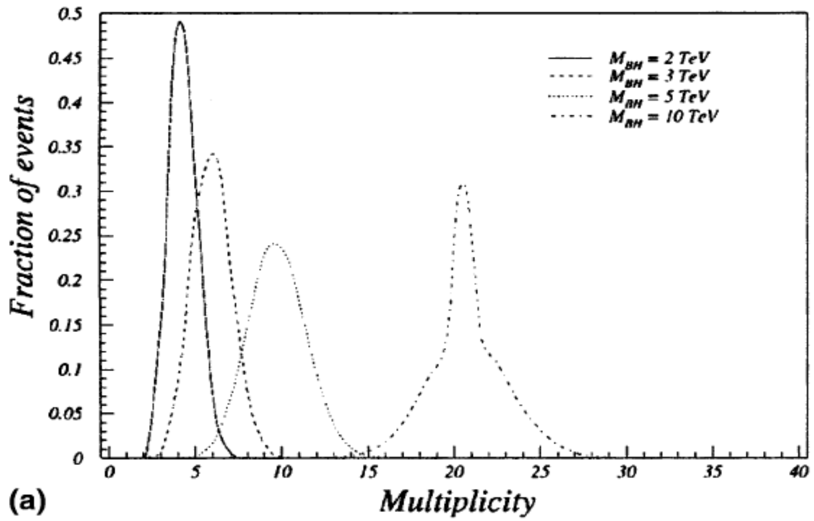
$E > 10^{20}$ eV ~ 20 events

The first bang: production & decay of BH (I)

Mini-BH production and decay simulated with CHARYBDIS

Harrison,Richardson, Webber, hep-ph/0307305

- Developed to simulated BH production in hadron colliders
- Careful treatment of BH decay. Pythia for standard particle decay and hadronisation
- Democratic decay into all SM particles
- Conservation of charge and total angular momentum. No lepton nb conservation



(a)

M_D=1 TeV, n=3

The first bang: production & decay of BH (II)

- Settings: nb of extra dimensions n=3 and n=6

  Planck mass M_D=1,2,3 TeV

  fixed BH masses M_{BH}= $2M_D$, $3M_D$, $5M_D$

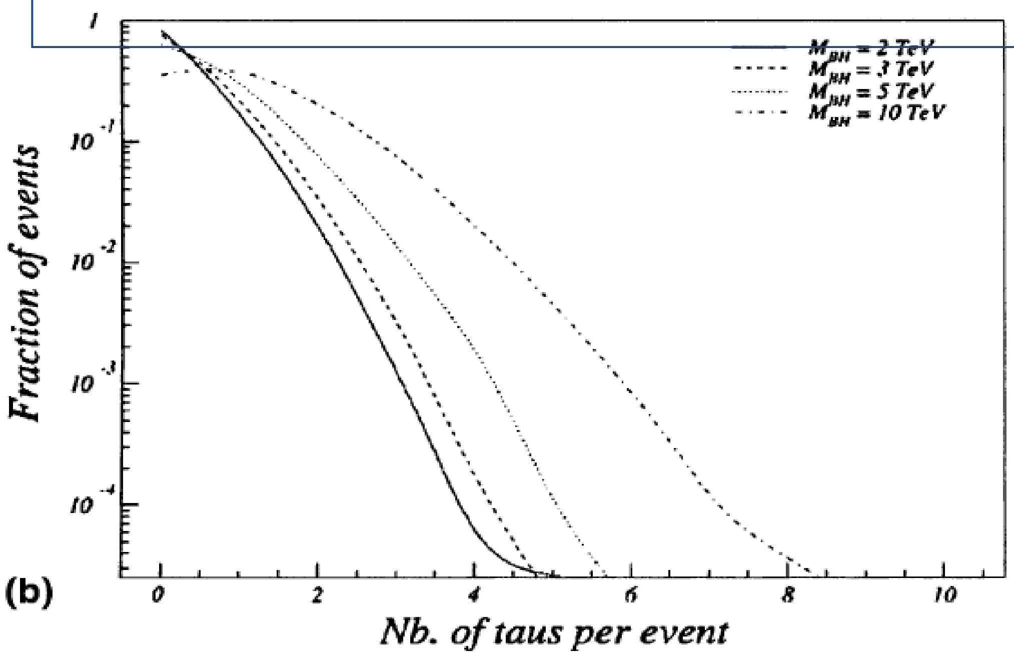
- No explicit cross-section model. Fixed BH masses.

  Results should be convoluted with a given M_{BH} spectrum

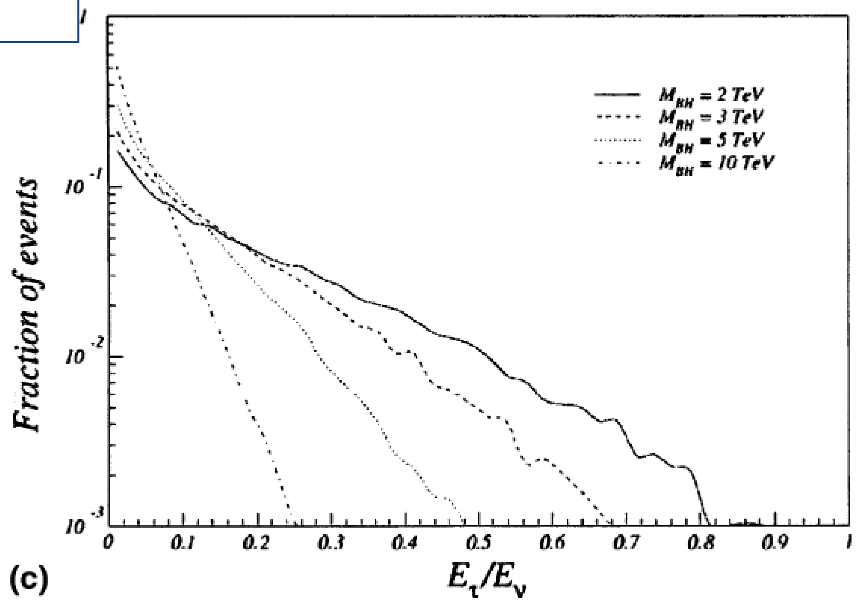
  (dependent on pdf extrapolation and specific cross-section model)

- Main parameter is $x=M_{BH}/M_D$. Dependence on n is moderate

MBH/Tev	<Nτ>
2	0.2
3	0.3
5	0.5
10	1.1



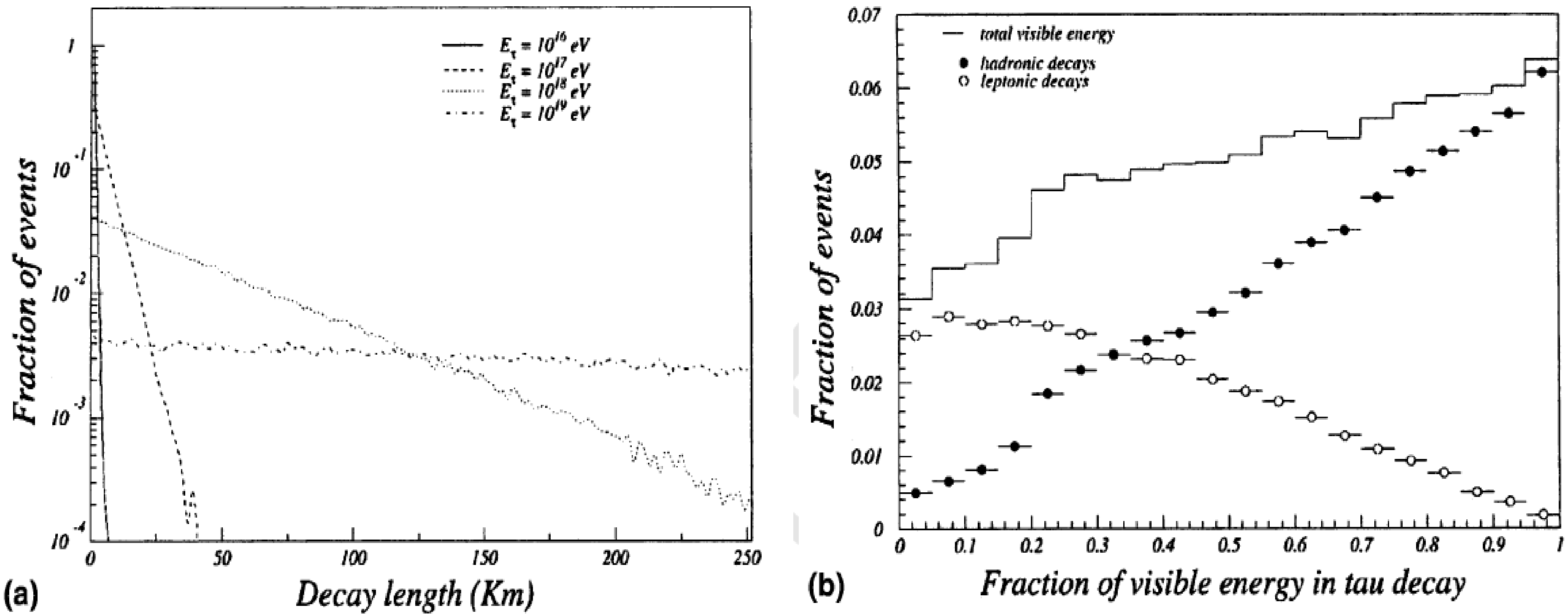
(b)



(c)

The second bang: the decay of energetic taus

- Taus from bh decays and W/Z/t decay treated using pythia
- $L_{int} >> L_{dec}$



Observation prospects (I)

Approach:

EUSO taken as case study

Order of magnitude computation with simple model

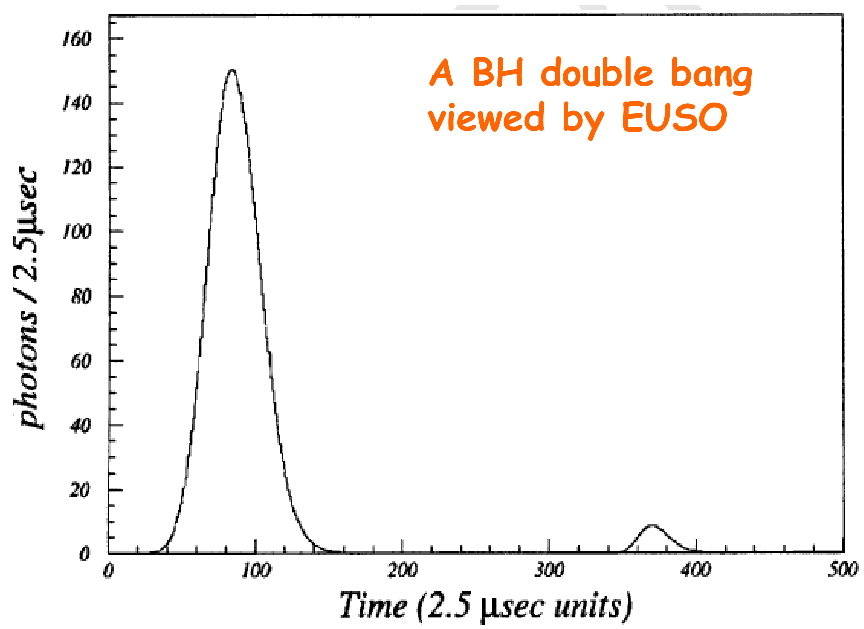
GIL + fluo model (Kakimoto) + LOWTRAN for atm

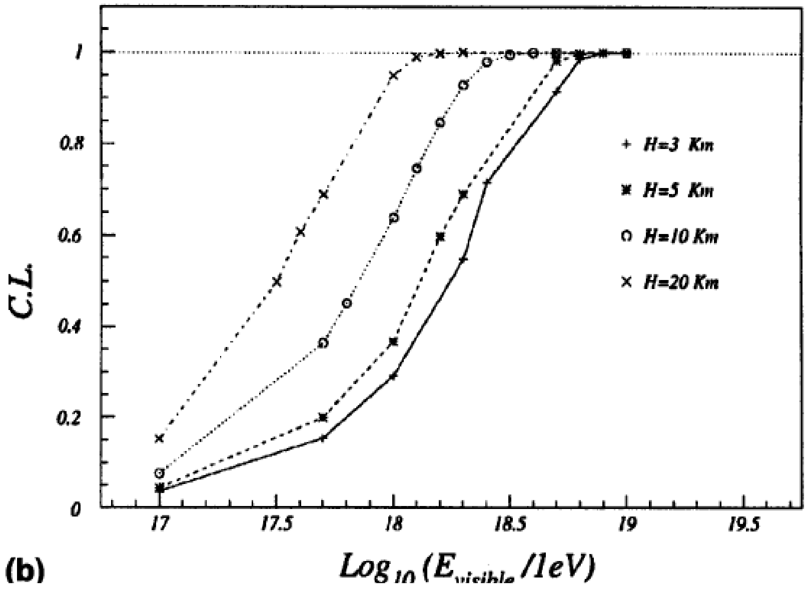
First bang randomly distributed horizontaly, and verticaly according to density profile

Observation window constrained by geometry (FOV) and signal to noise ratio

Lowering the energy threshold for the 2nd bang:

- Aligned with 1st bang in the focal surface
- Modifed Frequentist likelihood ratio method:
  Taking into account signal & background shape





(b)

UHECRON @ 100 EeV