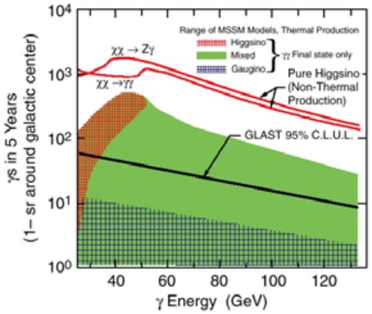
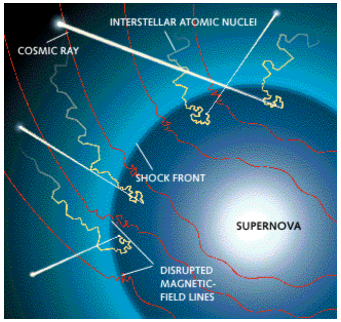
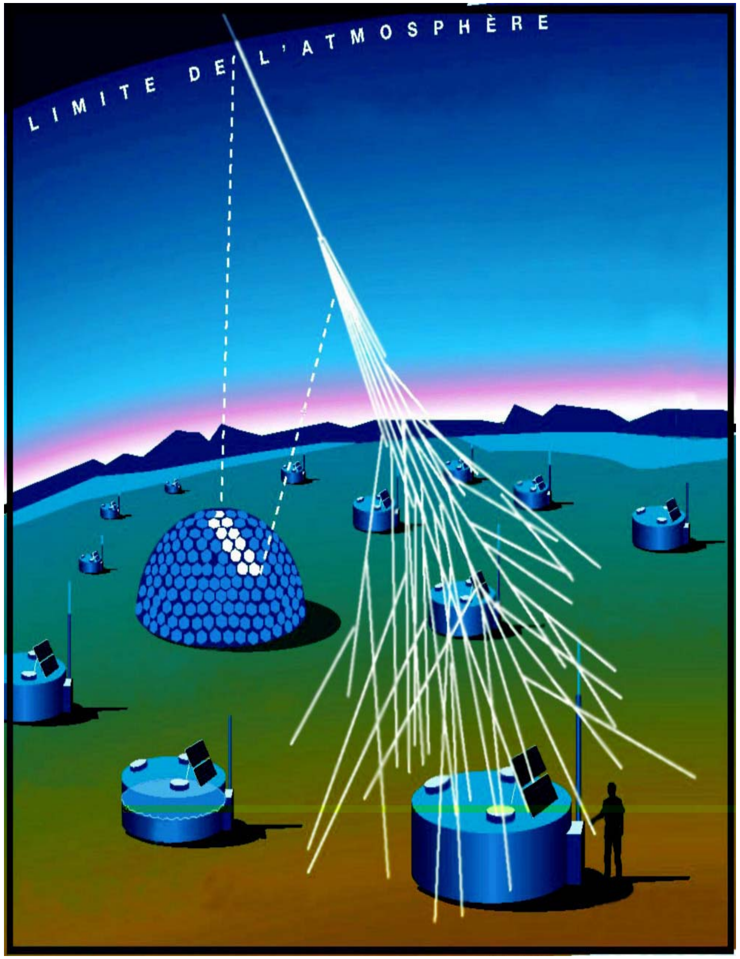
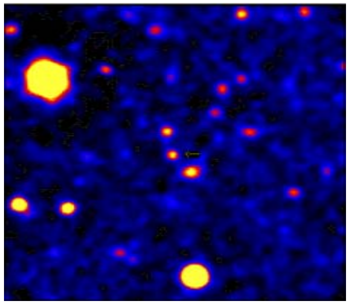
HIGH-ENERGY COSMIC RAYS

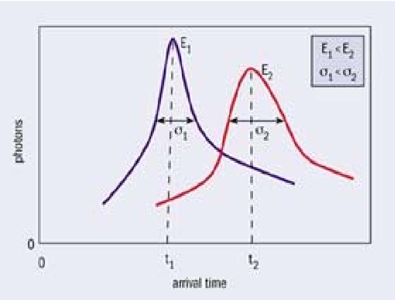
PART 2

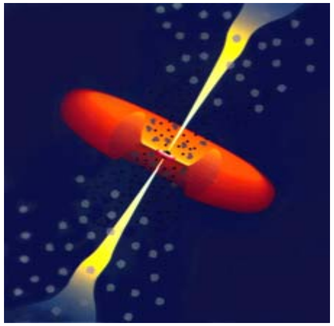










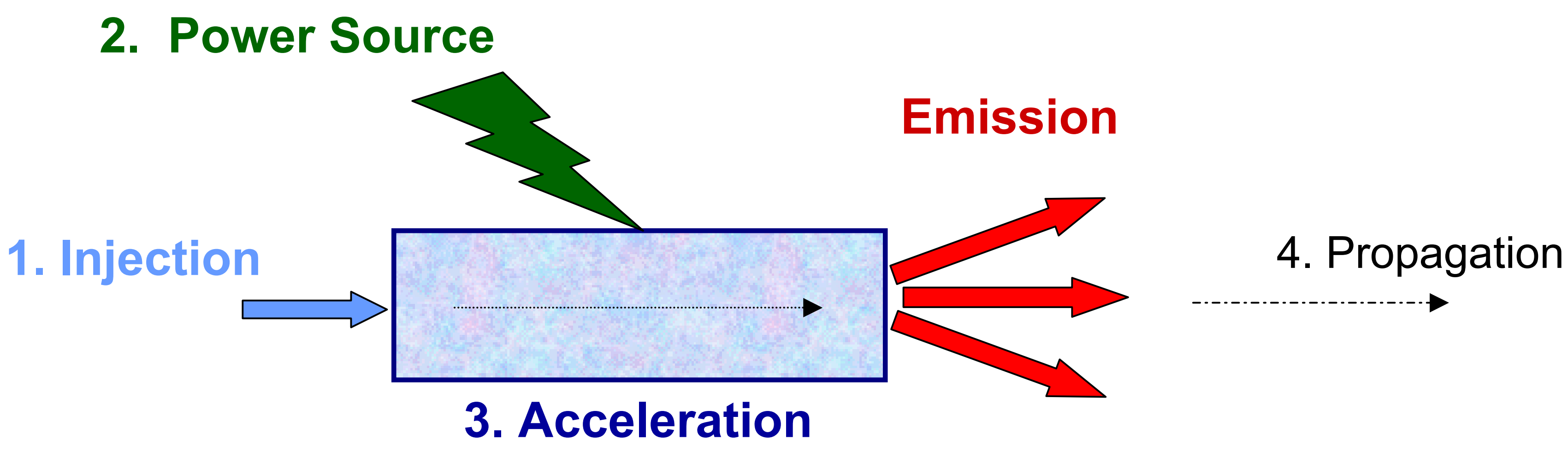


Rene A. Ong
University of California, Los Angeles

SLAC Summer Institute
4 August 2003

Cosmic Acceleration: Recap

To build a HE cosmic accelerator, we need the following parts:



So Far … ~10^{15} eV

General Picture: bulk of CR's are produced in a number of (discrete) galactic sources (SN's?) that fill the galaxy with energetic particles. This seems fine at "low" energy (< 10^{15} eV), but …

- Real difficulty in getting to much higher energies using conventional astrophysics.
- Variety of models proposed seem capable of reaching the range 10^{18} – 10^{19} eV, but they all stretch what know…

Reaching Higher Energies

Some possibilities:

- Pulsars – like Crab, but accelerating iron.
- Magnetars – pulsar-like sources with B ~ 10^{15} G.
- Induction from spinning (supermassive) black holes.

- Multiple SN's, or a SN explosion into a strong wind.
- Galactic shock waves.
- AGN (radio jet termination, quasar jets).
- Gamma-ray bursts – relativistic bulk motion.

Great deal of speculation – no clear consensus. Need more and better data at energies E > 10^{18} eV.

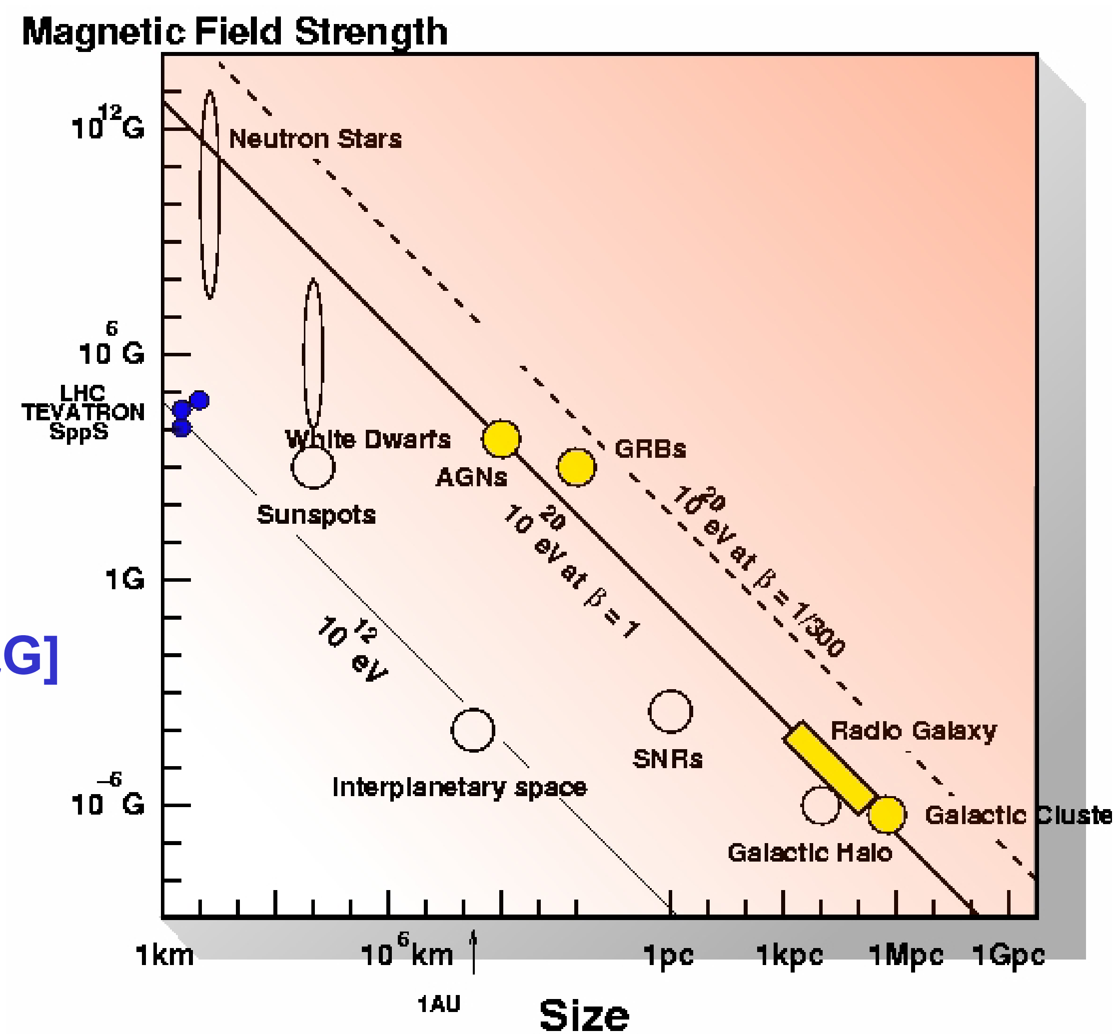
Magnetic Confinement

"Hillas Plot"

Minimum size of B field to contain particles being accelerated.

Achievable energy:

E [EeV] ~ Z R [kpc] B [μG]



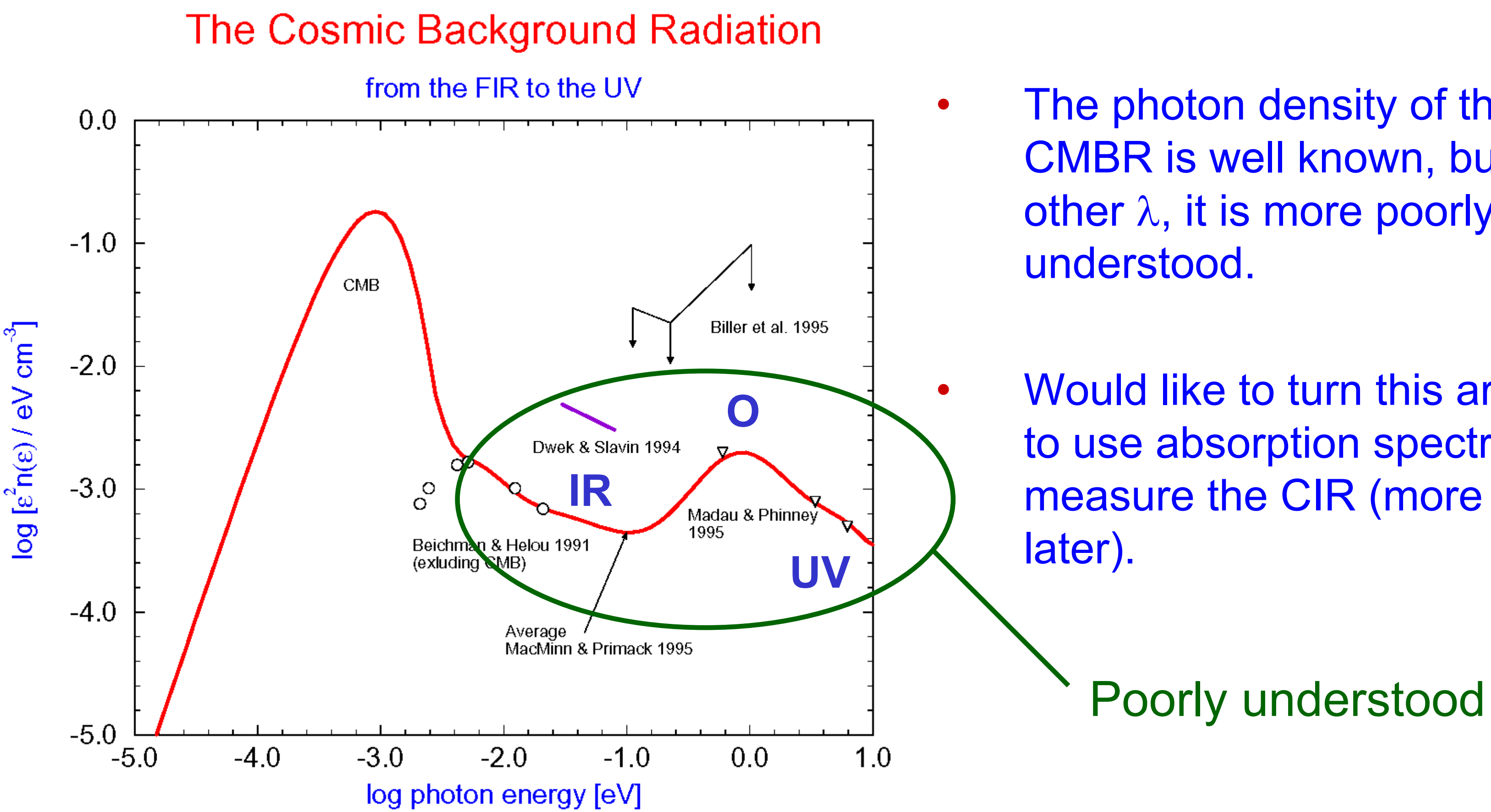
4. Propagation

How particles propagate depends on their type and energy.

Particle	Deflected ?	Interactions
Protons	yes	ISM (~ 10 g/cm^2) - spallation
Nuclei		CMBR $p\,\gamma_{cmbr} \rightarrow \Delta^+ \rightarrow \pi$'s
Gamma rays	no	Intergalactic radiation
		$\gamma\,\gamma \rightarrow e^+\,e^-$ (CMBR, CIR, etc.)
Neutrinos	no	~ None

Gamma-Ray Propagation

Gamma-rays will pair-produce off intergalactic radiation fields.



- The photon density of the CMBR is well known, but at other λ, it is more poorly understood.
- Would like to turn this around to use absorption spectra to measure the CIR (more on this later).

Gamma-Ray Horizon

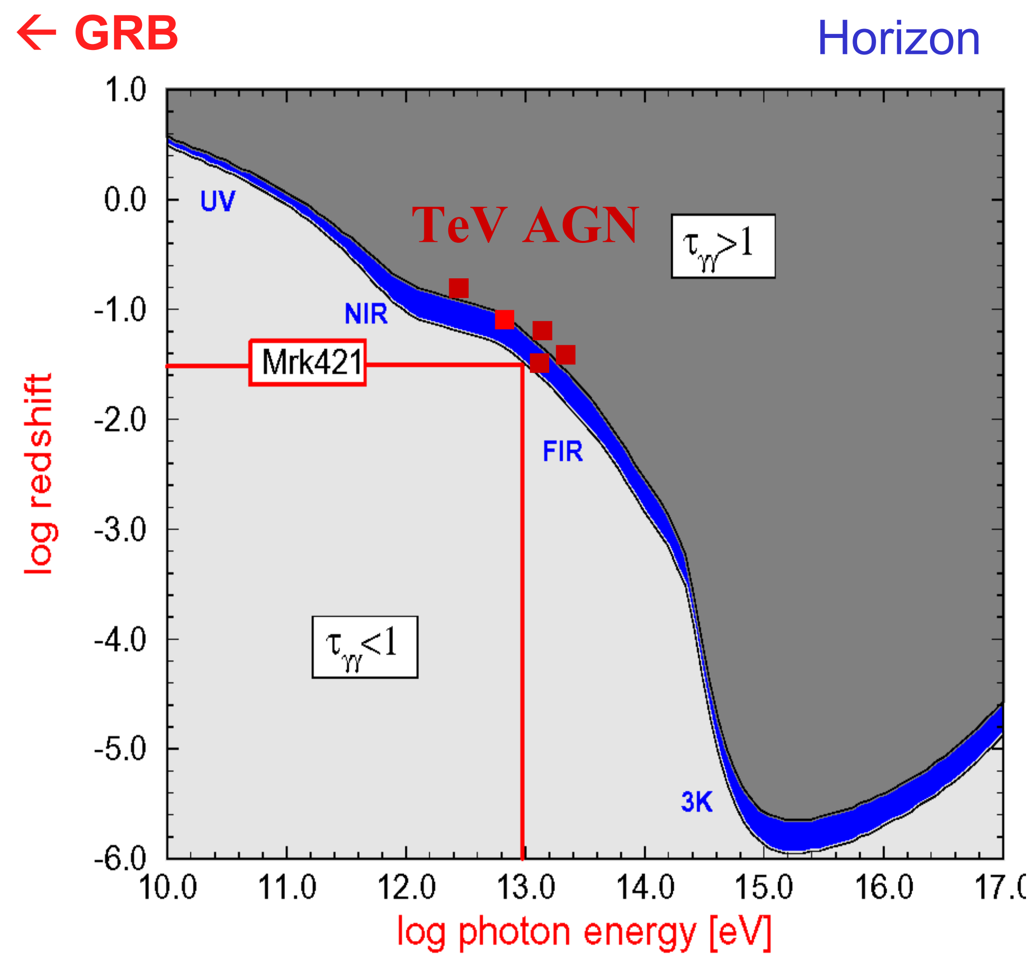
For n_{ir} = density of cosmic IR, the optical depth is:

$$\tau \sim n_{ir}\ \sigma_{\gamma\gamma}\ D(z)$$

For $E = (1+z)E_o$ γ-ray energy
$\varepsilon = (1+z)\varepsilon_o$ IR energy
threshold for absorption is:

$$(\varepsilon\ E) > 2\ (m_e c^2)^2$$

Allows us to calculate the γ-ray horizon. Universe is transparent below E ~ 1 GeV.

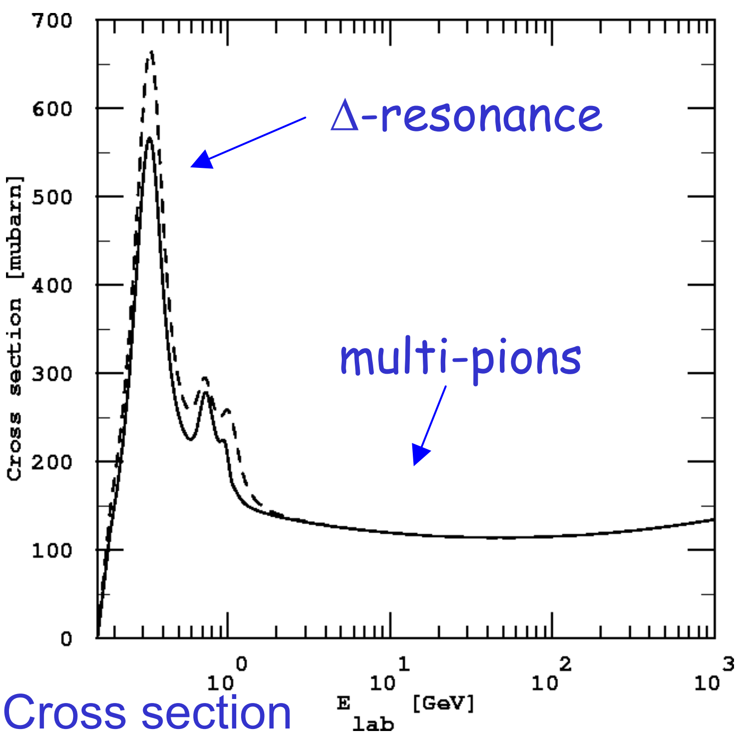


Cosmic Ray Horizon

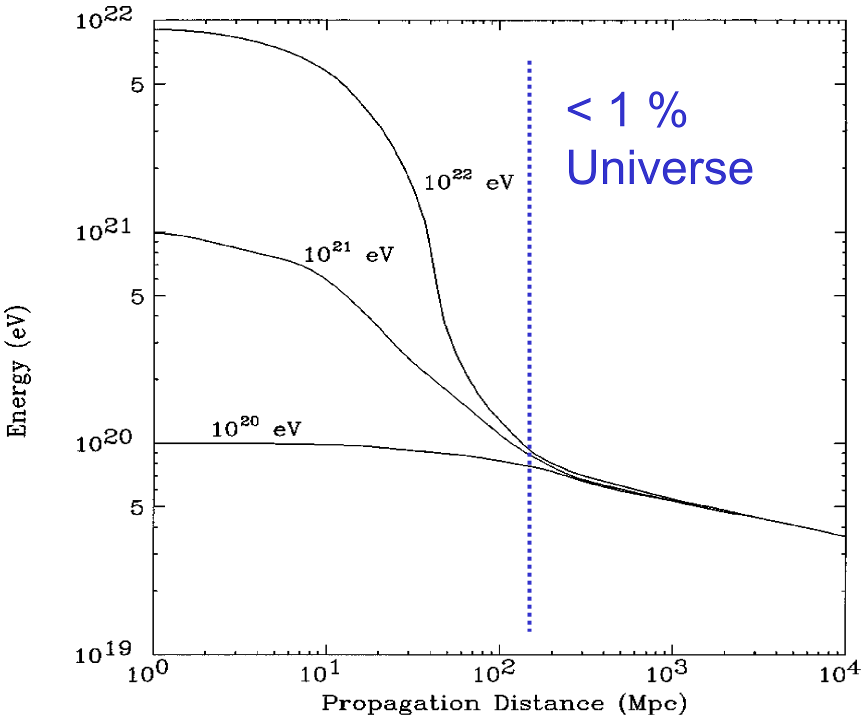
Soon after the discovery of the CMBR, it was pointed out that protons would be absorbed while traversing intergalactic space.

"GZK Cut-off" $\mathbf{P} + \gamma_{\mathbf{cmb}} \rightarrow \Delta^{+} \rightarrow \mathbf{p} + \pi^{0}$

$\rightarrow \mathbf{n} + \pi^{+}$

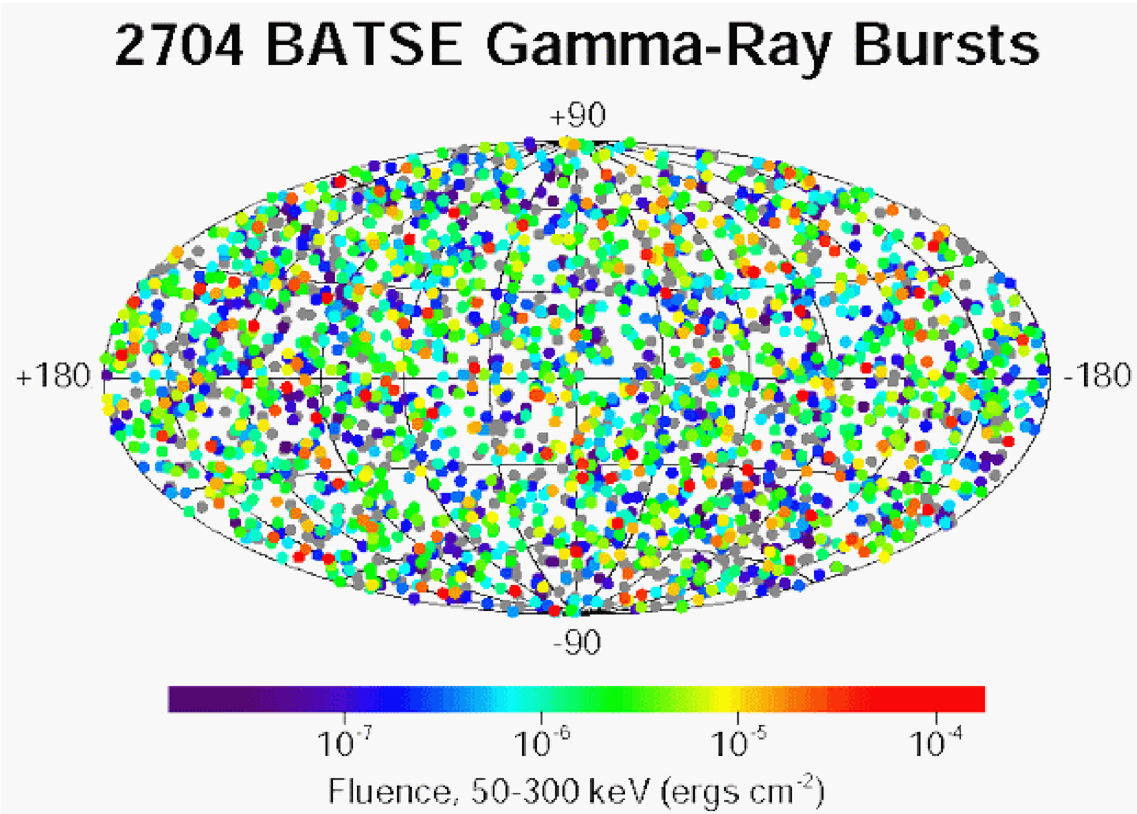


Cross section



KNOWN HE ASTROPHYSICAL SOURCES

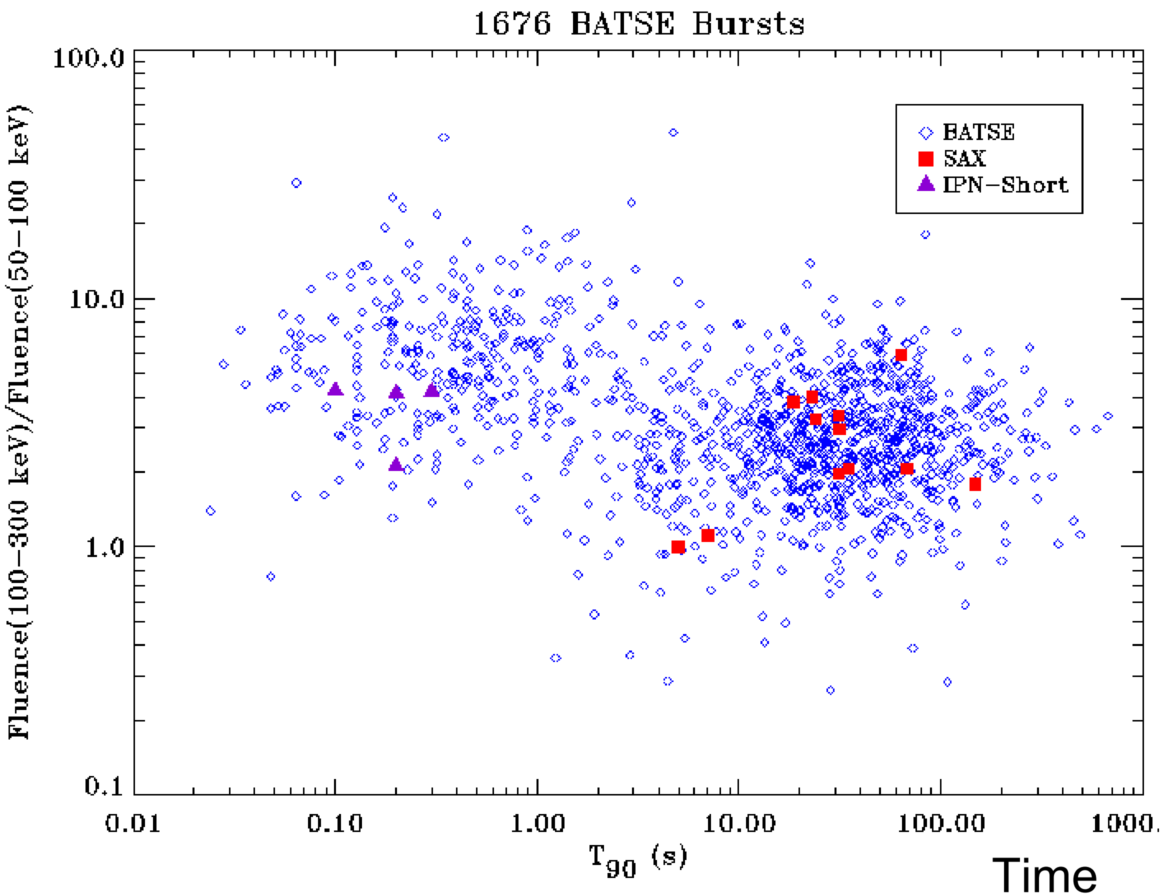
Gamma-Ray Bursts



- Isotropic distribution.
- ~ 1 burst /day.
- 0.01 s → hrs.
- Several seen to GeV.
- Complicated & unpredictable profiles.

GRB Populations

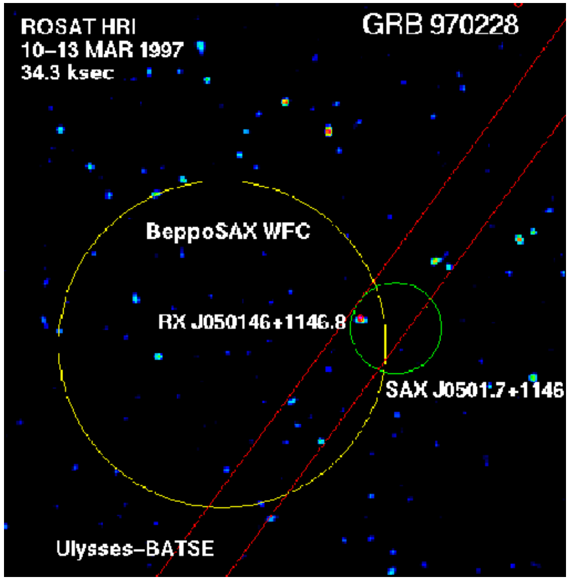
Hardness

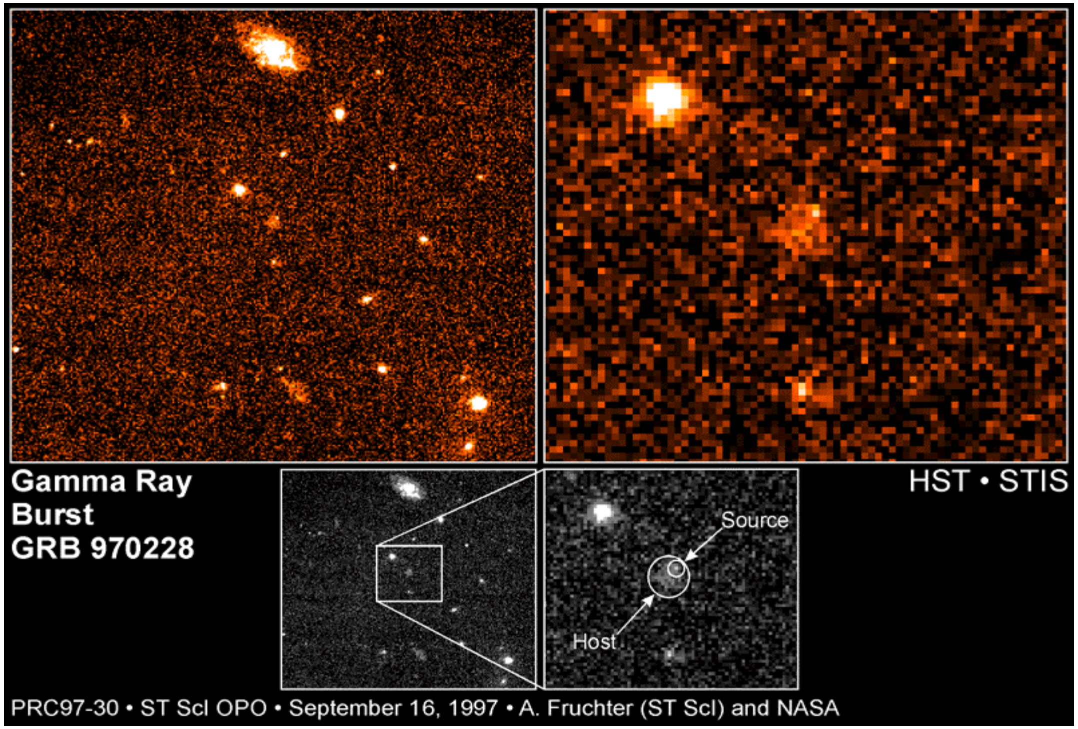


Time

- Two populations – different origins?

Afterglows Detected





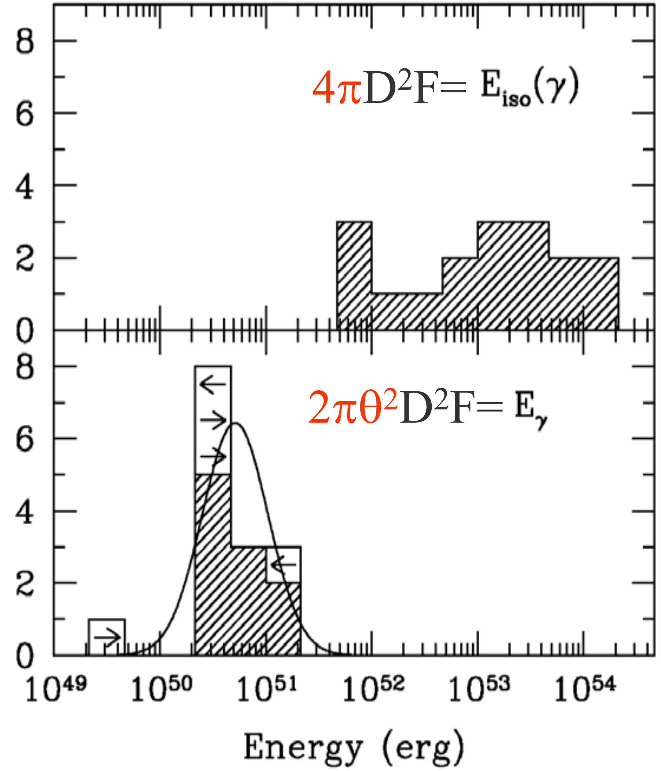
- 1997: Detection of X-ray afterglow → optical counterparts.
  → redshifts.

GRB Parameters

Some general GRB parameters:

- Luminosities are high (> 10^{51} ergs) – how do the g-rays escape in the first place? ("Compactness" problem).
  Sources are highly beamed (Γ > 100).

- Emission is beamed into relatively small opening angle. Correcting for this angle reduces spread in luminosity.



Sari

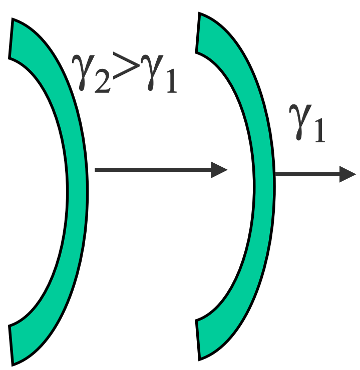
General GRB Picture

Many models and views! But, “general” wisdom is:

- Compact Source: NS-NS merger, WD collapse, hypernova
- Relativistic Energy: L ~ 10^{51} ergs, size R < 10^{7} cm
- KE → Internal E → Radiation: External and/or internal shocks.

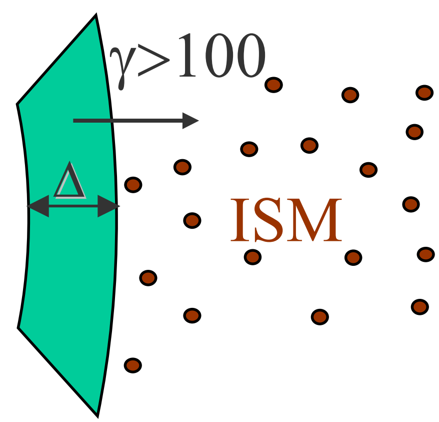
Internal:

“GRB”?



External:

Afterglow?

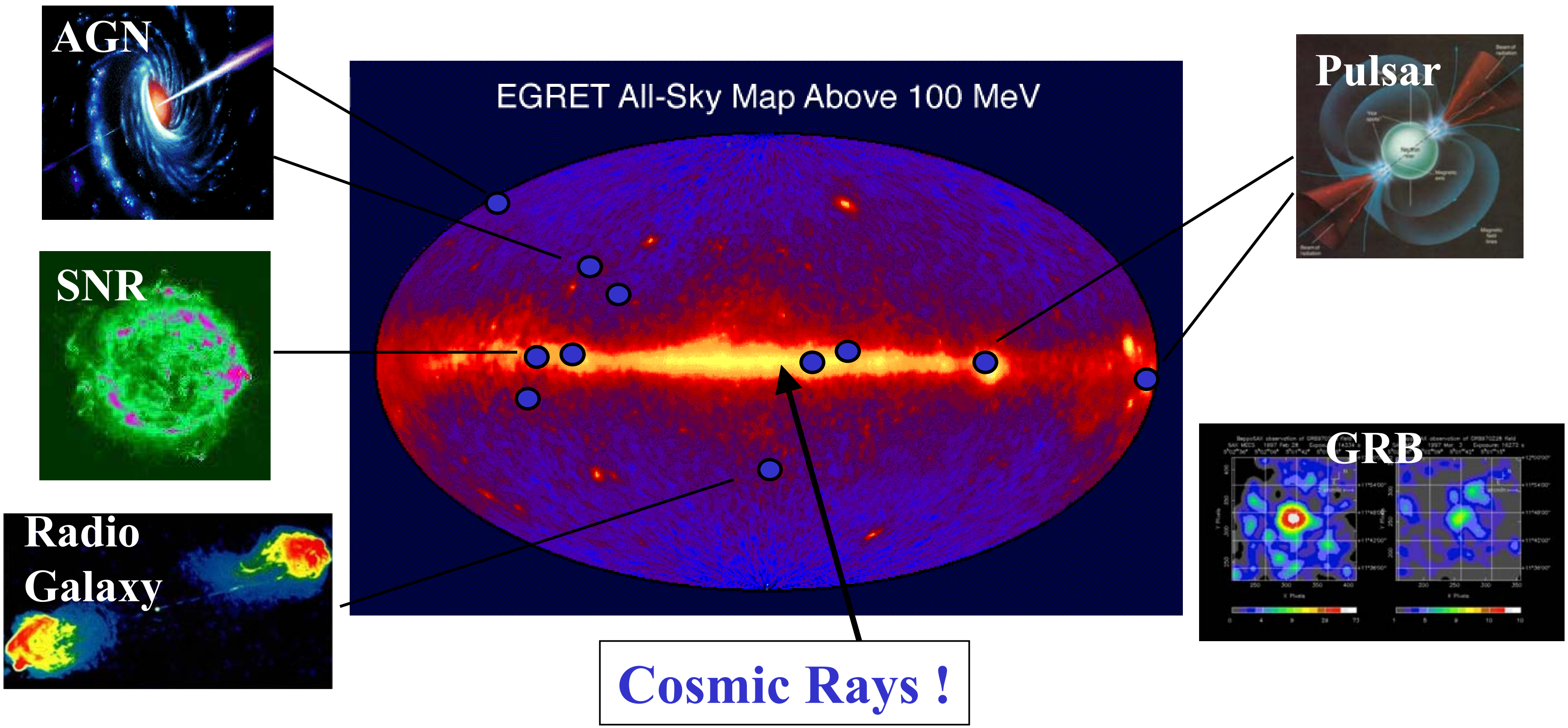


GRB's as Cosmic Accelerators

GRB's are very attractive possibilities for HE cosmic acceleration:

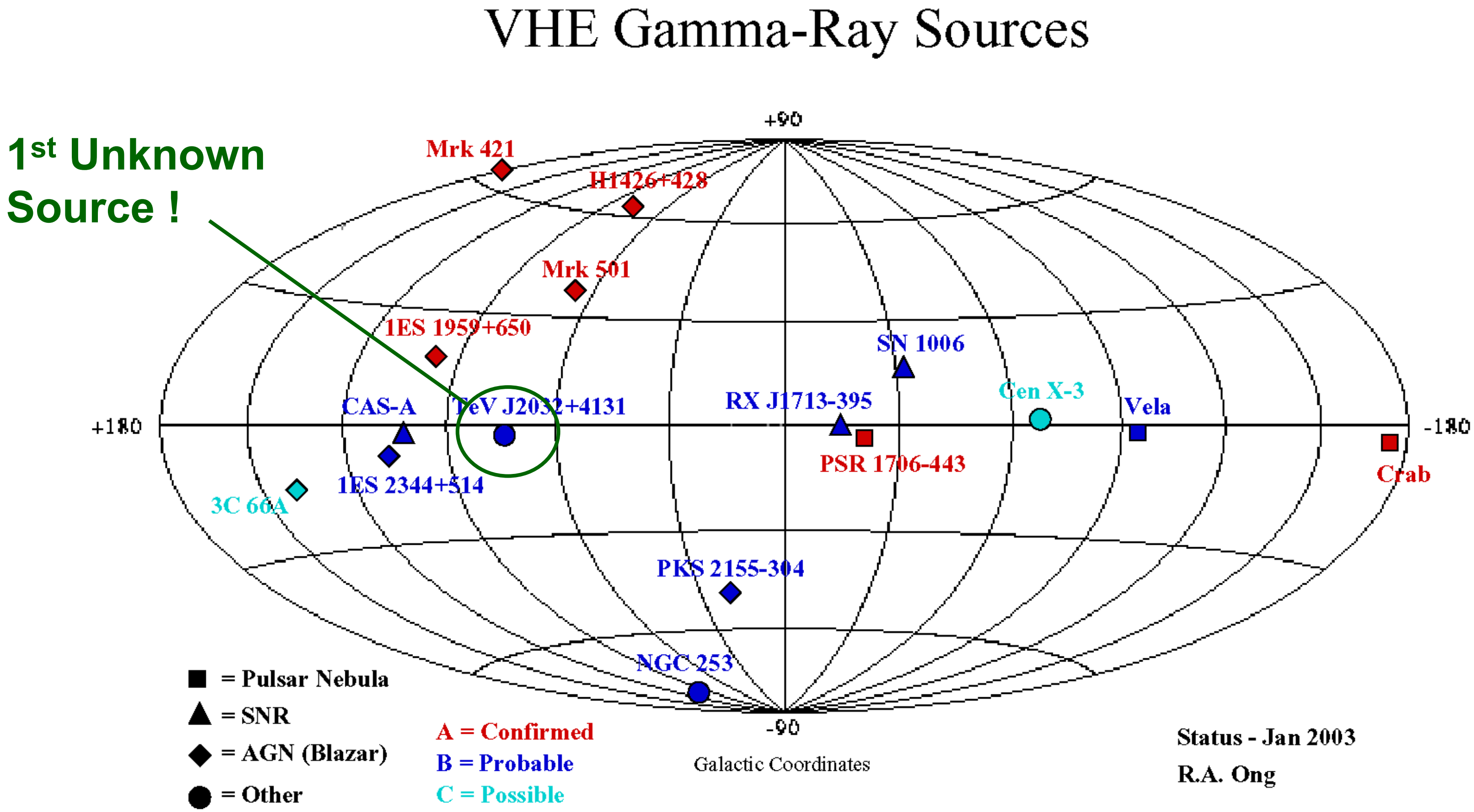
- Remarkable luminosities – brightest objects in Universe.
- Beaming angles → many unobserved GRB's (1000 /day ?)
- Non-thermal emission observed (synchrotron, polarization).
  meaning that particles are accelerated relativistically.
- Key thing – we must detect them with HE γ-rays or ν's.

GeV γ-ray Sky



- ~ 250 HE point sources, most unidentified.

TeV γ-ray Sky



- Pulsars, SNR's, AGN, Starburst galaxy …
- All detected by Cherenkov telescopes.

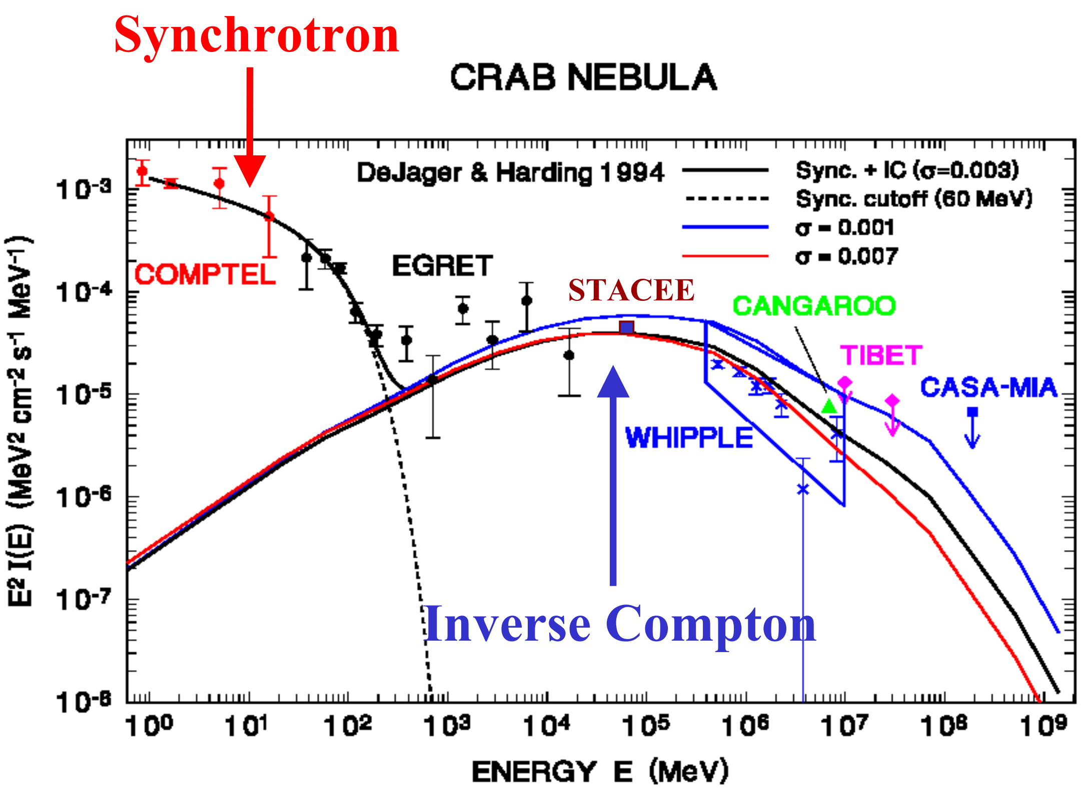
Stay tuned …talks by Krennrich, Tanimori

High-Quality Data

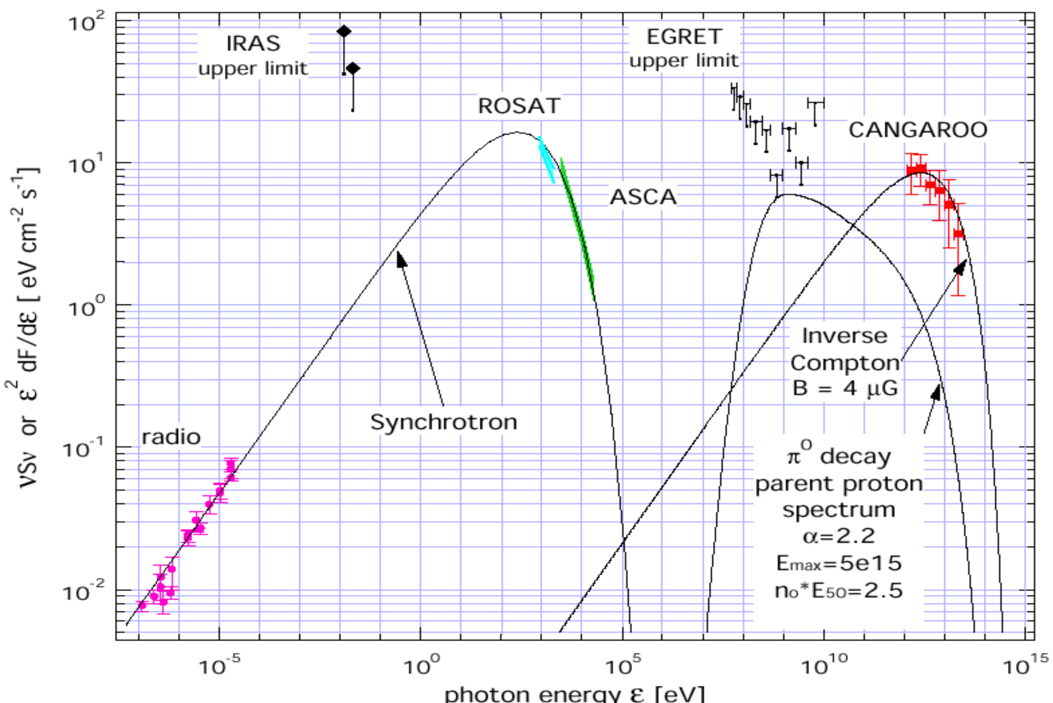
We are starting to get a detailed understanding of the workings of these HE sources …

Crab:

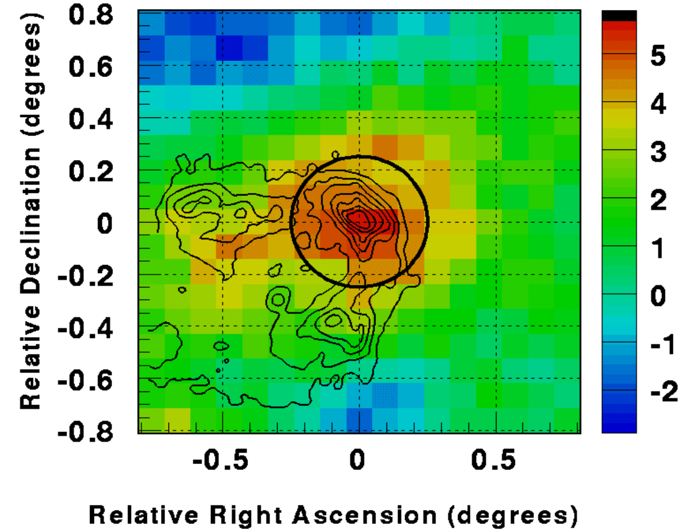
- Model of synchrotron and **IC** components.
- Constrains B field in Nebula and the degree of equipartition.



SN Remnants



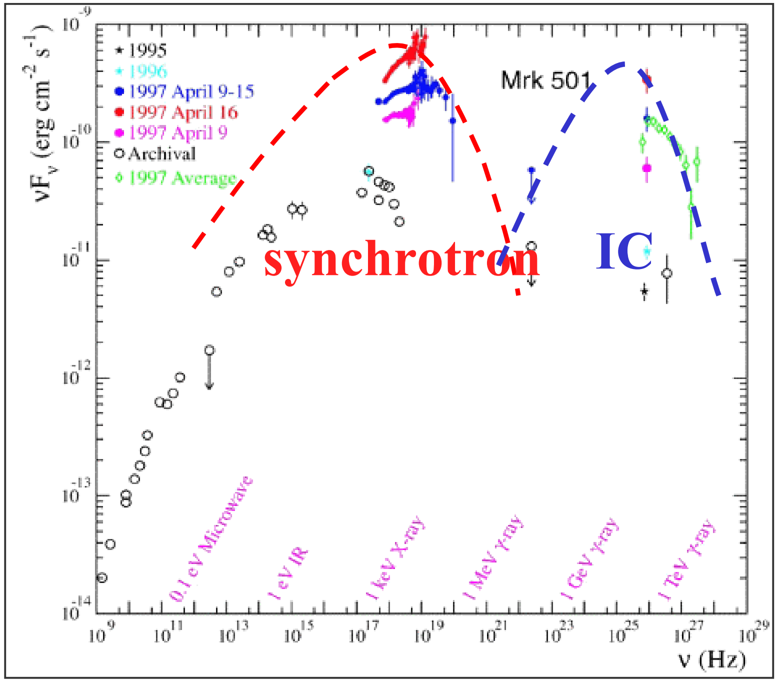
SN1006



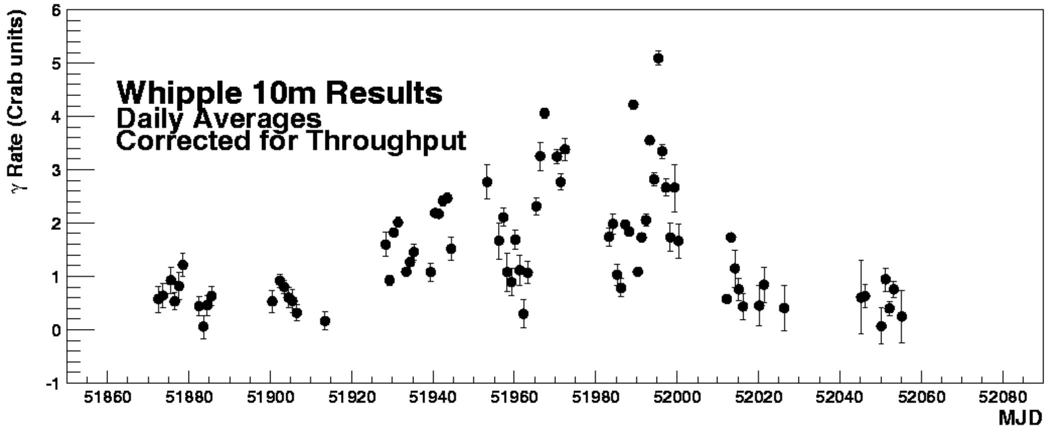
RX J1713

- 3 SNR's have been reportedly detected (??), but no "smoking gun" found for proton (CR) acceleration.

AGN Spectra and Variability



Mrk 501 SED

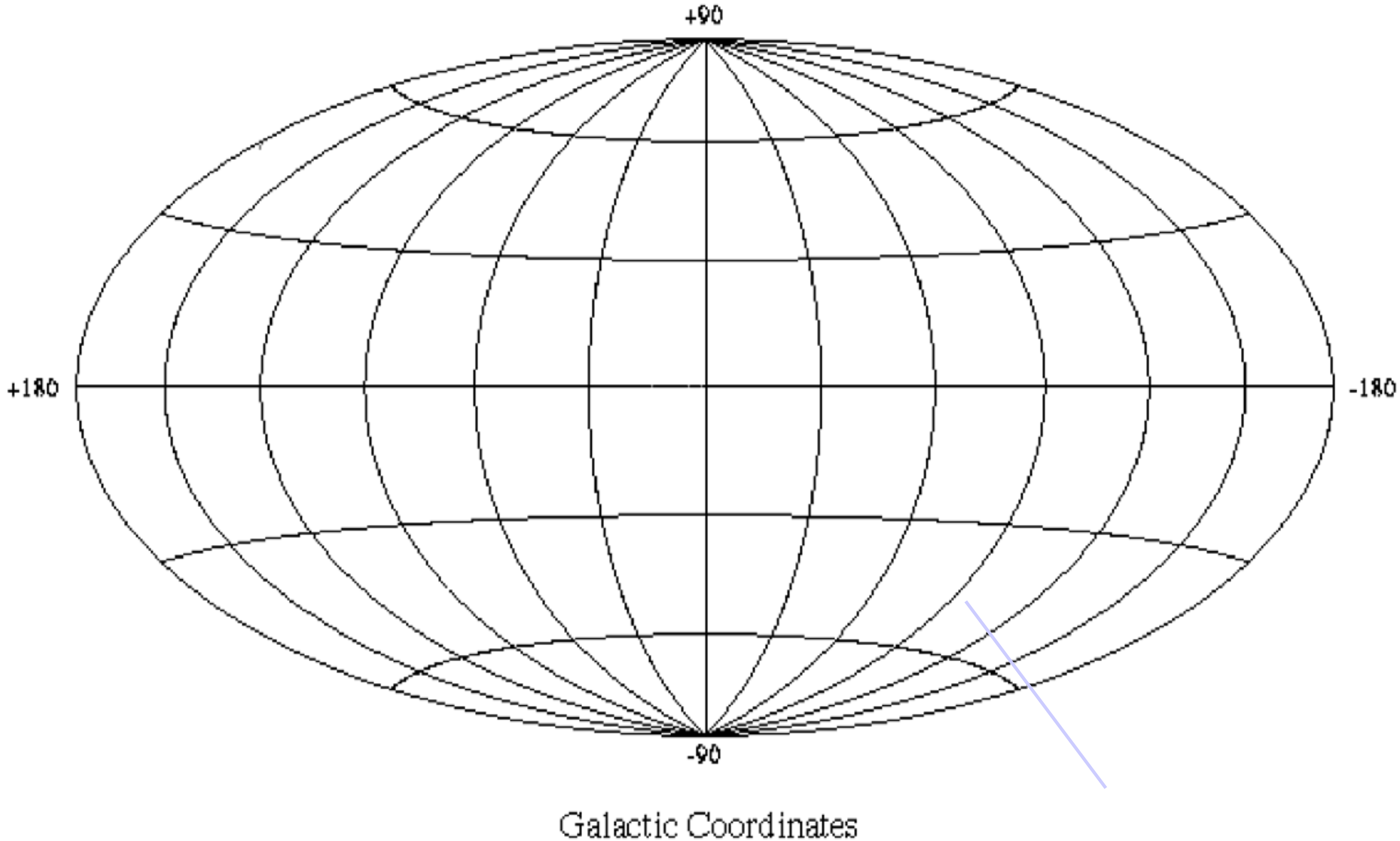


Mrk 421 Variability

Note: tiny error bars with clean sample of > 25,000 γ-rays!

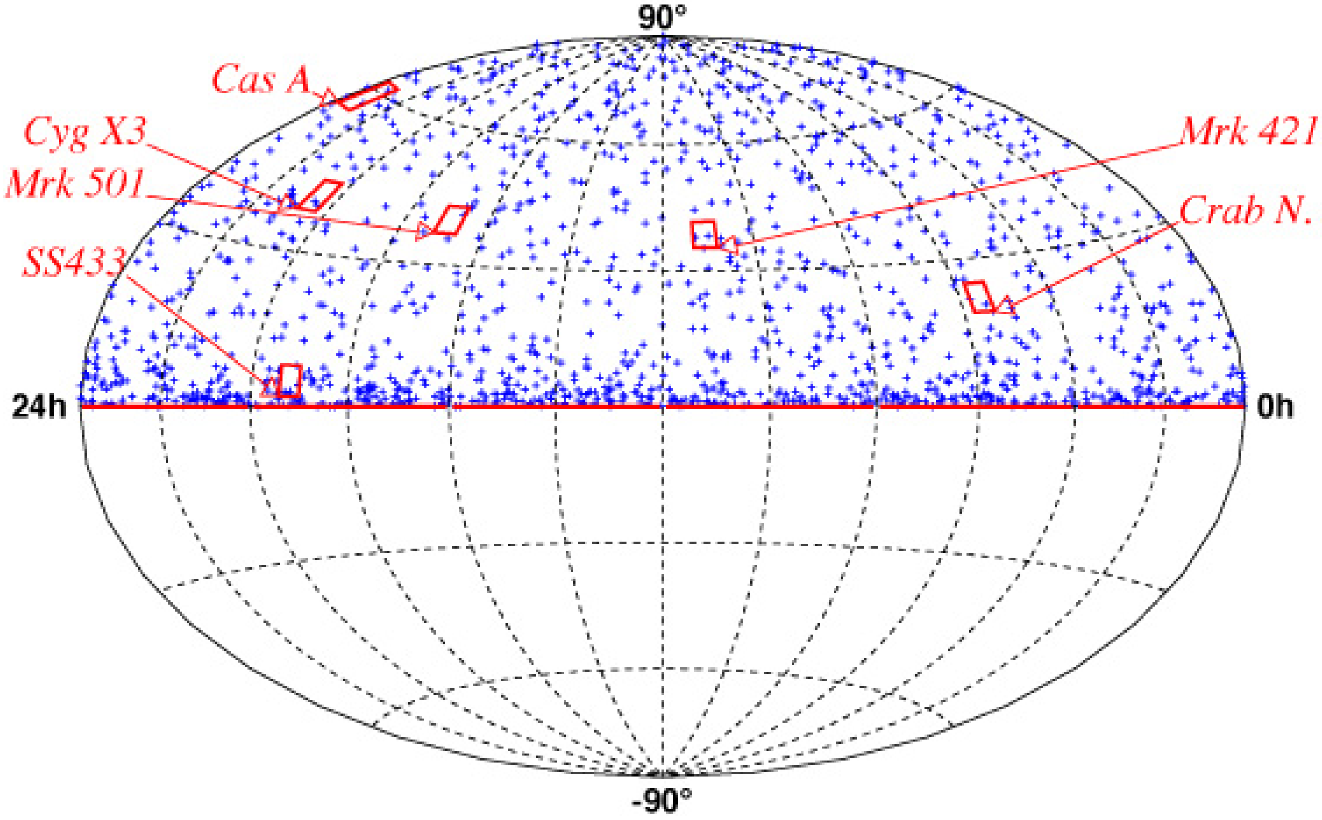
- Detailed spectral and variability measurements confront the models.
- Spectral variability now clearly detected.

HE ν Sky



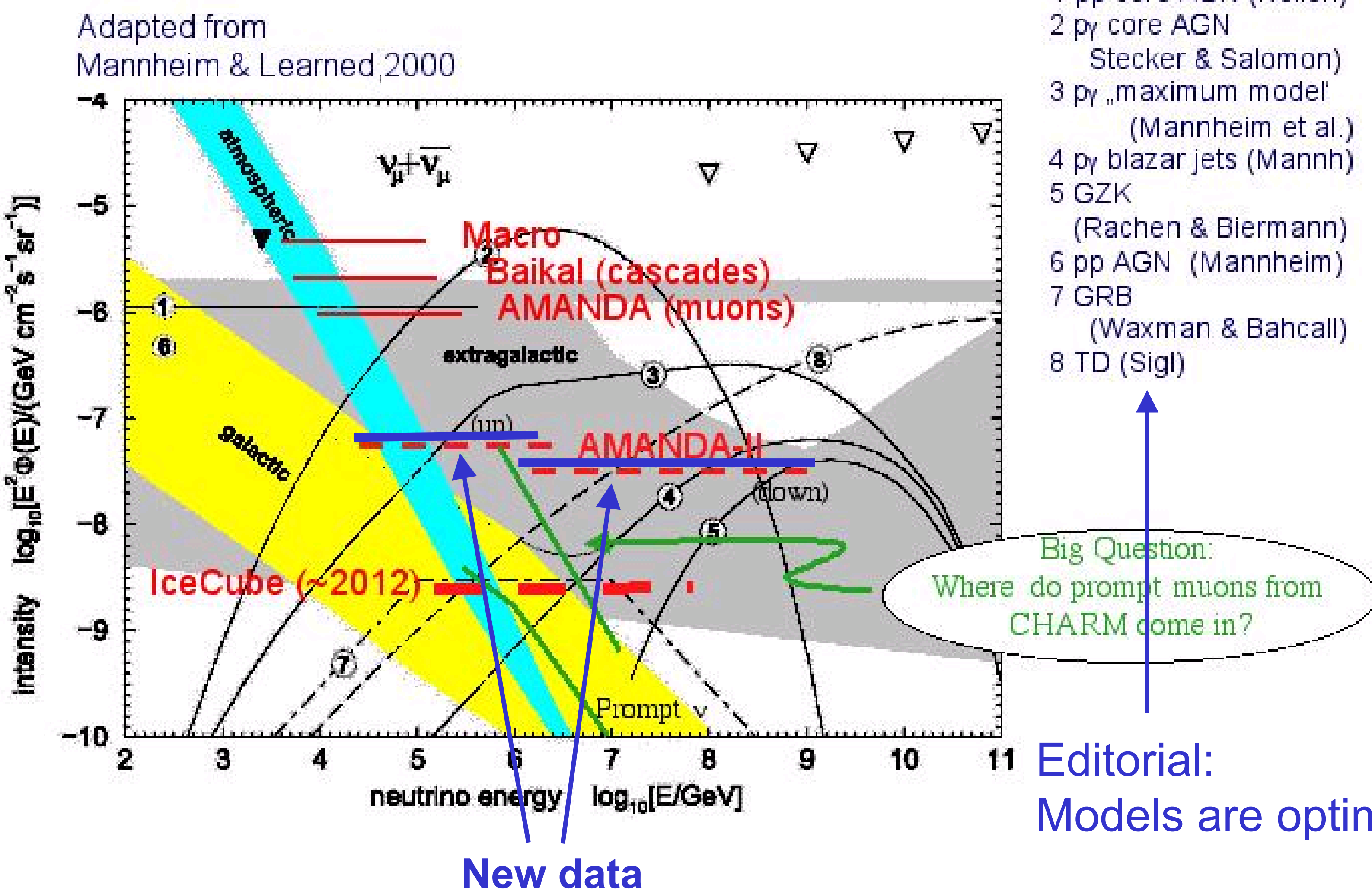
- No sources yet.

ν Limits (Point Source)



- AMANDA-II 2000 data: 1555 ν events.
- Flux limits within ~ factor of five of highest measured γ-ray flux.

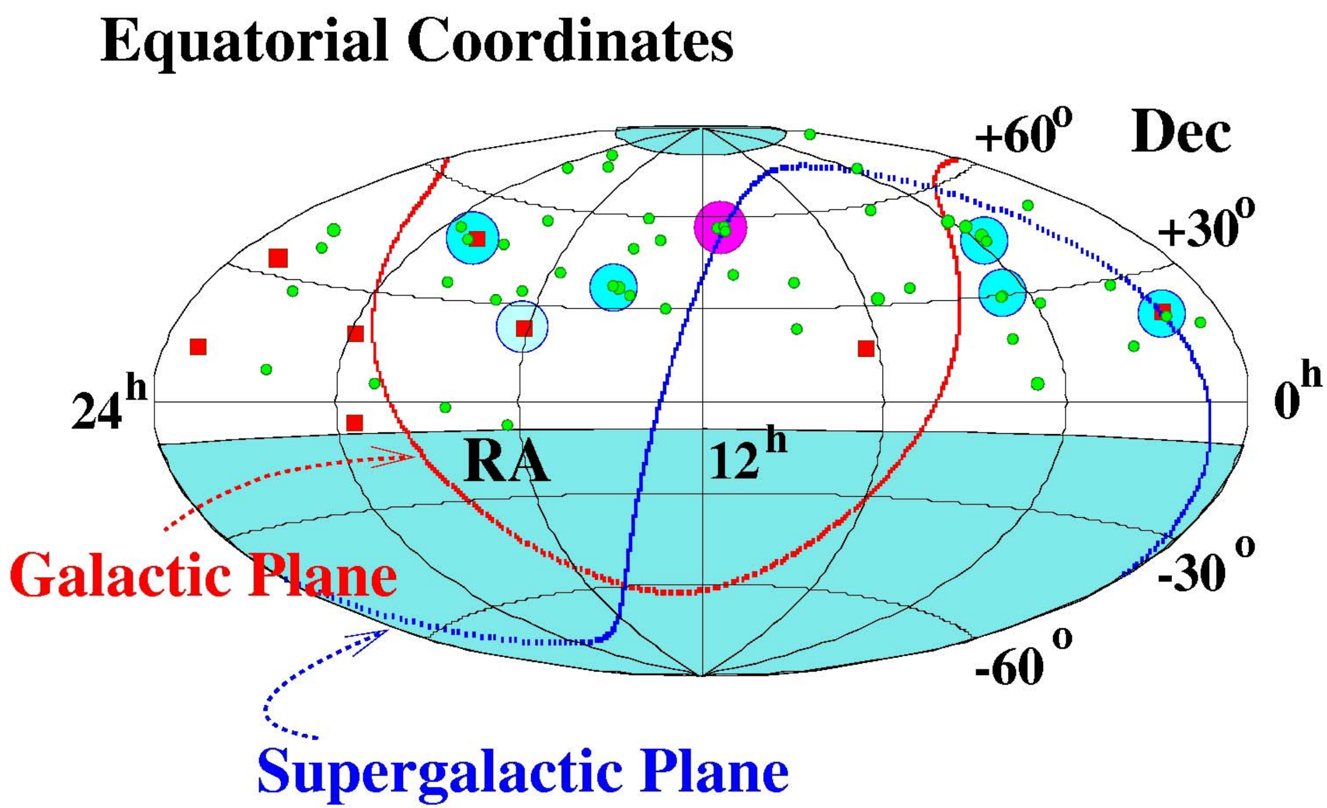
ν Limits (Diffuse)



1 pp core AGN (Nellen)
2 pγ core AGN
Stecker & Salomon)
3 pγ „maximum model'
(Mannheim et al.)
4 pγ blazar jets (Mannh)
5 GZK
(Rachen & Biermann)
6 pp AGN (Mannheim)
7 GRB
(Waxman & Bahcall)
8 TD (Sigl)

Editorial:
Models are optimistic.

> 10^{19} eV Sky



- Some evidence for clustering – not compelling.
- Low statistics !
- Should be much clearer in future.

(SOME) CONNECTIONS TO PARTICLE PHYSICS & COSMOLOGY

Topics

Selected topics:

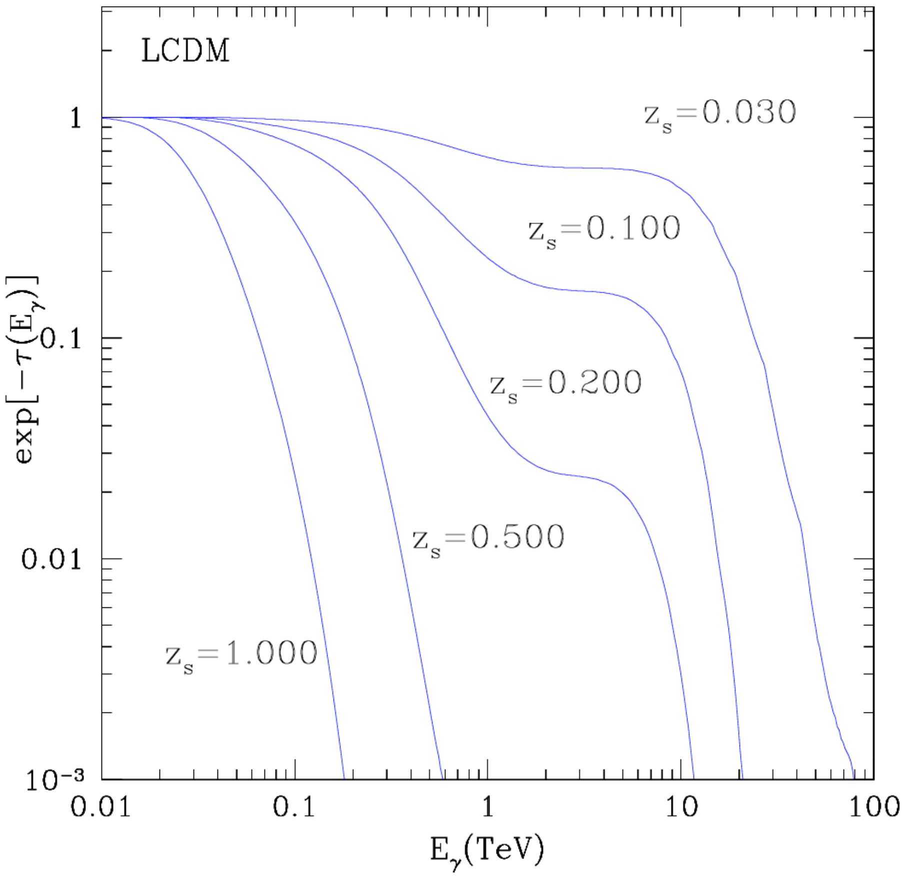
- Using γ-rays to measure diffuse radiation fields.
- SUSY & DM detection.
- "GZK Neutrinos".
- "Top-down" sources of $E > 10^{20}$ eV particles.

- (Using g-rays to probe space-time/quantum gravity ..
  → Testing fund. law at HE and long dist. scales).
- (Primordial black holes).

Much of this was nicely covered by John Ellis last Monday. Jonathan Feng will cover more.

Probing Intergalactic Space

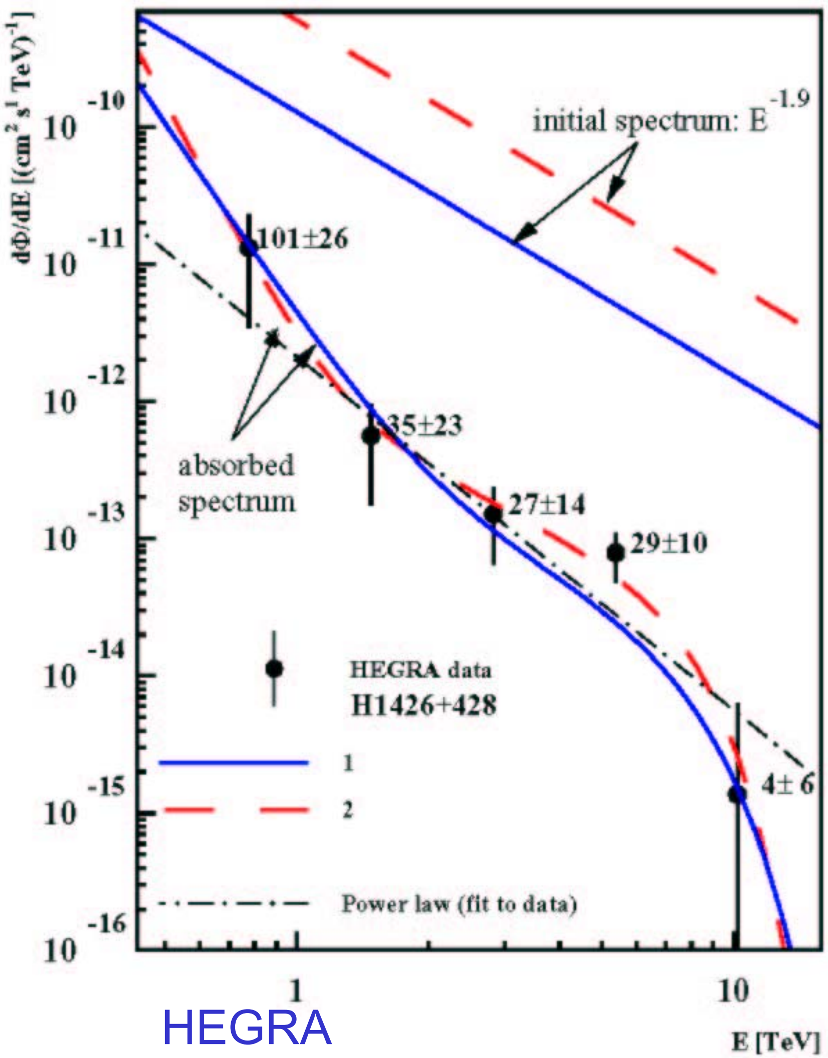
- 0.1 – 10 TeV γ-rays are absorbed by intergalactic radiation fields (IR/O/UV).
- These fields measure the total star/dust luminosity of Universe, but are poorly known.
- The γ-ray measurements have provided some of the best constraints to date.



(Primack et al. 1999)

Forward-evolution model.

Evidence for Absorption



HEGRA

- Some evidence for absorption from AGN already seen.
- Mrk 421/501 (z=0.03) see relatively little effect.
- More pronounced in H1426 at z=0.129. Very soft spectrum.

Need more sources at higher z.

→ Lower energy, better sensitivity.

STACEE telescope (New Mexico)

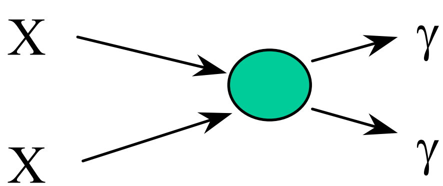
Fully operational at E=50-200 GeV.

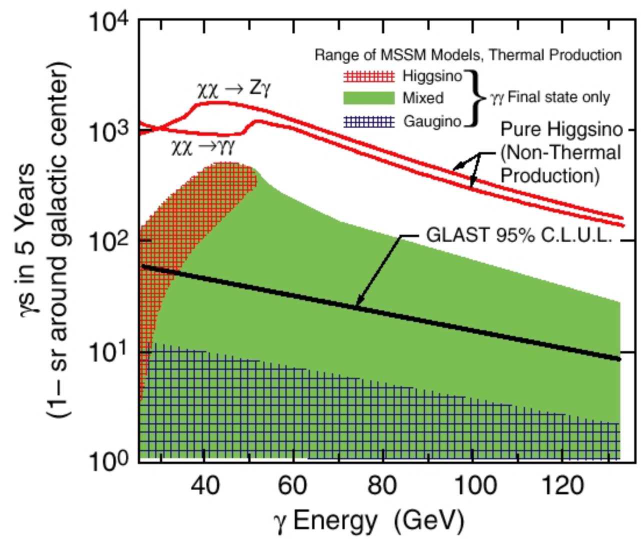
SUSY Detection

Galactic center

- Neutralinos can have enhanced density in GC.
- Annihilate to give g-rays with $E\gamma > 50$ GeV.
- Prospects depend strongly on the actual density.

Neutralino Annihilation

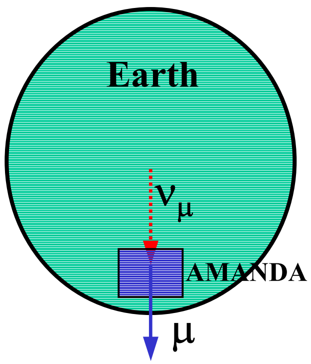


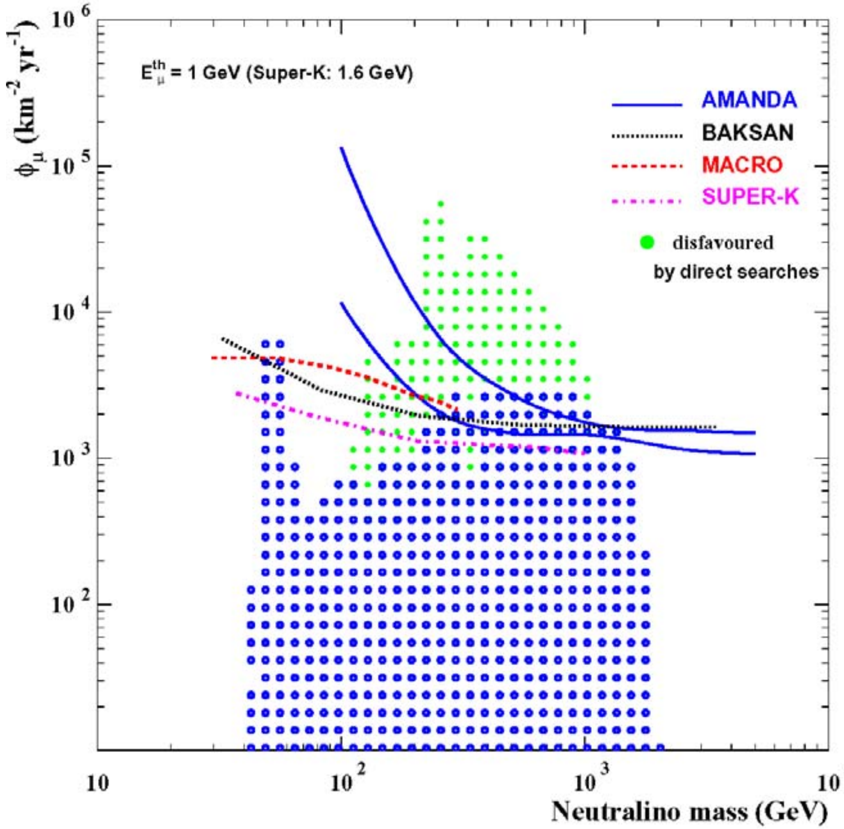


$$\text{Flux} \sim (\rho / M_x)^2 \, \sigma \, v$$

GLAST sensitivity

ν Detection of SUSY

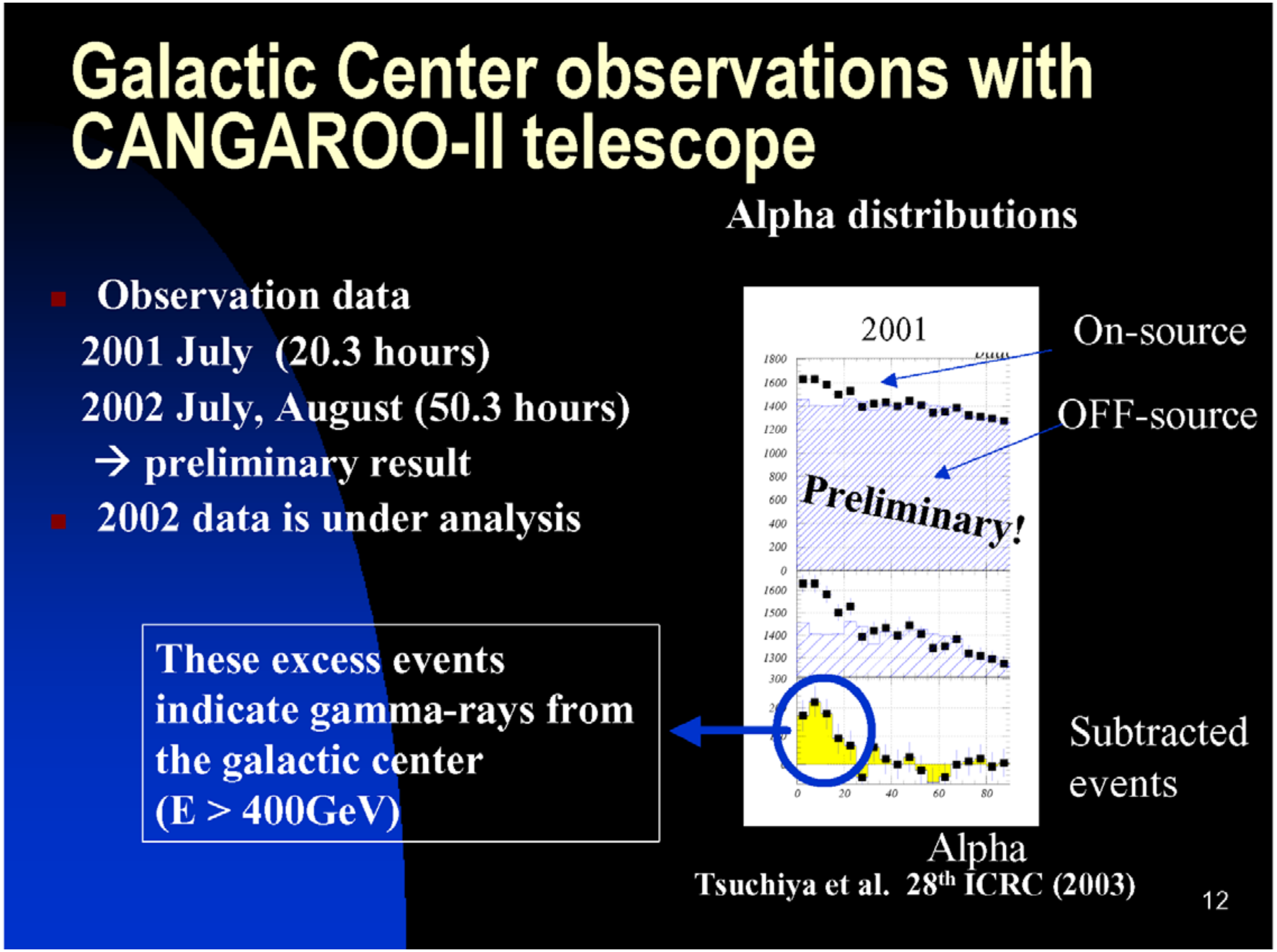




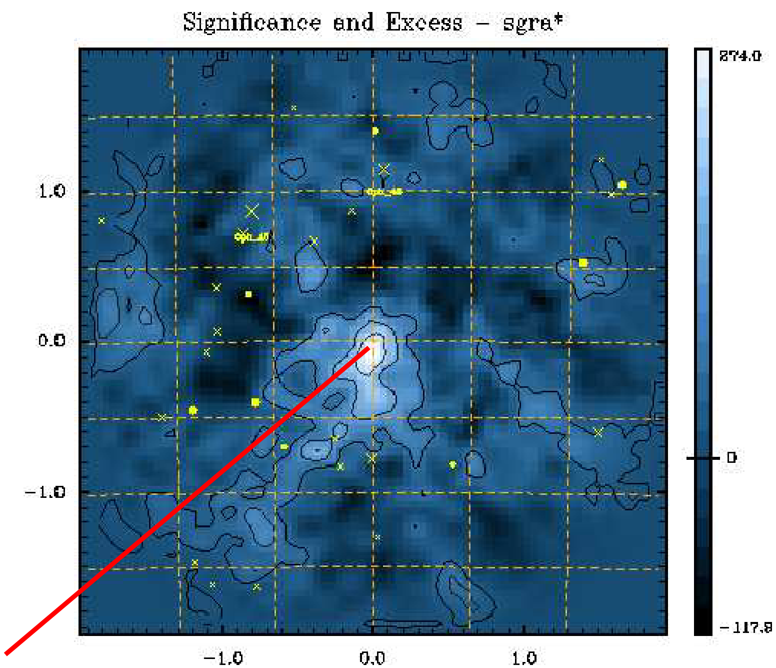
- WIMP's can get trapped in the center of the Sun/Earth.
- Annihilate → neutrinos.
- Sensitive to spin-dependent terms.

- AM-II results - eliminate the more extreme models.

Has DM Already Been Detected?



More on γ-rays

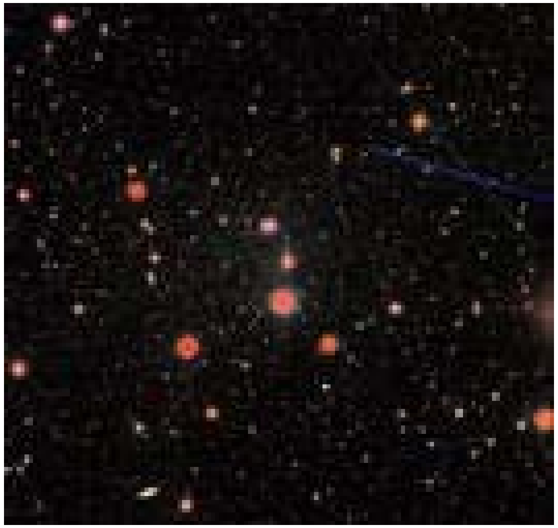


SGR A*

- Whipple result on GC
- Excess γ-ray map from 2000-2003 data (16 hrs).

STAY TUNED !

Core of Draco Dwarf



- Other good candidates include nearby galaxies with high mass/light: Draco, Ursa Minor, M32, M33.
- These are being pursued.

GZK Neutrinos

We expect neutrinos produced by the cascade particles in the GZK mechanism: **"GZK Neutrinos"**.

Process: $p\, \gamma_{cmbr} \rightarrow \Delta \rightarrow N\, \pi^{+/-} \rightarrow \nu$'s

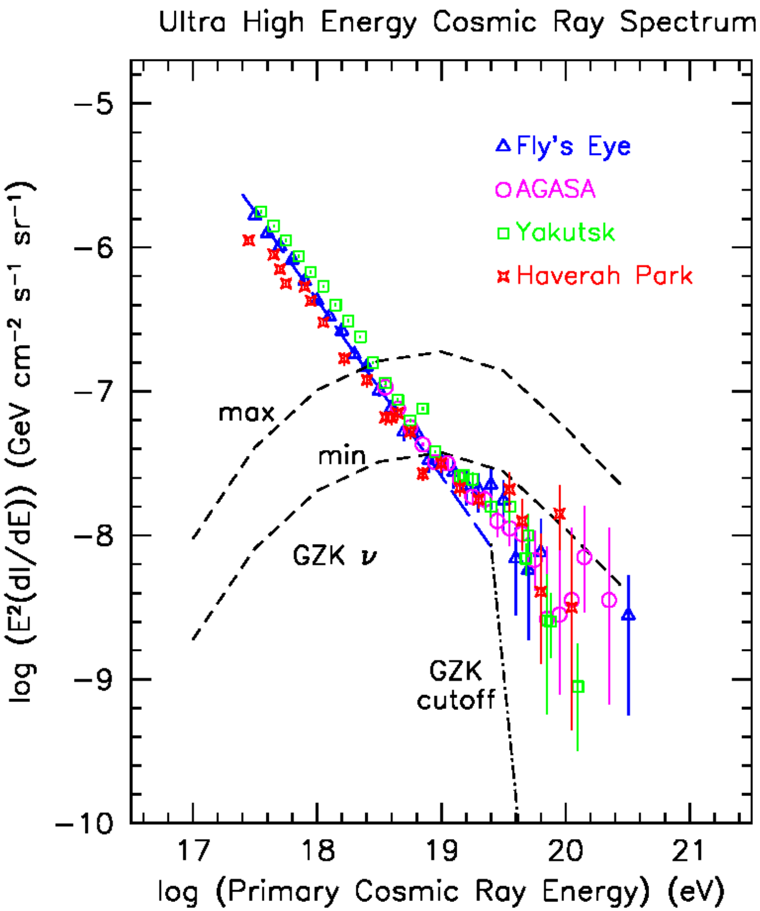
Flux will depend on:

- Distribution of sources of UHECR's.
  (Galactic sources = fewer GZK neutrinos)
- Upper end of the primary CR spectrum.
  (The higher, the better).

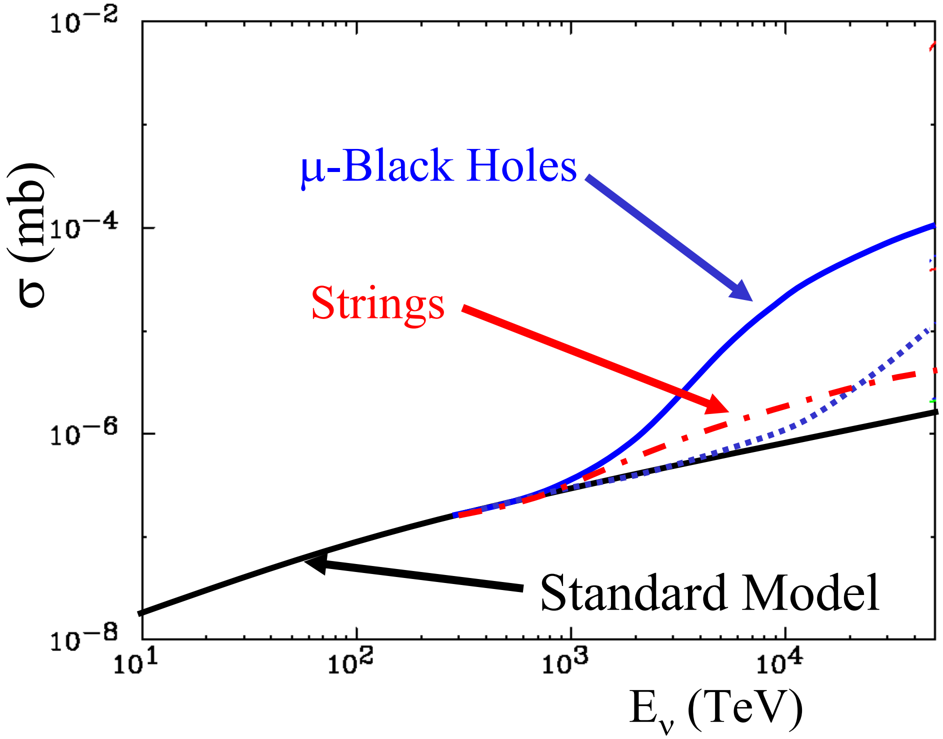
Detection of this diffuse flux would confirm our standard picture of the cutoff.

Guaranteed ?

GZK Neutrino Estimates



Predicted flux range.



Exciting possible enhancements.

"Top Down" Sources

There has been a cottage industry of folks working on ways to connect the highest-energy particles to new physics.

Ideas fall broadly into several camps:

- Radiation from topological defects.
- Decays of (massive) metastable relic particles.
  (e.g. heavy neutrinos that decay in the halo.
- Exotic neutrino interactions.
  (e.g. anomolous cross-sections, "Z-bursts")

Topological Defects

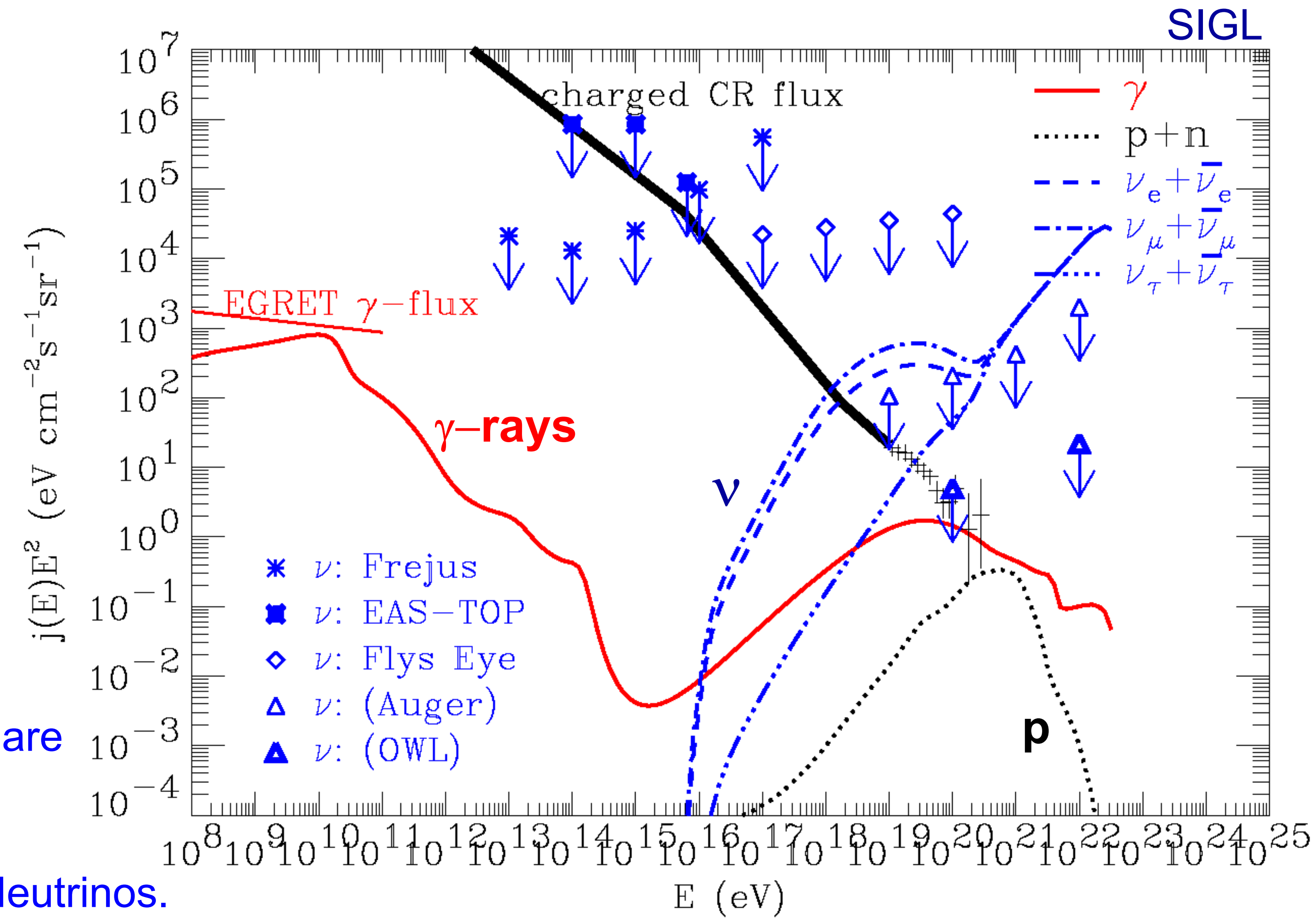
General Picture:

1. GUT Theories:
   - Unify forces at higher energy scale. Bigger gauge symmetry with gauge boson X.
   - X particles mediate q → l decay. Proton decay limits $m_x > 10^{15}$ GeV.
   - Allows baryons to freeze out earlier → higher density.

2. Phase transitions:
   - Associated with symmetry breaking – have certainly taken place in early Universe.
   - If transition is not "perfect" – leads to topological defects (Kibble).

3. Topological Defects (TD's):
   - Various types: Monopoles, Cosmic strings, domain walls (large).
   - Monopoles are a problem (inflated away). Strings might exist and decay to X → ql → UHE CR's.

TD Predictions



UHECR's are Photons !

Copious Neutrinos.

Metastable Superheavy Relics

Very interesting possibility. General picture:

MSRP's:

- Mass M > 10^{12} GeV.
- Long, but finite lifetime.
- Decay via instanton effects – violation of some conserved quantum #.
- Variety of candidates and scenarios.

Properties:

- Relation between lifetime and abundances must be satisfied.
- Lifetime ~ 10^{10} yr, abundance is relatively small $\Omega h^2 \sim 3 \times 10^{-12}$.
- Behaves like CDM – cluster in galactic halo – contribution there exceeds the extragalactic contribution (factor of 10?).

- Expect almost total suppression of GKZ effect !
- Not bound by EGRET γ-ray bkgnd limit.
- Possible anisotropy due to our location in MW galaxy.

Z - Bursts

"Z-bursts" : Very creative explanation for the > 10^{20} eV particles.

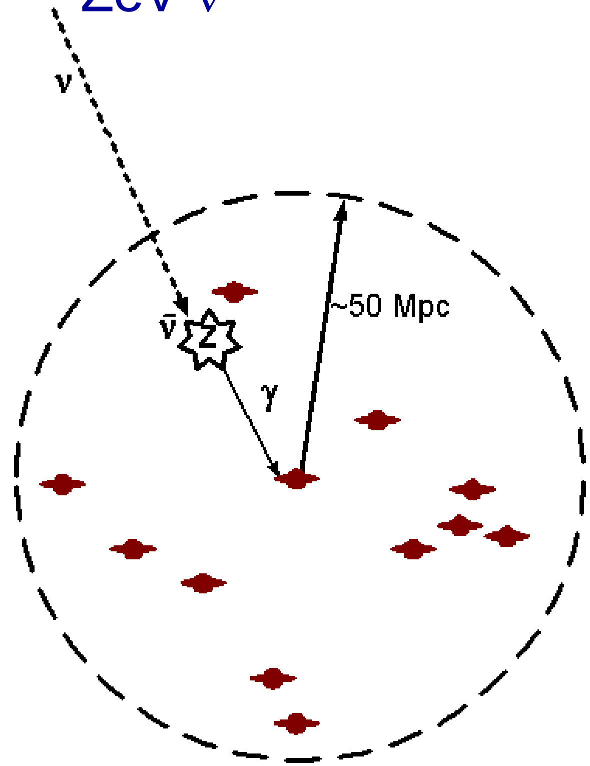
ν (E>ZeV) + ν_{2k} → Z_o → γ's,π's, N's

- Explains UHECR origin. High γ/p.
- MFP is just about right.
- Detect relic neutrinos.
- Consistent with Δ(m) neutrinos.

"Only" catch:

We need very powerful sources of ZeV neutrinos distributed throughout Universe.

ZeV ν



Weiler

The Next 5 Years

There is a remarkable range of phenomena associated with HE particles in the Universe. In the next 5-10 years, we hope to answer some of the major questions and make new, unexpected discoveries. Here, we highlight <u>some</u> of the experimental efforts.

An incomplete list of new projects:

- Gamma-rays: CANGAROO, <u>GLAST</u>, HESS, MAGIC, <u>SWIFT</u>, VERITAS
- Neutrinos: ANTARES, <u>ANITA</u>, IceCube, NEMO, NESTOR
- Cosmic-rays: Auger, <u>EUSO</u>, <u>OWL</u>, Telescope Array

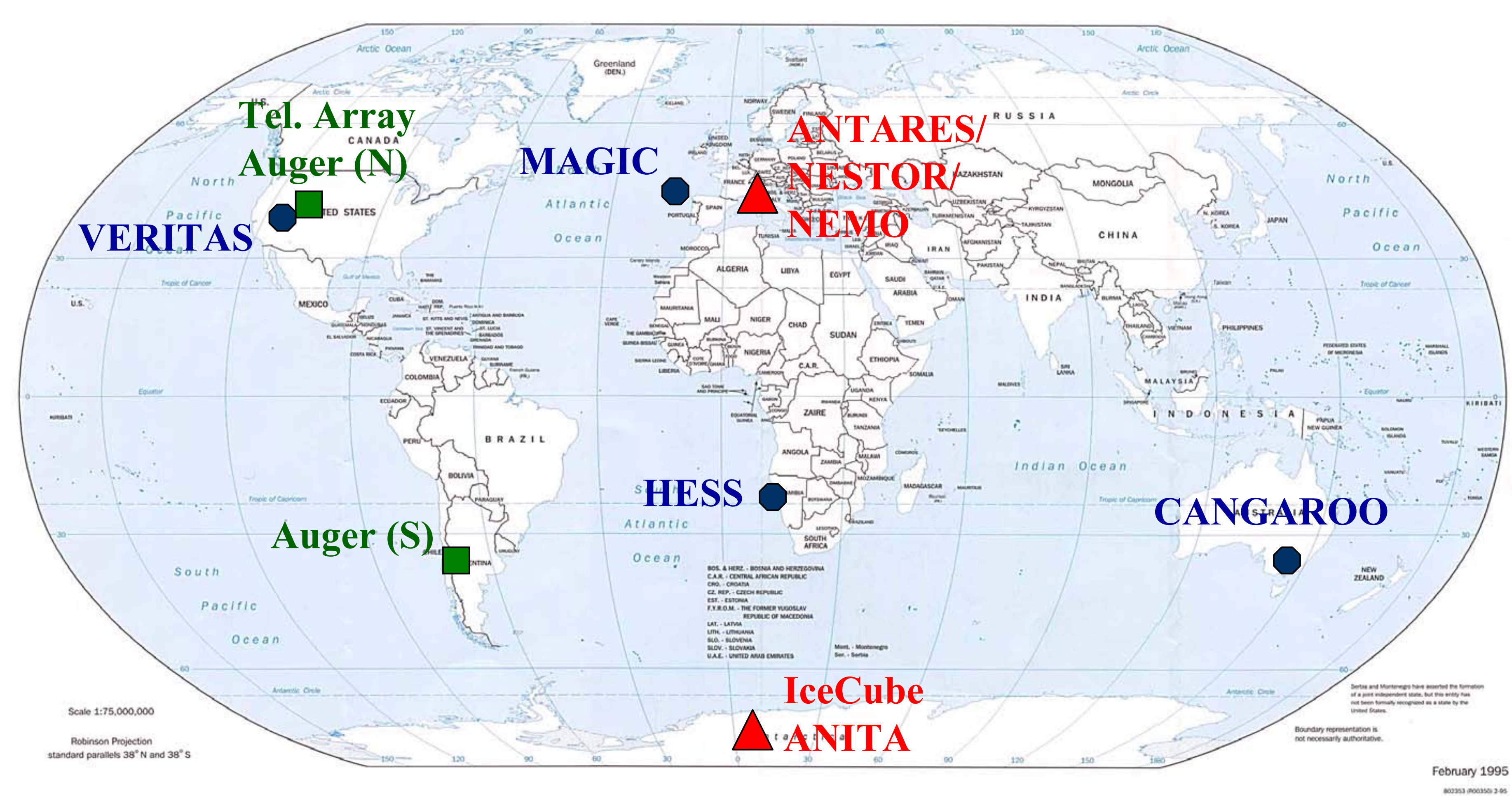
(Underlined = balloon/space based.
Above 10^{17}eV, detectors typically have sensitivity to multiple messengers).

Future Experiments

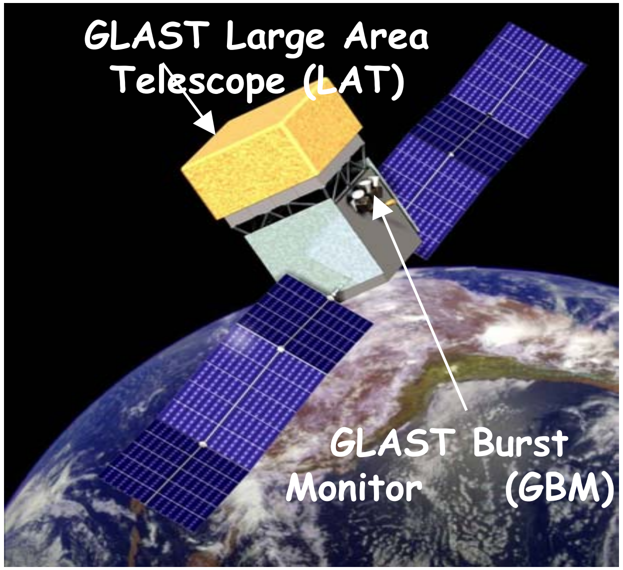
In space

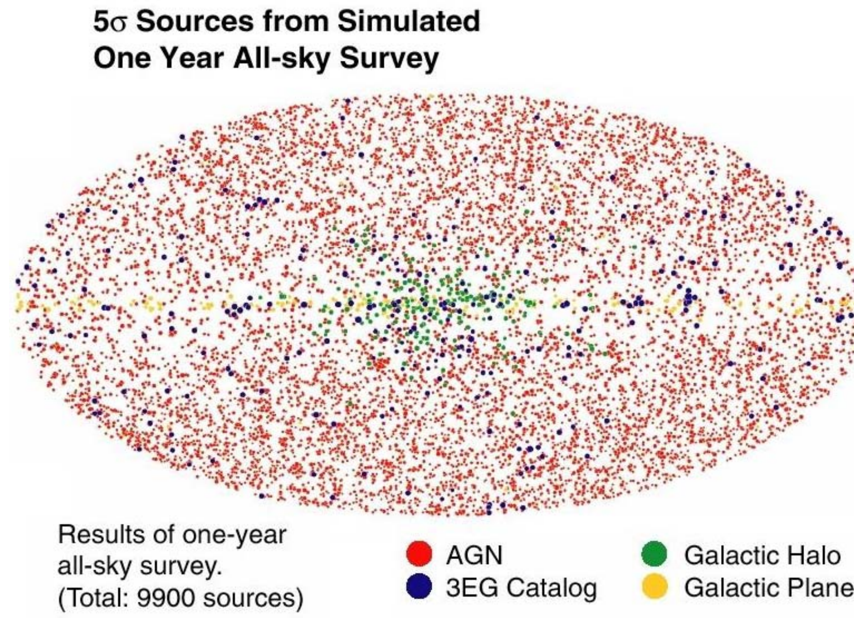
- SWIFT, GLAST
- EUSO, OWL

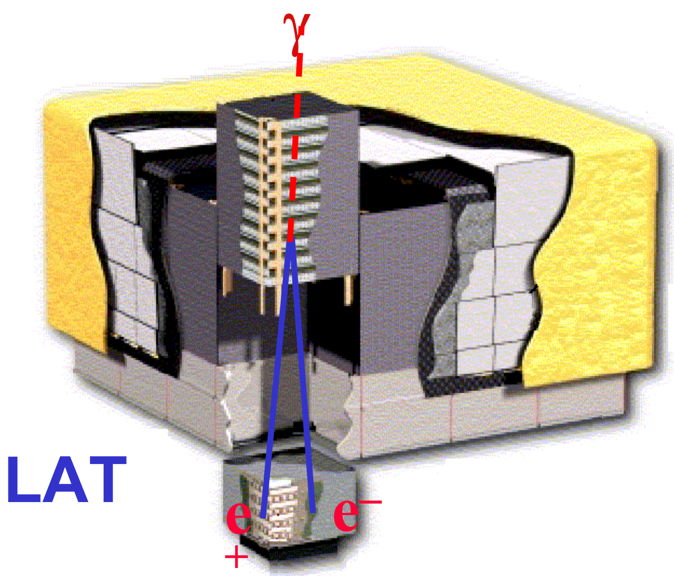
- ■ CR experiments
- ⬣ γ-ray telescopes
- ▲ Neutrino telescopes



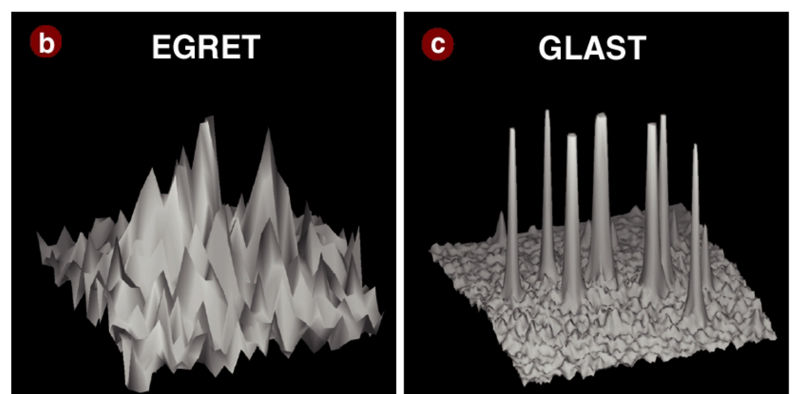
GLAST



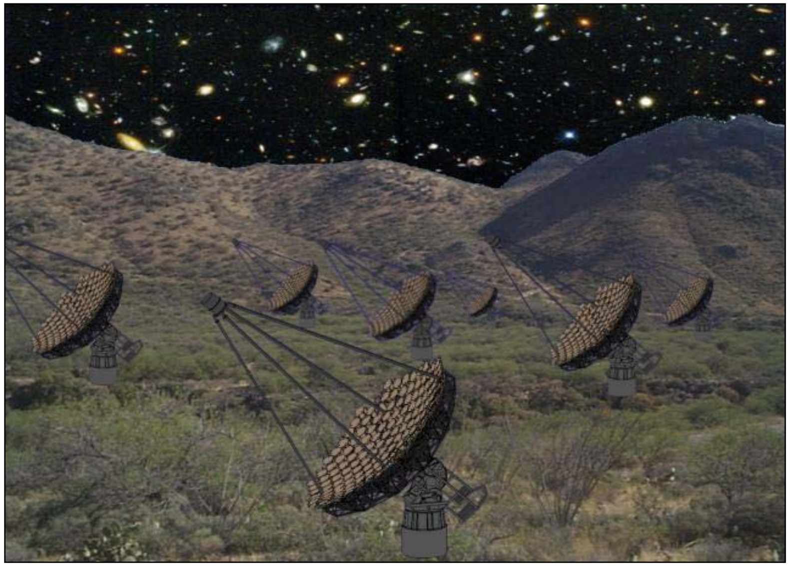


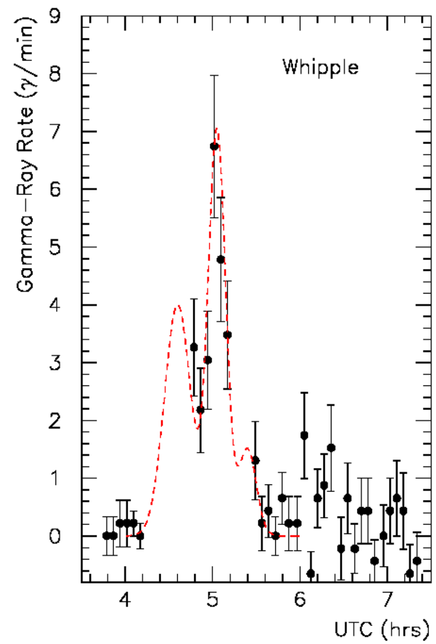


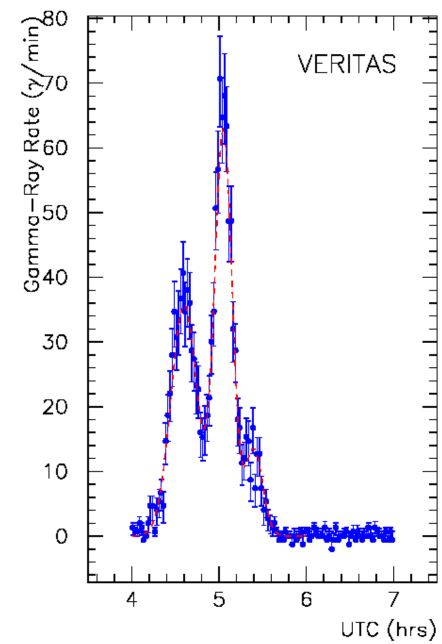
Many more sources, better localized.



VERITAS







AGN Signal

- Seven 12m reflectors.
- Site in southern Arizona.
- 5-10 sensitivity improvement.
- 6’ ang. resolution.
- Four telescopes in 2006.

500 MHz FADC

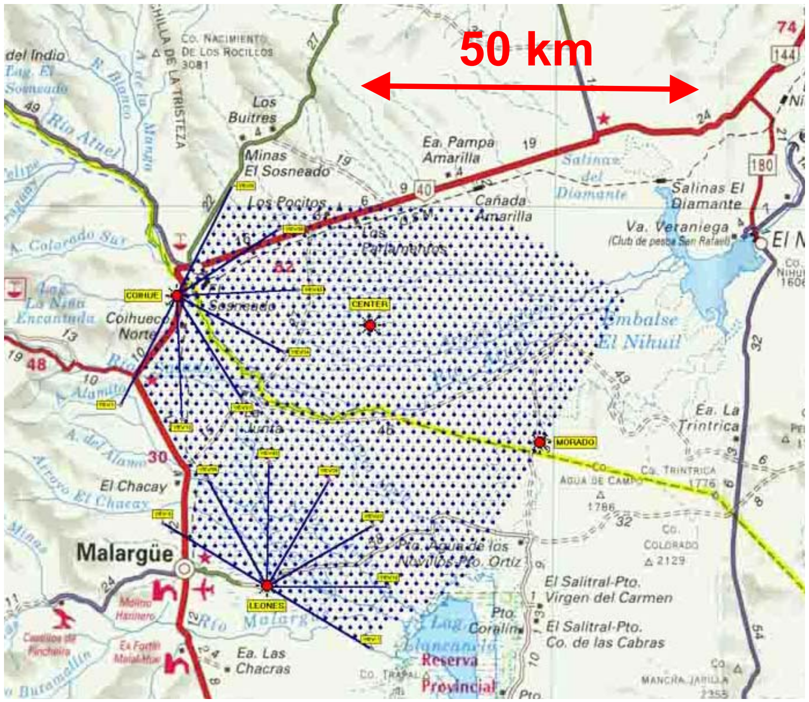
VERITAS & HESS

VERITAS is fully underway. (Finally)

First 12 reflector & Electroncs

HESS (Namibia)
Fully operational in 2004.

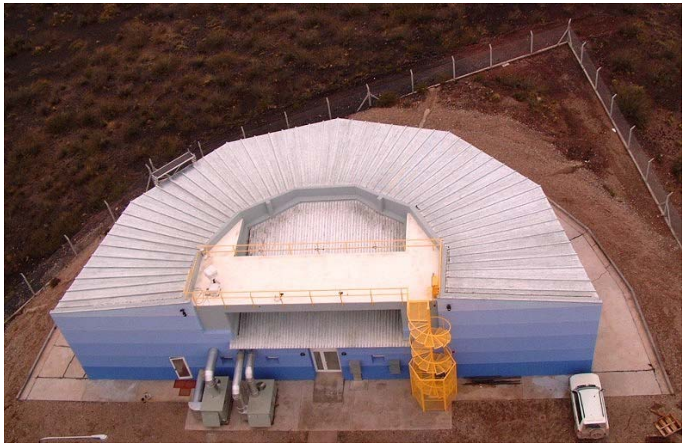
Auger Project



Surface detector in place.

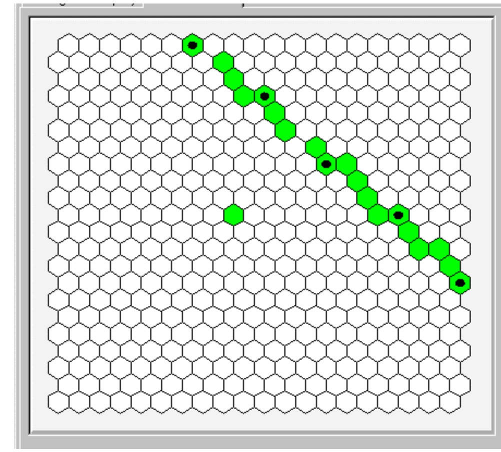
- Southern site in Argentina
- 1600 water detect., 4 fluorescence.
- > 3,000 km^2.
- Construction complete in 2006.

Auger Project

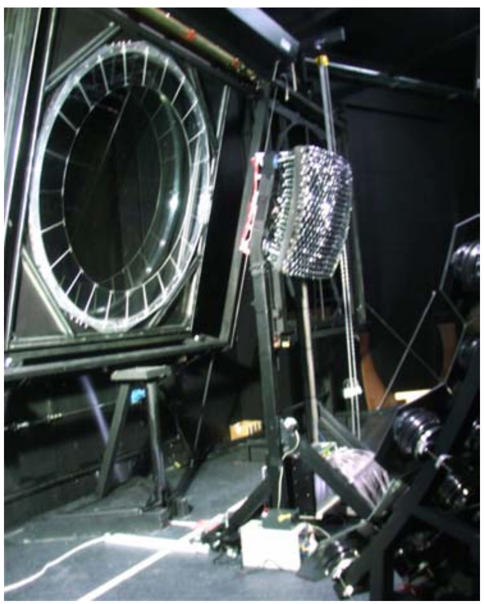


Hybrid Events

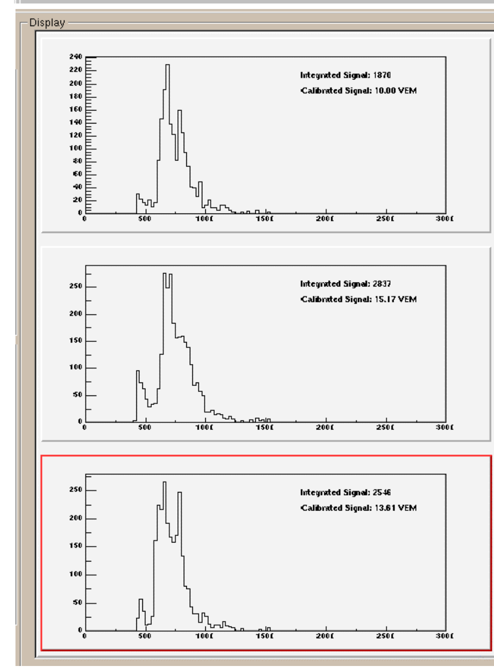
Fluoresence →



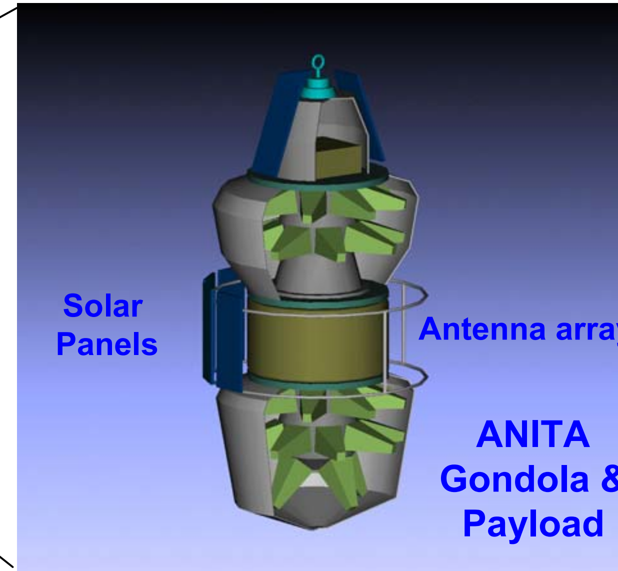
Fluoresence detector



Surface →



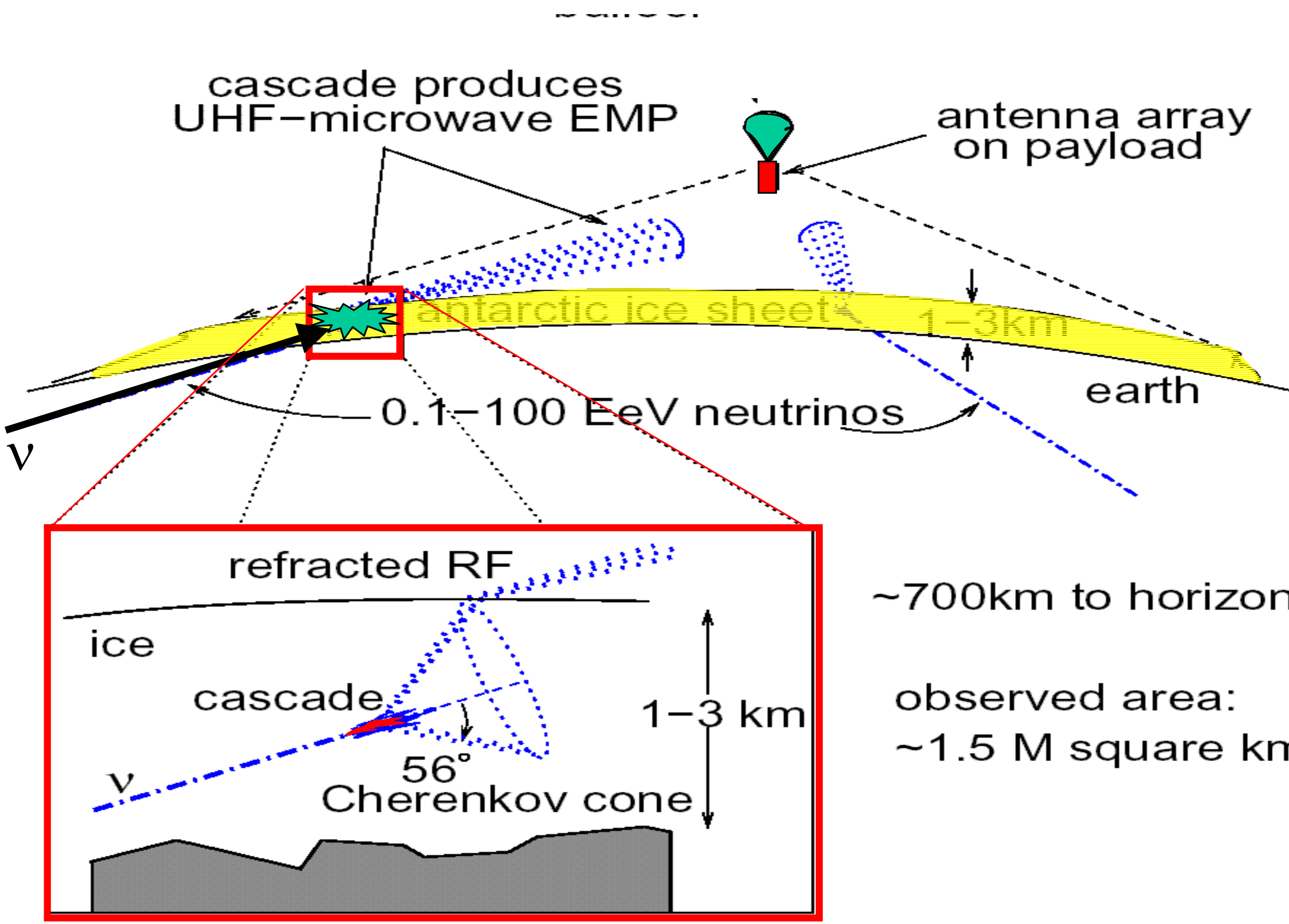
ANITA



ANtarctic Impulsve Transient Antenna

- Neutrino detection via Cherenkov radiation in South Pole ice.
- Enormous collection area.
- Intensity gradient, timing, polarimetry used to reconstruction ν shower.
- Sensitive to GZK neutrinos.

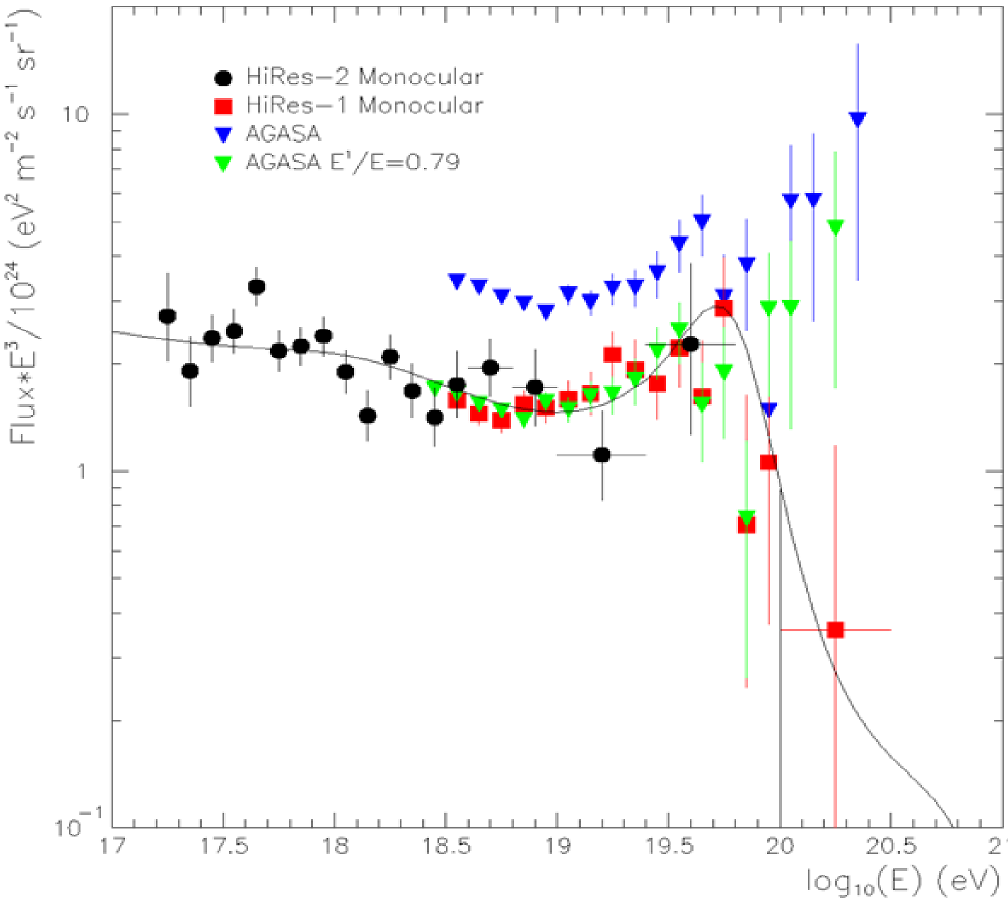
ANITA



~700km to horizon

observed area:
~1.5 M square km

So, what are the >10^{20} eV events?



- Statistics are insufficient.
- Energy calibration an issue.
- Auger will greatly improve.

Personal perspective:

- Spectrum continues.
- Relatively local.
- Larger B fields.
- Astrophysical, but not understood (NEW).

Crucial to probe even higher in energy!

Summary

- Studying very HE particles provides unique tests of the limits of physical laws.
- Probing astrophysics in regimes not well understood. Deep mysteries to be solved.
- Detection techniques are innovative and derive partially from particle physics.
- Great potential for discovery of physics beyond our standard models. (But, this physics is not yet required).

"The real voyage of discovery consists, not in seeking new landscapes, but in having new eyes."

Marcel Proust (1871-1922)