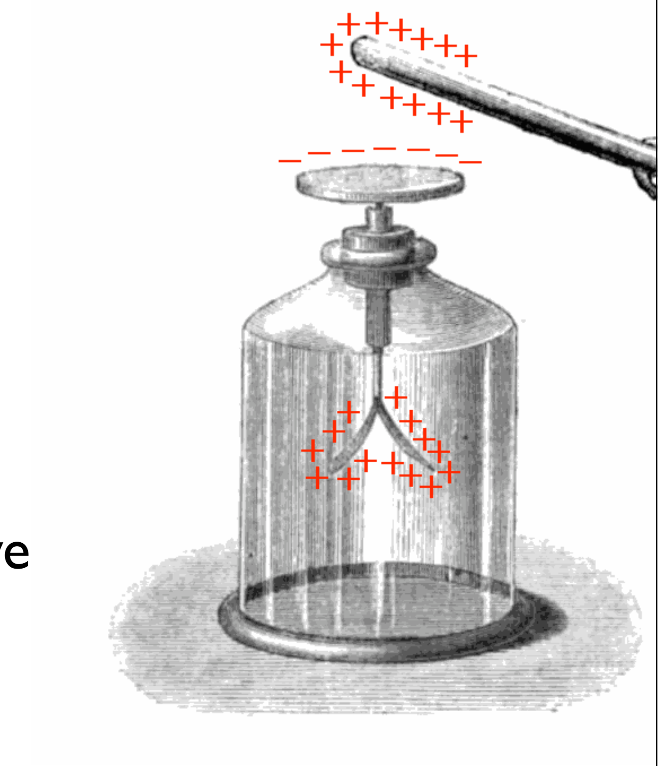
# High Energy Astrophysics I. Cosmic Rays & Neutrinos

*Péter Mészáros*
*Pennsylvania State University*

**NIC2014, Debrecen,**

# What are Cosmic Rays?



- **Early 1900s:** ***Electroscopes*** near radioactive radiation sources ***discharge***; at rate which is proportional to the radiation intensity
- However, even ***far*** from radioactive sources, the electroscope discharges slowly → some ***other*** source of radiation- but ***what?***
- **1910-1913:** various experiments try to identify sources. Italian physicist **Domenico Pacini** → if ***descend below*** the sea: → radiation intensity ***decreases with depth!***
- Austrian physicist **Victor Hess**, ***1911-13***: go ***up*** in ***balloons*** ≤ ***5 km*** altitude: radiation ***intensity*** first decreases for first km, but then ***increases with altitude !*** (..comes from above ***?!!***)

# Where the wild things come from

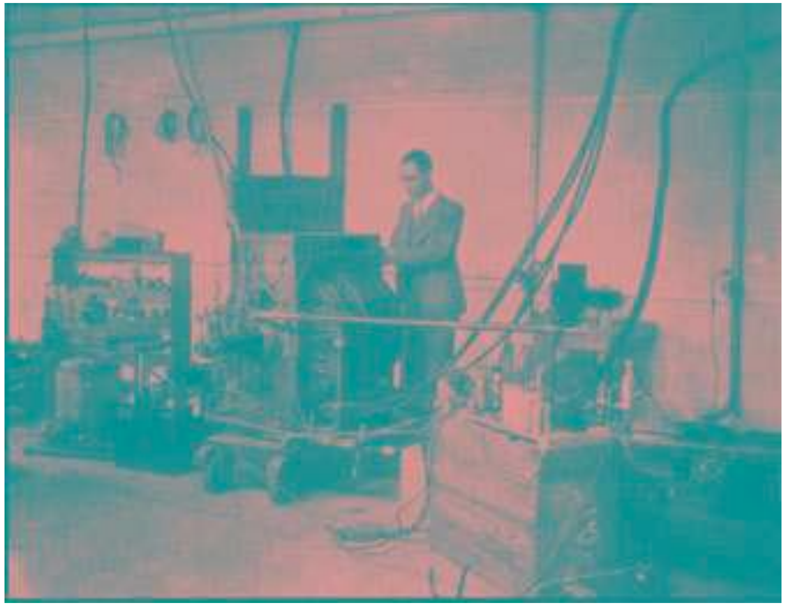
- Victor Hess at start of one of his ten balloon flights *(no oxygen)*
- One flight during total solar eclipse: radiation intensity did not change → ***not*** solar origin. Origin must be ***extraterrestrial!***
- Was 29 years old when he did these observations. *"A radiation of very high penetrating power enters the atmosphere from above".*
- Awarded the Physics Nobel Prize in 1936

# Mounting Clues

- A.H. Compton measured cosmic ray rates around the world (1935)
- Lemaitre, Vallarta, Johnson, Alvarez: incoming CRs follow Earth's ***geomagnetic*** latitude
- East-West asymmetry: the parent cosmic rays must be ***(positively) charged particles***

[ CR slides credit: Stephane Coutu ]

# New discoveries from CR atmospheric showers using new apparatus

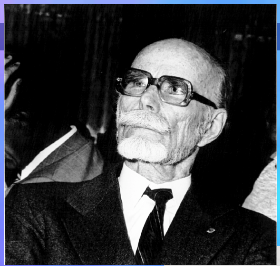


- ***Positrons*** (1932): Anderson -first antimatter
- ***Gamma-***rays (early 30s): Blackett, Occhialini
- ***Muons*** (1947-53): Anderson, Neddermeyer, Street, Stevenson (1936-37)
- ***Pions*** (1947): Occhialini, Powell, Lattes
- ***Kaons*** (1947-53), ***Lambda*** (1951), ***Xi*** (1952), ***Sigma*** (1953).....
- → Birth of ***particle physics !***

# Further progress

So far, all particles seen are made in the atmosphere...

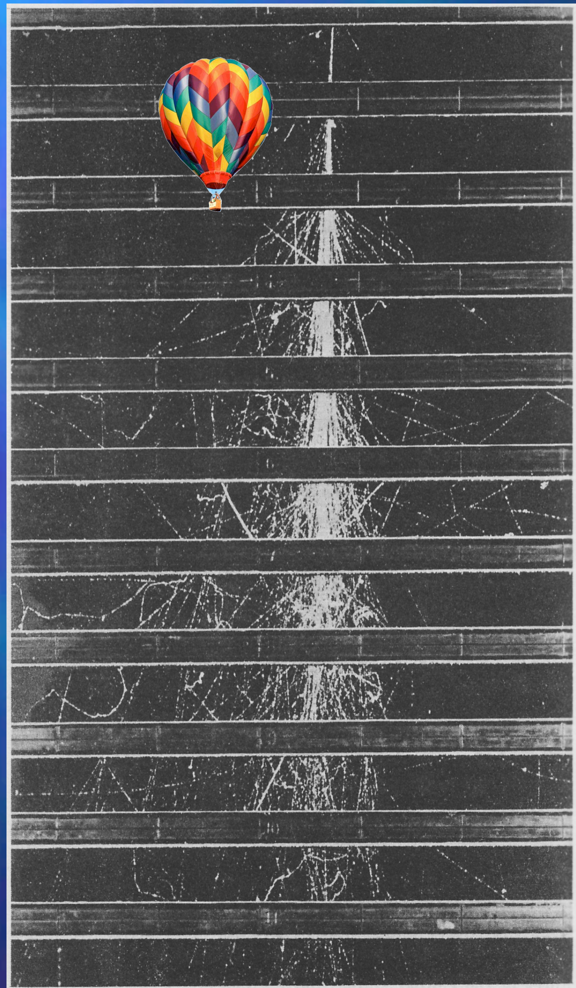
Pierre Auger discovers extensive air showers in 1938



[ CR slides (blue bkg.) credit: Stephane Coutu ]

Cosmic rays can be extraordinarily energetic > $10^{15}$ eV (millions of times the energy in the mass of a proton).

high energy particle

number of particles grows up to a maximum

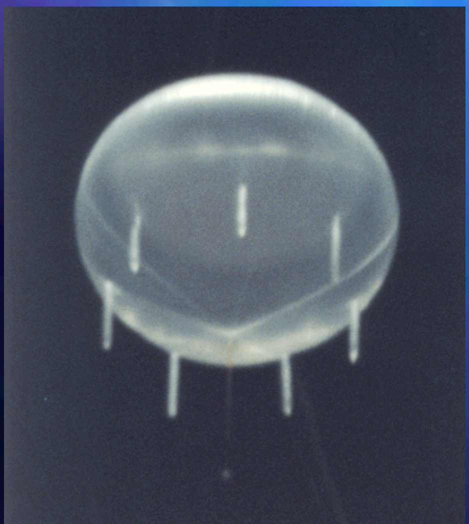
particles are depleted by absorbing material

Used balloons too (automated)

# Direct measurements

Starting in late 1940s, unmanned balloons up to 130,000 ft, up to tens of hours;
direct measurements of cosmic particles become possible;

- primary cosmic rays are 85% protons (1940s);
- there are nuclei too, 12% helium, 2% Li-Fe (1948-50);
- there are 1% electrons too (1961).

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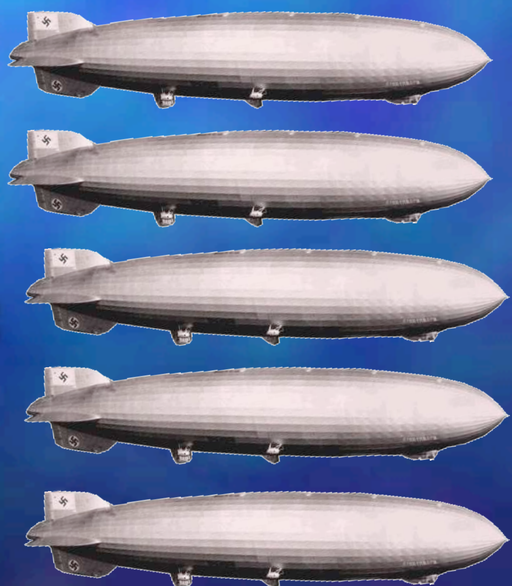
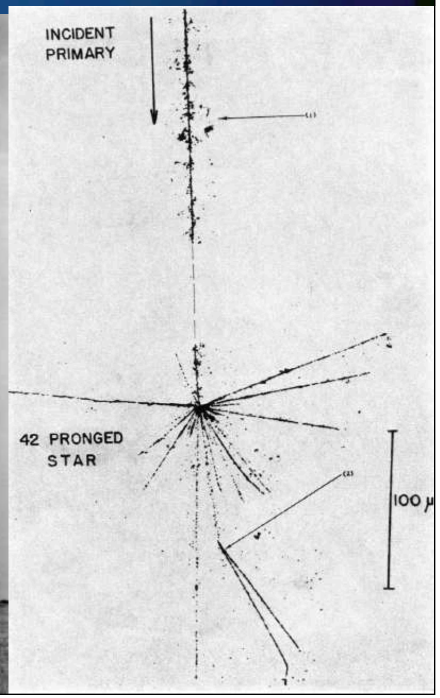
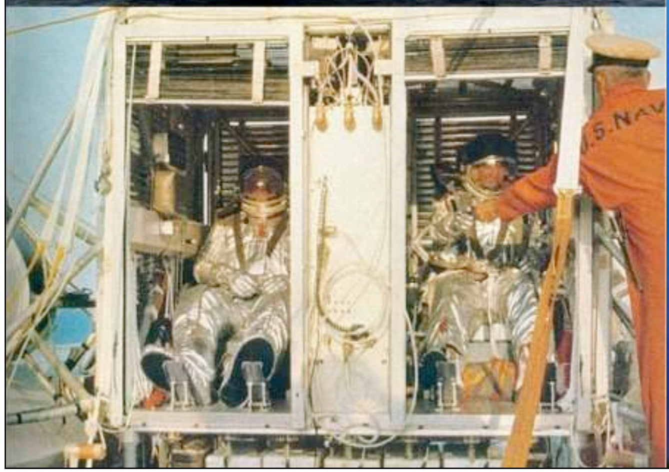




# Ballooning in the news

Stratolab 5, May 4, 1961
114 kft (Malcolm Ross ok,
Vic Prather drowned);
next day: Alan Shepard
on Mercury Freedom 7



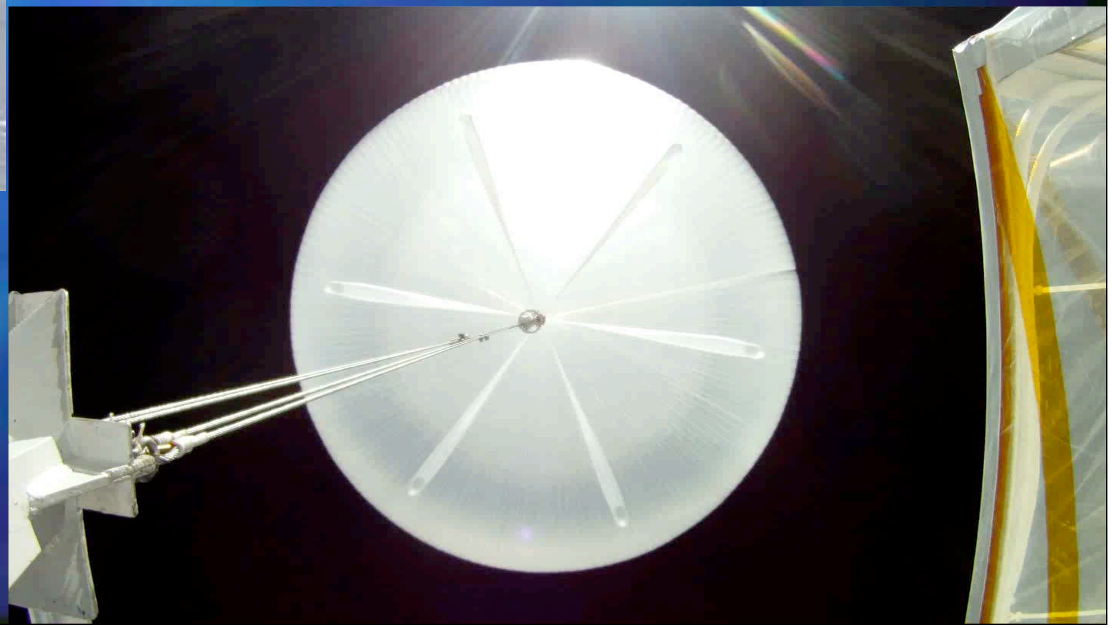
Nuclear Compton Telescope

NCT, Alice Springs, Apr 29, 2010 :
***the dangers of science .....***

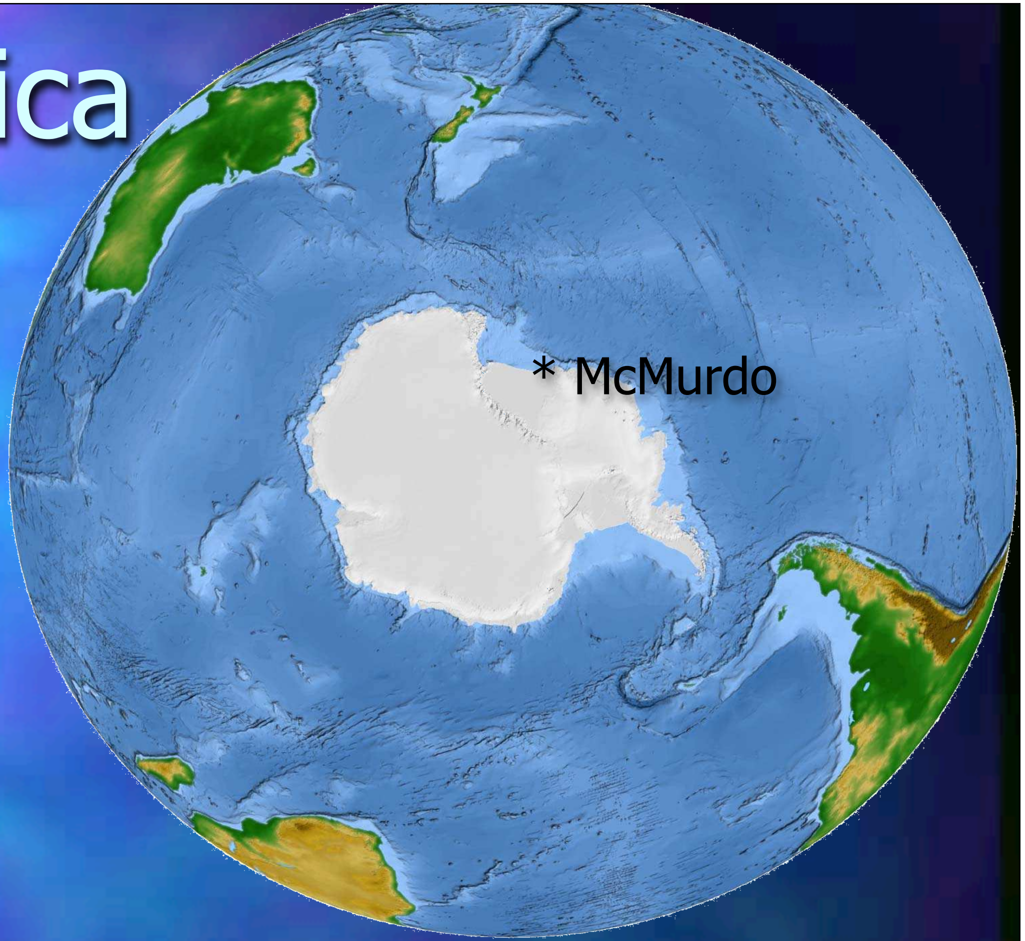
# Direct measurements

Since 1987: launches from McMurdo, Antarctica; flights up to 42 days!

## NASA/Columbia Scientific Balloon Facility (CSBF)



# Getting to Antarctica



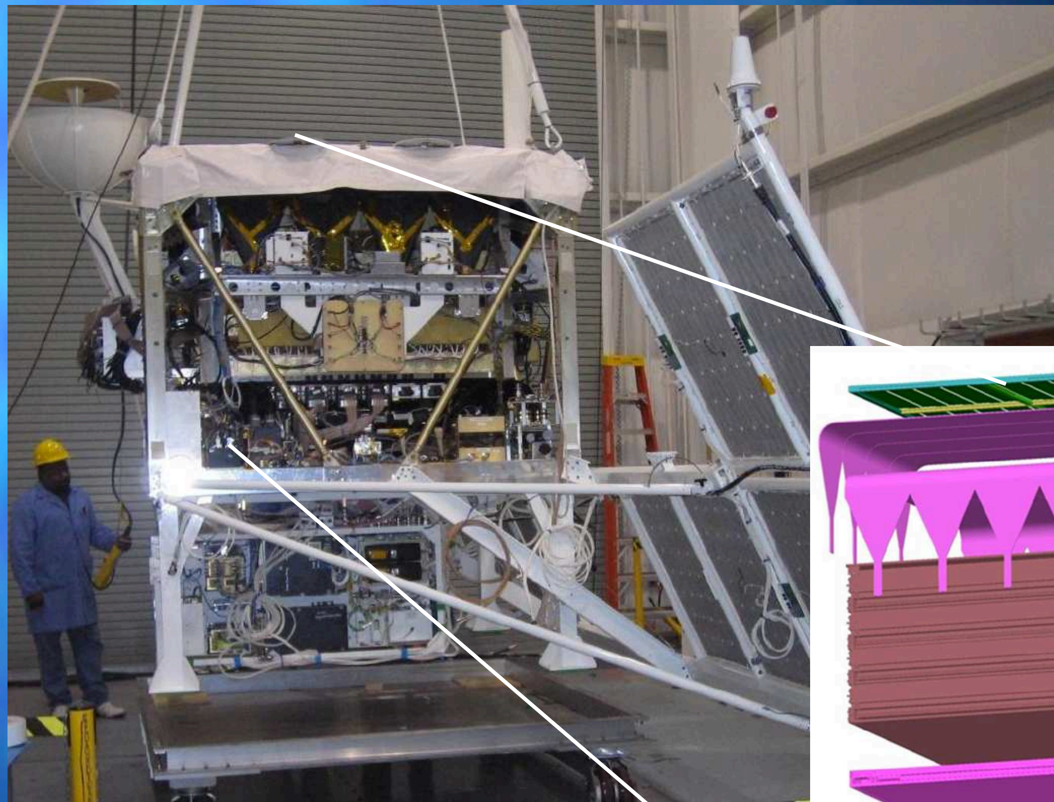

# McMurdo

# CREAM
# (Cosmic Ray Energetics And Mass)

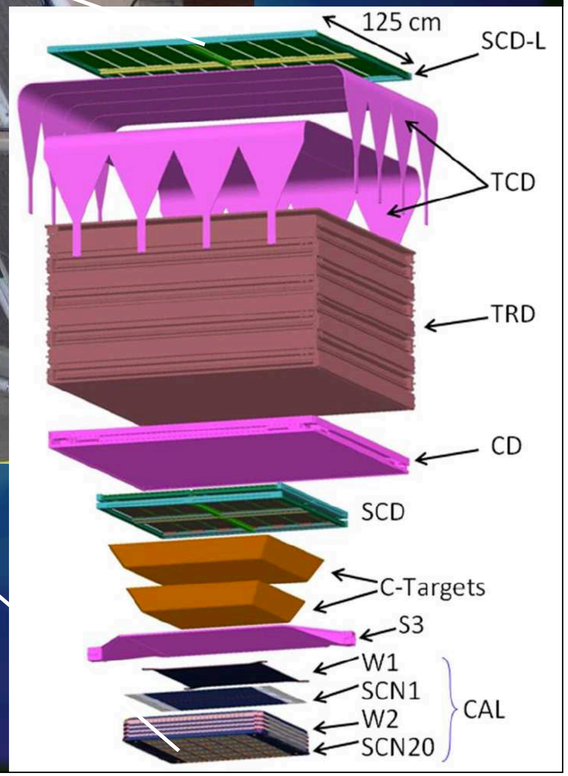
Since the 1960s, ever larger, more complex instruments flown on large balloons for longer durations;

e.g.: CREAM:

- 2004-present,
- 6 Antarctic flights,
- 160 days of exposure,
- flight 7 in Dec 2013.



Mass 1,300 kg, Power 400 W




Measure elemental energy distributions from H to Fe, from 100 GeV to ~200 TeV/nucleus (100 to 200,000 times the energyin a proton mass).

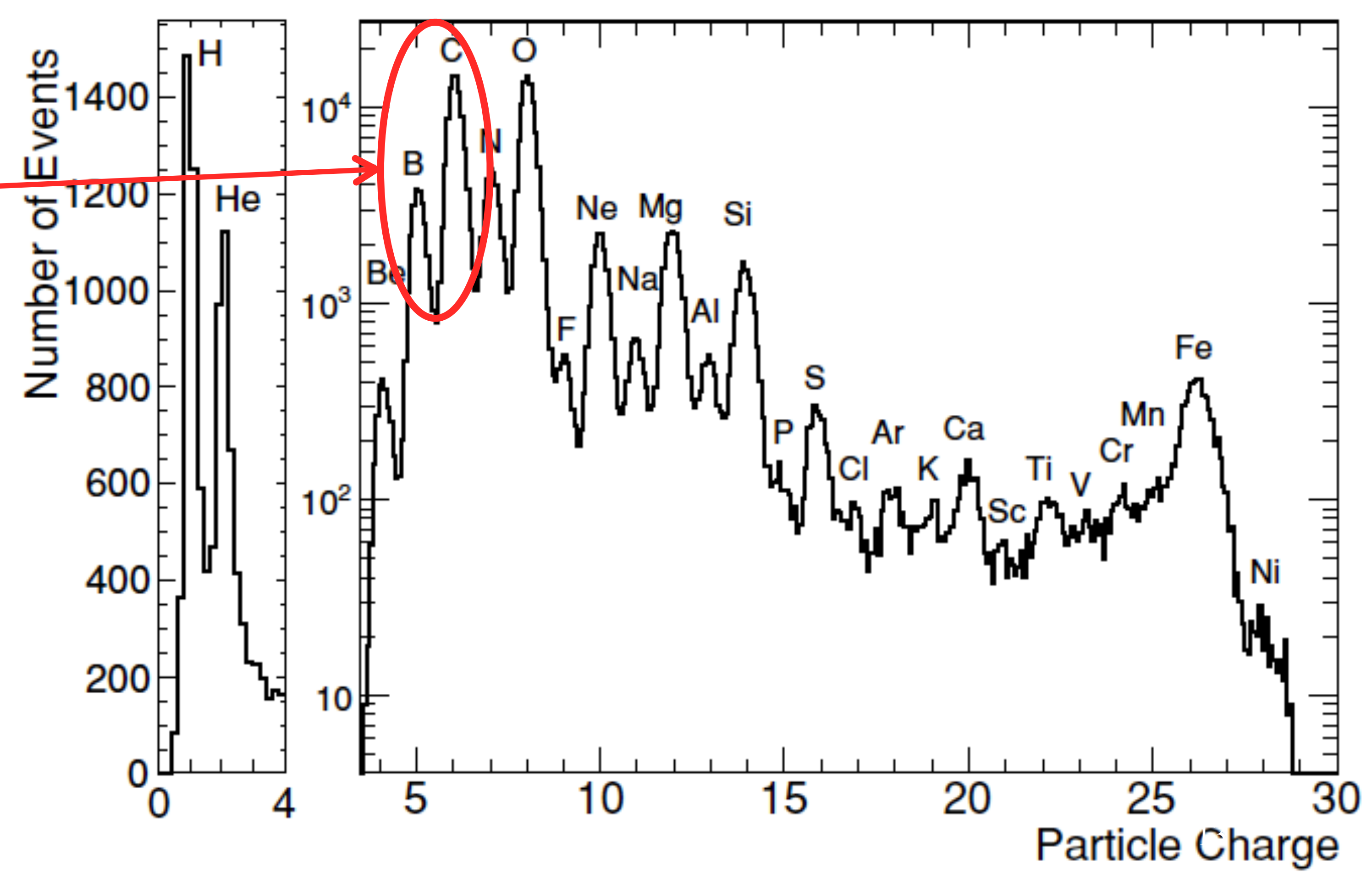
# Elemental abundances

Energy 1 GeV/n to 4 TeV/n, unmatched charge resolution (~0.2e) in this energy regime.

Ahn H.S. et al., ApJ 714, L89 (2010)

C primary, but B arises from spallation in interstellar collisions…

B/C tells the history of propagation (over 7-8 million years).



# *What accelerates CRs to these high energies?*

**1940s :**
**$E_{CR}$~Pev**
**($10^{15}$ eV)**

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## Enrico Fermi

Initially proposed scattering of CRs, bouncing off the magnetic field of interstellar clouds, (Fermi's ***2nd order*** mechanism), effic.

**$\Delta E/E \sim (V/c)^2$ /scatt.**

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$\Delta E/E \sim (V/c)^2$ /scatt.

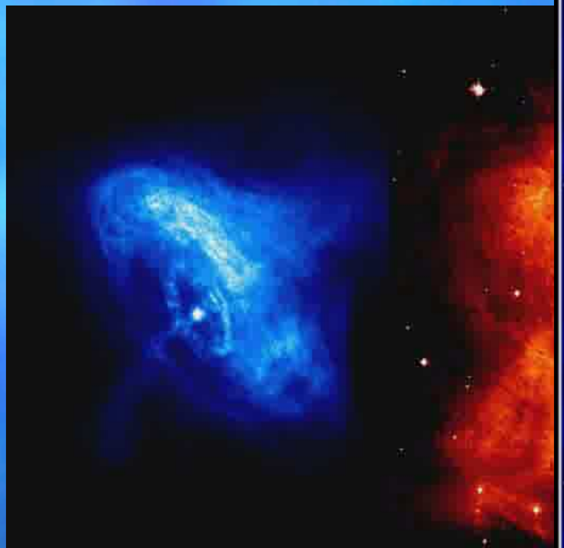
***BUT*: mechanism not very efficient**

# Fermi's next try: 1st order mech., ΔE/E~(V/c)

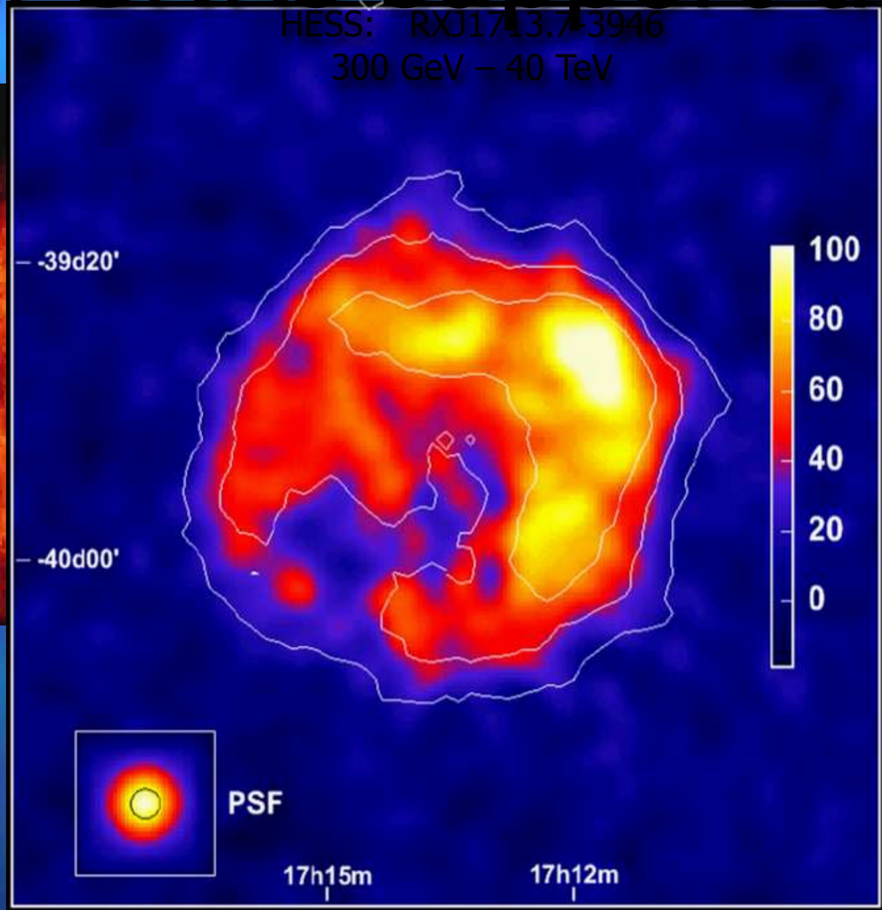
# Ground-based images of SNRs support this

Supernova remnants are a candidate for Galactic cosmic ray sources

CRAB (seen in 1054)
Chandra Hubble



HESS: RXJ1713.7-3946
300 GeV – 40 TeV




Enrico Fermi (1940s) shock acceleration, naturally predicts
$E^{-2.1}$ at the source ➔ ~ $E^{-2.6}$ at Earth

$$E_{max} \approx \beta cZeBL$$

→supernova shock works!
- but H only up to ~$10^{15}$ eV,
heavies up to ~Z$\times 10^{15}$ eV

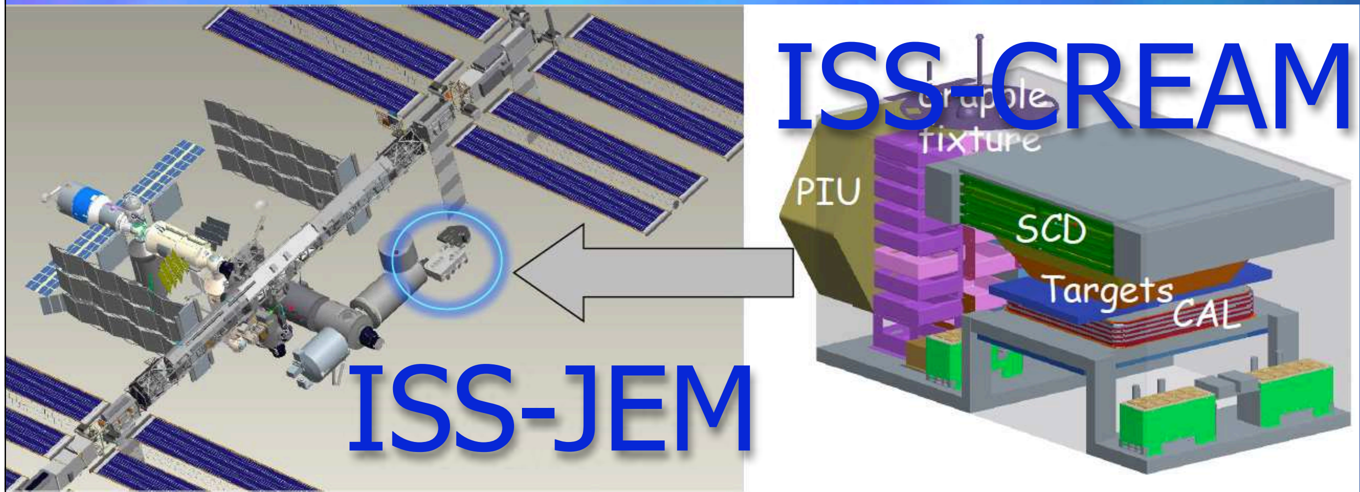
# Space measurements

Also can fly instruments on rockets and satellites e.g.:

- 1979: HEAO-3 Atlas-Centaur rocket;
- 1985: CRN Space Shuttle Challenger;
- 1997: ACE Delta II rocket;
- 2011: AMS International Space Station.

Long exposures (years), no residual atmospheric overburden, true vacuum, power from solar panels; but takes years (decades?) of development, testing, qualification, and can be very expensive (e.g., AMS cost is estimated at $2B - $4B)...

# Some new efforts

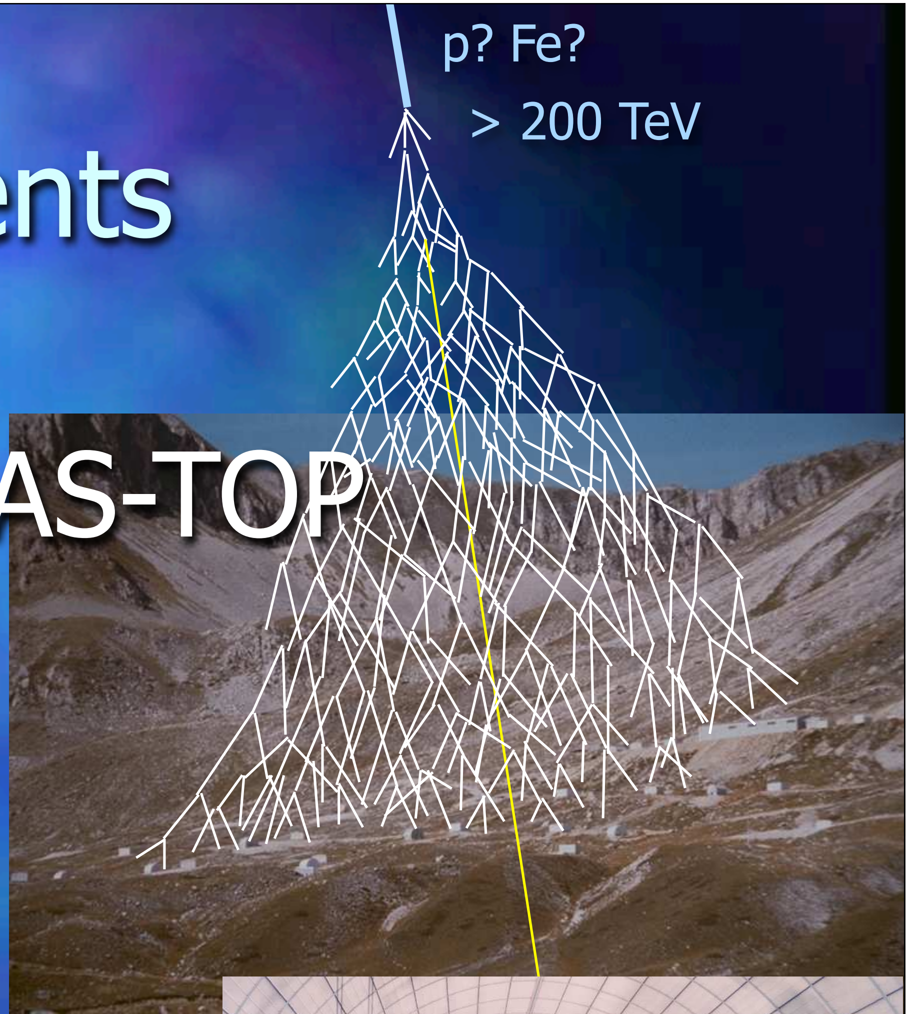



- New development: build a scaled-down version of CREAM to go to the ISS
→ ISS-CREAM !
- optimized for cosmic-ray nuclei, but also sensitive to electrons;
- long exposure in space will more than compensate for smaller size;
- in various stages of design, fabrication, qualification, commissioning;
- planned launch on SpaceX 5, 2014.

# Indirect measurements

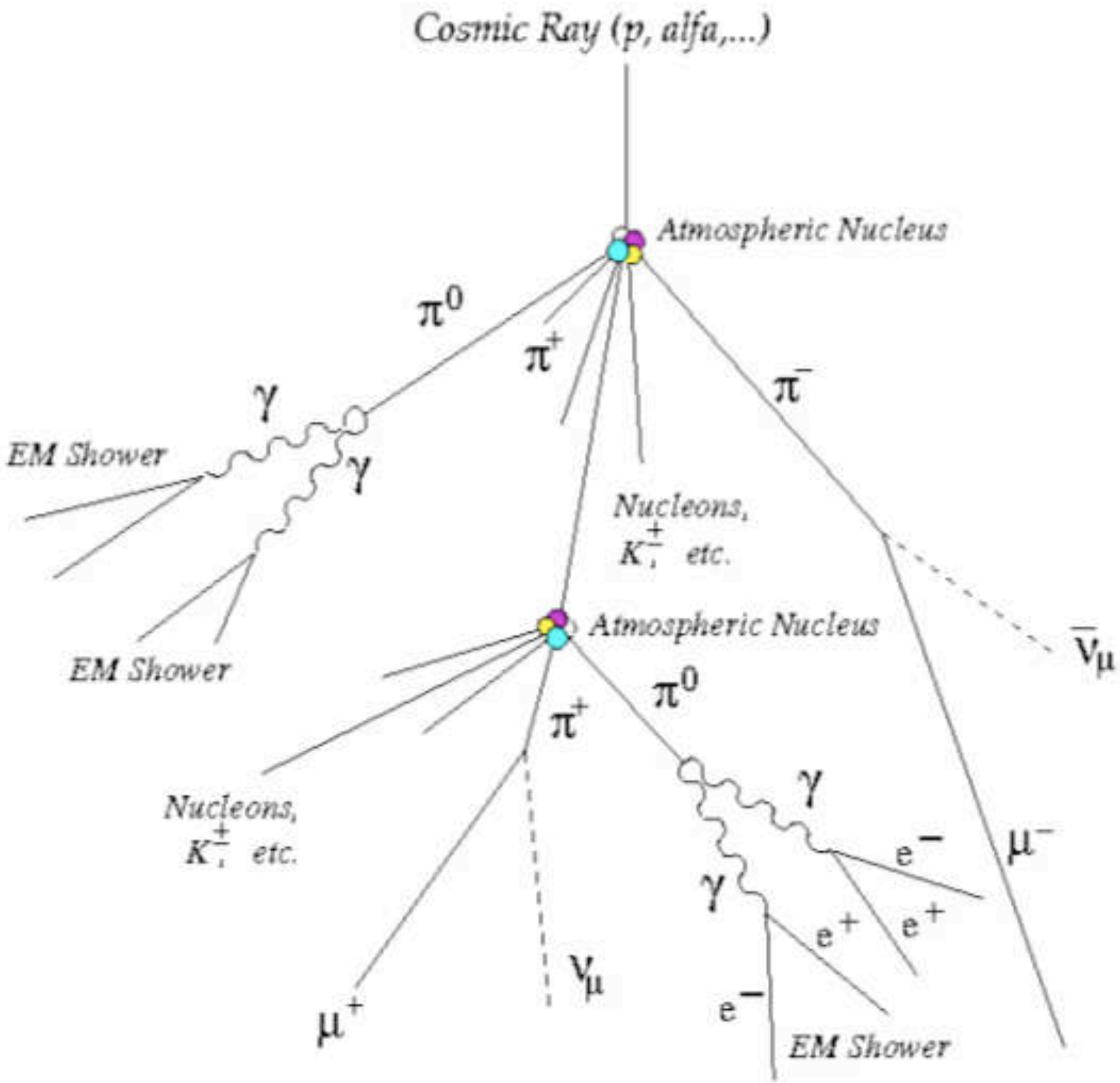
Beyond ~$10^{14}$ eV, particles become too rare for direct detection; can only be studied through their atmospheric secondaries.

e.g. in the Appenine mountains, Italy:

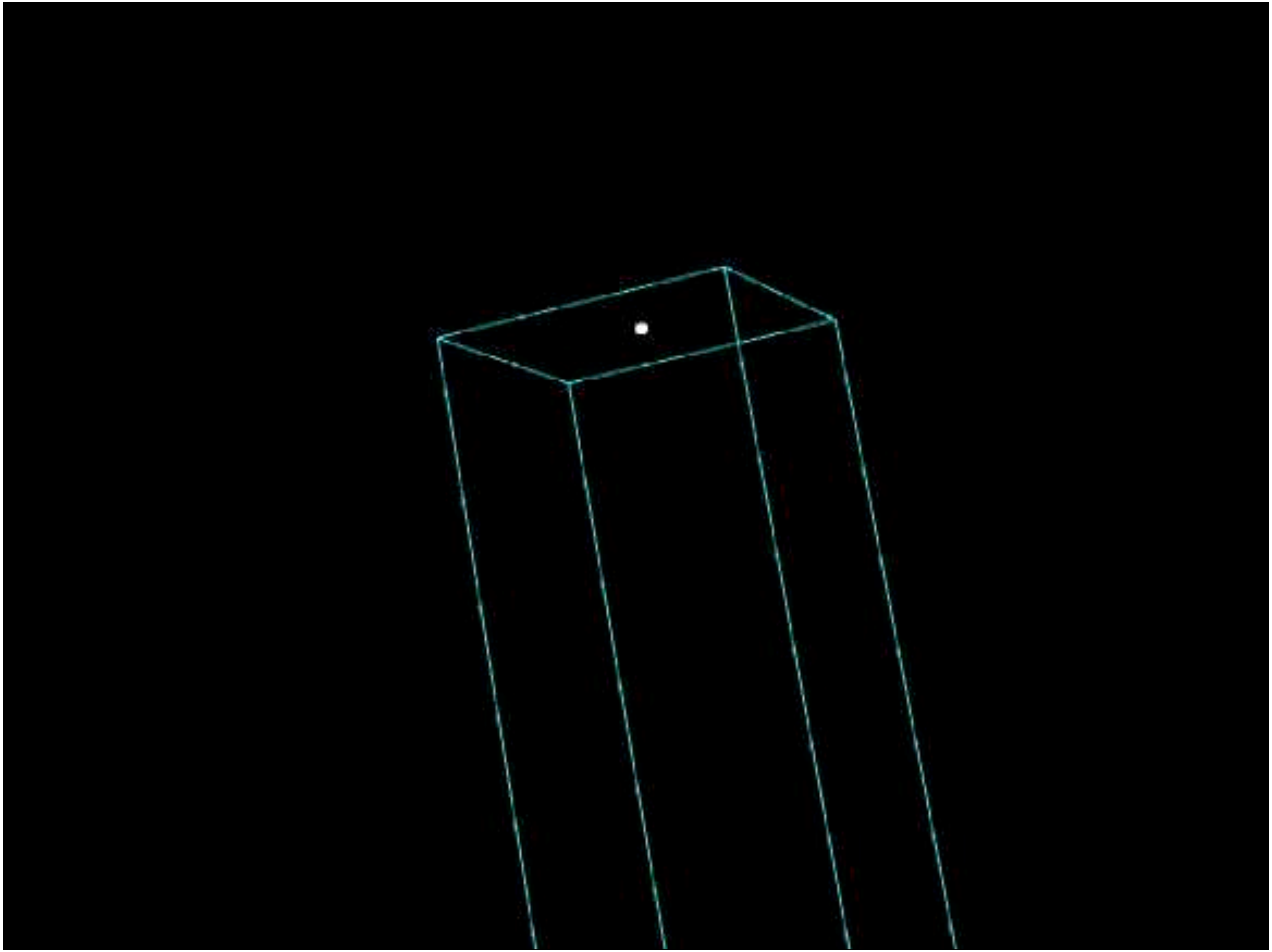



Gran Sasso Lab,  near L'Aquila

# *CR air shower*




- **Primary** CR (p, He,...heavies) **interact** at top of atmosphere
- Produce **cascade** of **secondary**, lighter particles
- Both ***EM*** ($e^{\pm}$,$\gamma$) and ***hadronic*** (N, K, π, μ, ν..) cascades
- ***Secondaries*** are ***detected*** in air or at ground level

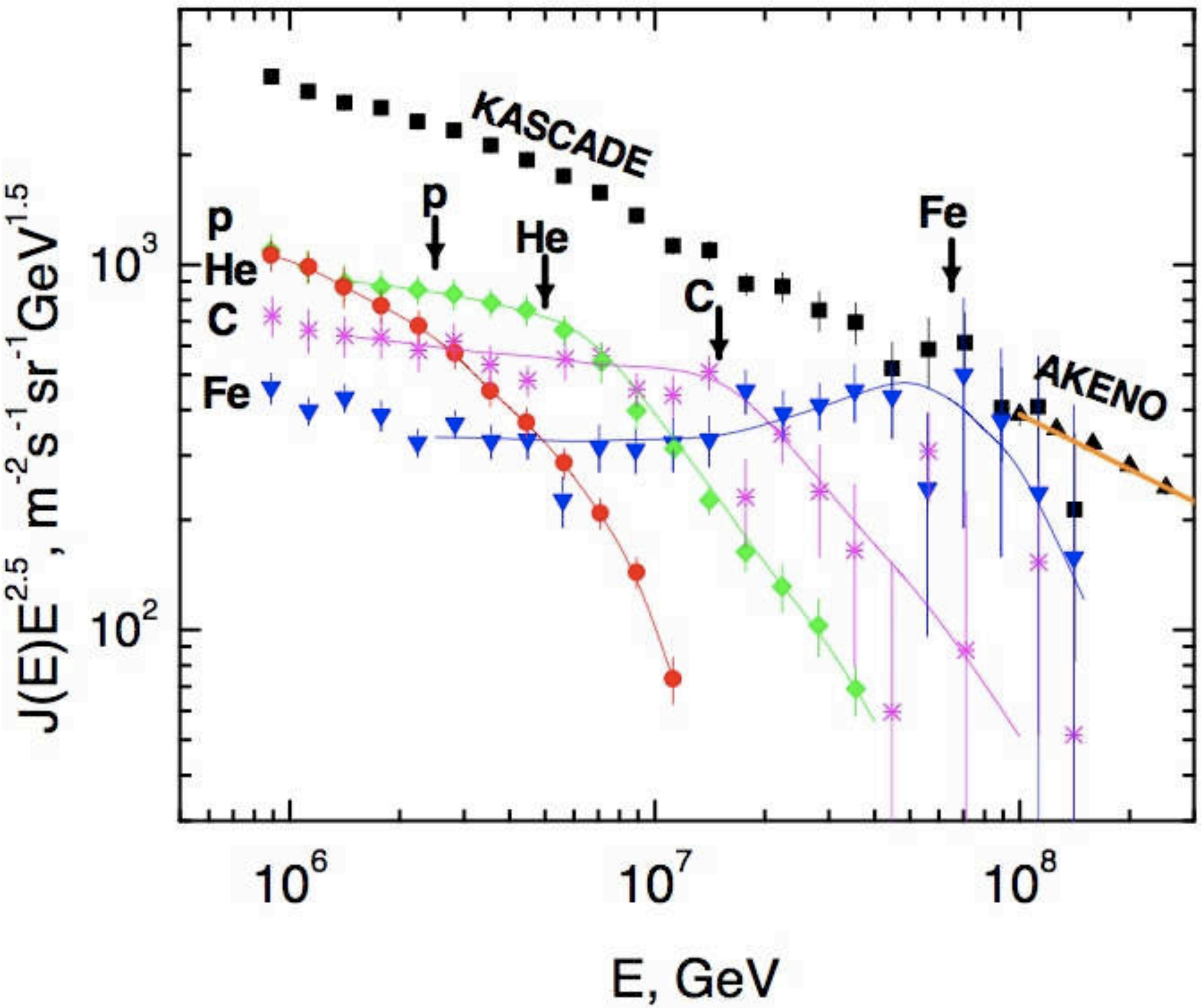


# KASCADE-Grande

**KA**rlsruhe **S**hower **C**ore **A**rray **DE**tector - Grande

- ***Indirect*** detection of primary CRs ($10^{16}$-$10^{18}$ eV) via ***secondaries***
- Monte Carlo simulations allow determination of ***chemical composition*** of primary CRs
- Beyond **$10^{15}$** eV, composition increasingly weighted towards ***heavy elements***, He, .., C, O, ..Fe

# CR spectrum @ $E < 10^{17}$ eV




- Spectrum steepens in a "***knee***"
- Knee energy depends on ***charge*** Z
- For ***p***, knee @ $10^{15}$ eV
- For ***Fe***, knee @ $10^{17}$ eV

$E_{max}$~βcZeBL ✔

# Push to even high energies

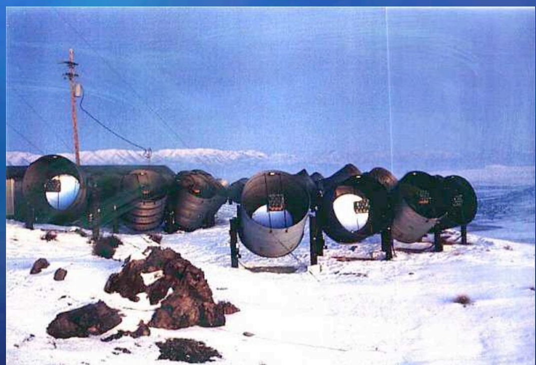
At the highest energies, extraordinary efforts are required to measure the air showers with enough statistical precision:

- Volcano Ranch 1959-1965, 100 $km^2$ yr total;
- Haverah Park 1963-1987, 300 $km^2$ yr total;
- Yakutsk 1973-2000, 500 $km^2$ yr total;
- Fly's Eye 1987-1995, 900 $km^2$ yr total;
- AGASA 1991-2003, 3,000 $km^2$ yr total;
- HiRes 1998-2006, 8,000 $km^2$ yr total;
- Auger since 2003, 21,000 $km^2$ yr so far;
- TA since 2008, 700 $km^2 \times \varepsilon T$ so far.

G. Zatsepin in Russia

J. Linsley at Volcano Ranch

Haverah Park after 20 years



Fly's Eye

AGASA station

***currently,***
***highest energy UHECR***
***observatory with largest***
***daily rate***
***is ...***

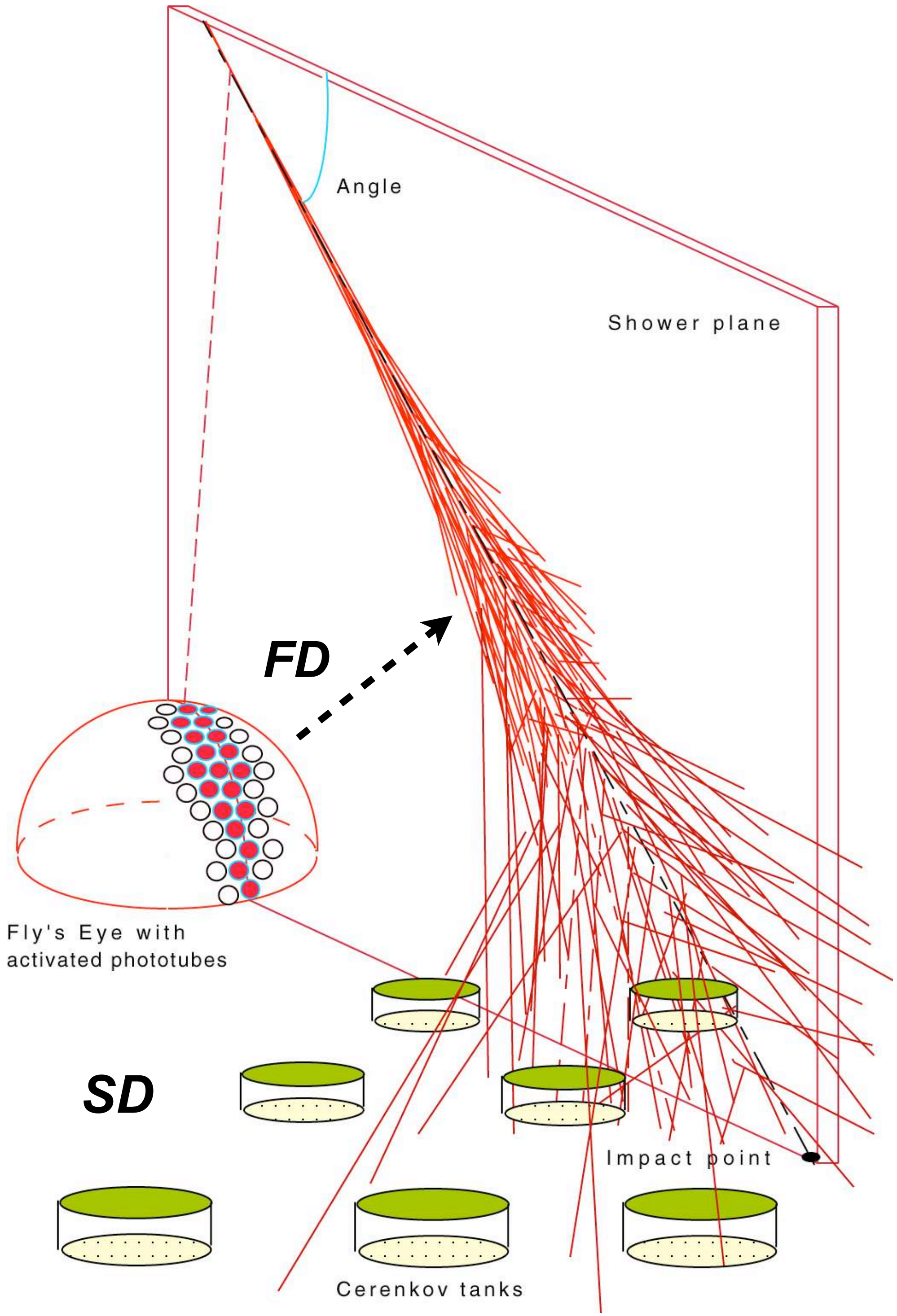
# Pierre Auger Observatory

International consortium, located in Argentina, Mendoza province

**Uses two techniques for detecting CR shower:**

- **detect air fluorescence produced by shower particles (FD)**
  (EM showers)

- **detect shower particles on the surface (SD)**
  (hadronic showers)



# Surface detectors (SD)

Muons from shower → Cherenkov light in water tank, detected by phototubes

Pierre Auger Observatory: Malargue, Mendoza, Argentina: ***E~ $10^{17}$ -$10^{21}$ eV***

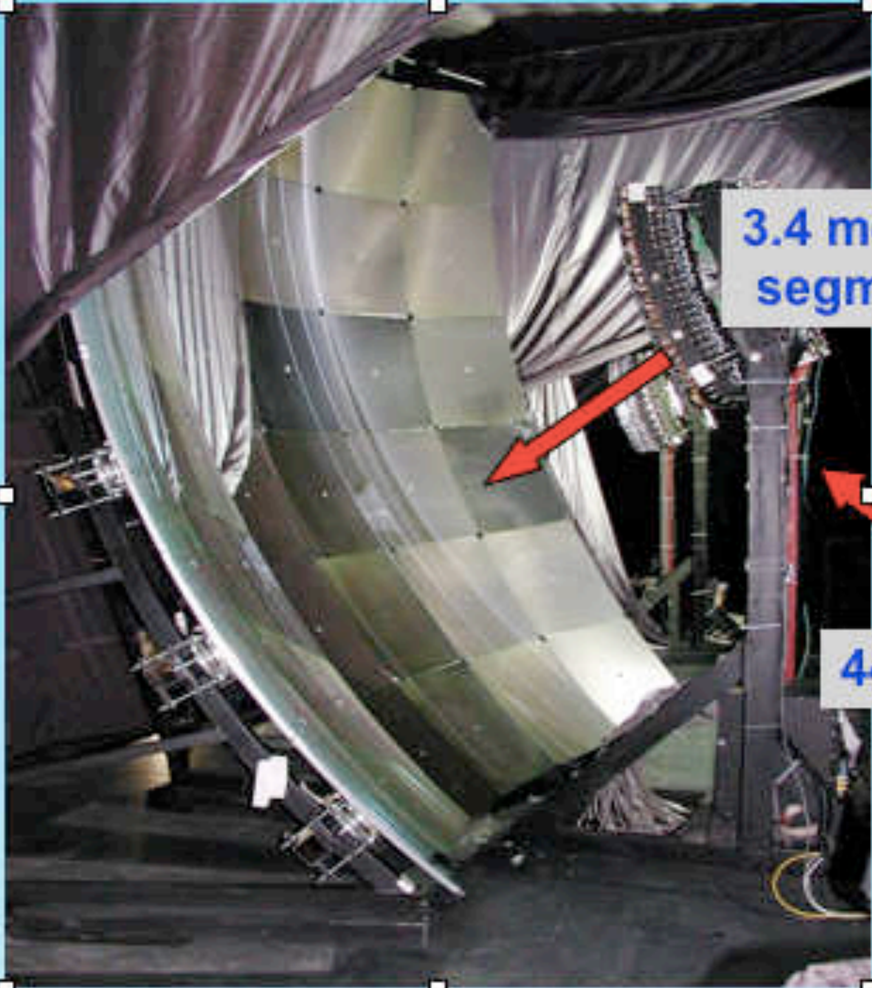
-***1600 surface detectors***: water ***Cherenkov*** tanks, 11 kliters ea., 1.5 km apart

-***32 air fluoresence telescopes***, 4x8 arrays of 30x30 deg. sky coverage

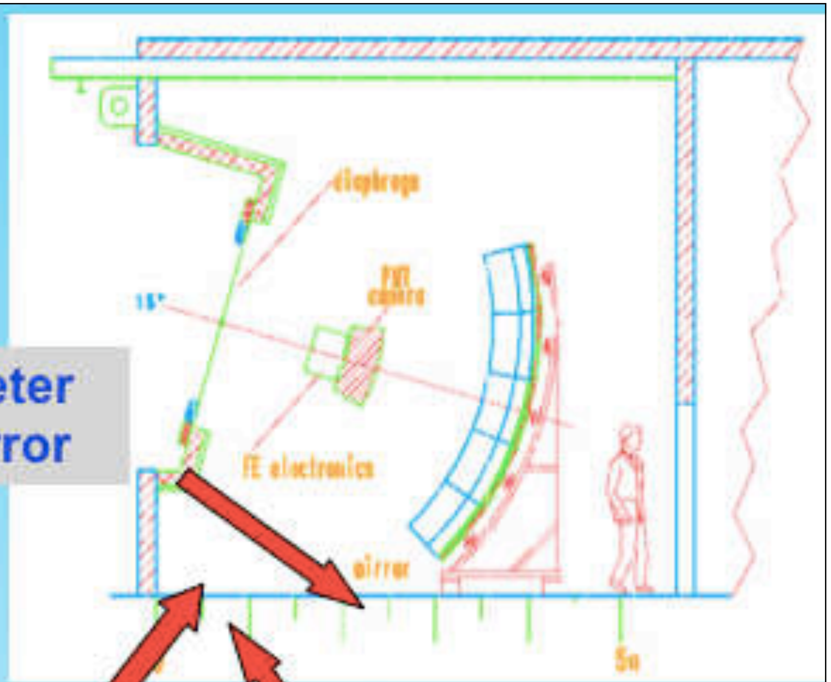


-Also: ***tau-nu*** (horiz.l shower capability: Earth-skimming & through Andes)

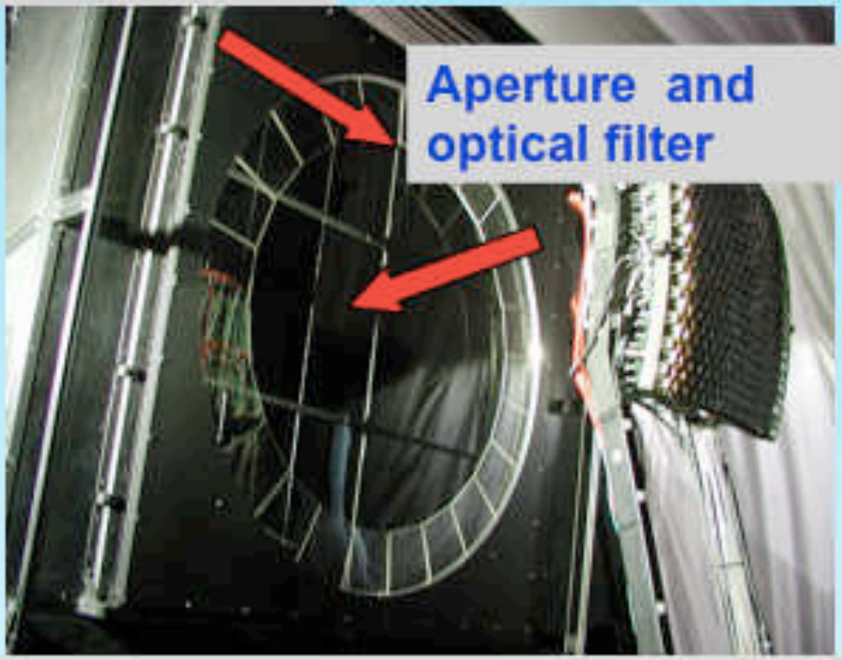
# Fluorescence detector (**FD**)



3.4 meter diameter segmented mirror




440 pixel camera

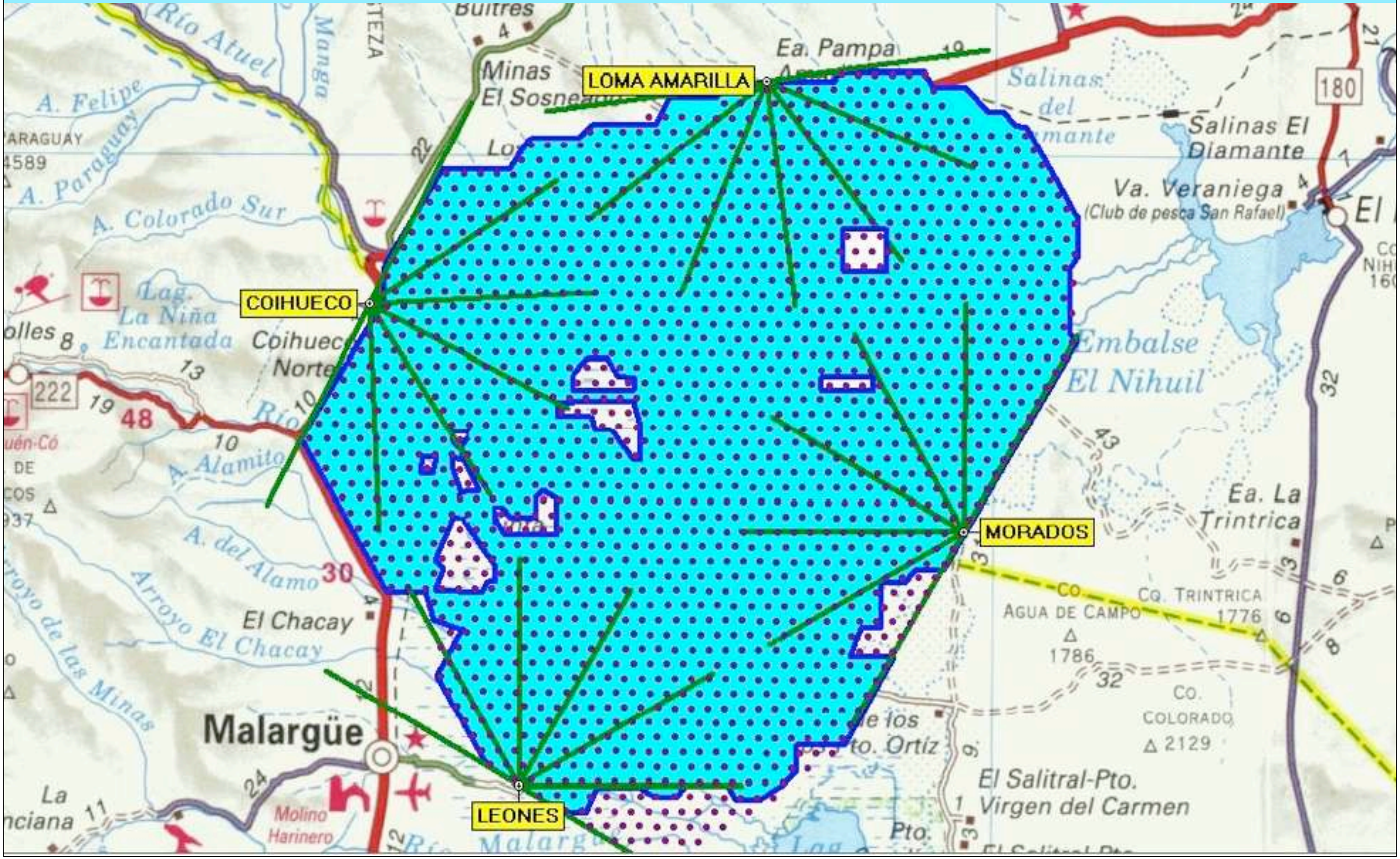


Aperture and optical filter

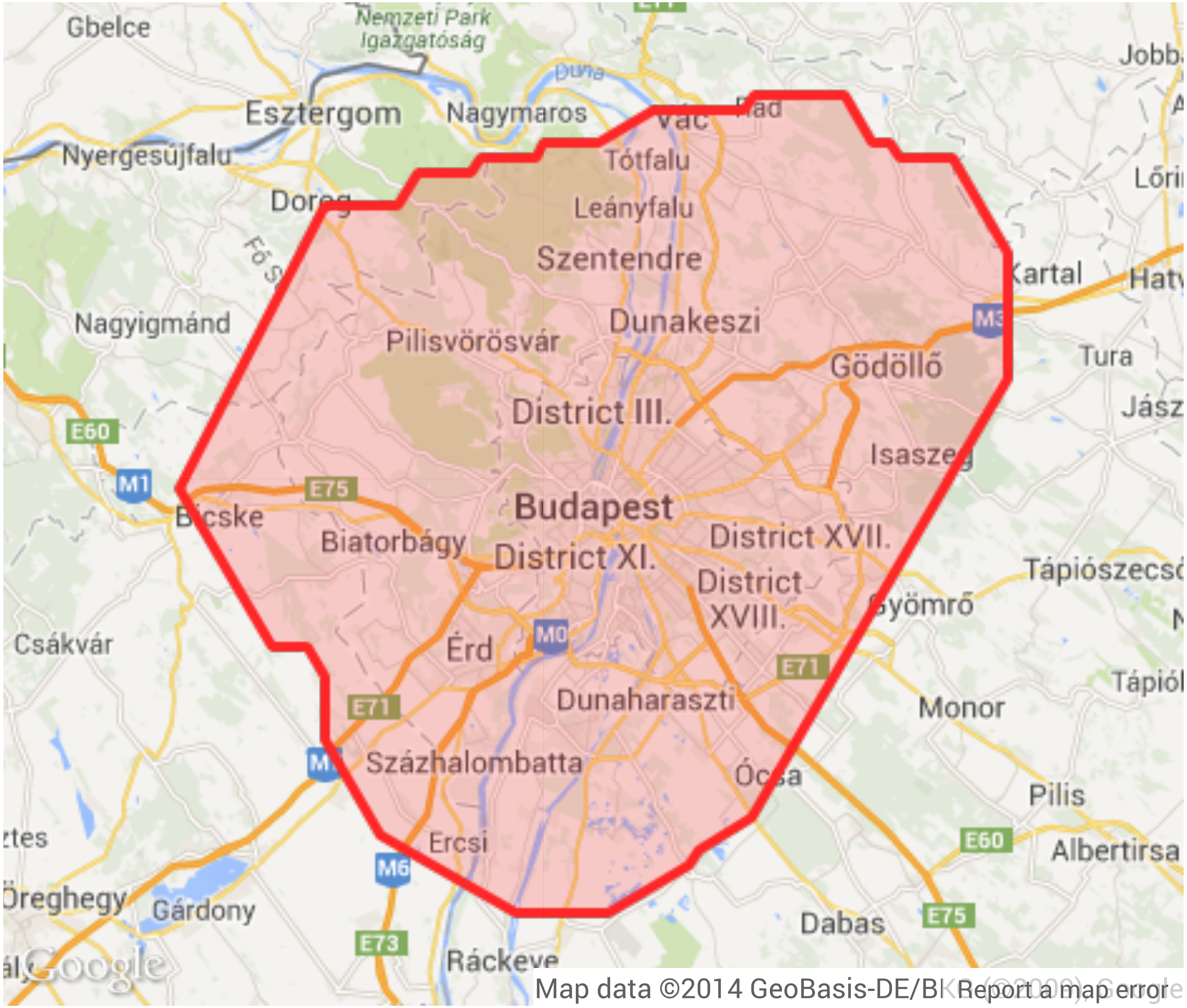
EM shower produces e± pairs, which impact on $N_2$ molecules → fluorescence light observed by FD

# Auger Obs. - 3000 km$^2$ uhecr detector

Mendoza, Argentina

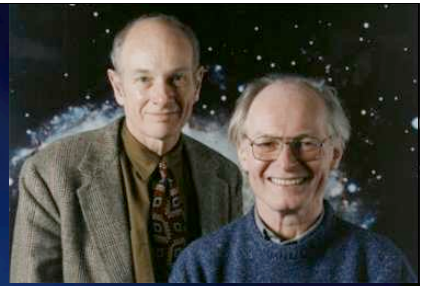


# Size of the Pierre Auger Observatory *(vs Budapest)*

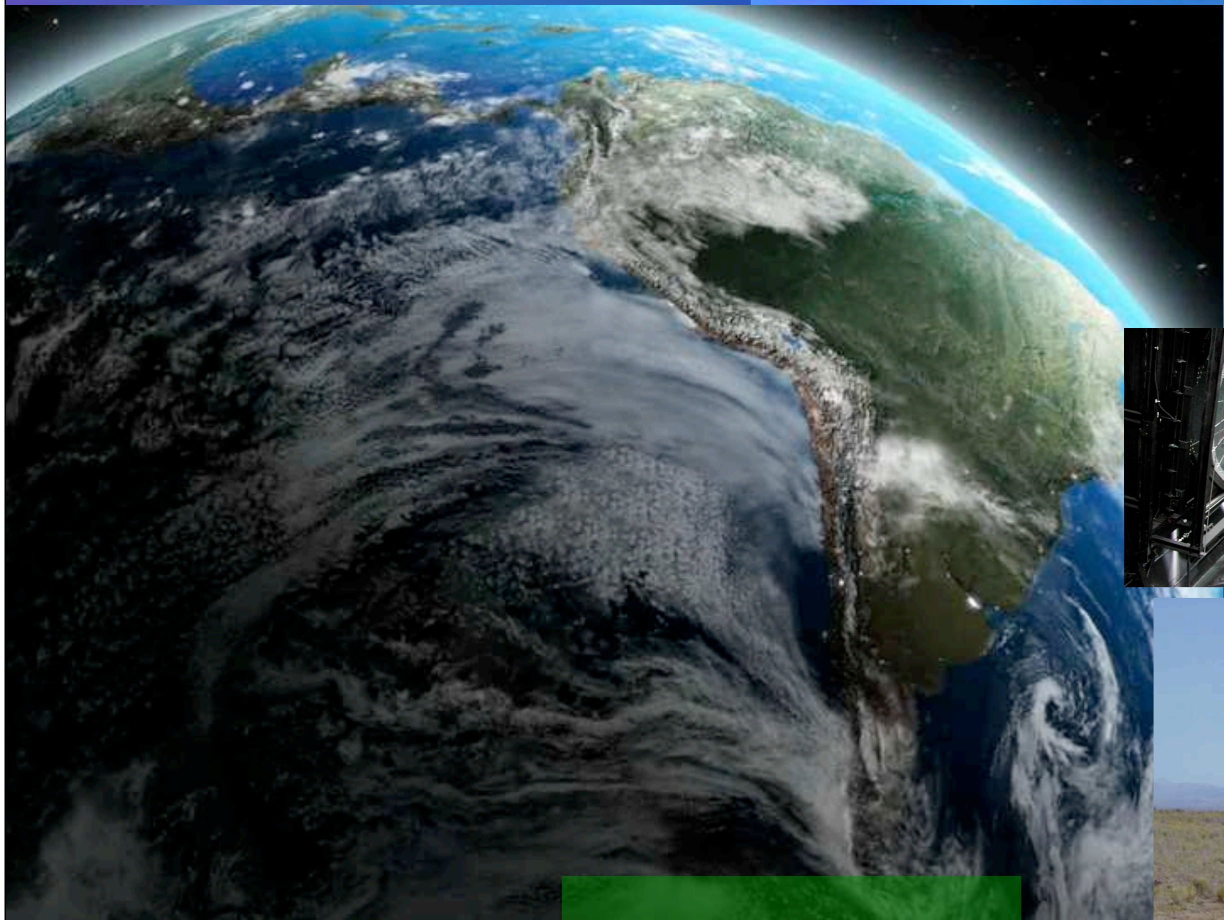


# The Pierre Auger Observatory

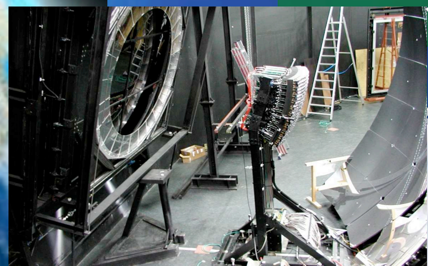
(movie credit: Auger collab.)

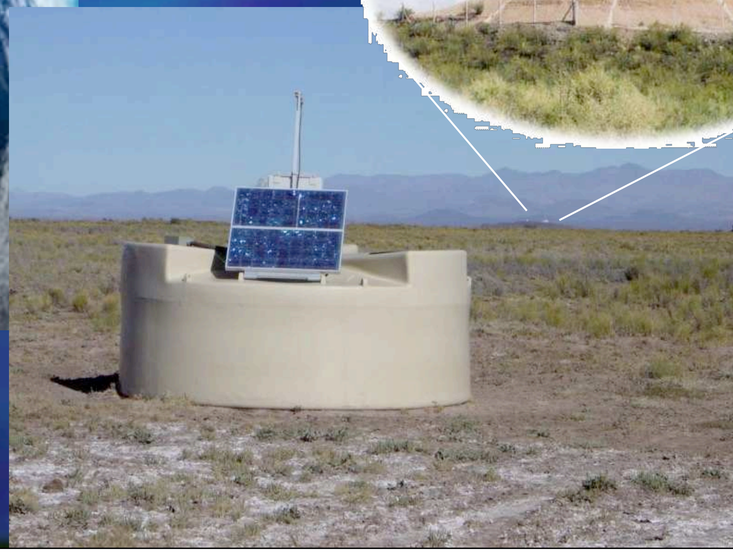


Jim Cronin
Alan Watson



**Fluorescence Detectors**
***4 Telescope enclosures***
***6 Telescopes per enclosure***
***24 (+3) Telescopes total***





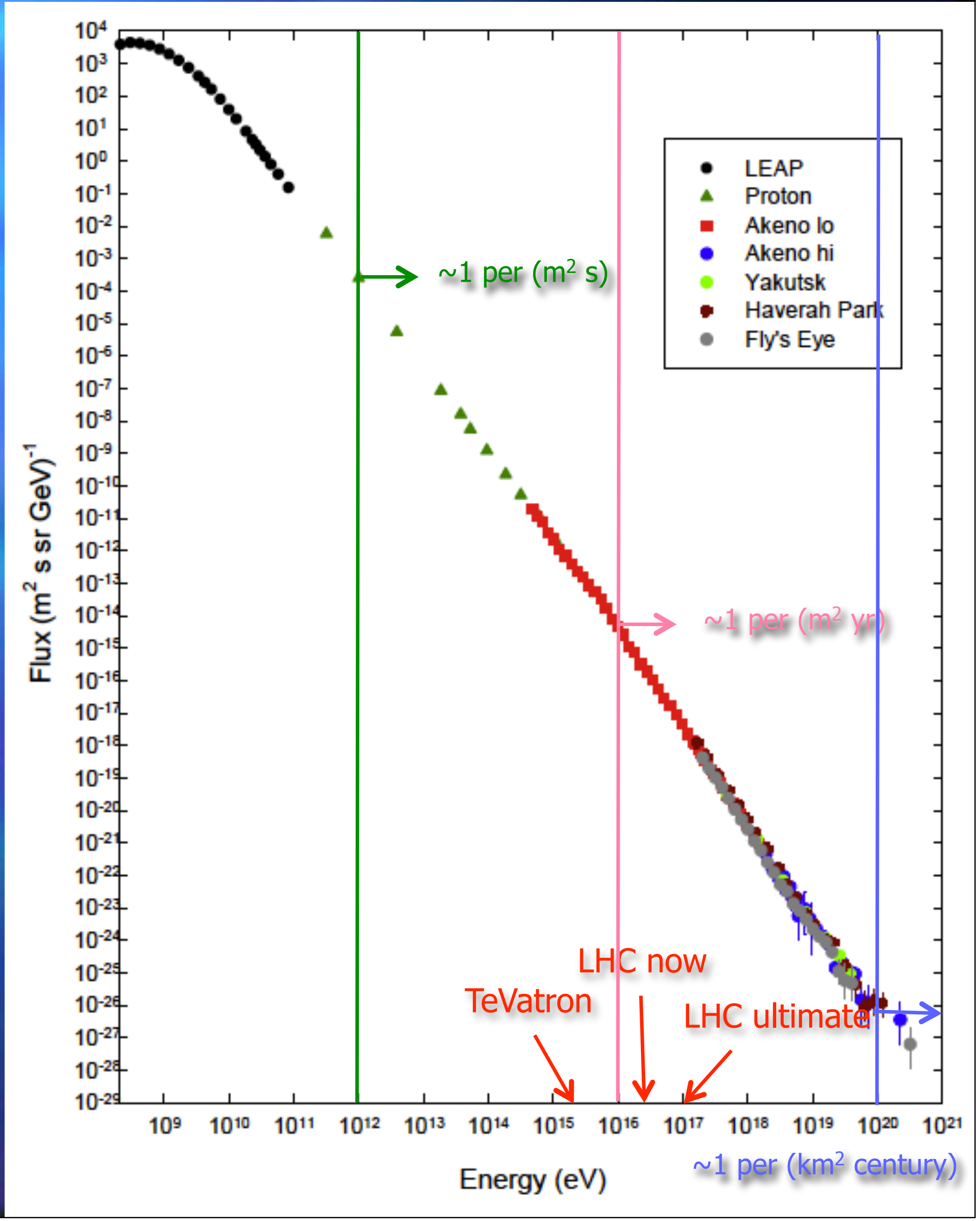
**Surface Array**
***1663 detector stations***
***1.5 km spacing***
***3000 km$^2$***

# The cosmic ray spectrum

Cosmic rays:

- high energy nuclei from H to Fe;
- ~<$10^9$ eV to >$10^{20}$ eV;
- rates plummet with energy...

11 orders of magnitude in energy;
31 orders of magnitude in intensity...



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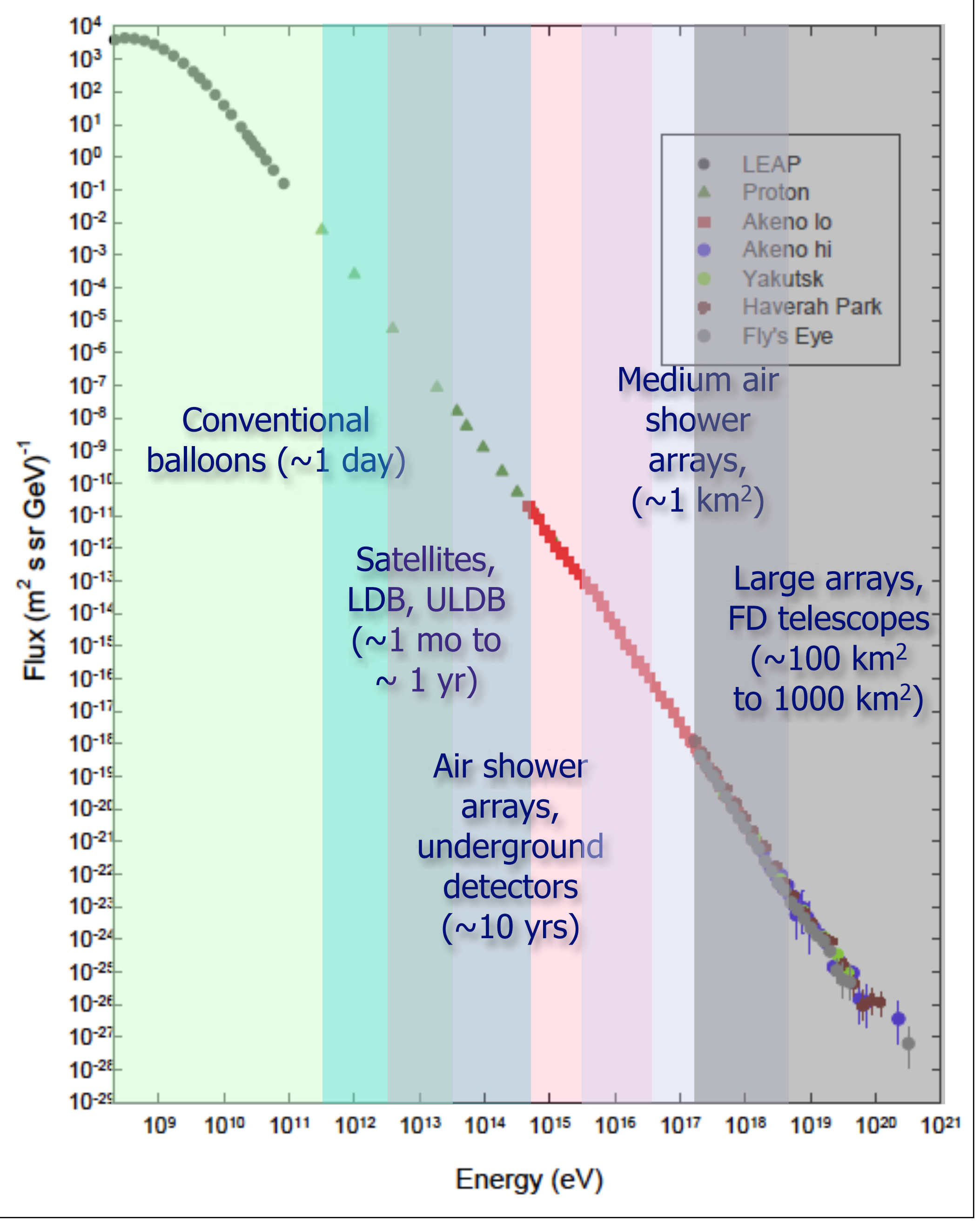

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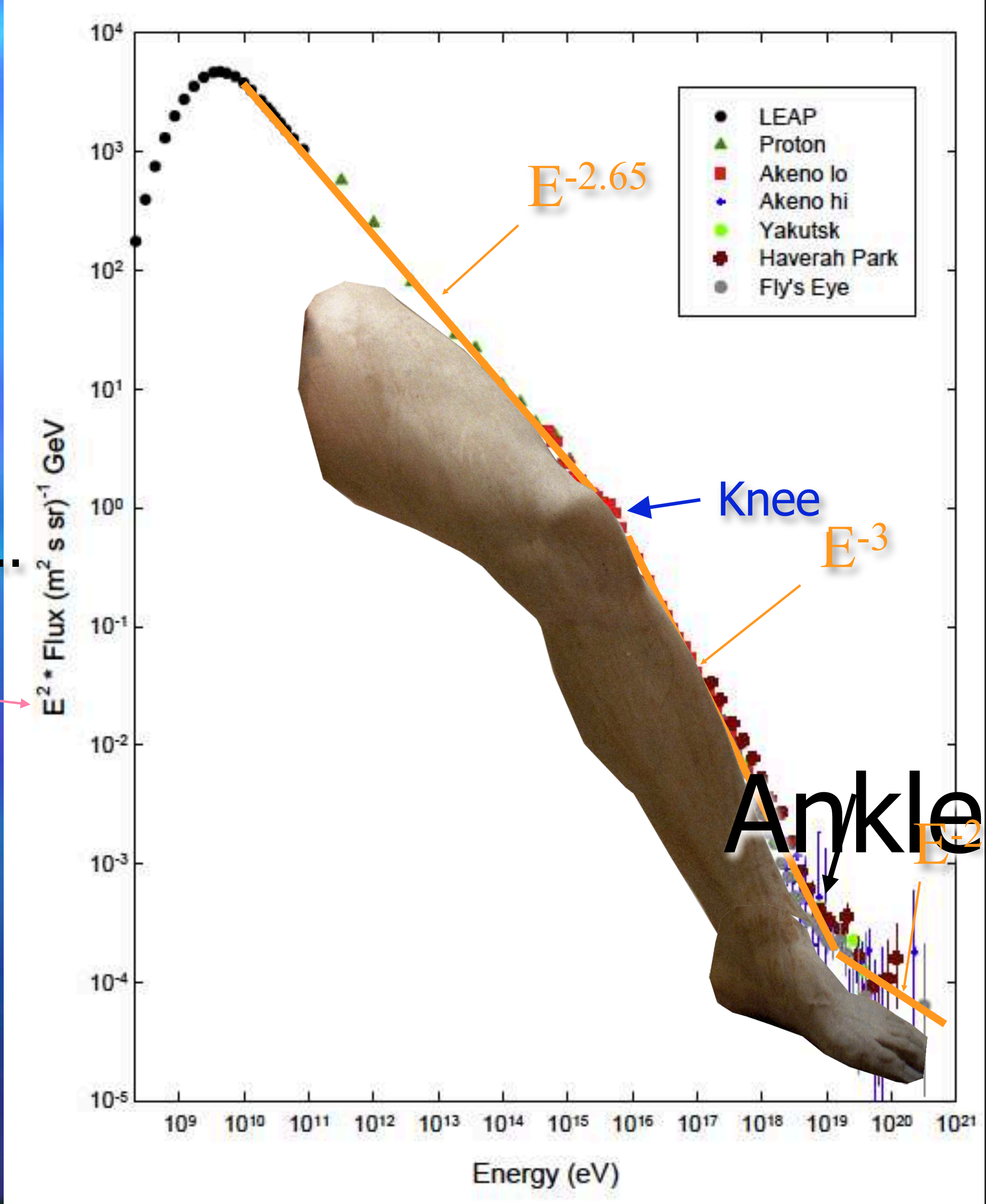
Fluxes rescaled by $E^2$

The Knee:
Limit to supernova acceleration?

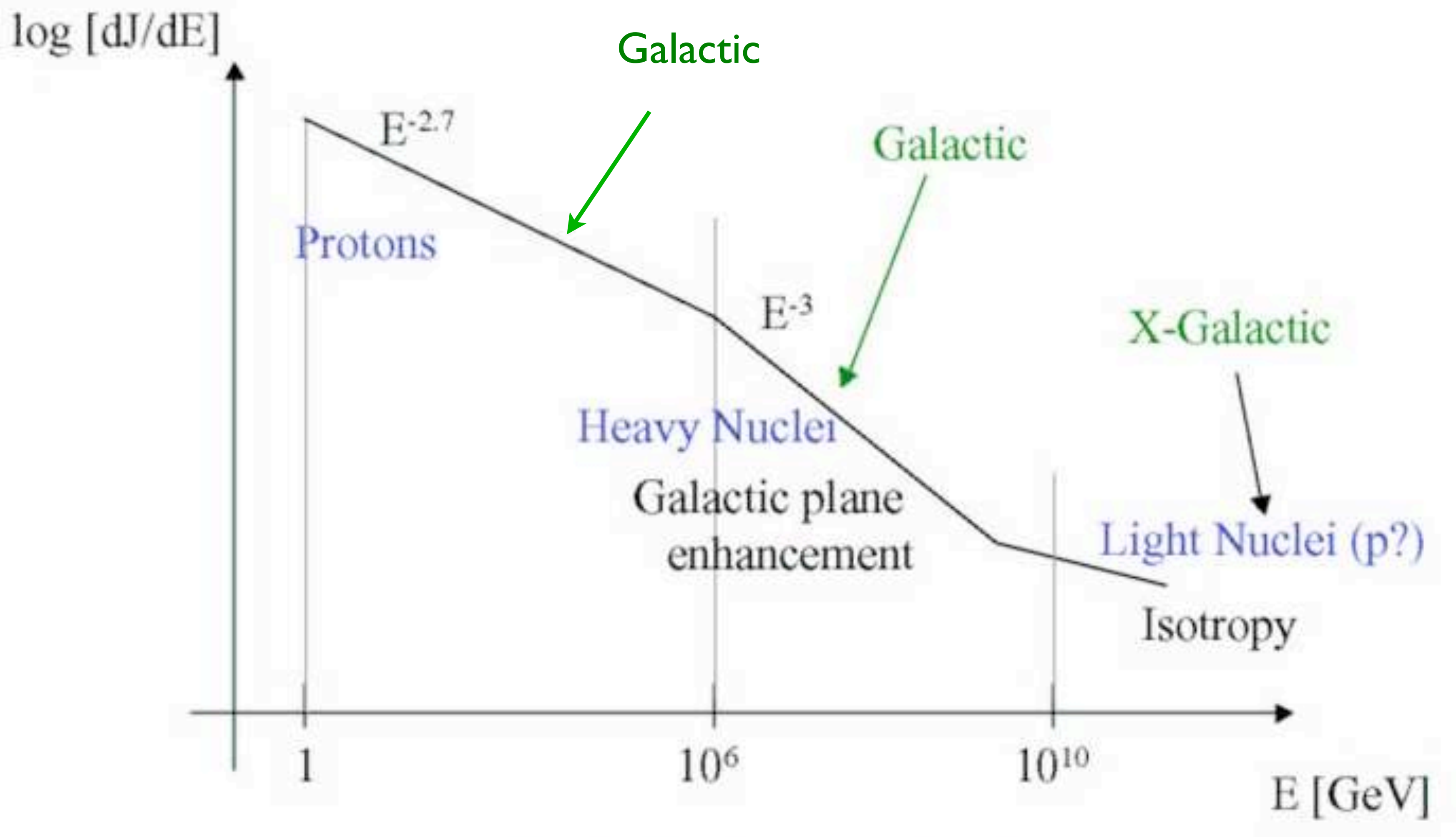
Clue: composition

The Ankle:
Transition to extragalactic sources?

Clue: anisotropies, energy cutoff



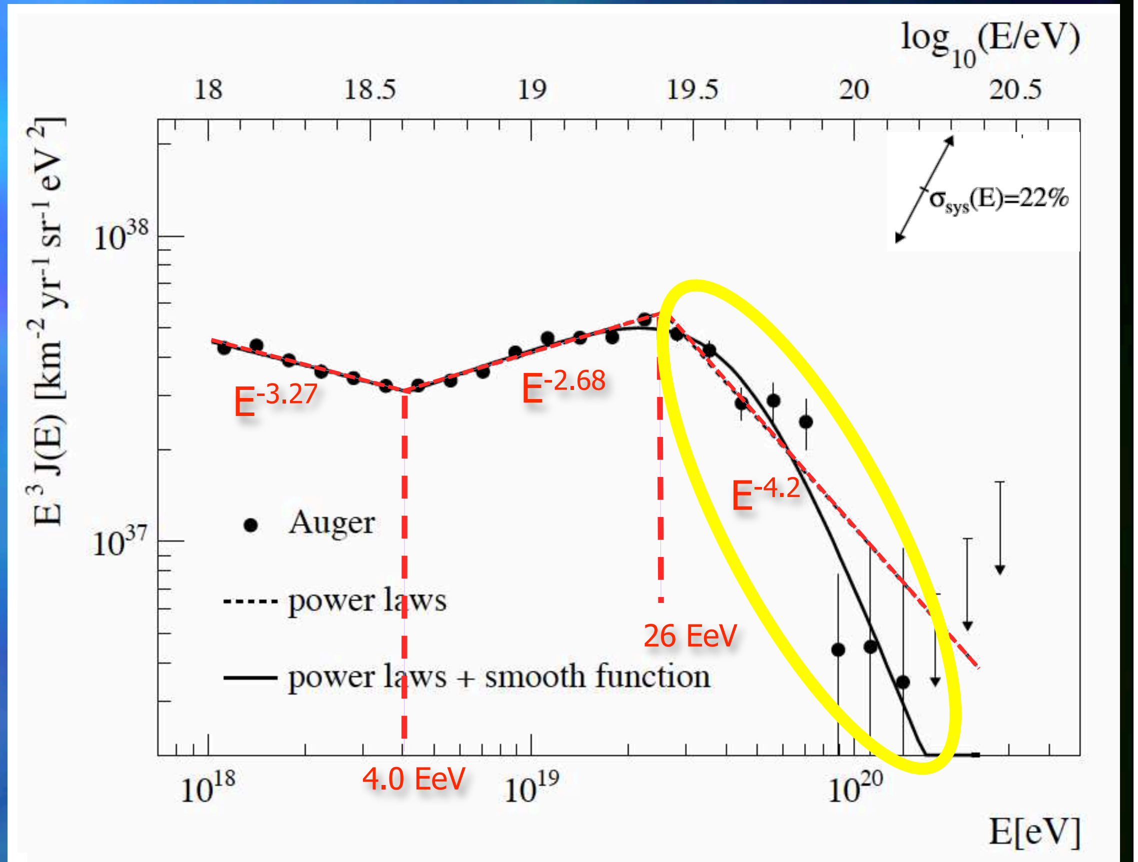
# Cosmic ray flux and Composition




$U_{cr}(1GeV)=1\ eV/cm^3$

# UHE spectrum

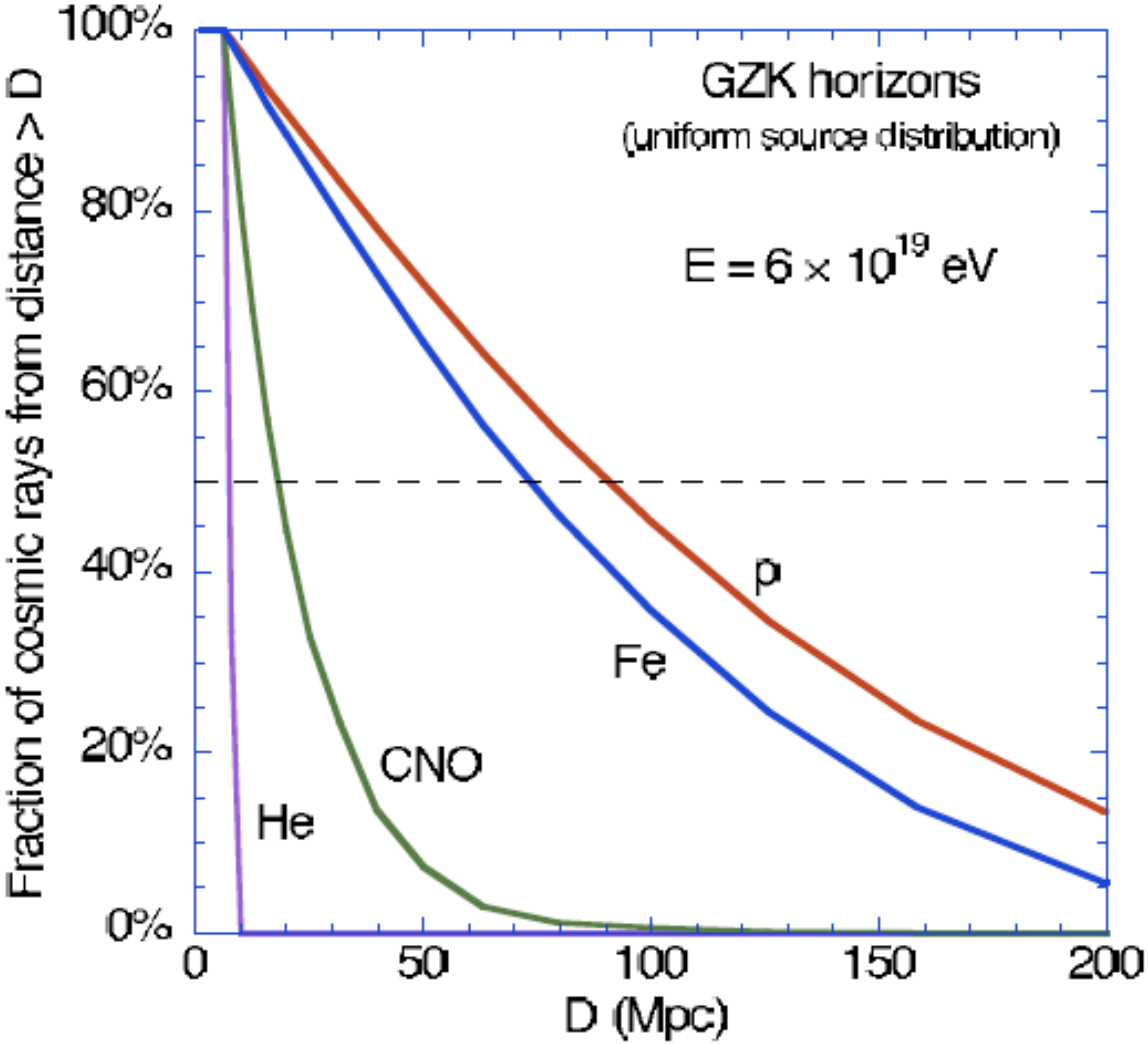
- Auger 2011
- 63,376 SD + 3,660 hybrid events;
- Exposure = 20,905 km$^2$ sr yr
  (7×AGASA, 2.6×HiRes).




GZK cutoff (or something very like it) definitely seen!

Sources must be within ~100 Mpc (300 Mly)… look for anisotropies!

# How far do they come from?

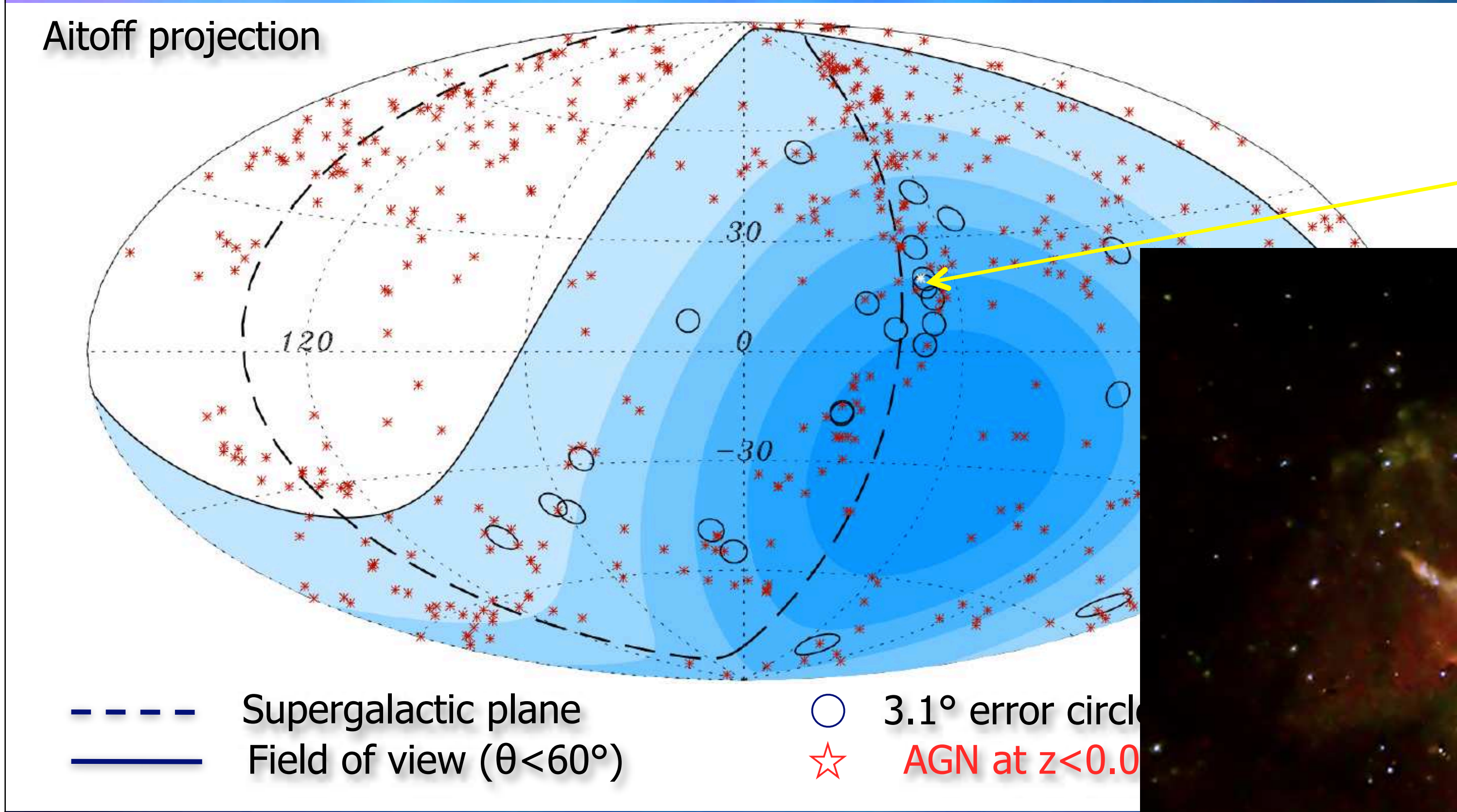



proton + $\gamma_{cmb}$
$\rightarrow \pi$ + nucleon

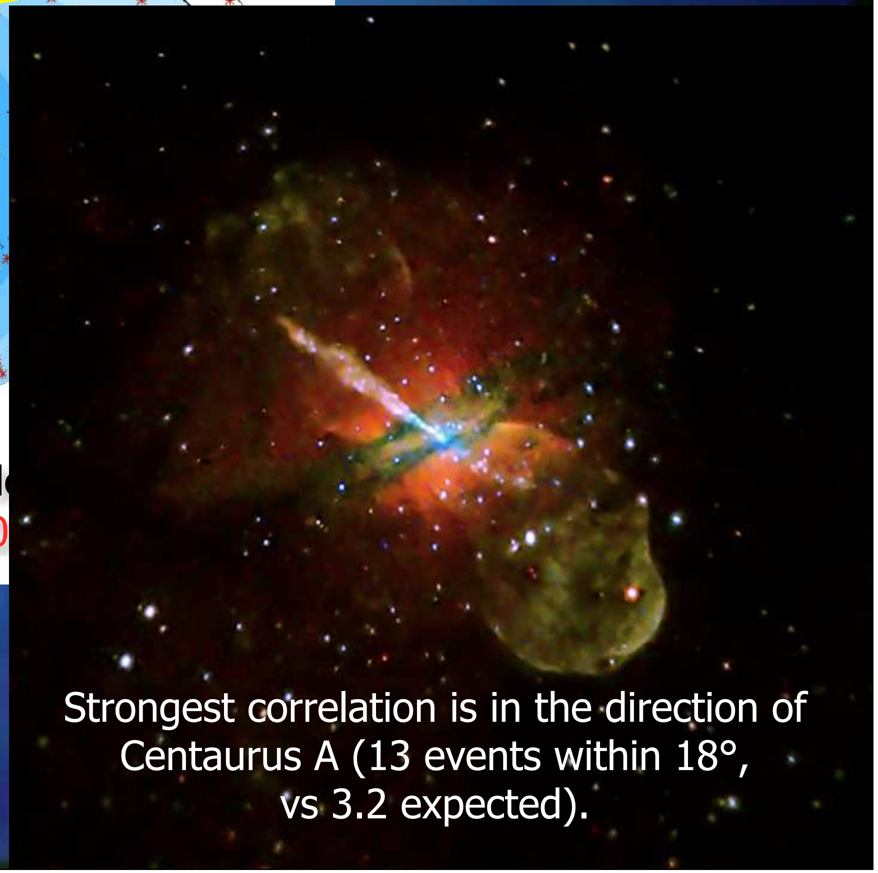
heavy nucl. + $\gamma_{IR}$
$\rightarrow$ photodissoc.

*"GZK radius"*
*$\lesssim$ 75-100 Mpc*
*(~200-300 Mlyr)*

# Cosmic ray astronomy?

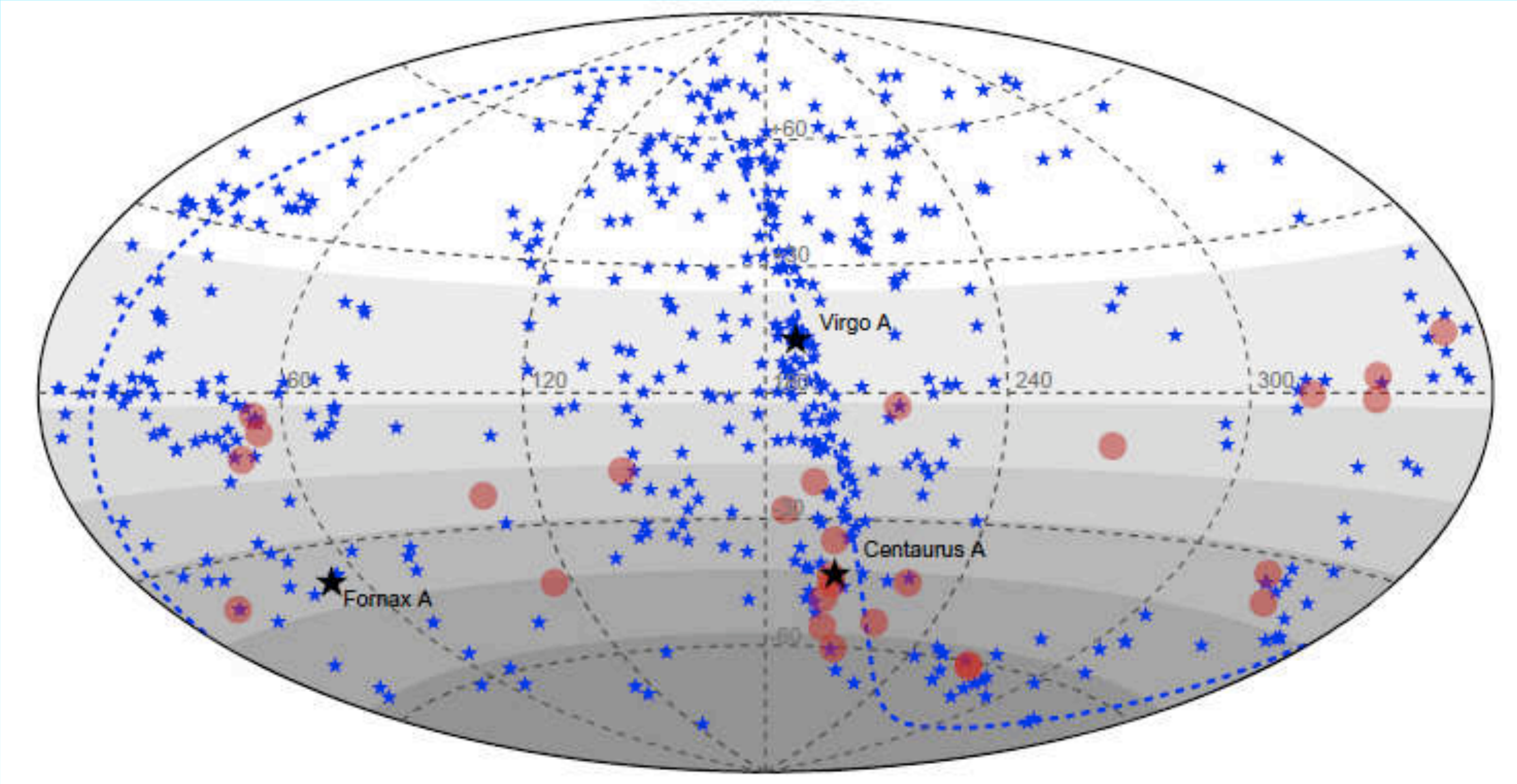

Centaurus A
(4.2 Mpc, 14 Mly)



Strongest correlation is in the direction of Centaurus A (13 events within 18°, vs 3.2 expected).

2007: Auger found a correlation between the arrival direction of the most energetic events ($> 5.6\times10^{19}$ eV) and known "nearby" AGNs (< 75 Mpc, 250 Mly).

# AUGER :
# UHECR spatial correlations with AGNs (or LSS)




- Dashed line: supergalactic equator
- Circles (proton): Events E> 5x10$^{19}$ eV, D<75 Mpc
- Asterisks : Veron-Cety catalog AGNs

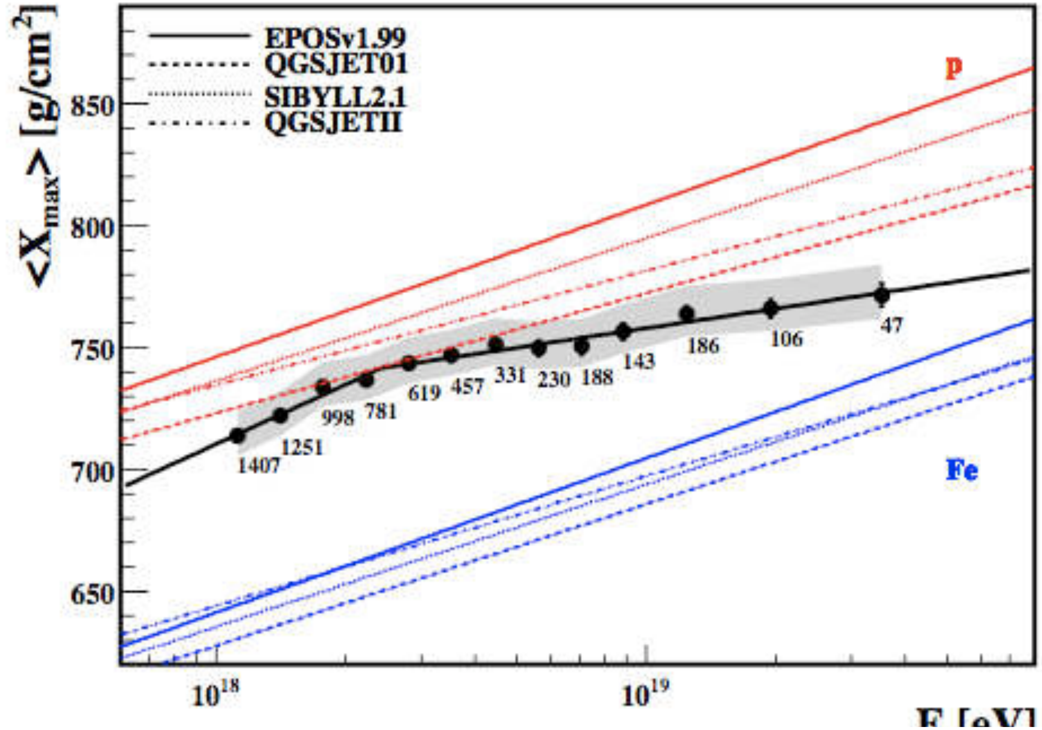
Science Nov 2007; but - newer: arXiv:1009.1855; also ICRC 11

# Auger spatial correlation

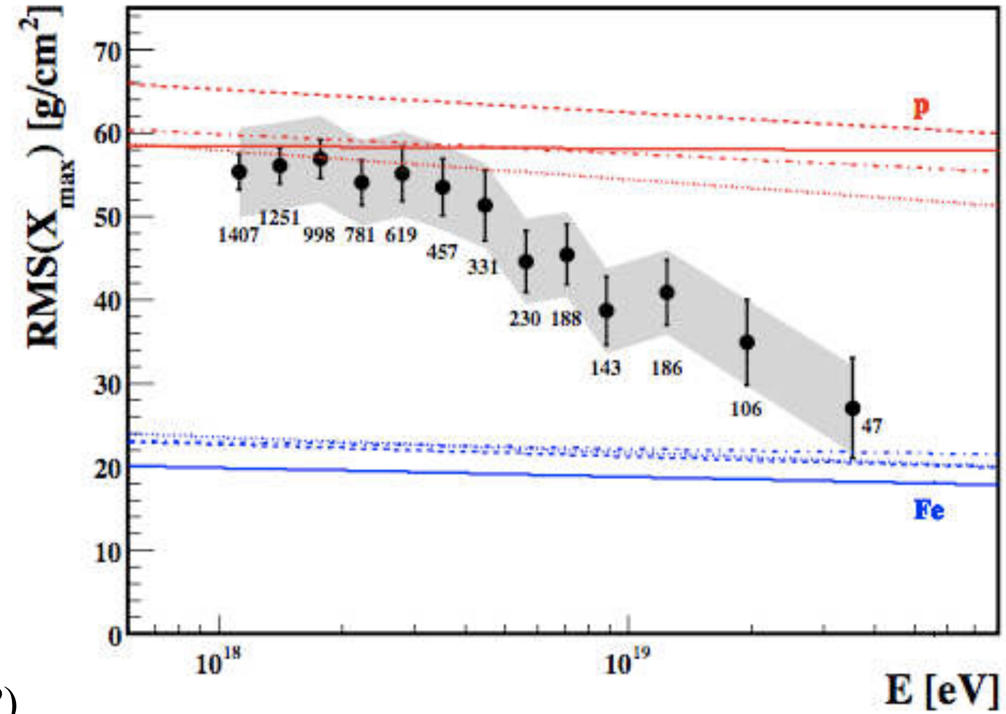
- Initially found 3-$\sigma$ corr. with VC AGNs within $\theta \leq 3.5^o$ and D< 75 Mpc, for 27 events E>$4.5 \times 10^{19}$ eV (Science, 2007)
- The above correlation would suggest protons
- But: there is even better correlation with "average" galaxies
- If heavy: $r_L$ smaller, rms. dev. angle $\theta \sim n^{1/2}\, \theta_s \sim (r/\lambda_B)^{1/2}\, (\lambda_B/r_L) \sim (r\lambda_B)^{1/2}\, /r_L$ is larger, many more gals. inside error circle
- ***Also: (*** arXiv:1009.1855, etc. ): ***now (>2011) the VCV-AGN significance has weakened to ≲ 2σ*** ***(see Allard talk)***
- ***Low or no VCV AGN corr.: also from HiRes*** ***(Sagawa talk)***

→ ***Could be sources are in galaxies - GRB ? HNs? MGRs? Or in other, less extreme and more common galaxies?***

→ ***Or could be they are heavy nuclei, larger error circle?***




# Auger : UHECR nuclear composition




## $X_{max}$ vs. E ↑

## rms($X_{max}$) vs. E →

*Xmax: depth of shower maximum*

*Dots: data points. Lines: Monte Carlo models*

***Fe: shallower showers, less dispersion than p, data indicates increased heavy comp. @ hi.en.***

(PAO coll., ICRC 2011, arXiv:1107.4804;
***also talks by Monasor & Ostapchenko (but..)***

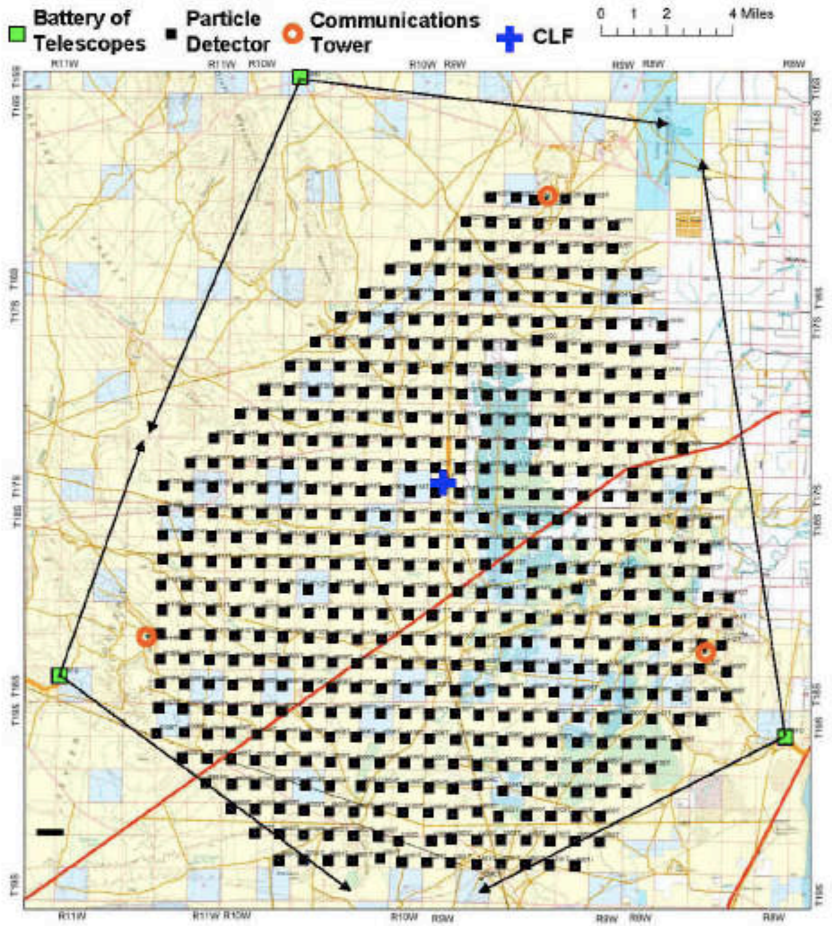
(Depth of muons, shower long.devel., etc: same trend?)

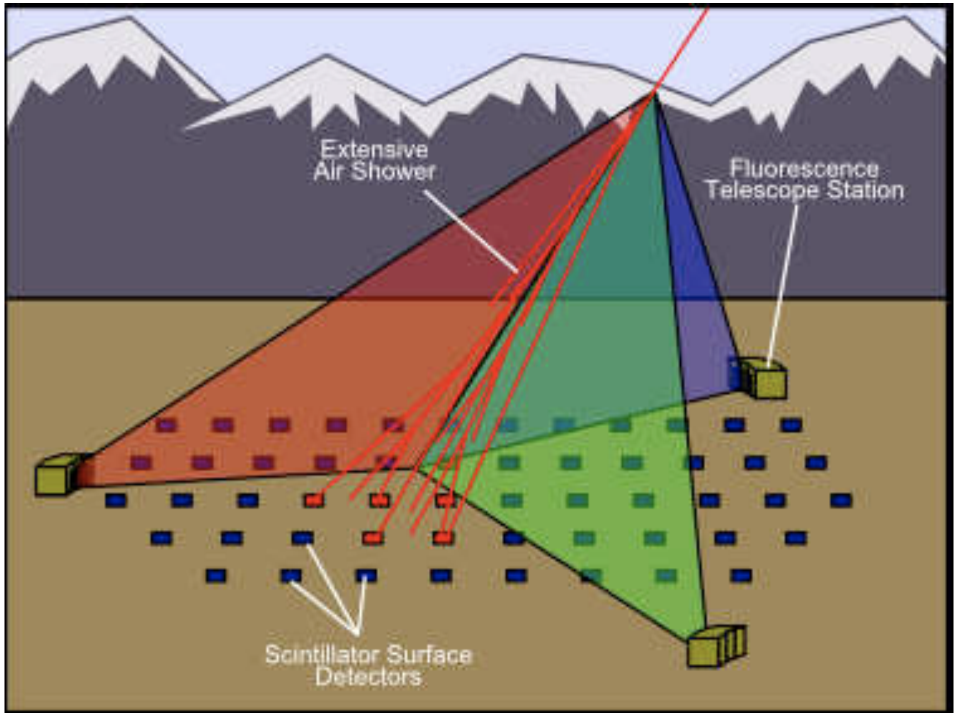
# ***GZK energy***

- ***"GZK"*** = Greisen-Zatsepin-Kuzmin (1967)
- ***"UHECR"*** = ultra-high energy cosmic ray, roughly $10^{18}$-$10^{21}$ eV = $\boldsymbol{10^{-2}}$ ***-10*** $\boldsymbol{E_{GZK}}$
- $\boldsymbol{E_{GZK}}$ ~ $10^{20}$ eV ≡ 100 EeV (Exa-electron-Volt) ≈ $1.6 \times 10^{8}$ erg ≈ ***16 Joule*** ≈ ***4 calories***
- $\boldsymbol{E_{GZK}}$ ≈ fast-serve ***tennis ball*** (~ 130 km/h), or ~ the energy of a small caliber pistol ***bullet***
- Significance: $E \gtrsim E_{GZK}$ protons encountering the ~$10^{-3}$ eV cosmic microwave (CMB) ***photons*** undergo catastrophic ***photo-hadronic*** losses, $\boldsymbol{p+\gamma \rightarrow \pi+N \rightarrow \nu, \gamma, e^{+}}$

Other (northern) UHECR experiment:

# Telescope Array (TA)



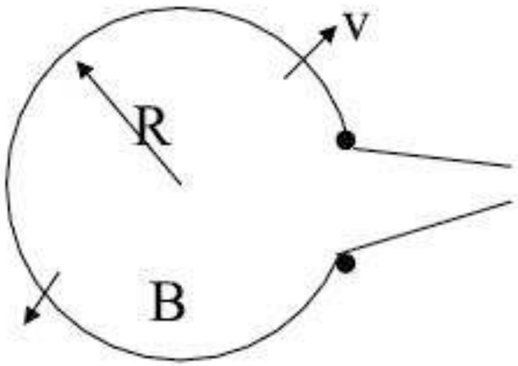

- Location: Utah - 700 km$^2$, 500 SD, 3 FD, 1.4 km altitude
- Hybrid designed, based on Akeno SD and HiRes Fly's Eye FD
- In operation: science results compatible ($\pm 1\sigma$) with Auger

# UHECR : maximum energy ?

(Electrical circuit analogy - the real physics boils down to the same)

*gyroradius:* $r_L \sim c t_{gy} \sim m_p c^2 \gamma / ZeB = \varepsilon_p / ZeB < R$ (*size of accel.*)

or (EM analog):




$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/v} = \beta BR$$

$$\rightarrow \varepsilon_p < \beta e B R$$

$$\Rightarrow L > 4\pi R^2 \frac{B^2}{8\pi} v > \frac{1}{2\beta}\left(\frac{\varepsilon_p}{e}\right)^2 c$$

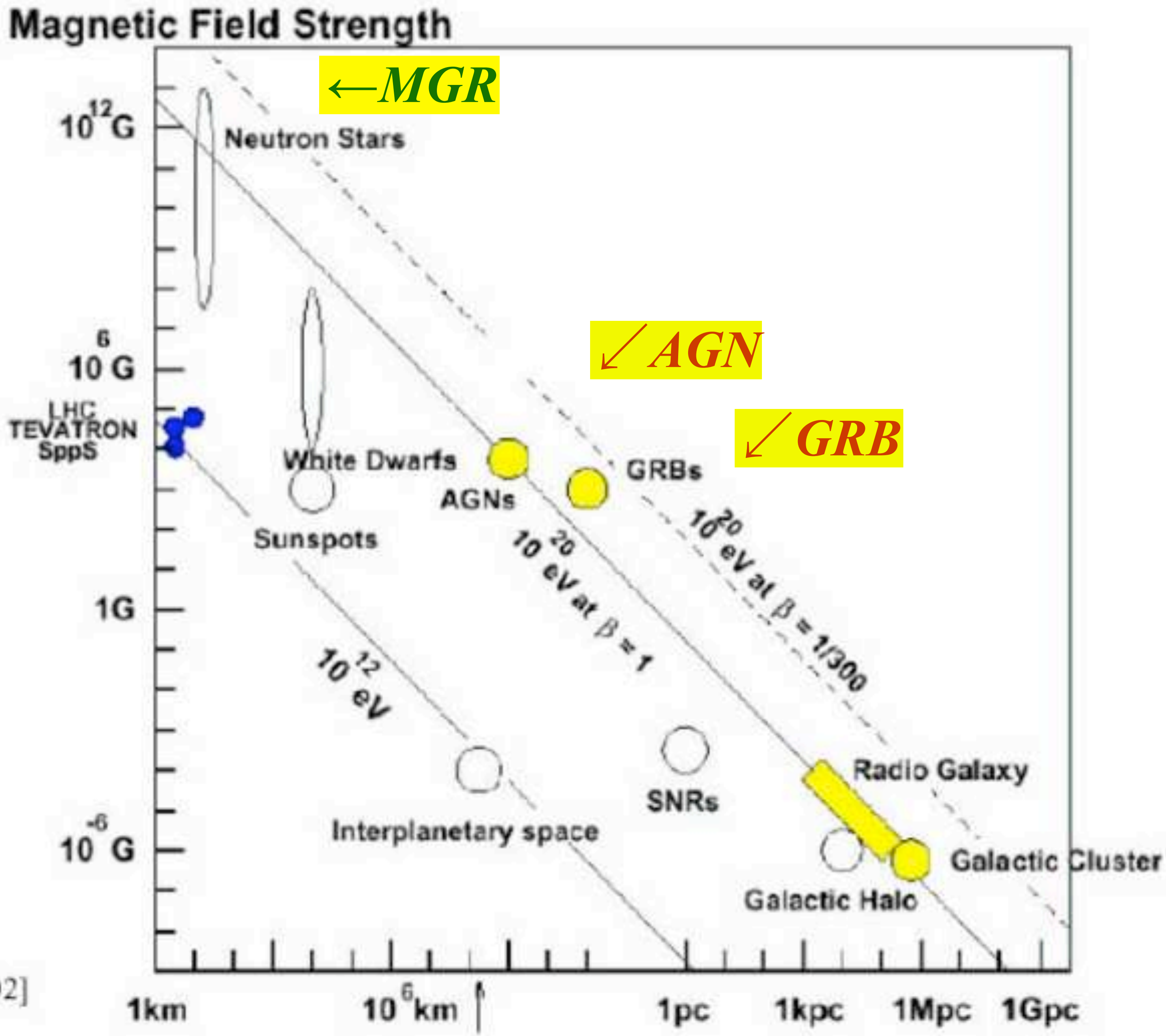
But if relativistic expansion, bulk Lorentz factor $\Gamma >> 1$,
then $\text{time}_{obs} \sim R/c\Gamma$, and $\text{size}_{obs} \sim R/\Gamma$, hence need

$$\Rightarrow L > 2\frac{\Gamma^2}{\beta}\varepsilon^2_{p,20} \times 10^{45} \text{erg/s}$$

⇒ ***GRB, AGN..?***

(only ***the strongest*** source types qualify !)

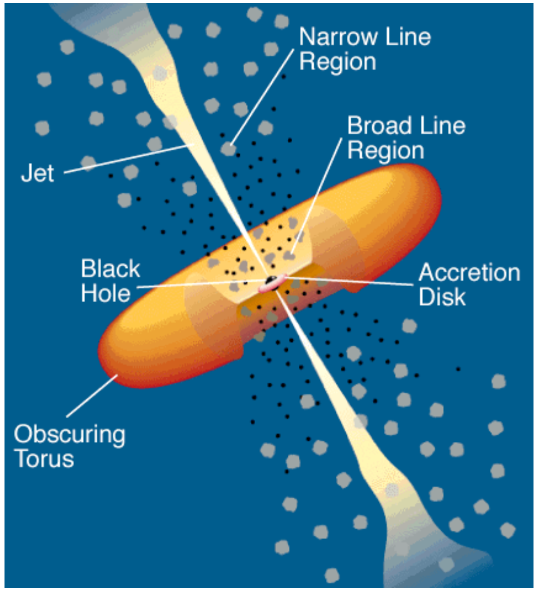
# The Suspects (Hillas plot)



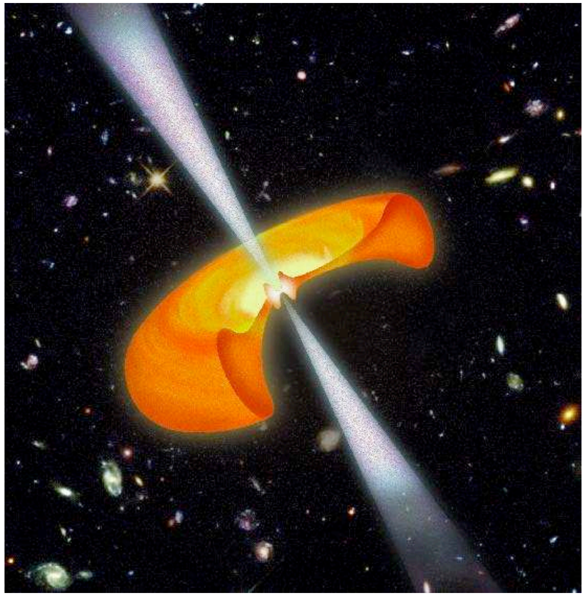

[K. Arisaka 02]

# Possible sources of UHECRs (& Neutrinos) extending to ***GZK energies***

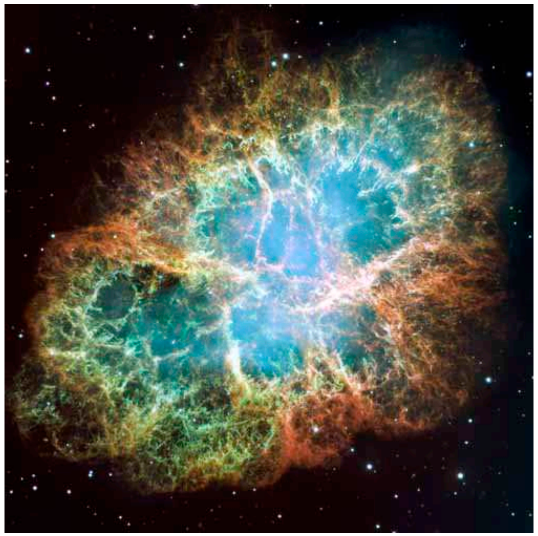
# Astrophysical UHECR Sources ?



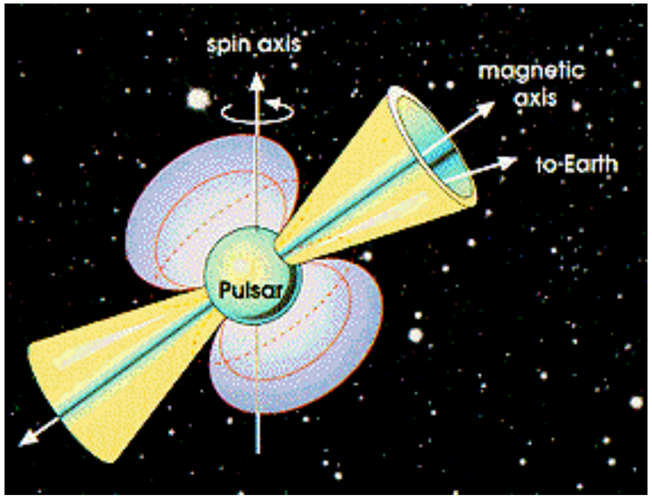

AGN
Active Galactic Nucleus



GRB
Gamma Ray Burst



HN
Hypernova




MGR
Magnetar

# Outlook for UHECR

- *The sources of the UHECR are still unknown..!*
- *They are almost certainly astrophysical sources (not TD)*
- *GRB remain good candidates, as well as AGNs, HNe, RQ, maybe MGRs.*
- *Will increasingly constrain such possibilities with GeV and TeV photon observations*
- *Will learn even more* ***if & when*** *astrophysical UHENUs are observed from any type of source*
- *Constraints from diffuse (and intrasource) γ-ray emission will also be very useful, and may remain for a long time the main constraint*
- *Composition and clustering will provide important clues*

# What is the **Relation** between ***UHECRs and UHENUs?***

UHECR = Ultra-High Energy Cosmic Rays
UHENU = Ultra-High Energy Neutrinos

define HE $\gtrsim 10^{9}$ eV (GeV)
VHE $\gtrsim 10^{12}$ eV (TeV)
UHE $\gtrsim 10^{18}$ eV (EeV)

# TeV Neutrinos

Observing astrophysical neutrinos allows conclusions about the acceleration mechanism of Cosmic Rays

(can also be from leptonic processes…)

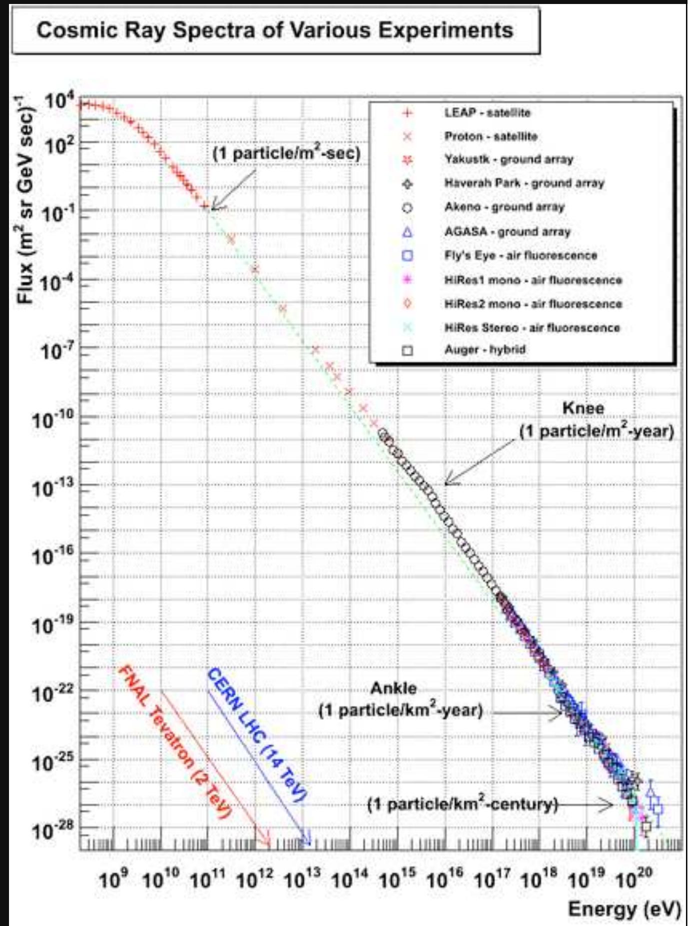
$$\mathrm{p} + \gamma \rightarrow \pi^0 + \mathrm{p}$$
$$\hookrightarrow \gamma + \gamma + \mathrm{p}$$
$$\rightarrow \pi^+ + \mathrm{n}$$
$$\hookrightarrow \mu^+ + \nu_\mu + \mathrm{n}$$
$$\hookrightarrow \mathrm{e}^+ + \nu_{\bar{\mu}} + \nu_\mathrm{e} + \nu_\mu + \mathrm{n}$$

or p, …

TeV gamma rays

Cosmic rays?

TeV neutrinos




- **Neutrinos from cosmic ray interactions in:**
  - Atmosphere
  - Cosmic Microwave Background
  - Gamma Ray Bursts (Acceleration Sites)
  - Active Galactic Nuclei (Acceleration Sites)
  - ?

Slides: C. Kopper 14 Moriond

# Astro VHE neutrinos

*At the simplest level:*

- Fermi acceleration: particle power law $dN_{p,e}/dE \sim E^{-q}$
- $e^{\pm}, B \rightarrow \gamma$ (PL $\gamma$s, act as targets for the accelerated p)
- $p, \gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_\mu \rightarrow e^{\pm}, \nu_e, \nu_\mu$
- For PL $dN_{e,p}/dE$ and $dN_\gamma/dE$ $\rightarrow$ **$dN_\nu/dE$ also PL**
- Parameters: $\epsilon_p$ , $\epsilon_e$ , $\epsilon_B$ : energy ratios of p,e,B to $E_{tot}$
- $E_{tot}$: total burst energy, $\Gamma$: bulk Lorentz factor

# How can one detect UHENUs?

# $\nu$ Interactions

- Due to SM Weak Interactions

$$\sigma^{\nu p} \sim 10^{-38}\text{cm}^2 \frac{E_\nu}{\text{GeV}}$$

- Let's consider for example atmospheric $\nu's$?

$$\Phi_\nu^{\text{ATM}} = 1\,\nu\,\text{per cm}^2\,\text{per second} \quad \text{and} \quad \langle E_\nu \rangle = 1\text{ GeV}$$

- How many interact? In a human body:

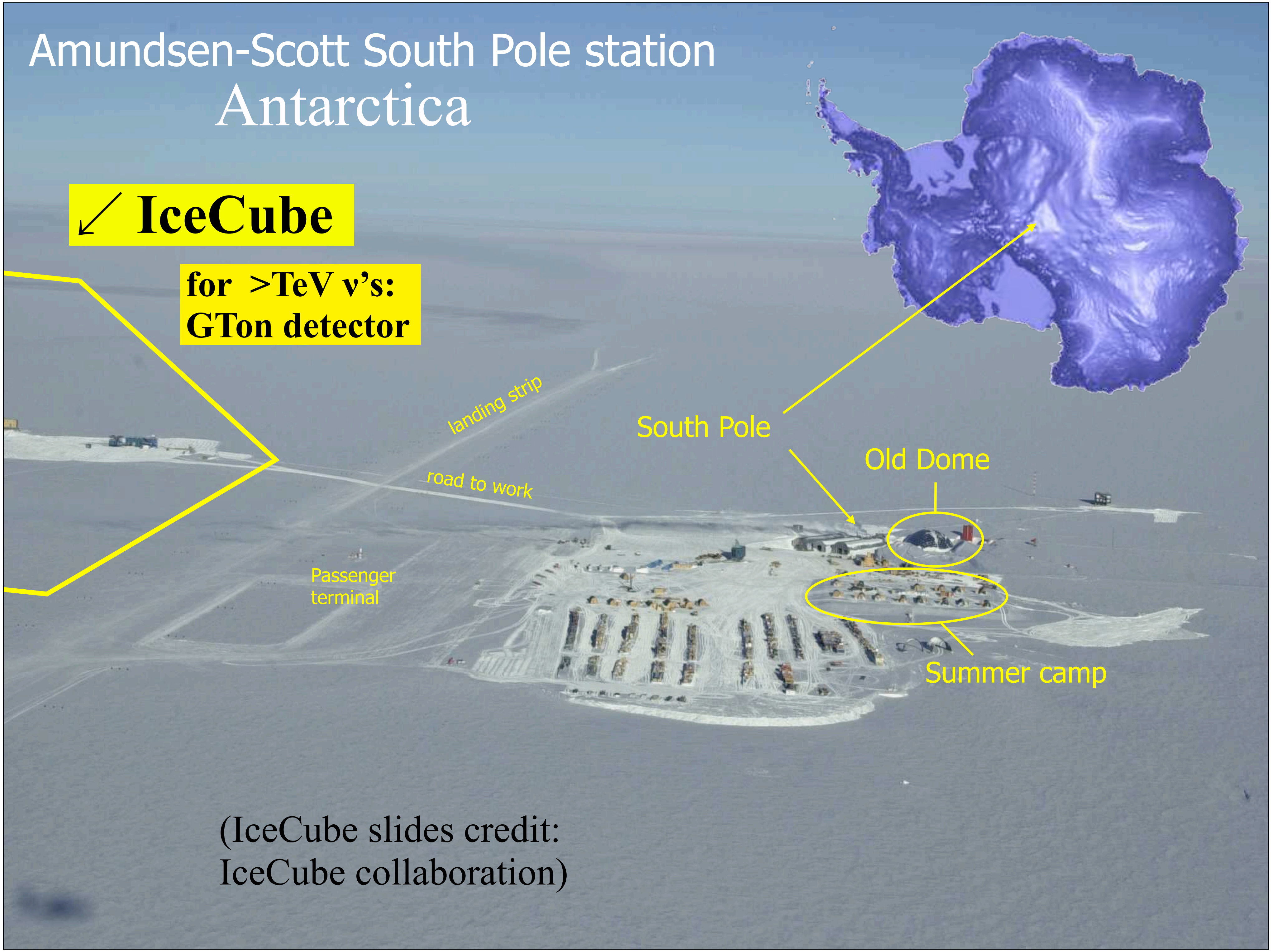
$$N_{\text{int}} = \Phi_\nu \times \sigma^{\nu p} \times N_{\text{prot}}^{\text{human}} \times T_{\text{life}}^{\text{human}} \quad (M \times T \equiv \text{Exposure})$$

$$N_{\text{protons}}^{\text{human}} = \frac{M^{\text{human}}}{gr} \times N_A = 80\text{kg} \times N_A \sim 5 \times 10^{28}\text{protons}$$
$$T^{\text{human}} = 80\,\text{years} = 2 \times 10^9\,\text{sec}$$

$\Big\}$ Exposure$_{\text{human}}$ $\sim$ Ton $\times$ year

$$N_{\text{int}} = (5 \times 10^{28})\,(2 \times 10^9) \times 10^{-38} \sim 1\,\text{interaction per lifetime}$$

$\Rightarrow$ Need huge detectors with Exposure $\sim$ KTon $\times$ year (for GeV $\nu$'s)


Amundsen-Scott South Pole station
Antarctica
↙ IceCube
for >TeV ν's:
GTon detector
landing strip
South Pole
Old Dome
road to work
Passenger
terminal
Summer camp
(IceCube slides credit:
IceCube collaboration)

# The IceCube Collaboration

http://icecube.wisc.edu

## 36 institutions, ~270 members

### Canada
University of Alberta

### US
Bartol Research Institute, Delaware
Pennsylvania State University
University of California - Berkeley
University of California - Irvine
Clark-Atlanta University
University of Maryland
University of Wisconsin - Madison
University of Wisconsin - River Falls
Lawrence Berkeley National Lab.
University of Kansas
Southern University, Baton Rouge
University of Alaska, Anchorage
University of Alabama, Tuscaloosa
Georgia Tech
Ohio State University

### Barbados
University of West Indies

### Sweden
Uppsala Universitet
Stockholms Universitet

### UK
Oxford University

### Germany
Universität Mainz
DESY-Zeuthen
Universität Dortmund
Universität Wuppertal
Humboldt-Universität zu Berlin
MPI Heidelberg
RWTH Aachen
Universität Bonn
Ruhr-Universität Bochum

### Belgium
Université Libre de Bruxelles
Vrije Universiteit Brussel
Universiteit Gent
Université de Mons-Hainaut

### Switzerland
EPFL, Lausanne

### Japan
Chiba University

The first results from the full detector!

### New Zealand
University of Canterbury

### ANTARCTICA
Amundsen-Scott Station

# Why The South Pole?

- Deep (3km) clear ice
  - on land (not on water as at north pole)
- Excellent infrastructure
  - new south pole station
- No distractions, easy to focus on work
- No polar bears

36 institutions, ~270 members, 10 countries:

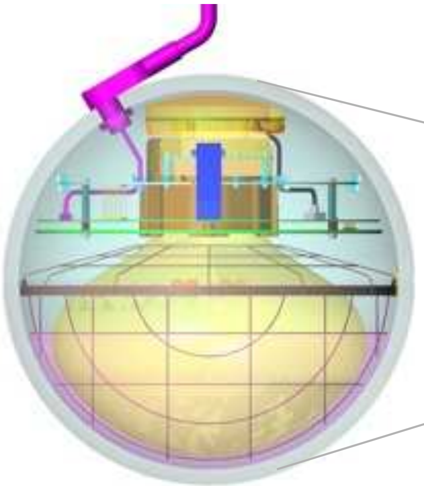
# ICECUBE

5160 DOMs on 86 strings

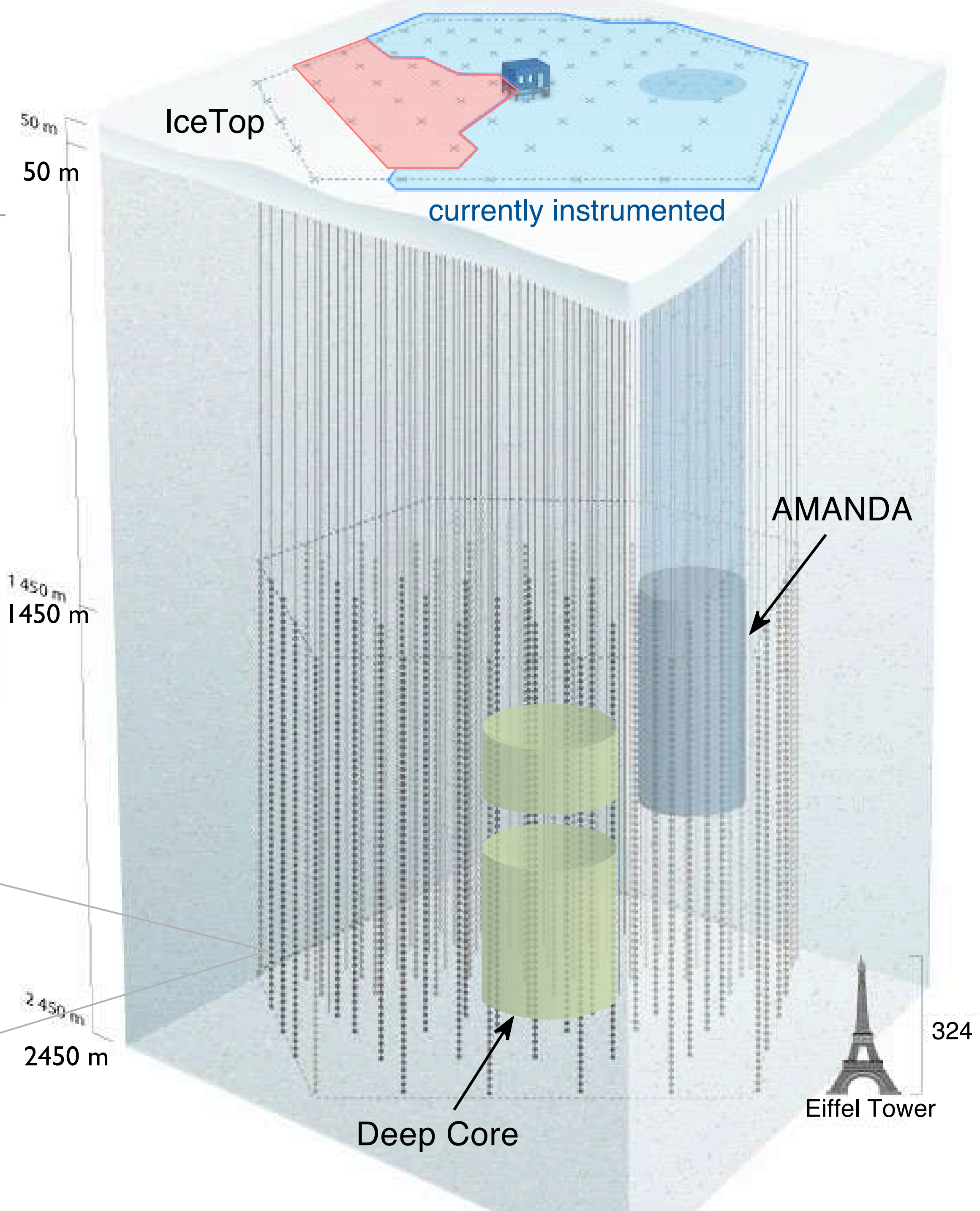
160 tank ice-Cherenkov surface air shower array (IceTop) –

Includes DeepCore infill array (sensitivity to lower energies)

**86 strings - completed in 2010**



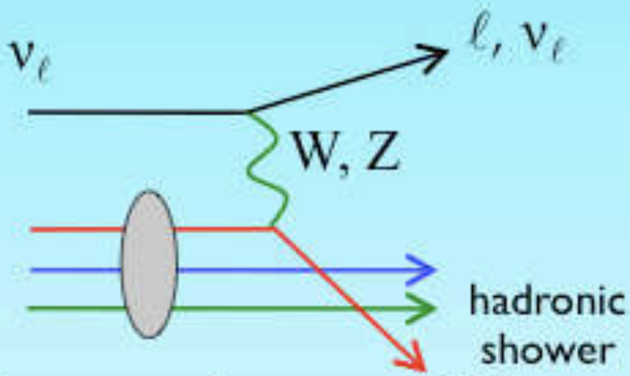
Digital Optical Module (DOM)



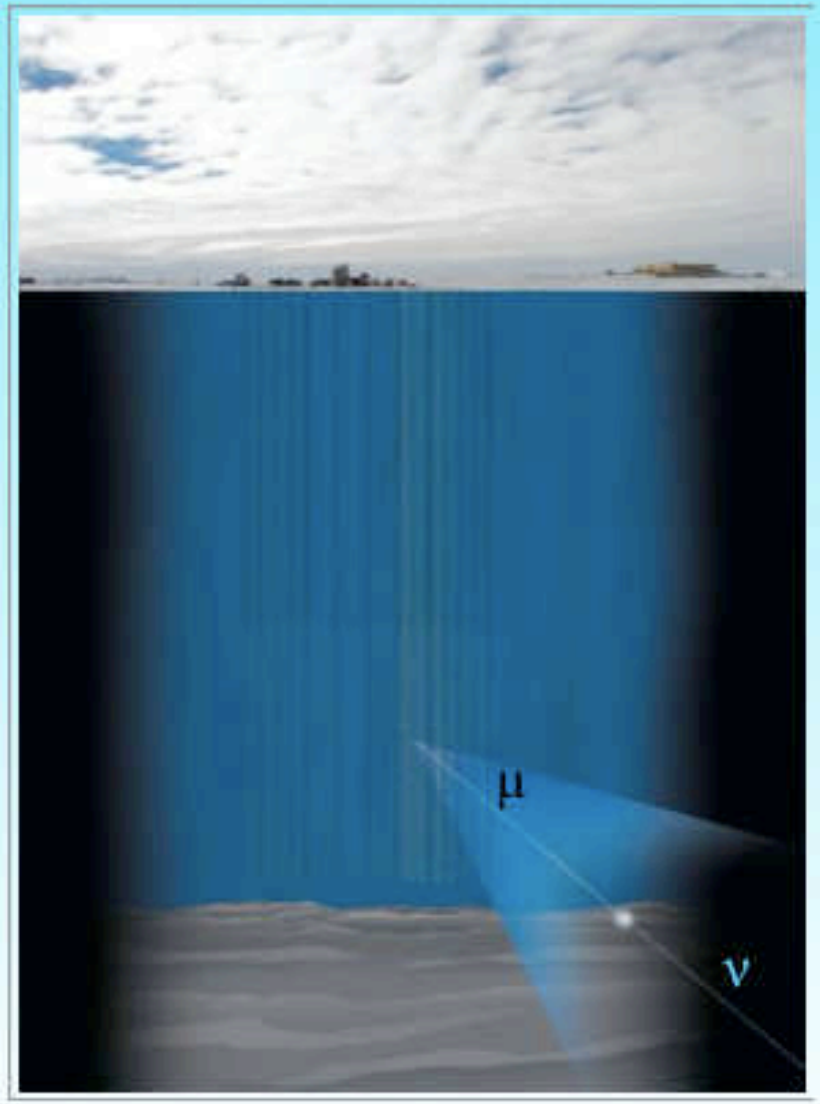

***1 GTon*** instrumented volume, USD 300M (30c/Ton= ***80 ft/tonna***)

# Neutrino Telescopes

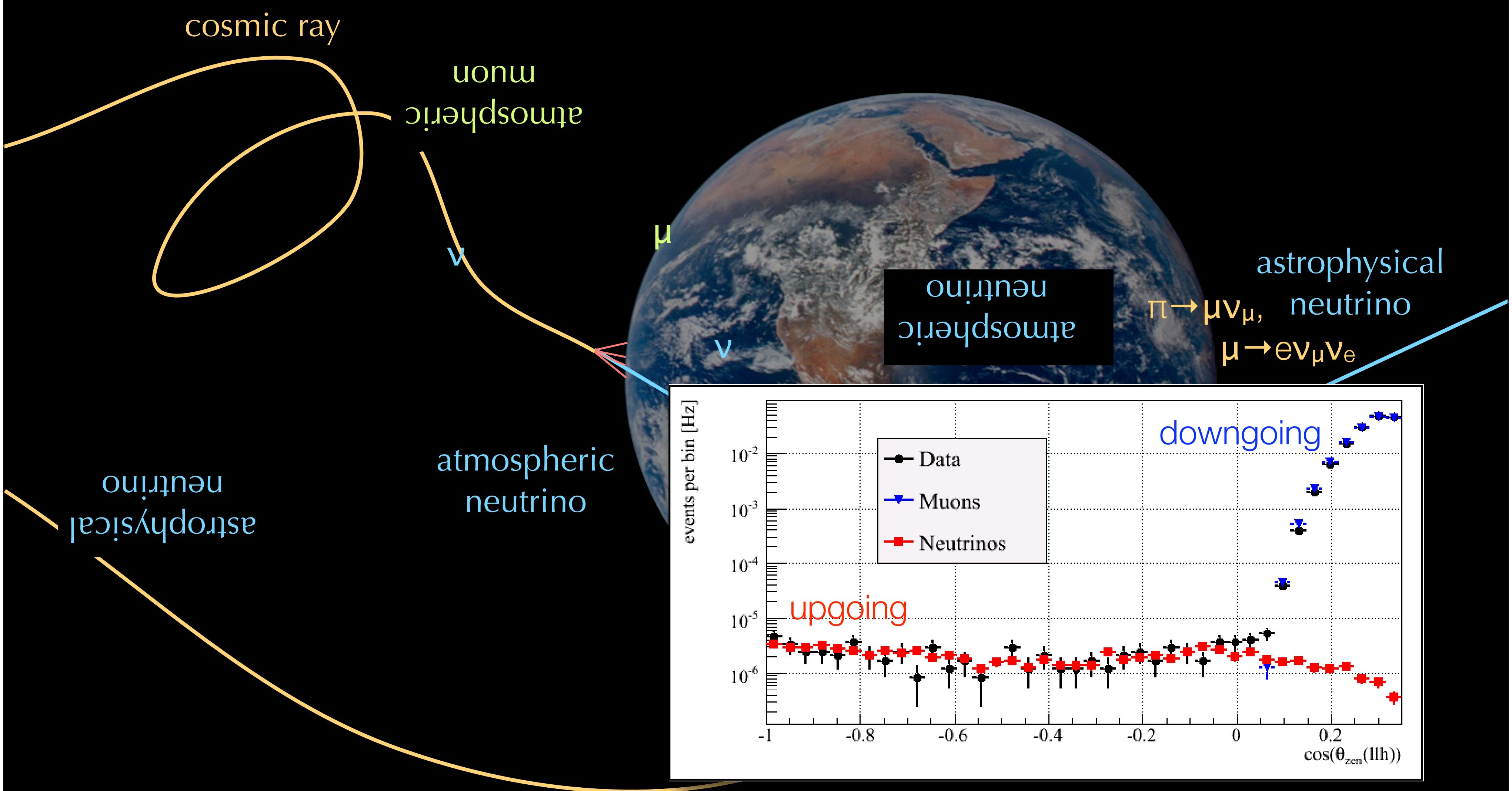
- Neutrinos interact in or near the detector




  - $\mathcal{O}$(km) muons from $\nu_\mu$ (CC)
  - $\mathcal{O}$(10 m) particle cascades from $\nu_e$, low energy $\nu_\tau$, and NC interactions
  - Cherenkov radiation detected by optical sensors



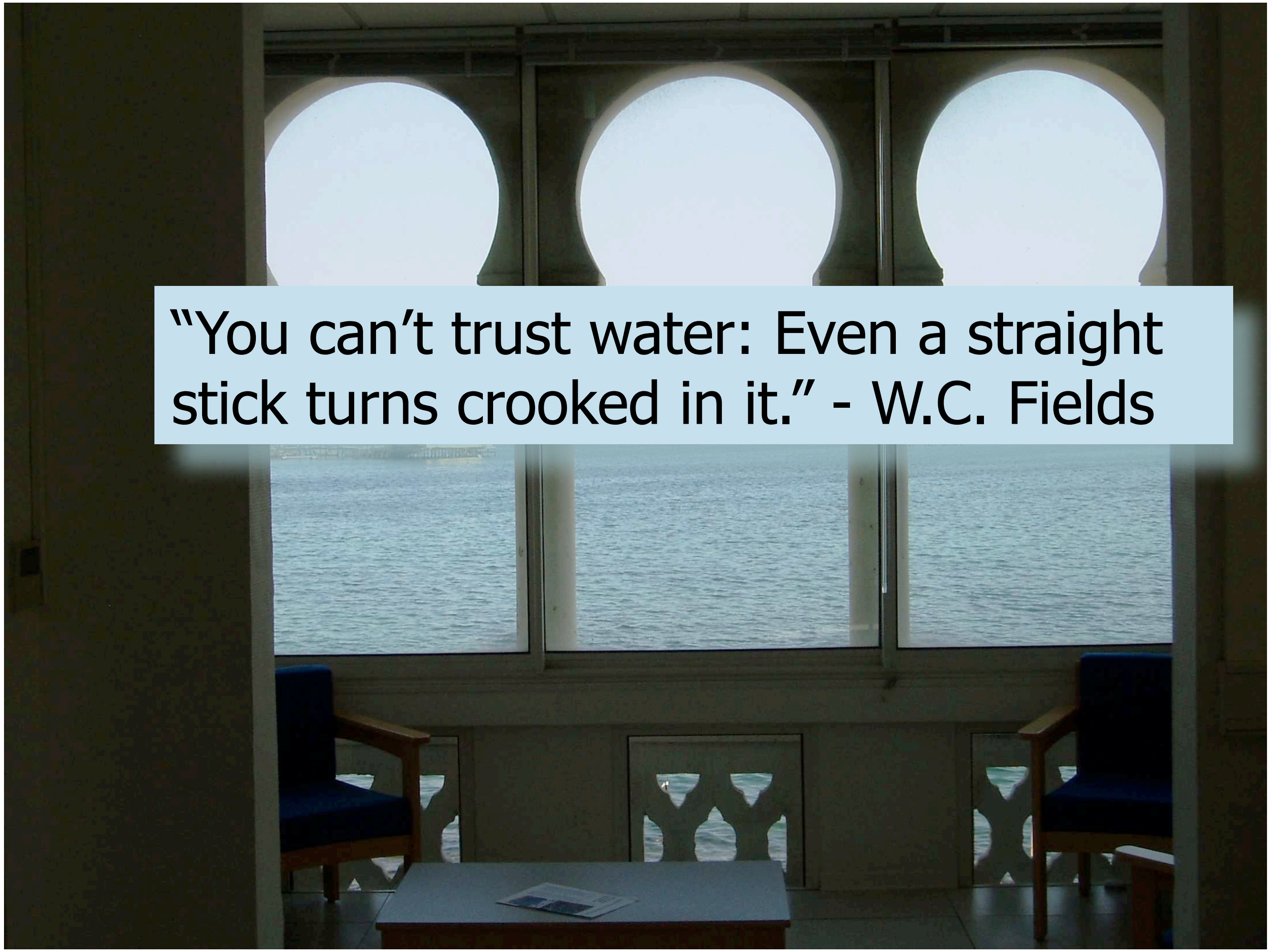
# Signals and Backgrounds




Spiffy animation by T. DeYoung

# IceCube sees the same Substance from its control room as its Competitor, **ANTARES**

***BUT***: View from ANTARES Control Room

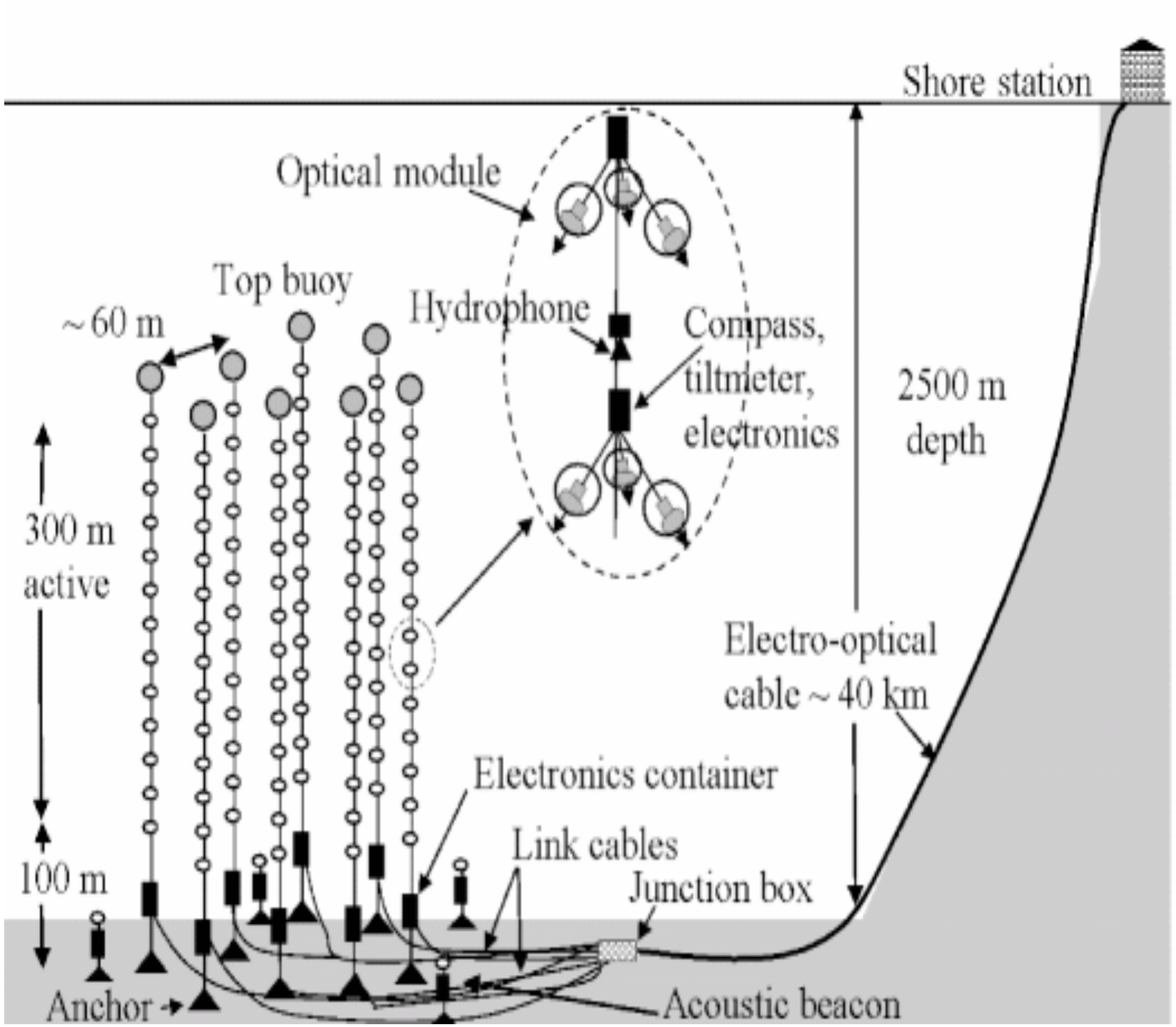



ANTARES (off the Mediterranean coast of southern France- almost Club Med..) successfully built a working 12-line neutrino telescope . Small (0.15 km$^3$) compared to IceCube, but...

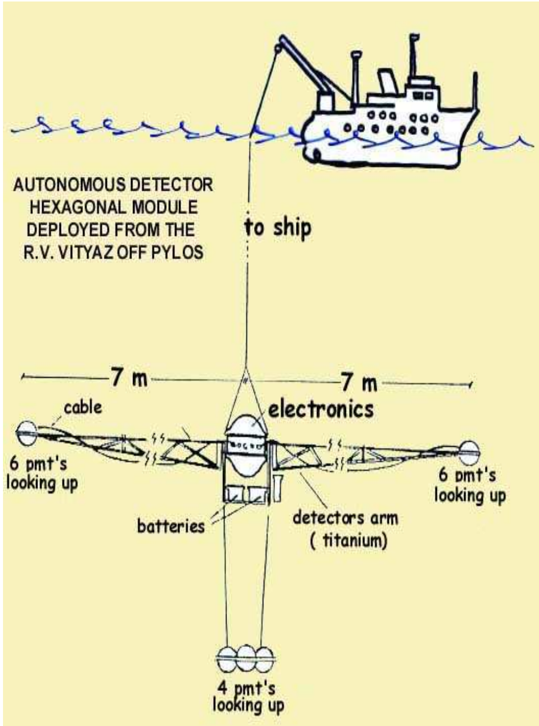
**Antares is a prototype for the Next Big EU Nu-detector:**

# ***KM3NeT***

# KM3NeT



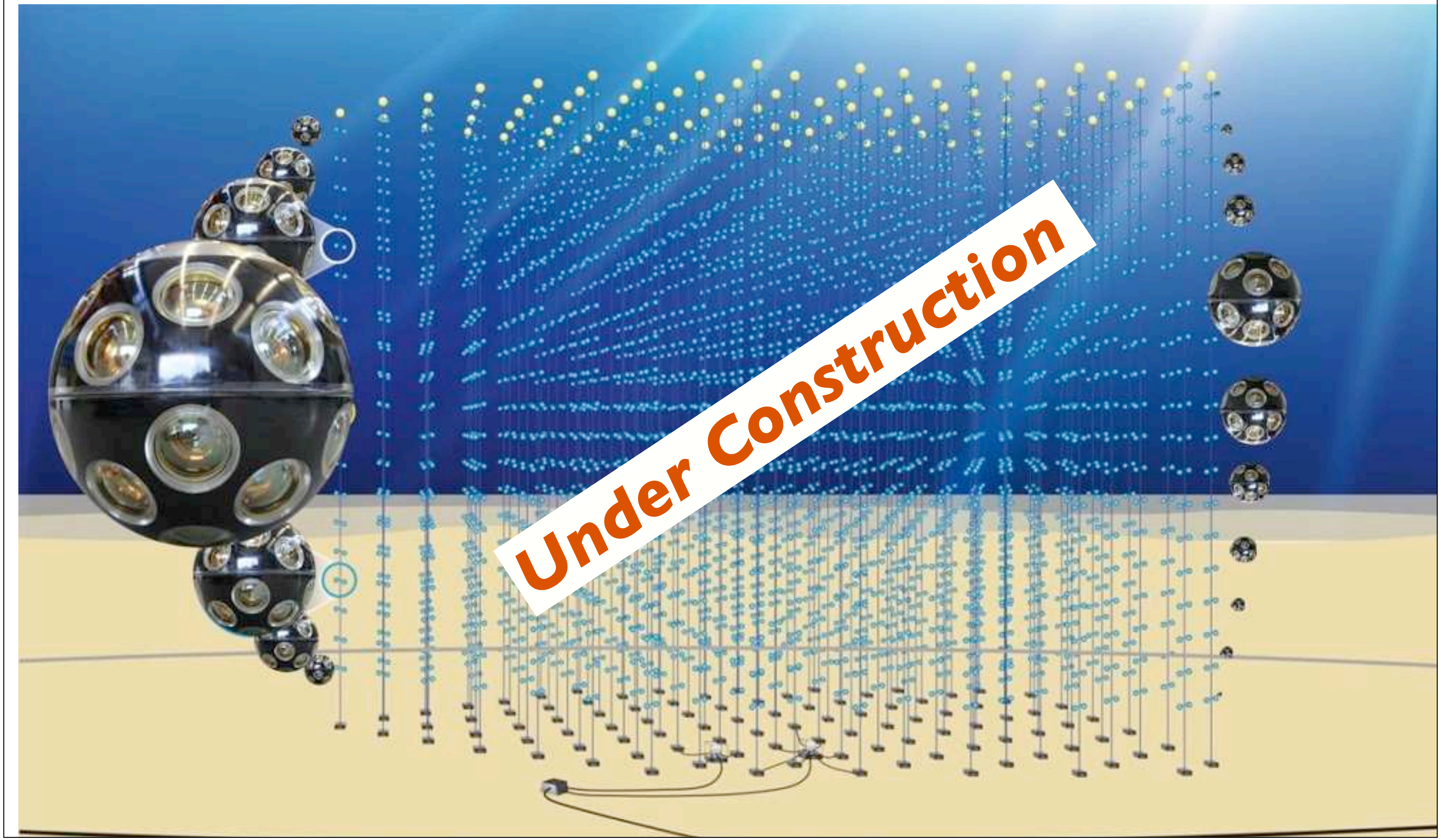

- •EU collaboration
- •Site: Mediterranean
- • Based on: **Antares, Nestor, Nemo**




- Km[3] water Cherenkov detector
- Deployment approx. 2016
- Complement ICECUBE: $\lambda_{sc,abs}$~(100,10m) $H_2O$, $\lambda_{sc,abs}$~(20,100m) Ice
- Northern site: at lower E, complementary sky coverage

# KM3NeT : 2016

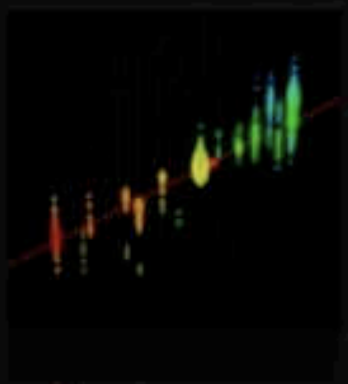
Total volume ~4 km$^3$, **3** Mediterranean sites: France, Italy, Greece



# Neutrino Event Signatures

## Signatures of signal events


### CC Muon Neutrino

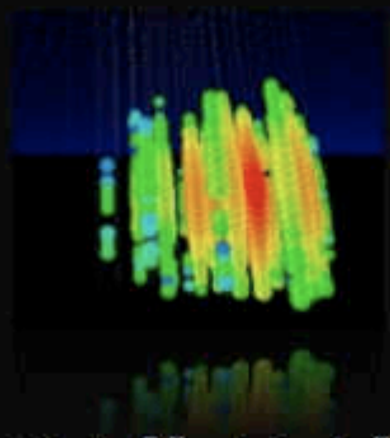


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

### Neutral Current / Electron Neutrino



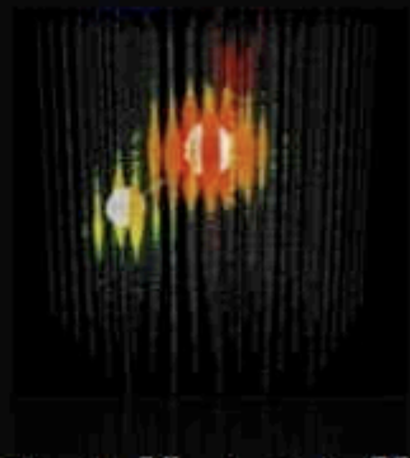
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution
(at energies ≳ 100 TeV)

### CC Tau Neutrino



$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" (≳10PeV) and other signatures (simulation)

(not observed yet)

# Flavor composition at source

- Pionic:

$$p, \gamma(p,p) \rightarrow \pi^+ \rightarrow \mu^+, \nu_\mu \rightarrow e^+, \bar{\nu}_\mu, \nu_e \rightarrow [1;2;0]_{src}$$

- Damped muons :

$$\pi^+ \rightarrow \mu^+, \nu_\mu \quad (+cooled\ muons) \rightarrow [0;1;0]_{src}$$

- Prompt :

$$\pi^+ \ (dense:\ interact\ before\ decay) \ \rightarrow [1;1;0]_{src}$$

- Beta beam :

*(neutron decay)* $n \rightarrow p^+, e^-, \bar{\nu}_e \rightarrow [1;0;0]_{src}$

# Flavor oscillations in vacuum

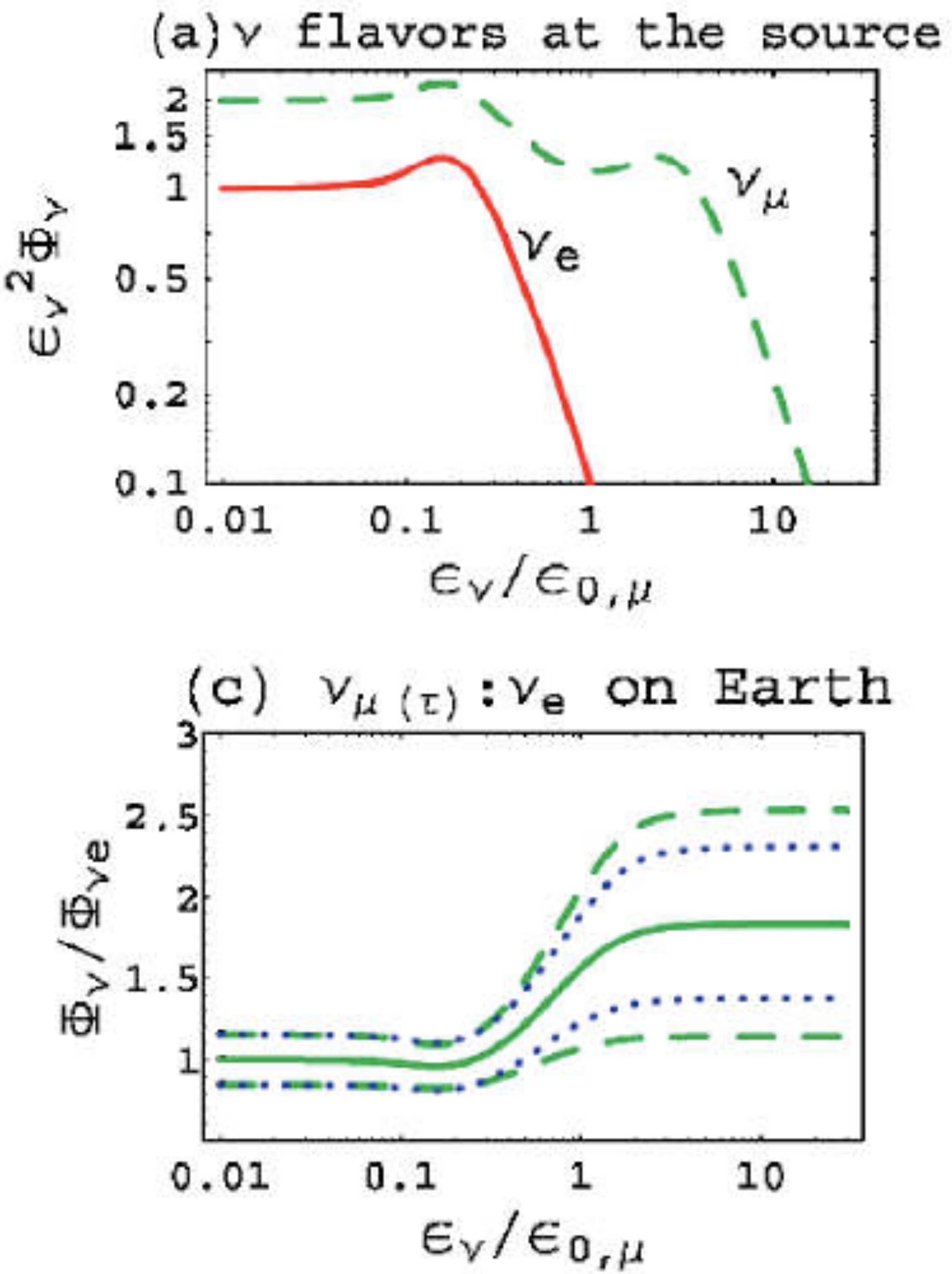
Vacuum oscillations: $[i,j,k]_{obs}=P_{osc} \cdot [i,j,k]_{src}$ ,

where "tri-bi-maximal" vac. osc. probability matrix

$$P_{TBM} \simeq \frac{1}{18} \begin{bmatrix} 10 & 4 & 4 \\ 4 & 7 & 7 \\ 4 & 7 & 7 \end{bmatrix}$$

Thus, approximate flavor composition observed is:

- Pionic: $P_{TBM}\,[1,2,0]_{src} = [1\ ;\ 1\ ;\ 1]_{obs}$
  Damped muons: $P_{TBM}\,[0,1,0]_{src} = [1\ ;\ 1.8\ ;\ 1.8]_{obs}$ ,
  Prompt (dense): $P_{TBM}\,[1,1,0]_{src} = [1\ ;\ 0.6\ ;\ 0.6]_{obs}$,
  Beta beam: $P_{TBM}\,[1,0,0]_{src} = [5\ ;\ 2\ ;\ 2]_{obs}$




# *Flavor flux & flavor ratios*

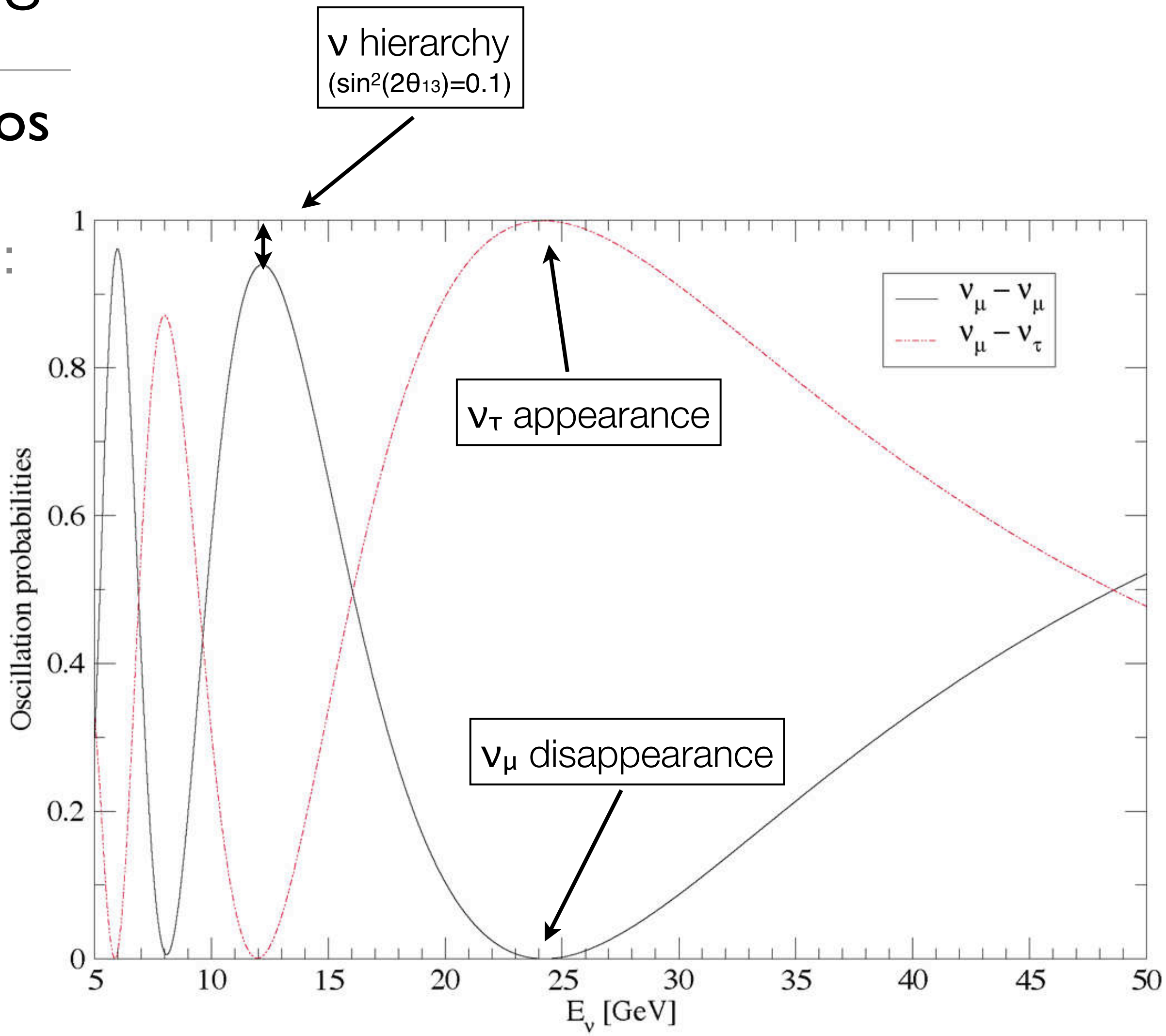
Kashti-Waxman 05, PRL 95, 181101

- For typical p,γ→π process (also p,p):
- $\varepsilon_{0\mu}$ is neutrino energy where μ-cooling sets in
- Flavor ratios above and below $\varepsilon_{0\mu}$ are ≠
- Diagnostic for p,γ-p,p
- Also $\varepsilon_{0\mu}$ dep. on B, $E_p$, etc., diagnostic for phys. conds. in accel. region

# Deep Core : fundamental physics

## Using atmospheric neutrinos

- muon neutrino disappearance : feasable
- tau neutrino appearance : reasonable
- neutrino mass hierarchy : difficult




Mena, Mocioiu & Razzaque 08, PRD 78, 093003

for vertically up-going neutrinos

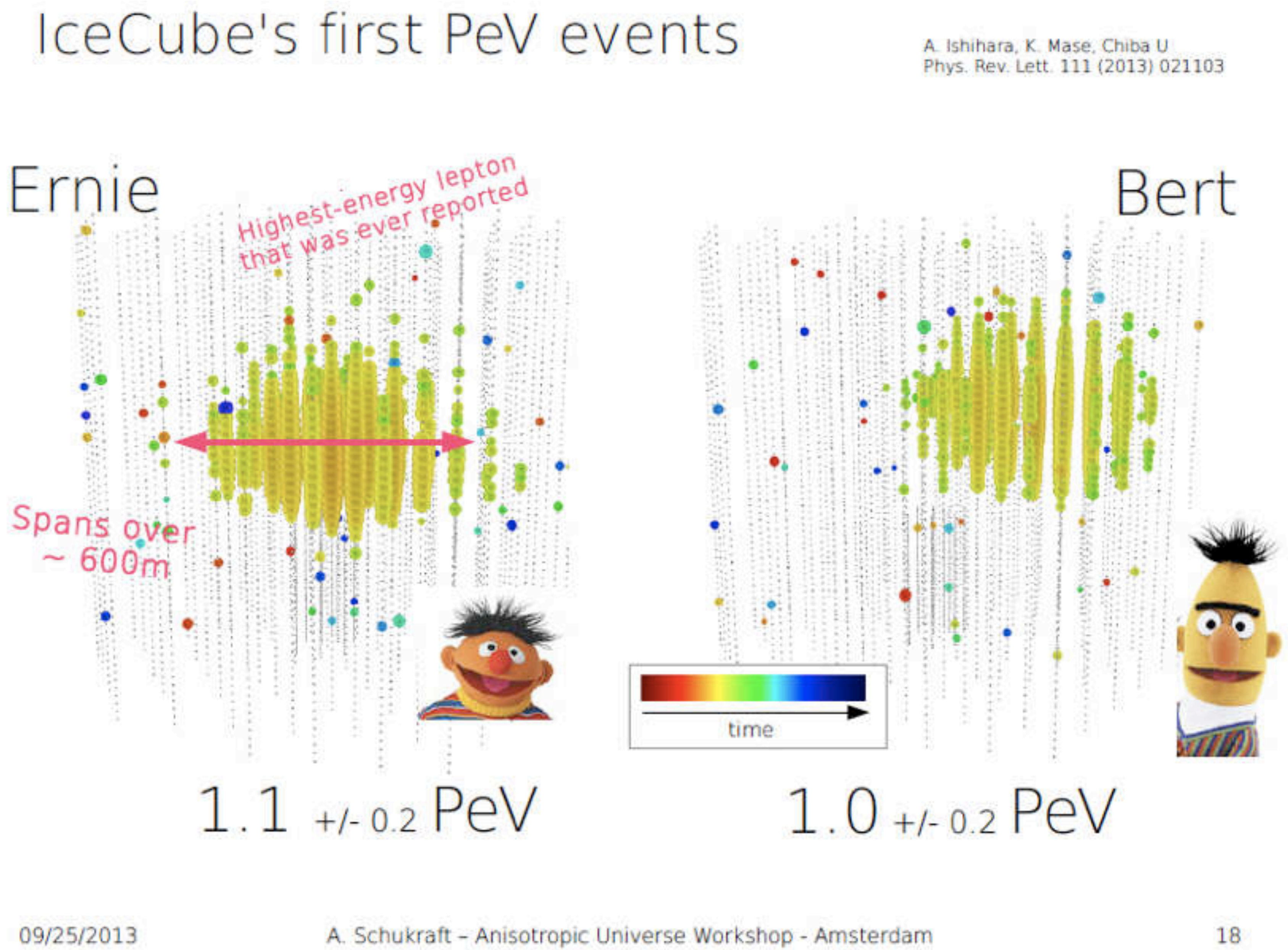
baseline = Earth's diameter

## and finally .... Science!

## *late 2013: ICECUBE announced*

**The first detection of "certified" astrophysical neutrinos**

# Non-atmospheric PeV nus: extragalactic CR tracers?



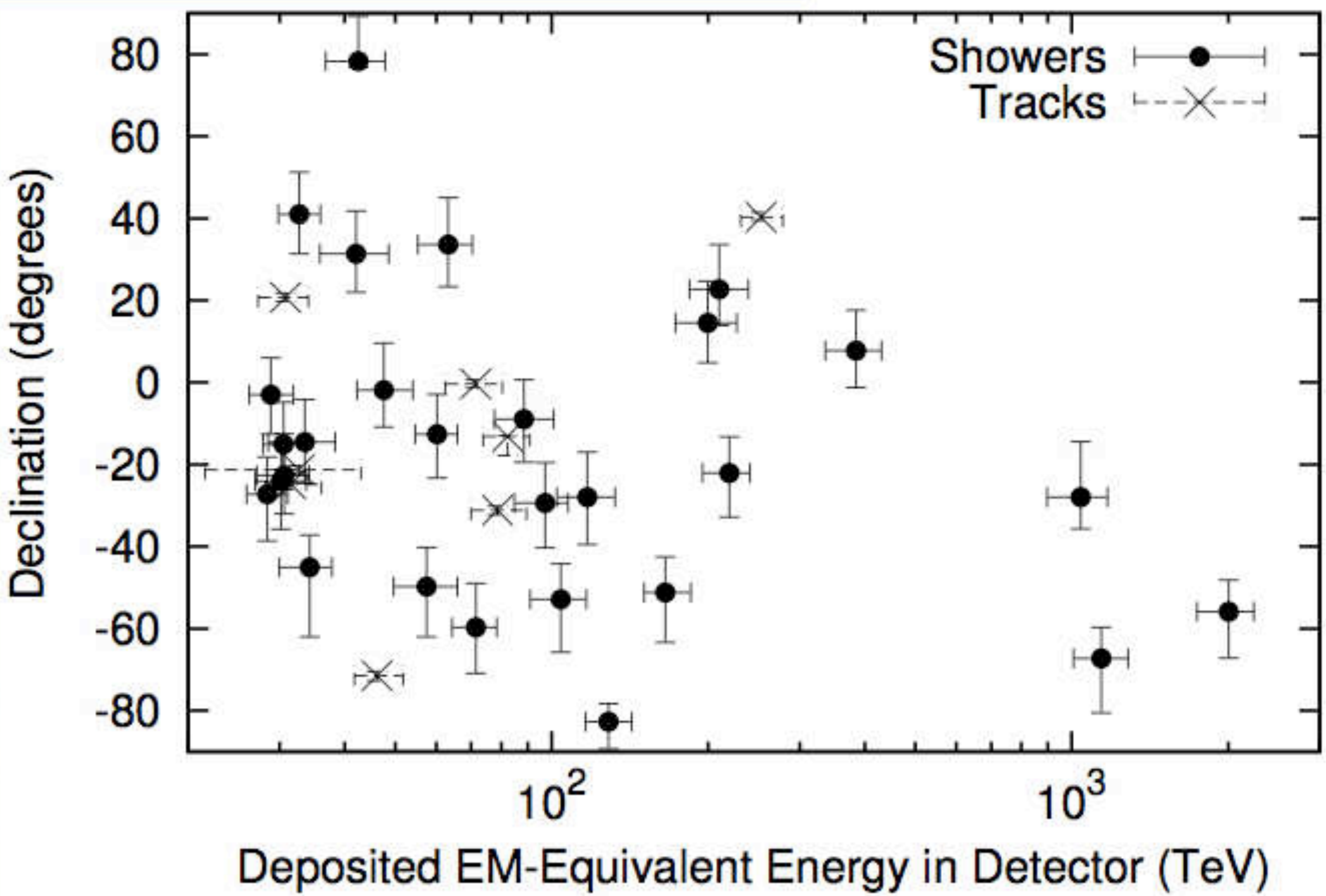

IC3col, 2013 PRL 111.021103

# Updated HESE Results (3 Year)

- 988 day sample
- detected 37 events
- expected background of 8.4 ± 4.2 cosmic ray muon events and 6.6+5.9 atmospheric neutrinos.

(Sullivan, Beyond IceCube 2014)

$5.7\sigma$



# Atmospheric neutrino flux and diffuse limit

- high-energy atmospheric $\nu_\mu/\nu_e$-spectrum as seen by **IC-40** & **IC-79/DC**

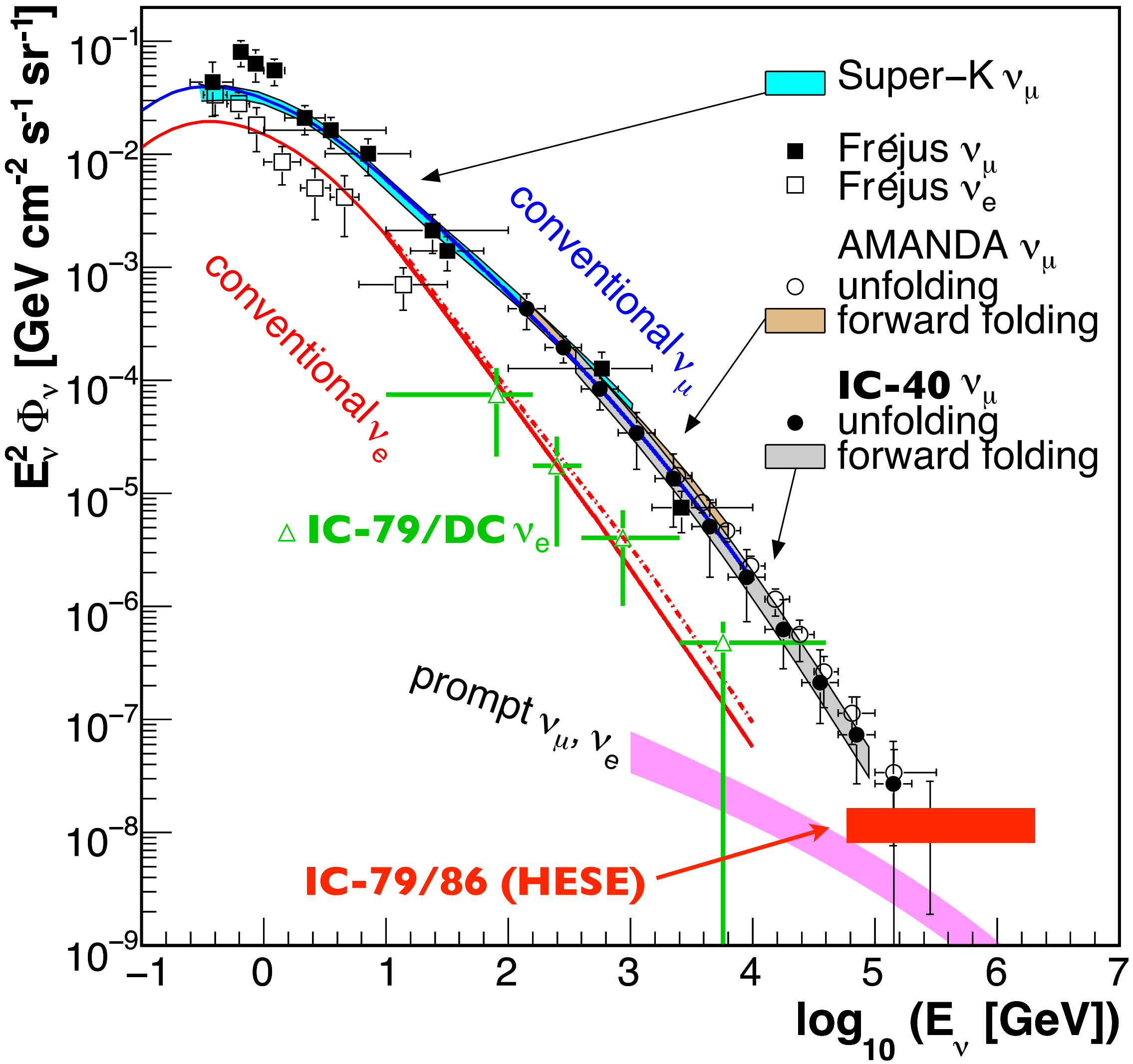
  [IceCube'11,'12]

- predicted prompt atmospheric $\nu$-fluxes (charmed meson decay)

  [Enberg *et al.*'08]

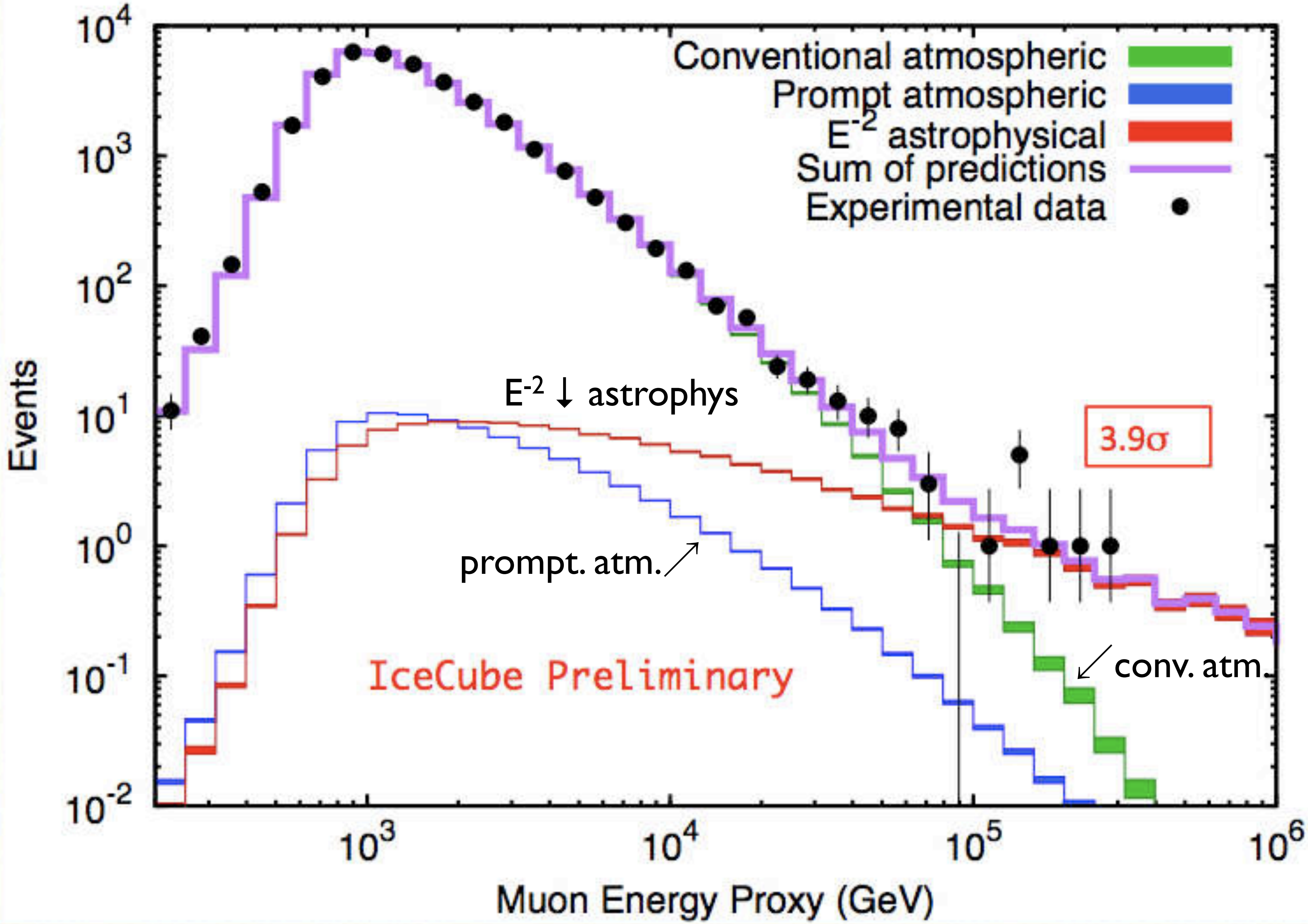
➜ high-energy starting event (HESE) analysis

  [IceCube Science'13]



# IC79,86-1 $\nu_\mu$ diffuse neutrinos

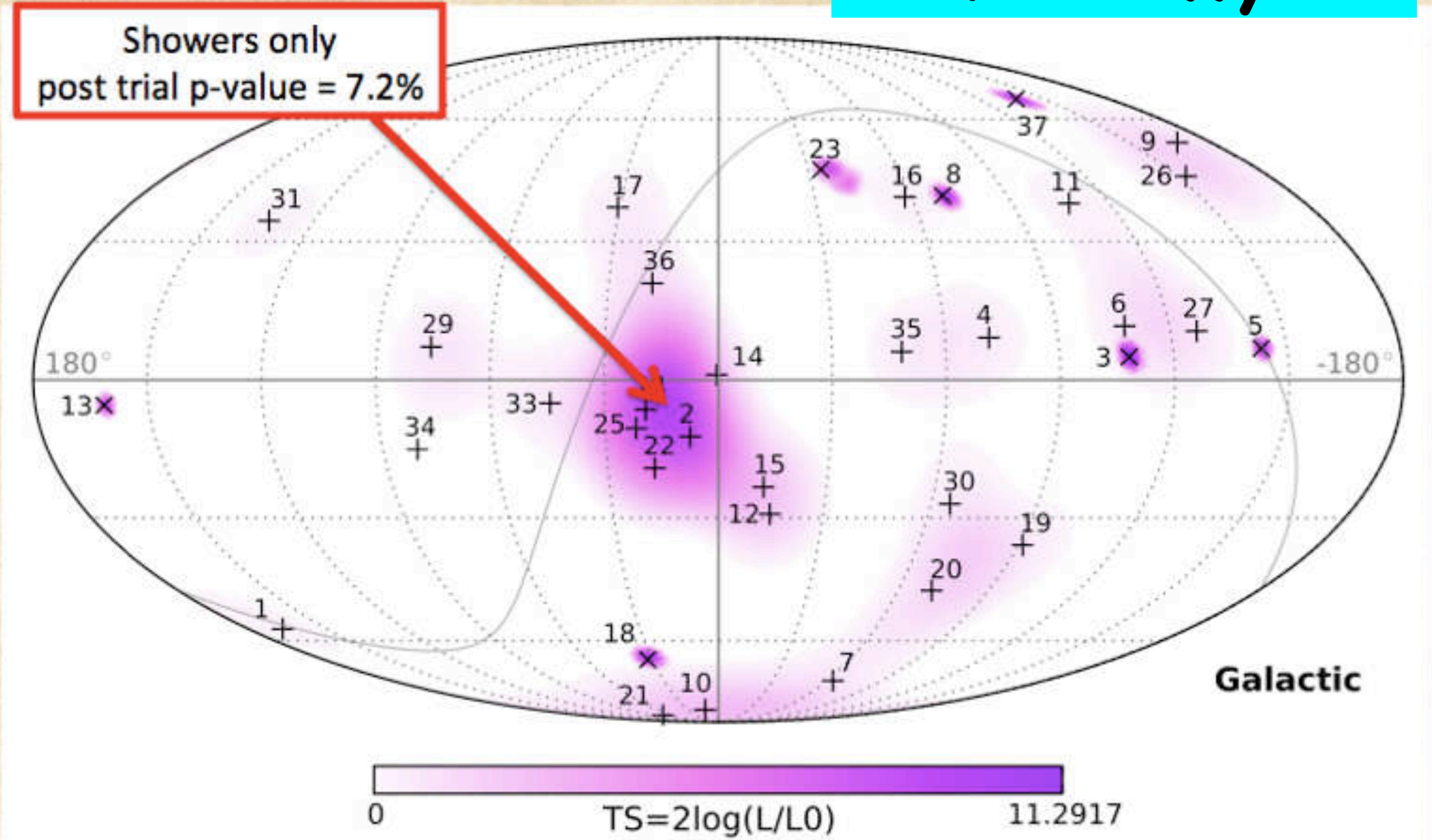
(Sullivan, Beyond IceCube 2014)



# HESE 3 Year Results

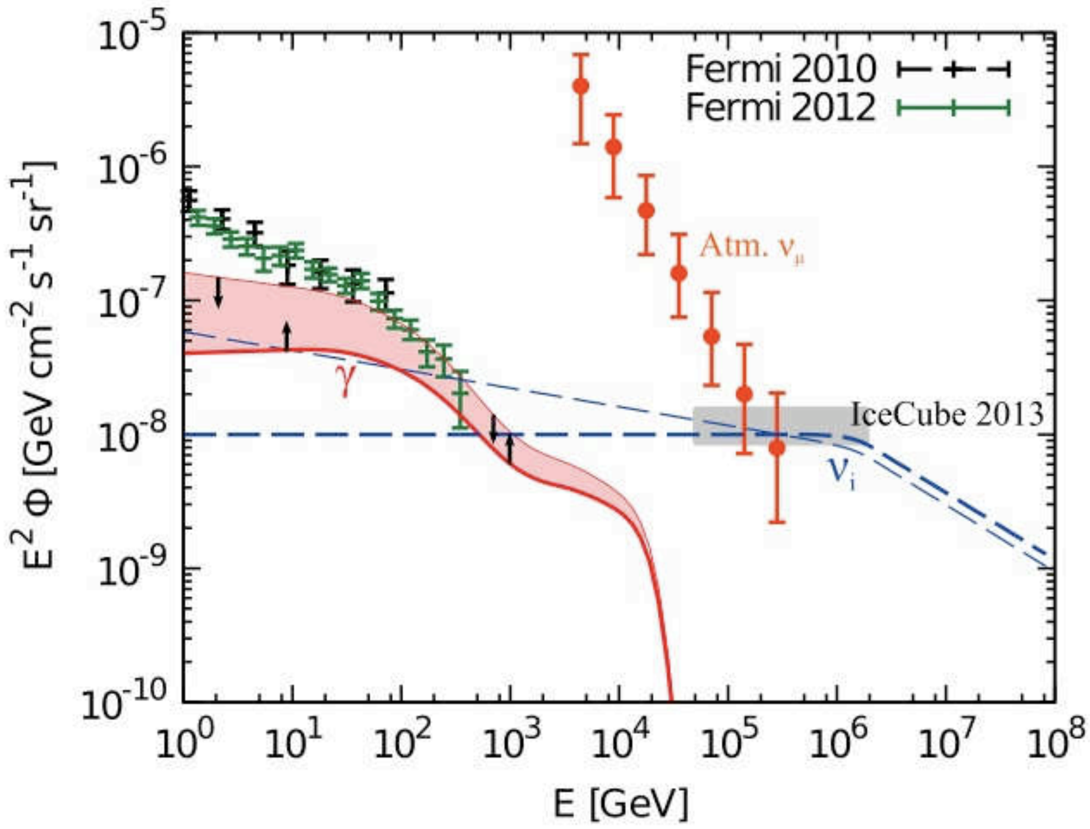
***Any obvious sources ?***

**Not really...!**



# More generally:

- Could ***pp*** sources might explain the ***PeV nu*** bkg ***?***
- In a model-indep. way, just assuming spectr. $E^{-2}$ or $E^{-2.2}$, the ***answer*** is ***yes*** - also suggesting a break @ few PeV




Murase, Ahlers, Lacki 2013, PRD, 88:121301

# Some specific pp scenarios

***Need: enough CR energy budget, pp efficiency***

- ***Radio Galaxies***: CRs 10-100 EeV, escape into cluster IGM, where produce ***pp nus*** in the LSS ✔
- ***IGS*** (cluster accretion shocks): CRs @ 100PeV, then ***pp nu*** in IGM , & $t_{diff} \sim t_{inj}$ → sp. break ✔
- ***SBGs*** (starburst gals): may expect higher $B_{ISM}$, both SNe, HNe →CRs @ 100PeV, → ***pp nus*** ✔
- ***HNe*** (hypernovae) could be candidates (rate?)

Murase, Ahlers, Lacki 2013, PRD, 88:121301

# Could these be GRB, or HNe?

- ***No "normal" GRB*** in coincidence with observed PeV events, ✘, (but they could be `choked' or low γ-luminosity GRBs)
- A ***small fraction*** of PeV sources (close to the Galactic Center) might be ***galactic*** TeV ***uni-ID sources*** - which ***could*** be ***hypernovae (HNe);*** and CR protons of 10-100 PeV, via pp → PeV νs ✔; **BUT**: only 1/28 best fit - or 3/28 at 90% CL (Fox, Kashiyama & Mészáros, 2013, ApJ, 774:74)
- A plausible ***guess:*** the ***isotropic*** component may be extragalactic ***hypernovae*** (***HNe***) in ultraluminous ***IR galaxies*** (***ULIRG***s); or ***starburst galaxies*** ✔ (He, et al, 2013, PRD, 87:063011; Murase, et al, 2013, PRD, 88:121301)
- ***Note:*** nu-spectrum must ***steepen*** above few PeV, since Glashow resonance [barnue, $e^-$ →(W)hadrons] @ 6.3 PeV is ***not seen*** → corresponding CR spectral slope ***does not*** extend to GZK energies ⇒ the PeV and GZK CR sources may be ***different?***

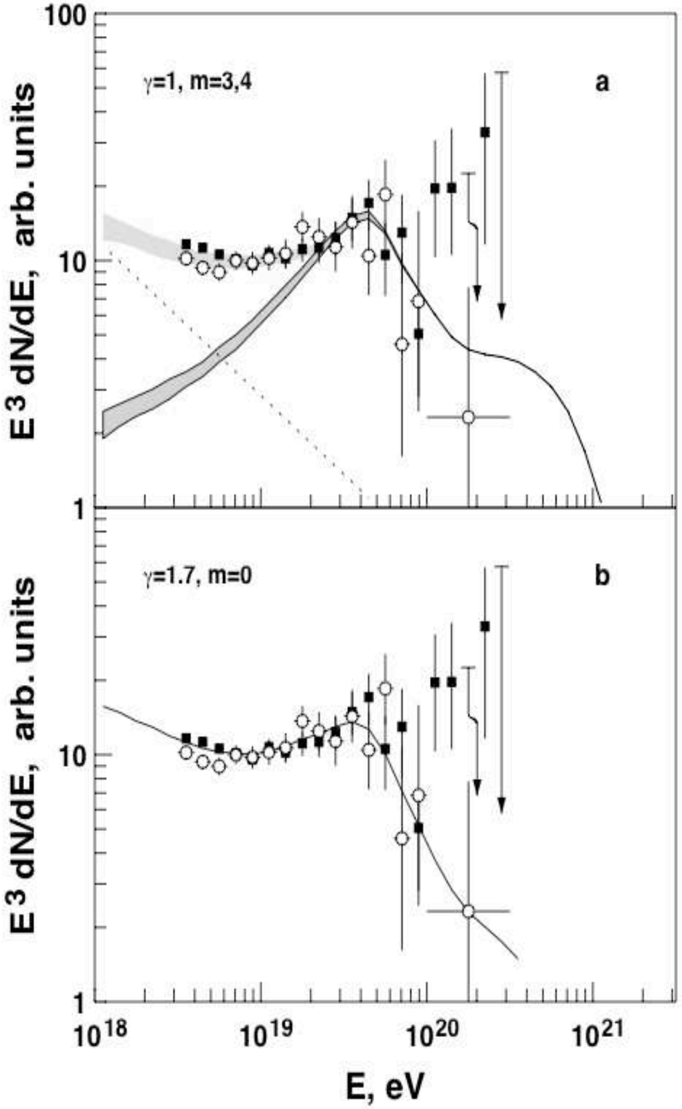
# Going above and beyond ...

# Cosmogenic Neutrinos

**2 ≠CR models**
↓ **same GZK** CR fit

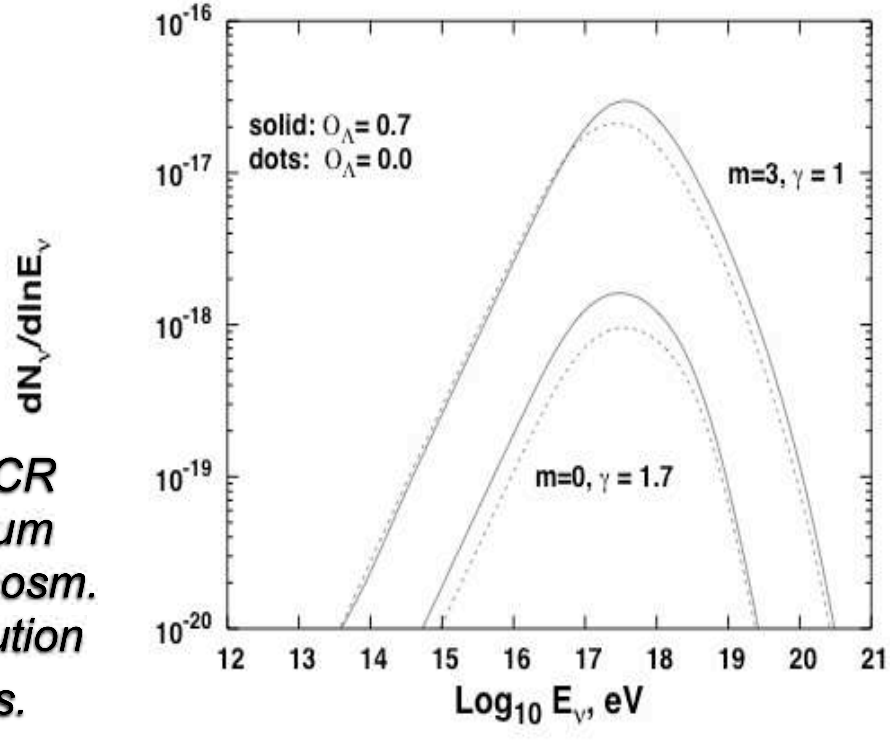
*from* **GZK CRs** *to* **GZK νs**

➡ ***get $E_\nu \gtrsim 10^{19}$ eV ?***




**But … lead to ≠ *GZK ν flux* ↓**

*Can infer GZK CR injection spectrum and/or source cosm. luminosity evolution via their GZK νs.*



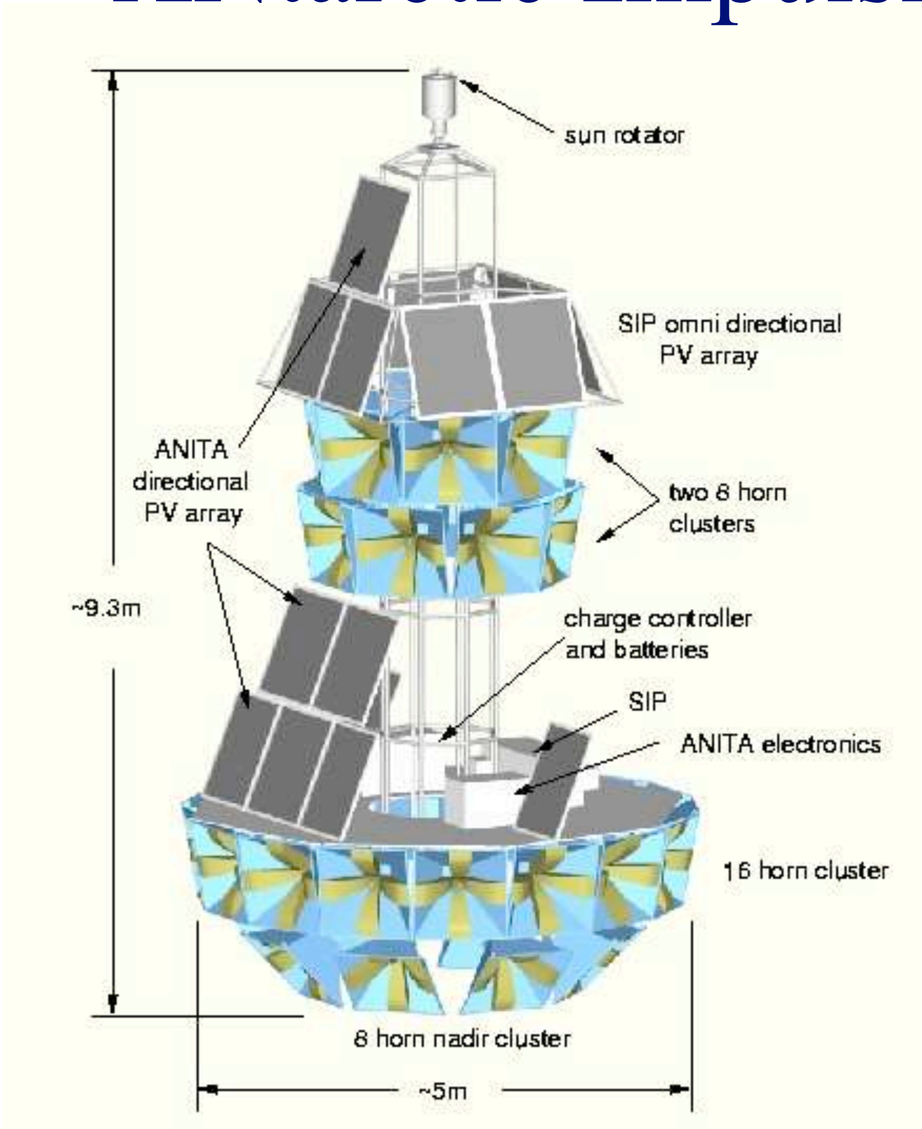


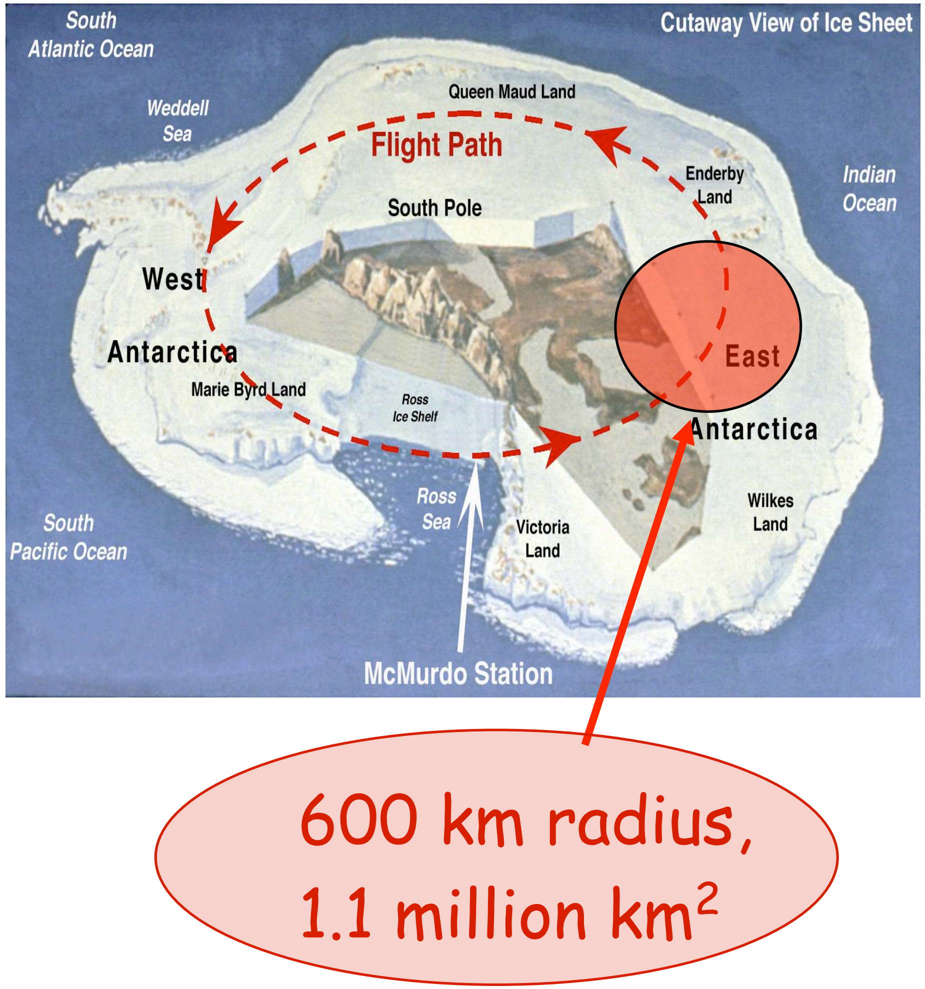

Seckel & Stanev astroph/050244

# Potential of Cosmogenic $\nu$s for CR Composition

- If CRs have large fraction of heavies, depending on source distance, photodissociation opt. depth could be <1 $\rightarrow$ only some of them break up into p,n
- Implies smaller fraction contributes to $\pi^+$ and cosmogenic $\nu$ production (Anchordoqui et al 06)
- Cosmogenic $\nu$ flux vs. CR flux may help resolve discrepancy between Auger $X_{max}$ data and apparent correlation with AGN suggesting protons

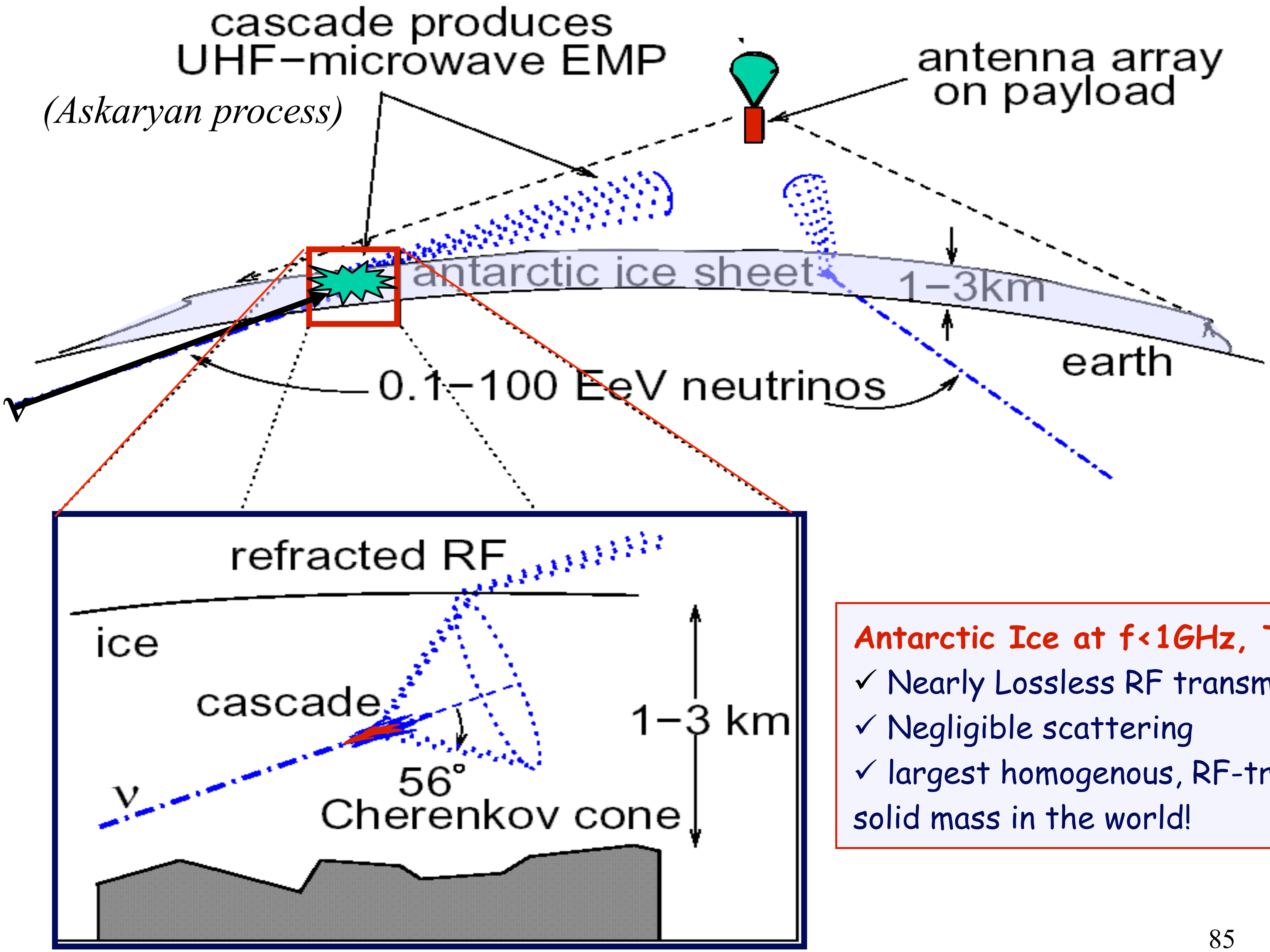
# ANtarctic Impulsive Transient Antenna



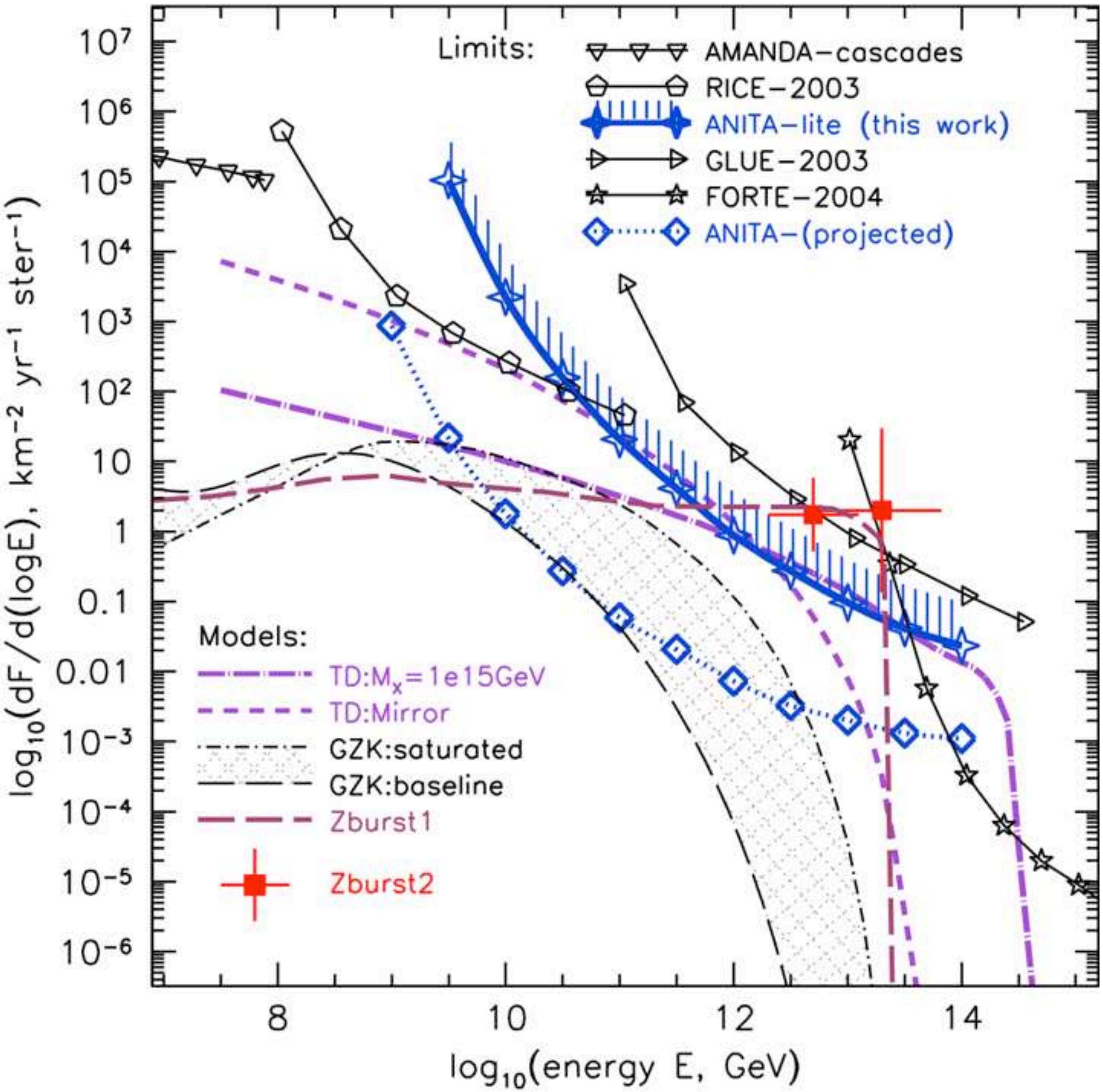




- Launched & flown 30 days in early 07 - results being analyzed

# ANITA




**Antarctic Ice at f<1GHz, T<-30C**
- ✓ Nearly Lossless RF transmission
- ✓ Negligible scattering
- ✓ largest homogenous, RF-transmissive solid mass in the world!




# ANITA GZK limits

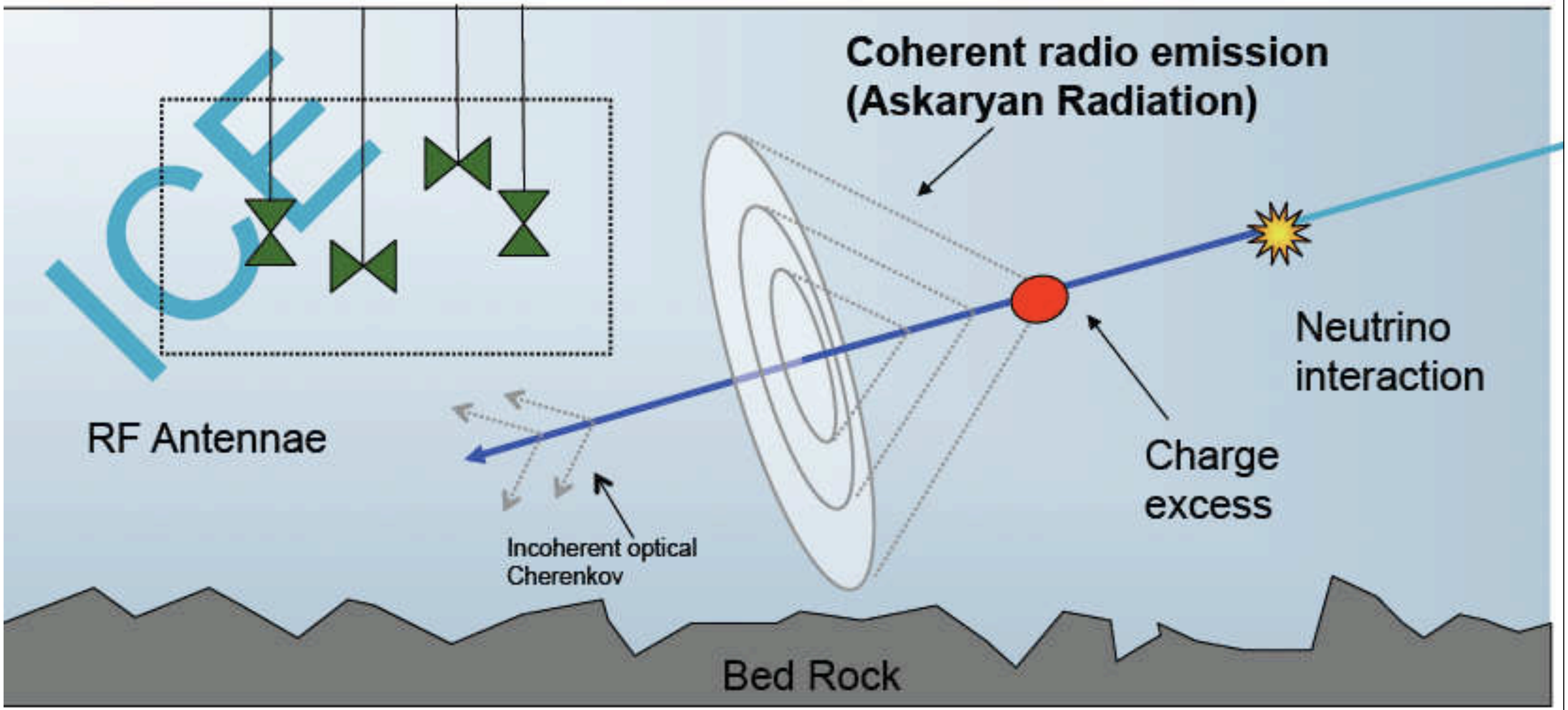
Barwick et al, PRL 96:171101

# Introducing the Askaryan Radio Array (ARA)

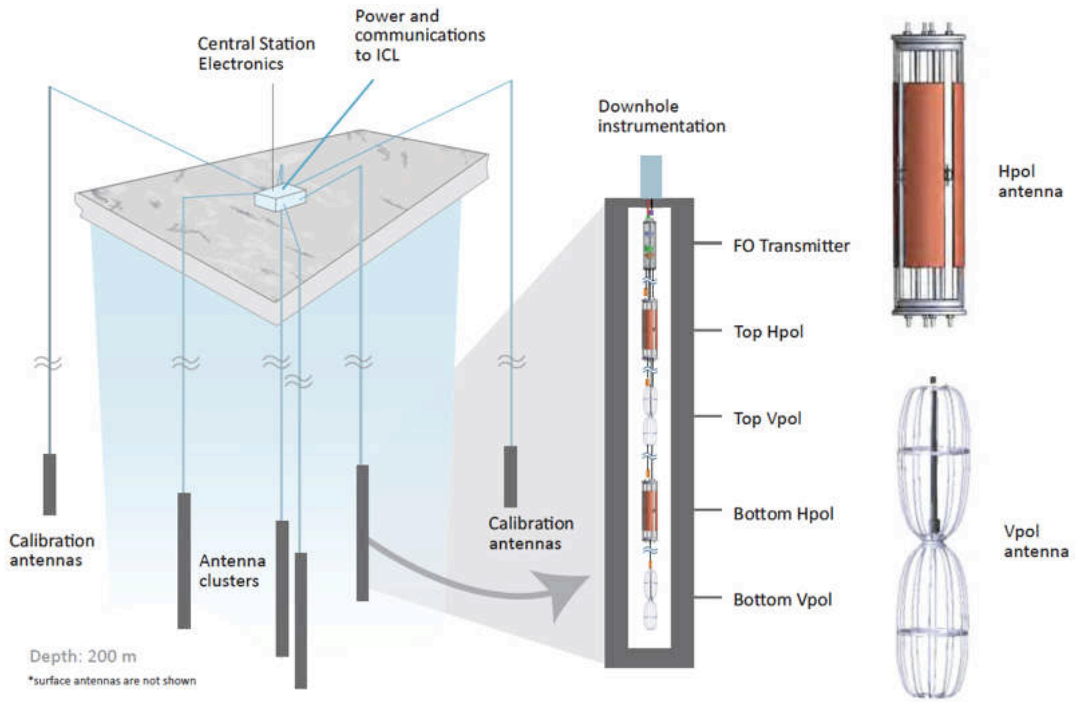
Detect radio emission from neutrino induced particle cascades in Antarctic ice

Achieve O(10km$^3$) detection volume per station using array of antenna clusters

Use timing and polarisation information fo neutrino reconstruction



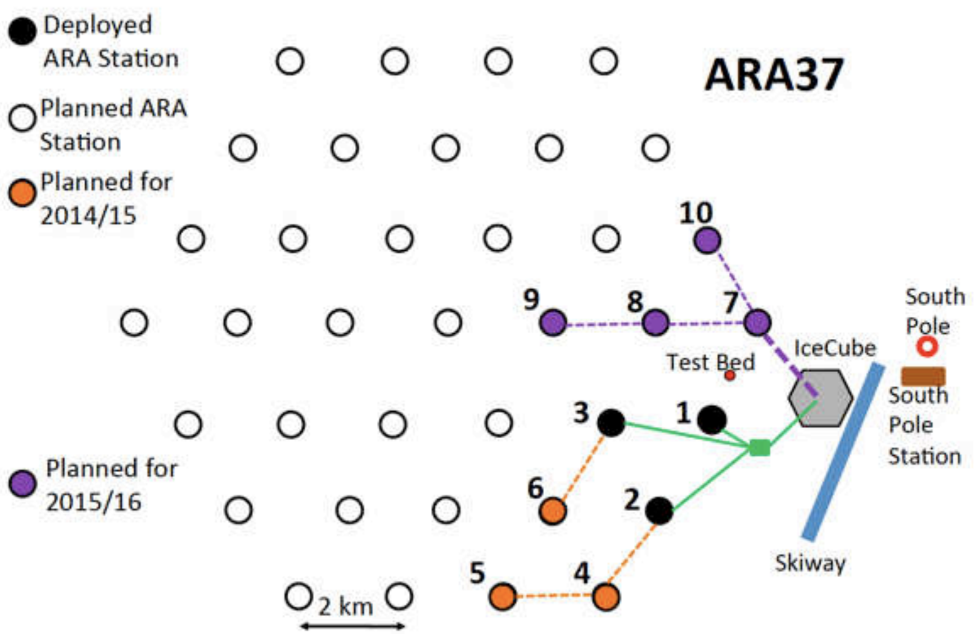

- 100 Gton detector, next to IceCube, sensitive up to $10^{21}$ eV (under construction)



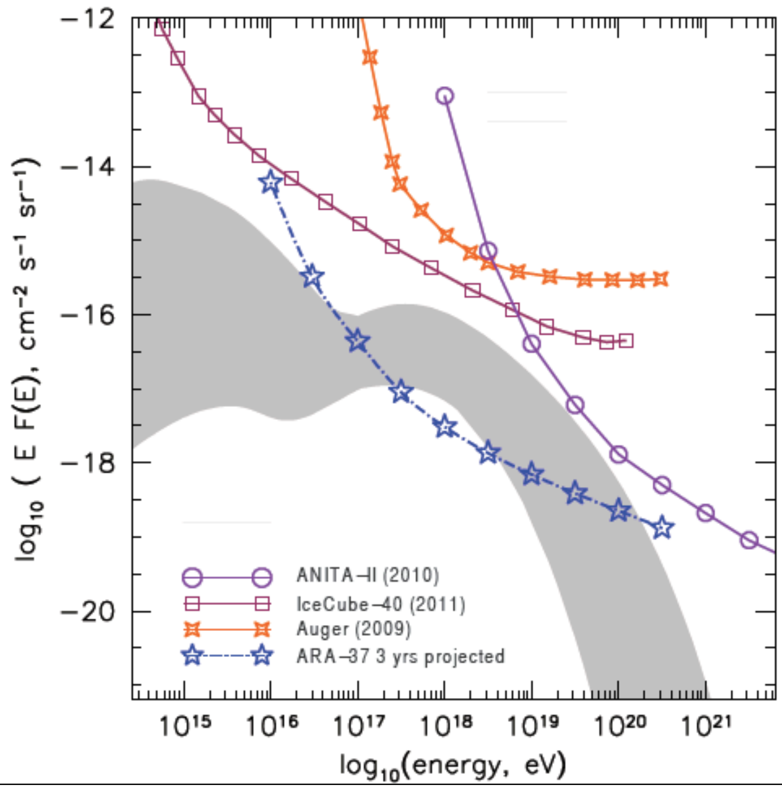

# ARA

## *Askaryan Radio Array*

- 100 km$^2$ array @ South Pole,
- Next to Icecube
- Detect GZK nus (<$10^{21}$ eV)
- 37 stations, 3 deployed, 13 under construction (funded) by 2016



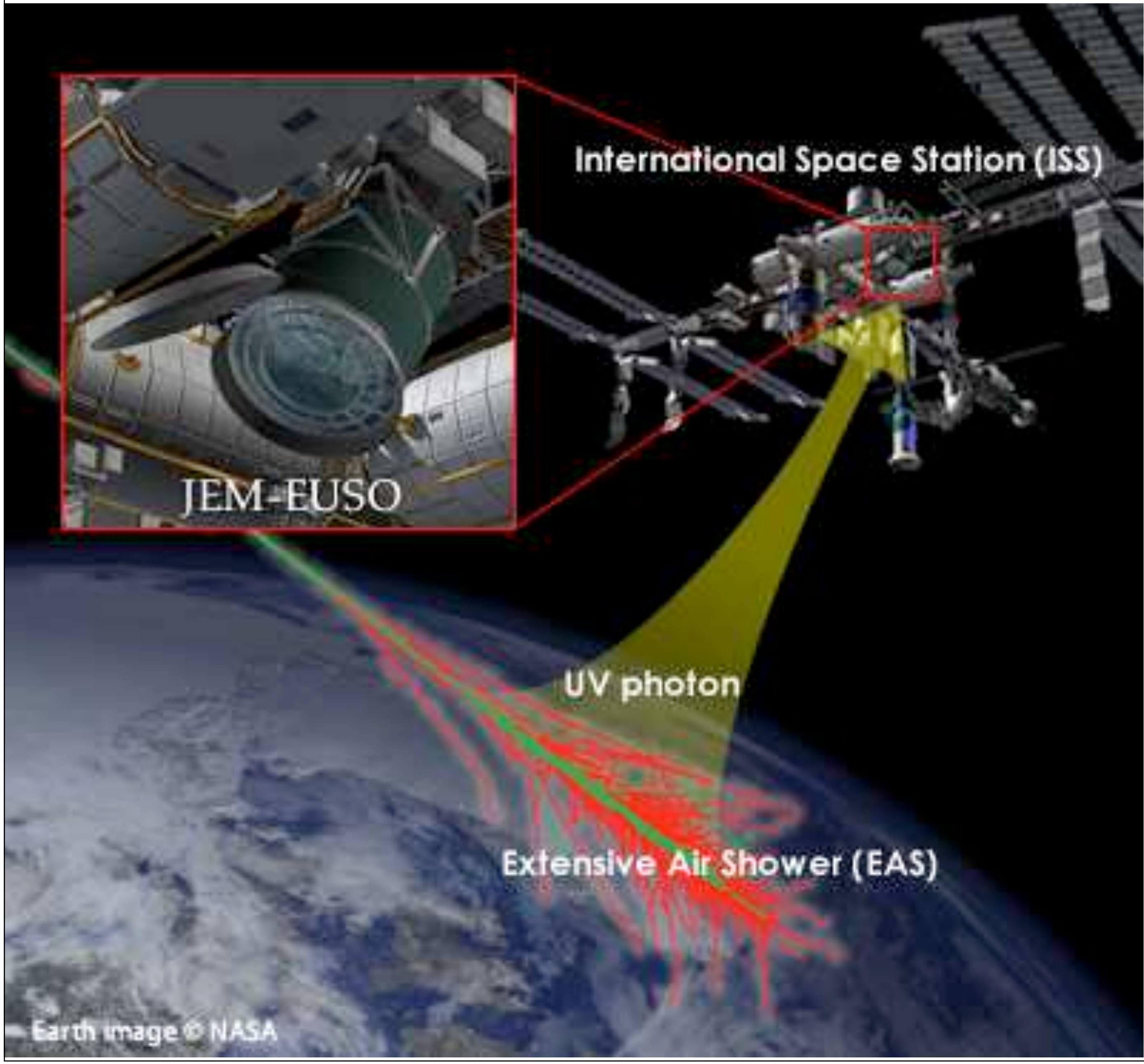

The collaboration is right now budgeted to build 10 of their planned 37 detectors over the next two years.
Image: ARA Collaboration



# LOFAR : Low Frequency Array

LOPES LOFAR prototype, Karlsruhe

# JEM EUSO




- ISS project, orig. ESA/NASA/RSA/JAXA; precursor for **OWL** (free-flyer)
- $5.10^{19} – 10^{21}$ eV EECRs, EENUs
- Monocular 2.5m Fresnel lens, measure EAS via atmos. fluor. emiss
- Thresh: $3.10^{19}$ eV; Effic. @ $10^{20}$ eV : 300-1000 event/yr
- **Current plan: JEM/JAXA on ISS, 2017**

# Outlook

- *The sources of UHECR (and of UHENU) are still unknown*
- *Will learn much about best candidates (GRB, AGN, MGR) from GeV and TeV photon observations; many with good photon statistics*
- *Will constrain particle acceleration / shock parameters, compactness of emission region (dimension, mag.field,.)*
- *UHECR : chemical composition, angular correl.: sources?*
- *UHE ν will allow test of proton content of jets, proton injection fraction, test shock acceleration physics, magn. field*
- *If UHE ν NOT detected in GRB, AGN → jets are Poynting dominated!*
- *Probe ν interactions at ~ TeV CM energies*
- *Constraints on stellar birth & death rates @ high-z, first structures?*
- *Cosmogenic nus: probe CR origins, sources*

# Outlook: UHECR/UHENU

- *The sources of the UHECR are still unknown..!*
- *They are almost certainly astrophysical sources (not TD)*
- *GRB are good candidates, as well as AGNs, HNe, ...*
- *Will increasingly constrain such possibilities with GeV and TeV photon observations*
- *Will learn even more if & when astrophysical UHENUs are observed from* any *type of* identifiable *source*
- *PeV & sub-PeV neutrinos of* astrophysical *origin have been (almost certainly) detected*
- *Current challenge: identify* sources *of PeV/sub-Pev nus*
- *Multi-messenger observations, CR composition, clustering will provide important clues*

# High Energy Astrophysics II. Cosmic Sources of CRs, νs, γs & Diffuse Radiation

*Péter Mészáros*
*Pennsylvania State University*

**NIC2014, Debrecen,**

# Who? What?

(extragalactic)

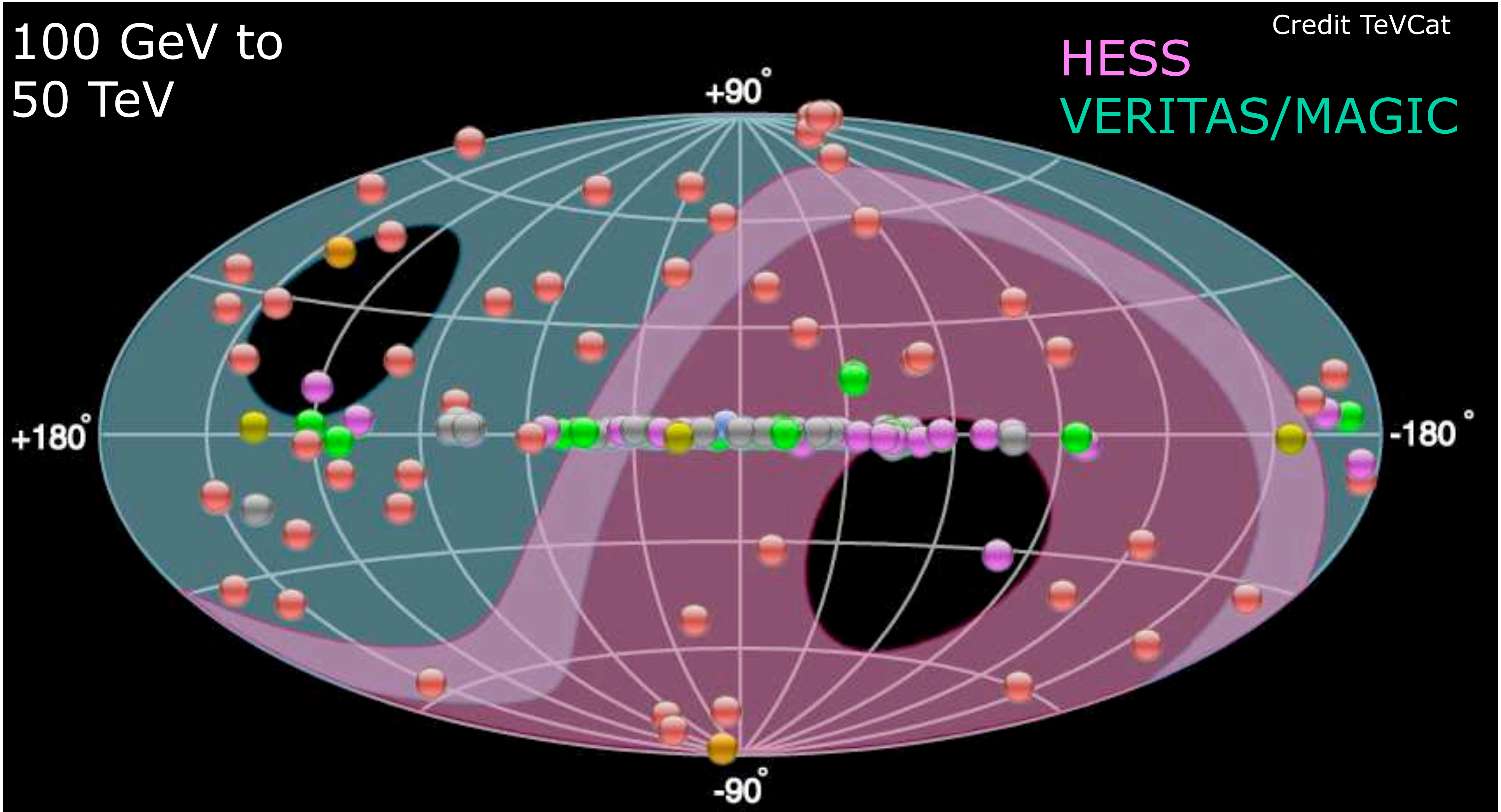
- AGNs
- GRBs, HNe
- SFGs, SBGs (star-forming or starburst gals)
- GMSs, GSs (galactic merger or gal. shocks)
- $\Rightarrow$ IGB, INB, ICRB (intergalact. $\gamma$, CR, $\nu$ bkg)

[ Other (mainly galactic): SNe, HNe, PWNe, Binaries ]

- ***Photons*** are the most common and useful cosmic messengers (by far - in number, information content, etc)- so, start with

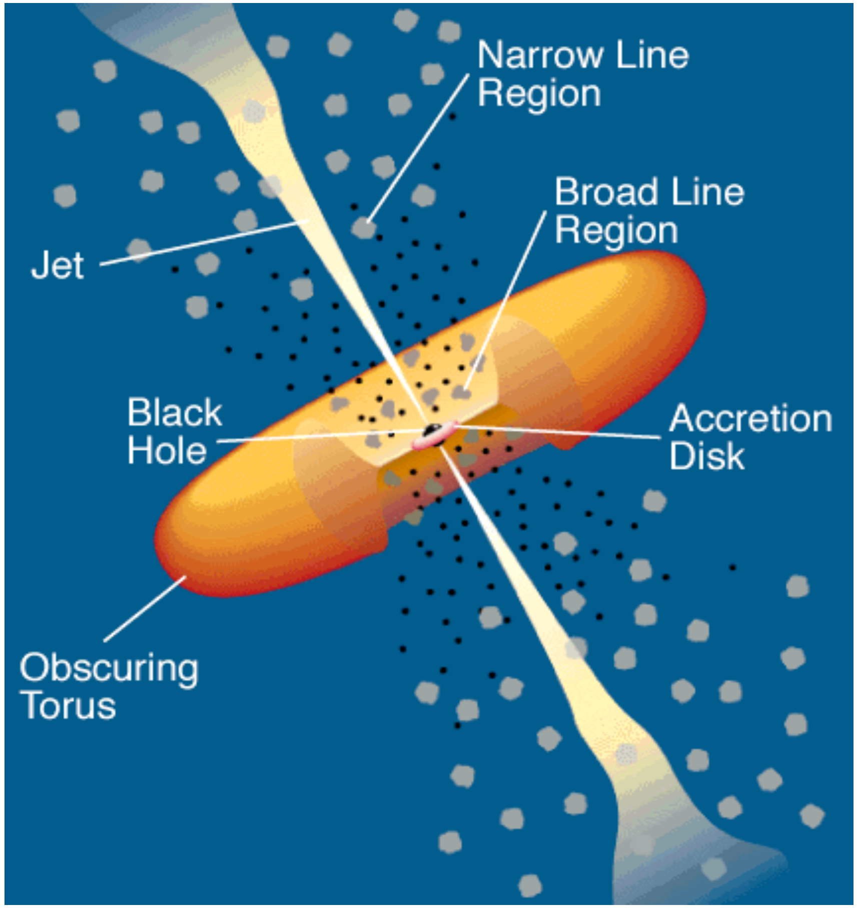
# Extragalactic gamma-ray sources

100 GeV to
50 TeV




The extragalactic TeV sky is dominated by blazars (mainly BL Lacs)

# AGN as UHE γ sources

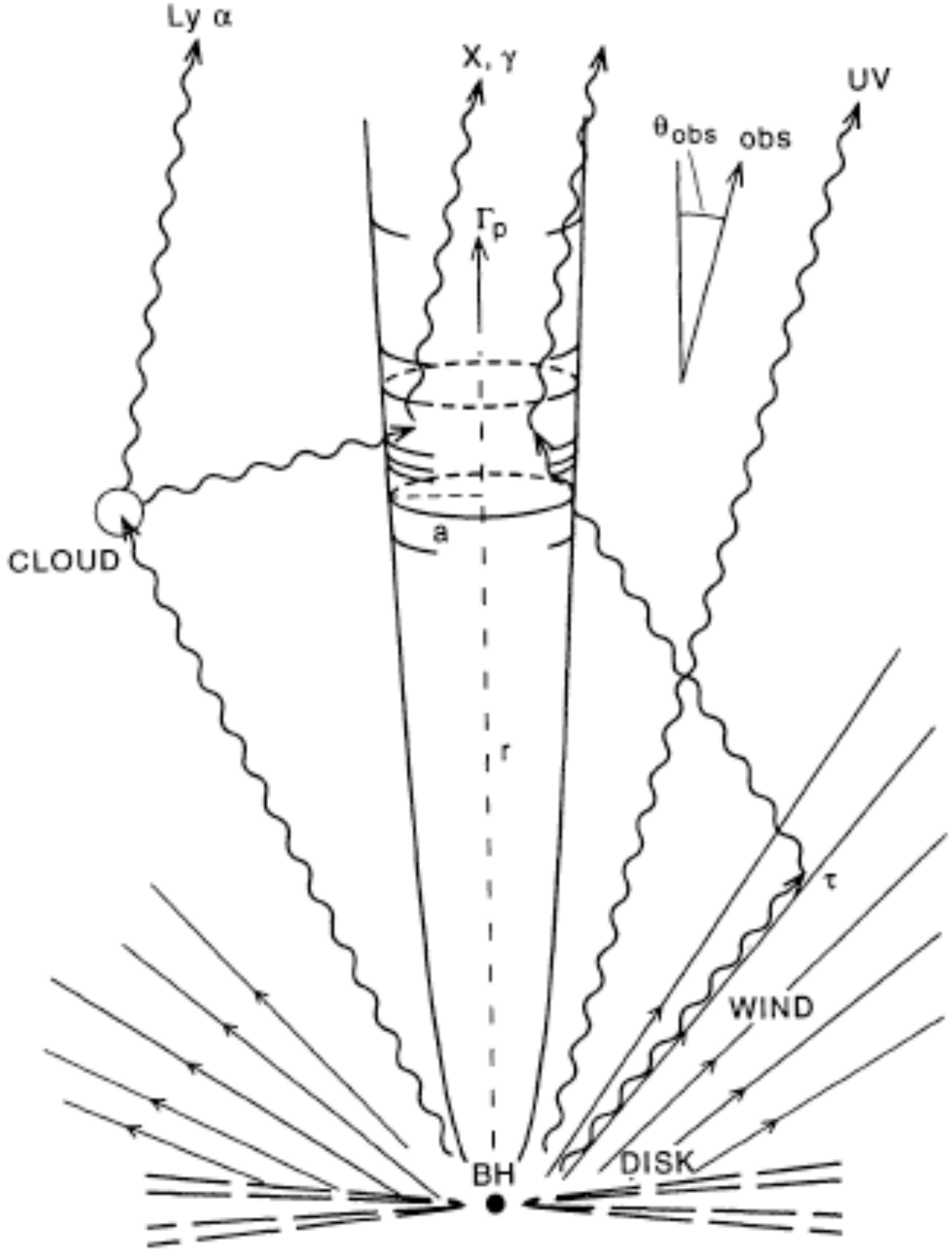


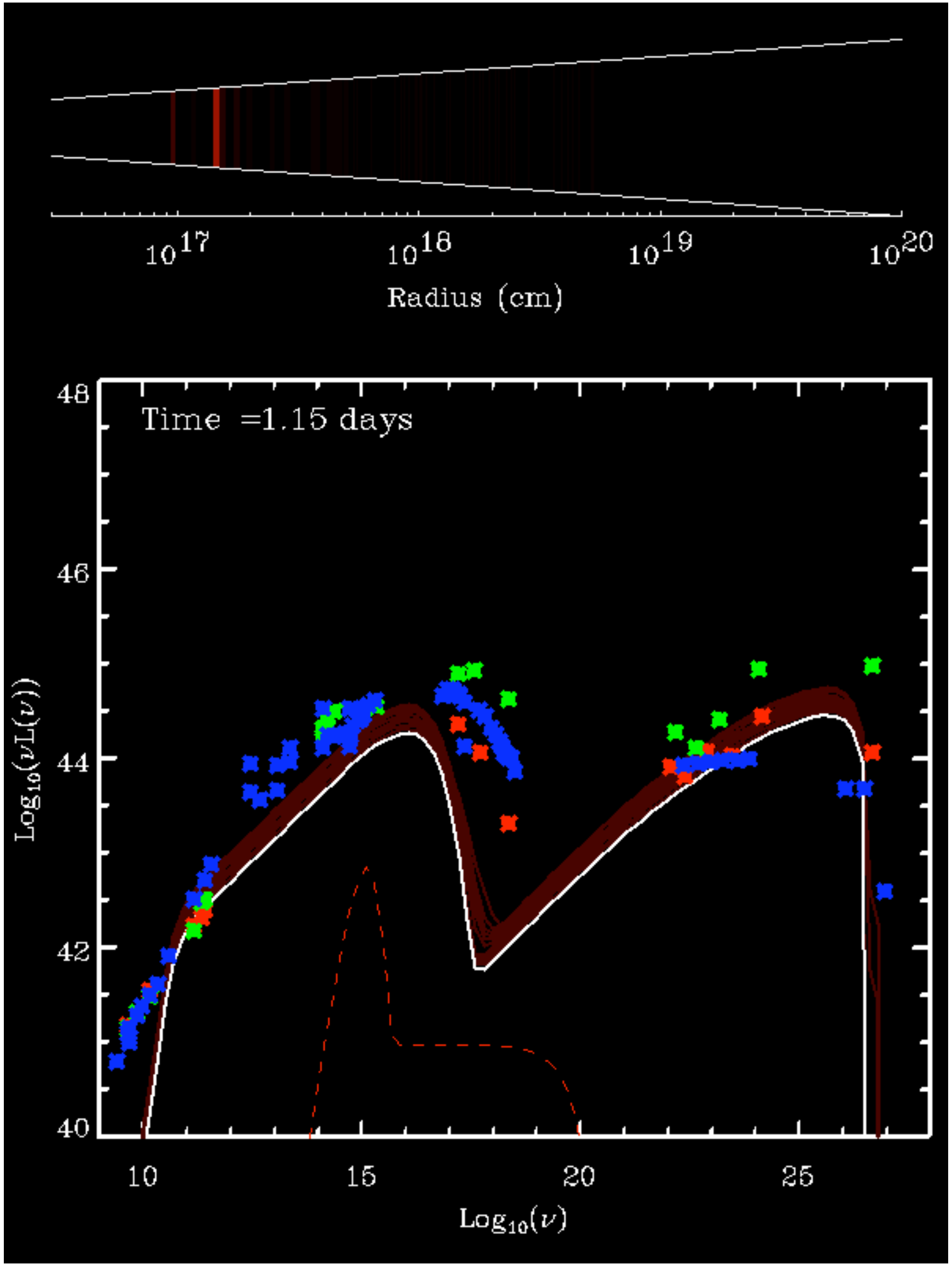

- Massive BH ($10^7$-$10^8$ $M_{sun}$ ) fed by accretion disk → jet
- Lorentz factor $\Gamma_{j,agn}$ ~ 10-30
- UV target photons from (1) accr. disk, (2) BLR line clouds
- Typical ("leptonic") model: $e^{\pm}$ accel. in jet shocks, and

  SSC (sync-self-compton); SEC(sync-exter.compton)
- Typical hadronic model: p accel, in jet shocks, pγ photomeson interactions, → EM cascades

# AGN Jet lepto-model

Sikora et al



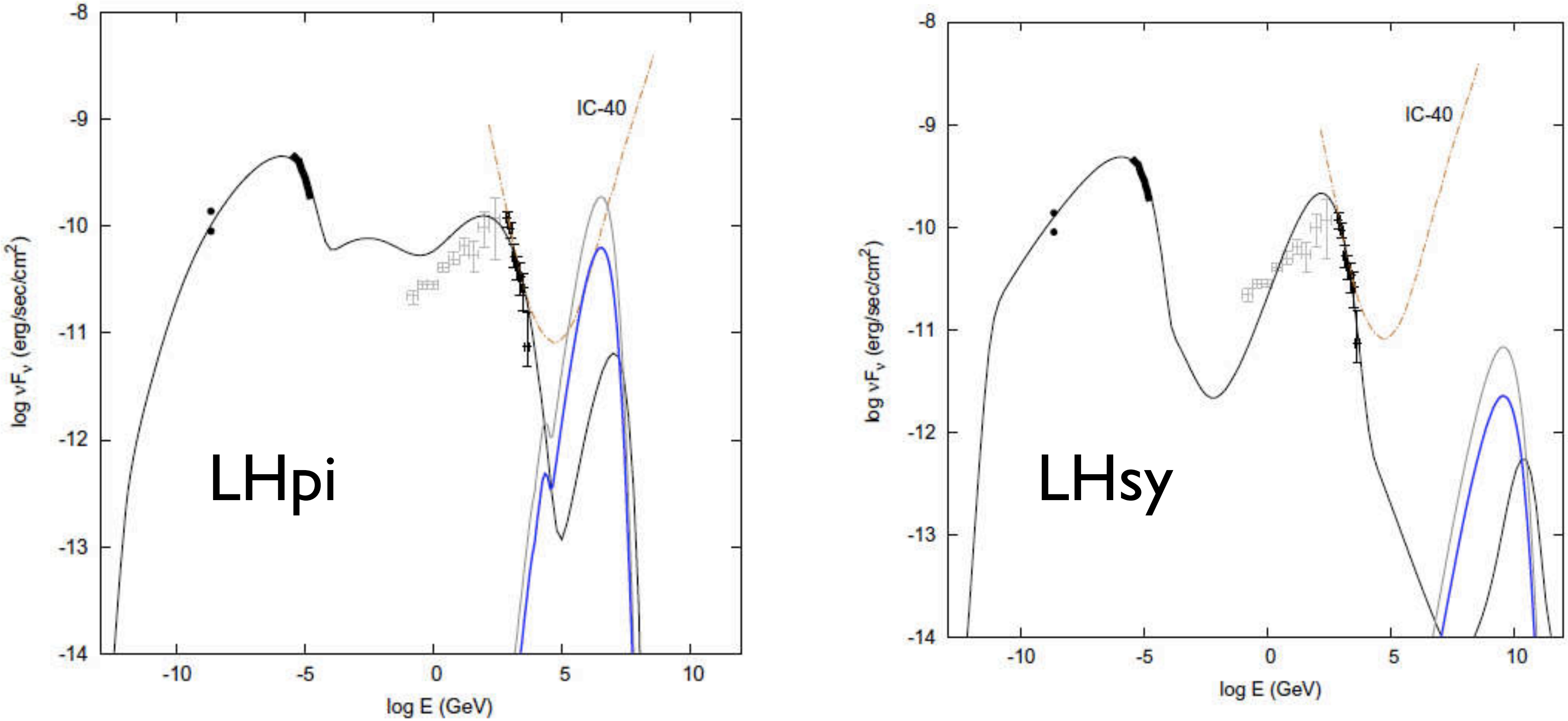



# MRK 421

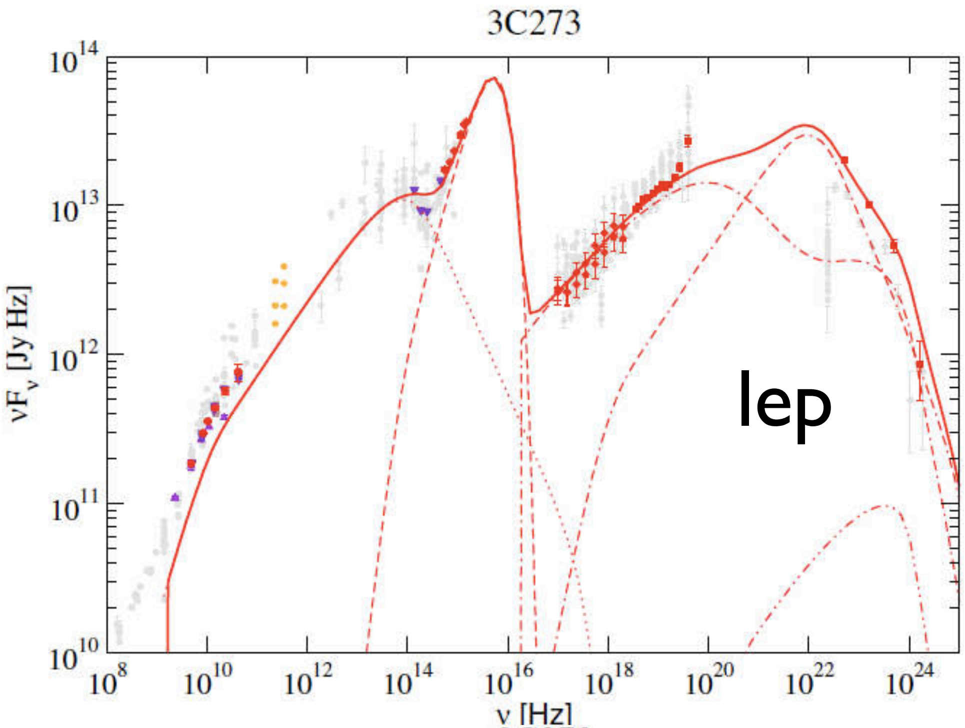
Ghisellini et al, Spada et al,
leptonic IS model, 2004

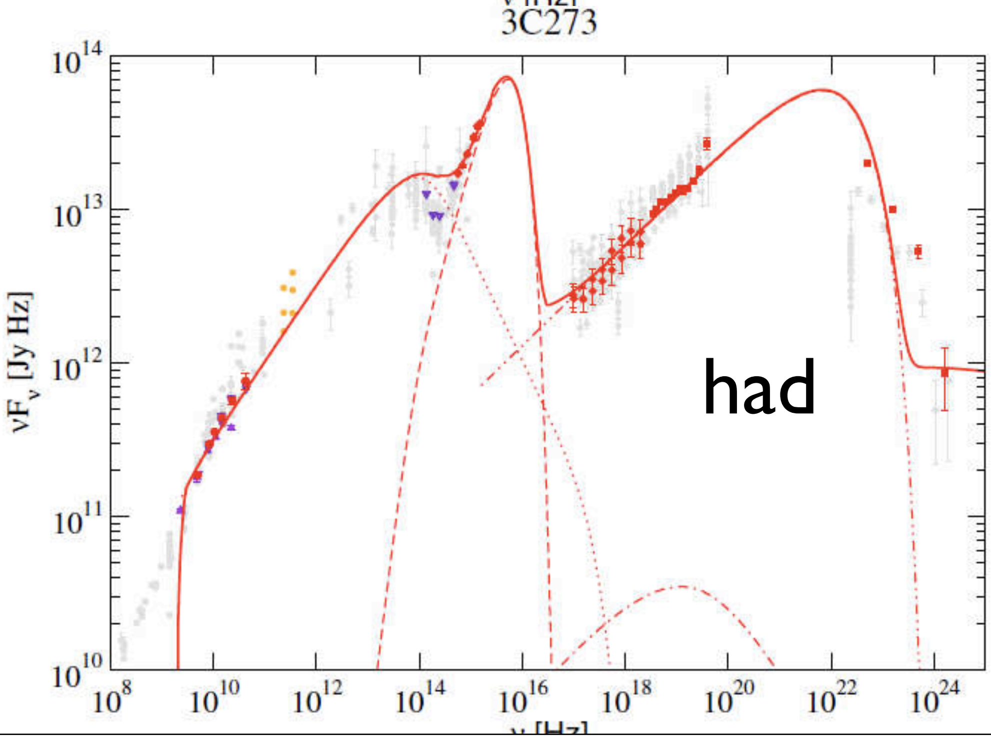
# Mrk 421-leptohadronic

Dimitrakoudis, Petropoulou, Mastichiadis '14 ApPh 54:61




- Two Lepto-Hadronic models: LHpi (γ from pi-decay) and LHsy (γ from p-sync.)
- Use kinetic eqs. for primaries & decay products, full SOPHIA code for p,γ
- Fit requires very flat $\Gamma_p$, $\Gamma_e$ ~1.2, 1.5 (e.g.Niemec-Ostrowski)



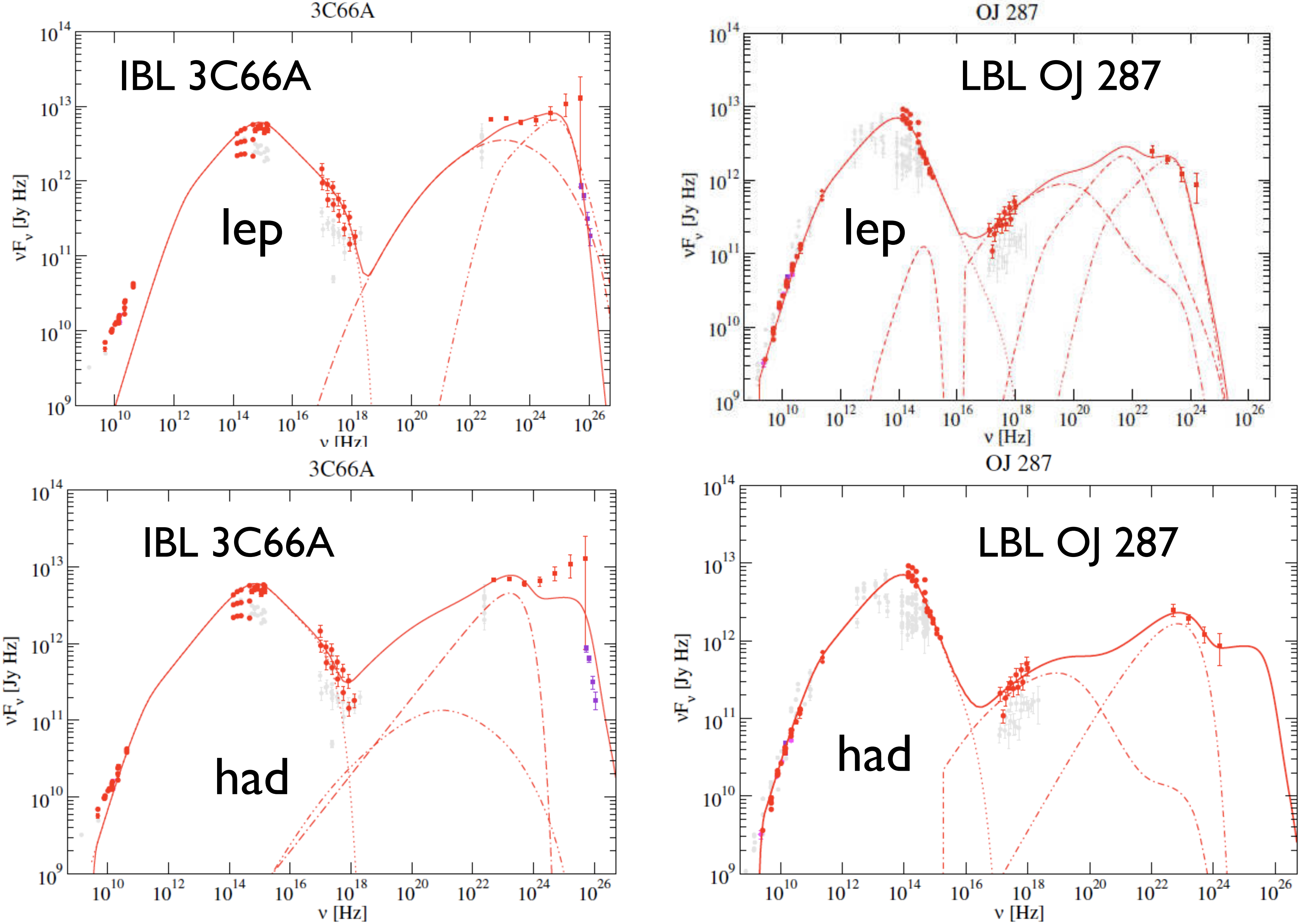




# FSRQ 3C273

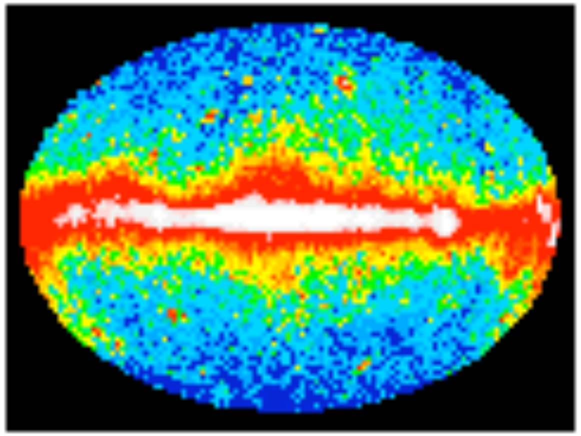
Boettcher, Reimer, Sweeney, Prakash '14, apj 768:54

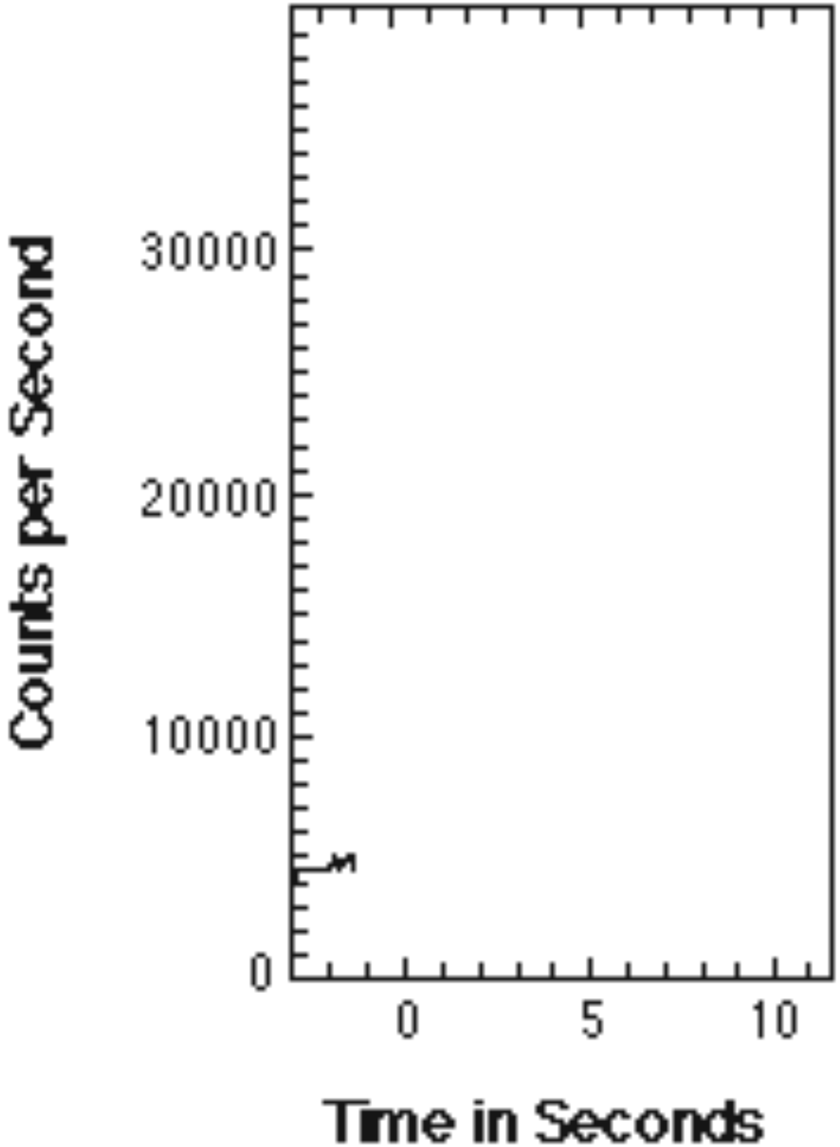
- Compare ***two*** models :
- (1) ***leptonic*** SSC, EC
- (2) ***lepto-hadronic*** w. semi-analyt. cascades)
- Photon targets from accr. disk, BLR clouds
- Fit 6 FSRQ, 4 LBL, 2 IBL

Boettcher et al'14, apj 768:54



# GRBs & the gamma-ray sky






When "ON", a GRB outshines blazars by up to $10^5$ - or even the Sun (in gamma-rays)

# GRB: *basic numbers*

- Rate: ~ 1/day inside a Hubble radius
- Distance: $0.1 \le z \le$ **9.3 !** $\rightarrow D \sim 10^{28}$ cm
- Fluence: $\sim 10^{-4} - 10^{-7}$ erg/cm$^2$

  $$F = \int flux.dt \sim 1 \ \text{ph/cm}^2 \ (\gamma\text{-rays !})$$

- Energy output: $10^{53} (\Omega/4\pi) D^2_{28.5} F_{-5}$ erg

  but, jet: $(\Omega_j/4\pi) \sim 10^{-2} \rightarrow E_{\gamma,tot} \sim 10^{51}$ erg

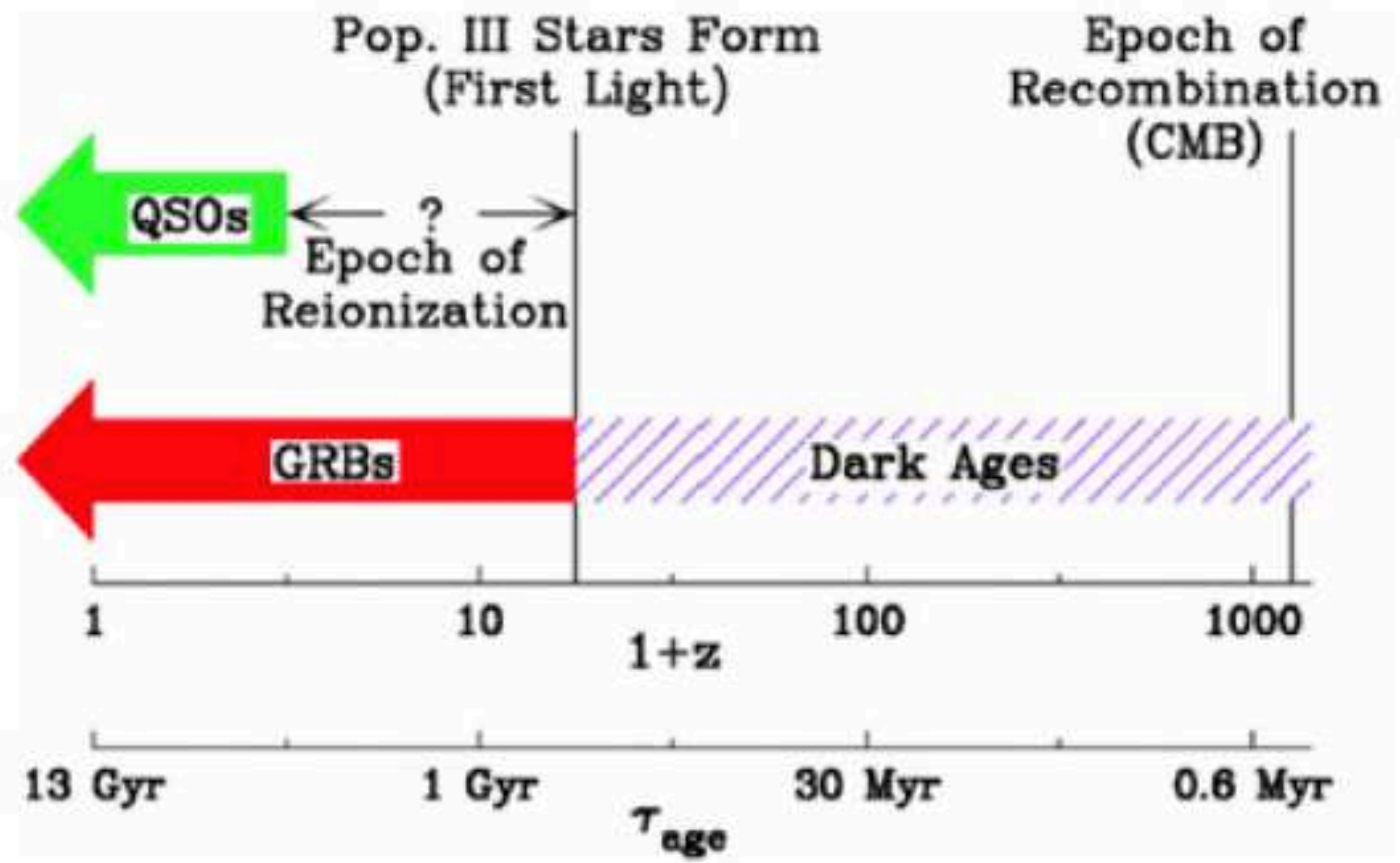
  ***$\rightarrow E_{\gamma,tot} \sim L_\odot$ in $10^{10}$ year $\sim L_{gal}$ in 1 year***

- Rate[GRB ($\gamma$−obs)] $\sim 10^{-6}(2\pi/\Omega)$ /yr/gal $\rightarrow$1/day ($z \le 3$)

  but Rate [GRB (uncollimated)] ~ $10^{-4}$ /yr/gal,

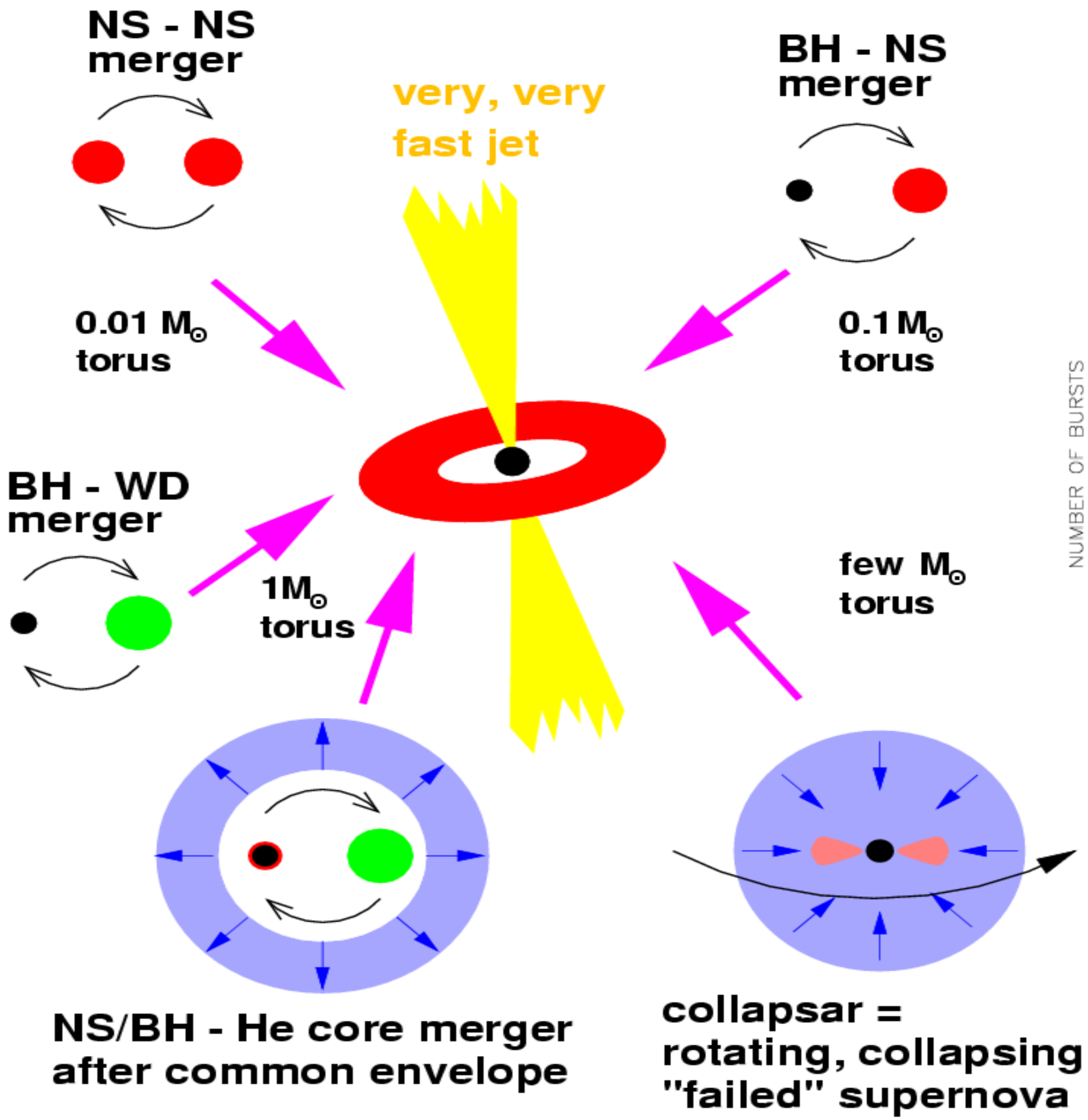
  while Rate [SN (core collapse] ~ $10^{-2}$/yr/gal, or $10^7$ /yr ~ 1/s ($z < 3$)

# GRBs in Cosmological Context



# GRB: standard paradigm

## Hyperaccreting Black Holes

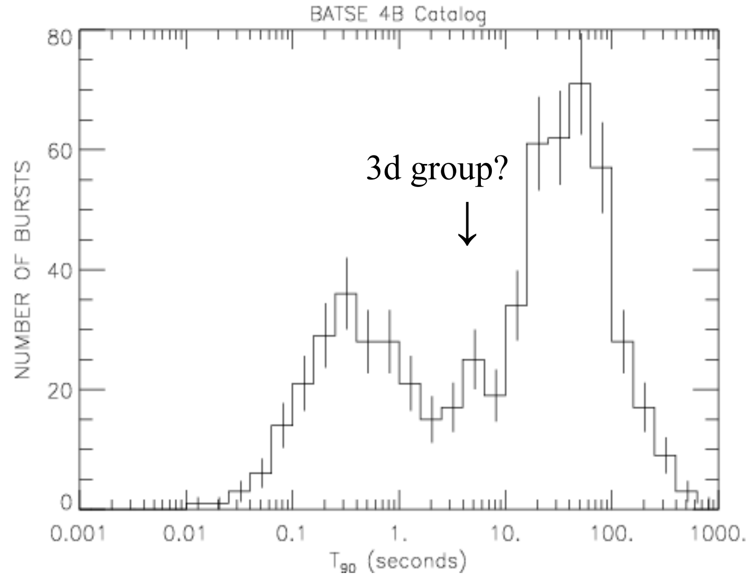



M. Ruffert, H.-Th. Janka, 1998

Bimodal distribution of $t_\gamma$ duration

← ↓**Short**

($t_g$< 2 s)




→ ↑**Long**

($t_g$ >2 s)

# Explosion → FIREBALL

- $E_\gamma \sim 10^{51}\ \Omega_{-2}\ D^2_{28.5}\ F_{-5}$ erg
- $R_0 \sim c\ t_0 \sim 10^7\ t_{-3}$ cm

→ ***Huge energy in very small volume***

- $\tau_{\gamma\gamma} \sim (E_\gamma/R^3{}_0 m_e c^2)\sigma_T R_0 >> 1$

→ ***Fireball:*** ***$e^\pm,\gamma,p$ relativistic gas***

- $L_\gamma \sim E_\gamma/t_0 >> L_{Edd} \rightarrow$ expanding (v~c) fireball

(Cavallo & Rees, 1978 MN 183:359)

- Observe $E_\gamma > 10$ GeV …but

$\gamma\gamma \rightarrow e^\pm$, degrade 10 GeV →0.5 MeV?

$E_\gamma\ E_t > 2(m_e c^2)^2/(1-\cos\Theta) \sim 4(m_e c^2)^2/\Theta^2$

→ ***Ultrarelativistic*** flow → $\mathbf{\Gamma \geq \Theta^{-1} \sim 10^2}$ **(bulk Lorentz factor)**

(Fenimore etal 93; Baring & Harding 94)

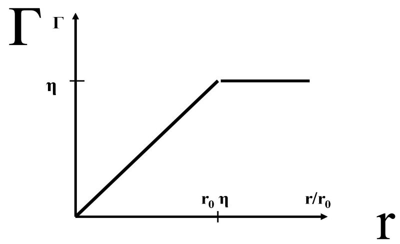
# *Relativistic Outflows*

- Energy-impulse tensor : $\mathbf{T_{ik} = w\, u_i\, u_k + p\, g_{ik}}$ ,
  $\mathbf{u^i}$ : 4-velocity, $\mathbf{g_{ik}}$= metric, $g_{11}=g_{22}=g_{33}=-g_{00}=1$, others 0;
  ultra-rel. enthalpy: $w = 4p \propto n^{4/3}$ ; w, p, n : in comoving-frame
- 1-D motion : $u^i=(\gamma,u,0,0)$, where $\mathbf{u = \Gamma\, (v/c)}$,
  **v** = 3-velocity, **A**= outflow channel cross section :
- Impulse flux — $Q=(w\,u^2+p)\,A$
  energy flux — $L= wu\,\Gamma\, c\, A$
  particle number flux — $J= n\, u\, A$
- Isentropic flow : **L, J constant** →
  $\mathbf{w\,\Gamma / n = constant}$ (*relativistic Bernoulli equation*);
  for ultra-rel. equ. of state $p \propto \mathbf{w} \propto n^{4/3}$ , and cross section $A \propto r^2$

→ $n \propto 1 / r^2\, \Gamma$ comoving density drops

→ $\Gamma \propto r$ "bulk" Lorentz factor initially grows with **r**.

- But, eventually saturates,
  $\Gamma \rightarrow E_j/M_jc^2$ ~ constant



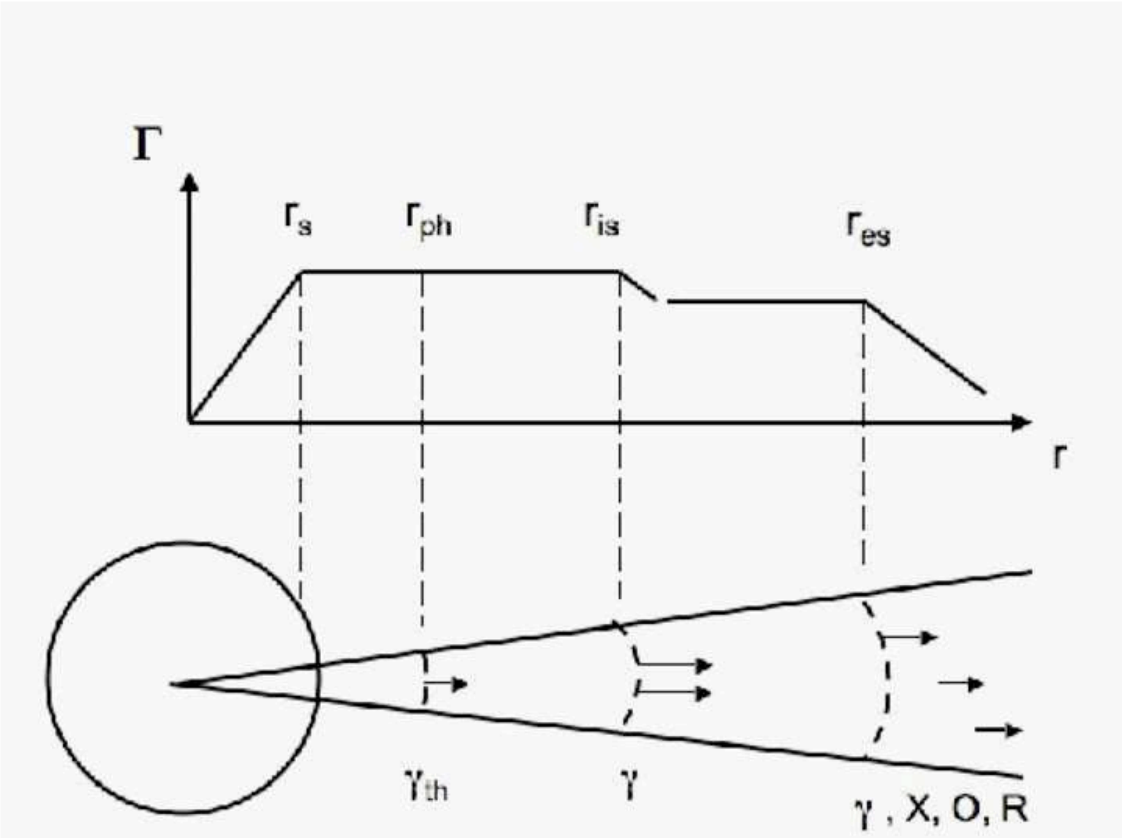

***Γ∝r → Γ~const.***

*Also expect:*

## Internal & External Shocks

in optically thin medium :

# LONG-TERM BEHAVIOR




- **Internal** shocks (or other, e.g. magnetic dissipation) at radius $r_i$~$10^{12}$cm

  →**γ-rays** (***burst***, $t_\gamma$~sec)

- **External** shocks at $r_e$ ~$10^{16}$cm;

  progressively decelerate, get **weaker and redder** in time (Rees & Meszaros 92)

- Decreasing Doppler boost: → roughly, expect **radio** @ ~1 week , **optical** @ ~1 day (Paczynski, & Rhoads 93, Katz 94)

- PREDICTION :

  Full quantitative theory of:

- External ***forward*** shock spectrum

  **softens** in time:

  **X-ray, optical, radio** …

  →**long fading afterglow**

  **(t ~ min, hr, day, month)**

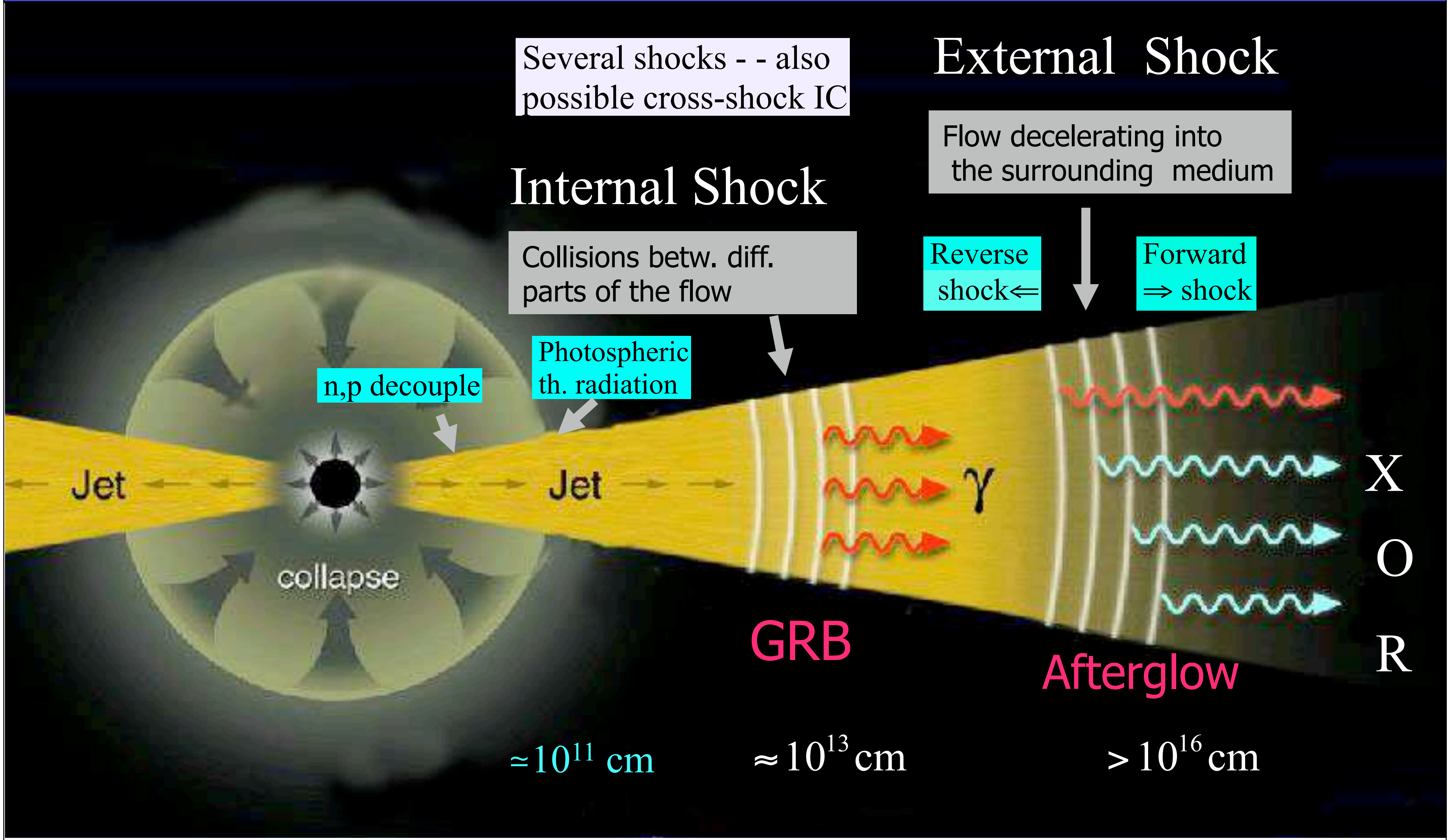
- External ***reverse*** shock (less relativistic, cooler, denser):

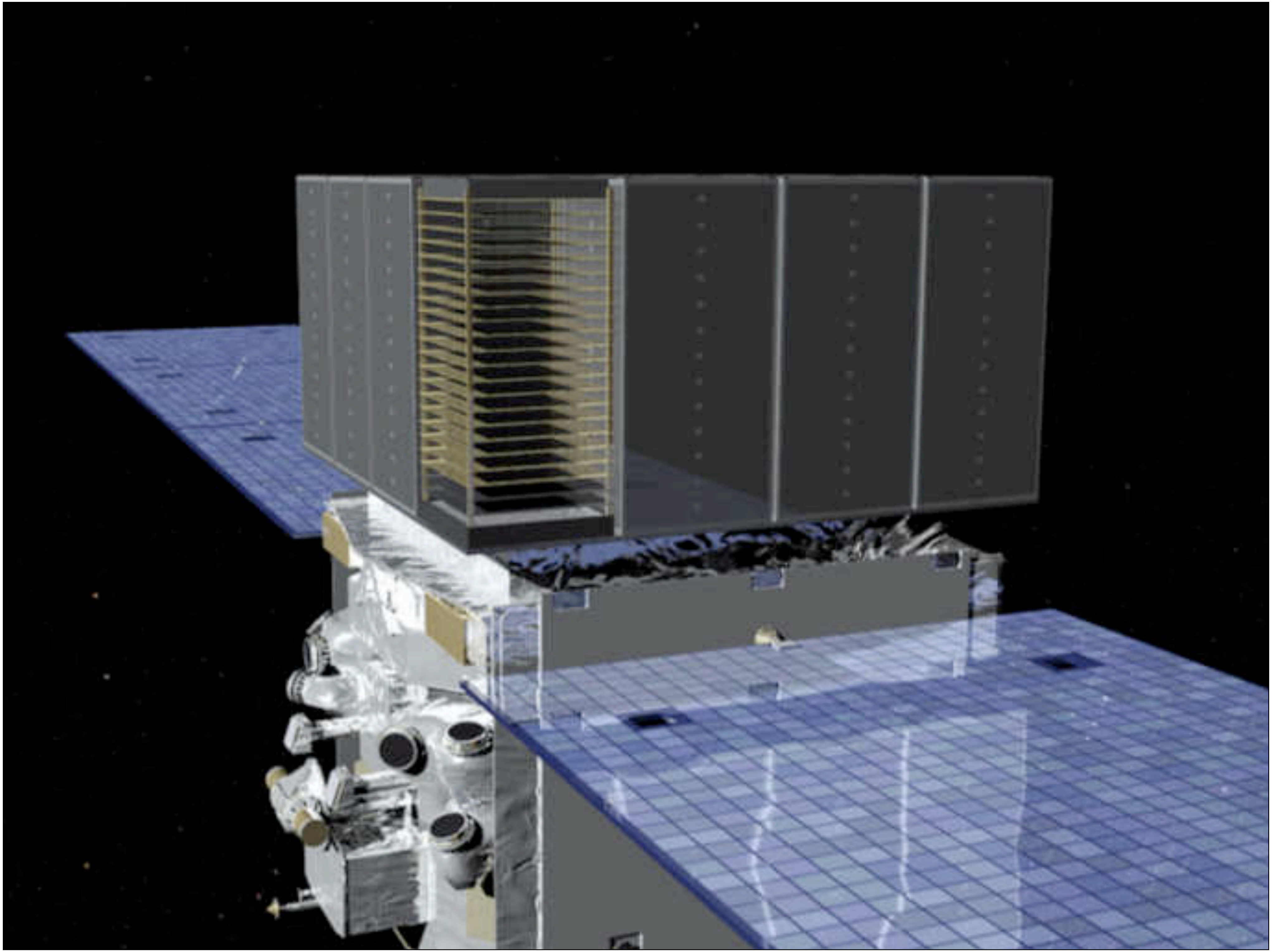
  ***Prompt*** **Optical** → **quick fading**

  ( t ~ mins)

  (Meszaros & Rees 1997 ApJ 476,232)

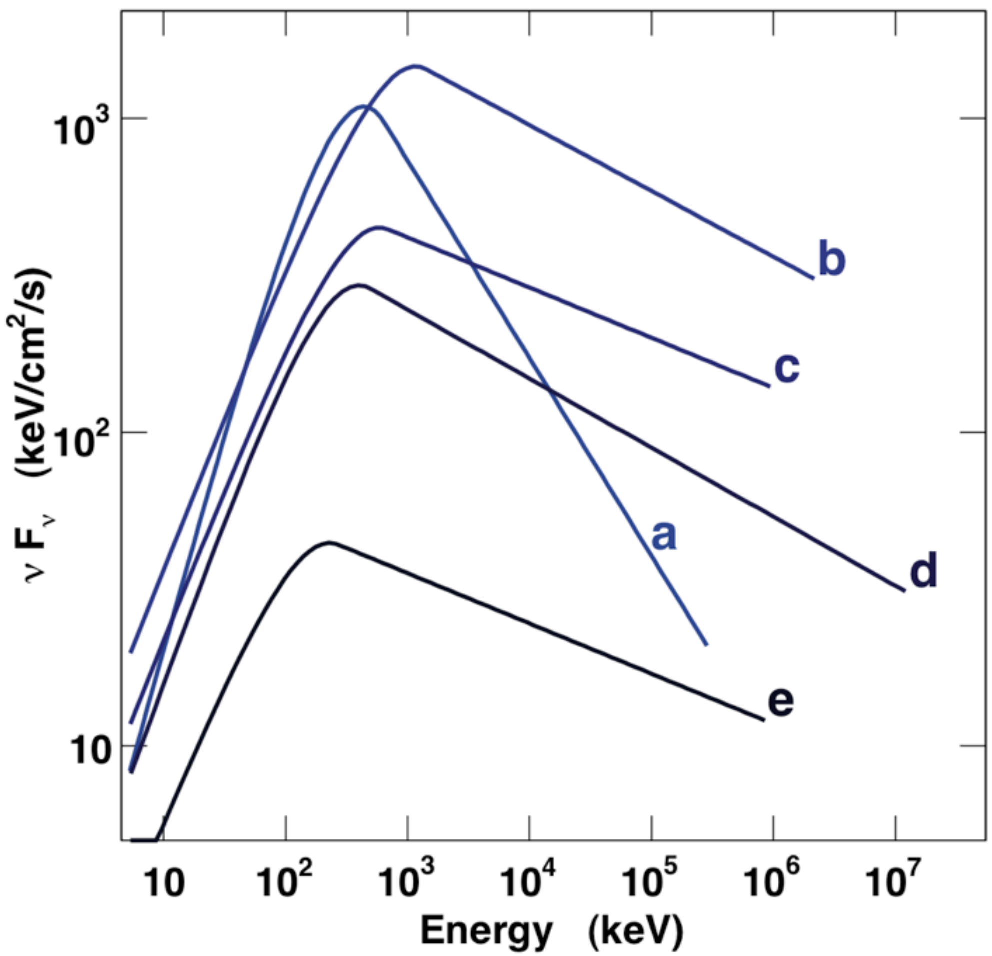
# Fireball Shock Model of GRBs





# GRB 080916C

## ***Spectrum*** : up to ~***10 GeV*** (obs.)



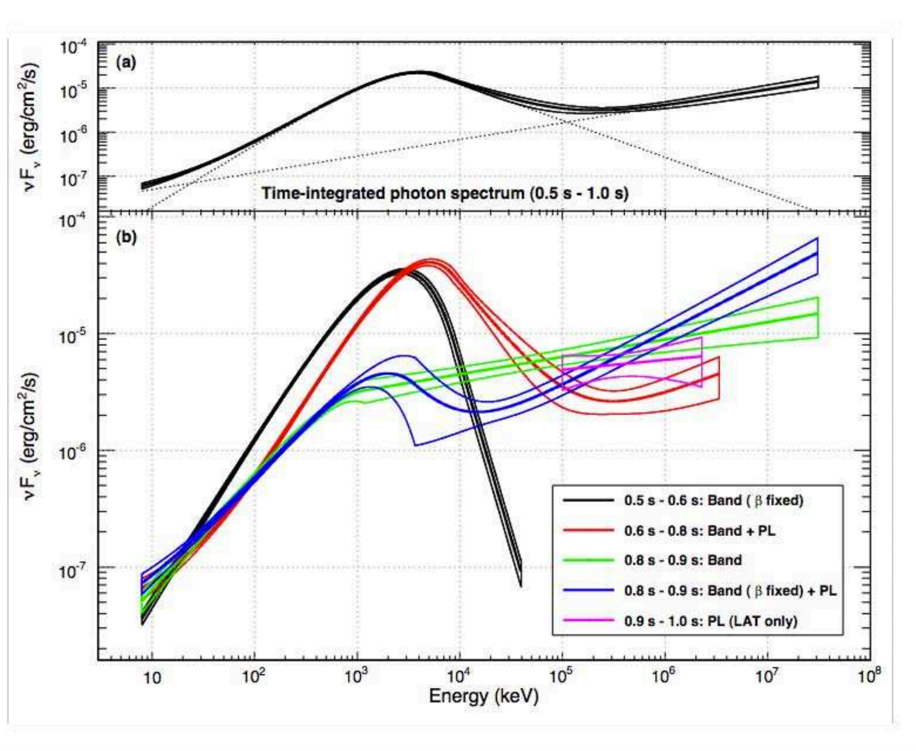

- "***Band***" (broken power-law) fits, joint GBM/LAT, in ***all*** time intervals
- "Soft-to-hard" spectral time evolution
- ***Long***-lived ($10^3$ s) GeV afterglow
- ***Little*** evidence for ***2nd*** spectr. comp. (in ***some*** cases)

Mészáros

**But:** *in other bursts,*

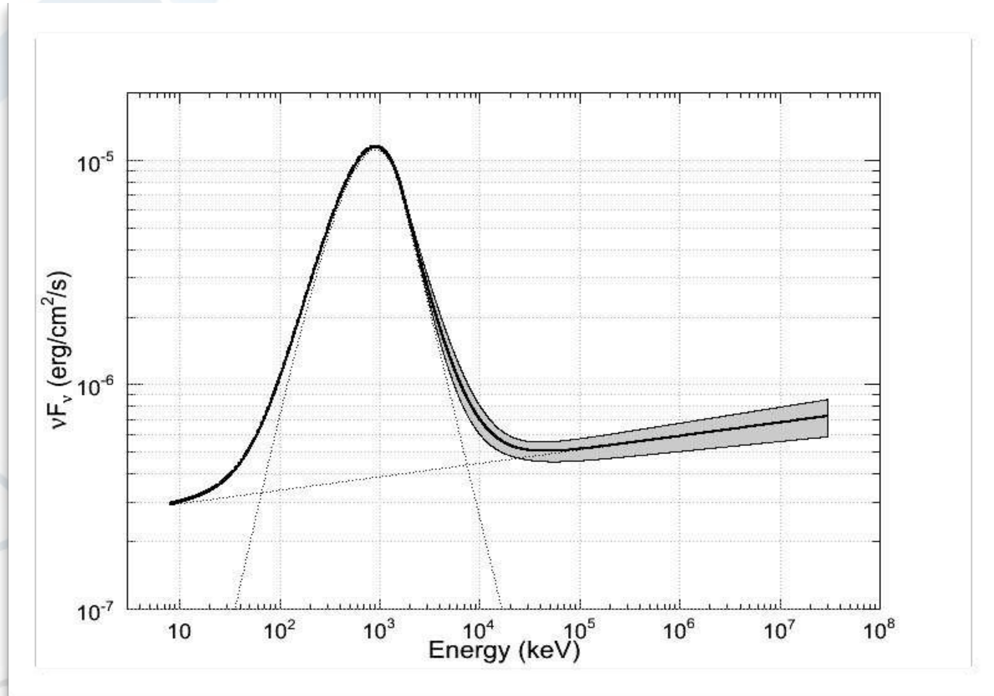
# Evidence of the "extra components" (>3-5σ)

**GRB 090510**
***Ackermann, et al. 2010, ApJ, 716, 1178***




Joint spectral fit (of binned data) :
GBM<40MeV
standard LAT data>100MeV

**GRB 090902B**
***Abdo et al. 2009,ApJ, 706L, 138A***



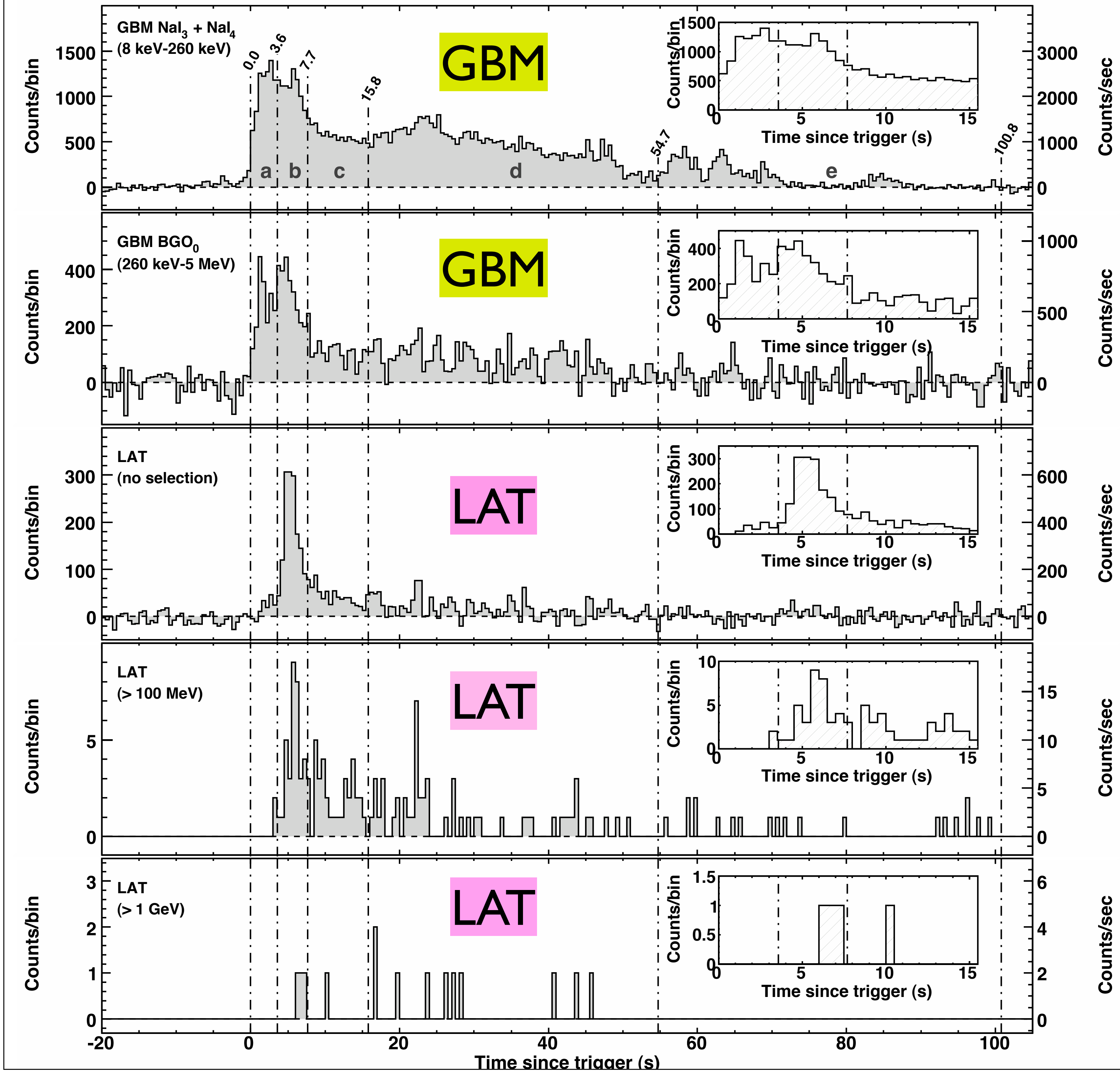

- Constrains main keV-MeV component
- Spectral evolution during prompt phase
- **Additional PL component seen at high and low energies**

# Some observed photon energies and redshifts

| $E_{obs}$(GeV) | z |
|---|---|
| 13.2 | 4.35 |
| 7.5 | 3.57 |
| 5.3 | 0.74 |
| 31.3 | 0.90 |
| 33.4 | 1.82 |
| 19.6 | 2.10 |
| 2.8 | 0.897 |
| 4.3 | 1.37 |

- Even ***z>4*** bursts result in ***$E_{obs}$~10 GeV*** photons
- Some z~1 bursts produce ***$E_{obs}$≥30 GeV*** photons ( ***130 GeV*** in rest frame!)

- ***⇒ encouraging for low $E_{th}$ ACTs: HAWC, CTA...***




# GRB 080916c

*Light-curve*
*E↓*

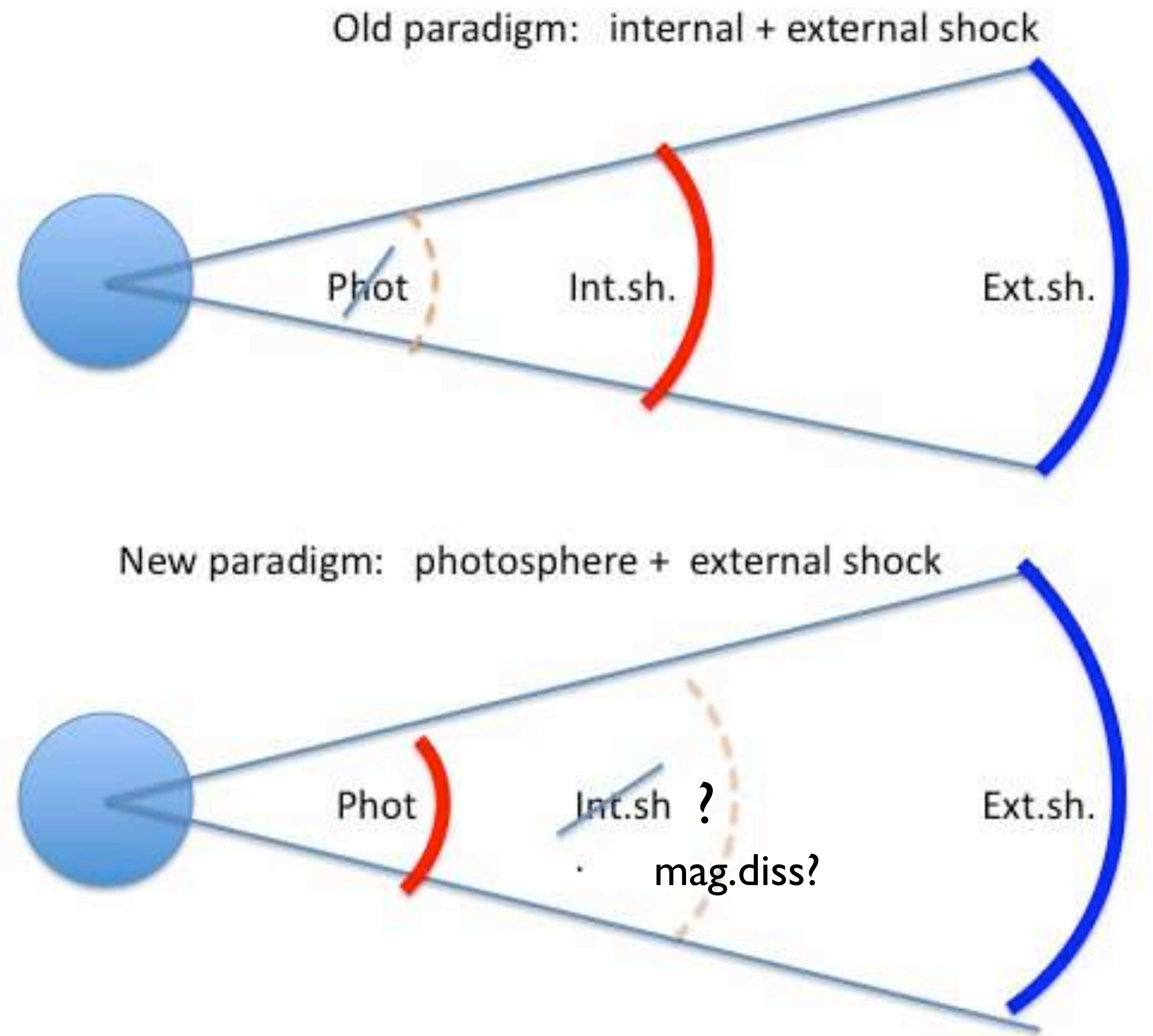
Abdo, A. and Fermi coll., 09, Sci. 323:1688

***Note :***

GeV photons ←"lag" behind MeV!

Mészáros

# *(A) Evolving Fireball paradigm:*




≤ 2005

≥2005

# Recent thrusts in exploring the prompt emission:

A) De-emphasize internal shocks (inefficent)

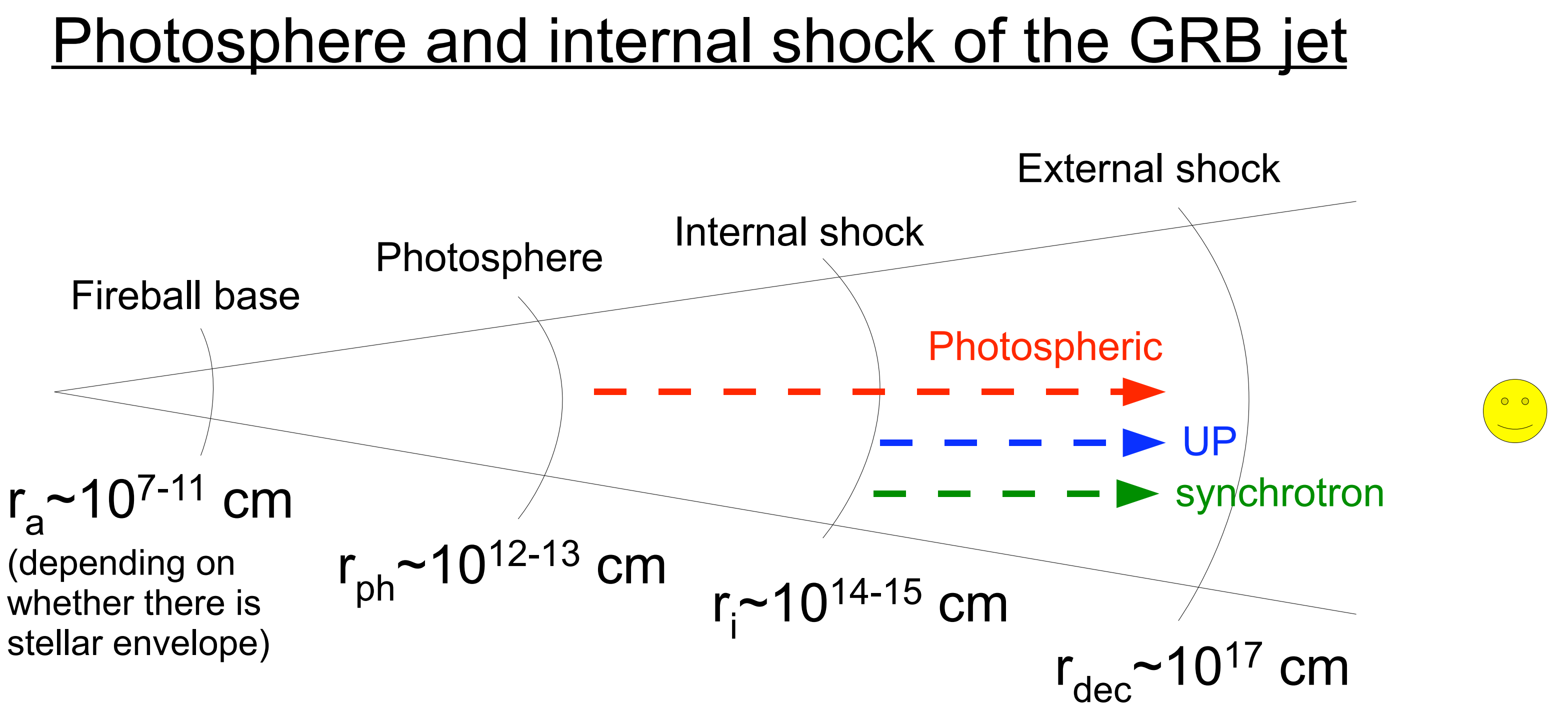
→ ***dissipative photospheric models***

or:

B) ***Modify*** internal shocks : ***slow heating***,
(i) turbulence behind shocks (Fermi 2nd ord),
(ii) magnetic dissipation (high rad. efficiency),
(iii) hadronic cascades (naturally slower heat'g)

# A "leptonic" model:

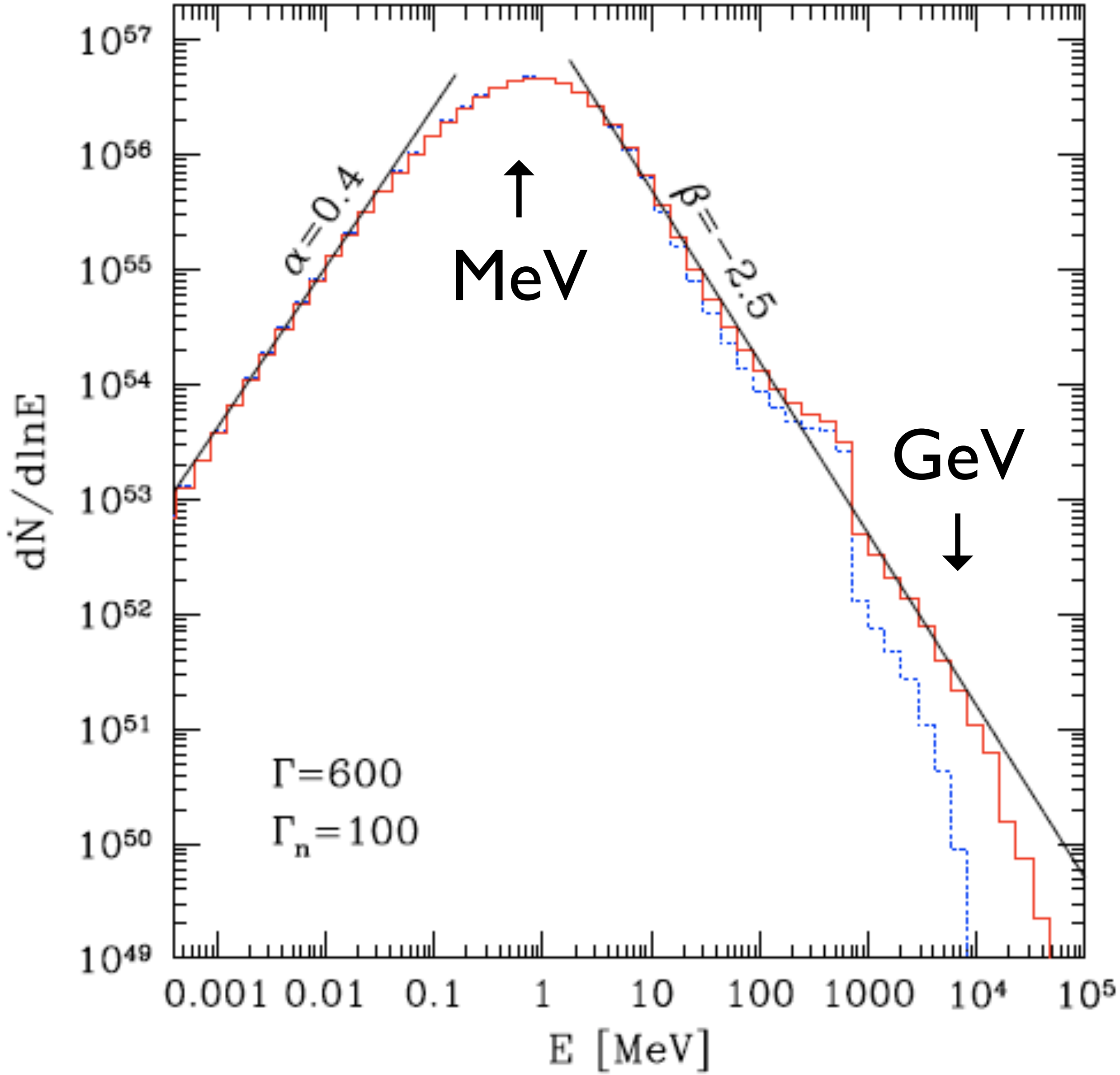
Toma, Wu, Mészáros, 2011, MN 415:1663




The photospheric emission can naturally provide a high γ-ray efficiency and the typical photon energy of the Band spectrum, ~ 1 MeV (Paczynski 86; Goodman 86).

The dissipation below the photosphere could cause the emission to be non-thermal (Meszaros & Rees 00; Rees & Meszaros 05; Pe'er et al. 05; Ioka et al. 07; Beloborodov 09)

# p-n coll. →e±→γ-spectrum



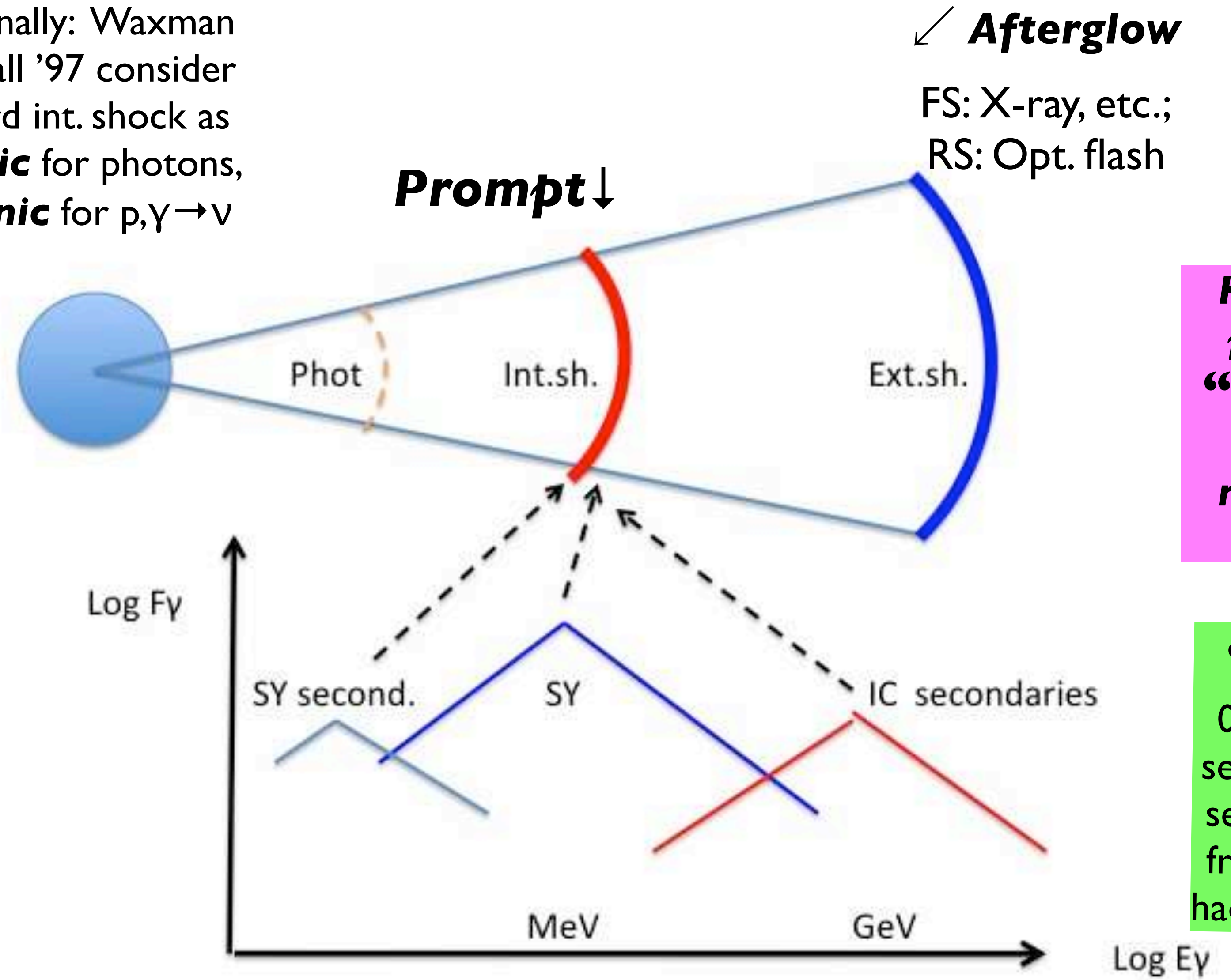

- The result is a thermal peak at the ~MeV Band peak, plus
- a high energy tail due to the non-thermal $e^{\pm}$, whose slope is comparable to that of the observed Fermi bursts with a "single Band" spectrum
- The "second" higher energy component (when observed) must be explained with something else

(Beloborodov, 2010)

# Self-consistent hadronic int. shock

Calculate ***self-consistent*** CR proton, photon & neutrino spectra

• Originally: Waxman & Bahcall '97 consider standard int. shock as ***leptonic*** for photons, ***hadronic*** for p,γ→ν




**New Feature:**

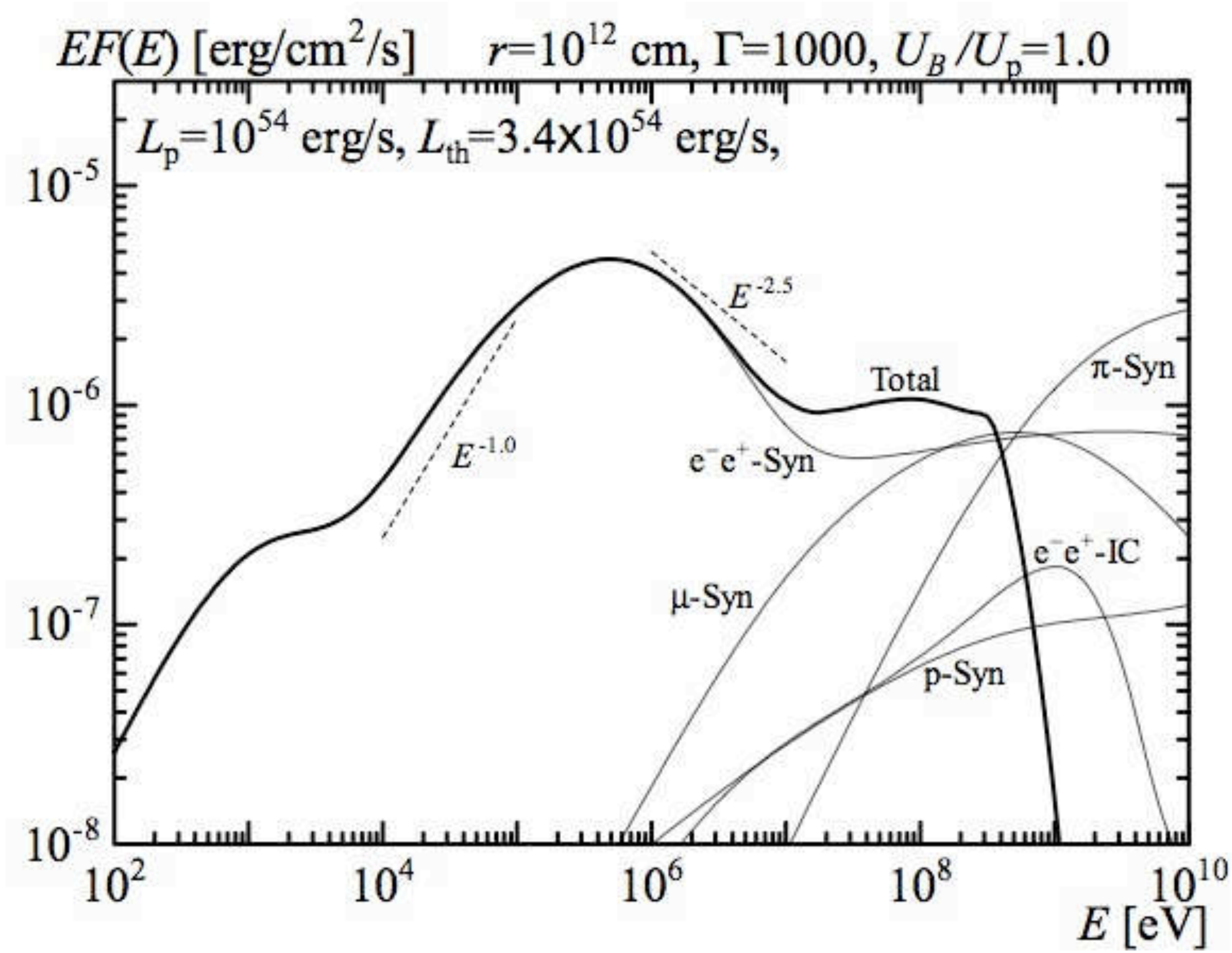
***Hadron accel. + photomeson →***
**"dissipation"**
→inject copious ***relativistic sec'y leptons***

•↙ Asano & PM, 09-12 on, calculate second'y ***photons*** & second'y ***neutrinos*** from both original & hadronic sec'y leptons

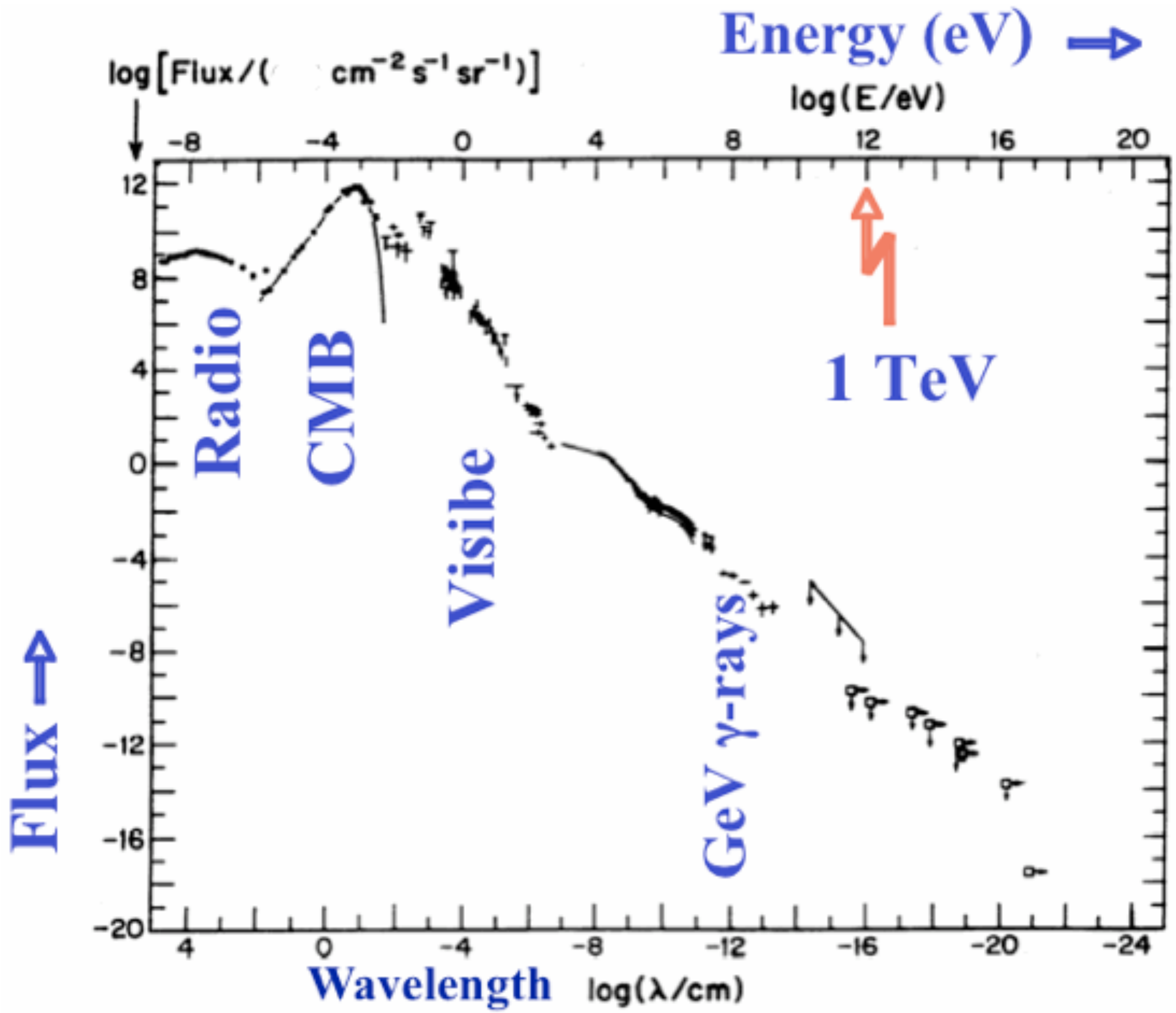
also: Murase et al, 2012, ApJ 746:164

# IS w. hadronic cascades, γ

Murase, Asano, Terasawa & PM'12, ApJ746:164



# Universal Diffuse Number Flux of ***Photons***



Aggregate of all sources:

→ ***diffuse radiation background***

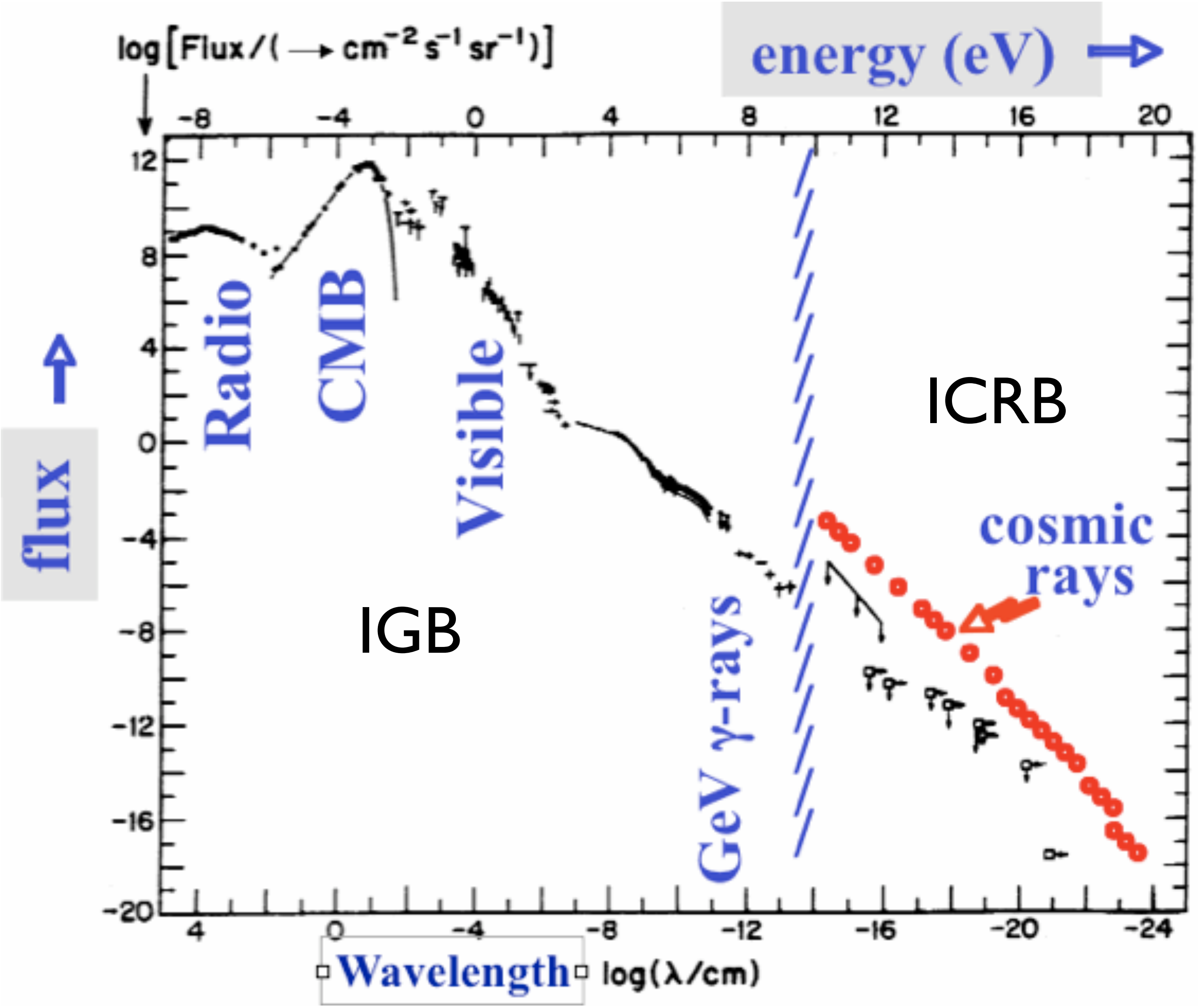
***IXB*** = isotropic (X) background

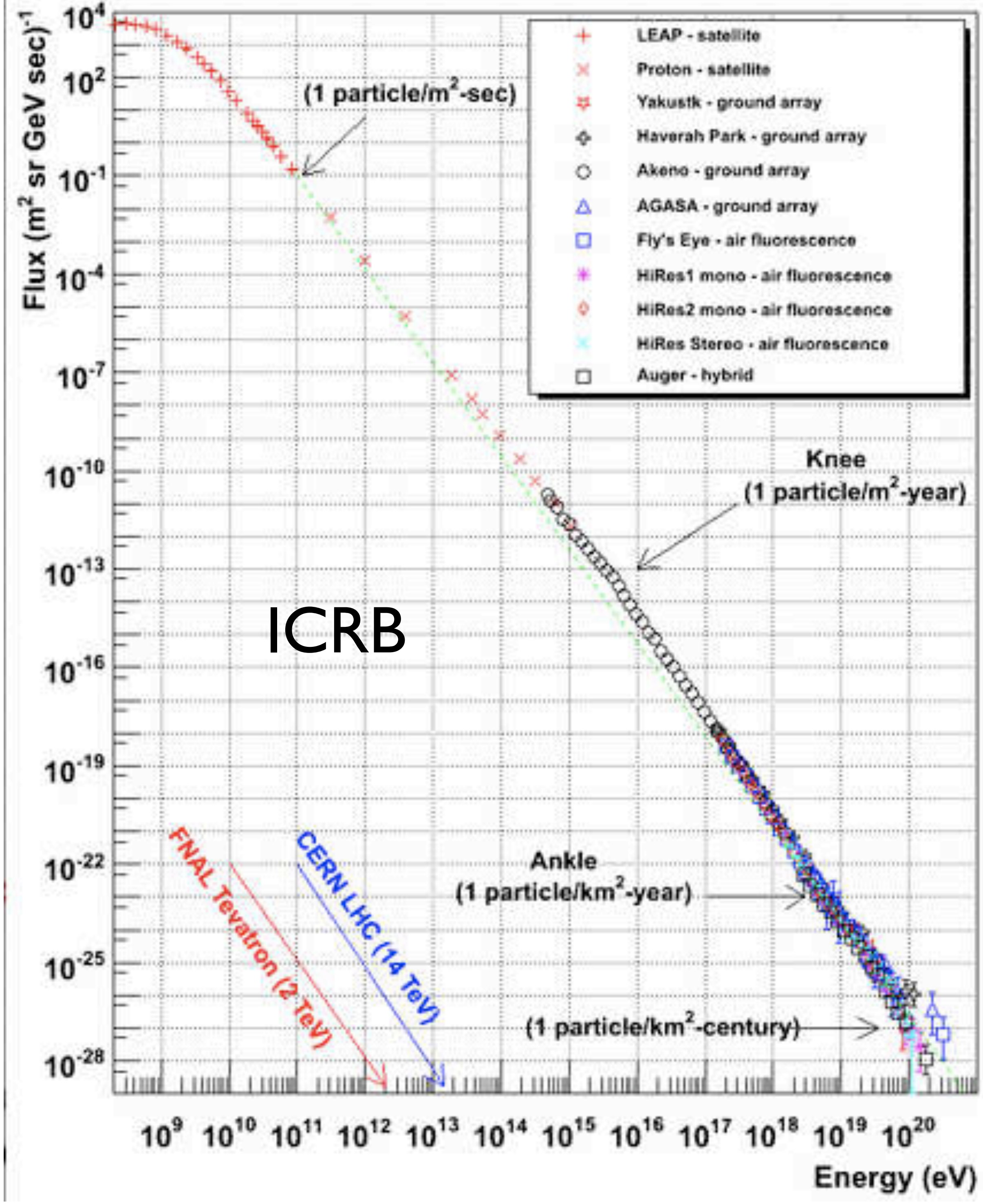
where

***IGB, INB, ICRB*** is

Isotropic $\gamma$, $\nu$, cr bkg.

# Universal Diffuse Number Flux of ***Photons & Cosmic Rays***

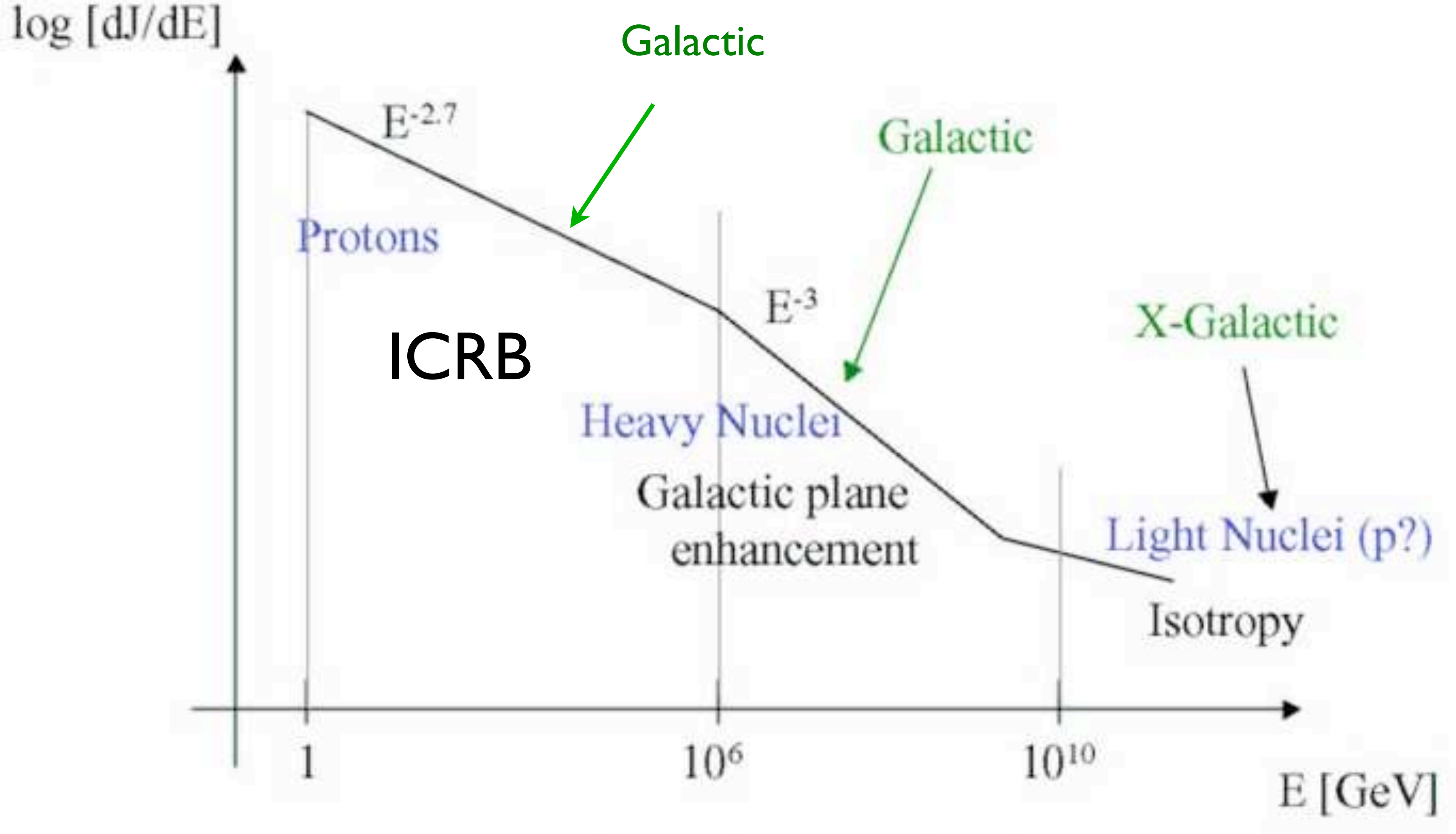





# Cosmic Ray Spectrum

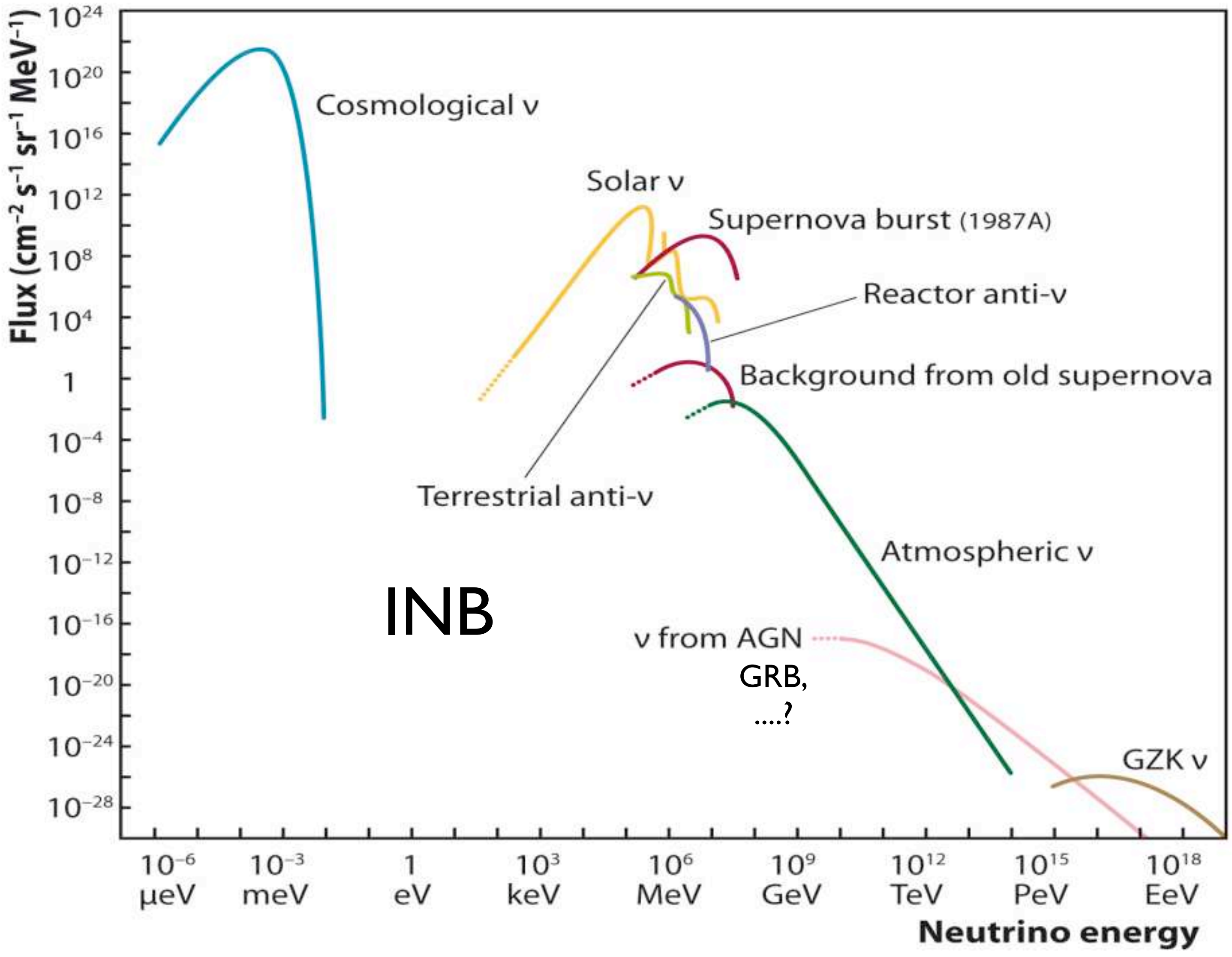
11 dex in energy
32 dex in # flux!

# Cosmic ray flux and Composition

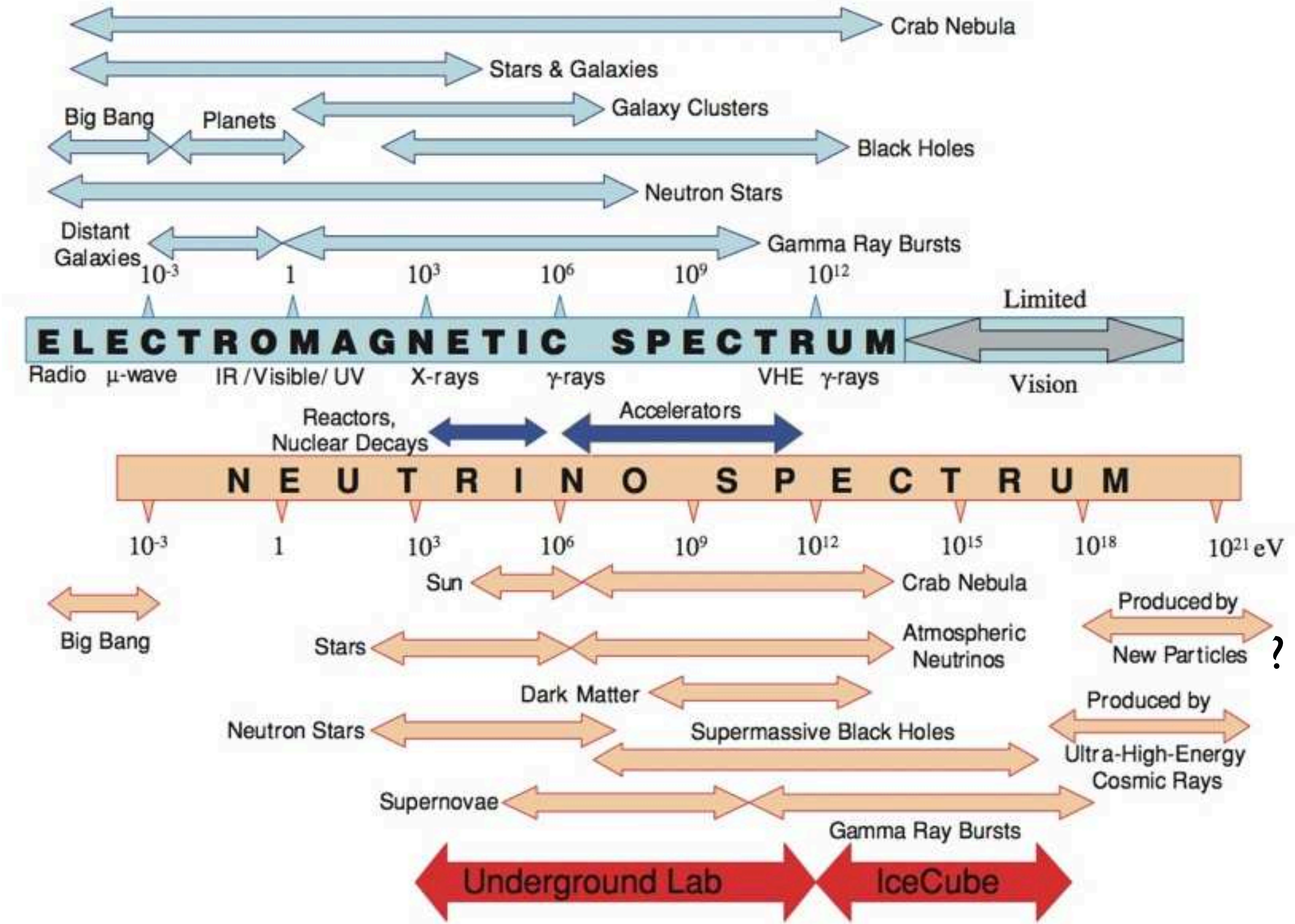



$U_{cr}(1GeV)=1\ eV/cm^3$

# Universal Diffuse Number Flux of ***Neutrinos***



# Electromagnetic vs. Neutrino Energy Spectral Domains



# What is the **Relation** between ***UHECRs and UHENUs?***

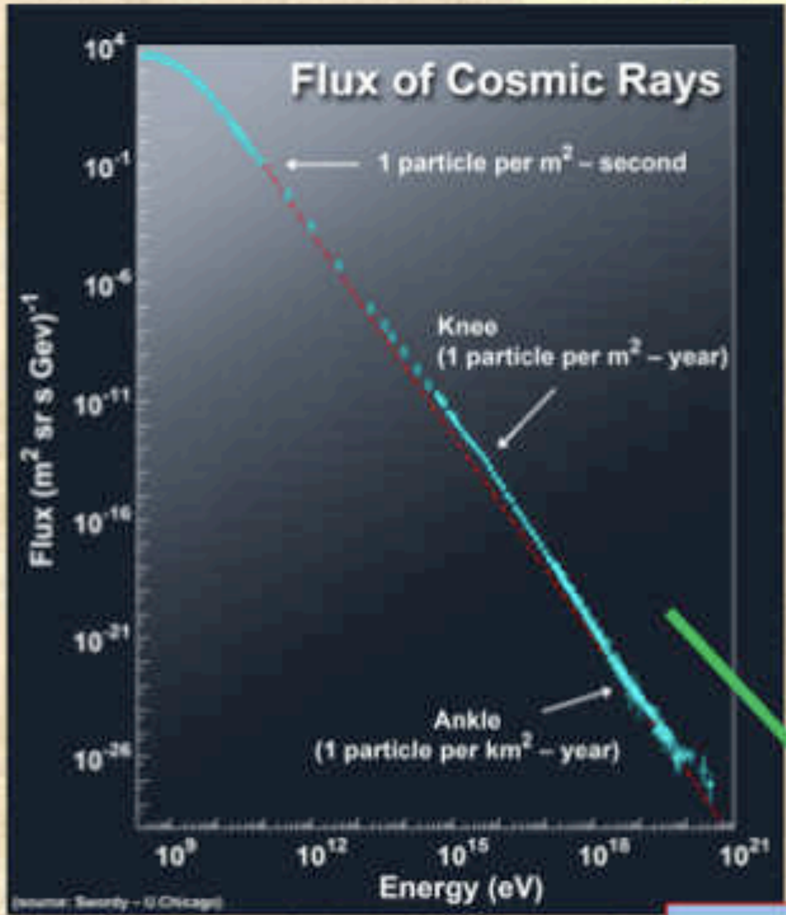
UHECR = Ultra-High Energy Cosmic Rays
UHENU = Ultra-High Energy Neutrinos

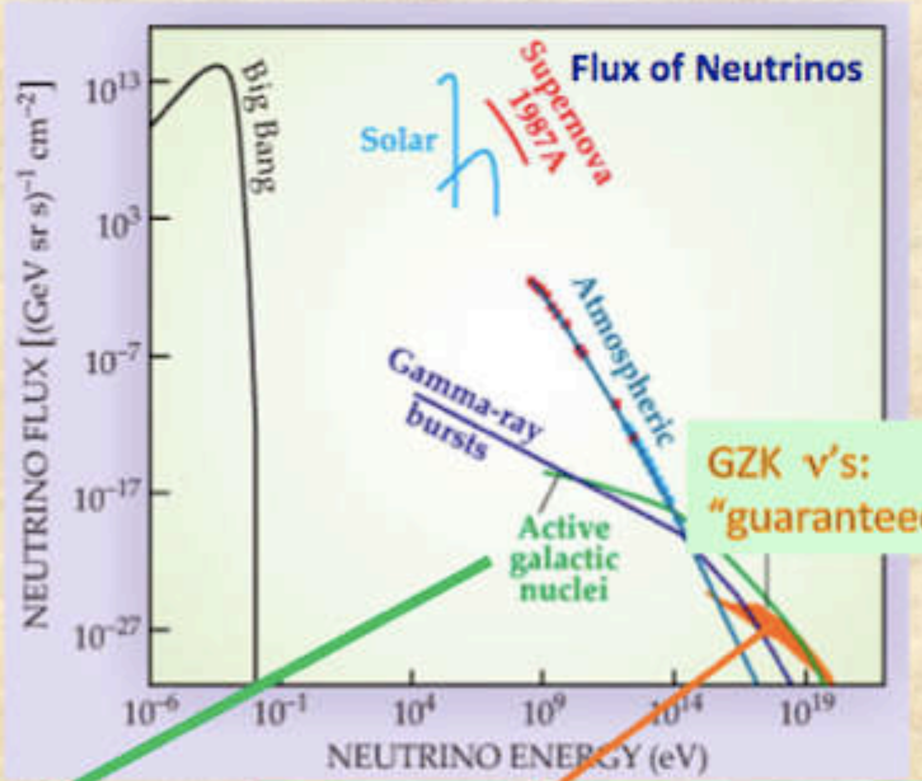
define HE $\gtrsim 10^{9}$ eV (GeV)
VHE $\gtrsim 10^{12}$ eV (TeV)
UHE $\gtrsim 10^{18}$ eV (EeV)

# Cosmic Rays and Neutrinos

Driving theme: Origin of Cosmic Rays

(Sullivan14)

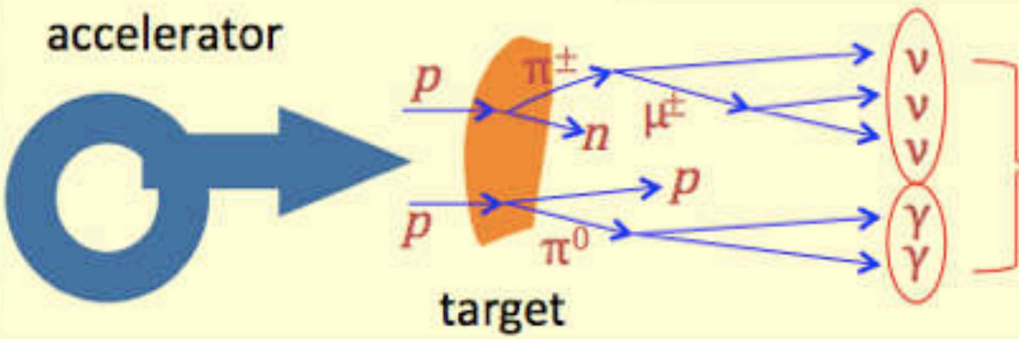



GZK ν's: "guaranteed"

$$\gamma_{cmb}\, p \rightarrow \Delta^+ \rightarrow \begin{array}{l} n\,\pi^+ \rightarrow n\,\mu\nu \\ p\,\pi^0 \rightarrow p\,\gamma\gamma \end{array}$$

CR – ν connection

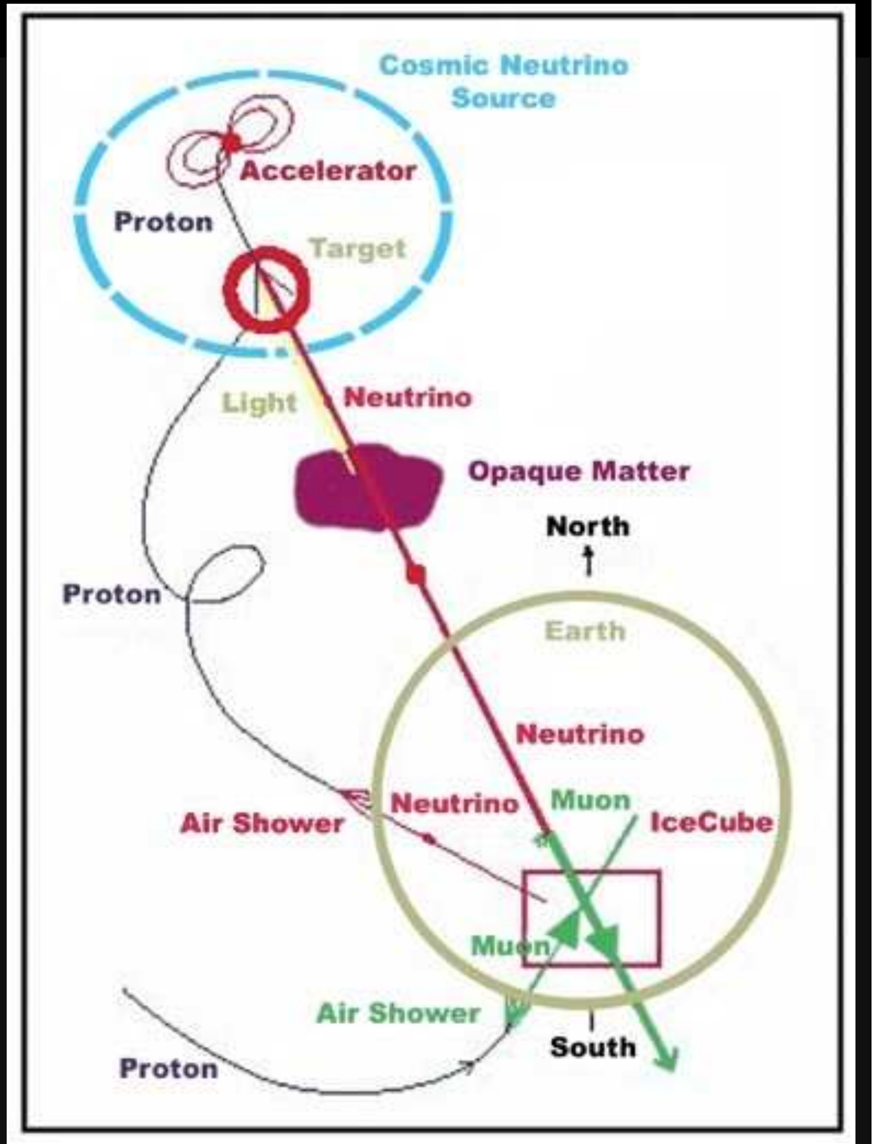


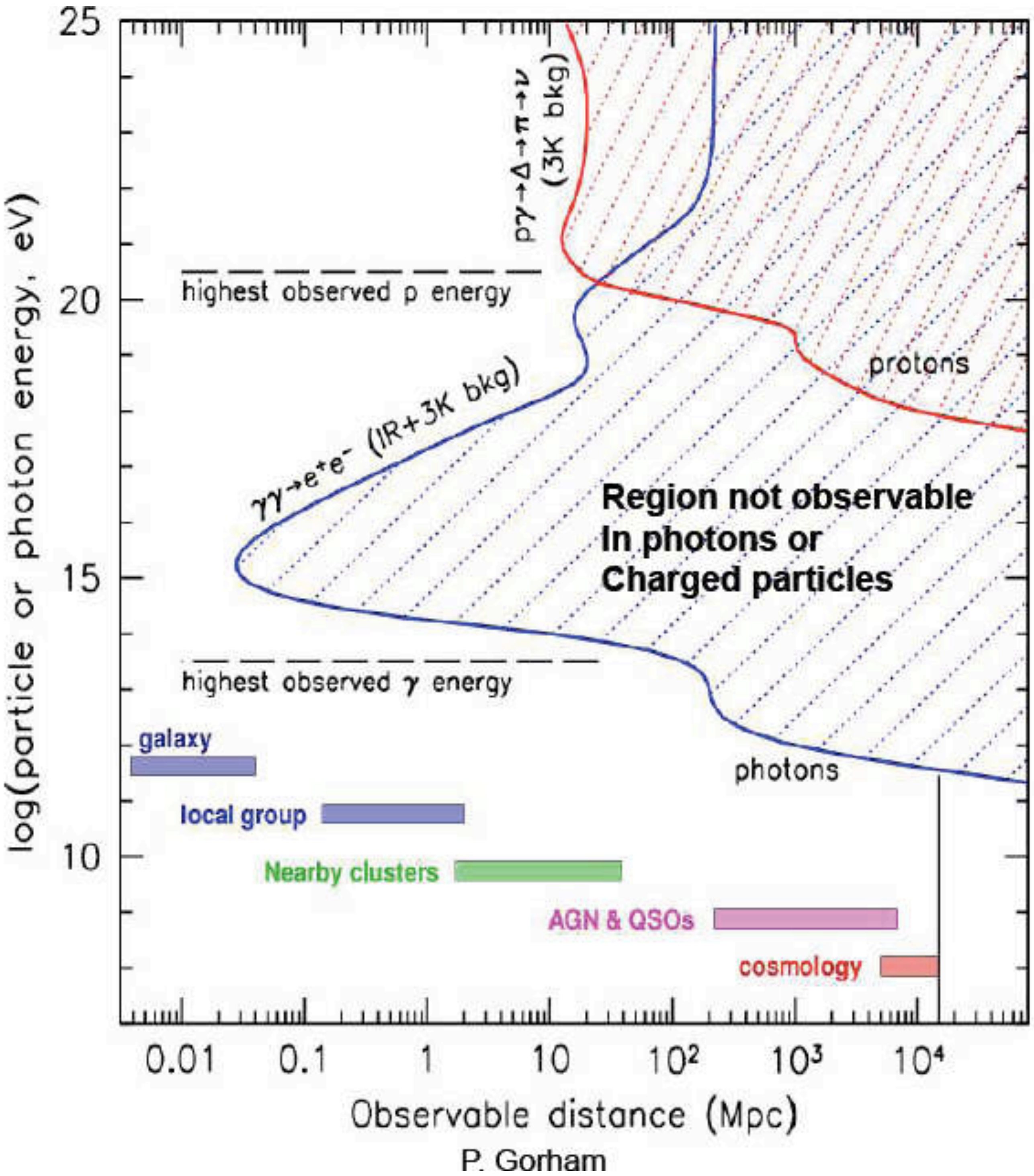

the γ – ν connection
for hadronic accelerators

# Why Neutrinos?

Neutrinos are ideal astrophysical messengers

- Travel in straight lines
- Very difficult to absorb in flight





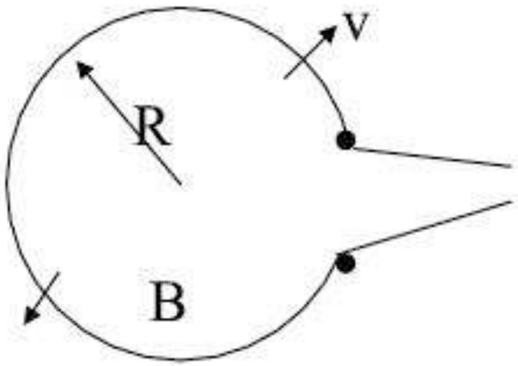

# *And ...*

- Unlike photons and charged particles, which at high energies get absorbed in flight,
- the neutrino mean free path is essentially the Hubble horizon; i.e. unbounded

# UHECR : maximum energy ?

*gyroradius:* $r_L \sim ct_{gy} \sim m_p c^2 \gamma / ZeB = \varepsilon_p / ZeB < R$ (*size of accel.*)

or (EM analog):




$$V = \frac{1}{c}\dot{\Phi} \sim \frac{1}{c}\frac{BR^2}{R/\mathrm{v}} = \beta BR$$

$$\rightarrow \varepsilon_p < \beta eBR$$

$$\Rightarrow L > 4\pi R^2 \frac{B^2}{8\pi} v > \frac{1}{2\beta}\left(\frac{\varepsilon_p}{e}\right)^2 c$$

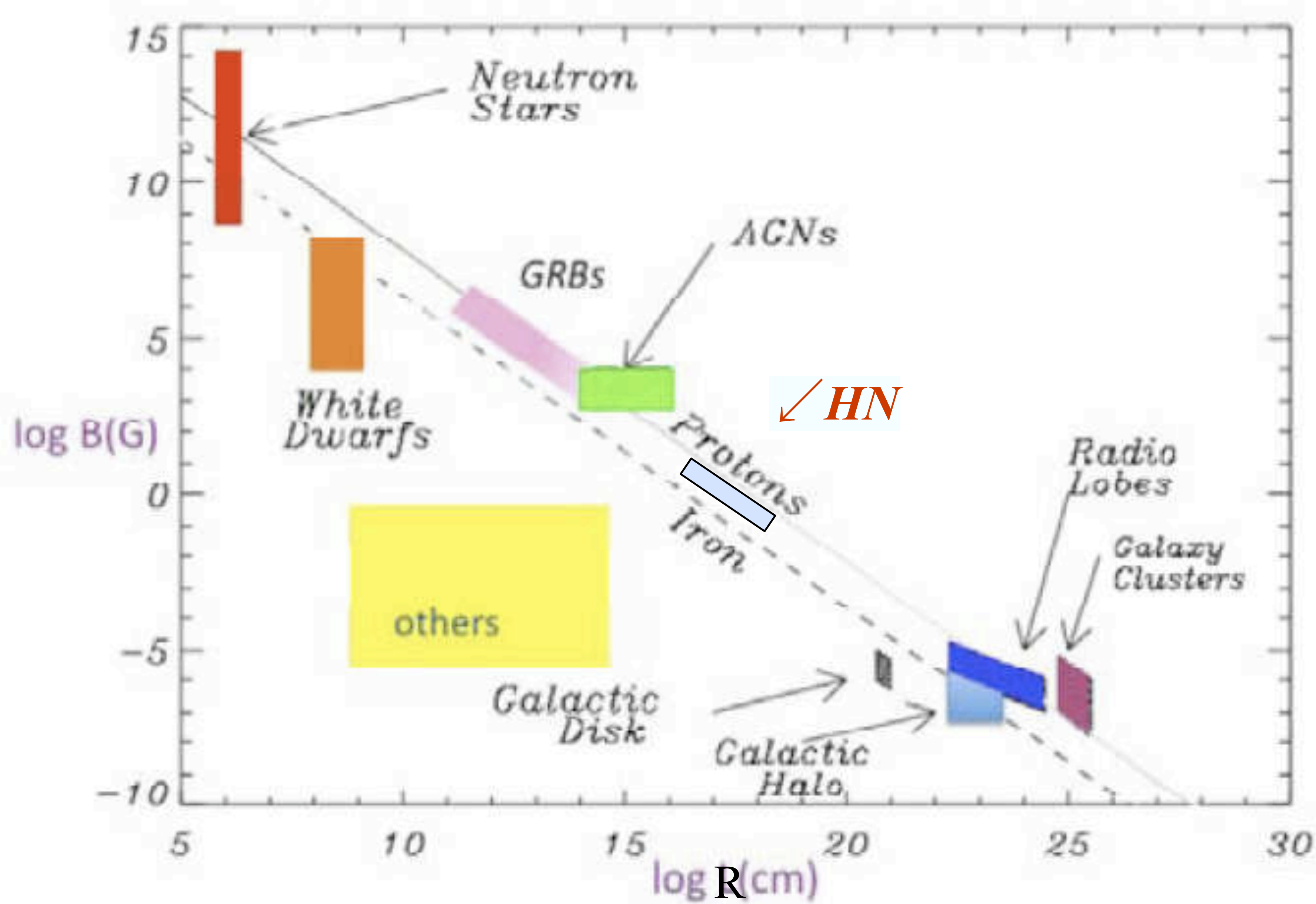
But if relativistic expansion, bulk Lorentz factor $\Gamma >> 1$,
then $time_{obs} \sim R/c\Gamma$, and $size_{obs} \sim R/\Gamma$, hence need

$$\Rightarrow L > 2\frac{\Gamma^2}{\beta}\varepsilon_{p,20}^2 \times 10^{45} \mathrm{erg/s}$$

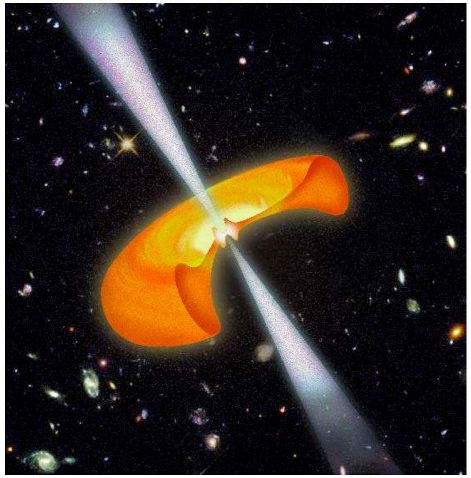
**⇒ *GRB, AGN..?***

(only strongest qualify !)

# *Maximum $E_p$ for various sources (Hillas plot)*



# GRB ? $E_{max}$ :



- Require : $r'_L = E'/ZeB' \geq R'$)
- $\Rightarrow$ $E_{max} \sim \Gamma\, Z\, e\, B'\, R'$

*- primed: comoving;*
*- unprimed : lab frame;*
*- Γ: jet Lorentz factor*

- but, what are R', B' for a GRB?
- we have $R' \sim R/\Gamma$; and external shock occurs at R where $E_0 \sim n\, m_p\, c^2\, R_{dec}^3\, \Gamma^2$
  $\rightarrow R \sim R_{dec} \sim (E_0/n m_p c^2)^{1/3}\, \Gamma^{-2/3}$
- for B', energy equip. : $B'^2/8\pi \sim \varepsilon_B\, n\, m_p\, c^2\, \Gamma^2$
  $\rightarrow B' \sim \varepsilon_B^{1/2} (8\pi\, n\, m_p\, c^2)^{1/2}\, \Gamma$ , so
- $E_{max} \sim Ze(8\pi\varepsilon_B)^{1/2}\, E_0^{1/3}\, (n\, m_p\, c^2)^{1/6}\, \Gamma^{1/3}$ , or
- $E_{max} \sim 2 \times 10^{20}\; Z\, E_{53}^{1/3}\, \varepsilon_{B,-2}^{1/2}\, \Gamma_2^{1/3}\, n^{1/3}$ eV

# AGN ?   two main types

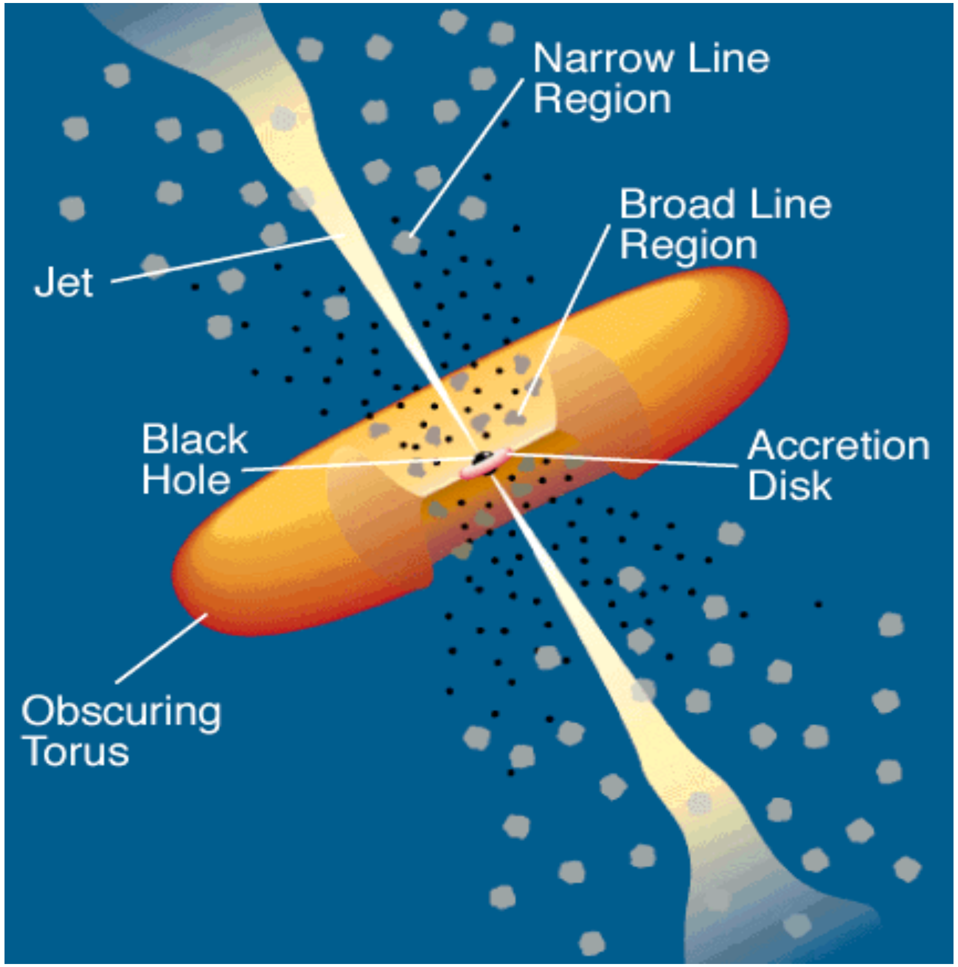
(~1% of all galaxies)

Radio-loud: M87 (jet ~10%) **(RL)**

Radio-quiet: M81 (no jet ~90%) **(RQ)**

# RL AGN

## as UHE $\gamma$, CR, $\nu$ sources




- Big brother of GRB: massive BH ($10^7$-$10^8$ $M_{sun}$ ) fed by
  an accretion disk $\rightarrow$ jet
- But, jet $\Gamma_{j,agn} \sim$ 10-30
  ( while $\Gamma_{j,grb} \sim 10^2$ - $10^3$ )
- UV photons from disk; in addition, line clouds provide extra photons
  (+back-scatter)
- Typical (“leptonic”) model:
  SSC (sync-self-compton);
  SEC(sync-exter.compton)

# But: are RL (jet) AGNs the UHECR sources?

- The AGNs in the VC catalog inside 75 Mpc are generally weak, not strong-jet (radio-loud, RL) AGNs - and no longer statistically favored; but...
- There is possible evidence for :
  a) large angle deflections (heavy elements); and
  b) non-jet (radio-quiet) AGNs are abundant...
- Independently, correlation with matter (normal galaxies) is strong

# Alternative UHECR: RQ AGNs

Pe'er, Murase, Mészáros, 2009, PRD 80, 123018 (arXiv:0911.1776)

- Could be that culprits are radio-quiet **(RQ) AGNs**
- Enough of them inside GZK radius
- Evidence for small jets in RQ AGNs
- Evidence for heavy CR composition ($X_{max}$ vs. E)
- Can accelerate **heavy elements** to right GZK energies, $E_{max} \sim ZeBR \sim 10^{20}\, Z_{26} B_{-3} R_{10}$ eV (if $B \sim 10^{-3}$G, $R \sim 10$ pc)
- Can survive photo-dissociation
- Heavy elements have larger rms. deviation angles
- Correlation with matter (gal) distribution is good.

# Another alternative: Hypernovae?


← ***supernova***
SN 1006 (X-ray)

***- Hypernovae:***
similar but ~ $10\text{-}10^2$ times ***more energetic***; and portion of ejecta reaches ≥ ***semi-relativistic*** speed, possibly anisotropic

***~500 times the rate density of GRBs***

# Hypernova ejecta as UHECR sources

(XY Wang et al, 2007, PRD 76:3009; Budnik et al, 2008, ApJ 673:928)

- Type Ib/c but isotropic equiv ***$E_{HN}$~3-5x10$^{52}$ erg***
- ***500*** times GRB rate, and ***$10^{-1}$-$10^{-2}$*** usual SNIa ***rate***
- ***Semi-relativistic (v~c, or $\Gamma\beta \geq 1$)*** comp. in outflow (shock accelerates down the envelope gradient)
- Assume shock expands in WR progenitor wind, magnetic field fraction $\varepsilon_B$ of equipartition

$$B^2/8\pi = 2\epsilon_B \rho_w(R) c^2 \beta^2 \qquad \rho_w(R) \propto R^{-2}$$

Max. CR energy:

$$\varepsilon_{\max} \simeq ZeBR\beta = 4\times 10^{18} Z \times \epsilon_{B,-1}^{1/2} \left(\frac{v}{10^{10}\mathrm{cms}^{-1}}\right)^2 \left(\frac{\dot{M}}{3\times10^{-5}\mathrm{M}_\odot \mathrm{yr}^{-1}}\right)^{1/2} v_{w,3}^{-1/2} \mathrm{eV}$$

→ Proton: $E_{max}$ ~$10^{19}$ eV, and Fe: $E_{max}$ ~2.6 $10^{20}$ eV

Origin of $10^{19}$-$10^{21}$ eV UHECR: may be GRB - but what about $10^{16}$-$10^{19}$ eV?

# HYPERNOVAE?

- Radio, x-ray & gamma-ray observations of SN1998bw/GRB980425 :
- sub-energetic GRB—GRB980425: E~1e48 erg (d=38 Mpc)
- Radio afterglow modeling: E>1e49 erg, → Gamma~1-2
- X-ray afterglow: E~5e49 erg, → beta=0.8

→ **Mildly relativistic ejecta component**

E_SN=3-5e52 erg
$V_{avg}$=0.1c


SN shock acceleration in the Envelope?

Tan et al. 01
Woosley et al. 99

Other SN/GRB w. semi-relativistic ejecta: →

- SN2003lw/GRB031203
- SN2006aj/GRB060218

# Maximum energy of accelerated particles

1) Type Ib/c hypernovae expanding into stellar wind of WR star

2) equipartition magnetic field B, both upstream and downstream

$$B^2/8\pi = 2\epsilon_B \rho_w(R) c^2 \beta^2 \qquad \rho_w(R) \propto R^{-2}$$

**Maximum energy:**

Hillas

Bell & Lucek 01

$$\varepsilon_{\rm max} \simeq ZeBR\beta = 4 \times 10^{18} Z \times \epsilon_{B,-1}^{1/2} \left(\frac{v}{10^{10}{\rm cms}^{-1}}\right)^2 \left(\frac{\dot{M}}{3{\times}10^{-5}{\rm M}_\odot{\rm yr}^{-1}}\right)^{1/2} v_{w,3}^{-1/2} {\rm eV}$$

**Protons can be accelerated to ~$10^{19}$ eV**
**Heavy nuclei can be accelerated to ~Z*$10^{19}$eV**

# Flux level--- energetics

**Kinetic energy generation rate:**

$$\dot{\epsilon}_k(z=0) = R_{\rm HN} E_{k,{\rm HN}}$$
$$= 2.5 \times 10^{46} \left(\frac{R_{\rm HN}}{500{\rm Gpc^{-3}yr^{-1}}}\right) {\rm erg\ Mpc^{-3}\ yr^{-1}}$$

**Compare w. normal GRBs**

| | Hypernova (v=0.1c) | Normal GRBs |
|---|---|---|
| Rate (z=0) | ~500 ${\rm Gpc^{-3}\ yr^{-1}}$ | ~1 ${\rm Gpc^{-3}\ yr^{-1}}$ |
| kinetic energy | 3-5e52 erg | 1e53-1e54erg |

**The required rate :**

$$R_{\rm HN} = 750 Z^{-1.2} (f_z/3)^{-1} {\rm Gpc^{-3} yr^{-1}}$$

Normal Ib/c SN rate:

$$\sim 2 - 5 \times 10^4\ {\rm Gpc^{-3} yr^{-1}}$$

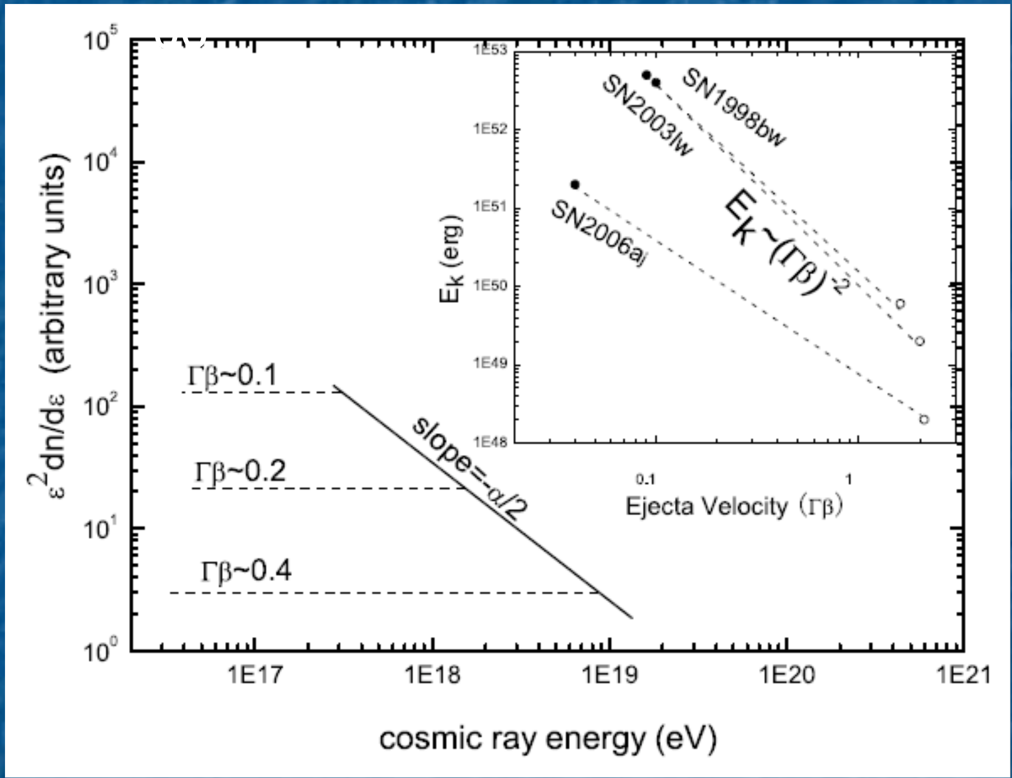
sub-energetic GRB rate:

$$100 - 1800\ {\rm Gpc^{-3} yr^{-1}}$$

Soderberg et al. 06

# Energy distribution with velocity

Data from Soderberg et al.




Wang, Razzaque, Meszaros, Dai 07

- Normal SN $E_k \propto (\Gamma\beta)^{-5}$

Very steep distribution -> negligible contribution to high-energy CRs

Berezhko & Volk 04

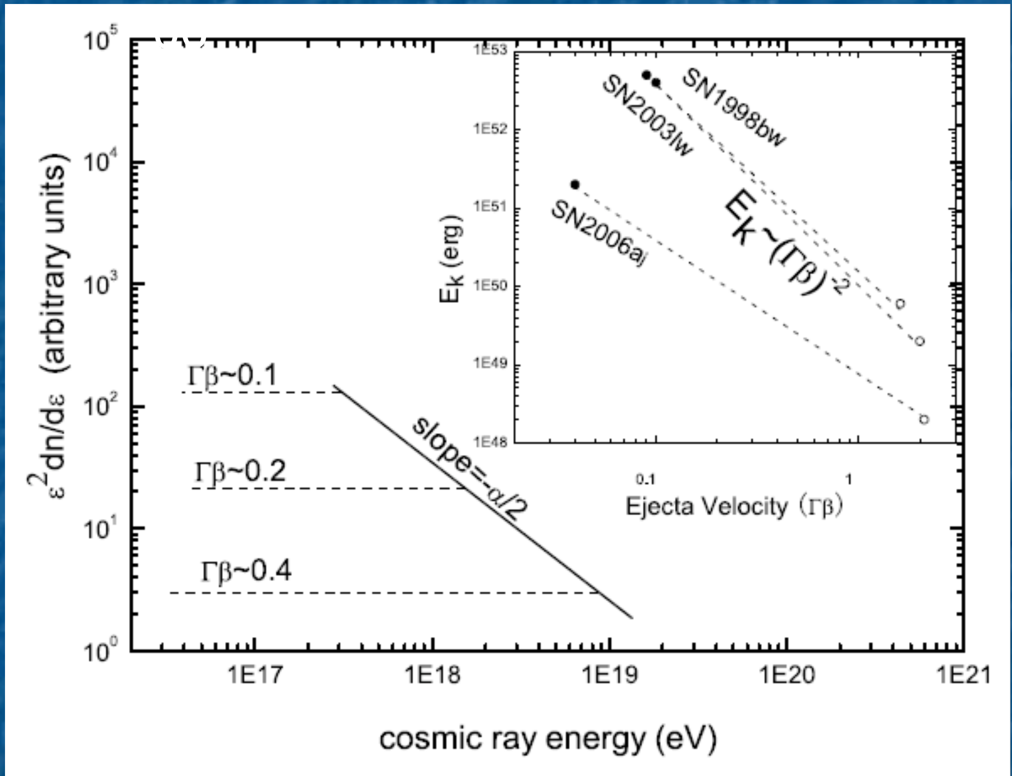
- Semi-relativistic hypernova: high velocity ejecta with significant energy $E_k \sim (\Gamma\beta)^{-2}$

CR spectrum: $\varepsilon^2 (dN/d\varepsilon) \propto \varepsilon^{-\alpha/2}$

$\alpha \sim 2$

# Energy distribution with velocity

Data from Soderberg et al.

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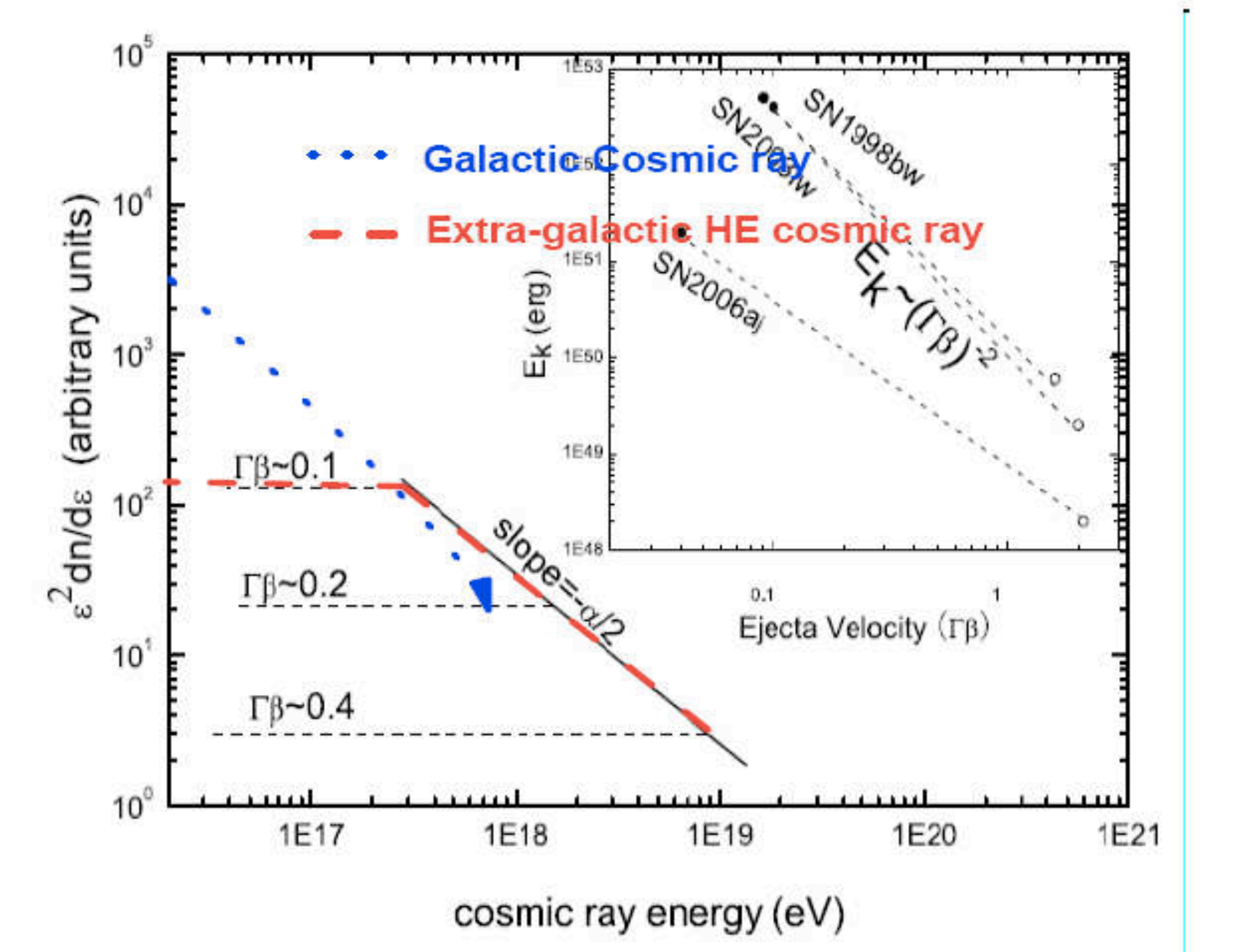
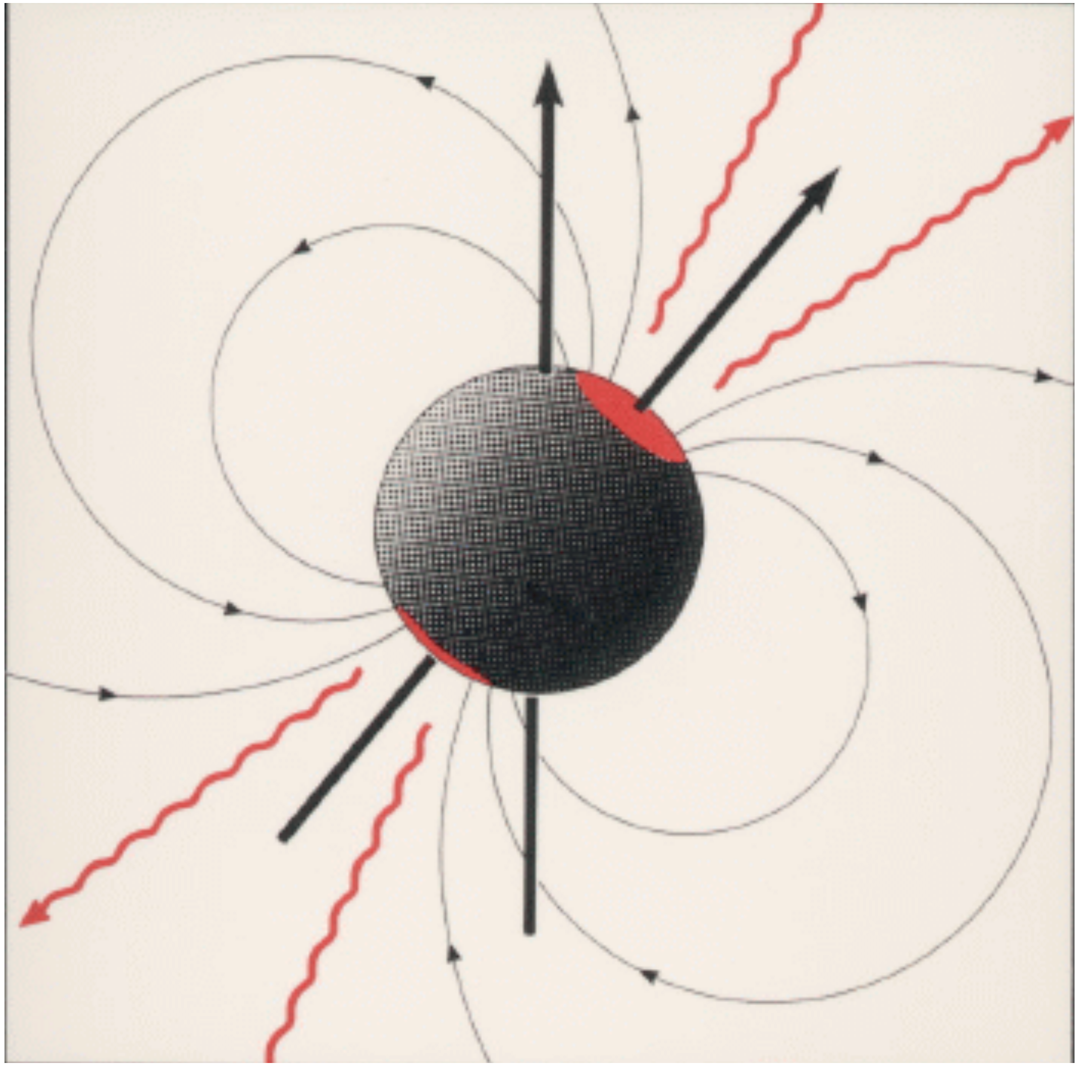
$\alpha \sim 2$

# Transition from GCRs to EGCRs



# What about Magnetars ?



***Pulsar***: spinning neutron star: R~10 km and magnetic field usually $B \sim 10^{12}$ G;

but ***MAGNETAR***: $B \sim 10^{14}\text{-}10^{15}$ G ($10^{10}\text{-}10^{11}$ Tesla)

# Magnetars as UHECR sources?

- Surface magnetic field strengths $B_s \sim 10^{14}$-$10^{15}$ G (whereas "normal" NS have only $\lesssim 10^{12}$-$10^{13}$ G)
- Fraction $\lesssim$ 0.1 CC SNe may result in magnetars
- Newly-born magnetar $R \sim 10^6$ cm, $\Omega = 2\pi/P \sim 10^4 P_{-3}^{-1}$
- Light-cylinder $R_{LC} \sim c/\Omega \sim 5 \times 10^6 P_{-3}$ cm (→accel.)
- $B_{LC} \sim B_s (R_s/R_{LC})^3 \sim 10^{13} P_{-3}^{-3}$ G

**→ $E_{max} \sim ZeBR(v/c) \sim 10^{21} Z B_{s,15} P_{-3}^{-2}$ eV**

Or: In PNS wind, wake-field acceleration can lead to UHECR energies $E(t) \lesssim 10^{20}$ eV $Z \eta_{-1} \mu_{33}^{-1} t_4^{-1}$

One possible type of

# GZK UHECR/UHENU

astrophysical source

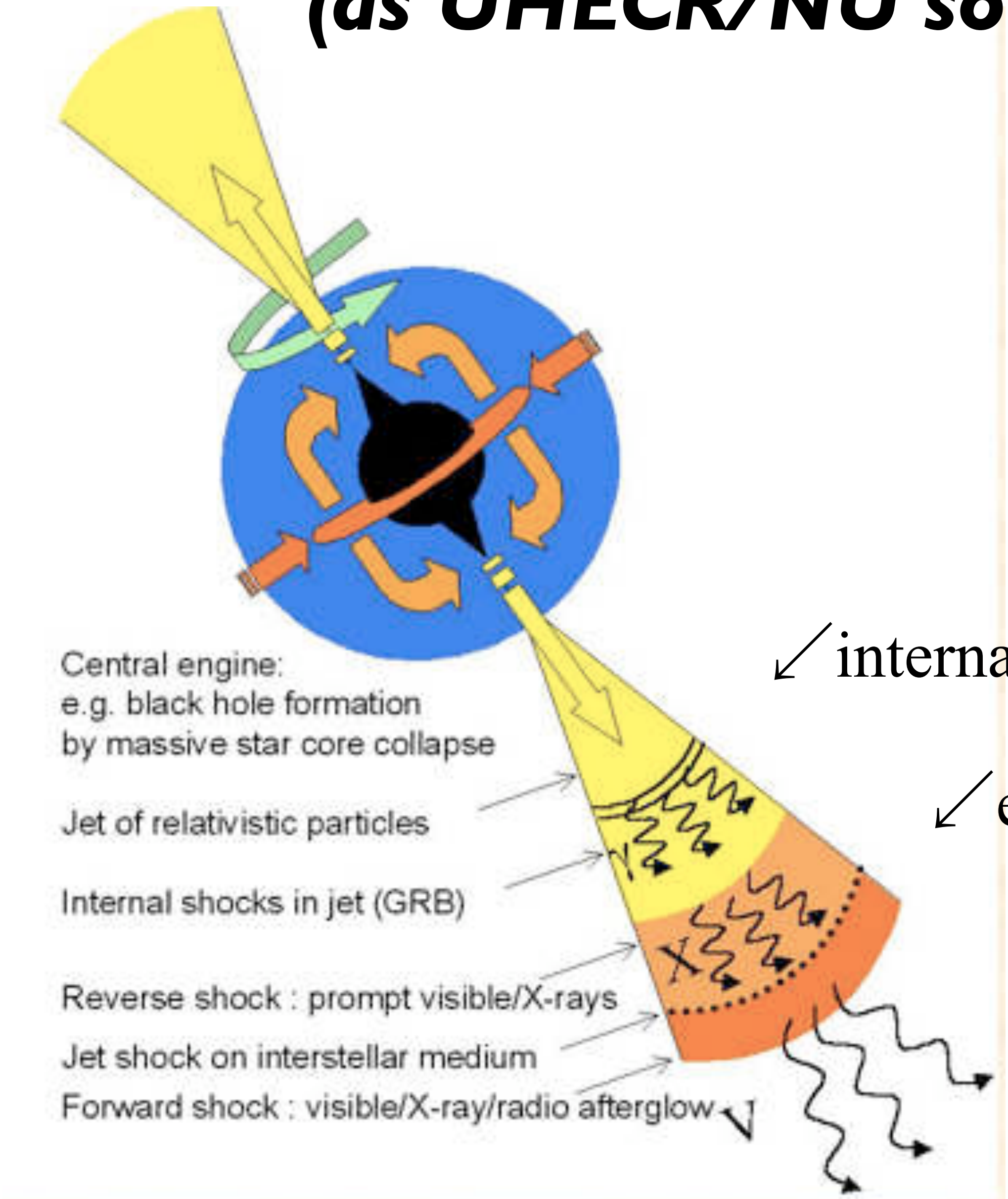
# Standard(+) Model of GRB

## *(as UHECR/NU source)*

Int. & ext. shocks, accelerate electrons e,B →γ (*leptonic*);

***and***

accel. protons too (?) pγ→ν, γ (***hadronic***)



# GRB VHE neutrinos

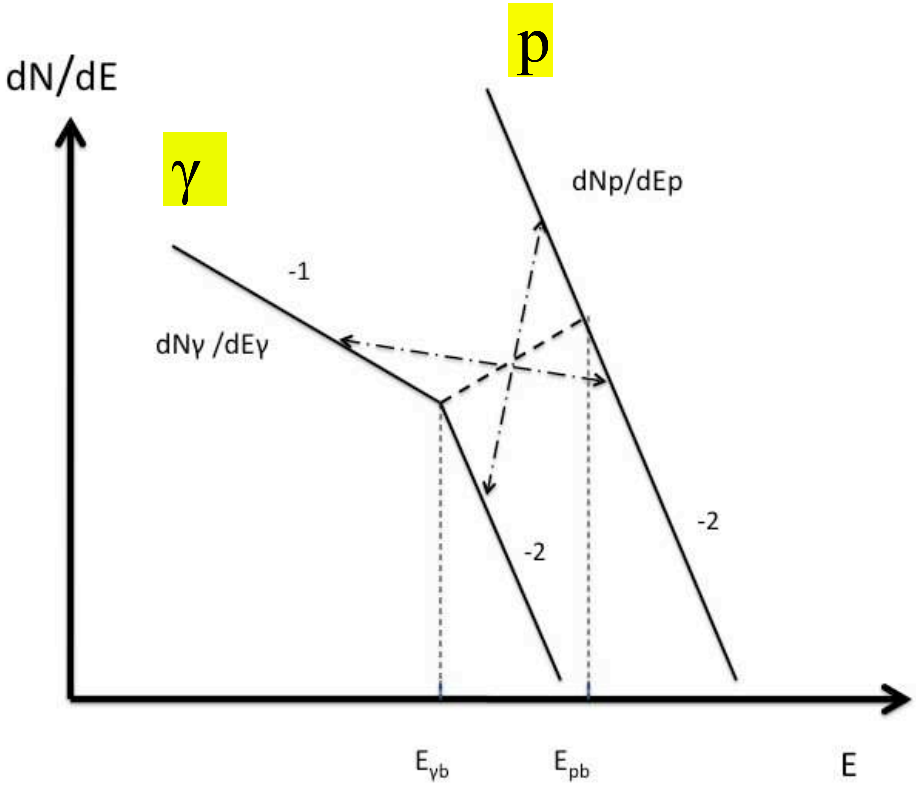
At the simplest level:

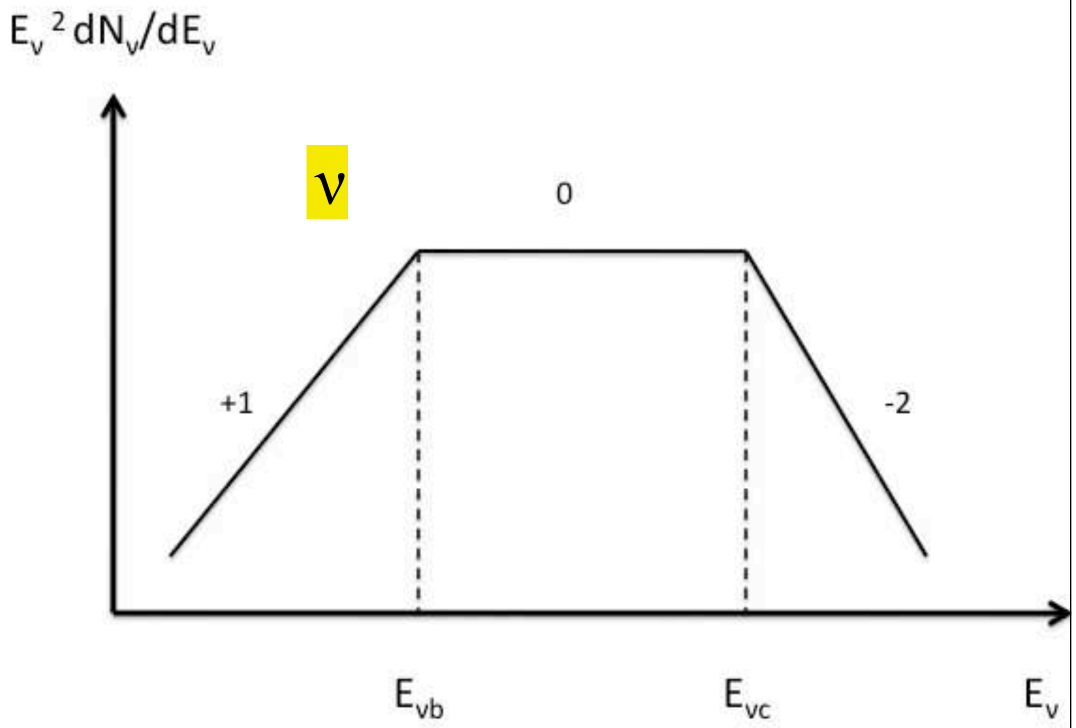
- $R_d$, $R_{ph}$ : dissipation radius where particles accelerated
- Fermi (or mag, reconn.) accel. $dN_{p,e}/dE \sim E^{-q}$
- $e^{\pm}, B \rightarrow \gamma$
- $p, \gamma \rightarrow \pi^{\pm} \rightarrow \mu^{\pm}, \nu_\mu \rightarrow e^{\pm}, \nu_e, \nu_\mu$
- For PL $dN_{e,p}/dE$ and $dN_\gamma/dE \rightarrow dN_\nu/dE$ also PL
- Parameters: $\epsilon_p$ , $\epsilon_e$ , $\epsilon_B$ : energy ratios of p,e,B to $E_{tot}$
- $E_{tot}$: total burst energy, $\Gamma$: bulk Lorentz factor

# Simple p,γ→Δ→... model

pγ→Δ interaction of a Band-γ spec. with an $E^{-2}$ proton spec. is

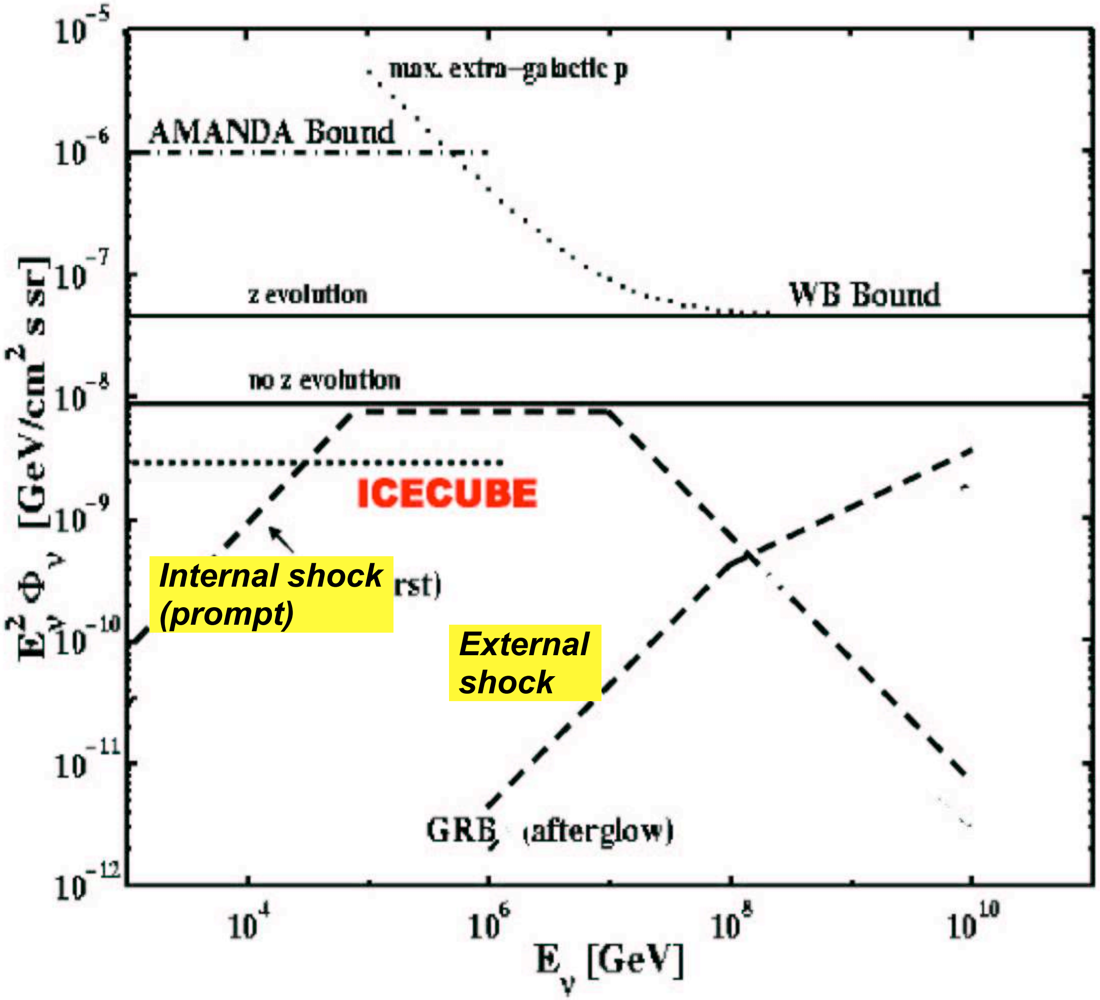
(WB 97)



# $\nu$s from p$\gamma$ from int. & ext. shocks

***NOTE: internal shock (old paradigm ) + simple Δ-res. approx.***



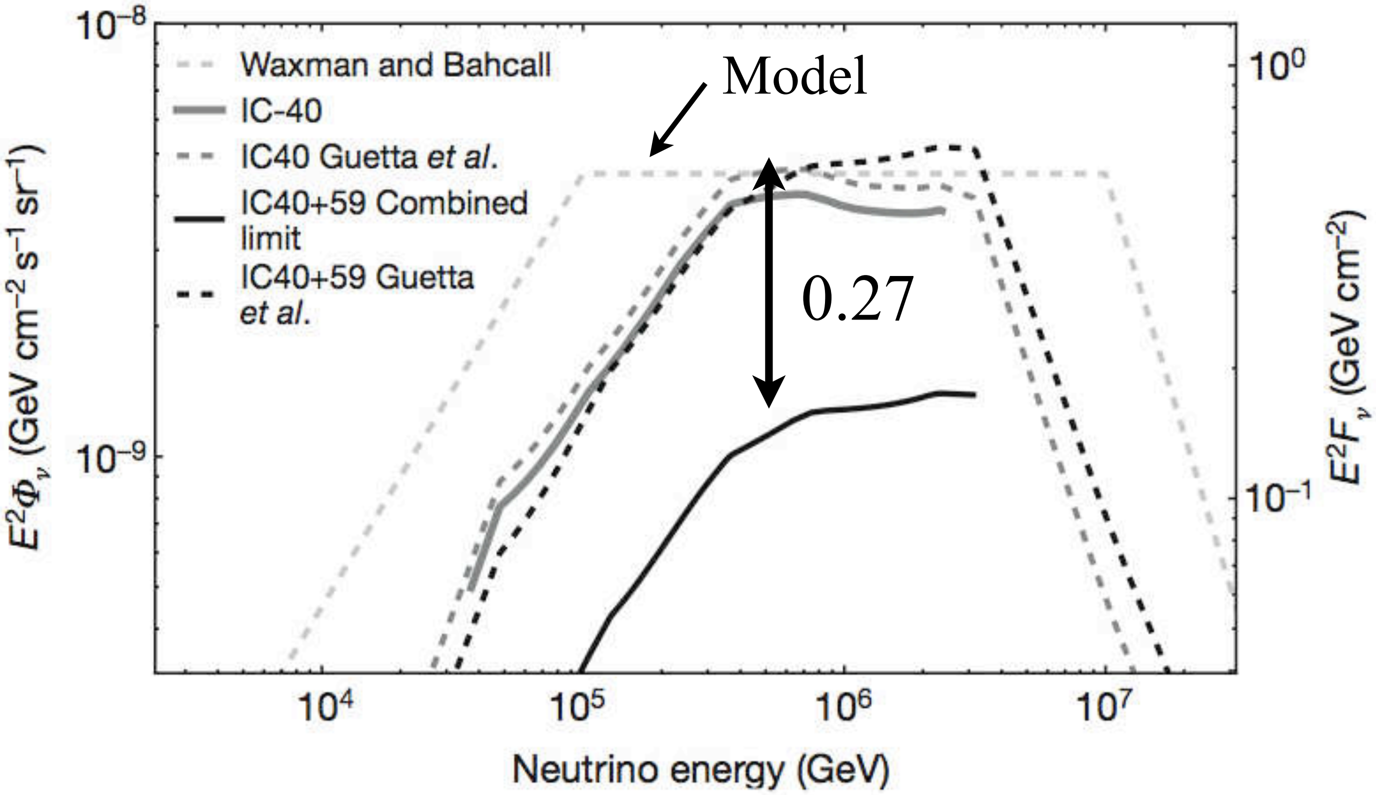

Waxman, Bahcall 97 & 99 PRL

- **Δ**-res.: $E'_p\, E'_\gamma \sim 0.3\,GeV^2$ in comoving frame, in lab:
  - $\rightarrow E_p \geq 3\times10^6\, \Gamma_2^{\,2}$ GeV
  - $\rightarrow E_\nu \geq 1.5\times10^2\, \Gamma_2^{\,2}$ TeV
- Internal shock p$\gamma_{MeV}$ $\rightarrow$ ~100 TeV $\nu$ s
- ( External shock p$\gamma_{UV}$ $\rightarrow$ ~ 0.1-1 EeV $\nu$ s )
- Diffuse flux: det.w. km$^3$

# Data: IC40+59 search for VHE nus from 190 GRB (105 northern)

Nature 484:351 (2012), the Icecube collab.; Abbasi and 242 others (incl. P.M.)

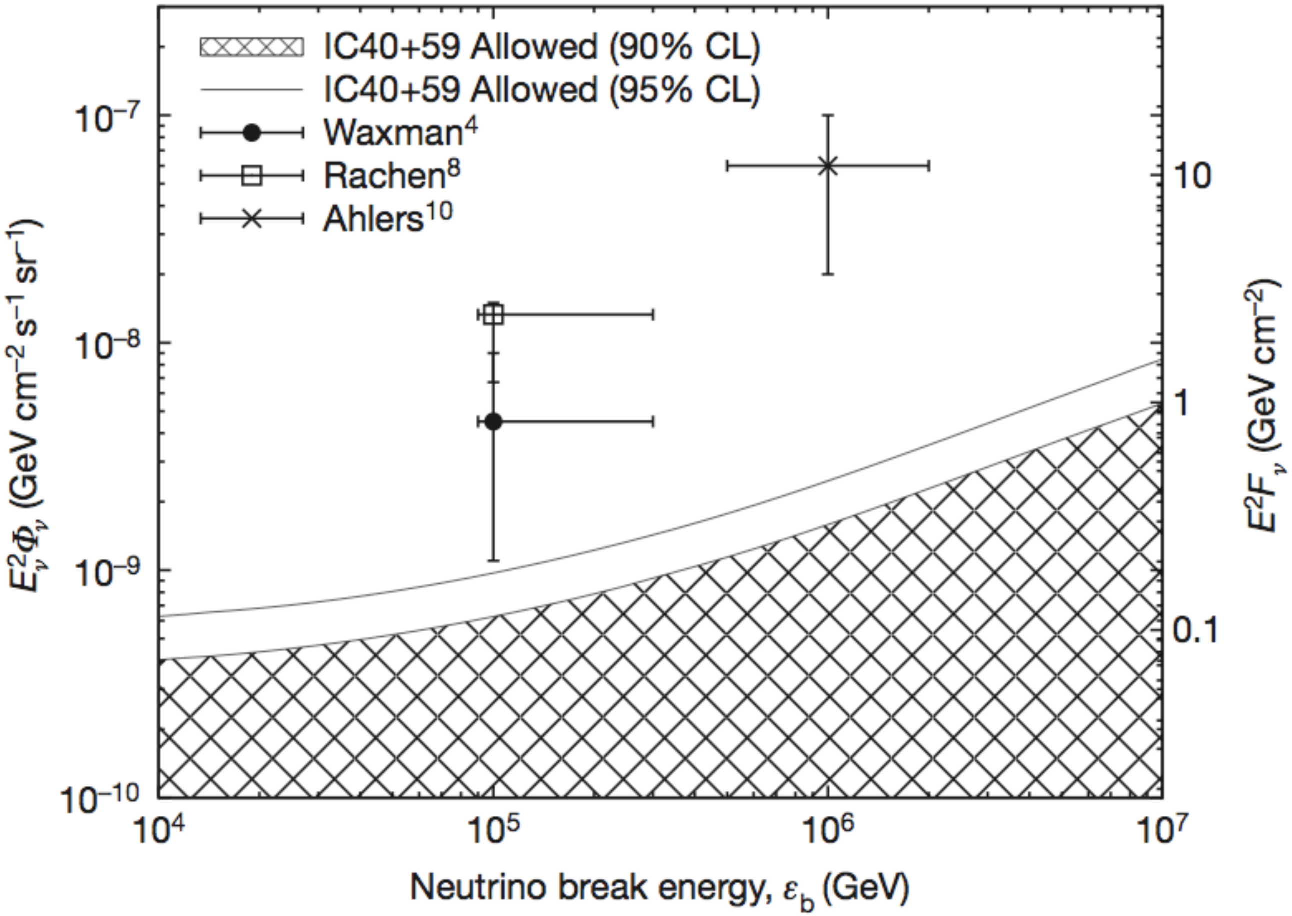
(A) Model dependent search




Data is factor 0.27 below model $F_\nu$ at 90% CL

- Analyze 190 GRBs localized w. γ-rays betw, $T_{start}$ & $T_{end}$
- Use the WB'97 and Guetta'04 proton acceleration model in internal shocks, with $E^{-2}$ spectr, $\epsilon_p/\epsilon_e=10$, and $p\gamma \rightarrow \Delta\text{-res} \rightarrow \nu_\mu$
- Nu-flux normalized by obs. γ-ray flux, get $F_\nu$ for 190 (right axis), and diffuse flux (all) assuming 677 $yr^{-1}$

# Model-independent ULs




- Take observed γ-ray flux and γ-ray spectral break energy
- Use these to infer the ν flux and the ν spectral break energy
- The ν-flux UL implies a UHECR proton flux UL, given by hatched region
- But (internal shock) models capable of explaining observed UHECR flux (data pts) are above this UL

# IC59 2-year ***conclusions*** (190 GRBs)

***Nature 484:351 (2012)***

- The fireball (more accurately: ***internal shock***) model **overpredicts** the TeV-PeV nu-flux by a ***factor 3.7*** , (asuming $L_p/L_e$=10, Δ-res only, Lorentz Γ~300-600)
- For a ***model independent*** fit, the 95% CL nu-flux UL is ***2-3σ below*** what would be expected ***if the GRBs contribute most of GZK*** UHECR flux.
- In these models, either ***$L_p/L_e$*** must be substantially below factor 3-10 assumed here, ***or*** the production ***efficiency of neutrinos*** is lower than was assumed.

# ***A significant achievement:***

- These are ***conservatively*** stated conclusions
- The ***first time*** VHE nus have put a significant ***constraint*** on a well-calculable astrophysical UHECR-UHENU model, at ***90-95% CL***
- This is very ***valuable***
- Icecube is doing ***exciting*** astrophysics
- A significant first step towards ***GZK physics***

# But, on closer look at IC3 analysis...

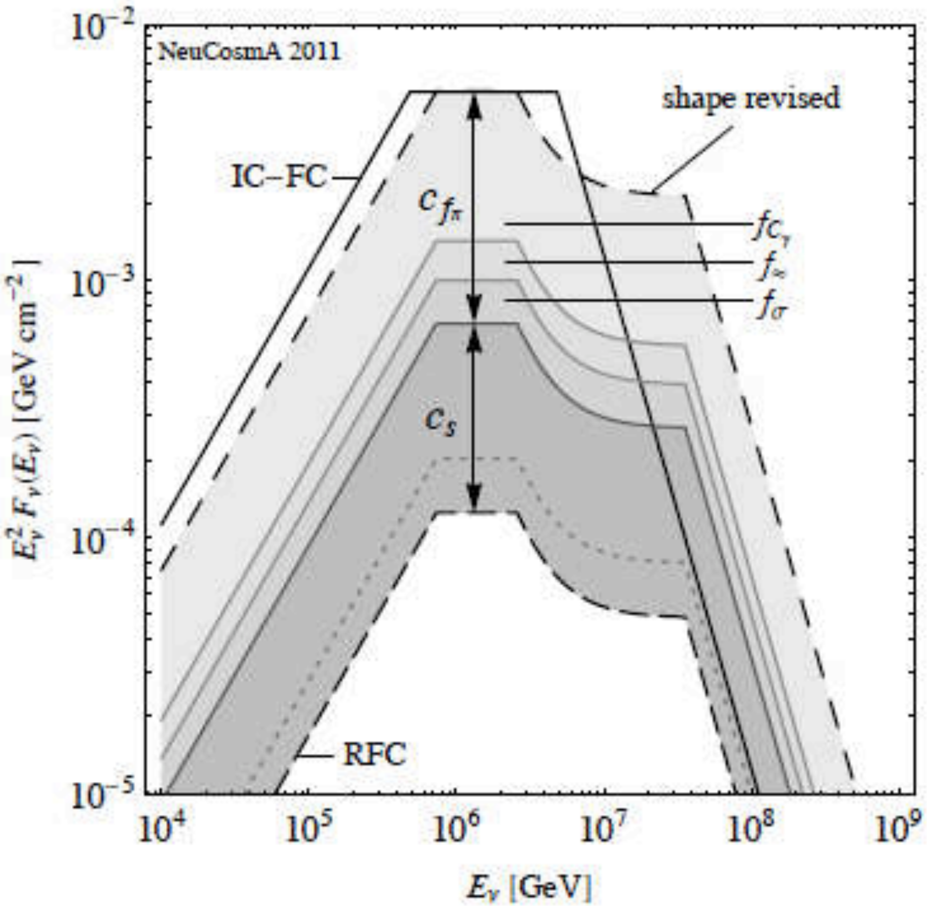
(Li '12, PRD 85:027301)

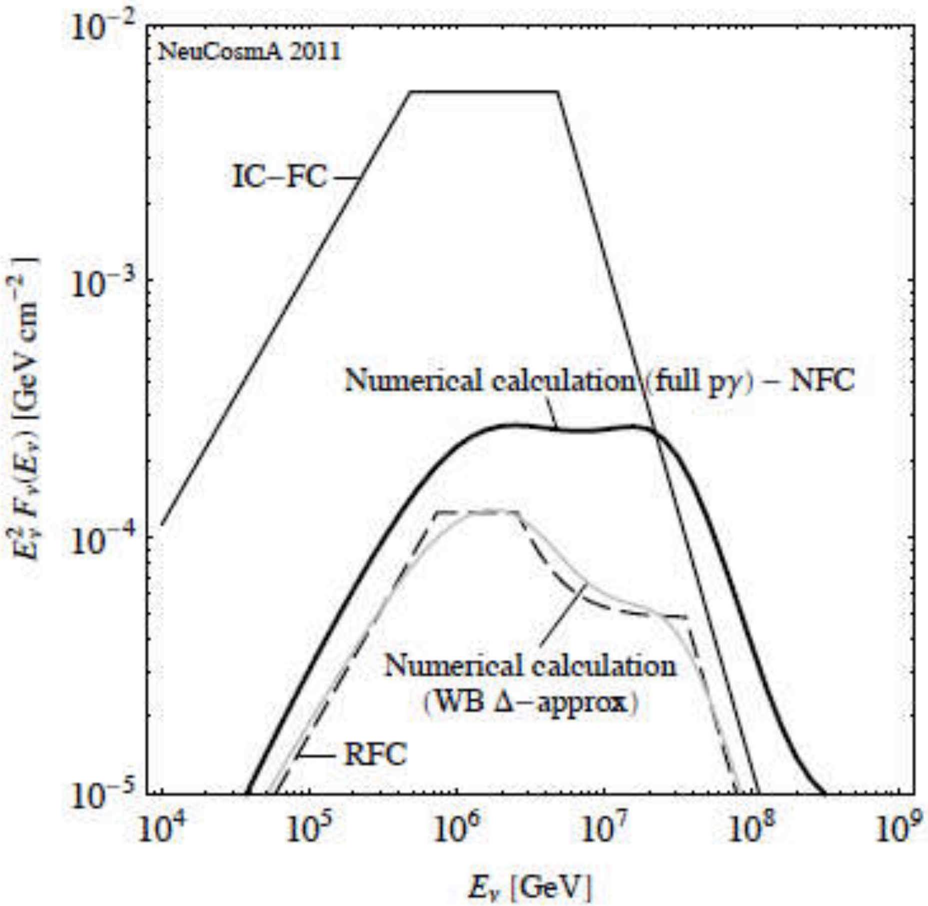
- IC22-59 analysis used a ***simplified*** version of WB97 , which results in overestimated model nu-fluxes
- Assumed $F_\nu^{IC} / F_p = (1/8)\, f_{\pi,b}$ , where 1/8 because 1/2 $p\gamma$ lead to $\pi^+$ and each $\nu_\mu$ carries 1/4 $E_\pi$, and $f_{\pi,b} = f_\pi (E=E_b)$
- But $f_\pi (E) = f_{\pi,b}$ is OK only for $E_b < E < E_{\pi,cool}$;
- Also for $E<E_b$ , have $f_\pi \propto E$, because of decr. # of photons
- Result: ***model $\nu_\mu$ flux overestimated by factor ~5*** (at least)
- ***In addition***, ignored multipion, Kaon decay, etc.

# *In greater detail..*

Even using the (old paradigm) int. shock model, the simplifications have an effect

(Hümmer et al '11, PRL 108:231101)

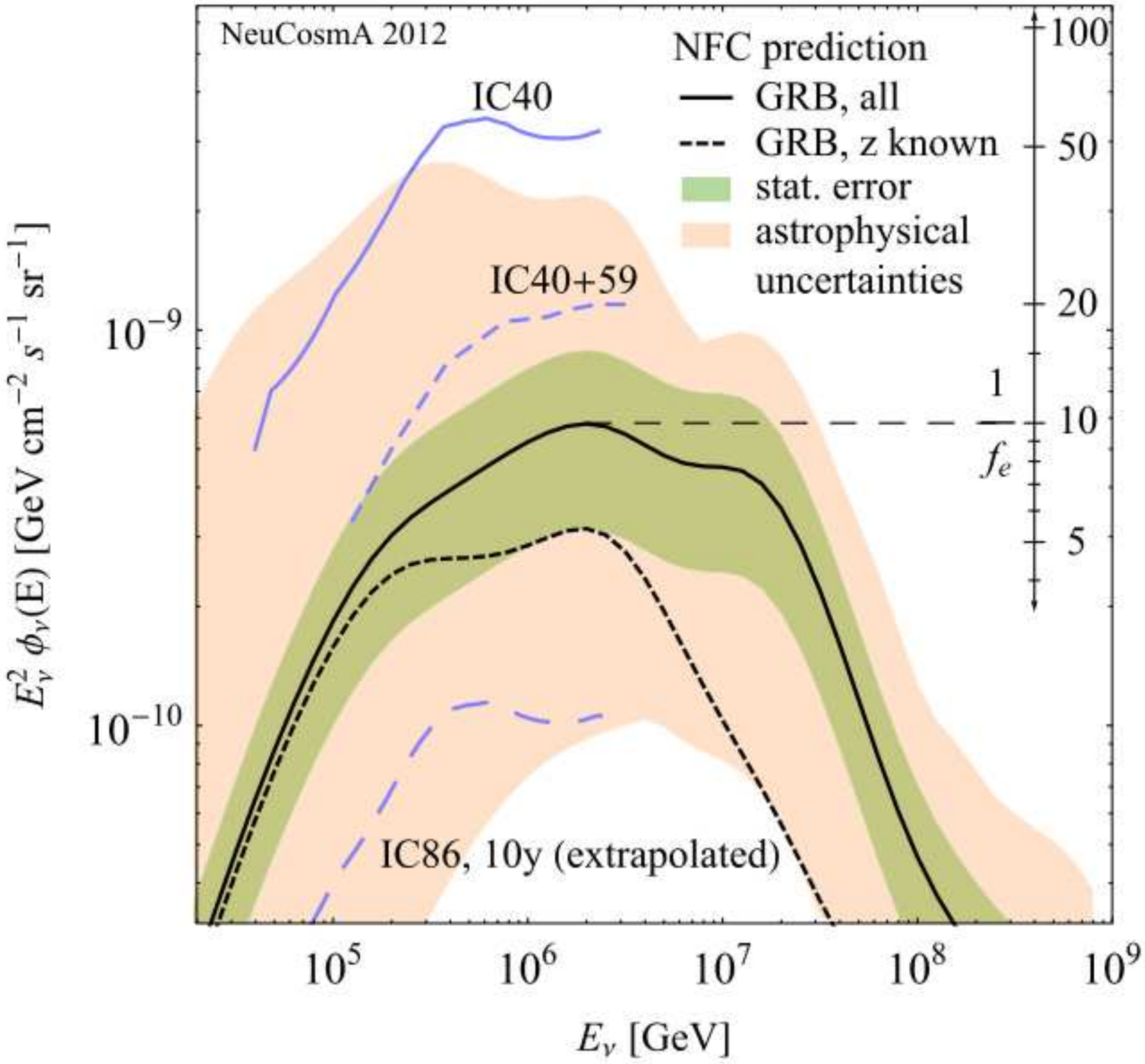



- IC-FC: IceCube Fball. Calc.
- RFC: "Revised" Fball.Calc. ⇒
- NFC: Numerical Fball.Calc.

- $f_C$: energy of all photons approx. by break energy
- $f_\approx$ : 0.7 (rounding error in one eq.)
- $f_\sigma$ : 2/3(negelected width of Δ-res.)
- $C_s$ : correct en. loss of second's & E-dep of proton mfp

# So for stand. IS model ....




- Even using the old standard paradigm of ***internal shock***, but with more detailed physics (incl. multi-pion and Kaon production, ≠ cool'g. break for π, μ, and numerical as opposed to analytical calcul.)
- ⇒ ***$F_\nu$ predictions below IC40+59 !***

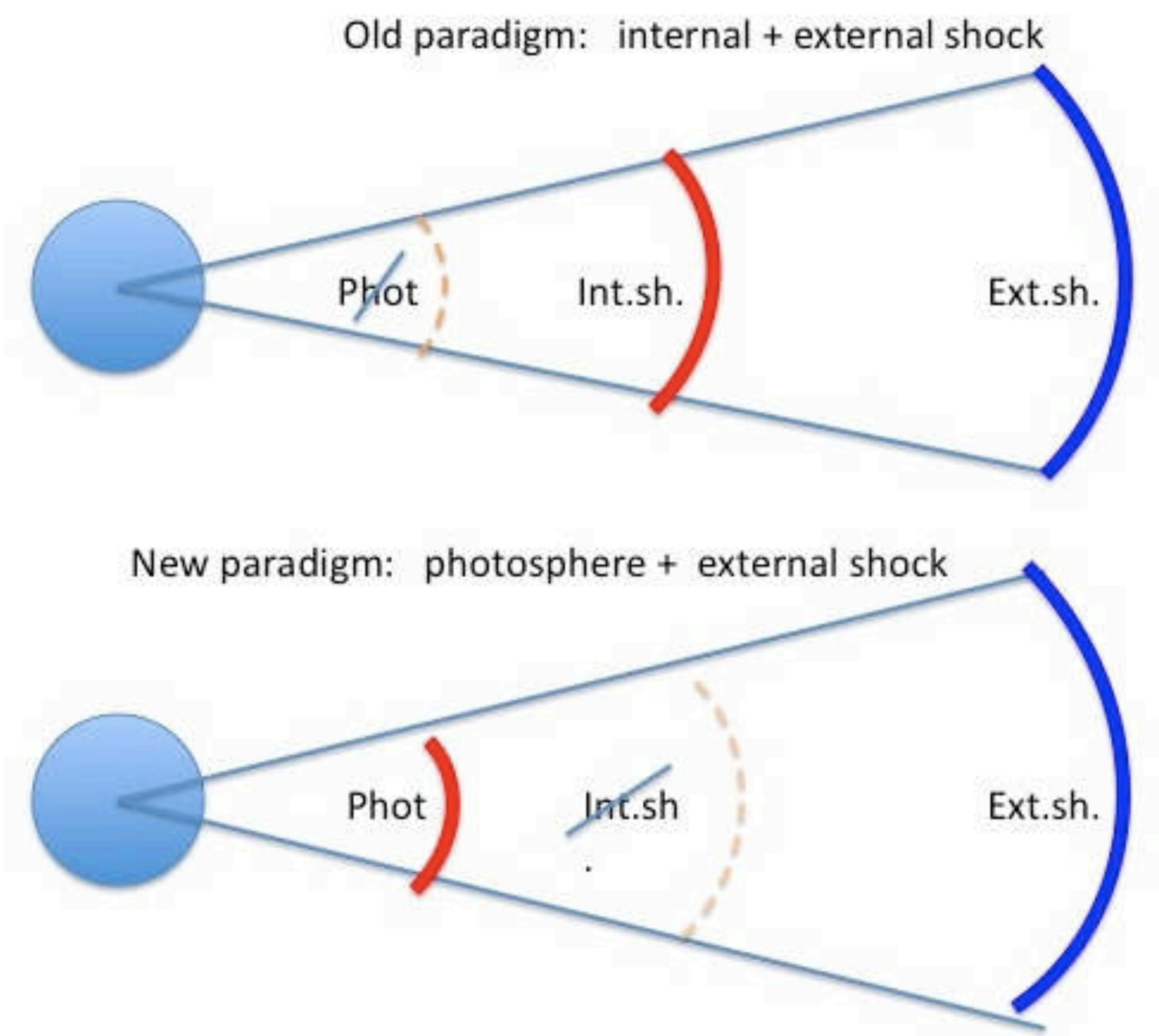
**(← Hümmer et al,** '11, PRL 108:231101**)**

(Also:
Li, '12, PRD 85:027301 ;
He, et al '12, ApJ 752:29)

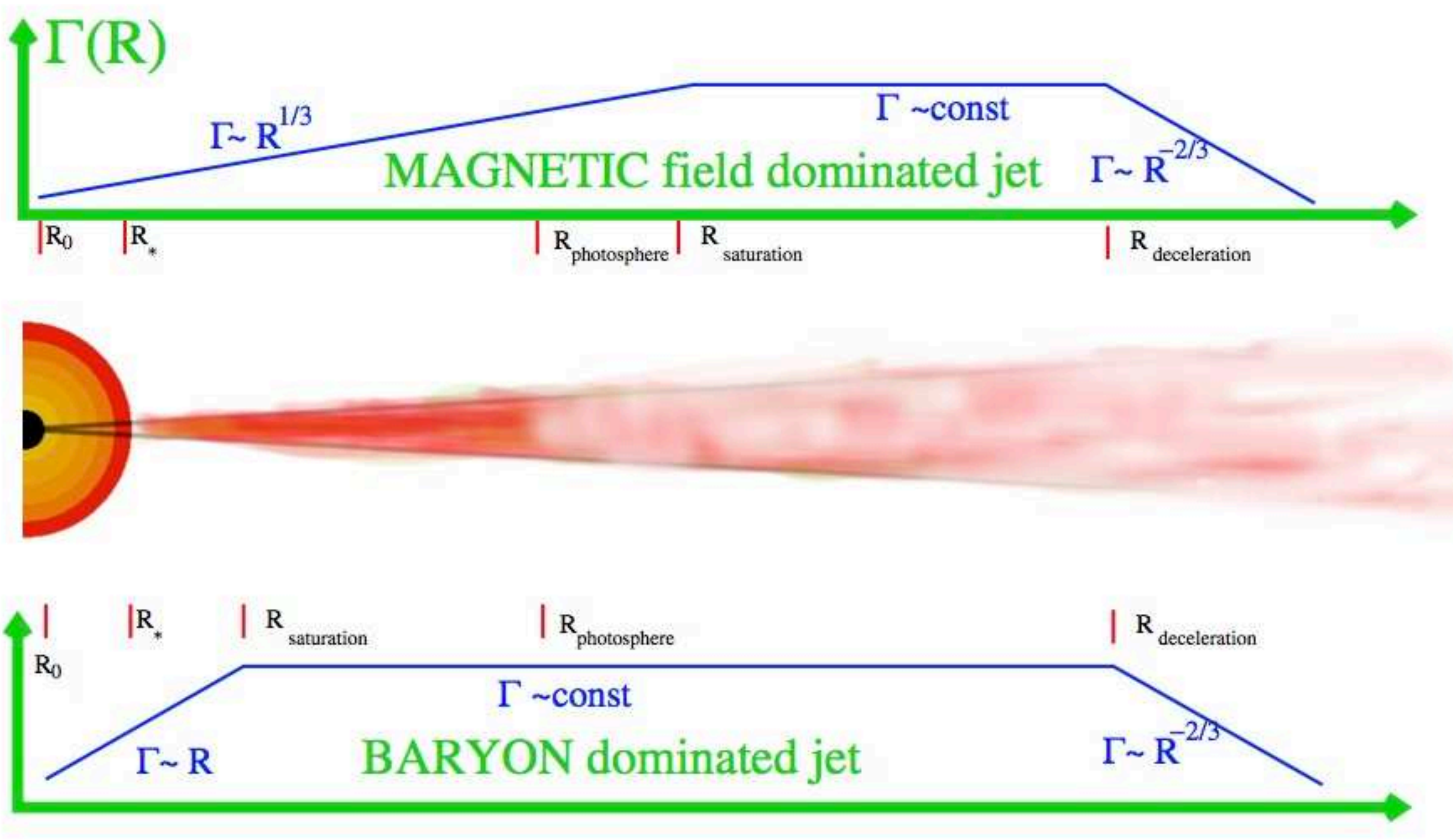
# ***Furthermore, note that .....***

- Internal shock model is ***expedient***: it is the best documented so far, and easy to calculate $\Rightarrow$ its use is ***widespread***
- ***But*** ... int. shocks known (past 10 years) to have ***difficulties*** for gamma-ray phenomenology (efficiency, spectrum, etc)
- ***And***, acceleration rate of ***protons vs. electrons*** is unknown; are protons injected into accel. process at $=$ or $\neq$ rate as electrons? Only energy restriction on model is $L_p/L_e \lesssim 10$.
- ***Even*** if GRB are ***not*** GZK sources, model indep. searches leave the interesting possibility of ***lower, but observable*** neutrino fluxes from GRB
- **AND:** ***Alternatives to int. shock*** are being investigated (less easy to calculate; e.g. ***photospheric & hadronic*** models)

# Photospheric & internal shock GRB models

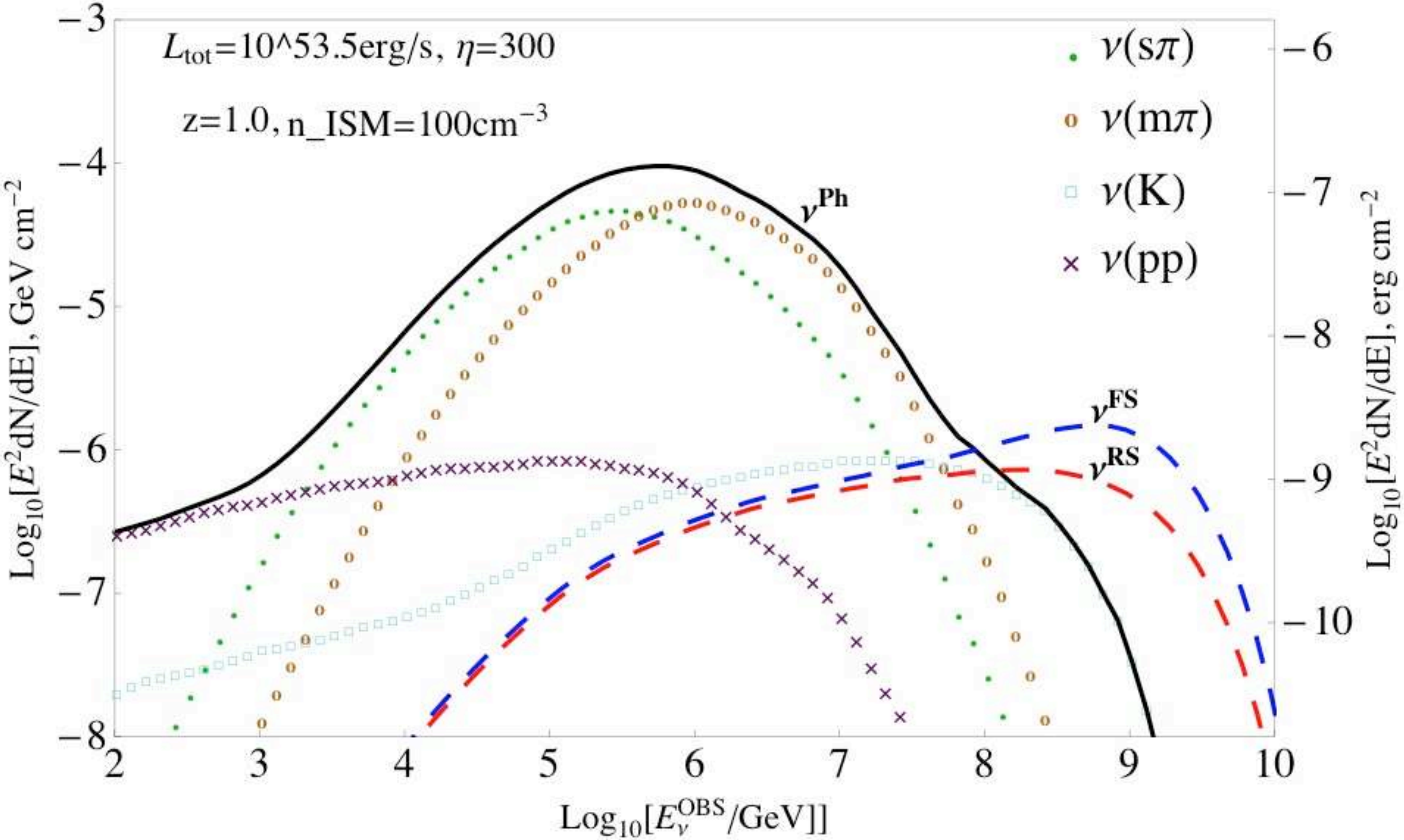


# Other GRB dynamics subtlety:

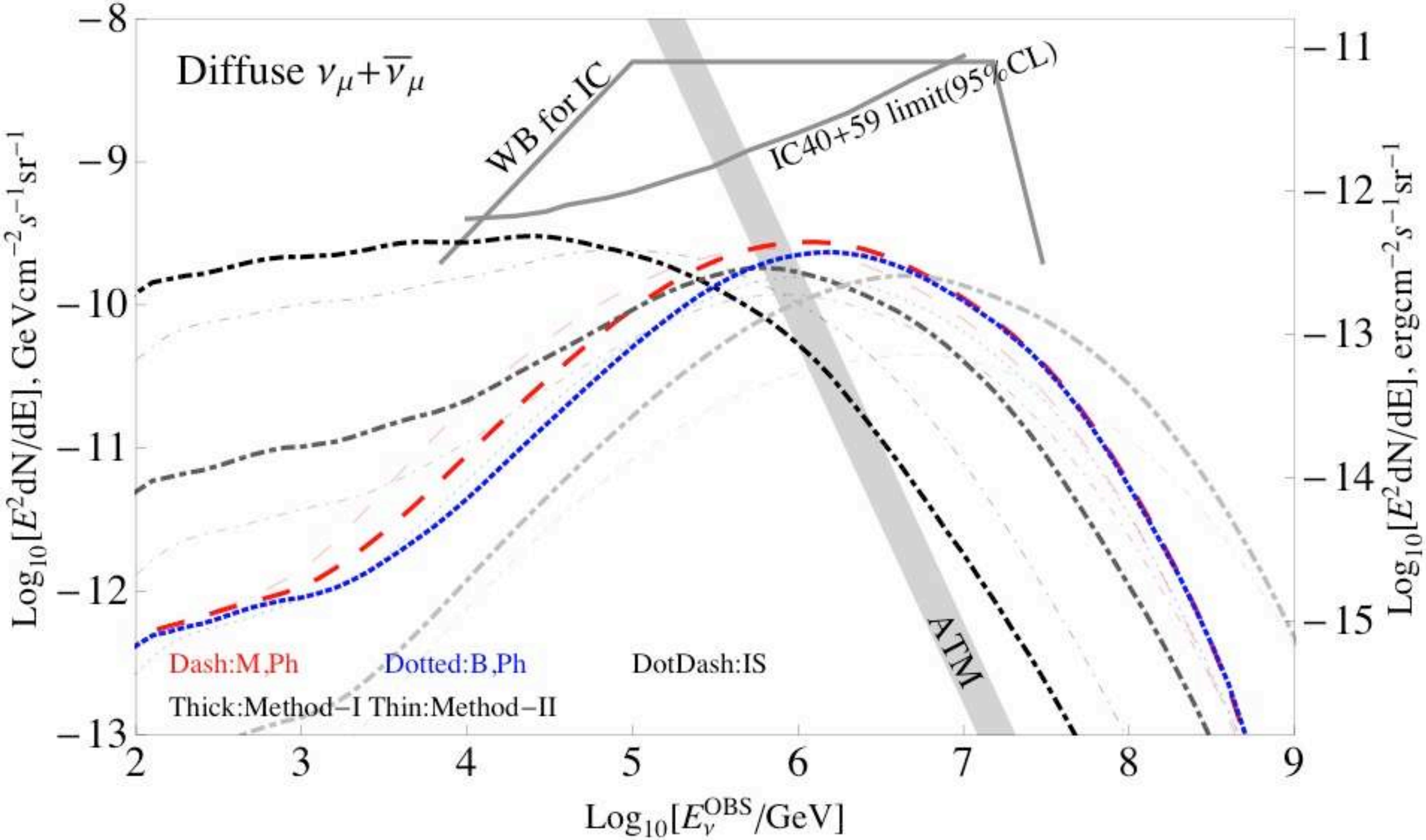


# $\nu_\mu$ from magn.dissip.phot. + ext.sh.

Gao, Asano, Mészáros '12, JCAP 11:058



# Diffuse nu from MPh, Bph, IS, η=300 & IC3 lim.




Gao, Asano, Mészáros ’12, JCAP 11:058

# Recent IC3 results on IS& Phot. GRB



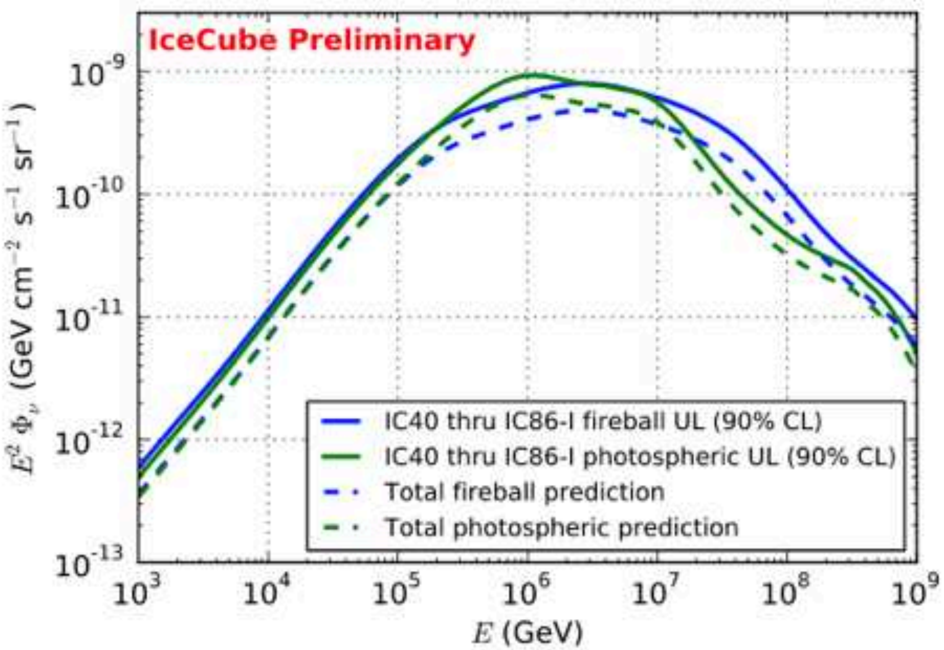



**Figure 3**: Fireball and photospheric model quasi-diffuse flux predictions and 90% CL upper limits from the combined analysis of four years of IceCube data. Full systematic treatment is deferred to a later publication, so these limits include an assumed 6% systematic uncertainty, which is the estimated uncertainty in the most recently published analysis. The fireball and photospheric model limits are 1.72 and 1.47 times the model predictions, respectively, so these models are not yet constrained by our results.

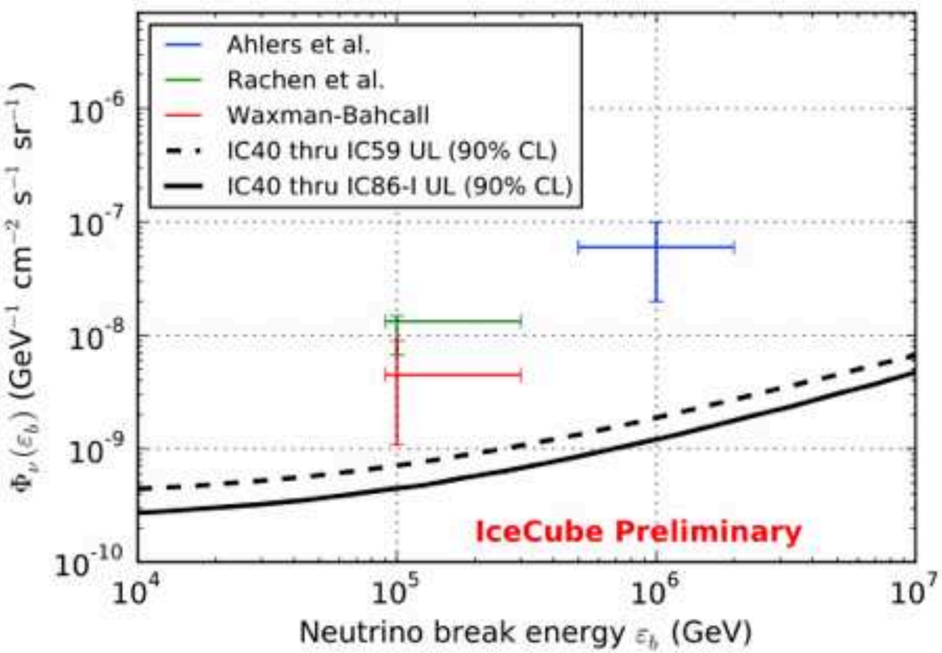



**Figure 4**: Compatibility of some models [20, 21, 22] of cosmic-ray-normalized neutrino fluxes with observations. The 90% CL upper limits from the published IC40+IC59 analysis [2] as well as the new four year analysis are shown in comparison with some model predictions indicated as points with error bars. Without modification, these models are excluded by our results.

# What about nus from "nearby monster" GRB 130427A?

- At z=0.34 and $L_{iso}$ ~$2x10^{54}$ erg, ***GRB130427A*** was expected to be ***best*** candidate for nu-detection
- ***But,*** IceCube : ***No Detection***! (GCN 14520)
- Is this ***suprising***?
- At least 2 reasons ***why not:***

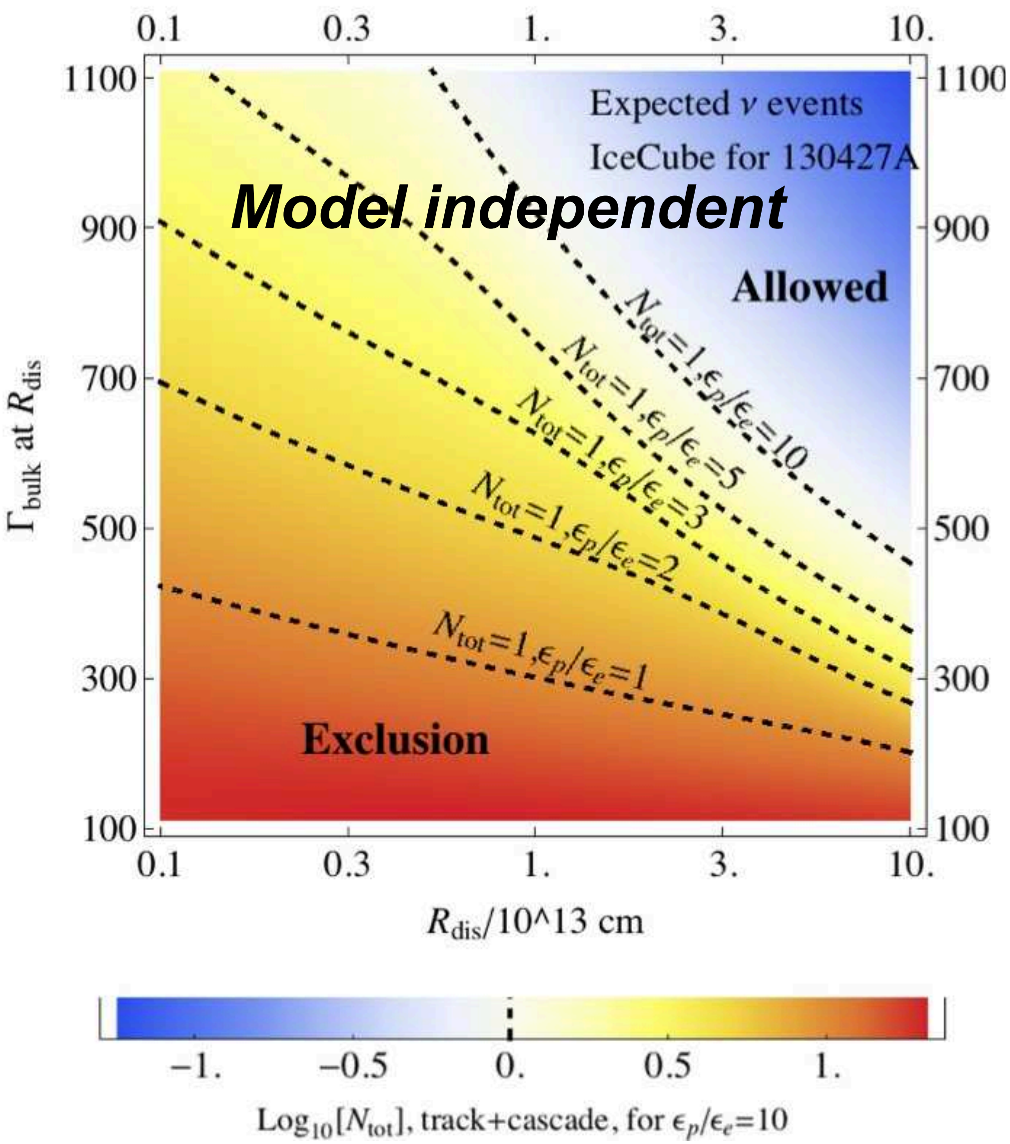
1. Expect no ν-detection in ***standard int. shock*** for this GRB (in IC40+59)
2. Expect no ν-detection in ***one out of two*** other '***non-standard***' models for this GRB (in IC40+59)

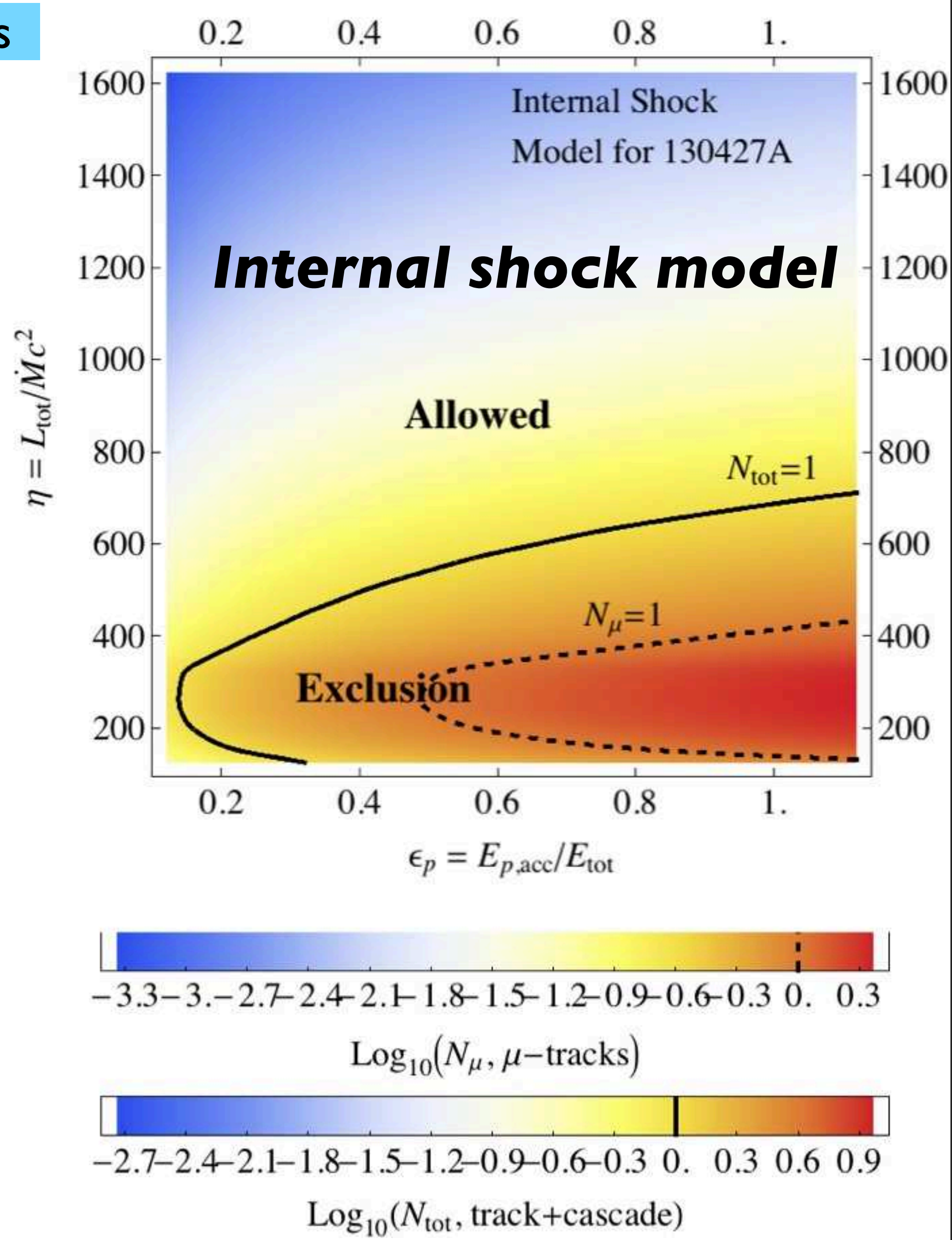
# Back to GRB 130427A: nus?

("Best", brigtest, nearest single candidate)

Gao, Kashiyama, Mészáros 2013, ApJ, 772:L4

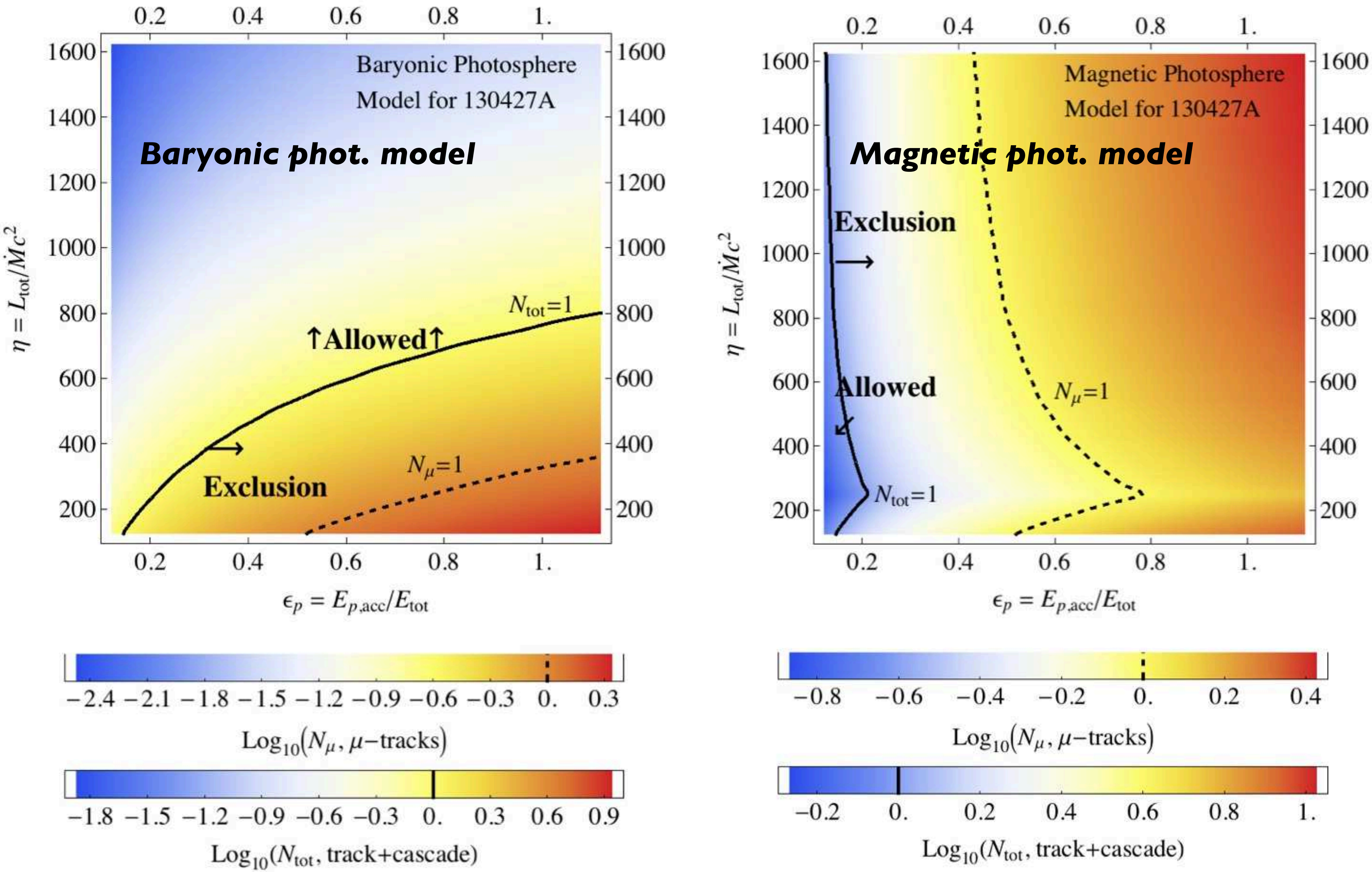
Calc. ULs using all recent corrections to physics



# 130427A baryonic & magnetic photosph. model

Gao, Kashiyama, Mészáros 2013, ApJ, 772:L4



# That is:

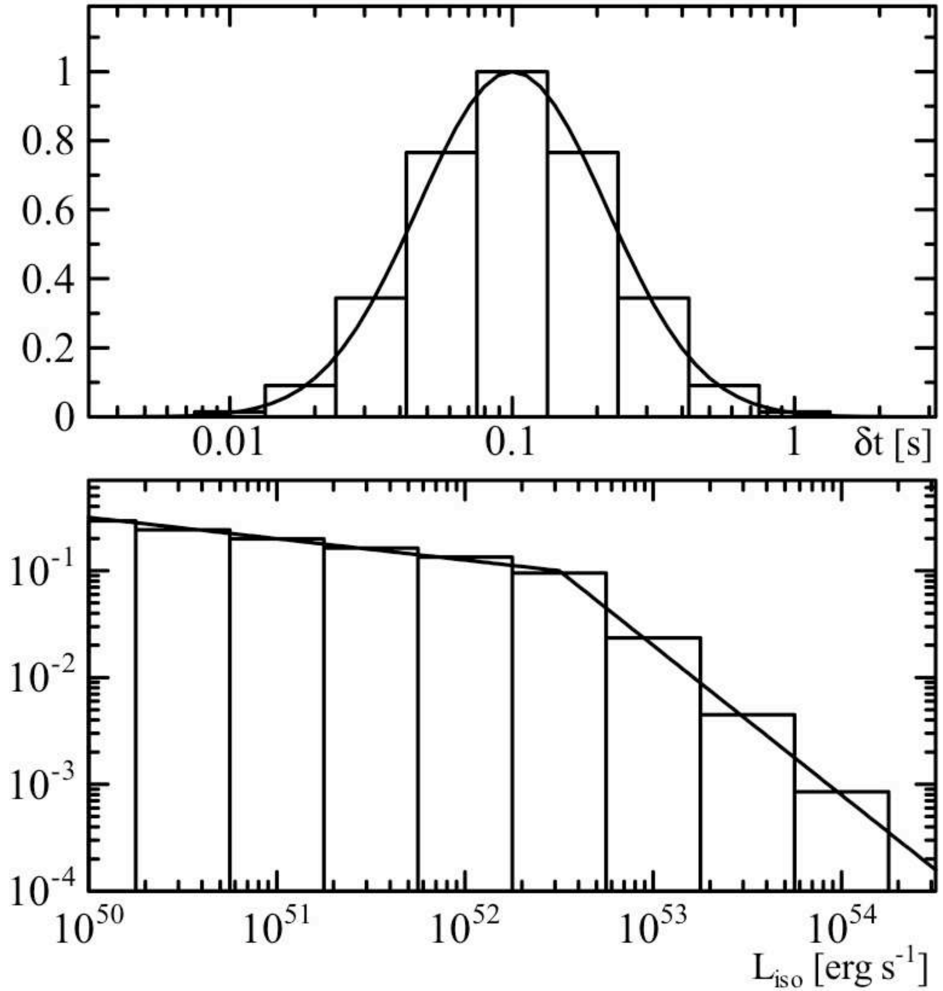
- IceCube neutrino ULs on the diffuse nu-bkg ***do not constrain*** the (fixed radius, i.e. ***steady state) IS model*** so far; will need several more years to get near the ULs
- IceCube ULs on GRB130427A ***do not*** constrain ***either*** the ***IS*** or ***baryonic phot.*** models, but ***do*** constrain ***mag. phot.*** model
- Will need consider better, time-dep models incl. effects of pair formation for model fits

# *A more accurate Internal Shock GRB CR/nu calculation:*

- All previous GRB neutrino/CR calculations were ***time-independent*** (steady-state)
- Now can go ***one better*** on that, and do ***time-dependent***

# Time-dependent CR escape, gamma-rays & neutrinos

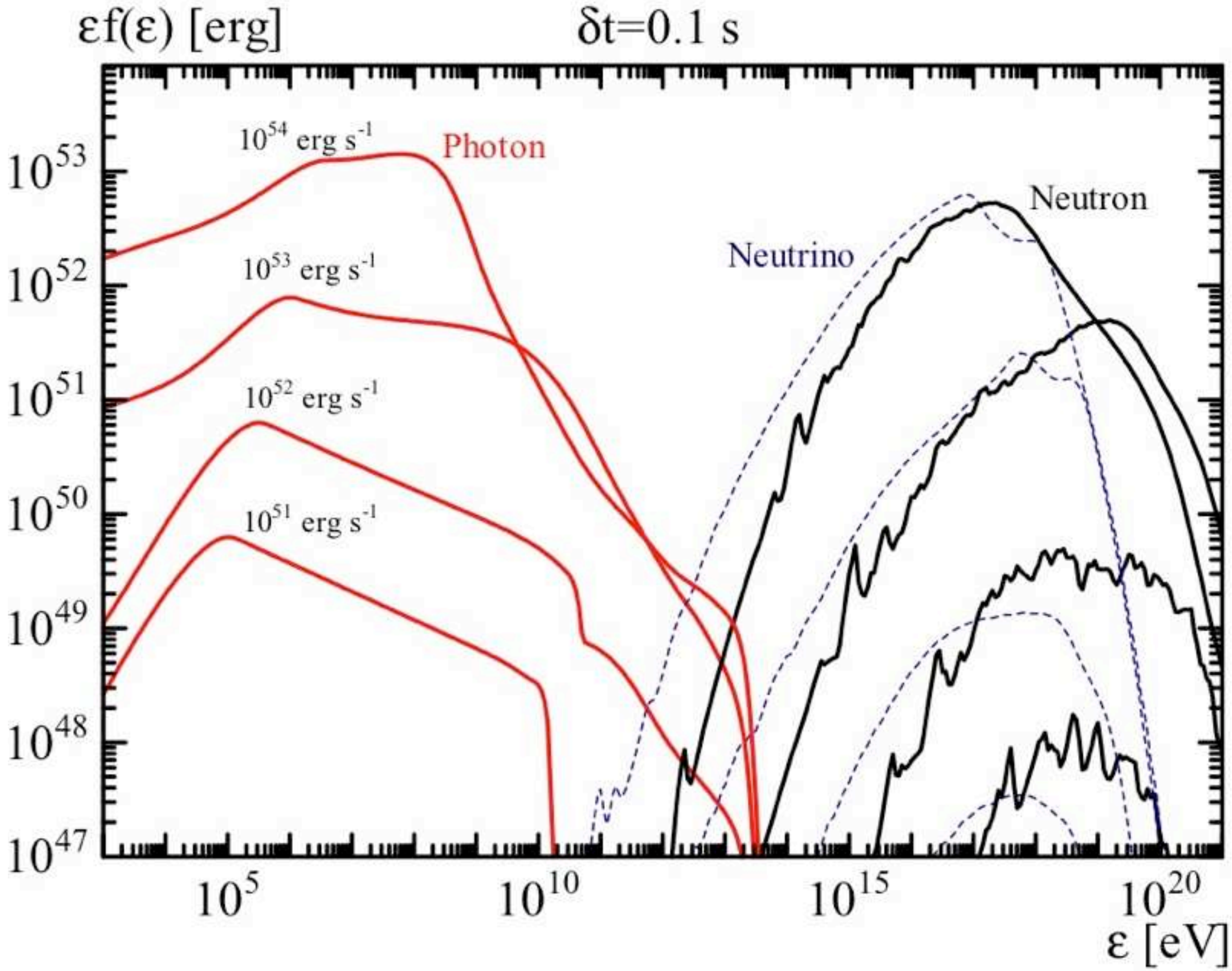
Asano & Mészáros, ApJ acc., arX:1402.6057




- Assume Internal Shock model ***but*** allow for shell motion and expansion, over $R_0$ - $30R_0$.
- Use Nakar-Piran'02 variab. time distrib, and Wanderman-Piran'10 Lum. distrib., z<6
- Initial radius R0 dep. on δt; ph. sp. assumed Band, obeying $E_p$-$L_{iso}$ Yonetoku-Nava relatn.
- Inject protons $E^{-2}$ spectrum, $\Gamma$=300, $f_p$=10 as benchmark
- MC cascades, 2 cases: neutron conversion and sudden release

# Spectra at source

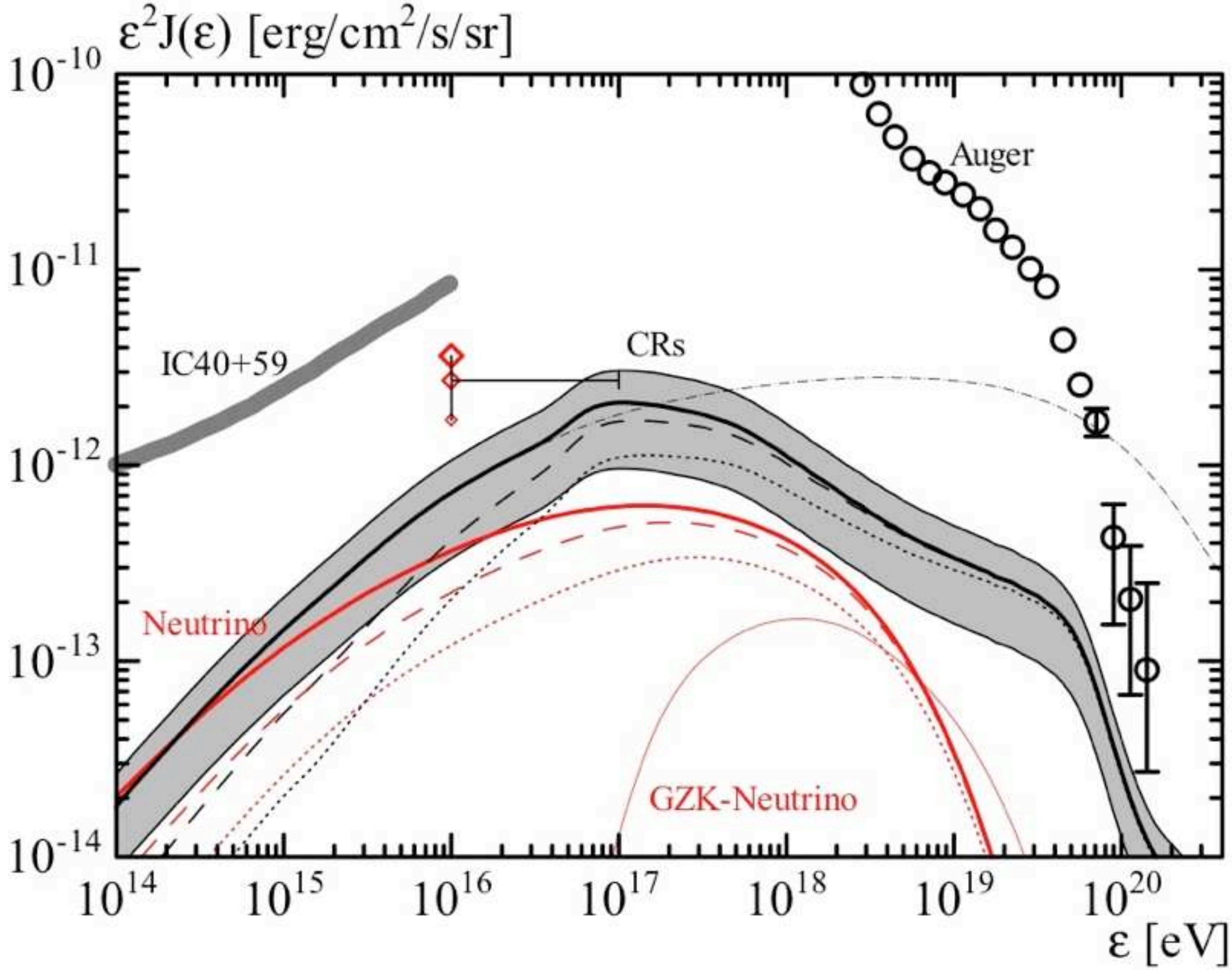
Asano & Mészáros, ApJ acc., arX:1402.6057




- Time integrated spectra from one shell (at source)
- Shown for δt=0.1 s and various lumin, for theneutron conversion model
- Blue is $\nu_\mu + \nu_e$ and their anti-flavors, before oscillation

# CR + nu Diffuse Bkg

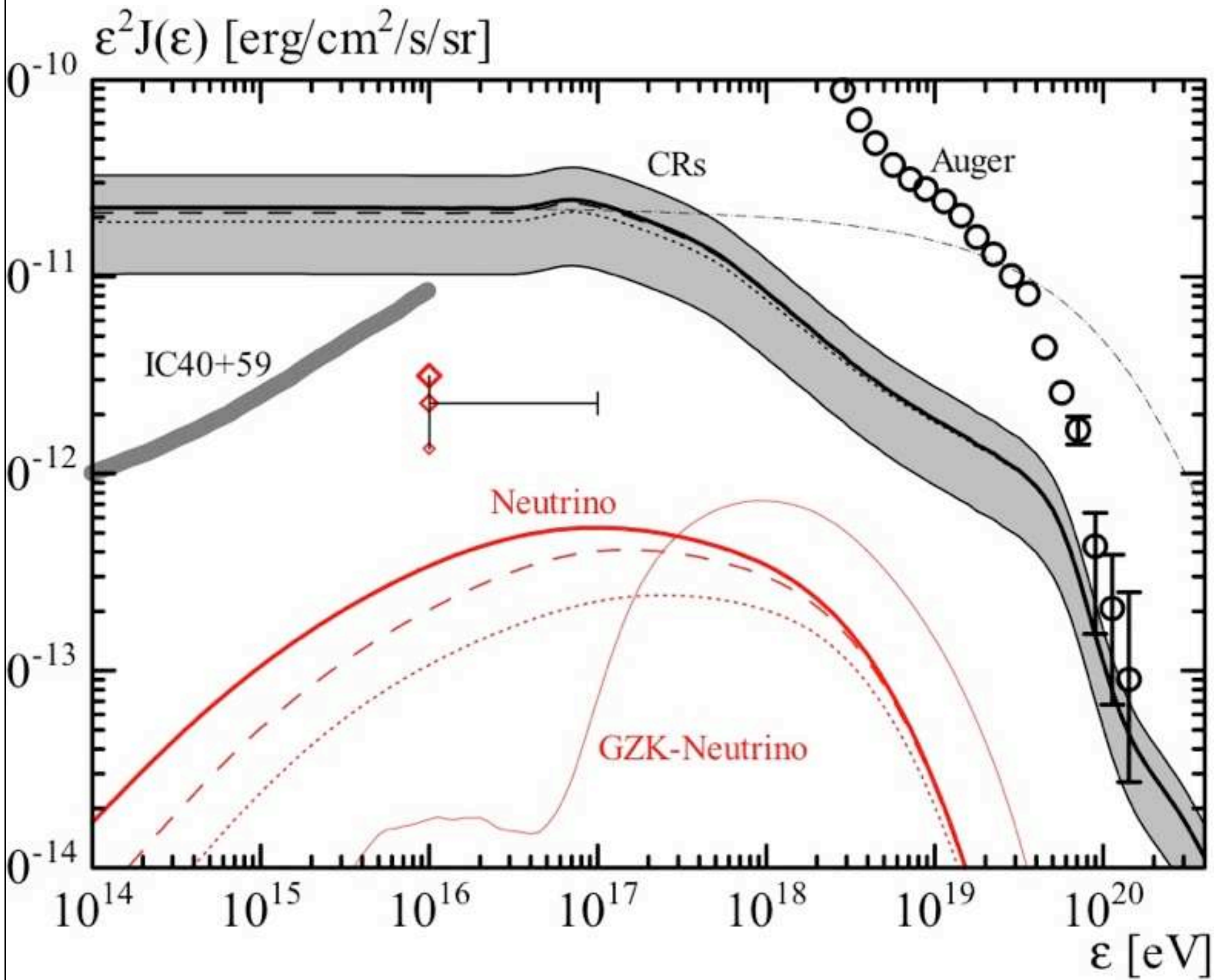
Asano & Mészáros, ApJ acc., arX:1402.6057




- Diffuse CR (black) and $\nu_\mu$+anti-$\nu_\mu$ (red, after osc) for ***neutron conversion model.***
- Thin dash-dot: CR w/o photomeson & BetheH ; Dash(dot): CR/$\nu$ w/o GRB L >$10^{54}$($10^{53.5}$)erg/s
- Thin red: cosmogenic nu
- Gray thick: IC3 40+59 diffuse UL for brokenPL
- Diamond: our integrated flux assuming broken PL & uncert. break range

# CR + nu Diffuse Bkg

Asano & Mészáros, ApJ acc., arX:1402.6057




- Diffuse CR (black) and $\nu_\mu$+anti-$\nu_\mu$ (red, after osc) for ***sudden release model.***
- Thin dash-dot: CR w/o photomeson and BH ; Dash(dot): CR/ν w/o GRB L >$10^{54}$($10^{53.5}$)erg/s
- Thin red: cosmogenic nu
- Gray thick: IC3 40+59 diffuse UL for brokenPL
- Diamond: our integrated flux assuming broken PL & uncert. break range

# *In other words:*

- IceCube neutrino ULs on the diffuse nu-bkg ***do not*** constrain the ***GRB IS model*** so far; will need several years to get near the ULs
- IceCube ***does not*** constrain the GRB IS model's ability to produce $10^{19}$-$10^{21}$ eV UHECR
- Even moderate $L \sim 10^{53}$ erg/s GRBs with $f_p \sim 10$ are able to explain GZK CRs (***but*** below the ankle need other sources- known this for long)
- Thus, GRBs ***do not*** explain the diffuse PeV nus
- But GRBs ***may contribute*** significantly to the observed flux of ***$10^{19}$-$10^{21}$ eV UHECR***

More recently,

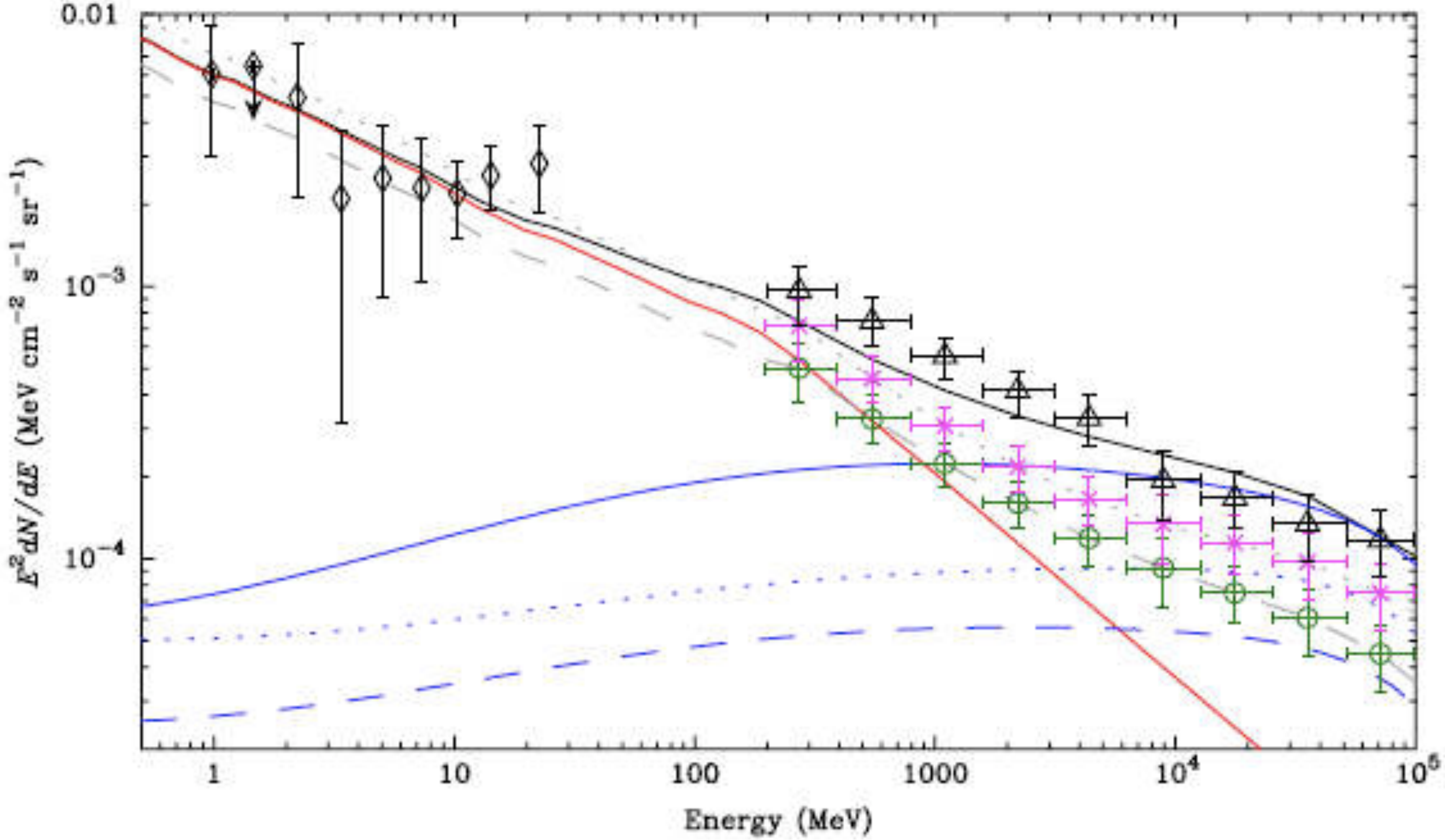
***late 2013: ICECUBE announced***

# The first detection of "certified" astrophysical neutrinos

# The PeV ***INB-IGB*** Connection: GRBs? AGNs? SFGs? HNe? GMSs?

- ***PeV nu INB*** obs. by IC3 is ~$10^{-8}$ GeV/cm$^2$/s/sr, but ***IC3 limit*** on GRB nus is factor ~10 below ( "standard" IS or photosphere- ICRC13) → could be ***EM dim/nu-bright GRBs***? ( Liu & Wang 13, ApJ 766:73, Murase & Ioka, 13, PRL 111:121102)
- ***PeV nu INB*** from hadronic ***low lum. AGNs***: scaling $L_p$ from $L_e$ via $L_{phot}$, , argue that ***FR1 RG***s (higher density knots) ~ reproduce via ***pp*** the PeV nu bkg (Becker Tjus+, arXiv:1406.0506) → ***also IGB?***
- ***PeV nus*** from individual ***bright*** radio-gamma AGNs (***blazars*** in TANAMI sample), interpreting X-γ flux as due to ***pγ*** photohadronic interactions, conclude that 6 of these blazars within 1σ error box of the three PeV events could account for the ***INB*** (Krauss, et al, 1406.0645) →***IGB?***
- Starburst galaxies (***SBGs***), if responsible for PeV nu ***INB*** via ***pp,*** can contribute ~***20%*** of the gamma background (***IGB***) (Chang et al, 1406.1099)

# IGB (Fermi) & resolved sources

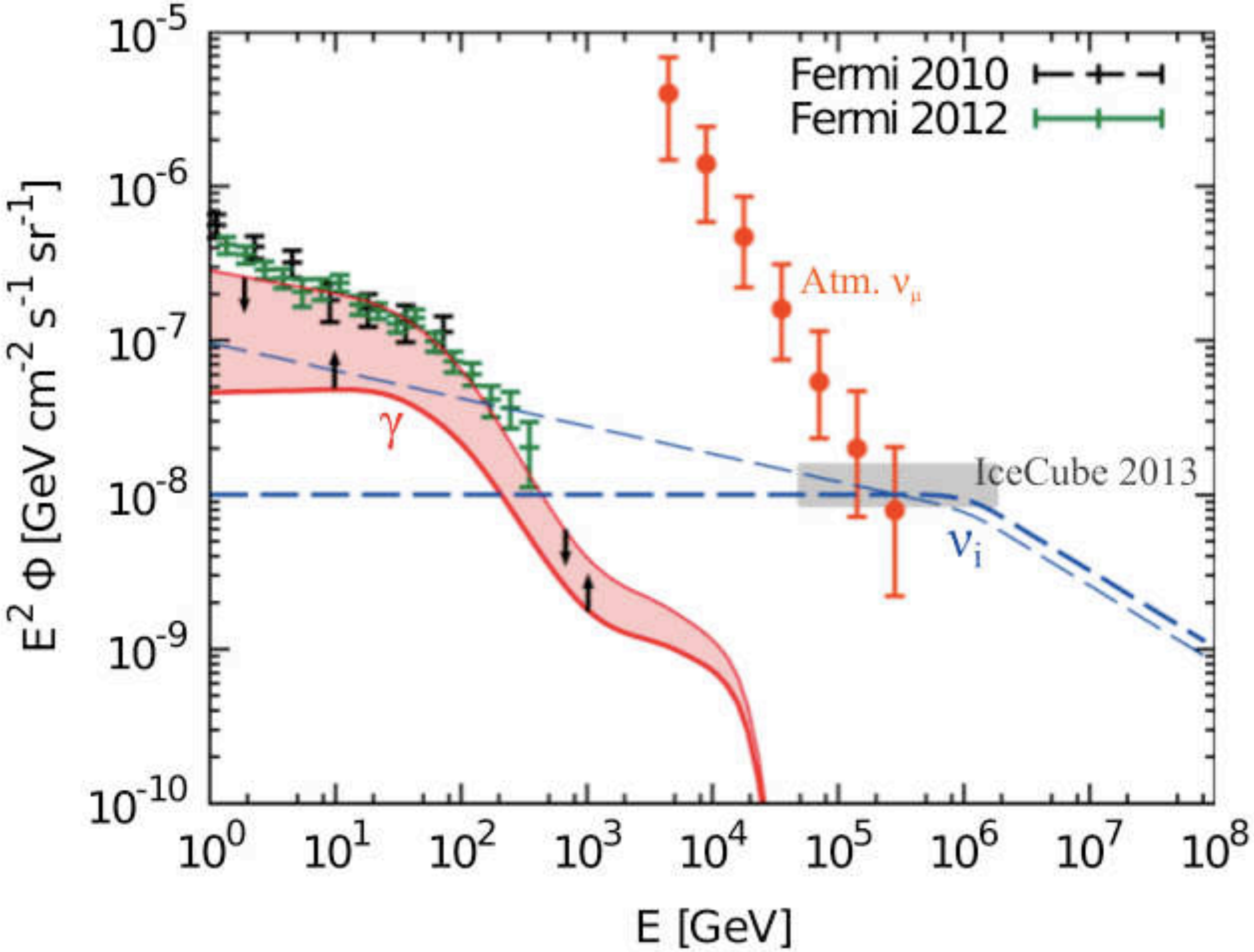



Abazajian+11,
PRD 84:103007

- Black triangle: Fermi IGB spectrum, Abdo+2010, PRL 104:101101
- Red line: FSRQ, blue line: BL Lac contributions
- Magenta star/green circle: upper/lower 95% CL forecast of Fermi-LAT 95% CL 5 year sensitivity

# INB & IGB from pp sources

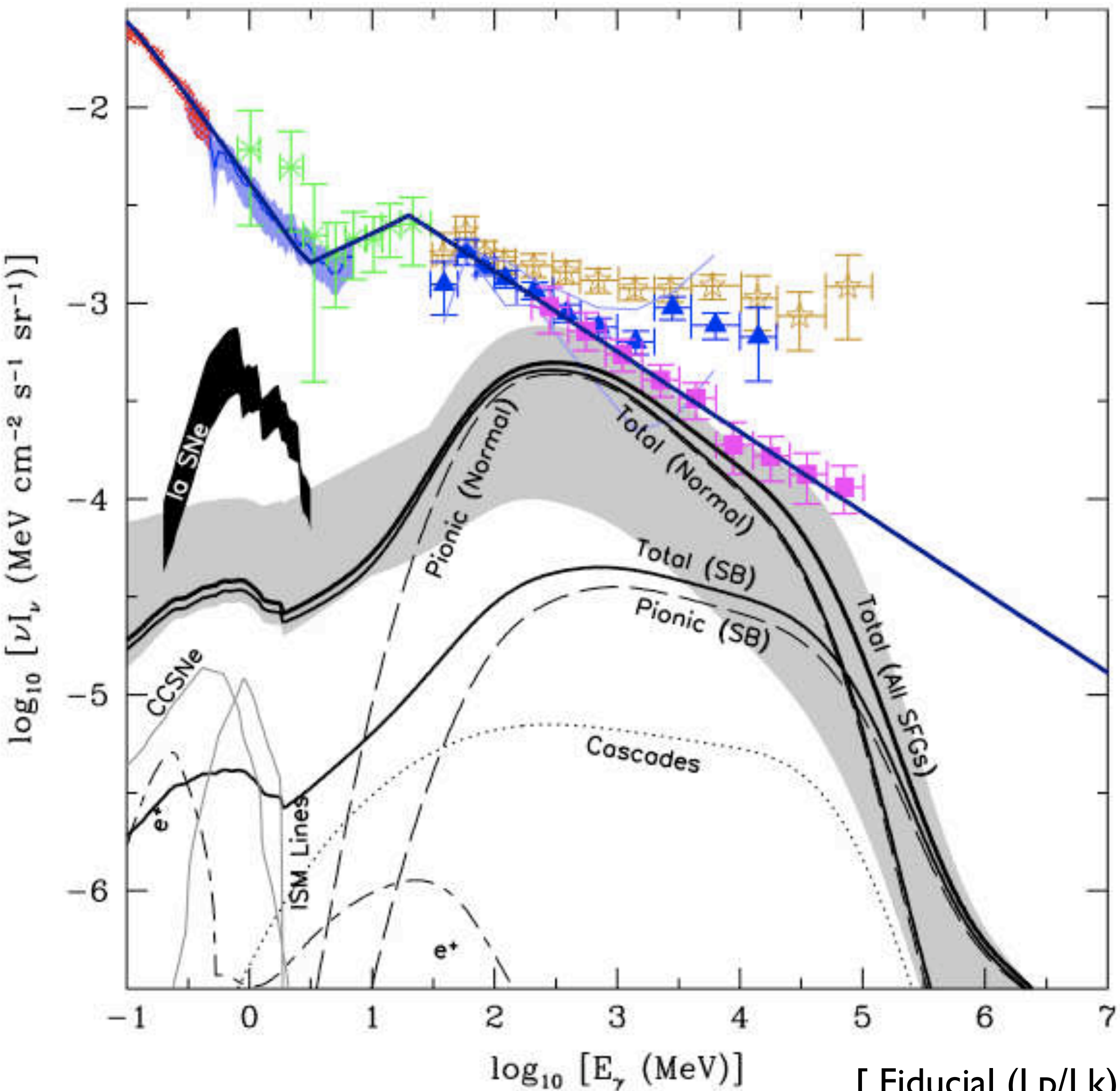
Murase, Ahlers, Lacki 13
PRD 88, 121301




See also He+13, PRD 87:063011, Liu+14, PRD 89:083004, Tamborra+, 1404.1189, Chang & Wang, 1406.1099, Kashiyama & Mészáros, 1405.3262

- Stress pp vs. p$\gamma$ because no >>GeV threshold
- Use IC3 det. of PeV $\nu$s, consider $\pi^\pm \rightarrow \nu$ DNG & $\pi^0 \rightarrow 2\gamma$ IGB & satisfy Fermi/LAT bound, also lack of Glashow reson.
- Conclude $\Gamma_p$ ~2.0-2.18 with cutoff <3-4 GeV ✔
- Sources could be galaxy cluster shocks (IGS) or SFG/SBG - cutoff may be $t_{diff}$ ~$t_{inj}$ (or $t_{diff}$ ~$t_{pp}$,$t_{adv}$ )

# SFG-SBG and the IGB



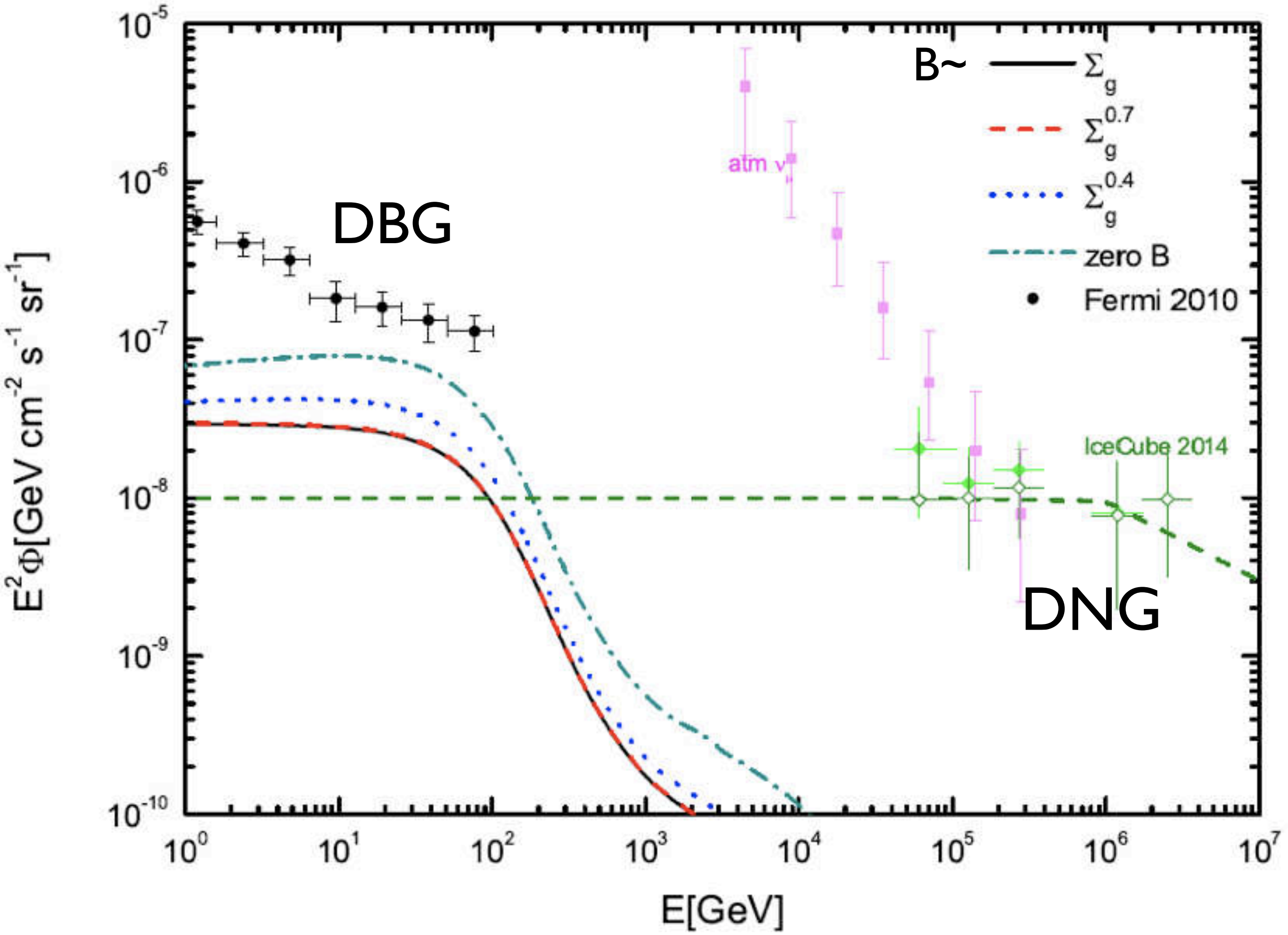

Lacki+14, apj 786:40

- Red: CXB; blue: SMM: green X: COMPTEL, gold star: EGRET, blue triangle: EGR error est; magenta square: Fermi
- Black line: total γ IGB (i) from SFG (normal) & (ii) from SBG (SB), inc. $\pi^{\pm}$ (pionic bump), etc. Gray shade: uncertainty estimate of SF IGB
- One-zone leaky box CR evolution, input from SNR α SFR, PL injection $E_{p,max}$ ~PeV, $E_{e,max}$ ~TeV, w. diffusive & γγ losses, constrain by GHz radio

[ Fiducial (Lp/Lk)snr=0.1, SBG/SFG=0.15 (0.8, 0.05) ]

# SBG & IGB - host sy losses

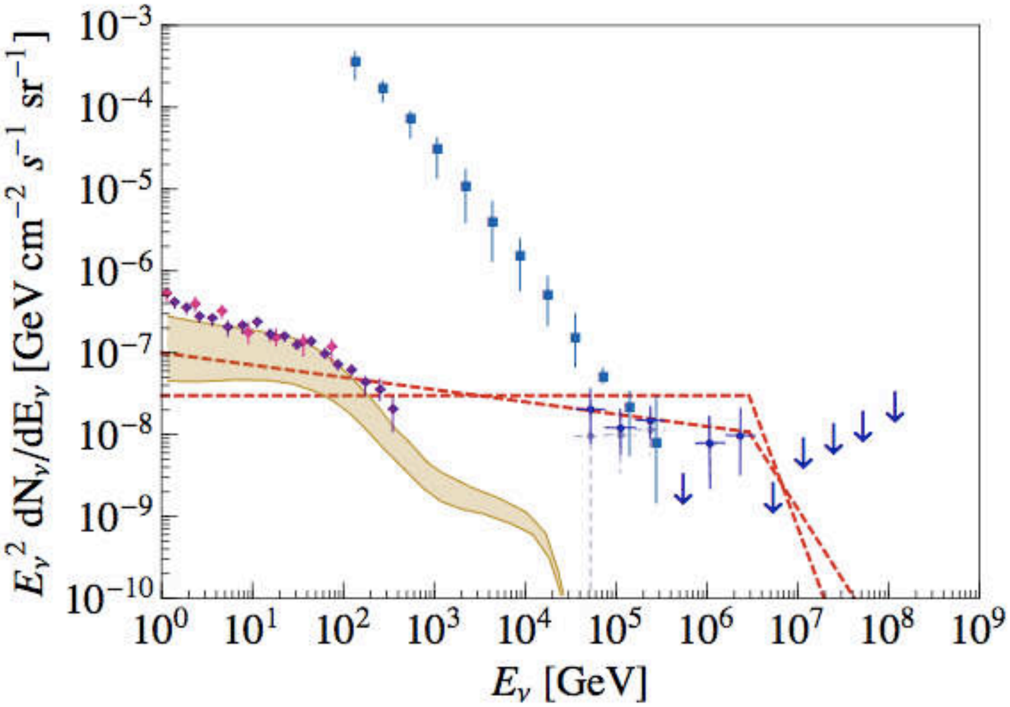
Chang & Wang, 1406.1988

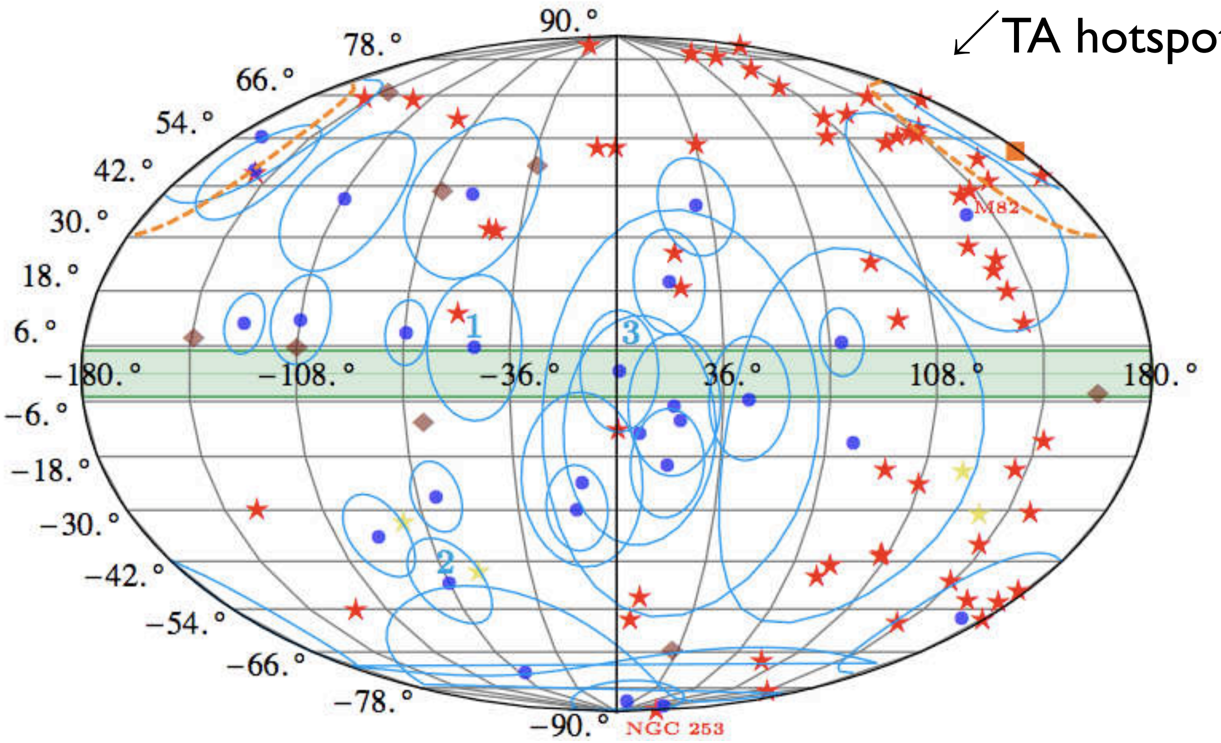



- Calibrate $\pi^0 \to 2\gamma$ flux using IC3 PeV nu obs. flux,
- Assume due to SBG
- Inside host galaxy , consider $\gamma\gamma$ casc. of primary $\pi^0$ & $\pi^\pm$ IC upscatt. photons.
- If ***no*** sync. losses, $\Phi_{\gamma,casc} \sim 0.5\ \Phi_{\gamma,dbg}$
- If incl. sync.losses inside host SBG (B~mG) then $\boldsymbol{\Phi_{\gamma,casc} \sim 0.2\ \Phi_{\gamma,igb}}$

However: if IGB & INB arise in less excited galaxies (e.g. SFGs), $B_{ism}$ may be smaller → the sy losses are smaller, and $\Phi_{\gamma,casc}$ larger

# INB, IGB & SFGs

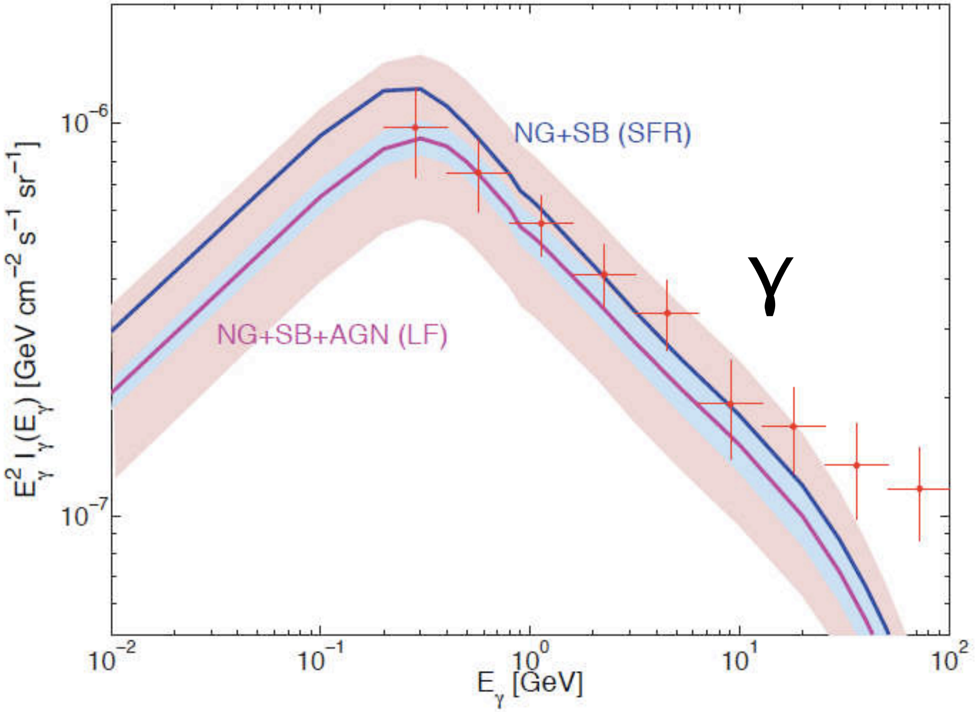


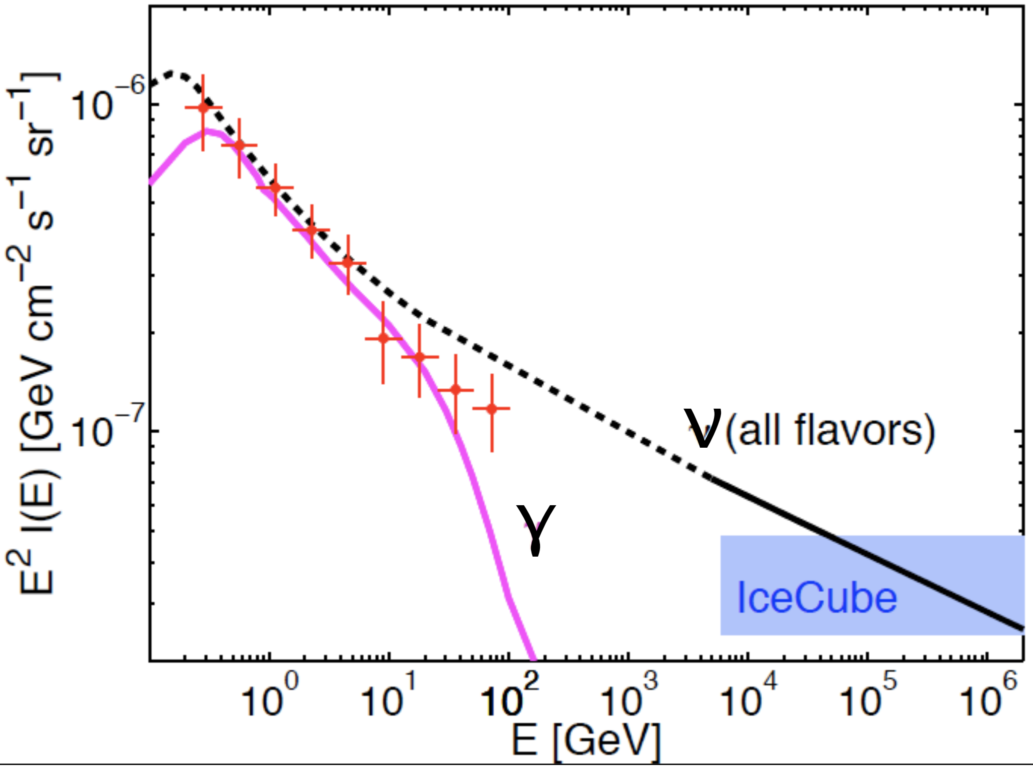




↙TA hotspot

Anchordoqui+14, 1405.7648

- Consider straight π±→ν DNG & π0→2γ IGB, so that spectrum does not violate Glashow ✔
- Check location of showers (circles) and tracks (♦) and known SFGs
- M82, NGC253, NGC4945, SMC, IRAS18293 "corr" w. showers - but no tracks .
- Will need 10 yrs w. IC3, or a next gen. detector, to detect >5 track events which corr. with SFGs at > 99% CL



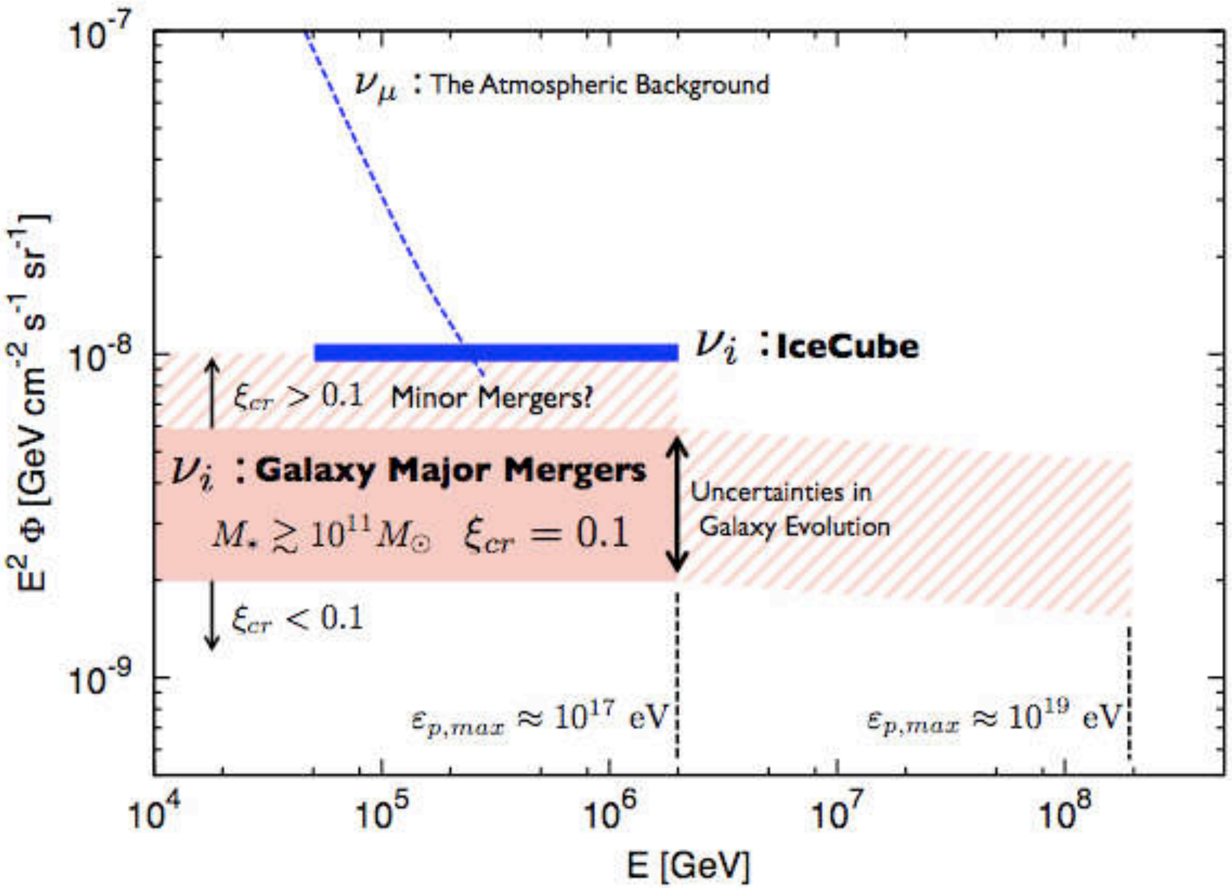

# IGB, INB & SFG, SBGs

Tamborra, Ando, Murase
1404.1189

- Use Fermi correl $L_\gamma \sim L_{fir}^{1.17}$ and Herschel PEP/herMES LumFcn of FIR bright gals to z~<4
- ↖Deduce can fit Fermi IGB
- Under same assumptions, find also that if 100 PeV CRs can be confined in host galaxies, ← can fit also IC3 PeV INB

# Galaxy mergers, INB & IGB

Kashiyama & Mészáros, 1405.3262




- ***Every galaxy*** merged at least ***once*** in the last ***Hubble time***
- ***Major mergers*** → $E_{gms} \sim 10^{58.5}$ erg, $R \sim 10\text{-}4$ Mpc$^{-3}$ Gyr$^{-1}$ $v_s \sim 10^{7.7}$ cm/s $Q_{cr,gms} \sim 3 \times 10^{44}$ erg Mpc$^{-3}$ yr$^{-1}$ $\varepsilon_{cr,max} \sim 10^{18.5}$ Z eV
- ***pp*** → PeV **ν**s, 100 GeV **γ**s
- **ν:** Indiv. GMS: 0.01 μ/yr, INB: ***20-60%*** IC3 obs.flux
- **γ**: Individual GMS flux: ~$3.10^{-13}$ erg/cm2/s, CTA? ***IGB*** ~$10^{-8}$ GeV/cm$^2$/s/sr , about ***10-30%*** Fermi IGB
- Minor mergers: uncertain, could add up to 70-100%

# Outlook & Issues

- ***Both in AGNs and GRBs, major question is whether basic emission is leptonic or hadronic - contribution to the observed CRs/UHECRs and PeV nus?***
- ***Location of the GeV(TeV) emission region (inner/outer jet, photosphere?) Role of (which?) target photon sources***
- ***Role of pair cascades in VHE spectrum formation***
- ***Do galaxy/cluster shocks and/or galaxy merger shocks contribute much (all?) of SFG/SBG VHE radiation?***
- ***Relative contribution of AGNs, SFG/SBG/GMS to the IGB and/or the INB? is pp, pγ or leptonic dominant in γ?***

# Outlook (continued)

- *The sources of the UHECR are still unknown..!*
- *They are almost certainly astrophysical sources (not TD)*
- *GRB remain good candidates, as well as AGNs, HNe, RQ, maybe MGRs.*
- *Will increasingly constrain such possibilities with GeV and TeV photon observations*
- *Will learn even more **if & when** astrophysical UHENUs are observed from any type of (individual) source*
- *Constraints from diffuse (and intrasource) γ-ray and nu emission will also be very useful, and may remain for a long time the main constraint*
- *Composition and clustering will provide important clues*