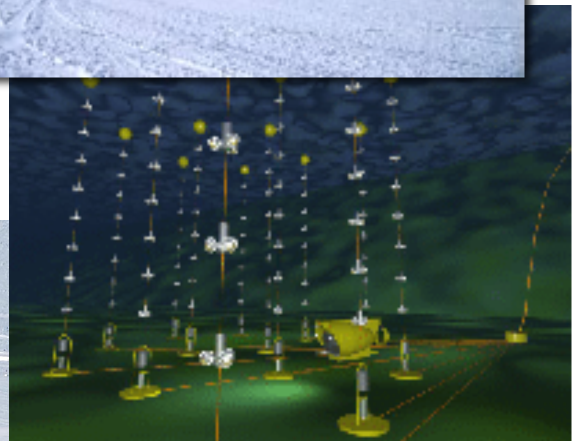
Seeing the high energy universe

Subir Sarkar

Lecture 2



UK HEP Young Experimentalists and Theorists Institute, IPPP Durham, 10-12 Jan 2010

Where there are high energy cosmic rays, there *must* also be neutrinos …

GZK interactions of extragalactic UHECRs on the CMB

“guaranteed” cosmogenic neutrino flux

➔ may be altered *significantly* if the primaries are not protons but heavy nuclei

UHECR candidate accelerators (AGN, GRBs, …)

“Waxman-Bahcall flux” … normalised to observed UHECR flux

➔ sensitive to ‘cross-over’ energy above which they dominate, also to composition

‘Top down’ sources (superheavy dark matter, topological defects)

motivated by trans-GZK events observed by AGASA

➔ all such models are now *ruled out* by new Auger limit on primary photons

It was proposed that UHECRs are produced *locally* in the Galactic halo from the decays of metastable supermassive dark matter particles

… produced at the end of inflation by the rapidly changing gravitational field

→ **energy spectrum** determined by QCD fragmentation
→ **composition** dominated by photons rather than nucleons
→ **anisotropy** due to our off-centre position

Simulation of galaxy halo (Stoehr *et al* 2003)

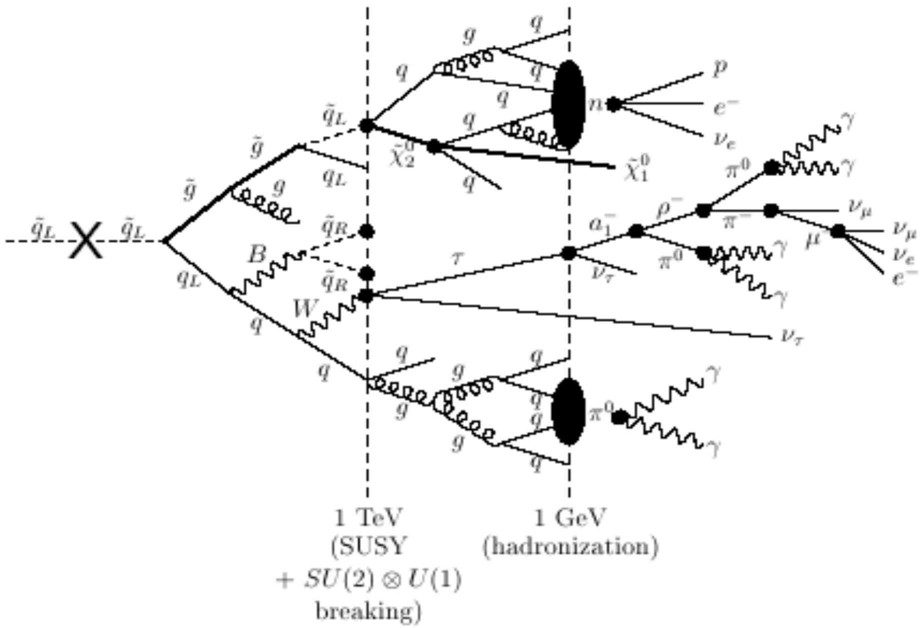
(Berezinsky, Kachelreiss & Vilenkin 1997; Birkel & Sarkar 1998)

Modelling SHDM (or TD) decay

Most of the energy is released as neutrinos with some photons and a few nucleons …

X → partons → jets (→ ~90% ν, 8% γ + 2% p+n)

(Barbot & Drees, AP 20:5,2003)



Perturbative evolution of parton cascade tracked using (SUSY) DGLAP equation … fragmentation modelled semi-empirically

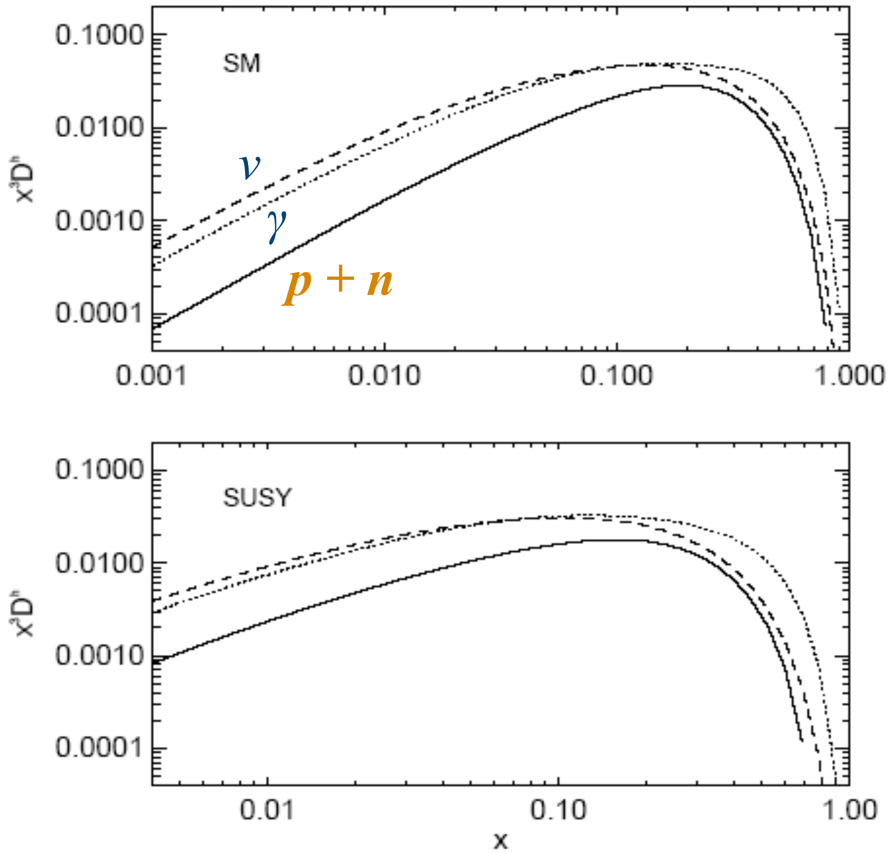
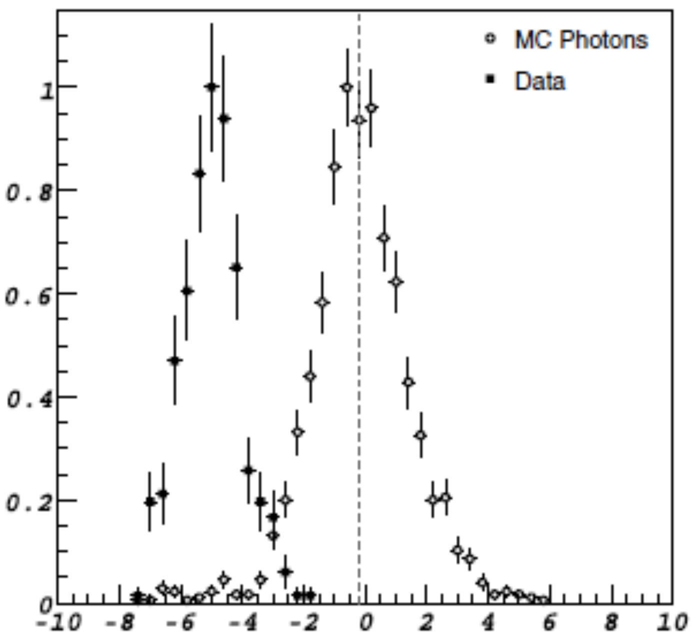


FIG. 6. Fragmentation functions for baryons (solid lines), photons (dotted lines) and neutrinos (dashed lines) evolved from M_Z up to $M_X = 10^{12}$ GeV for the SM (top panel) and for SUSY with $M_{\rm SUSY} = 400$ GeV (bottom panel).

(Toldra & Sarkar, NP B621:495,2002)

The fragmentation spectrum shape *matches* the AGASA data at trans-GZK energies … but *bad* fit to Auger

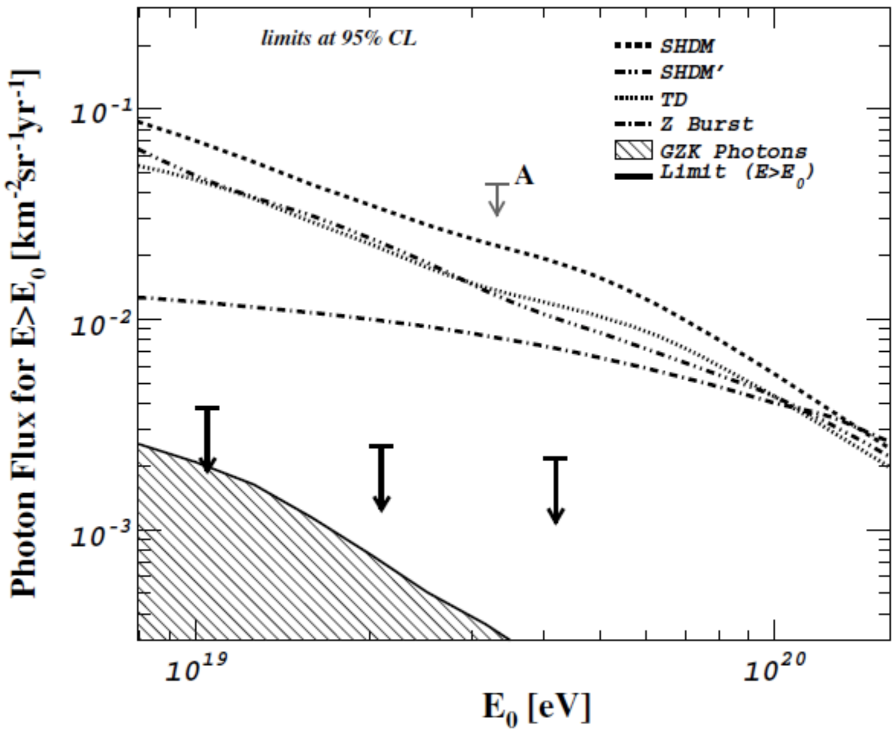
Such models are *falsifiable* … in fact now ruled out by photon limit from Auger!

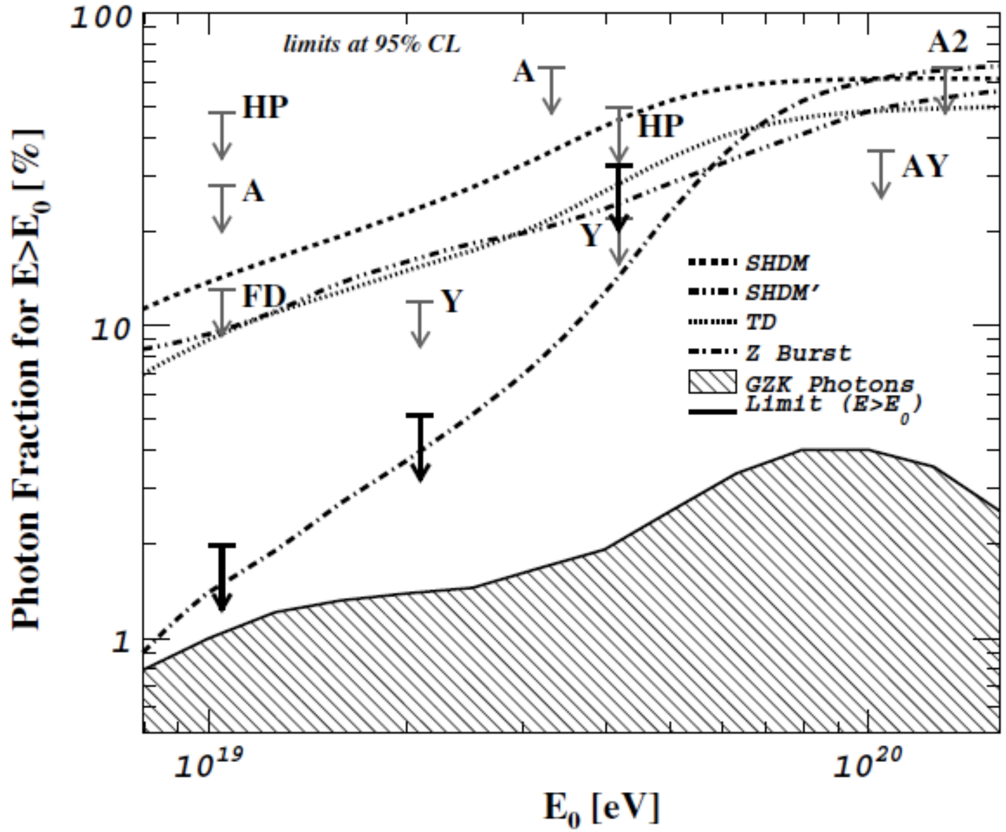


Auger has demonstrated that UHECRs are *not* photons … rules out ‘top down’ models of their origin

(AP 27:255,2007; 29:243,2008; 31:399,2009)

This also means that the large neutrino fluxes in such models are ruled out … we can rely only on astrophysical sources





The "guaranteed" cosmogenic neutrino flux

GZK mechanism :

$$p + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$$

$$n \rightarrow p + e^- + \bar{\nu}_e$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

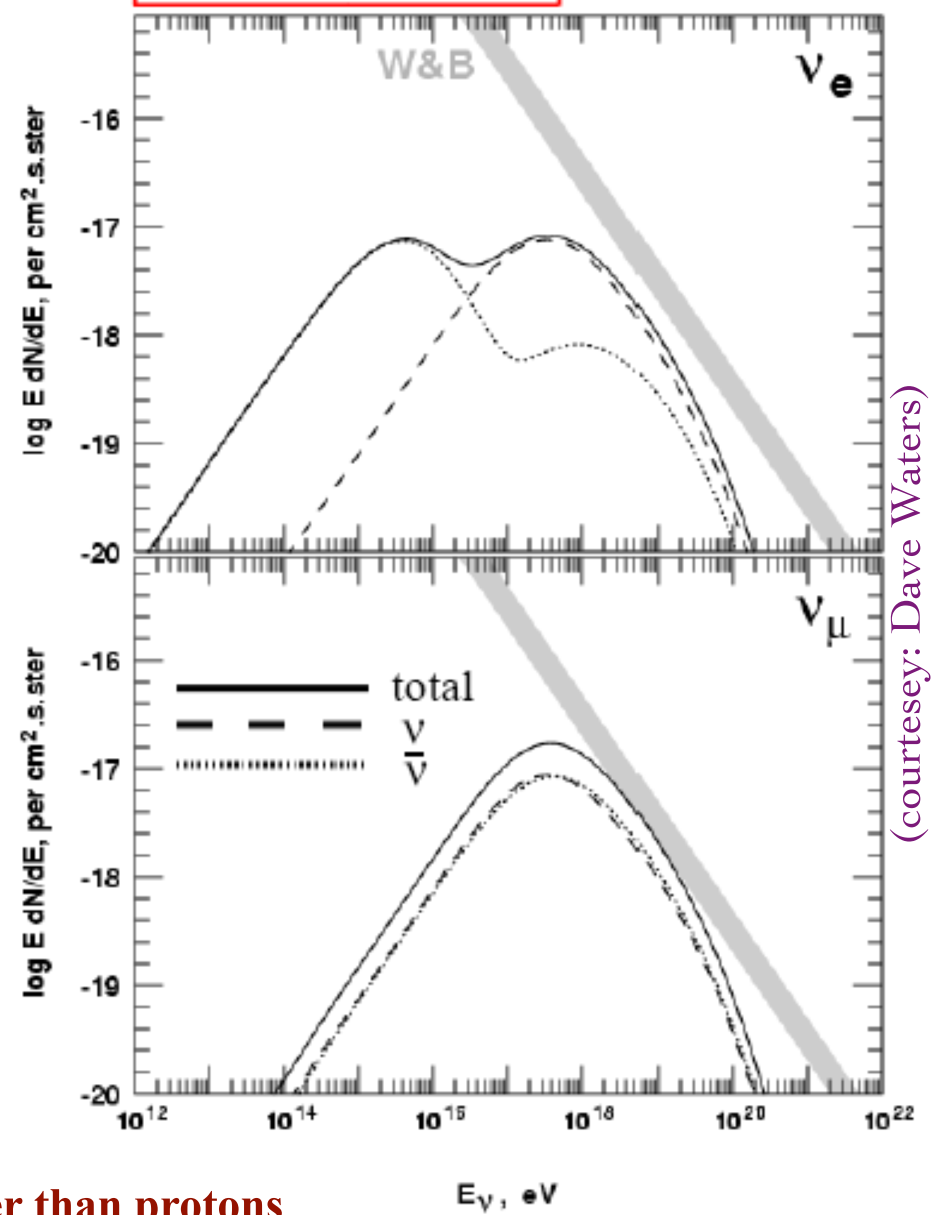
$E_{THRESH.} \sim 6 \times 10^{19}$ eV

- Uncertainties in flux calculations :
  - UHECR luminosity; ρ_{CR}(local) $\neq \langle\rho_{CR}\rangle$
  - injection spectrum
  - cosmological evolution of sources
  - IRB & optical density of sources

factors of ~2 uncertainty each;
factor of ~4 overall (?)

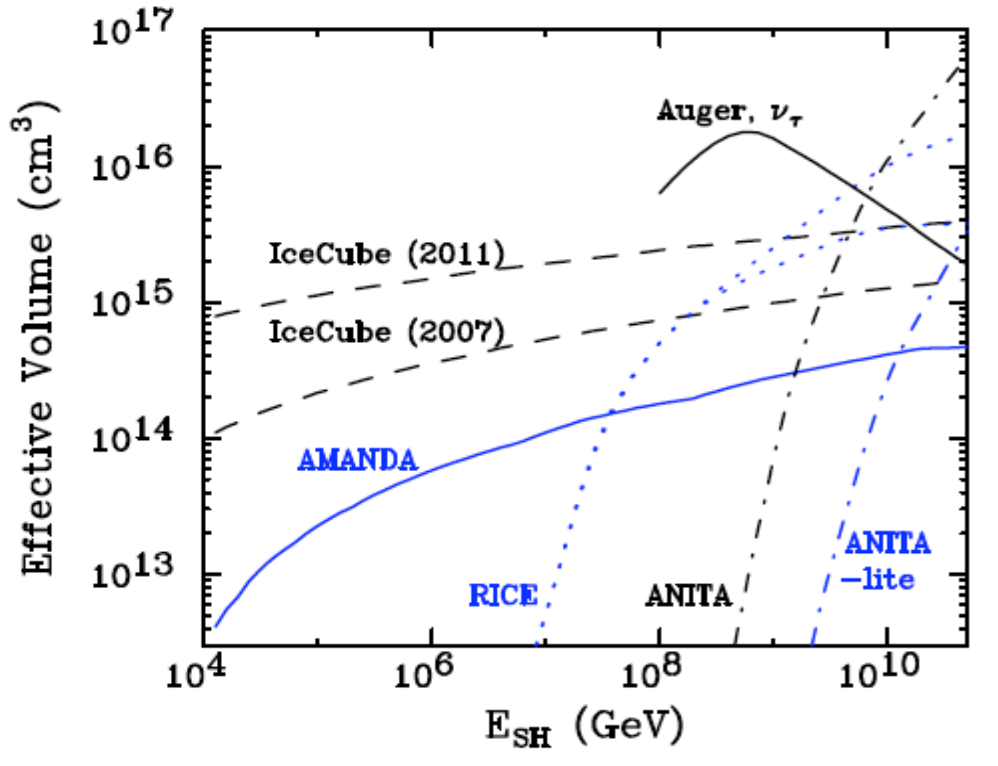
… would be smaller if primaries are heavy nuclei rather than protons

Engel, Seckel, Stanev (2001)



(courtesey: Dave Waters)

Estimated (cosmogenic ν) rates in running/near future experiments



	Event Rate	Current Exposure	2008 Exposure	2011 Exposure
AMANDA (300 hits)	0.044 yr^{-1}	3.3 yrs, 0.17 events	NA	NA
IceCube, 2007 (300 hits equiv.)	0.16 yr^{-1}	NA	0.4 events	NA
IceCube, 2011 (300 hits equiv.)	0.49 yr^{-1}	NA	NA	1.2 events
RICE	$\sim$ 0.07 yr^{-1}	2.3 yrs, 0.1-0.2 events	0.2-0.3 events	0.3-0.4 events
ANITA-lite	0.009 per flight [15]	1 flight, 0.009 events	NA	NA
ANITA	$\sim$ 1 per flight	NA	1 flight, $\sim$ 1 event	3 flights, $\sim$ 3 events
Pierre Auger Observatory	1.3 yr^{-1} [19]	NA	$\sim$ 2 events	$\sim$ 5 events

Halzen & Hooper [astro-ph/0605103]

The sources of cosmic rays *must* also be neutrino sources

Waxman-Bahcall Bound :

- $1/E^2$ injection spectrum (Fermi shock).
- Neutrinos from photo-meson interactions in the source.
- Energy in ν's related to energy in CR's :

$$[E_\nu^2 \Phi_\nu]_{\rm WB} \approx (3/8)\, \xi_Z\, \epsilon_\pi\, t_{\rm H}\, \frac{c}{4\pi}\, E_{\rm CR}^2 \frac{d\dot{N}_{\rm CR}}{dE_{\rm CR}}$$

Fraction of CR primary energy converted to neutrinos

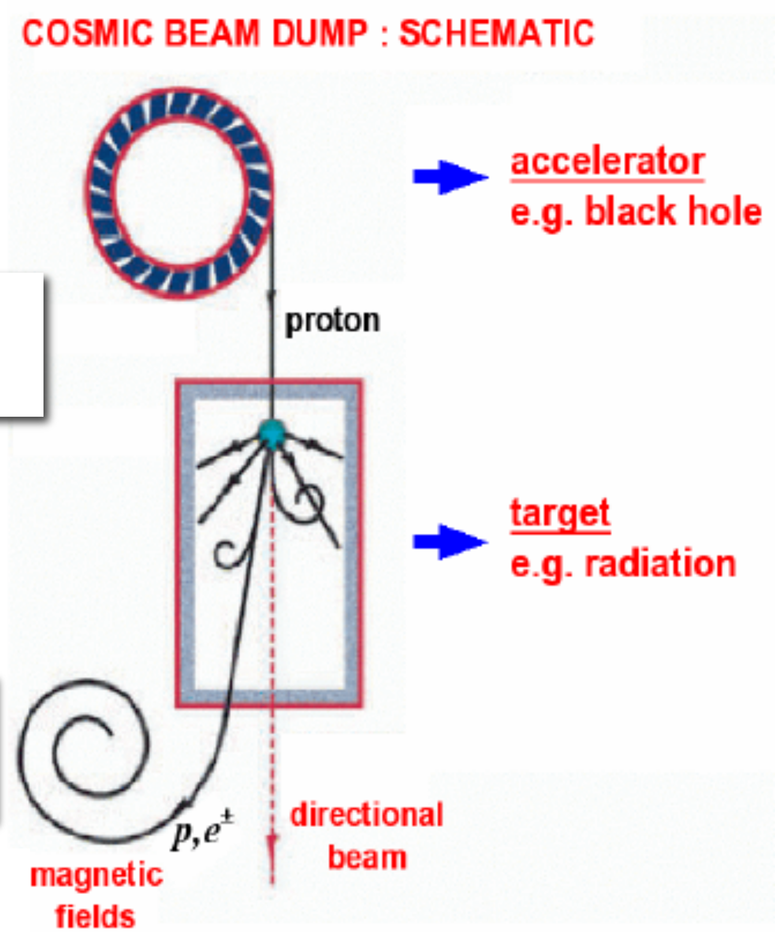
Hubble time

From rate of UHE CR's (10^{19}-10^{21} eV)

$$\approx 2.3 \times 10^{-8}\, \epsilon_\pi\, \xi_Z\, \mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

➡Making a reasonable estimate for ϵ_π etc allows this to be converted into a flux prediction

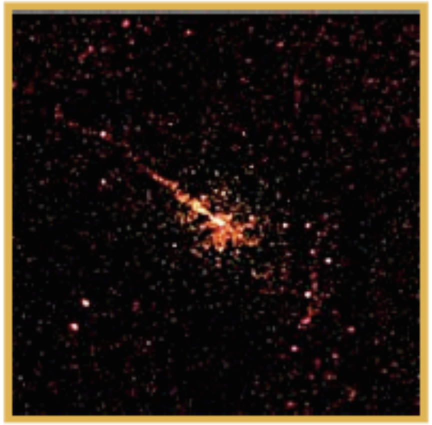
(would be higher if extragalactic cosmic rays become dominant at energies below the 'ankle')



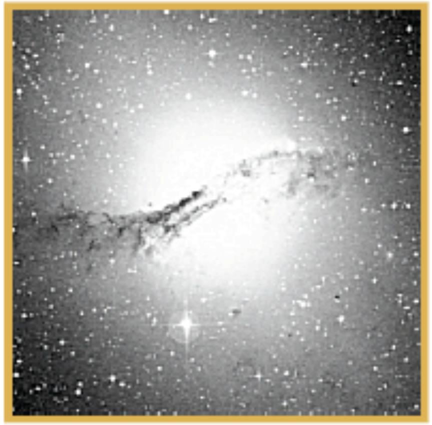
(Courtesey: David Waters)

Centaurus A – Peculiar Galaxy

Distance: 11,000,000 ly light-years (3.4 Mpc) Image Size = 15 x 14 arcmin Visual Magnitude = 7.0


X-Ray: Chandra

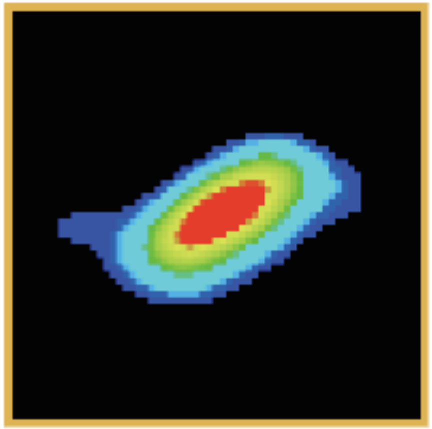

Ultraviolet: GALEX

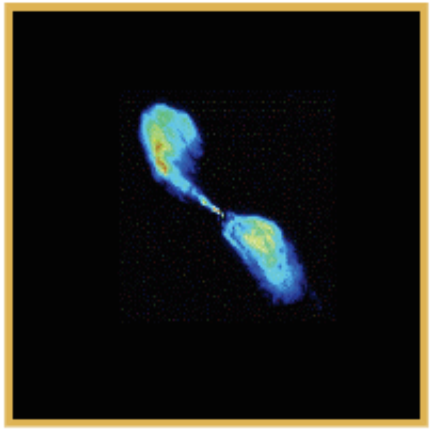

Visible: DSS


Visible: Color ©AAO


Near-Infrared: 2MASS


Mid-Infrared: Spitzer


Far-Infrared: IRAS


Radio: VLA

Estimate of ν flux from *p-p*:

$$\frac{dN_\nu}{dE} \leq 5 \times 10^{-13} \left(\frac{E}{\mathrm{TeV}}\right)^{-2} \mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$$

~ 0.02-0.8 events/km^2 yr

Halzen & Murchadha [arXiv:0802.0887]

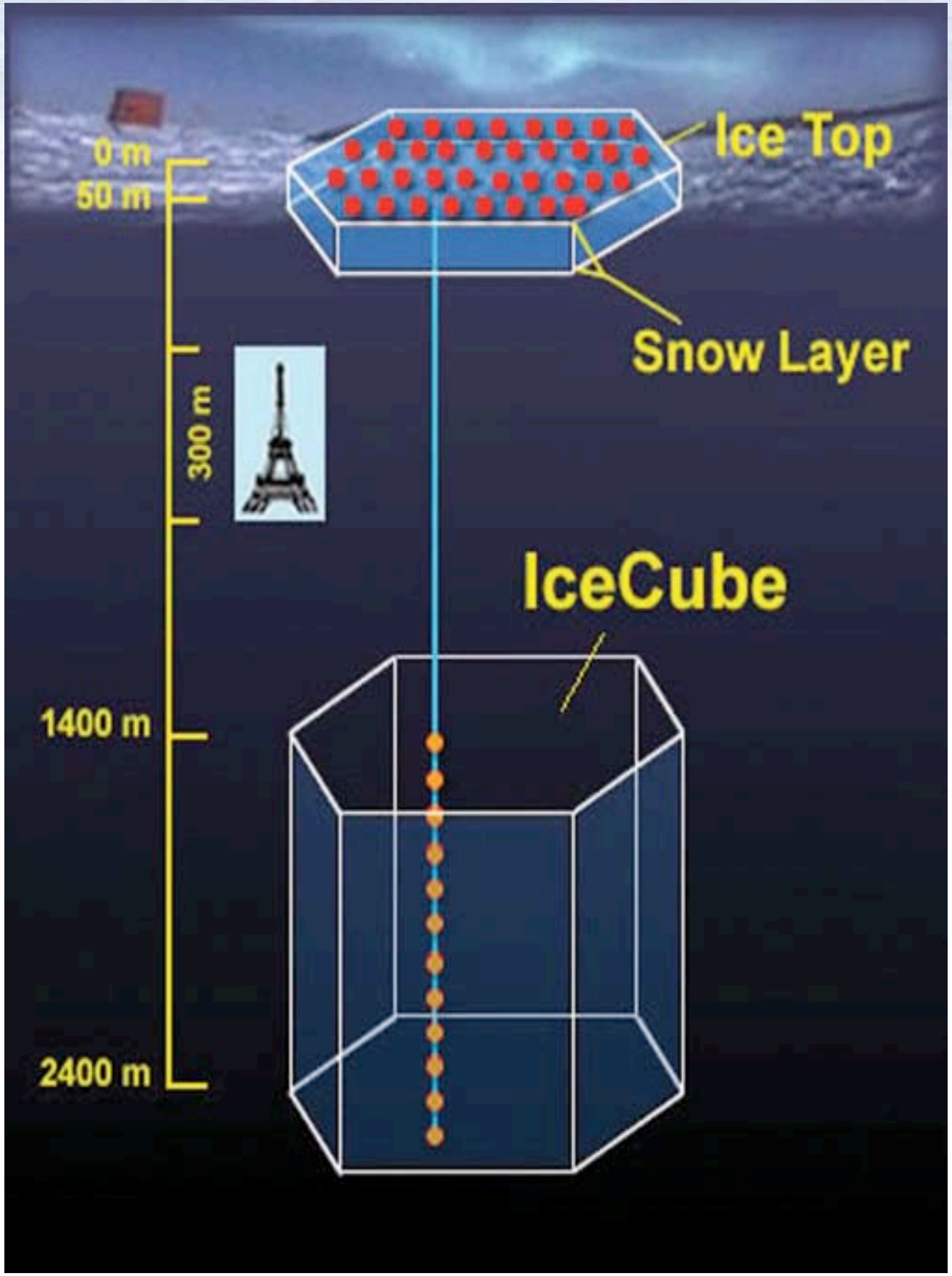
Deep ice array:

- 80 strings/60 OMs each (17 m apart)
- 125 m between strings
- hexagonal pattern over 1 km^2
- geometry optimized for detection of TeV – PeV (EeV) neutrinos

Surface array: IceTop

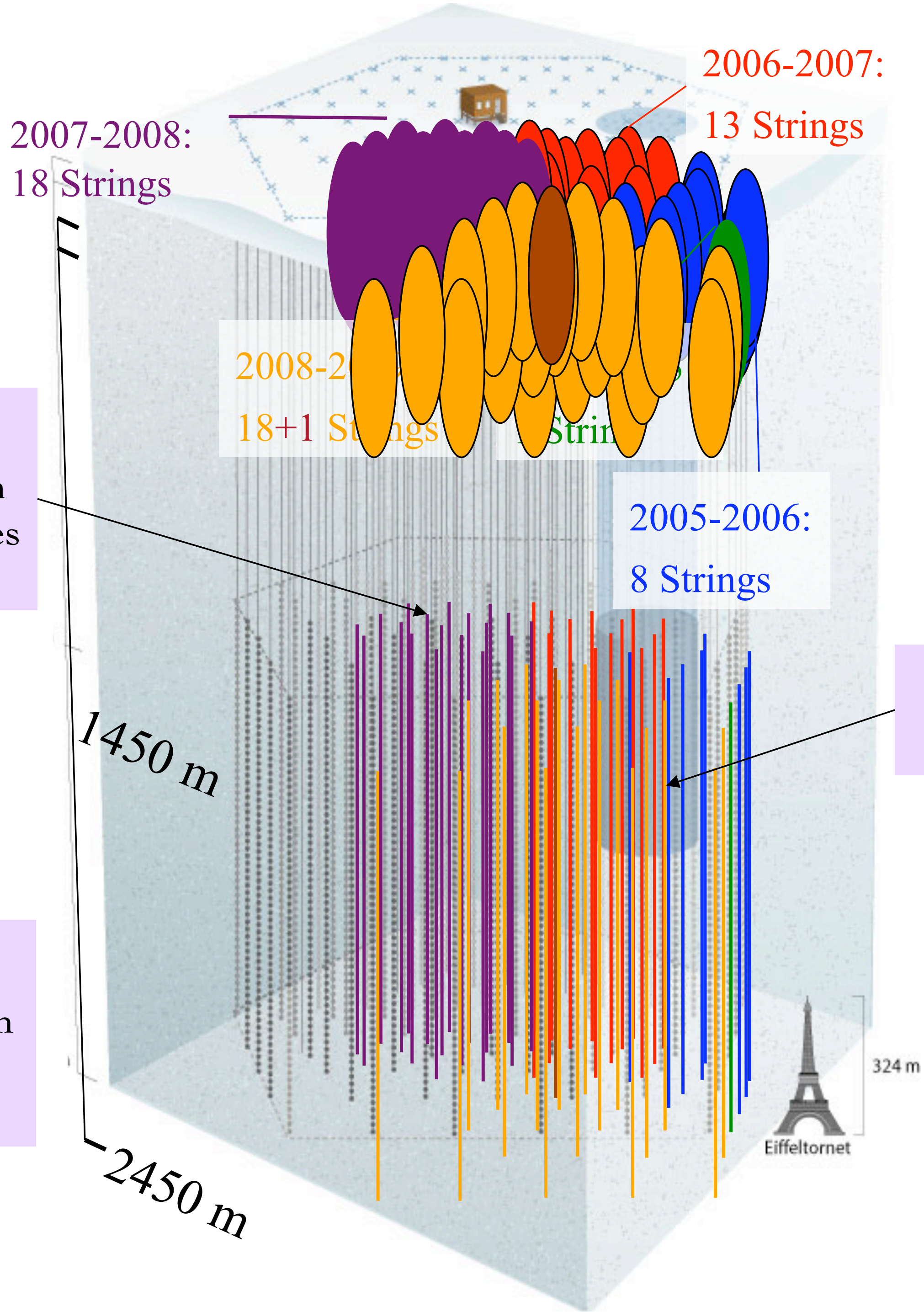
- 2 frozen-water tanks (2 OM's each) on top of every string

IceCube



IceCube Neutrino Observatory

IceTop
air shower array
threshold ~ 300 TeV



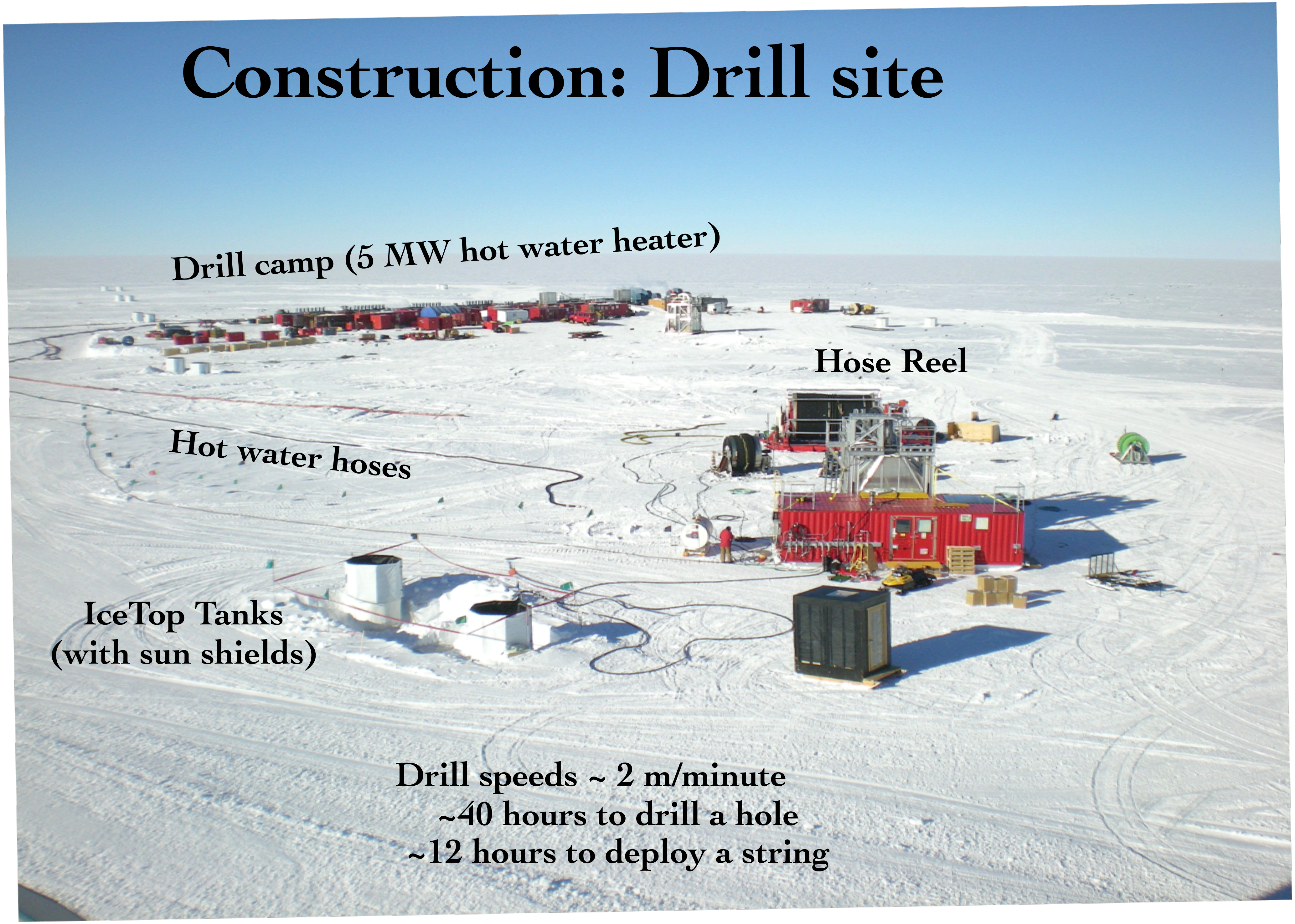
Deep Core
6 strings/60 Modules each
7 or 10 m between Modules
72 m between Strings

AMANDA
19 strings/677 modules

InIce
80 strings/60 modules each
17 m between modules
125 m between strings

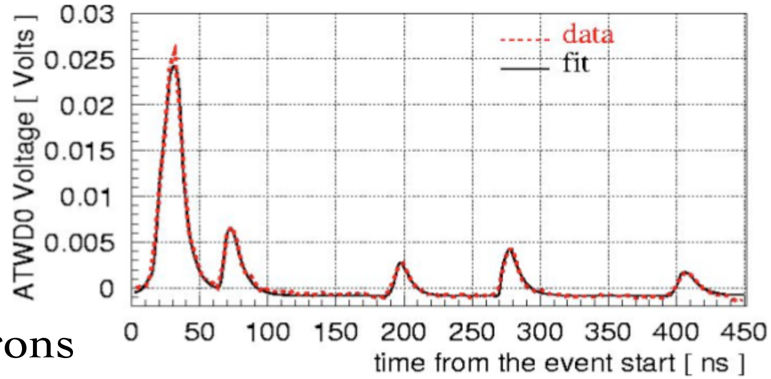
Hot news
Array nearly
completed in
2009-10!

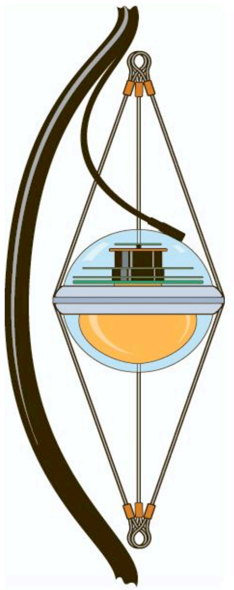
Construction: Drill site

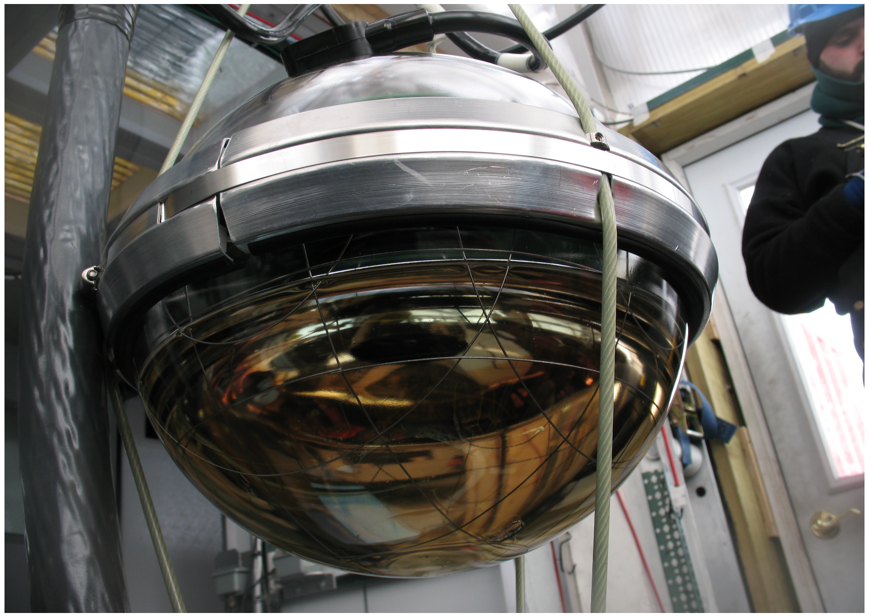


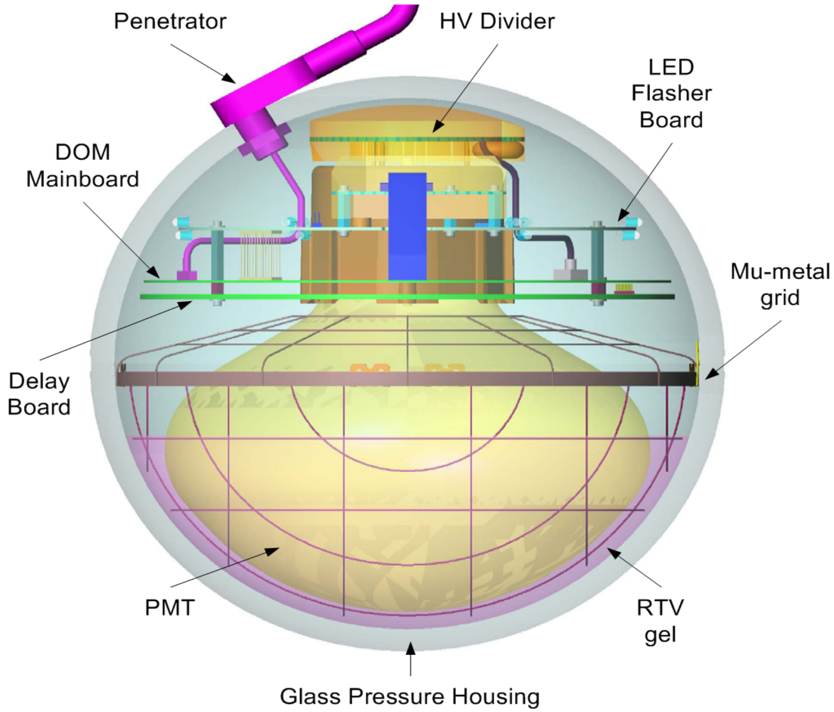
Digital Optical Modules

10" Hamamatsu Photomultiplier tubes (PMT)
3.5 W Power
Internal digitization and timestamping:
 ATWD: 300 MHz (400 ns)
 fADC: 40 MHz (6400 ns)
Dynamic range: from one to thousands of photo-electrons
Transmit digital data to surface

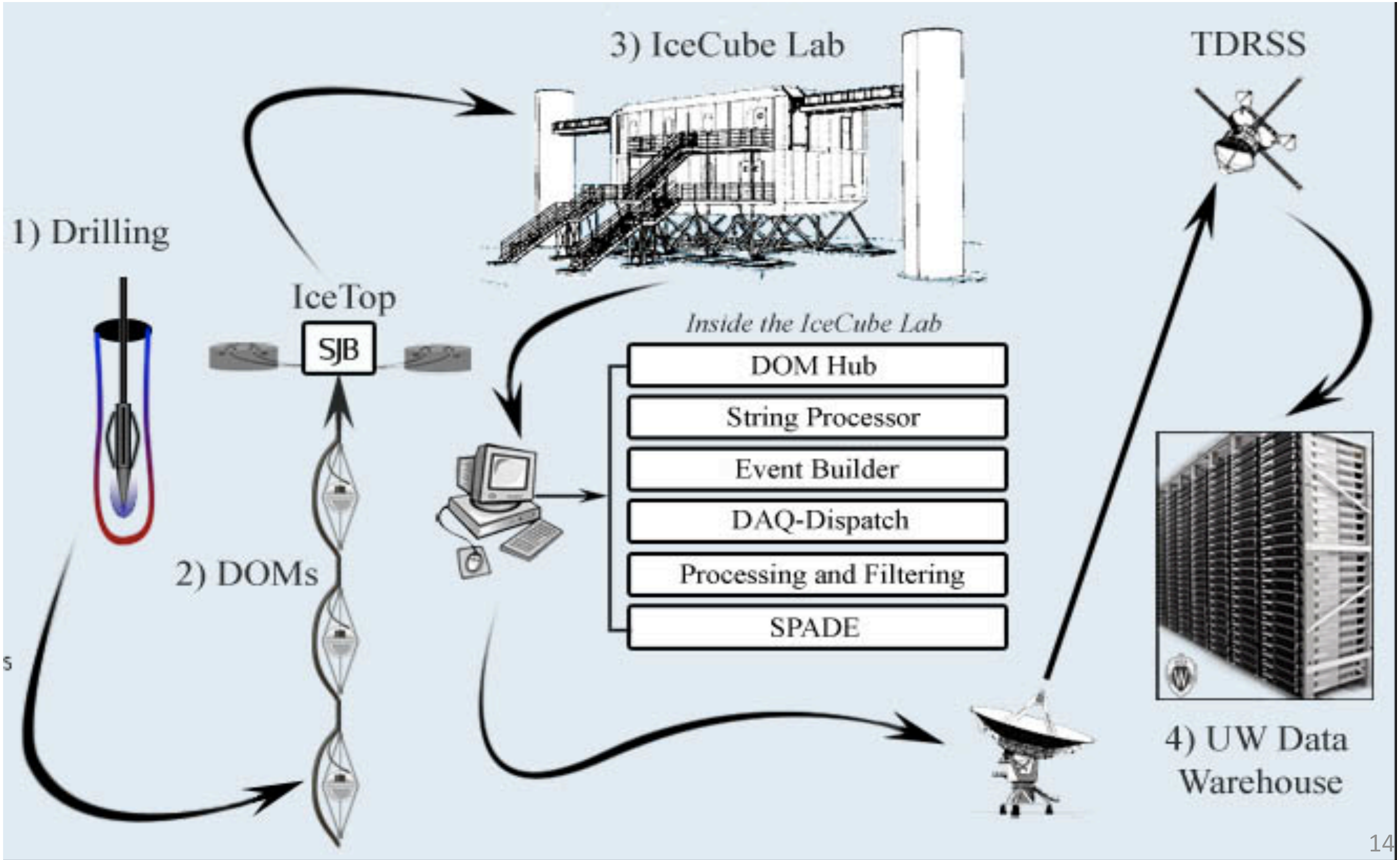








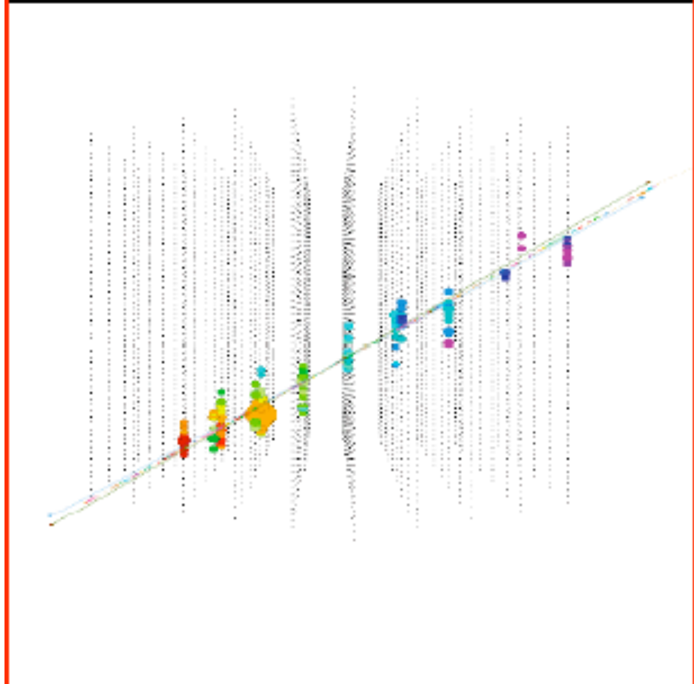
Data Acquisition



ν_μ

E_μ = 10TeV

~90 DOMs hit

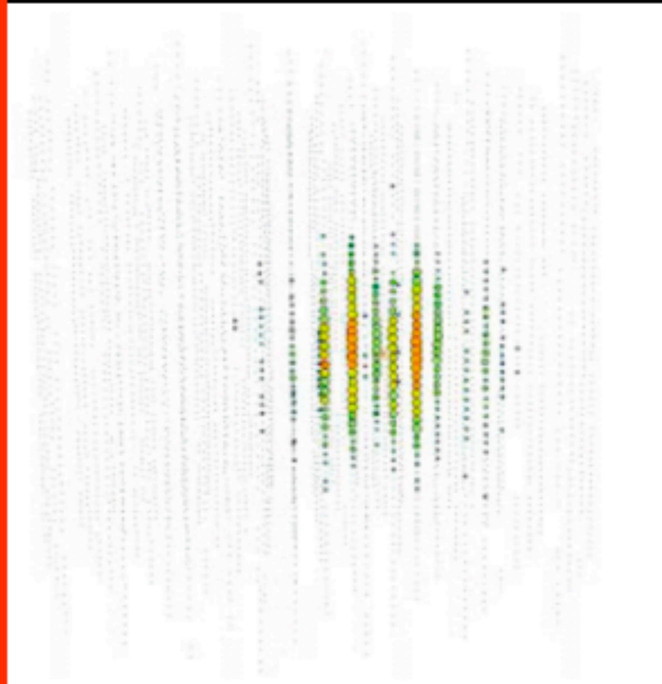


E~dE/dx , e>1TeV
E res. : Δlog(E)~0.3
ang res : 0.8-2 deg

ν_e

E = 375 TeV

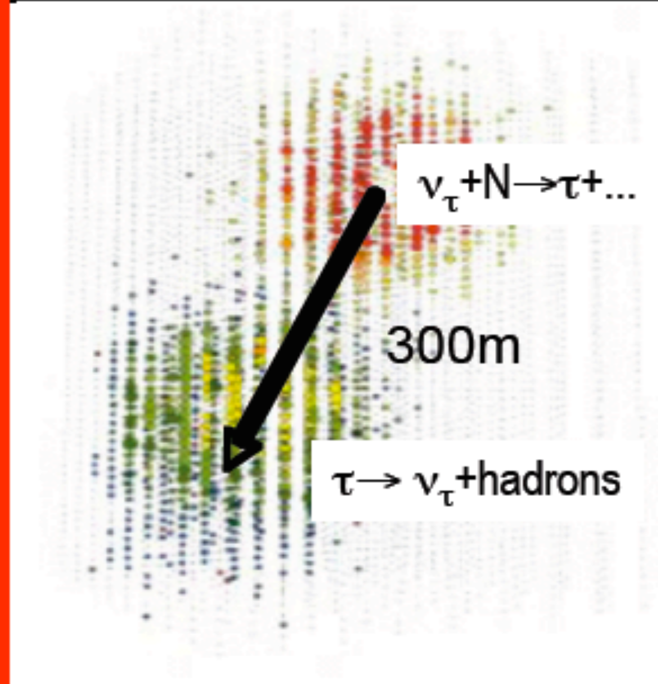
"spherical" shell



poor angular resolution
E res : Δlog(E)~0.1-0.2

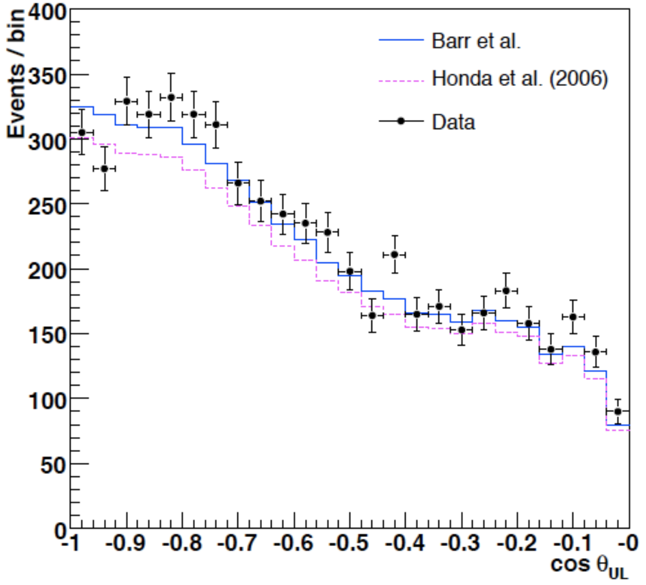
ν_τ

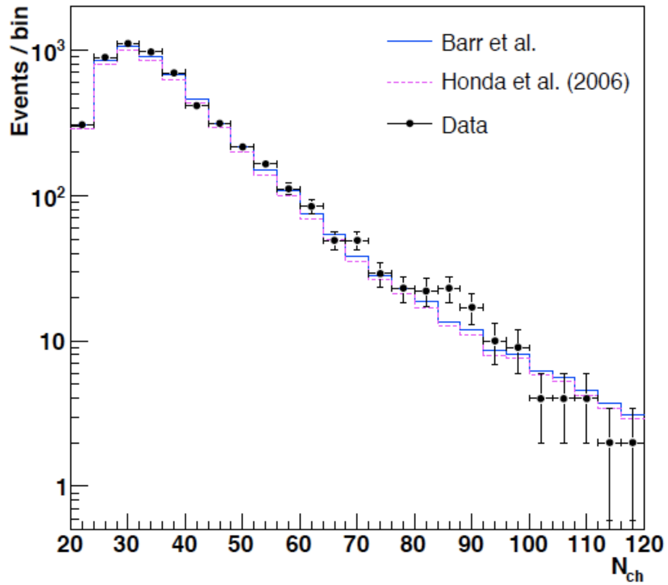
E = 10 PeV
2 bangs separated by
~ 50*(E_τ/PeV)

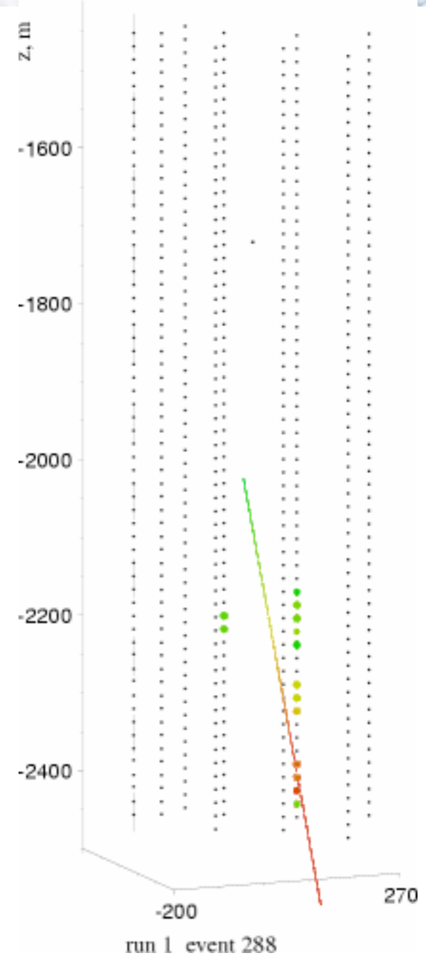


very low background
pointing capability
good E measurement

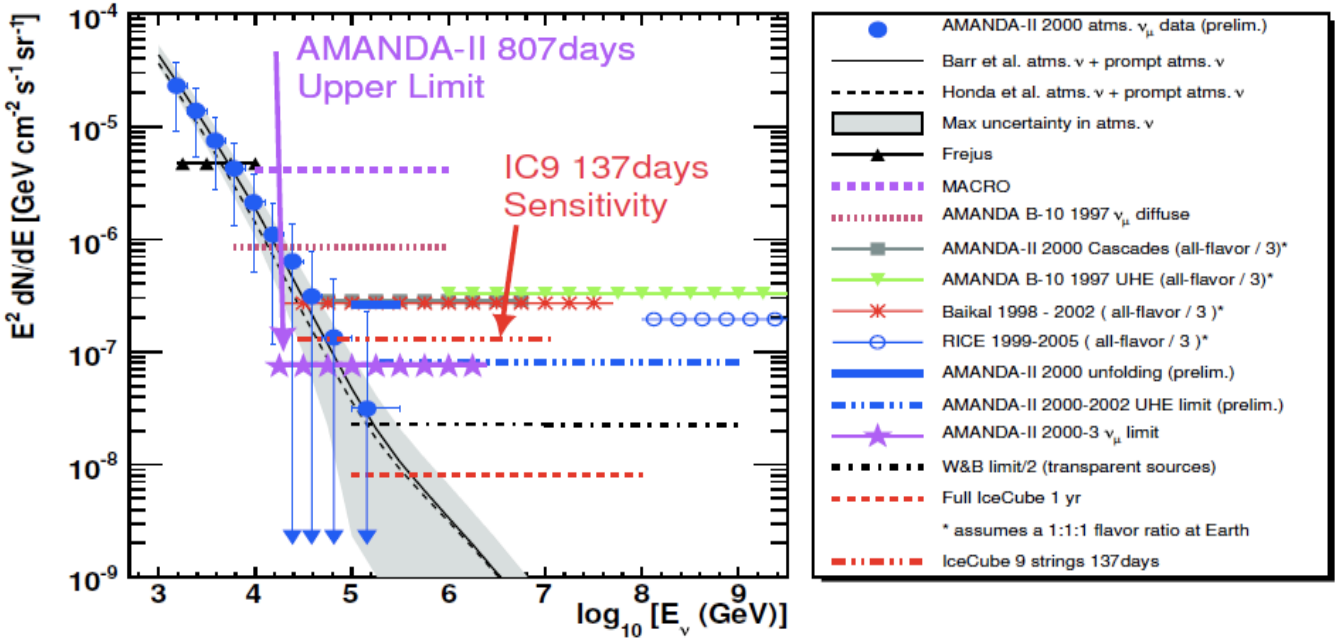
We measure atmospheric neutrinos …



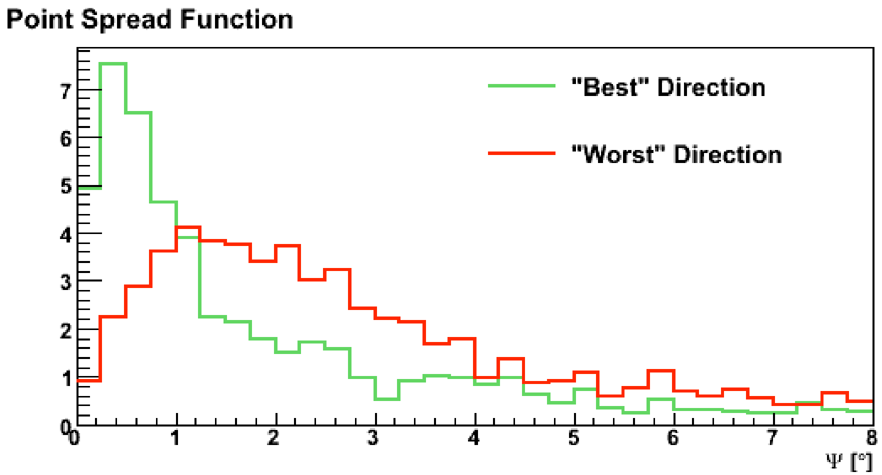


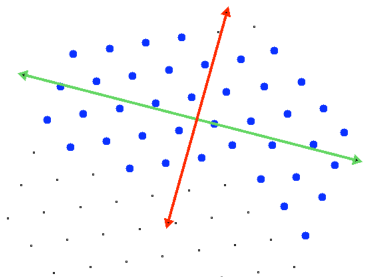


Resulting sensitivity to diffuse flux …

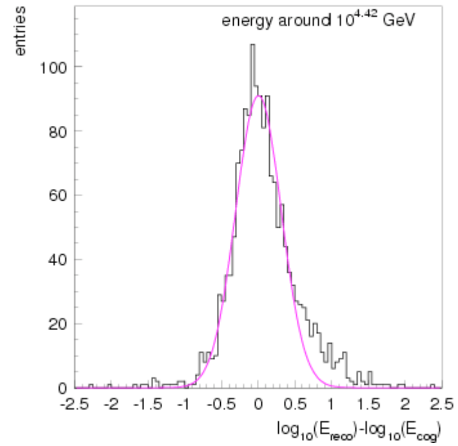


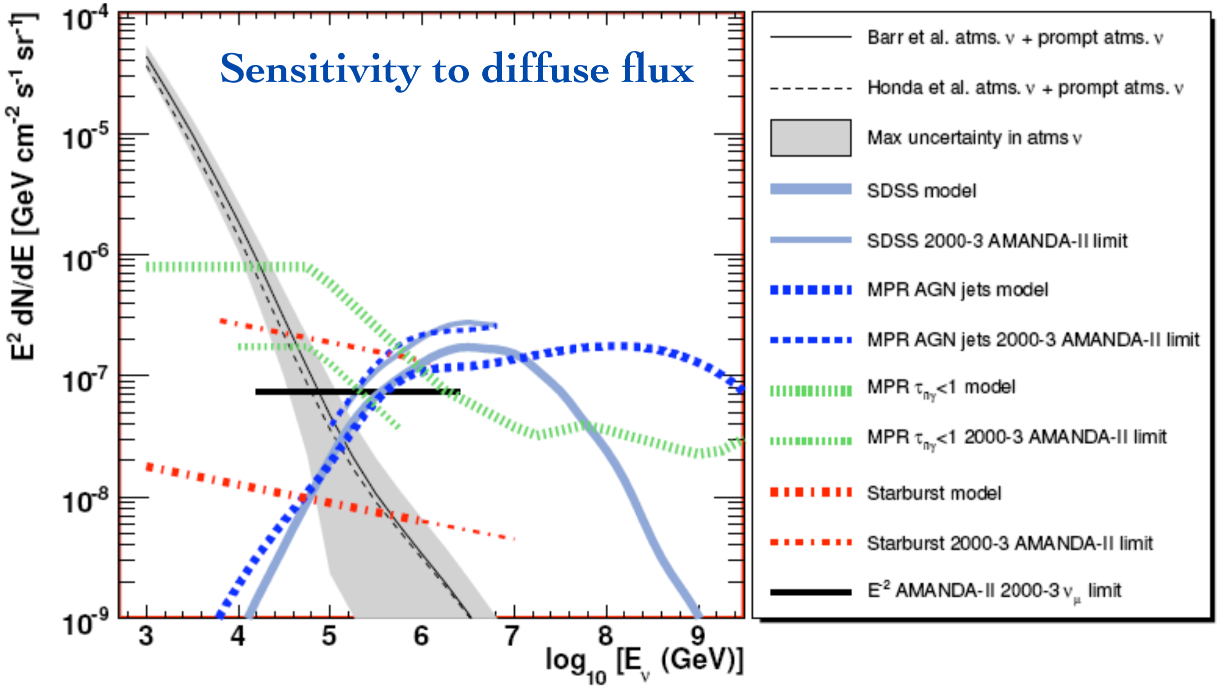
beginning to constrain optimistic models of AGN, GRB etc
… also looking for coincidences with TeV γ-ray flares

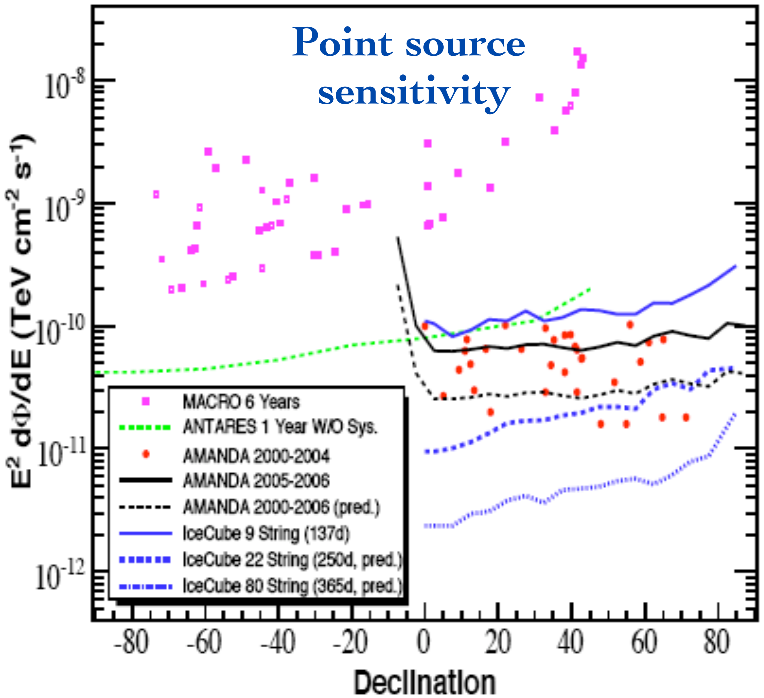




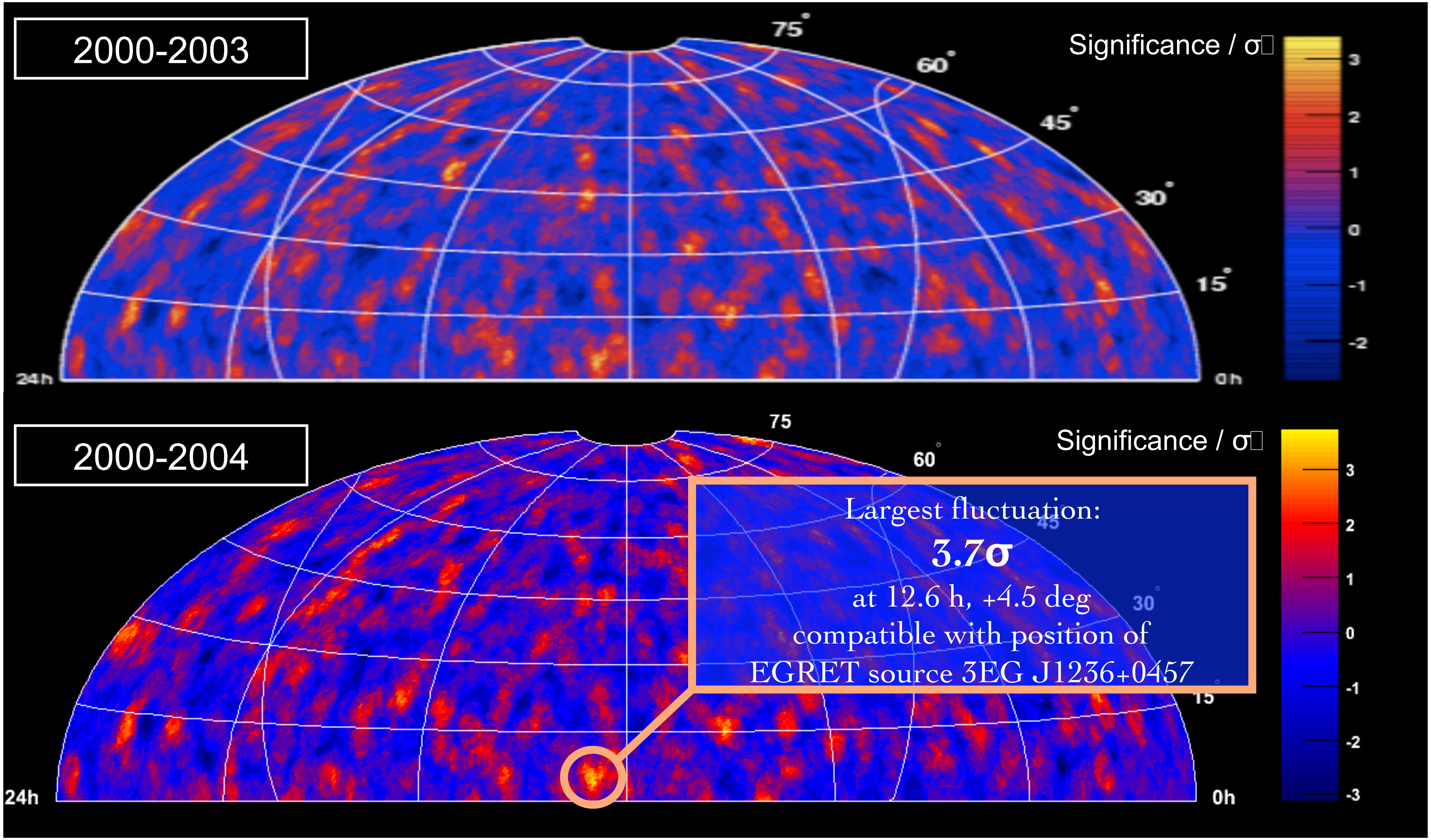
Energy Resolution
$s(\log_{10}E) \sim 0.3$





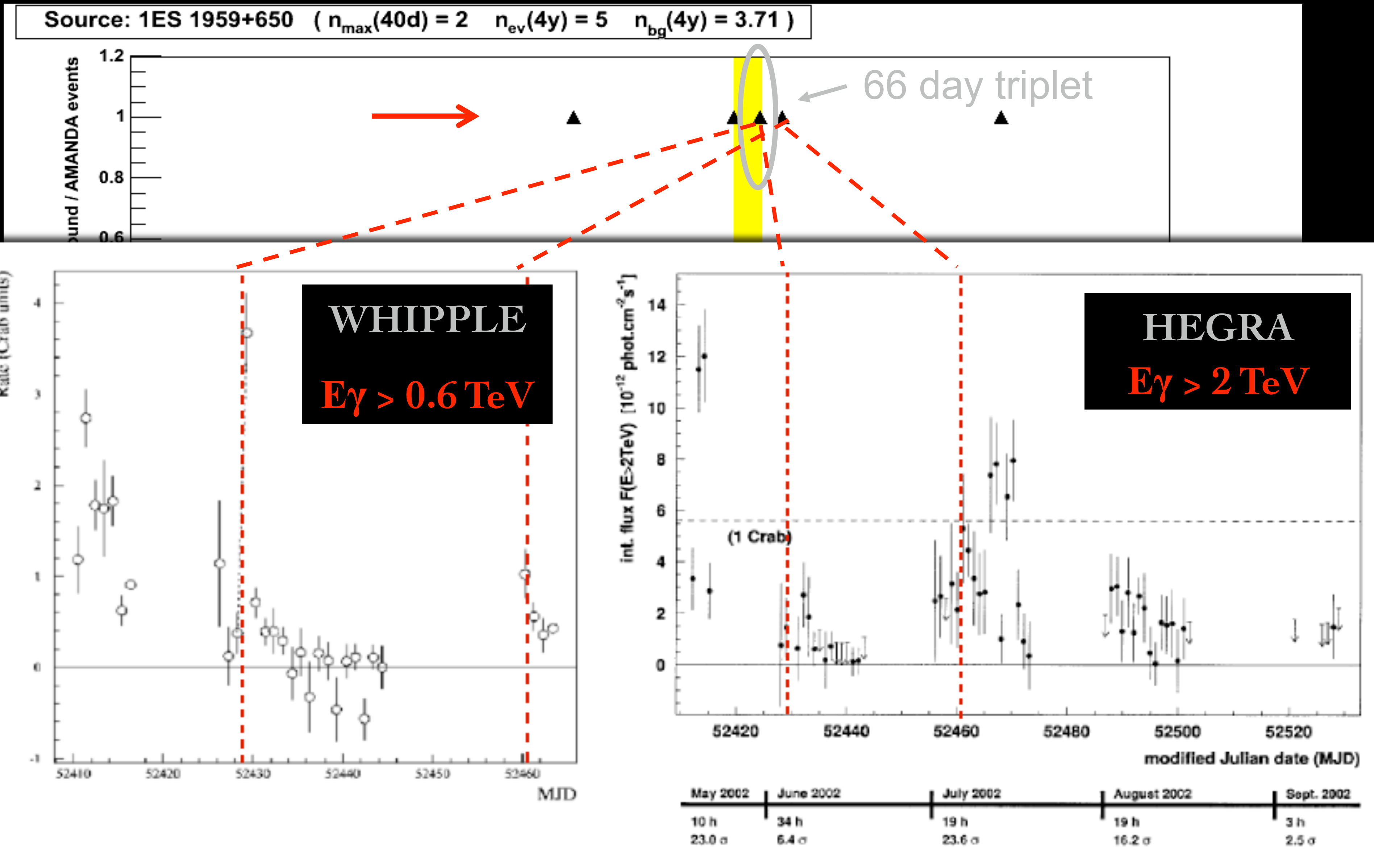


AMANDA search for point sources of TeV-PeV neutrinos

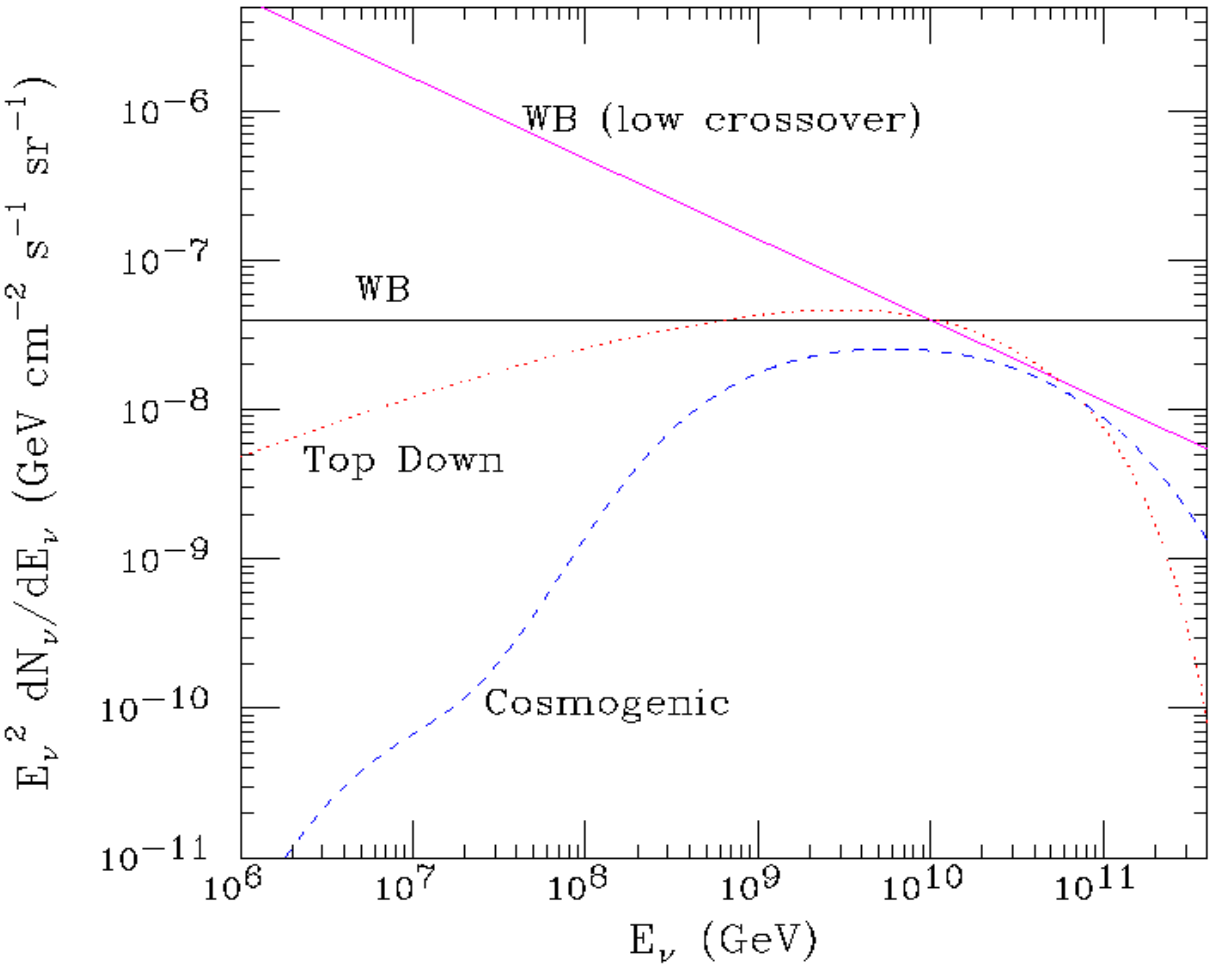


But 69 out of 100 randomised sky maps show a higher excess!

AMANDA events coincident with ‘orphan flare’ in 1ES1959+650 !



Plausible UHE cosmic neutrino fluxes



Anchordoqui, Han, Hooper & Sarkar, AP 25:14,2006

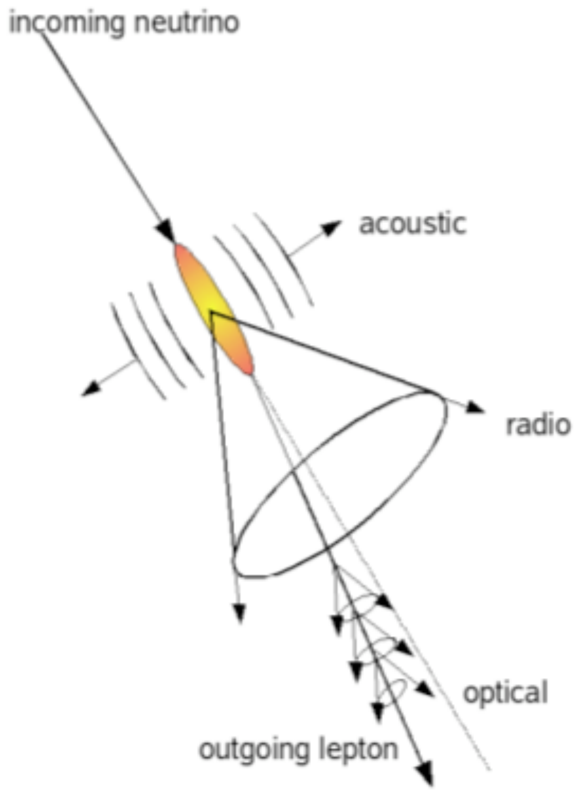
WB flux is enhanced in models where extragalactic sources are assumed to dominate from ~10^{18} eV … close to being ruled out (Ahlers, Anchordoqui & Sarkar, PR D79:083009,2009)

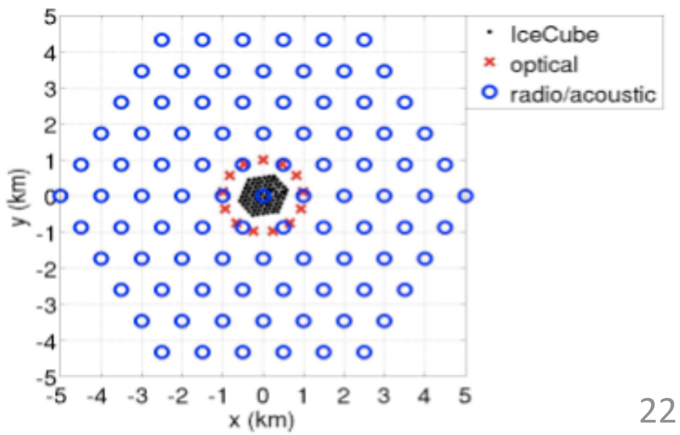
To see cosmic νs may require >100 km^3 detection volume (ANITA, IceRay…)

Future detection methods

- A high-energy ν -N interaction has three signatures in ice:
  - Optical (Cherenkov): lepton
  - Radio: hadronic and electromagnetic cascades
  - Acoustic: hadronic cascade

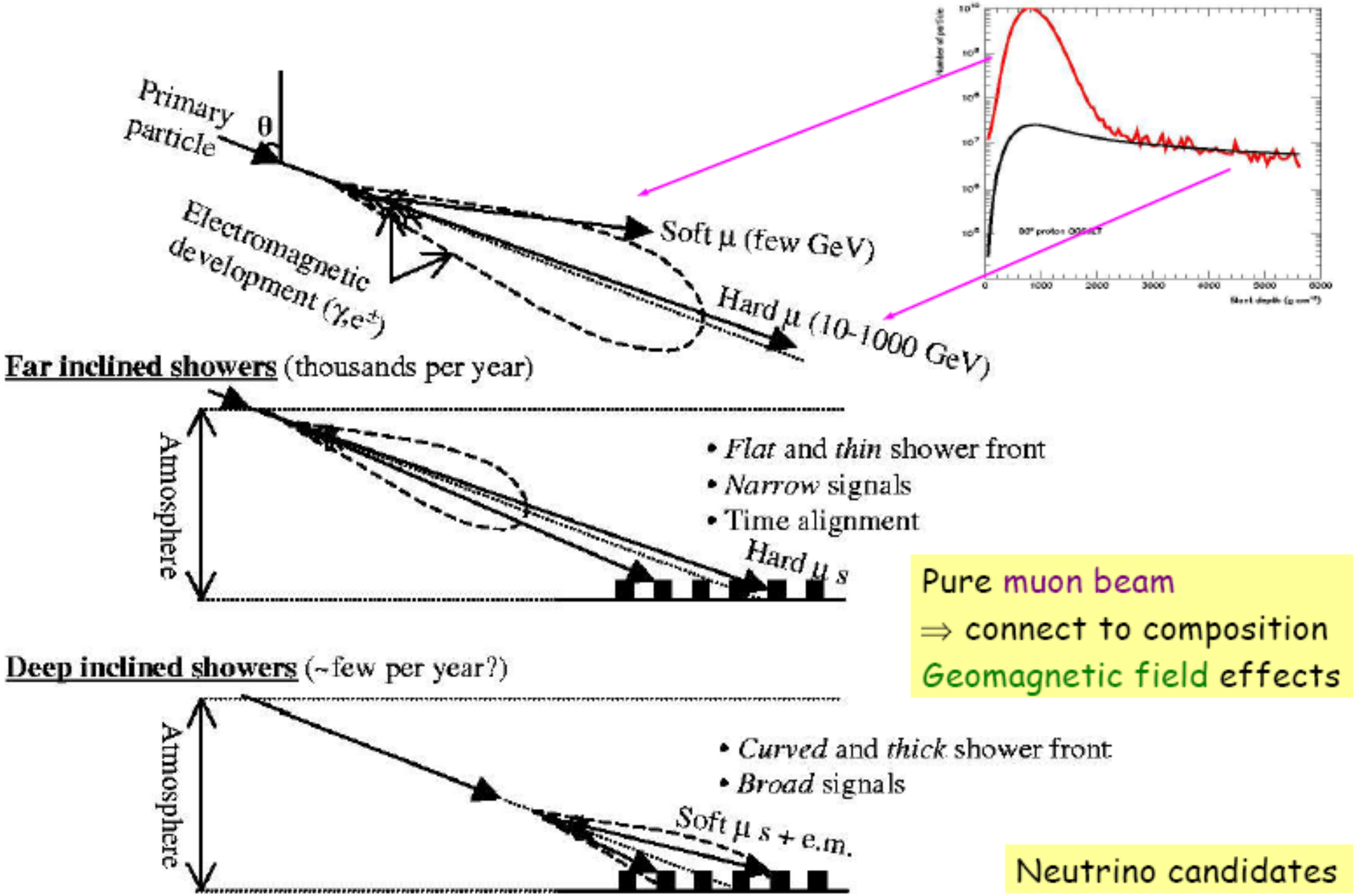
- Towards a 100 km^3 hybrid detector
  - Goal: detect ~100 GZK neutrinos in a few years
  - Better background rejection through coincident detection
  - Control systematics

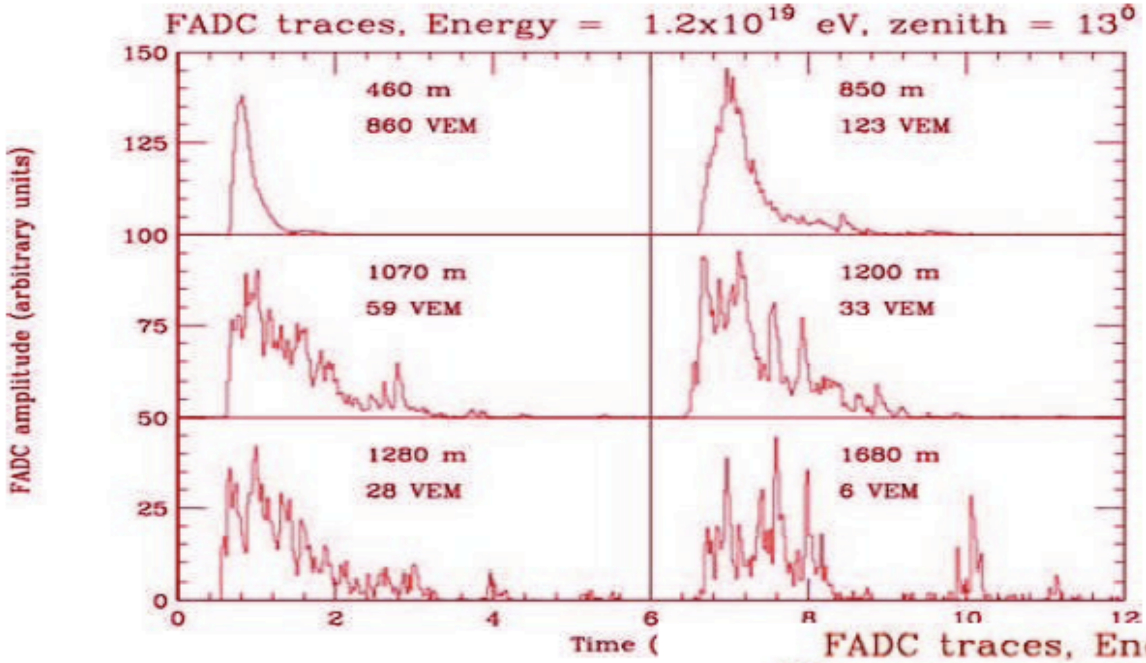




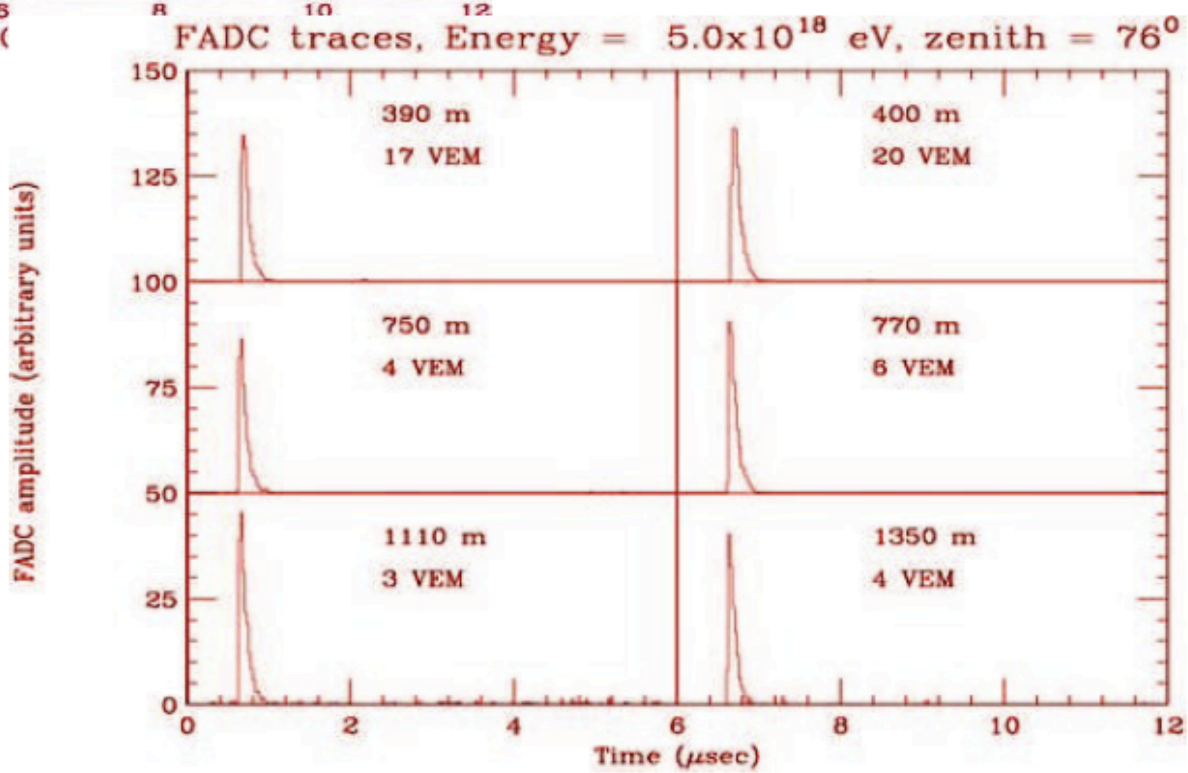
An unexpected bonus – UHE neutrino detection with air shower arrays

Rate ~ cosmic neutrino flux, ν-N #-secn





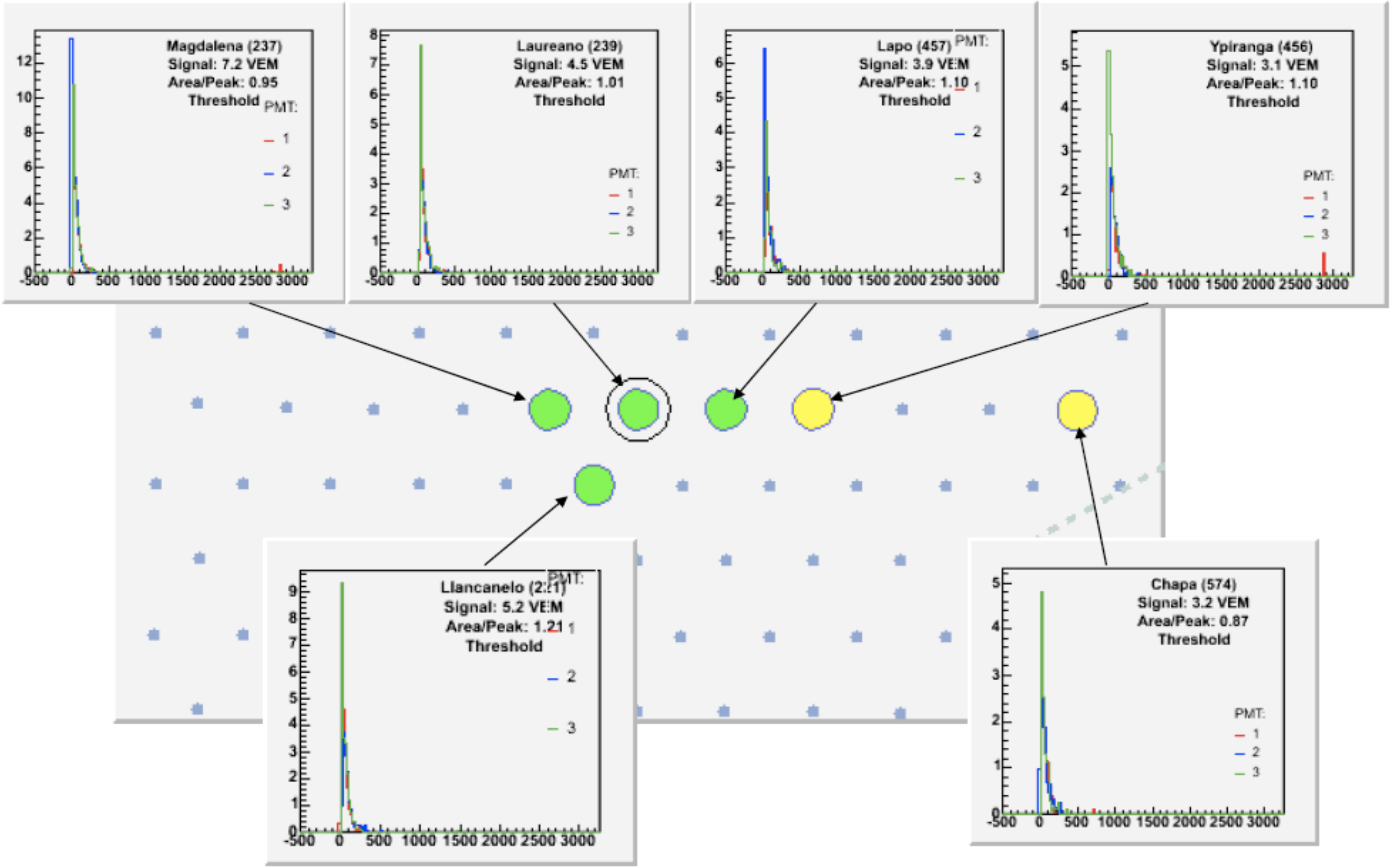
'young' shower



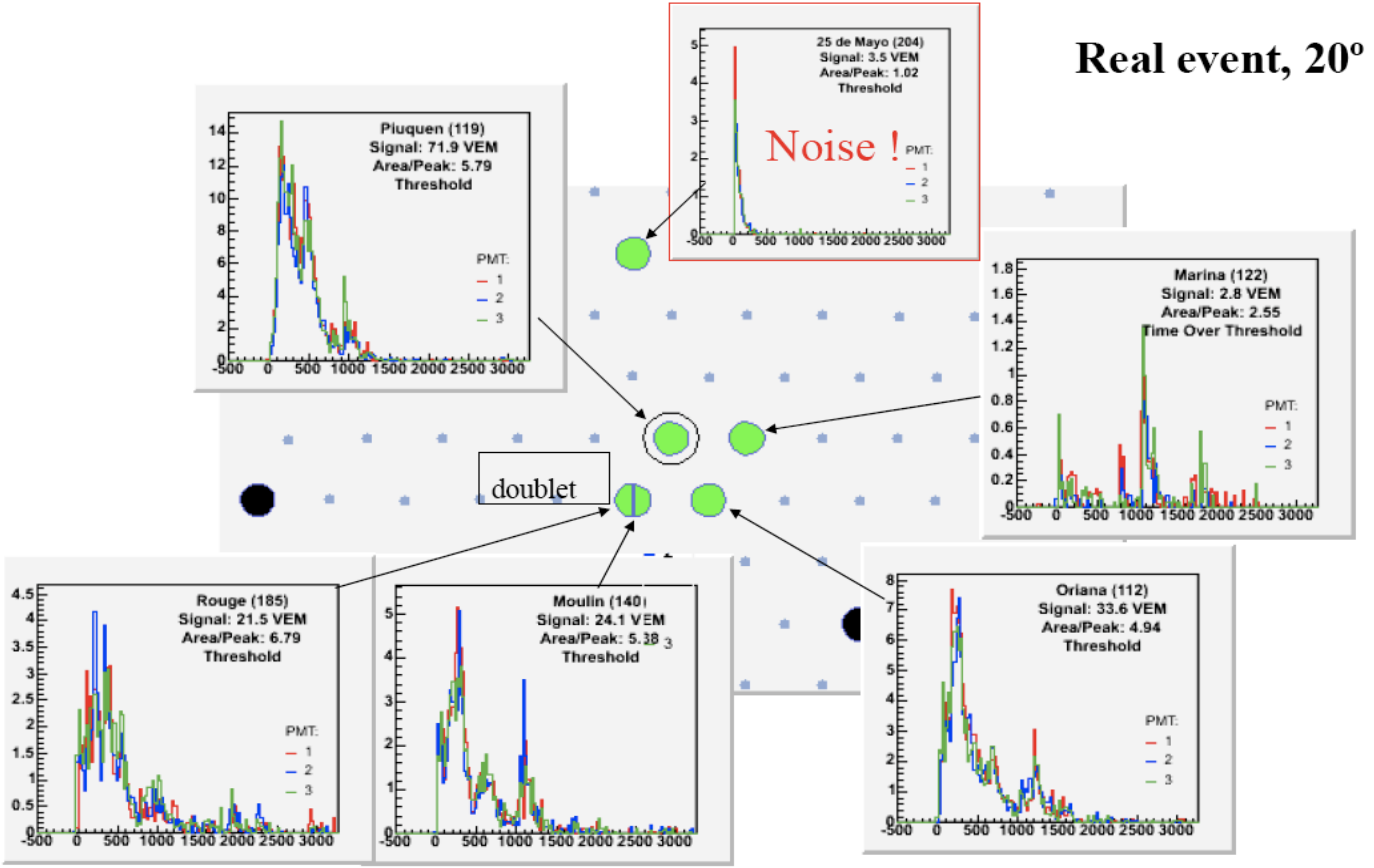
'old' shower

INCLINED EVENT

Real event, 80°

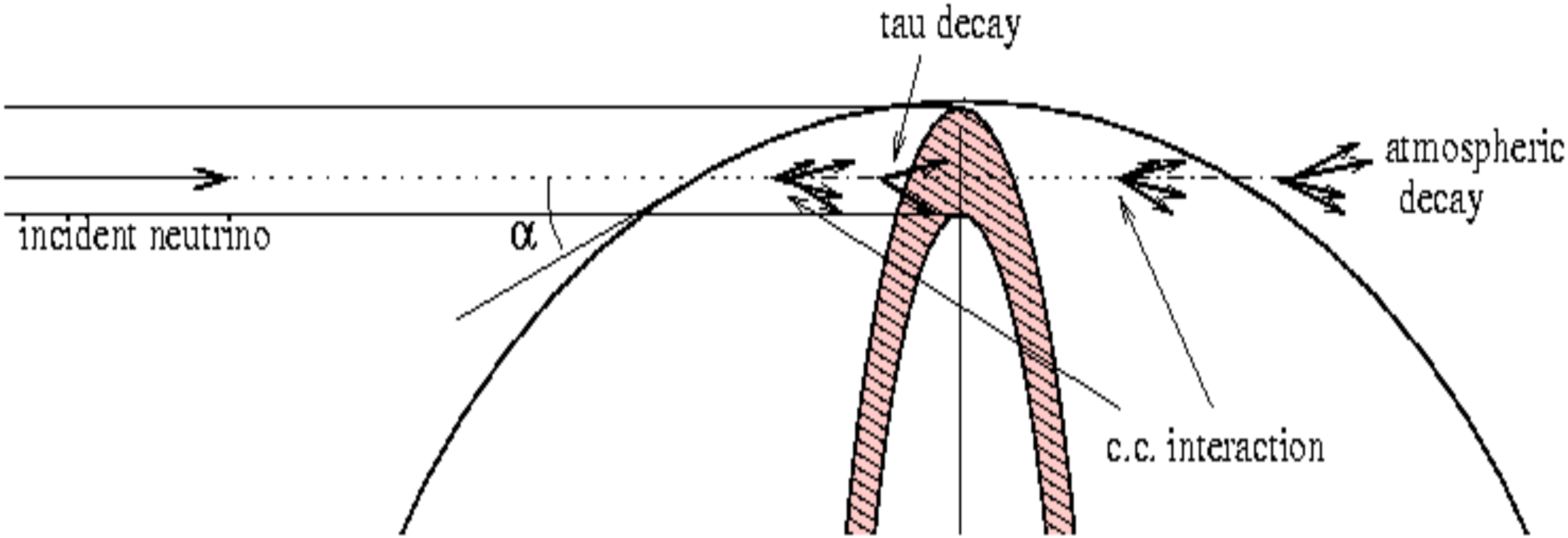


VERTICAL EVENT



Auger also sees Earth-skimming $\nu_\tau \rightarrow \tau$ which generates *upgoing* hadronic shower

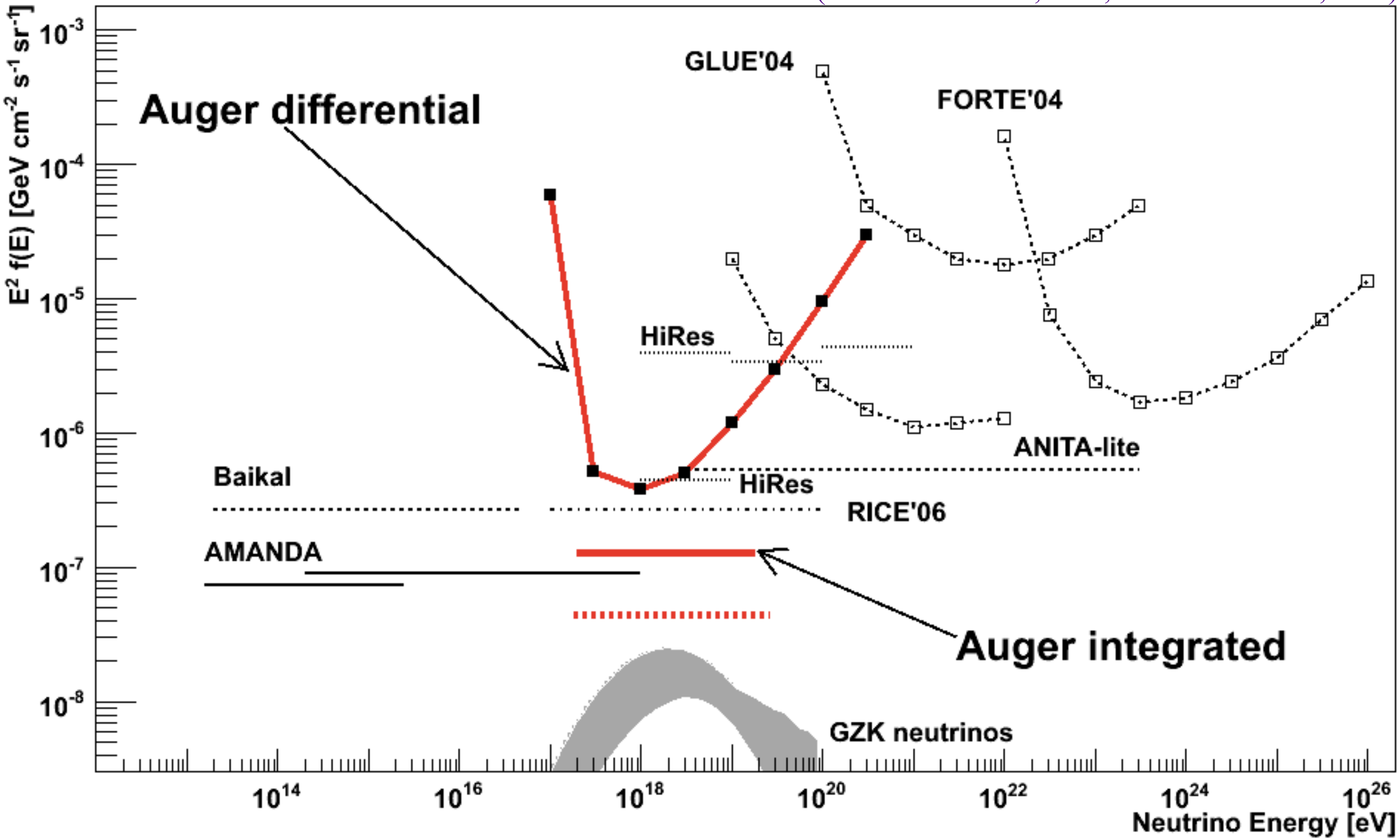
Rate ~ cosmic neutrino flux, but *not* to ν-N #-secn



… so if we can detect both quasi-horizontal and Earth-skimming events, then can get handle on ν-N #-secn *independently* of absolute flux!

No neutrino events yet … but getting close to "guaranteed" cosmogenic flux

(PRL 100:211101,2008; PR D79:102001,2009)



(NB: To do this we need to know *ν-N* cross-section at ultrahigh energies)

Colliders & Cosmic rays

The LHC will soon achieve ~14 TeV cms …

But 1 EeV (10^{18} eV) cosmic ray initiating giant air shower

⇒ **50 TeV** cms (rate ~ 10/day in 3000 km^2 array)

New physics would be hard to see in hadron-initiated showers

(#-secn TeV^{-2} vs GeV^{-2})

… but may have a dramatic impact on *neutrino* interactions

→ can probe new physics both **in and beyond the Standard Model** by observing **ultra-high energy cosmic neutrinos**

ν-N deep inelastic scattering

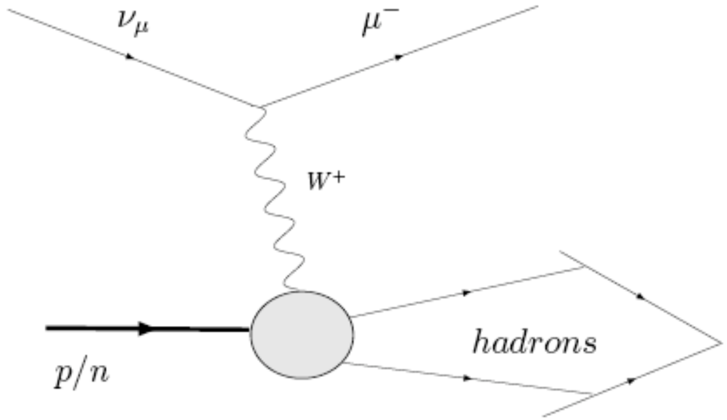
$$\frac{\partial^2\sigma^{CC,NC}_{\nu,\bar\nu}}{\partial x\partial y} = \frac{G_F^2 M E}{\pi}\left(\frac{M_i^2}{Q^2+M_i^2}\right)$$

Q^2 ↑ propagator ↓

$$[\frac{1+(1-y)^2}{2}F_2^{CC,NC}(x,Q^2) - \frac{y^2}{2}F_L^{CC,NC}(x,Q^2)$$

$$\pm y\left(1-\frac{y}{2}\right)xF_3^{CC,NC}(x,Q^2)]$$

Q^2 ↑ parton distrib. fns ↓



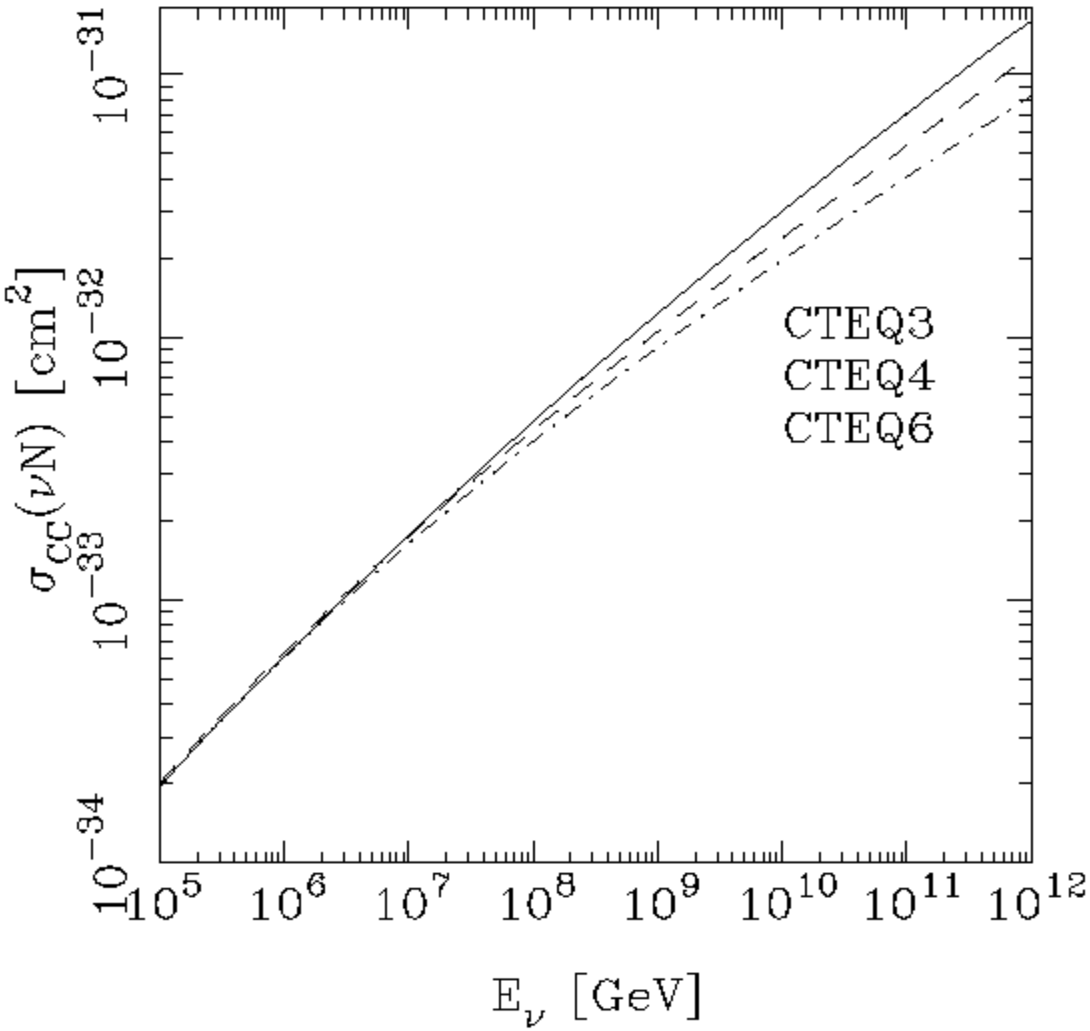
Most of the contribution to #-secn comes from: $Q^2 \sim M_W^2$ *and* $x \sim \frac{M_W^2}{M_N E_\nu}$

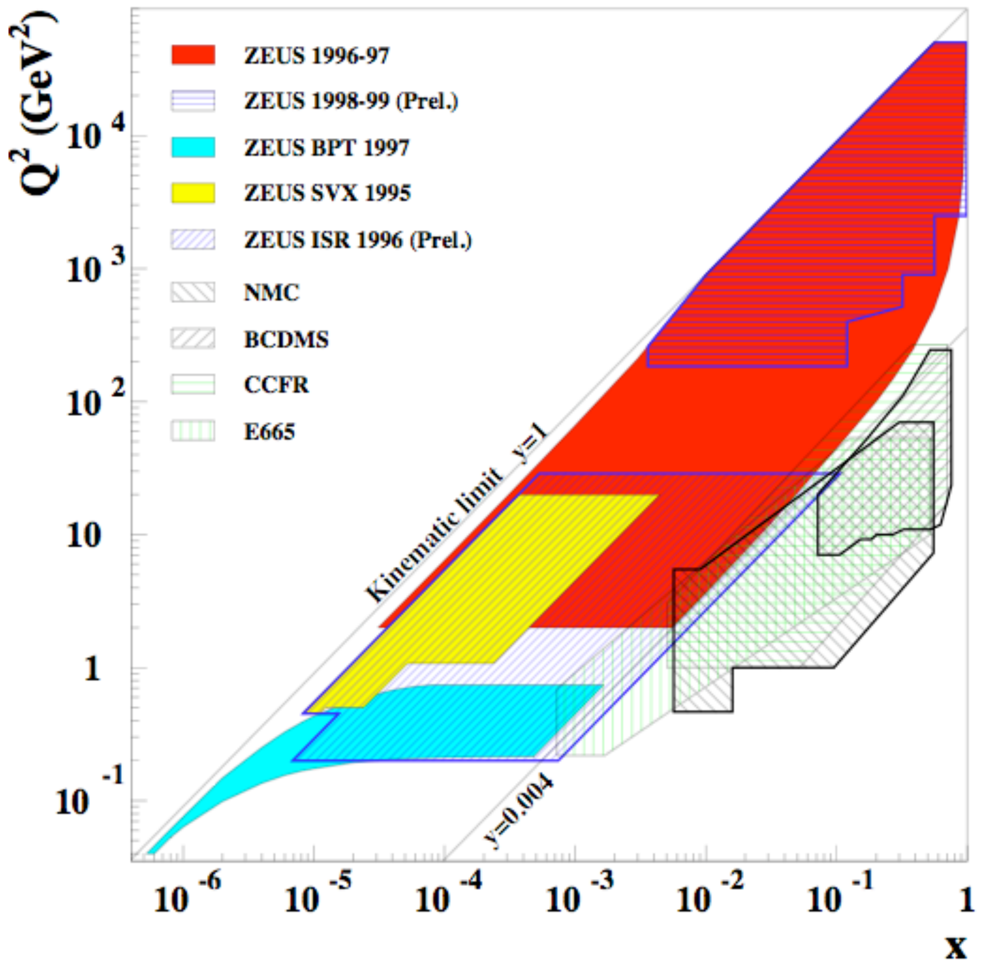
At leading order (LO) : $F_L = 0$, $F_2 = x(u_v + d_v + 2s + 2b + \bar{u} + \bar{d} + 2\bar{c})$,

$xF_3 = x(u_v + d_v + 2s + 2b - \bar{u} - \bar{d} - 2\bar{c}) = x(u_v + d_v + 2s + 2b - 2\bar{c})$

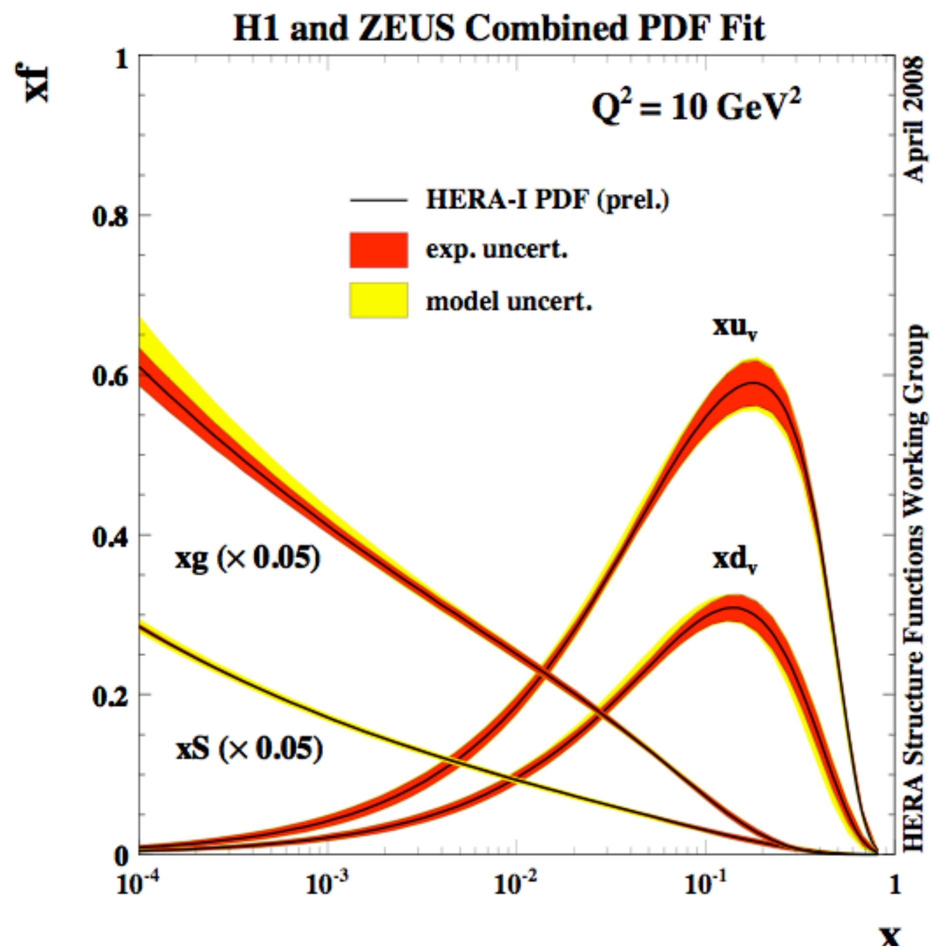
At NLO in α_s, it gets more complicated ... but is still calculable

Many calculations have been made using available "off the shelf" parameterisations of PDFs by e.g. the CTEQ group … most are based on ***out-of-date data*** and have ***no estimates of uncertainties***



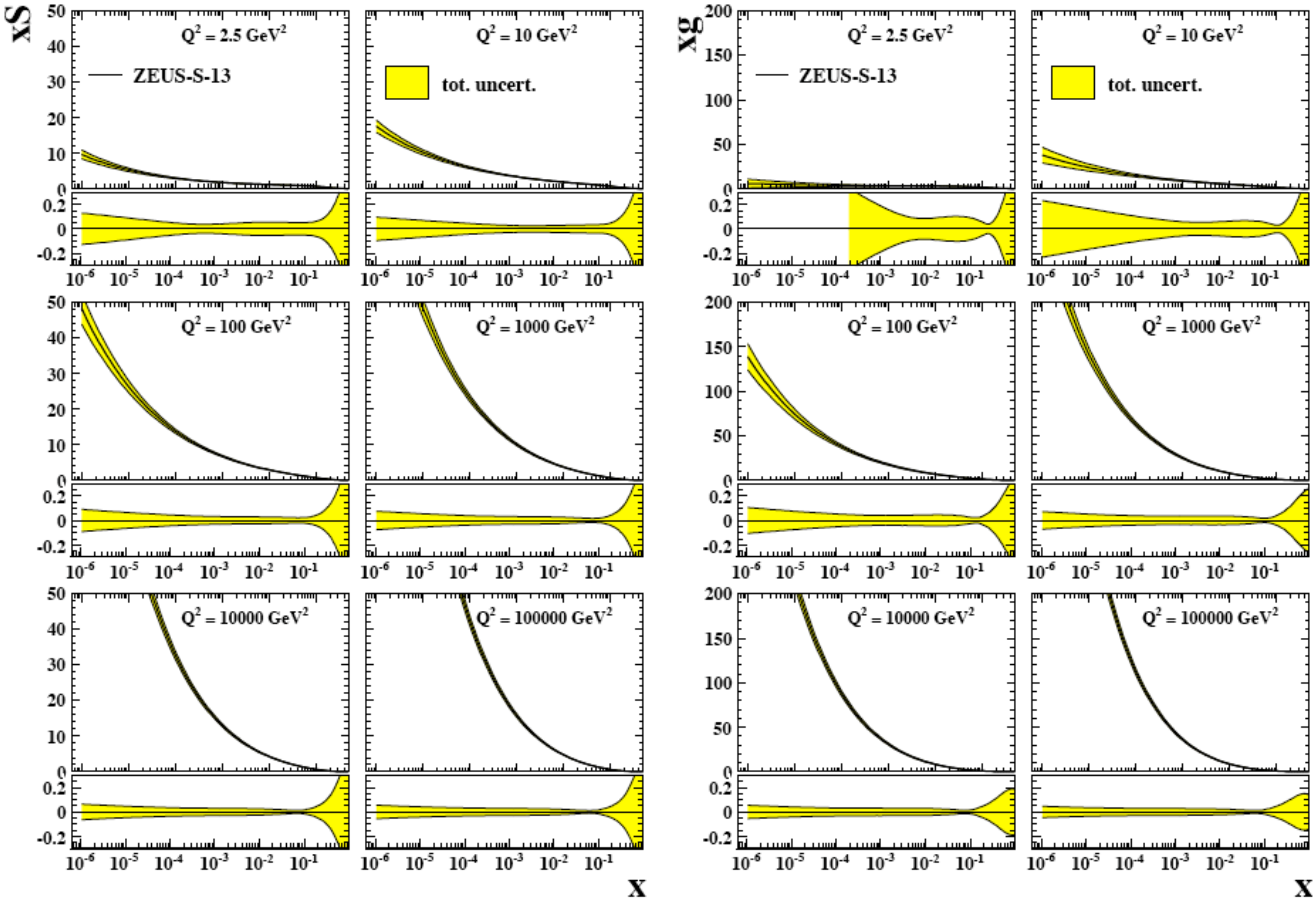


The H1 and ZEUS experiments at HERA have made great progress by probing a much deeper kinematic region



Most surprising result is the steep rise of the gluon structure function at low Bjorken x ➔ significant impact on ν scattering

Parton distribution functions from the ZEUS-S global data analysis

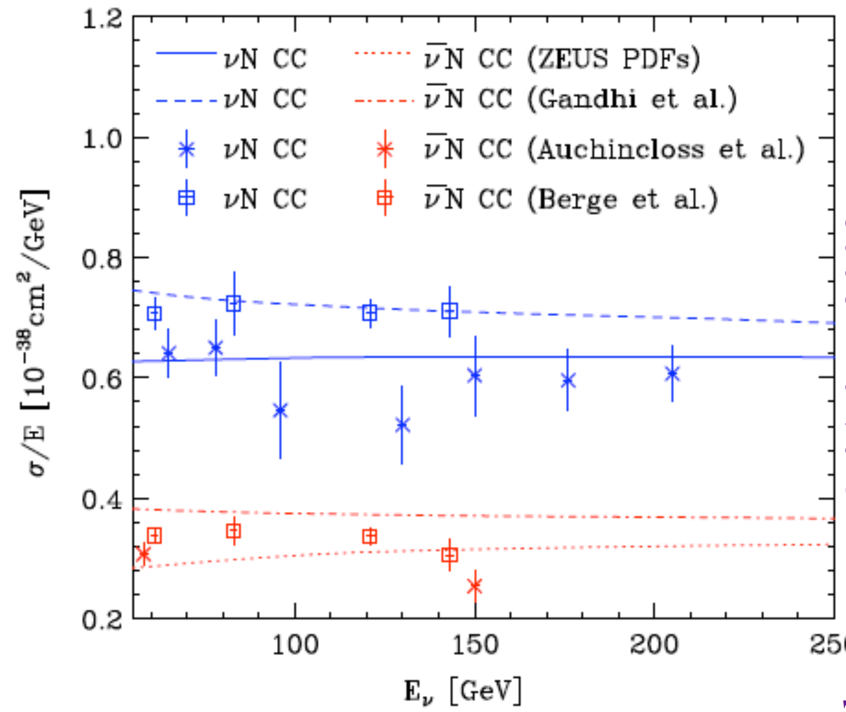


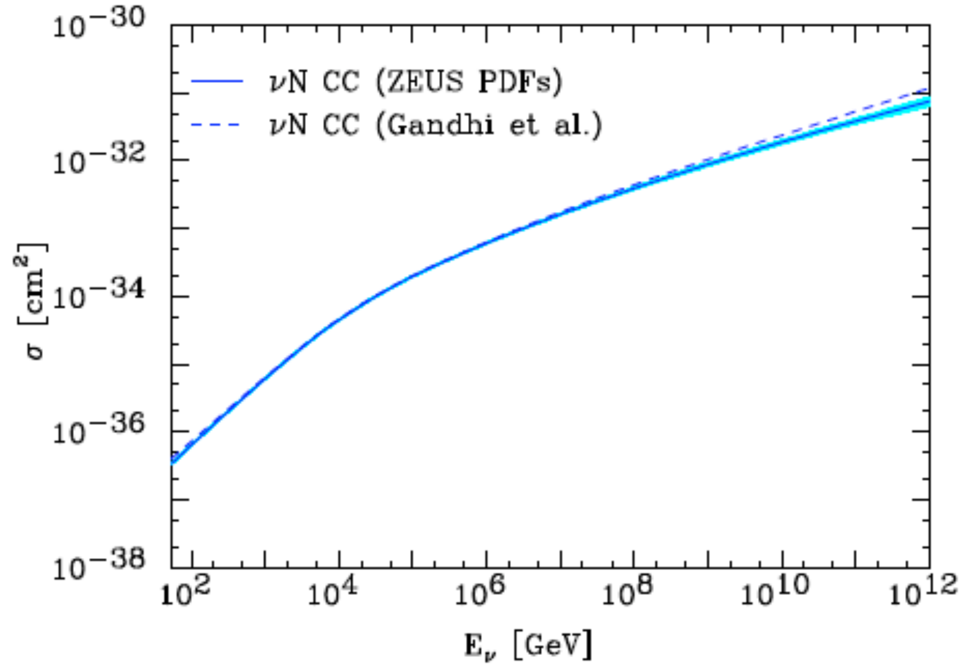
Cooper-Sarkar & Sarkar, JHEP 01:075,2008

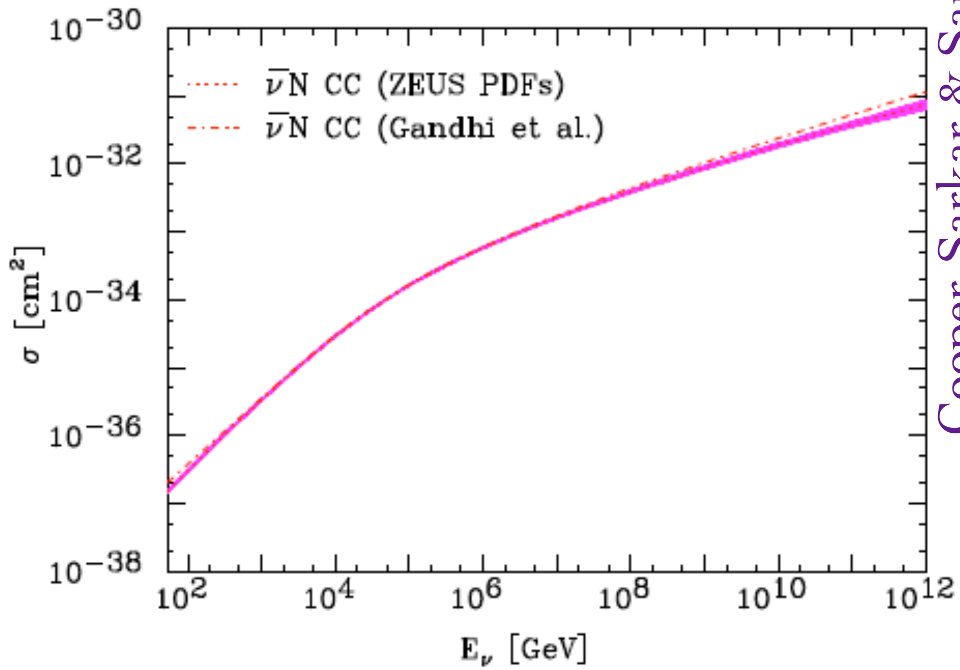
using DGLAP evolution of the PDFs (at NLO, incl. heavy quark corrections)

The #-section is up to ~40% *below* the previous 'standard' calculation by Gandhi *et al* (1996) … more importantly the (perturbative SM) *uncertainty* has now been calculated

Being used by Auger, IceCube etc … to be incorporated in ANIS MC

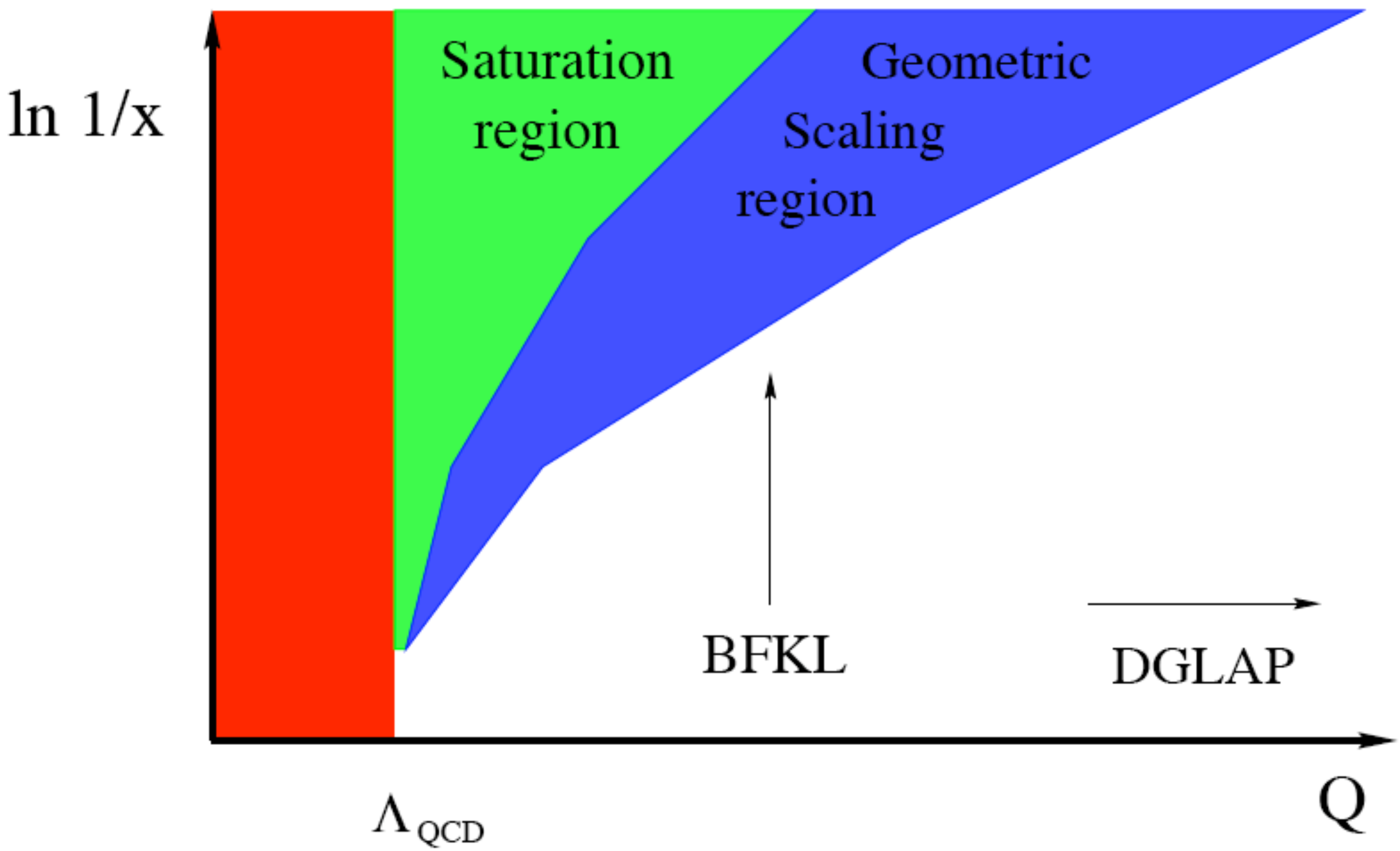






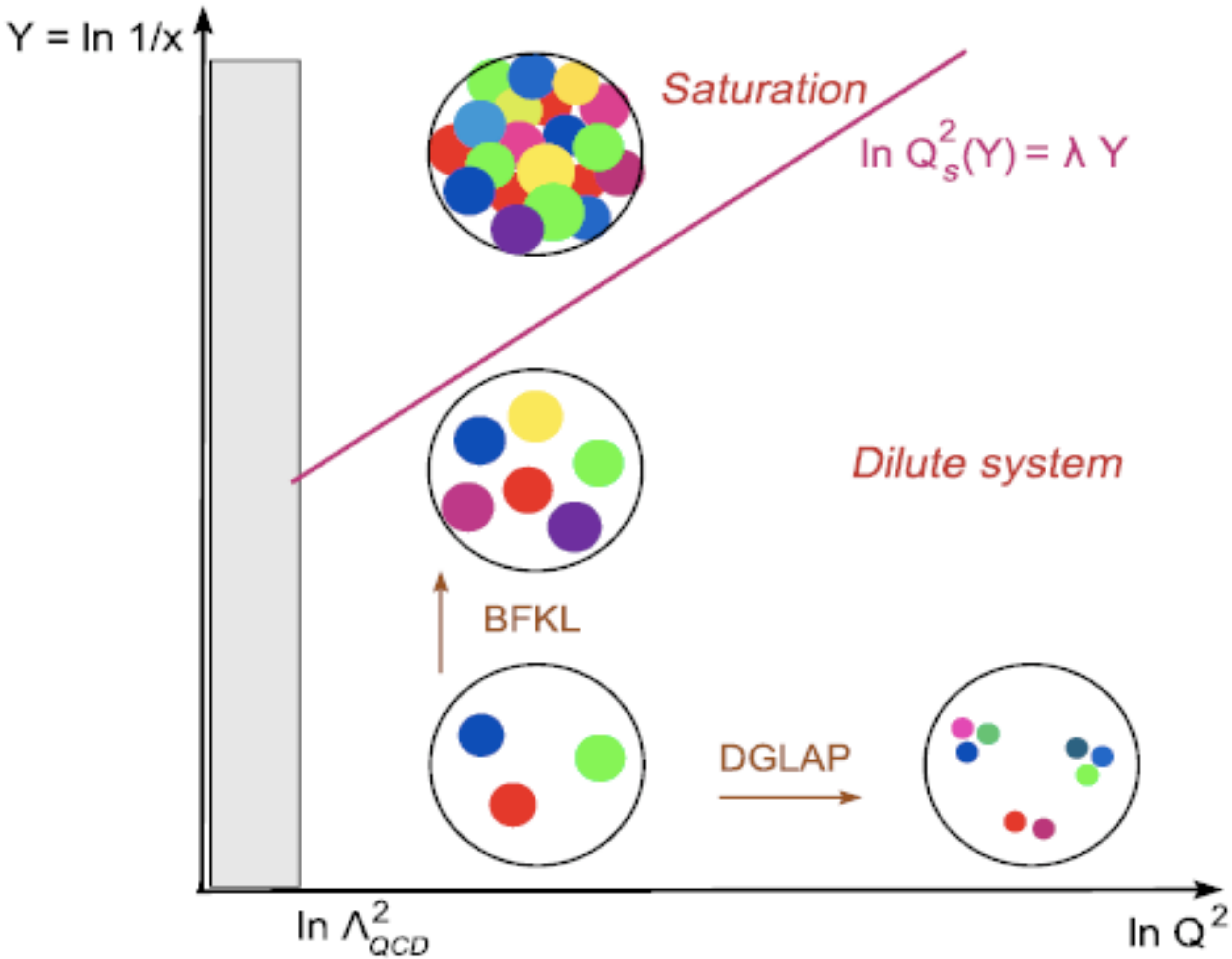
Cooper-Sarkar & Sarkar, JHEP 01:075,2008

As the gluon density rises at low x, non-perturbative effects become important … a new phase of QCD - Colour Gluon Condensate - has been postulated to form



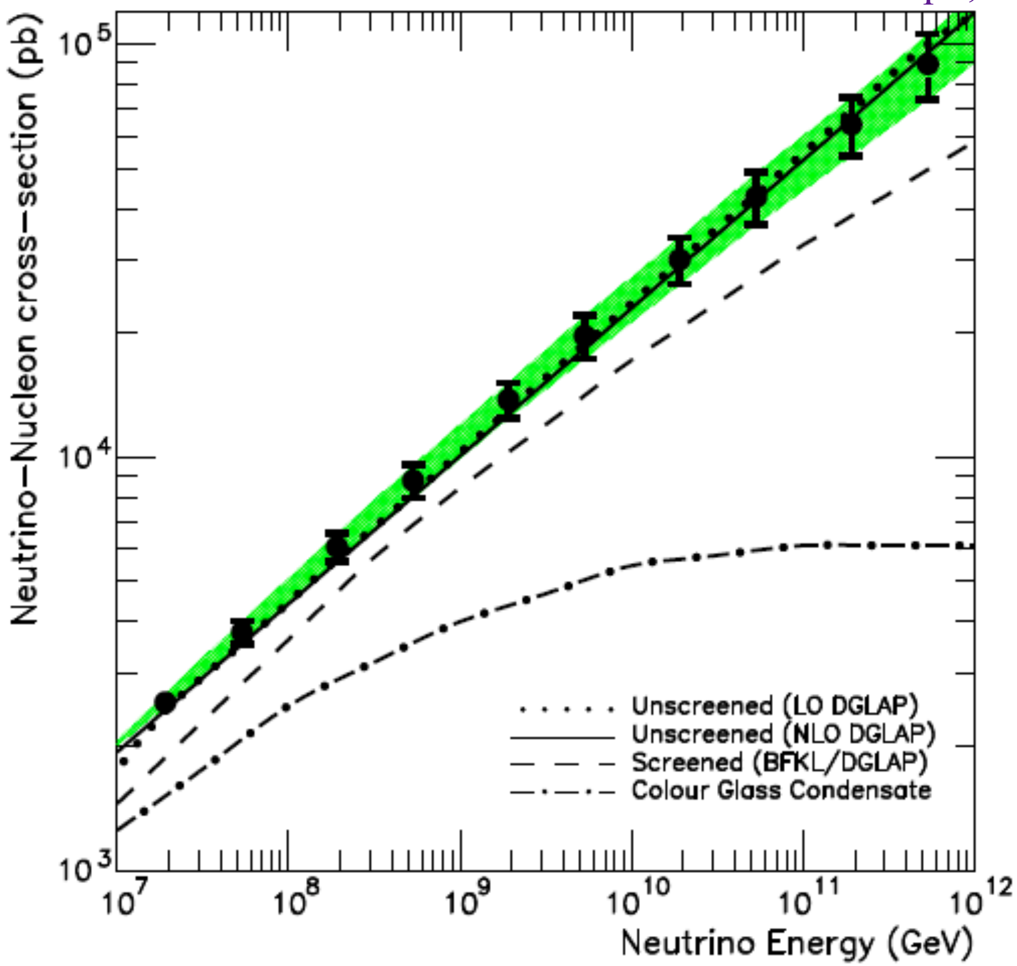
This would *suppress* the ν-N #-secn below its (unscreened) SM value

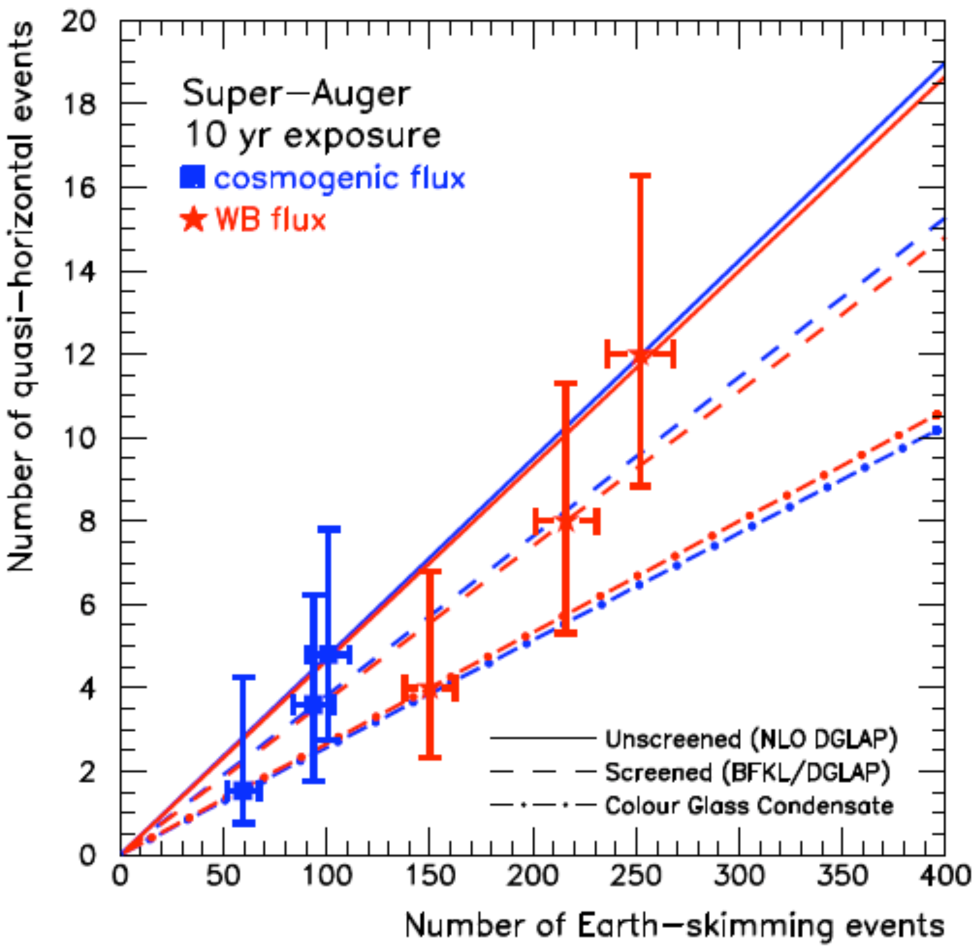
Challenging theoretical area … and very active
(because of related physics of 'glasma' from
significant experimental developments at RHIC … soon LHC)



Beyond HERA: probing low-x QCD with cosmic UHE neutrinos

Anchordoqui, Cooper-Sarkar, Hooper & Sarkar, PR D74:043008,2006



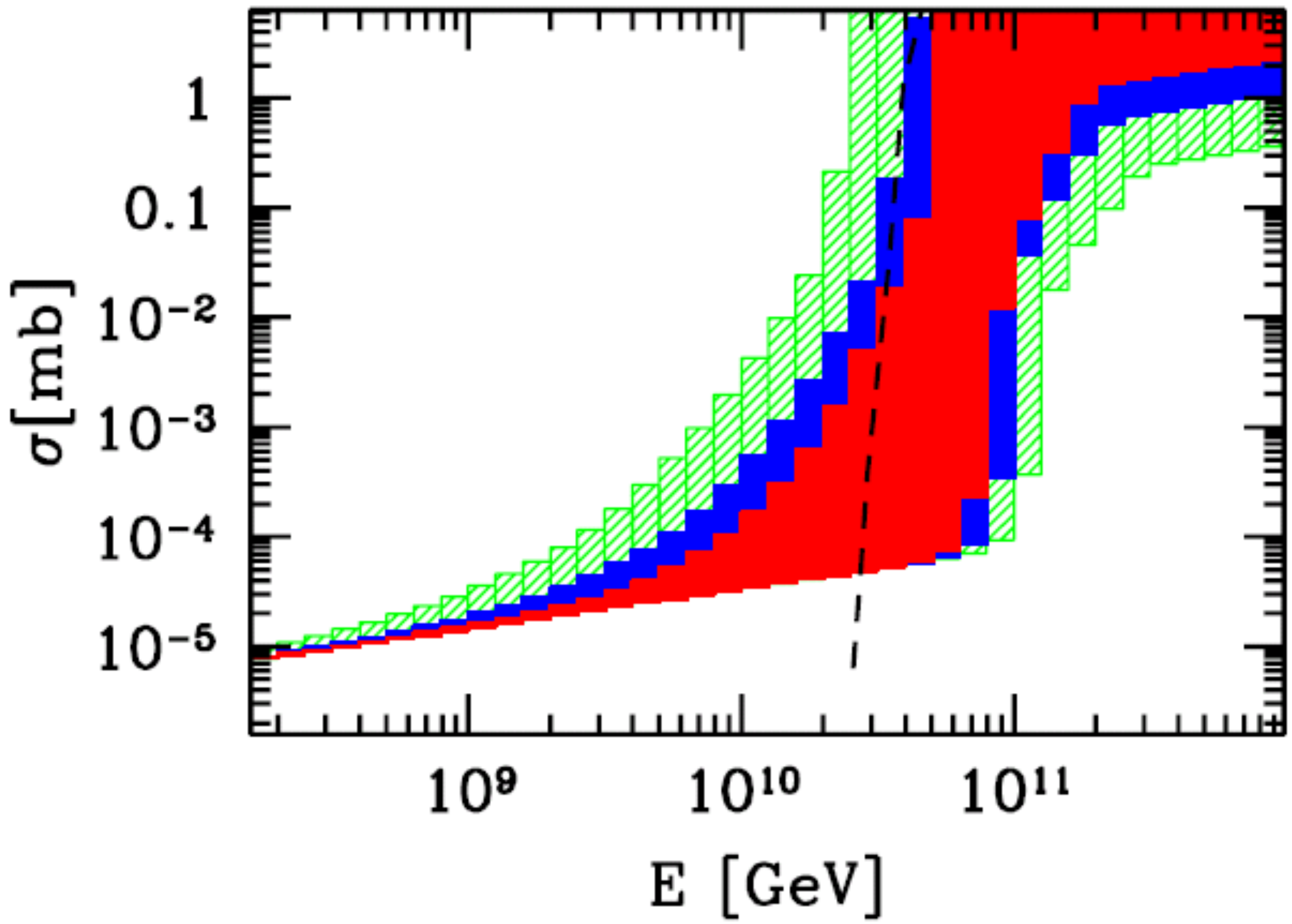


The steep rise of the gluon density at low-x must saturate (unitarity!)
➔ suppression of the ν-N σ-secn

The ratio of quasi-horizontal (all flavour) and Earth-skimming (ν_τ) events *measures* the cross-section

Electroweak instanton-induced interactions in the SM

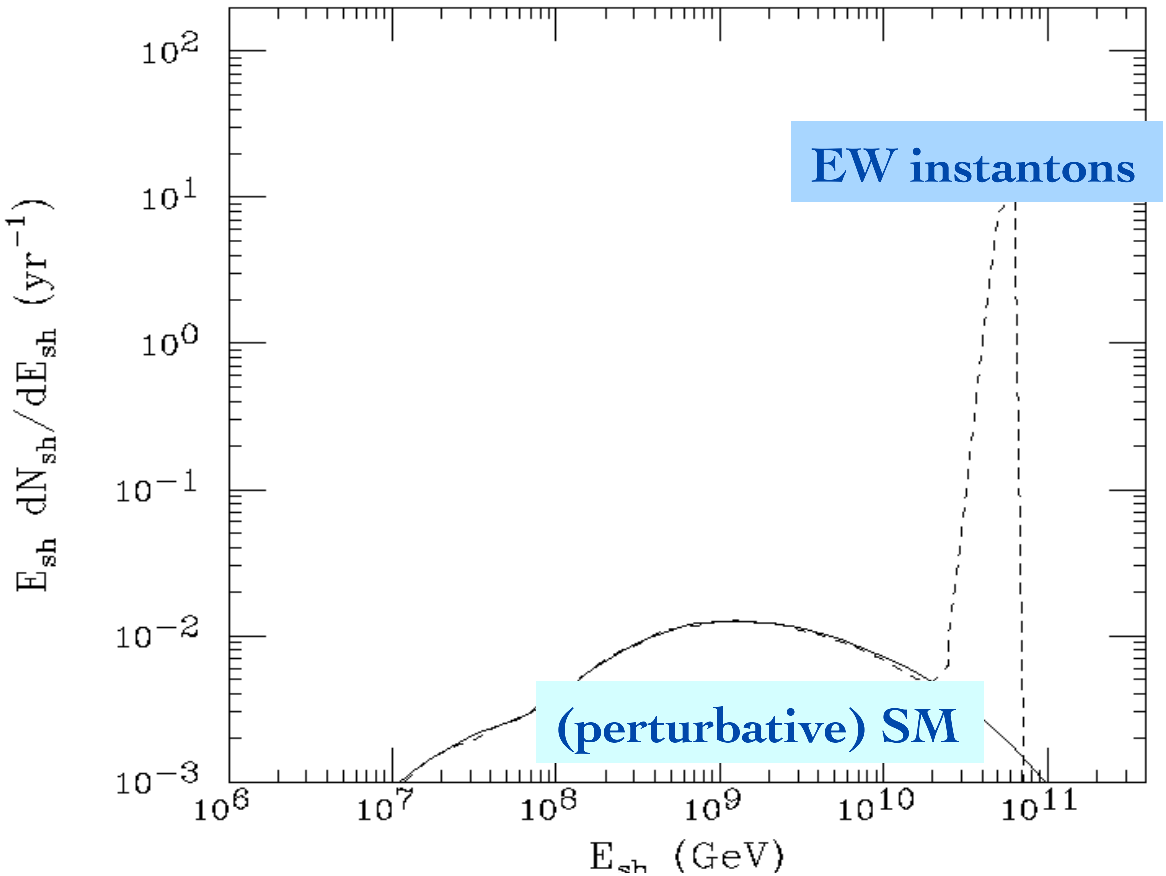
Non-perturbative transitions between degenerate SM vacuua (with different B+L #)
are exponentially suppressed below the "sphaleron" mass: ~ M_W/α_W ~ 8 TeV
… but huge cross-sections are predicted for ν-N scattering at higher cms energies
(would enable neutrinos to generate apparently hadronic super-GZK air showers)



Ahlers, Ringwald & Tu, AP 24:438.2006

Electroweak instantons at Auger

Quasi-horizontal ν_τ showers (assuming cosmogenic flux)



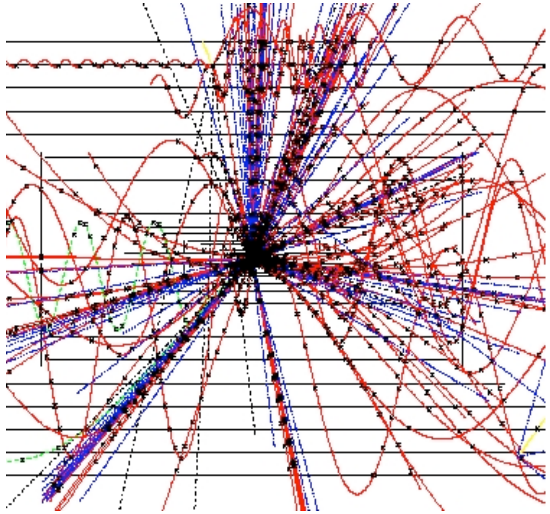
Large **deviations from perturbative SM expected above 10^{10} GeV**

predict 4.3 QH showers/yr ⇒ probably ruled out already

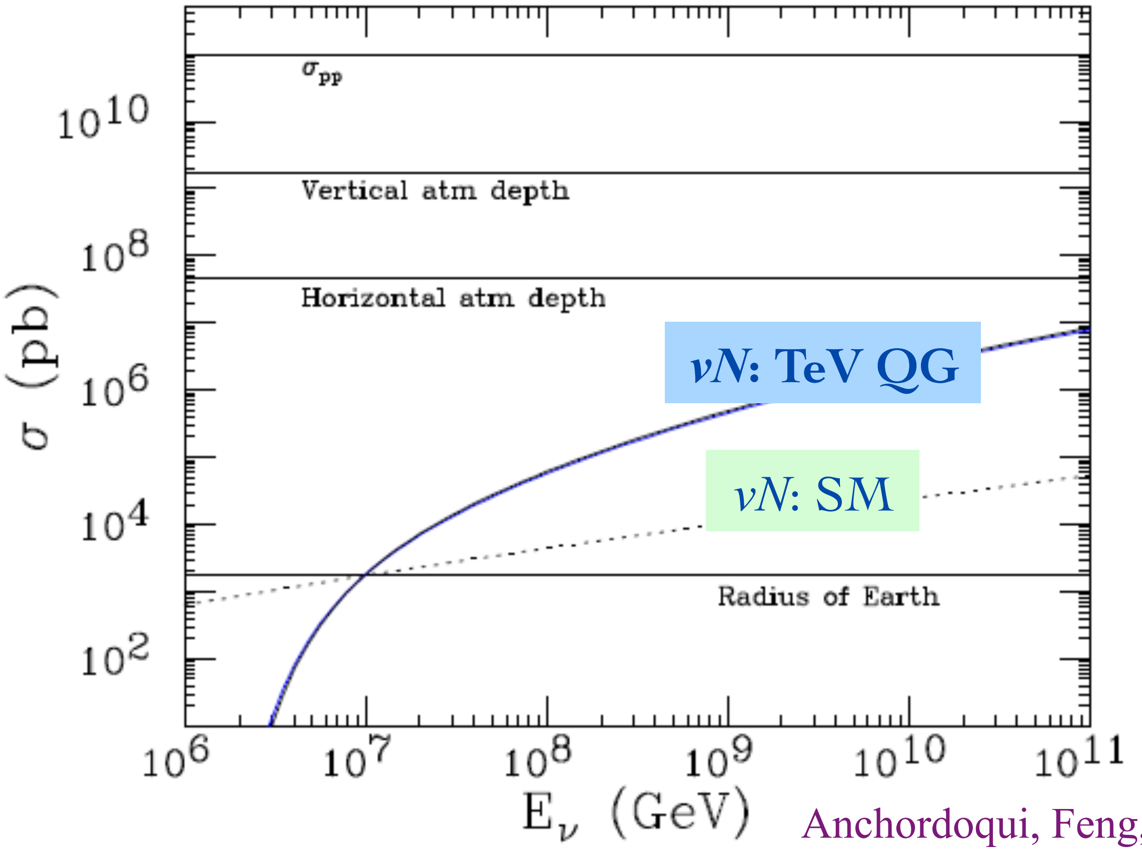
Anchordoqui, Han, Hooper & Sarkar, AP 25:14,2006

TeV scale quantum gravity?

If gravity becomes strong at the TeV scale (as in some brane-world models) then at cms energies well *above* this scale, **black holes** will form with $M \sim \sqrt{\hat{s}}$ and $A \sim \pi R^2_{\text{Schwarzschild}}$



(courtesey: Albert De Rocek)



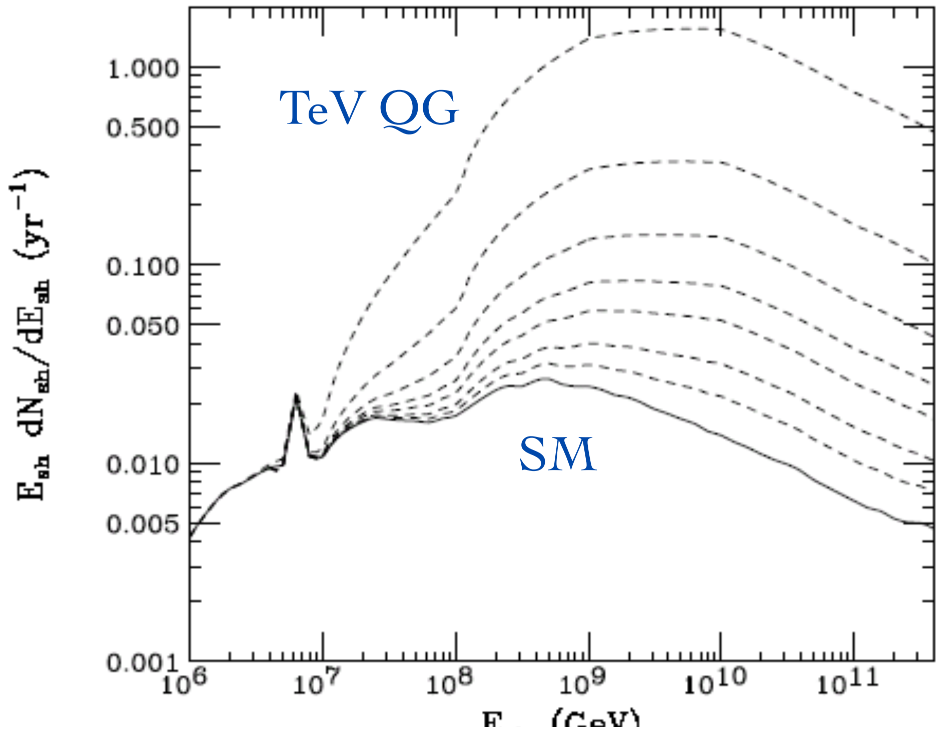
… and then evaporate rapidly by Hawking radiation (+ gravitational waves?)

This will enhance the neutrino scattering #-secn significantly

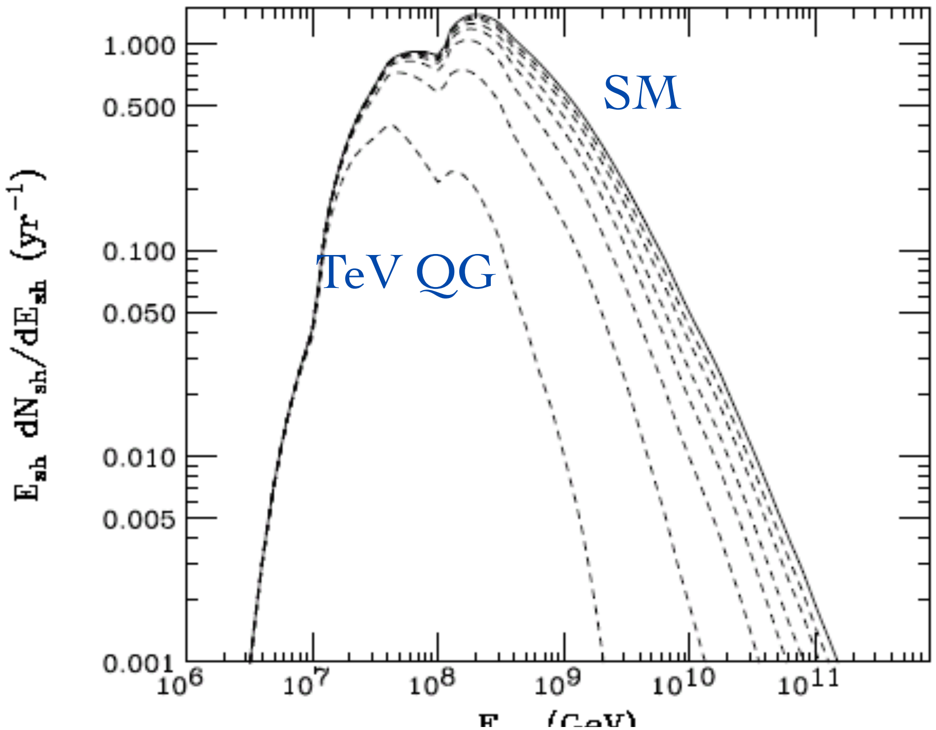
Anchordoqui, Feng, Goldberg & Shapere, PR D68:104025, 2003

Testing TeV scale quantum gravity (assuming WB flux)

Quasi-horizontal ν showers



Earth-skimming ν_τ showers



Auger is well suited for probing microscopic black hole production

QH/# ES= 0.04 for SM, but ~10 for Planck scale @ 1 TeV

Anchordoqui, Han, Hooper & Sarkar, AP 25:14,2006

Summary

Prospects are good for the identification of the sources of medium energy cosmic rays by γ-ray astronomy ... but more work is needed on theory

Auger will soon answer crucial questions about the energy spectrum, composition and anisotropies of ultra-high energy cosmic rays … the theoretical situation is even more challenging

The detection of ultra-high energy cosmic neutrinos is eagerly anticipated – will provide complementary information and identify the sources

Cosmic ray and neutrino observatories provide an unique laboratory for tests of new physics beyond the Standard Model

"The existence of these high energy rays is a puzzle, the solution of which will be the discovery of new fundamental physics or astrophysics"

Jim Cronin (1998)