The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2246-22

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Are Km3 neutrino telescopes sufficiently large to detect astrophysical neutrino sources?

Paolo LIPARI
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Italy

Are Km3 telescopes sufficiently large to observe astrophysical neutrinos ?

Paolo Lipari
NUSKY workshop
Trieste 20-24 may 2011

The idea to observe the Universe using Neutrinos is profoundly fascinating.

The insights about Nature that are possible with this: "New Way" to look at the Sky can be profound.

Neutrino Astronomy is an old "DREAM"

The scientific significance of this idea has been recognized very early after the "invention" of the neutrino

The "dream" has become a reality with Solar and SuperNova neutrinos [E ~ 0.5 – 30 MeV]

What about “high energy neutrinos” ?

Still an open problem .....
.... a very difficult challenge .....

The “High Energy Universe”:

Fundamental, fascinating question
With many uncertainties and open problems

A century old problem (the origin of cosmic rays)

A “quantum leap” in understanding
Gamma Astronomy [GeV !, TeV !]
[multi-wavelength observations ! Radio, X-rays]

Field with great “dynamism”

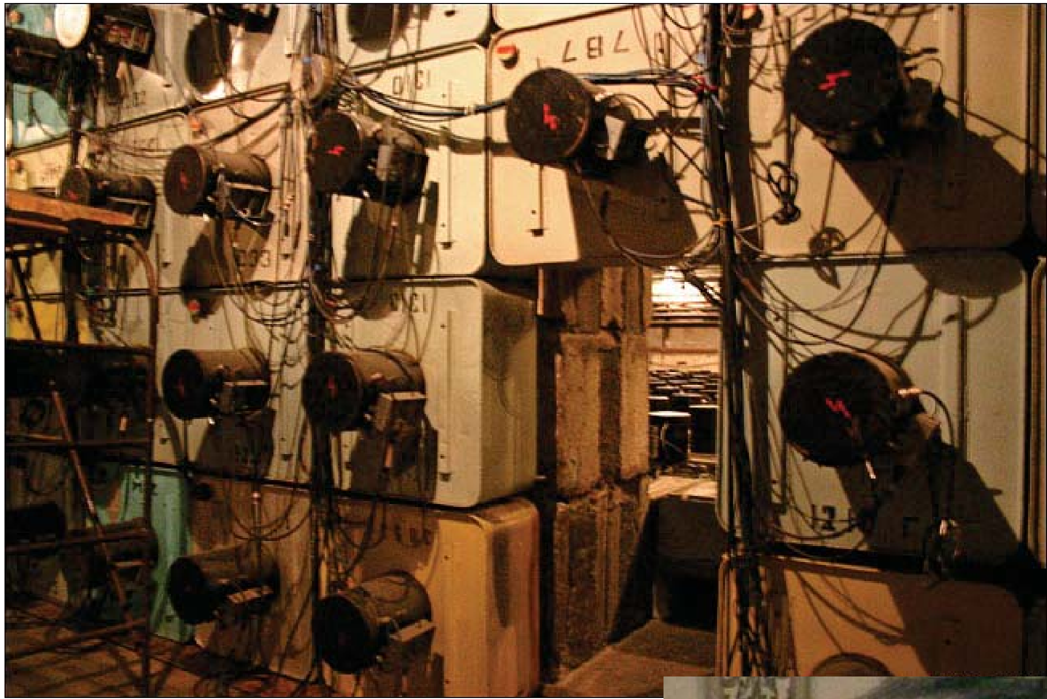
"The estimate of the neutrino flux may be too low, since regions that produce neutrinos abundantly may not reveal themselves in the types of radiation yet detected"

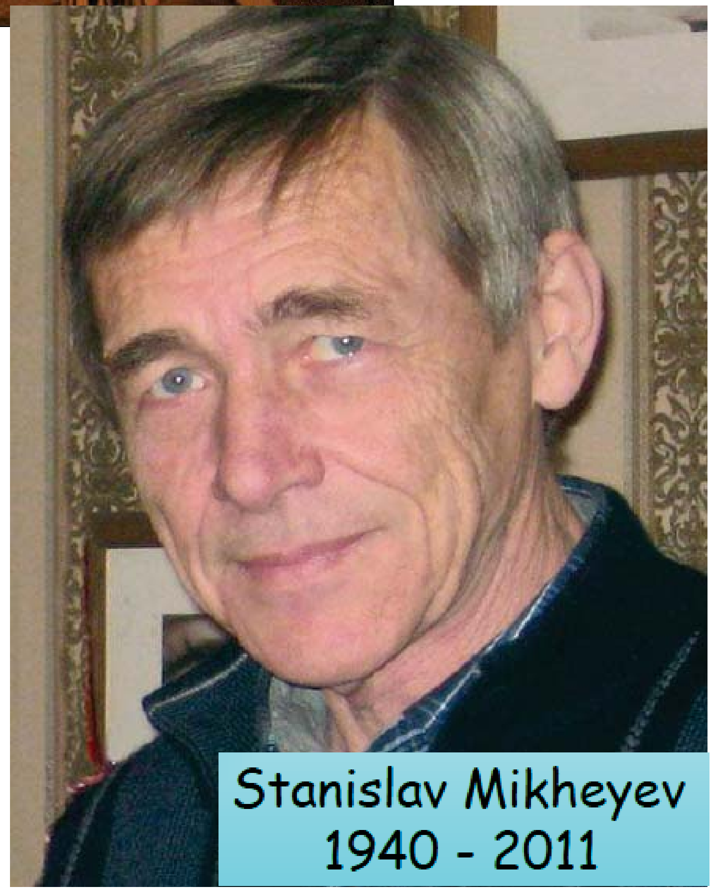
Kenneth Greisen 1960 (Review on CR)
advocating the construction of neutrino telescopes:

The "hunt" for the elusive astrophysical neutrinos.....

Long history of larger and larger detectors:

Baksan Neutrino Observatory



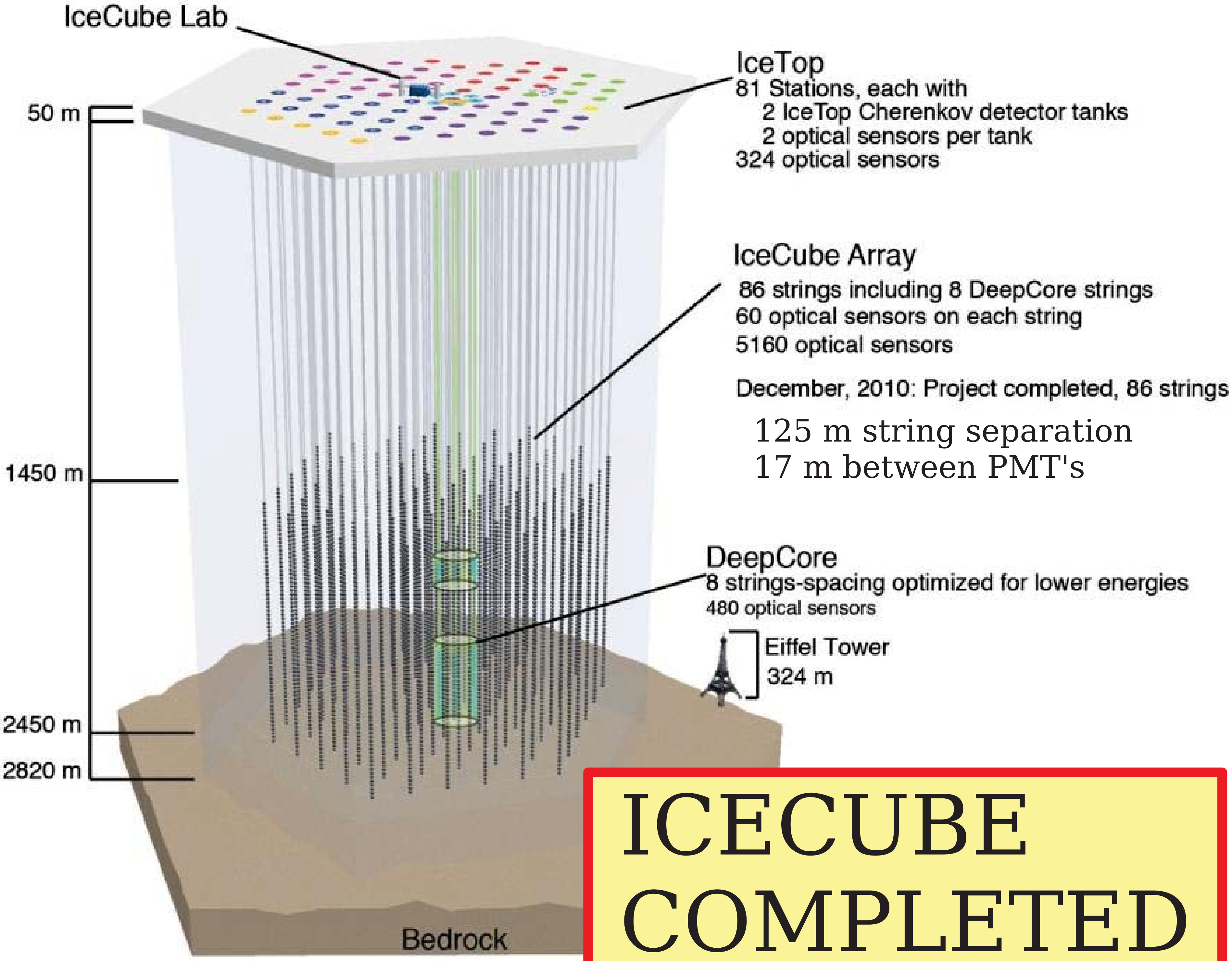


Neutrino Telescopes of growing size.

BAKSAN
MACRO at Gran Sasso (~1000 m^2)
BAIKAL
AMANDA at the South Pole (~10^4 m^2)
ANTARES

The "KM^3 concept"

"The 'natural size' for a neutrino telescope is 1 Km^3 of water / ice"


IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
50 m
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
125 m string separation
17 m between PMT's
1450 m
DeepCore
8 strings-spacing optimized for lower energies
480 optical sensors
Eiffel Tower
324 m
2450 m
2820 m
Bedrock
ICECUBE
COMPLETED

CONGRATULATIONS !

Extraordinary effort.
Remarkable technical success.

Beautiful results!
(CR anisotropies from down-going muons)

….. But still waiting for evidence of
Astrophysical Neutrinos …..

Very interesting upper limits,
But no signal in an exposure of order (½ Km^3 year)

…. yes, yes, of course ….

it is still too early, we have to be patient,
more statistics and improved analysis soon ! …..

However: let us consider the situation at the present "unstable" moment, soon before the time when the significance of this wonderful concept will be established.

Will virtue be rewarded ?

No evidence for Astrophysical Neutrinos in ½ Km3 yr

Disappointment ? .....YES ....OF COURSE !! ....

Surprise ? NO. Signals at this level were expected only in optimistic/serendipitous scenarios.

Problem ? YES. IceCube (in the present configuration) will only just "scratch the surface" of neutrino astronomy.
[there are already lessons to be extracted]

Disappointment....

The development of the
"Beaded String" concept for neutrino telescopes
has improved the sensitivity
by two orders of magnitude !

These telescopes *could* have discovered sources!

The limits [on the diffuse neutrino fluxes]
are falsifying physical scenarios that are viable.
and do have interesting astrophysical significance.

....and then...
there is "SERENDIPITY"...

The "princes of Serendip"
have not smiled
to Francis and Tom and their friends ....

(perhaps their smile is beyond that corner ?...)

Francis Halzen: 1996

Table 1: New windows on the Universe

Telescope	Intended use	Actual results
optical (Galileo)	navigation	moons of Jupiter
radio (Jansky)	noise	radio galaxies
optical (Hubble)	nebulae	expanding Universe
microwave (Penzias-Wilson)	noise	3K cosmic background
X-ray (Giacconi. . .)	moon	neutron stars. . .
radio (Hewish, Bell)	scintillations	pulsars
γ-ray (???)	thermonuclear explosions	γ-ray bursts
Neutrino Telescopes	{SNR, AGN,...}	{???}

½ Km3 -year exposure and no neutrinos …

Surprise ? Not Really.

“Historic” review: Gaisser, Halzen, Stanev. Phys. Rep. 1995.

Table 5

	Muon energy	Events per year in 0.1 km^2	
		Ref. [72]	Ref. [75]
Atmospheric (angle averaged, per steradian)	> 1 GeV	7800	8300
	> 1 TeV	129	104
		$\cos\theta = 0.05$	$\cos\theta = 0.95$
Atmospheric in 1° circle, Ref. [75]	> 1 GeV	12.6	5.6
	> 1 TeV	0.21	0.05
		no abs.	with abs.
Extraterrestrial fluxes (angle averaged)	> 1 GeV	32.7	32.0
$\phi_\nu = 2.7 \times 10^{-5}(E_\nu/\mathrm{GeV})^{-1.7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	> 1 TeV	4.3	3.8
$\phi_\nu = 4.0 \times 10^{-8}(E_\nu/\mathrm{GeV})^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$	> 1 GeV	8.8	6.6
	> 1 TeV	5.0	3.3
		plane of galaxy	AGN
Astrophysical diffuse fluxes (per steradian)	> 1 GeV	12–20	80–200
	> 1 TeV	1.5–3.0	40–200
	also $\nu_e(6.3\,\mathrm{PeV}) + e \to W^-$		0.3 per 1000 kton
Astrophysical point sources ($E_\mu > 1$ TeV)			
Galactic source (Eq. 37)/100			2.6
Extragalactic source			0.1–10
500 GeV WIMPS from ⊙			20

Reasonable prediction [at the time]
But overestimates (by factor of 10).

Now: natural questions:

1. What is the meaning of the new limits.
2. Can one make better predictions today ?
3. Are there “guaranteed” sources

What if 2 years from now no signals ?
Which directions should one follow ?

[are these legitimate/appropriate questions?]

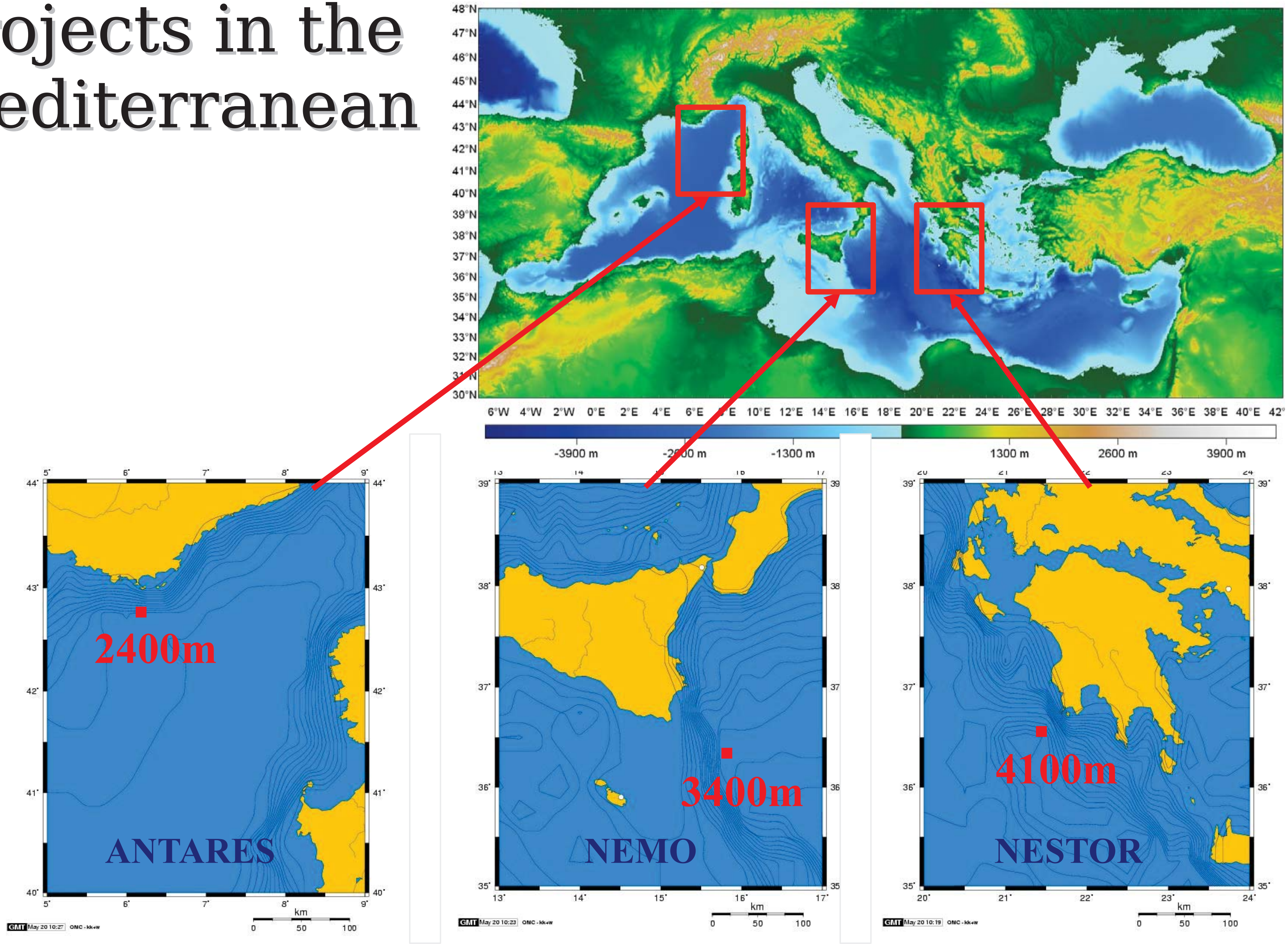
For the “KM^3 concept”

the “moment of truth” has arrived.

Difficult choices for the proponents of
a neutrino detector of similar conception in the
Mediterranean Sea

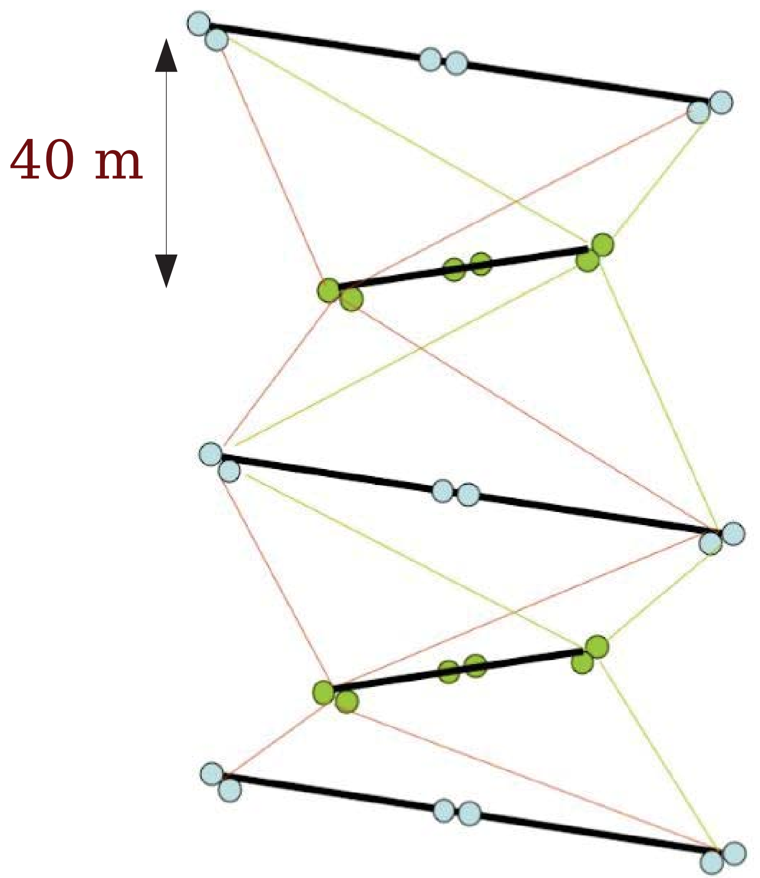
[looking at the Southern hemisphere of
the celestial sphere]

Projects in the Mediterranean



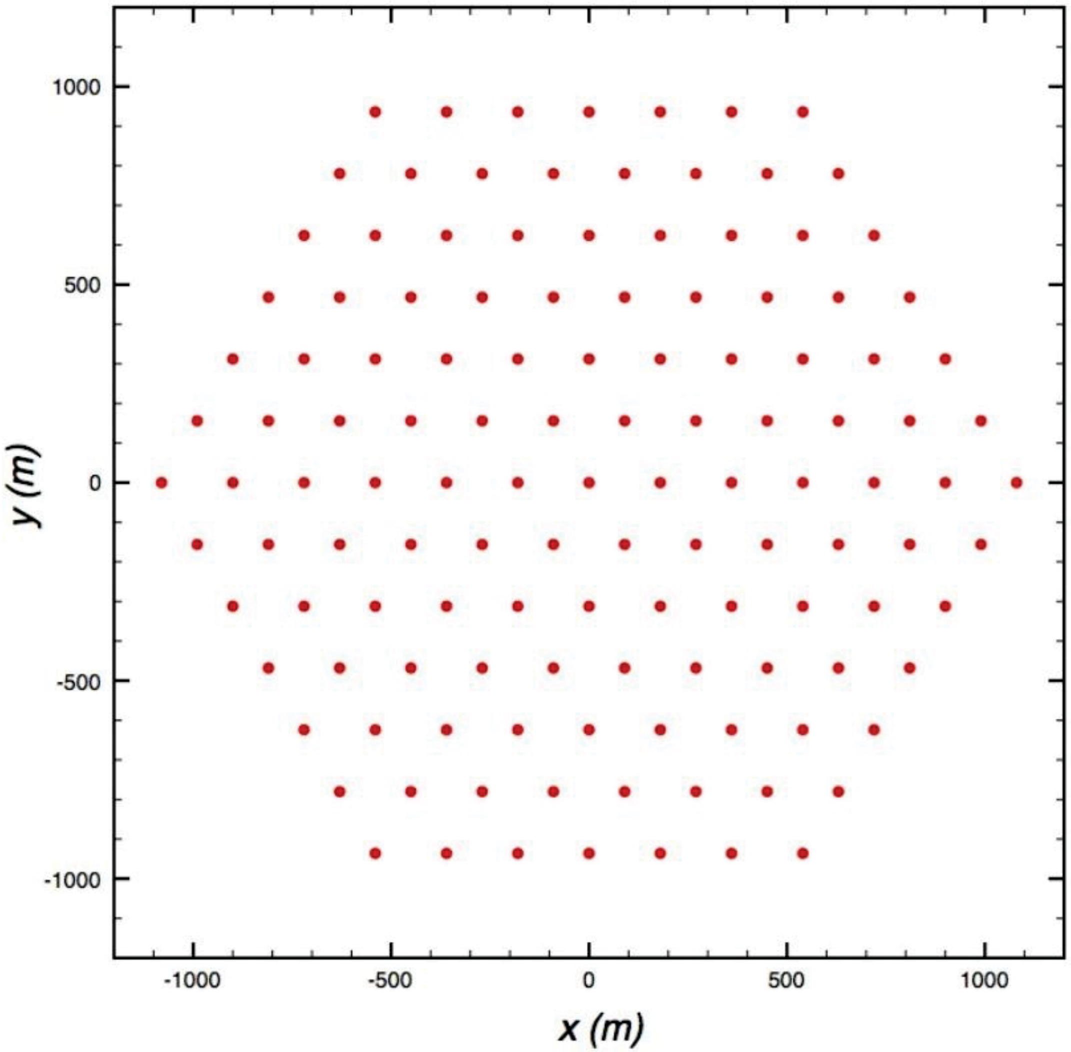
Possible structure of a "KM3" detector in the Mediterranean Sea:

"tower" [6 PMT's]



Detection Unit layout.

127 towers (180 m)



Multi-Site ?!

A detector in the Mediterranean Sea
has one crucial advantage with respect
to IceCube at the South Pole:

A view of the CENTER of our GALAXY

Galactic Center
Galactic sources

In principle also a better angular resolution
for the muon direction (less scattering in water).

Therefore smaller integration cone in the
study of point sources: smaller background.

For a neutrino telescope in the Mediterranean,
to obtain [after a very important effort]
only Upper Limits on astrophysical neutrinos
[several years after IceCube]
would be a VERY unsatisfactory result.

How does one protects him/her self from this danger?

One can make the telescope bigger....
[but how much bigger ?]

What are the most interesting scientific goals?
What is the best design (for these goals)?

Should one perhaps change the concept ?
Different technique (acoustic, radio, taus)

We talk about:

NEUTRINO ASTRONOMY

Radio-astronomy
Optical-astronomy
X-ray astronomy
......

But really there are several

NEUTRINO ASTRONOMIES

$$10^{10}\ \mathrm{eV} \lesssim E_\nu \lesssim 10^{21}\ \mathrm{eV}$$

Very broad energy range

NEUTRINO ASTRONOMIES

$$E_\nu \sim [10^{10} \div 10^{12}]\ \text{eV}$$

Dark Matter

$$E_\nu \sim [10^{13} \div 10^{14}]\ \text{eV}$$

Point sources

$$E_\nu \sim [10^{14} \div 10^{17}]\ \text{eV}$$

GRB [exploration]

$$E_\nu \sim [10^{17} \div 10^{20}]\ \text{eV}$$

Cosmogenic Neutrinos

$$E_\nu \gtrsim 10^{20}\ \text{eV}$$

"Exotic" (TD decay...)

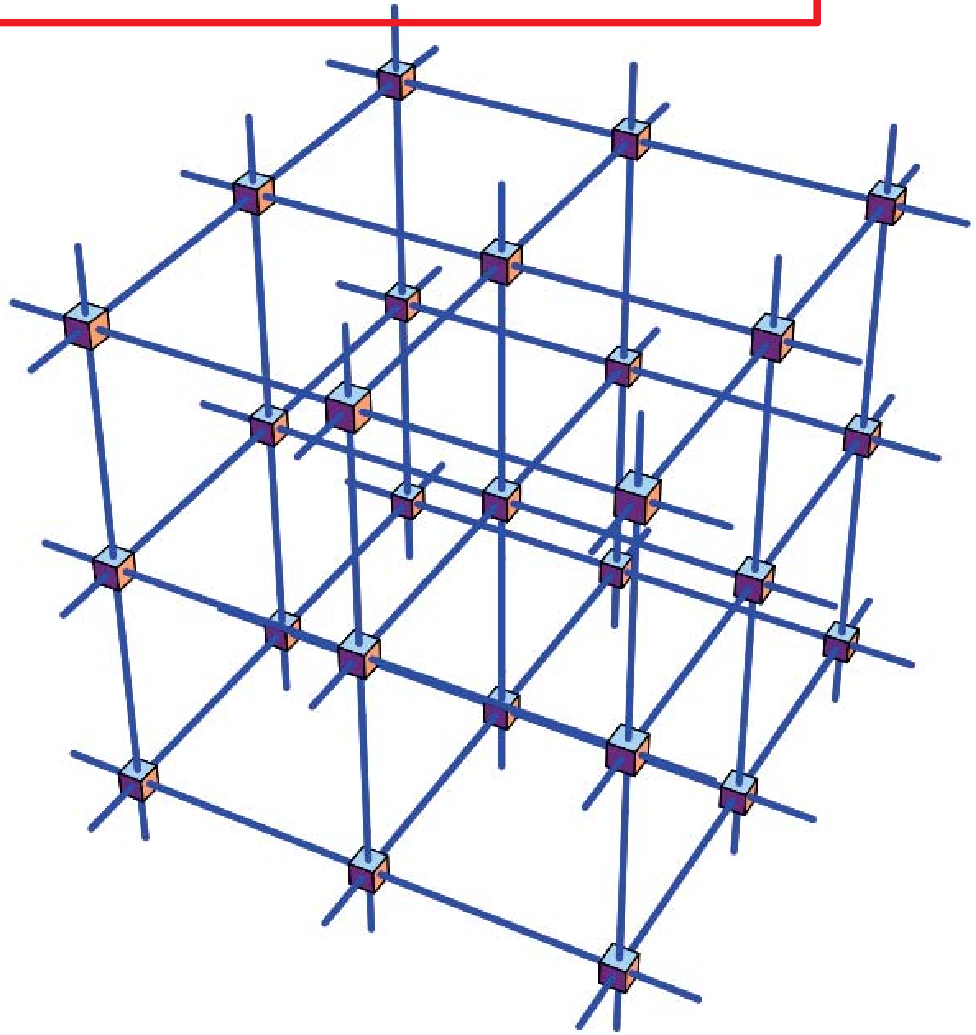
EXTRA-GALACTIC NEUTRINOS

AGN
GRB
......

Main candidate sources

Intimate relation with
UHECR [extragalactic cosmic rays]

The 3-dimensional lampposts ensemble "paradox" [Kepler – Olbers paradox].



Linear sequence of lampposts:

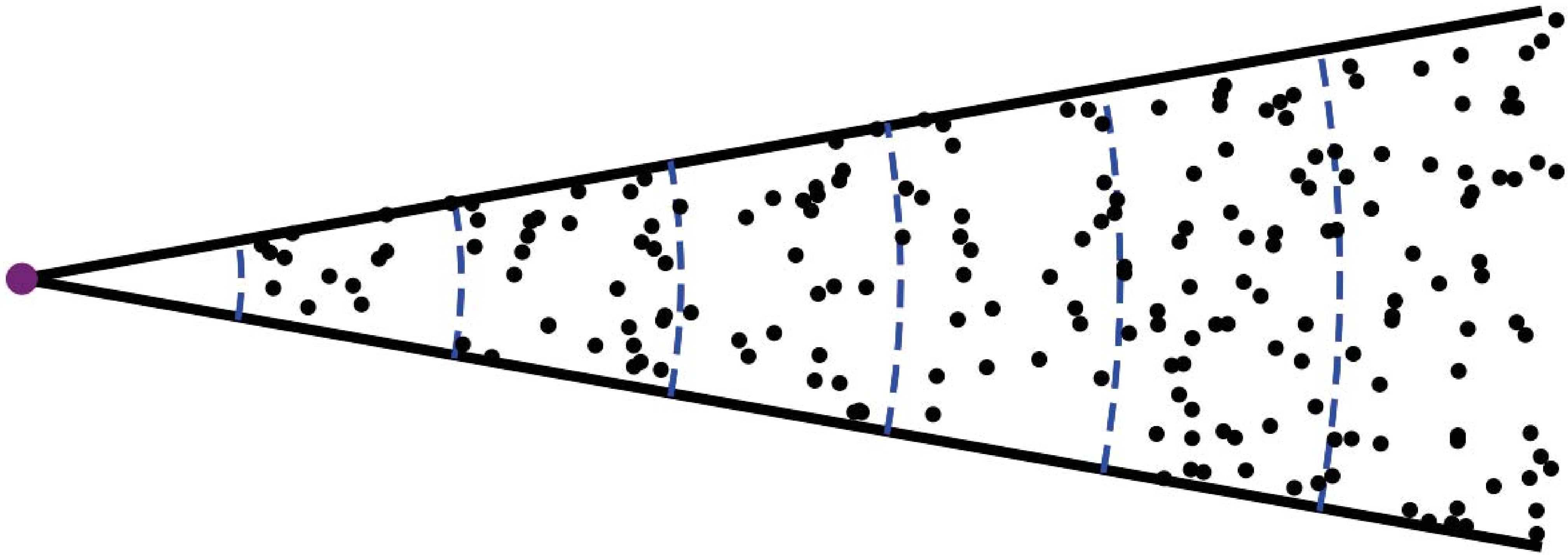
Most of the light you receive from the nearest lamppost

3D ensemble of lampposts: [Euclidean static space]

Light diverges !

Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ...

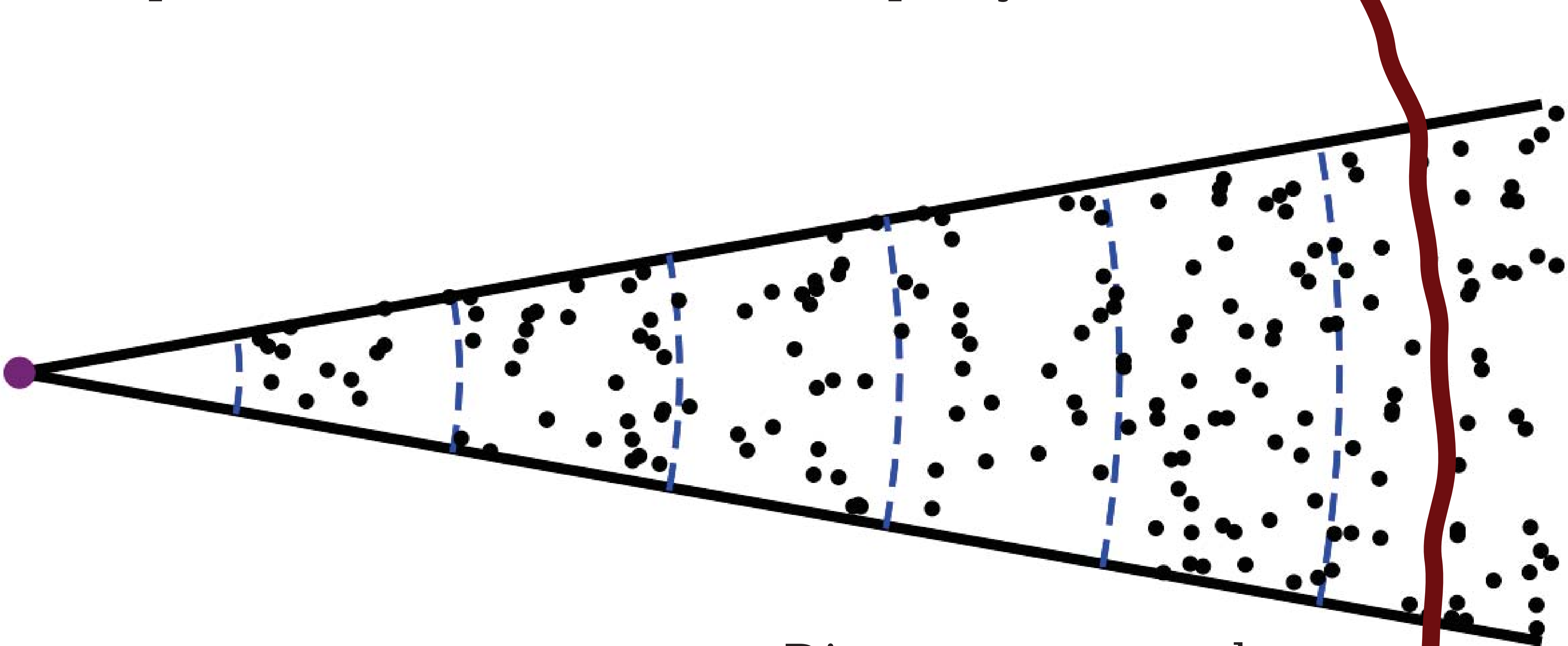
All spherical shells contribute equally.: DIVERGENCE!



$$\left(\frac{1}{4\pi\, R^2}\right) \quad \left(4\pi\, R^2\, \Delta R\right)$$

Homogeneous (in average) density of sources:
spherical shells between radii: 1, 2, 3, 4, ...

All spherical shells contribute equally.: DIVERGENCE!



Divergence cured
By cosmological effects

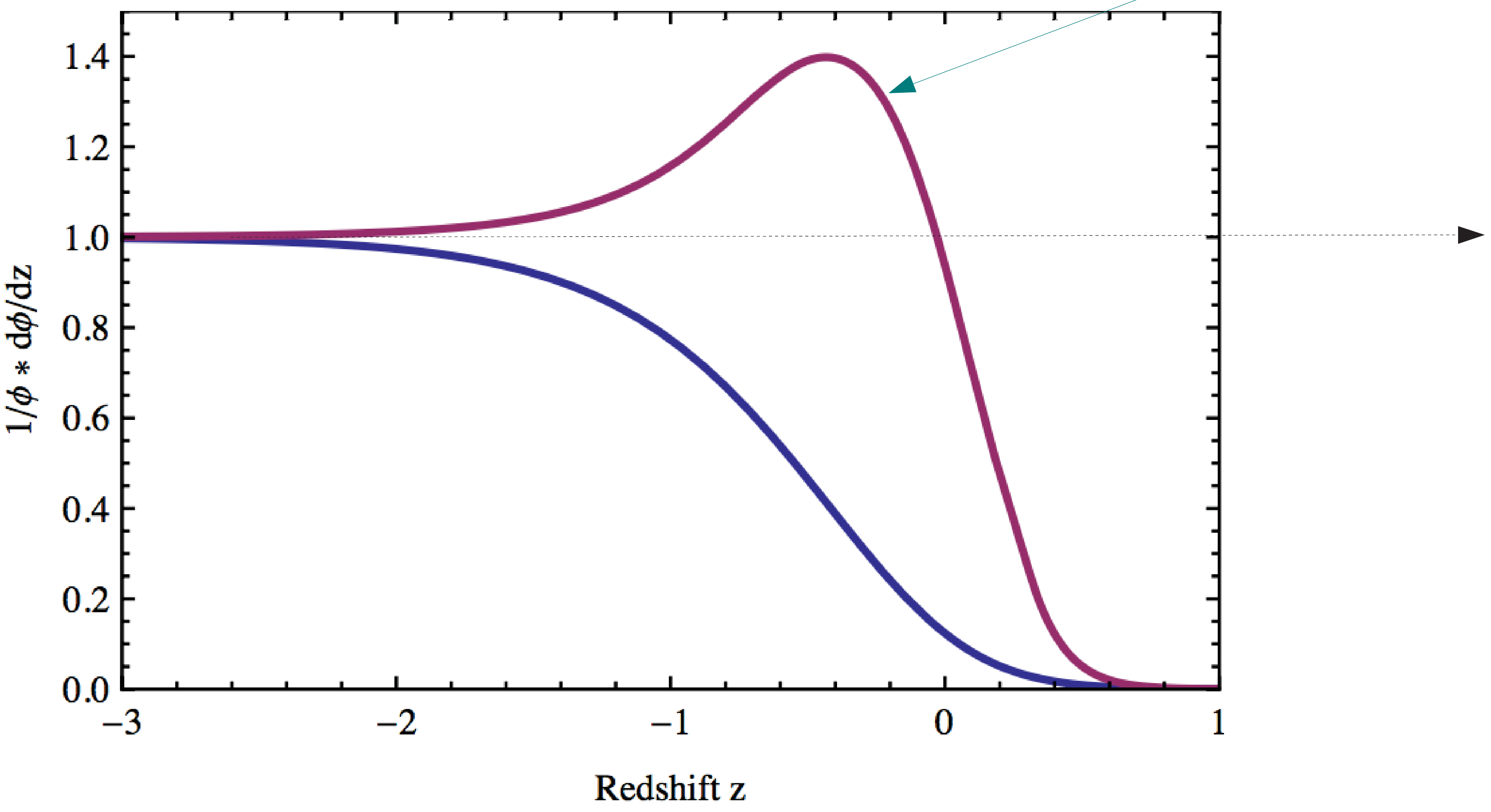
$$\left(\frac{1}{4\pi R^2}\right) \quad (4\pi R^2 \, \Delta R)$$

$$R_{\rm Hubble} = \frac{c}{H_0} \simeq 3 \text{ Gpc}$$

Solution of the Paradox:
The expansion of the universe.

Cosmological effects "cut" the integration
For $r > c/H_0$

Source Evolution



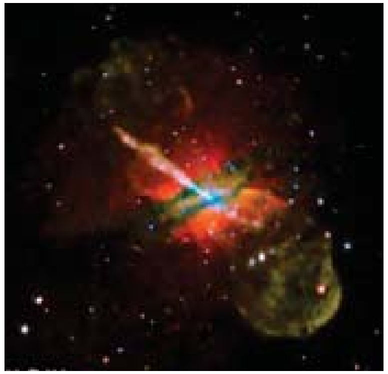
LARGEST extragalactic signal comes from large distances, dominated by the sum of many very faint unresolved sources.

“DIFFUSE ISOTROPIC” flux

CEN A

the closest AGN: (3.5 Mpc)

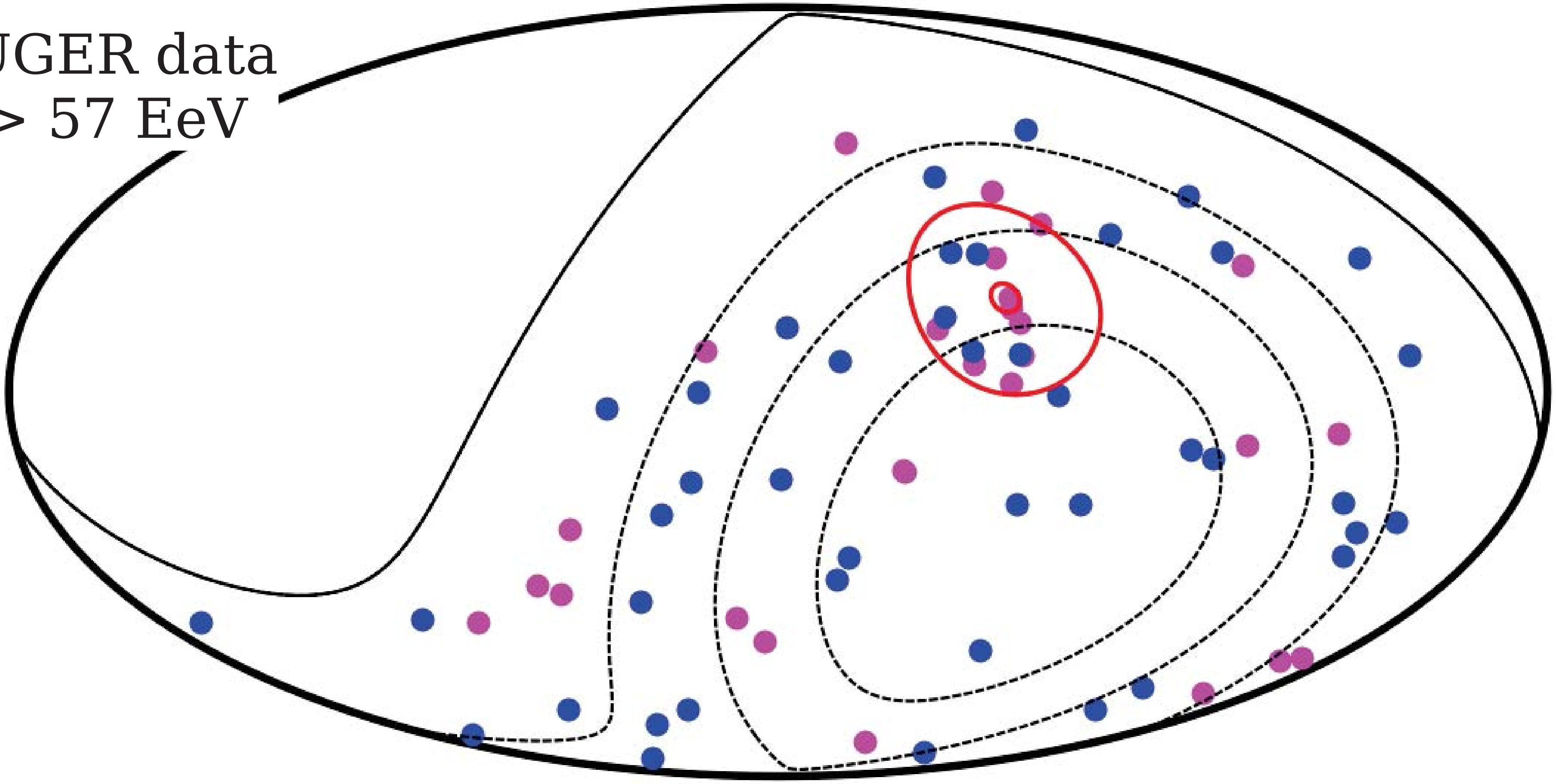
3 events within 3 degrees
13 events within 18 degrees



Point source of UHCR ?

Point source of neutrinos ??

AUGER data
E > 57 EeV



November 2008 (13 + 14 events)
Update september 2010 (+42 events)

3, 20 degrees circles

Say one observes $N_0 \simeq 1$ events from CEN A in IceCube.

What are the implications for the diffuse flux?

If you have 1 CEN A, you have infinitely many others essentially identical sources distributed in the universe, each contributing to the neutrino event rate in IceCube.

If the comoving volume that contains 1 "CEN A-like" source is a sphere of radius R_0

Then the total number of events from all CEN A -like sources is:

$$N_{\rm all} = N_0 \left(\frac{R_{\rm Hubble}}{R_0} \right) \xi_\alpha$$

The quantity ξ_α is an adimensional number of order unity

$$\xi_\alpha = \int_0^\infty \frac{dz\ (1+z)^{-\alpha}}{\sqrt{\Omega_m (1+z)^3 + \Omega_\Lambda}} \frac{\mathcal{L}(z)}{\mathcal{L}(0)}$$

Depends on:

[1] Cosmological parameters $\Omega_m \quad \Omega_\Lambda$

[2] The spectral shape [power law index]

[3] The cosmological evolution of sources.

(may be CEN-A-like sources are more/less abundant or more/powerful at different epochs)

$\xi_\alpha \simeq 0.53 - 0.22\,(\alpha - 2)$ No source evolution

$\xi_\alpha \simeq 2.2 - 1.23\,(\alpha - 2)$ Source evolution

$$R_0 \simeq d_{\text{Cen A}}$$

Most "natural choice"

$$N_0 \simeq 1 \Longrightarrow N_{\text{diffuse}} \simeq 1000\ \xi$$

$$R_0 \simeq 10\ d_{\text{Cen A}}$$

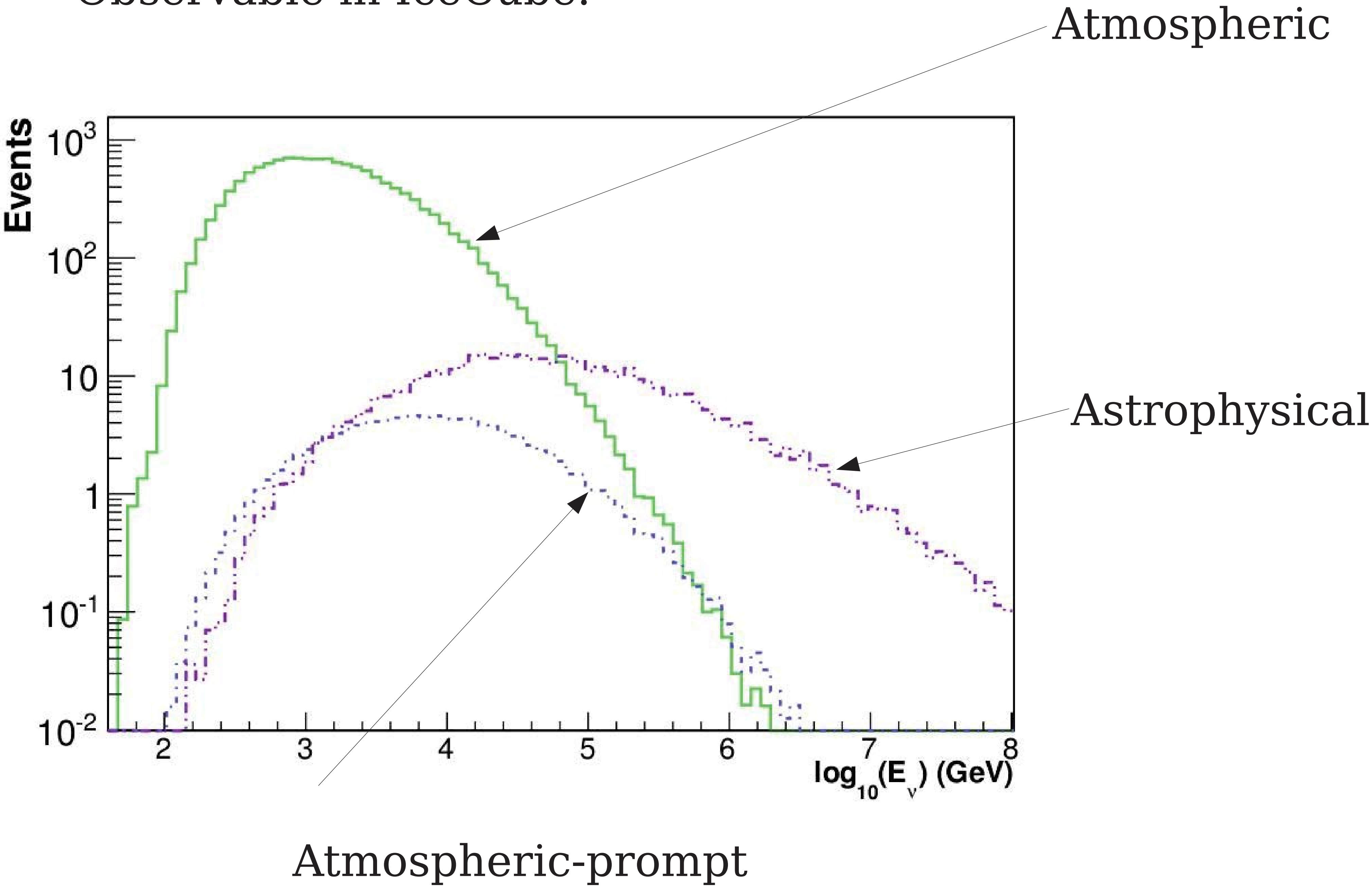
Cen A "specially" close

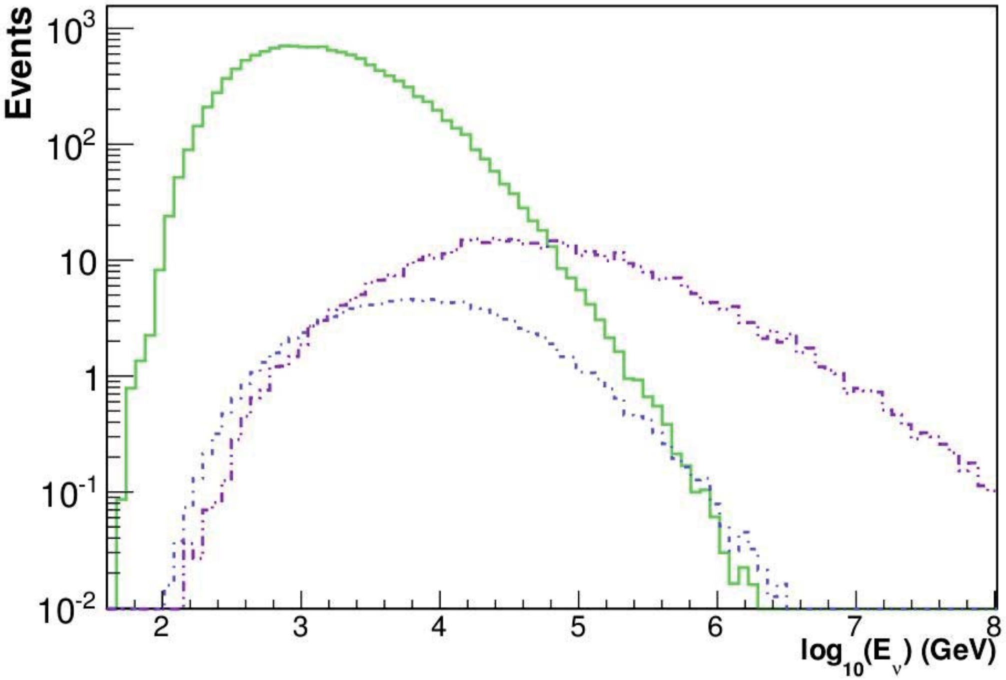
$$N_0 \simeq 1 \Longrightarrow N_{\text{diffuse}} \simeq 100\ \xi$$

$$N_{\text{diffuse}} \lesssim 50\ [\text{Km}^3\text{yr}]^{-1}$$

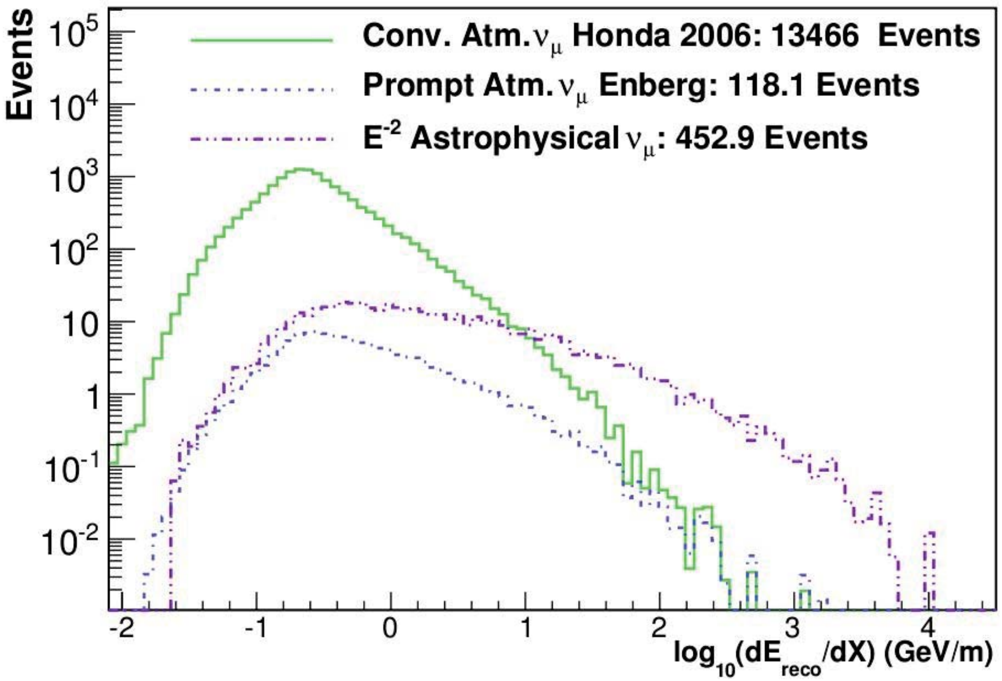
Limit from IceCube 40

[MonteCarlo] Energy Spectrum of Neutrinos Observable in IceCube.





Neutrino Energy

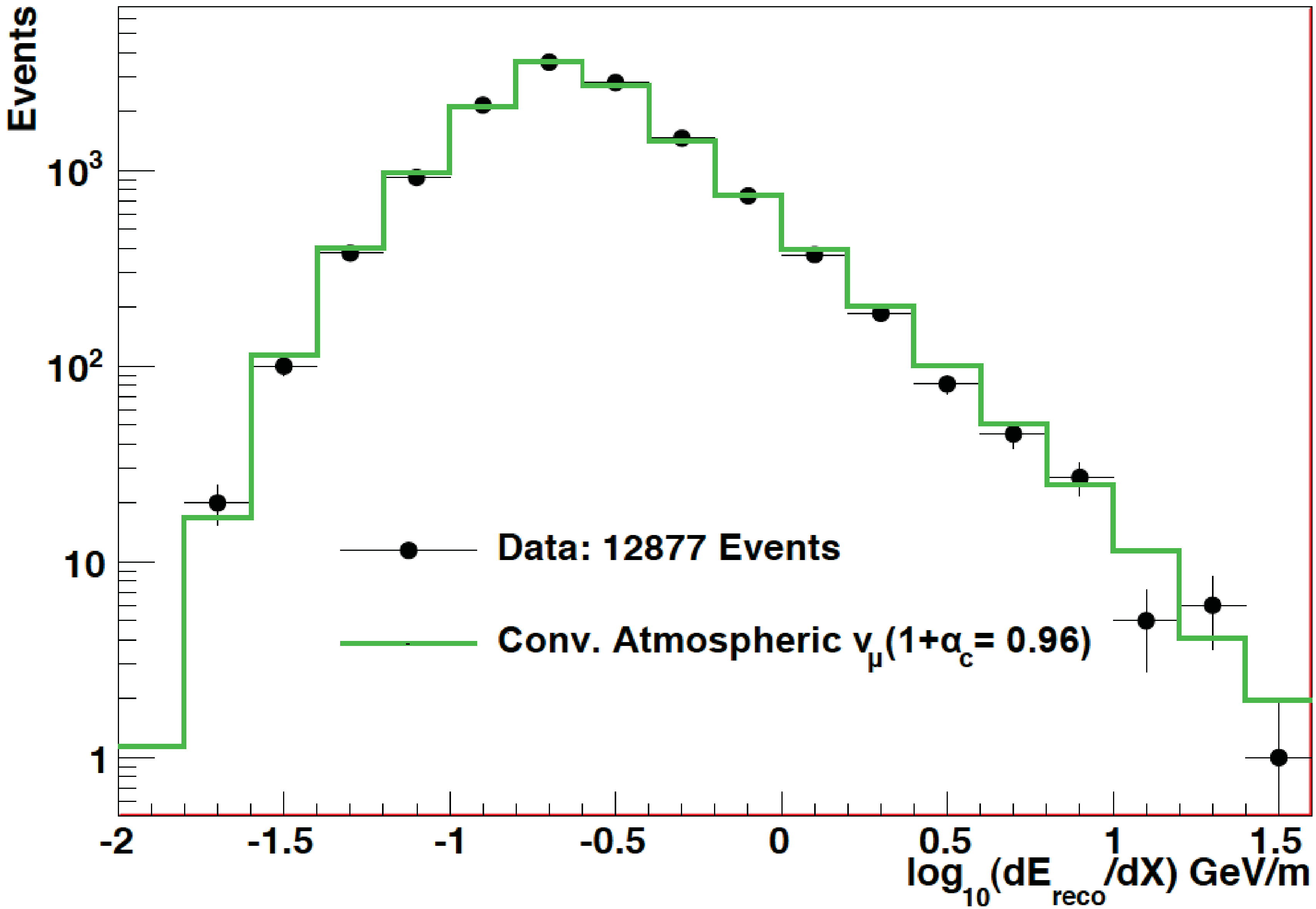


Reconstructed
Neutrino Energy

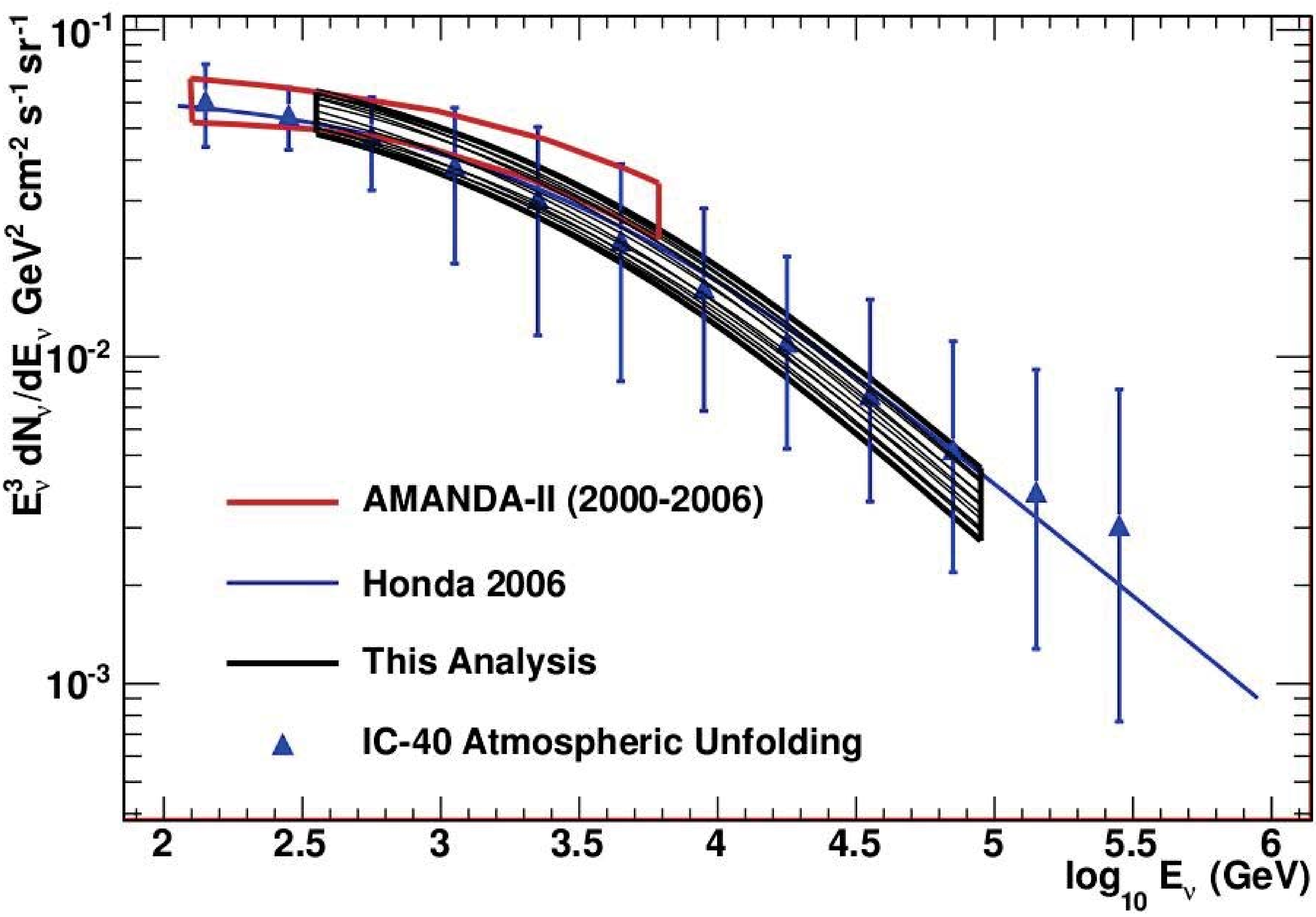
[From Muon Radiation]

$$-\frac{dE}{dX} \simeq \alpha + \frac{E}{\lambda_\mu} = \alpha \left(1 + \frac{E}{\varepsilon_\mu}\right)$$

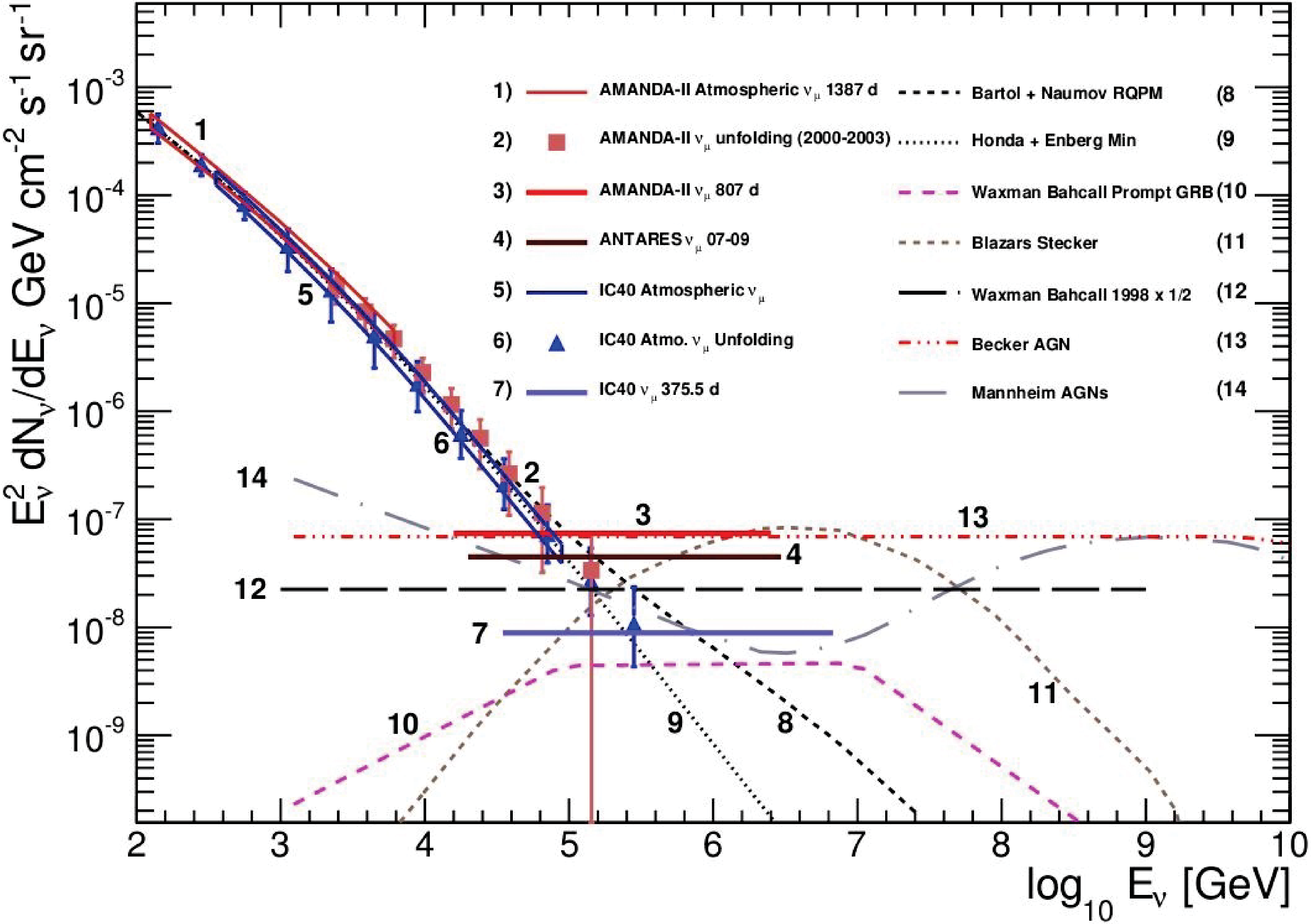
A Search for a Diffuse Flux of Astrophysical Muon Neutrinos with the IceCube 40-String Detector



No excess over atmospheric neutrinos



$E_\nu^3\, dN_\nu/dE_\nu$ GeV^2 cm^{-2} s^{-1} sr^{-1}
10^{-1}
10^{-2}
10^{-3}
2
2.5
3
3.5
4
4.5
5
5.5
6
$\log_{10} E_\nu$ (GeV)
AMANDA-II (2000-2006)
Honda 2006
This Analysis
IC-40 Atmospheric Unfolding



1) AMANDA-II Atmospheric ν_μ 1387 d
2) AMANDA-II ν_μ unfolding (2000-2003)
3) AMANDA-II ν_μ 807 d
4) ANTARES ν_μ 07-09
5) IC40 Atmospheric ν_μ
6) IC40 Atmo. ν_μ Unfolding
7) IC40 ν_μ 375.5 d
Bartol + Naumov RQPM (8
Honda + Enberg Min (9
Waxman Bahcall Prompt GRB (10
Blazars Stecker (11
Waxman Bahcall 1998 x 1/2 (12
Becker AGN (13
Mannheim AGNs (14
E_ν^2 dN_ν/dE_ν GeV cm^-2 s^-1 sr^-1
log_10 E_ν [GeV]

Diffuse neutrino flux limit:

$$\phi_{\nu_\mu}(E)\,E^2 \leq 8.9 \times 10^{-9}\ \frac{\mathrm{GeV}}{\mathrm{cm^2\,s\,sr}}$$

$$N_{\mu\uparrow} \simeq 2\pi\ \left[A\,t\right]\ \Phi_{\nu_\mu}\left(\geq 1\ \mathrm{TeV}\right)\ \langle \varepsilon_{\nu\to\mu} \rangle$$

$$\langle \varepsilon_{\nu\to\mu} \rangle \simeq 3 \times 10^{-6}$$

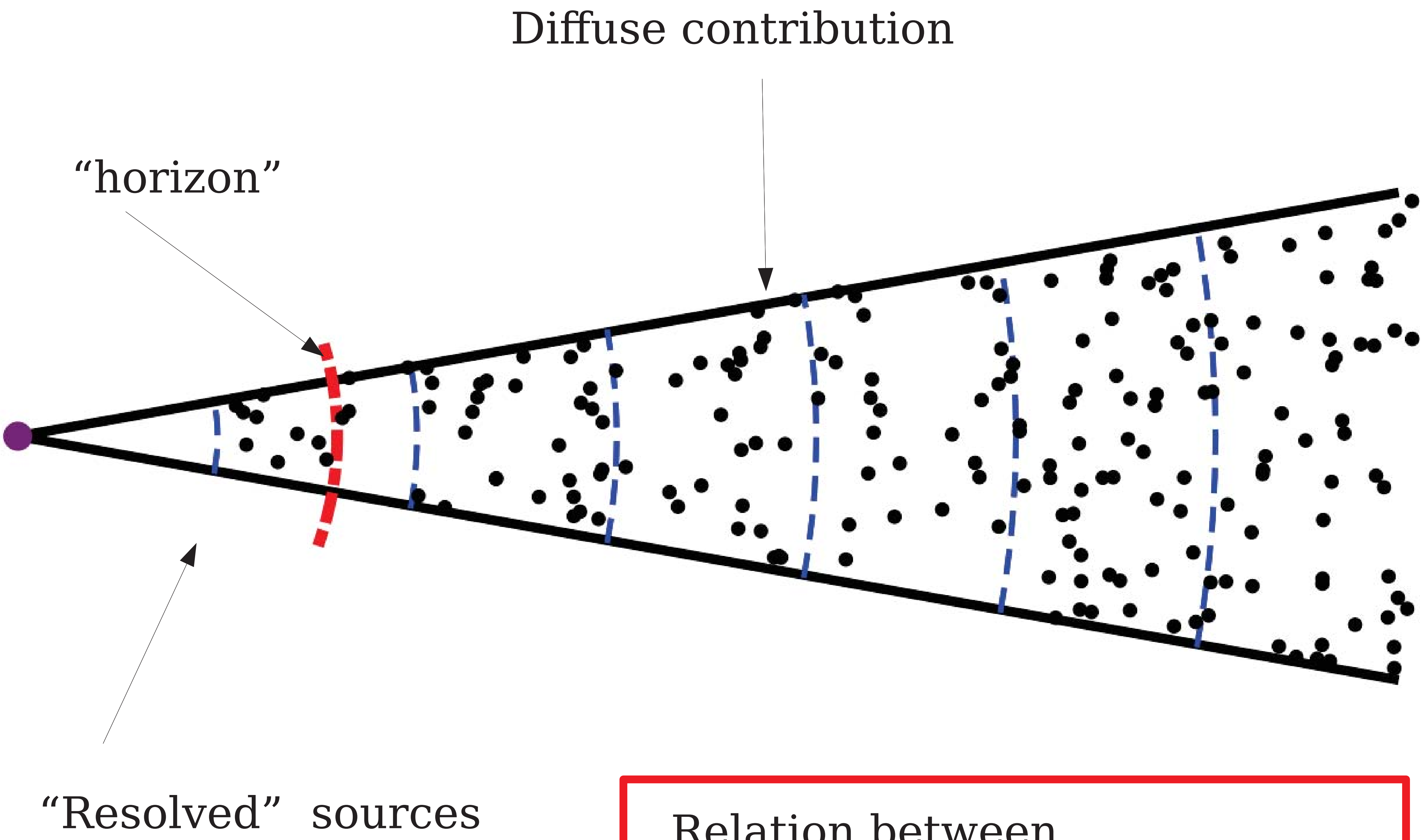
$$N_{\mu\uparrow} \simeq 50\ \frac{\mathrm{events}}{\mathrm{Km^2\ \ yr}}$$

Existing (published) limit on the diffuse neutrino flux implies:

$$\mathcal{L}_\nu \lesssim 1.2 \times 10^{36} \ \frac{\text{erg}}{\text{decade s Mpc}^3}$$

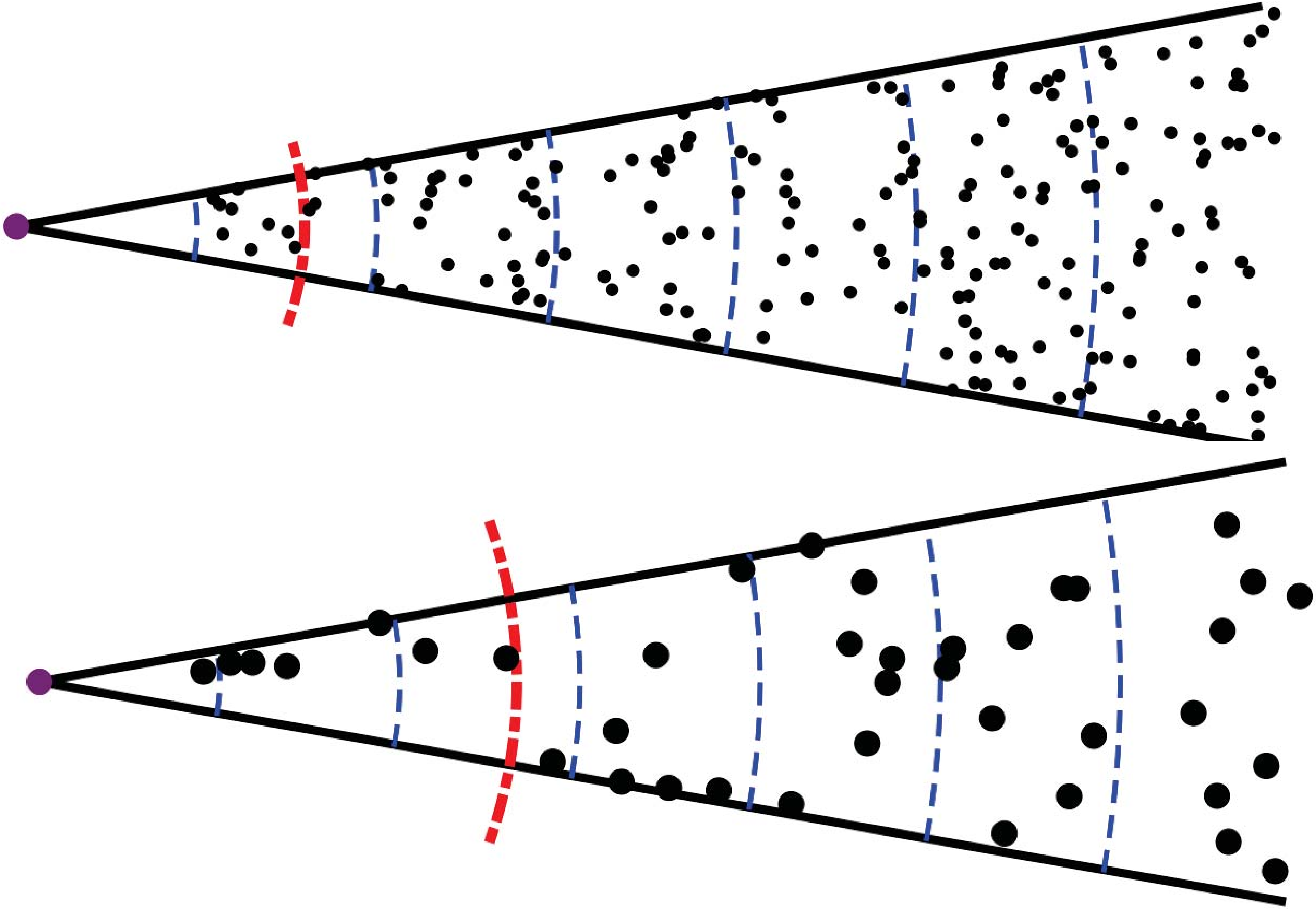
$$\mathcal{L}_{\text{SN}}^{\text{kin}} \simeq 3 \times 10^{40} \ \text{erg}/(\text{Mpc}^3\text{s})$$

$$\mathcal{L}_{\text{AGN}}^{\text{bolometrix}} \simeq 2 \times 10^{40} \ \left(\frac{\text{erg}}{\text{s Mpc}^3}\right)$$



Relation between
The diffuse flux
And the detected Point Sources

If Ice-Cube does not discover "soon"
a diffuse flux, the observation of
extragalactic-point-sources become improbable.



$$\phi_{\text{inclusive}} \propto \mathcal{L} = n_{\text{sources}}\ L$$

$$\phi_{\text{source}} \propto \frac{L}{r^2} \implies r_{\text{horizon}} \propto \sqrt{L}\,\sqrt{A\,t}$$

$$N_{[\text{det sources}]} = n_{\text{sources}} \left(\frac{4\,\pi}{3}\,r_{\text{h}}^3\right)$$

$$N_{[\text{det sources}]} \equiv N_{\text{sources}}[\langle n_\mu \rangle \geq 1]$$

$$N_{[\text{det sources}]} \propto \frac{\mathcal{L}}{L}\,\left(\sqrt{L}\right)^3$$

$$N_{[\text{det sources}]} \propto \frac{\mathcal{L}}{L}\left(\sqrt{L}\right)^3$$

Obtain from diffuse flux

Estimate from Astrophysical considerations.

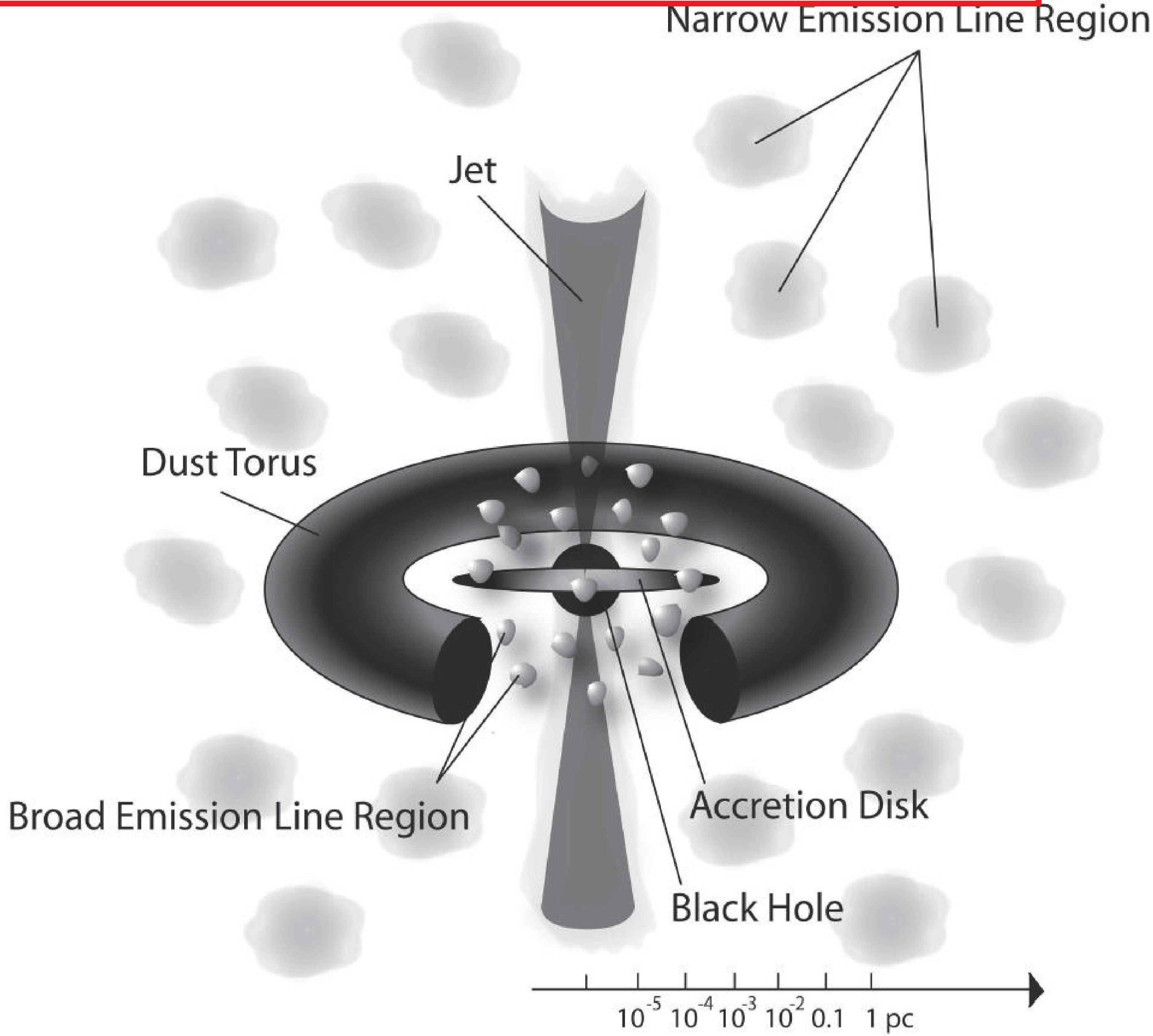
$$N_{[\text{det sources}]} \sim 1.2\,\mathcal{L}_{35}\,\sqrt{L_{45}}\,(A\,t)^{3/2}_{\text{Km}^2\text{yr}}$$

We know there are extragalactic neutrinos
because there are (extra galactic) cosmic rays,
and the sources of CR are also sources of neutrinos.

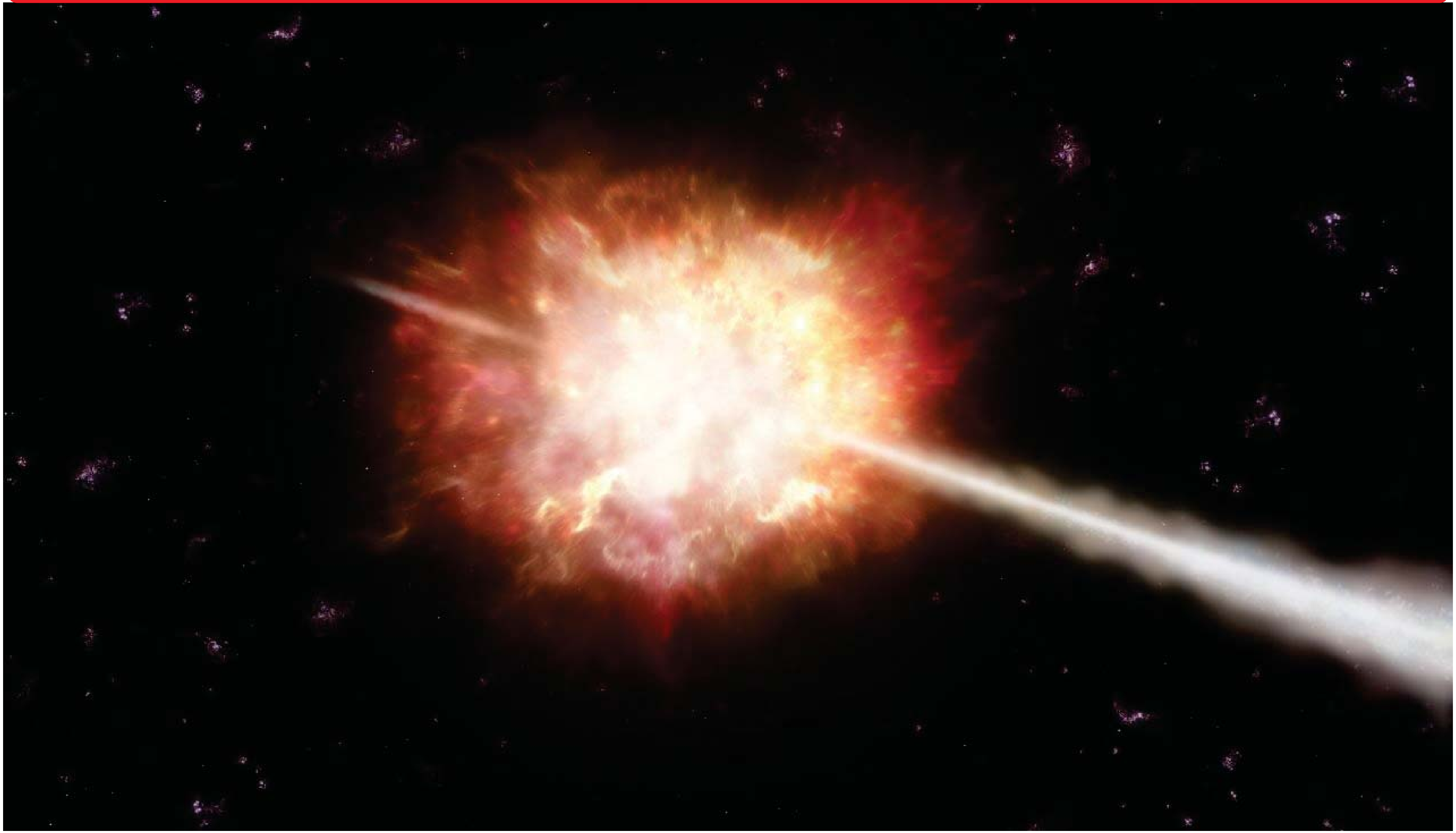
A more precise prediction requires a model
for the CR production (and source).

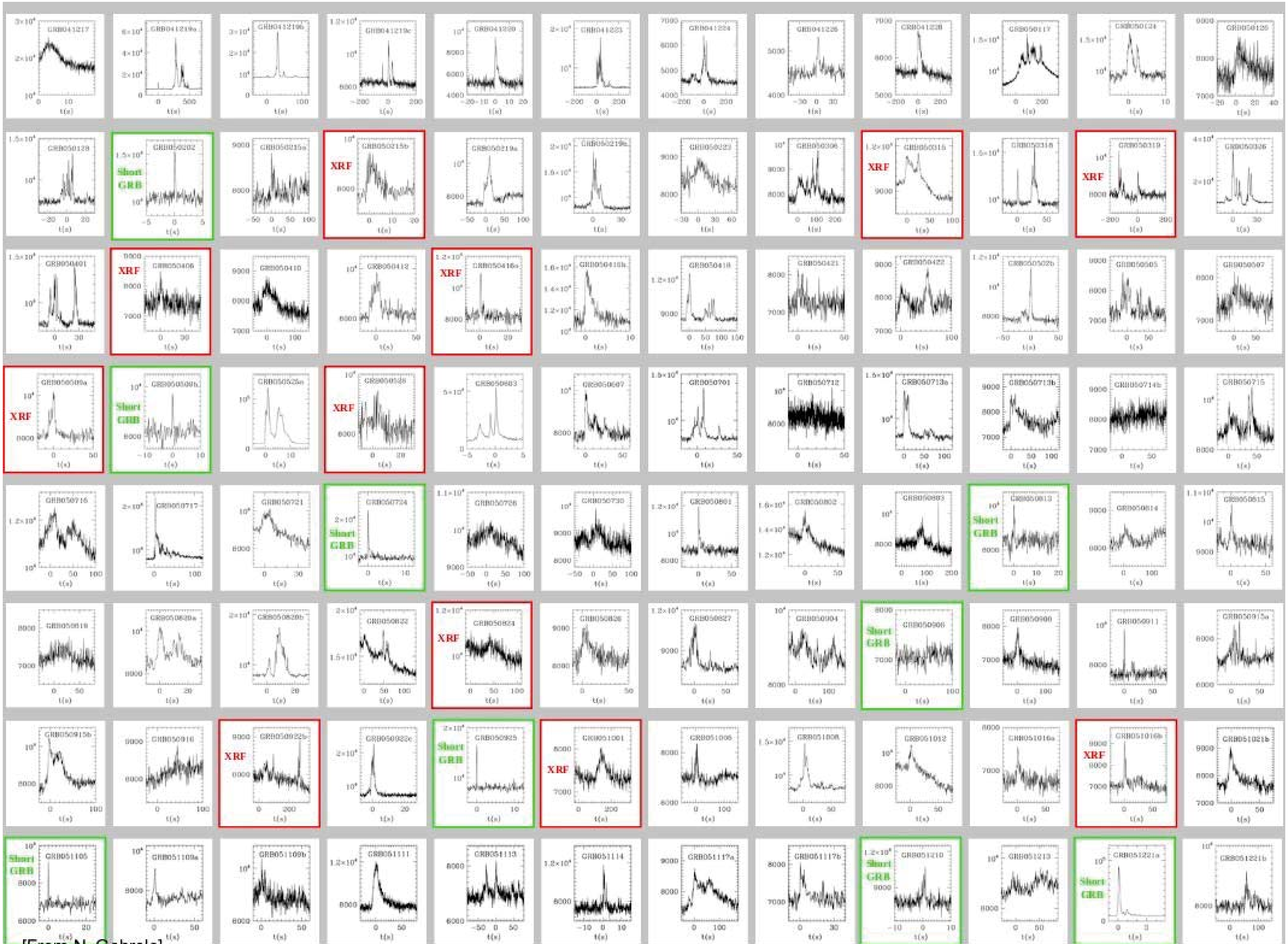
AGN 's
GRB's
[or something else]

ACTIVE GALACTIC NUCLEI

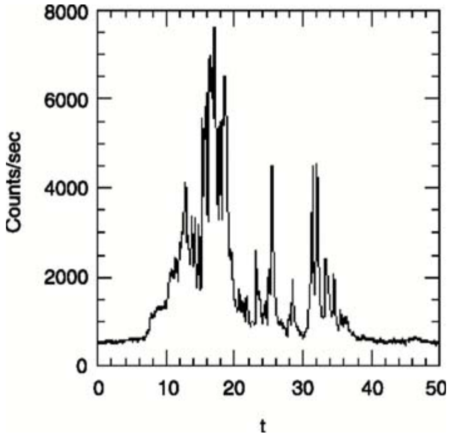


Gamma Ray Bursts

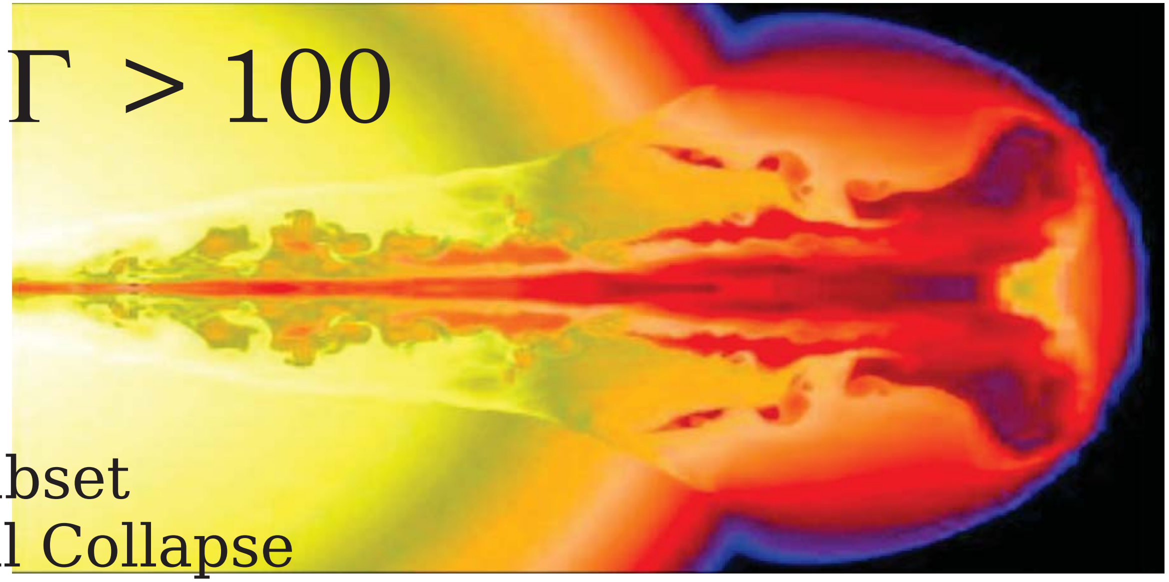




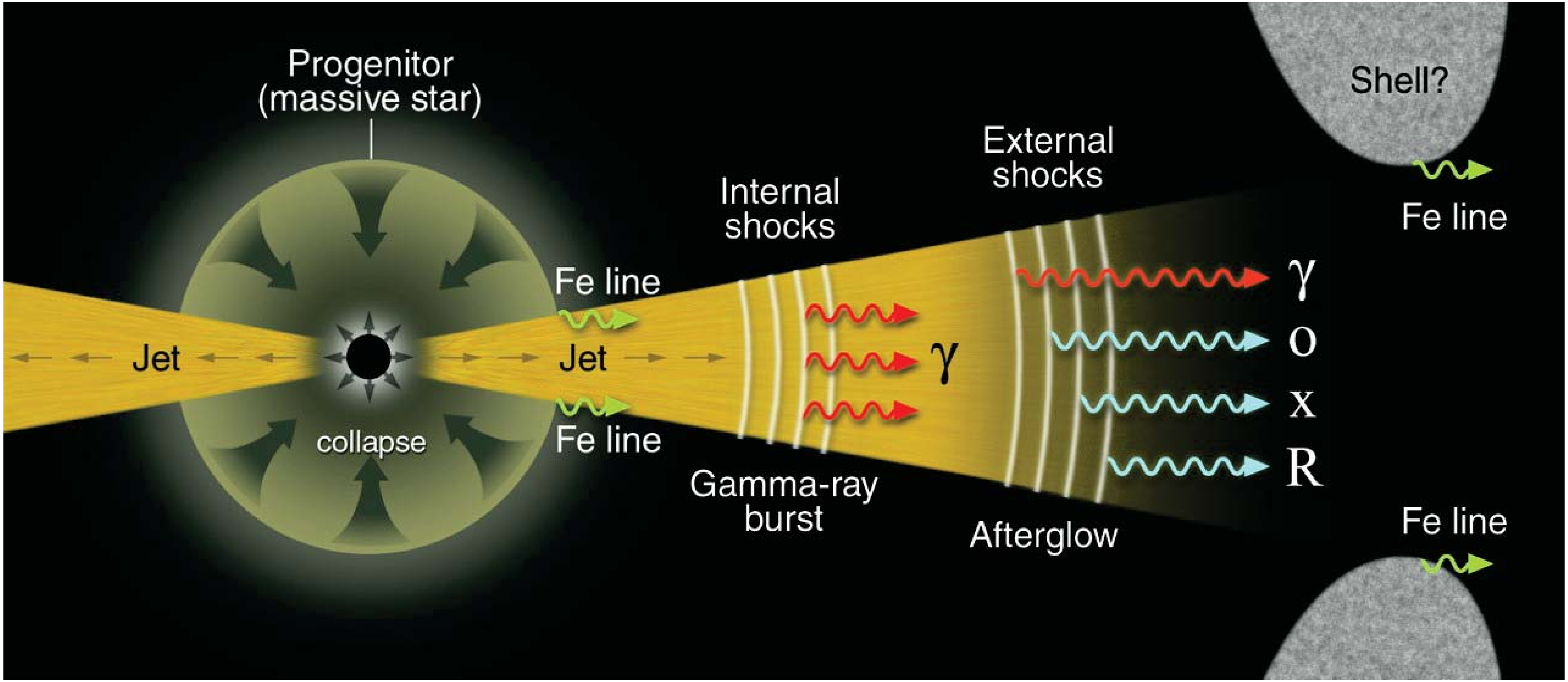
[From N. Gehrels]



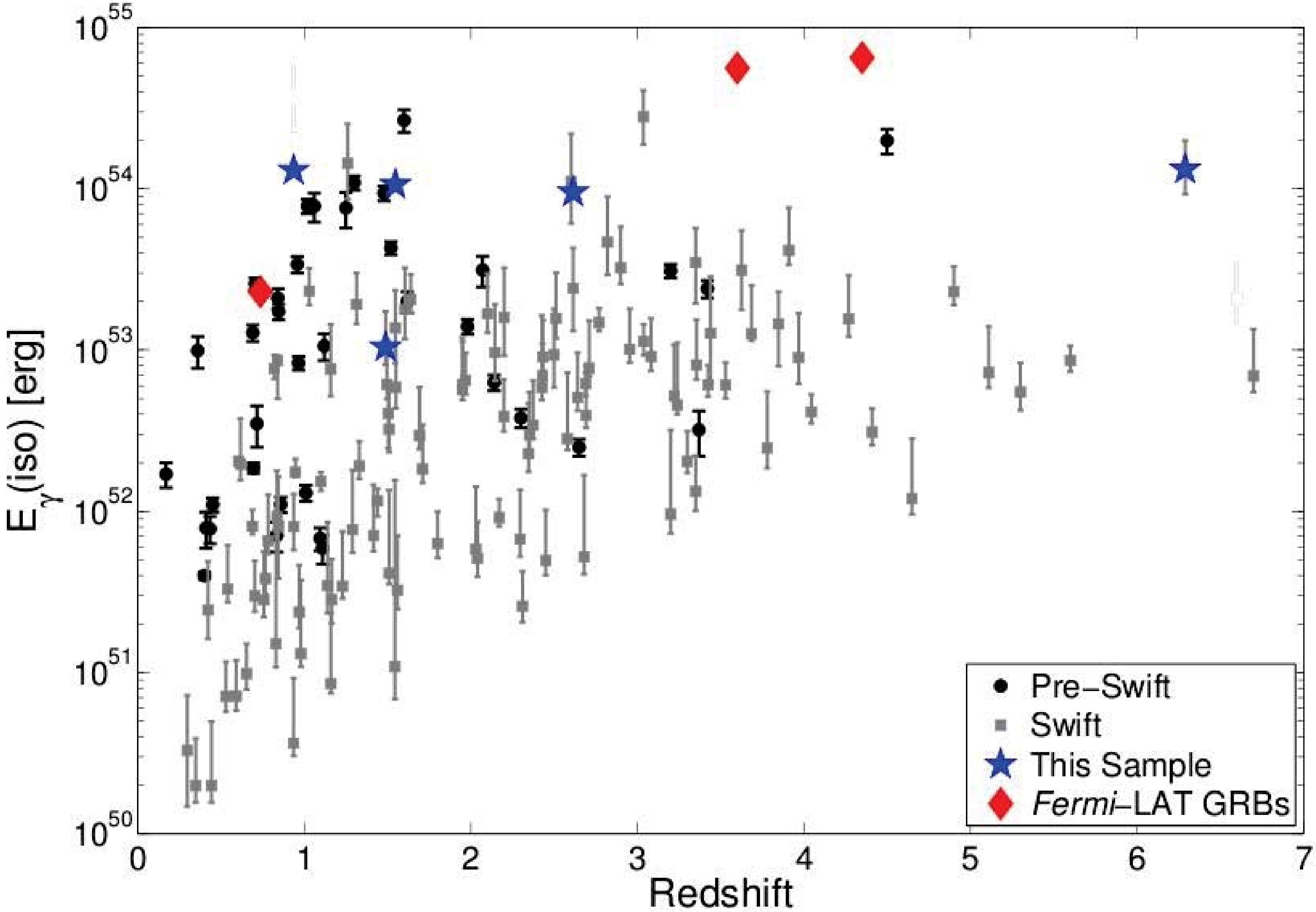
$\Gamma > 100$

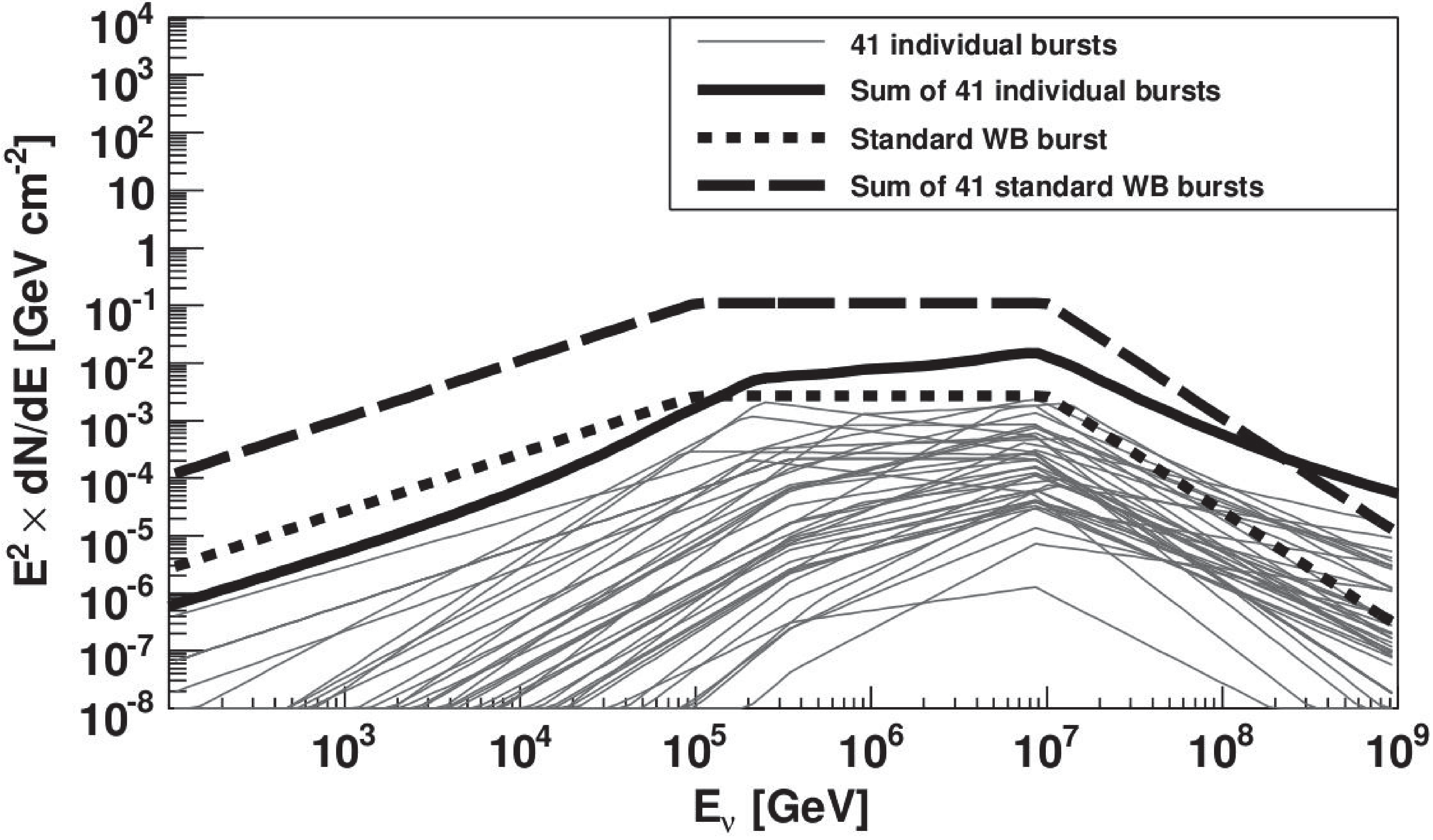


GRB : associated with a subset
of SN Stellar Gravitational Collapse



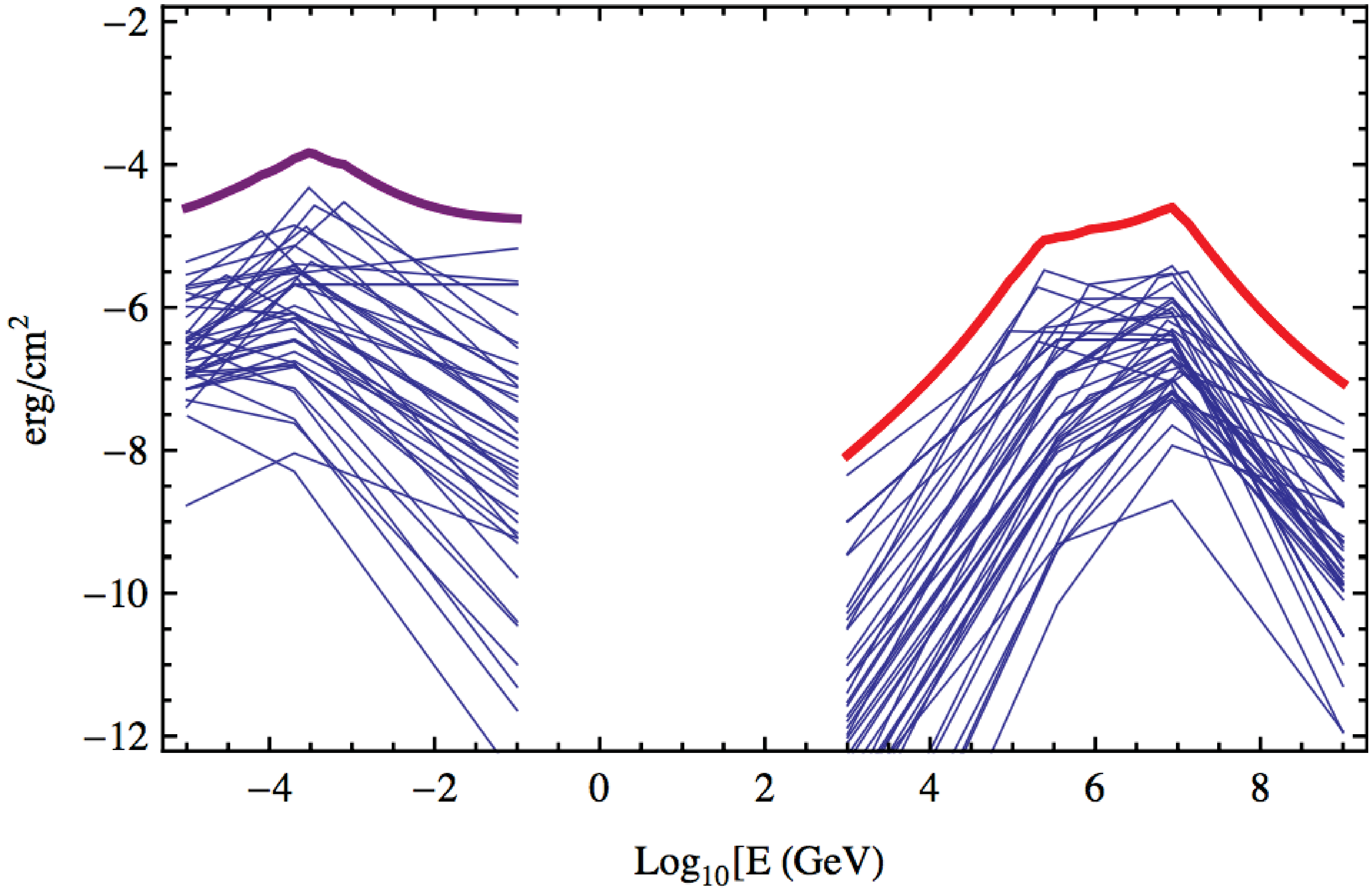
Extraordinary Large (beamed) Energy Output





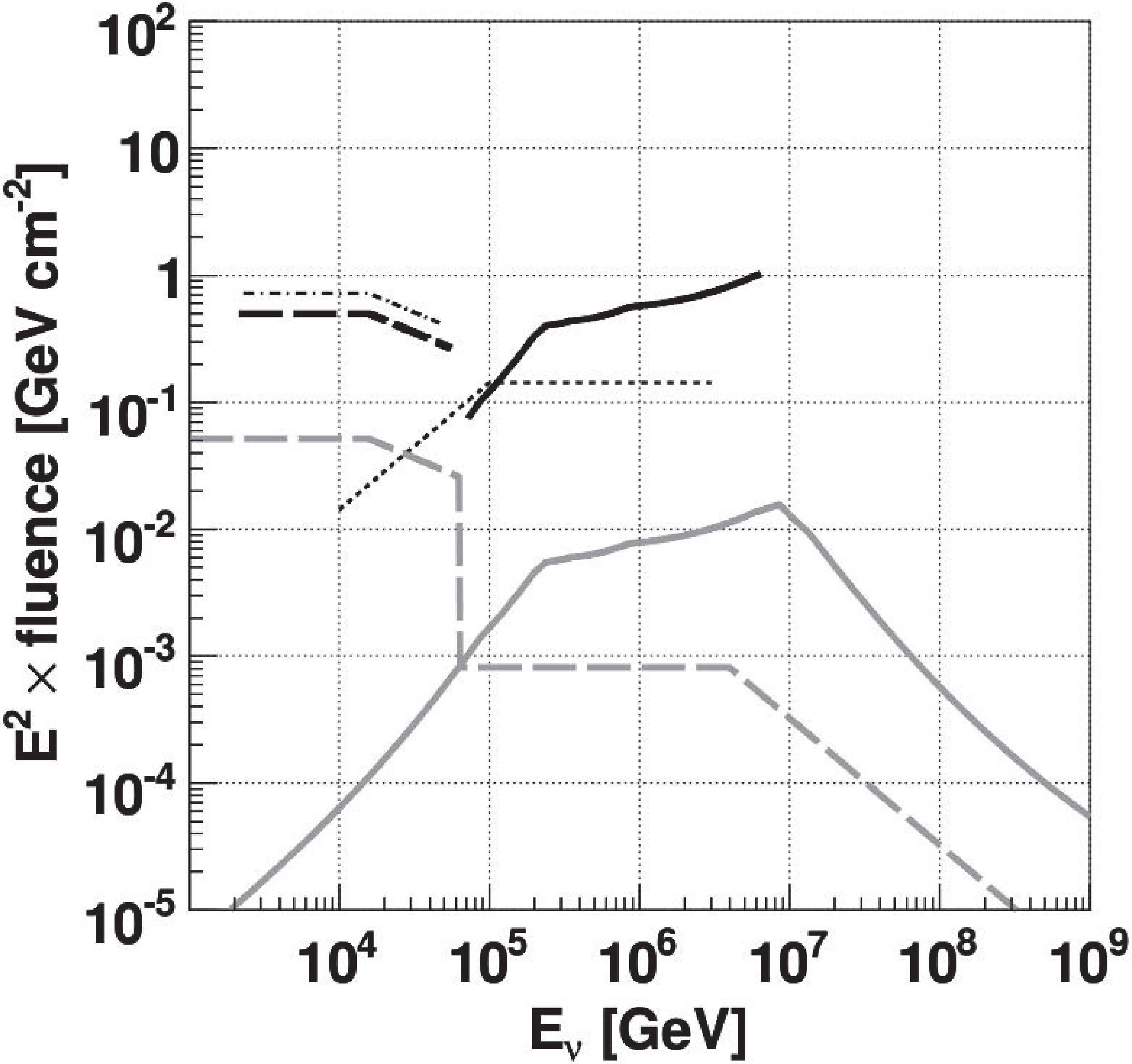
41 individual bursts
Sum of 41 individual bursts
Standard WB burst
Sum of 41 standard WB bursts
$E^2 \times dN/dE$ [GeV cm^{-2}]
10^4
10^3
10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^3
10^4
10^5
10^6
10^7
10^8
10^9
E_ν [GeV]

41 GRB used by AMANDA [Waxman/Bahcall model]



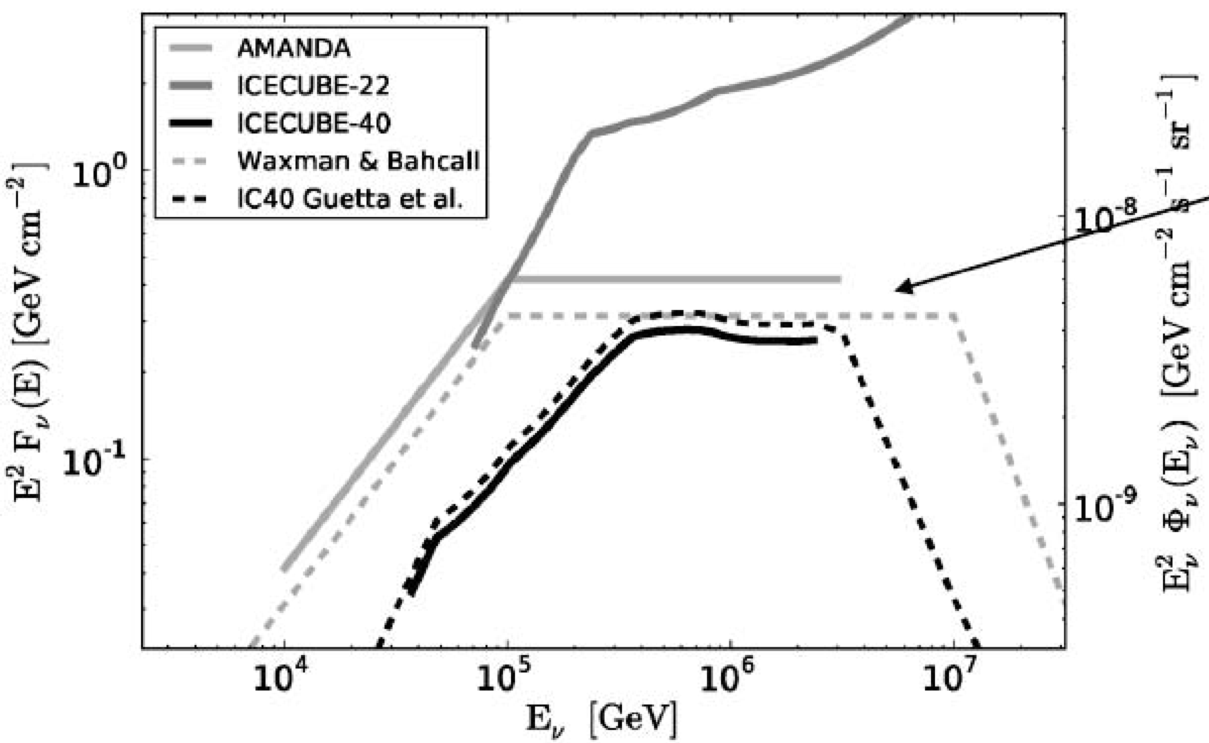
Photon detection

Neutrino assumed spectrum



10^2
10
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
$E^2 \times$ fluence [GeV cm^{-2}]
10^4
10^5
10^6
10^7
10^8
10^9
E_ν [GeV]

GRB ν's: IC40 constraints



$$\frac{\varepsilon^2 dQ / d\varepsilon}{10^{44} \mathrm{erg/Mpc^3 yr}} = 1$$

- No ν's for 117 GRBs (~1 expected, at 90%CL <2)
- IC is achieving relevant sensitivity

Gamma Ray bursts are obviously
VERY attractive as a neutrino source!

[time coincidence with event visible in photons
up to very large redshift !!]

Prediction from GRB has been forcefully motivated
[talks of E.Waxman, S.Razzaque]
but remains [warning : personal opinion !]
very speculative.
[possible problems with energy budget?]

Can the model be falsified with
Neutrino Data ?
[possible, but some room to "escape"]

What will we learn?

- Detection: highly informative
  - Identify CR source
  - Strong support: Baryon
    dissipa
  - Fundamental/ν physics

From E.Waxman talk

Question: how can One falsify this model !?

- Non-detection: ambiguous
  - 10/km^{2}yr is an order of mag. (proportional to ζ x dQ/dE x f_π)
  - Significant non-detection (<<10/km^{2}yr, <<1ν/100GRB)

    Poynting jet (no p)

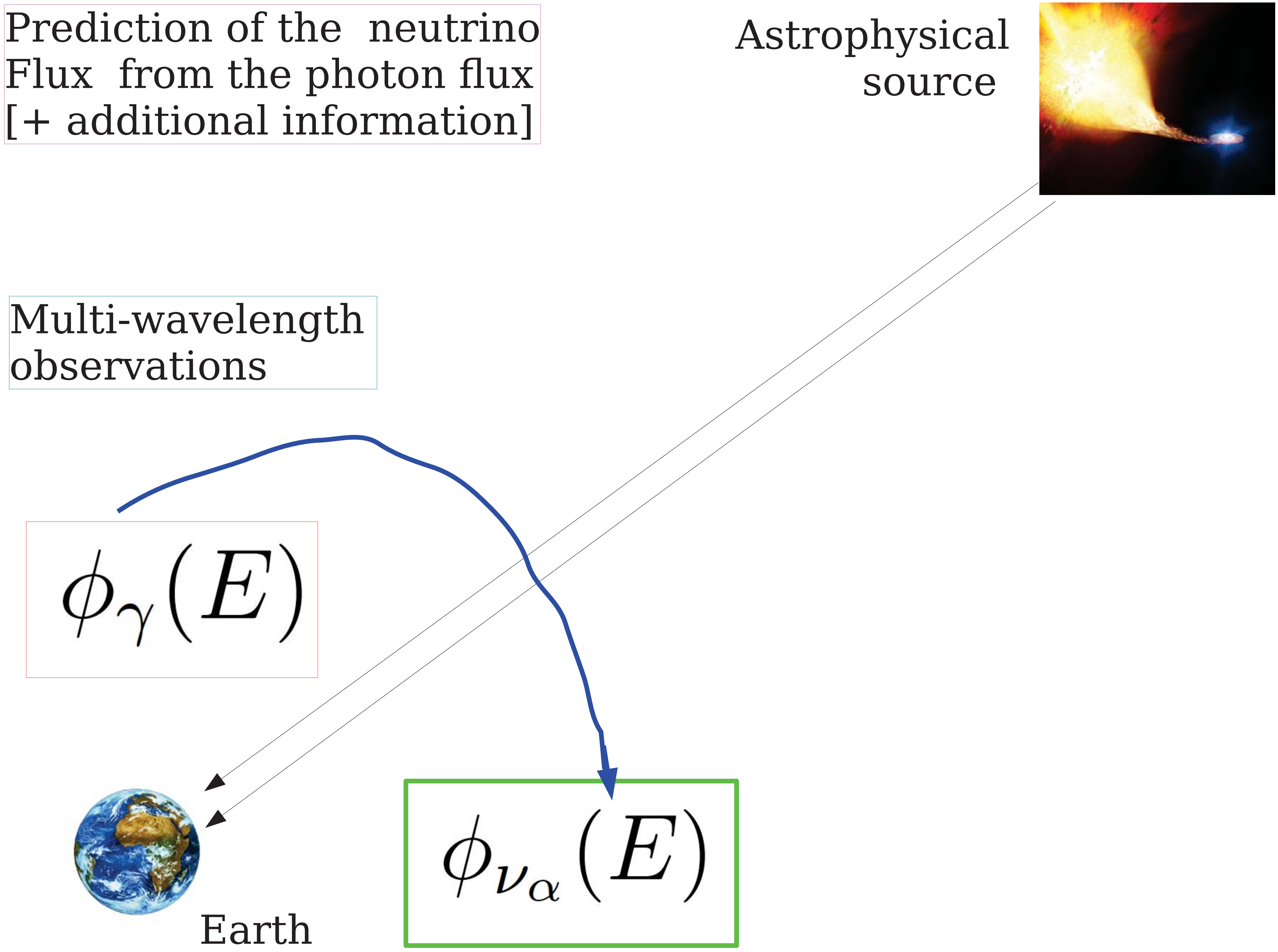
    or

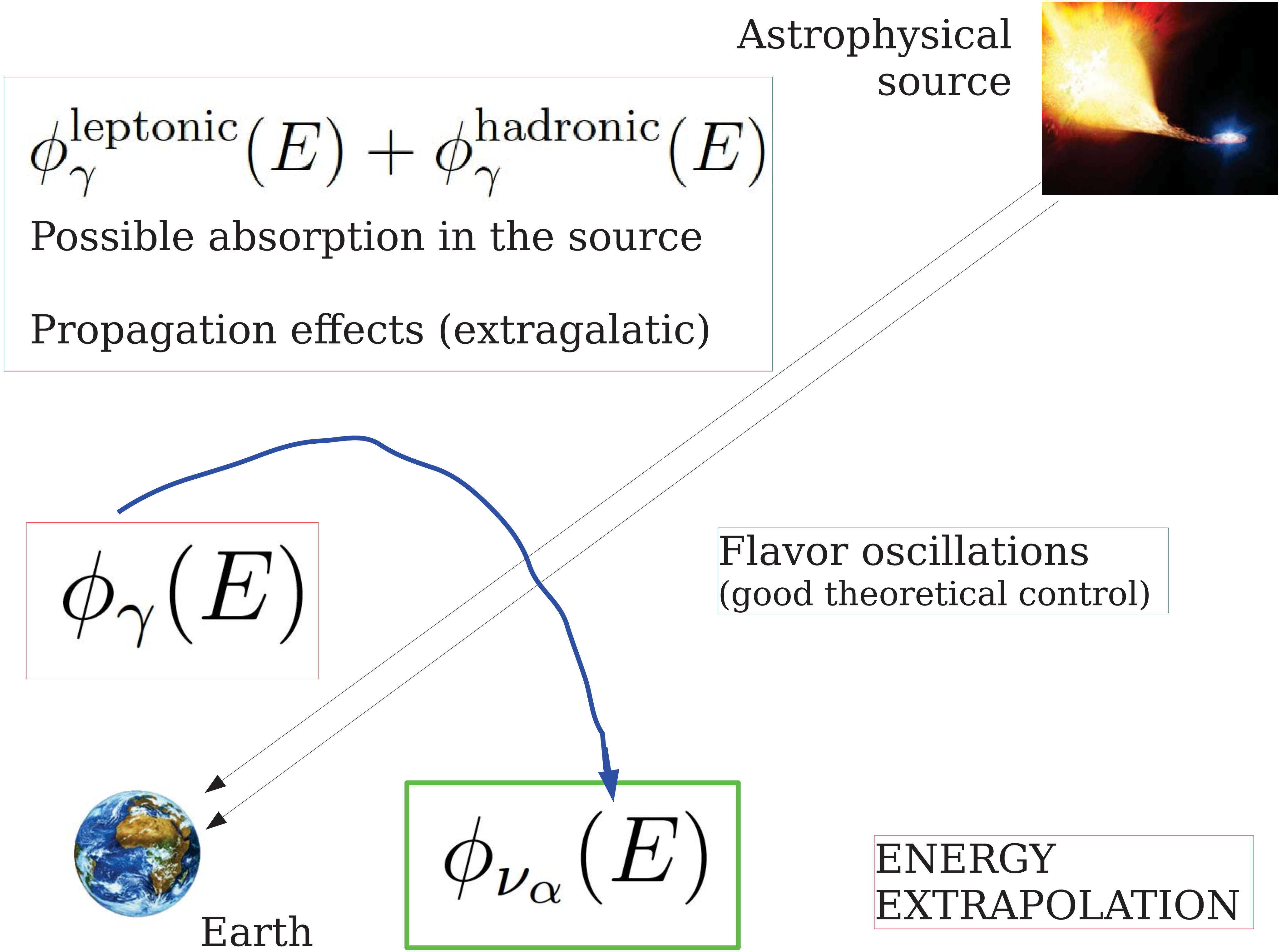
    Dissipation mechanism (eg no p acceleration to relevant E)

    or

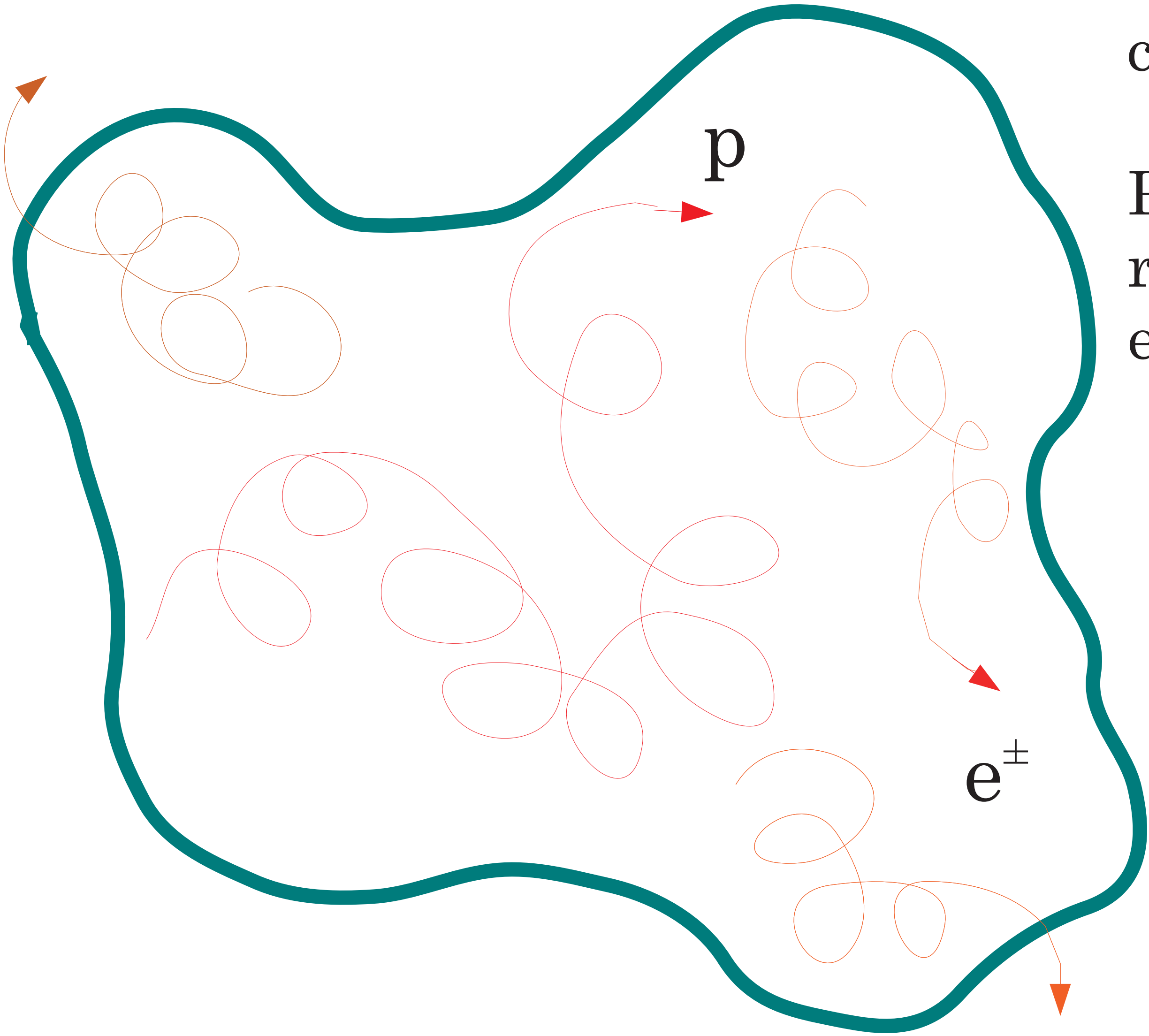
    Radiation mechanism ($\rightarrow f_\pi$<<0.2)

Neutrino Point Sources


Prediction of the neutrino Flux from the photon flux [+ additional information]
Astrophysical source
Multi-wavelength observations
$\phi_\gamma(E)$
$\phi_{\nu_\alpha}(E)$
Earth



Astrophysical source
$\phi_\gamma^{\mathrm{leptonic}}(E) + \phi_\gamma^{\mathrm{hadronic}}(E)$
Possible absorption in the source
Propagation effects (extragalatic)
$\phi_\gamma(E)$
Flavor oscillations
(good theoretical control)
$\phi_{\nu_\alpha}(E)$
ENERGY EXTRAPOLATION
Earth



Astrophysical Object containing:

Populations of relativistic protons, Nuclei electrons/positrons

Emission of:

Γαμμα rays

Neutrinos

Cosmic Rays

$$p + \text{target} \rightarrow \text{many particles}$$

$$\rightarrow p(n) + \pi^{+} + \pi^{-} + \pi^{\circ}$$

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

$$\pi^{\circ} \rightarrow \gamma + \gamma$$

$$\mu^{+} \rightarrow e^{+} + \nu_{e} + \overline{\nu}_{\mu}$$

"Hadronic Emission"

$$e^{\mp} + B \rightarrow e^{\mp} + \gamma_{\text{synchrotron}}$$

"Leptonic Emission"

$$e^{\mp} + \gamma_{\text{soft}} \rightarrow e^{\mp} + \gamma_{\text{Inverse Compton}}$$

1. Neglect photon absorption in propagation from source

2. Neglect photon absorption INSIDE the source

Rule of thumb :

Summing over all 6 neutrino types (2 * 3 flavors)

1 “hadronic-photon” ≈ 1 Neutrino

“Counting + Energy spectra”

$$p + p \to \pi^+ + \pi^- + \pi^\circ + K^+ + K^- + \ldots$$

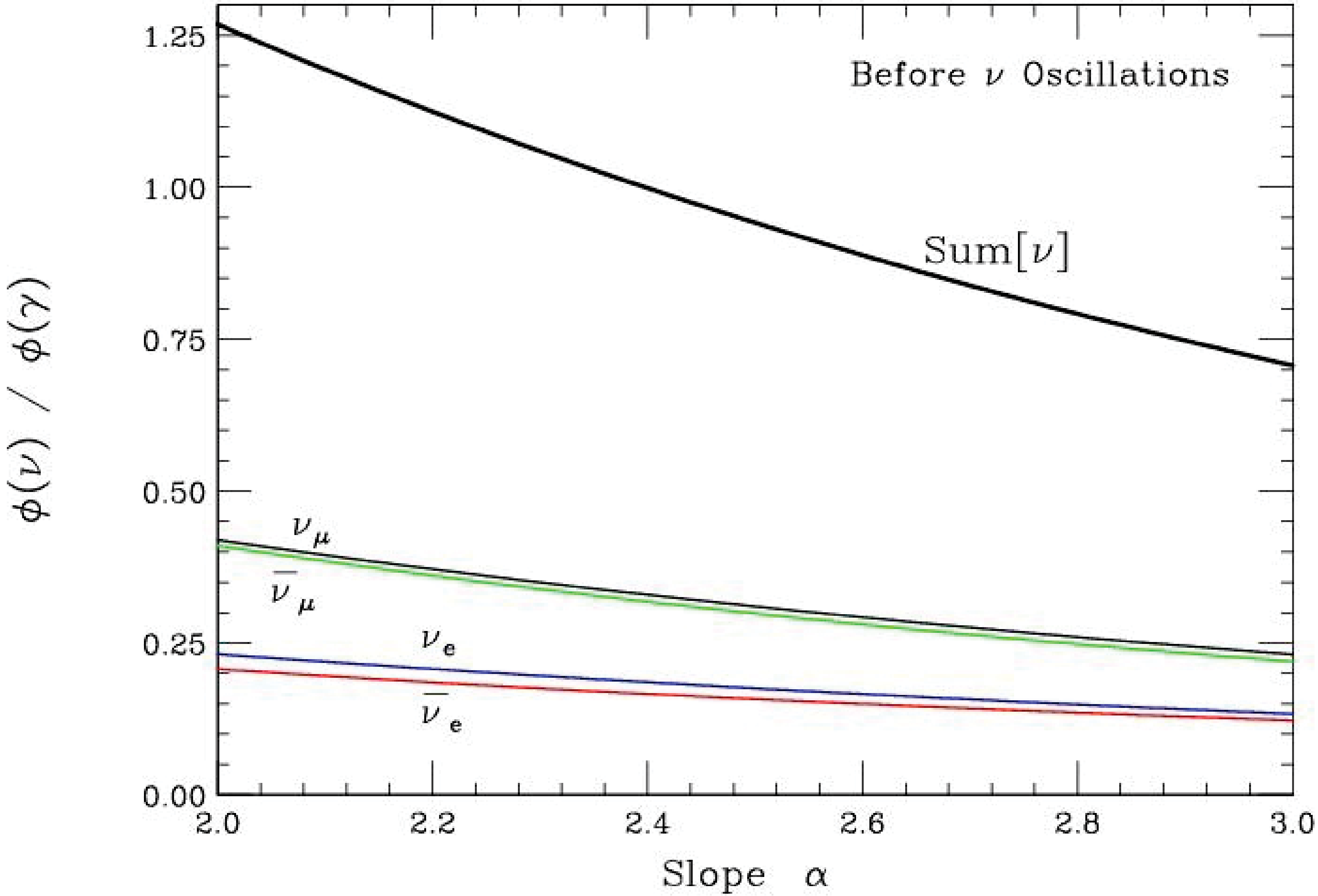
$$\pi^+ \hookrightarrow \mu^+ \; \nu_\mu \qquad \pi^\circ \hookrightarrow \gamma \; \gamma$$

$$\mu^+ \hookrightarrow e^+ \; \nu_e \; \overline{\nu}_\mu$$

Very very naively
2 * 3 / 1*2 wrong!

Exact Power Law spectra: $K\ E^{-\alpha}$

$\phi(\nu)\ /\ \phi(\gamma)$



$$\{\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau\} \simeq \{1+\epsilon, 1-\epsilon, 2, 2, 0, 0\}$$

Effect of Neutrino Oscillations

$$\langle P(\nu_\alpha \to \nu_\beta)\rangle = \langle P(\overline{\nu}_\alpha \to \overline{\nu}_\beta)\rangle = \sum_j |U_{\alpha j}|^2 \, |U_{\beta j}|^2$$

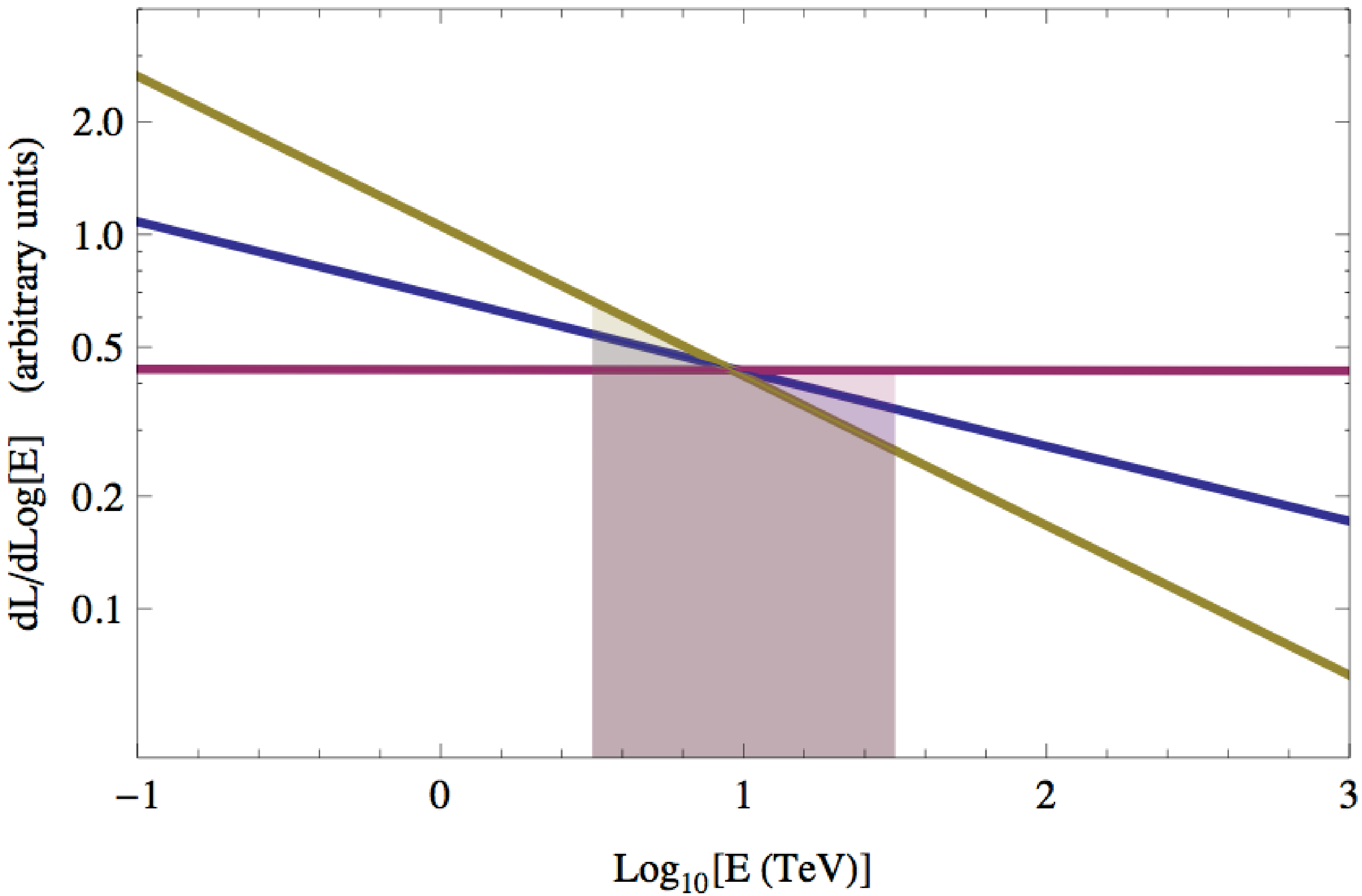
$$\simeq \begin{pmatrix} 0.6 & 0.2 & 0.2 \\ 0.2 & 0.4 & 0.4 \\ 0.2 & 0.4 & 0.4 \end{pmatrix} \qquad (1)$$

Before Oscillations

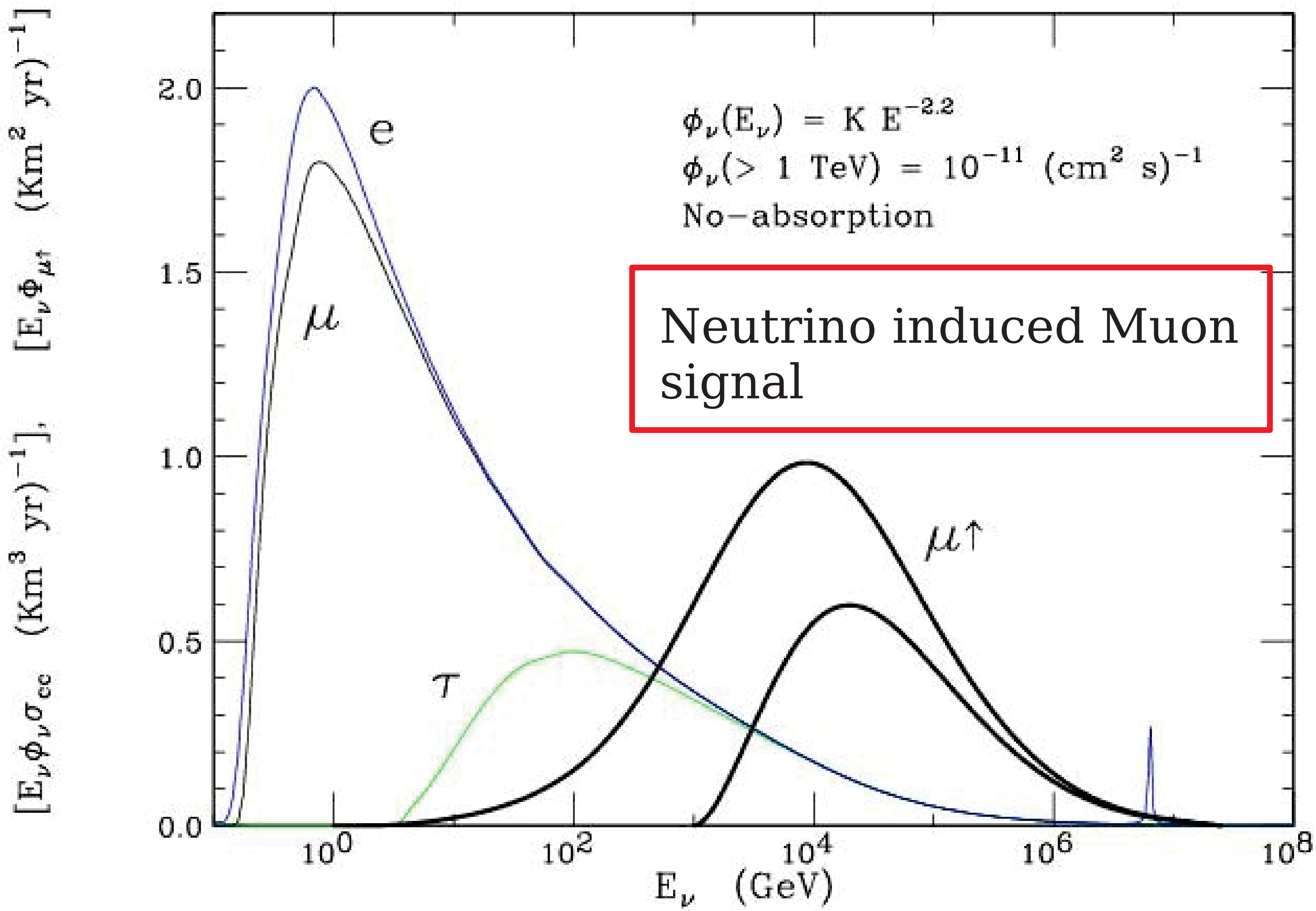
$$\{\nu_e, \overline{\nu}_e, \nu_\mu, \overline{\nu}_\mu, \nu_\tau, \overline{\nu}_\tau\} \simeq \{1+\epsilon, 1-\epsilon, 2, 2, 0, 0\}$$

After Oscillations

$$\{\nu_e + \overline{\nu}_e, \nu_\mu + \overline{\nu}_\mu, \nu_\tau + \overline{\nu}_\tau\} = \{1, 1, 1\}$$



$$\phi_\nu(E) = \frac{1}{4\,\pi\,r^2}\left[\frac{L^{\mathrm{decade}}(E_*)}{\ln 10}\;E_*^{\alpha-2}\right]\;E^{-\alpha}$$



Neutrino induced Muon signal

$$\Phi_{\mu\uparrow} \simeq (1 \div 5) \left[\frac{\phi_\nu(\geq 1\ \text{TeV})}{10^{-11}\ (\text{cm}^2\,\text{s})^{-1}} \right]\ (\text{Km}^2\ \text{yr})^{-1}$$

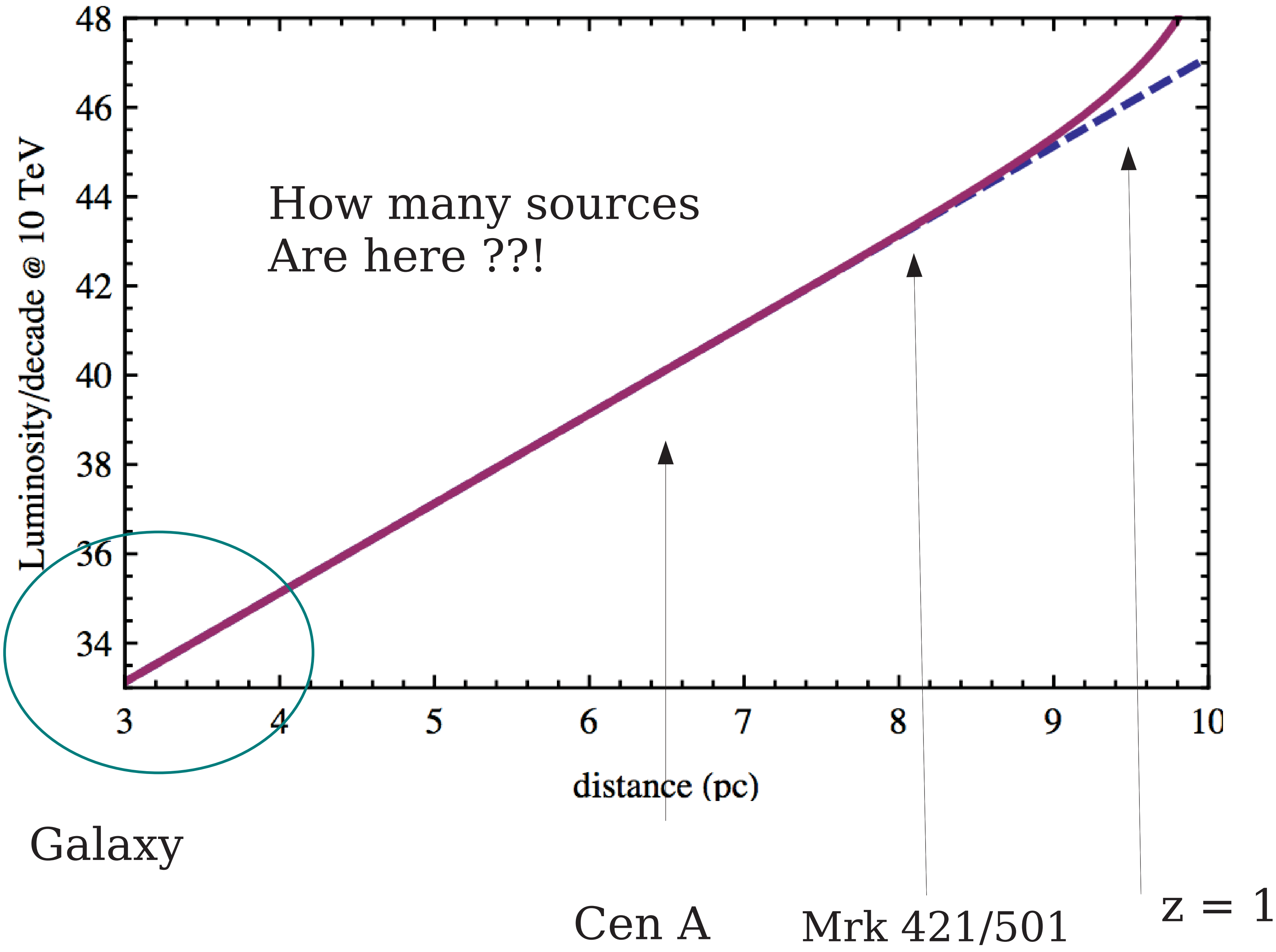
Energy Response: Peak @ 20 TeV

From the Neutrino Flux to the Muon induced signal.

$$N_{\mu\uparrow} \simeq 7.5 \times \left(\frac{L}{10^{34}\ \mathrm{erg/s}}\right) \left(\frac{\mathrm{Kpc}}{r}\right)^2 \left(\frac{A\,t}{\mathrm{Km}^2\,\mathrm{year}}\right)$$

$$N_{\mu\uparrow} \simeq 0.4 \times \left(\frac{L}{10^{46}\ \mathrm{erg/s}}\right) \left(\frac{A\,t}{\mathrm{Km}^2\,\mathrm{year}}\right) \frac{1}{z^2}$$

Line : 1 (muon event)/(km2 yr)

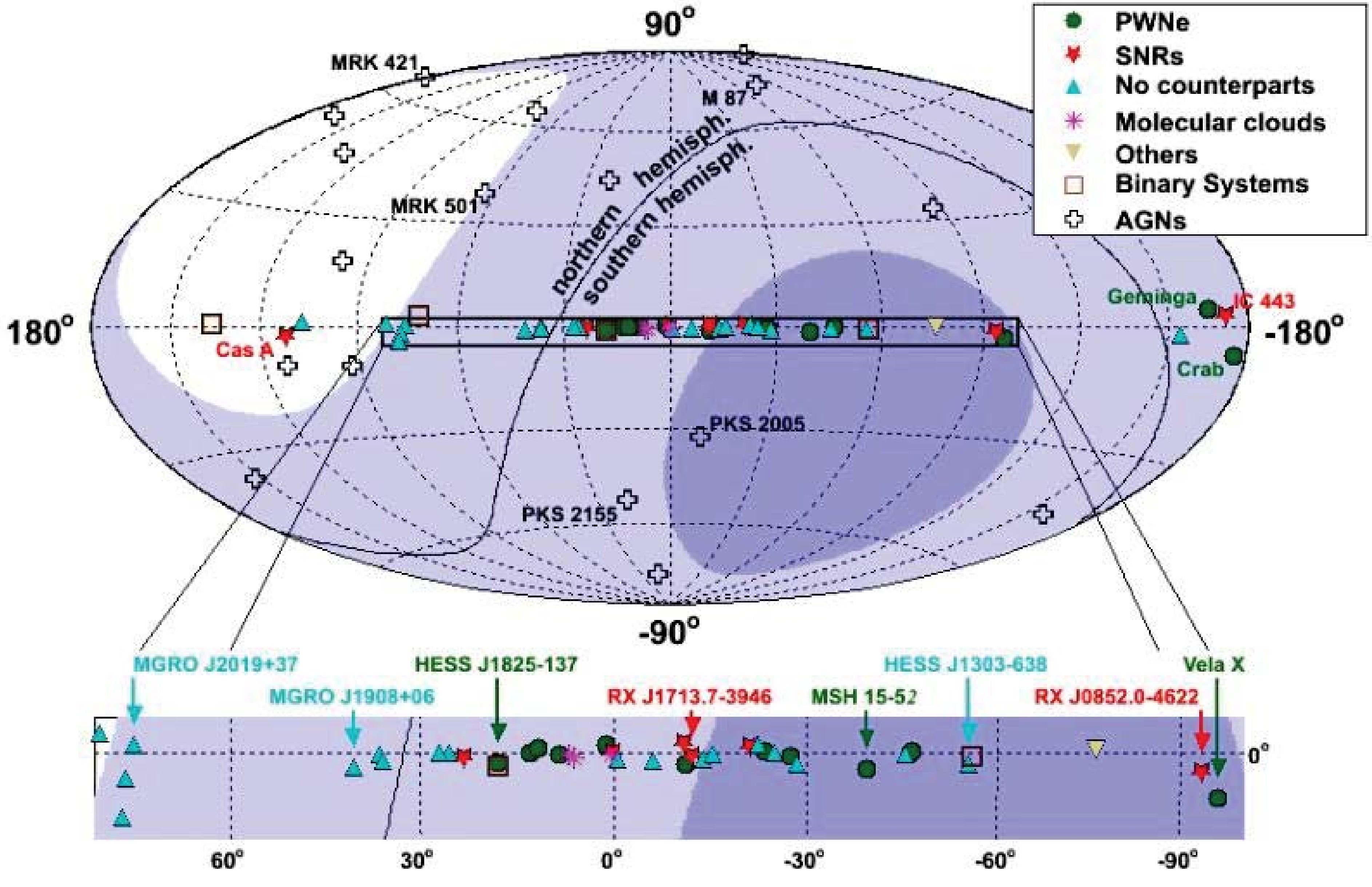


Very direct connection with TeV Gamma Astronomy !!

A field that in the last few years has been Collecting remarkable results.

We have (HESS) a scan of the Milky Way disk !
We know which one are the brightest TeV sources In our Galaxy, and the luminosity of these sources.

SNR
Pulsars
Pulsars Wind Nebulae
μ Quasars



PWNe
SNRs
No counterparts
Molecular clouds
Others
Binary Systems
AGNs
90°
-90°
180°
-180°
MRK 421
M 87
MRK 501
northern hemisph.
southern hemisph.
Cas A
Geminga
IC 443
Crab
PKS 2005
PKS 2155
MGRO J2019+37
MGRO J1908+06
HESS J1825-137
RX J1713.7-3946
MSH 15-52
HESS J1303-638
RX J0852.0-4622
Vela X
0°
60°
30°
0°
-30°
-60°
-90°

HESS

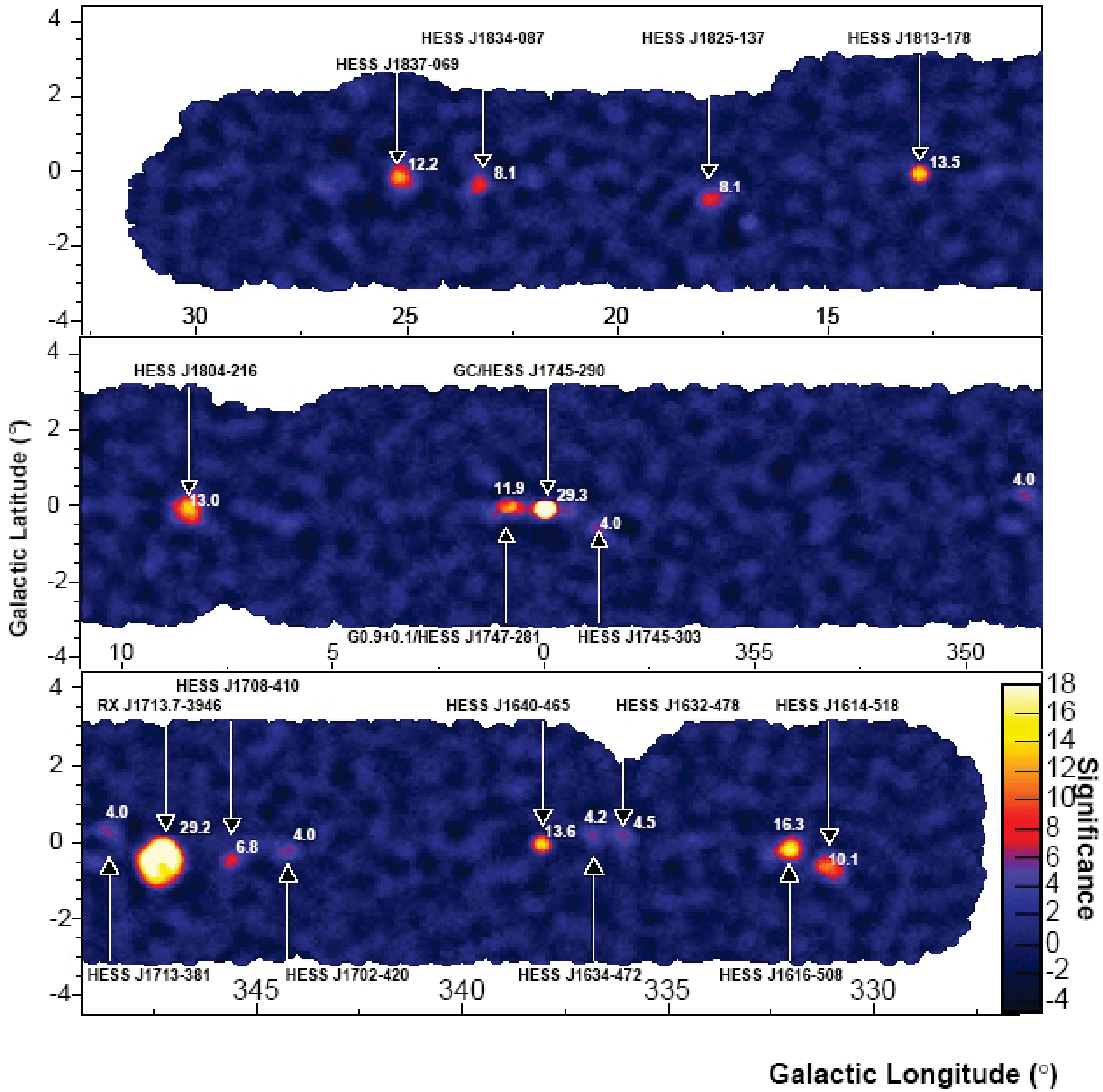
Science
March - 2005

"SCAN"

of the

Galactic Plane

15 New Sources
+ 3 Known



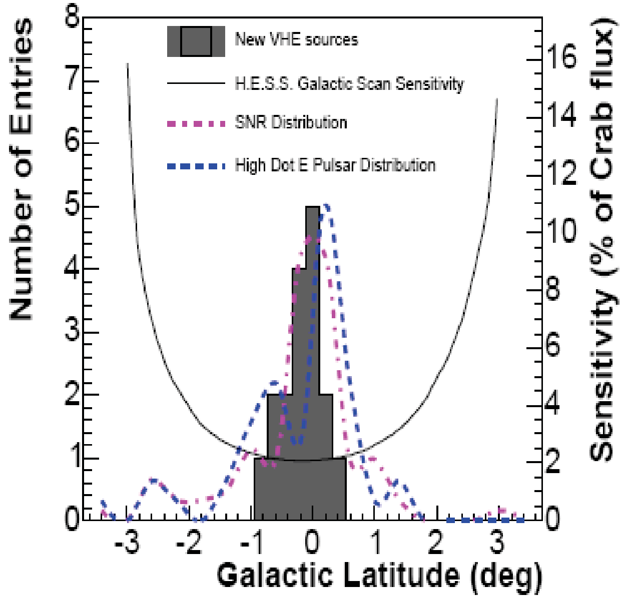


Table 3. Galactic sources.

	RA (h m)	Dec (° ′)	Flux[a]	Γ[b]	*s*[c]	Type	Association[d]
G1	02 40	+61 15	2.7	2.6	p	XRB	LSI+61 303
							E0241+6103
G2	05 35	+22 01	22–37	2.4–2.8	p	PWN	Crab nebula
G3	06 16	+22 31	0.6	3.1	p	SNR	IS443
G4	06 33	+05 21	0.9	2.5	p	UID	Monoceros?
							E0634-0521?
G5	08 35	−45 34	9	1.7, 3.4	e	PWN	Vela X
				1.5(14)			
G6	08 52	−46 20	21	2.1	m	SNR?	R0852-4622
G7	10 23	−57 45	4.5	2.5	e	UID	Westerlund2
					stellar cluster in H II region		
G8	13 02	−63 49	1.3	2.7	p	BP	P1259-63
G9	13 03	−63 11	4.3	2.4	e	UID	
G10	14 18	−60 58	2.6	2.2	e	PWN?	G313.3+0.1?
G11	14 20	−60 45	3.5	2.2	e	PWN?	P1420-6048?
							E1420-6038?
G12	14 28	−60 51	1.3	2.2	e	UID	
G13	14 42	−62 29	2.7	2,5	e	SNR	RCW86
G14	15 14	−59 09	5.7	2.3	e	PWN	MSH15-52
							P1509-58
G15	16 14	−51 49	8.1	2.5	e	UID	
G16	16 16	−50 53	6.7	2.4	e	PWN?	P1617-5055
G17	16 26	−49 05	4.9	2.2	e	UID	
G18	16 32	−47 49	5.3	2.1	e	UID	I16320-4751?
G19	16 34	−47 16	2.0	2.4	e	UID	I16358-4726?
							G337.2+0.1?
G20	16 40	−46 31	3.0	2.4	p	UID	G338.3-0.0?
							E1639-4702?
G21	17 02	−42 04	9.1	2.1	e	UID	P1702-4128?
G22	17 08	−41 04	2.7	2.5	p	UID	
G23	17 13	−38 11	0.7	2.3	e	UID	G348.7+0.3?
G24	17 13	−39 45	17	2.3	m	SNR	R1713.7-3946
			19	2.0(12)			G347.3-0.5?
G25	17 18	−38 33	0.3	0.7(6)	e	PWN?	
G26	16 32	−34 43	6.1	2.3	e	UID	

CRAB Nebula
SNR: RX 1713.7 -3946 (SN 393A)
SNR: R0952-4622 (Vela

Table 4. Galactic sources—continued.

	RA (h m)	Dec (° ′)	Flux[a]	Γ[b]	*s*[c]	Type	Association[d]
G27	17 45	−29 00	2.5	2.2	p	UID (Galactic Center)	
G28	17 45	−30 22	2.5	1.8	e	UID	E1744-3011?
G29	17 47	−28 09	0.8	2.4	p	SNR?	G0.9+0.1
G30	18 00	−24 00	1.9	2.5	e	SNR?	W28
			0.8	2.7	e	molecular cloud	
G31	18 04	−21 42	5.7	2.7	e	UID	G8.7-0.1
							P1803-2137?
G32	18 10	−19 18	4.6	2.2	e	PWN?	
G33	18 13	−17 50	2.7	2.1	p?	UID	G12.82-0.02?
G34	18 26	−13 44	20	2.4	m	PWN	G18.0-0.7
			21	2.2(25)			P1826-1334
G35	18 26	−14 49	1.9	2.1	p	XRB	LS 5039
			2.3/0.1	1.9/2.5	gamma ray flux varies with 3.9d		
G36	18 33	−10 33	0.5	2.1	p	SNR	G21.5-0.9
						PWN	P1833-1034
G37	18 34	−08 45	2.6	2.5	e	UID	G23.3-0.3
							W41?
G38	18 37	−06 56	5.0	2.3	e	UID	G25.5+0.0
G39	18 41	−05 33	12.8	2.4	e	UID	
G40	18 46	−02 59	0.6	2.3	p	SNR?	Kes75
					e	PWN?	P1846-0258
G41	18 57	+02 40	6.1	2.4	e	UID	
G42	18 58	+02 05	0.6	2.2	p?	UID	
G43	19 08	+06 30	8.8[h]	2.3	e	SNR?	G40.5-0.5
			3.2	2.1			
G44	19 12	+10 10			e	PWN?	P1913+1011?
G45	19 58	+35 12	2.3[g]	3.2	p	XRB	Cyg X-1
G46	20 19	+37 00	8.7[h]	2.3	e	PWN?	G75.2+0.1
G47	20 32	+41 30	0.6	1.9	e	UID	Cyg OB2?
			9.8[h]	2.3		?	
G48	23 23	+58 49	0.7	2.5	p?	SNR	Cas A

[a] Flux in the unit of 10^{-12} cm^{-2} s^{-1} TeV^{-1} at 1 TeV.
[b] Spectral index Γ when fitted by $E^{-\Gamma}$. See text for details.
[c] p: point-like, e: extended. m: morphological structure studied.

Table 5. Extragalactic sources.

	RA	Dec	Flux[a]	Γ[b]	z[c]	Name
E1	02 32 53.2	+20 16 21	0.62	2.5	0.140	1ES 0229+200
E2	03 49 23.0	−11 58 38	0.45	3.1	0.188	1ES 0347−121
E3	05 50 40.8	−32 16 18	~0.3	2.8	0.069	PKS 0548-322
E4	10 15 04.1	+49 26 01	~0.3	4.0	0.212	1ES 1011+496
E5	s11 03 37.7	−23 29 31	0.4	2.9	0.186	1ES 1101−232
E6	11 04 27.6	+38 12 54	12–97	2.4–3.1(3)	0.031	Mkn 421
E7	11 36 26.4	+70 07 28	0.9	3.3	0.046	Mkn 180
E8	12 21 22.1	+30 10 37	1.3	3.0	0.182	1ES 1218+304
E9	12 30 54.4	+12 24 17	1	2.9	0.004	M87
E10	12 56 11.1	−05 47 22	[e]		0.536	3C279
E11	14 28 32.7	+42 40 20	1–2	2.6–3.7	0.129	H 1426+428
E12	15 55 43.2	+11 11 21	0.1–0.2	4.0	0.36?	PG1553+113
E13	16 53 52.1	+39 45 37	0.5–100	1.9–2.3(5)	0.034	Mkn 501
E14	19 59 59.9	+65 08 55	4–120	2.7–2.8	0.047	1ES 1959+650
				1.8(4–10)		
E15	20 09 29.3	−48 49 19	0.2	4	0.071	PKS 2005-489
E16	21 58 52.7	−30 13 18	2–3	3.3–3.4	0.116	PKS 2155-304
E17	22 02 43.3	+42 16 40	~0.3	3.6	0.069	BL Lacetae
E18	23 47 06.0	+51 42 30	1–5	2.3–2.5	0.044	1ES 2344+514
E19	23 59 07.9	−30 37 41	~0.3	~3.1	0.165	H 2356−309

[a] Flux in the unit of 10^{-12} cm^{-2} s^{-1} TeV^{-1} at 1 TeV.

[b] Spectral index Γ when fitted by $E^{-\Gamma}$.

[c] Red shift.

TeV Galactic Sources
Measured by HESS, MAGIC

Have FLUX:

Flux ($E_\gamma > 1$ TeV) = 0.11 - 2.1

UNIT : $10^{-11}\ (\mathrm{cm}^2\ \mathrm{s})^{-1}$

Three Brightest sources in the TeV sky:

CRAB NEBULA

2 young SNR
Vela Junior
RX 1713.7-3946

$$\Phi(E > 1\ \mathrm{TeV}) \simeq 10^{-11}\ (\mathrm{cm}^2\,\mathrm{s})^{-1}$$

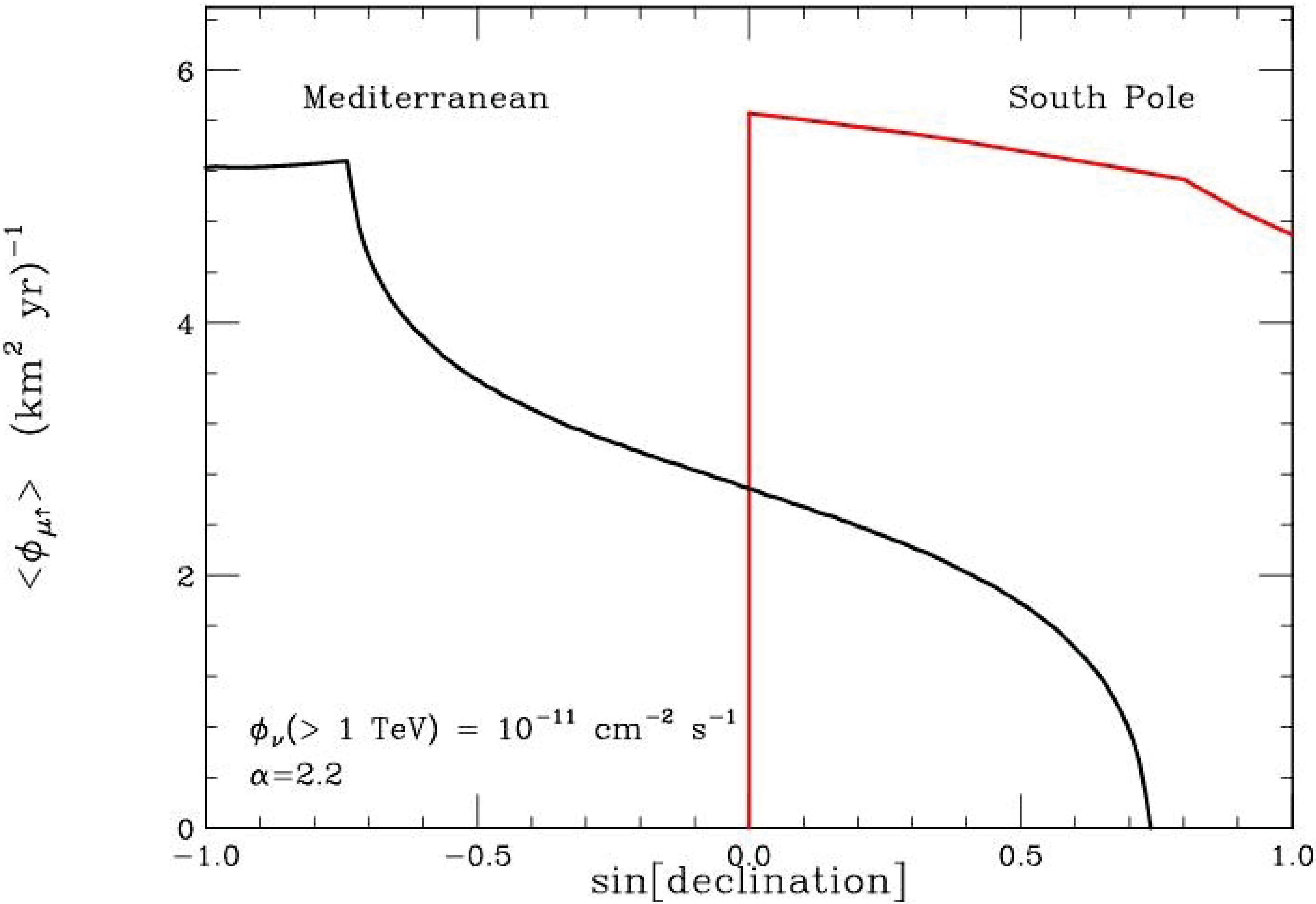
TeV Photons in a Cherenkov Telescope

$$\sim 10\ \frac{\mathrm{events}}{\mathrm{hour}}$$

$$\phi(E) \propto E^{-2}$$

Up-going muons Neutrino telescope

$$\sim 2\ \frac{\mathrm{events}}{\mathrm{Km}^2\,\mathrm{yr}}$$



Mediterranean
South Pole
$\phi_\nu(> 1\ \mathrm{TeV}) = 10^{-11}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
α=2.2
$<\phi_{\mu\uparrow}>\ (\mathrm{km}^2\ \mathrm{yr})^{-1}$
sin[declination]
6
4
2
0
−1.0
−0.5
0.0
0.5
1.0

IF TEV emission of the
brightest TeV sources
is of hadronic nature

Detection with neutrinos
is within reach .....

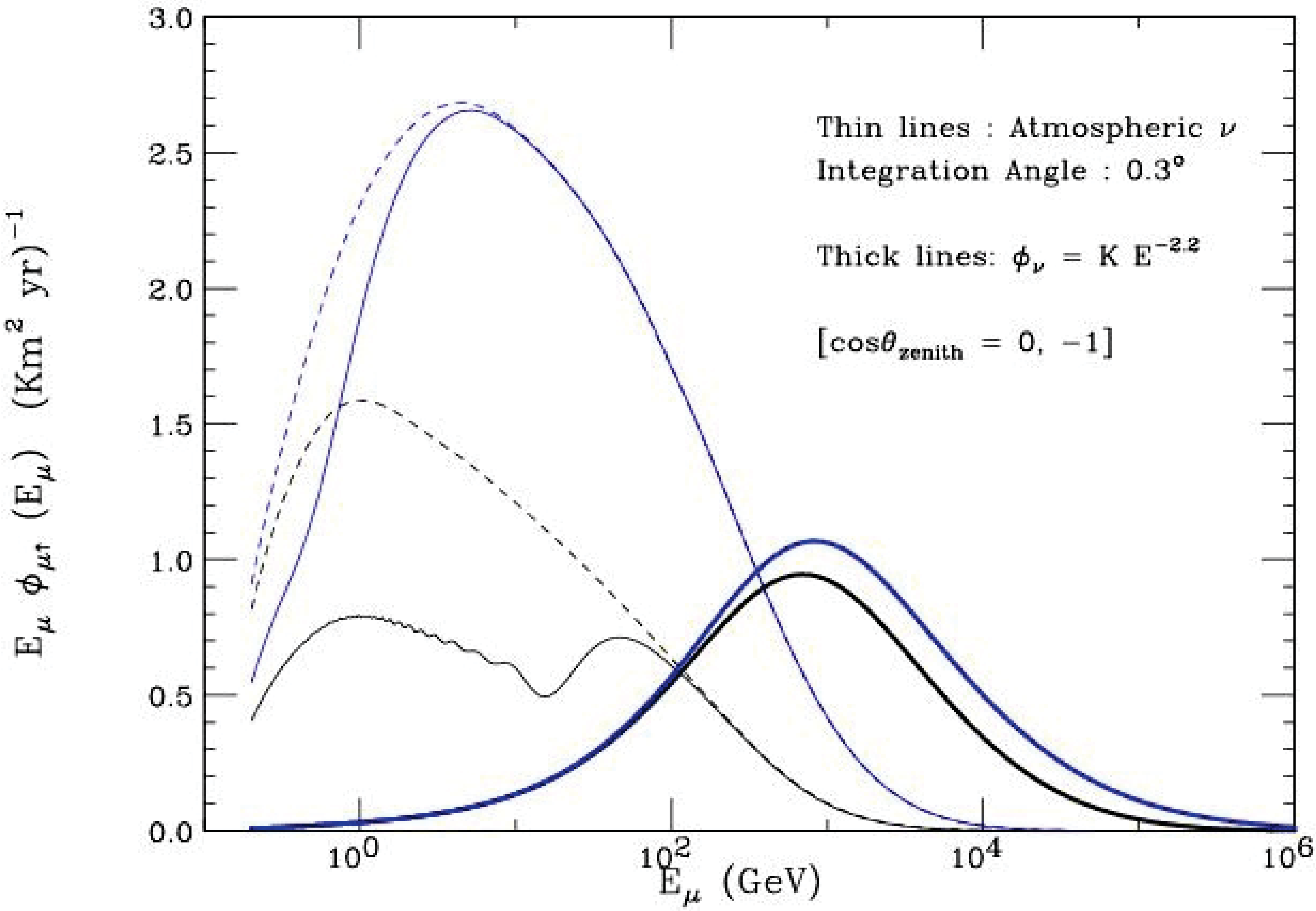
Few events / (km2 yr)

...but

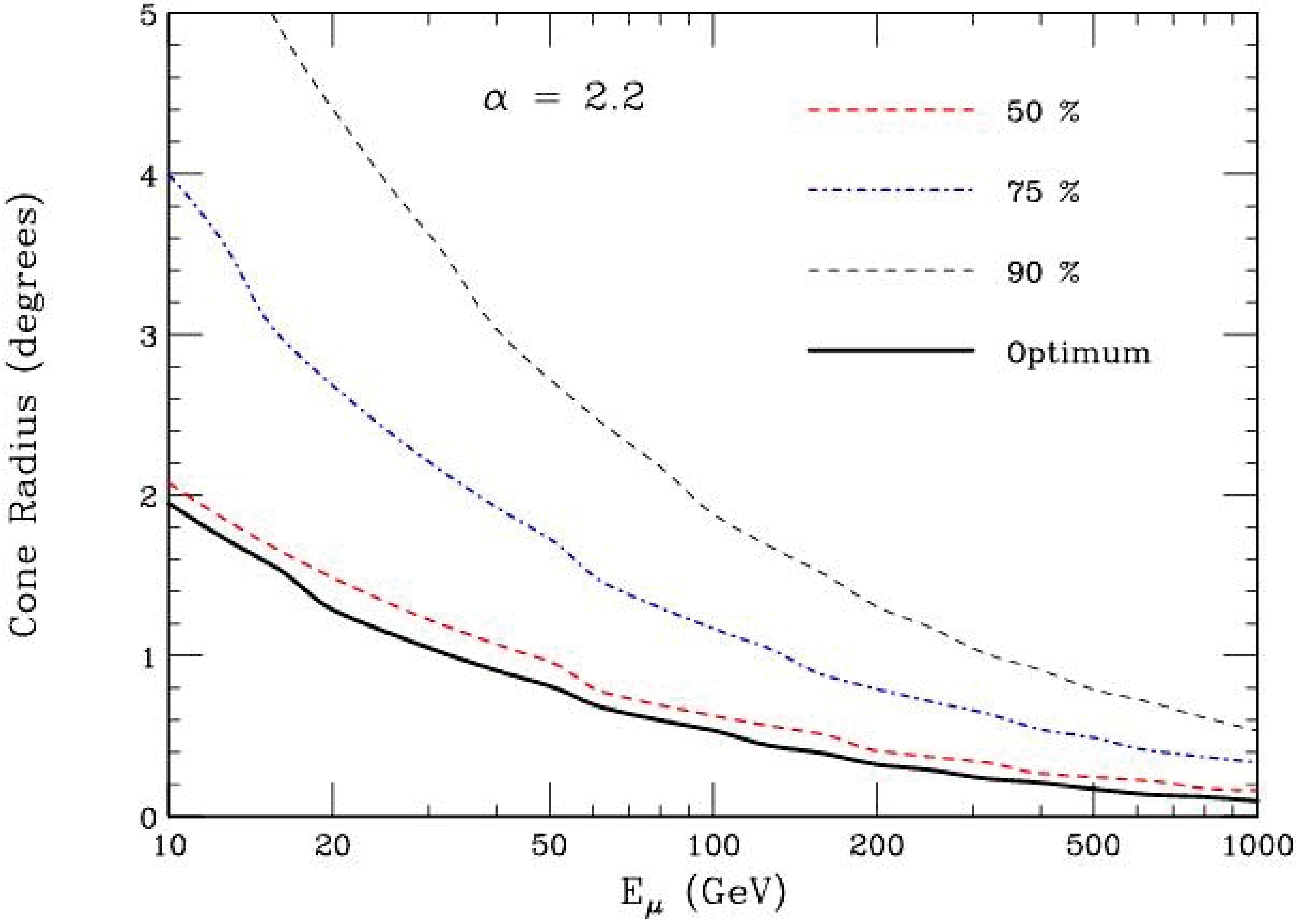
NOT EASY !

BACKGROUND

Atmospheric Neutrinos



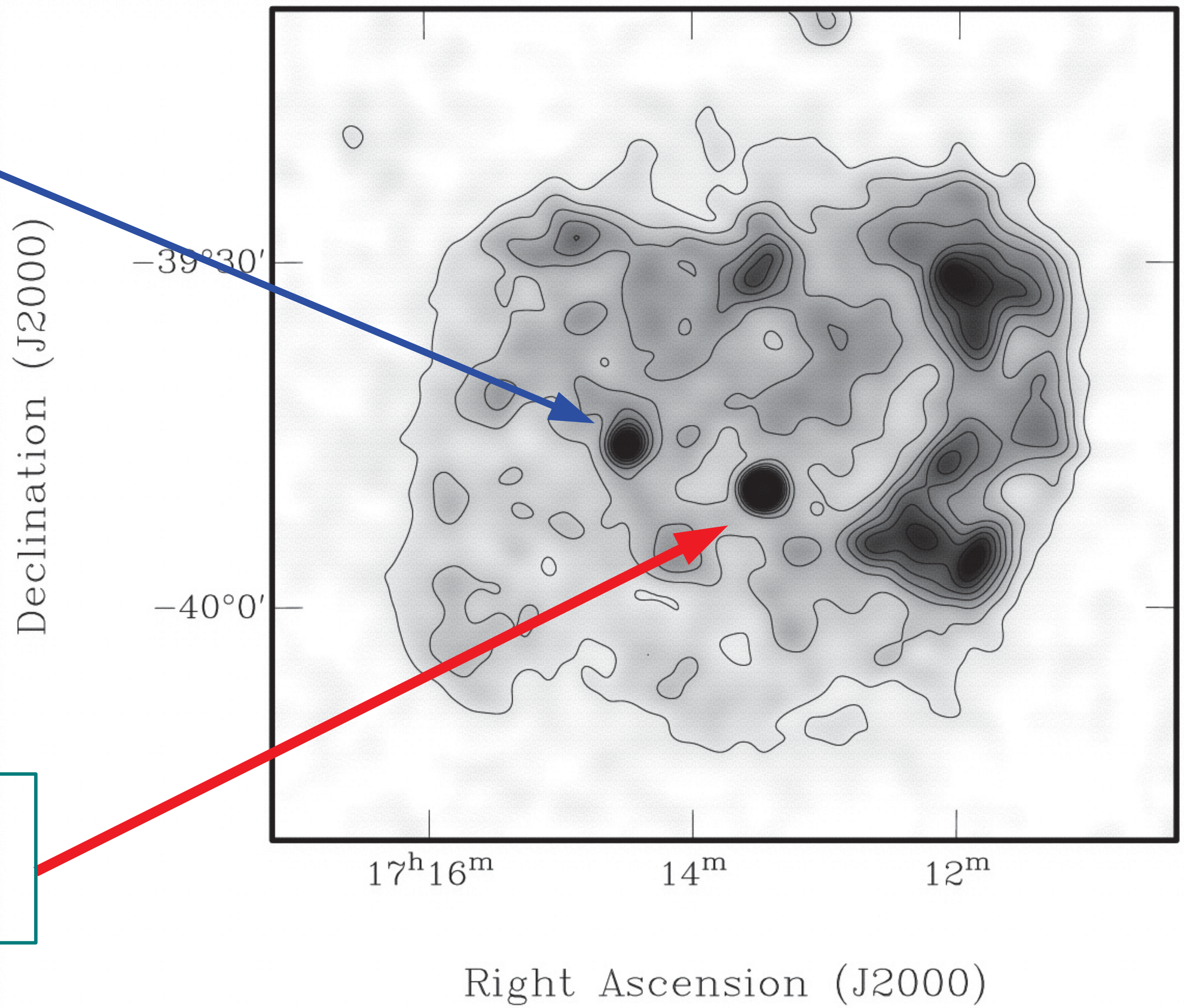
Angular Distribution of the Neutrino – induced Muons



SuperNova RX J1713.7-3946

Discovered in 1996 by the Roentgen Satellite (Rosat)

Foreground star

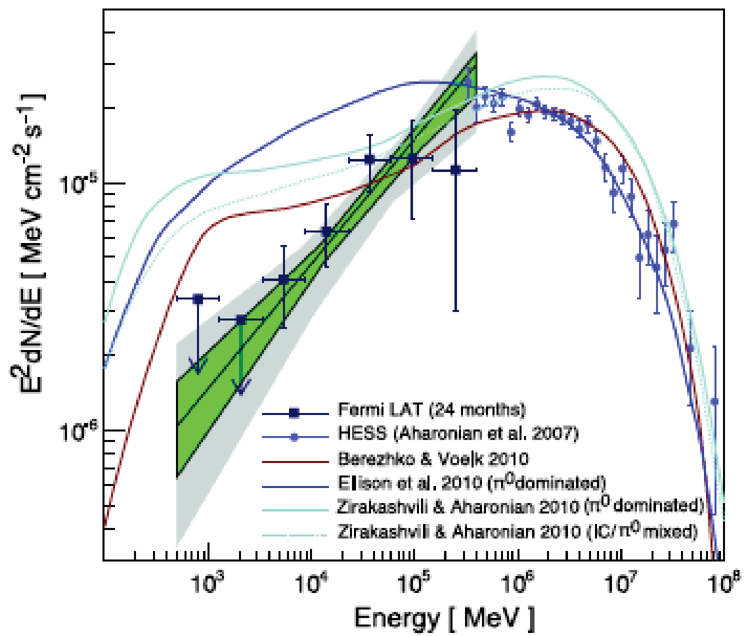


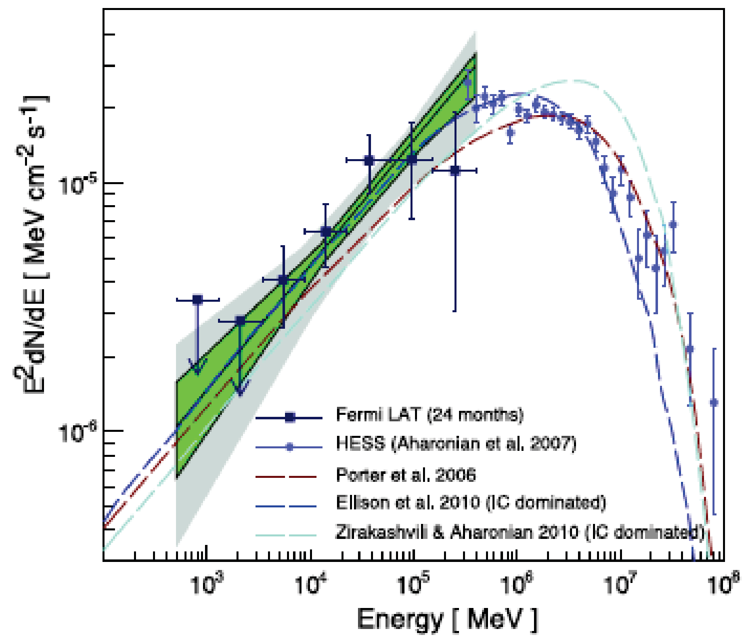
Point Source (Neutron Star)

Observations of the young Supernova remnant RX J1713.7−3946 with the *Fermi* Large Area Telescope

astro-ph/1103.5727.
29th march 2011

Favors
leptonic interpretation.





Critical Question:

Can Multi-wavelength Observations Identify the origin of the emission ?

Neutrino Astronomy should be considered in the context of the scientific programs toward the understanding of the "High Energy Universe".

Neutrino Astronomy
Gamma Astronomy
Cosmic Ray Astrophysics

What is the significance of the observations of a small number of neutrinos from several sources ?

[Can the hadronic nature of the emission be established *without* neutrinos, from multiwavelength observations?]

Power of discrimination is widely considered as important

What about "ABSORBED SOURCES ?"

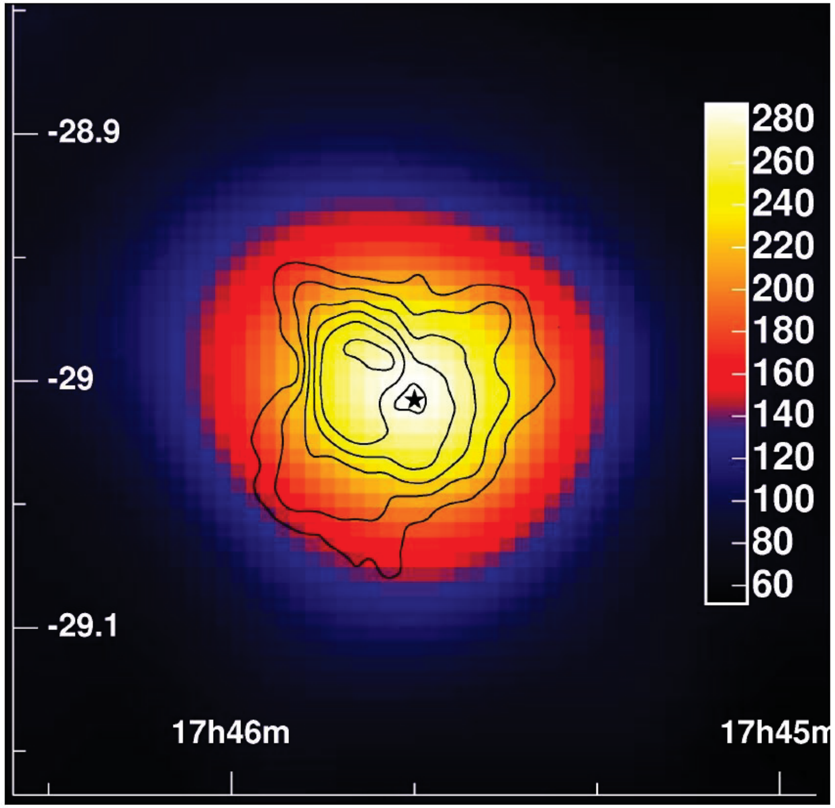
(Much) Higher flux in neutrinos than in photons ?

Best cases for making a bet:

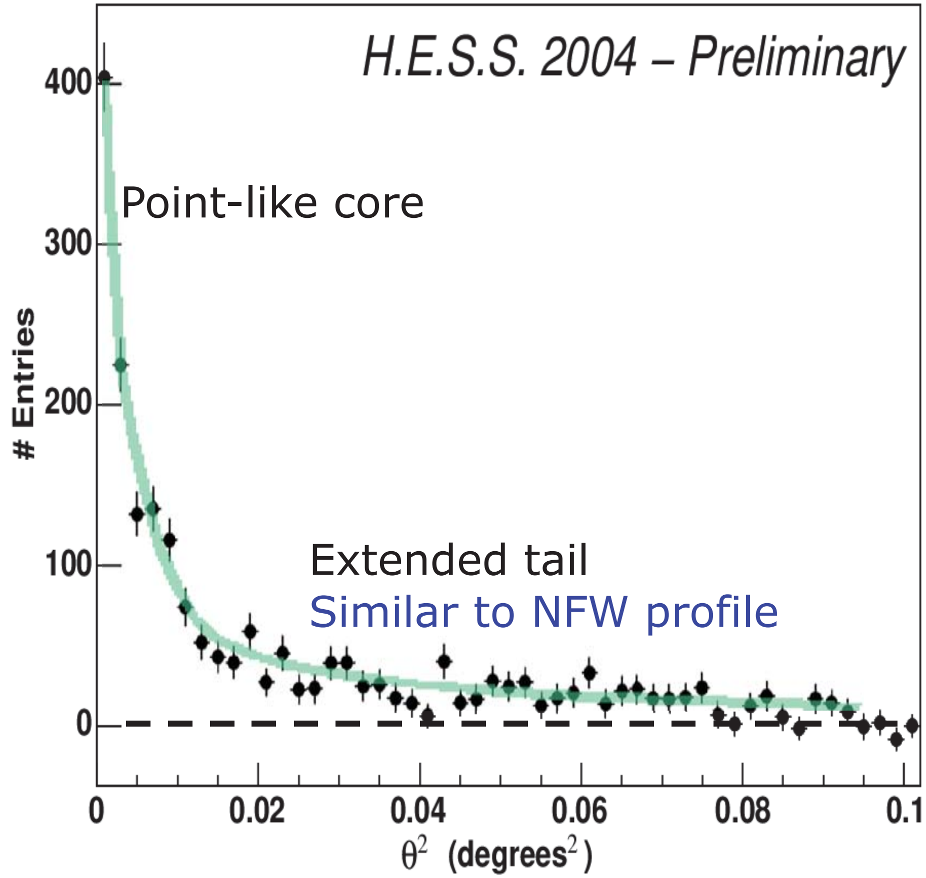
- GALACTIC CENTER (of course !)
- MicroQuasars

..... Surprises ? ......

GALACTIC CENTER

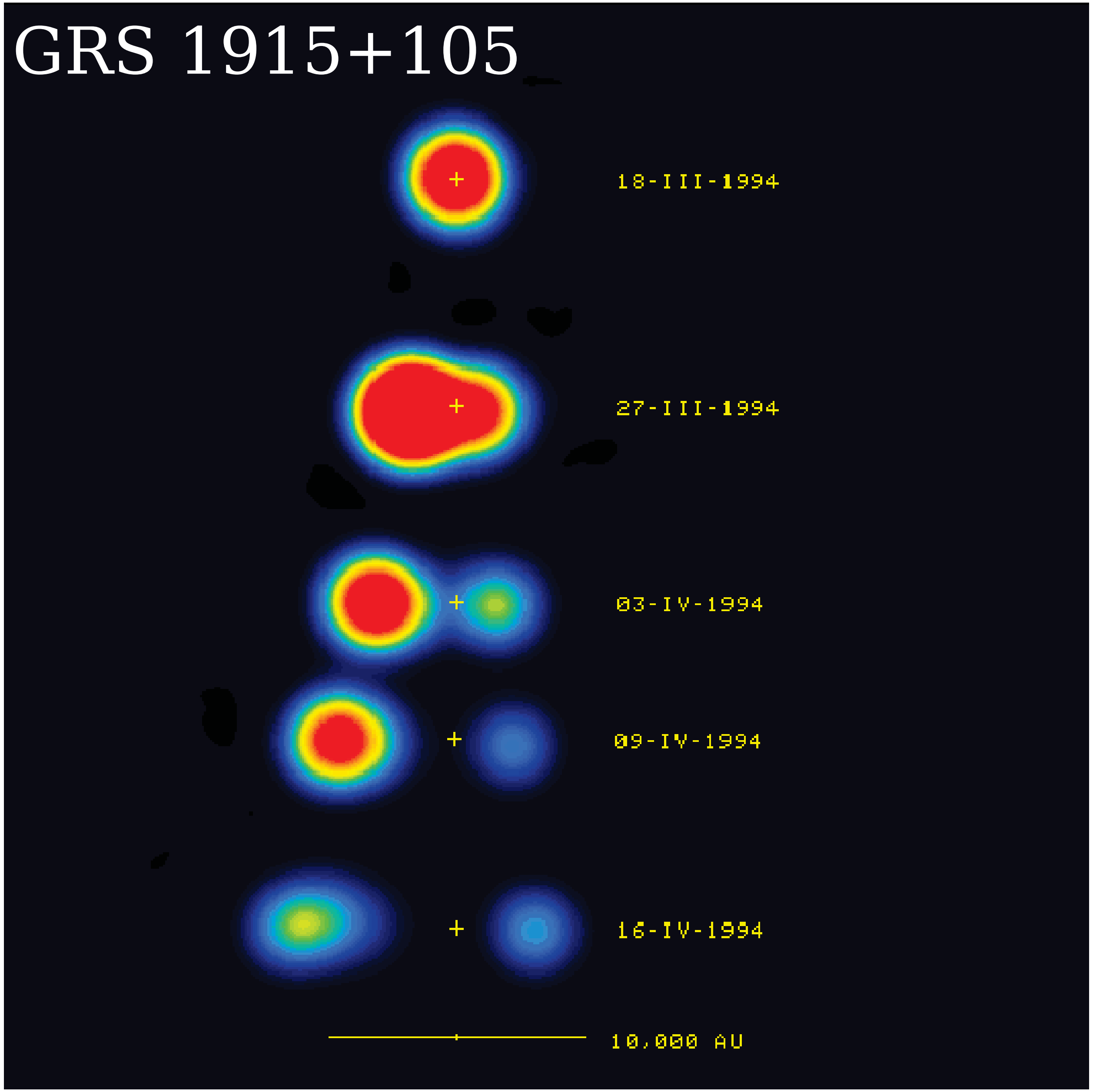


Colors: H.E.S.S.
Contours: Radio



Angular distribution

MICROQUASARS

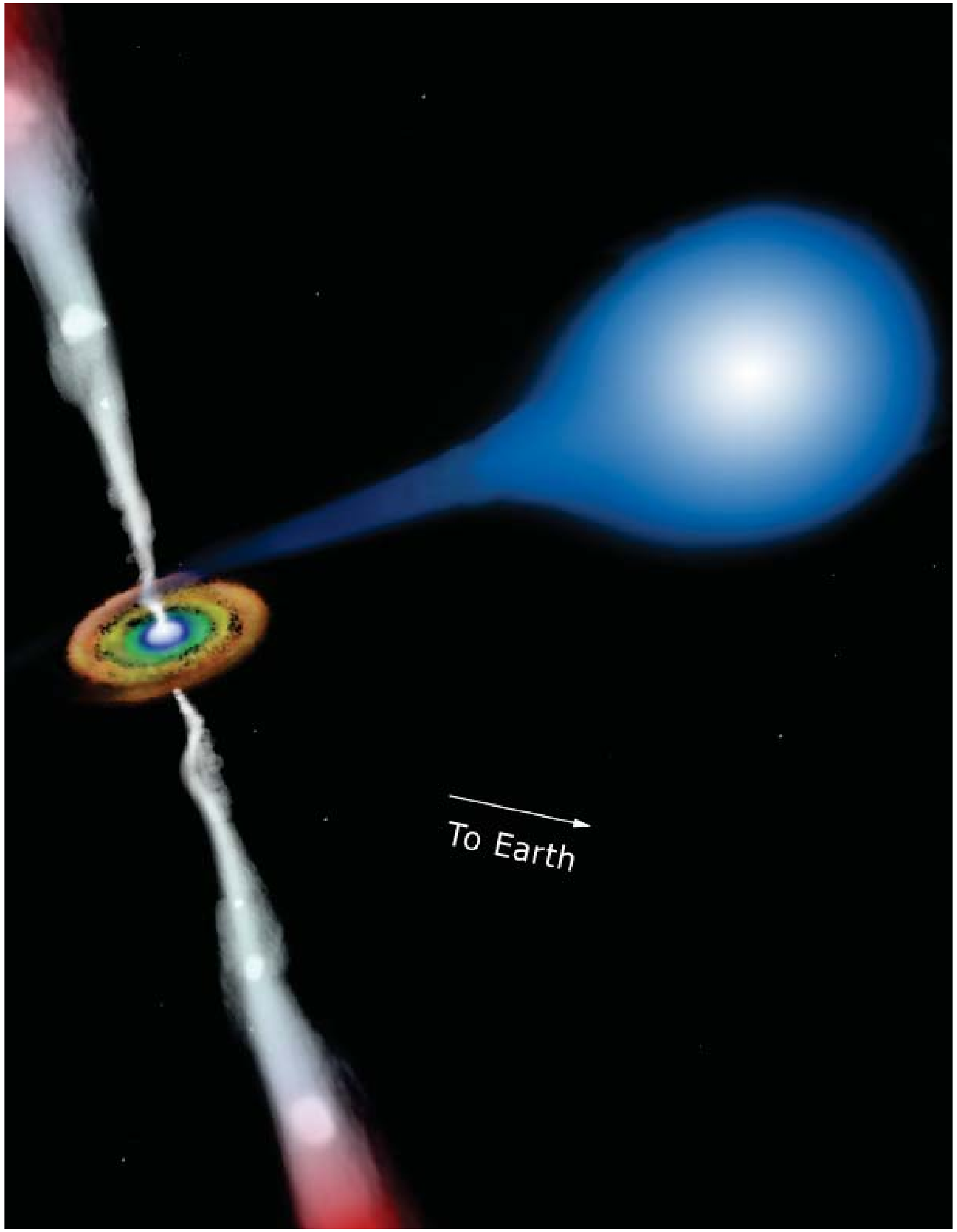


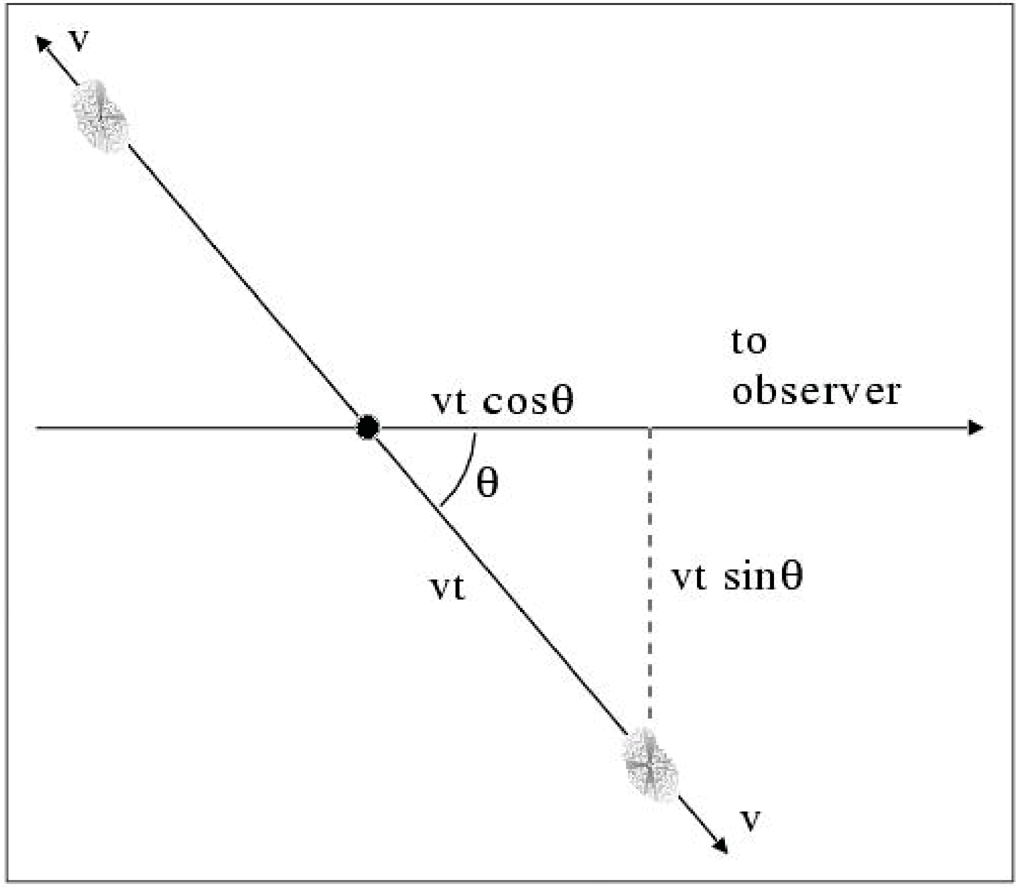
Galactic binary system with one stellar mass black hole

Symmetric emission of Plasma "blobs"

Detection in Radio (VLBI)

Geometry of the emission of the two jets





Intense radiation field
Of the companon star
Absorbs TeV photons [?]

NEUTRINO ASTRONOMIES

$$E_\nu \sim [10^{10} \div 10^{12}]\ \text{eV}$$

Dark Matter

$$E_\nu \sim [10^{13} \div 10^{14}]\ \text{eV}$$

Point sources

$$E_\nu \sim [10^{14} \div 10^{17}]\ \text{eV}$$

GRB [exploration]

$$E_\nu \sim [10^{17} \div 10^{20}]\ \text{eV}$$

Cosmogenic Neutrinos

$$E_\nu \gtrsim 10^{20}\ \text{eV}$$

“Exotic” (TD decay...)

Additional Topics for a complete discussion:

- Atmospheric Neutrinos
- Cosmogenic "GZK" Neutrinos
- Exotic Physics Neutrinos
  (Top-Down Models)
- Dark Matter Annihilation Neutrinos
  (from the Sun or the Center of the Earth)
- "Interdsciplinary studies"

Final comments (instead of conclusions)

Best Wishes
to the Observers !!

Final comments (instead of conclusions)

The interest of Neutrino Astronomy is remarkable.

The difficulties are great.

Detector optimization requires identifying
“Physics priorities”

Focus on Galactic Sources
Deeper searches for Extra-galactic Sources
Search for GRB emission
“GZK” cosmogenic neutrinos.

Better angle, energy (for muon) resolution

Very large “sparse” detectors ?