Perspectives for Neutrino Astronomy

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Workshop:
"Recent Developments in Astronuclear and Astroparticle Physics"

Trieste 20th november 2012

Astrophysics with four MESSENGERS

- Photons

Essentially all the information
We have on the Universe around us
has been obtained with photons.

The history of Astrophysics is the
EXTENSION of the range of
wavelength available for observations

- Neutrinos
- Cosmic Rays ($p, e^-, \bar{p}, e^+, \ldots$)
- Gravitational waves

Astrophysics with four MESSENGERS

- Photons
- Neutrinos → A New Messenger with very different properties that will allow to "SEE" the universe in a profoundly different way
- Cosmic Rays ($p, e^-, \bar{p}, e^+, \ldots$)
- Gravitational waves

Astrophysics with four MESSENGERS

- Photons
- Neutrinos
- Cosmic Rays ($p, e^-, \bar{p}, e^+, \ldots$)
- Gravitational waves

Study the structure and properties of the SOURCES

Study properties of the NEUTRINOS (oscillations, decay...)

Astrophysics with four MESSENGERS

- Photons
- Neutrinos
- Cosmic Rays (p, e^-, $\bar{p}, e^+$, ...)
- Gravitational waves

Relation between these fields

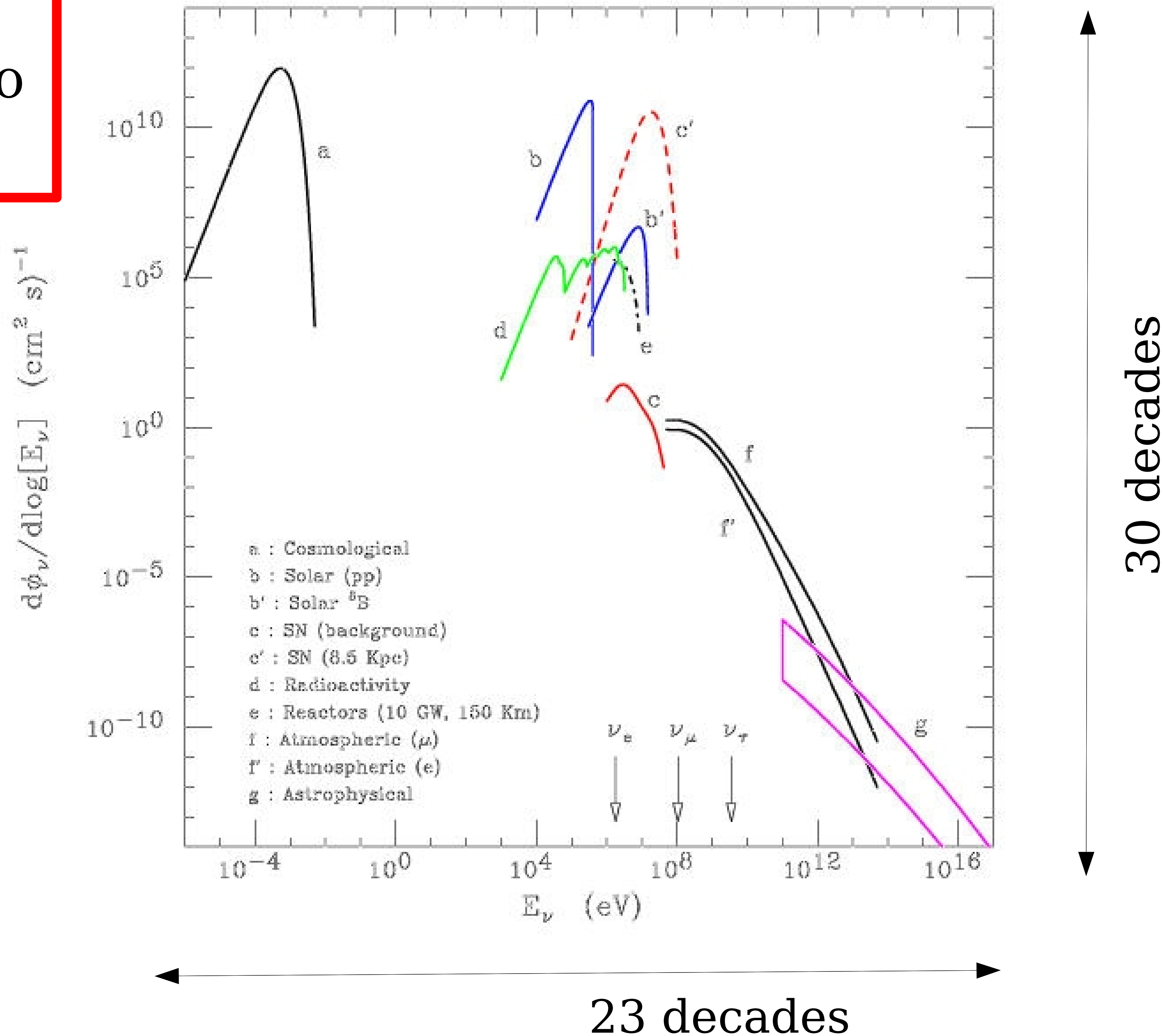
Observing same Objects / Events with ALL messengers at the same time ....

SPACE is
FULL of NEUTRINOS

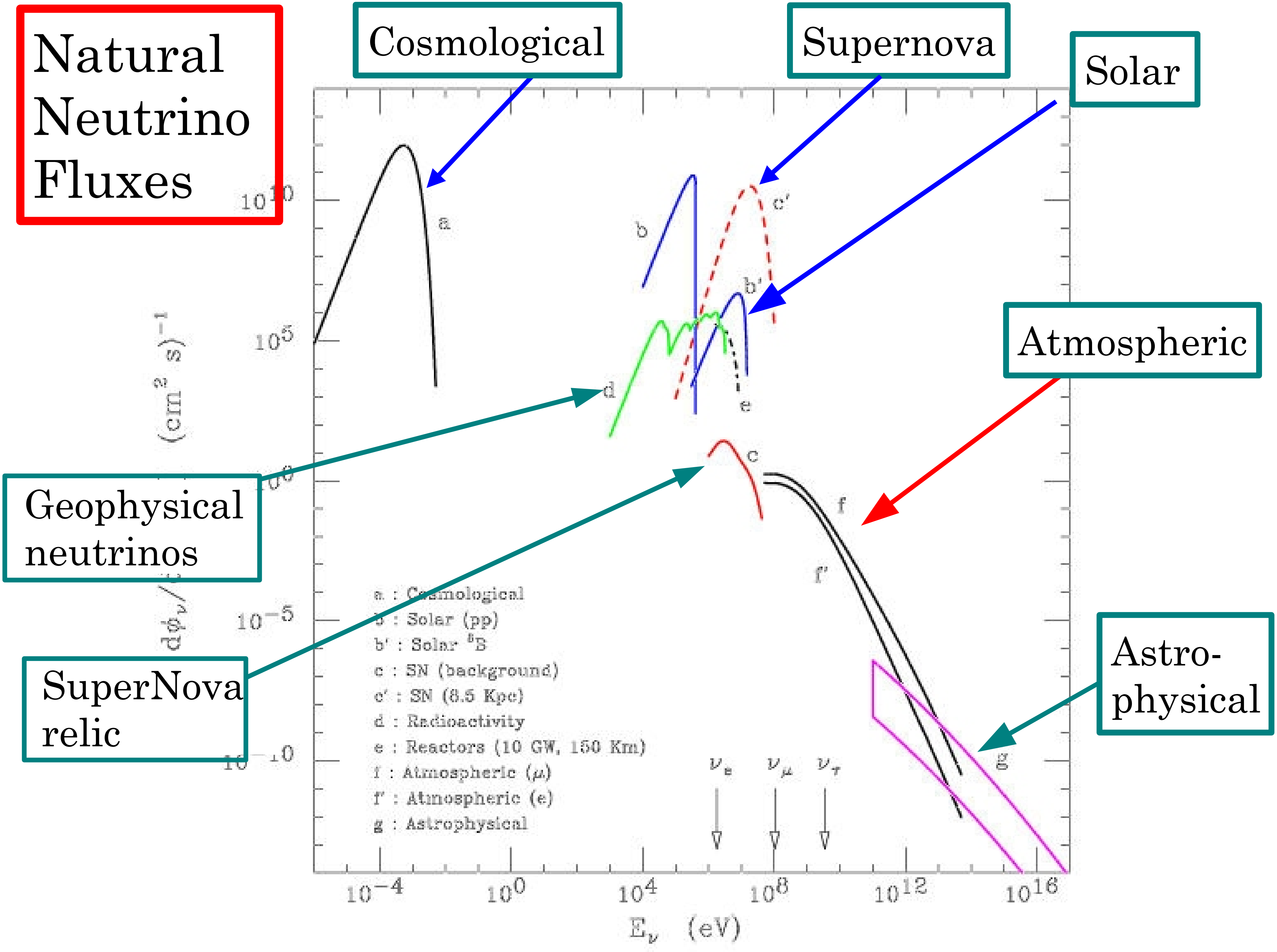
that come from a
variety of sources

in a very broad
interval of energies

Natural Neutrino Fluxes



Natural Neutrino Fluxes



The Cross Section of the Neutrino is VERY SMALL

PROBLEM :

Detection is Very Difficult

Require Very Large Detectors

OPPORTUNITY:

Neutrinos come from DEEP INSIDE Astrophysical Objects

Possibility of
"Modifications" of the neutrino flux
during propagation.

Investigate :
Flavor Oscillations (with very long path-lengths)
Decay (with very long lifetimes)
....

Important difficulty:
Properties of the neutrinos at the source
must be sufficiently well understood.

What could one learn about the neutrino properties
When astrophysical neutrinos are finally detected ?

Extraordinary Long Baselines

$$L_{\rm galactic} \simeq 3 \times 10^{22}~{\rm cm}$$

$$L_{\rm extra} \simeq 1.3 \times 10^{28}~z~{\rm cm}$$

Oscillations with very small Dm2

[Pseudo-Dirac neutrinos
Mass doublet with tiny
Mass splitting]

$$\Delta m^2 \sim 10^{-18}~{\rm eV}^2$$

Neutrino decay (9 orders of magnitude improvement)

Neutrino cross sections at very high energy

Neutrino Astronomy (or Astrophysics) has just been born at the end of the last Century

TWO (+1) ASTROPHYSICAL OBJECTS have been “seen” in Neutrinos”

The SUN

SuperNova SN1987A

The Earth: Geophysical Neutrinos

SOLAR NEUTRINOS

Source of Energy of the SUN : Nuclear Fusion

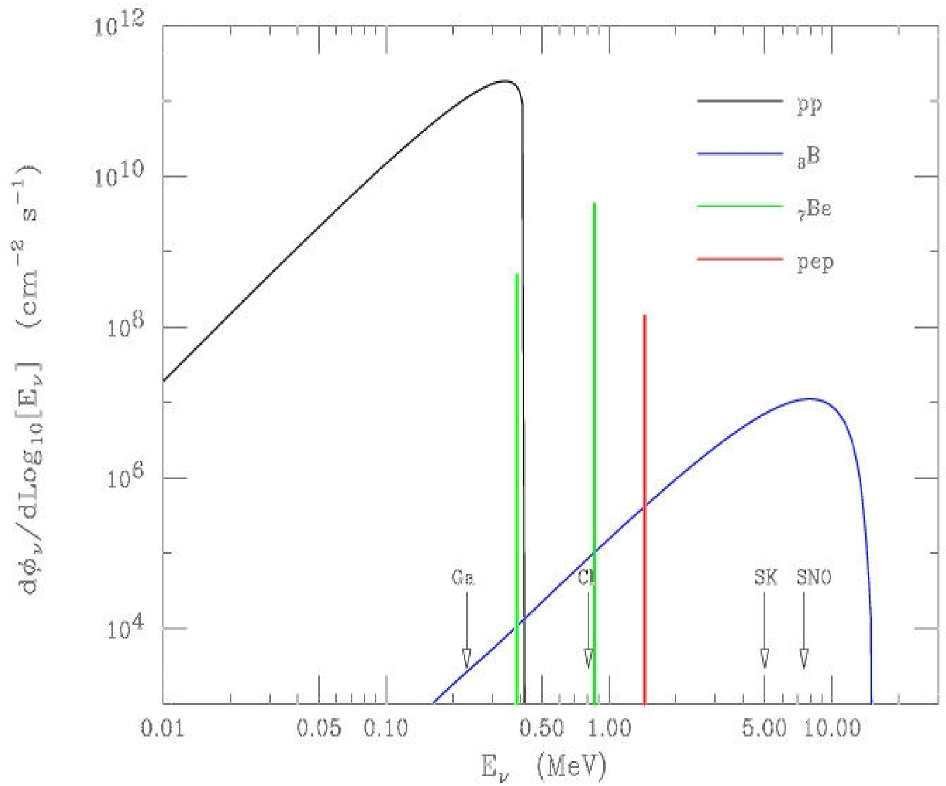
$$4p + 2e^- \rightarrow {}^4\mathrm{He} + 2\nu_e$$

Energy Released per each Cycle

$$Q = 4m_p + 2m_e - m_{He} = 26.73 \ \mathrm{MeV}$$

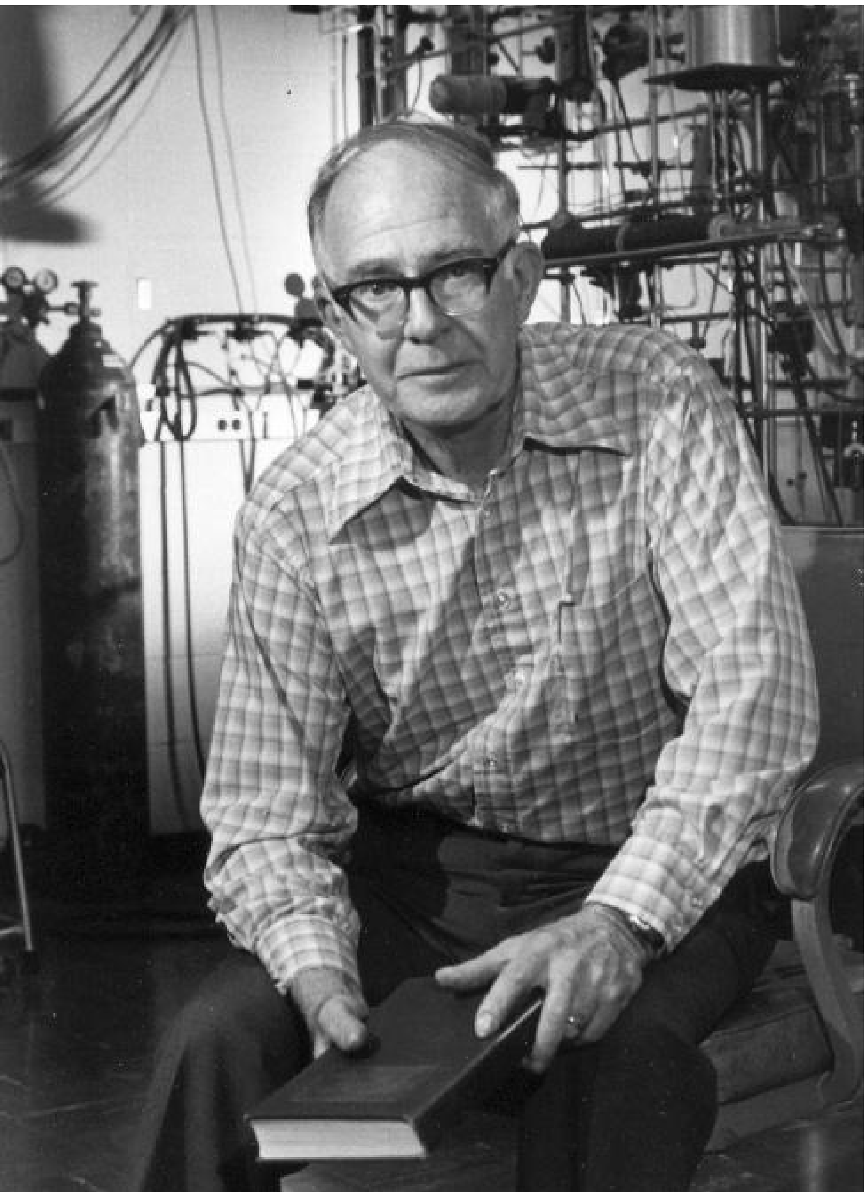
$$\Phi_{\nu_e} \simeq \frac{1}{4\pi\, d_\odot^2} \, \frac{2\, L_\odot}{(Q - \langle E_\nu \rangle)}$$

$$\phi_{\nu_\odot} \sim 6 \times 10^{10} \ (\mathrm{cm}^2 \ \mathrm{s})^{-1}$$



SOLAR NEUTRINOS. II. EXPERIMENTAL*

Raymond Davis, Jr.
Chemistry Department, Brookhaven National Laboratory, Upton, New York
(Received 6 January 1964)



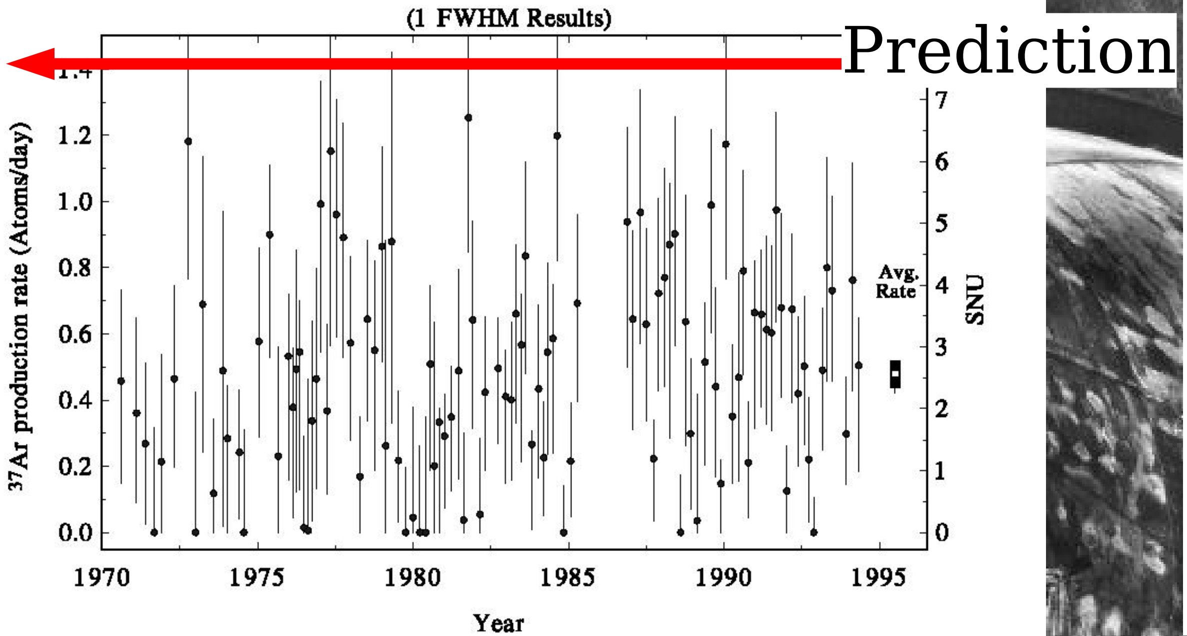
$$\nu_e + {}^{37}\mathrm{Cl} \rightarrow {}^{37}\mathrm{Ar} + e^-$$

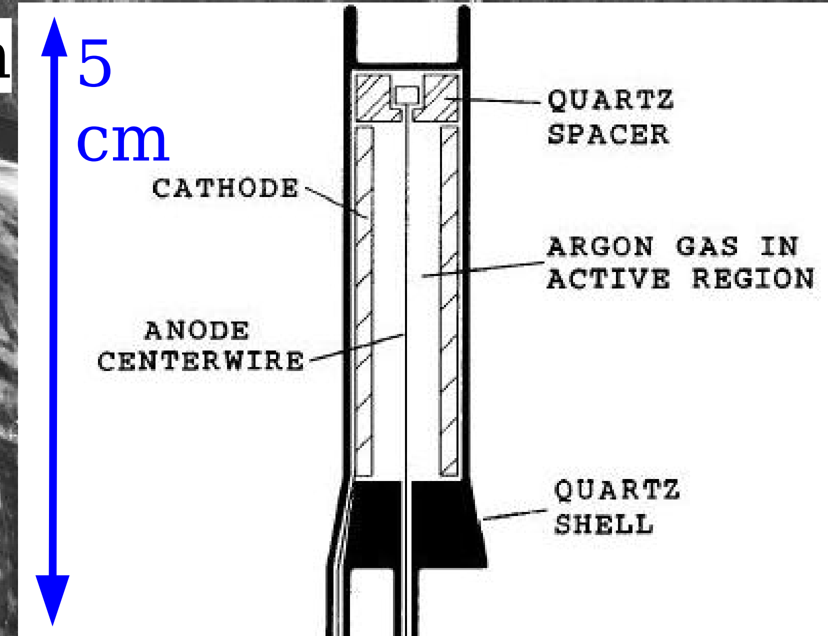
On the other hand, if one wants to measure the solar neutrino flux by this method one must use a much larger amount of C_2Cl_4, so that the expected ^{37}Ar production rate is well above the background of the counter, 0.2 count per day. Using Bahcall's expression,

$$\sum \varphi_\nu(\mathrm{solar})\, \sigma_{\mathrm{abs}}$$

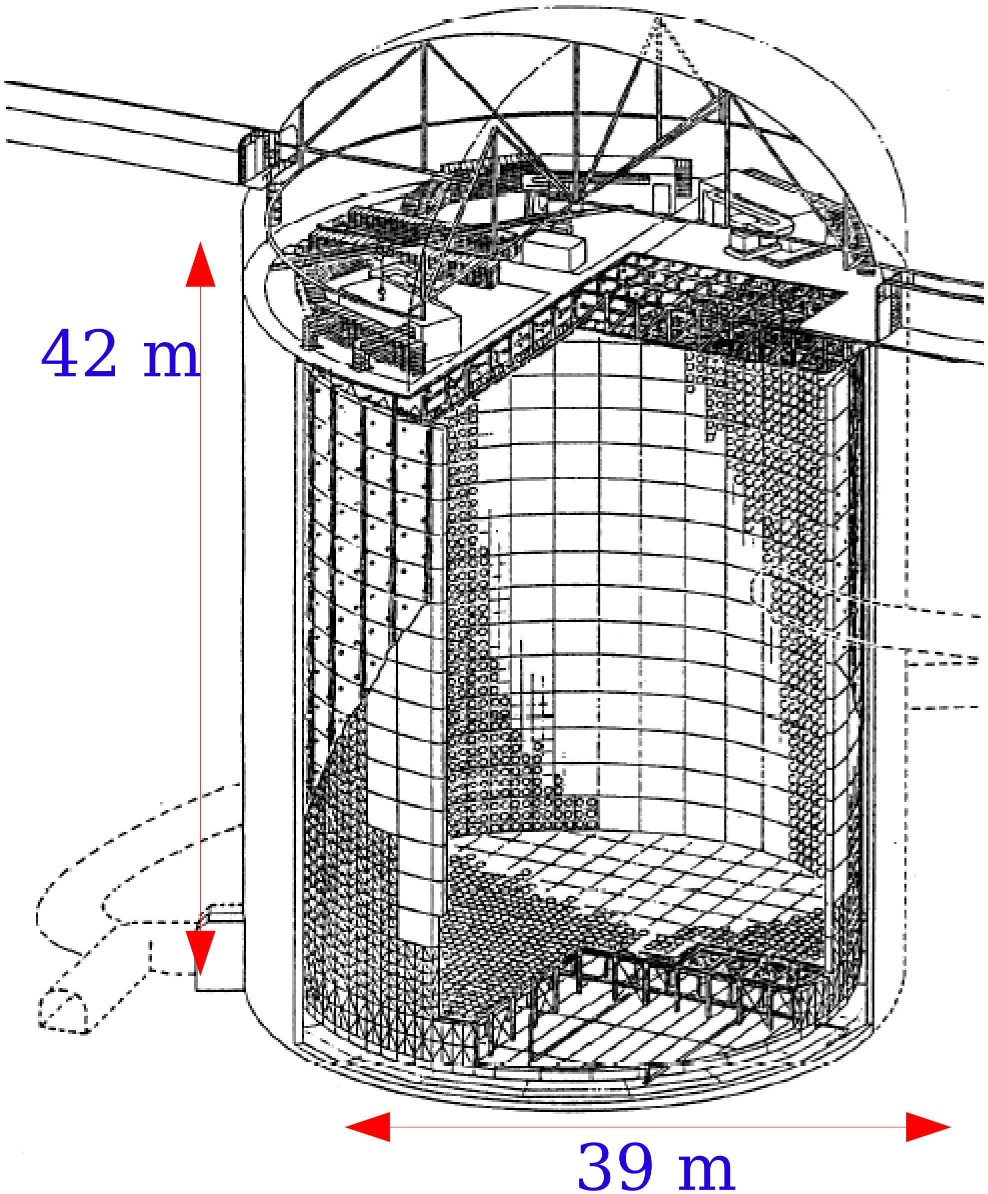
$$= (4 \pm 2) \times 10^{-35}\ \mathrm{sec}^{-1}\ ({}^{37}\mathrm{Cl\ atom})^{-1},$$

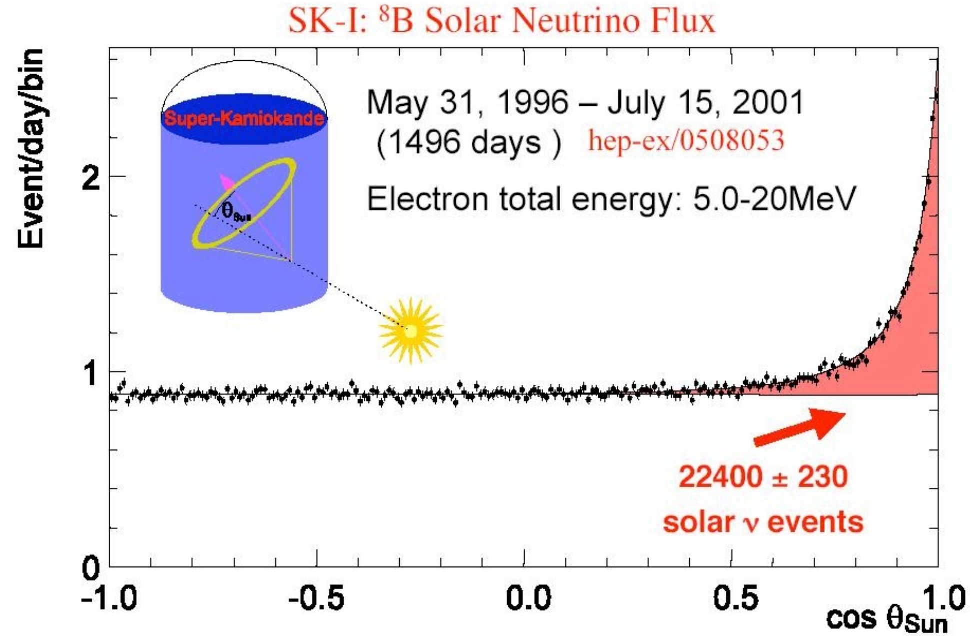
then the expected solar neutrino captures in 100 000 gallons of C_2Cl_4 will be 4 to 11 per day, which is an order of magnitude larger than the counter background.


(1 FWHM Results)
Prediction
37Ar production rate (Atoms/day)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
1
2
3
4
5
6
7
SNU
Avg. Rate
1970
1975
1980
1985
1990
1995
Year

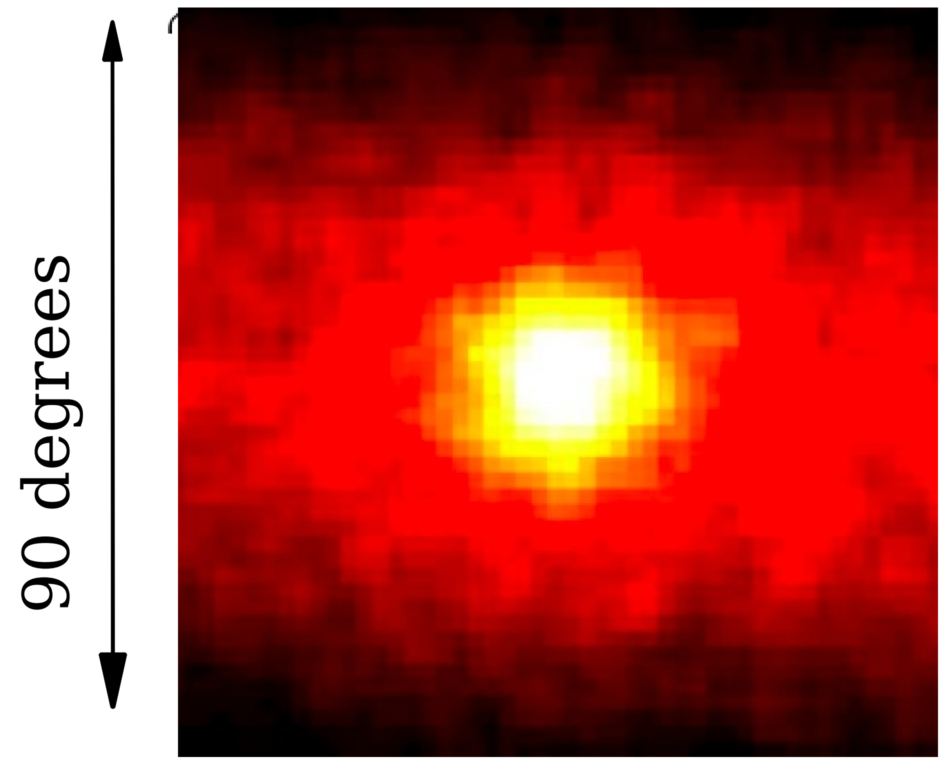

5 cm
QUARTZ SPACER
CATHODE
ARGON GAS IN ACTIVE REGION
ANODE CENTERWIRE
QUARTZ SHELL

Super Kamiokande





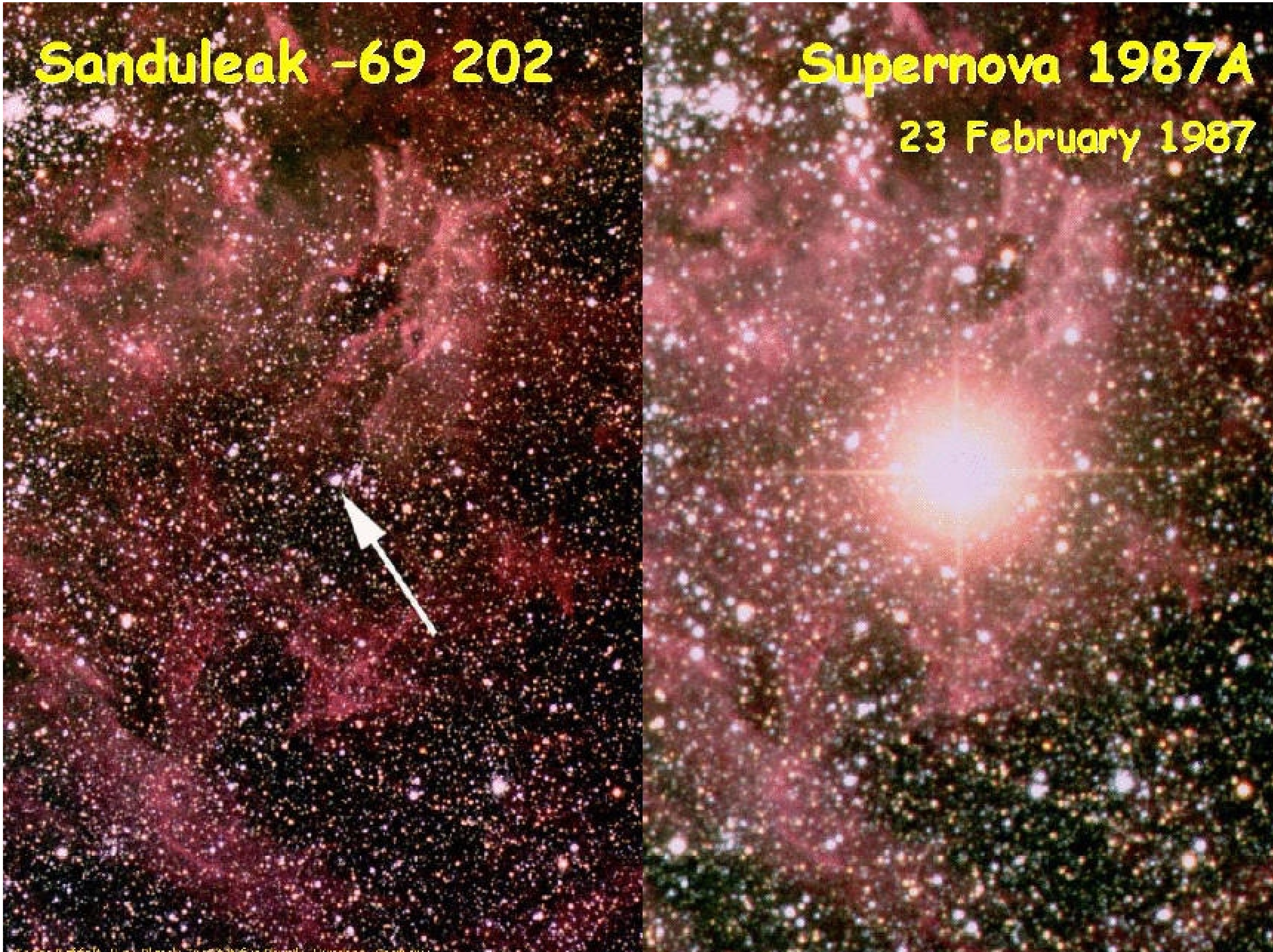
DATA/SM = 0.465± 0.015

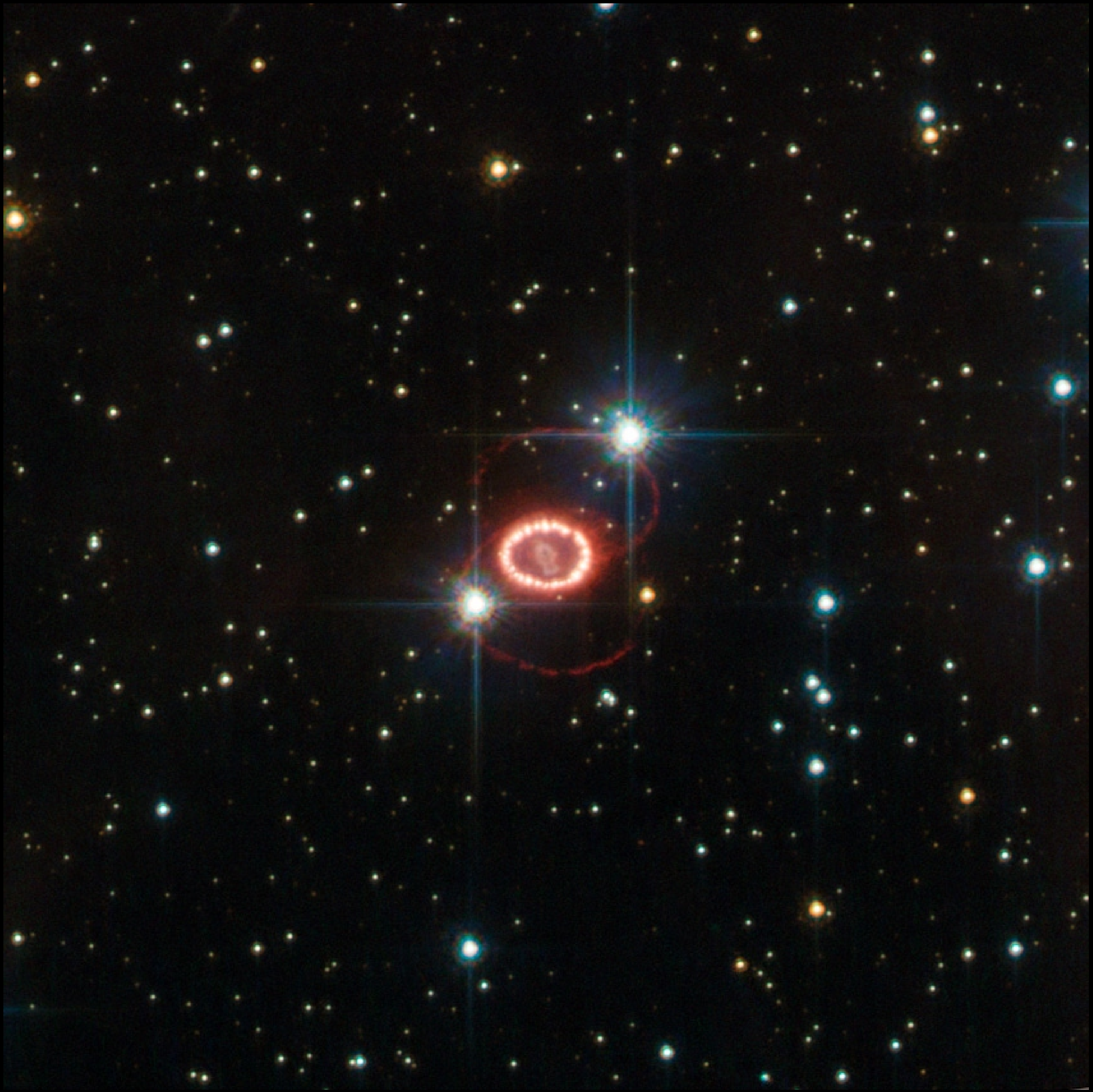


NEUTRINOS
from
SUPERNOVAE
EXPLOSIONS
(Gravitational Collapse)

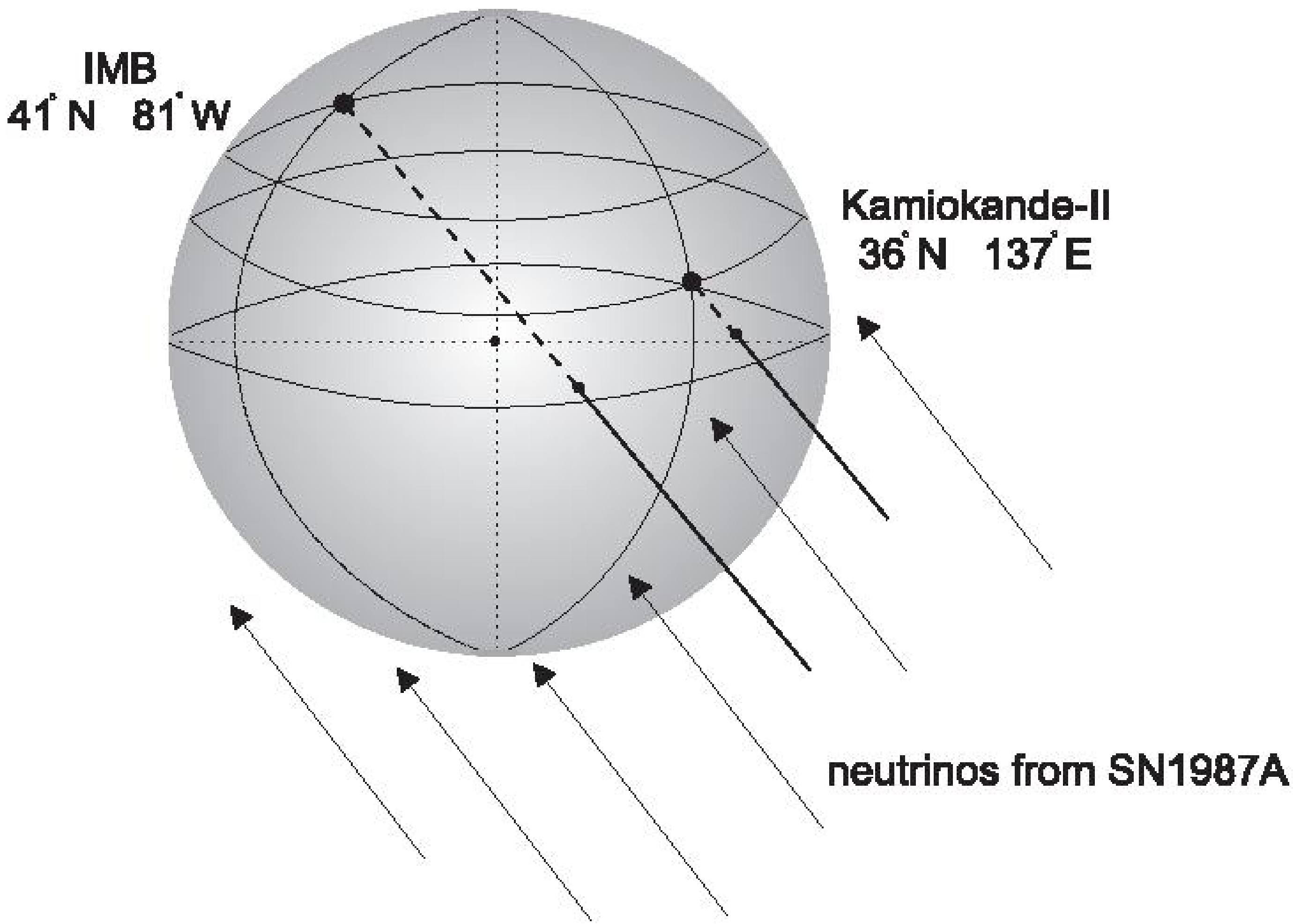
Energy 30 MeV

Neutrinos from Supernovae

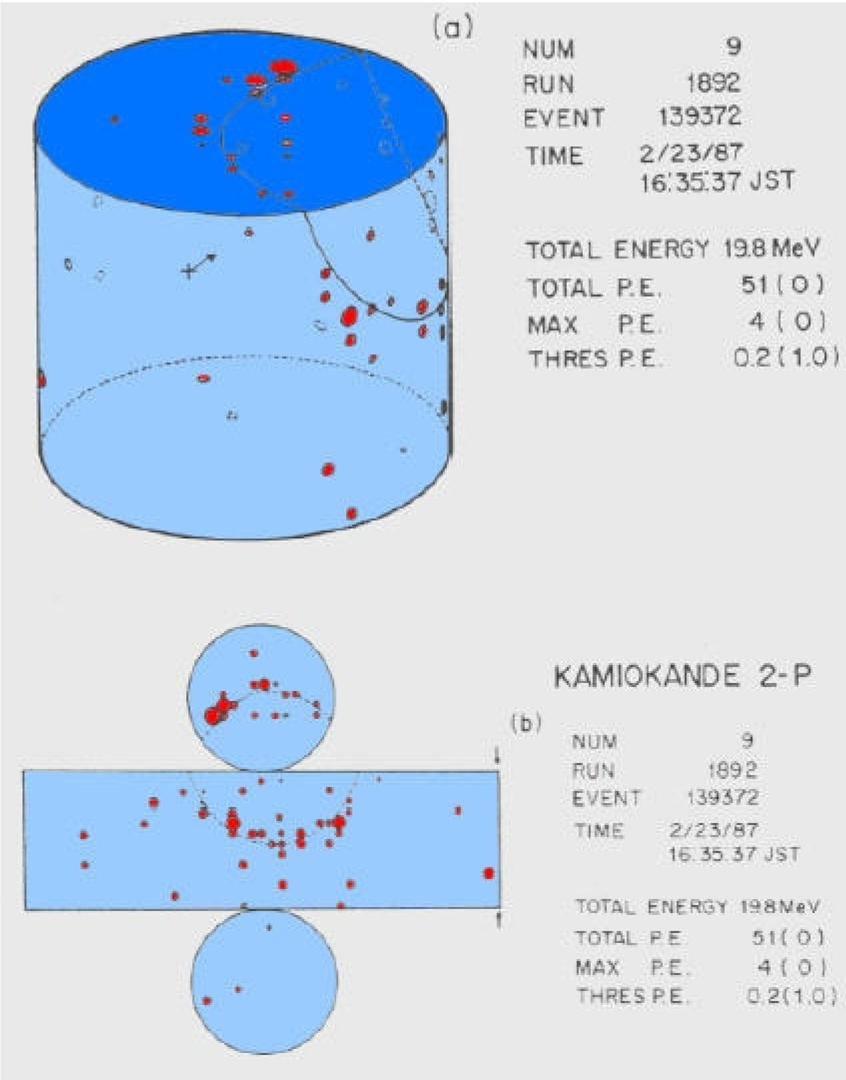


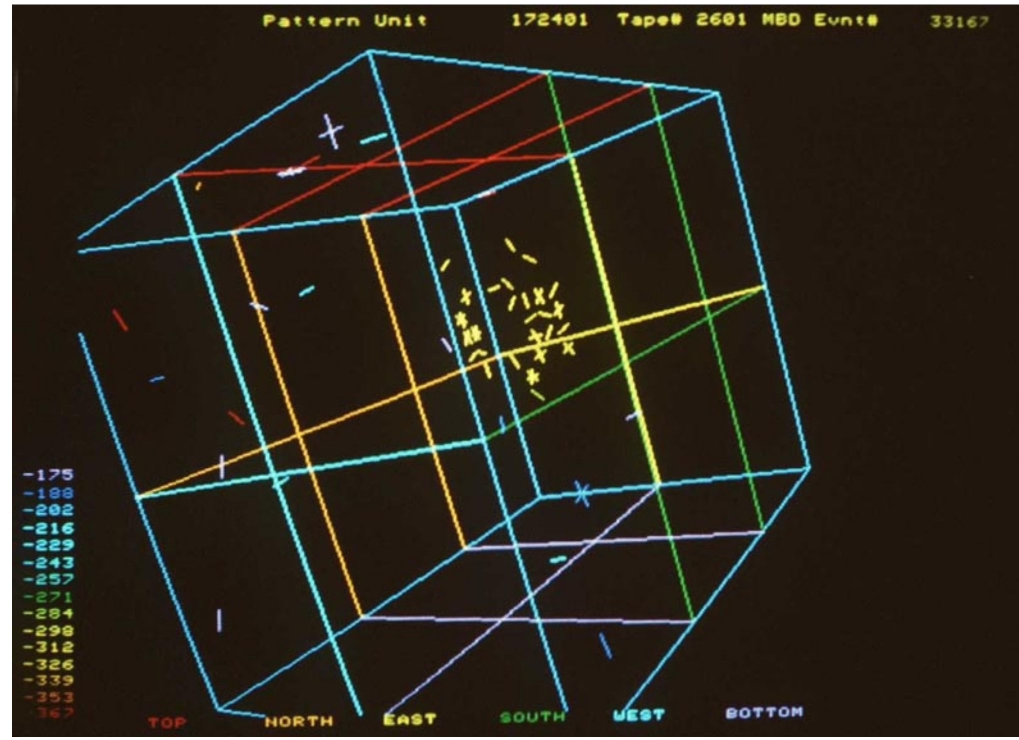


The neutrinos from SN1987A
still the subject of many works every year !



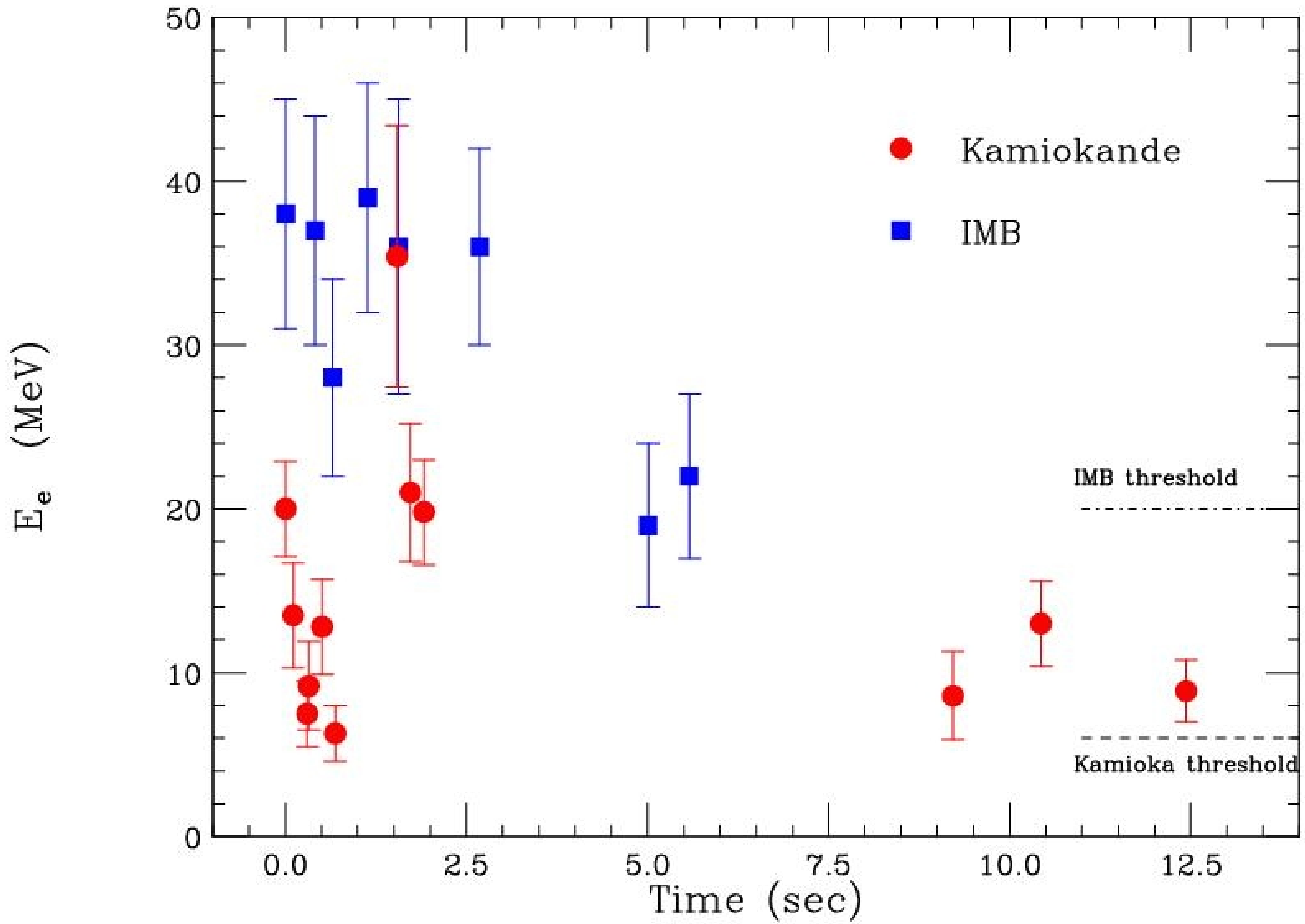
SN1987A



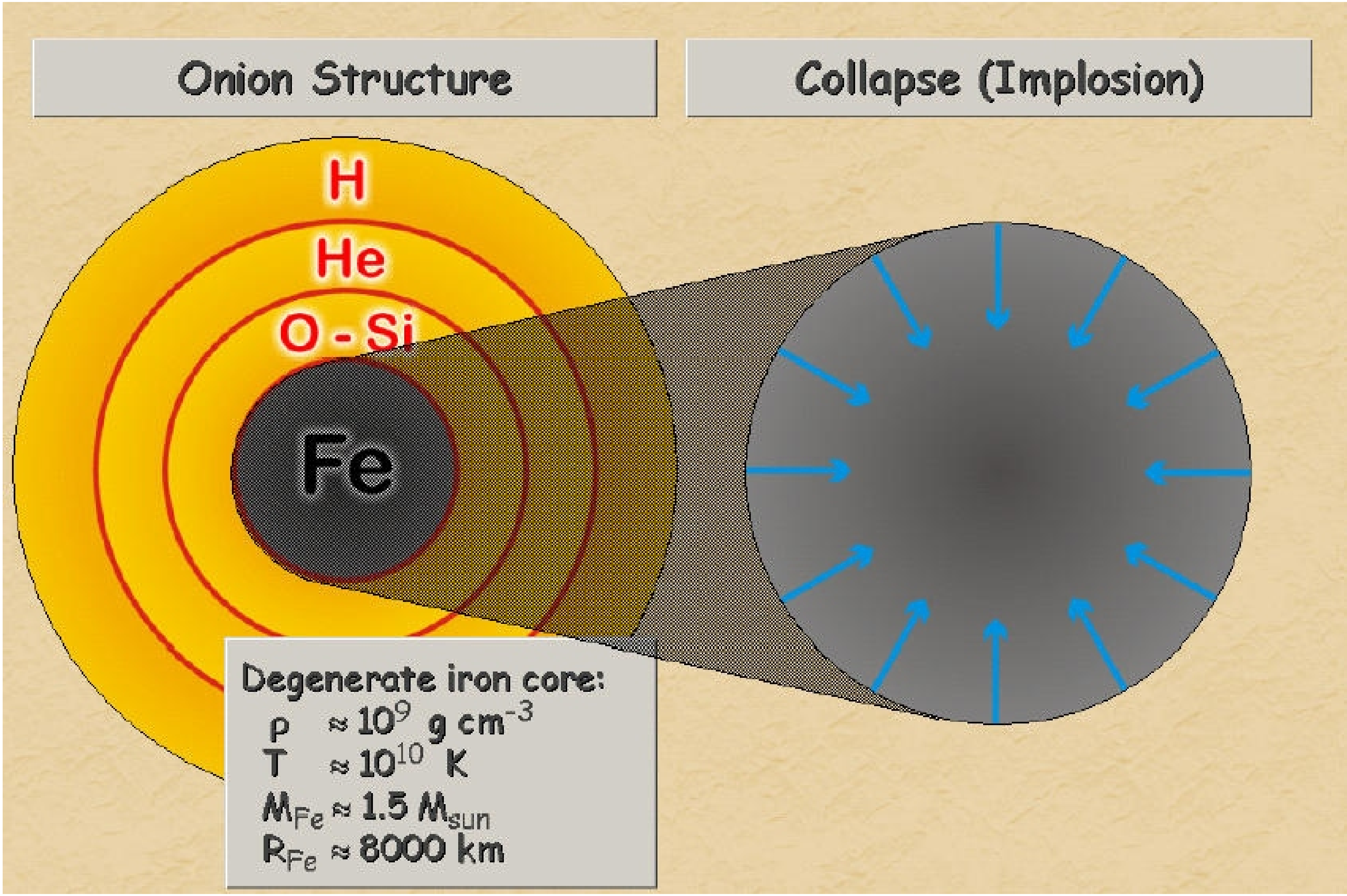


Detector	$N_{\rm events}$	$\langle E_{e^+}\rangle$ [MeV]
KII	11	15.4 ± 1.1
IMB	8	31.9 ± 2.3

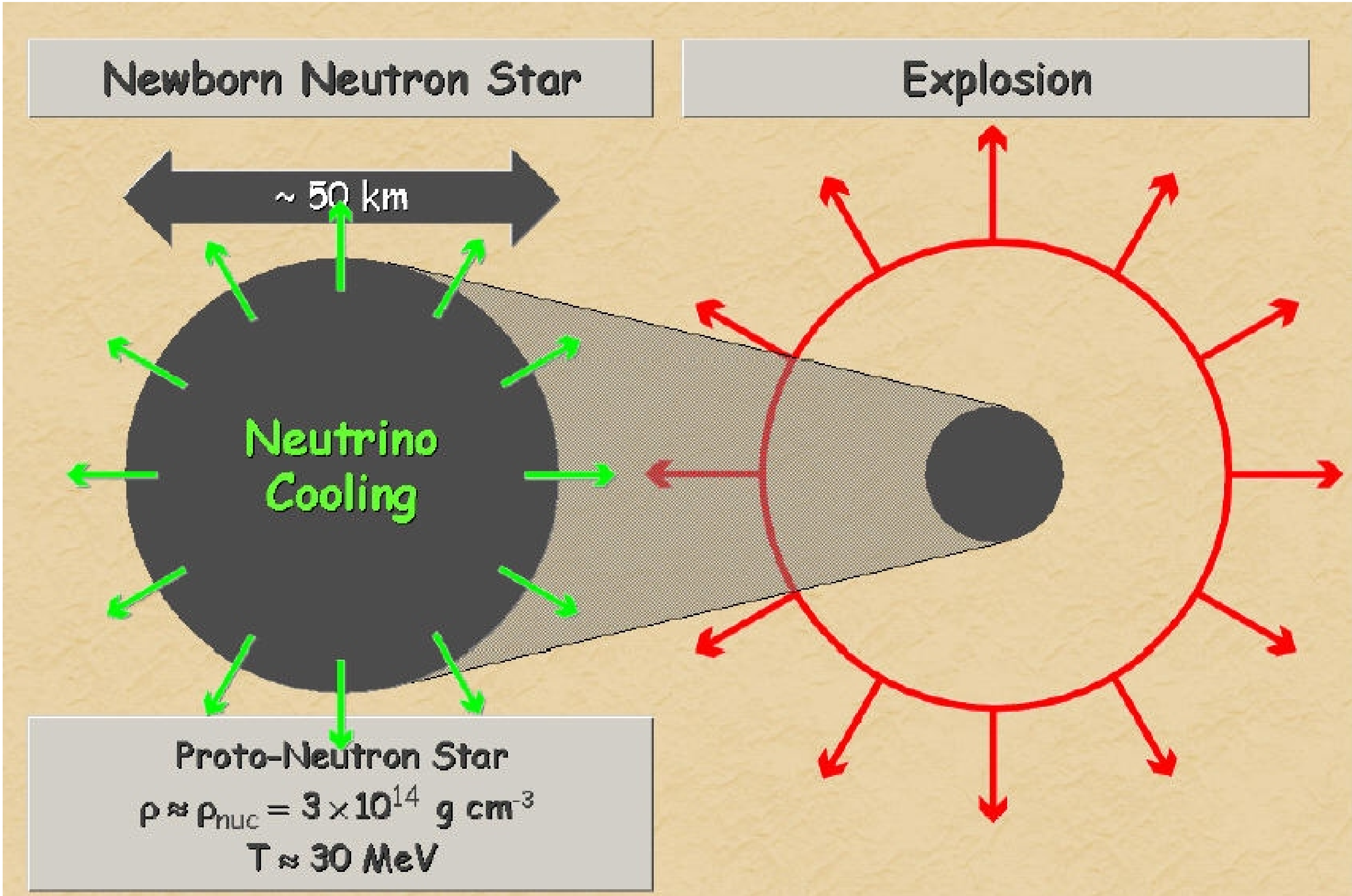
Kamiokande + IMB detection of SN1987A



Controversial Results from other detectors [LSD – Mont Blanc]

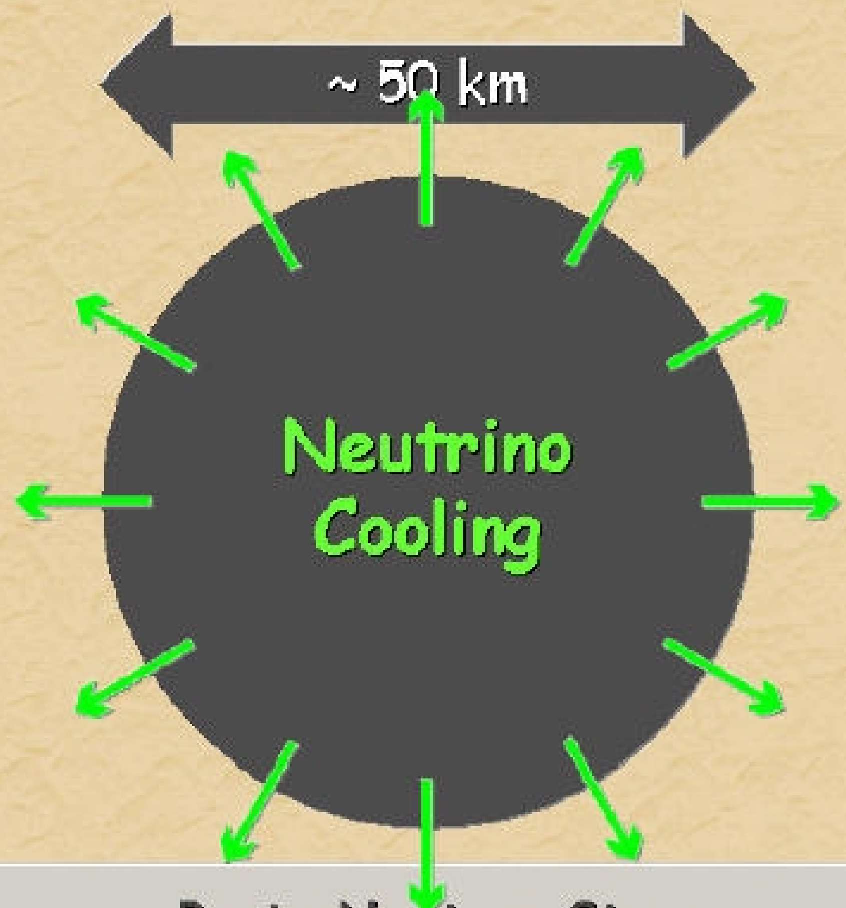


From Georg Raffelt



From Georg Raffelt

Newborn Neutron Star



Proto-Neutron Star

$\rho \approx \rho_{nuc} = 3 \times 10^{14}\ \mathrm{g\ cm^{-3}}$

$T \approx 30\ \mathrm{MeV}$

Gravitational binding energy

$E_b \approx 3 \times 10^{53}\ \mathrm{erg} \approx 17\%\ M_{SUN}\, c^2$

This shows up as

99% Neutrinos

1% Kinetic energy of explosion (1% of this into cosmic rays)

0.01% Photons, outshine host galaxy

Neutrino luminosity

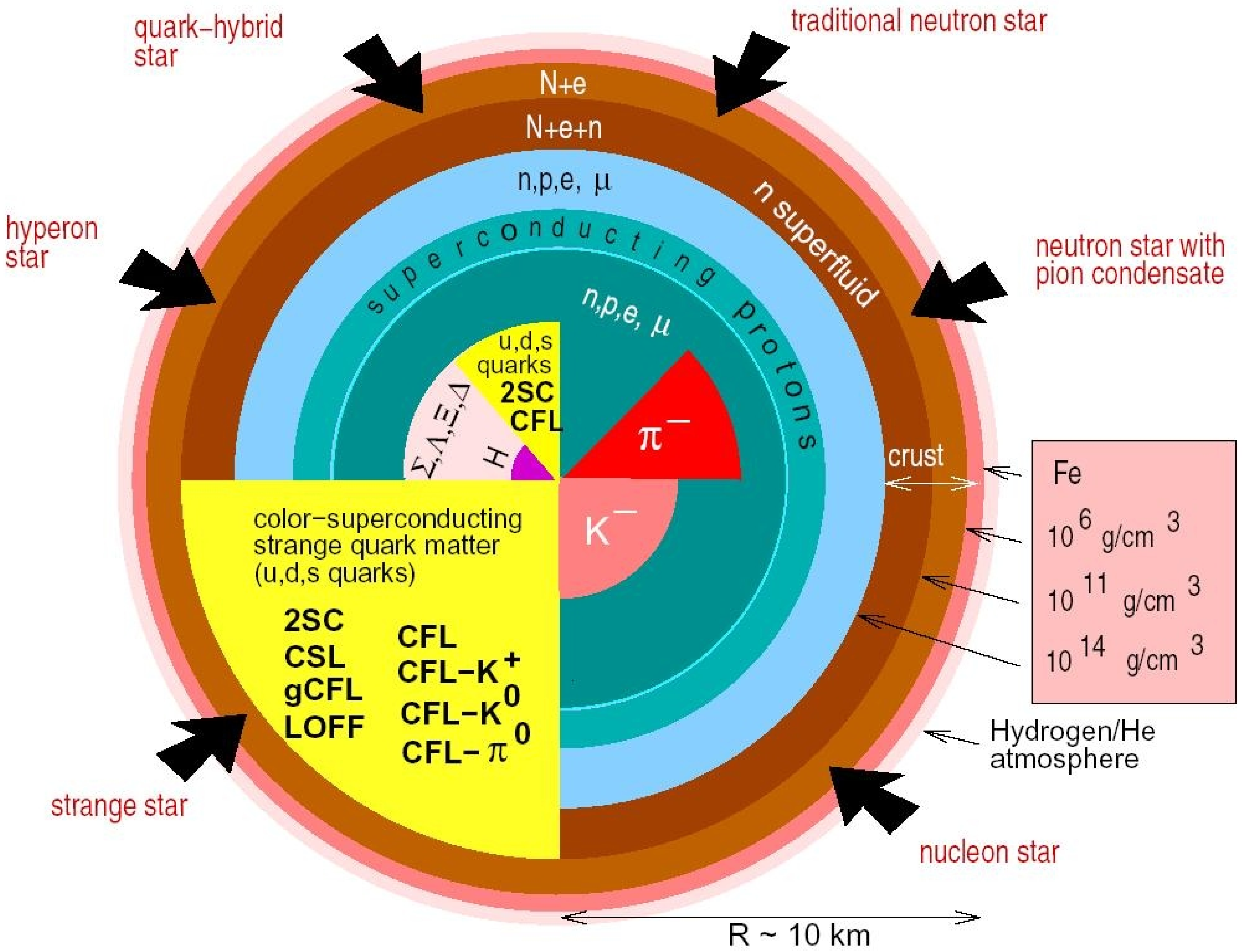
$L_\nu \approx 3 \times 10^{53}\ \mathrm{erg} / 3\ \mathrm{sec}$

$\approx 3 \times 10^{19}\ L_{SUN}$

While it lasts, outshines the entire visible universe

From Georg Raffelt

NEUTRON STAR STRUCTURE

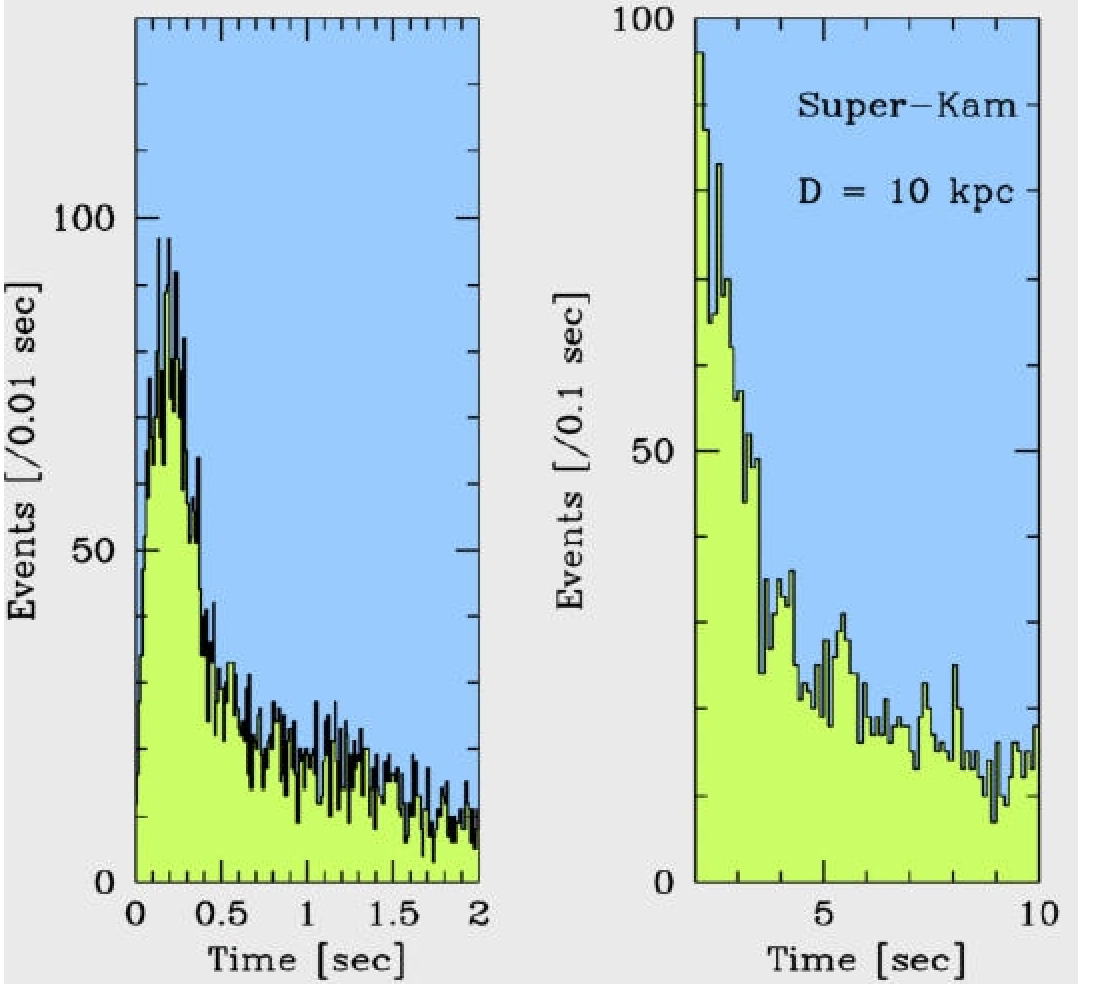


23 february 1987

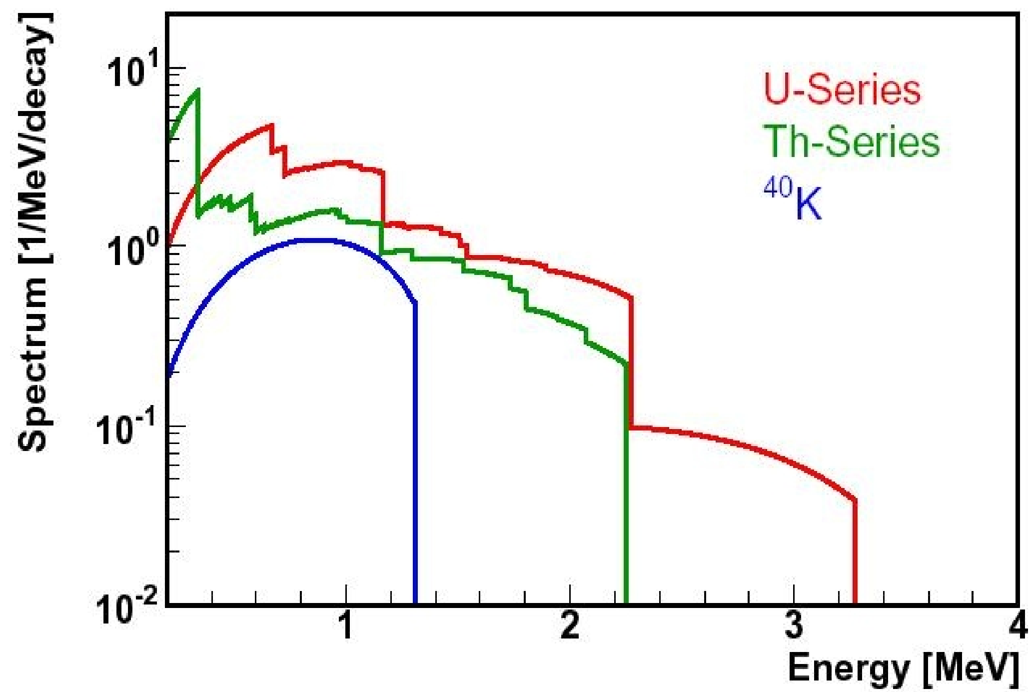
.... 25.5 years ago ....

We want a new close-by
(... but not too much.....)
Gravitational Collapse
Supernova

Scientific Potential
(with the new detectors)
is very important



GEOPHYSICAL (anti)-NEUTRINOS



$$^{238}\mathrm{U} \xrightarrow[100\%]{} {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6e^{-} + 6\bar{\nu}_e + 51.7\ [\mathrm{MeV}]$$

$$^{232}\mathrm{Th} \xrightarrow[100\%]{} {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4e^{-} + 4\bar{\nu}_e + 42.7\ [\mathrm{MeV}]$$

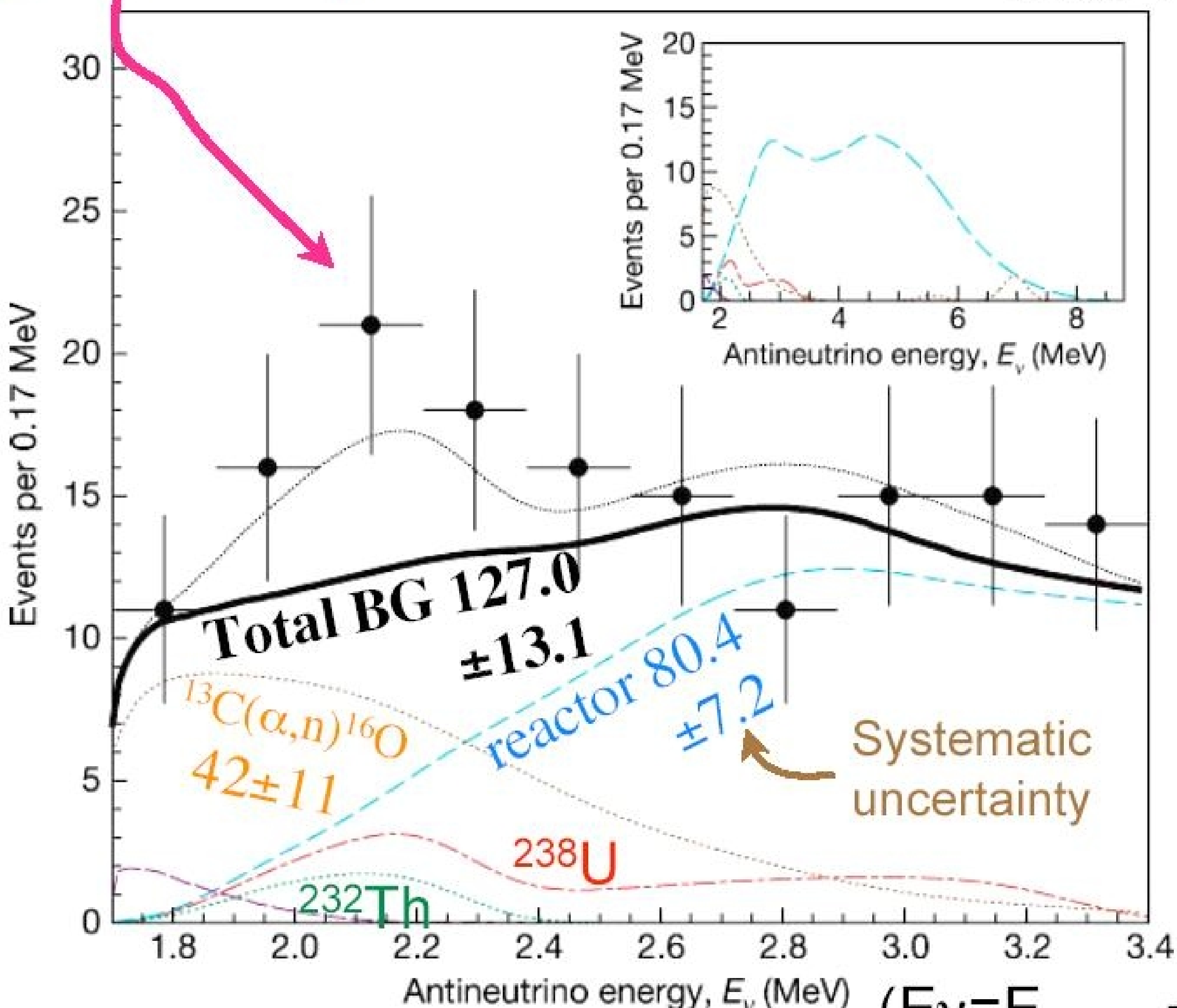
$$^{40}\mathrm{K} \xrightarrow[89.28\%]{} {}^{40}\mathrm{Ca} + e^{-} + \bar{\nu}_e + 1.311\ [\mathrm{MeV}]$$

$$^{40}\mathrm{K} + e^{-} \xrightarrow[10.72\%]{} {}^{40}\mathrm{Ar} + \nu_e + 1.505\ [\mathrm{MeV}]$$

Geoneutrino results

152 events observed
"signal" 25^{+19}_{-18}

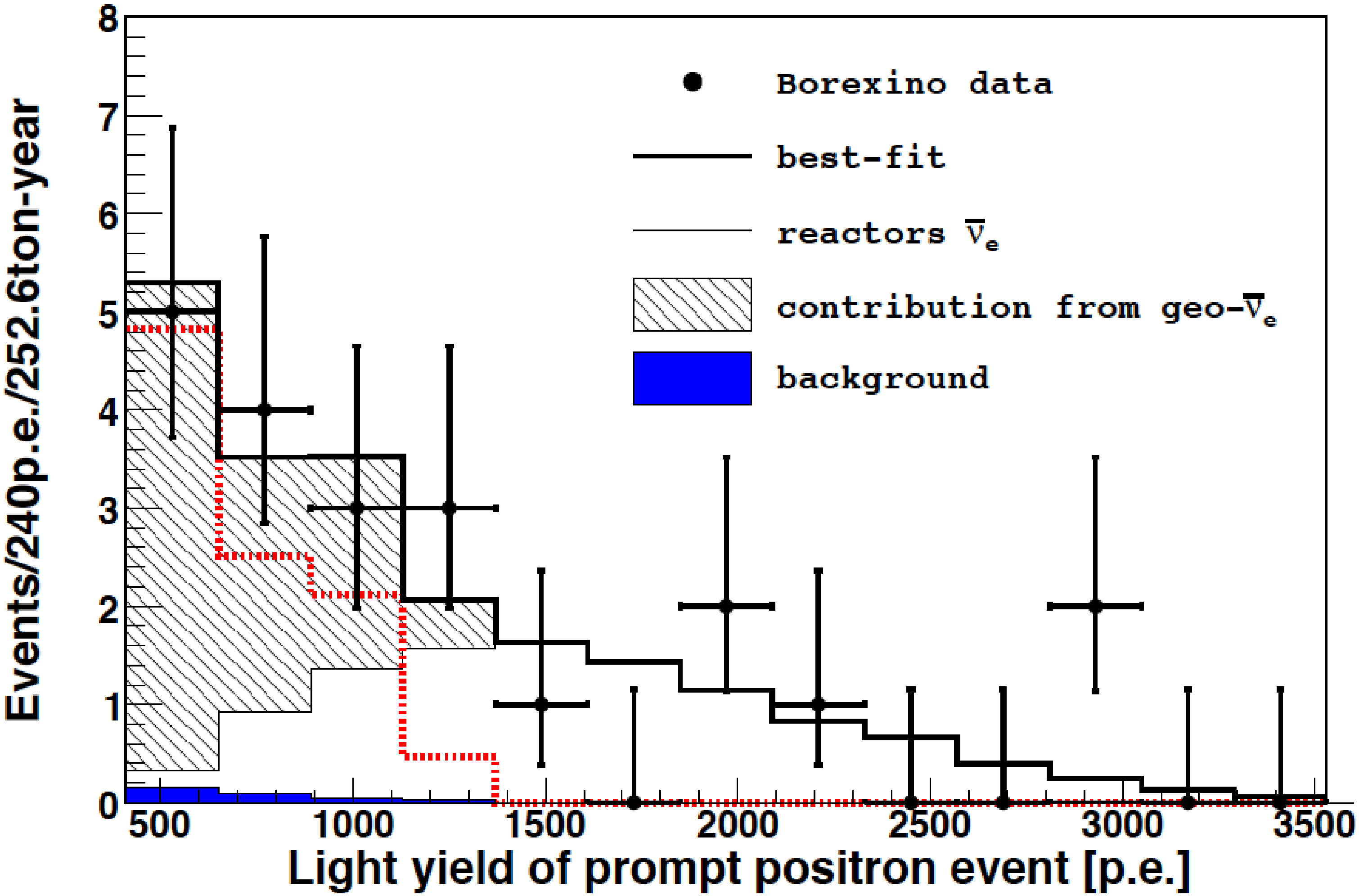
Nature 436, 28 July 2005



Data-set:
749.1 days
(Mar. 9, 2002
-Oct. 30, 2004)

Fiducial:
5 m radius

($E\nu = E_{prompt} + 0.8MeV$)



BOREXINO

(march 2010)

$$9.9^{+4.1}_{-3.4}$$ Events (1 sigma)

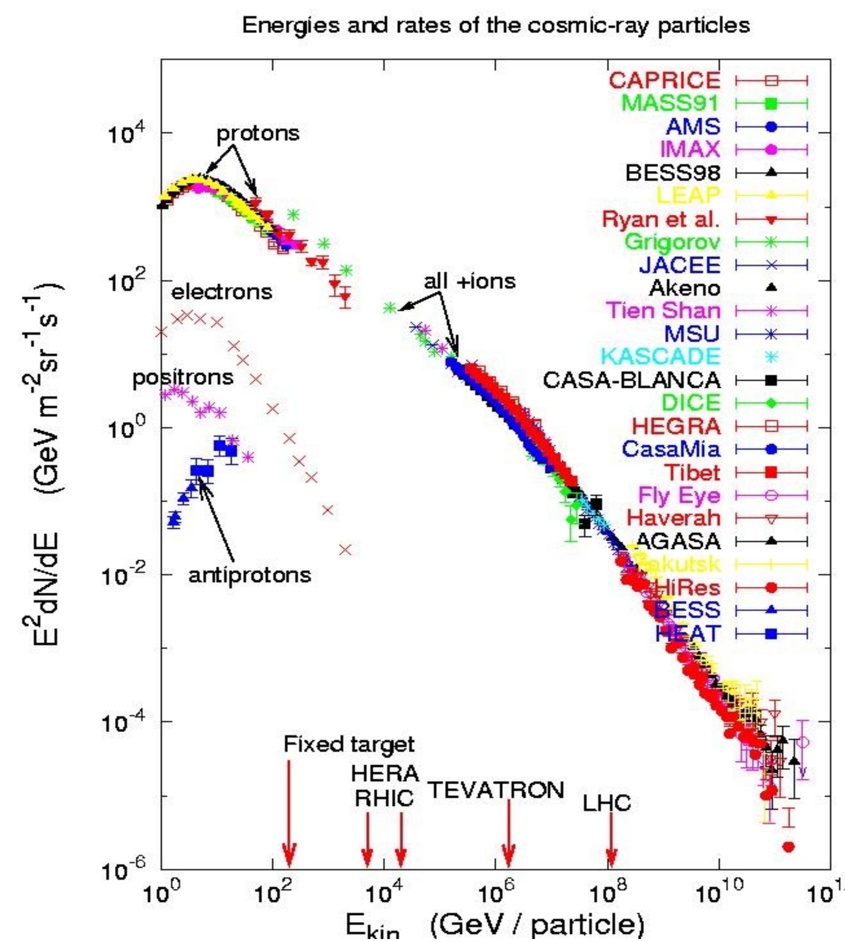
$$3.9^{+1.6}_{-1.3}\left(^{+5.8}_{-3.2}\right)\ \text{events}/(100\ \text{ton}\cdot\text{yr})$$

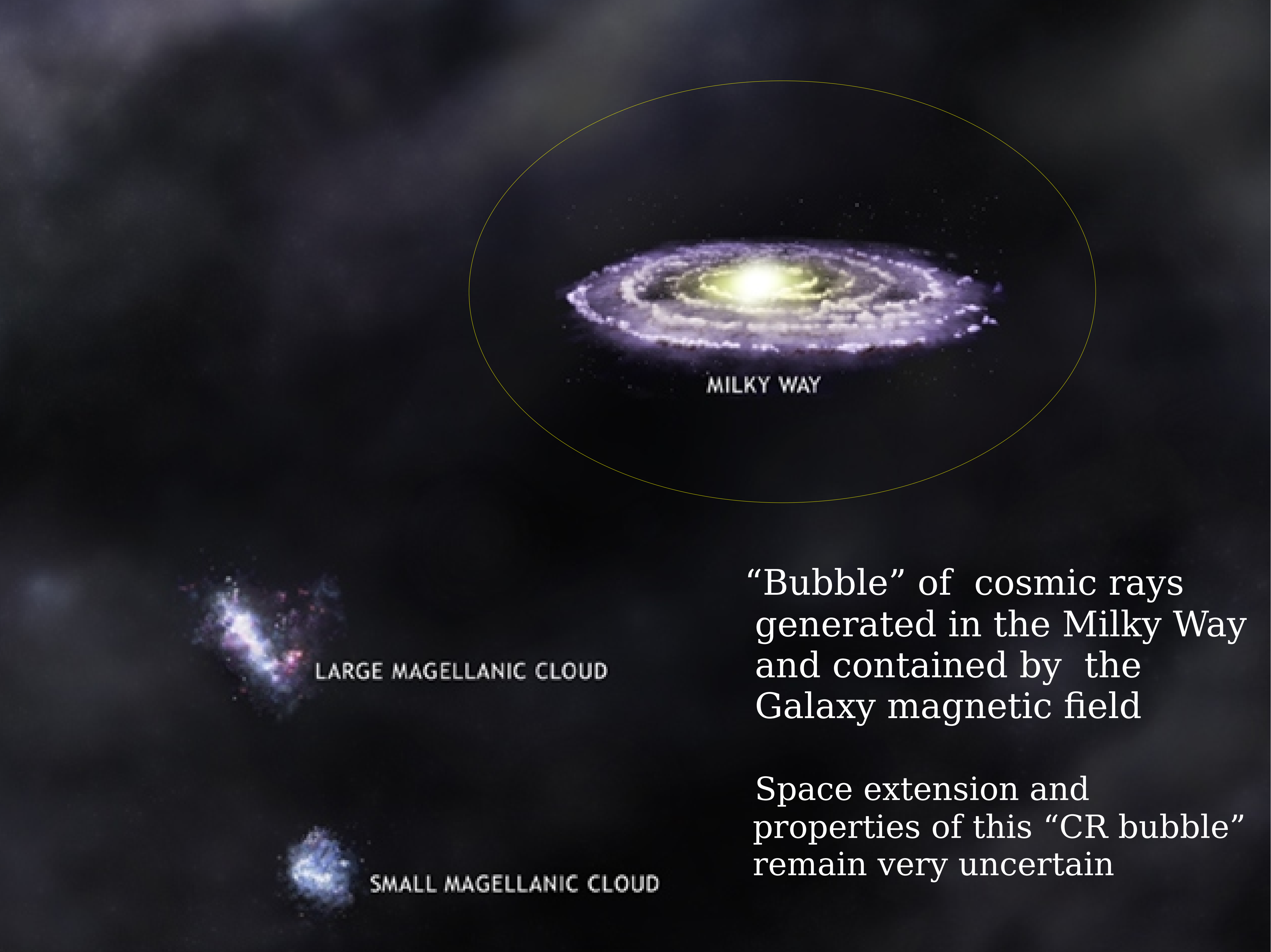
Neutrinos associated to the "High Energy Universe"

Cosmic Rays

Discovery of Cosmic Rays
beginning of
High Energy Astrophysics

Victor Hess
before the balloon flight of 1912




MILKY WAY
LARGE MAGELLANIC CLOUD
SMALL MAGELLANIC CLOUD
“Bubble” of cosmic rays generated in the Milky Way and contained by the Galaxy magnetic field
Space extension and properties of this “CR bubble” remain very uncertain

$$\phi_j(E) = \frac{c}{4\pi} n_j(E)$$

Flux of Cosmic Rays

$$N_j(E) = \int d^3x \, n_j(E, \vec{x})$$

Cosmic Rays contained
In the Milky Way

$$N_j(E) = Q_j(E) \times T_j(E)$$

$p, \quad \text{nuclei}(Z, A)$

$\overline{p}, \quad e^-, \quad e^+$

Different particles

Injection
of cosmic rays

Containment
time

Injection
of cosmic rays

Containment
time

$$N_j(E) = Q_j(E) \times T_j(E)$$

$$L_j = \int dE\ E\ Q_j(E)$$

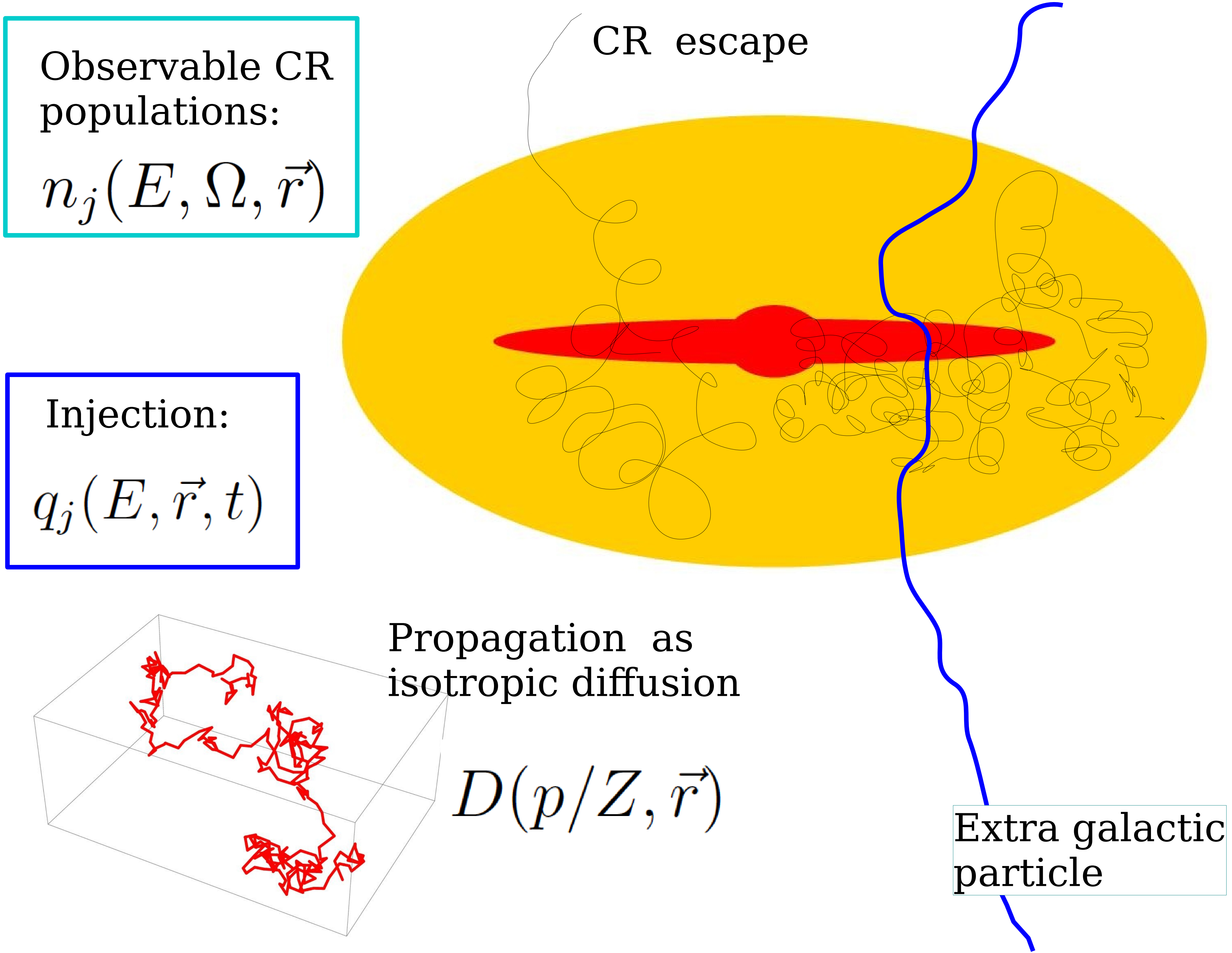
LARGE Power
Requirement

$$\sim 5 \times 10^7\ L_\odot$$

Spectral Shape
[Dynamics of acceleration process]

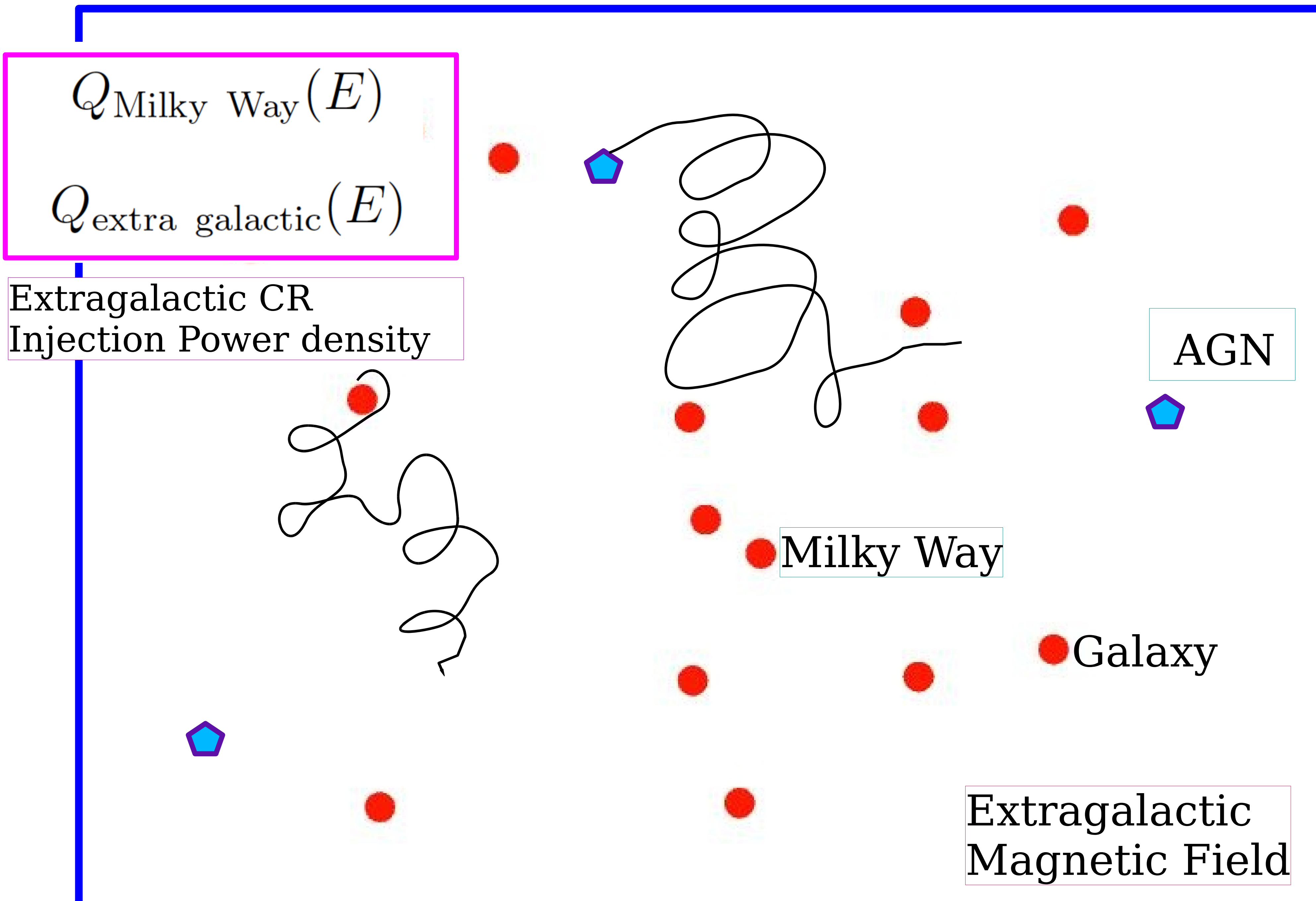
Source
Identification

Key problem!



Observable CR populations:
$n_j(E, \Omega, \vec{r})$
Injection:
$q_j(E, \vec{r}, t)$
CR escape
Propagation as isotropic diffusion
$D(p/Z, \vec{r})$
Extra galactic particle

Piece of extragalactic space: Non MilkyWay-like sources



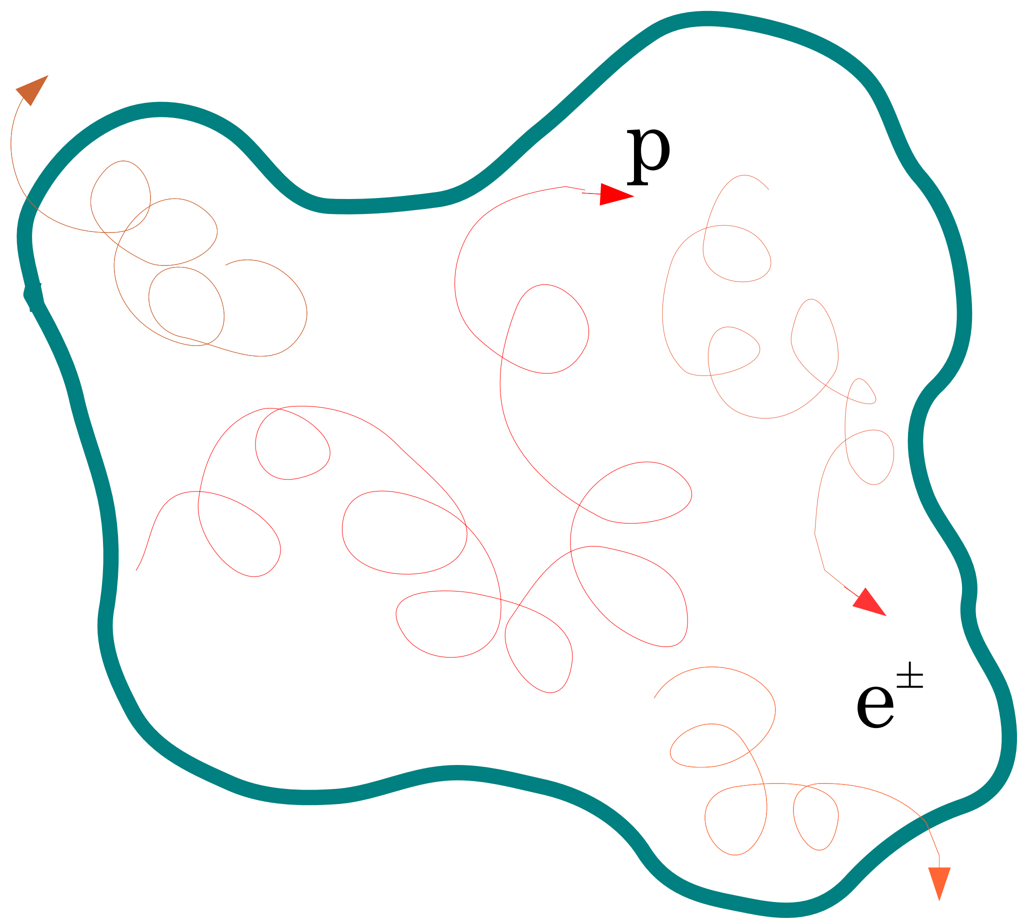
Intimate Relation between :

Cosmic Ray Physics

High Energy Gamma Astronomy

Neutrino Astronomy

“ASTROPHYSICAL” NEUTRINOS



Astrophysical Object containing:

Populations of relativistic protons, Nuclei electrons/positrons

Emission of:

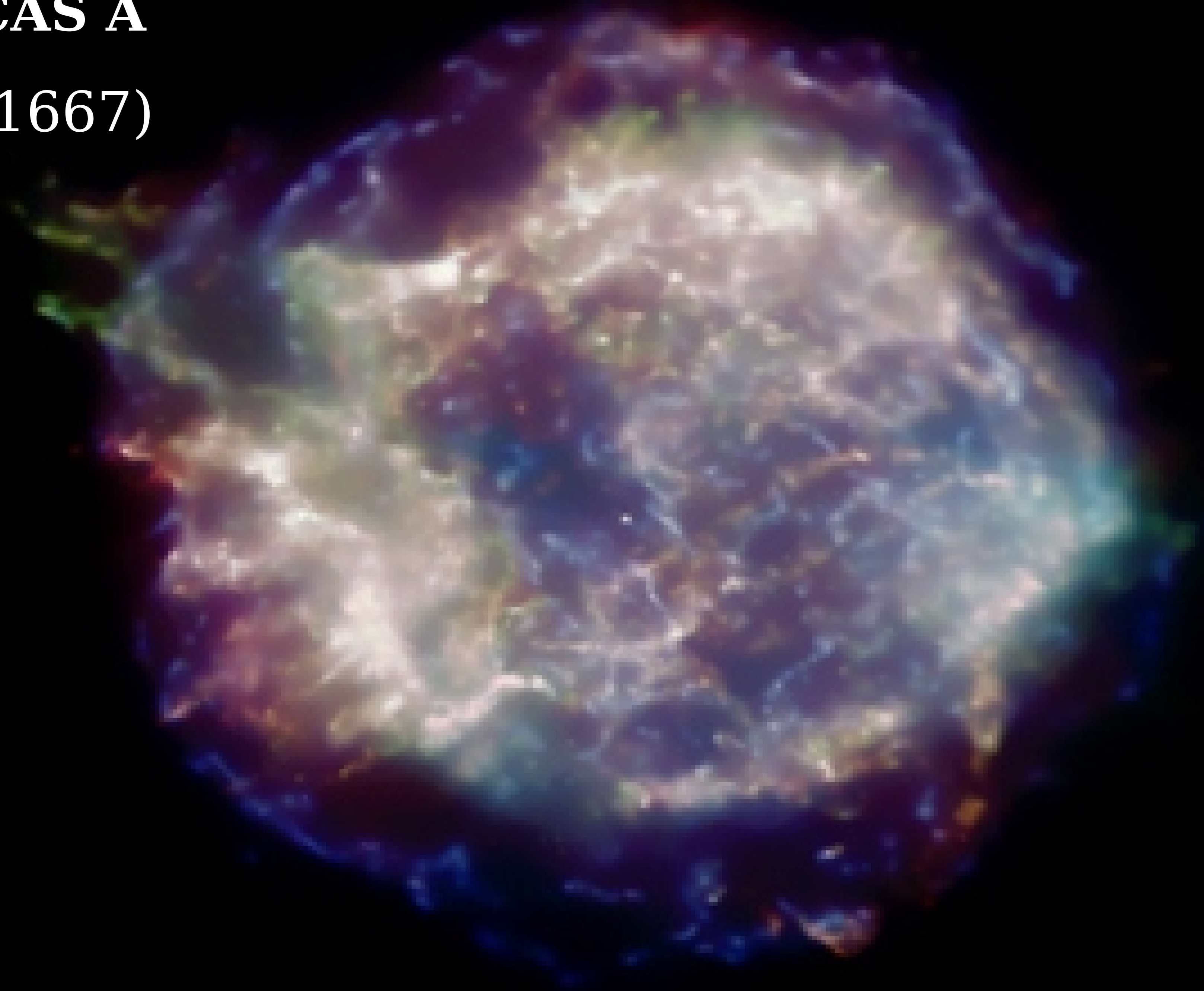
Γαμμα rays

Neutrinos

Cosmic Rays

CAS A

(1667)



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

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

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

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

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

"Hadronic Emission"

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

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

"Leptonic Emission"

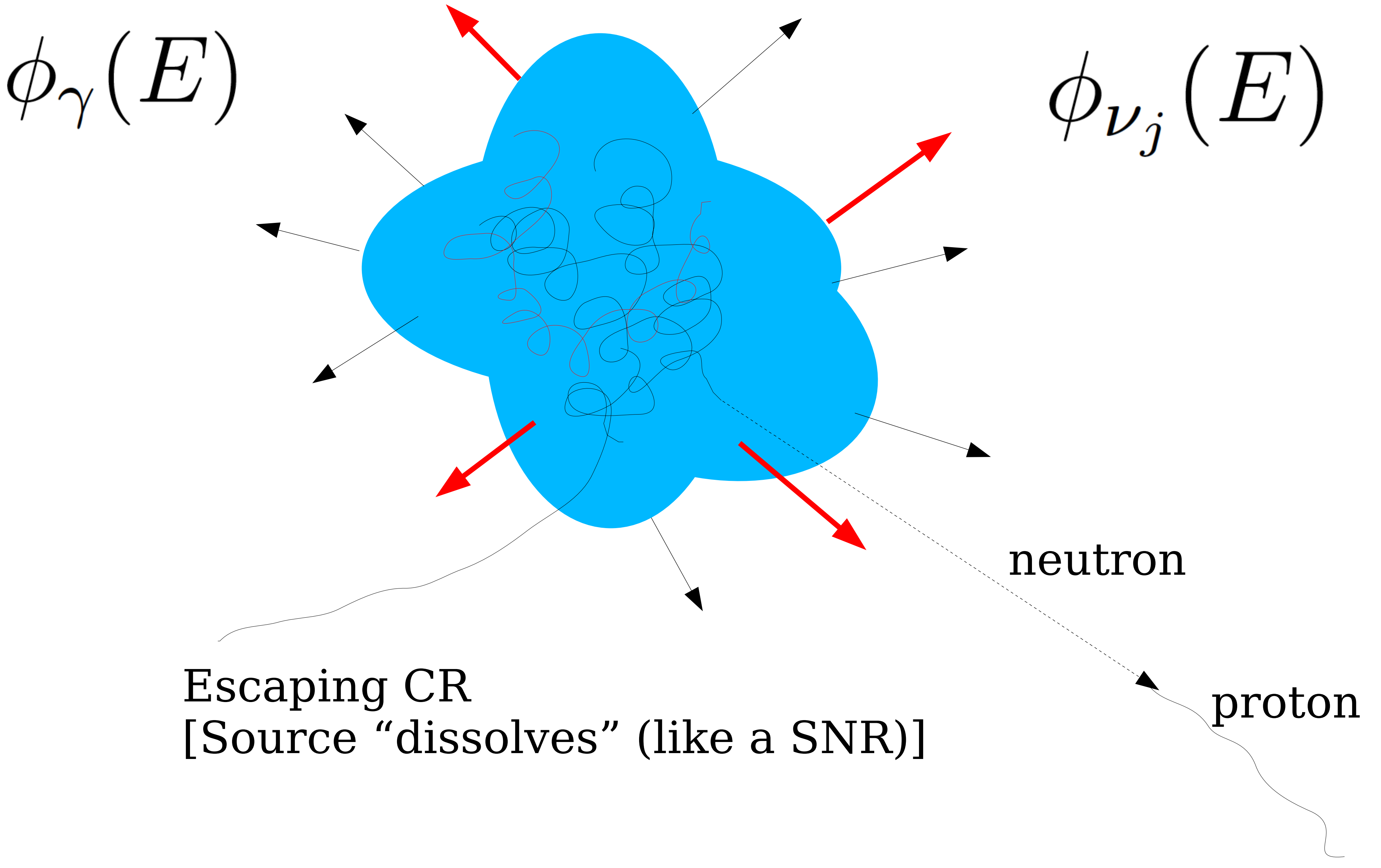
Relation between

PHOTONS and NEUTRINOS

Assuming HADRONIC production for the photons:

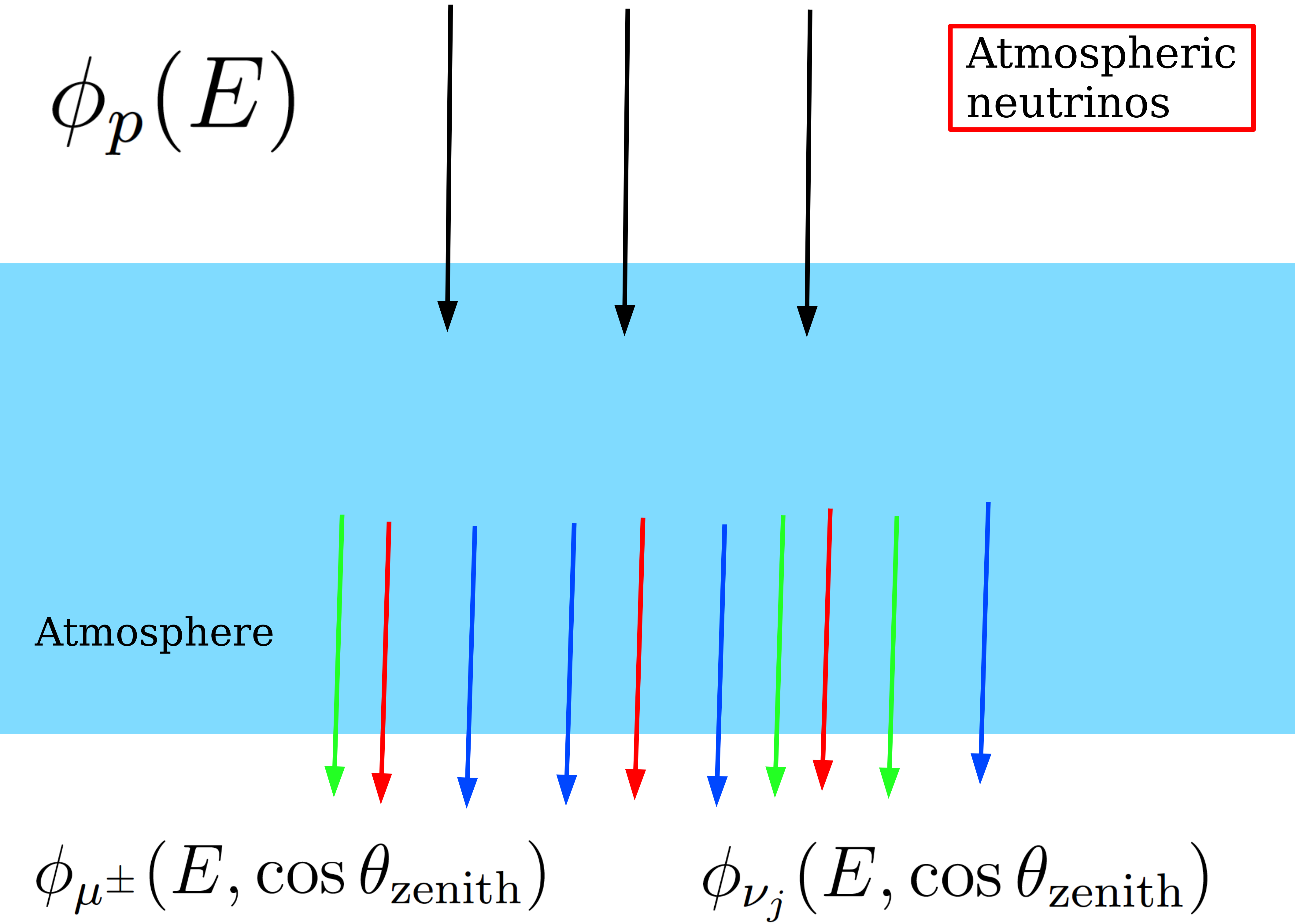
In the absence of photon absorption

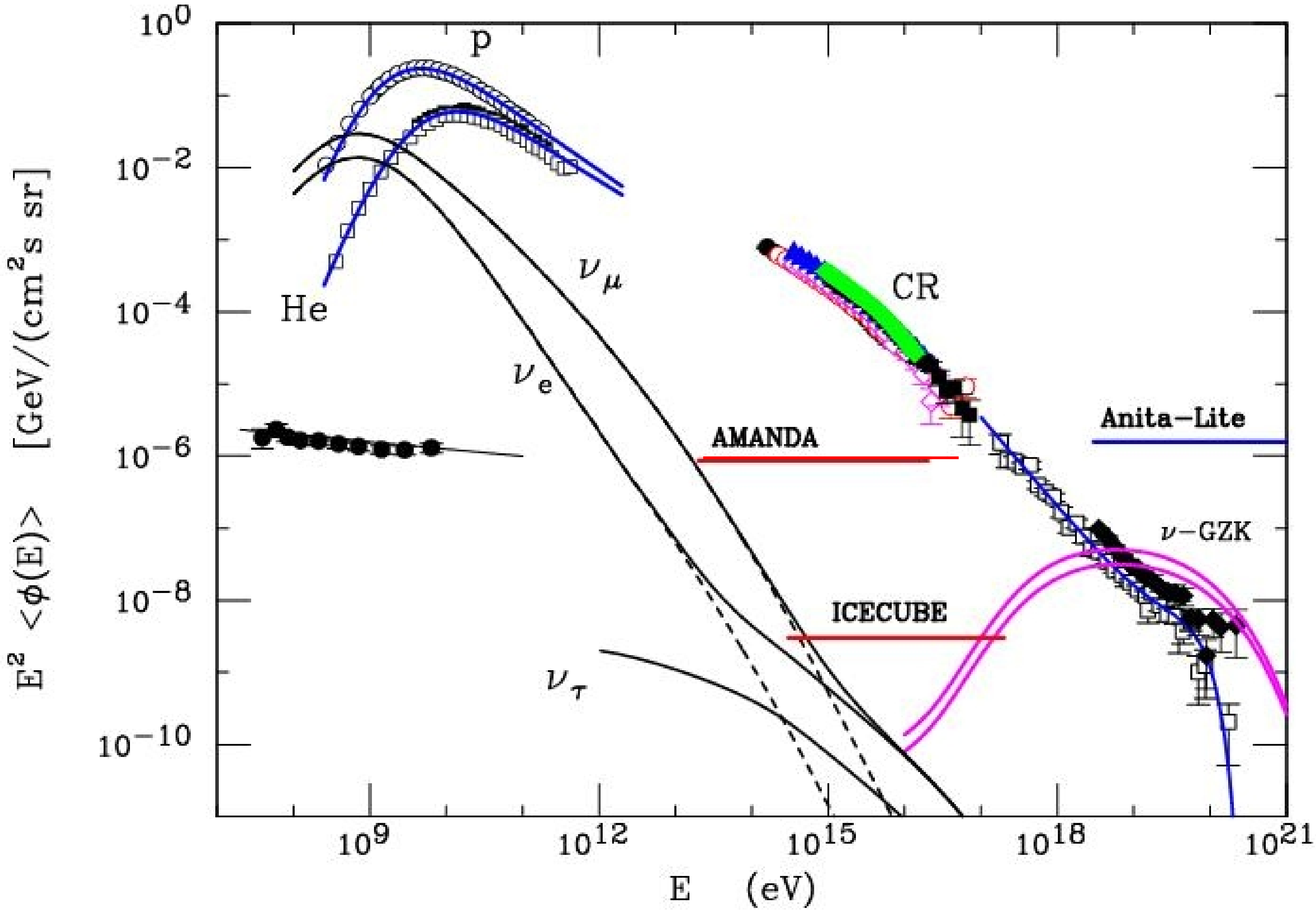
One Photon ~ One Neutrino



Production of Cosmic Rays
versus neutrino/photon spectra

Foreground of
Atmospheric Neutrinos


$\phi_p(E)$
Atmospheric neutrinos
Atmosphere
$\phi_{\mu^\pm}(E, \cos\theta_{\mathrm{zenith}})$
$\phi_{\nu_j}(E, \cos\theta_{\mathrm{zenith}})$

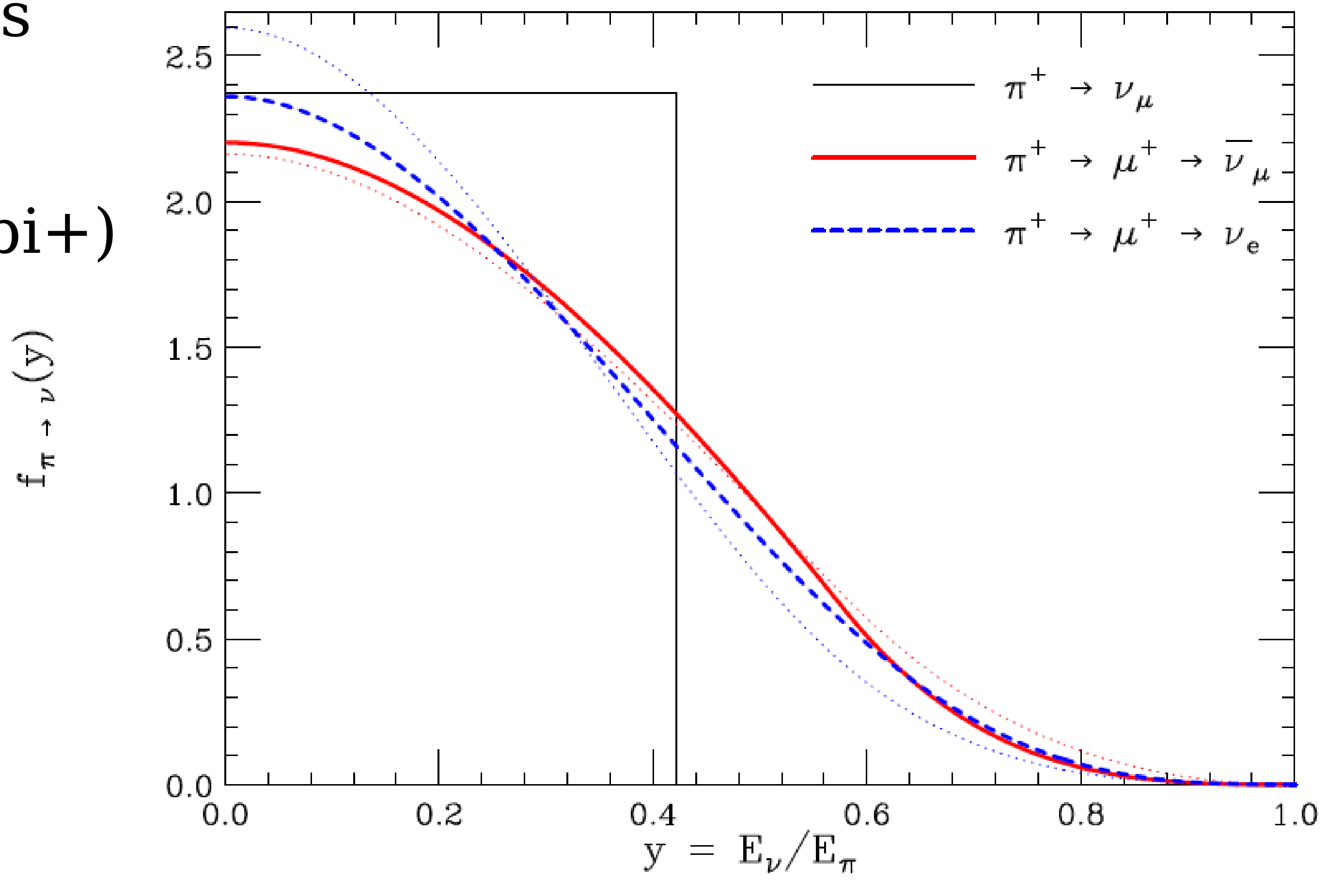


p
He
ν_μ
ν_e
ν_τ
CR
AMANDA
ICECUBE
Anita−Lite
ν−GZK
$E^2 \langle \phi(E) \rangle$ [GeV/(cm^{2}s sr]
E (eV)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^9
10^{12}
10^{15}
10^{18}
10^{21}

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

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

Spectra of neutrinos
generated in the
chain decay of
of a charged pion (pi+)



Contribution of Kaons
(very important for electron neutrinos)

$$K^+ \rightarrow \mu^+ + \nu_\mu \qquad (\mathrm{BR} = 0.634)$$

$$K^+ \rightarrow \pi^\circ + e^+ + \nu_e \qquad (\mathrm{BR} = 0.0482)$$

$$K^+ \rightarrow \pi^\circ + \mu^+ + \nu_\mu \qquad (\mathrm{BR} = 0.0318)$$

$$K_L \rightarrow \pi^\mp + e^\pm + \nu_e(\overline{\nu}_e) \qquad (\mathrm{BR} = 0.194)$$

$$K_L \rightarrow \pi^\mp + \mu^\pm + \nu_\mu(\overline{\nu}_\mu) \qquad (\mathrm{BR} = 0.135)$$

Interaction
versus
Decay
for mesons

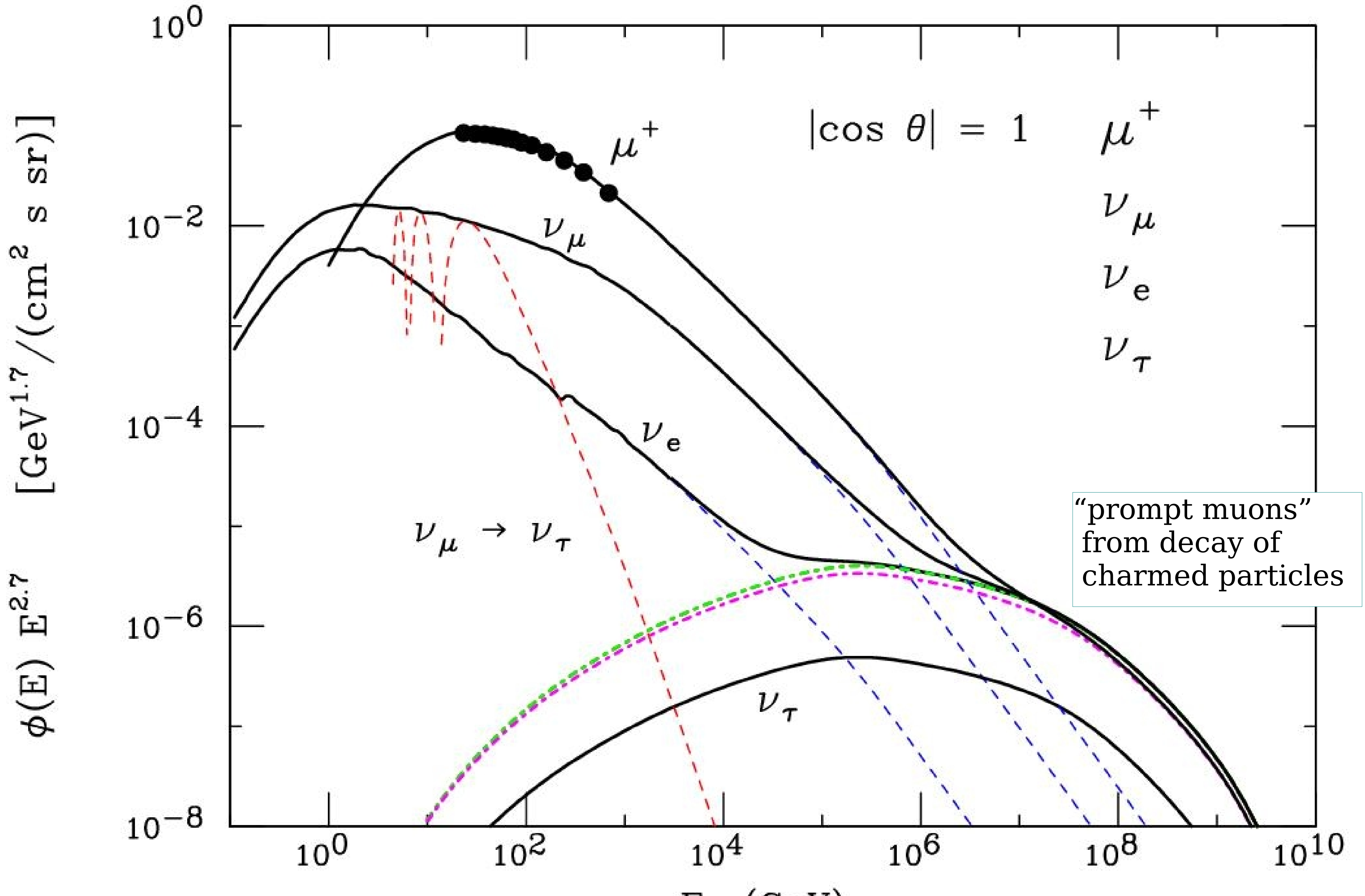
$$\ell_{\rm dec} = c\tau\,\beta\frac{E}{m}$$

$$\ell_{\rm int} = \frac{\lambda_{\rm int}(E)}{\rho} = \frac{A}{N_A\,\sigma_A(E)}\,\frac{1}{\rho}$$

$$P_{\rm dec} = \frac{\ell_{\rm int}}{\ell_{\rm int}+\ell_{\rm dec}} = \left(1+\frac{E}{\varepsilon_0}\right)^{-1}$$

$$\varepsilon_0 = \frac{m\,\lambda_{\rm int}}{c\tau\,\rho}$$

Particle	$(m\ h_0)/(c\tau)$ (GeV)	B.R.	Decay Mode
π^+	114	1	$\mu^+\ \nu_\mu$
π^-	114	1	$\mu^-\ \overline{\nu}_\mu$
K^+	844	0.634	$\mu^+\ \nu_\mu$
K^+	844	0.0487	$\pi^\circ\ e^+\ \nu_e$
K^+	844	0.0327	$\pi^\circ\ \mu^+\ \nu_\mu$
K^-	844	0.634	$\mu^-\ \overline{\nu}_\mu$
K^-	844	0.0487	$\pi^\circ\ e^-\ \overline{\nu}_e$
K^-	844	0.0327	$\pi^\circ\ \mu^-\ \overline{\nu}_\mu$
K_L	203	0.194	$\pi^+\ e^-\ \nu_e \quad (\pi^-\ e^+\ \overline{\nu}_e)$
K_L	203	0.136	$\pi^+\ \mu^-\ \nu_\mu \quad (\pi^-\ \mu^+\ \overline{\nu}_\mu)$
D^+	3.8×10^7	0.172	$e^+\ \nu_e\ X \quad (\mu^+\ \nu_\mu\ X)$
D^-	3.8×10^7	0.172	$e^-\ \overline{\nu}_e\ X \quad (\mu^-\ \overline{\nu}_\mu\ X)$
D^0	9.6×10^7	0.0687	$e^+\ \nu_e\ X \quad (\mu^+\ \nu_\mu\ X)$
$\overline{D}^0$	9.6×10^7	0.0687	$e^-\ \overline{\nu}_e\ X \quad (\mu^-\ \overline{\nu}_\mu\ X)$
Λ_c	2.4×10^8	0.045	$e^+\ \overline{\nu}_e\ X \quad (\mu^+\ \nu_\mu\ X)$
D_s^+	8.5×10^7	0.064	$\tau^+\ \nu_\tau$
D_s^-	8.5×10^7	0.064	$\tau^-\ \overline{\nu}_\tau$



$|\cos\theta| = 1$
μ^+
ν_μ
ν_e
ν_τ
$\nu_\mu \rightarrow \nu_\tau$
"prompt muons"
from decay of
charmed particles
$\phi(E)\ E^{2.7}\ [\mathrm{GeV}^{1.7}/(\mathrm{cm}^2\ \mathrm{s\ sr})]$
E (GeV)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^2
10^4
10^6
10^8
10^{10}

Relation between:

- Cosmic Rays in the source
- Photon, Neutrino Flux

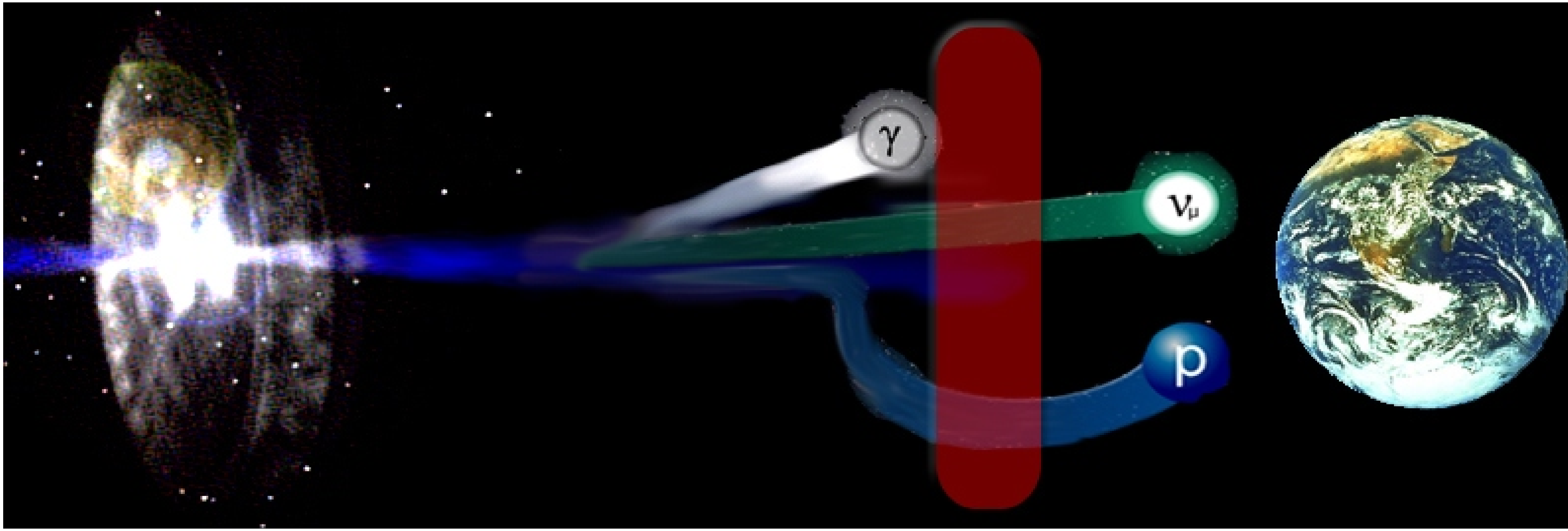
$$N_p(E) \simeq K\ E^{-\alpha}$$

Power law
c.r. population

Photon, neutrino fluxes also power law with same esponent

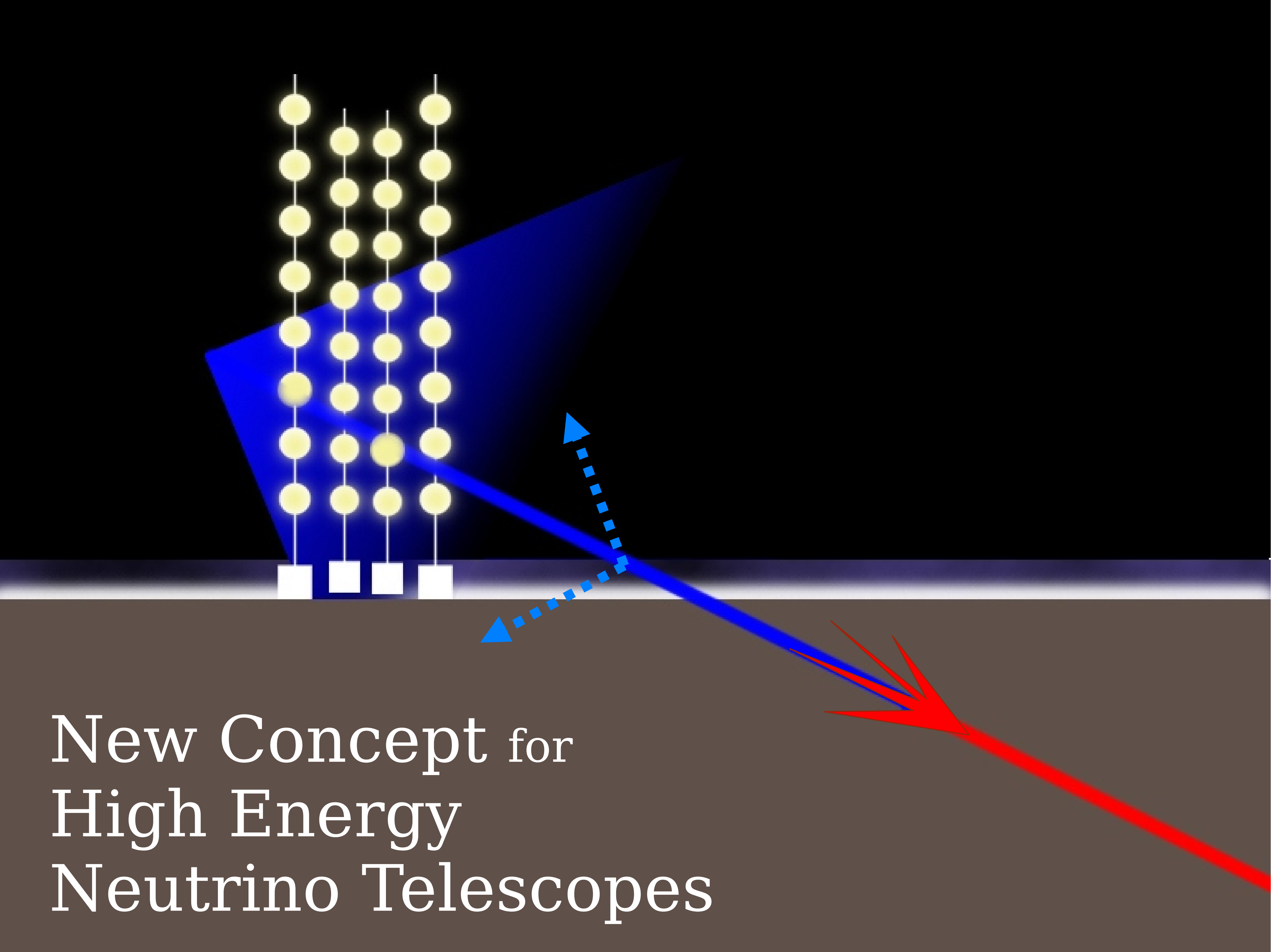
$$\phi_{\nu_j}(E) \simeq K\ E^{-\alpha} \times [\sigma_{pp}\, c\, n_{\rm target}] \times Z_{p\nu_j}(\alpha)$$

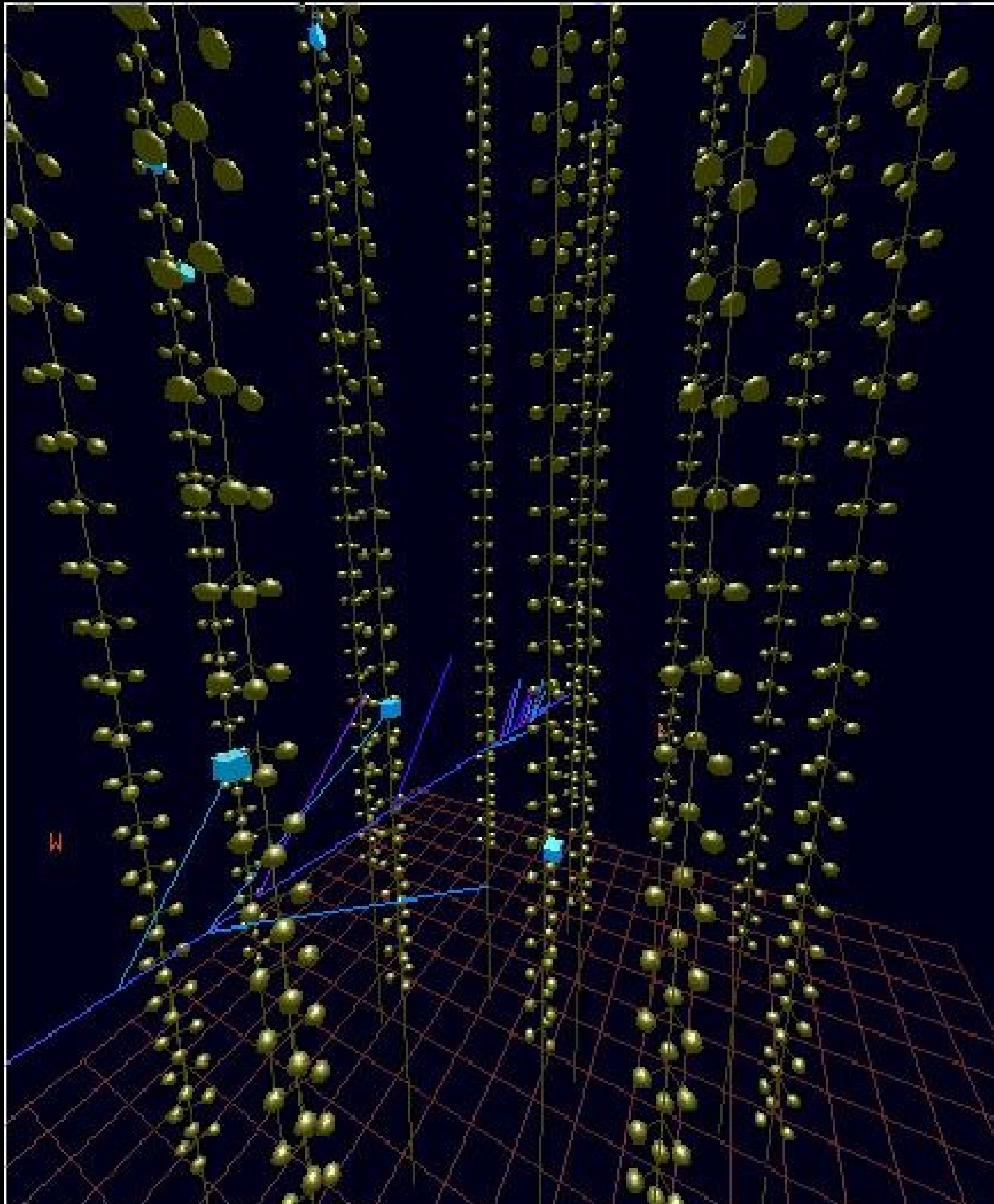
$$\phi_{\gamma}(E) \simeq K\ E^{-\alpha} \times [\sigma_{pp}\, c\, n_{\rm target}] \times Z_{p\gamma}(\alpha)$$

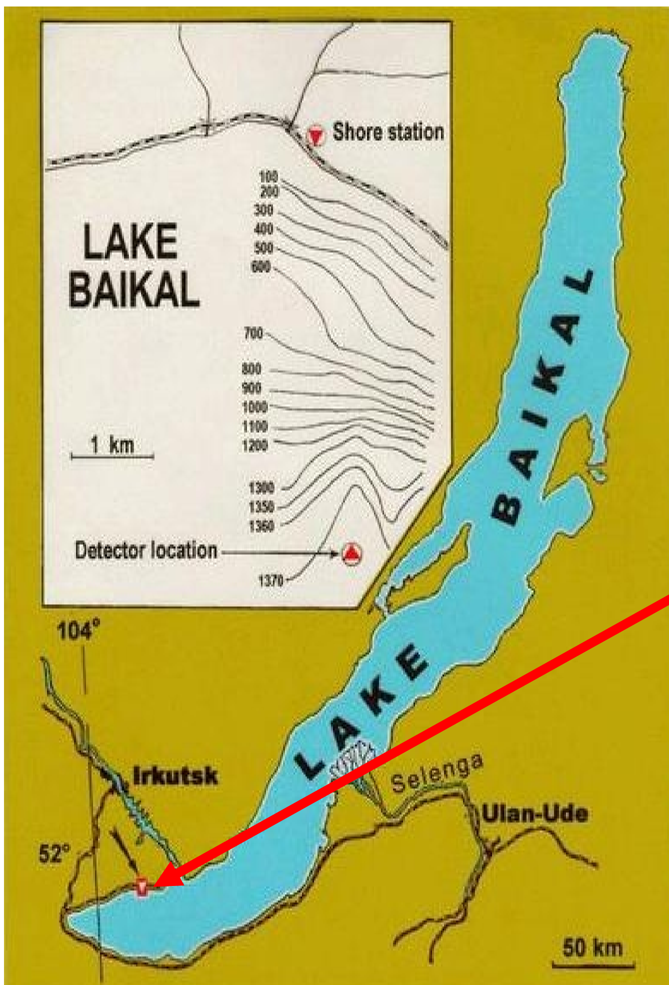


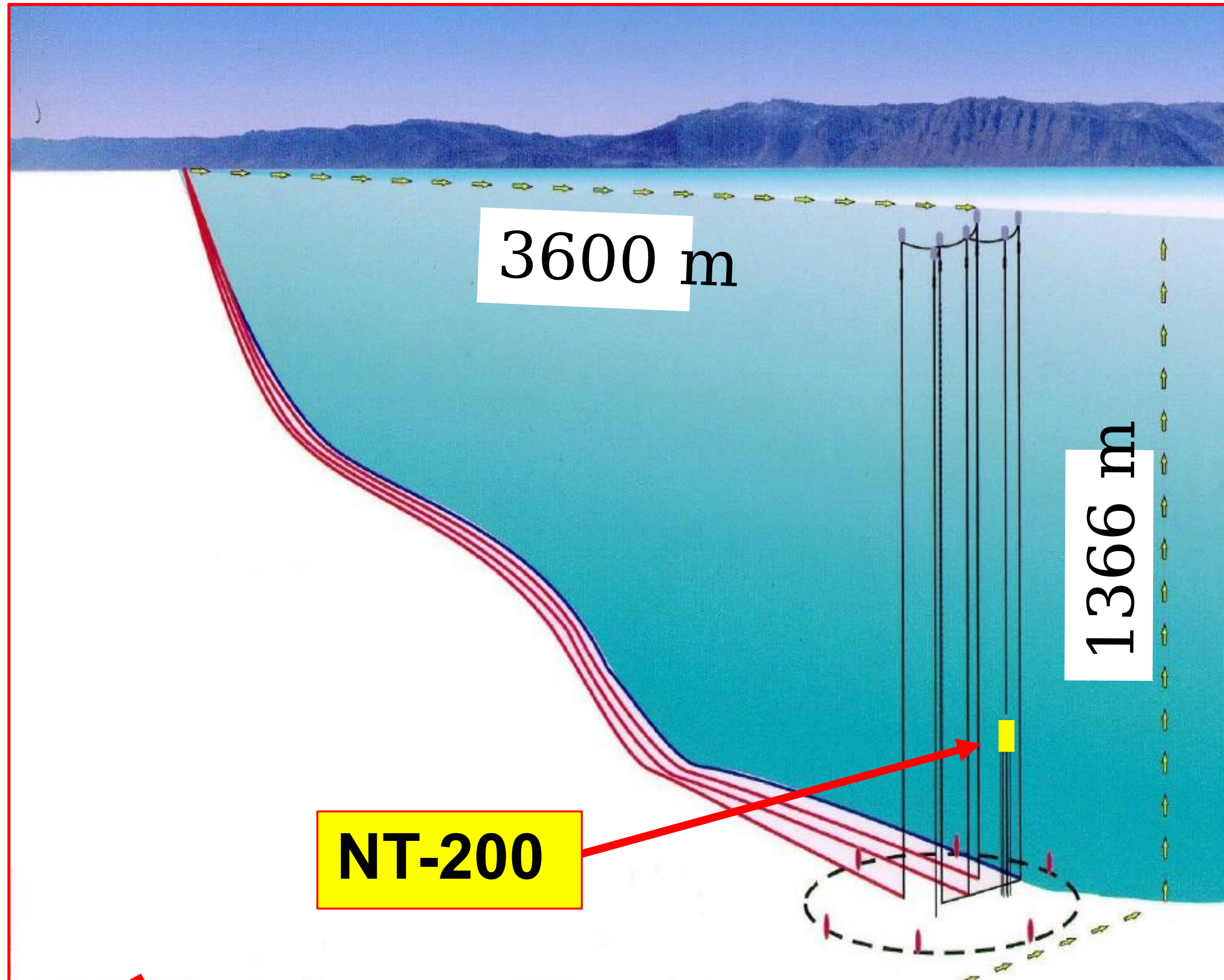
Neutrino advantages :

1. Straight line propagation
2. No absorption


New Concept for
High Energy
Neutrino Telescopes


W

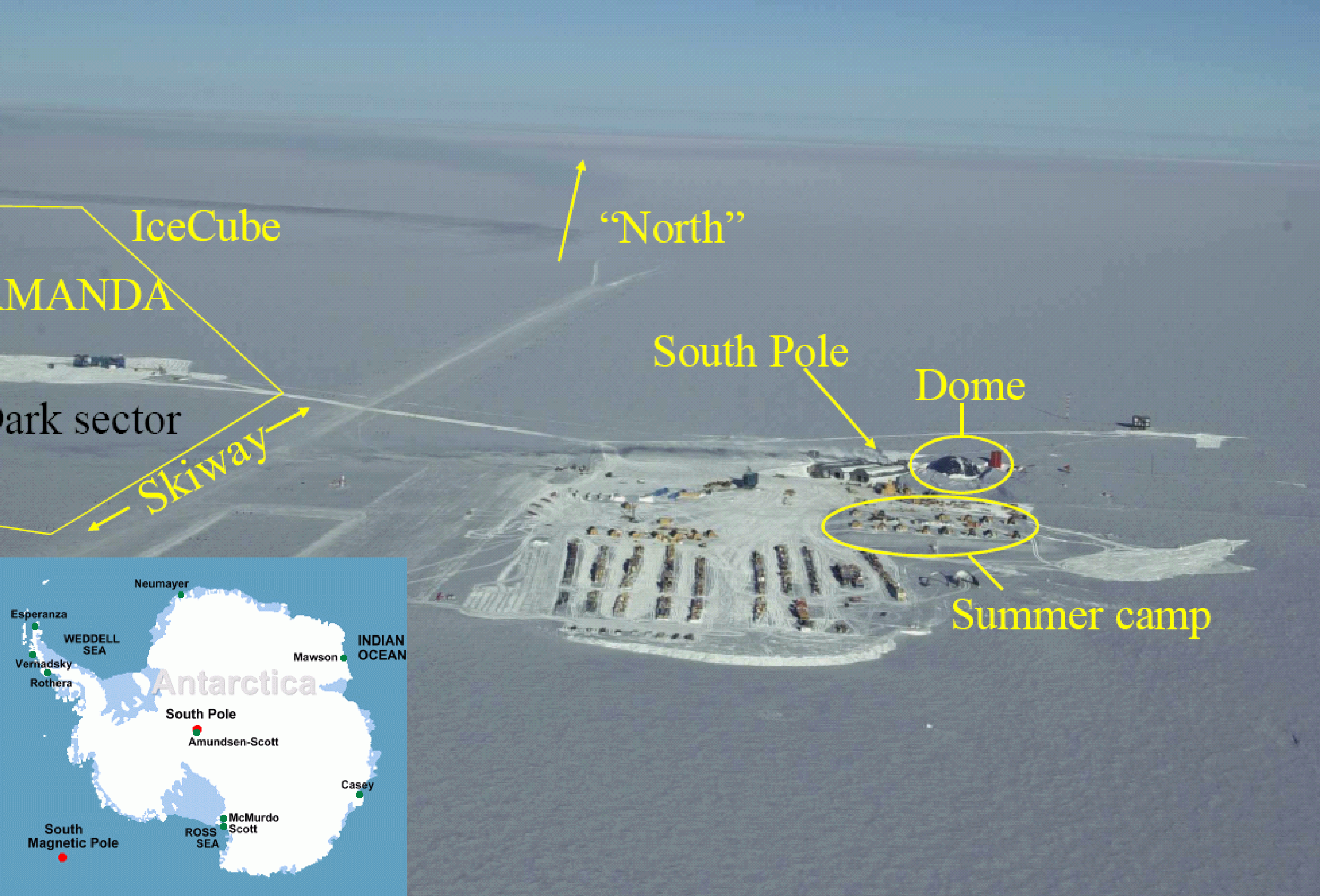


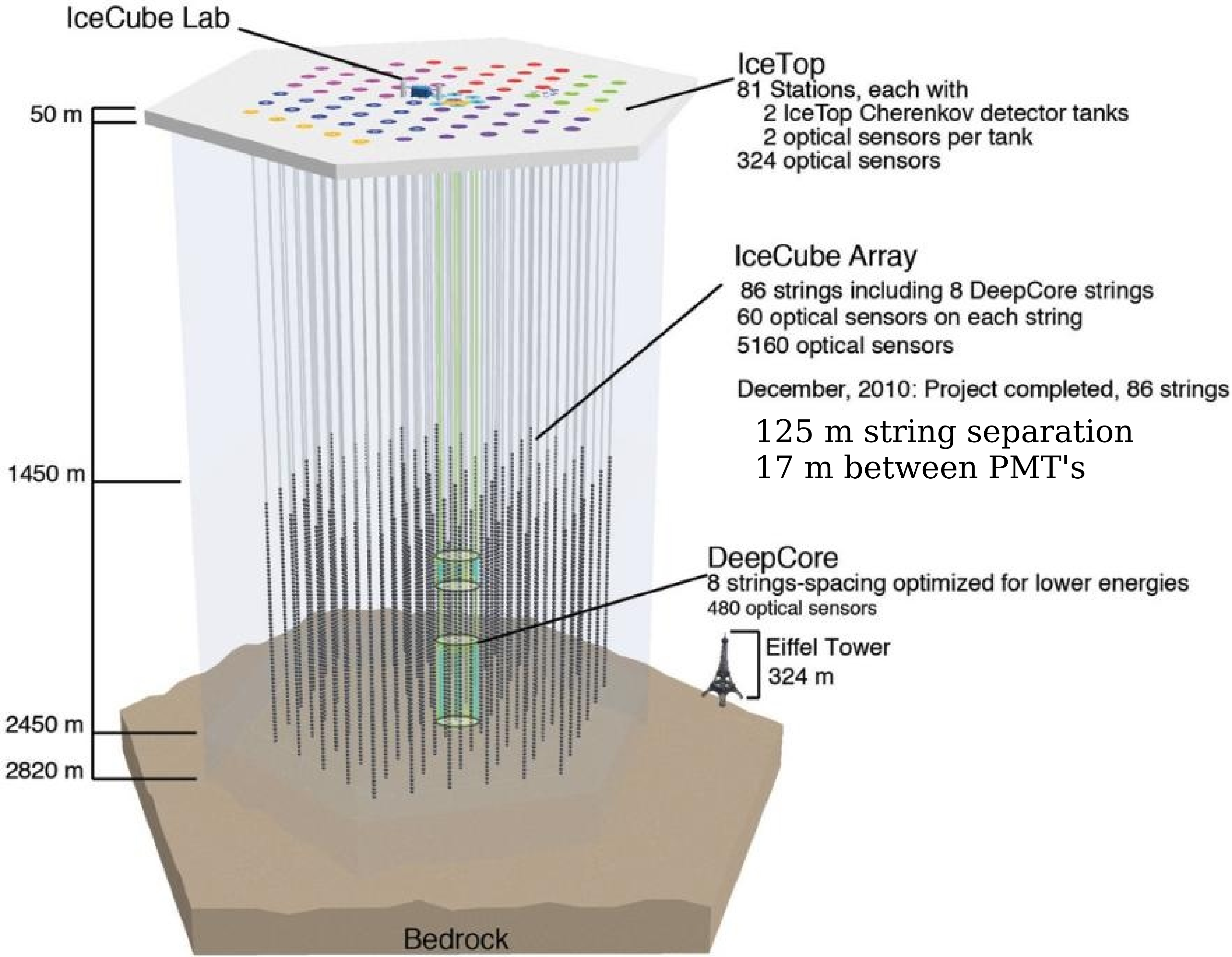


Pioneering work
in Lake Baikal (Soviet Union)

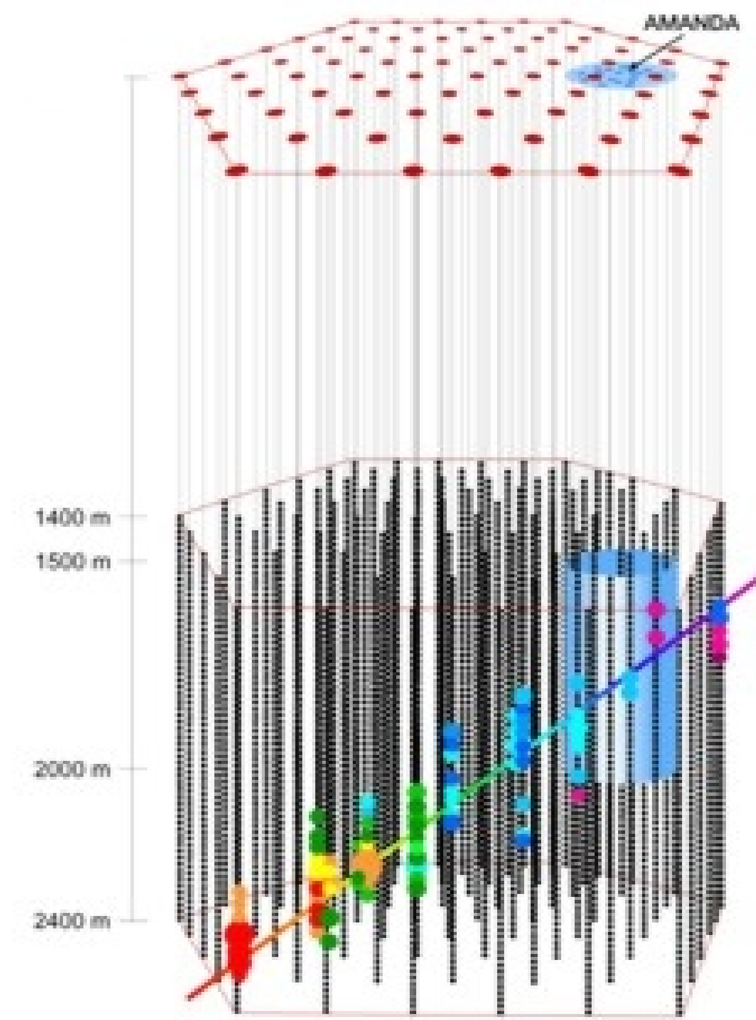
- 4 cables x 4km to shore.
- 1070m depth

Amundsen-Scott South Pole station



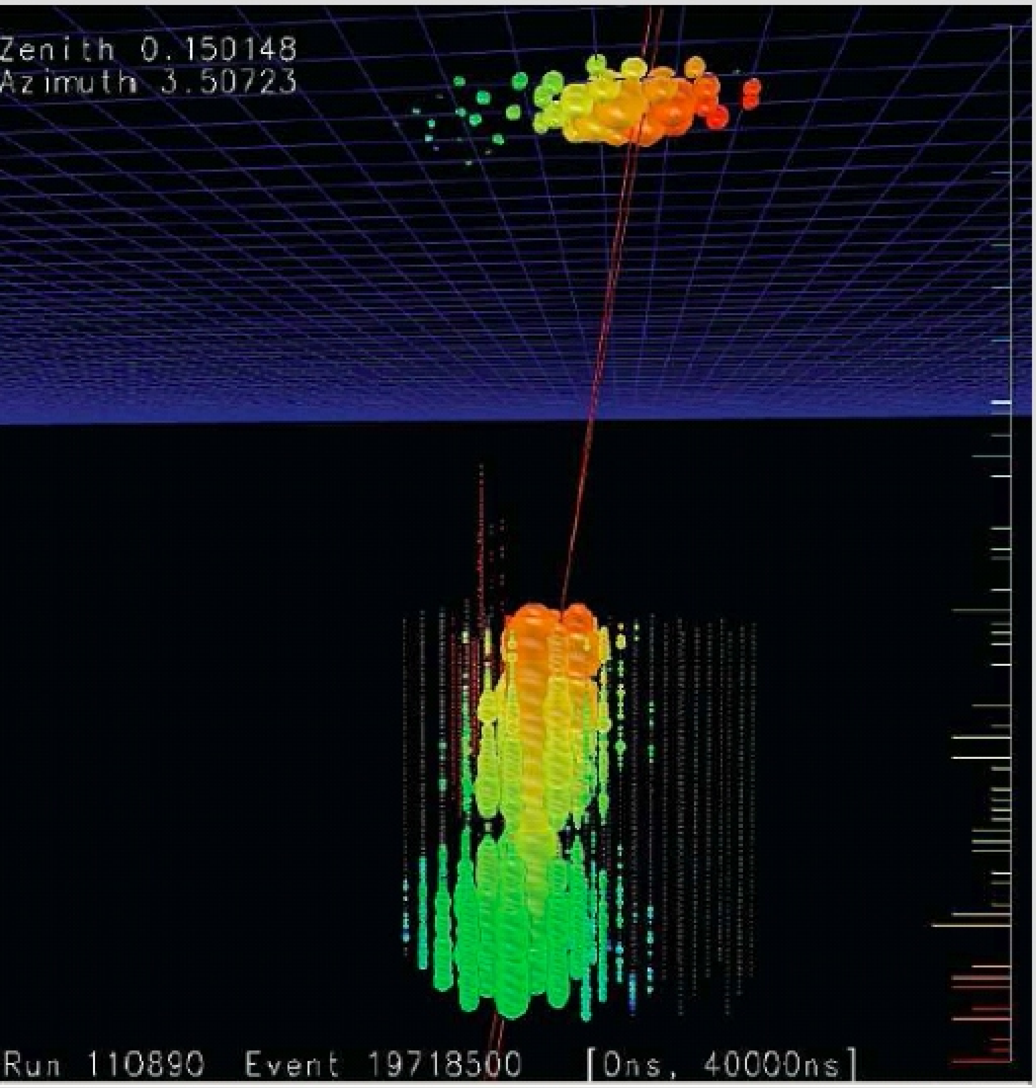

IceCube Lab
IceTop
81 Stations, each with
2 IceTop Cherenkov detector tanks
2 optical sensors per tank
324 optical sensors
IceCube Array
86 strings including 8 DeepCore strings
60 optical sensors on each string
5160 optical sensors
December, 2010: Project completed, 86 strings
125 m string separation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

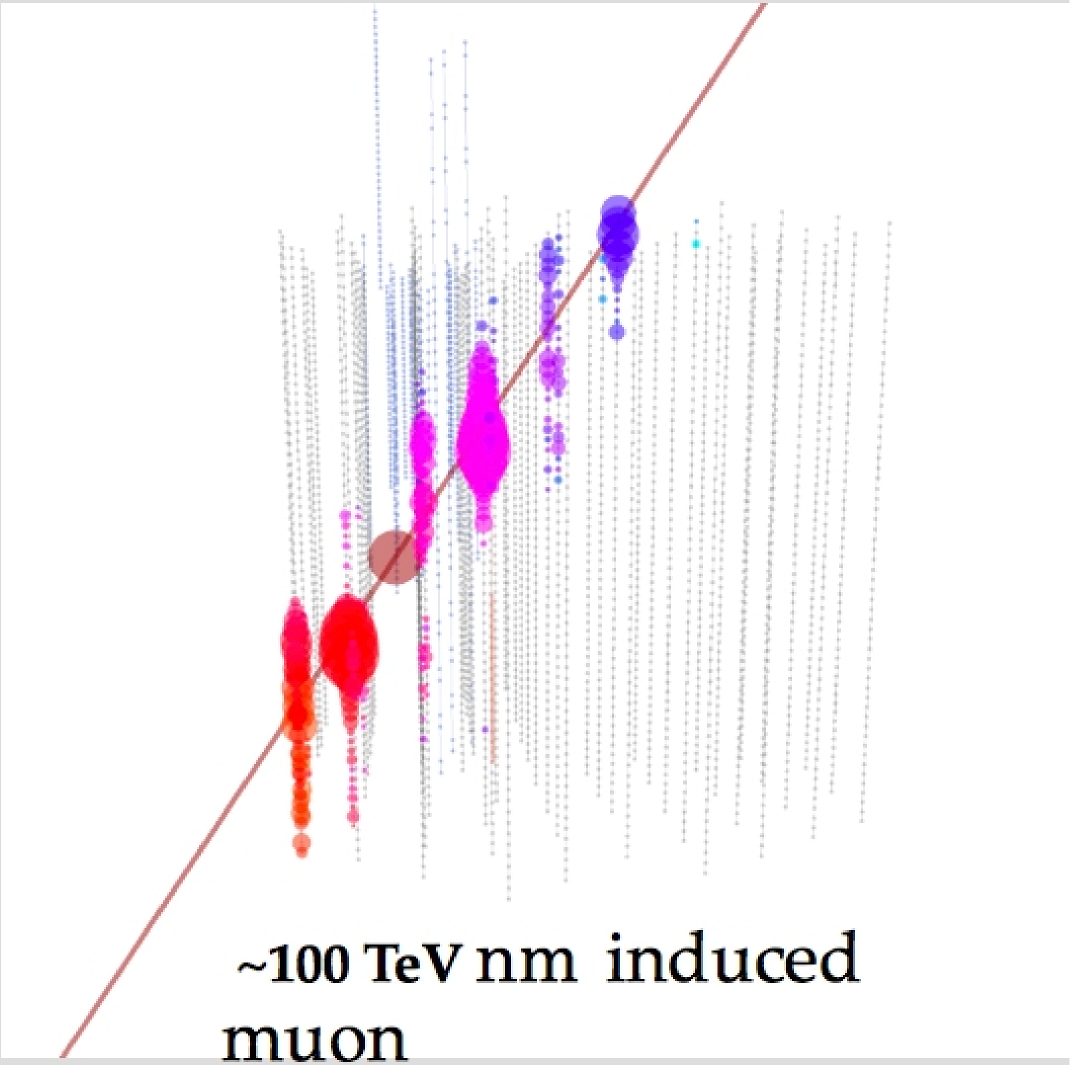
Deployment of the strings



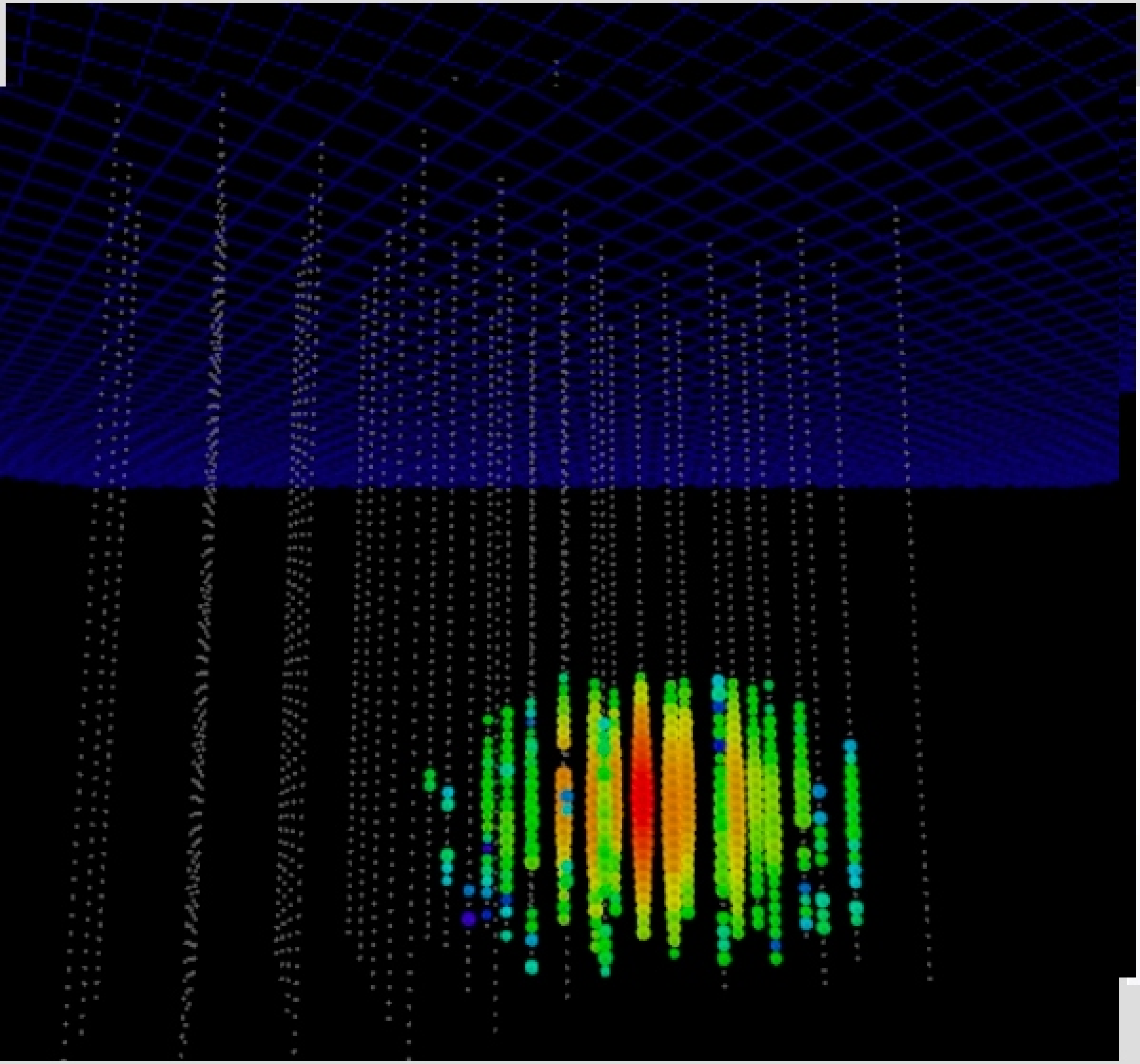
High-energy events in IceCube-40

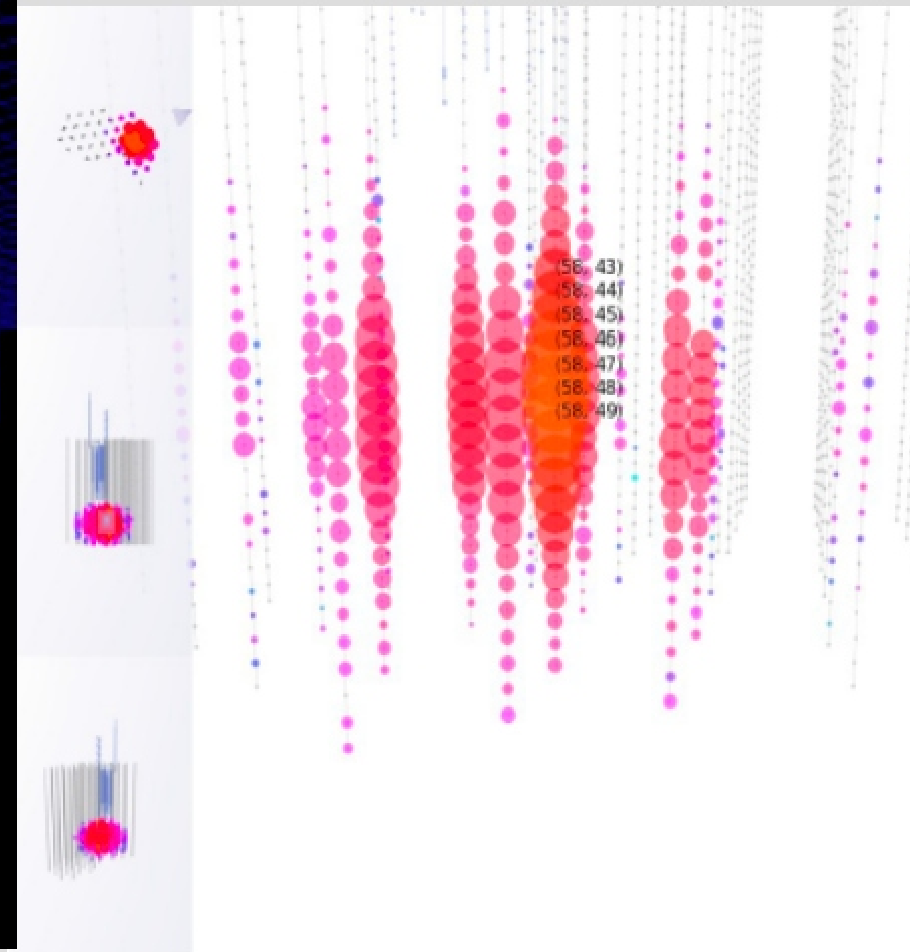
~ EeV air shower



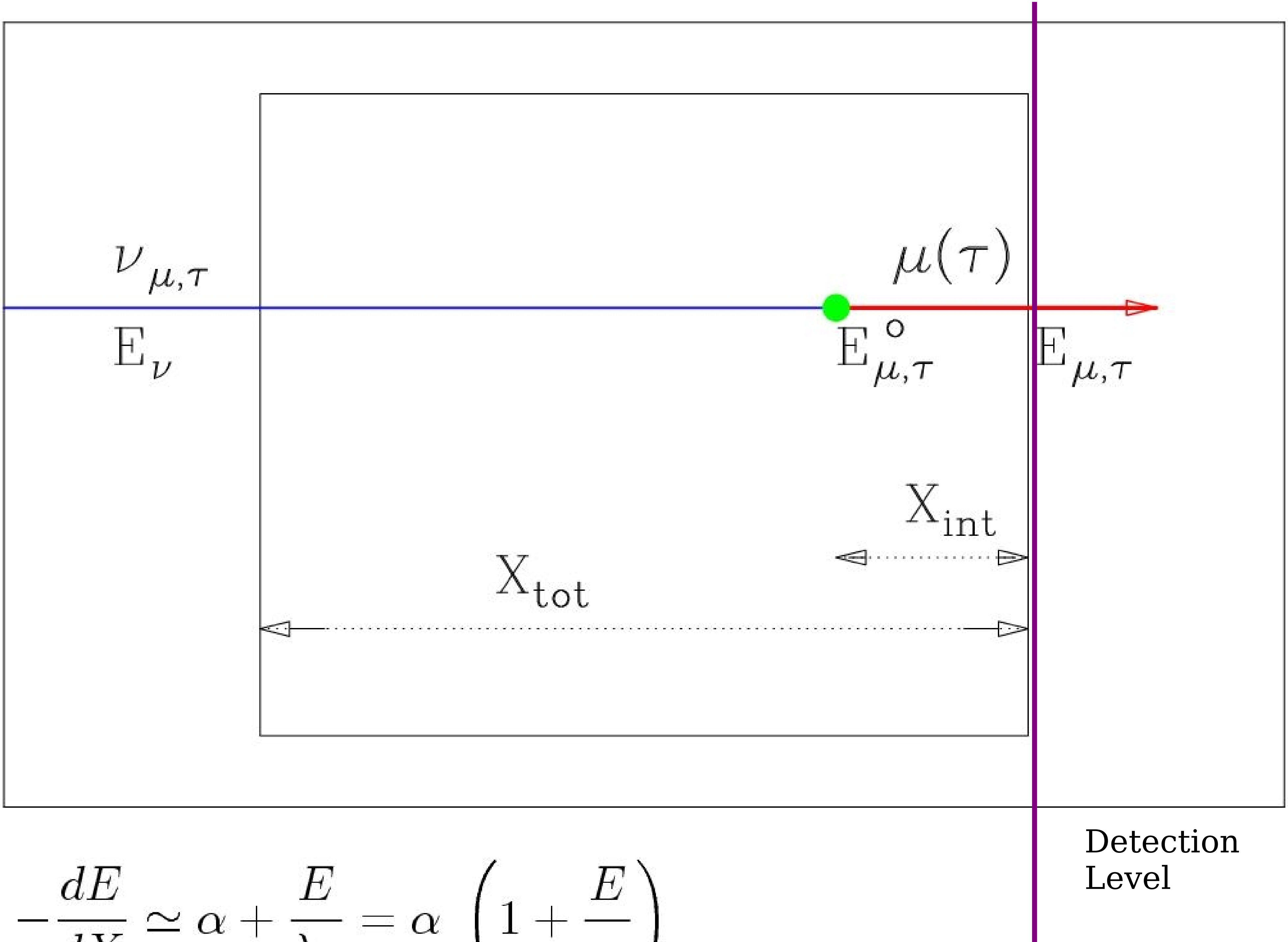


More events



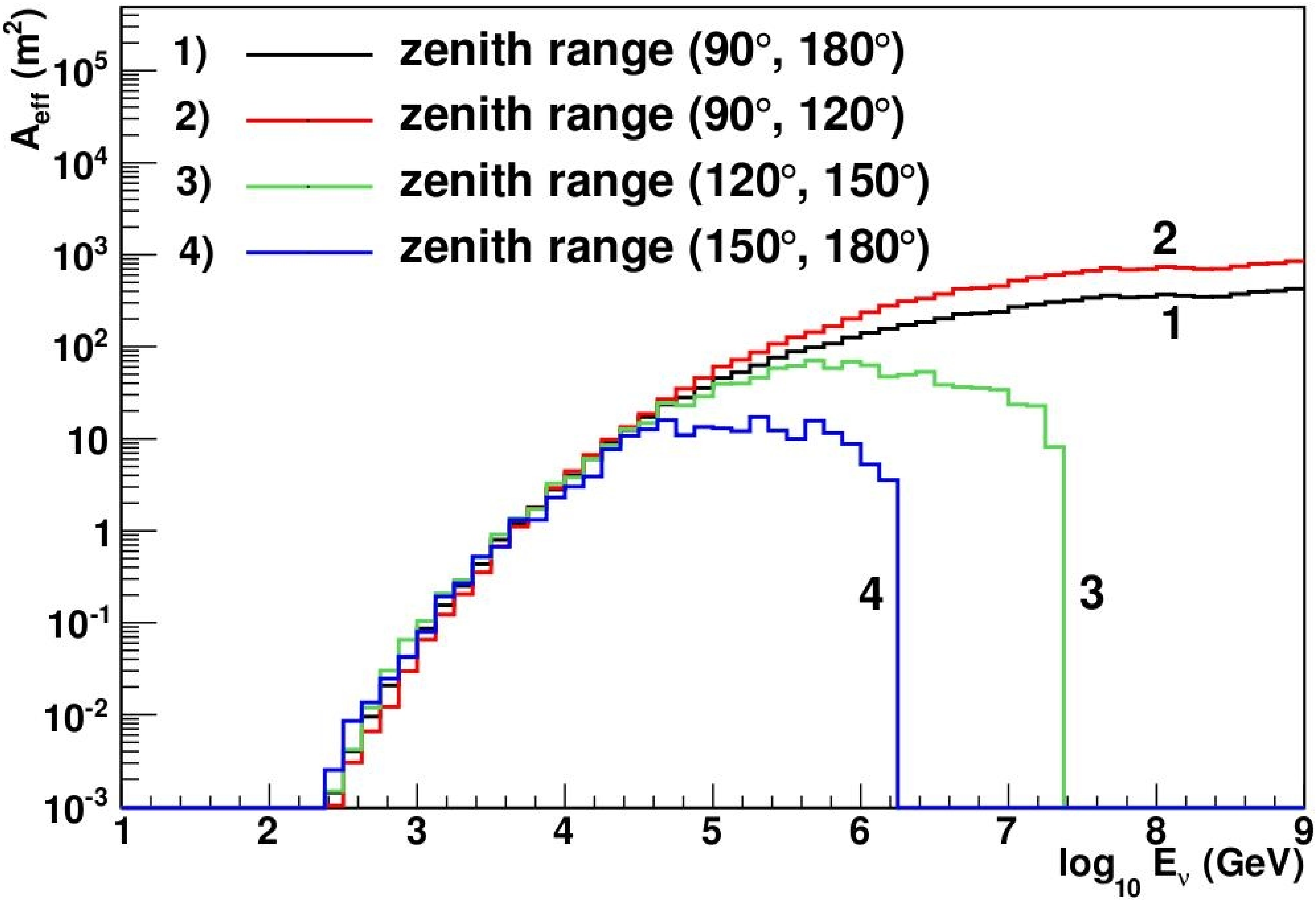


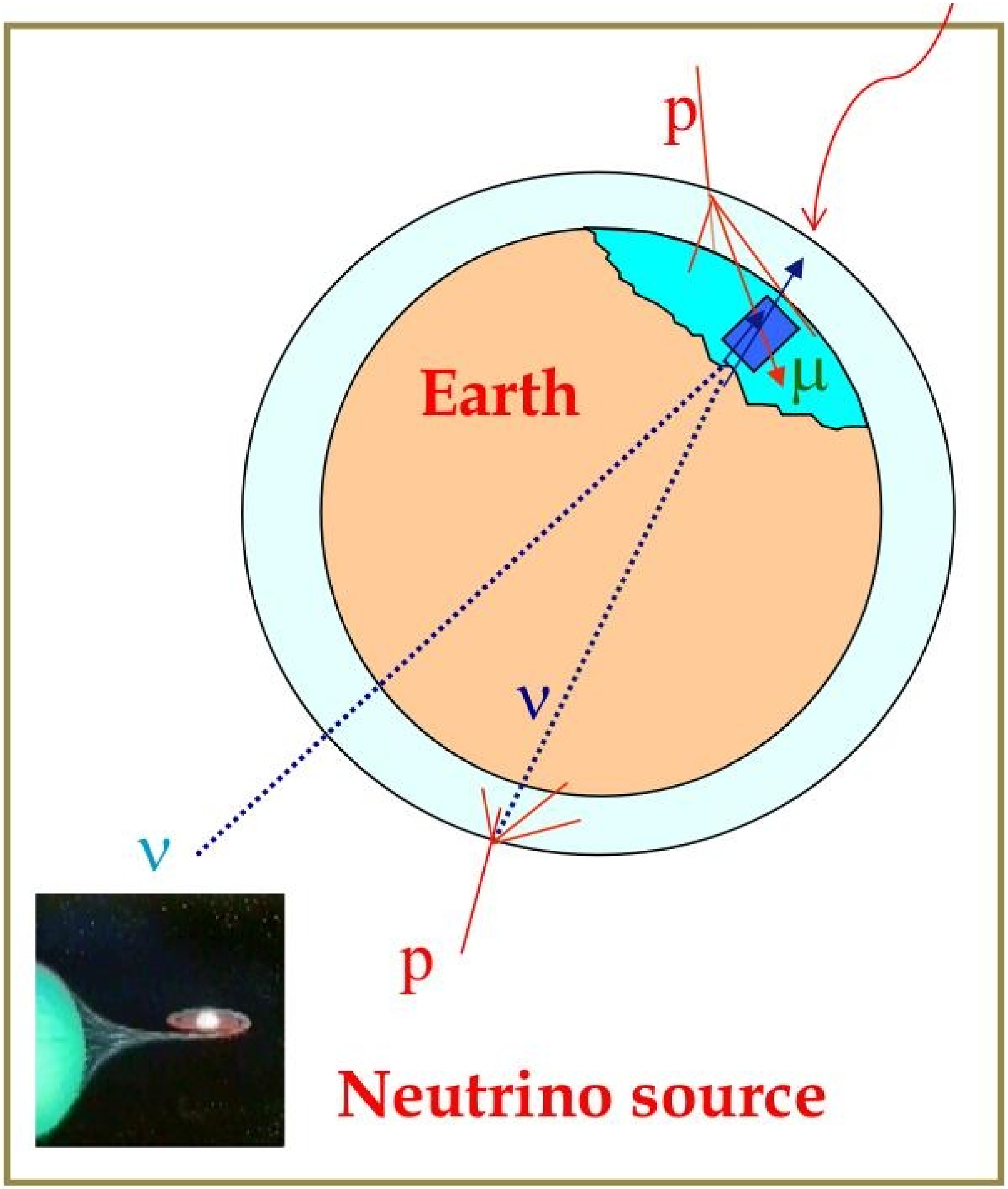
A cascade event, candidate for a high energy **ne** ~50 TeV

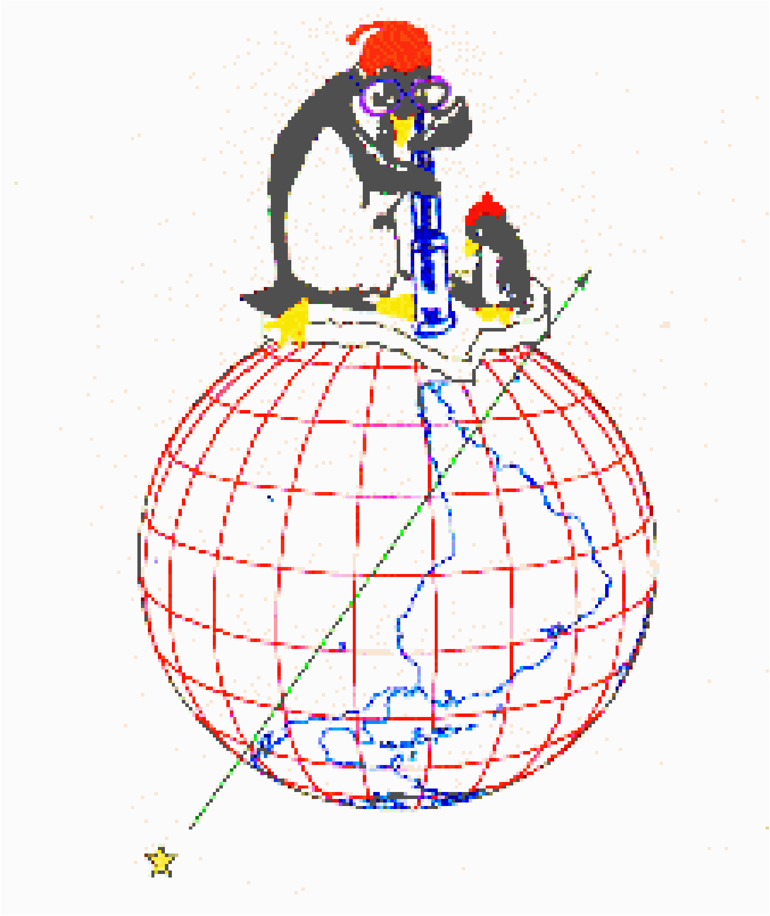


$$-\frac{dE}{dX} \simeq \alpha + \frac{E}{\lambda_\mu} = \alpha \left(1 + \frac{E}{\varepsilon_\mu}\right)$$

IceCube Effective AREA (as a function of Neutrino Energy)







See only
½ of the SKY

Neutrinos from
Cosmic Ray Sources

"Cosmogenic Neutrinos"

Neutrinos from DM annihilation

NEUTRINO POINT SOURCES

Components of the Neutrino Flux

$$\phi_{\nu_\alpha}(E,\Omega) = \phi_{\rm atm}^{\rm standard}(E,\Omega) + \phi_{\rm atm}^{\rm prompt}(E,\Omega)$$

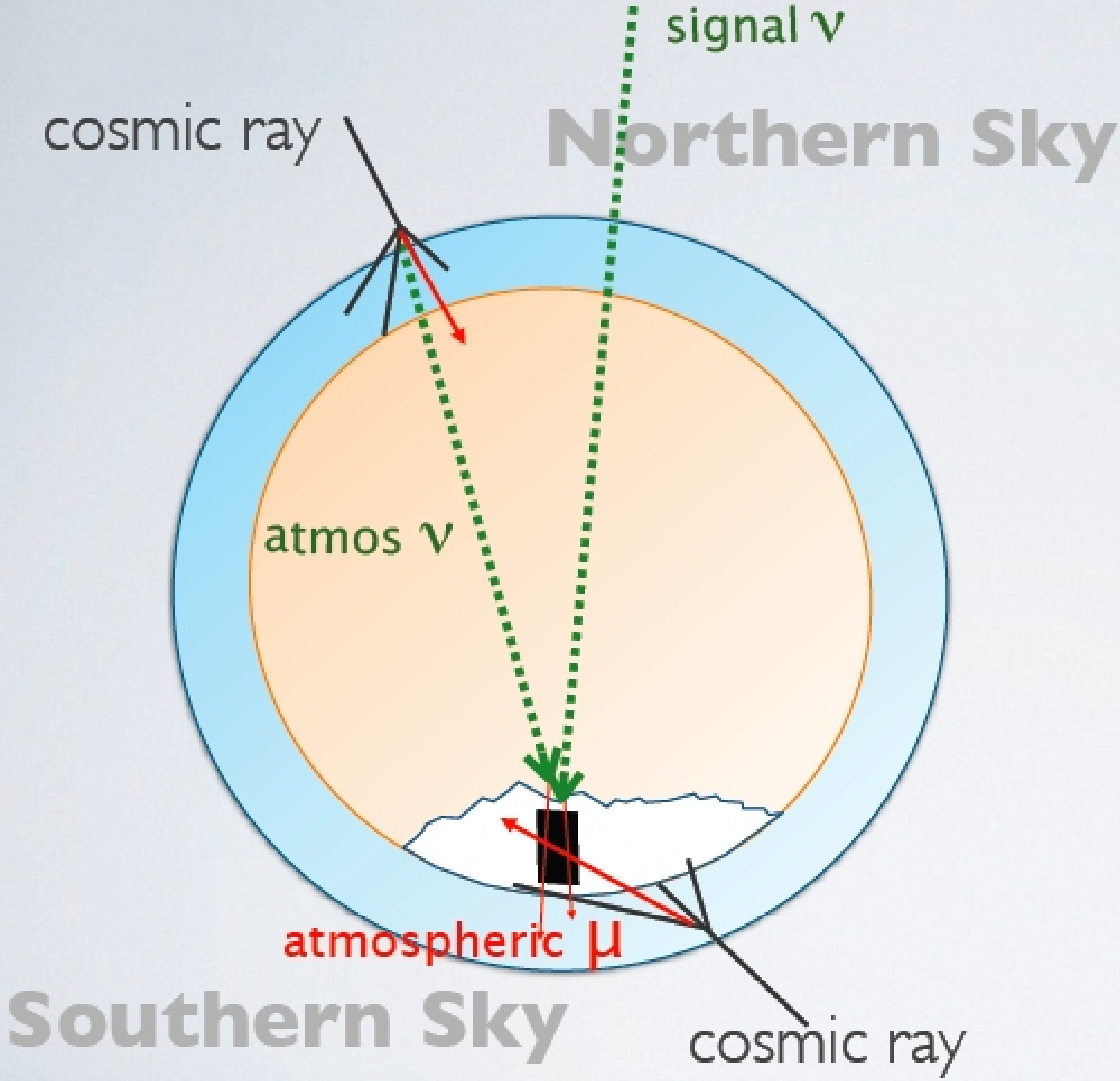
$$+ \phi_{\rm Galactic}(E,\Omega) + \phi_{\rm Extra\ Gal}(E,\Omega)$$

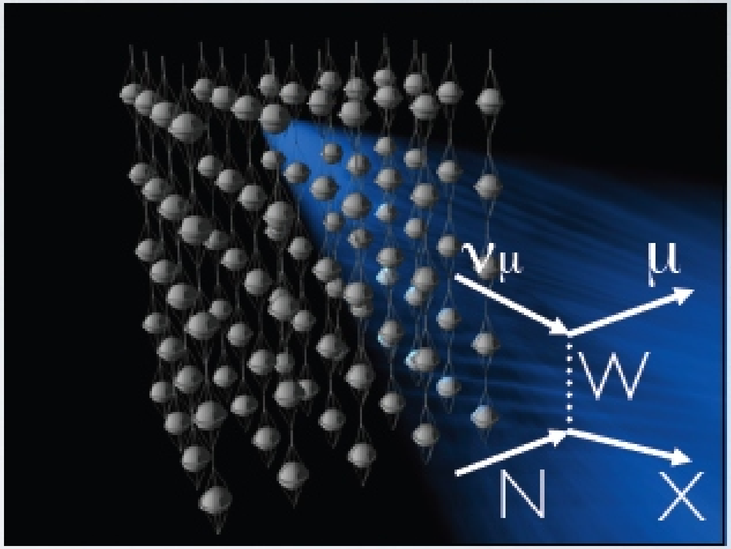
$$+ \sum_{\rm Galactic} \phi_j(E)\ \delta[\Omega - \Omega_j]$$

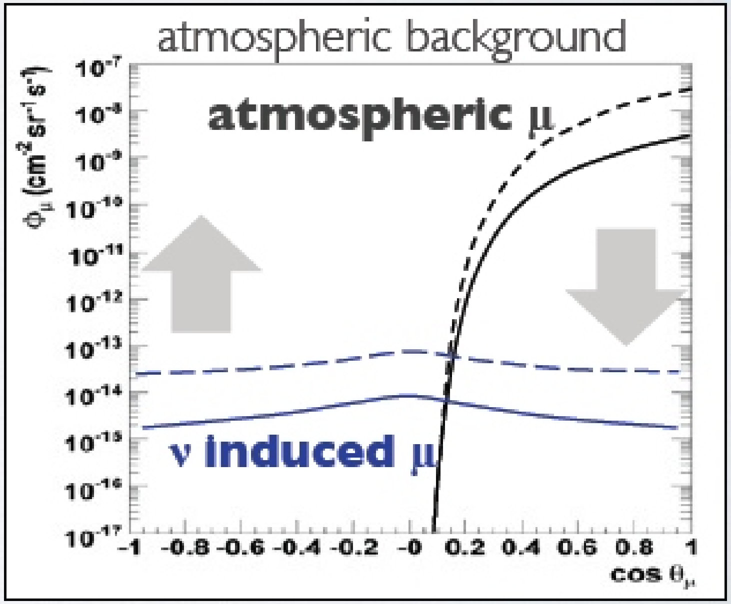
$$+ \sum_{\rm Extra\ Gal} \phi_k(E)\ \delta[\Omega - \Omega_k]$$

$$\sum_k \phi_k(E)\,\delta[\Omega - \Omega_k] \Longrightarrow \phi_{\rm Diffuse}(E)$$

DETECTION PRINCIPLE

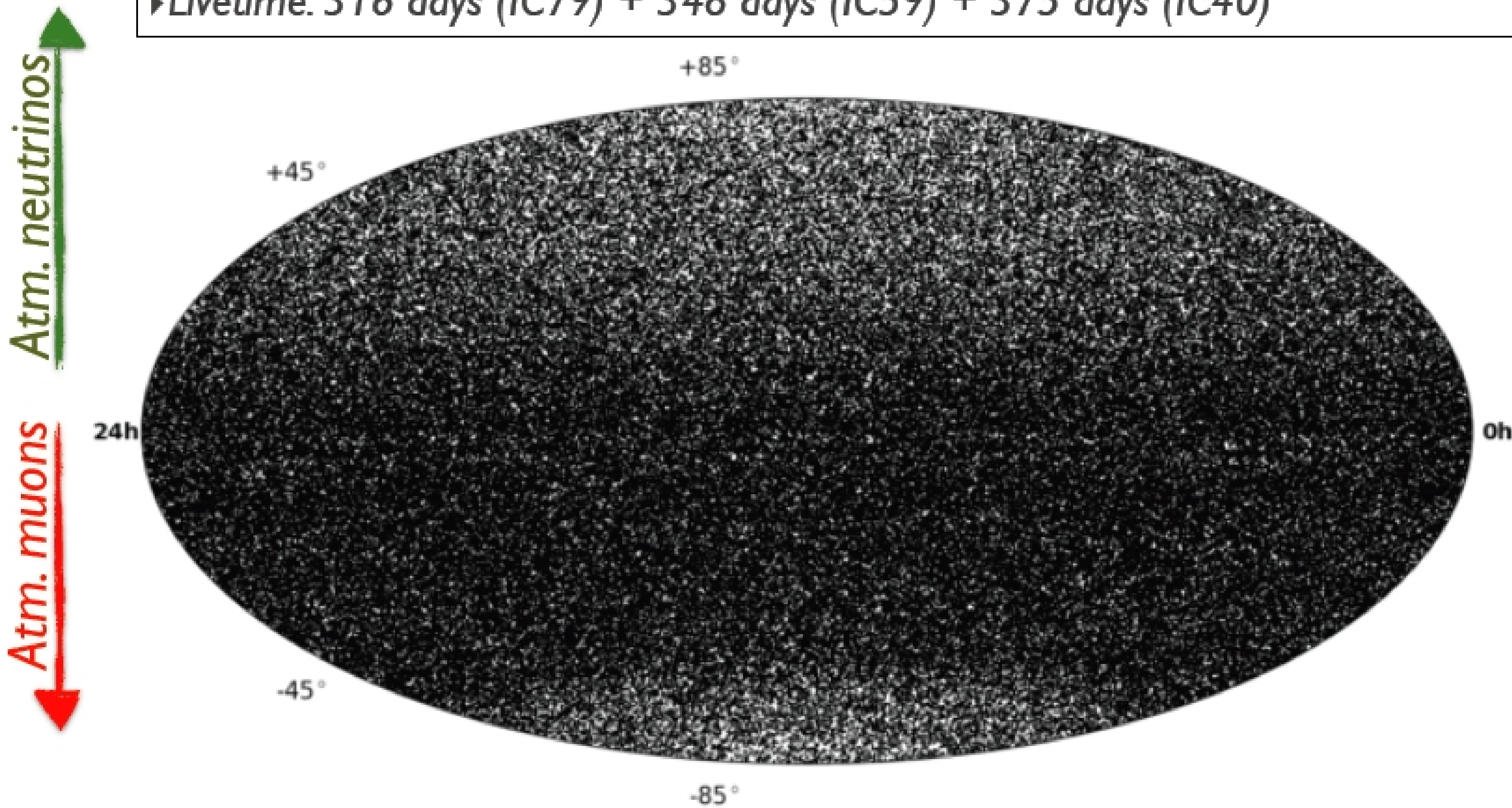






+IC79 SKYMAP

- *Total events (IC40+IC59+IC79): 108317 (upgoing) + 146018 (downgoing)*
- *Livetime: 316 days (IC79) + 348 days (IC59) + 375 days (IC40)*



+IC79 SKYMAP

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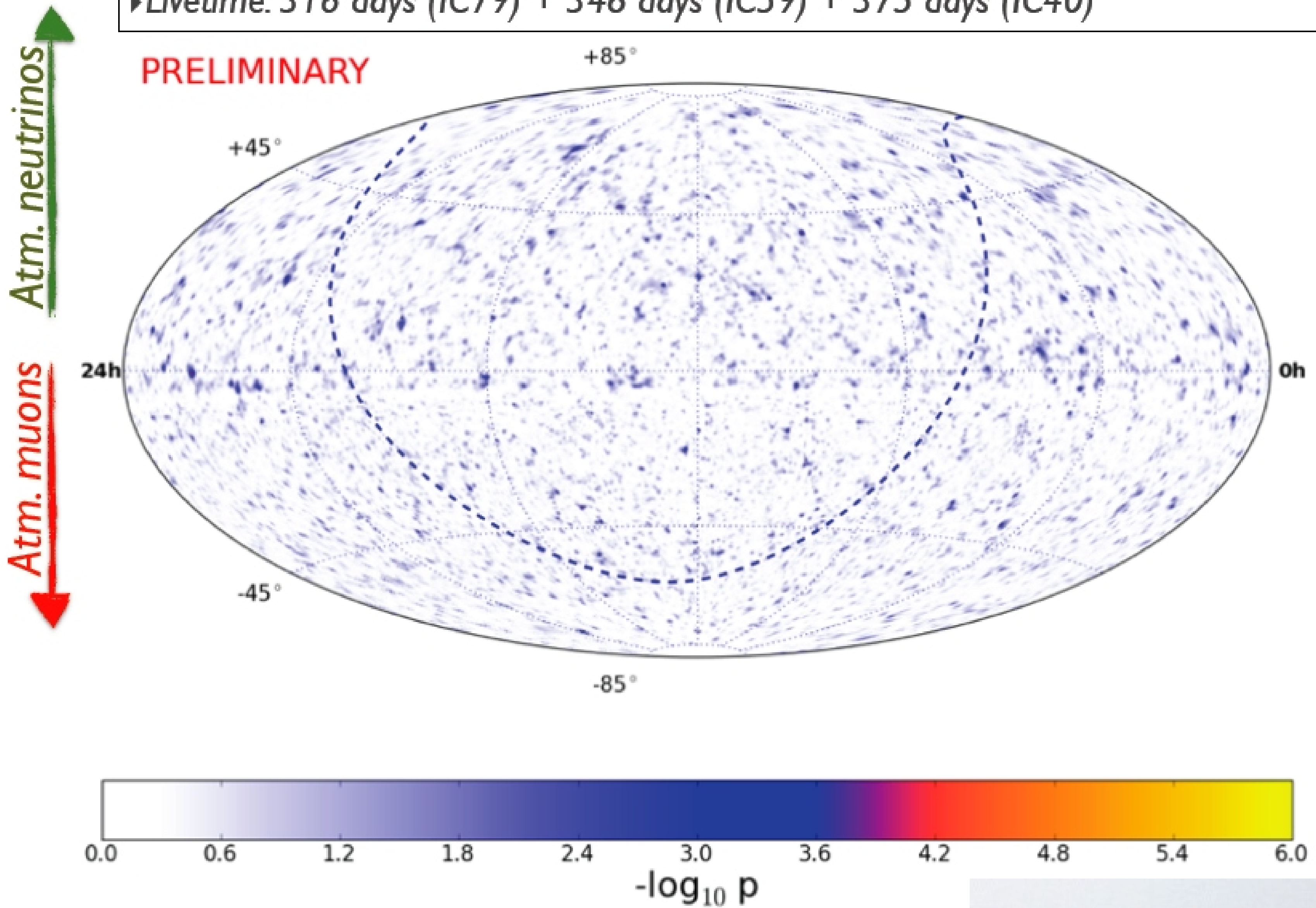


IceCube selected sources

(13 galactic SNR etc, 30 extragalactic active galaxies, etc.)

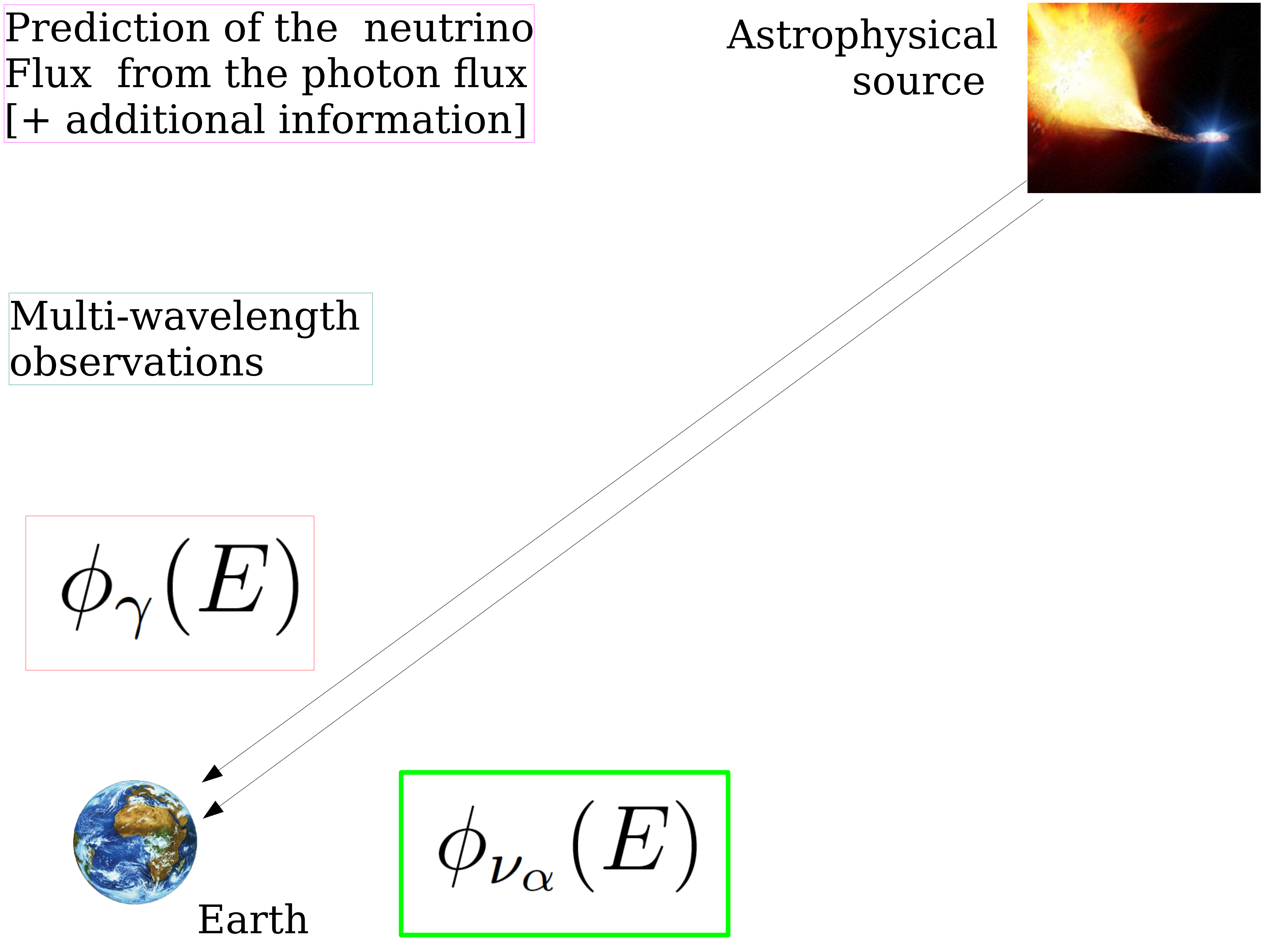
No significant detections at this point

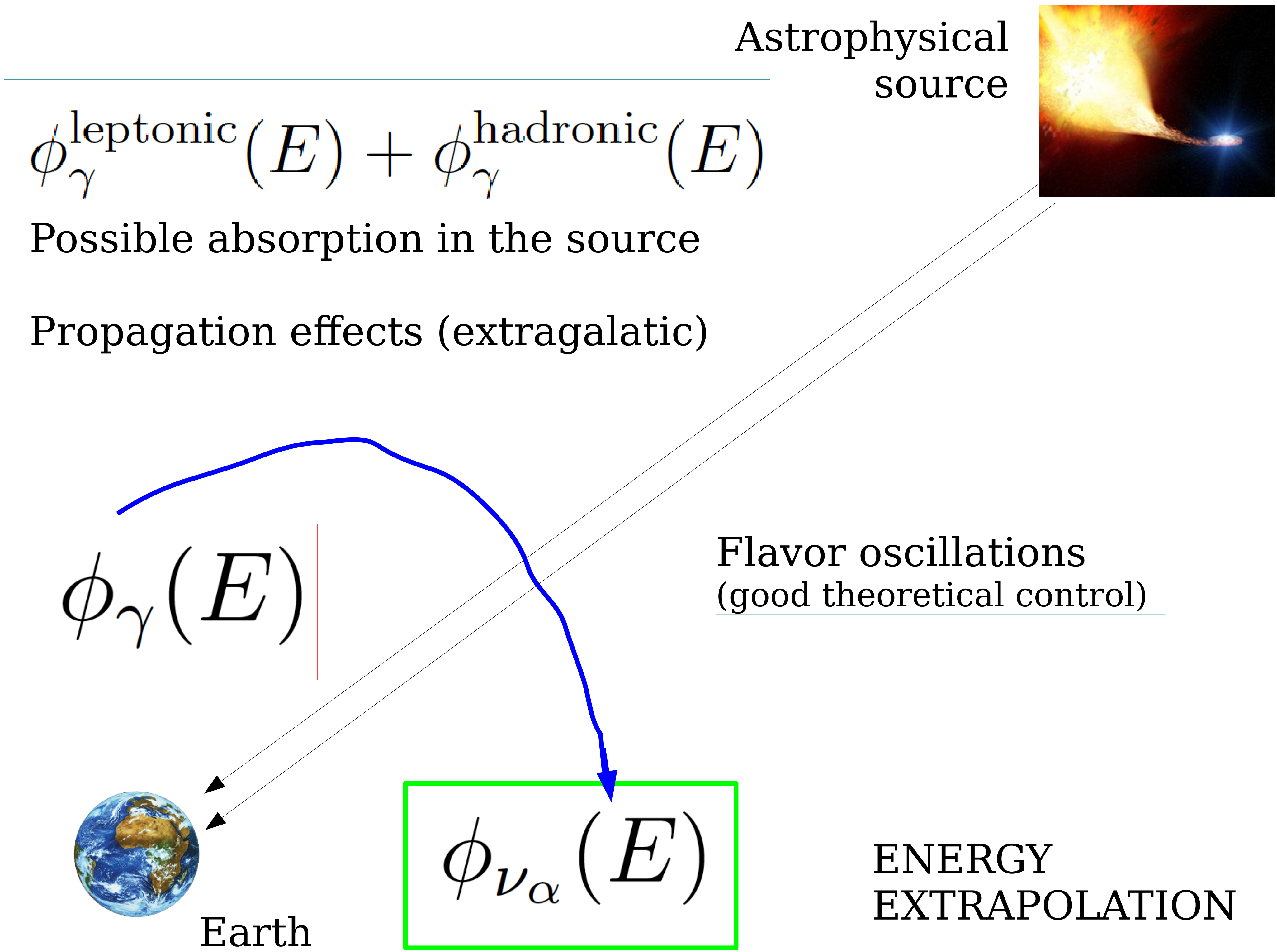
Source	RA (deg)	Dec (deg)	Type	Distance	P-value
Cyg OB2	308.08	41.51	UNID	-	–
MGRO J2019+37	305.22	36.83	PWN	-	–
MGRO J1908+06	286.98	6.27	SNR	-	0.38
Cas A	350.85	58.81	SNR	3.4 kpc	–
IC443	94.18	22.53	SNR	1.5 kpc	–
Geminga	98.48	17.77	Pulsar	100 pc	–
Crab Nebula	83.63	22.01	SNR	2 kpc	–
1ES 1959+650	300.00	65.15	HBL	z = 0.048	–
1ES 2344+514	356.77	51.70	HBL	z = 0.044	–
3C66A	35.67	43.04	Blazar	z = 0.44	0.42
H 1426+428	217.14	42.67	HBL	z = 0.129	–
BL Lac	330.68	42.28	HBL	z = 0.069	0.4
Mrk 501	253.47	39.76	HBL	z = 0.034	0.19
Mrk 421	166.11	38.21	HBL	z = 0.031	–
W Comae	185.38	28.23	HBL	z = 0.1020	–
1ES 0229+200	38.20	20.29	HBL	z = 0.139	0.39
M87	187.71	12.39	BL Lac	z = 0.0042	0.38
S5 0716+71	110.47	71.34	LBL	z > 0.3	0.49
M82	148.97	69.68	Starburst	3.86 Mpc	–
3C 123.0	69.27	29.67	FRII	1038 Mpc	–
3C 454.3	343.49	16.15	FSRQ	z = 0.859	0.48
4C 38.41	248.81	38.13	FSRQ	z = 1.814	0.3

PKS 0235+164	39.66	16.62	LBL	z = 0.94	0.18
PKS 0528+134	82.73	13.53	FSRQ	z = 2.060	0.49
PKS 1502+106	226.10	10.49	FSRQ	z = 0.56/1.839	–
3C 273	187.28	2.05	FSRQ	z = 0.158	–
NGC 1275	49.95	41.51	Seyfert Galaxy	z = 0.017559	–
Cyg A	299.87	40.73	Radio-loud Galaxy	z = 0.056146	0.44
Sgr A*	266.42	-29.01	Galactic Center	8.5 kpc	0.49
PKS 0537-441	84.71	-44.09	LBL	z = 0.896	0.44
Cen A	**201.37**	**-43.02**	**FRI**	**3.8 Mpc**	**0.14**
PKS 1454-354	**224.36**	**-35.65**	**FSRQ**	**z = 1.42**	**0.14**
PKS 2155-304	329.72	-30.23	HBL	z = 0.116	–
PKS 1622-297	246.53	-29.86	FSRQ	z = 0.815	0.27
QSO 1730-130	263.26	-13.08	FSRQ	z = 0.902	–
PKS 1406-076	212.24	-7.87	FSRQ	z = 1.494	0.36
QSO 2022-077	306.42	-7.64	FSRQ	z = 1.39	–
3C279	194.05	-5.79	FSRQ	z = 0.536	0.45
TYCHO	6.36	64.18	SNR	2.4 kpc	–
Cyg X-1	299.59	35.20	MQSO	2.5 kpc	–
Cyg X-3	308.11	40.96	MQSO	9 kpc	–
LSI 303	40.13	61.23	MQSO	2 kpc	–
SS433	287.96	4.98	MQSO	1.5 kpc	0.48

CONCLUSIONS

- ***No evidence of a neutrino point source*** has been found in the combination of 3 datasets: IC79+IC59+IC40
- The ***IC59 untriggered flare*** analysis have the most significant result but still compatible with a background fluctuation.
- More analysis on the IC79 dataset are still on-going: time-dependent searches, stacking sources, extended sources skymaps.
- IceCube sensitivity is getting in the region where a non-discovery from a point-source is becoming meaningful.


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



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

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

TeV Photons in a Cherenkov Telescope

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

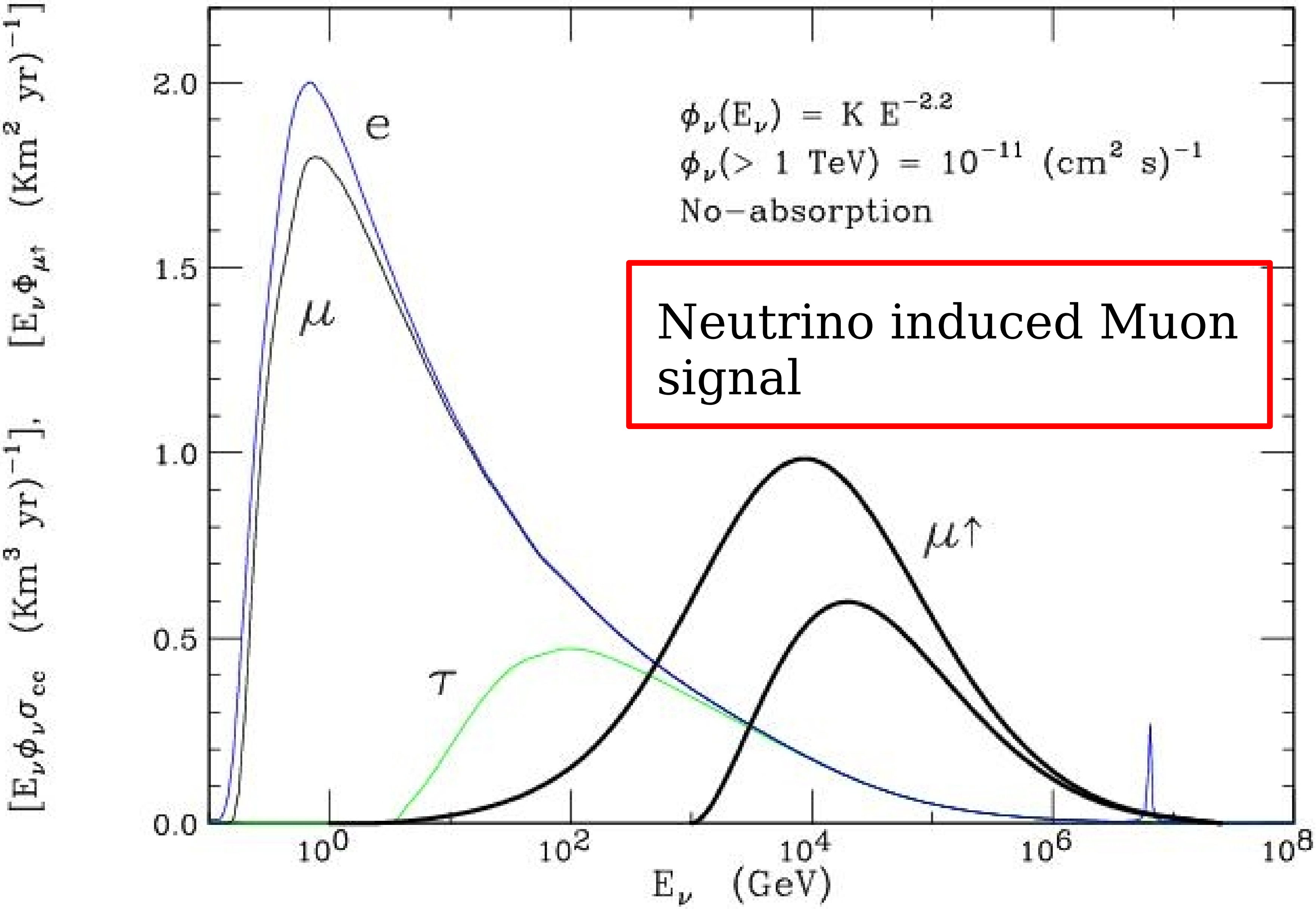
$$\phi(E) \propto E^{-2}$$

Up-going muons Neutrino telescope

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

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

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

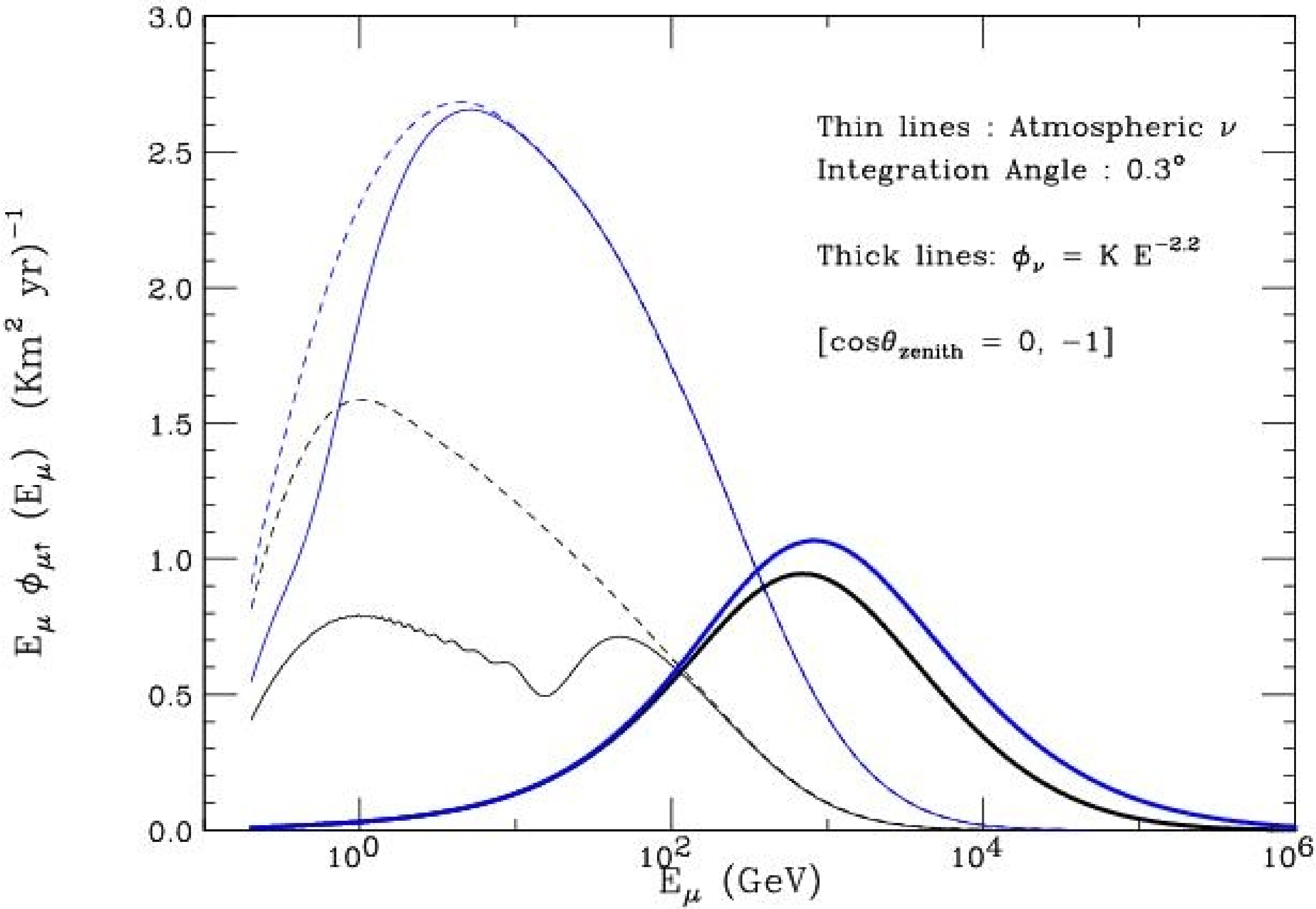


$$\Phi_{\mu\uparrow} \simeq (1 \div 5)\left[\frac{\phi_\nu(\geq 1\ \mathrm{TeV})}{10^{-11}\ (\mathrm{cm}^2\,\mathrm{s})^{-1}}\right]\ (\mathrm{Km}^2\ \mathrm{yr})^{-1}$$

Energy Response:
Peak @ 20 TeV

BACKGROUND

Atmospheric Neutrinos



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

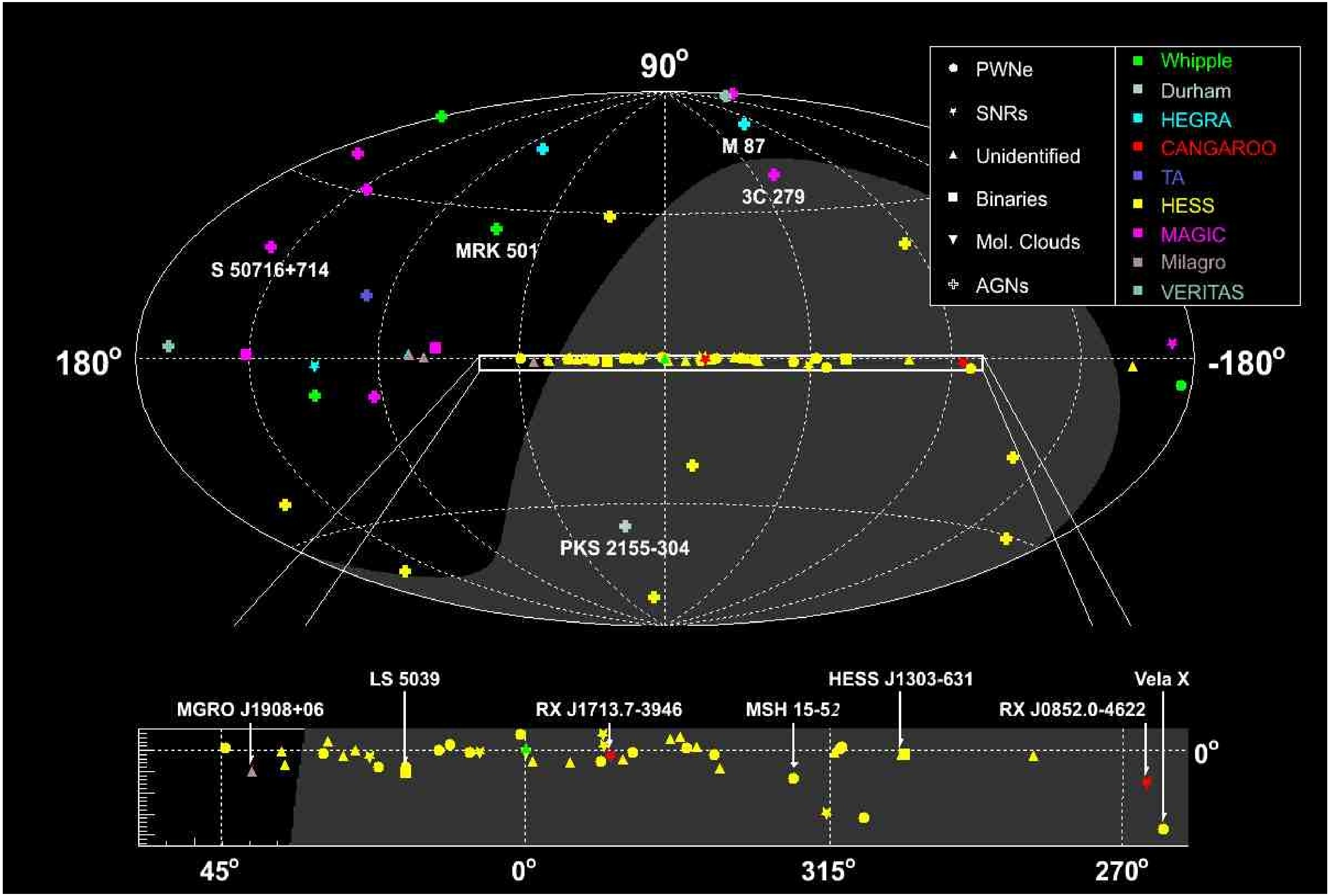
detection with neutrinos is within reach .....

Few events / (km2 yr)

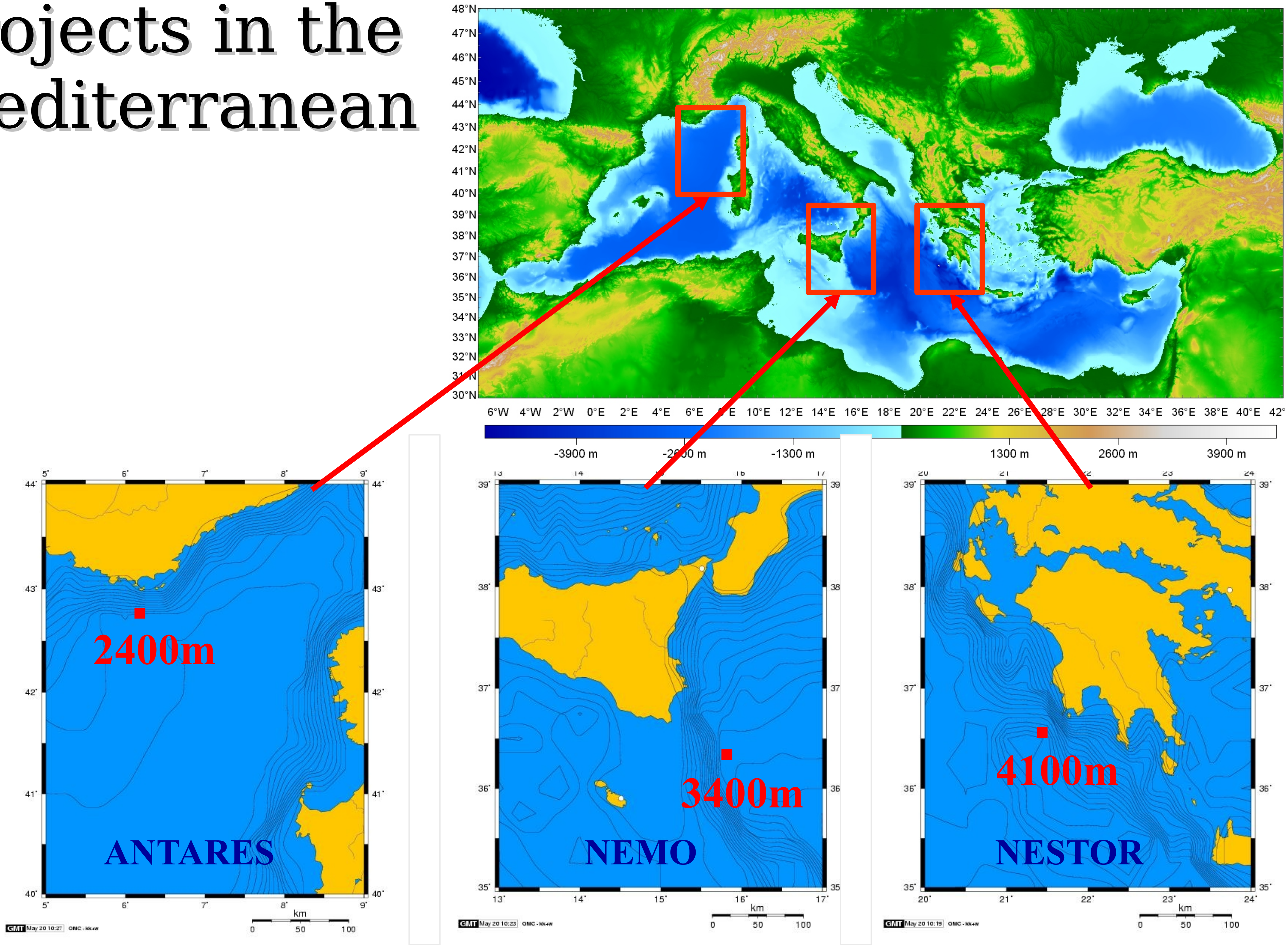
...but

NOT EASY !

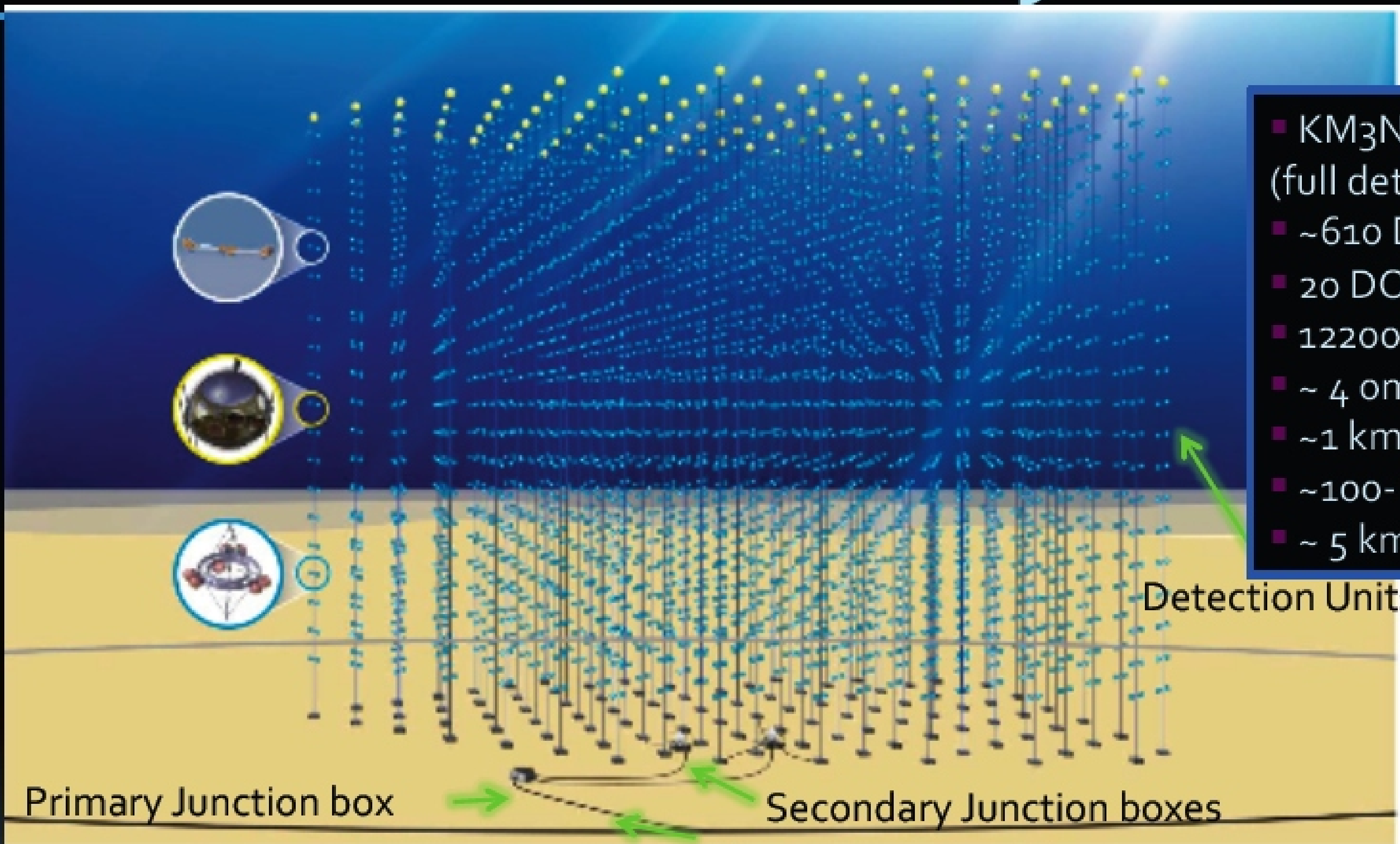
HE γ-ray sources



Projects in the Mediterranean



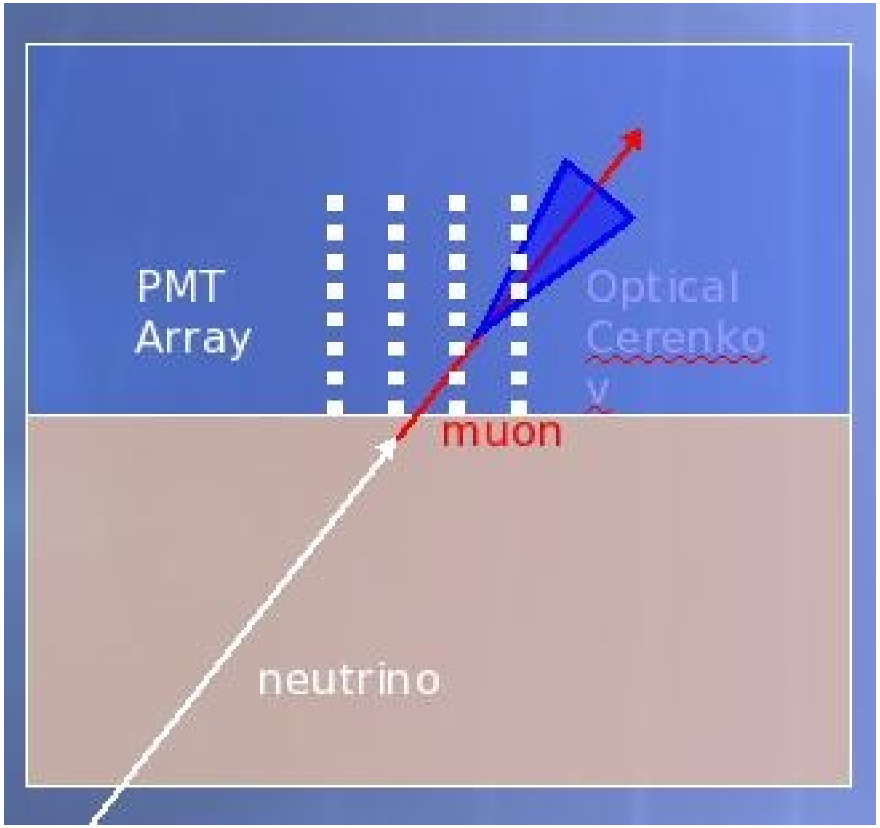
KM3NeT lay-out



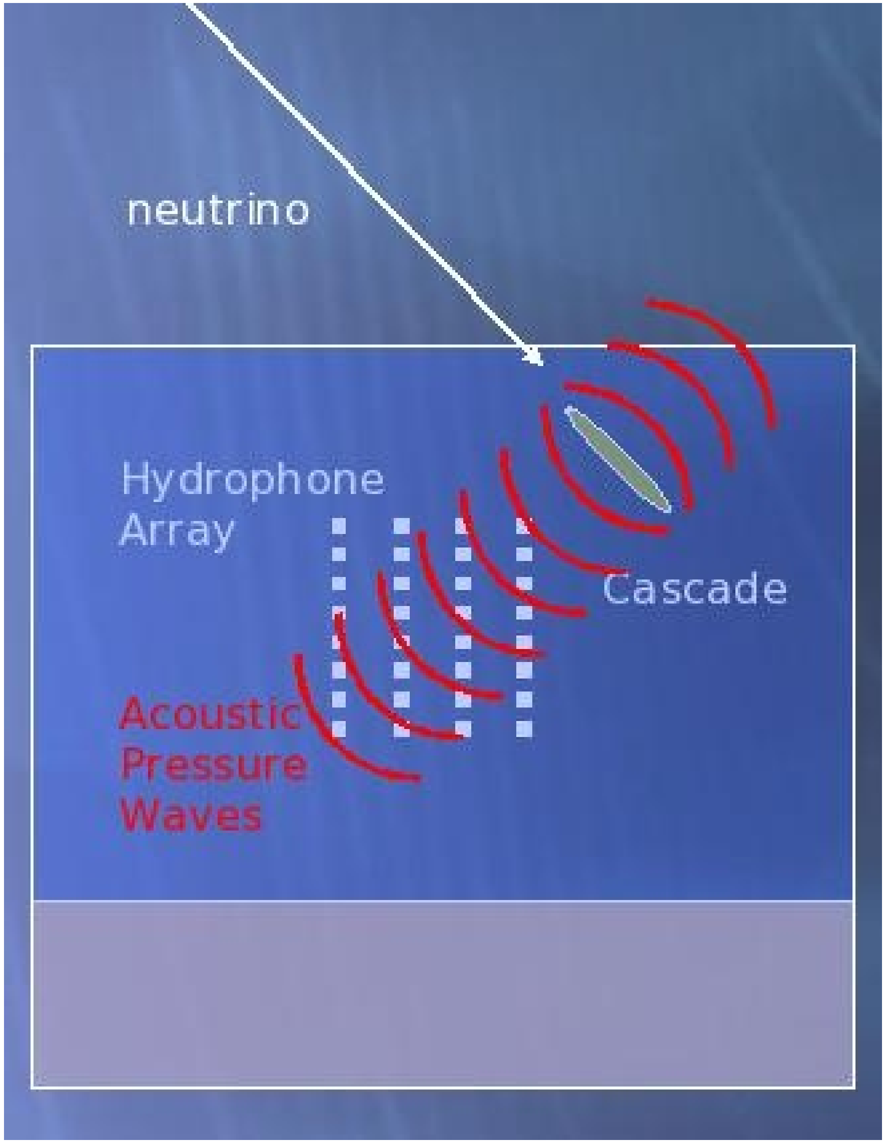
- KM3NeT in numbers (full detector)
- ~610 DU
- 20 DOM/DU
- 12200 DOM
- ~ 4 0m DOM spacing
- ~1 km DU height
- ~100- 180 m DU distance
- ~ 5 km^3 volume

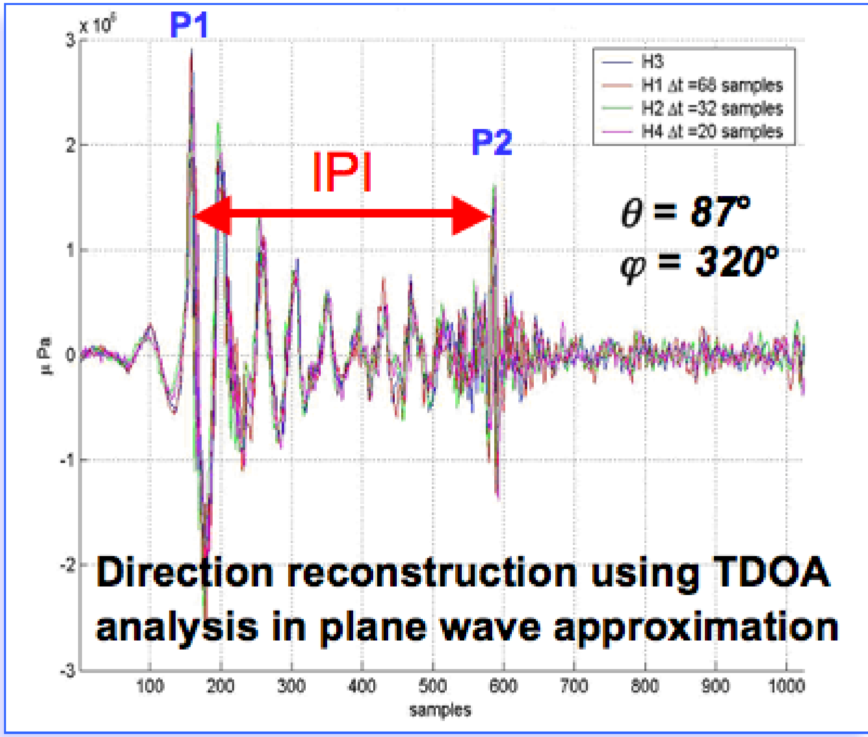
Optical Module (OM) = pressure resistant/tight sphere cointaining photo-multplier
Detection Unit (DU) = mechanical structure holding OMs, enviromental sensors, electronics,… *DU is the building element of the telescope*
Construction in several blocks => Multi-site option

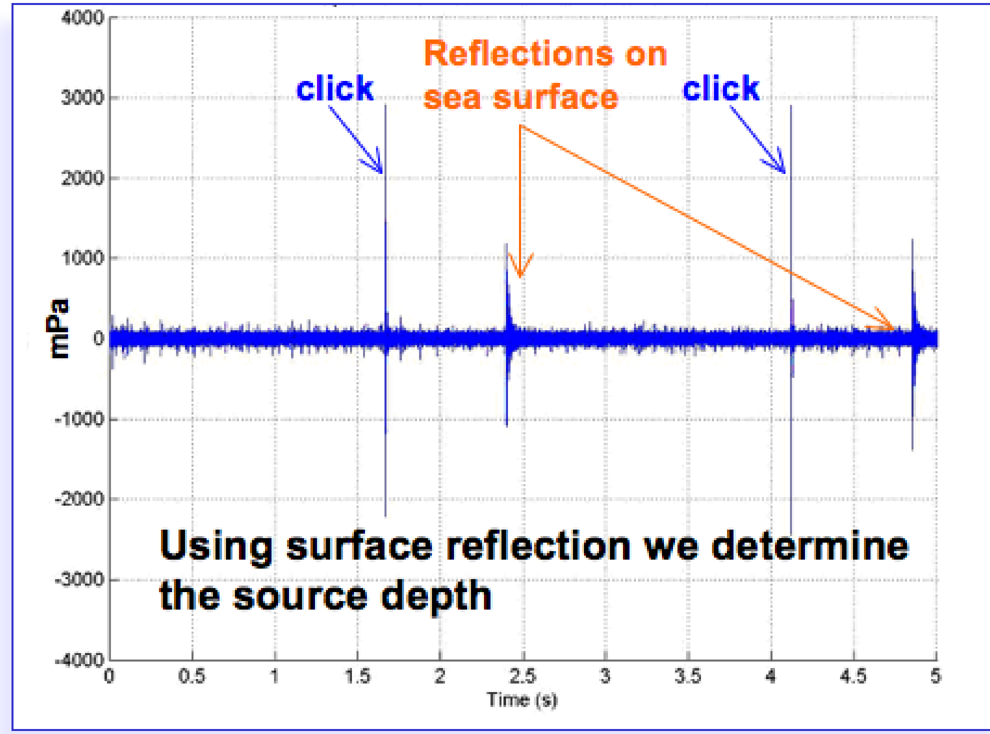
“OPTICAL Method”

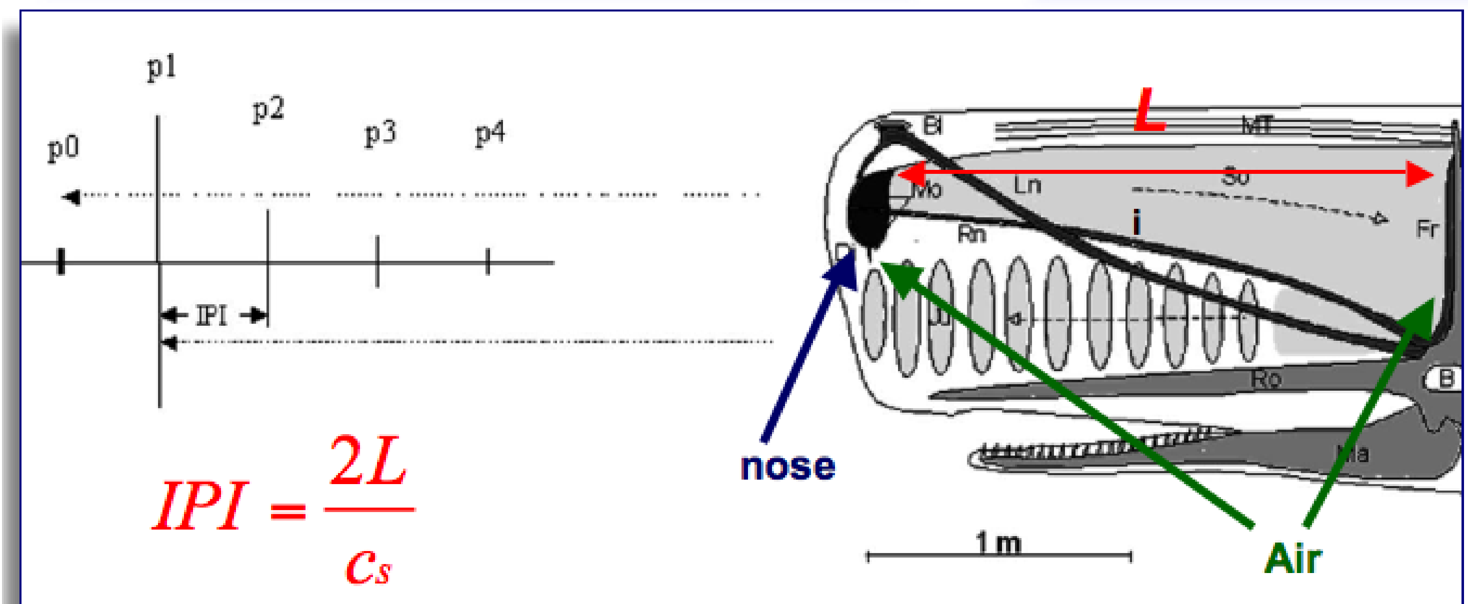


“ACOUSTIC Method”









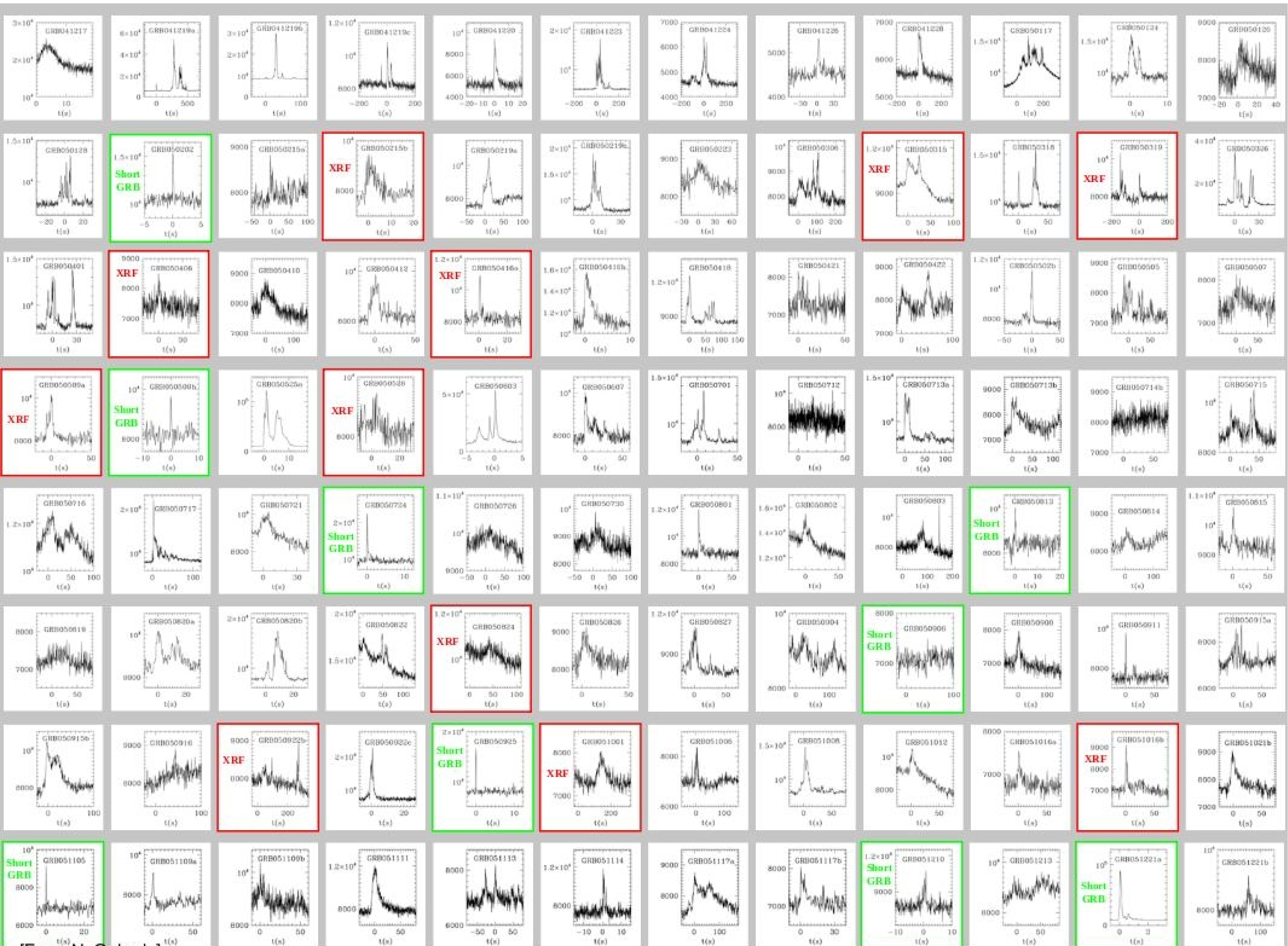
Depth = 560 ± 5 m

L = 3.41 ± 0.05 m
Size = 9.72 - 10.50 m

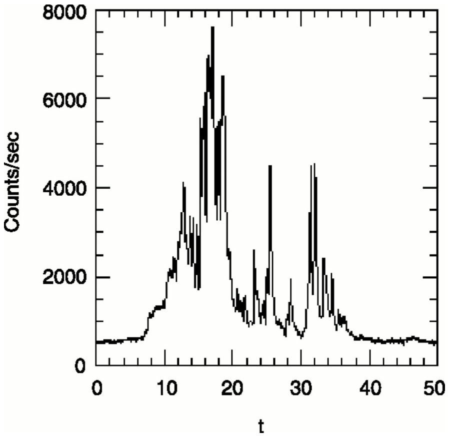
Young male or female


INTERDISCIPLINARY studies

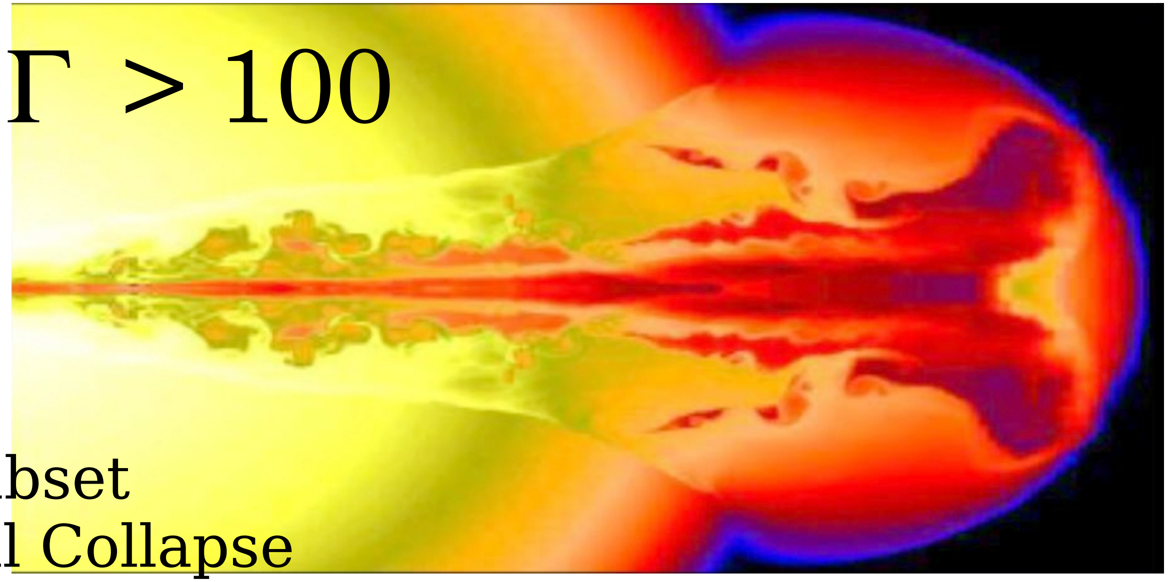
Gamma Ray Bursts



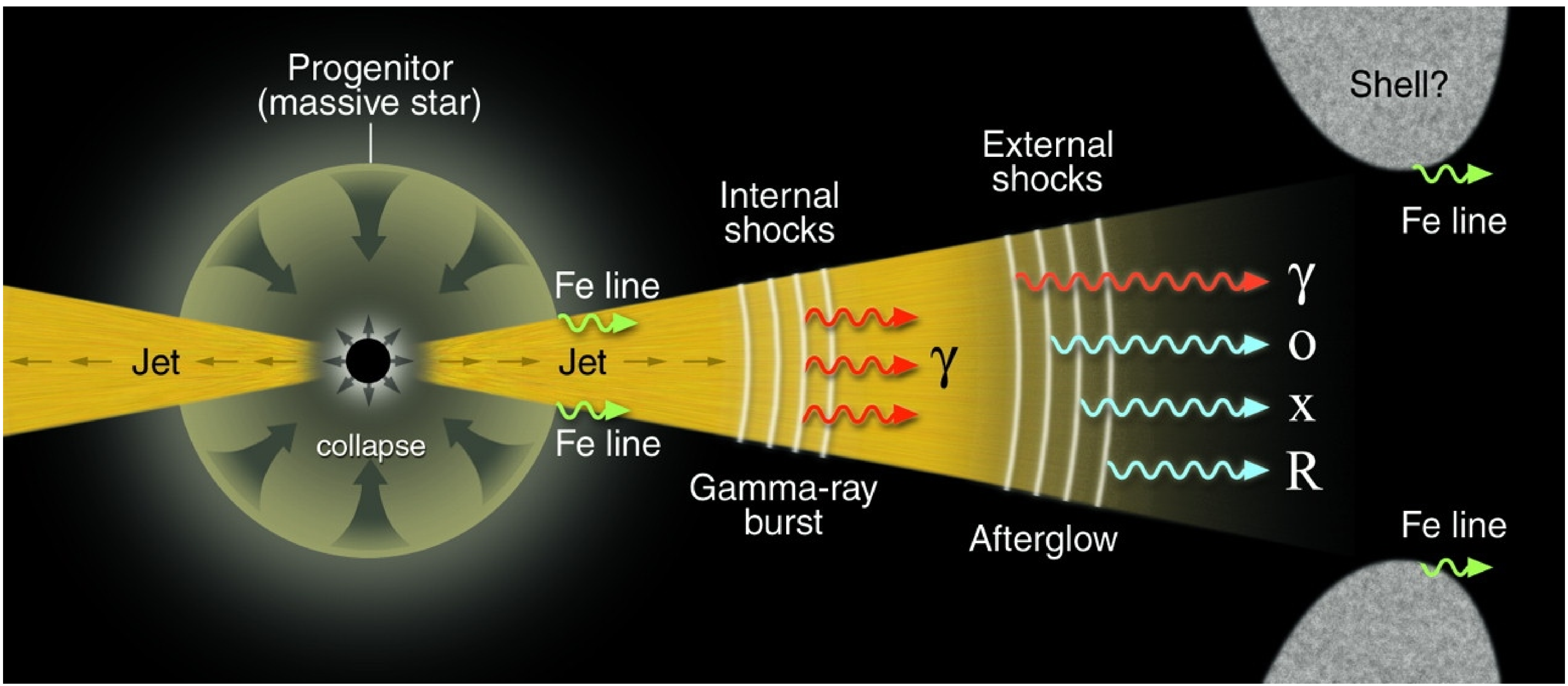
[From N. Gehrels]



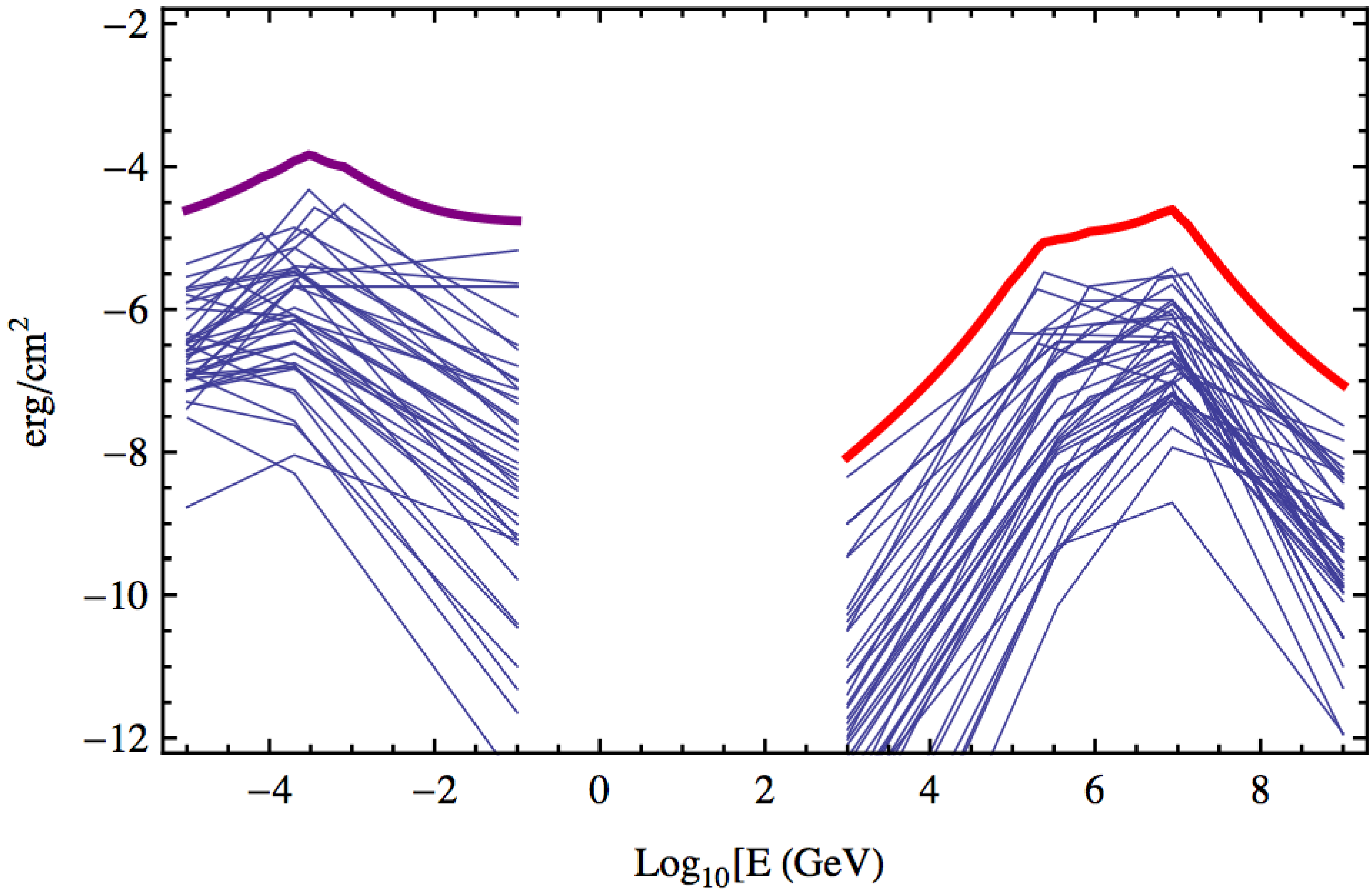
$\Gamma > 100$



GRB : associated with a subset
of SN Stellar Gravitational Collapse



41 GRB used by AMANDA



Photon detection

Neutrino assumed spectrum

EXTRA-GALACTIC NEUTRINOS

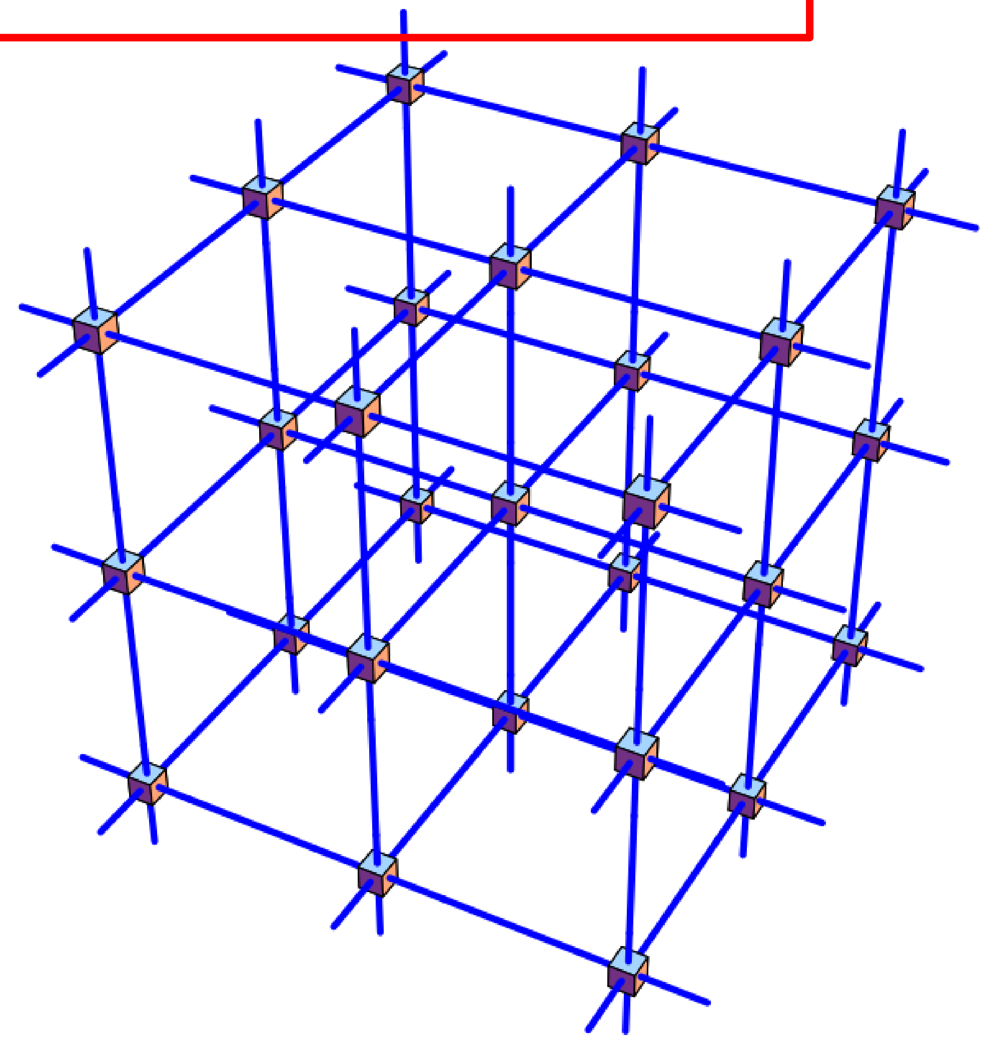
UNRESOLVED FLUX

Sum of all High Energy
Neutrino Sources

Individual Sources

AGN
GRB's

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



Linear sequence of lampposts:

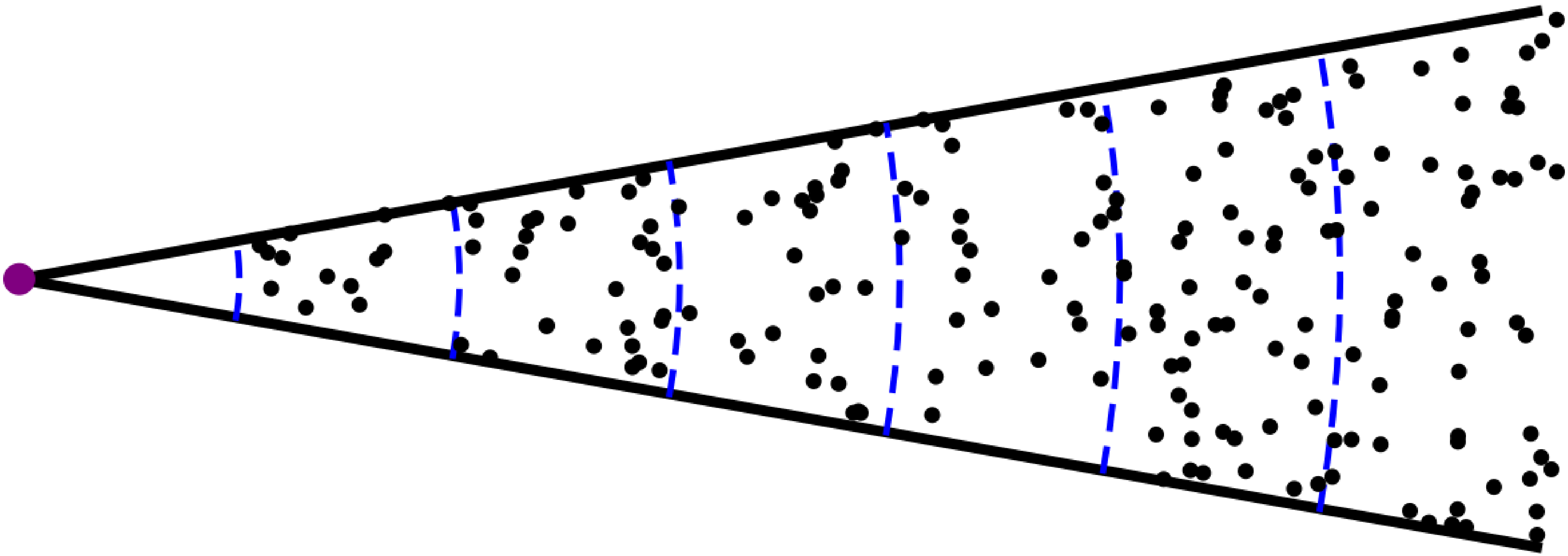
Most of the light you receive from the nearest lamppost

3D ensemble of lampposts: [Euclidean static space]

Light diverges !

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

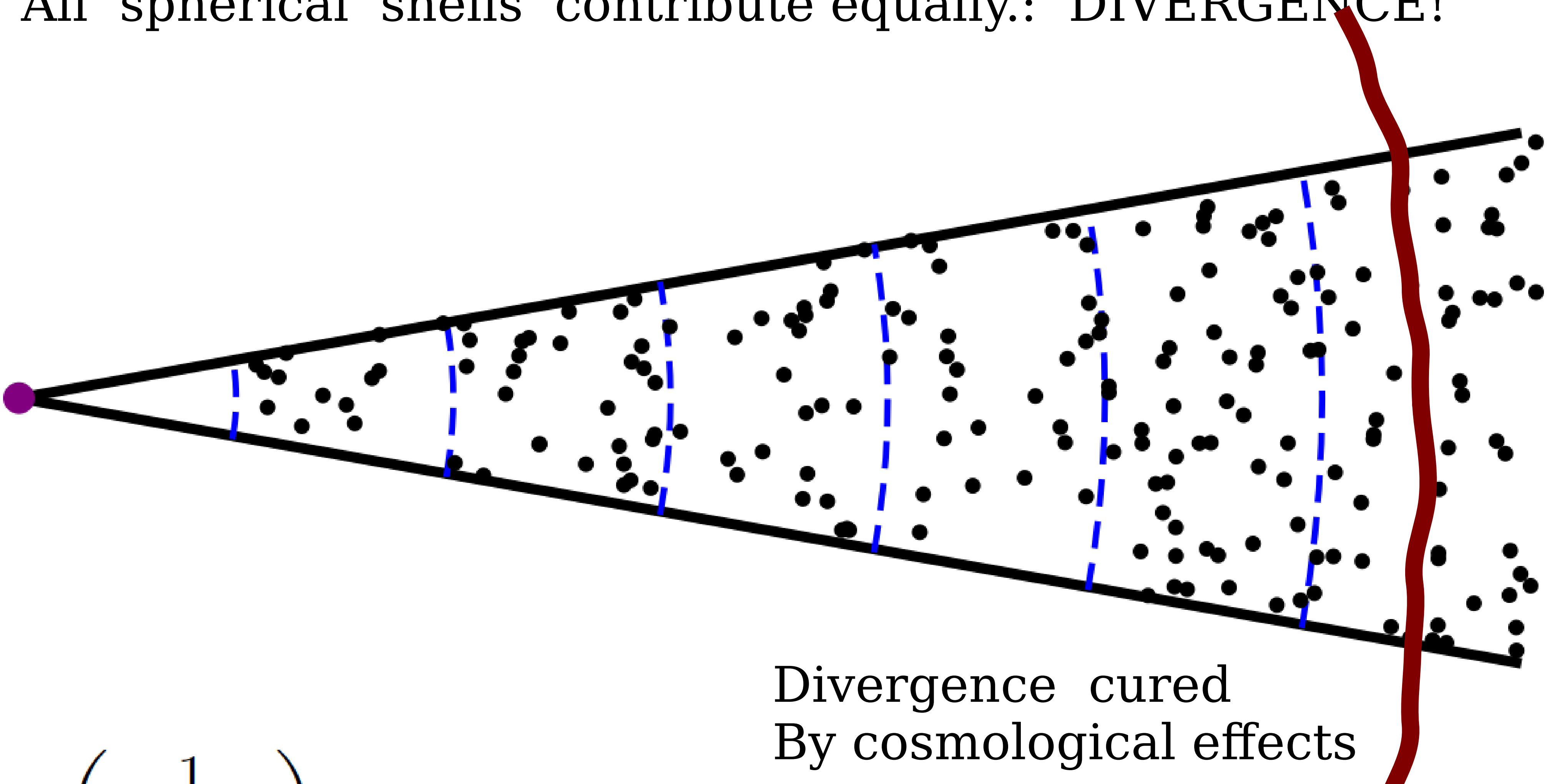
All spherical shells contribute equally.: DIVERGENCE!



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

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

All spherical shells contribute equally.: DIVERGENCE!

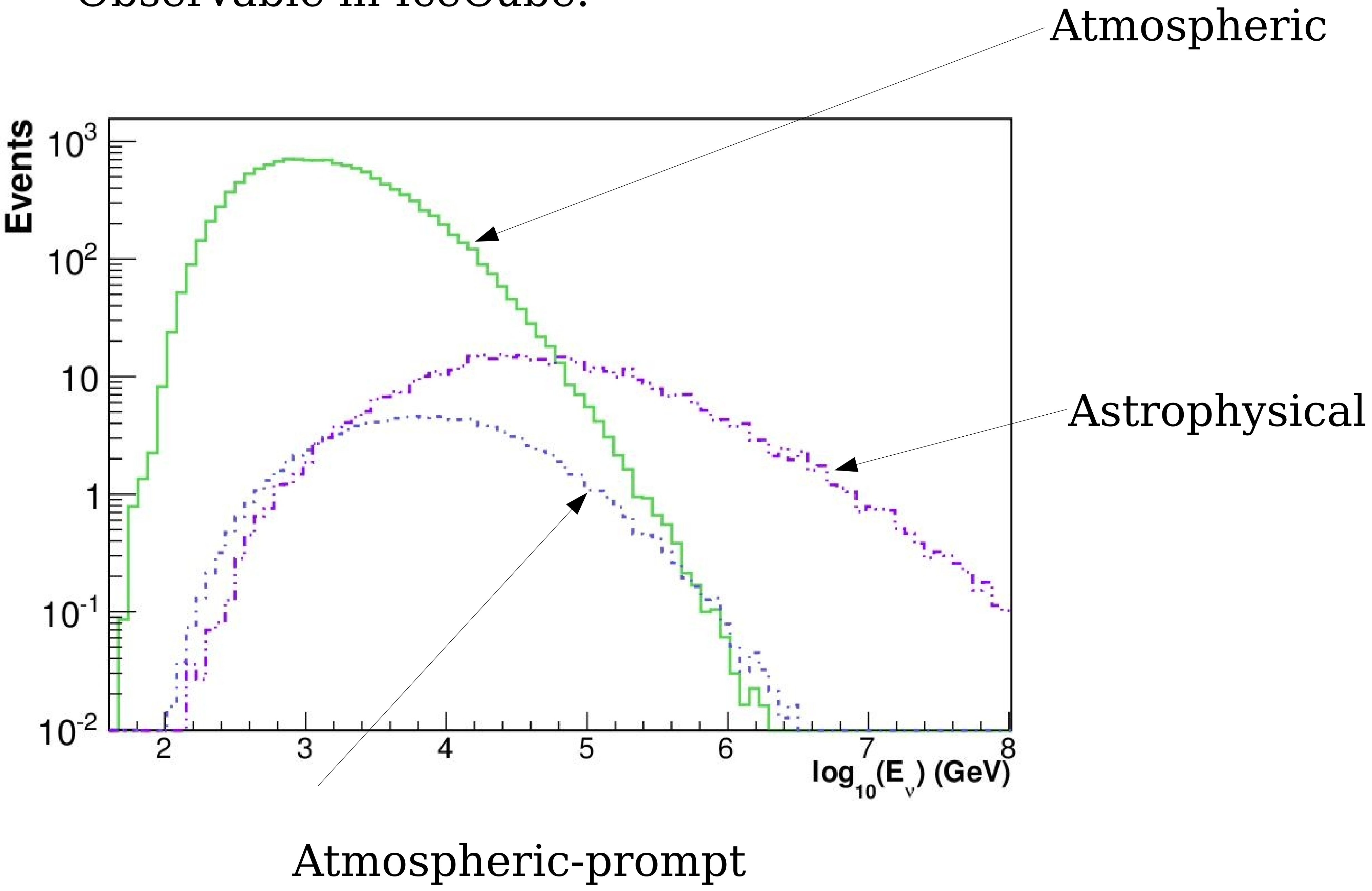


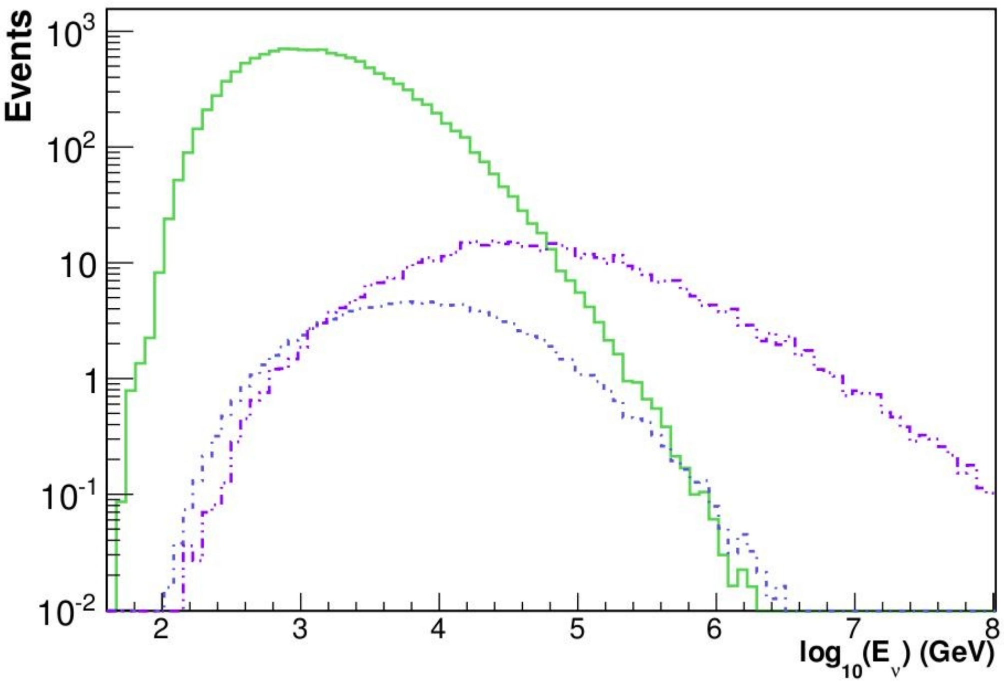
Divergence cured
By cosmological effects

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

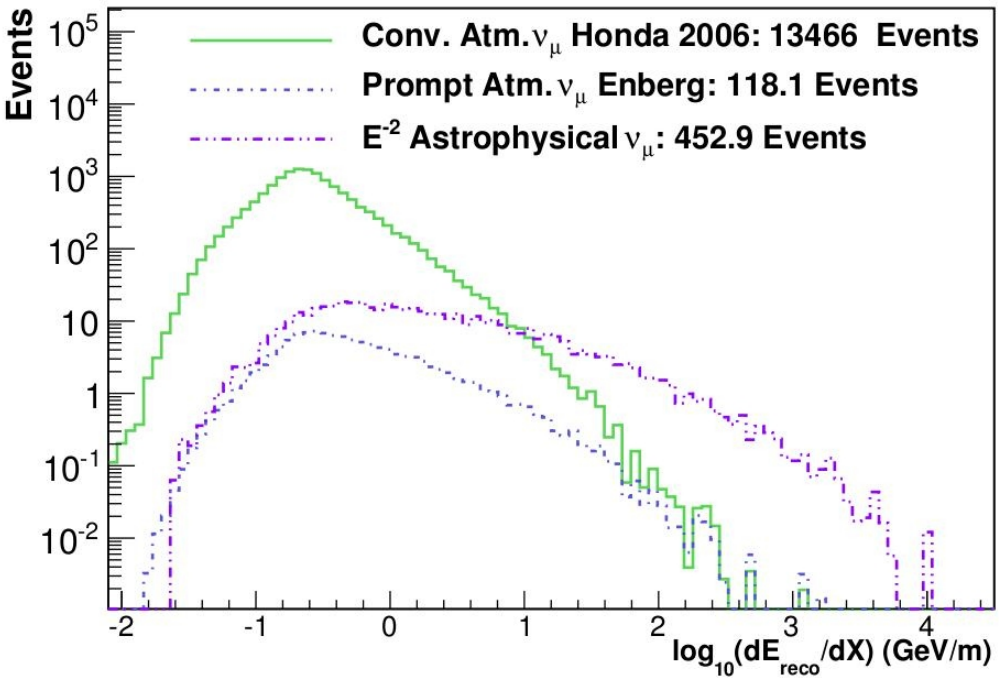
$$R_{\text{Hubble}} = \frac{c}{H_0} \simeq 3 \text{ Gpc}$$

[MonteCarlo] Energy Spectrum of Neutrinos Observable in IceCube.





Neutrino Energy

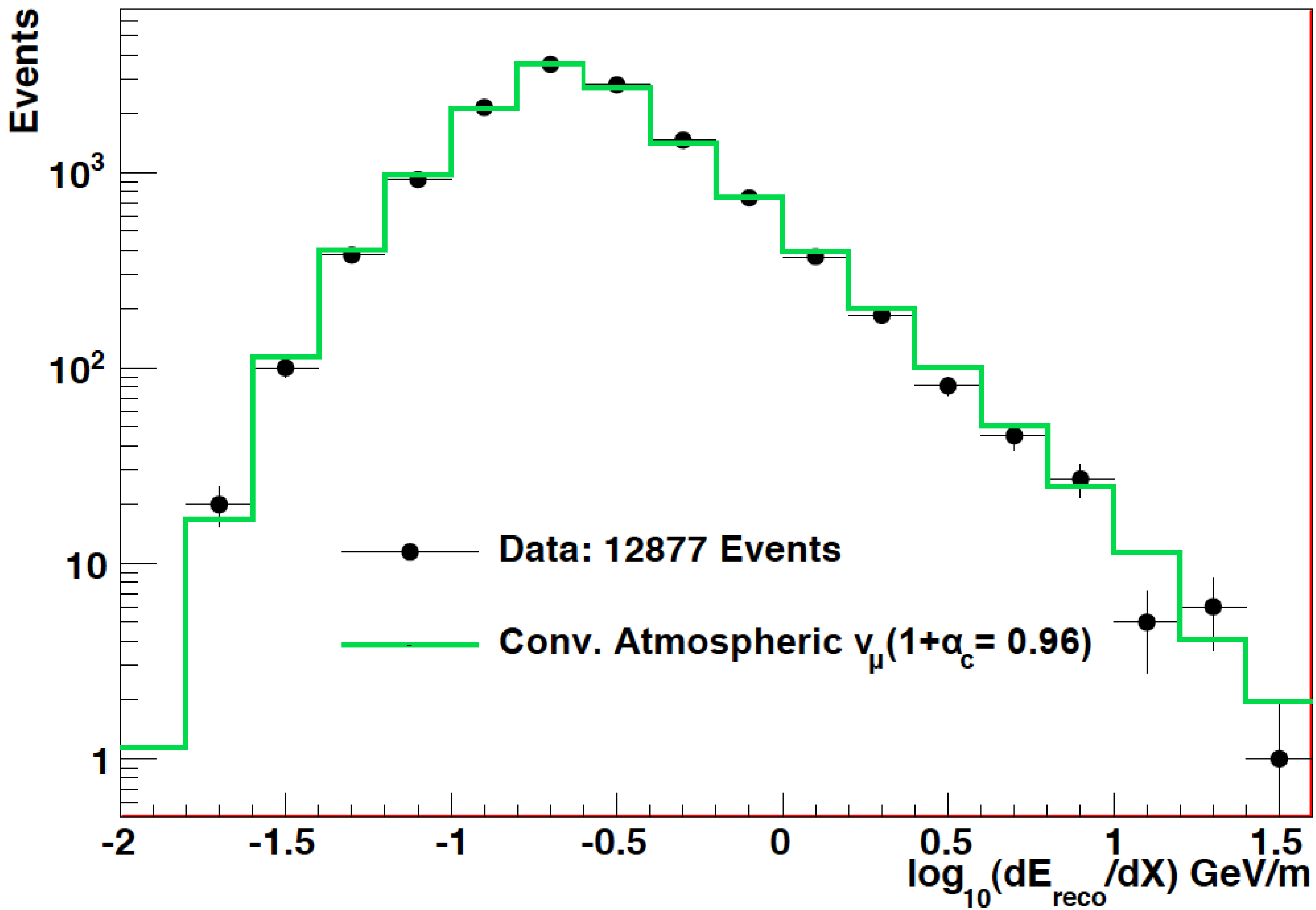


Reconstructed
Neutrino Energy

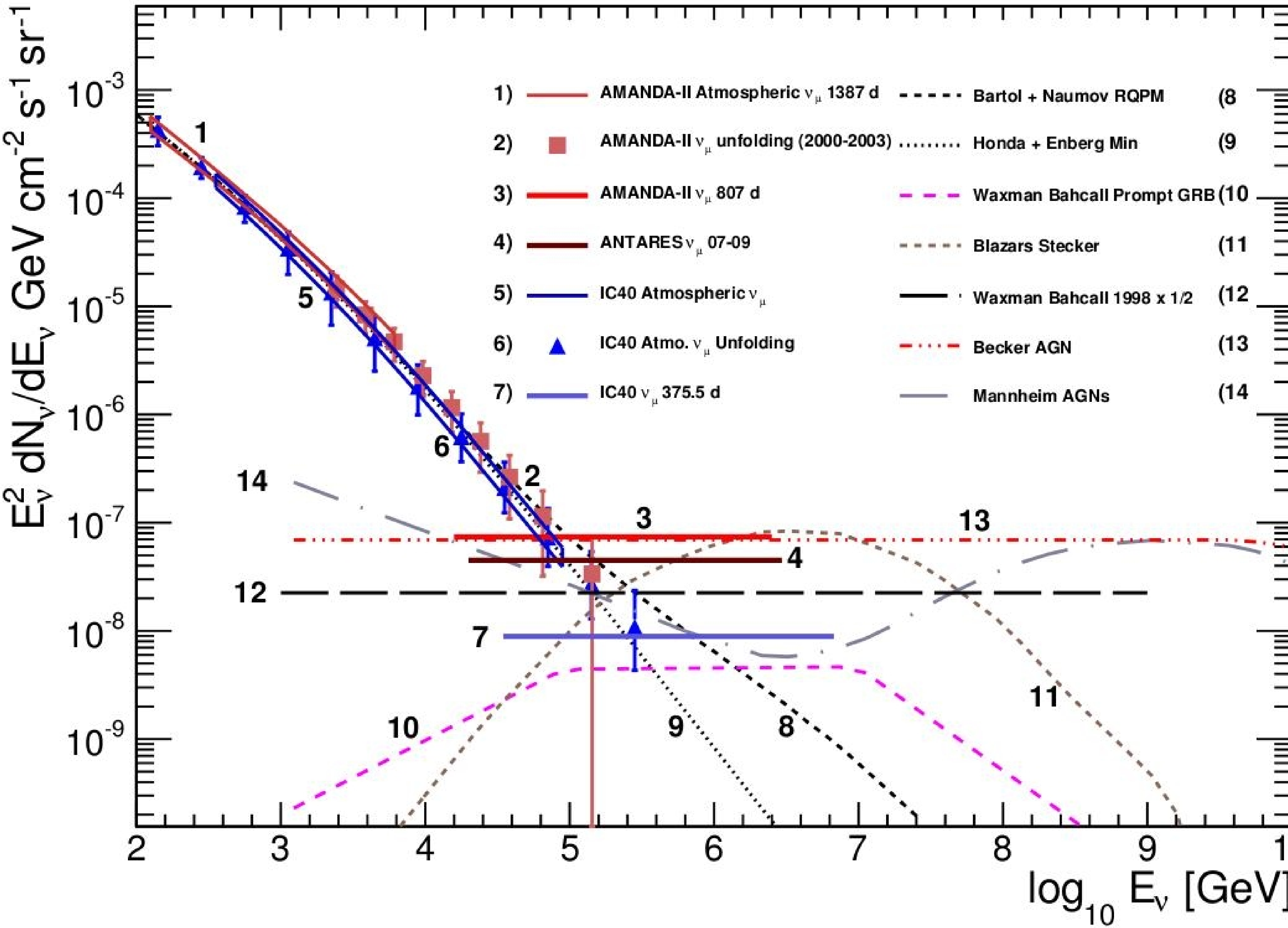
[From Muon Radiation]

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

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

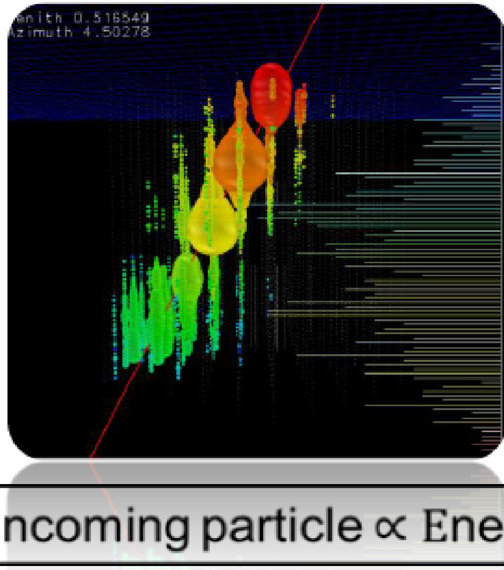


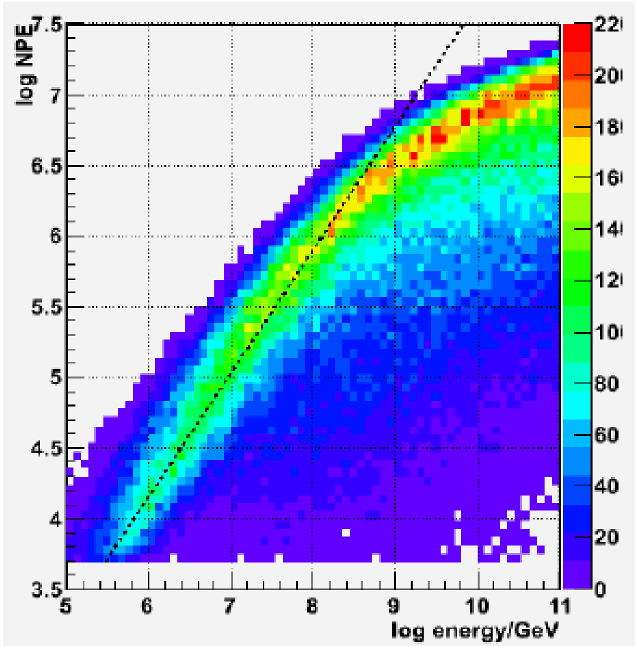
No excess over atmospheric neutrinos



$E_\nu^2\, dN_\nu/dE_\nu$ GeV cm^{-2} s^{-1} sr^{-1}
$\log_{10} E_\nu$ [GeV]
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

The Event Selection

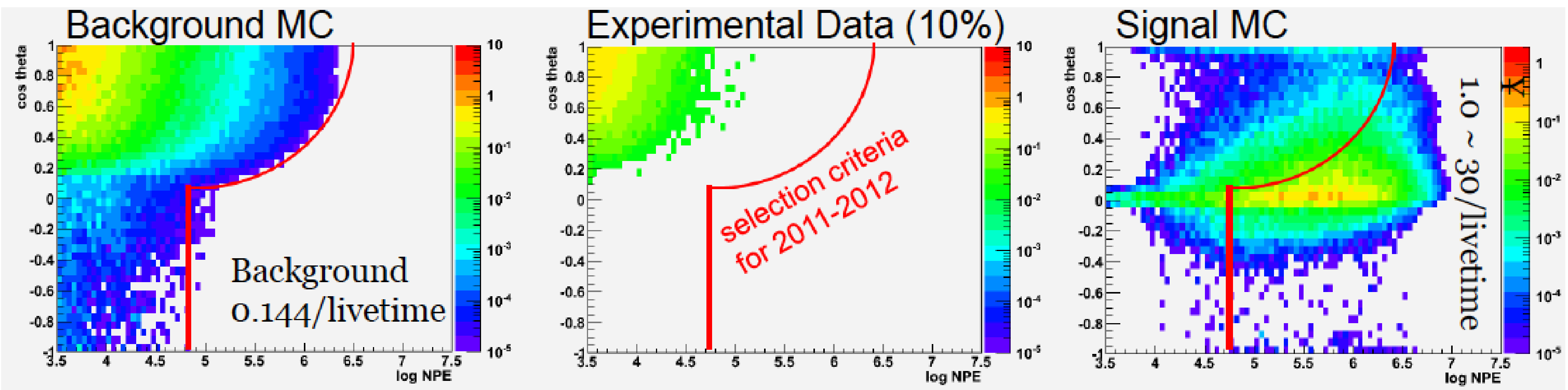




channel # > 300

Energy of incoming particle ∝ Energy-losses in detector ∝ number of photo electrons (NPE)

- Optimization based MC and MC verification based on 10% experimental ‘burn’ sample

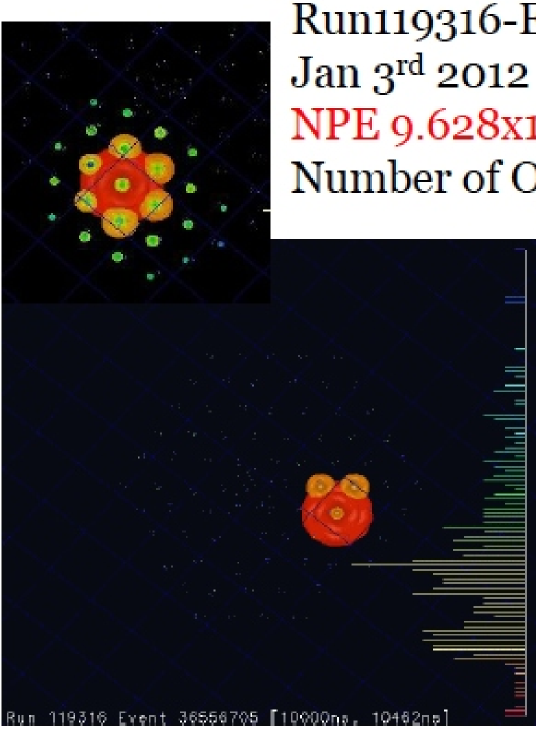


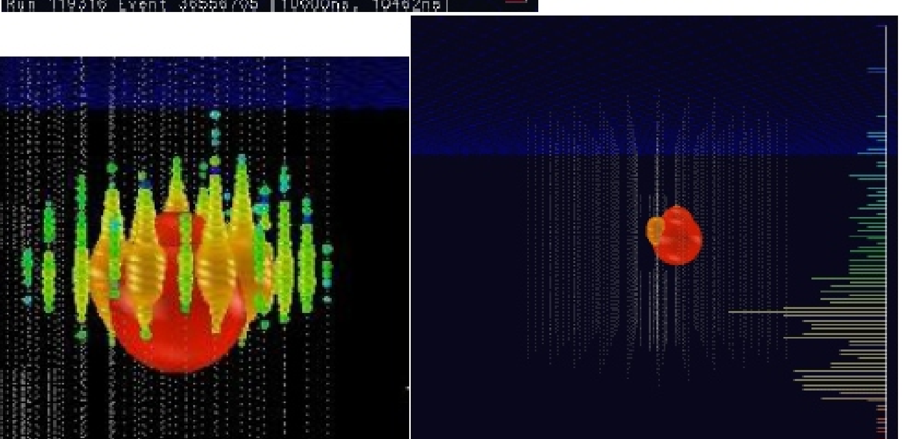
Two events passed the selection criteria

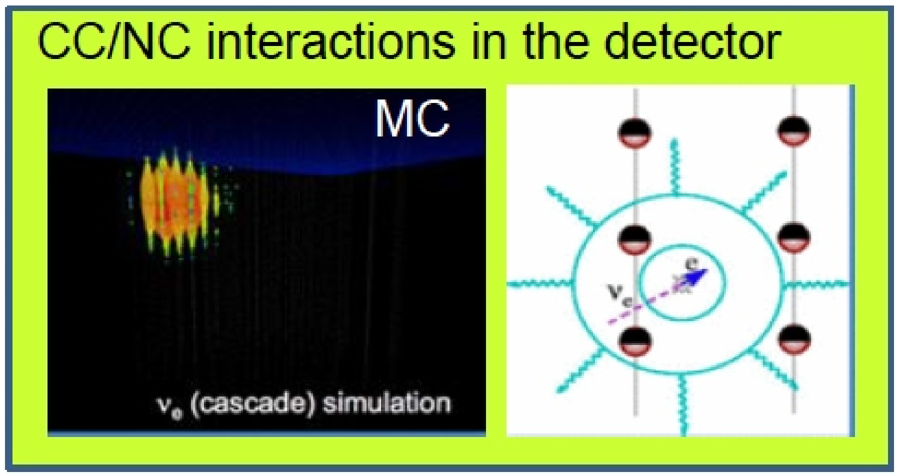
2 events / 672.7 days - background (atm. μ + conventional atm. ν) expectation 0.14 events

preliminary p-value: 0.0094 (2.36σ)

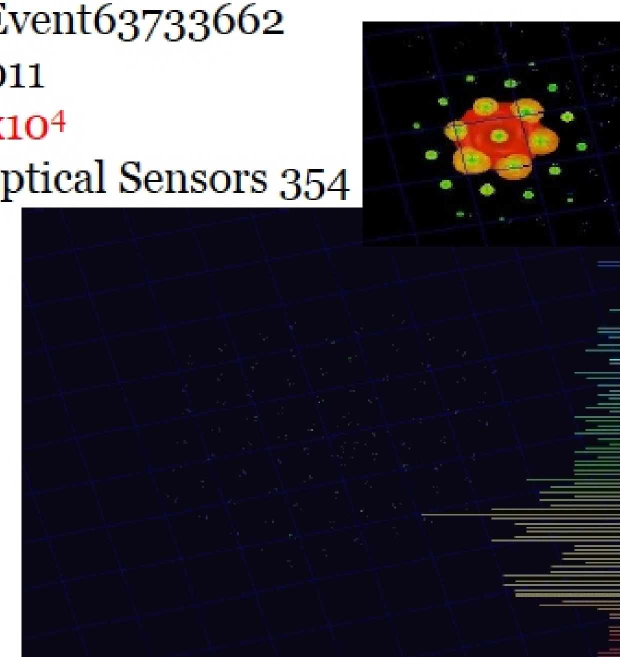
Run119316-Event36556705
Jan 3rd 2012
NPE $9.628\text{x}10^4$
Number of Optical Sensors 312

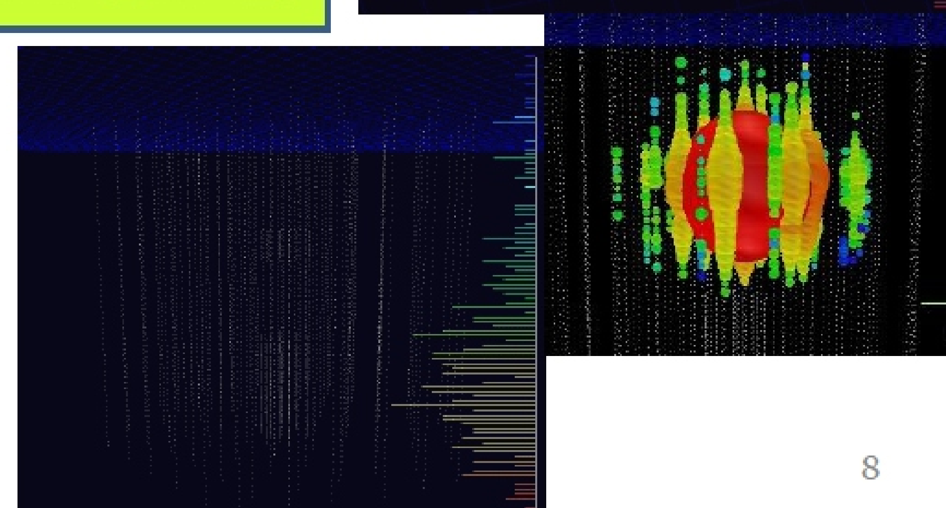






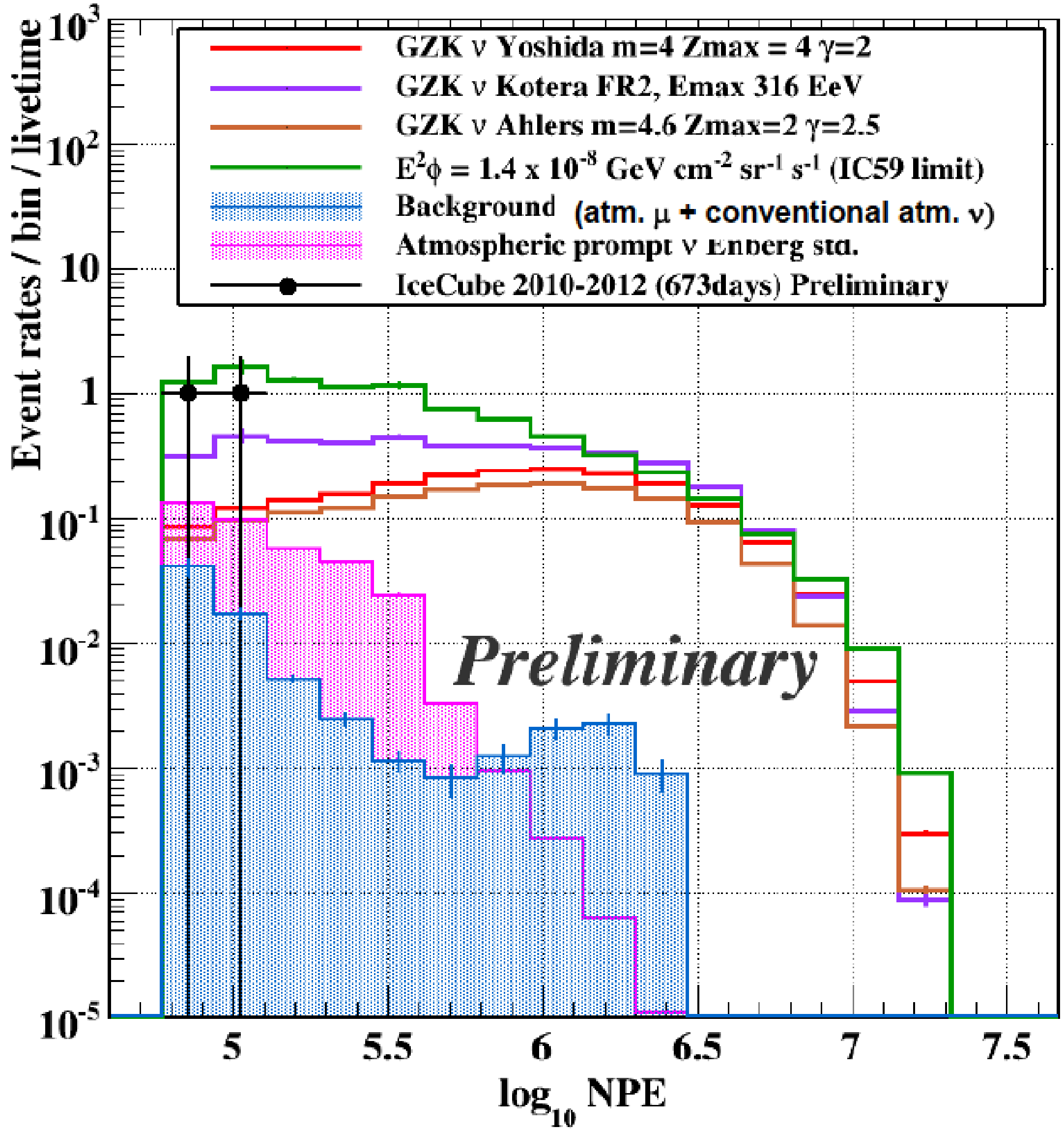
Run118545-Event63733662
August 9th 2011
NPE $6.9928\text{x}10^4$
Number of Optical Sensors 354





2 events with Large energy depositions in IceCube (Neutrino 2012)

Event Brightness (NPE) Distributions 2010-2012



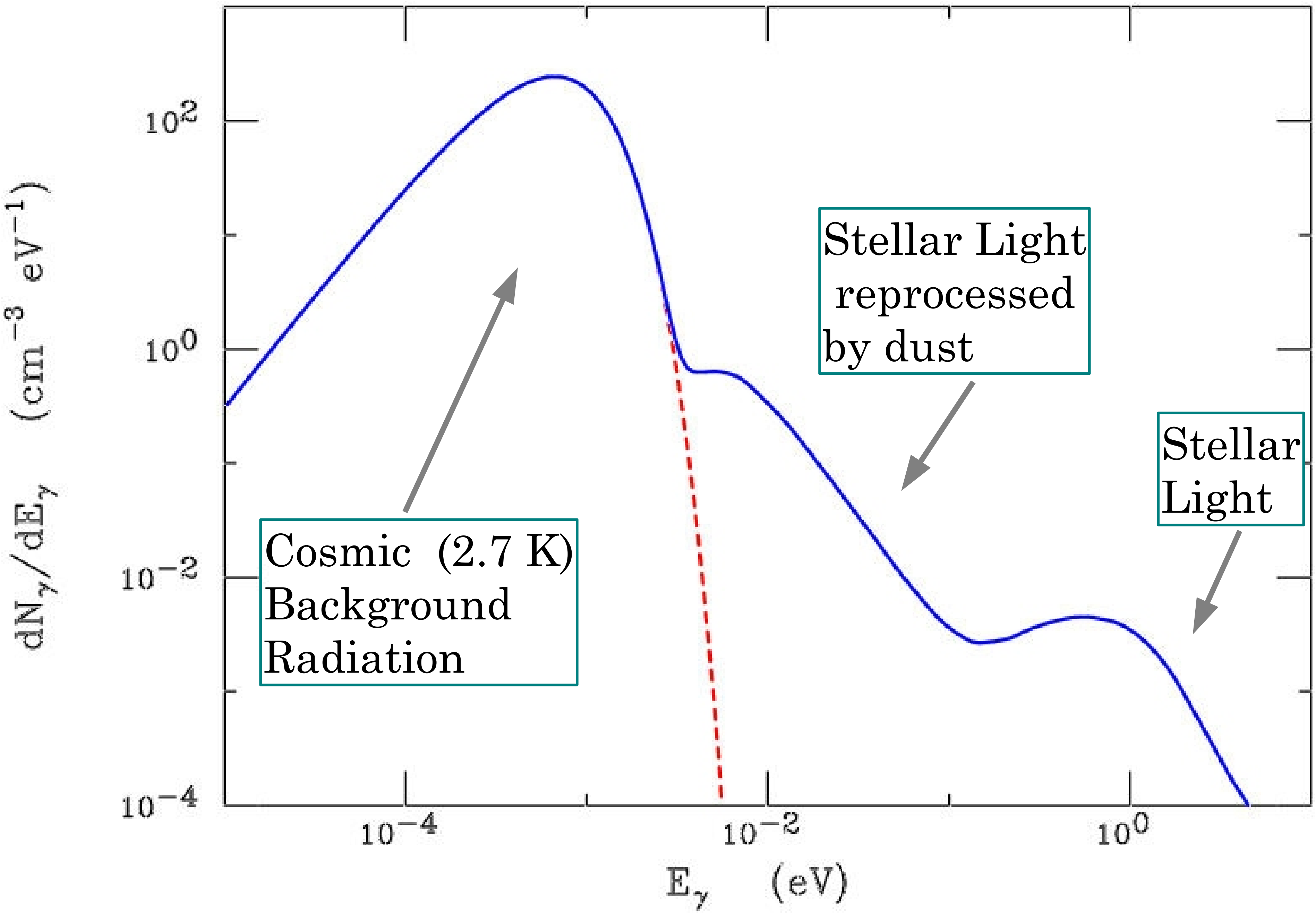
- Observed 2 high NPE events near the NPE threshold
- **No** indication
  - that they are instrumental artifacts
  - that they are cosmic-ray muon induced
- Possibility of the origin includes
  - cosmogenic ν
  - on-site ν production from the cosmic-ray accelerators
  - atmospheric prompt ν
  - atmospheric conventional ν

“Cosmogenic Neutrinos”

“GZK (Greisen-Zatspin-Kuzmin) neutrinos”

Neutrinos generated by the interaction
of Ultra High Energy Cosmic Rays (E > 10^{19} eV)
with the (2.7°) Cosmic Microwave Background Radiation

Average Photon Density in the Universe



Threshold for photon-hadronic interactions:

$$p + \gamma \rightarrow p + \mathrm{hadrons}$$

Threshold for pion production

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

$$p + \gamma \rightarrow n + \pi^{+}$$

$$E_p \, \varepsilon_\gamma \gtrsim m_p \, m_\pi$$

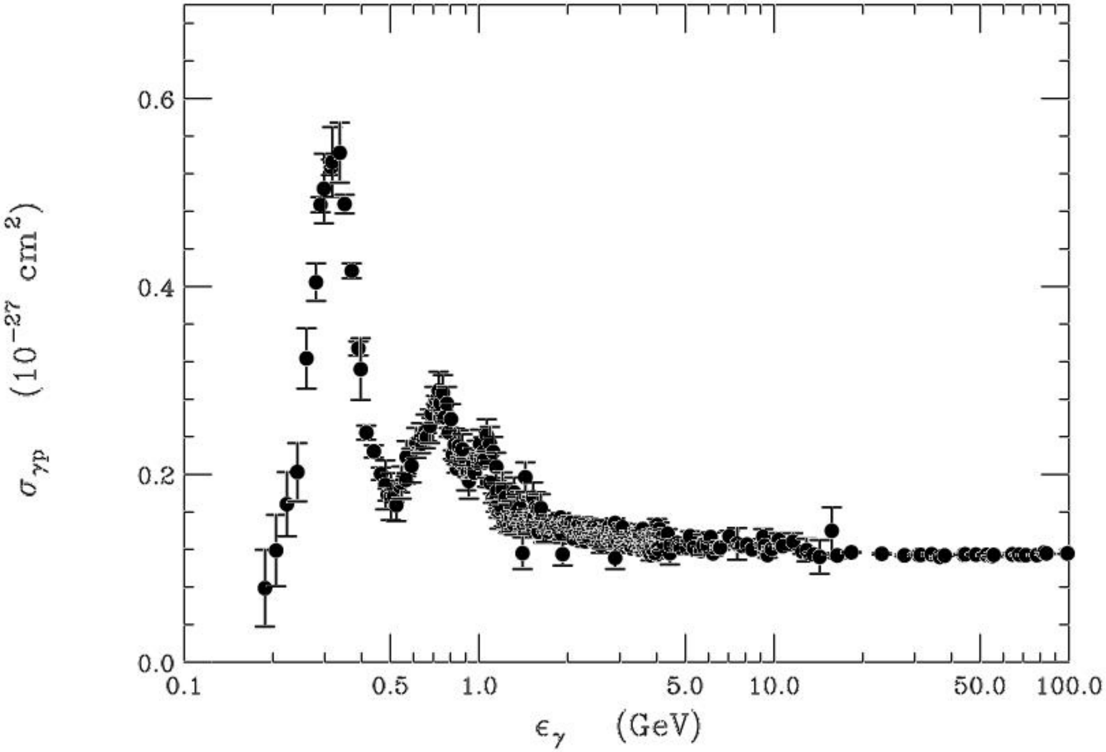
$$E \geq \frac{(m_p + m_\pi)^2 - m_p^2}{2\,\varepsilon\,(1 - \cos\theta_{\gamma e})} \geq \frac{(m_p + m_\pi)^2 - m_p^2}{4\,\varepsilon}$$

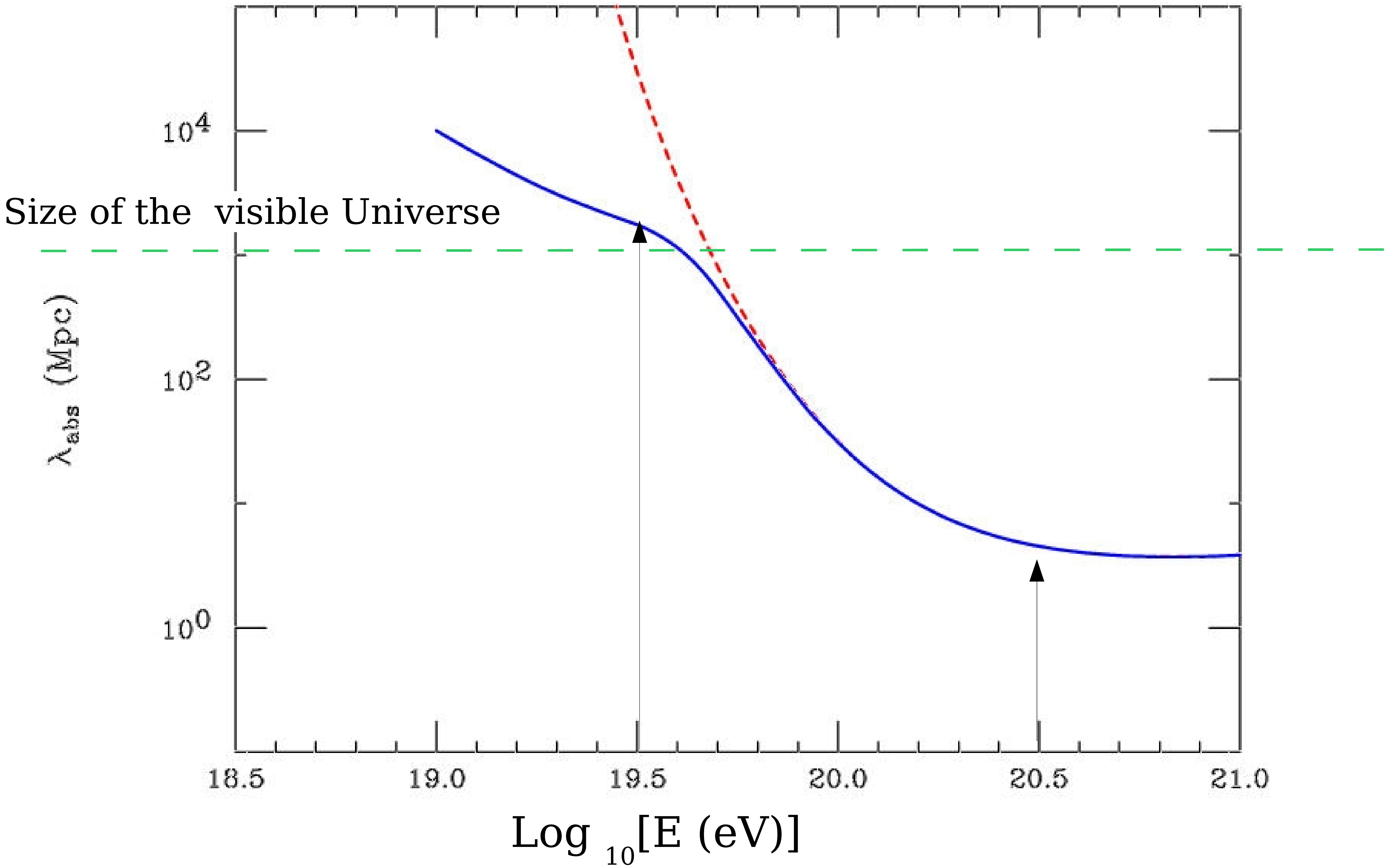
Interaction Length

$$\frac{1}{\lambda_{\text{int}}} = \int d^3 p_\gamma \; n_\gamma(p) \quad (1 - \cos\theta_{p\gamma}) \; \sigma_{\gamma p}(s)$$

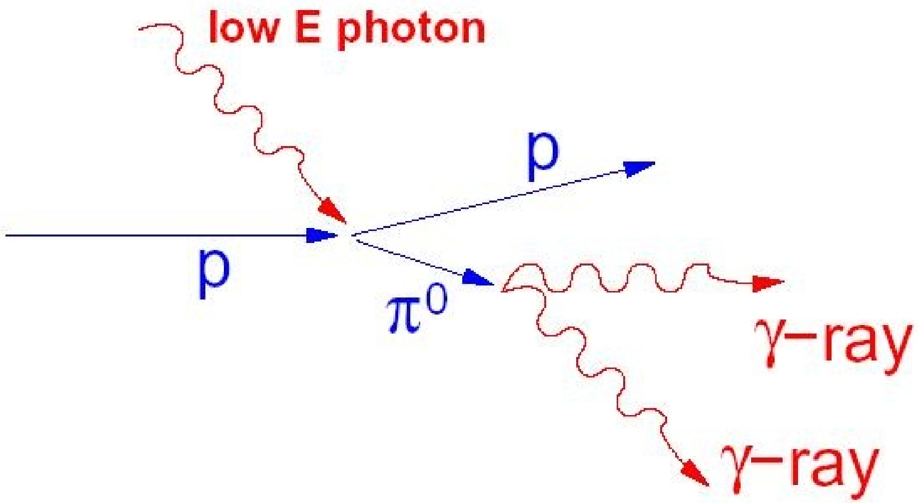
Qualitative analyisis

$$\begin{aligned} \lambda &\simeq (n_\gamma \, \sigma)^{-1} \\ &\simeq [(400 \text{ cm}^{-3} \; (0.5 \times 10^{-27} \text{ cm}^2]^{-} \\ &\simeq [2 \times 10^{-25} \text{ cm}^{-1}]^{-1} \\ &\simeq 5 \times 10^{24} \text{ cm} \\ &\simeq 2 \text{ Mpc} \end{aligned}$$

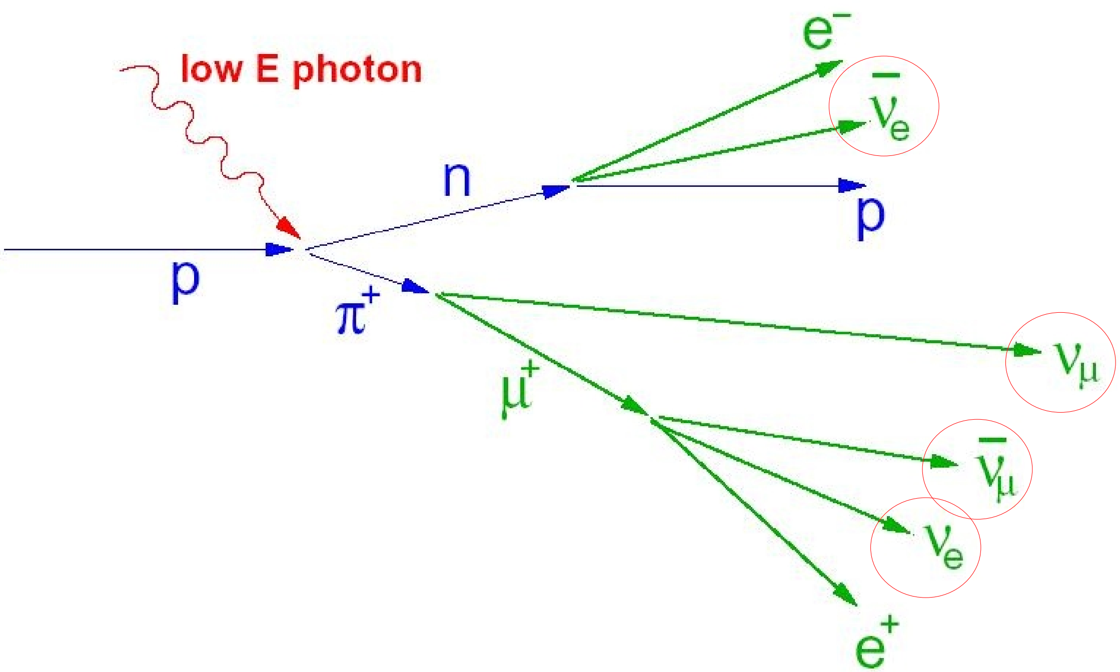



Size of the visible Universe
λ_{abs} (Mpc)
10^4
10^2
10^0
18.5
19.0
19.5
20.0
20.5
21.0
$Log_{10}[E (eV)]$

Energy Loss Mechanisms for Protons:

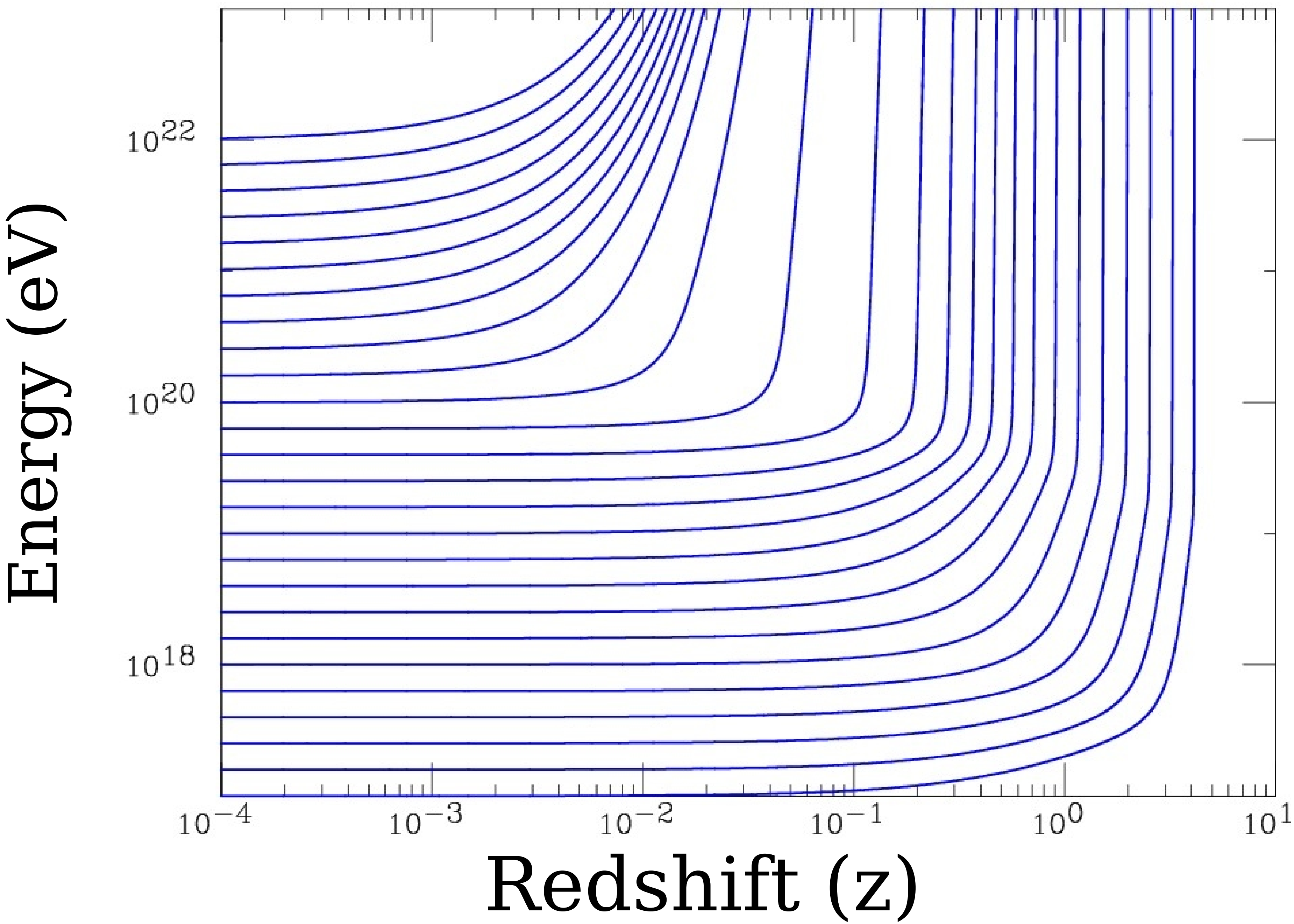


Greisen-Zatsepin- Kuzmin (GZK) suppression

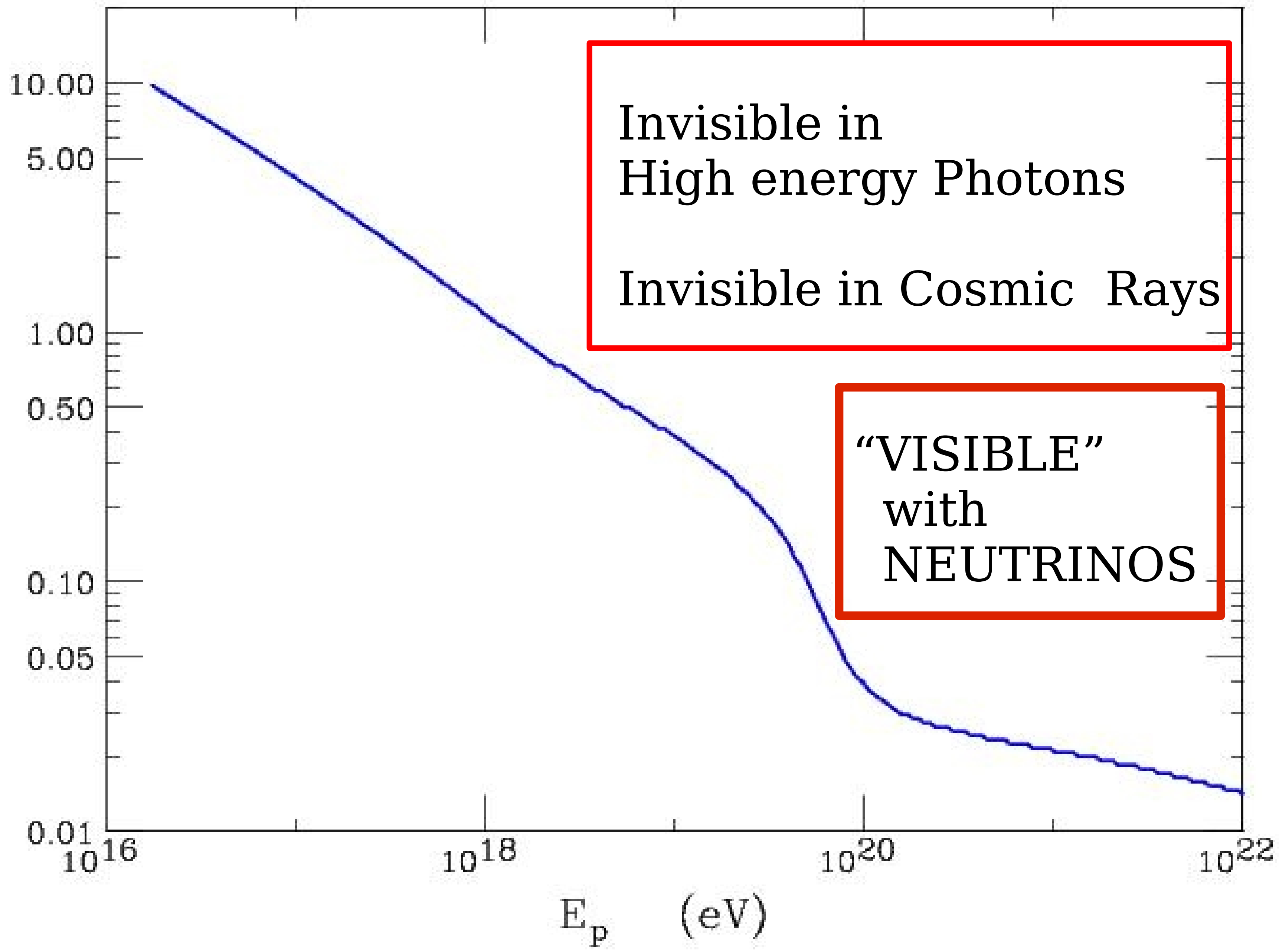


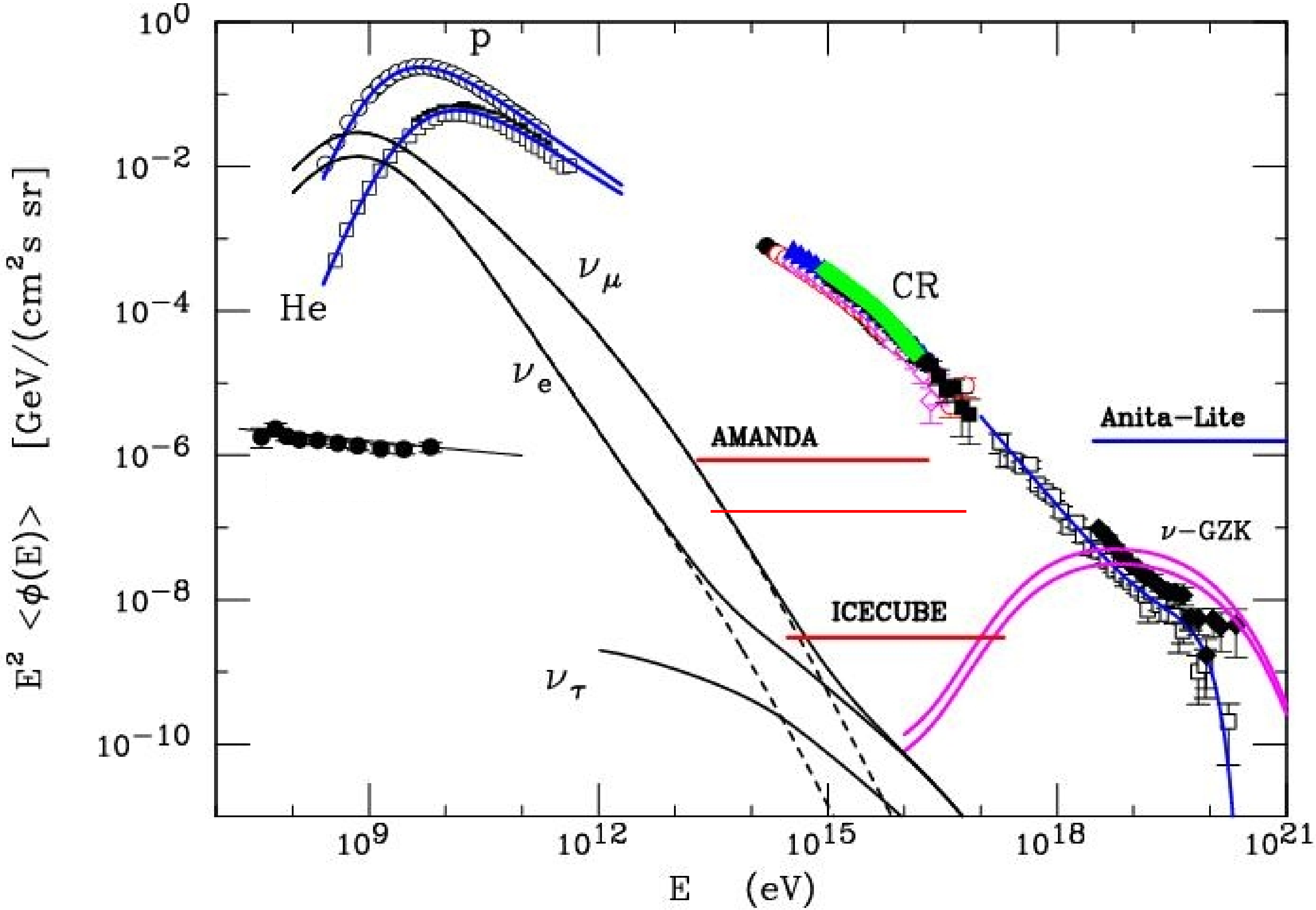
NEUTRINO PRODUCTION

Proton Energy Evolution with Redshift



High Energy Proton Horizon





p
He
CR
ν_μ
ν_e
ν_τ
AMANDA
ICECUBE
Anita−Lite
ν−GZK
$E^2 \langle\phi(E)\rangle$ [GeV/(cm^{2}s sr)]
E (eV)
10^0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
10^9
10^{12}
10^{15}
10^{18}
10^{21}

Neutrino Astronomy: beyond the “Km3 concept”

Radio, Acoustic,.....

Radio Detection of neutrinos

ANITA-II over Antarctica

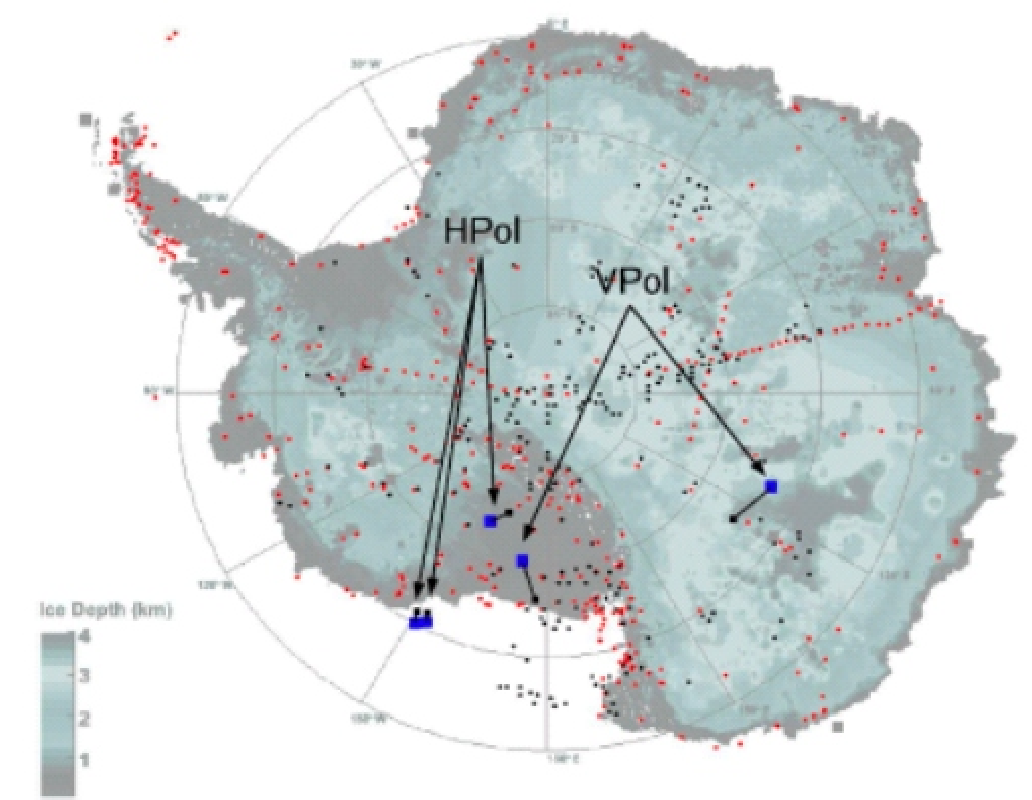


FIG. 3: Events remaining after unblinding. The Vpol neutrino channel contains two surviving events. Three candidate UHECR events remain in the Hpol channel. Ice depths are from BEDMAP [12].

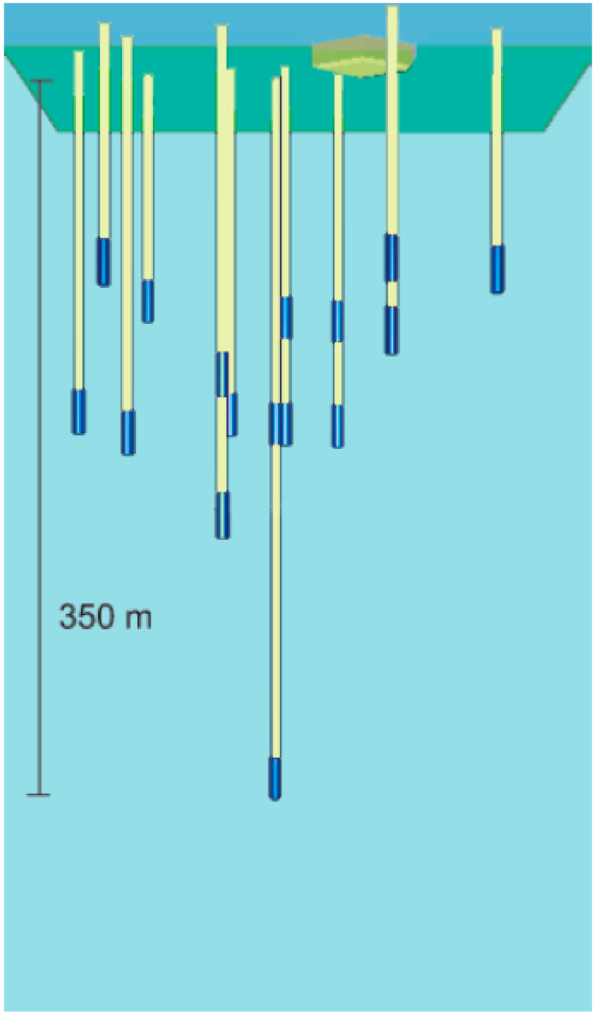
http://arxiv.org/abs/1003.2961

Vpol:1 neutrino candidate;

HPol:3 >25 1019 eV

RICE experiment architecture

- Antarctic ice is neutrino target
- In-ice array of radio antennas
- 20 channels, 200-500 MHz
- Depths 100-300 meters
- Signal digitized at the surface
- Deployed near South Pole Station



10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA)

- a very large radio neutrino detector at the South Pole

Ref: Allison et al., Astropart.Phys. 35 (2012) 457-477, arXiv:1105.2854 (Design and performance paper)

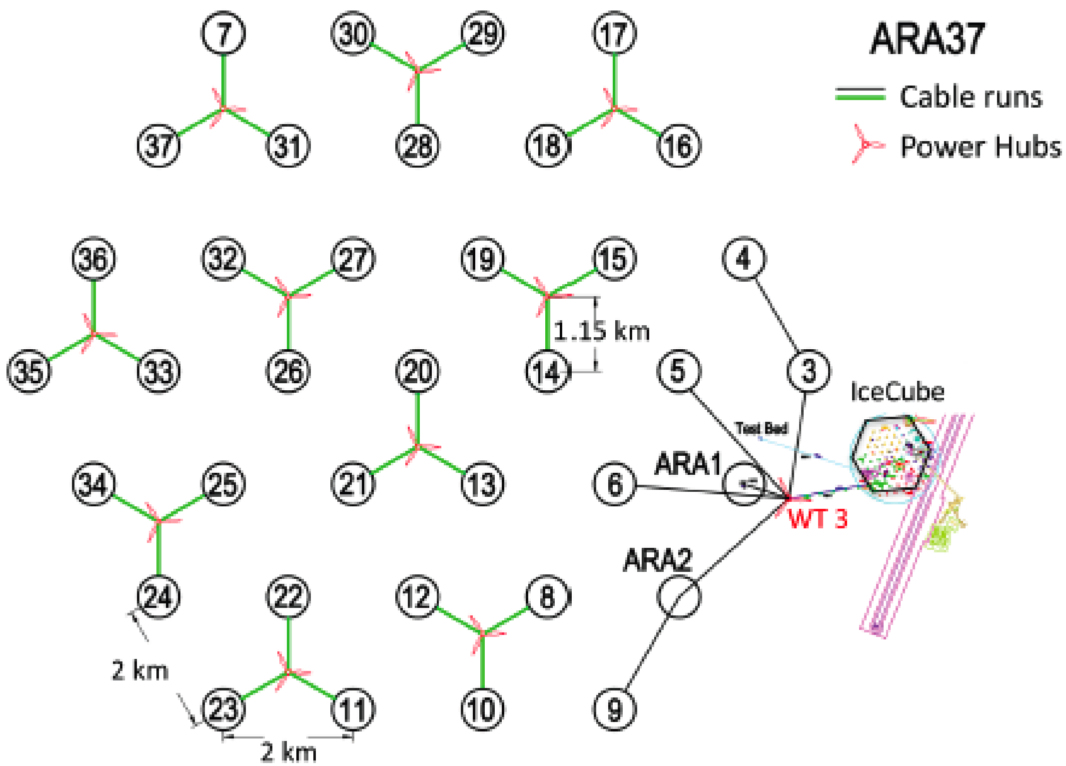
Poster session at this conference:
→ H. Landsman, ARA Design and Status
→ J. Davies, ARA prototype and first station

Scientific Goal:

- Discover and determine the flux of highest energy cosmic neutrinos.
- Understanding of highest energy cosmic rays, other phenomena at highest energies.

Method:

Monitor the ice for radio pulses generated by interactions of cosmic neutrinos with nuclei of the 2.8km thick ice sheet at the South Pole



Areal coverage: ~150km^2

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

ARA field activities on the ice

Status:

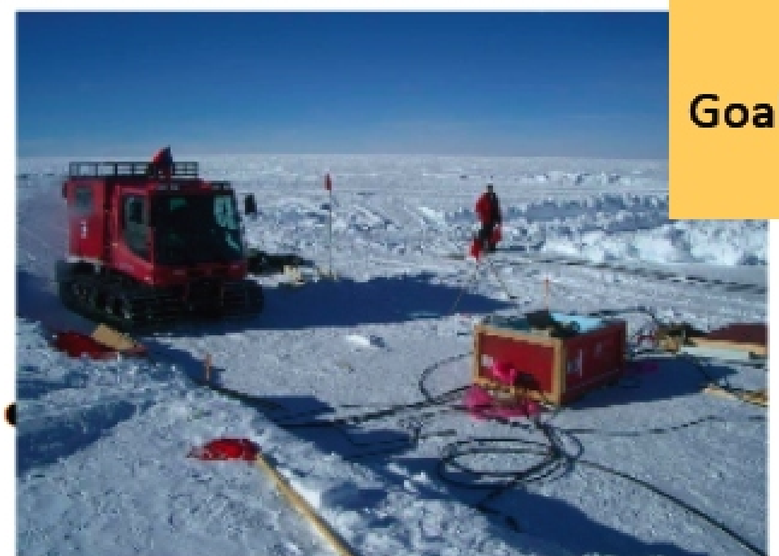
2010/11: Test detector deployed

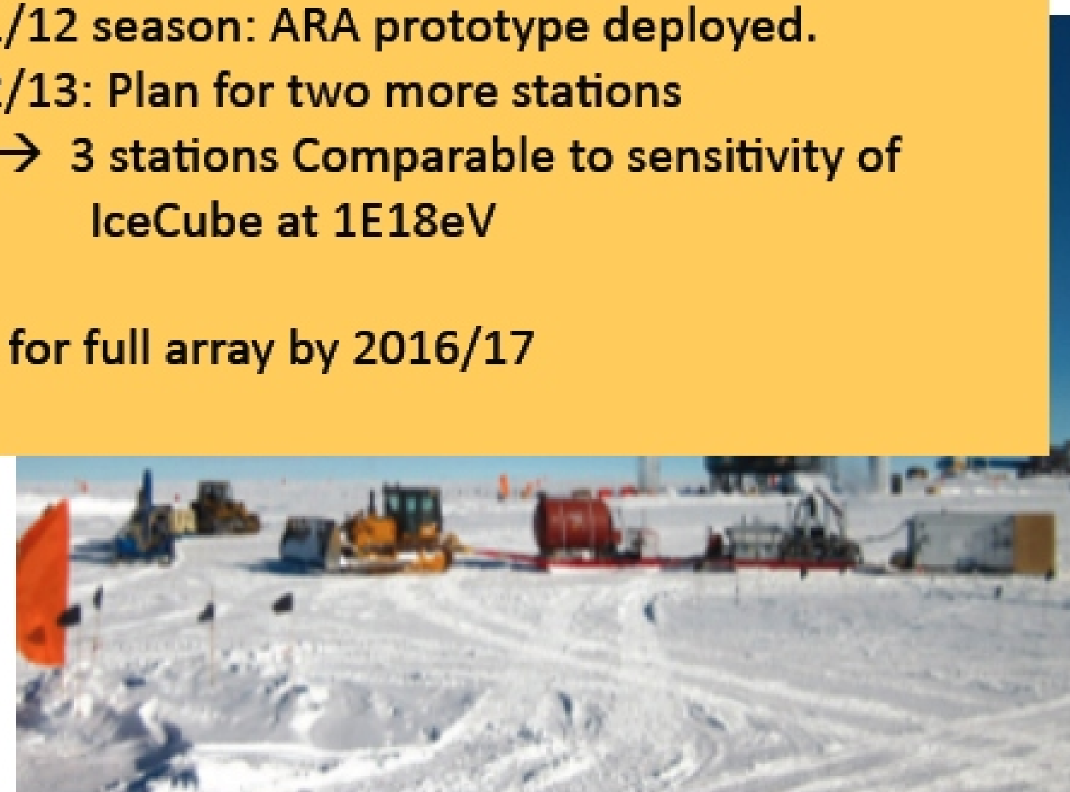
2011/12 season: ARA prototype deployed.

2012/13: Plan for two more stations

→ 3 stations Comparable to sensitivity of IceCube at 1E18eV

Goal for full array by 2016/17



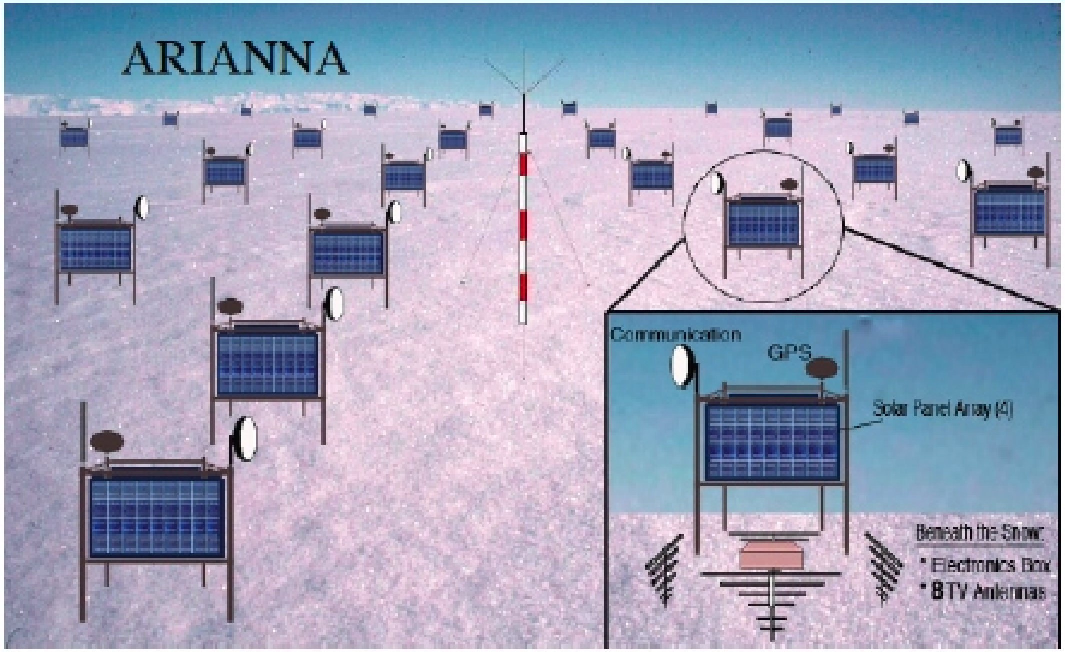


10^7 to 10^{11} GeV: Radio ice Cherenkov detection

ARIANNA

- L. Gerhardt et al., Nucl.Instrum.Meth. A624 (2010) 85-91
- Poster 18-3: J. Tatar. S. Barwick

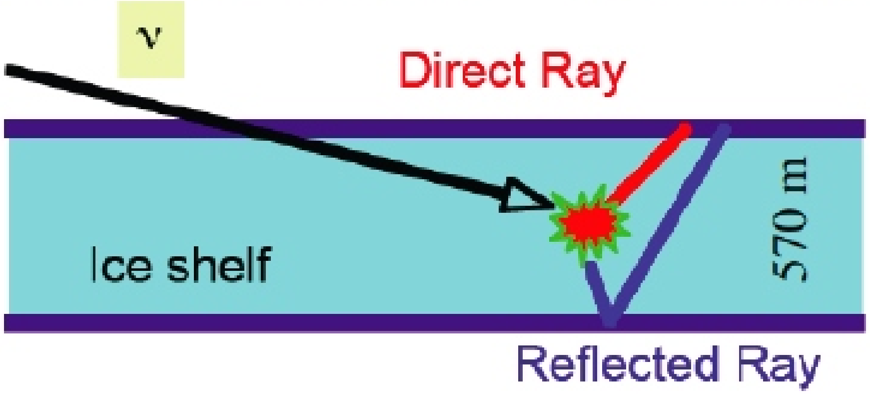
31 x 31 array
[30 km x 30 km]

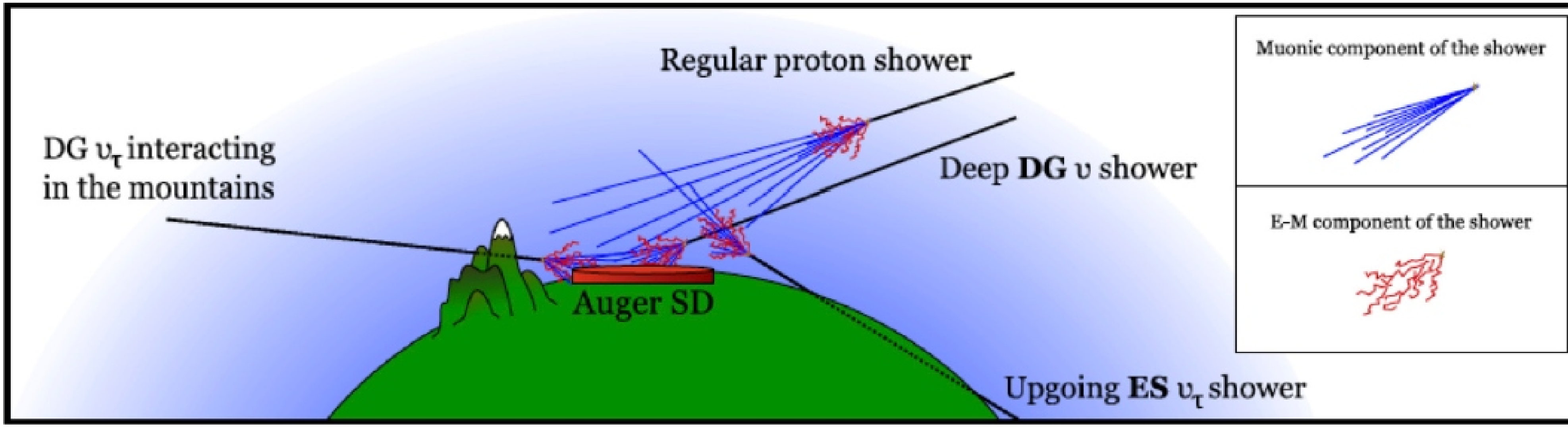


ARIANNA

US, S. Korea, England, New Zealand

Barwick, astro-ph/0610631





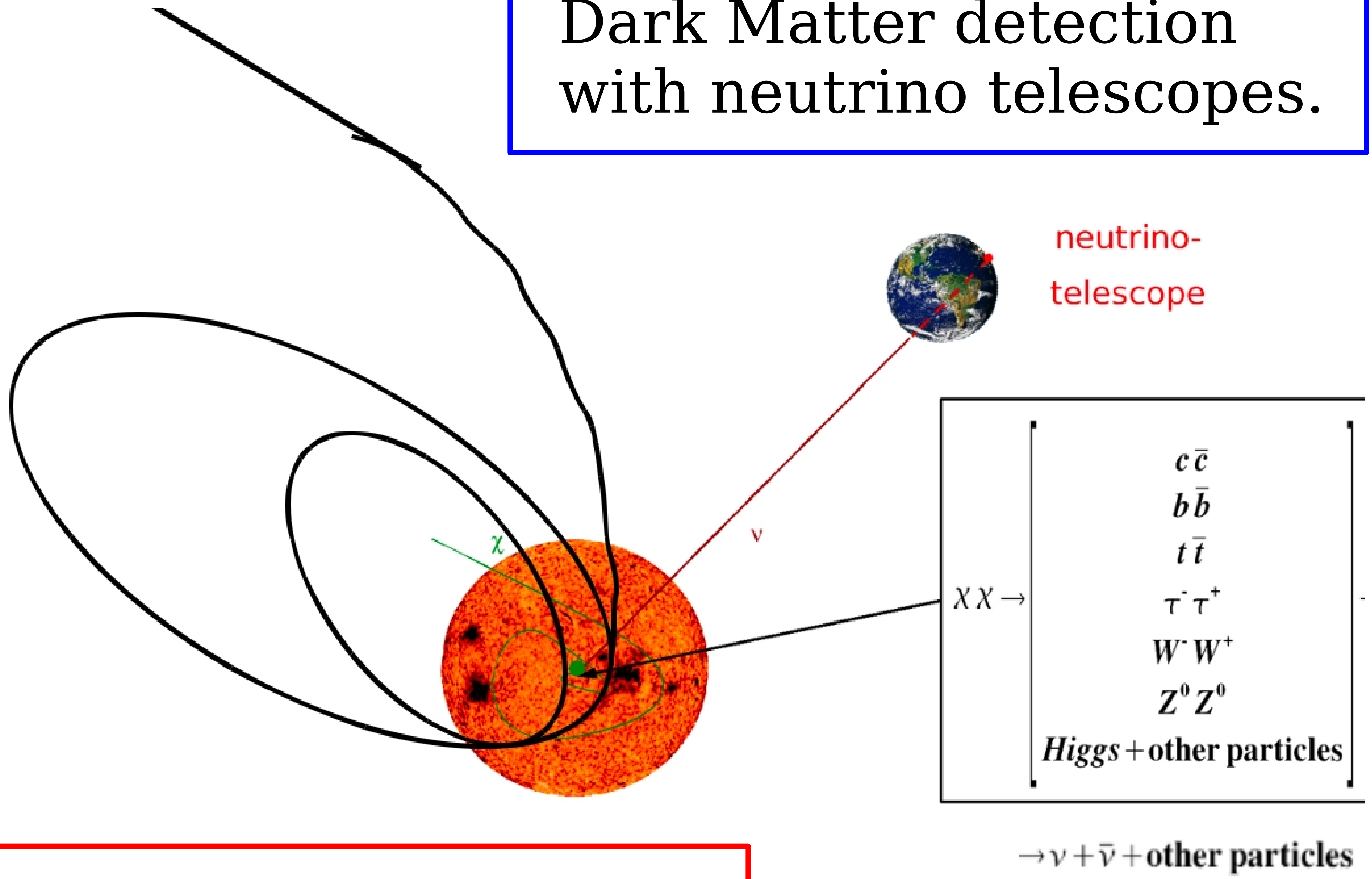
Regular proton shower
DG υτ interacting
in the mountains
Deep DG υ shower
Auger SD
Upgoing ES υτ shower
Muonic component of the shower
E-M component of the shower

Dark Matter

(in the form of WIMPs)

Detection with Neutrino Telescopes

Dark Matter detection with neutrino telescopes.



Accretion of DM Particles in the Sun (and Earth)

Number of neutrinos in the sun

$$\frac{dN}{dt} = C_c - C_a N^2 - C_e N$$

Capture Rate

Annihilation Rate

Evaporation Rate

$$\Gamma_a(t) = \eta \int_{\text{Sun}} d^3\mathbf{x} \, \langle \sigma_{\text{ann}} v \rangle \, n^2(t, \mathbf{x}) = \frac{C_a}{2} N^2$$

$$\frac{dN}{dt} = C_c - C_a N^2$$

$$N(t) = \sqrt{\frac{C_c}{C_a}} \tanh\left\{\frac{t}{\tau_c}\right\}$$

$$\tau_c \equiv (C_c C_a)^{-1/2}$$

$$\xrightarrow{t \gg \tau_c} \sqrt{\frac{C_c}{C_a}}$$

$$t = t_\odot = 4.6 \text{ Gyr}$$

$$\tau_{c,\odot} \approx 10^8 \text{ yr}$$

$$\Gamma_a(t) = \frac{C_c}{2} \tanh^2\left\{\frac{t}{\tau_c}\right\} \xrightarrow{t \gg \tau_c} \frac{C_c}{2}$$

Annihilation Rate

SuperKamiokande detector

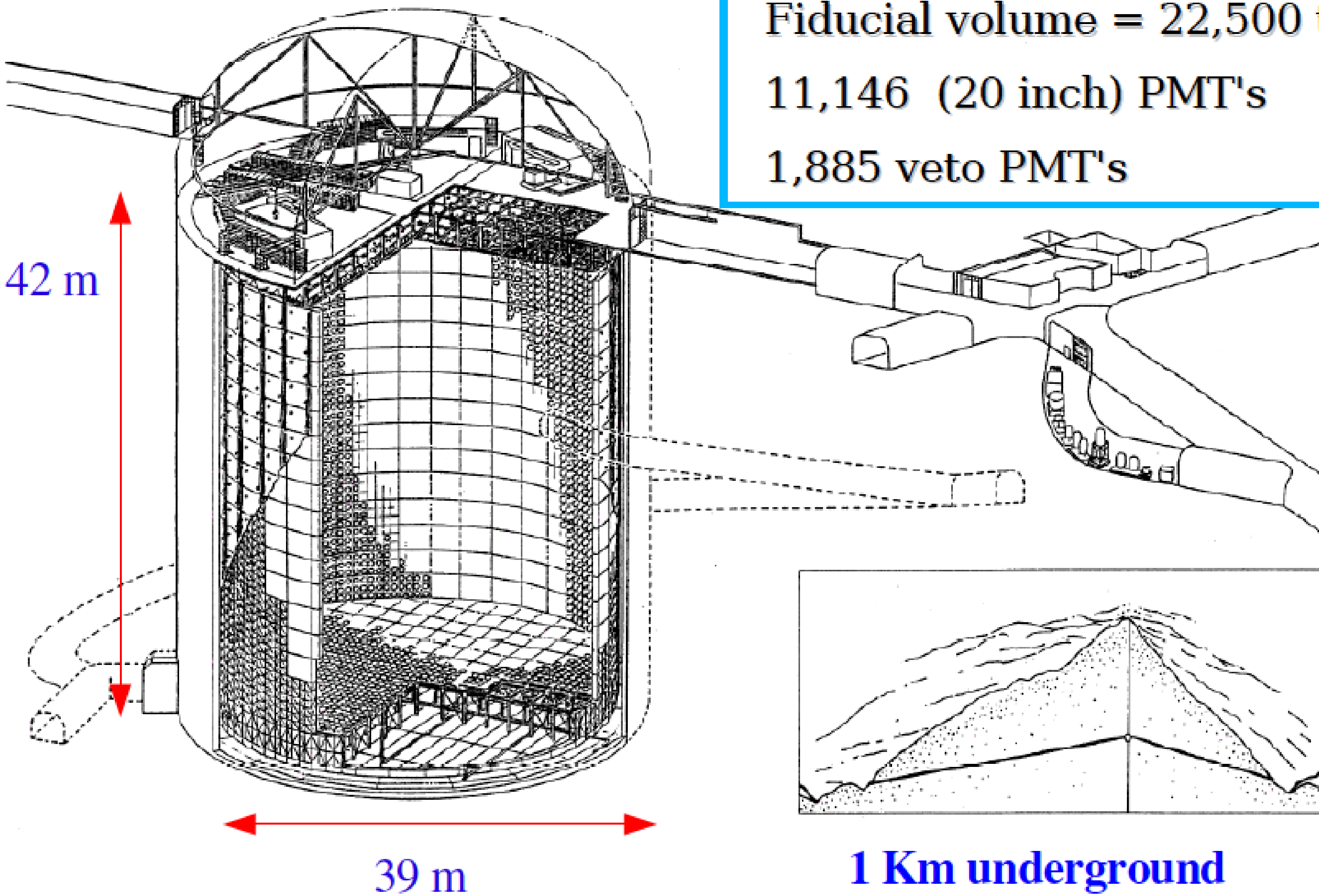
50,000 tons of ultrapure water

2 m of water = veto counter

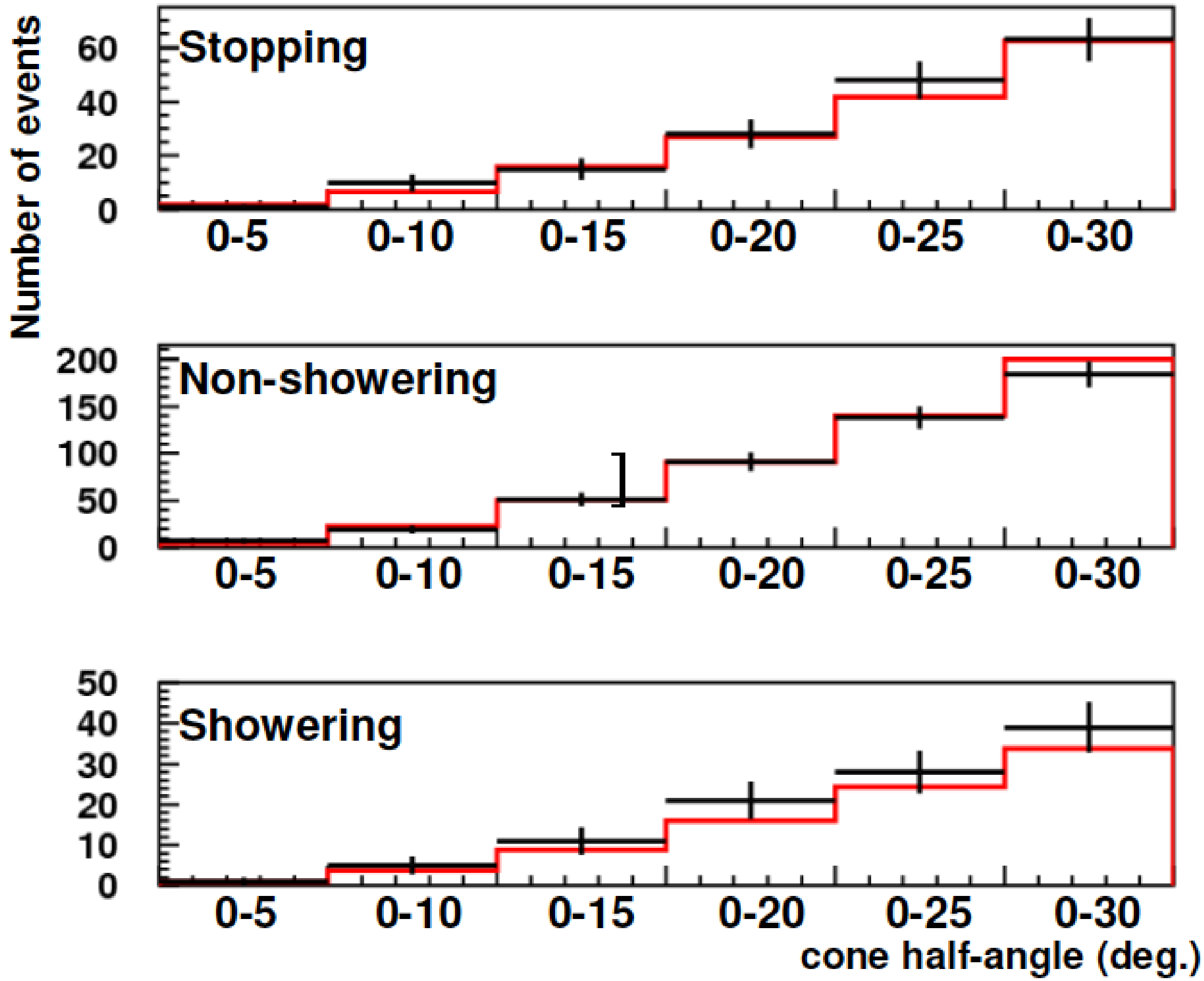
Fiducial volume = 22,500 tons

11,146 (20 inch) PMT's

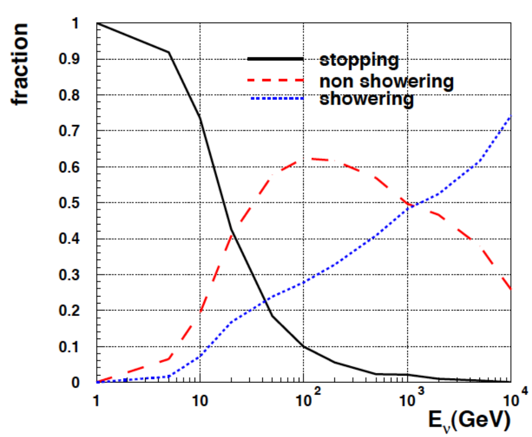
1,885 veto PMT's

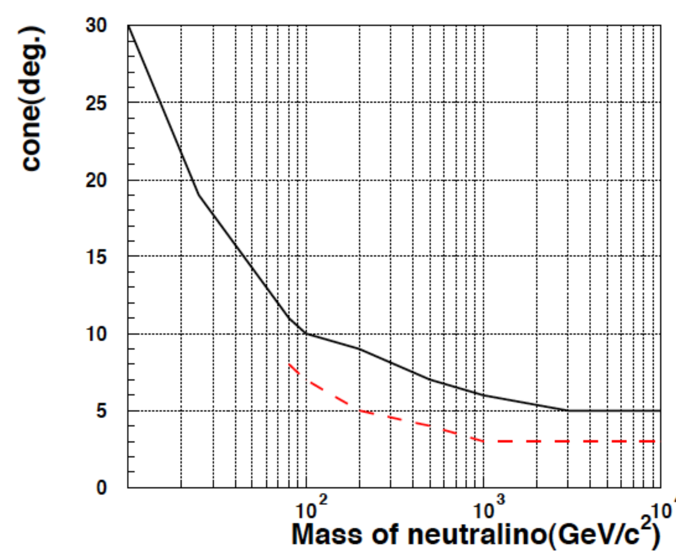


1 Km underground

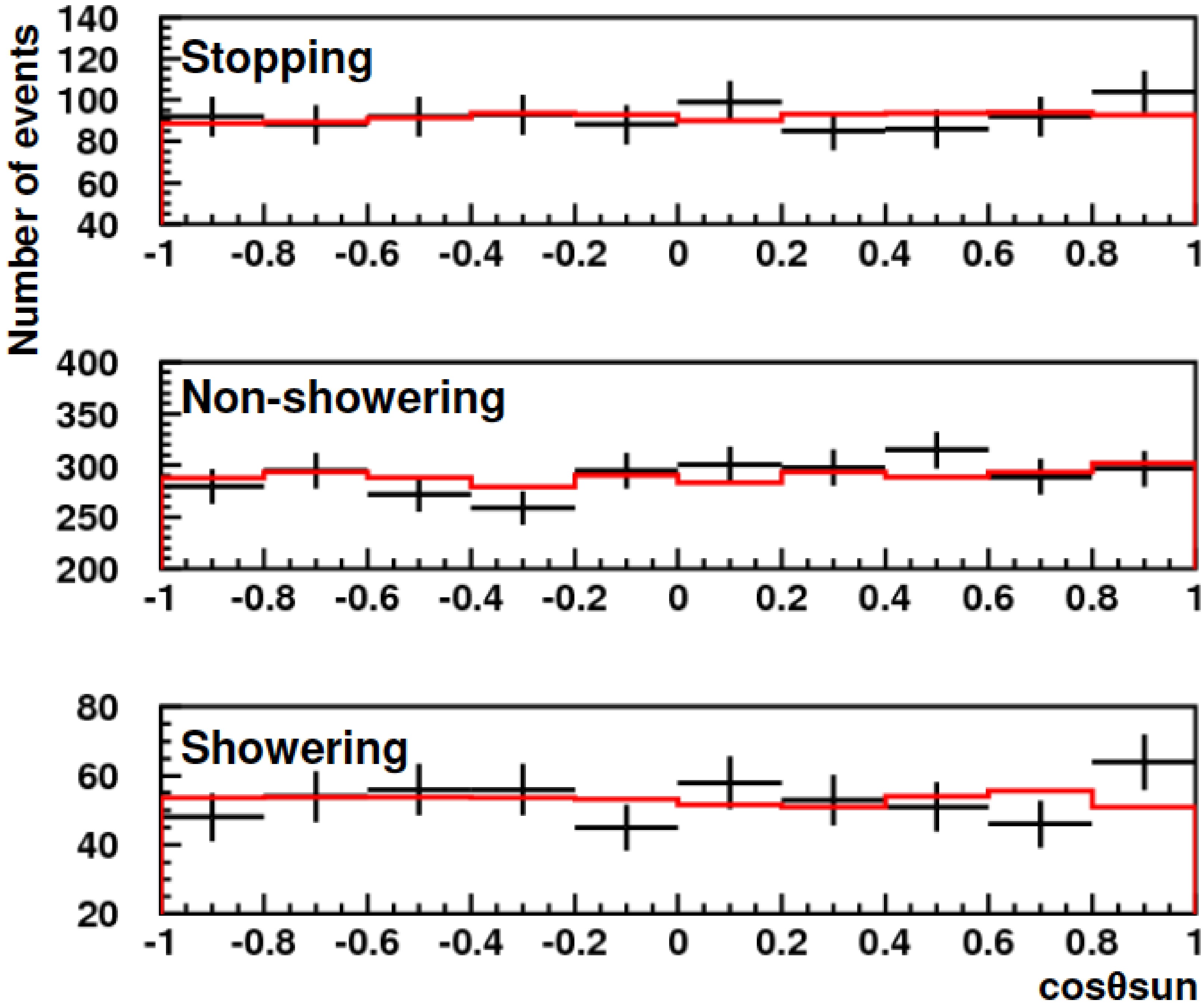


Red line=
estimated
Background
from atmospheric
neutrinos

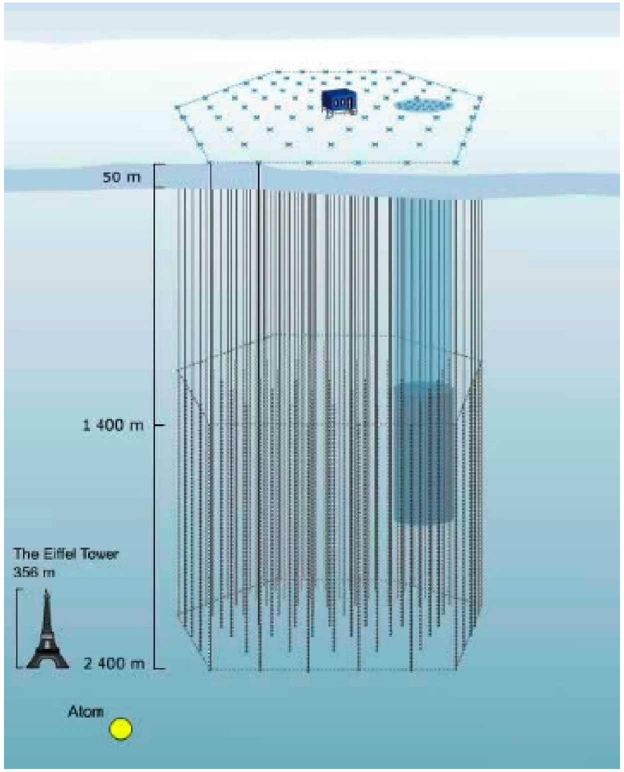


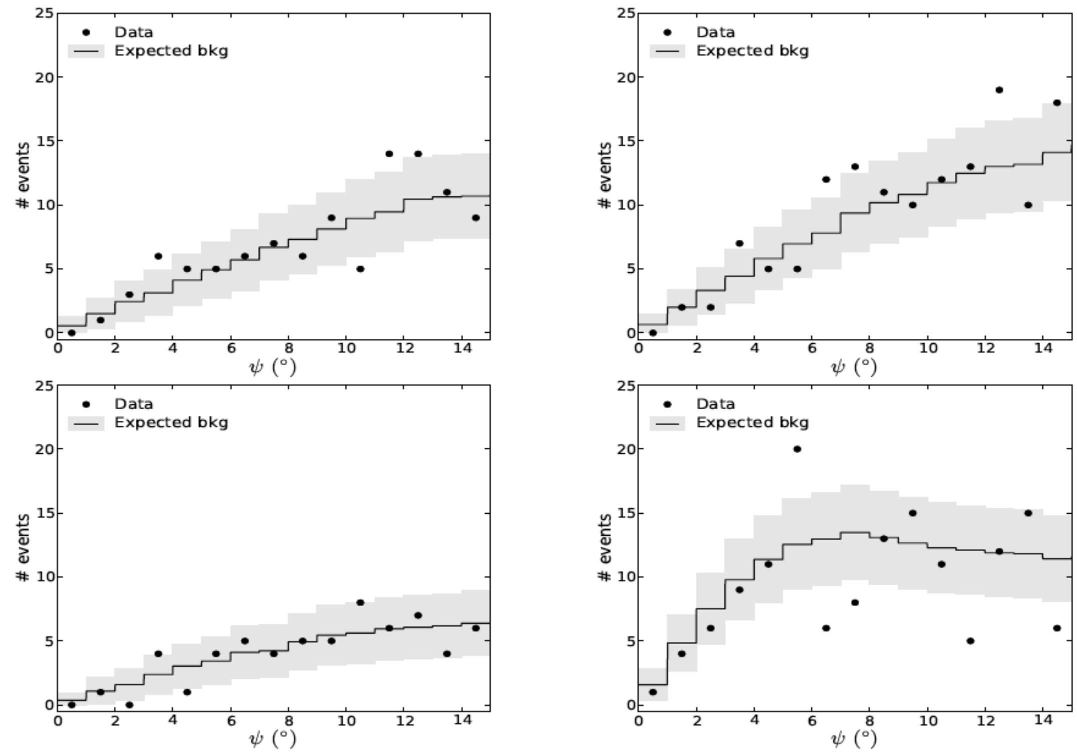


No excess from the sun direction (cos theta = 1)



IceCube study DM muons from the direction of the Sun



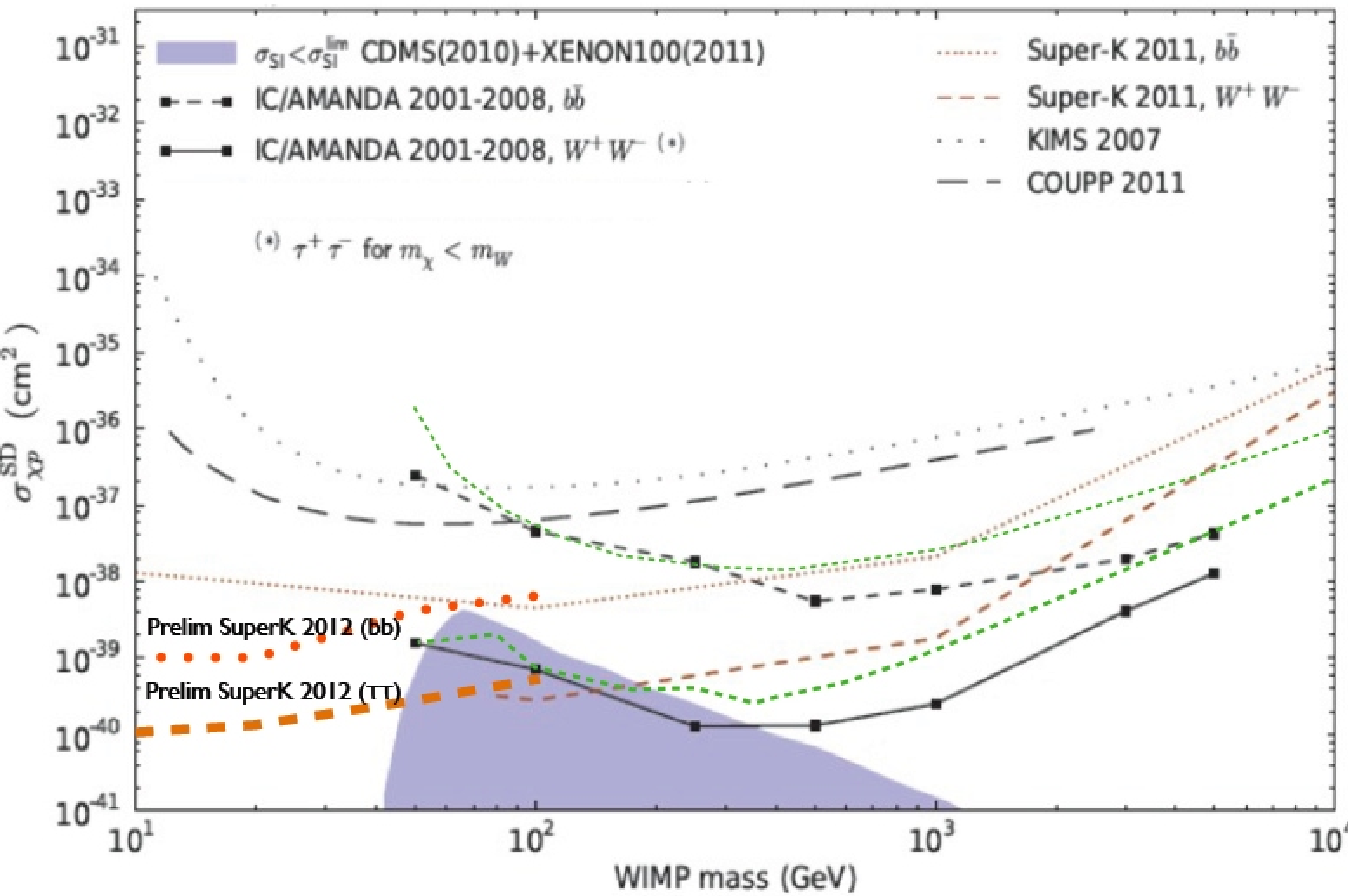


$m_{\tilde{\chi}_1^0}$(GeV)	channel	$\bar{\Psi}$(deg)	$V_{\rm eff}$ (m^3)	μ_s^{90}	Γ_A(s^{-1})	Φ_μ (km^{-2} y^{-1})	$\sigma_{\chi p}^{\rm SD}$ (cm^2)	$\sigma_{\chi p}^{\rm SI}$ (cm^2)
50	$\tau^+\tau^-$	8.0	7.40×10^4	10.8	8.11×10^{23}	1.95×10^4	1.86×10^{-39}	7.55×10^{-42}
	$b\bar{b}$	13.1	5.49×10^3	19.0	1.73×10^{26}	1.81×10^5	3.97×10^{-37}	1.61×10^{-39}
100	W^+W^-	5.3	4.33×10^5	7.8	1.19×10^{23}	4.27×10^3	9.60×10^{-40}	2.41×10^{-42}
	$b\bar{b}$	9.0	4.81×10^4	11.7	7.06×10^{24}	2.30×10^4	5.70×10^{-38}	1.36×10^{-40}
250	W^+W^-	2.8	9.33×10^6	6.2	2.99×10^{21}	4.38×10^2	1.41×10^{-40}	1.95×10^{-43}
	$b\bar{b}$	4.7	3.35×10^5	7.4	3.24×10^{23}	3.76×10^3	1.53×10^{-38}	2.10×10^{-41}
500	W^+W^-	2.4	2.26×10^7	5.3	9.23×10^{20}	2.40×10^2	1.70×10^{-40}	1.73×10^{-43}
	$b\bar{b}$	3.4	1.50×10^6	6.6	4.98×10^{22}	1.24×10^3	9.15×10^{-39}	9.05×10^{-42}
1000	W^+W^-	2.2	3.23×10^7	5.1	6.78×10^{20}	2.04×10^2	4.95×10^{-40}	4.22×10^{-43}
	$b\bar{b}$	2.7	3.88×10^6	5.9	1.39×10^{22}	6.05×10^2	1.01×10^{-38}	8.67×10^{-42}
3000	W^+W^-	2.2	3.12×10^7	5.2	1.01×10^{21}	2.16×10^2	6.56×10^{-39}	4.97×10^{-42}
	$b\bar{b}$	2.6	8.00×10^6	5.6	5.18×10^{21}	3.70×10^2	3.37×10^{-38}	2.56×10^{-41}
5000	W^+W^-	2.2	3.05×10^7	5.2	1.19×10^{21}	2.14×10^2	2.17×10^{-38}	1.60×10^{-41}
	$b\bar{b}$	2.4	9.24×10^6	5.7	4.32×10^{21}	3.48×10^2	7.81×10^{-38}	5.78×10^{-41}

New Preliminary SuperK 2012 Result

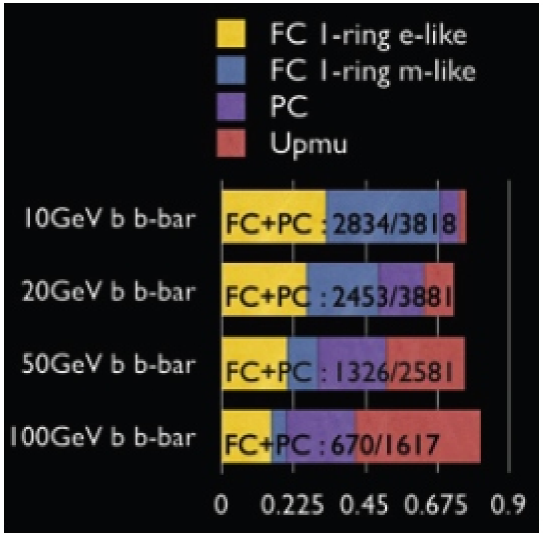
Antares result (green line)

T. Tanaka et al. Astrophys. J. 742, 78 (2011)
R. Abbasi et al. Phys. Rev. D 85, 042002 (2012)



Significant improvement in low-mass WIMP region !

Data from SKI-III (2806days)



Energy / Angular Fit
Derive 90% Bayesian upper limit on allowed WIMP induced events

see:

PLEIADVM CONSTELLATIO.

Quod tertio loco à nobis fuit obseruatum, est ipsius-
met LACTEI Circuli essentia, seu materies, quam Per-

PLEIADUM CONSTELLATIO

.....Expect the unexpected ....

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,...} {???}