טכניון

המכללה האקדמית להנדסה
אורט בראודה
ORT BRAUDE COLLEGE

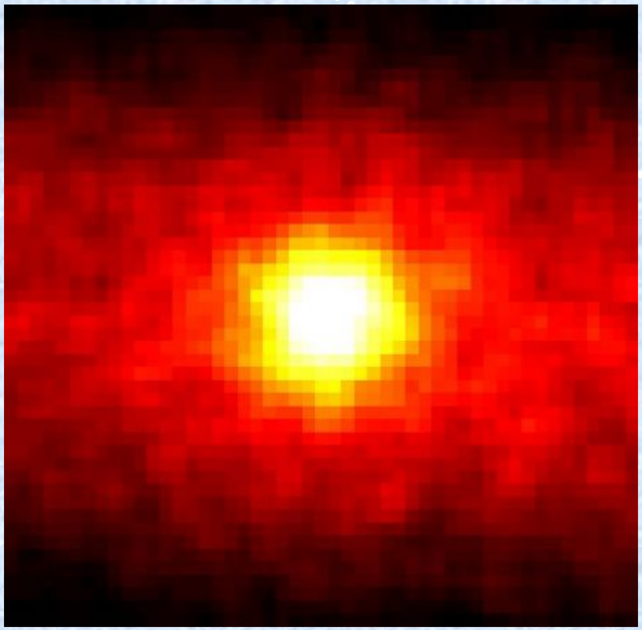
OAR

Neutrinos from Astrophysical sources in the IceCube and ARA Era

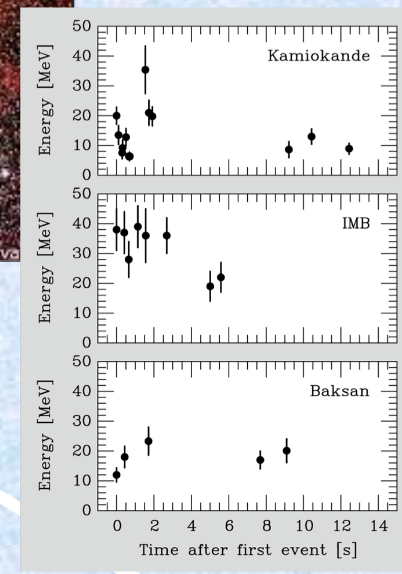
Dafne Guetta

Extraterrestrial Neutrinos

Neutrino image of the
(interior of the) sun.
Low energy neutrinos measured
by the SuperK underground detector.



Supernova 1987a



Observation of neutrinos, MeV scale, confirm process of core collapses

Energy: order MeV
→ Direct evidence of nuclear process in the sun and neutrino physics

Are there neutrino sources at higher energie
Possibly extragalactic?

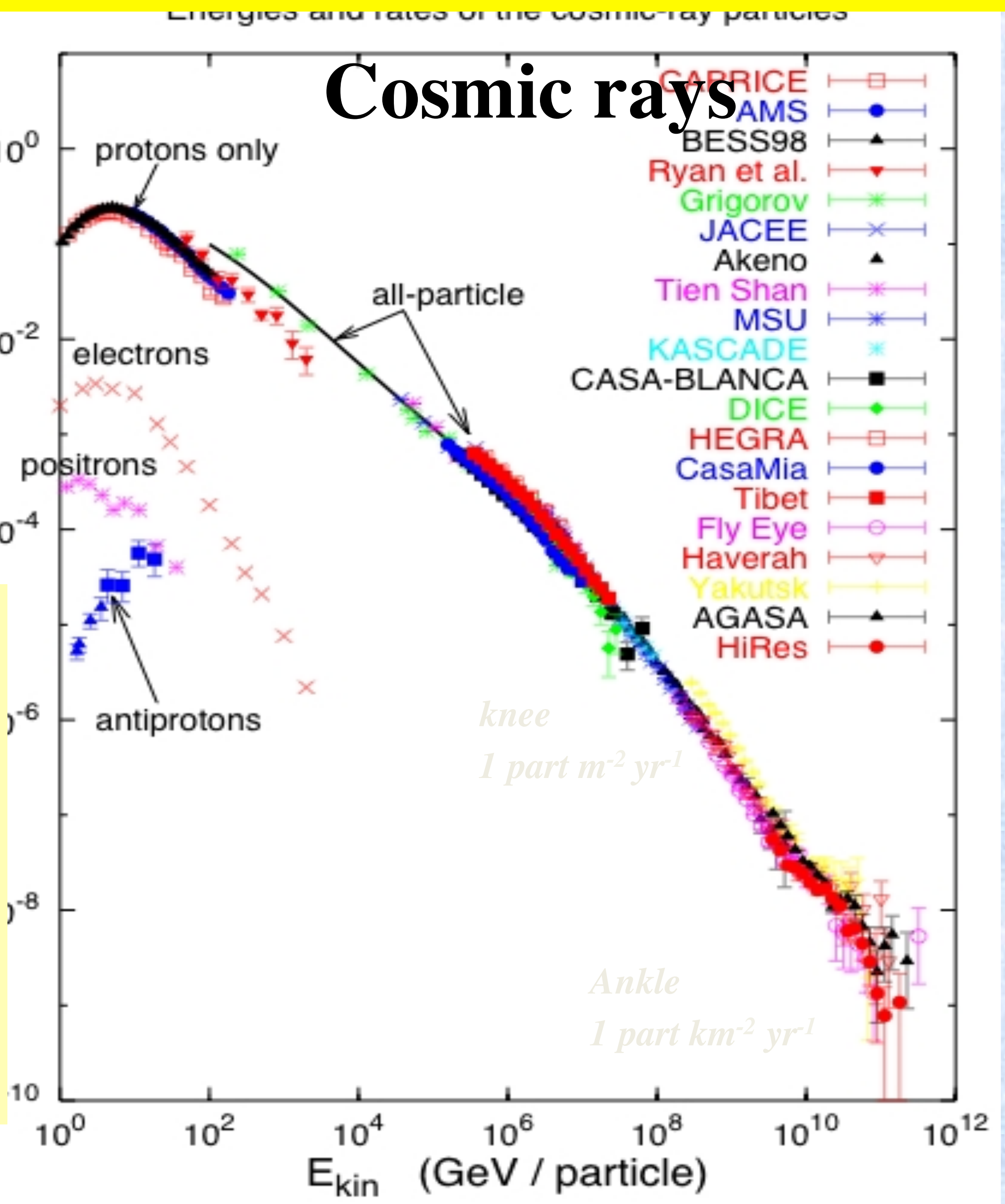
Cosmic Rays and Neutrino Sources

Can neutrinos reveal origins of cosmic rays?

$$p\gamma \rightarrow p\pi^0, n\pi^+$$

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

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



Cosmic ray interaction in accelerator region

Prime Candidates

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts

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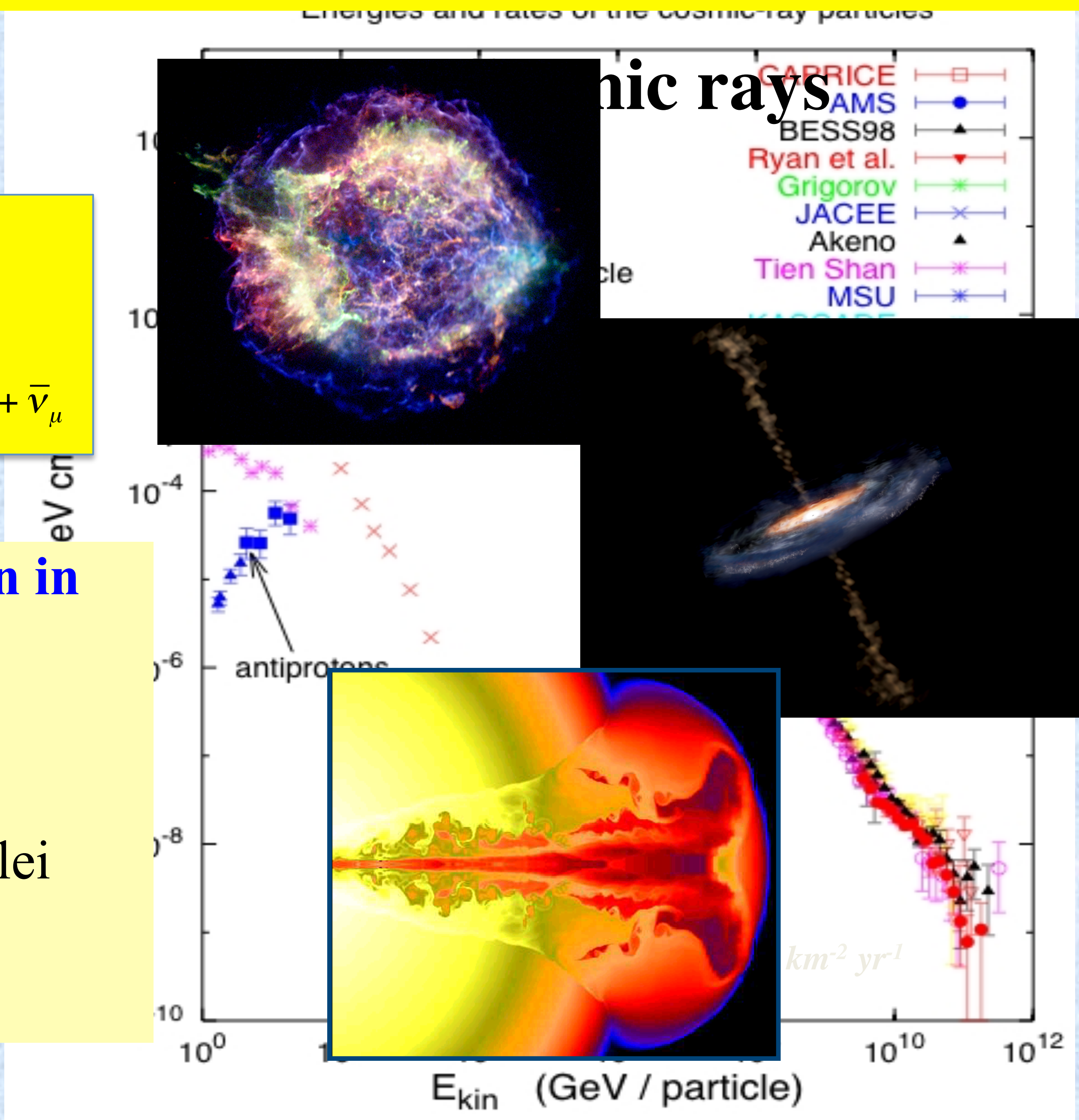


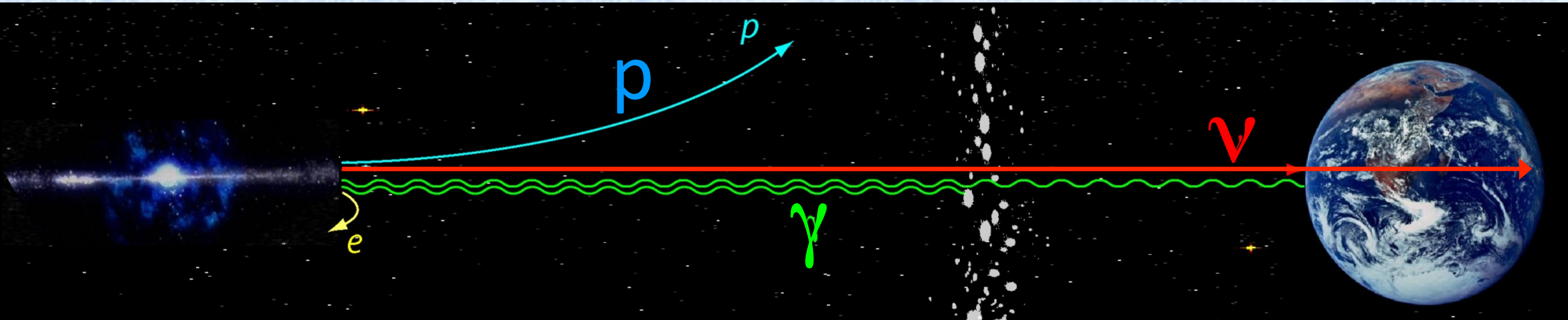
Cosmic neutrinos?

Why look for them?

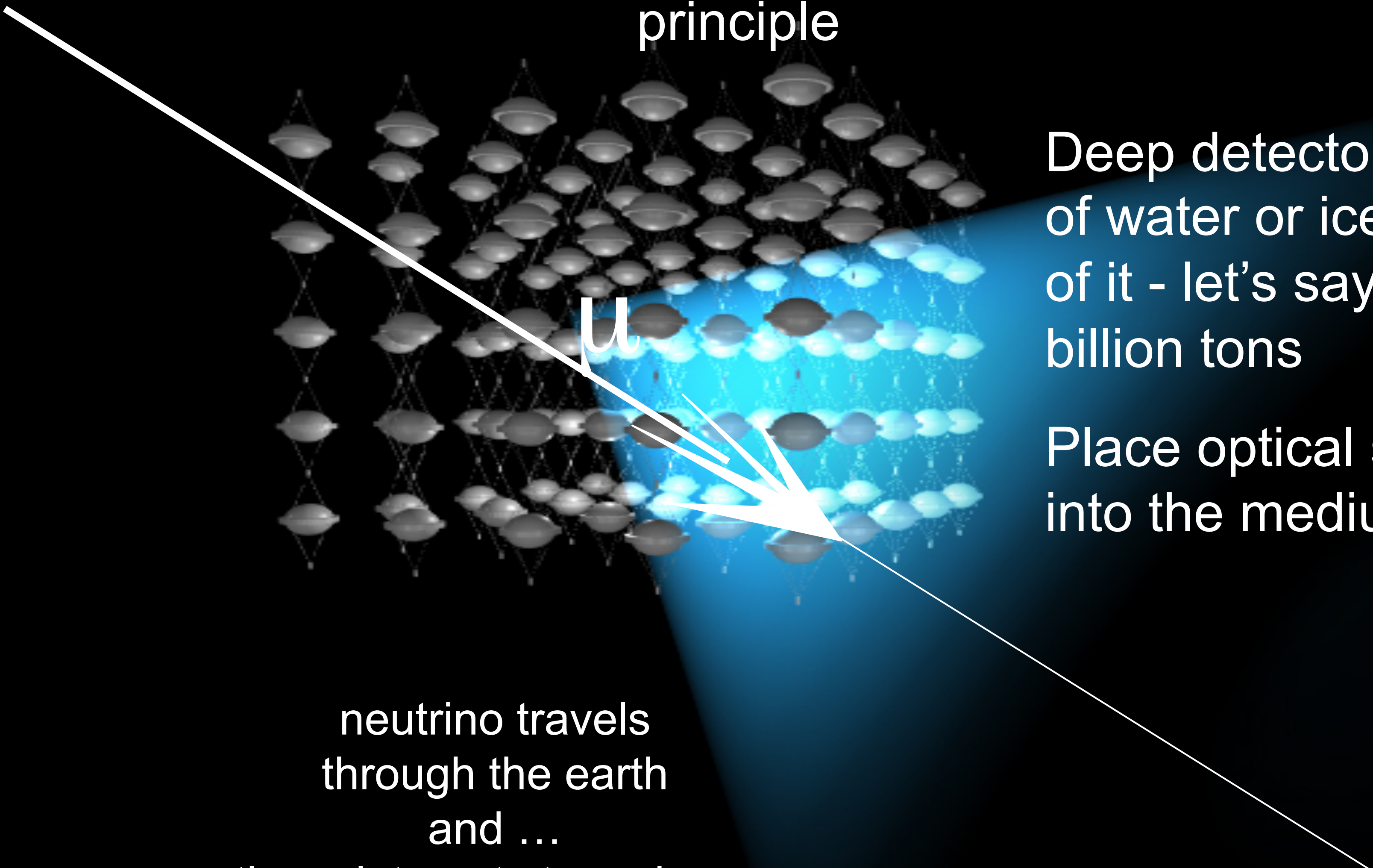
- They could tell us about the origin of high energy cosmic rays, which we know exist.
  - There are numerous ways how neutrinos can tell us about fundamental questions in nature: dark matter, supernova explosions, …

Can they reach us?

- High energy neutrinos will pass easily and undeflected through the Universe
  - That is **not** the case for other high energy particles: such as photons or other cosmic rays, eg protons.



How to catch them? Detection principle

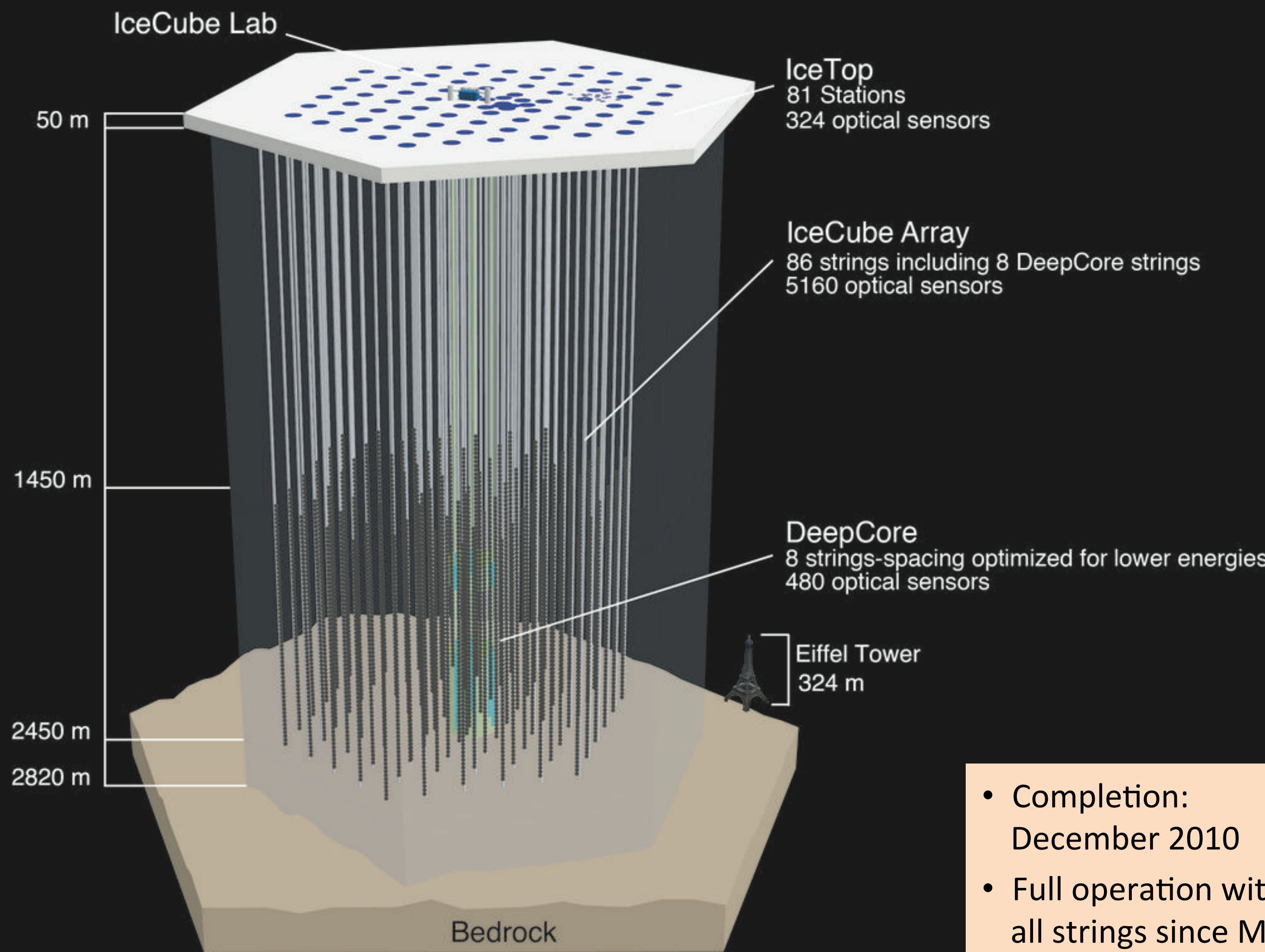


Deep detector made of water or ice – lots of it - let’s say 1 billion tons

Place optical sensors into the medium

neutrino travels through the earth and …
sometimes interacts to make a muon that travels through the detector

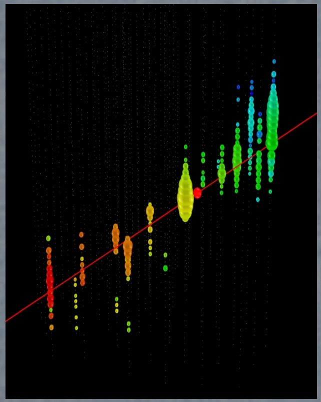
IceCube



- Completion: December 2010
- Full operation with all strings since May 2011.

Neutrino Event Signatures

CC Muon Neutrino

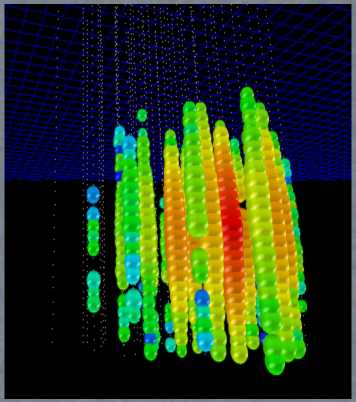


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
$< 0.5°$ angular resolution

Neutral Current /Electron Neutrino



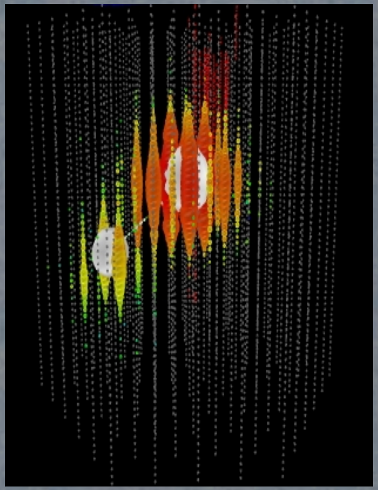
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

$\approx \pm 15\%$ deposited energy resolution
$\approx 10°$ angular resolution
(at energies $\gtrapprox 100$ TeV)

CC Tau Neutrino

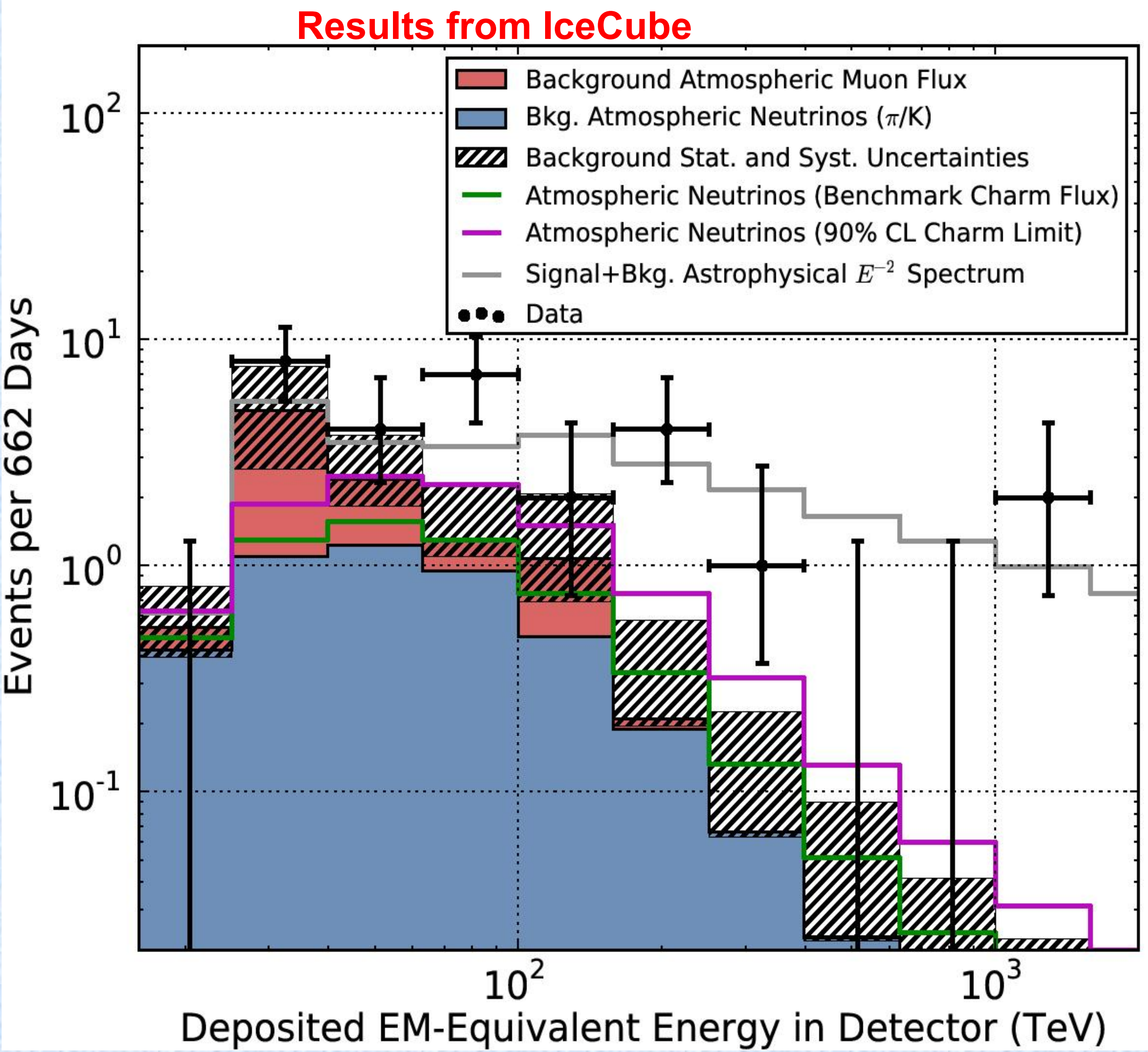


$$\nu_\tau + N \rightarrow \tau + X$$

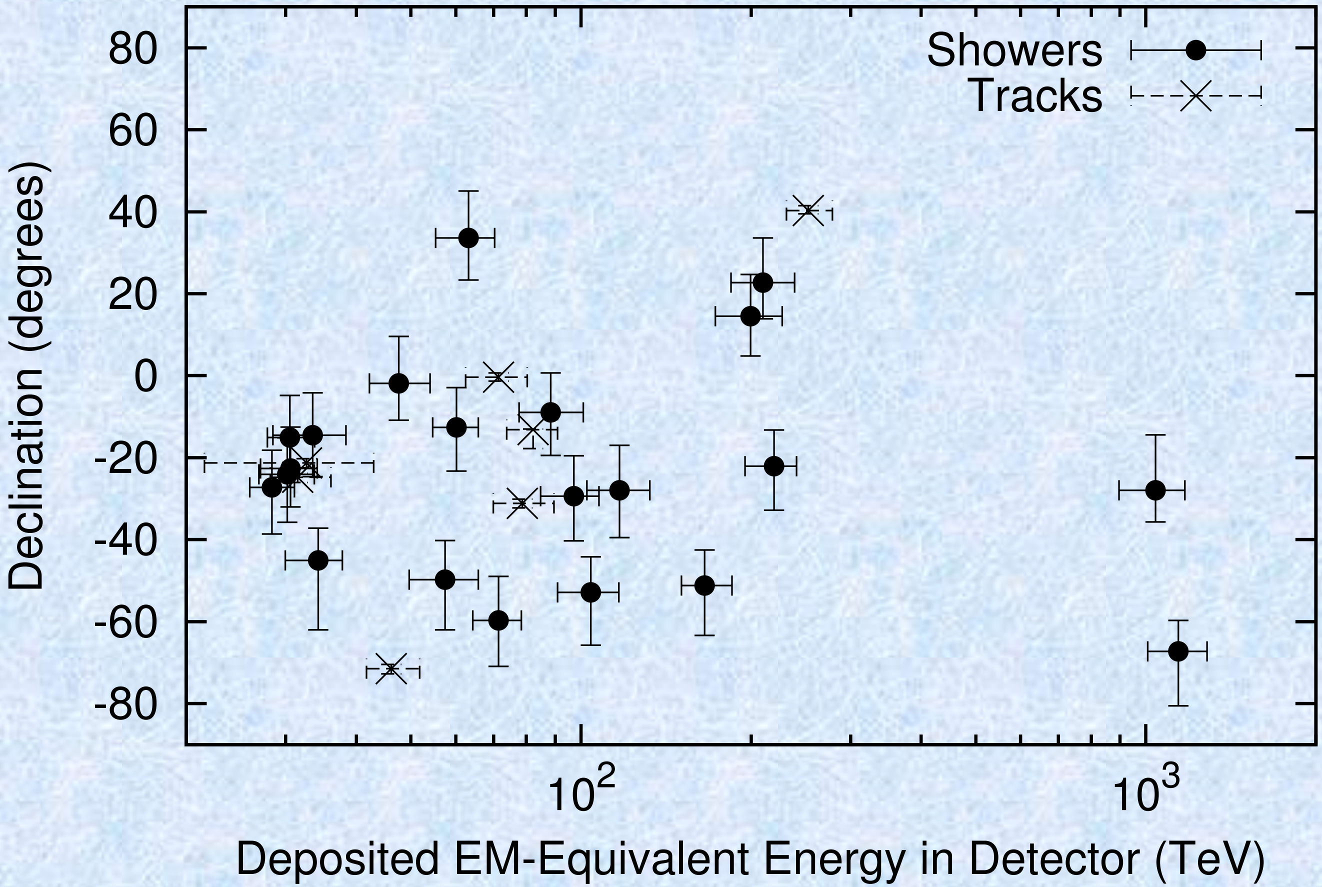
"double-bang" and other signatures (simulation)

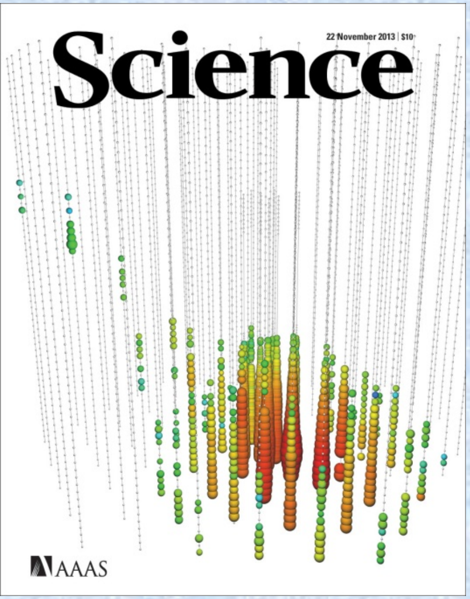
(not observed yet)

- Harder than atmospheric ν



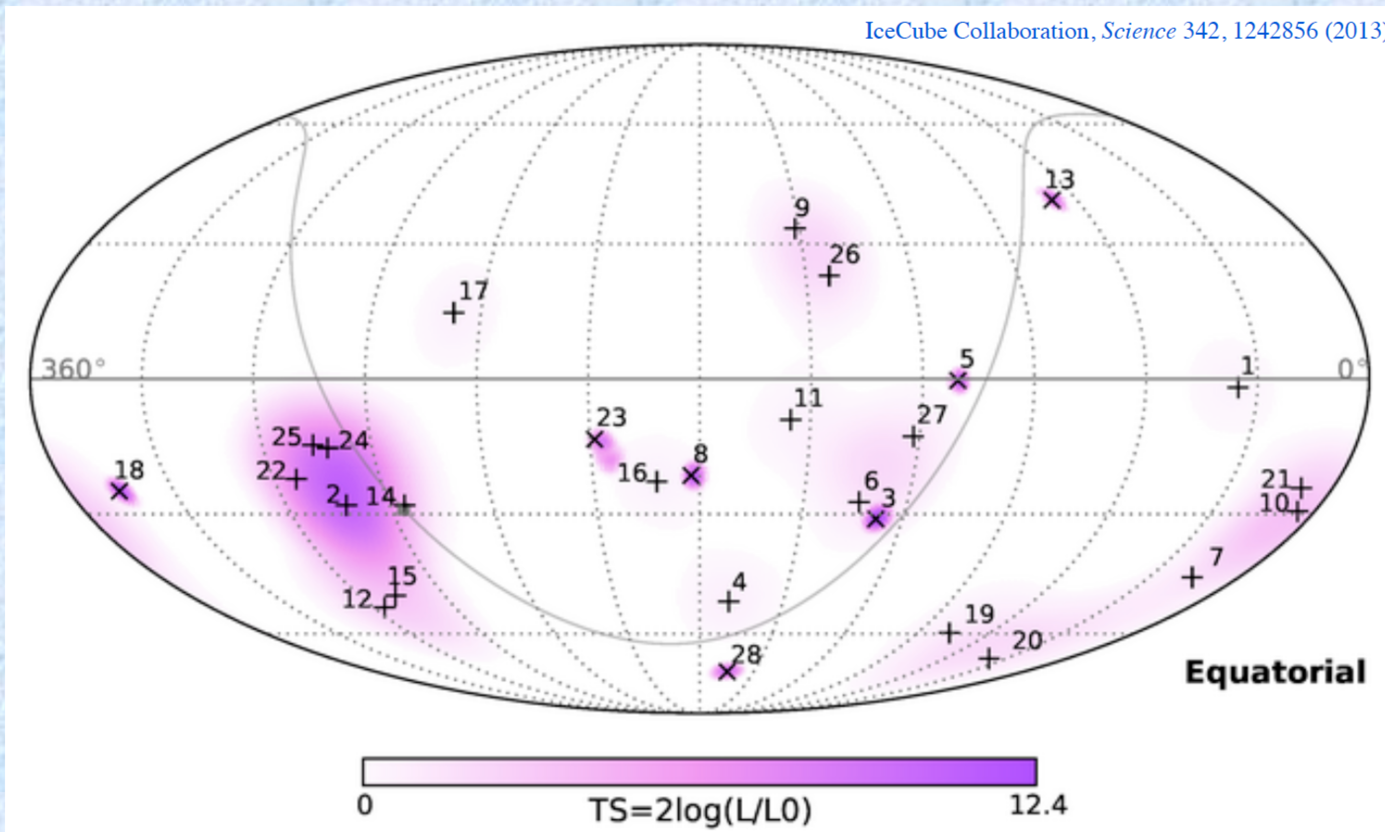
Declination vs energy





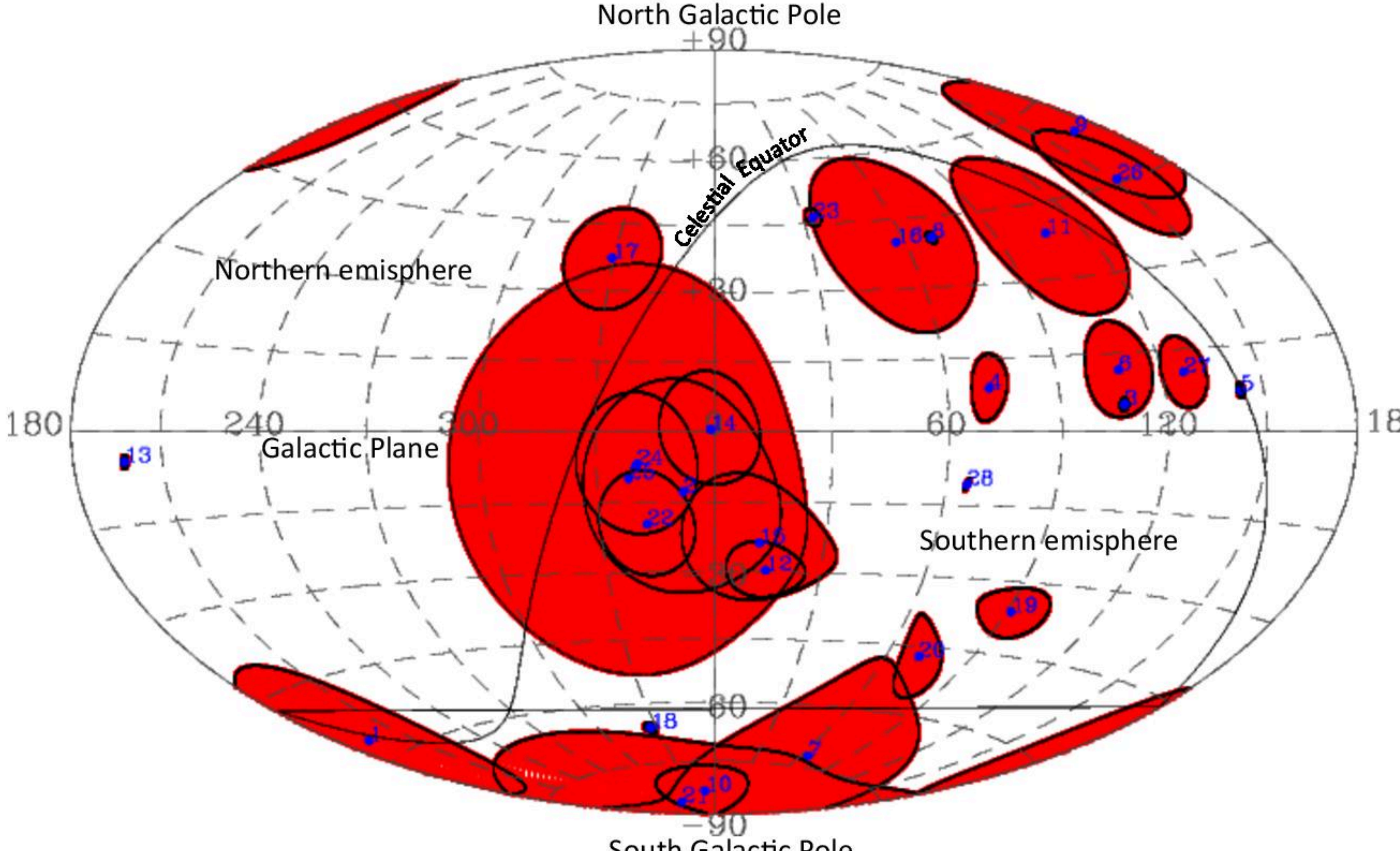
Evidence for astrophysical neutrinos of very high energy.

28 events,
Including the two with energies of more than 10^15 eV



NO SIGNIFICANT CLUSTERING OBSERVED.

IceCube neutrino events in galactic coordinates



Zappacosta, Guetta & Fiore

Possible candidate sources

- Solar System neighborhood
  - **Local Bubble** (X-ray emitting local Supernova Remnant(s) surrouding the Solar System)
- Galactic
  - Low latitude (|b|<10 deg)
    - X-ray/γ-ray emitting sources (**binaries, microquasars**)
    - **Magnetars** (Soft Gamma-Ray Repeaters)
    - **Supernova Remnants** (SNR)
    - **Milky Way nucleus** (Sgr A*)
  - High latitude (high |b| values)
    - Diffuse (**Fermi bubbles**)
- Extragalactic
  - Local
    - **Local galaxies** (closest than Virgo Cluster)
  - Cosmological
    - **Clusters of Galaxies** (ClG; through accretion and merging shocks)
    - **Superclusters** (Scl; through accretion shocks in the filamentary distribution of the cosmic web)
    - **Supernovae** (?) (SNe; probably from shock breakouts)
    - AGNs:
      - **quasars, blazars (jets)**
      - **Radiogalaxies: hot spots** in radio lobes are sites of particle re-acceleration
    - **Gamma Ray Bursts** (GRB; jets, internal shocks)

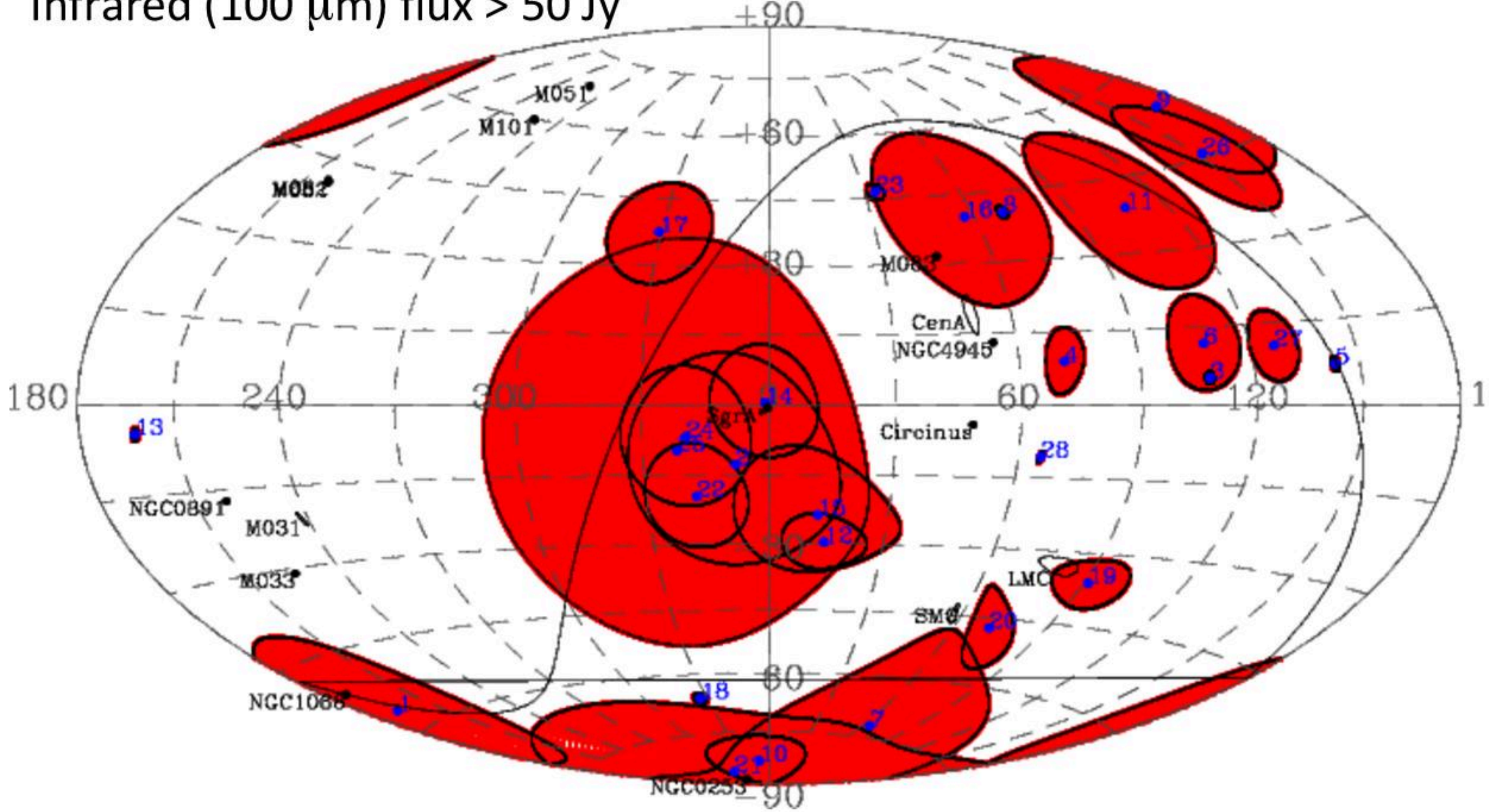
Explored candidate sources

- Solar System neighborhood
  - **Local Bubble** (X-ray emitting local SNe Remnant(s) surrouding the Solar System) **NOT EXPLORED**
- Galactic
  - Low latitude (|b|<10 deg)
    - X-ray/γ-ray emitting sources (**binaries, microquasars**) **NOT FULLY EXPLORED**
    - **Magnetars** (Soft Gamma-Ray Repeaters) **NOT EXPLORED**
    - ~~**Supernova Remnants** (SNR~~) **NO COINCIDENCE**
    - **Milky Way nucleus** (Sgr A*) **COINCIDENCE**!
  - High latitude (high |b| values)
    - ~~Diffuse (**Fermi bubbles**~~) **NO SIGNIFICANT COINCIDENCE**
- Extragalactic
  - Local
    - **Local galaxies** (closest than Virgo Cluster) **SOME COINCIDENCES**!
  - Cosmological
    - ~~**Clusters of Galaxies** (ClG; through accretion and merging shocks)~~ **LOW SIGNIFICANCE COINCIDENCE**
    - ~~**Superclusters** (Scl; through accretion shocks in the the cosmic web)~~ **UNCONCLUSIVE COINCIDENCES**
    - ~~**Supernovae** (?) (SNe; probably from shock breakouts)~~ **LOW SIGNIFICANCE COINCIDENCE**
    - AGNs:
      - **quasars, blazars** (jets) **NOTHING SIGNIFICANT SO FAR**
      - **Radiogalaxies: hot spots** in radio lobes are sites of particle re-acceleration **NOT EXPLORED**
    - ~~**Gamma Ray Bursts** (GRB; jets, internal shocks~~) **RULED OUT AS ONLY CANDIDATES BY ICECUBE COLL.**

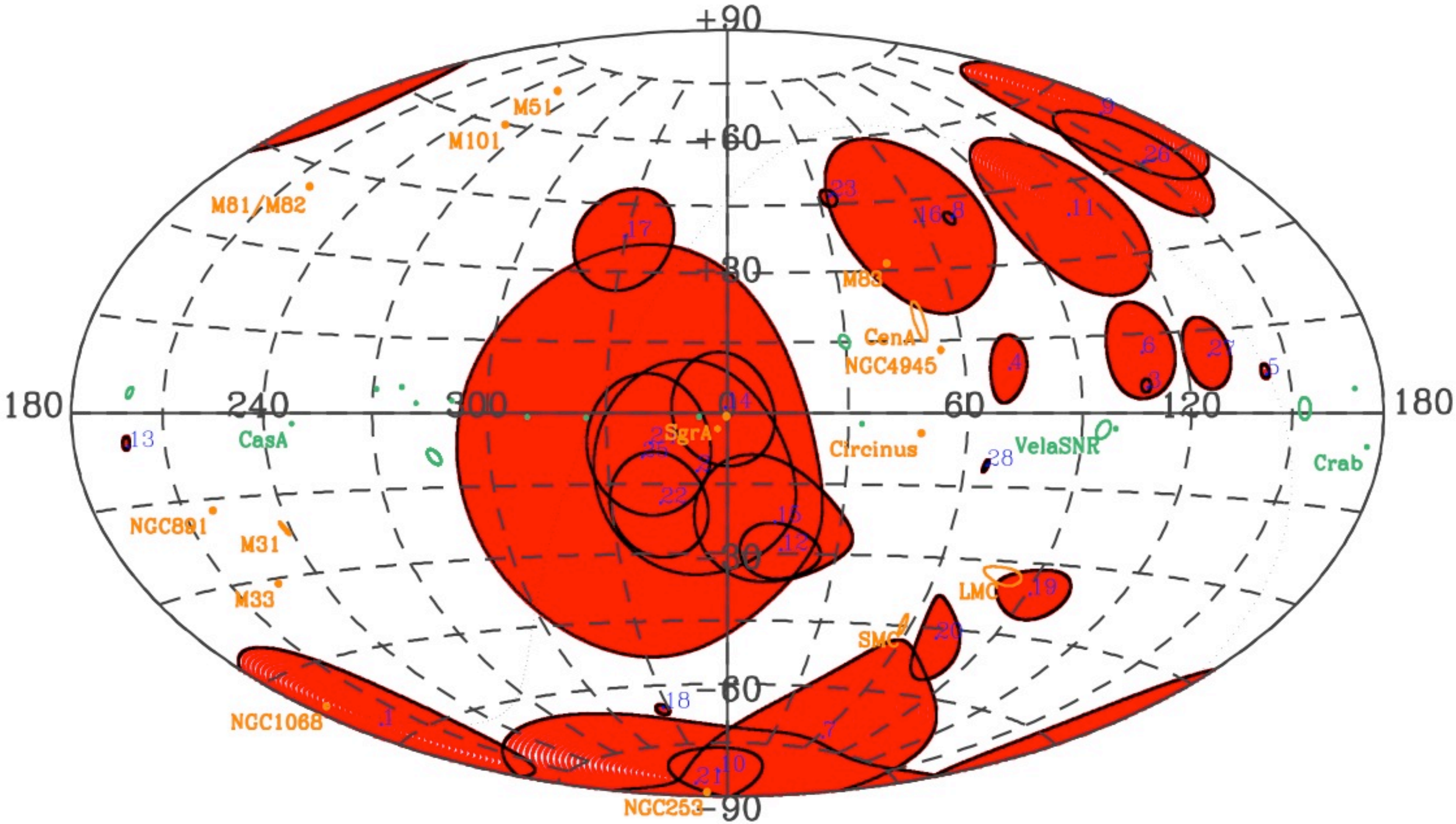
Local Galaxies

Selection of the closest and massive galaxies in the Milky Way neighborhood

- recession velocities v<1200 km/s
- Infrared (100 μm) flux > 50 Jy



Local Galaxies and Supernova Remnants



One more year of data have been inspected with the same method

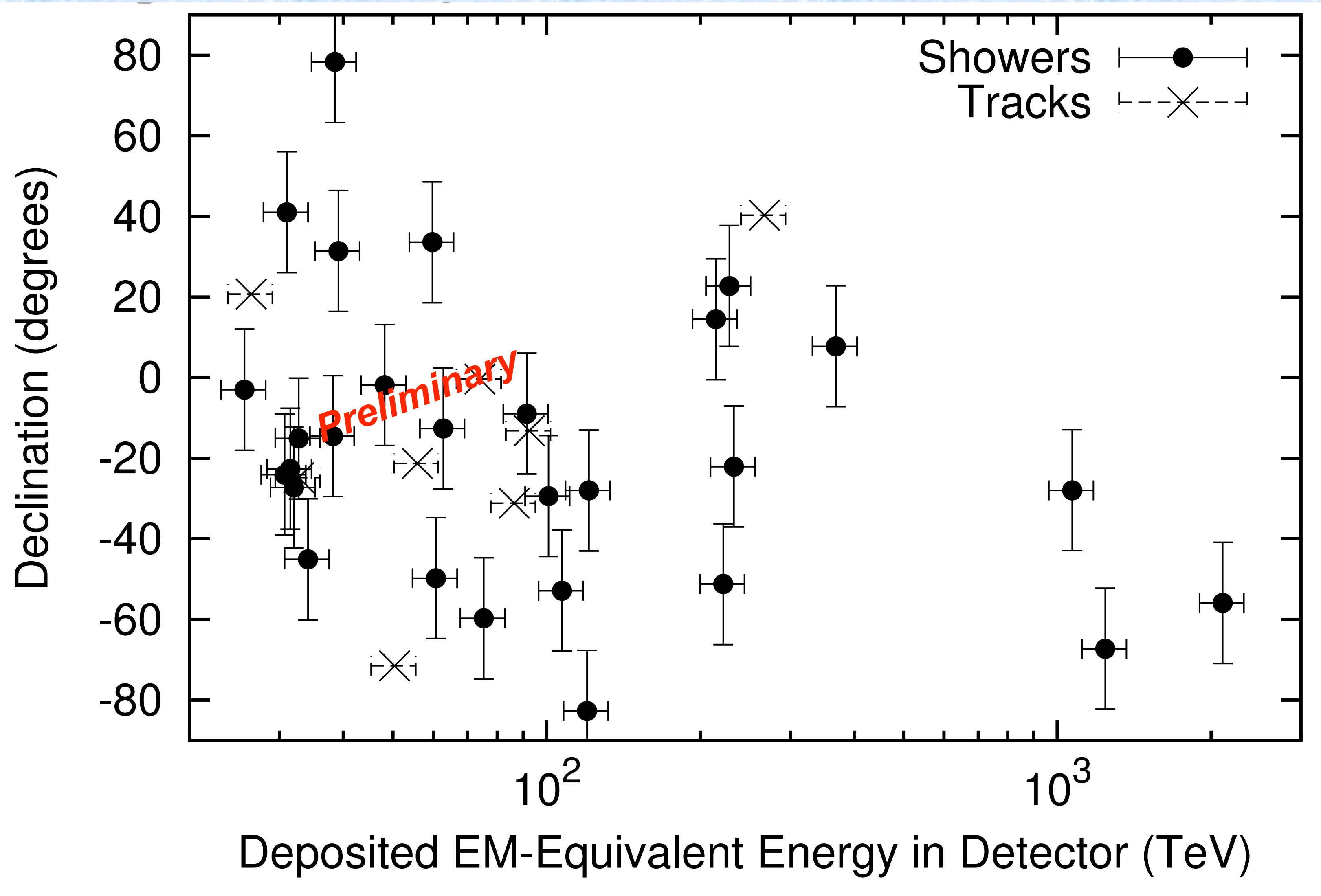
Additional data confirm the reported results:

8 more events

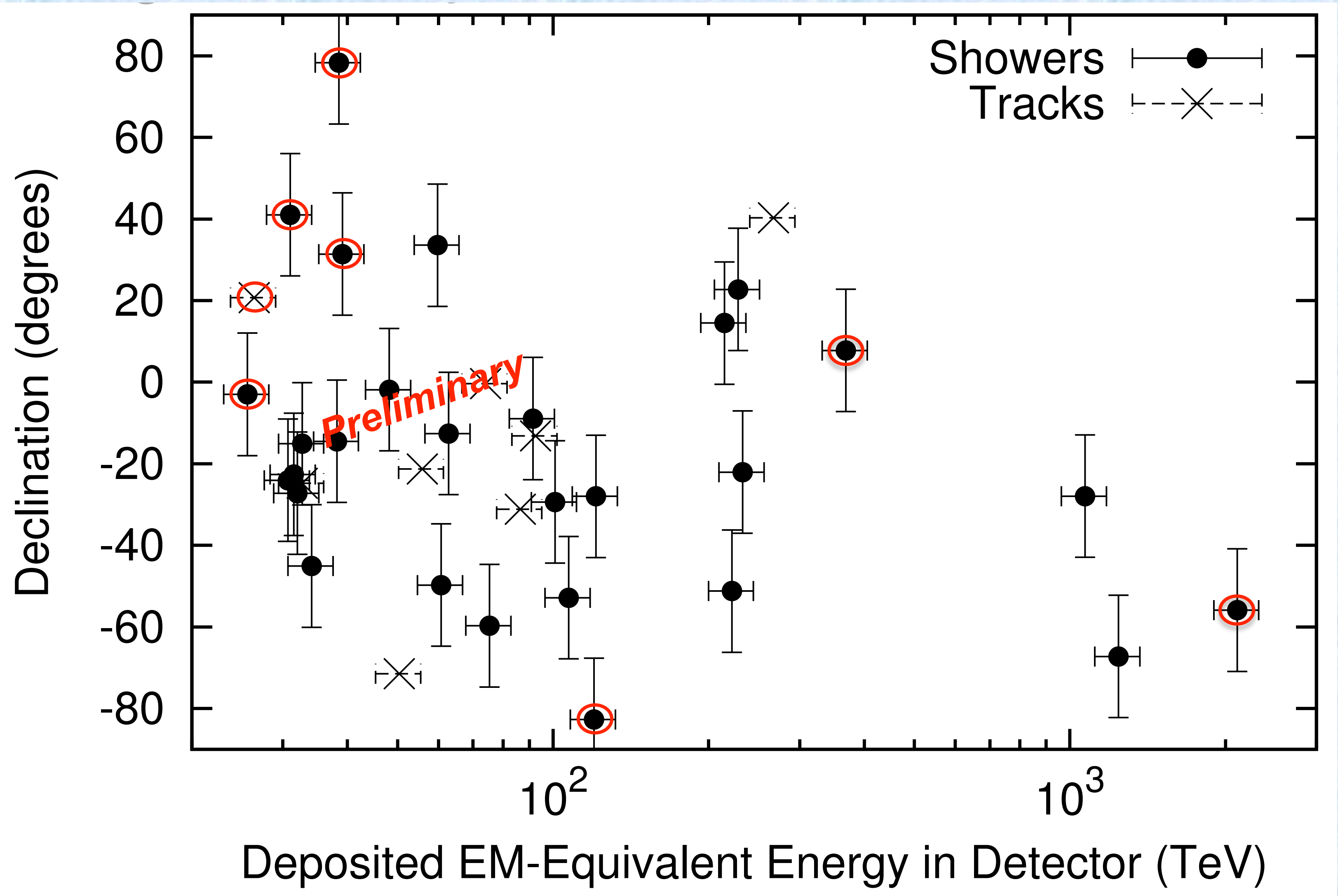
One events at 2 PeV

Same characteristics

From 2 to 3 years: Declination vs energy



From 2 to 3 years: Declination vs energy



Most events in Southern hemisphere (downgoing).

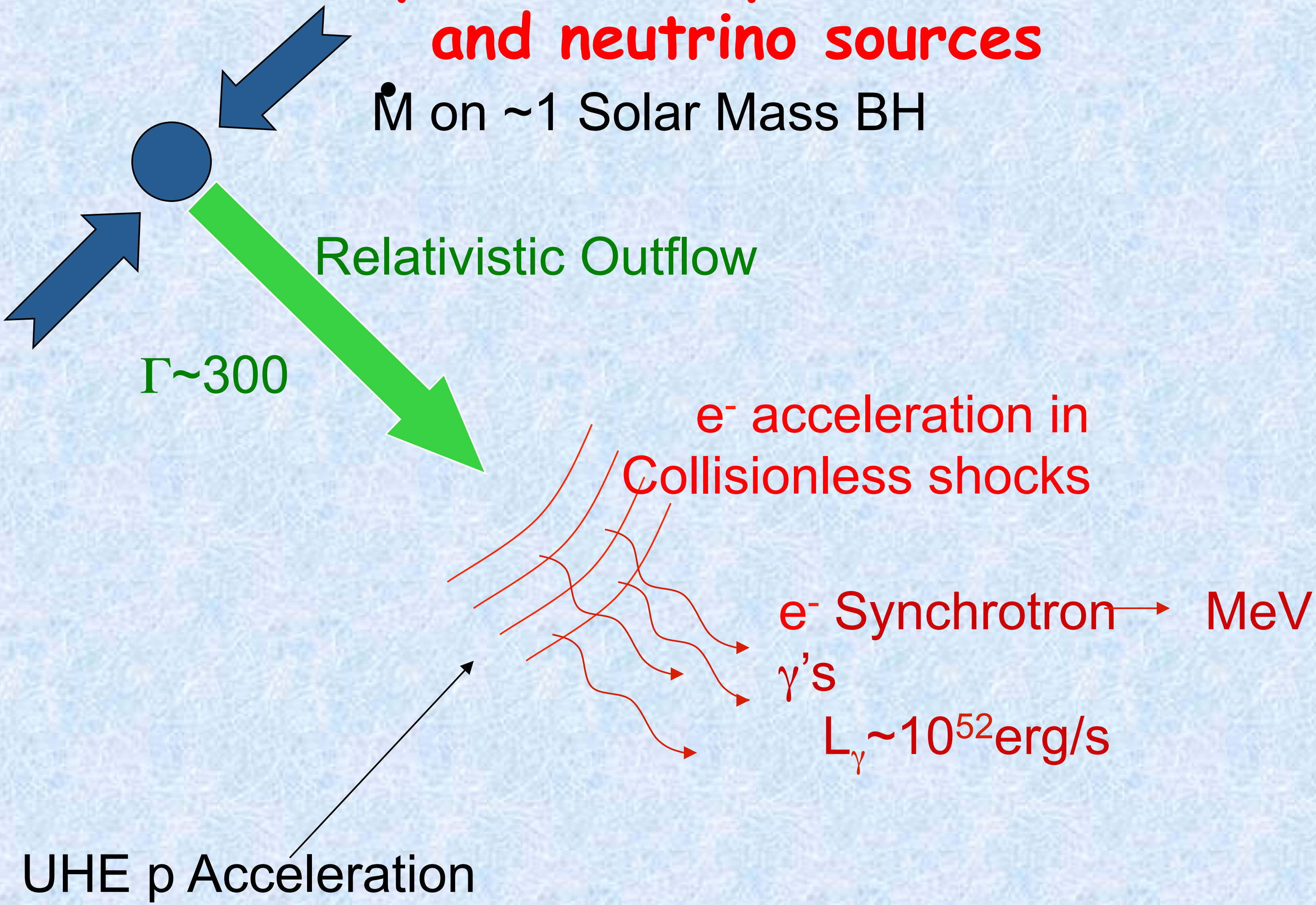
An astrophysical neutrino flux?!

- IceCube data provide strong evidence for an astrophysical neutrino flux
- Consistent with:
  - 1:1:1 all flavor neutrino flux – as expected for astrophysical sources (we have not seen many muons yet though, but we didn't expect many)
  - Isotropic distribution, north, south – specifically no evidence for galactic association.

The data suggest that we see an extragalactic neutrino flux.
The level of this flux is exactly and thus intriguingly so at the level of the Waxman-Bahcall upper bound.
- Is it a clue for it's origins? (Waxman arXiv: 1301….)

Fundamental to have another neutrino telescope km3net!!!

Gamma-ray Bursts as particle accelerators and neutrino sources



[Meszaros, ARA&A 02;
Waxman, Lecture Notes in Physics 598 (2003).]
]

HE ν from GRBs

In the FB dissipation region: protons accelerated to ~ 10^{20}eV

photo-meson interaction of HE p with the FB photons

Internal shocks ν : ~ 100 TeV, coincident with GRBs

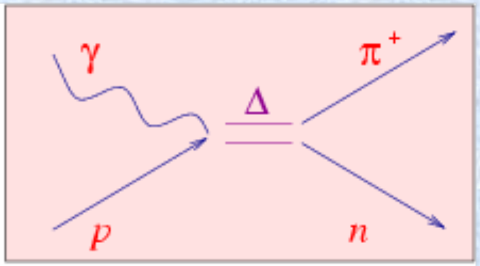
External shock ν : ~ Early afterglow ν ~ 100 PeV,delayed

[Waxman & Bahcall '97,'99,Guetta Spada & Waxman 2001
Guetta, Nir & Landsman in preparation]

The main mechanism: photomeson interaction

$$\gamma + p \to n + \pi^+ \; ; \quad \pi^+ \to \mu^+ + \nu_\mu \to e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

$$(\varepsilon_p / \Gamma)(\varepsilon_\gamma / \Gamma) \geq 0.3\,\mathrm{GeV}^2$$



In each collision $E_\nu \sim 0.05\, E_p$

Fireball

Int. Shocks $E_\gamma \sim$ MeV: $E_p \sim 10^{16}$ eV ⇨ $E_\nu \sim 10^{14}$ eV

Ext. shock $E_\gamma \sim$ keV : $E_p \sim 10^{19}$ eV ⇨ $E_\nu \sim 10^{17}$ eV

proton en. lost to pion production: $f_\pi \sim f(\Gamma, t_v, L)$

0.2 I.S.

0.01 E.S.

Burst to burst fluctuations look at each burst detected by BATSE [Guetta, Hooper, Halzen et al. 2003]

For a typical burst at z~1, E ~ 10^{53}erg

Internal shocks ν: "effective" f_π ~20% [Guetta Spada Waxman 2001]

⇨ Fluence $E^2_\nu dN/dE_\nu \sim 10^{-3}(f_\pi/0.2)(E_\nu/10^{14}\,\mathrm{eV})^\beta$ GeV/cm^2 $\begin{cases} \beta=0 & E_\nu > E_\nu^b \\ \beta=1 & E_\nu < E_\nu^b \end{cases}$

Detection probability ~ 0.01 per burst in km-cube neutrino telescope ⇨ **Ten events per yr correlated in time and direction with GRBs!**

External shock : "effective" f_π ~0.01 [Waxman & Bahcall 2000]

⇨ Fluence $E^2_\nu dN/dE_\nu \sim 10^{-4.5}(f_\pi/0.01)(E_\pi/10^{17}\,\mathrm{eV})^\beta$ GeV/cm^2 $\begin{cases} \beta=½ & E_\nu > E_\nu^b \\ \beta=1 & E_\nu < E_\nu^b \end{cases}$

0.06 events per yr in a km-cube detector delayed ~10s after the GRB

Implications

- J_{ν} ~ 10/ km^2 yr , E_ν ~ 100 TeV from internal shocks
- J_{ν} ~ 5/ km^2 yr , E_ν ~ 100 PeV from ext. shock + wind

Help to resolve open questions in astrophysics:

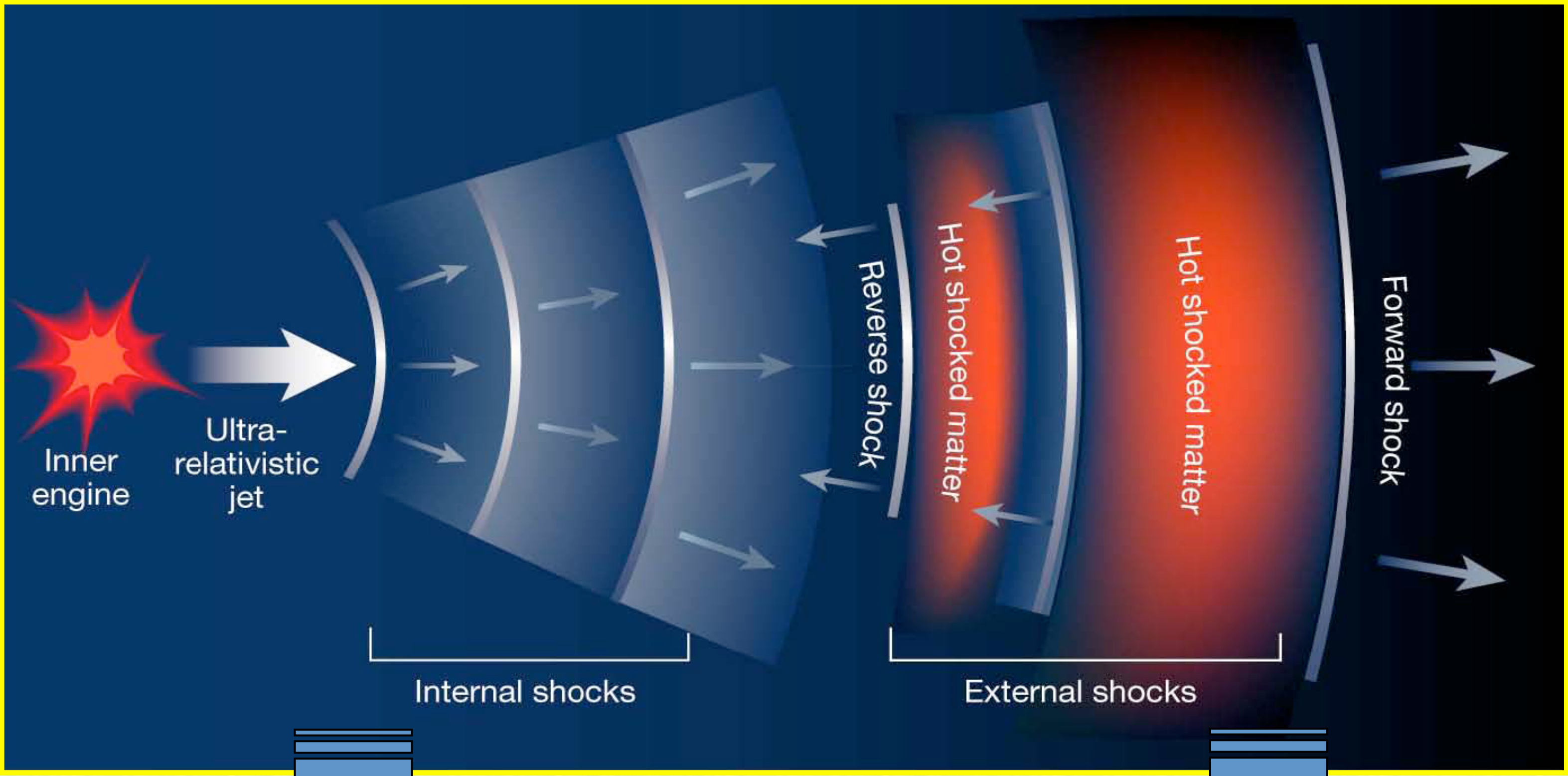
- **Baryonic component of the Jet: Composition of the jet is an open issue** e^+e^- or pe^- plasma? Still not clear
- What are the sources of UHECR?
- **GRBs progenitors**

Open questions related to GRBs

- Are GRBs the sources of UHECR? ☺
- The dynamics of GRB jet why Γ so high, fireball? ☺
- What is the dissipation mechanism that leads to the emission of γ-rays? Internal shocks? ☺
- Jet composition, are there hadrons in the jet? ☺
- Radiative processes and physical explanation to the broad band spectrum observed ☺

☺ = Neutrino telescopes may help answer these Qs

High Energy emission in GRBs: predictions



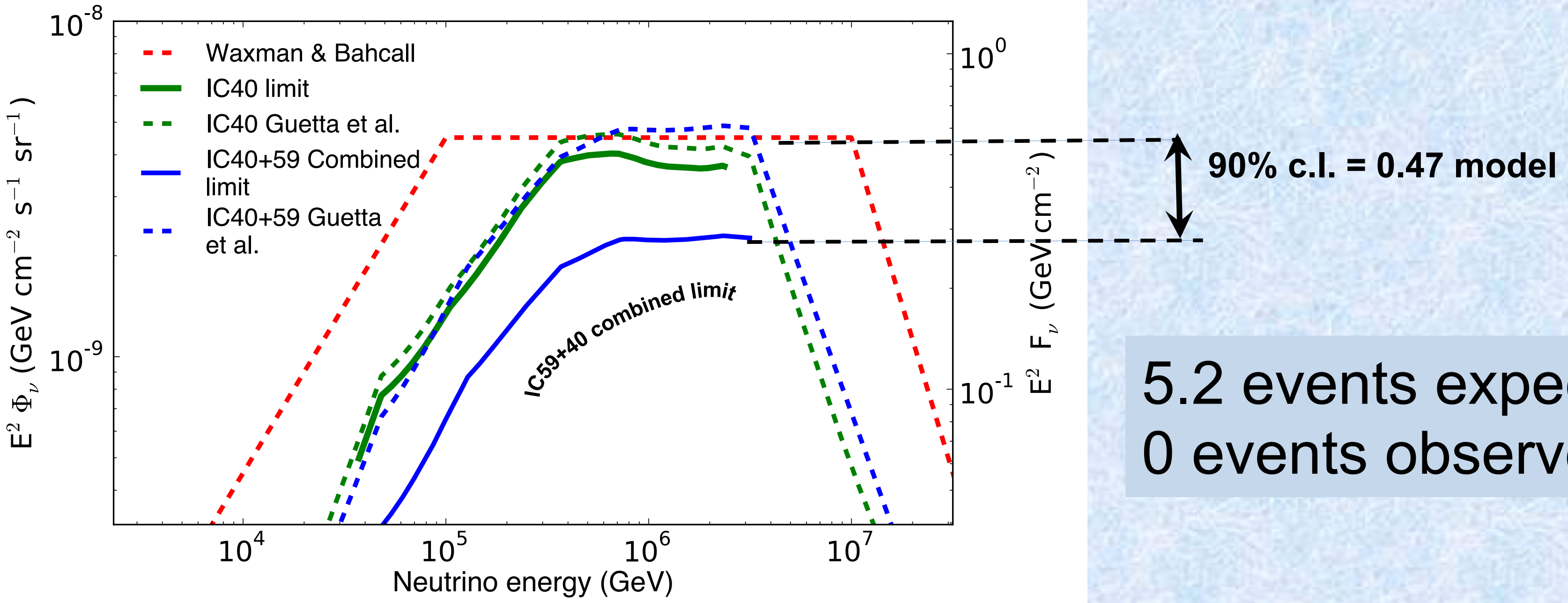
- SSC in internal shocks, 1 MeV-10 GeV (Guetta & Granot 2003, Meszaros et al., Galli & Guetta 2007)
- p-γ interaction, MeV – TeV (Gupta & Zhang 2007)

- SSC in RS, keV-GeV (Granot & Guetta 2003 Kobayashi et al. 2007)
- SSC in FS, MeV-TeV (Galli & Piro 2007)
- p-γ interaction in FS, GeV – TeV (Boettcher & Dermer 2003) p-sync. (Razzaque 2010)

Theoretical models for high-energy emission
- Fermi era-

MATTER DOMINATED	
LEPTONIC	**HADRONIC**
IS – Synchrotron	IS – Proton Synchrotron
IS – SSC	IS – π^0 decay
ES forward shock –synchrotron	ES – Proton Synchrotron
ES forward shock –SSC	ES – Proton SSC
ES reverse shock –synchrotron	Synchrotron and IC from secondary e^+e^-
ES reverse shock –SSC	Strong constraints from IceCube data
Inverse Compton on external photons	But we try our best…….
X-ray Flares –SSC	

(No) neutrinos in coincidence with gamma ray bursts



5.2 events expected
0 events observed

Nature Vol **484**, 351 (2012)

GRB fireball neutrino models tested.

GRBs as THE primary source of highest energy CR strongly disfavored for classes of models (neutron escape)

Results from IceCube: **No signal!!!**

- FB model challenged by Icecube?
- No! Maybe f_π is smaller (Hummer et al. 2012) **If effects of particle physics are taken into account**
- GeV emission from Fermi may be due to pion cascade, the ν flux related to GeV flux. Constrain on hadronic emission models
- Maybe the time window adopted by IceCube is too narrow: some quantum-spacetime models allow for departures from Lorentz invariance such that high-energy particles could experience systematic Planck-scale corrections to their travel times (see, e.g., Amelino-Camelia,LivingReviewRelativity16,5 and refs therein)

LIV implications

Amelino Camelia + Guetta + Piran

arXiv.org > astro-ph > arXiv:1303.1826

If there is in-vacuo dispersion what you actually expect is to never have conclusive GRB-neutrino detections!!

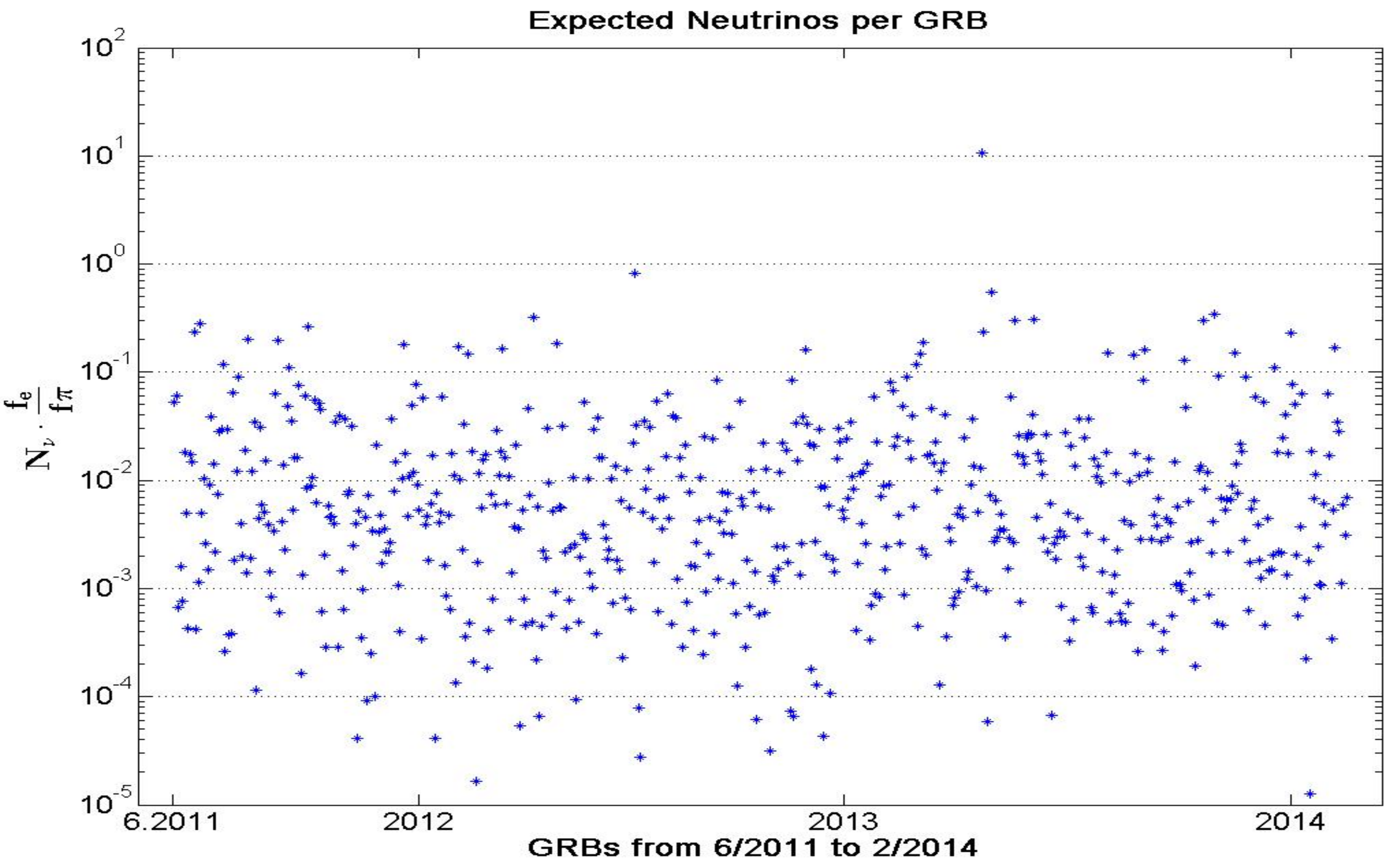
you cannot expect the GRB-neutrino signal to coincide temporally with the trigger of the (lower-energy) GRB-gamma-ray signal!!

Jacob+Piran,NaturePhys3 (2007) 87
AmelinoCamelia+Smolin, PhysRevD80 (2009) 084017

it will look like we have only background neutrinos but with a "funny" temporal distribution with respect to the GRB triggers

especially if we tightly select using directional criteria

Neutrino flux predictions from the GBM



Yacobi, Guetta & Behar in prep.

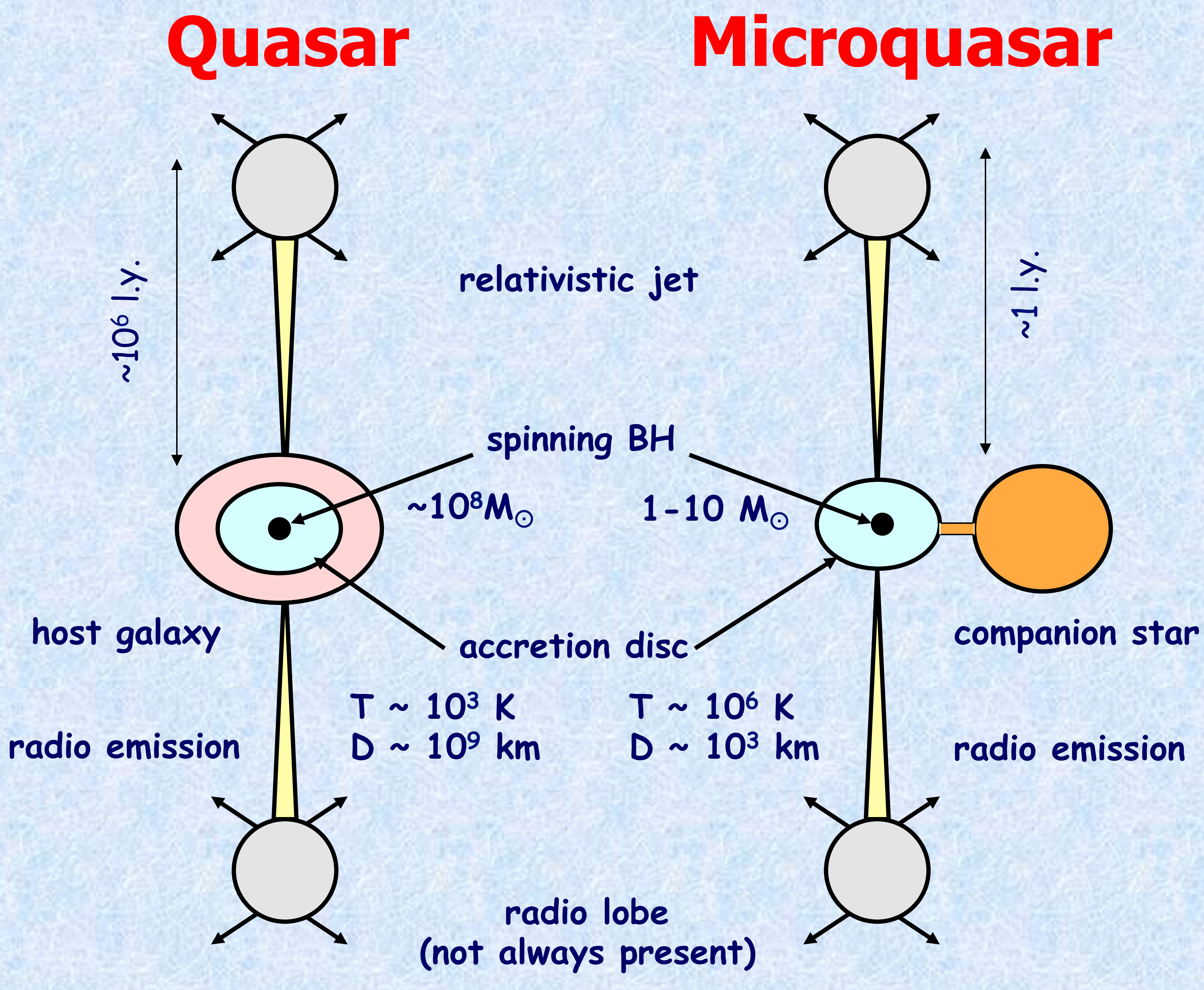
Neutrino signals from known Galactic Microquasars: The case of Cygnus X-3

Distefano, Guetta, Waxman & Levinson, 2003 , ApJ 575, 378
Baerwald & Guetta 2013 ApJ 773 159

Consider a sample of identified MQs and MQs candidates for which available data enables determination of jet parameters

Estimate the neutrino flux during the jet ejection events for the observed microquasars

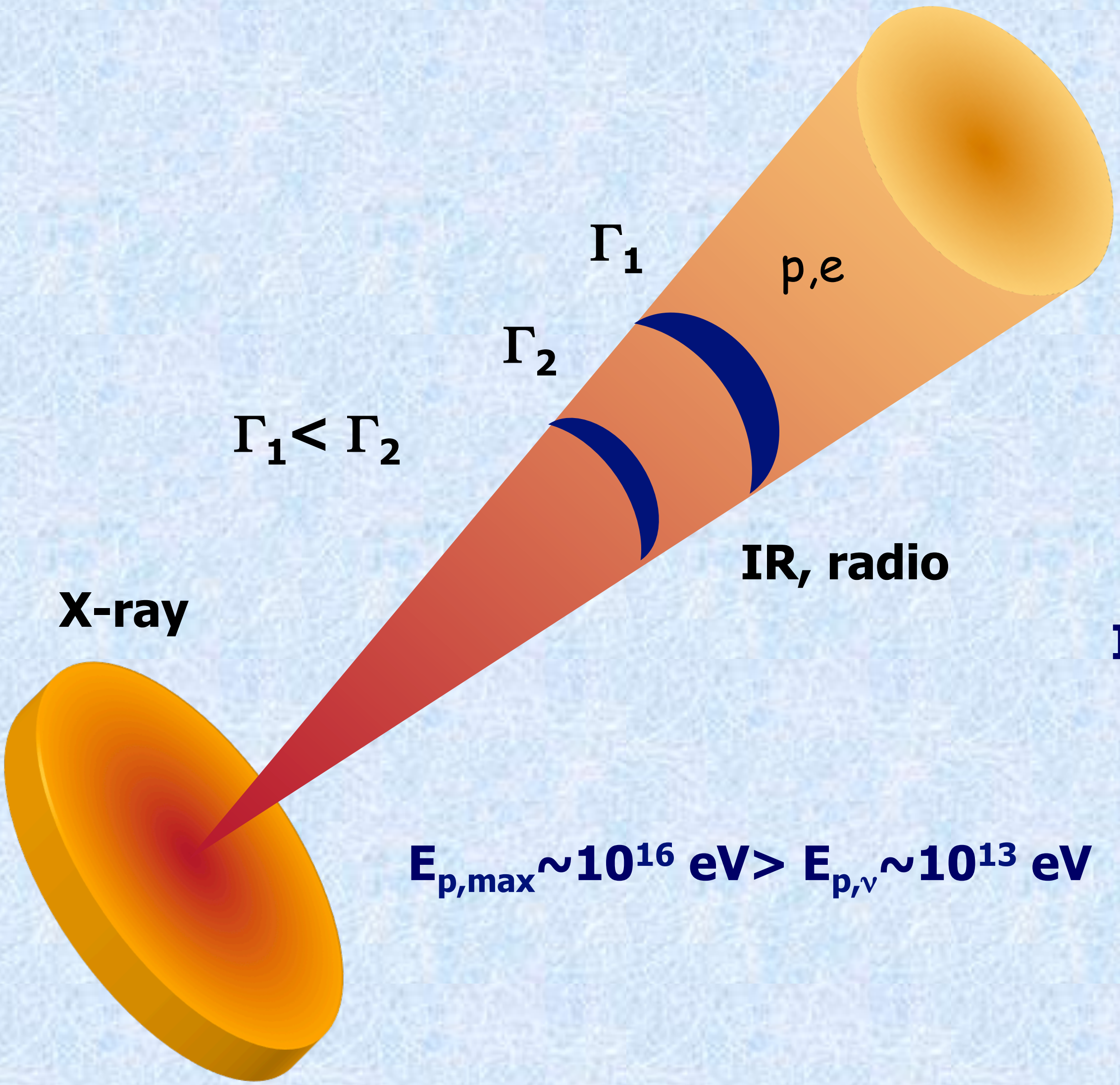
In particular for Cygnus X-3 detected by AGILE.


Quasar
Microquasar
relativistic jet
~10⁶ l.y.
~1 l.y.
spinning BH
~10⁸M☉
1-10 M☉
host galaxy
accretion disc
companion star
T ~ 10³ K
D ~ 10⁹ km
T ~ 10⁶ K
D ~ 10³ km
radio emission
radio emission
radio lobe
(not always present)

Internal shock model

Semi-continuous jets with internal shocks

Levinson & Waxman, 2001



$E_{p,max} \sim 10^{16}$ eV > $E_{p,\nu} \sim 10^{13}$ eV

Plasma shells with different Lorentz factors collide

↓

Internal shocks propagating along the jet

↓

Acceleration of p-e

Neutrino flux at Earth

ν_μ flux at Earth

$$f_{\nu_\mu} \sim \frac{1}{2}\eta_p f_\pi \delta^4 \frac{L_{jet}/8}{4\pi D^2}$$

$$1\,\mathrm{TeV} \leq E_{\nu_\mu} \leq 100\,\mathrm{TeV}$$

f_π depends on the jet LF, Γ, and on L_{jet}

η_p~10%: fraction of L_{jet} carried by accelerated protons

L_{jet}: kinetic luminosity of the jet

δ: jet Doppler factor $\delta=[\Gamma(1-\beta\cos\theta)]^{-1}$

D: source-Earth distance

Microquasars: XRBs with jet resolved in the radio band. In events monitored with good resolution is possible to estimate the jet parameters: Resolved Microquasars

Kinetic luminosity of the jet for resolved microquasars

Source name	D (kpc)	θ	β	L_{jet} (erg/sec)
CI Cam	1	83	0.15	$5.7 \cdot 10^{37}$
XTE J1748-288	8	64	0.73	$1.8 \cdot 10^{39}$
Cygnus X-3	7.2	12	0.81	$1.7 \cdot 10^{39}$
LS 5039	3	68	0.4	$8.7 \cdot 10^{36}$
GRO J1655-40	3.1	81	0.92	$1.6 \cdot 10^{40}$
GRS 1915+105	12.5	70	0.92	$2.4 \cdot 10^{40}$
Circinus X-1	10	70	0.1	$7.6 \cdot 10^{38}$
LS I +61°303 (b)	2	0.2	0.43	$1.6 \cdot 10^{37}$
LS I +61°303 (q)	2	0.2	0.43	$5.7 \cdot 10^{36}$
XTE J1550-564	2.5	74	0.83	$2.0 \cdot 10^{38}$
SS433	3	80	0.3	$1.0 \cdot 10^{39}$
V4641 Sgr	0.5	63	0.85	$8.0 \cdot 10^{37}$
V4641 Sgr	9.6	6	0.999	$1.2 \cdot 10^{40}$
Scorpius X-1	2.8	44	0.95	$1.0 \cdot 10^{38}$

Expected number of events in a km^3 telescope

muon-neutrino detection probability

$$P_{\nu\mu} \sim 1.3 \cdot 10^{-6} \frac{E_\nu}{1\,\mathrm{TeV}} \quad (E_\nu > 1\,\mathrm{TeV})$$

Rate of events :

$$\dot{N}_\mu \sim 0.2 \eta_{p,-1} f_\pi \delta^4 D_{22}^{-2} L_{j,38} A_{eff,km^2} \quad \mathrm{day}^{-1}$$

$$N_\mu = \dot{N}_\mu \Delta t$$

Atmospheric ν background

$$N_{atm}^{\nu} \sim 3 \cdot 10^{-2} \left(\frac{\Delta\Omega}{\deg} \right)^2 t_{day} \frac{A_{eff}}{1\,\mathrm{km}^2}$$

Expected fluxes and neutrino events in a km^2 detector

Source name	Flux (erg/ cm^2 sec)	Δt (days)	N_μ	N_{atm} $\Delta\Omega=0.3°$
CI Cam	$2.2 \cdot 10^{-10}$	~0.56	0.05	0.002
XTE J1748-288	$3.1 \cdot 10^{-10}$	~20	2.5	0.054
Cygnus X-3	$4.0 \cdot 10^{-9}$	~3	5	0.008
GRO J1655-40	$7.4 \cdot 10^{-10}$	~6	2	0.016
GRS 1915+105	$2.1 \cdot 10^{-10}$	~6	0.5	0.016
P=16d Circinus X-1*	$1.2 \cdot 10^{-10}$	~4	0.2	0.011
P=26d LSI +61°303*	$4.5 \cdot 10^{-11}$	~7 (burst)	0.1	0.019
	$9.1 \cdot 10^{-12}$	~20 (quiesc)	0.1	0.054
XTE J1550-564	$2.0 \cdot 10^{-11}$	~5	0.04	0.014
V4641 Sgr	$(0.2 \div 32) \cdot 10^{-9}$	~0.3	0.03÷4	0.001
LS 5039	$1.7 \cdot 10^{-12}$	persistent	0.2	1
SS433	$1.7 \cdot 10^{-9}$	persistent	252	1
Scorpius X-1	$6.5 \cdot 10^{-12}$	persistent	1	1

Constraint on hadronic emission model

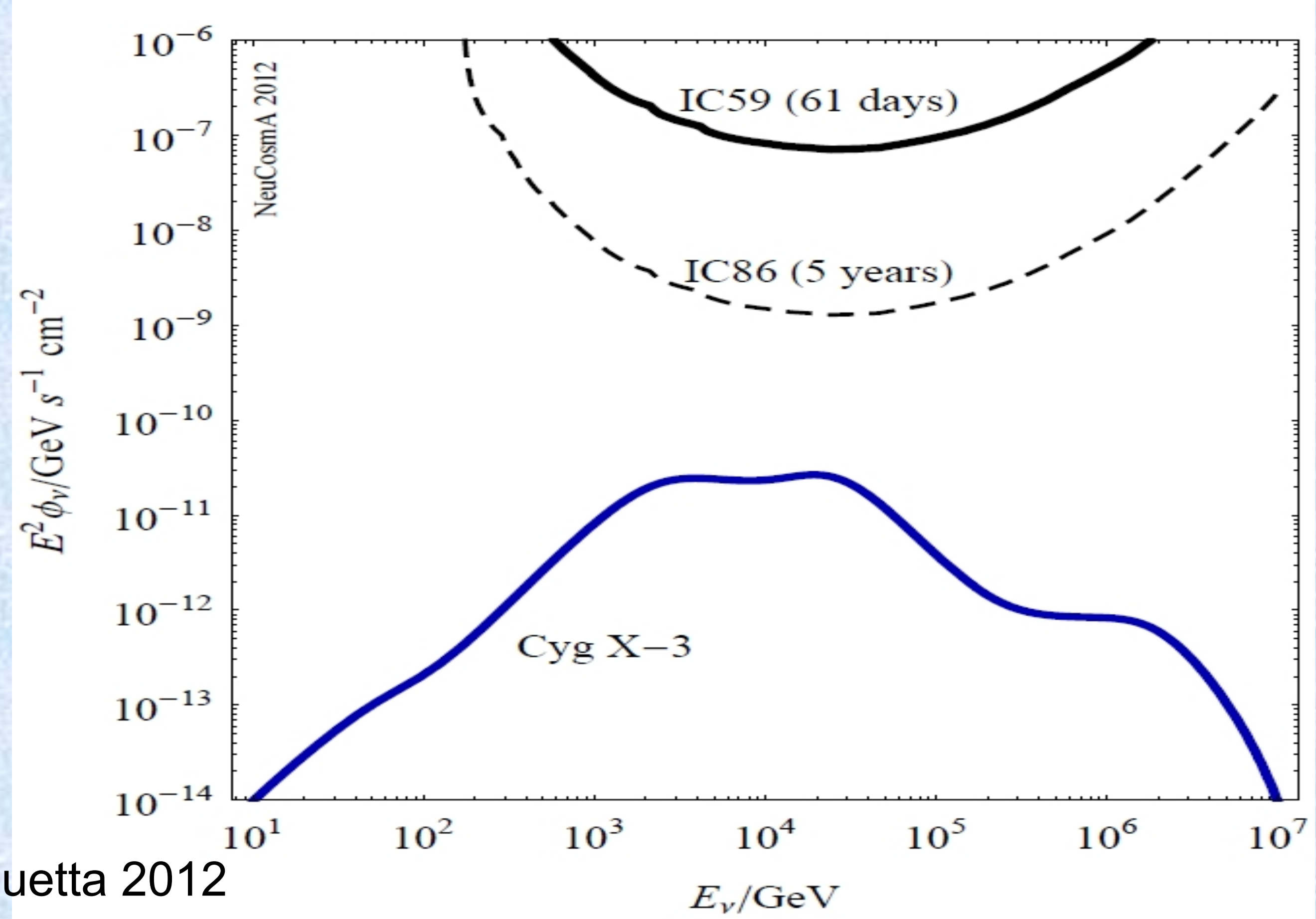
The AGILE discovered several transient $\gamma-$ray emission episodes from Cygnus X-3 in the energy range 100MeV -50GeV during the periods 2009 Jun-Jul and 2009 Dec.-2010 mid-Jun.

How many neutrinos would be expected if the observed -ray emission by AGILE was actually coming from the decay of photohadronically produced π^0 into photons. The photons from such decays would have to cascade down to lower energies and may lose a part of their energy during this process.

As a consequence the nominal amount of expected neutrino events would reach about 5.2 events for the 61 days of flaring in 2009. This can be ruled out from IceCube upper limits!!

Expectations vs Observations

MQs signals well above the atmospheric background! However no neutrino has been detected, fπ too optimistic, we revised fπ apart from the Δ-resonance such as higher resonances, direct production of pions (t-channel), and high energy processes leading to multiple pions.



Baerwald & Guetta 2012

Outlook

- Microquasars are potential sources for neutrino astronomy, detection of ν from MQs first achievable goal for proposed underwater(ice) ν telescopes!!!

- Future program: Look at the Microquasars that emit in the TeV region and constrain hadronic models with IceCube data

Make prediction for the KM3NET telescope!

SOUTH POLE ASKARYAN RADIO ARRAY

Cosmic Rays and Neutrino Sources

Cosmic rays exist at highest energies:

The puzzle

No nearby (<50Mpc) sources observed. More distant sources are not observable in cosmic rays due to collisions with microwave background.

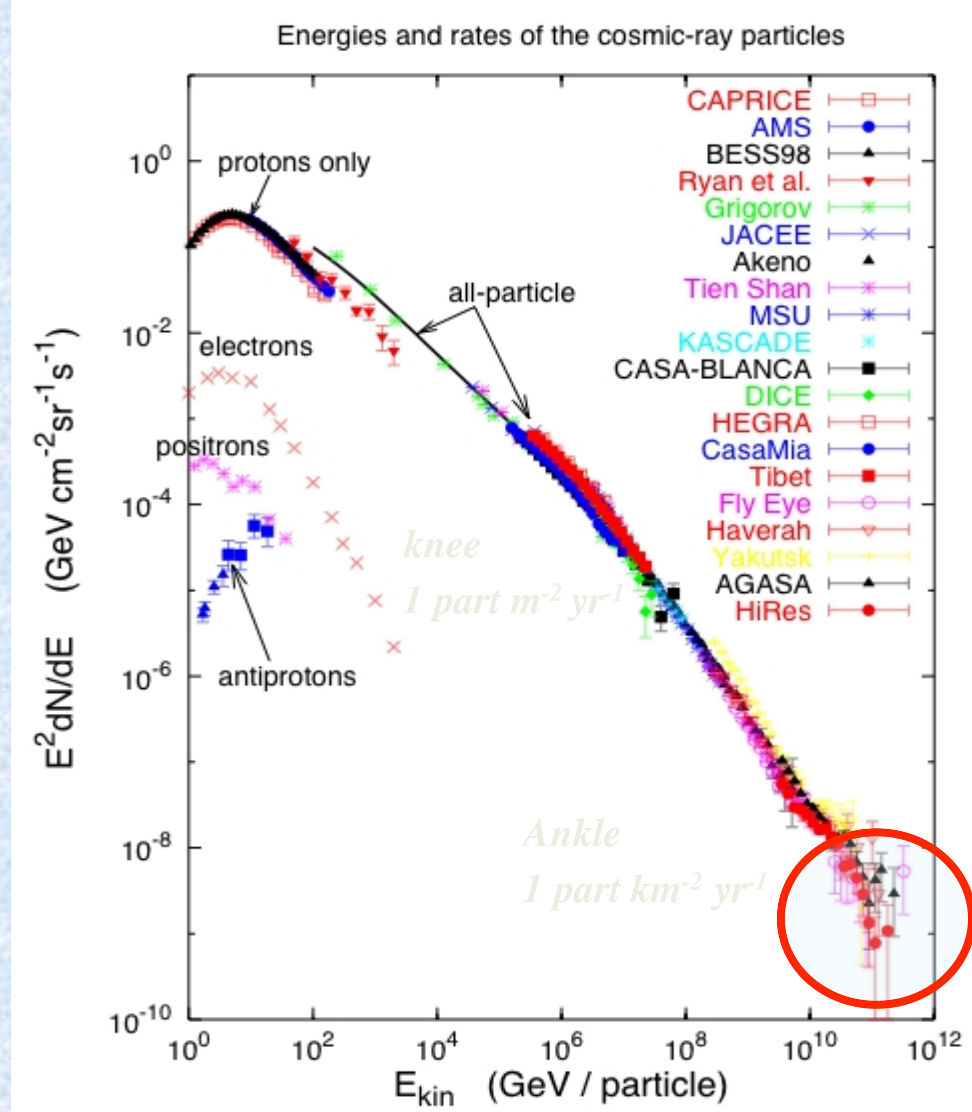
Neutrinos above $10^{17\text{-}19}$eV, GZK or cosmogenic neutrinos are at some level guarantueed.

However, fluxes will be small,

requires very large detectors

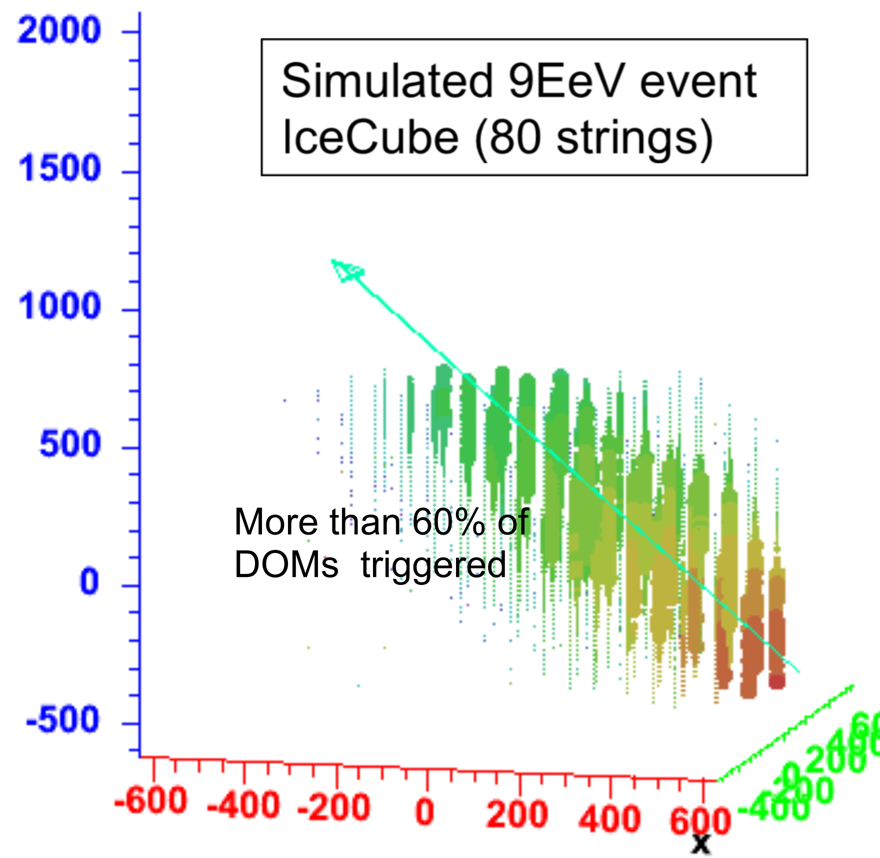
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

Gaisser 2005



Why not Build a Larger IceCube?

IceCube can detect cosmogenic neutrinos, but not enough of them …



Current IceCube configuration:
Yields less than 1 cosmogenic event/ year

Making IceCube bigger is an option:
Some geometry optimization is possible, though:

- Still need dense array scattering
- Still need deep holes for better ice

Any additional string will cost ~1M \$*

A larger detector requires a more efficient and less costly technology.

*Rough estimation, Real cost will likely be higher

107 to 1011GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA)

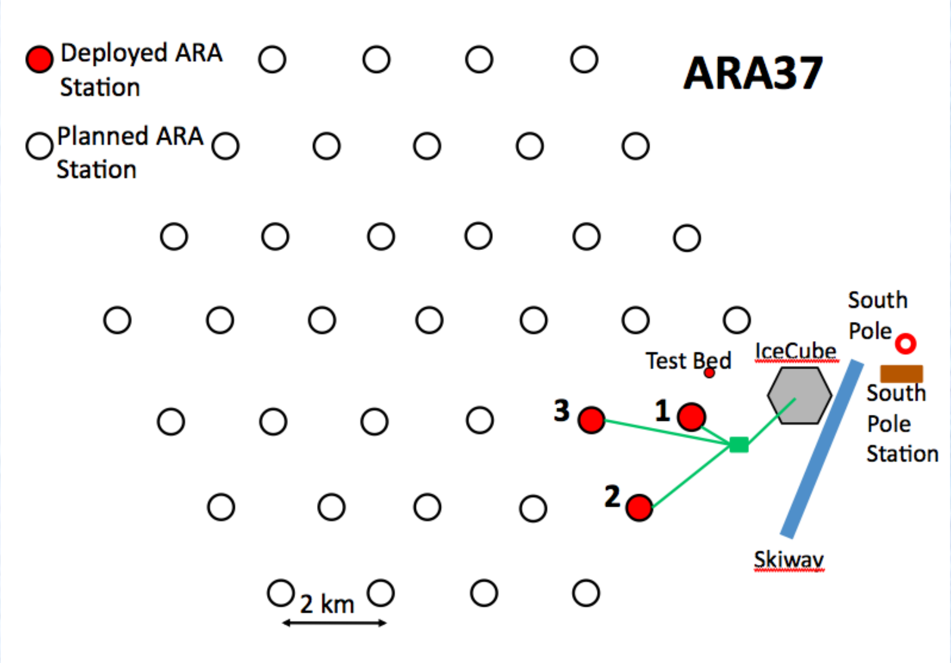
- a very large radio neutrino detector at the South Pole

Scientific Goal:

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

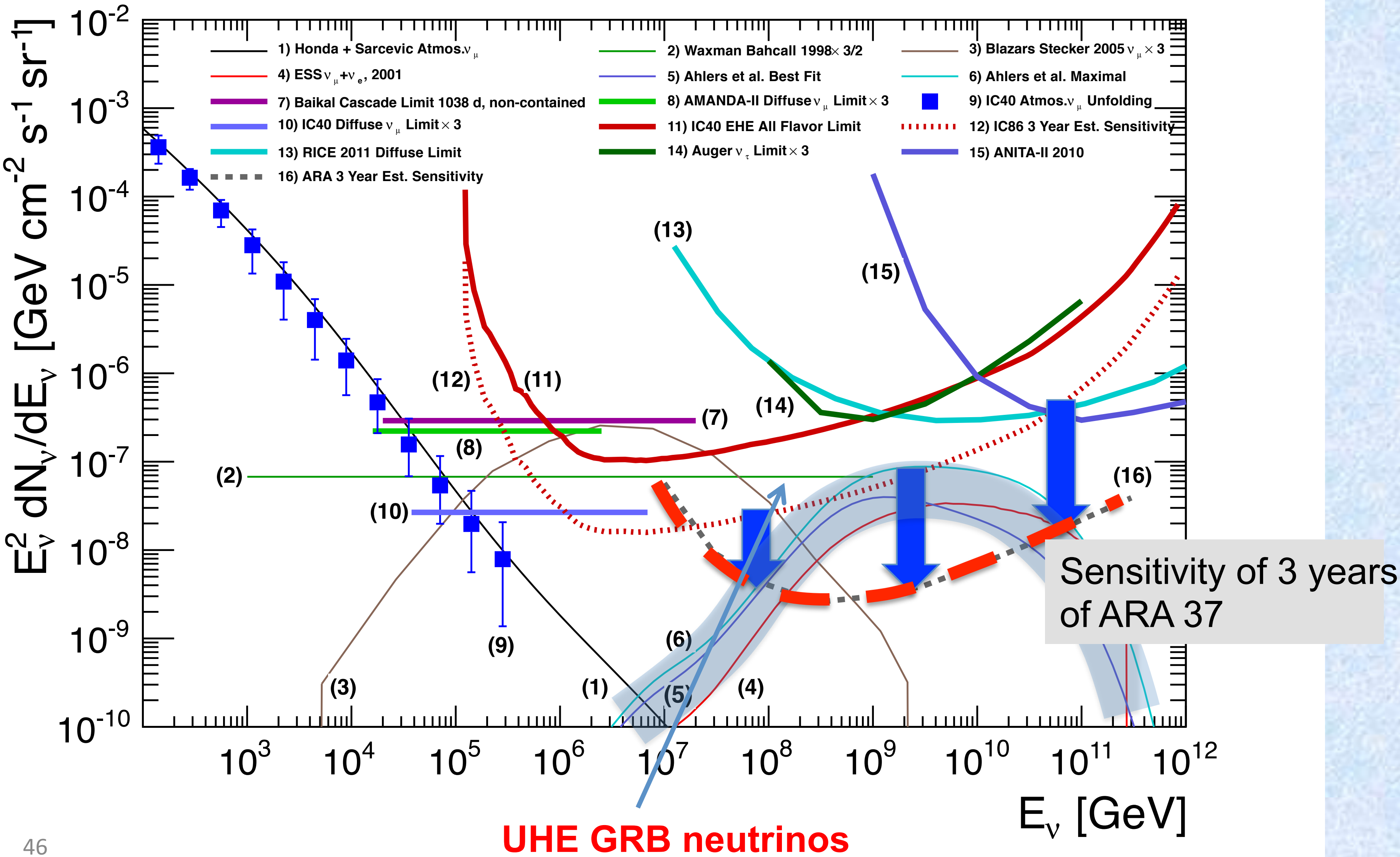
Method:

Monitor the ice for radio pulses generated by interactions of cosmic neutrinos



Areal coverage: ~150 km^2

The cosmic energy frontier, 10^7 to 10^{11} GeV
Cosmogenic or GZK neutrinos



SOUTH POLE
ASKARYAN RADIO ARRAY

ARA current status

<u>Phase 1 2010-2013 completed!</u>

- 4 in-ice stations installed
- Data is continuously flowing from South Pole

- 3 stations Comparable to sensitivity of IceCube at 10^{18}eV

<u>Phase 2: 2014-2016 :</u>
Additional 3 stations.
Proposal submitted to NSF. Awaiting decision

<u>Local (il) involvement:</u>
-BSF grant (Weizmann, with wisconsin Kansas, Ohio) for theoretical work, data analysis and online detector operation
(Guetta, Waxman, Landsman)

<u>In Weizmann:</u>
1 scientist (20%), 1 student in collaboration:
- Online detector operation and data flow
- Data analysis and simulation
- Possible future electronic design
- UHE neutrinos from GRBs