e1

טכניון

המכללה האקדמית להנדסה
אורט בראודה
ORT BRAUDE COLLEGE

OAR

Neutrinos from Astrophysical sources in the IceCube and ARA Era

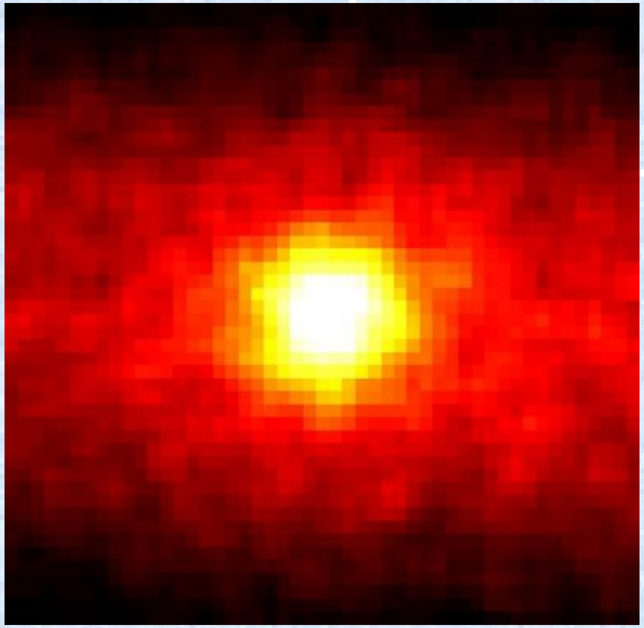
Dafne Guetta

Slide 1

e1 add Technion
ehud, 2/23/2014

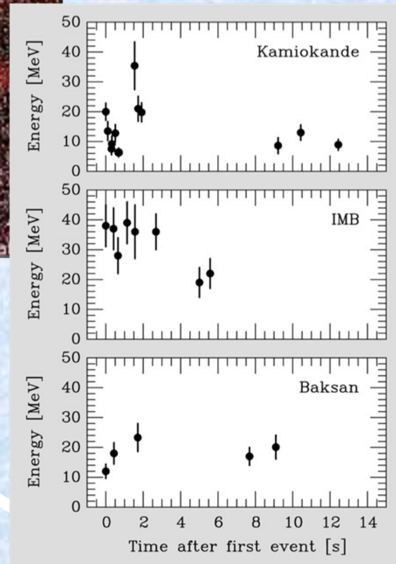
Extraterrestrial Neutrinos

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



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

Supernova 1987a



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

Are there neutrino sources at higher energies,
Possibly extragalactic?

Cosmic Rays and Neutrino Sources

Can neutrinos reveal origins of cosmic rays?

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

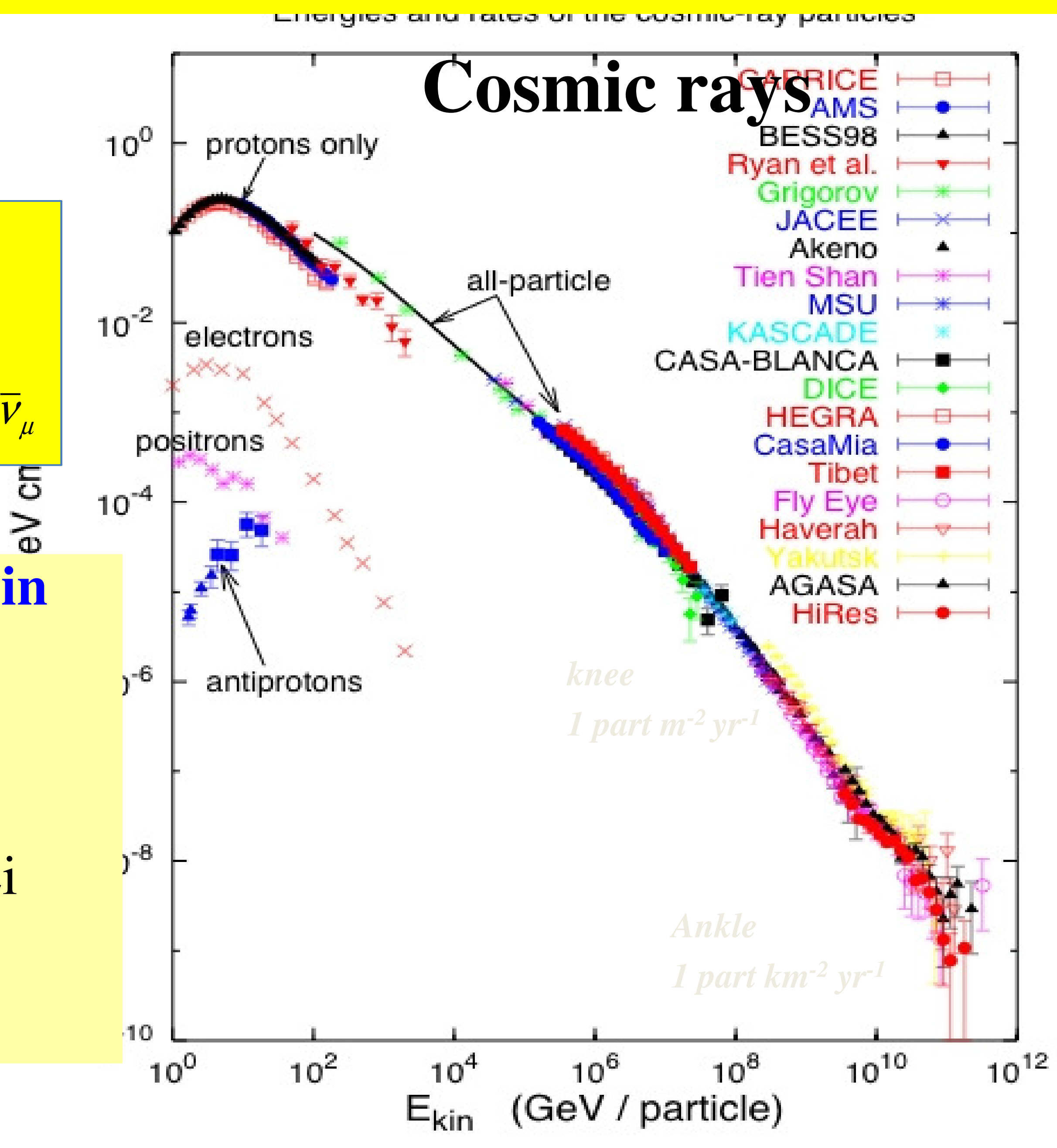
$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

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

Cosmic ray interaction in accelerator region

Prime Candidates

- SN remnants
- Active Galactic Nuclei
- Gamma Ray Bursts



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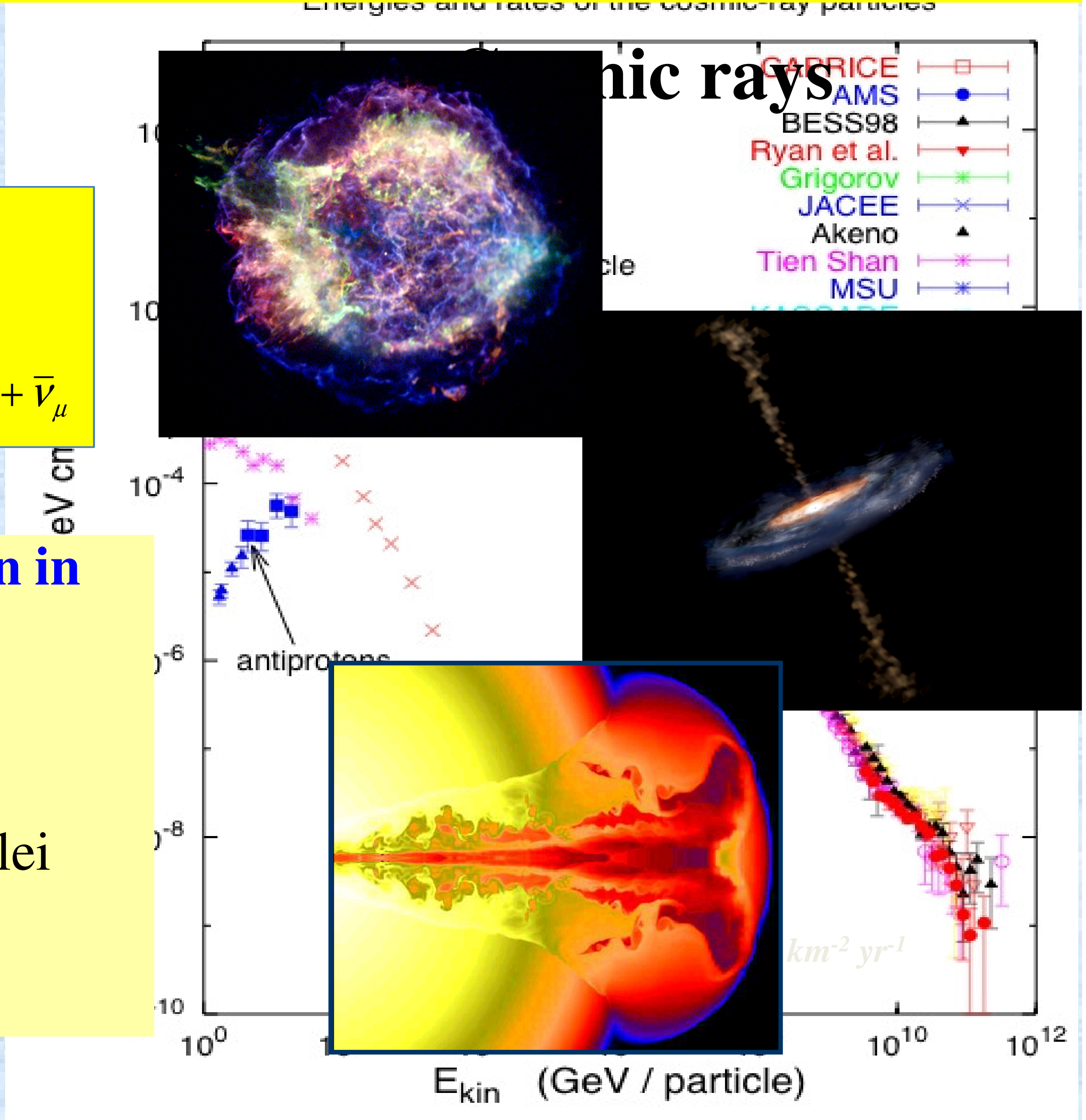


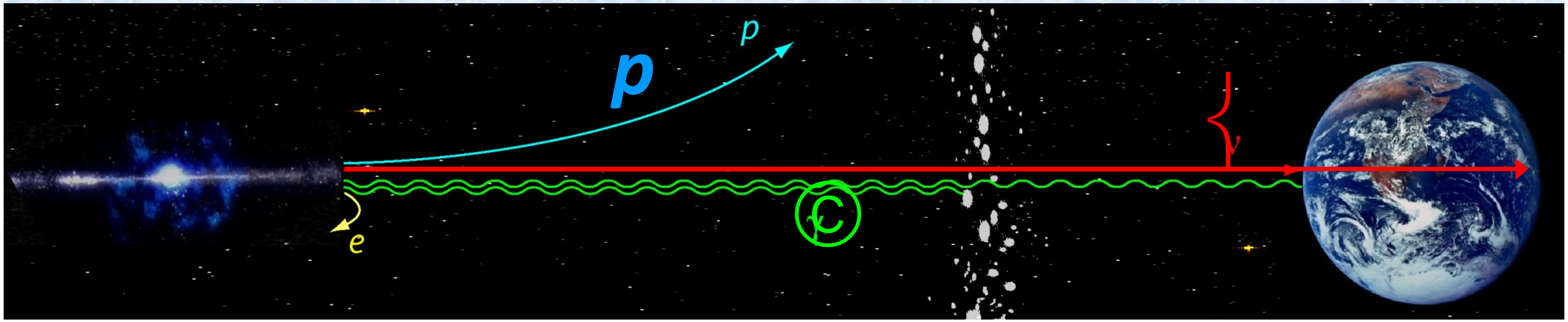
Cosmic neutrinos?

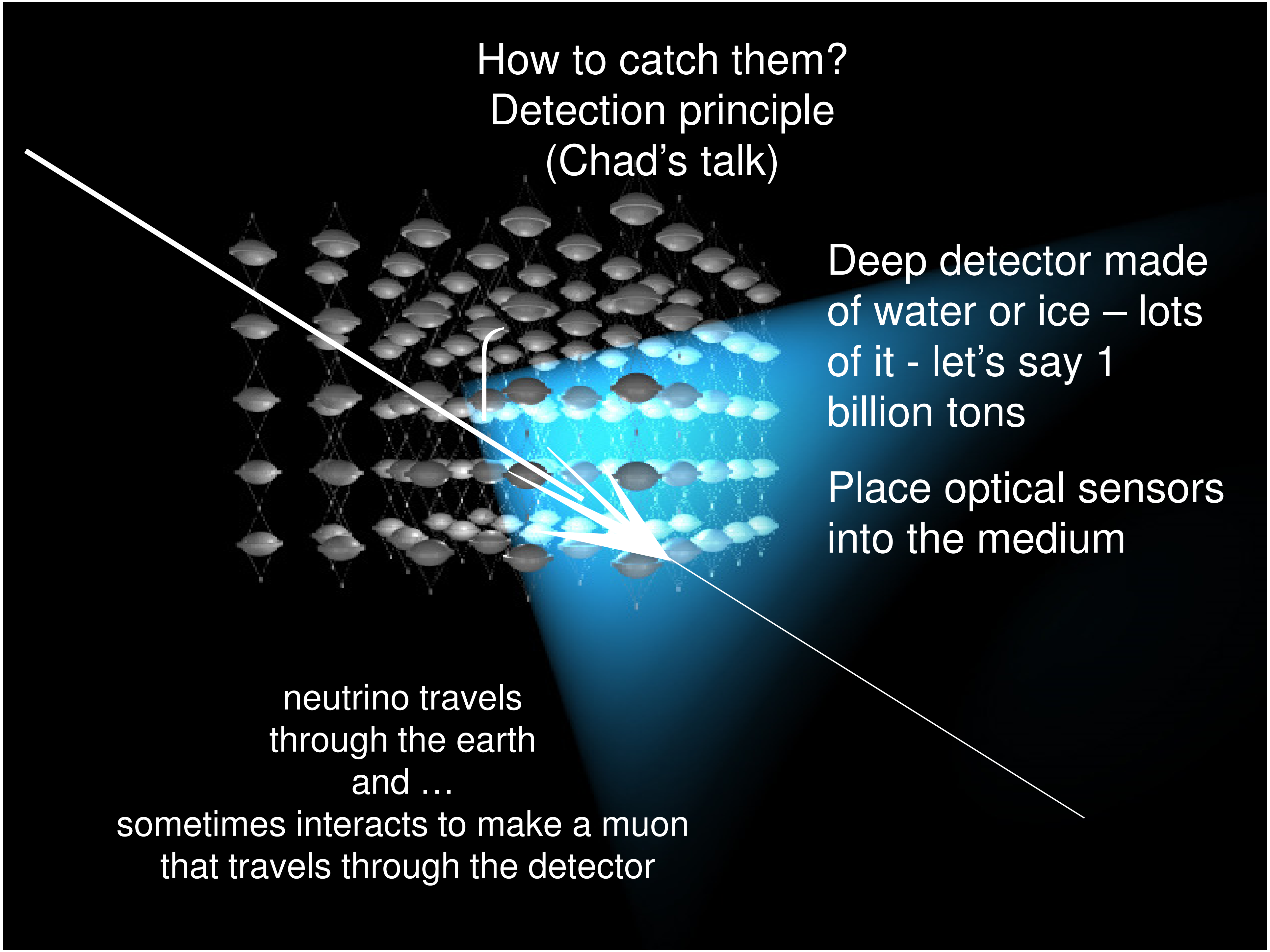
Why look for them?

- 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,
  - Composition of astrophysical jets …

Can they reach us?

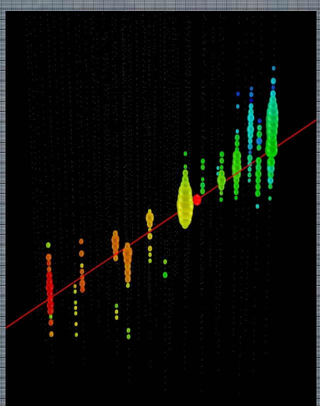
- High energy neutrinos will pass easily and undeflected through the Universe
  - That is **not** the case for other high energy particles: such as photons or other cosmic rays, eg protons.




How to catch them?
Detection principle
(Chad's talk)
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

Neutrino Event Signatures

CC Muon Neutrino

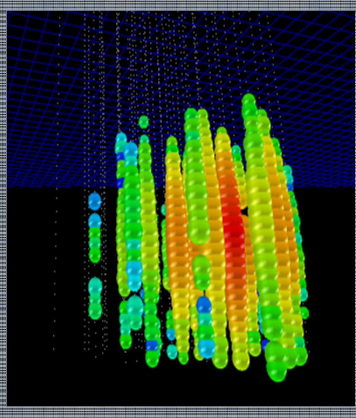


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 0.5° angular resolution

Neutral Current /Electron Neutrino



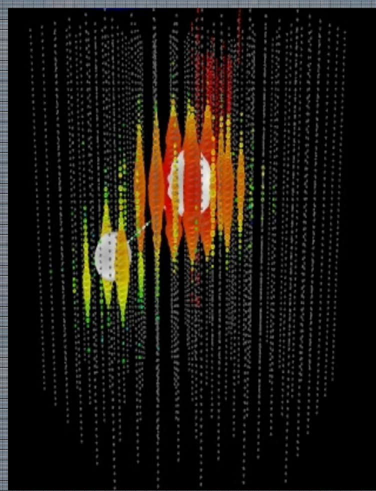
$$\nu_e + N \rightarrow e + X$$

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

cascade (data)

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

CC Tau Neutrino

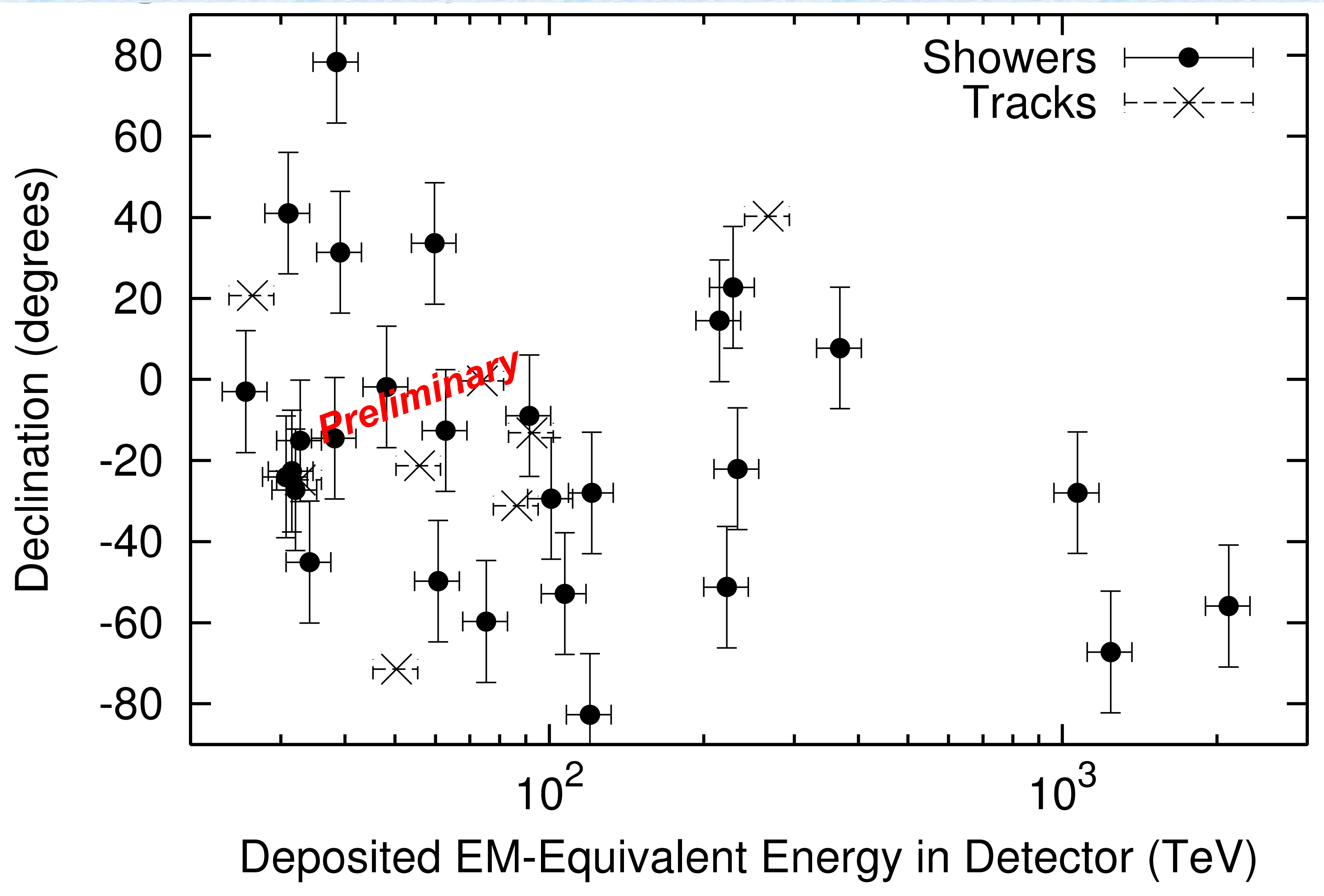


$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures (simulation)

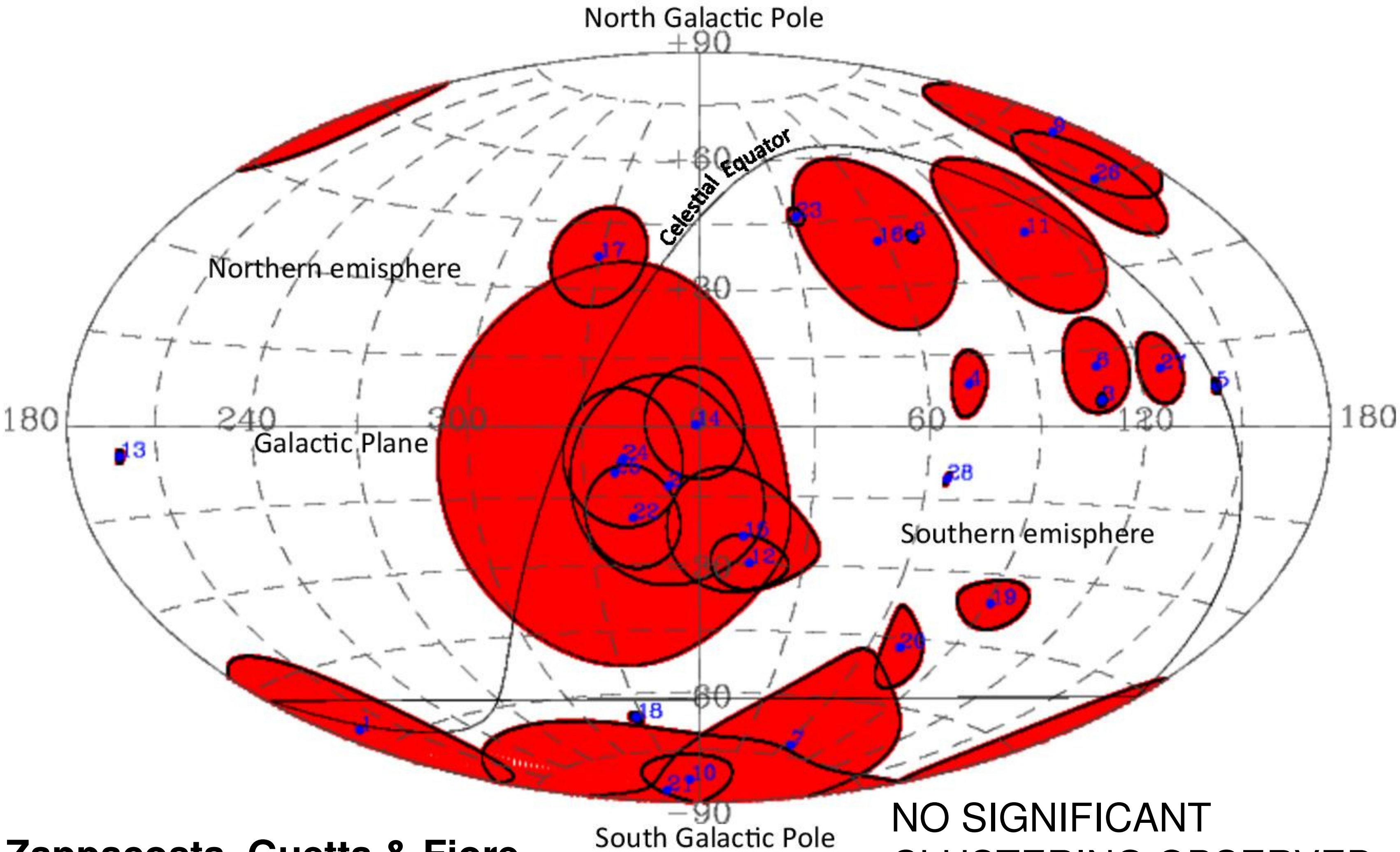
(not observed yet)

From 2 to 3 years: Declination vs energy



Evidence for astrophysical neutrinos of very high energy.

IceCube neutrino events in galactic coordinates



Zappacosta, Guetta & Fiore

NO SIGNIFICANT CLUSTERING OBSERVED.

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.**

Fundamental to have multiwavelength analysis to identify the sources (Eli's, Fabian's talks)

An astrophysical neutrino flux?!

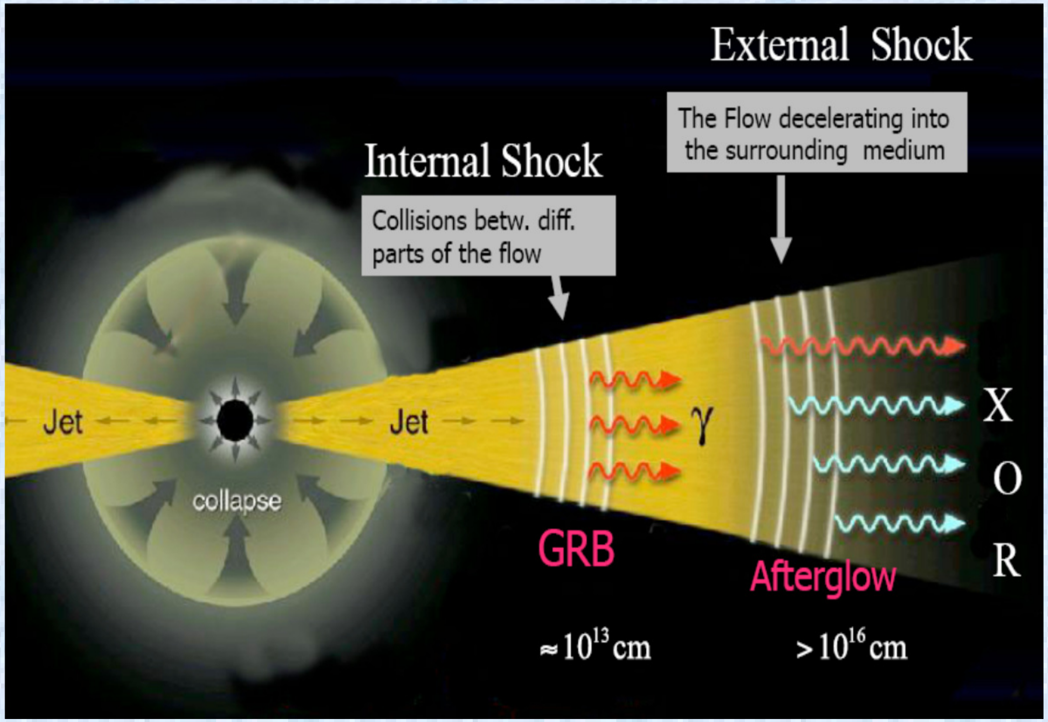
- IceCube data provide strong evidence for an astrophysical neutrino flux
- Consistent with:
  - 1:1:1 all flavor neutrino flux – as expected for astrophysical sources
  - Isotropic distribution, north, south – specifically no evidence for galactic association.

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? (Eli's talk)

Important to have another neutrino telescope km3net!!!

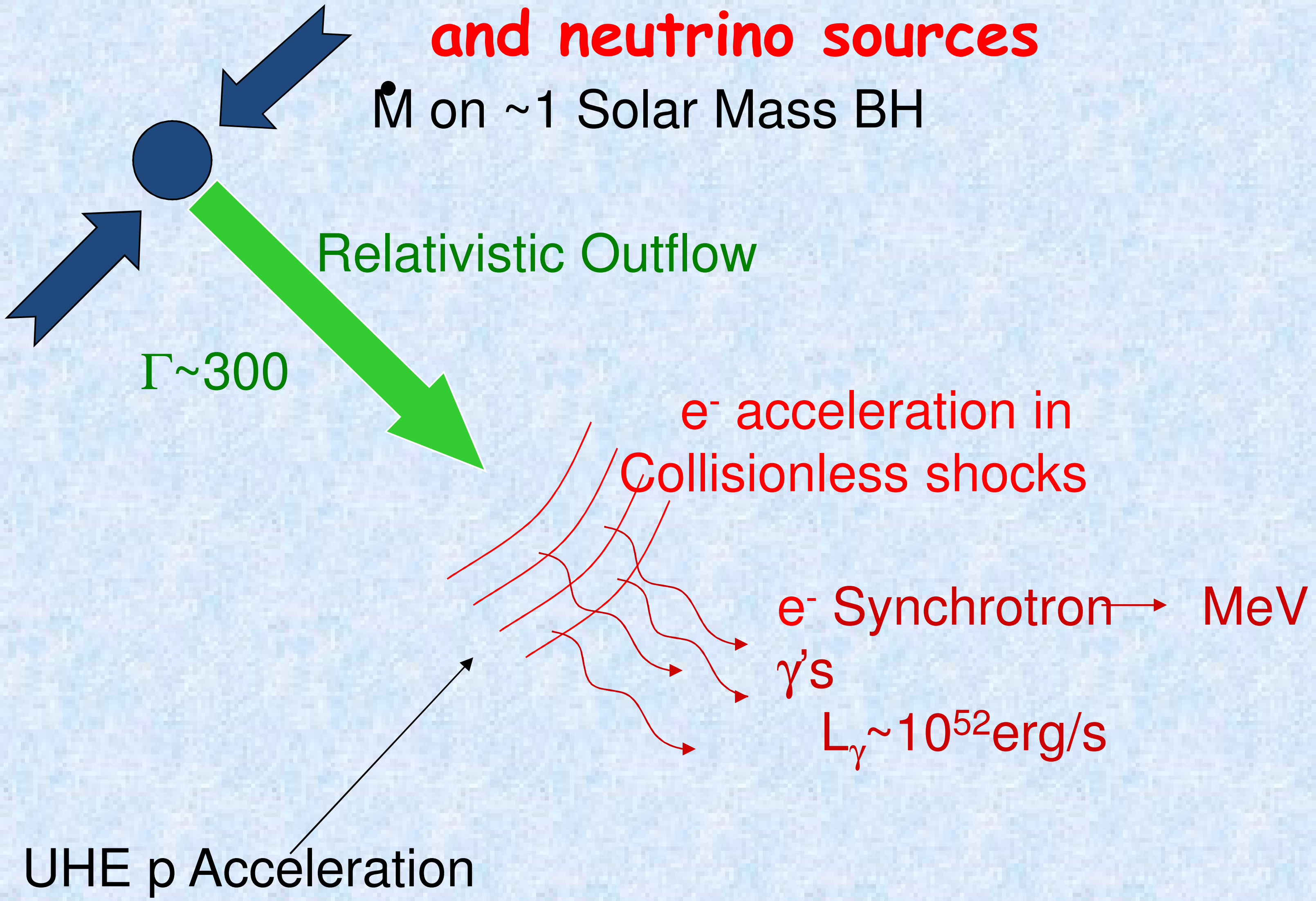
GRB Theoretical Framework:

- **Progenitors**:
  - Long: massive stars
  - Short: binary merger?
- **Acceleration**: fireball or magnetic?
- **Prompt γ-rays**: internal shocks? magnetic plasma?



- **Deceleration**: the outflow decelerates as it sweeps-up the external medium
- **Afterglow**: from the long lived **forward** shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray → optical → radio

Gamma-ray Bursts as particle accelerators and neutrino sources

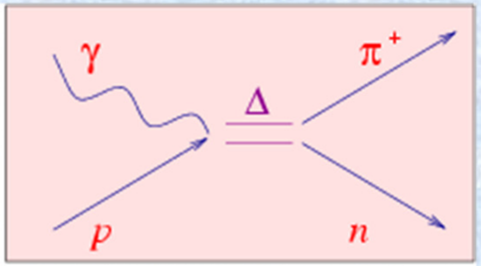


[Meszaros, ARA&A 02;
Waxman, Lecture Notes in Physics 598 (2003).]
]

The main mechanism: photomeson interaction

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

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



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

Fireball

Int. Shocks $E\gamma \sim$ MeV: $Ep \sim 10^{16}$ eV ⇒ $E\nu \sim 10^{14}$ eV

Ext. shock $E\gamma \sim$ keV : $Ep \sim 10^{19}$ eV ⇒ $E\nu \sim 10^{17}$ eV

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

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/cm²
$\begin{cases} \beta=0 & E_\nu > E_\nu^b \\ \beta=1 & E_\nu < E_\nu^b \end{cases}$

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/cm²
$\begin{cases} \beta=1/2 & E_\nu > E_\nu^b \\ \beta=1 & E_\nu < E_\nu^b \end{cases}$

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

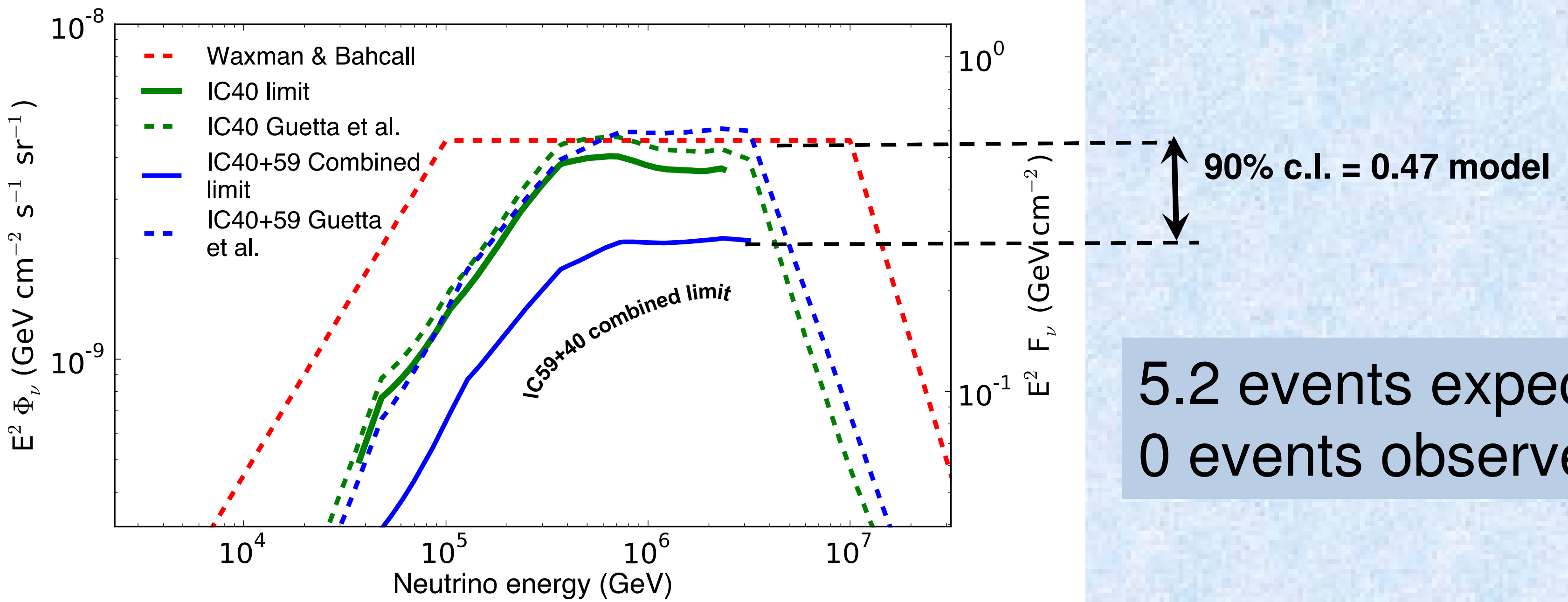
Implications

- $J_{\circ} \sim 10/\ km^2\ yr$, $E_\nu \sim 100$ TeV from internal shocks
- $J_{\circ} \sim 5/\ km^2\ yr$, $E_\nu \sim 100$ PeV from ext. shock + wind

Help to resolve open questions in astrophysics:

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

(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)

Fermi data: Constrain on Hadronic content $\frac{f\pi}{fe}$

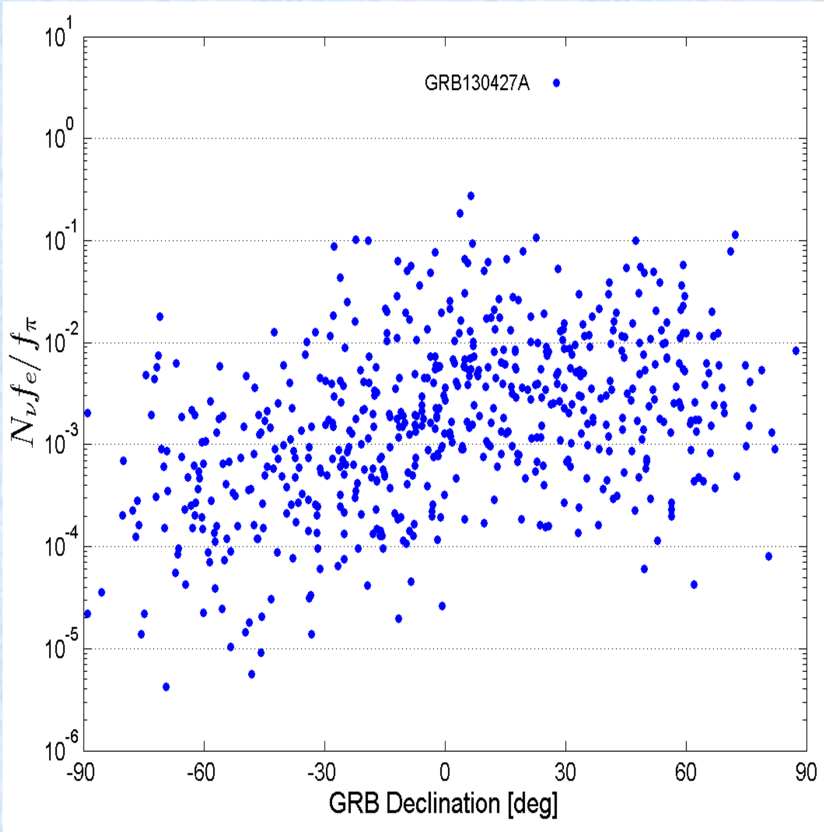
- GRB130427A alone yielding

$$N_\nu \frac{f_e}{f_\pi} \approx 3.5$$ lead to a

constraint of: $\frac{f\pi}{fe} < \frac{3}{3.5}$

- Estimation for IceCube entire

lifetime $\frac{f\pi}{fe} < \frac{3}{13}$ (95%CL)



Lee, Guetta & Behar 2014, ApJ 793, 48

Results from IceCube

- We use the lack of GRB-associated neutrinos over the entire lifetime of IceCube to constrain a overall hadronic fraction to $f_\pi/f_e < 0.25$

- We used the observed GeV GRB fluence to constrain individual GRBs down to $f_\pi/f_e \leq 0.03$

- This low hadronic fraction constraint, along with the failure of GRBs to explain the observed UHECRs (Abbasi et al. 2012) contribute to the growing questions regarding the physical presence of PeV-EeV protons in GRBs

- Constrain the fireball model

- The longer IceCube goes without detecting a GRB neutrino, the constraint on f_π/f_e will tighten

UHE neutrinos and ARA

The universe is opaque to HE Photons

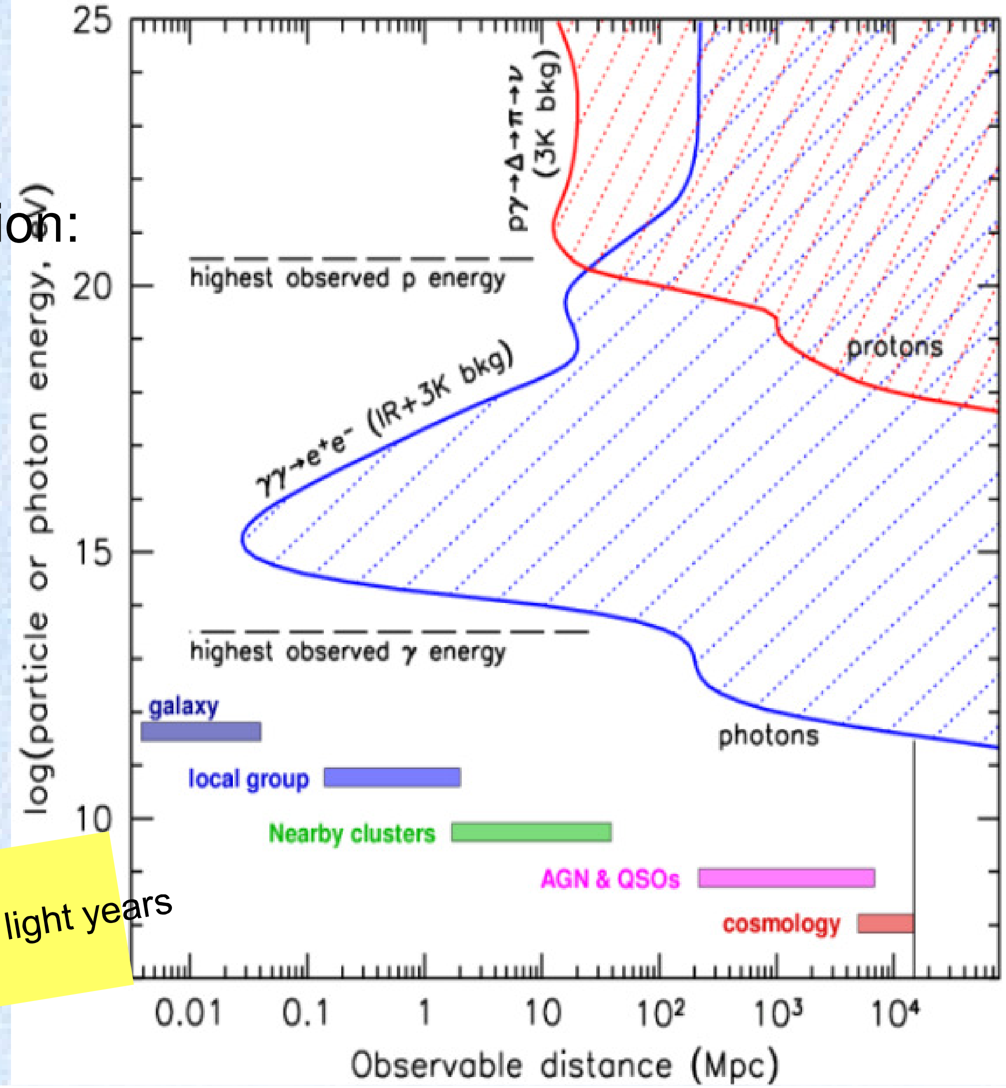
HE photons absorbed by pair production:

$$\gamma + \gamma_{bck} \rightarrow e^- + e^+$$

Photon with 10^{15} eV is limited to 0.1Mpc

- ❑EeV γ (10^{18} eV) on radio-waves
- ❑ PeV γ (10^{15} eV) on cosmic microwave background
- ❑ TeV γ (10^{12} eV) on infrared light

Reminder:
1 Parsec = 3.1×10^{13}Km = 3.3 light years
1Mpc=3,300,000 light years



The universe is also opaque to HE Protons

Proton interact with CMB (T=2.7k)

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

$p + \gamma \rightarrow \Delta^+ \rightarrow e^+ + e^- + p$

Pion photo production (dominant above 10^{19} eV):

Threshold energy: 5×10^{19} eV

Interaction length =10MpC

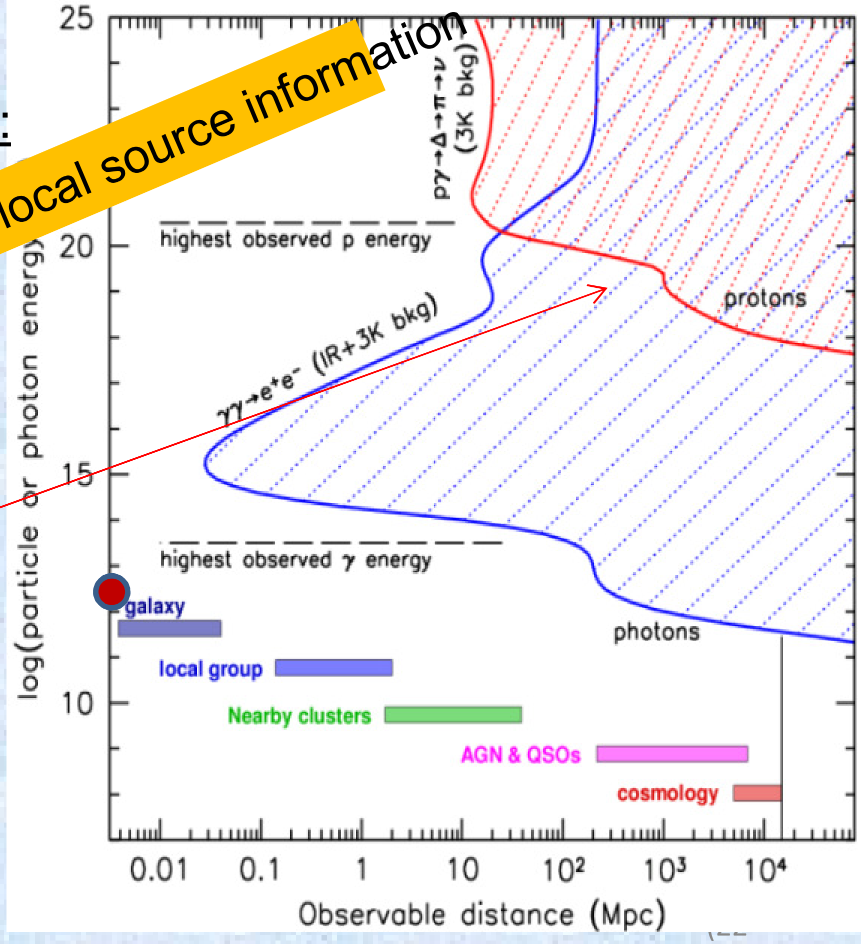
only extragalactic CR are effe… …alaxy R= 15kPC)

Pair Prodctio… …all depression 10^{18}-10^{20} eV):

Threshold energy: 7×10^{17} eV

GZK horizon – UHECR provide only local source information

"The dip"



Greisen-Zatsepin-Kuzmin (GZK) cutoff:
Upper bound to maximum energy for a proton traveling intergalactic distances.

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.

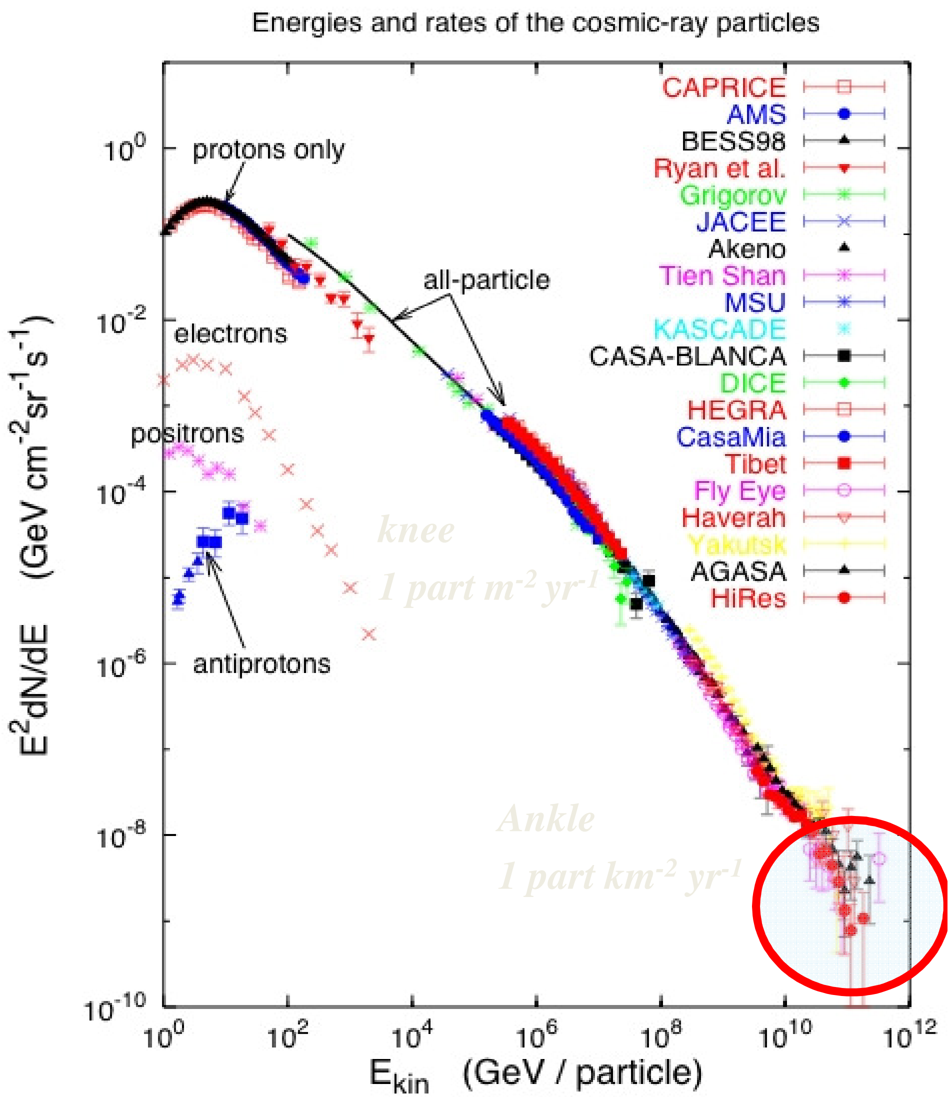
Neutrinos above $10^{17\text{-}19}$eV, GZK or cosmogenic neutrinos are at some level guarantueed.

However, fluxes will be small,

requires very large detectors

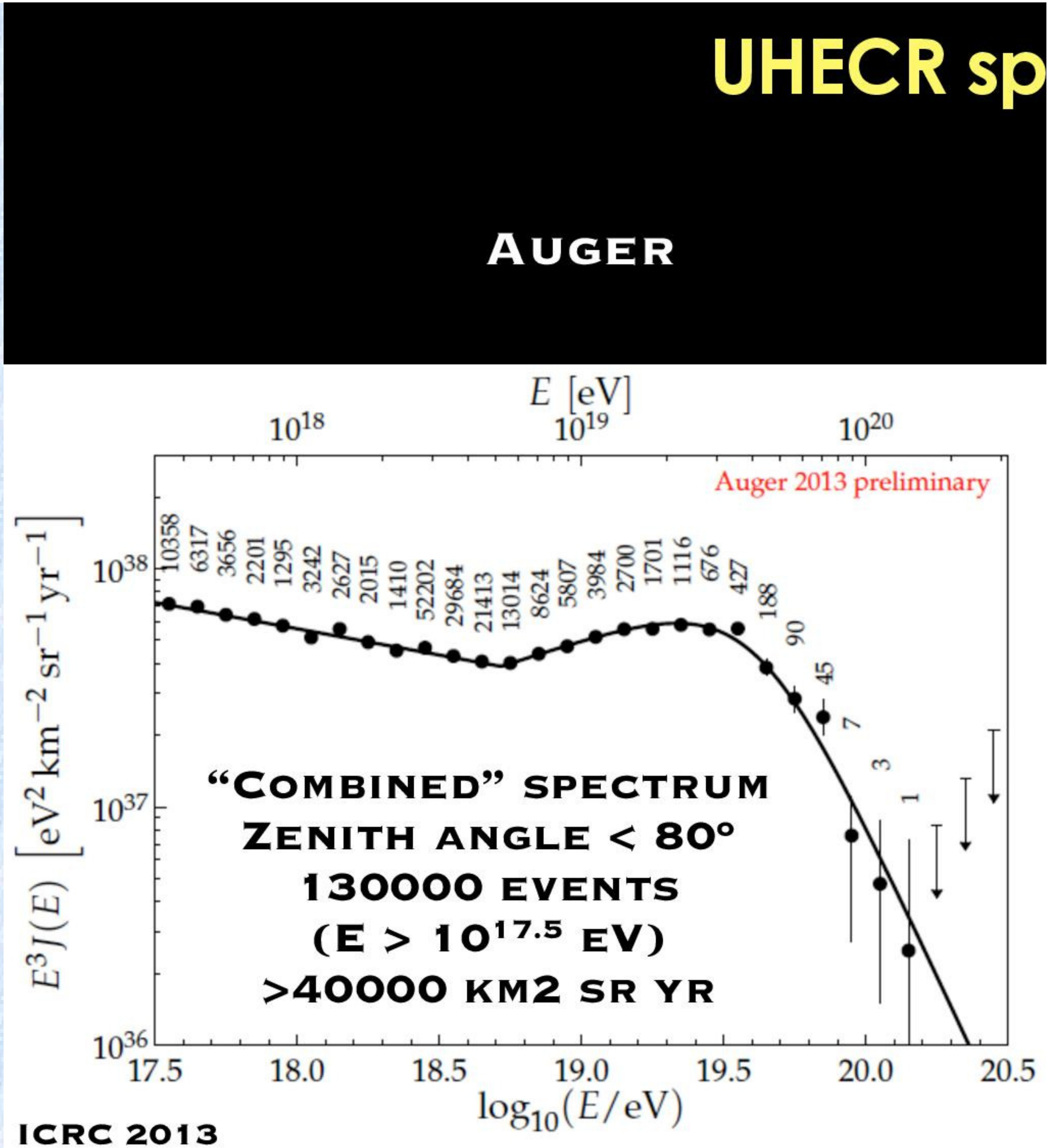
$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi^{0}$$
$$\rightarrow n + \pi^{+}$$

Gaisser 2005



UHECR Spectrum
Telescope Array and Auger confirm the steepening that agrees with GZK-like effect (Piera and Isabelle talks)

Is the steepening due to GZK cutoff?



UHE neutrinos from Gamma Ray Bursts

Nir, Guetta & Landsman in preparation

- Use the UVOT data on Swift to determine the photon flux of the reverse shock During the afterglow emission

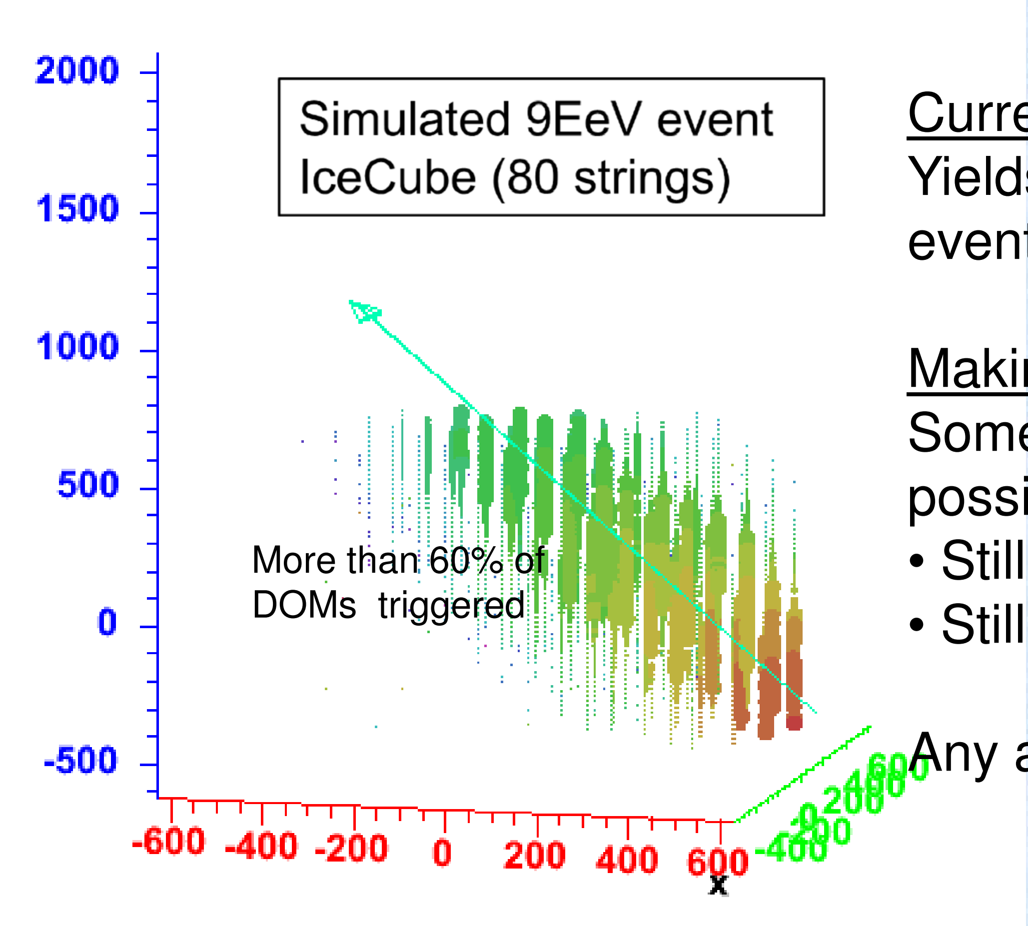
- The accelerated protons may interact with these low energy photons producing 10^{17} eV neutrinos

- The flux of these neutrinos may be constrained by the future ultra high energy neutrinos detector

SOUTH POLE ASKARYAN RADIO ARRAY

Why not Build a Larger IceCube?

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



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

<u>Making IceCube bigger is an option:</u>
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

ARA- Collaboration

- ARA is an international Collaboration
  - 14 institutions
  - ~50 authors

Design and Initial Performance of the Askaryan Radio Array Prototype EeV Neutrino Detector at the South Pole

P. Allison,[1] J. Auffenberg,[2] R. Bard,[3] J. J. Beatty,[1] D. Z. Besson,[4] S. Böser,[5] C. Chen,[6] P. Chen,[6] A. Connolly,[1] J. Davies,[7] M. DuVernois,[2] B. Fox,[8] P. W. Gorham,[8] E. W. Grashorn,[1] K. Hanson,[9] J. Haugen,[2] K. Helbing,[10] B. Hill,[8] K. D. Hoffman,[3] M. Huang,[6] M. H. A. Huang,[6] A. Ishihara,[11] A. Karle,[12] D. Kennedy,[4] H. Landsman,[2] A. Laundrie,[2] T. C. Liu,[6] L. Macchiarulo,[8] K. Mase,[11] T. Meures,[9] R. Meyhandan,[8] C. Miki,[8] R. Mo… M. Newcomb,[2] R. J. Nichol,[7] K. Ratzlaff,[13] M. Richman,[3] L. Ritter,[8] B. Rotter,[8] P. Sandstrom,[2] D. Se… J. Touart,[3] G. S. Varner,[8] M. -Z. Wang,[6] C. Weaver,[12] A. Wendorff,[4] S. Yoshida,[11] and R. Young…

(ARA Collaboration)

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…sics, Grad. Inst. of Astrophys.,& Leung Center for Cosmology and Particle Astrophysics, National Taiwan …
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SOUTH POLE ASKARYAN RADIO ARRAY

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KU

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מכון ויצמן למדע WEIZMANN INSTITUTE OF SCIENCE

107 to 1011GeV: Radio ice Cherenkov detection

Askaryan Radio Array (ARA)

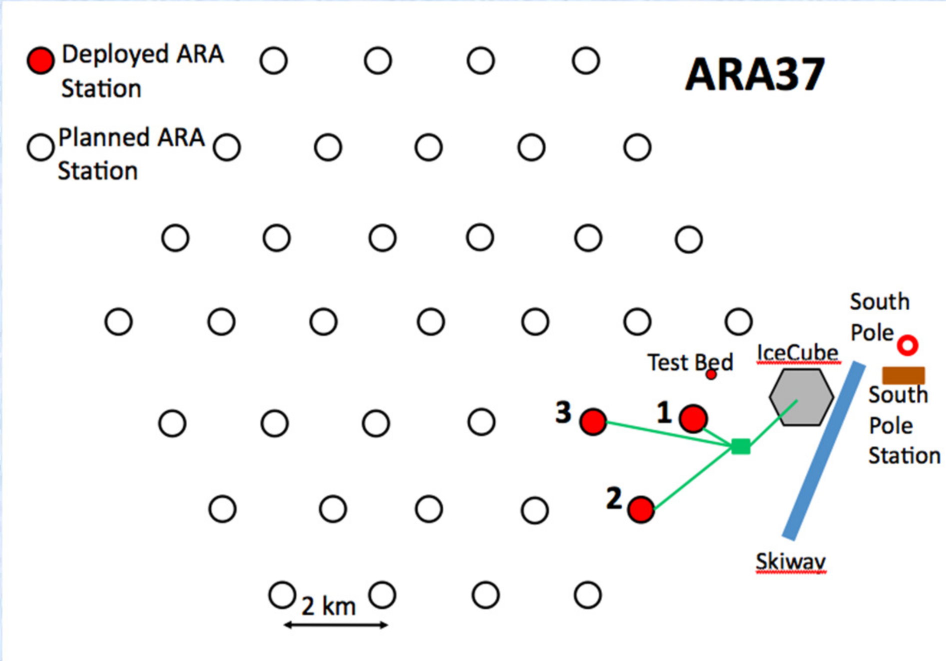
- a very large radio neutrino detector at the South Pole

Scientific Goal:

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

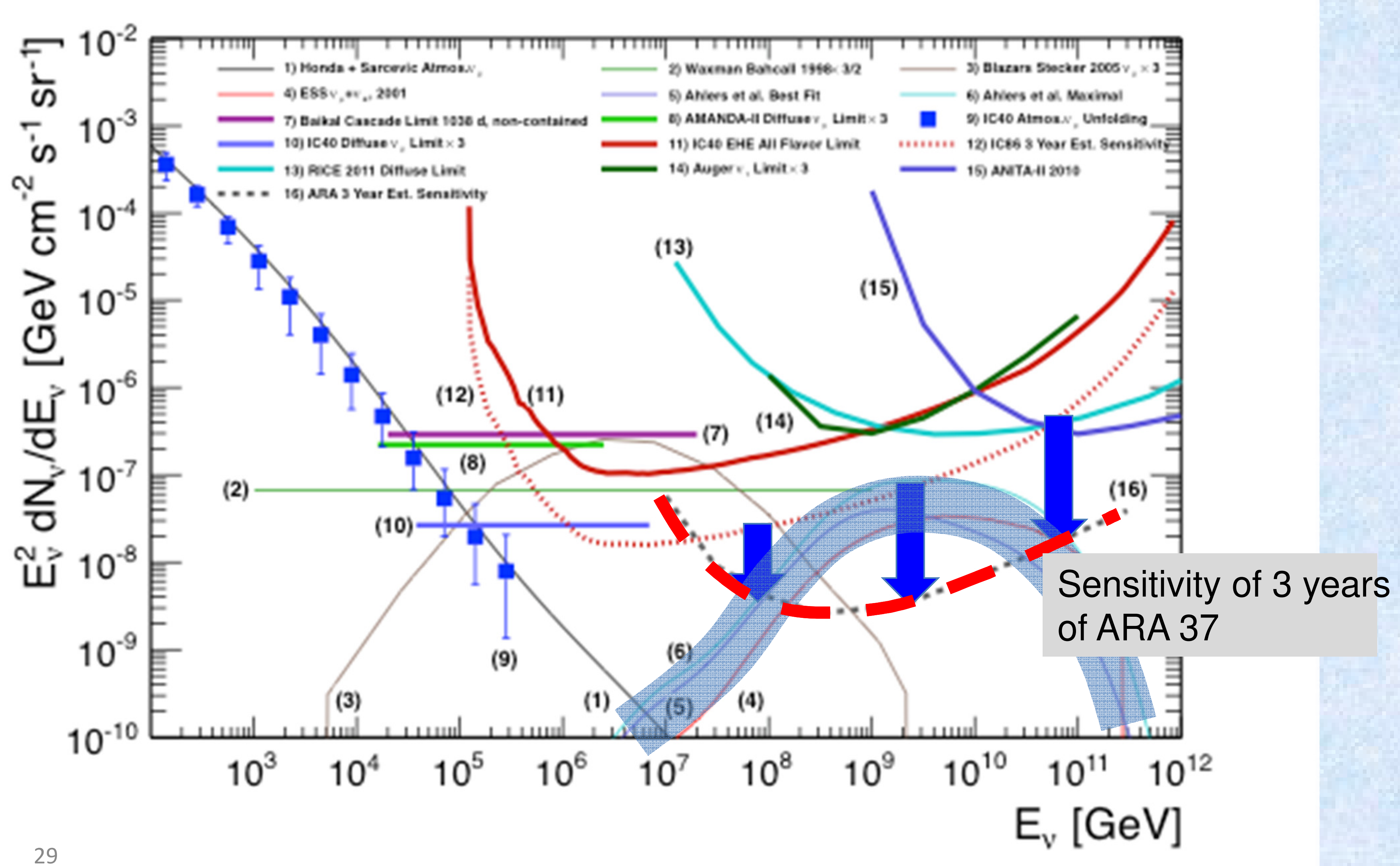
Method:

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



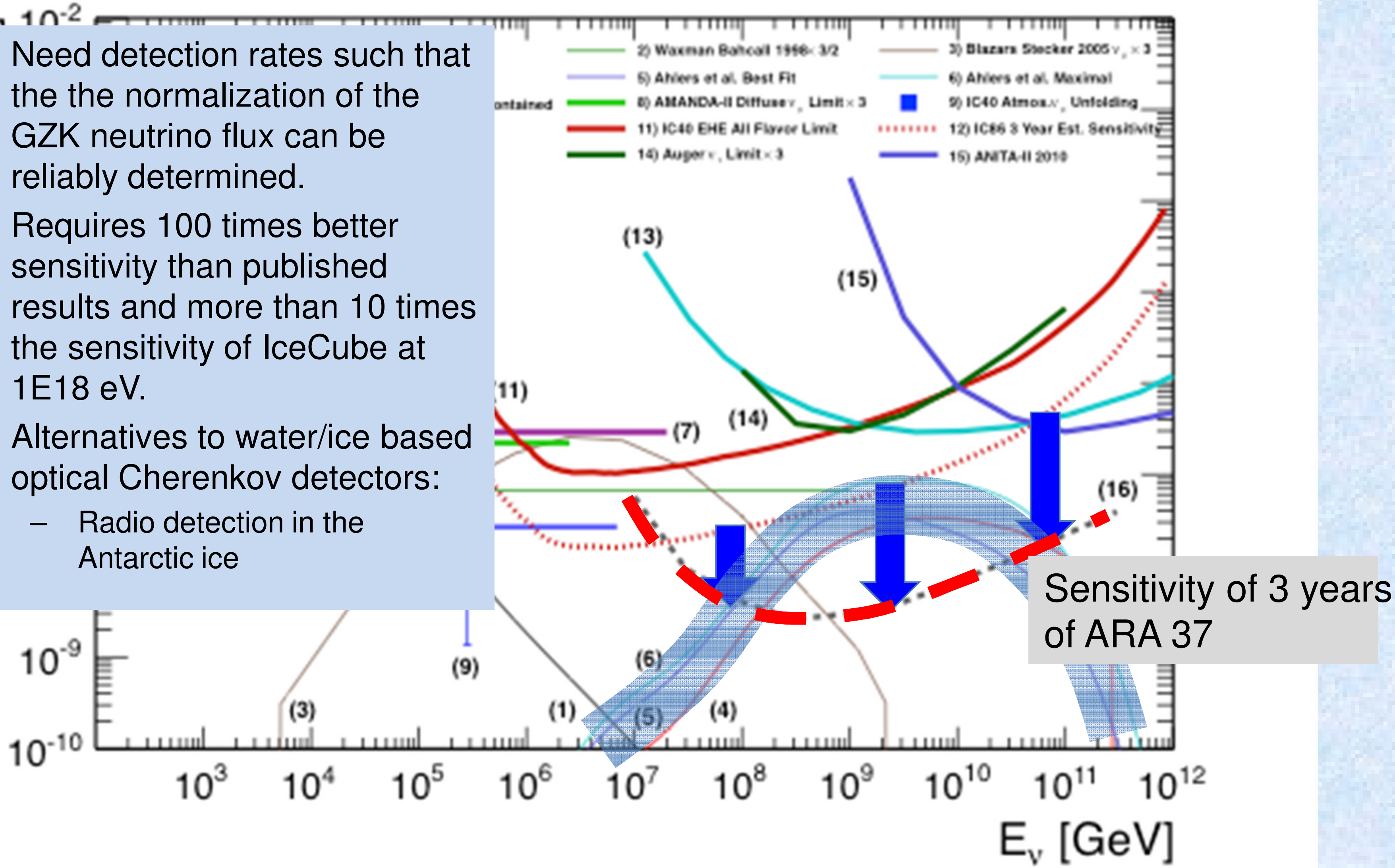
A real coverage: ~150 km^2

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



10^{16} – 10^{20} eV energy scale

- Need detection rates such that the the normalization of the GZK neutrino flux can be reliably determined.
- Requires 100 times better sensitivity than published results and more than 10 times the sensitivity of IceCube at 1E18 eV.
- Alternatives to water/ice based optical Cherenkov detectors:
  - Radio detection in the Antarctic ice



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

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

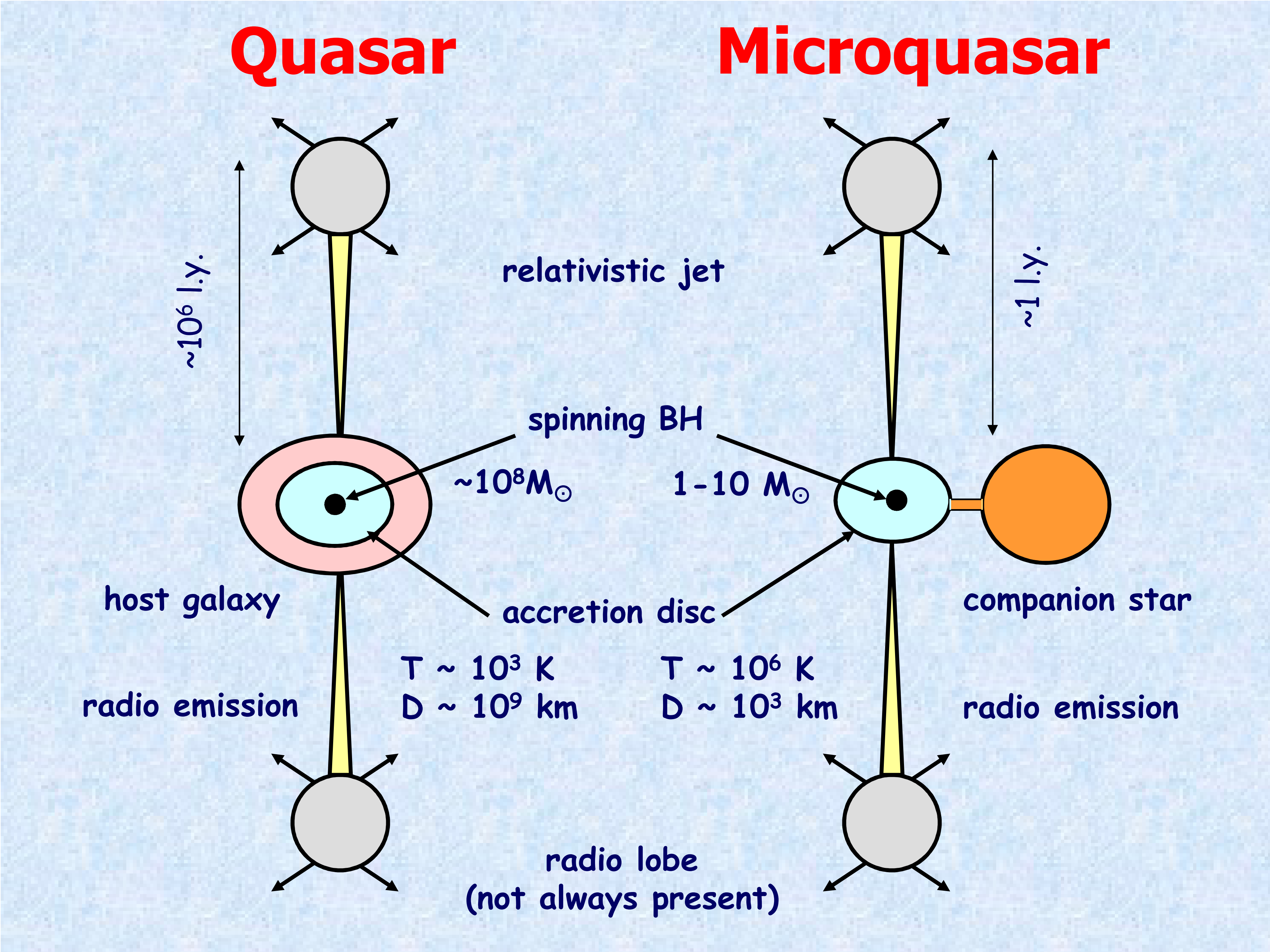
Consider a sample of identified MQs and MQs candidates

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.

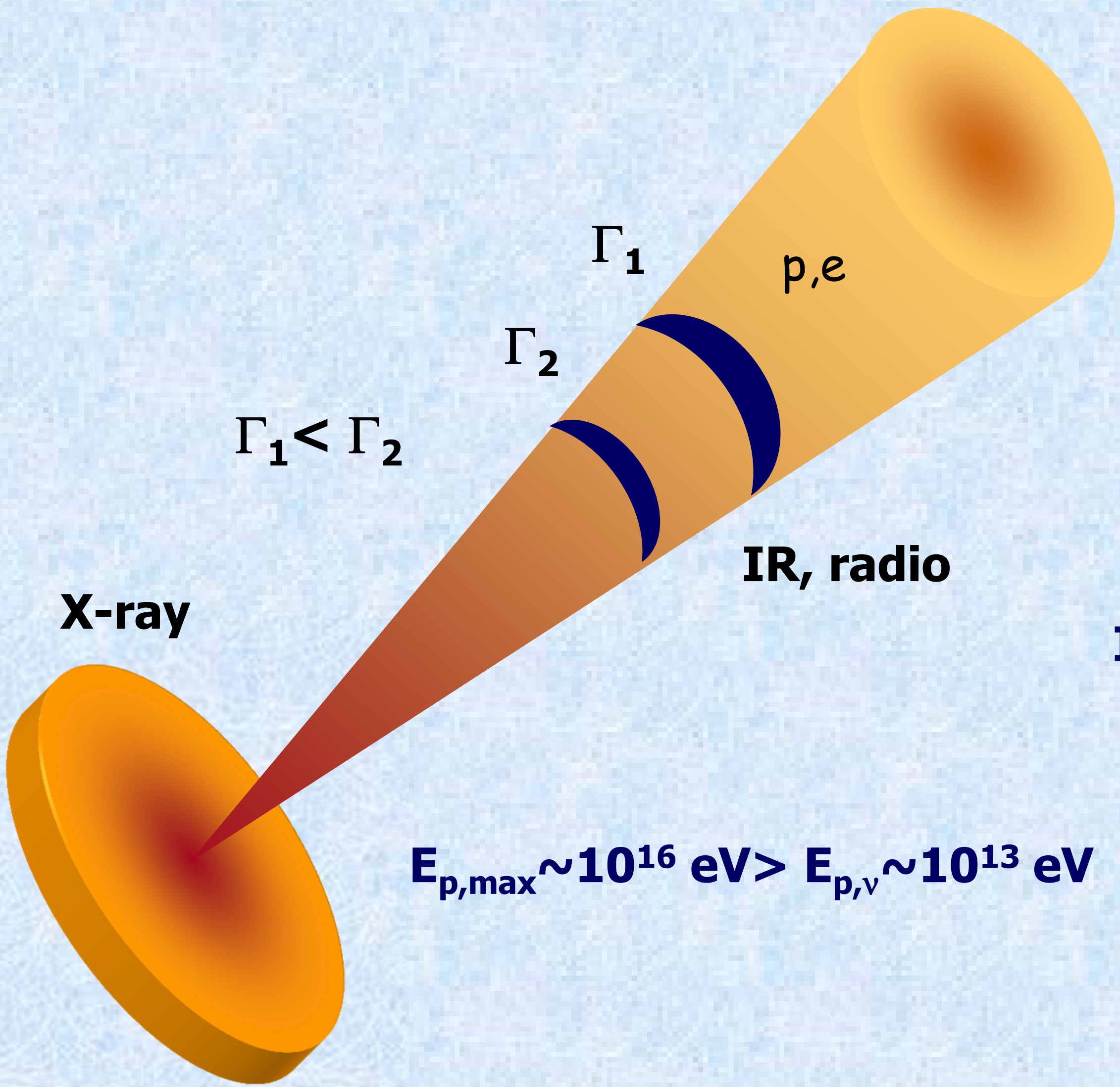


Quasar
Microquasar
relativistic jet
~10⁶ l.y.
~1 l.y.
spinning BH
~10⁸M☉
1-10 M☉
host galaxy
accretion disc
companion star
T ~ 10³ K
D ~ 10⁹ km
T ~ 10⁶ K
D ~ 10³ km
radio emission
radio emission
radio lobe
(not always present)

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

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

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

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

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

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} $\Delta\Omega=0.3^\circ$
	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	$0.03 \div 4$	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 γ–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. (Piano et al. 2012, A&A 545, 110)

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!!

Outlook on microquasars

- **Microquasars are potential sources for neutrino astronomy, IceCube not sensitive enough to several MQs maybe KM3NET**

- **Constraints: Look at the Microquasars that emit in the TeV region and constrain hadronic models with IceCube and ANTARES data**

Summary and Conclusions

- IceCube already put constrains on several astrophysical sources as possible source of high energy neutrinos like GRBs and microquasars

- Multiwavelegth analysis needed to identify the sources of high energy Neutrinos

- Ultra high energy neutrino telescope like ARA will be able to detect the neutrinos expected from the GZK and help to understand the origin of the UHECR cutoff and nature of the UHECR composition.