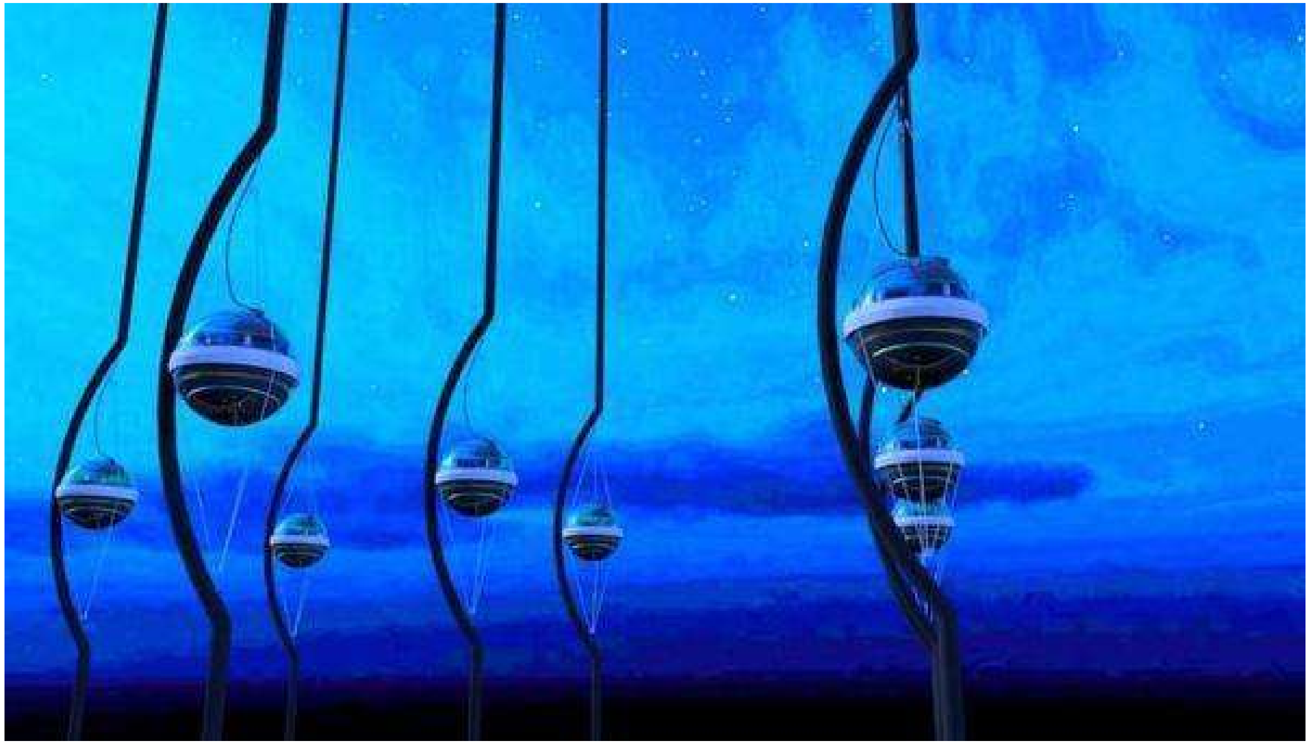
北京大学
Peking University

High Energy Neutrinos



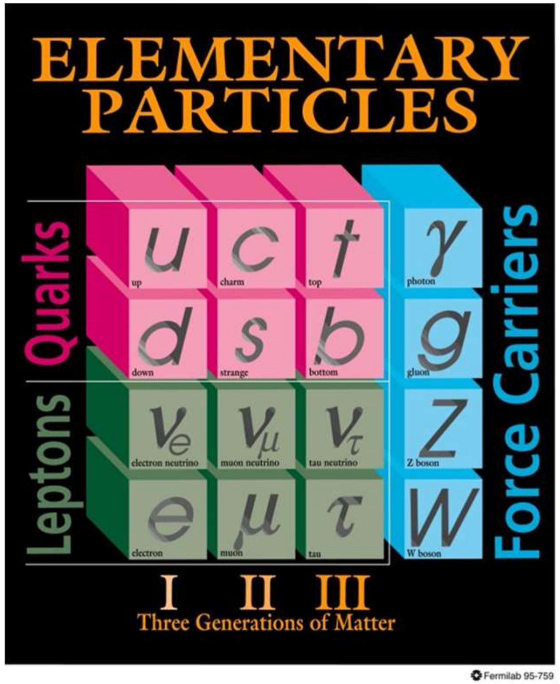
黎卓（北京大学天文学系）
2019-06-06

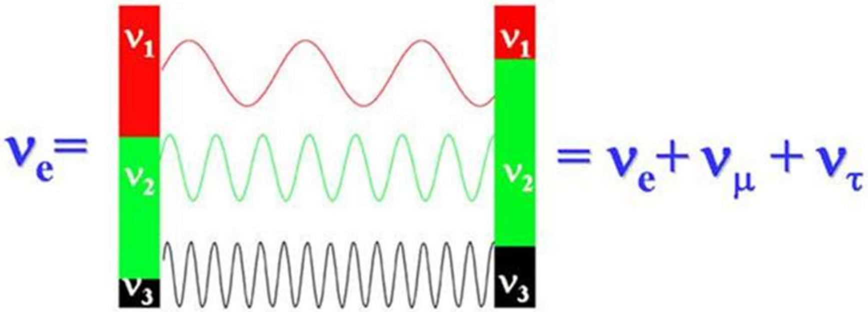
Outline

- What is HE neutrinos?
- Why study HE neutrinos?
- How to detect?
  - Current observation result
- Where are they from?
  - Theoretical analysis
- Open questions & prospects

Neutrino

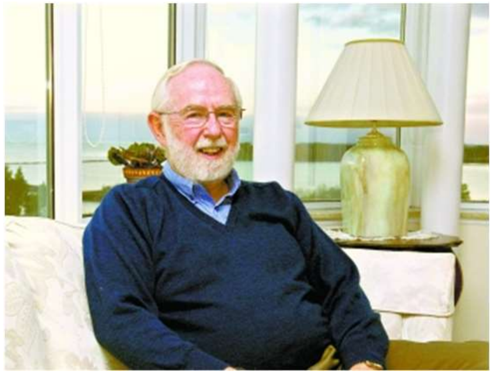
- Standard Model of particle physics
- One of leptons, with spin ½
- Three flavor: electron, muon, and tau neutrinos
- No charge, no EM and strong interactions, only weak interaction
- Massless in standard model, but with mass in modified model
- Sources: reactor/accelerator, sun/star, supernova, atmosphere, cosmic sources, big-bang…



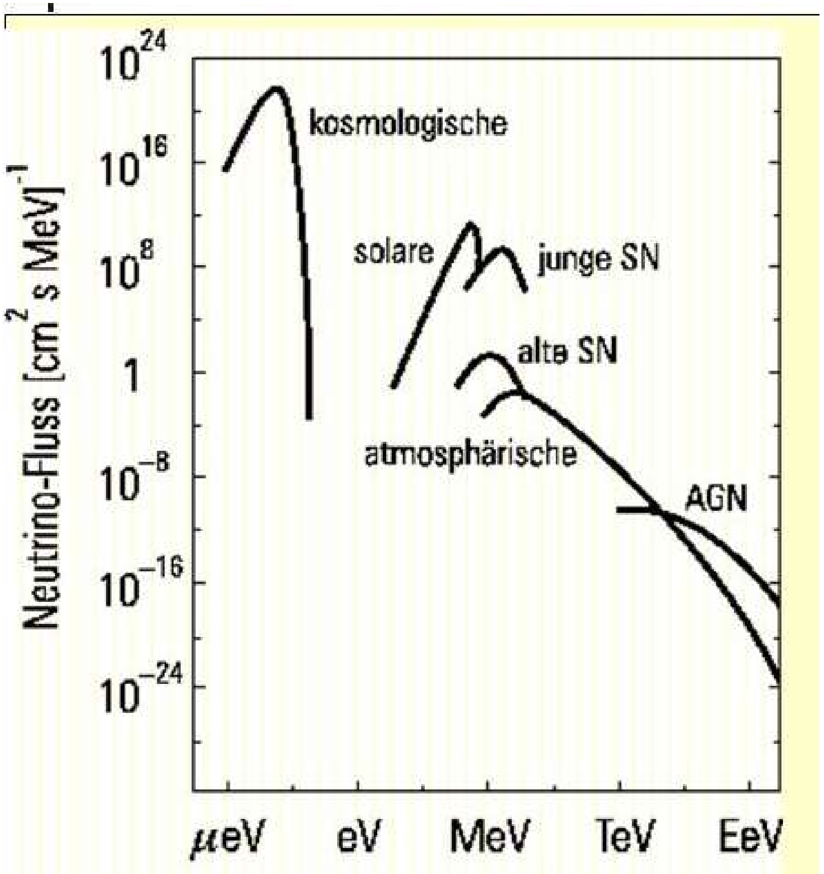


Nobel Prize for neutrinos

- 1988- Lederman, Schwartz & Steinberger
  - muon neutrino (1962)
- 1995- Reines
  - neutrino discovery (1956)
- 2002- Davis & Koshiba
  - solar neutrino (missing,1968); SN1987A neutrino (1987)
- 2015- Kajita & McDonald
  - neutrino oscillation (atmospheric,1998; solar, 2001)
- 20XX- IceCube?
  - HE astrophysical neutrinos (2013)



(expected) neutrino spectrum

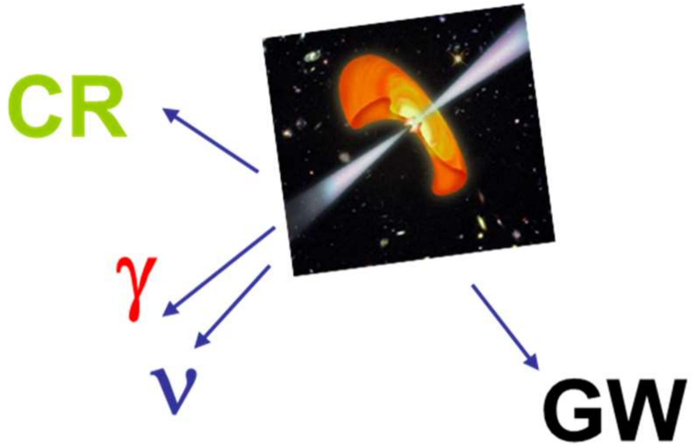


Cosmologic & SN neutrinos:

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

HE neutrinos:

$$p + \gamma(p) \rightarrow N + \pi^+$$
$$\pi^+ \rightarrow e^+ + \nu_e + \nu_\mu + \bar{\nu}_\mu$$

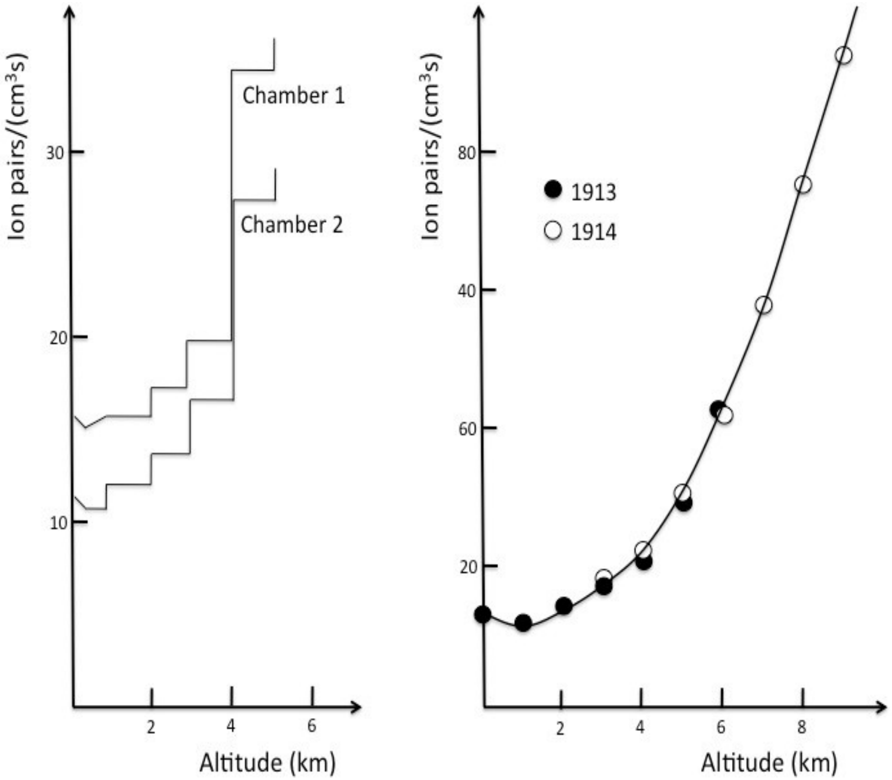


Why neutrinos?

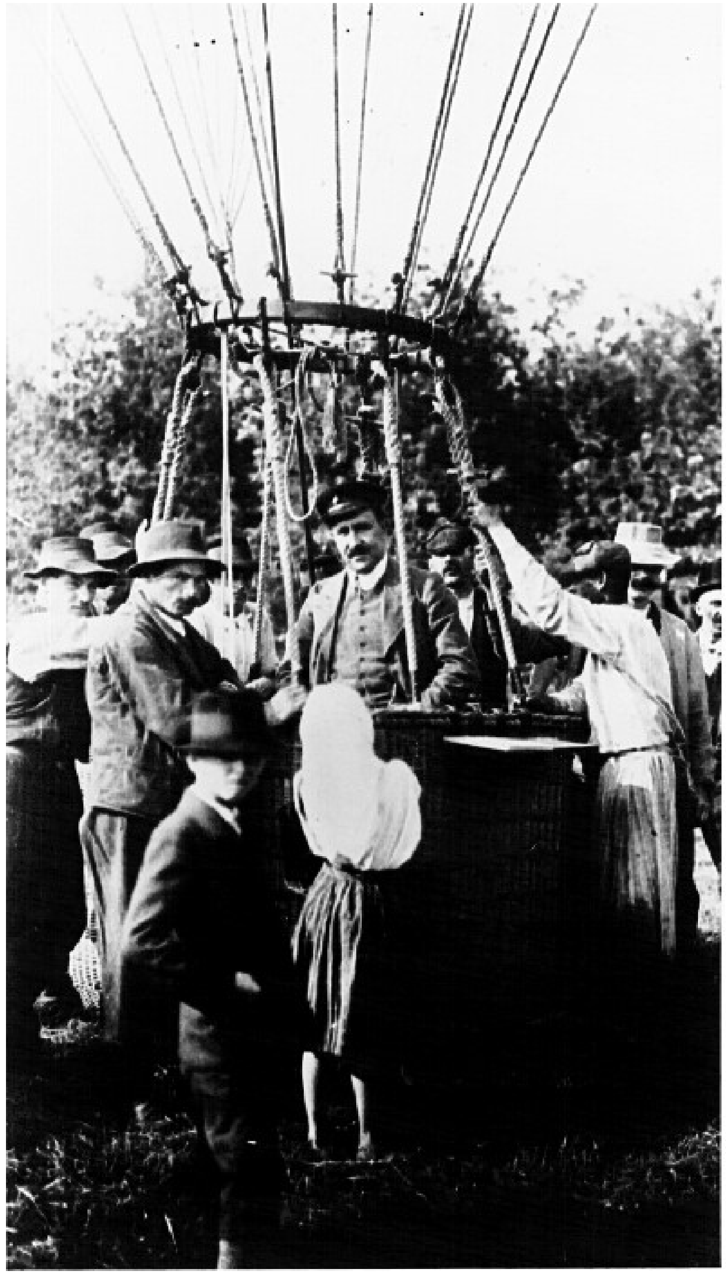
In astronomy, to look for cosmic ray sources

…

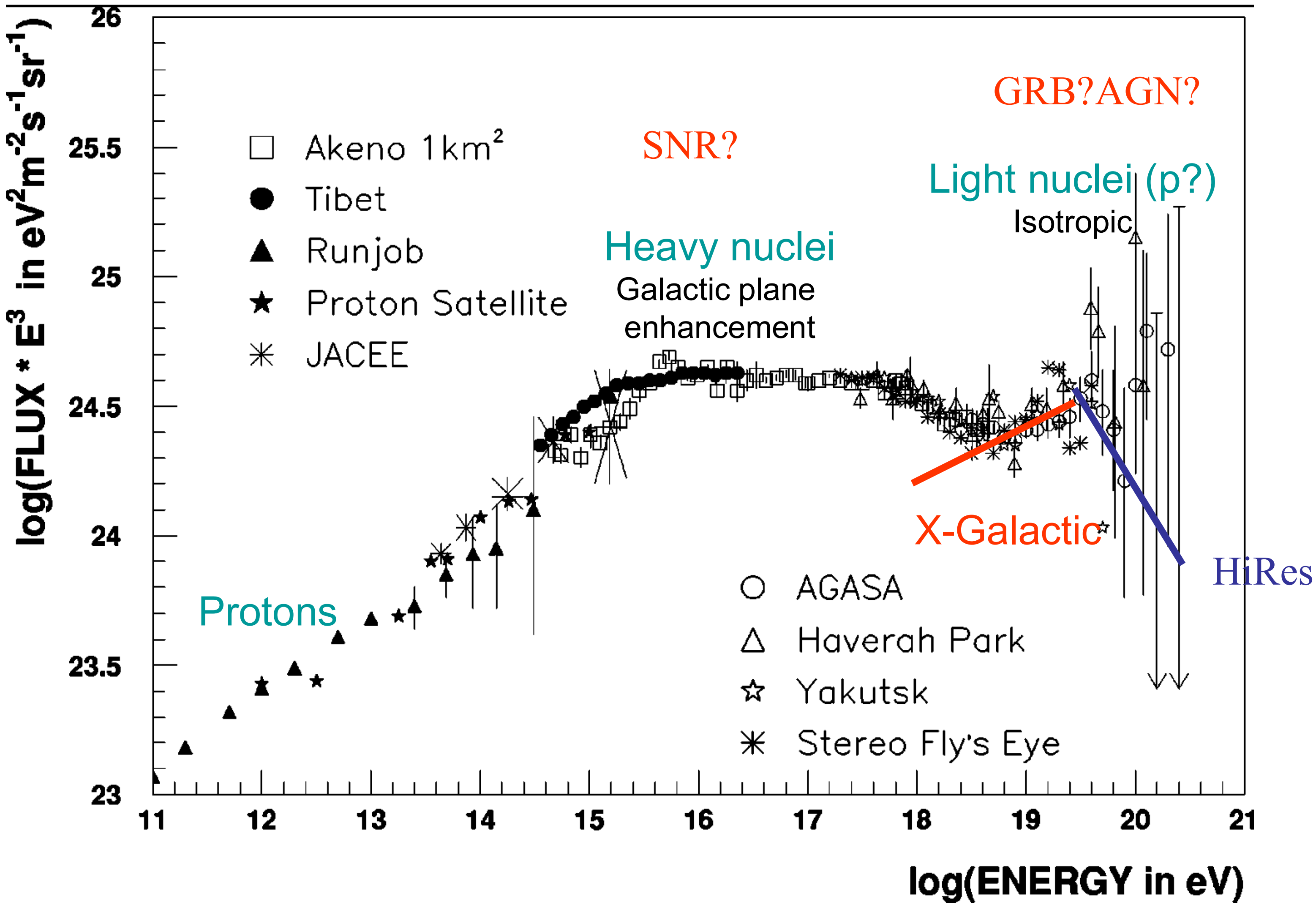
Cosmic rays discovery



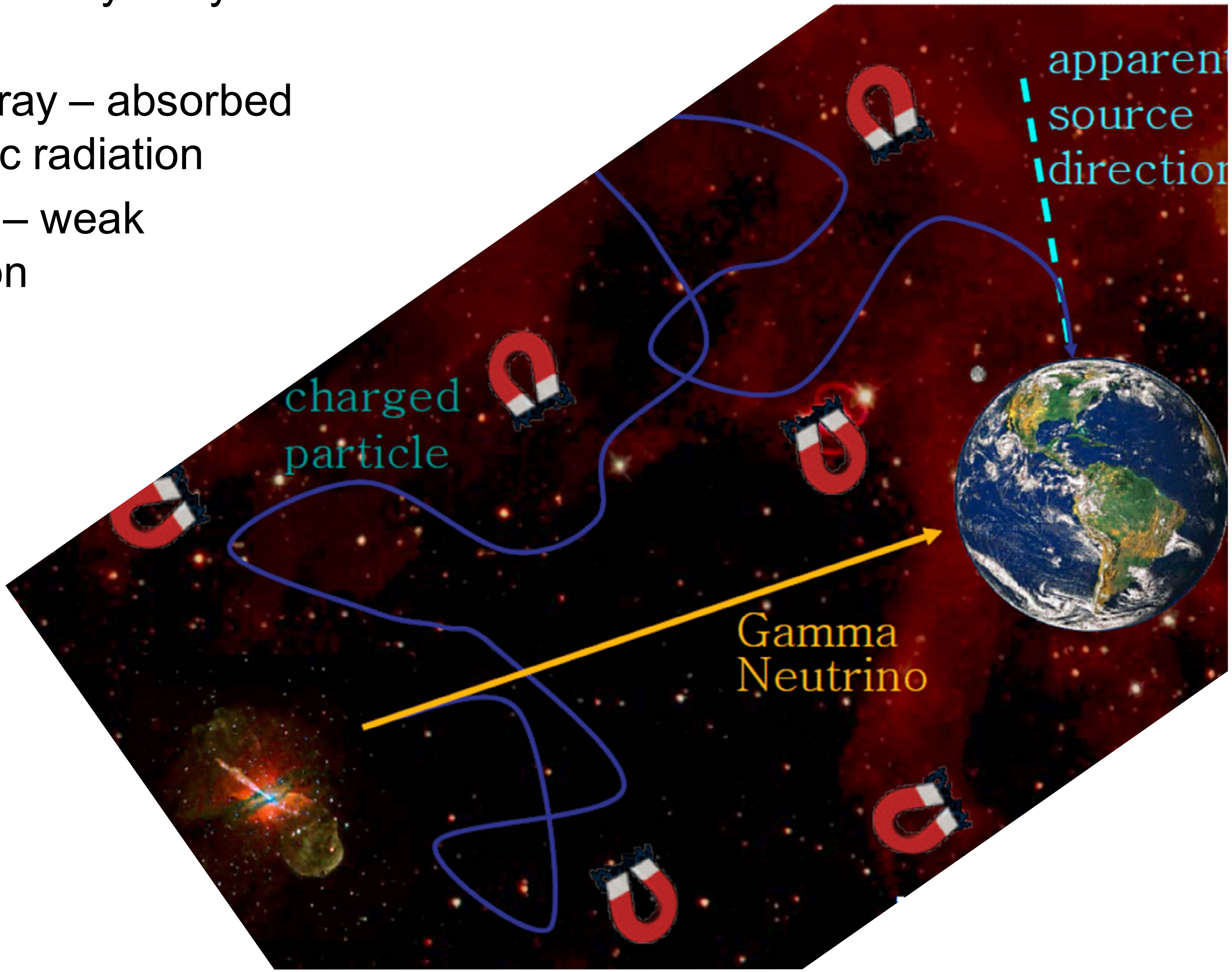
Hess, 1912

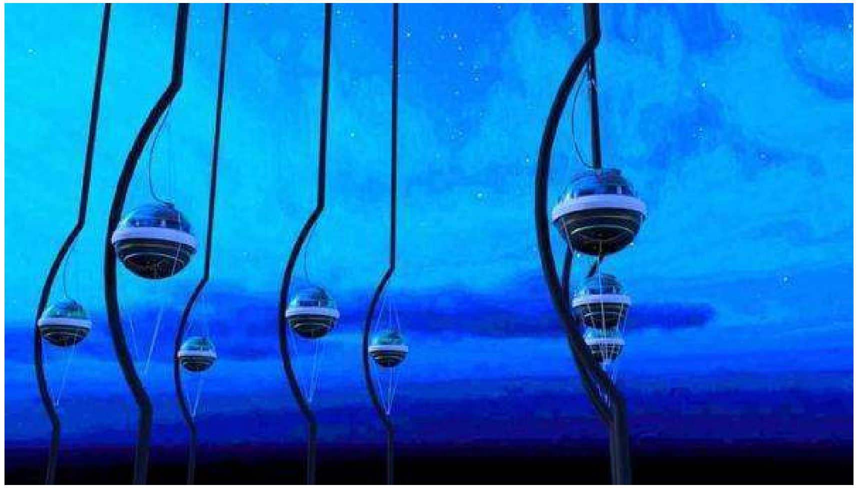


Ultra-High Energy Cosmic Ray: extragalactic



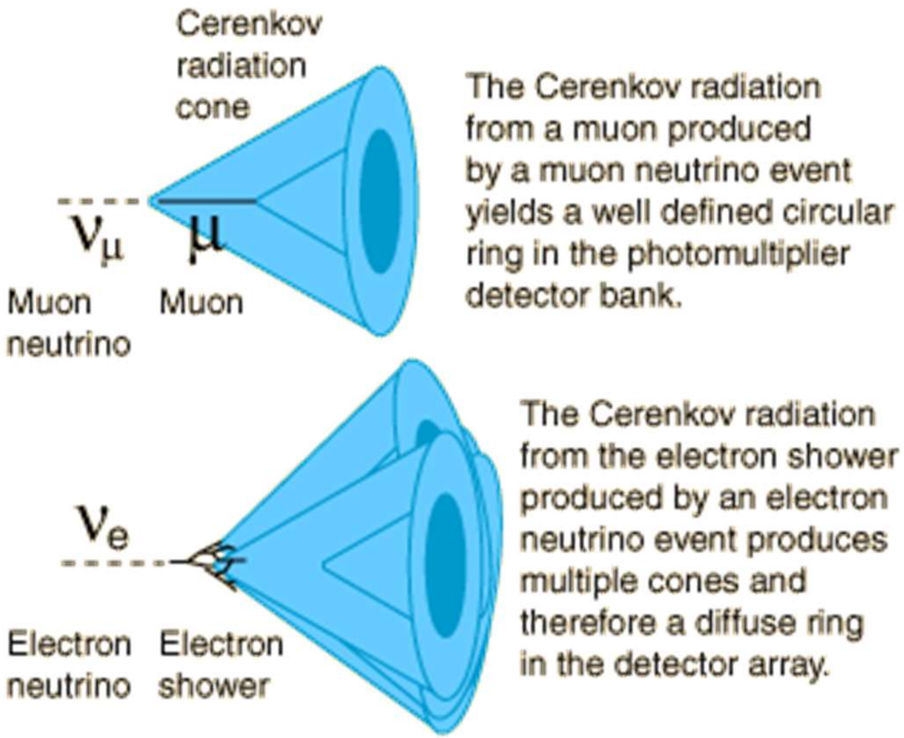
- CR source messengers
  - Cosmic ray - deflected/delayed by B field
  - Gamma-ray – absorbed by cosmic radiation
  - Neutrino – weak interaction





How to detect?

Cerenkov radiation



Diffuse neutrino upper bound

- Neutrinos from π production

$$p + \gamma(p) \rightarrow N + \pi^+$$

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

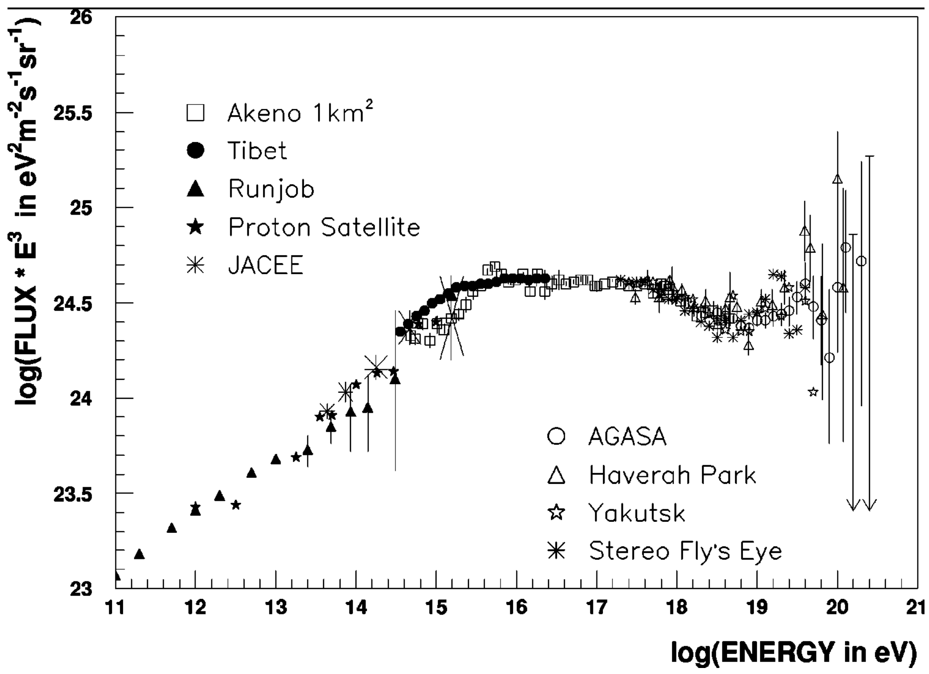
- If all *p* energy converted to π

$$\frac{j_\nu}{j_p} \approx \frac{1}{2} \times \frac{1}{2} \times \frac{1/H_0}{\lambda_{\rm GZK}/c}$$

- Waxman-Bahcall Bound from detected >10^19 eV CR flux :

$$\varepsilon_\nu^2 \frac{\mathrm{d}j_\nu}{\mathrm{d}\varepsilon_\nu} < 10^{-8} \zeta \frac{\mathrm{GeV}}{\mathrm{cm^2 s\, sr}}$$

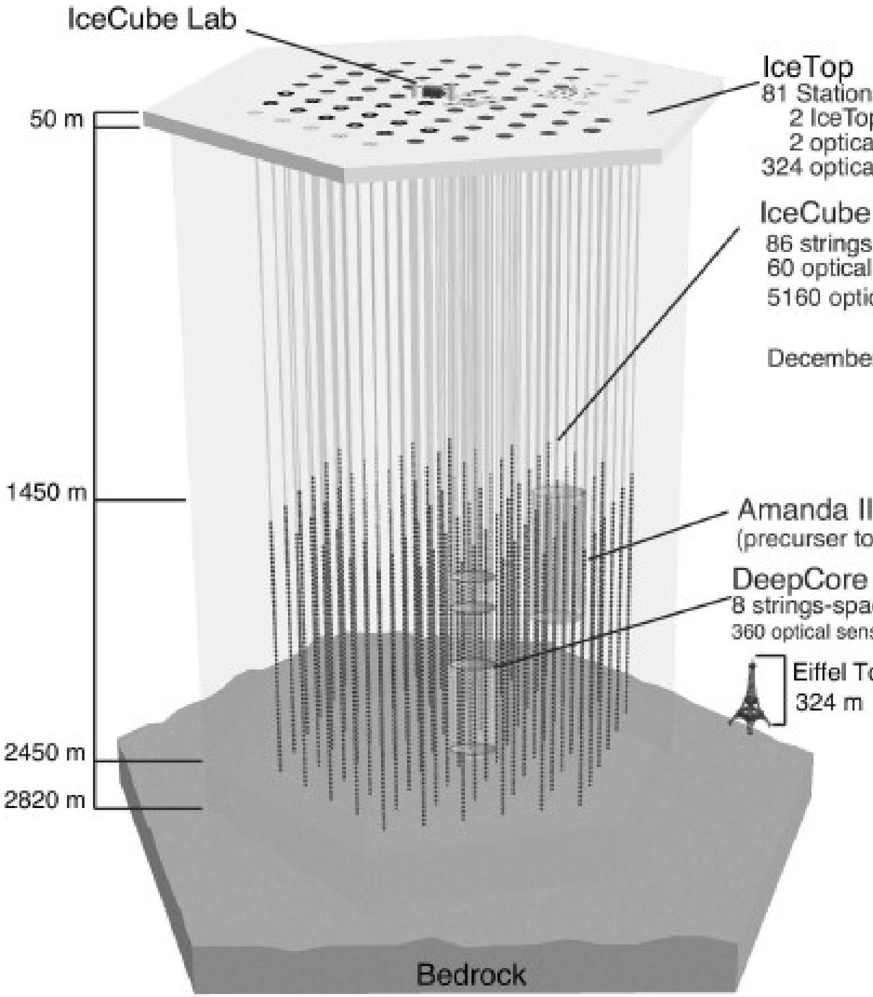
CR spectrum

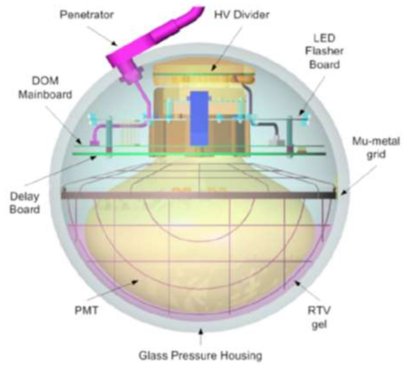


Waxman & Bahcall 1999

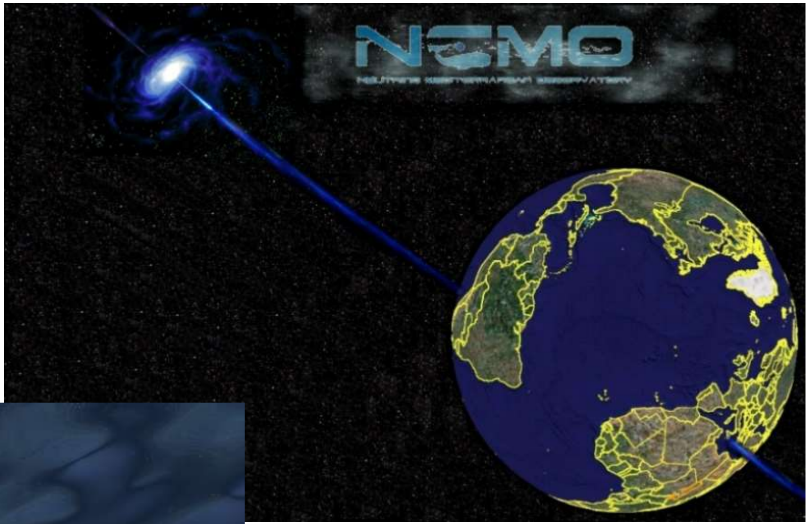
IceCube neutrino telescope

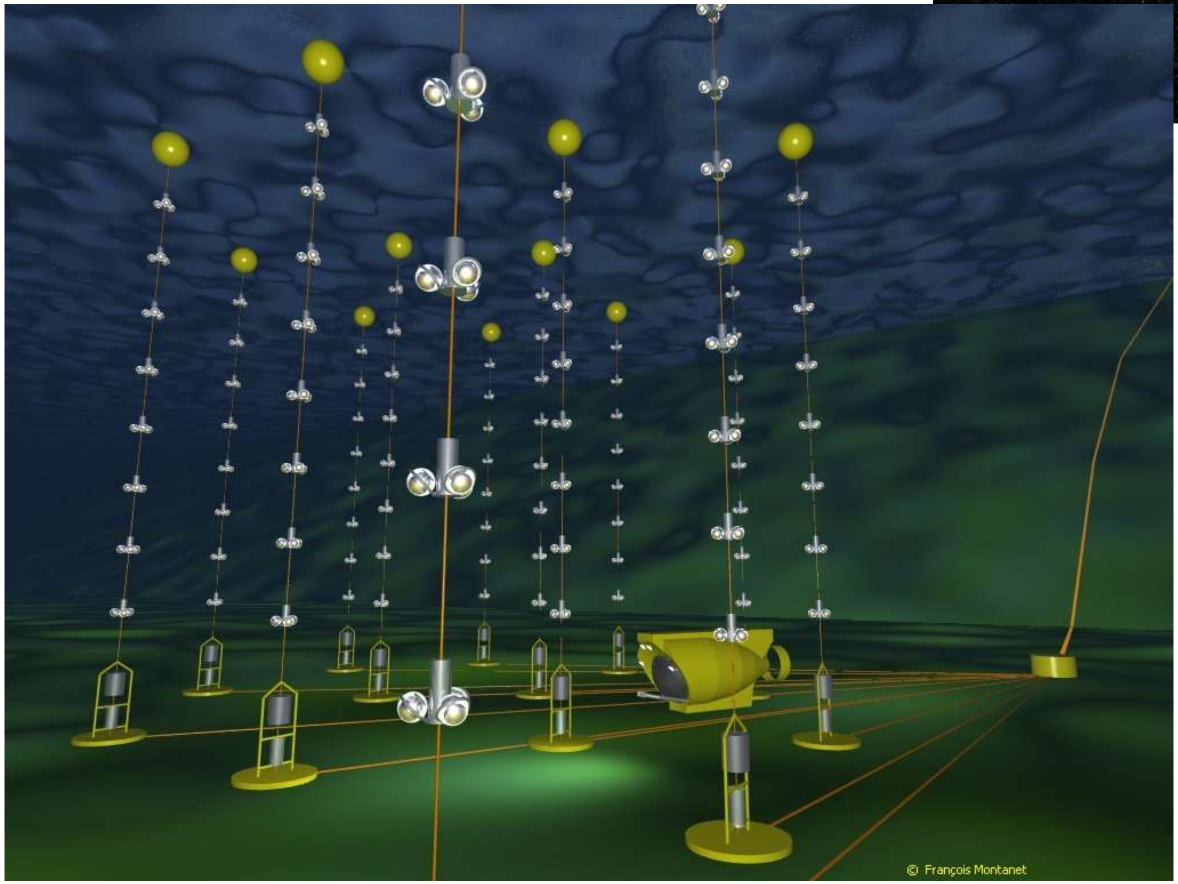
- Expected to reach sensitivity for XG sources
- Completion in 04/2011





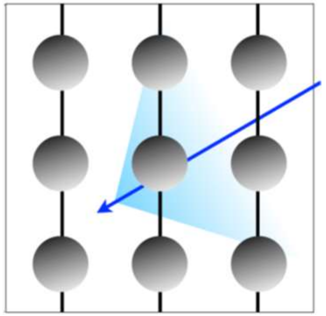
Mediterranean Sea

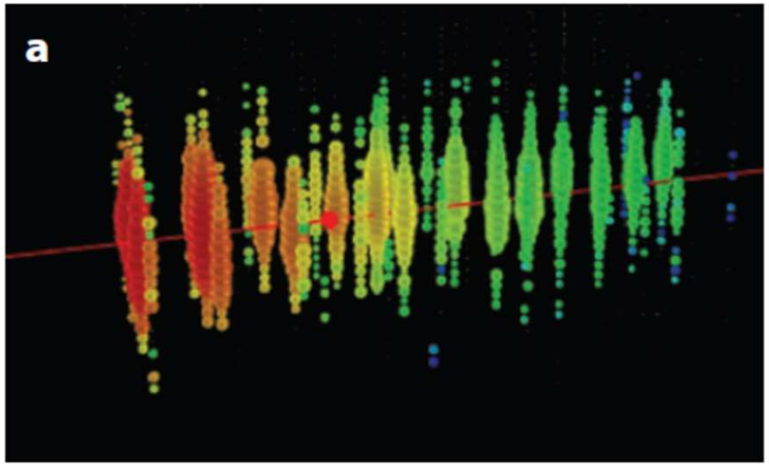


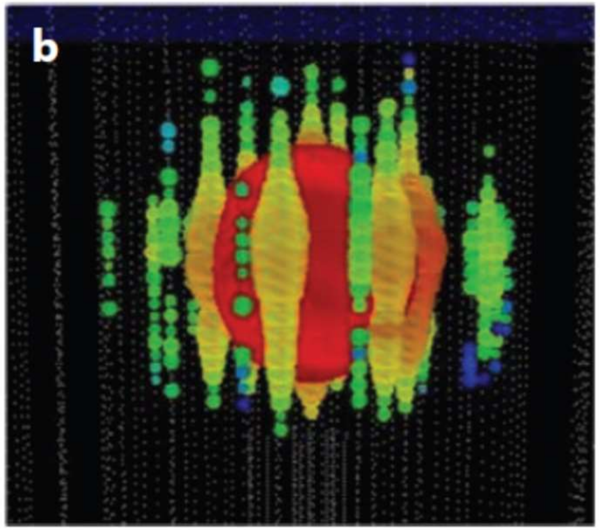


- Optical Cerenkov
- 0.1 km^2:
  - Antares
  - Nestro
  - NEMO
- $\Rightarrow$1 km^2: KM3NeT

Cherenkov light


Cherenkov light detection
in optical modules

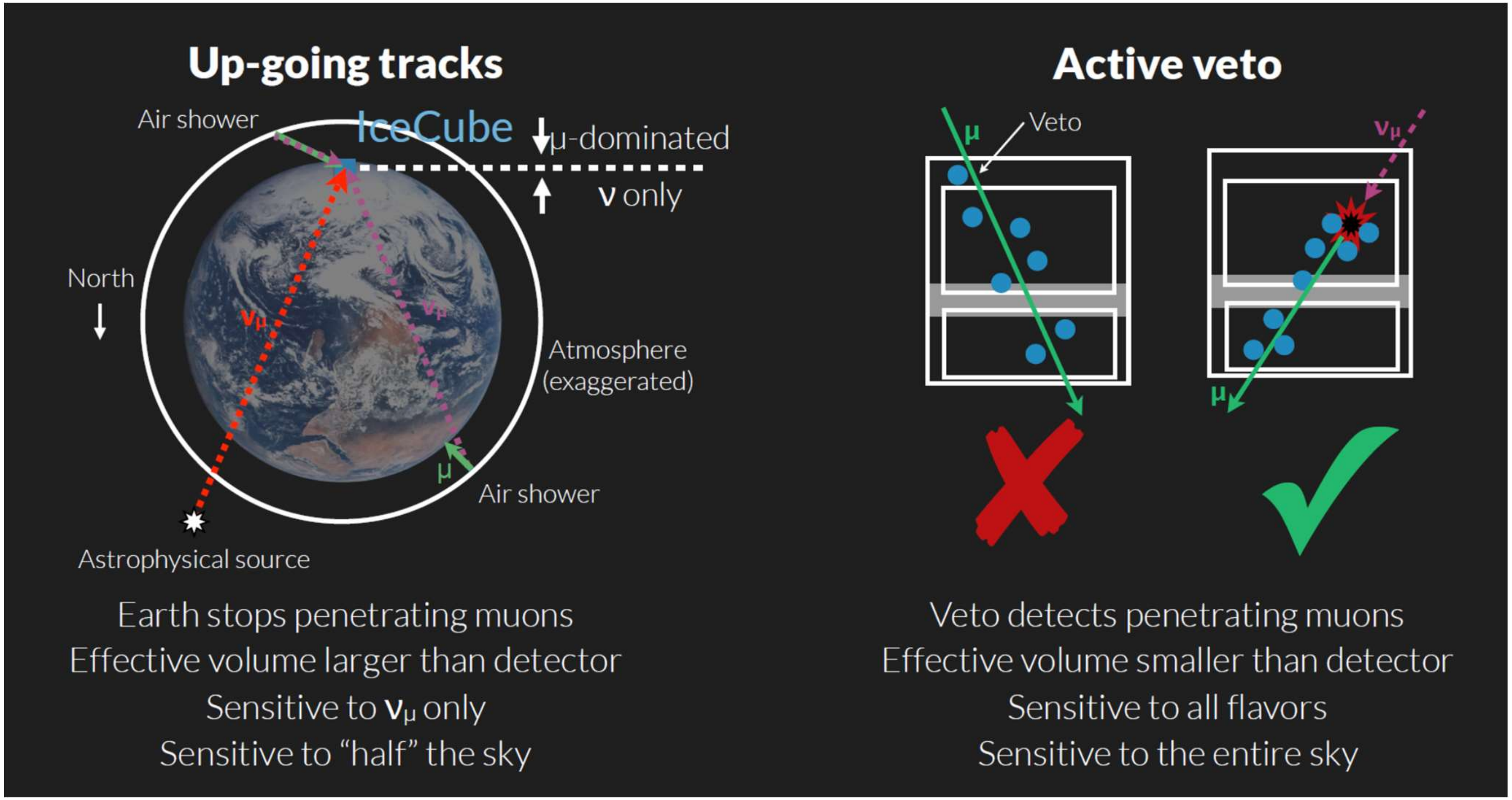




Track:
track-like light pattern from neutrino-induced muons
good direction measure, <1deg

Cascade:
Spherical light pattern by hadronic or EM particle showers
good energy measure

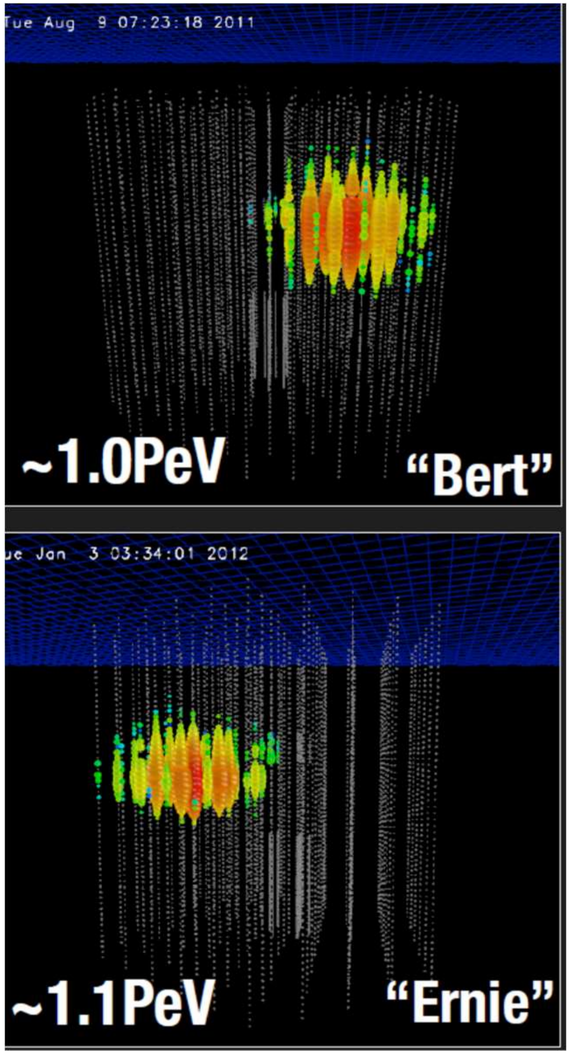
Isolating neutrino events: two strategies



from Kopper ICRC talk

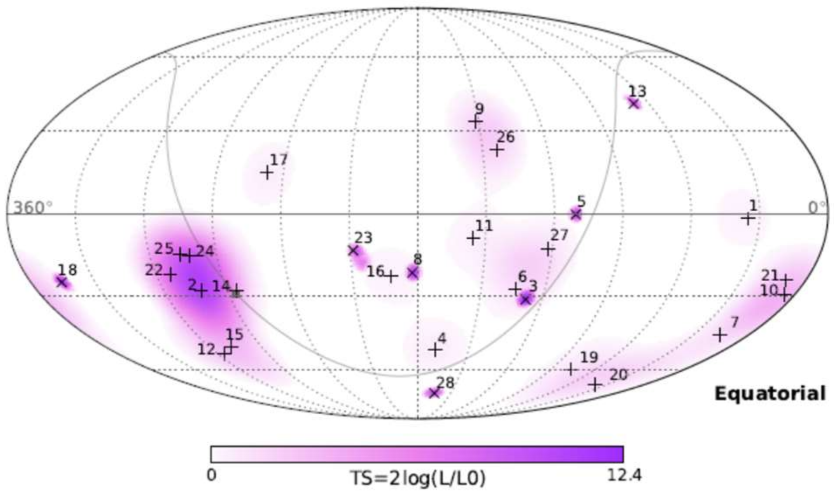
Current observation results?

High energy neutrino discovery



2010/5-2012/5 data:

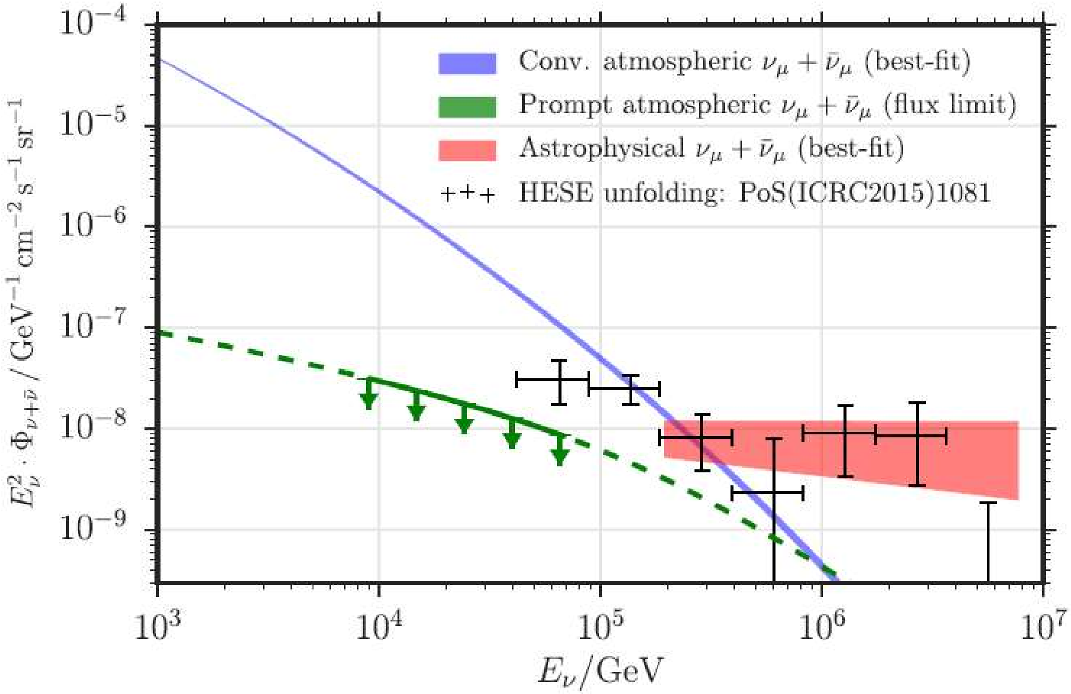
1. EeV GZK neutrino search
   - found two at 1 PeV
2. Follow-up search: 28 evts
   - Lower E
   - Interaction vertices within detector volume



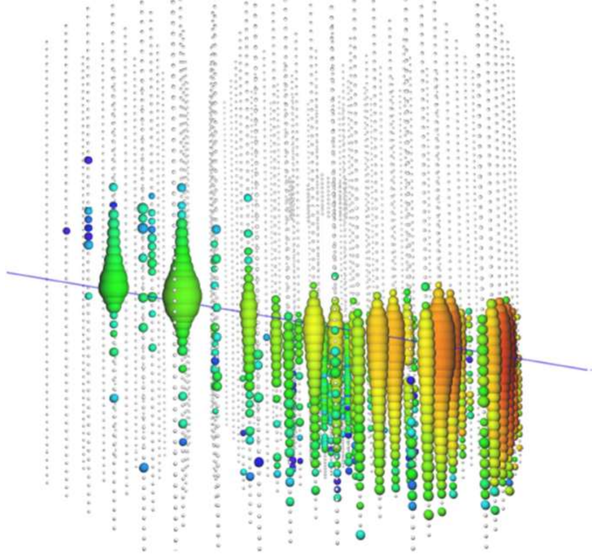
TeV-PeV neutrinos at IceCube

$E^2\Phi$~1e-8 GeV/cm2s sr @100TeV

starting evts (southern) consistent w/ upgoing track evts (northern)



2.6PeV track event

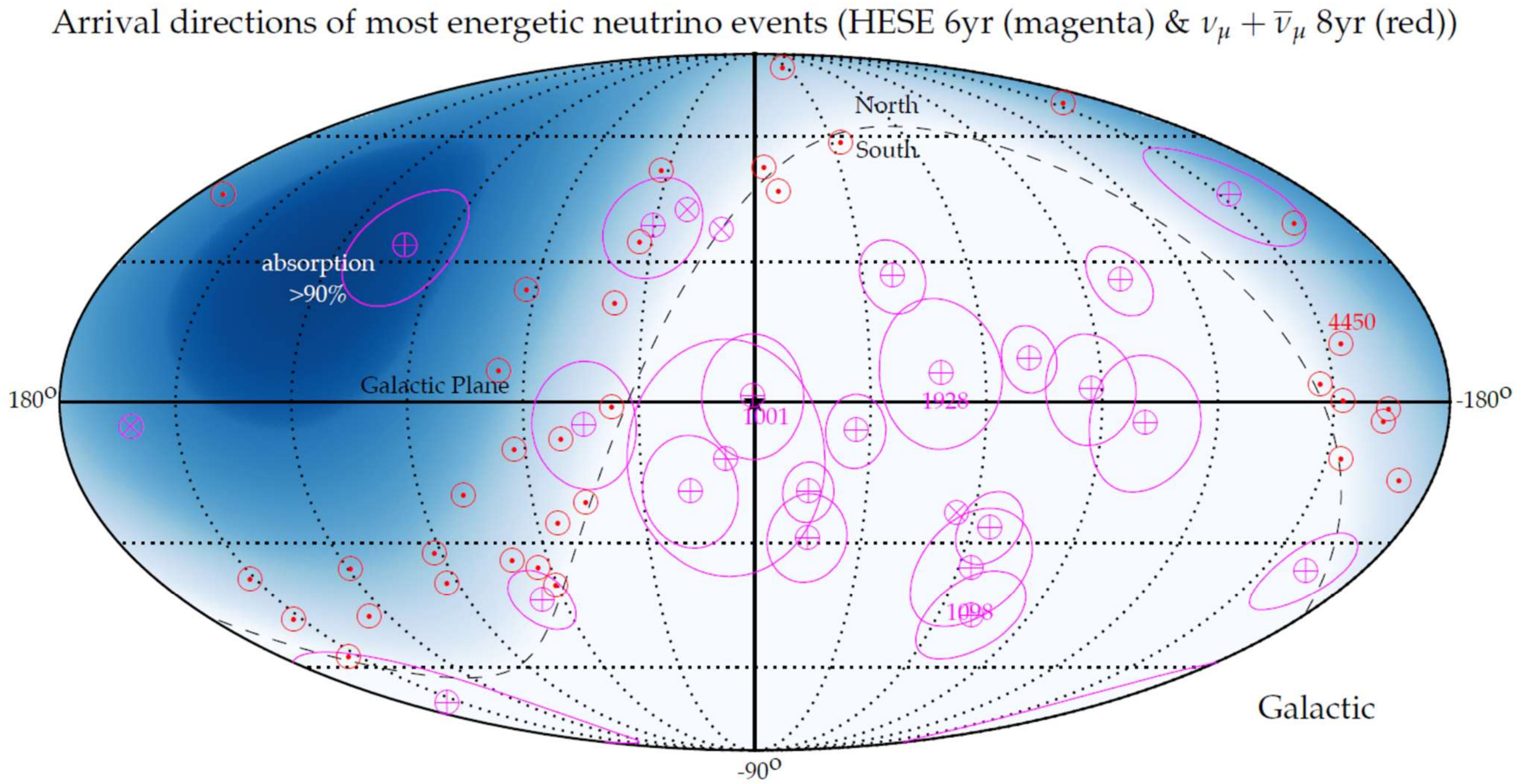


[IC 16, ApJ]

Hard spectrum at >200 TeV: s~-2

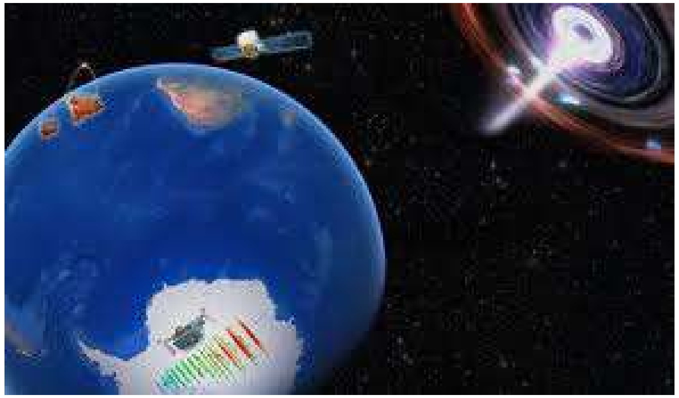
Cutoff at few PeV

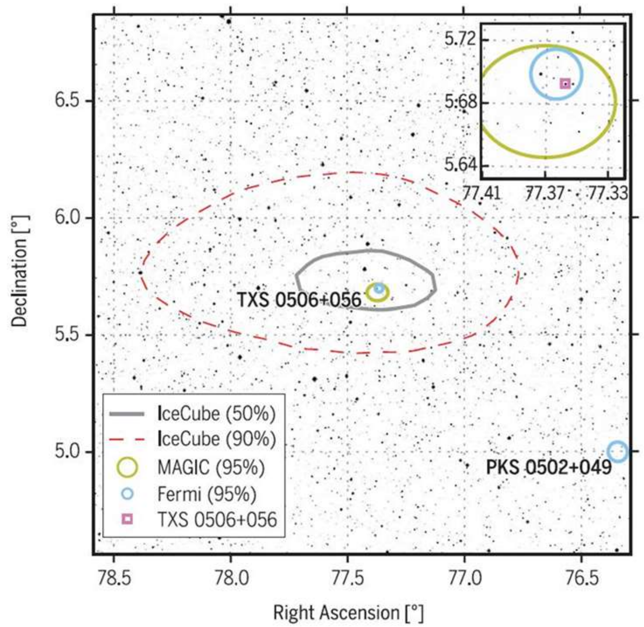
Neutrino arrival directions



no significant spot, no clustering in time
no correlation with GRBs

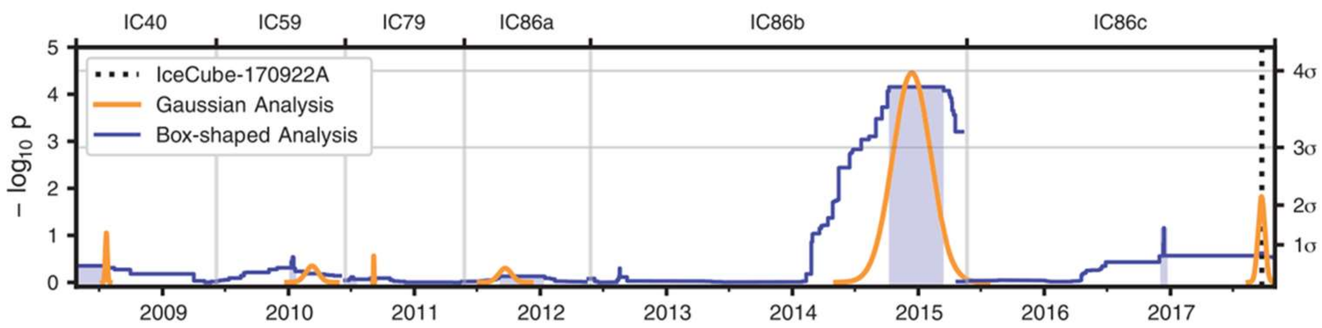
Neutrino-BL Lac association(?)





IC-170922A/TXS 0506+056 association, 4sigma coincidence [IC18a]

Neutrino burst/flare in archive data, 3.5sigma signal [IC18b]

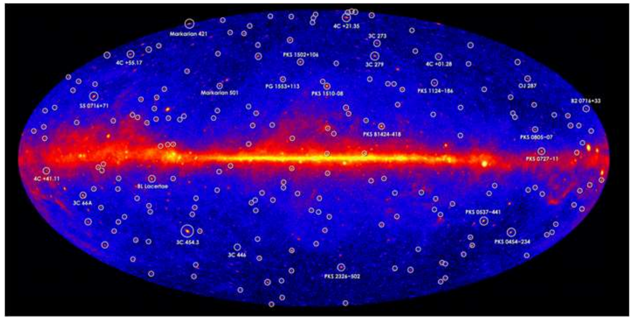


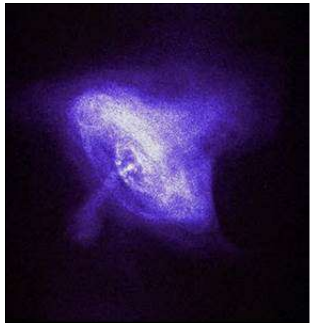
Where are they from?

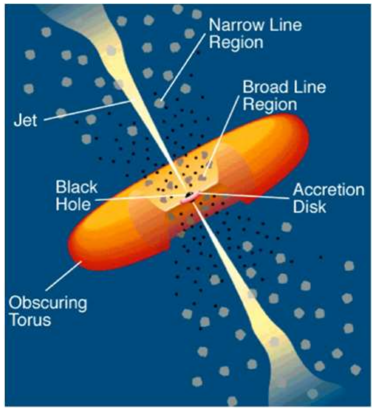
-- theoretical analysis

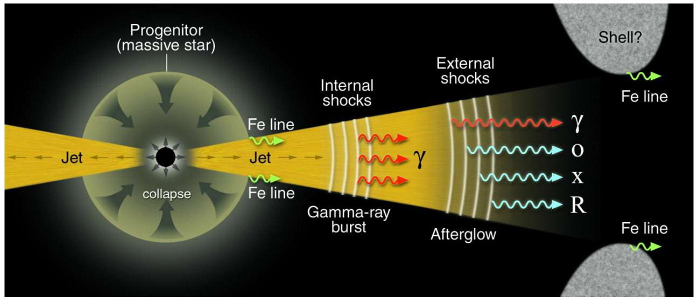
IceCube neutrino origin?

- Galactic origin
  - Diffuse emission (CR propagation)?
  - Galactic point sources?
- Extragalactic origin
  - Gamma ray bursts?
  - Blazars?
  - Star forming/starburst galaxies?

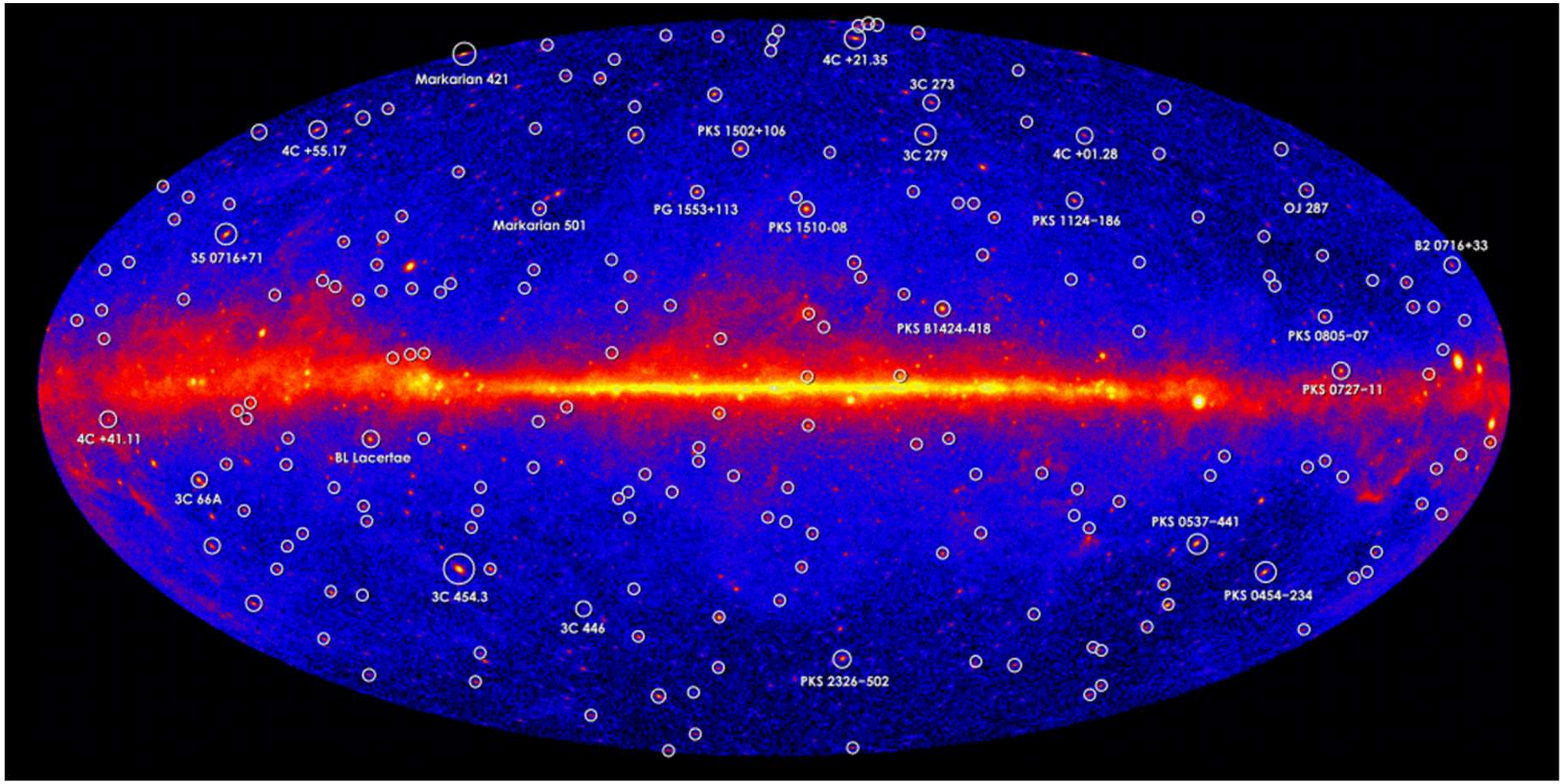








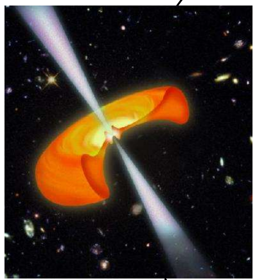
Fermi-LAT sky survey



Whether various candidate sources can produce the all-sky IceCube flux?

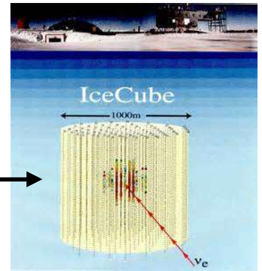
$$E_\nu^2 J_{\nu,\mathrm{IC}} \approx 1.2 \times 10^{-7} \mathrm{GeV cm^{-2} s^{-1}}$$ (single flavor)

Photon – neutrino connection



$$p + \gamma(p) \rightarrow \begin{cases} N + \pi^{\pm} \\ \quad \pi^{\pm} \rightarrow e^{\pm} + \overset{(-)}{\nu}_e + \nu_\mu + \bar{\nu}_\mu \\ \quad\quad e^{\pm} \rightarrow \text{syn/IC radiation} \\ N + \pi^{0} \end{cases}$$

$$\pi^{0} \rightarrow \gamma + \gamma$$



I

$$e^{-}(p) \rightarrow \text{synch/IC radiation}$$

II

Connections:

I. neutrino – secondary electron/gamma-ray

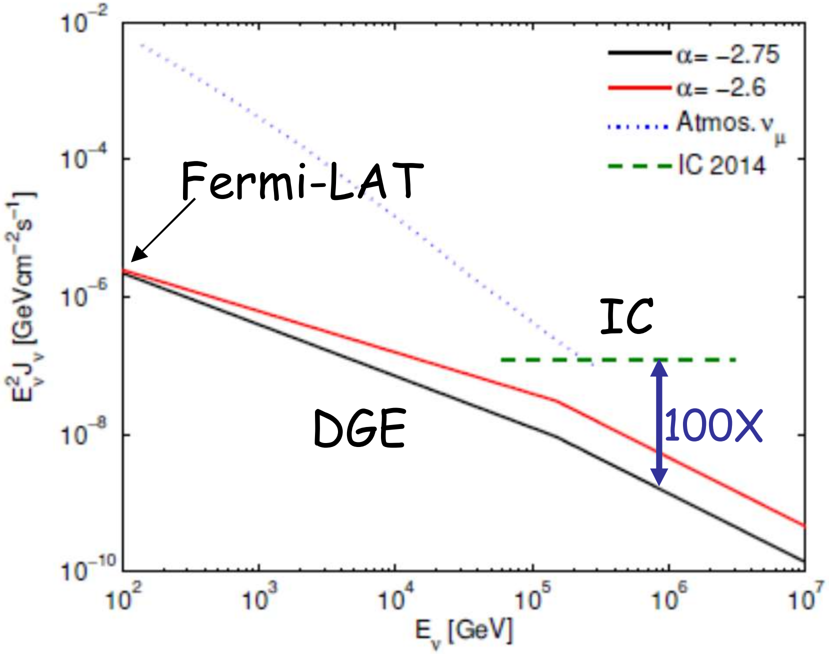
II. neutrino – primary electron/proton

Diffuse Galactic emission

- Connection I
- $\pi^+ : \pi^- : \pi^0 = 1:1:1$

  $E_\nu = \frac{1}{2} E_\gamma$

  $E_\nu{}^2 J_\nu(E_\nu) = \frac{1}{2} E_\gamma{}^2 J_\gamma(E_\gamma)$
- Extrapolation, 100GeV to PeV
  - Neutrinos follow CR spectrum
- DGE accounts for <1% IC flux



[Wang, Zhao, ZL 14]

Note on extended Galactic halo

- IC events require a total Galactic halo neutrino luminosity

  $L \sim R_{halo}^2 E^2 J \sim 10^6 L_{sun}$; $R_{halo} \sim 100\text{kpc}$
- Local galaxy number density

  $n_{gal} \sim 10^{-2}\text{Mpc}^{-3}$
- All-sky neutrino flux from all galaxies is

  $I = \xi_z (c/4\pi) L n_{gal} t_{Hubble} = 3.10^{-7}\text{GeVcm}^{-2}\text{s}^{-1}\text{sr}^{-1}$

  ($\xi_z \sim 3$ accounts for z-evolution)
- Overproduce: 10X IC flux

[Wang, Zhao, ZL 14]

Blazars

- 33 bright FSRQs, selected based on gamma flux
- FSRQs can only account for <10% IC neutrinos

IC upper limits to individuals

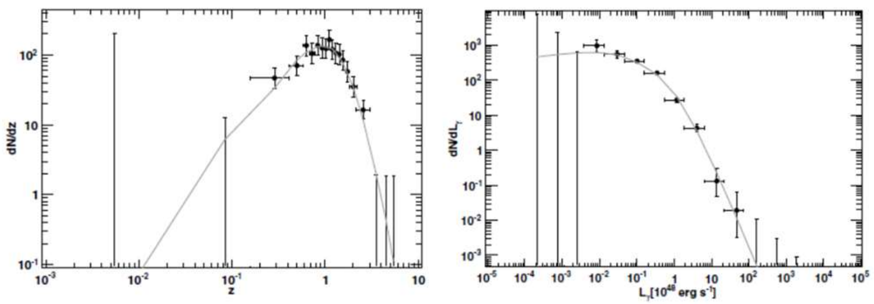
IC detection

$$\frac{\nu \text{ flux (stacked)}}{\gamma \text{ flux (stacked)}} < \frac{\nu \text{ flux (all - sky)}}{\gamma \text{ flux (all - sky)}} \times 10\%$$

[Wang & ZL, 2016]

Fermi-LAT detections of individuals

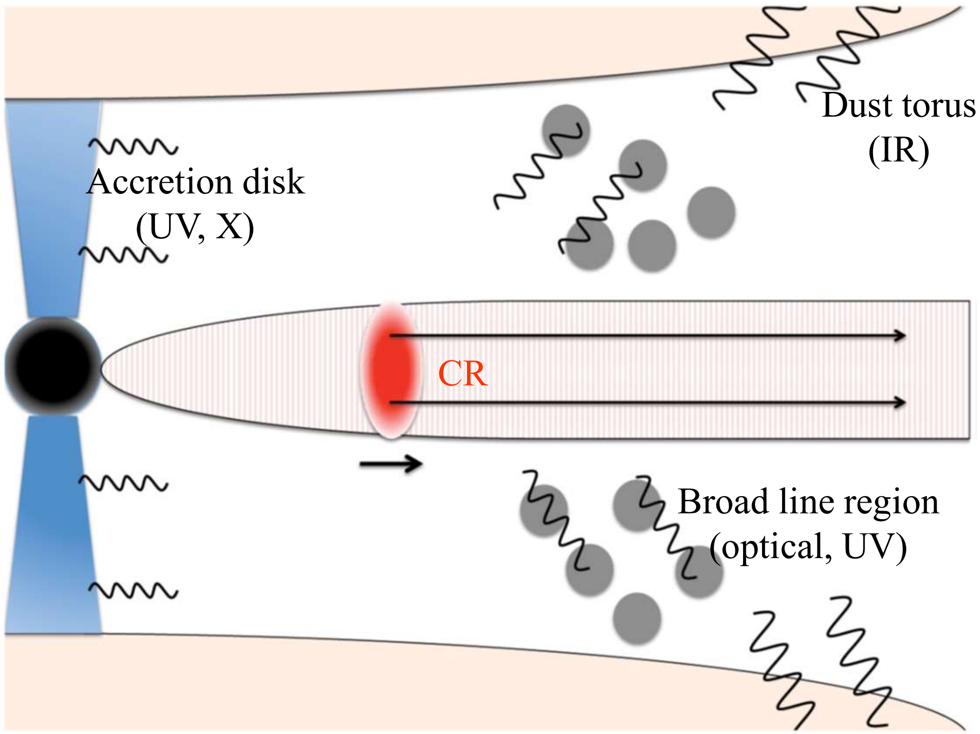
Derived from Fermi-LAT measured LF and their z-distribution:



[Fermi-LAT, Ajello+ 2012]

Blazar model

- Jet model
  - CR accelerated at Jet
  - Target photon: jet+disk+BLR+torus
  - Relativistic beaming; bright



Murase+14

Blazar: specific model

- Total flux: $J_\nu \sim \iint L_\nu(L_\gamma)\rho(L_\gamma, z)\mathrm{d}L_\gamma \mathrm{d}z$
- Per source

$$E_\nu L_{E_\nu} \approx \frac{1}{8} f_{p\gamma} E_p L_{E_p} \approx \frac{1}{8} f_{p\gamma} \hat{\xi}_{\rm cr} L_{\rm rad}$$

- Stacking search constrains CR loading

$$E_\nu^2 \Phi_{\nu,i} = \frac{1}{8} f_{p\gamma}(L_{\gamma,i}) \frac{L_{\rm rad}(L_{\gamma,i})}{L_{\gamma,i}} \hat{\xi}_{\rm cr} S_{\gamma,i}$$

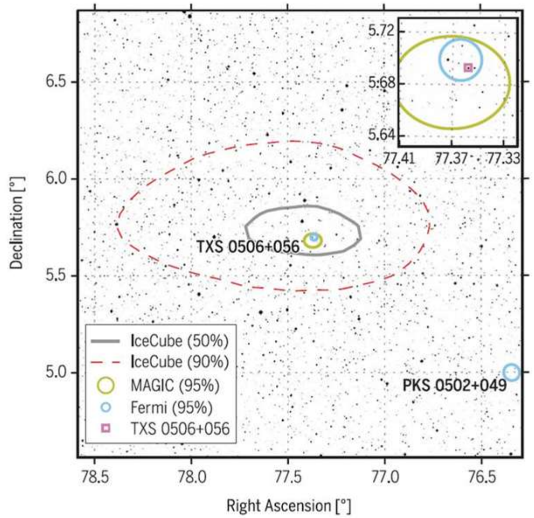
$$\sum_i E_\nu^2 \Phi_{\nu,i} < E_\nu^2 \Phi^{90\%}_{\nu_\mu+\bar{\nu}_\mu} \Rightarrow \hat{\xi}_{\rm cr} < 0.062 f^{-1}_{{\rm cov},-1} \zeta^{-1}$$

- Blazars account for <10% IC neutrinos

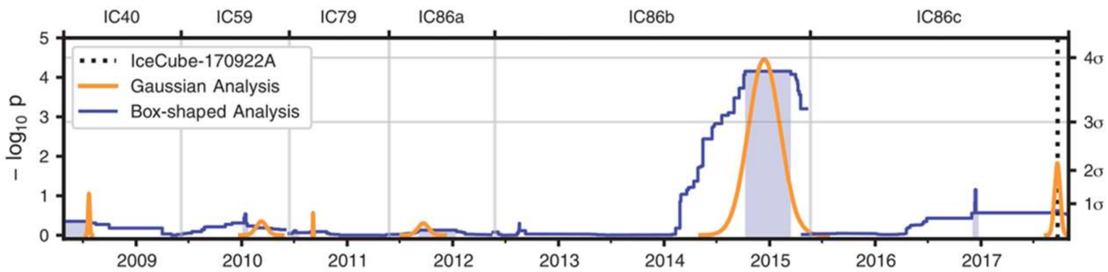
[Zhang, ZL 2017]

Comment on the neutrino/BL Lac association

IC-170922A/TXS 0506+056 association, 4sigma coincidence [IC18a]



Neutrino burst/flare in archive data, 3.5sigma signal [IC18b]



However,
IC limit of 27 LSP BL Lacs
→ $\hat{\xi}_{\rm cr} < 0.92\zeta^{-1}$
→LSP BL Lacs contribute <17% neutrinos

[Zhang, ZL 2017]

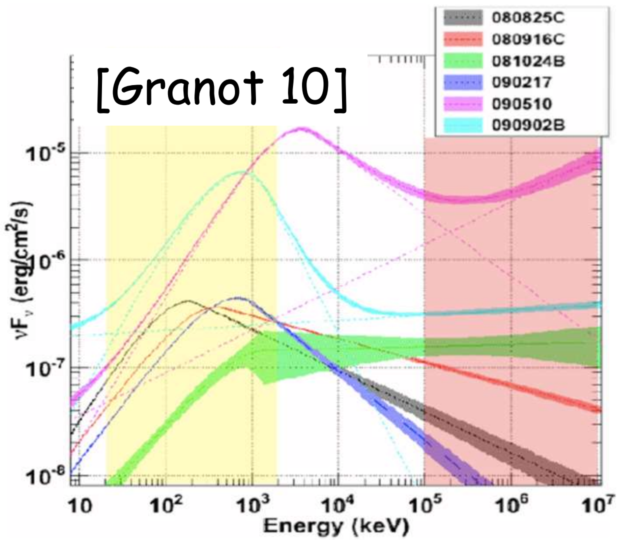
So,
TXS 0506+056 like BL Lacs should not contribute the bulk of the neutrino flux.

Gamma-ray bursts

- Fermi-LAT constrains 0.1-100GeV flux of GBM-triggered GRBs
- Translated to neutrino flux upper limit

➔average neutrino flux per GBM GRB

$$f_\nu < 2\times10^{-3}\,\mathrm{GeV\,cm^{-2}}$$ [ZL 2013]



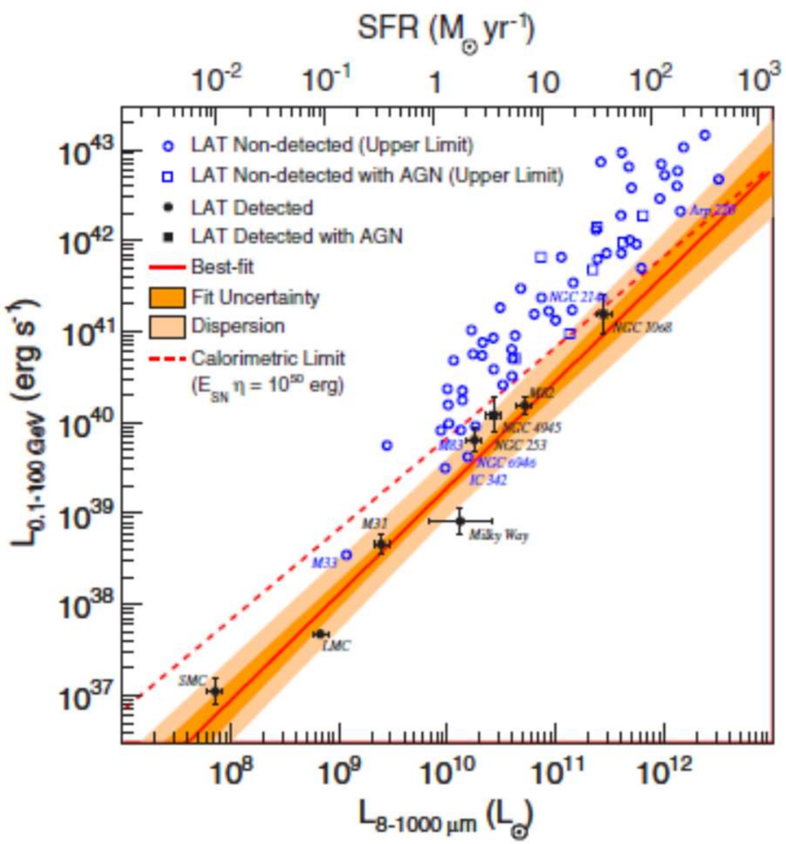
- All-sky GRB MeV gamma-ray flux is measured/calculated
  - GRB redshift distribution $R_{GRB}(z)$ and MeV luminosity function $\Phi(L)$ are well measured
- Assume neutrino/gamma~const.
- IC flux requires

➔average neutrino flux per GBM GRB

$$f_\nu = 1.3\times10^{-2}\frac{\Phi_{trig}}{0.7\Phi_{tot}}\frac{400\mathrm{yr}^{-1}}{\dot{N}_{trig}}\mathrm{GeV\,cm^{-2}}$$

[Wang, Zhao, ZL 14]

Starburst galaxies



$$\nu L_\nu(\mathrm{GeV})/\mathrm{SFR} \approx 10^{46} \mathrm{erg}/M_\odot$$

[Fermi-LAT, Ackermann+12]

GeV neutrino ~ GeV gamma

$$\sim \int \frac{\nu L_\nu}{SFR} \rho_{SFR}(z)\mathrm{d}z$$

extrapolated to PeV $\sim E_p^{-2.2}$

$$E_\nu^2 \Phi_\nu \approx 10^{-8} \frac{\xi_z}{3} \left(\frac{E_\nu}{1\mathrm{PeV}}\right)^{-0.2} \mathrm{GeV\,cm^{-2} s^{-1} sr^{-1}}$$

Consistent with observed flux and spectrum at >60TeV

[Wang, Zhao, ZL 14]

IceCube neutrino sources?

- ☹diffuse Galactic emission, <1%
- ☹GRBs, <10%
- ☹AGN jets, <10%
- ☺starburst galaxies
  - SNR CRs w/ 100PeV?

[Wang, Zhao, ZL 2014 JCAP; Wang, ZL 2016 SCPMA; Zhang, ZL 2017 JCAP]

$$E_p \lesssim 5 \frac{\mathcal{E} \epsilon_{B,-2}^{1/2} n_{-1}^{1/6}}{\mathcal{M}^{2/3}} \mathrm{PeV}$$

[ZL 2017]

- *Wind breakout of type II SNe*

BL1

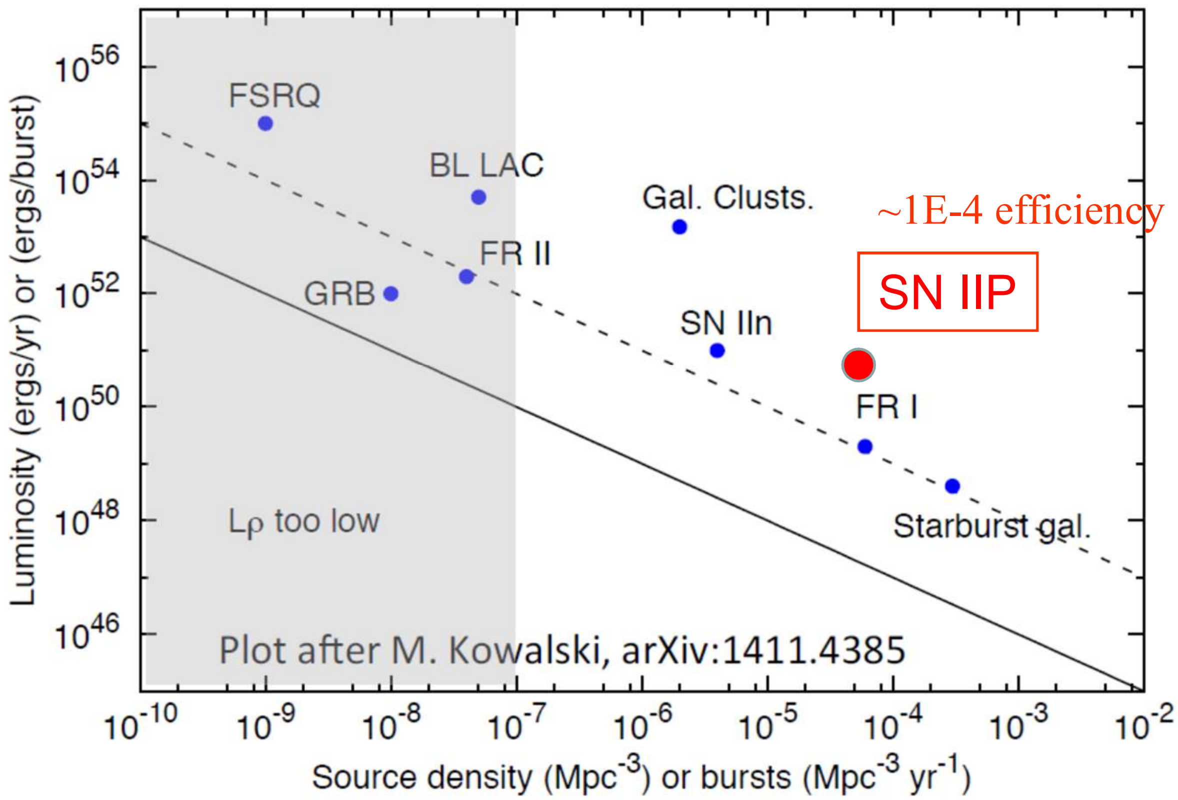
Implication from point source limits and presence of (strong) diffuse flux

Kowalski Plot

Source density and luminosity are related to produce the observed flux.

Absence of clustering sets a minimum on source density.

→Certain classes of sources disfavored.



Dashed line assumes 1% efficiency for production of neutrinos

Slide adapted from Gaisser

幻灯片 35

BL1 Badra Lai, 2017/11/5

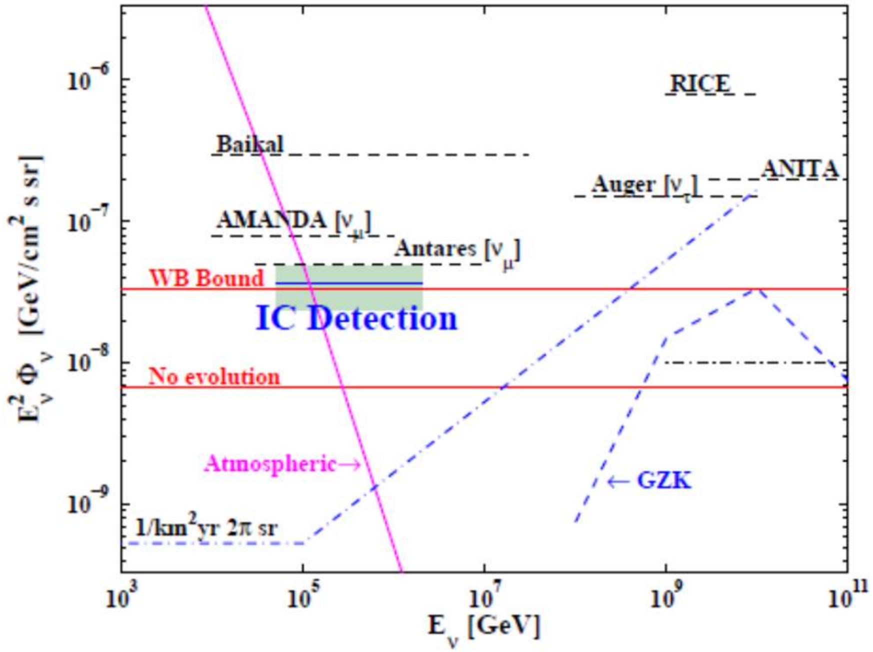
IC diffuse flux = WB bound
(@>60TeV)

- The same origin for both UHE CRs and IC neutrino-related HE CRs?

[Katz+2014]

- A possibility:
  GRBs in starbursts
  - GRB hosts are starbursts
  - GRB CRs produce pions efficiently in host galaxies

[Wang, Zhao & ZL, 2014]



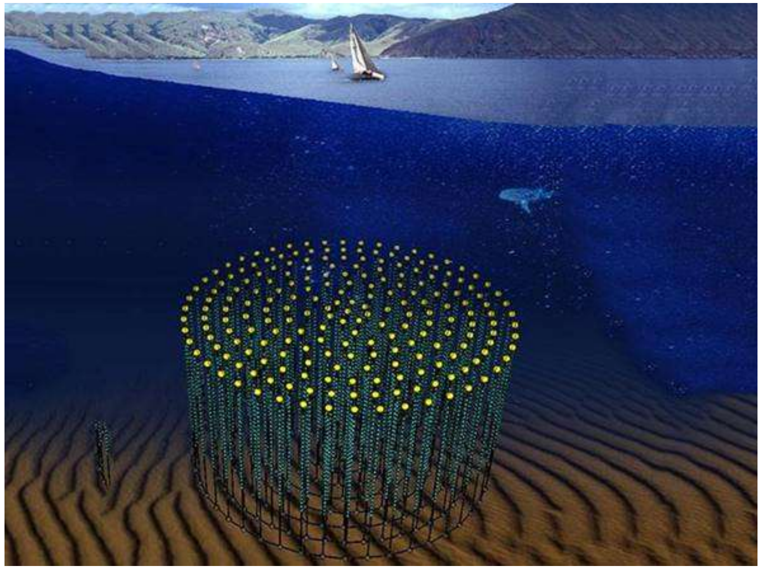
Prospects

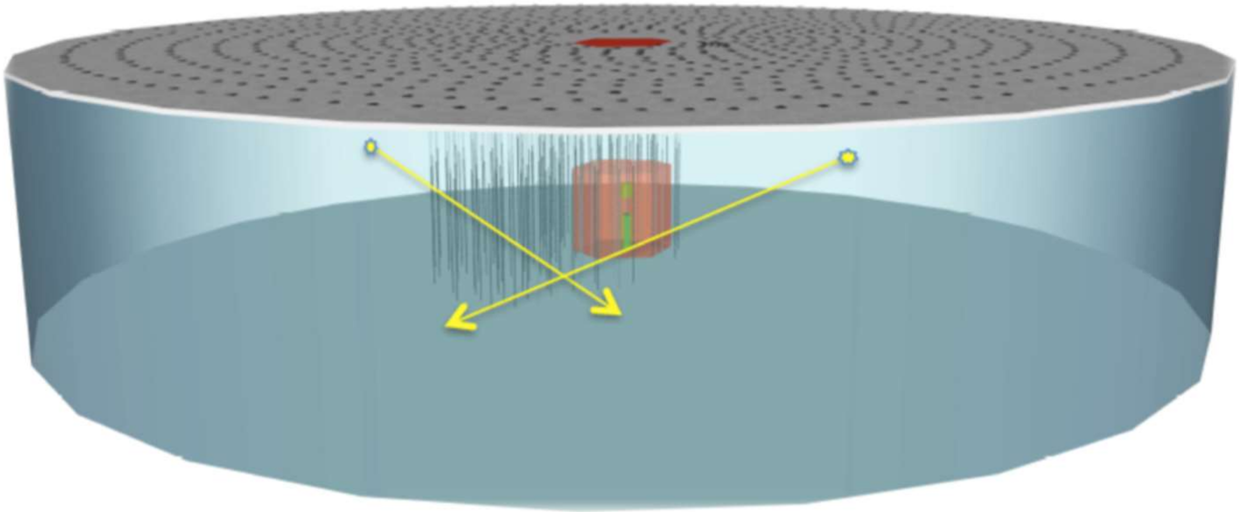
Frontier of HE neutrino astronomy

- Astrophysics
  - Identify UHECR sources (time/direction)
  - Constrain source physics & acceleration mechanism
    - e.g. resolve jet composition (lepton, or baryon)
  - GZK neutrinos
- Physics
  - Probe relativity
    - Einstein Equivalent Principle
  - Probe new physics
    - Violation of Lorentz-Invariant
  - Neutrino physics
    - Oscillation; τ appearance; CP violation…
    - Interaction cross section

Go larger: search point sources

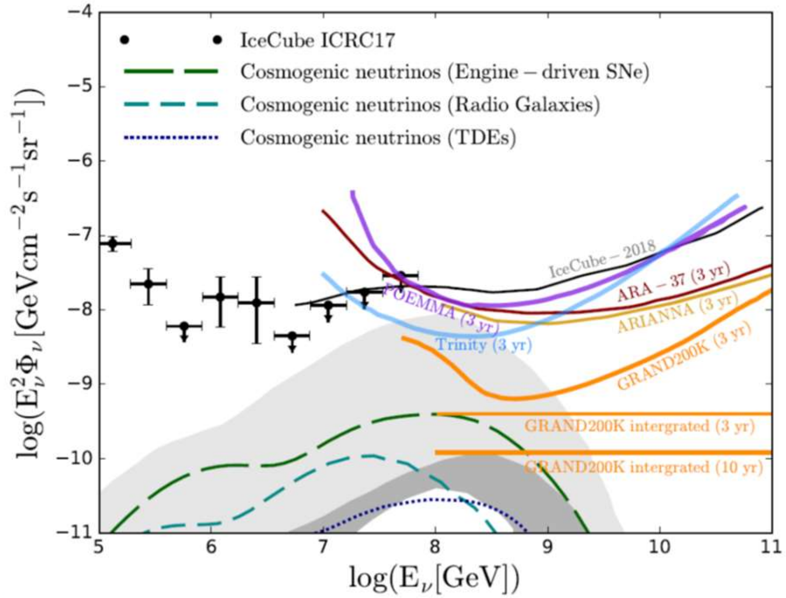
- IceCube-Gen2 / KM3Net
  - ~10 times IceCube
  - >PeV nu source,

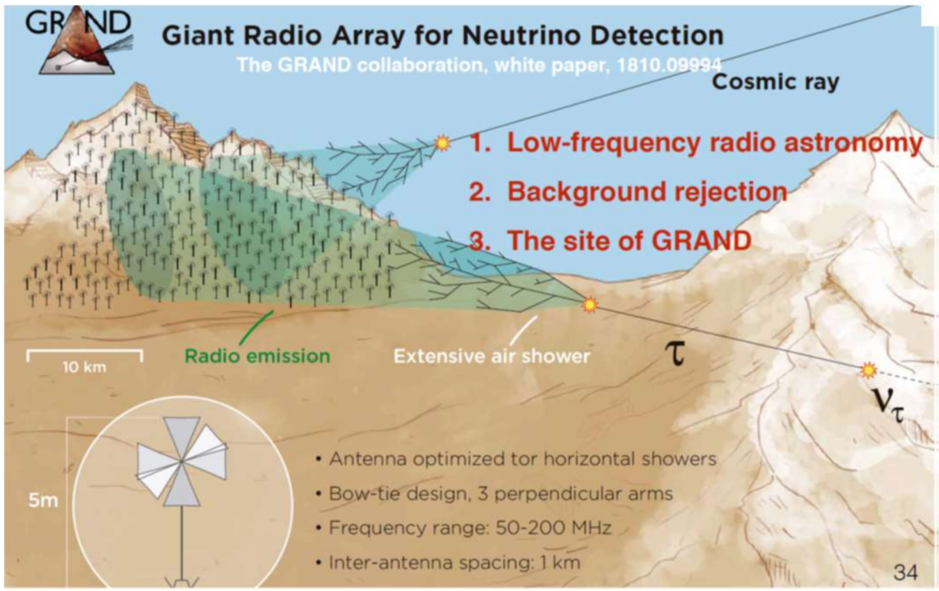


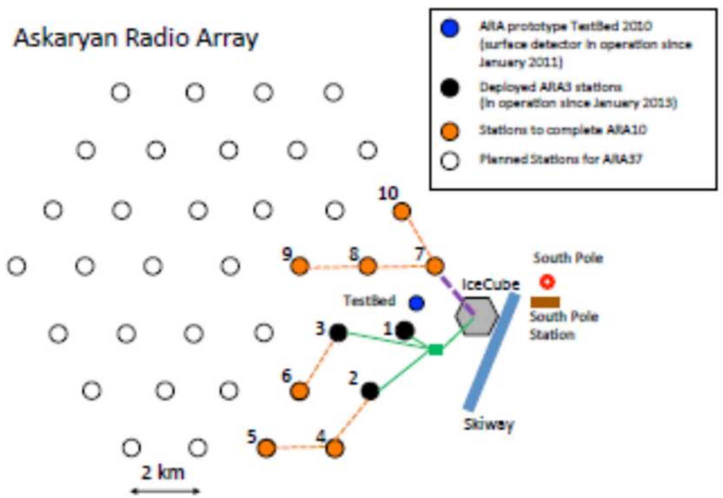


Go larger: higher energy, GZK neutrinos

- ANITA/ARA/ARIANA
  - Radio Cerenkov from ice showers
  - GZK nu
- GRAND
  - Radio Cerenkov from air showers
  - GZK nu
  - EeV nu sources

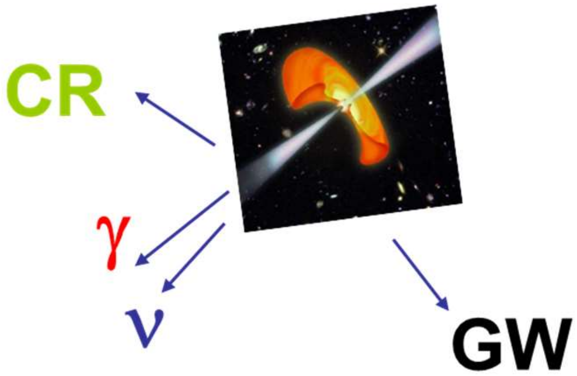


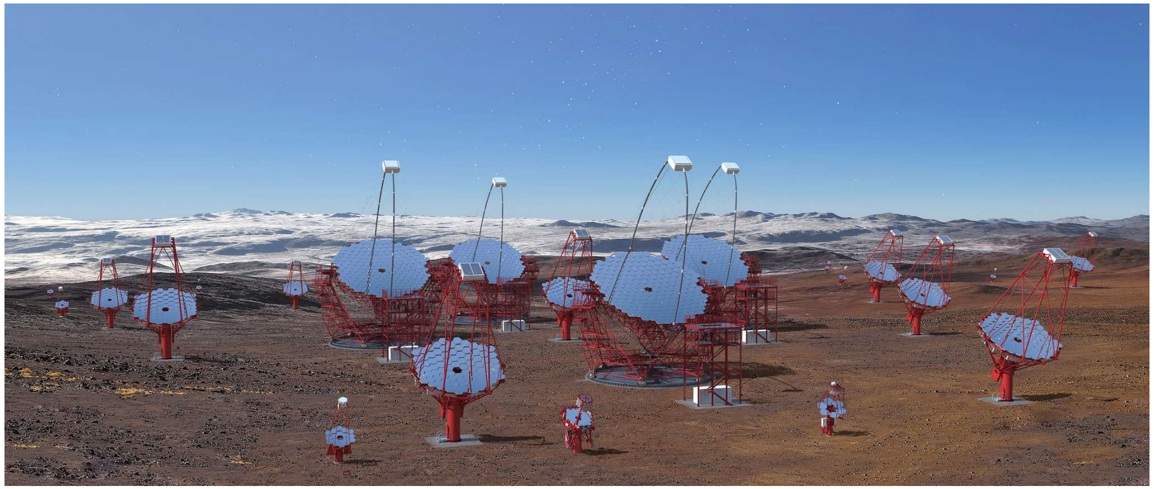




Multi-messenger astronomy

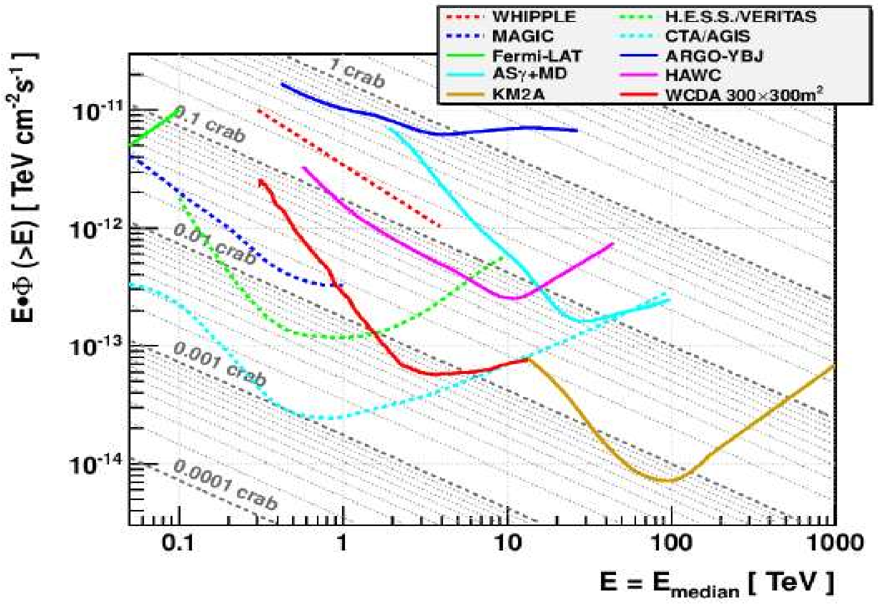
- UHECRs
  - Auger, TA…
- HE gamma-rays
  - LHAASO, CTA…
- HE neutrinos
  - IceCube, KM3Net, ARA, ARIANNA, GRAND…

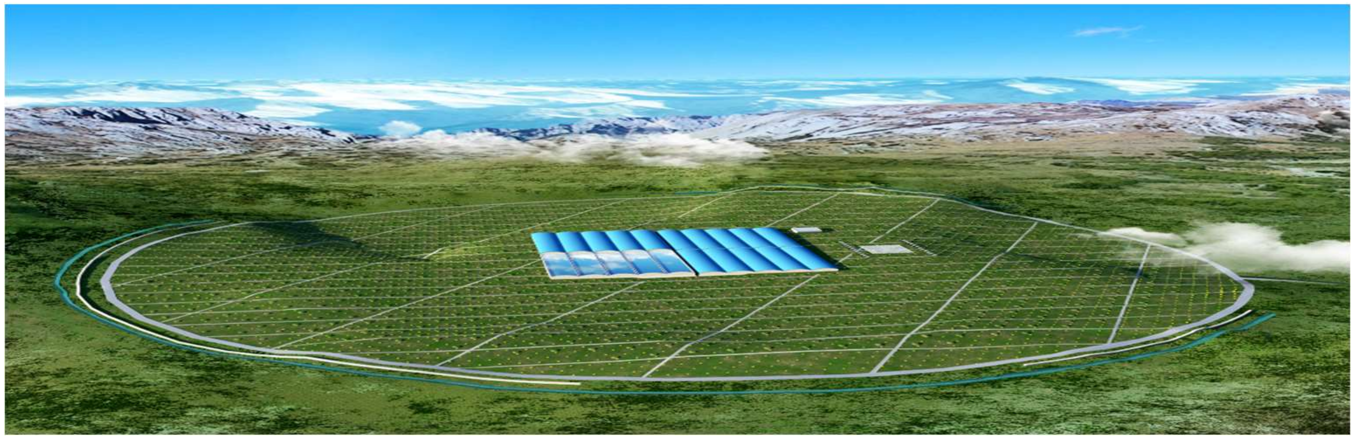




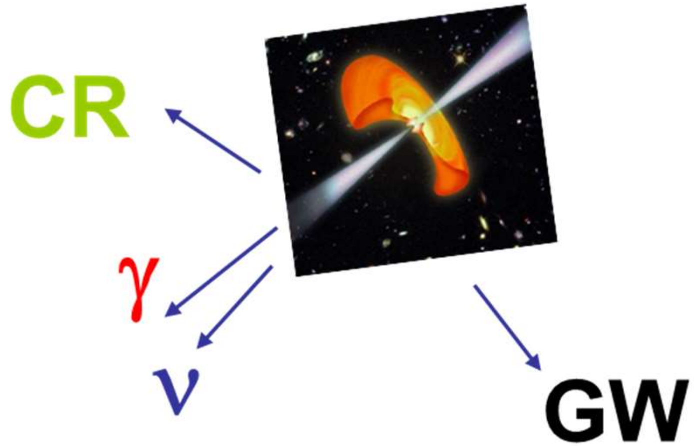
LHAASO's important role

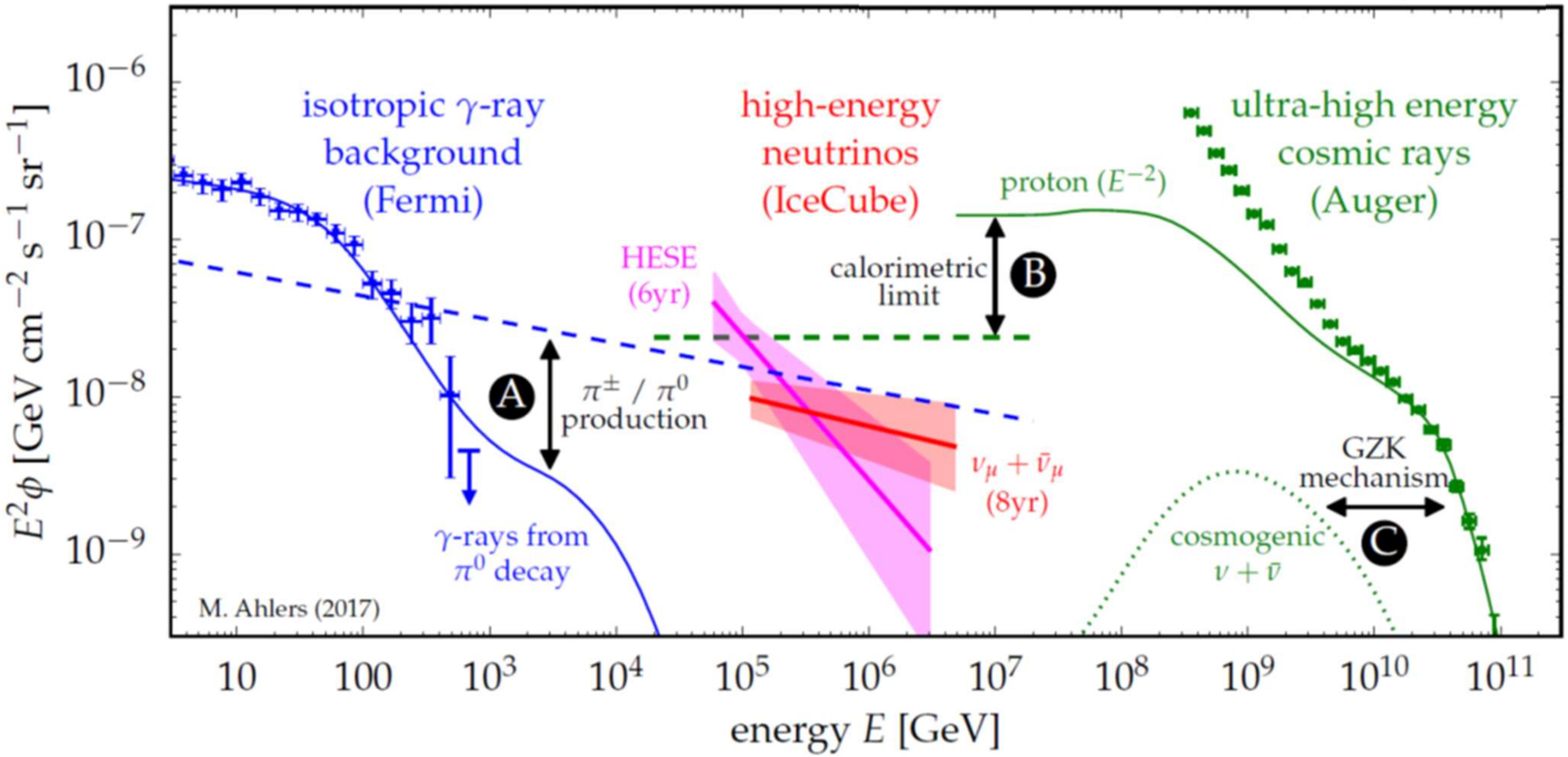
- Large field of view
- High duty cycle
- High sensitivity
  - unprecedented at 100TeV





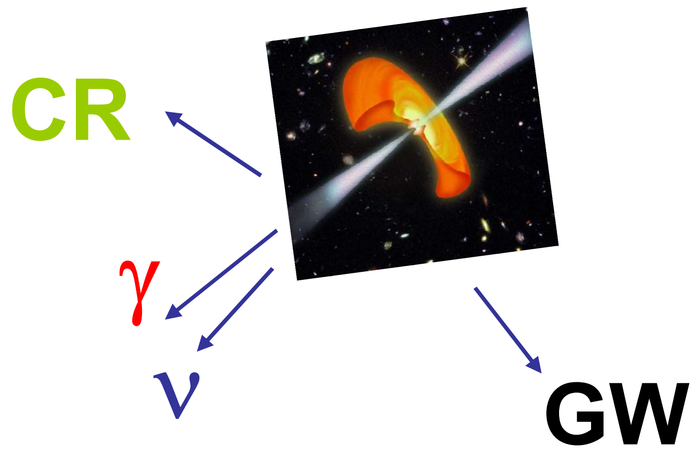
Multi-messengers





MM approach to identify sources?

- *Neutrino point source search*
  - *larger size, higher energy (but only for bright sources)*
- Neutrino-EM association
  - Cross correlations
  - Neutrino search for known EM candidate sources
    - Individuals; stacking
  - EM search for neutrino events (for transients)
    - Archive EM data for detected neutrino events
    - IceCube alert (<0.5deg sky area)



HE neutrino astronomy