HIGH-ENERGY ASTROPHYSICAL NEUTRINOS

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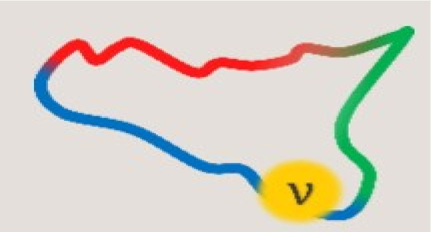
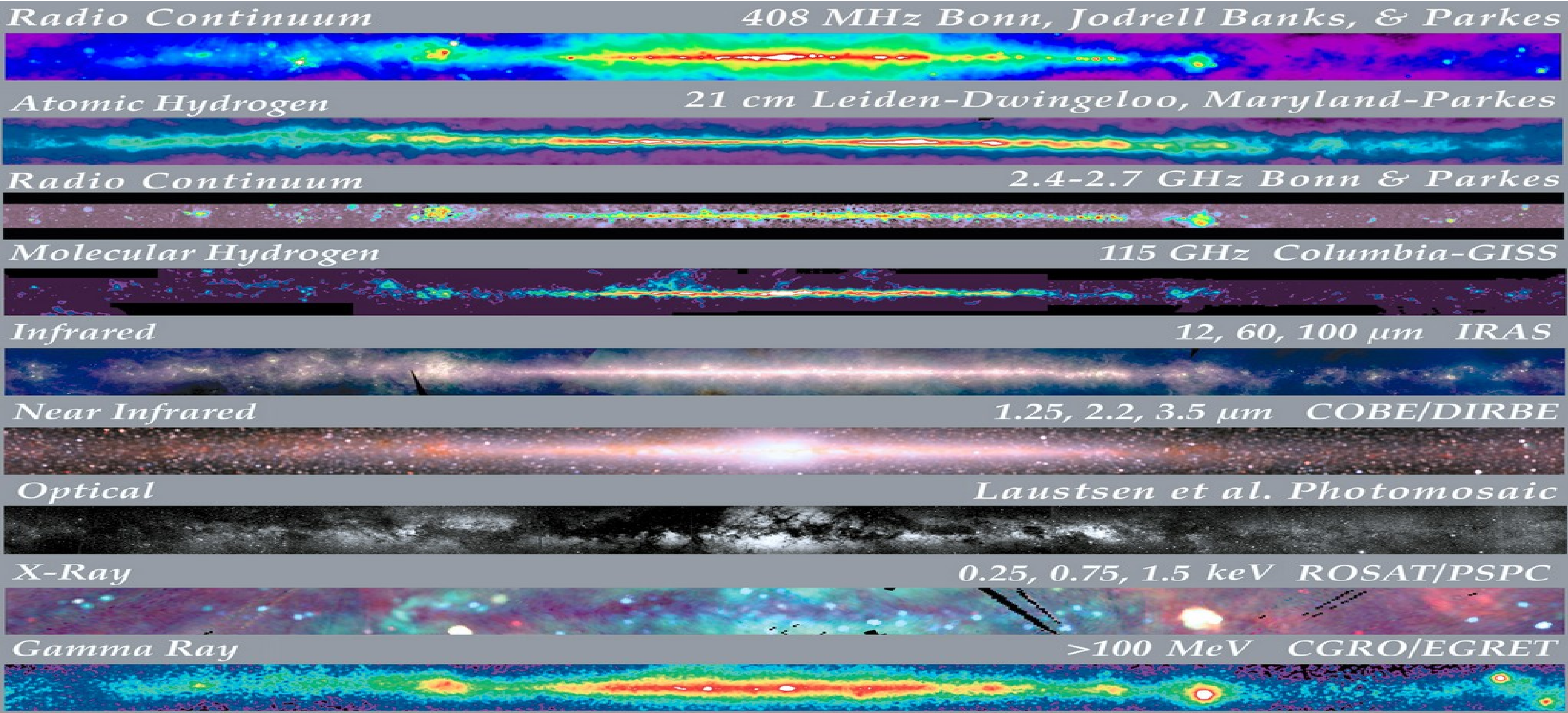
MAYORANA School, Modica 2023



MULTIWAVELENGTH ELECTROMAGNETIC ASTRONOMY

Traditionally, the sky has been observed in electromagnetic radiation
different wavelengths lead to different insights



multiwavelength M87

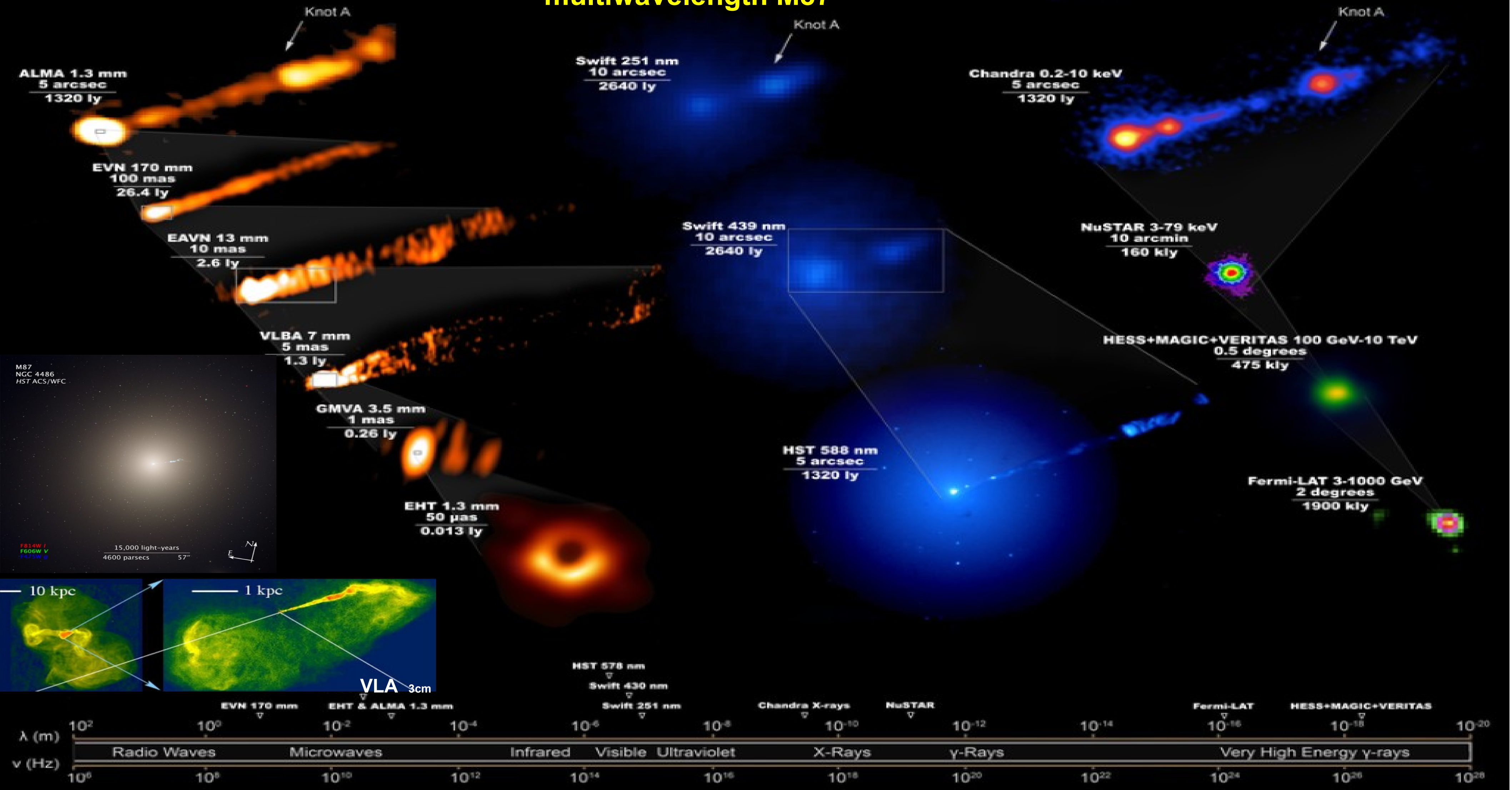
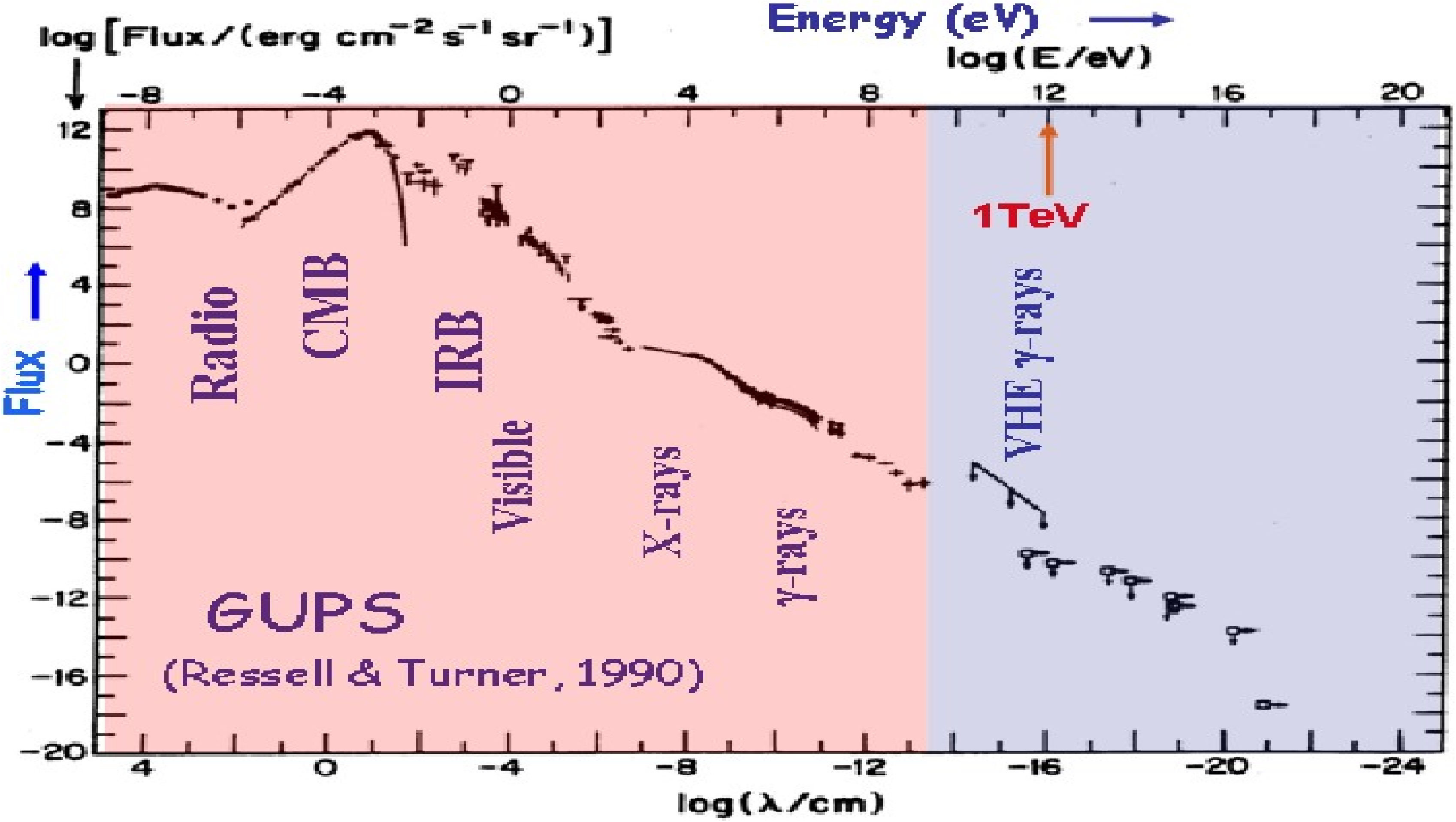


Image Credit: The EHT Multi-wavelength Science Working Group; the EHT Collaboration; ALMA (ESO/NAOJ/NRAO); the EVN; the EAVN Collaboration; VLBA (NRAO); the GMVA; the Hubble Space Telescope; the Neil Gehrels Swift Observatory; the Chandra X-ray Observatory; the Nuclear Spectroscopic Telescope Array; the Fermi-LAT Collaboration; the H.E.S.S collaboration; the MAGIC collaboration; the VERITAS collaboration; NASA and ESA. Composition by J. C. Algaba

DIFFUSE PHOTON BACKGROUND

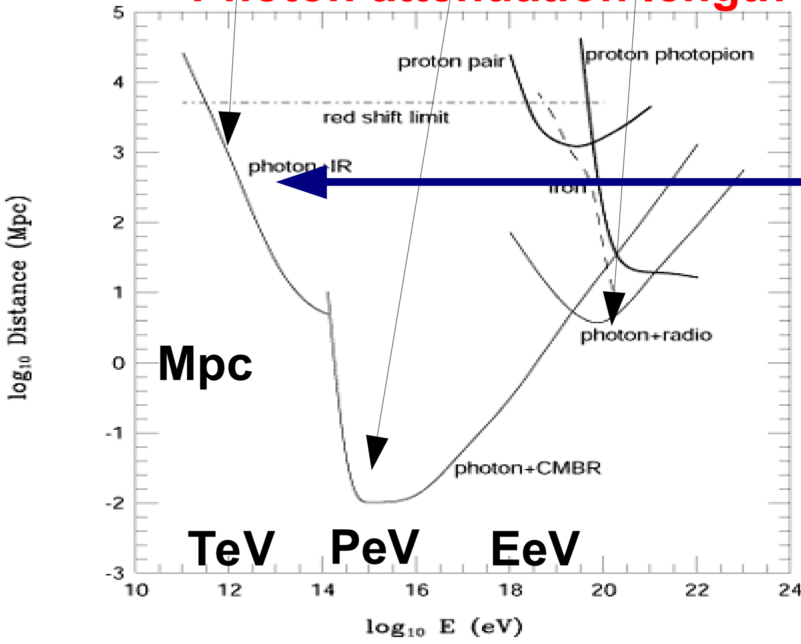


the Universe is filled with background radiation

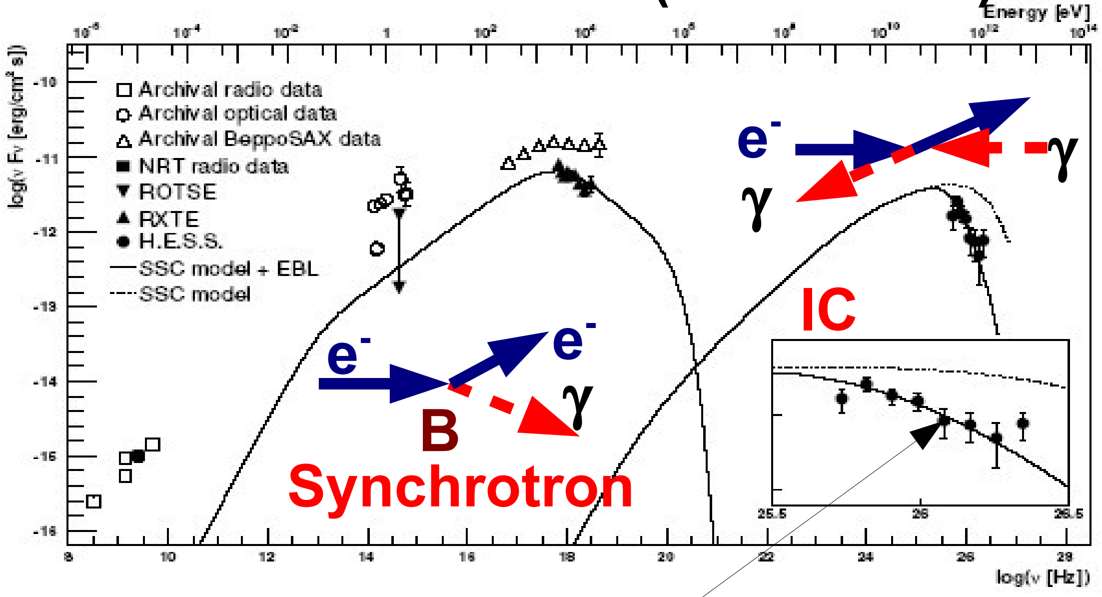
Distant γ sources are strongly attenuated by background photons (starlight, CMB, radio, ...): $\gamma\gamma \rightarrow e^+ e^-$

(MeV² = eV TeV = meV PeV)

Photon attenuation length



z=0.165 BLLac (H2356-309)



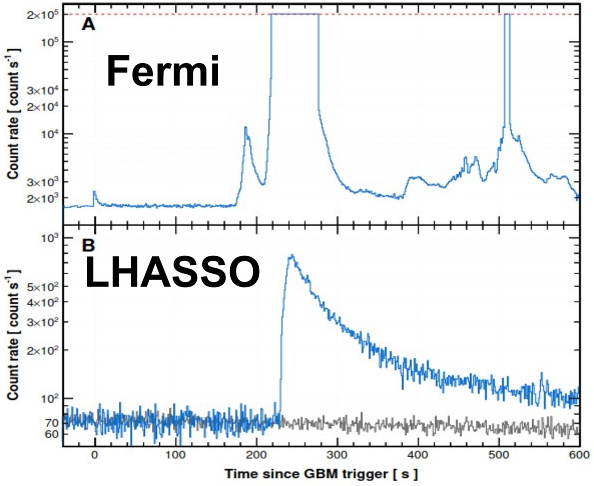
can even measure IR background from observed attenuation

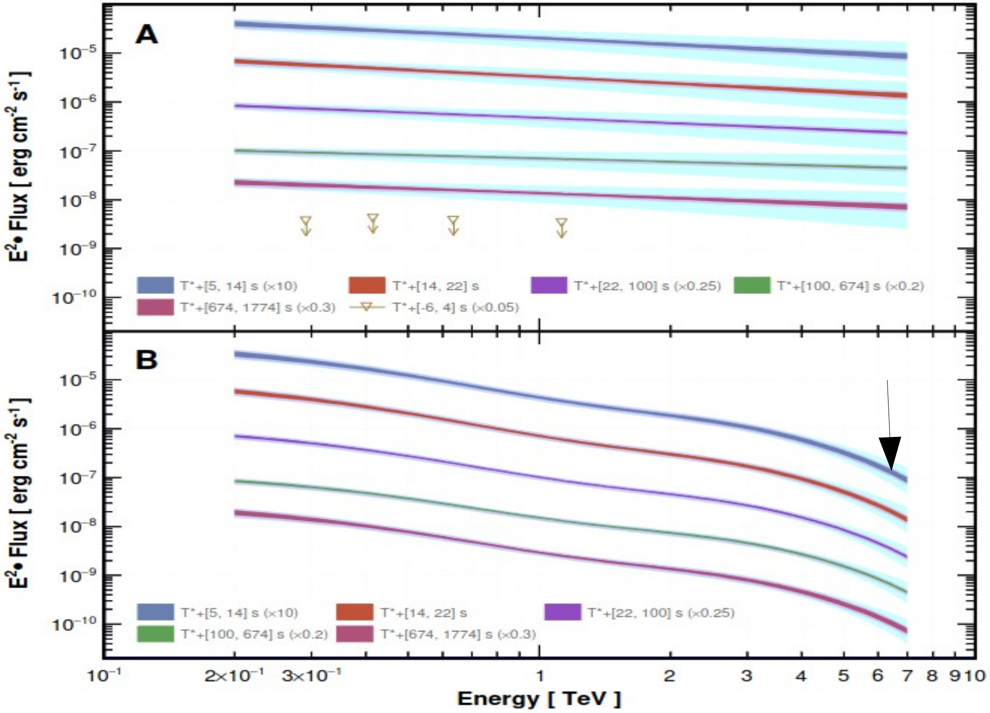
beyond few TeV, high redshift Universe is unobservable with photons

GRB 221009A Observed by LHAASO

redshift z=0.151 → distance ~ 740 Mpc

2306.06372





corrected for EBL attenuation

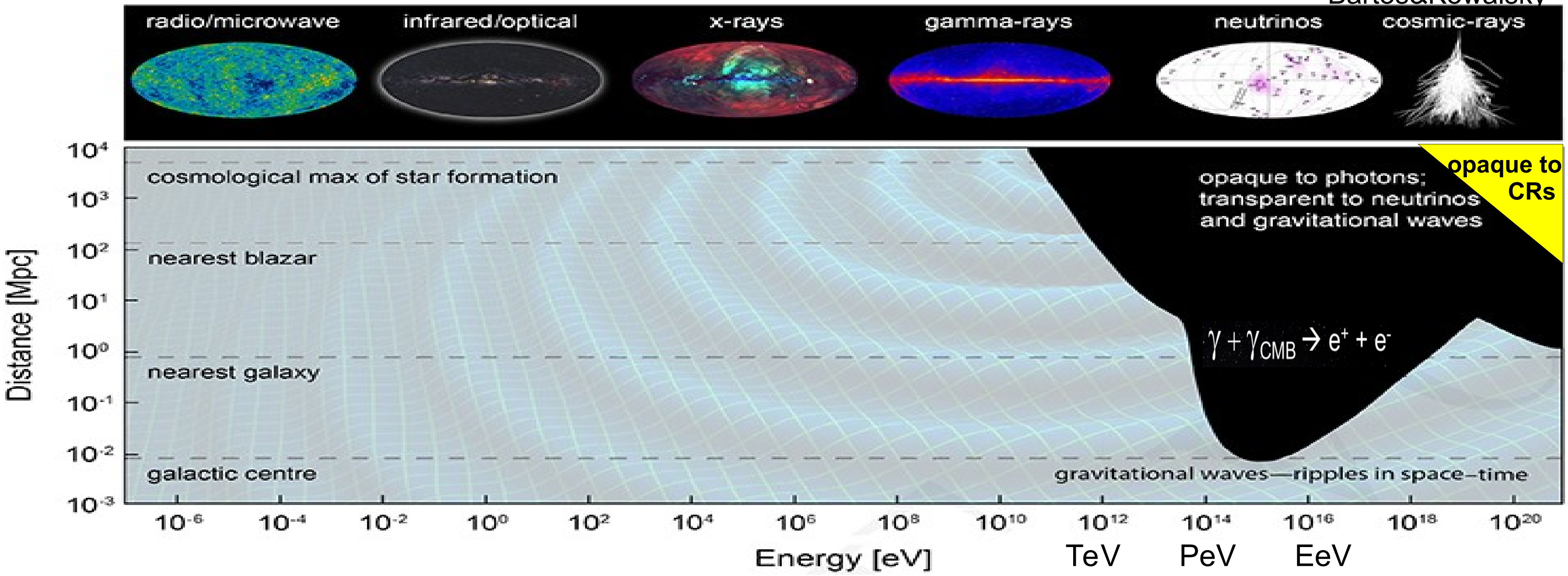
observed: suppressed by factor 100 at 7 TeV

re 2: **Intrinsic and observed flux spectra for five time-intervals.** (A) the intrinsic spectra corrected

moreover, absence of TeV emission in initial X-ray burst due to γ attenuation in dense inner jet?
TeV burst in external afterglow

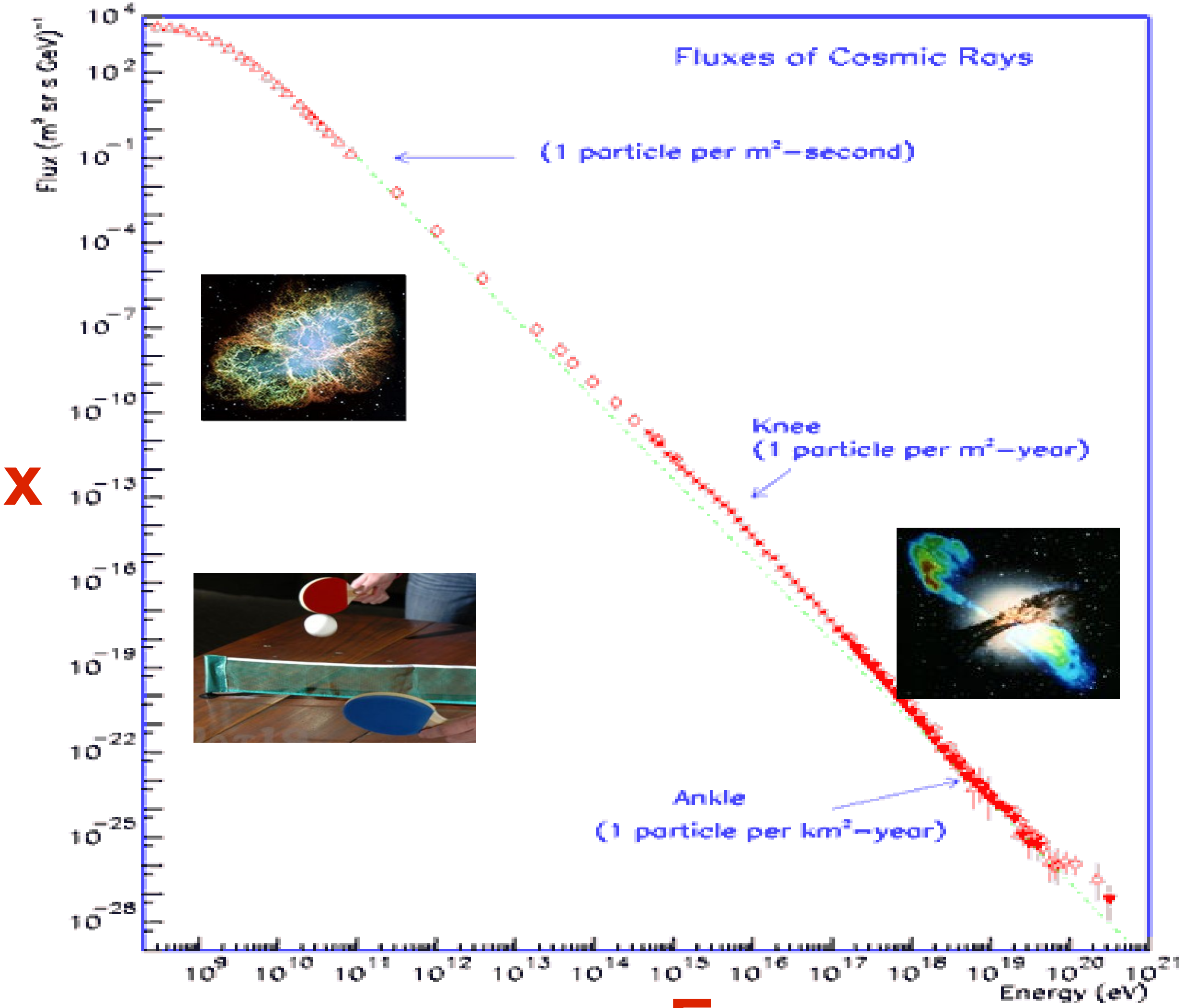
beyond TeV, photons get absorbed by radiation backgrounds

Bartos&Kowalsky



beyond 100 TeV, only Galactic sources visible in photons
sources at more than 100 Mpc (e.g. blazars) visible up to few TeV
beyond those energies only neutrinos and cosmic rays can reach us
moreover, while photons emitted from star photospheres,
neutrinos come from deep inside stars and supernovae
multimessenger searches now include also gravitational waves!

COSMIC RAY SPECTRUM

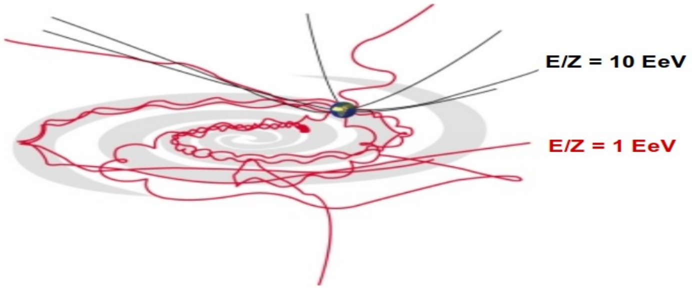


flux

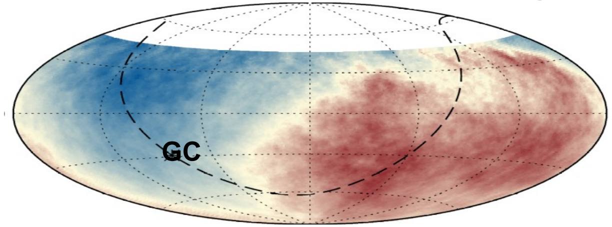
Energy

CR ANISOTROPIES

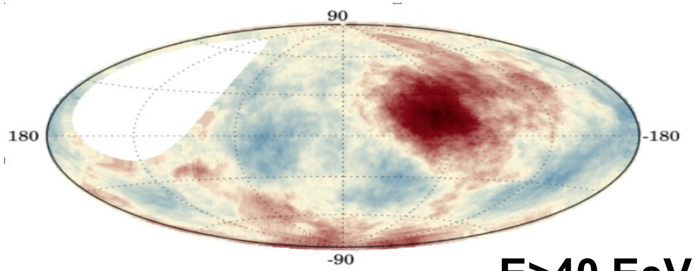
but CRs are charged particles



anisotropies with Auger



E>8 EeV

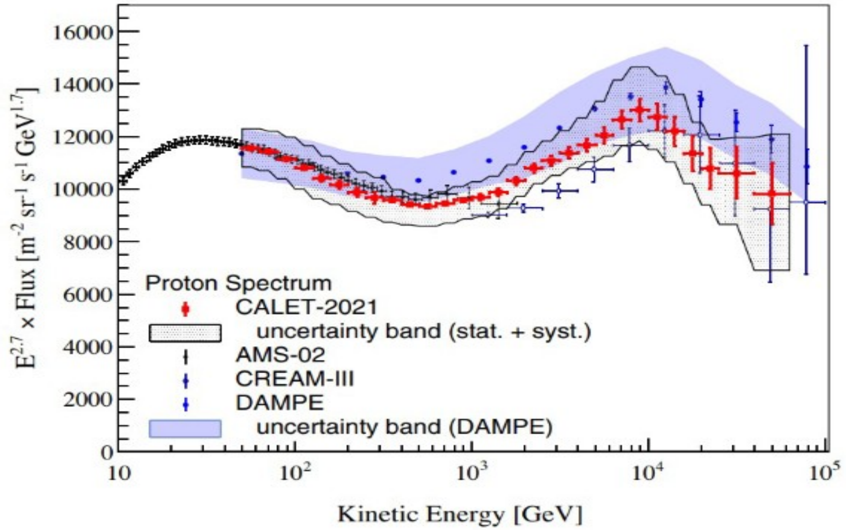


E>40 EeV

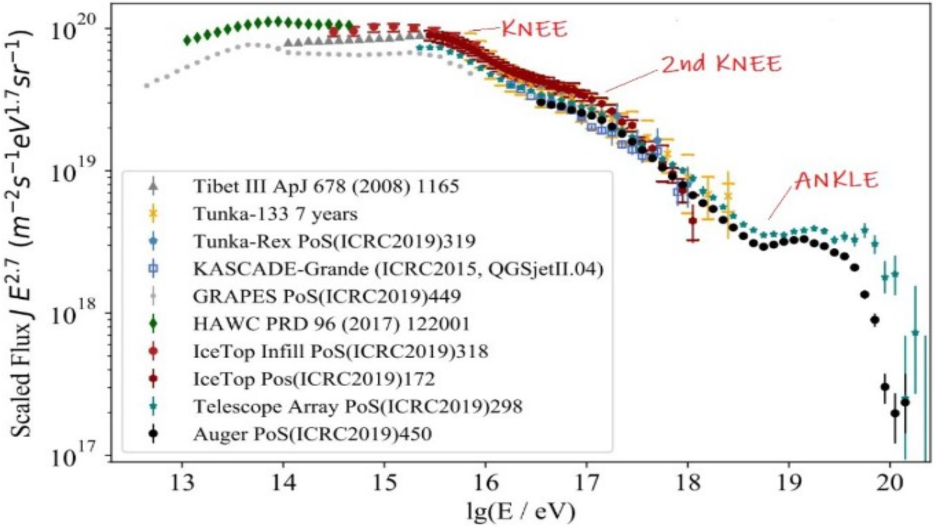
CR spectrum actually not so featureless

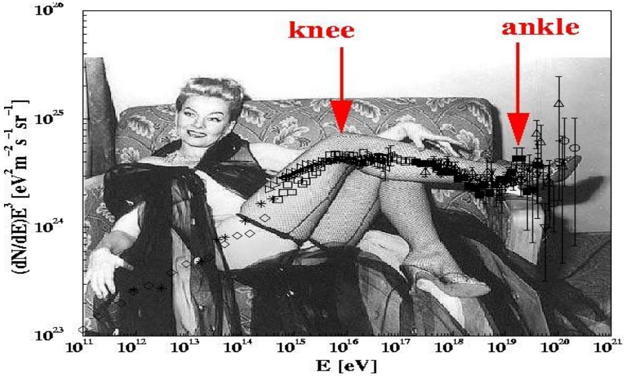
Flux x $E^{2.7}$

satellites



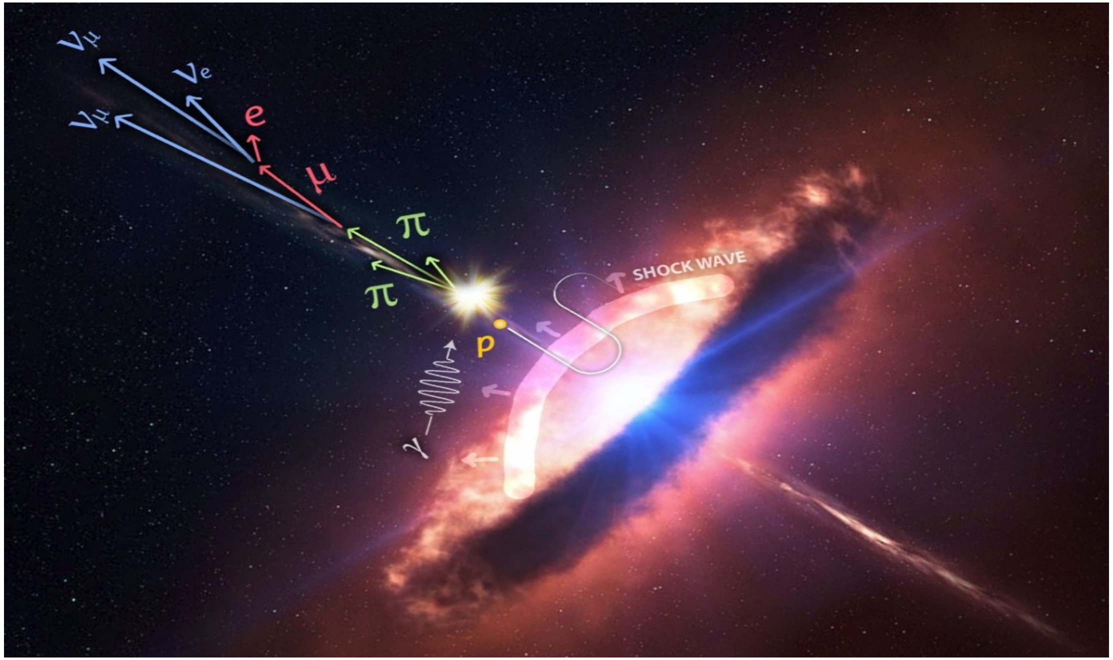
ground arrays





NEUTRINO ASTRONOMY AT VERY HIGH ENERGIES:

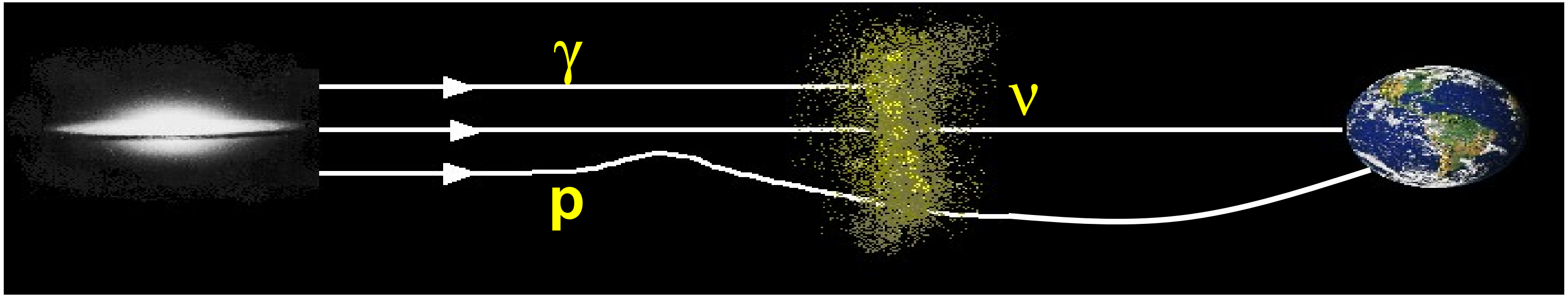
- NEUTRINOS PROPAGATE STRAIGHT AND UNATTENUATED
- NEUTRINOS GET PRODUCED IN CR SOURCES



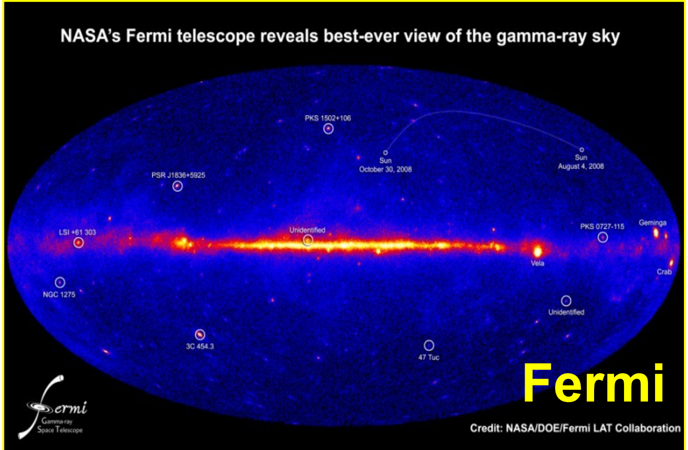
neutrinos may tell us where CRs get accelerated,
and they may also help us to learn a lot about their sources

THE ENERGETIC UNIVERSE

multi-messenger astronomy



γ rays

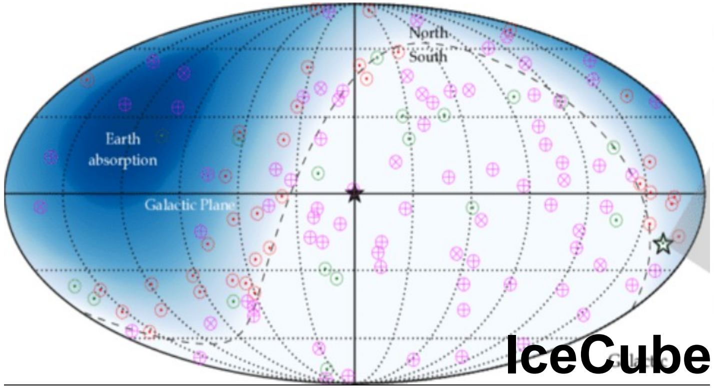


NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

Fermi

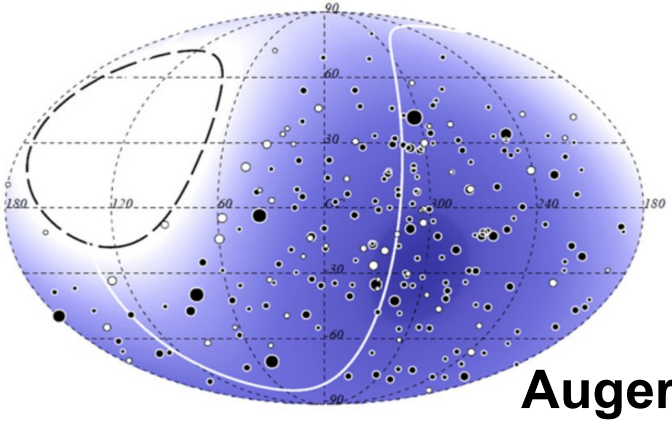
Credit: NASA/DOE/Fermi LAT Collaboration

neutrinos



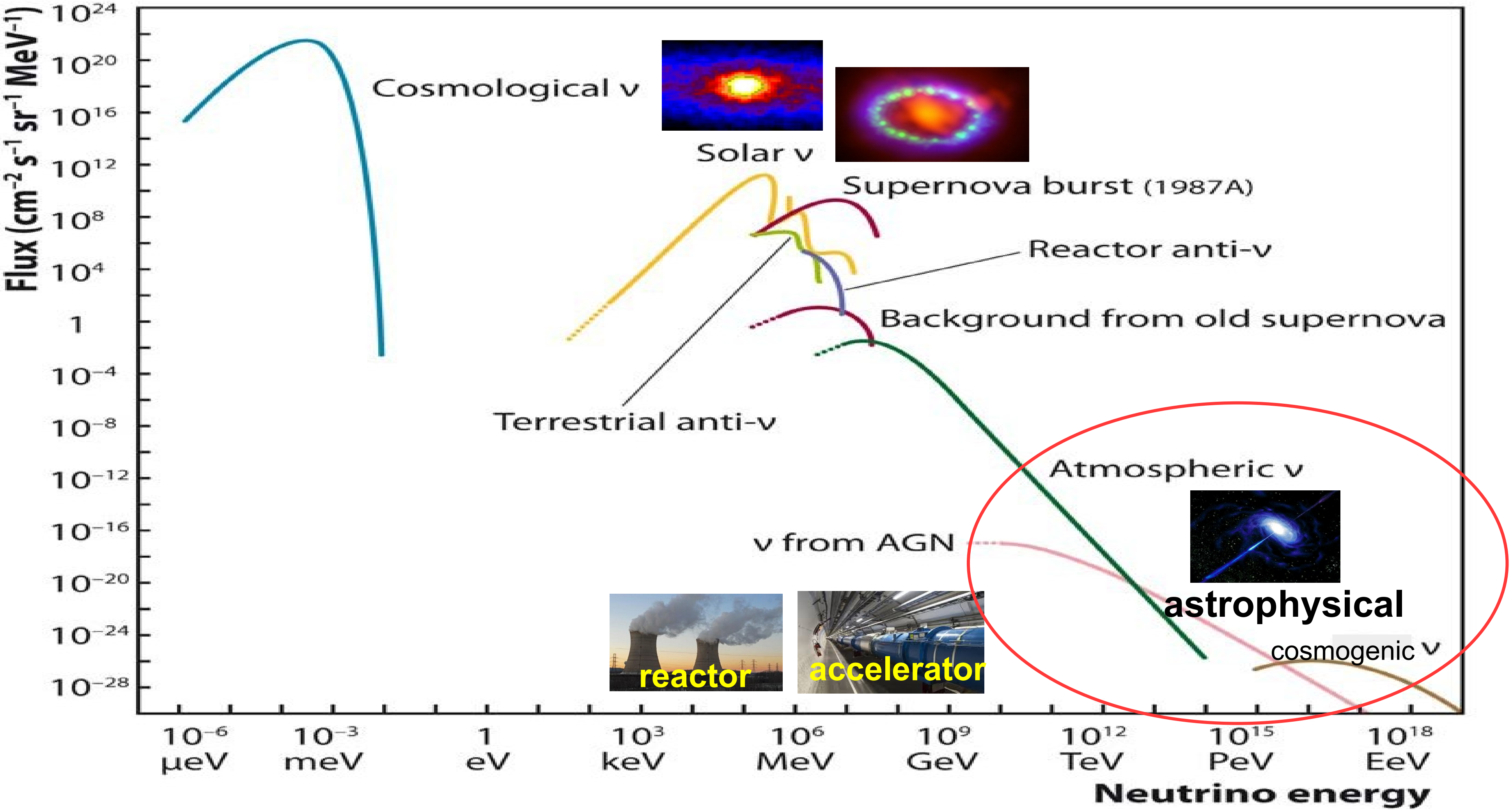
IceCube

UHE Cosmic rays

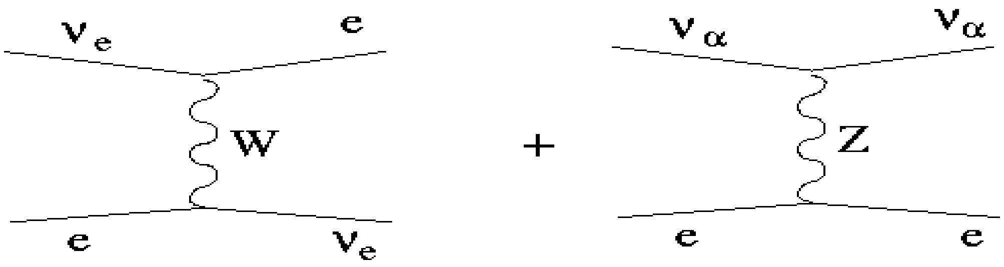


Auger

Neutrino spectra from different sources



Neutrino – electron interactions



$$H^{eff} = \frac{G_F}{\sqrt{2}} \left[\bar{\nu}_\alpha \gamma_\mu (1-\gamma_5) \nu_\alpha \right] \left[\bar{e} \gamma^\mu (c_L P_L + c_R P_R) e \right]$$

$$c_L = \delta_{\alpha e} + \sin^2\theta_W - \frac{1}{2} \qquad c_R = \sin^2\theta_W$$

For E_ν >> m_e:

$$\sigma(\nu l \rightarrow \nu l) = \frac{2G_F^2}{\pi} m_l E_\nu \left[c_L^2 + \frac{c_R^2}{3} \right]$$

$$(\sigma(\bar{\nu} l \rightarrow \bar{\nu} l) \ : \ c_L \Leftrightarrow c_R)$$

for antineutrinos:

$$\sigma(\nu_e e) \approx 4 \times 10^{-44} cm^2 \left(\frac{E_\nu}{10\, MeV} \right) \approx 2.5\, \sigma(\bar{\nu}_e e) \approx 6\, \sigma(\nu_{\mu,\tau} e) \approx 7\, \sigma(\bar{\nu}_{\mu,\tau} e)$$

(check it)

[for E_ν >> m_e it is directional → good for neutrino telescopes]

Neutrino nucleon CC interactions

For E_ν < 50 MeV (Quasi Elastic):

$$\sigma(\nu_e n \to p e) \approx \sigma(\bar{\nu}_e p \to n \bar{e}) \simeq \frac{G_F^2}{\pi} \cos^2\theta_c \left(g_V^2 + 3 g_A^2\right) E_\nu^2$$

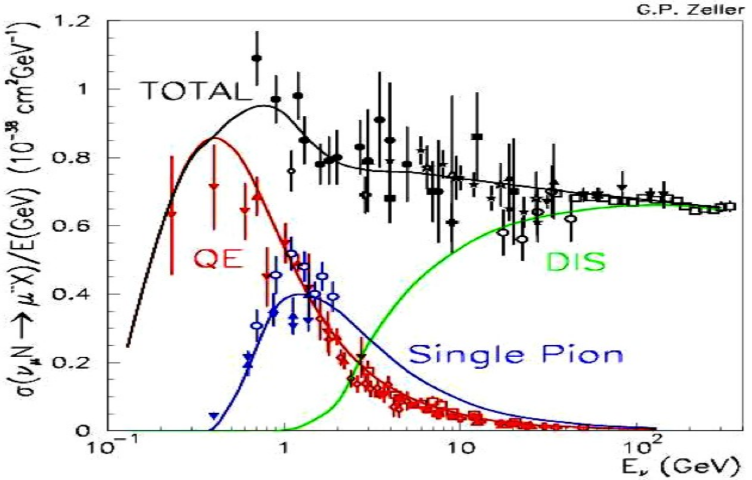
$$g_V = 1$$
$$g_A = 1.27$$

inverse beta decay (IBD) used to discover νs from reactors

Reines&Cowan

for E_ν > 50 MeV the nuclear form factors smooth-out the point-like behavior (QE x-section saturates):

$$\frac{\sigma}{E}$$



$$F_{V,A}(q^2) \approx F_{V,A}(0)\left[1 + \frac{q^2}{m_{V,A}^2}\right]^{-2} \qquad (m_{V,A} \simeq GeV)$$

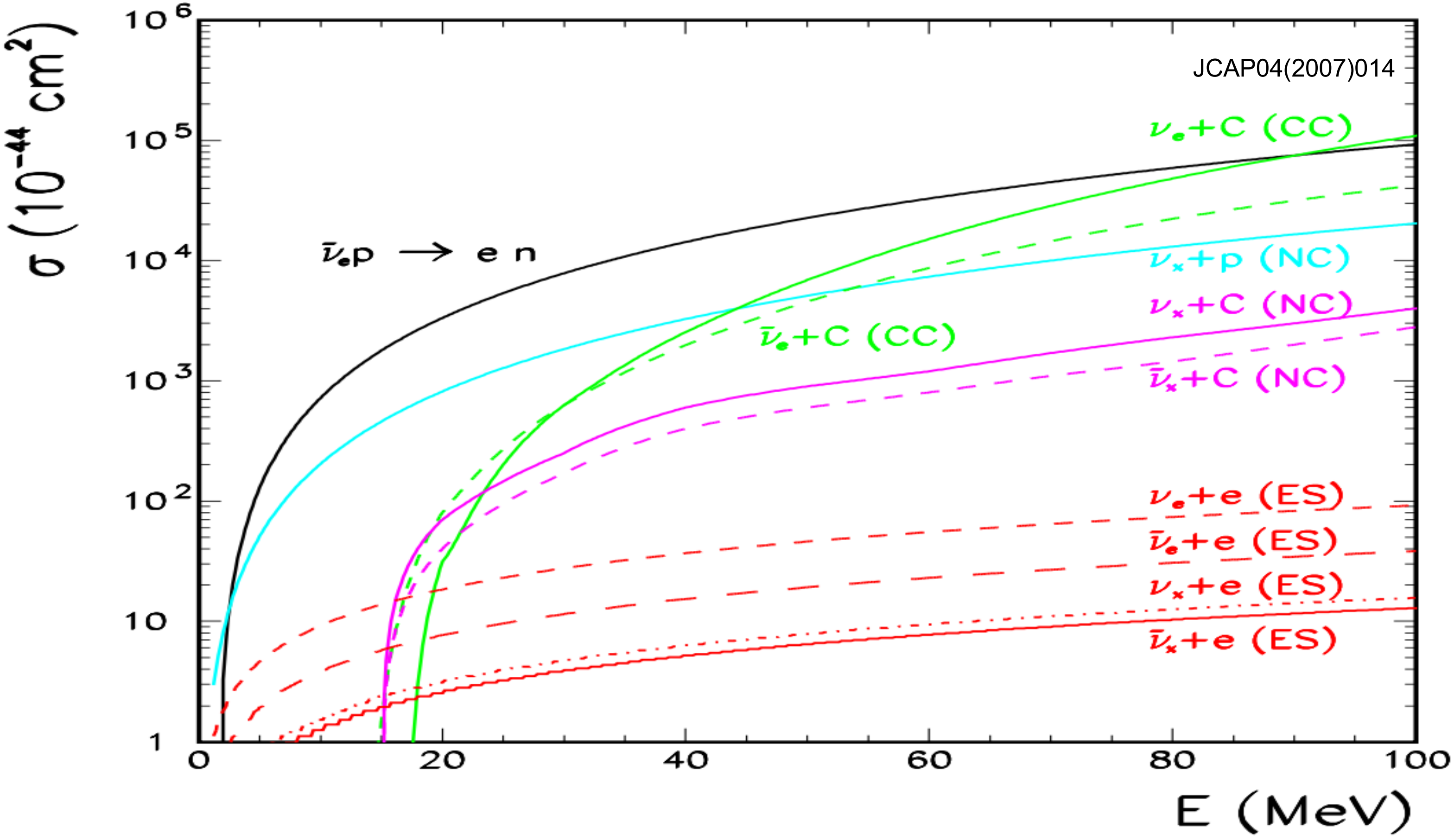
Quasi Elastic: $\nu_\mu p \to \mu n$

resonant: $\nu_\mu p \to \mu p \pi$

Deep Inelastic: $\nu_\mu p \to \mu X$

(see Formaggio&Zeller, RevModPhys 2012)

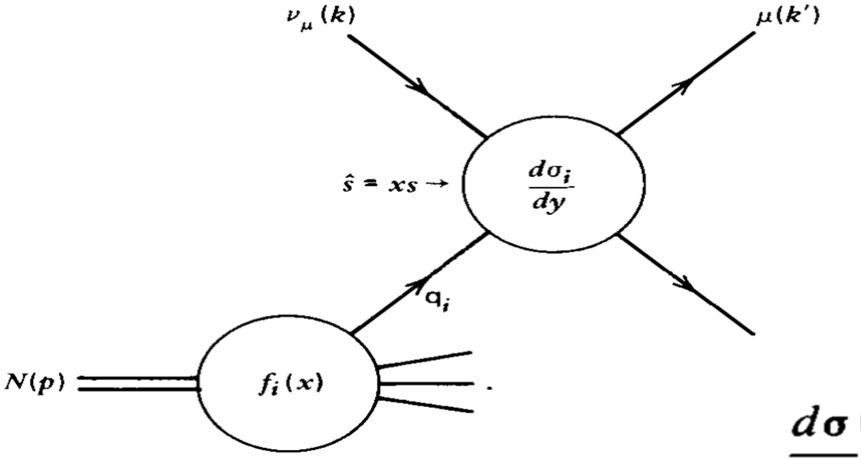
Neutrino cross sections below 100 MeV



CC cross sections with nuclei have larger thresholds (final state blocking)

Neutrino deep inelastic CC scattering (E >>100 MeV):

$$\frac{d\sigma\,(\nu N \to \mu X)}{dx\,dy} = \sum_i$$



$$= \sum_i f_i(x)\left(\frac{d\sigma_i}{dy}\right)_{\hat{s}=xs}.$$

$$\frac{d\sigma}{dy}(\nu_\mu \mathrm{d} \to \mu^- \mathrm{u}) = \frac{G^2 xs}{\pi},$$

$$\frac{d\sigma}{dy}(\bar{\nu}_\mu \mathrm{u} \to \mu^+ \mathrm{d}) = \frac{G^2 xs}{\pi}(1-y)^2$$

Scaling (Bjorken) variables:

$$x \equiv Q^2/2\mathrm{m}_N(E_\nu - E_l)\ ,\ \ y \equiv (E_\nu - E_l)/E_\nu\ ,\ \ Q^2 \equiv -(p_\nu - p_l)^2$$

isoscalar target

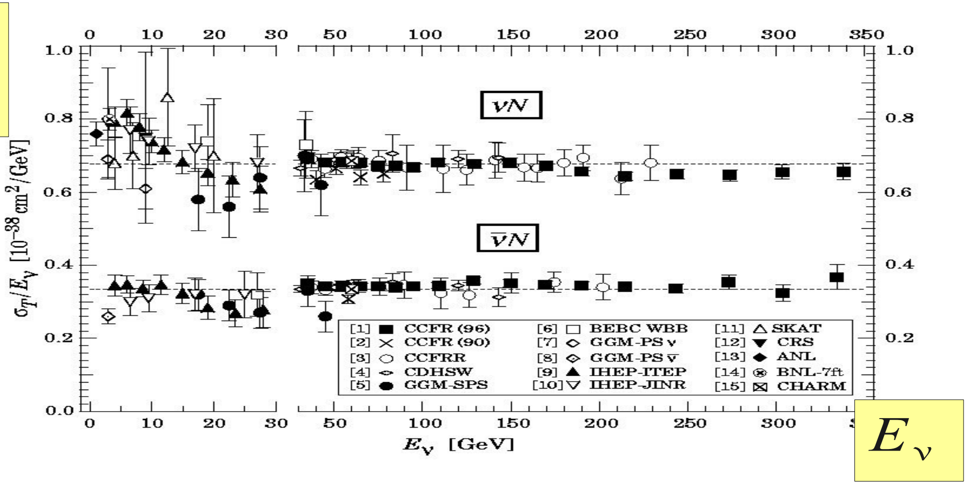
$$d^p(x) + d^n(x) = d(x) + u(x) \equiv \mathbf{q(x)}$$

$$\bar{u}^p(x) + \bar{u}^n(x) = \bar{u}(x) + \bar{d}(x) \equiv \mathbf{\bar{q}(x)}$$

Deep inelastic CC cross section:

$$\frac{d^2\sigma^{DIS}}{dx\,dy}(\nu N\rightarrow l\,X)=2\frac{G_F^2}{\pi}m_N E_\nu\frac{M_W^4}{(Q^2+M_W^2)^2}\left[xq(x,Q^2)+x(1-y)^2\bar{q}(x,Q^2)\right]$$

$$\frac{\sigma^{DIS}}{E_\nu}$$



E_ν

for $E_\nu < M_W^2/2m_N \simeq 5\,TeV$

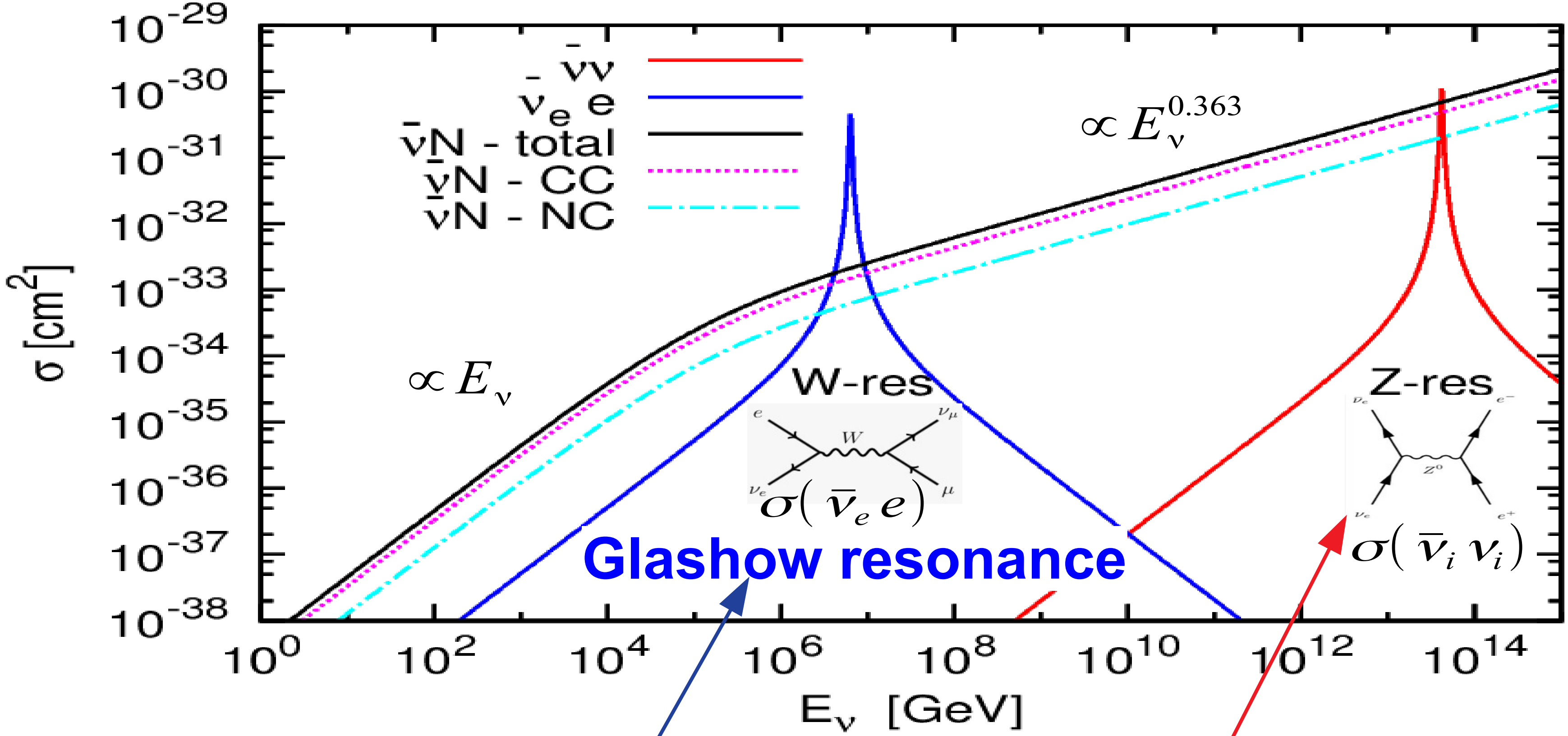
$\Rightarrow\ \sigma^{DIS}\propto E_\nu$

For $E_\nu \gg 5\,TeV$, W propagator ⇒ sensitivity to $Q^2 < M_W^2$
i.e., depends on small values of x (<< 1)

$$\sigma_{CC}(\nu N)\simeq\sigma_{CC}(\bar{\nu}N)\simeq 5.5\times 10^{-36}\,cm^2\,(E_\nu/GeV)^{0.363}$$

$$\sigma_{NC}(\nu N)\simeq\sigma_{NC}(\bar{\nu}N)\simeq 2.3\times 10^{-36}\,cm^2\,(E_\nu/GeV)^{0.363}$$

The W and Z resonances



W-resonance: $E_\nu \simeq M_W^2/2m_e \approx 6.3\,PeV$

Z-resonance: $E_\nu \simeq M_Z^2/2m_\nu \approx 4\times 10^{22}\,eV\,(0.1\,eV/m_\nu)$

Glashow ‘60

Weiler ‘84
ER ‘93

COSMIC NEUTRINO BACKGROUND

- decoupled from e^+e^- plasma at T~MeV (t~1s),
while CMB decoupled in e-p recombination at T~0.3eV (370 kyrs)

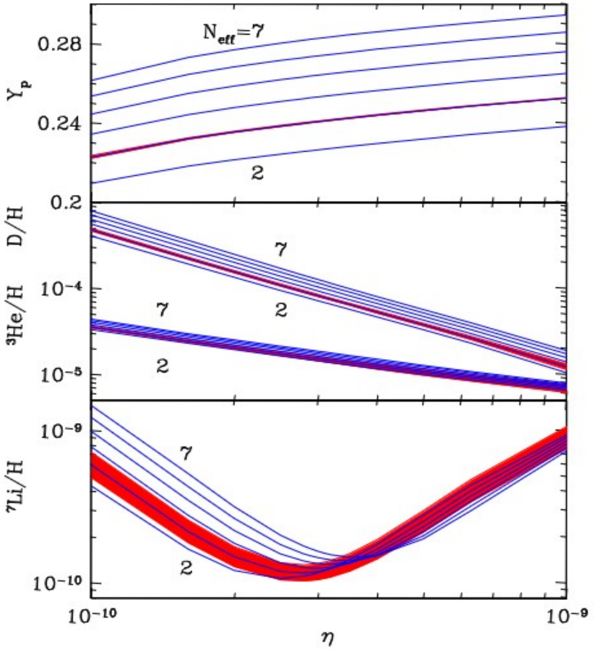
- affect Universe expansion (they contribute to radiation):

→ affect Big Bang Nucleosynthesis (BBN):
more neutrino families → faster expansion
→ less neutrons decay → more He → $N_\nu < 3.4$

→ affect matter-radiation equality → affect CMB
combining with BAO from galaxy surveys → $N_{eff} = 2.99$ +-0.33

become non-relativistic at $z_i = 188\ (m_i/0.1\text{eV})$
→ values of masses affect structure formation → $\Sigma\, m_i < 0.12$ eV

0105397



Today $T_\nu = 1.9K$ → $n_\nu = 56/cm^3$ per species (ν_α or anti ν_α)

(while $T_\gamma = 2.7K$ due to reheating when e^+e^- annihilated)

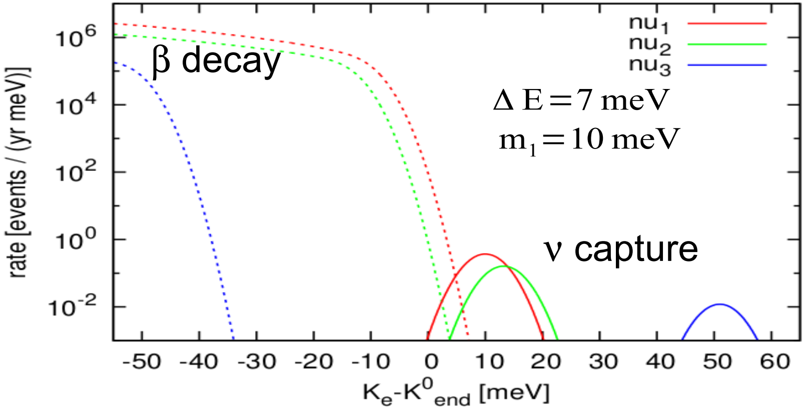
may be detected by capture on beta decaying nuclei such as Tritium: (Weinberg 62)

$$T \rightarrow {}^3He + e + \bar{\nu}_e + 18.6\,keV\,(\text{lifetime } 12.3\,yr)$$

$$\nu_e + T \rightarrow {}^3He + e + 18.6\,keV + E_\nu$$ **has no threshold**

1810.00505

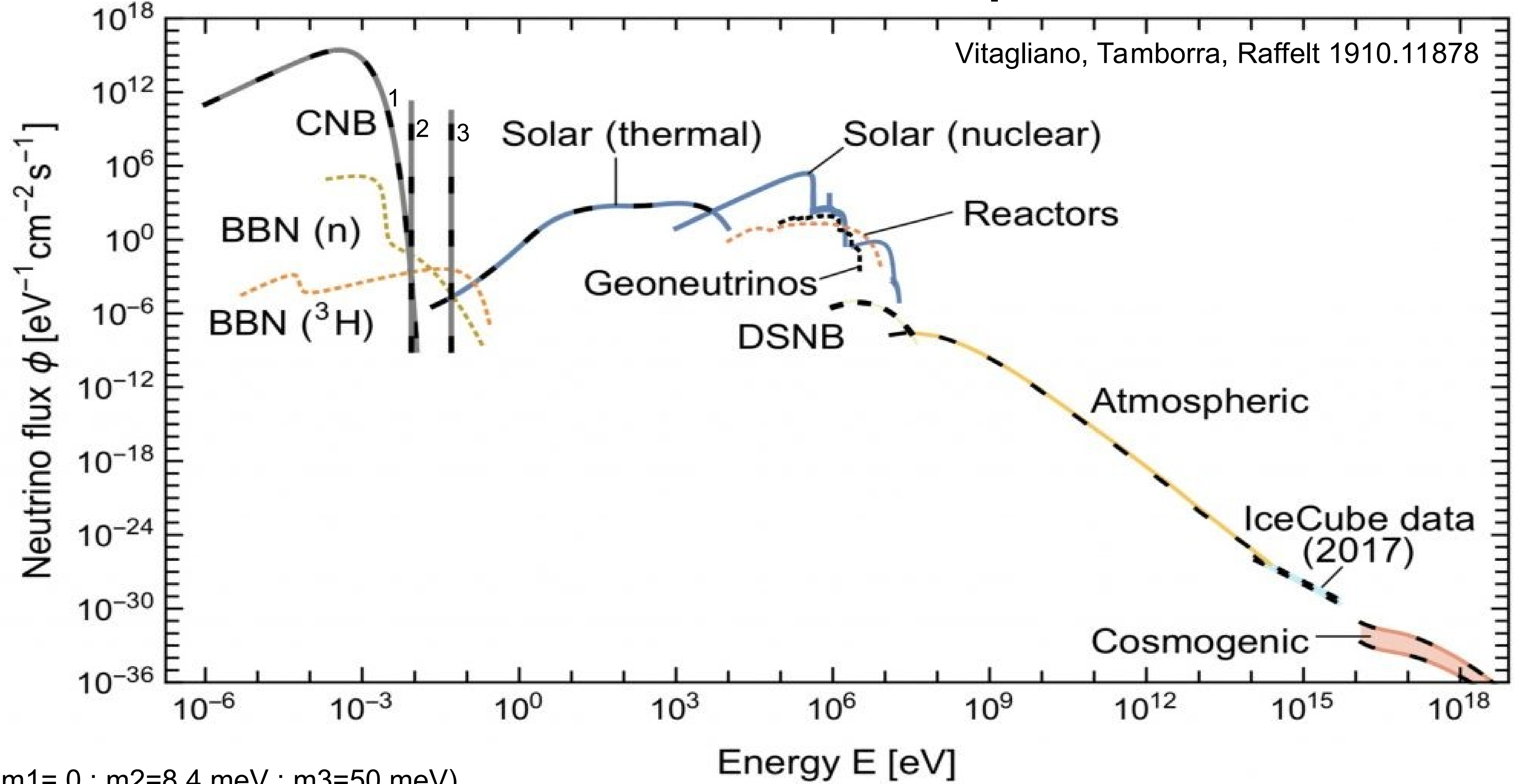
→ PTOLEMY experiment@GS
requires exquisite E resolution $(\text{aim at } \Delta E < 50\,meV)$



if neutrino non-relativistic now:
rate for Majorana = 2 rate of Dirac (half of states became sterile)

for 100 g of T: ~ 8 events/yr (Majorana), ~ 4 events/yr (Dirac)

Grand Unified neutrino spectrum

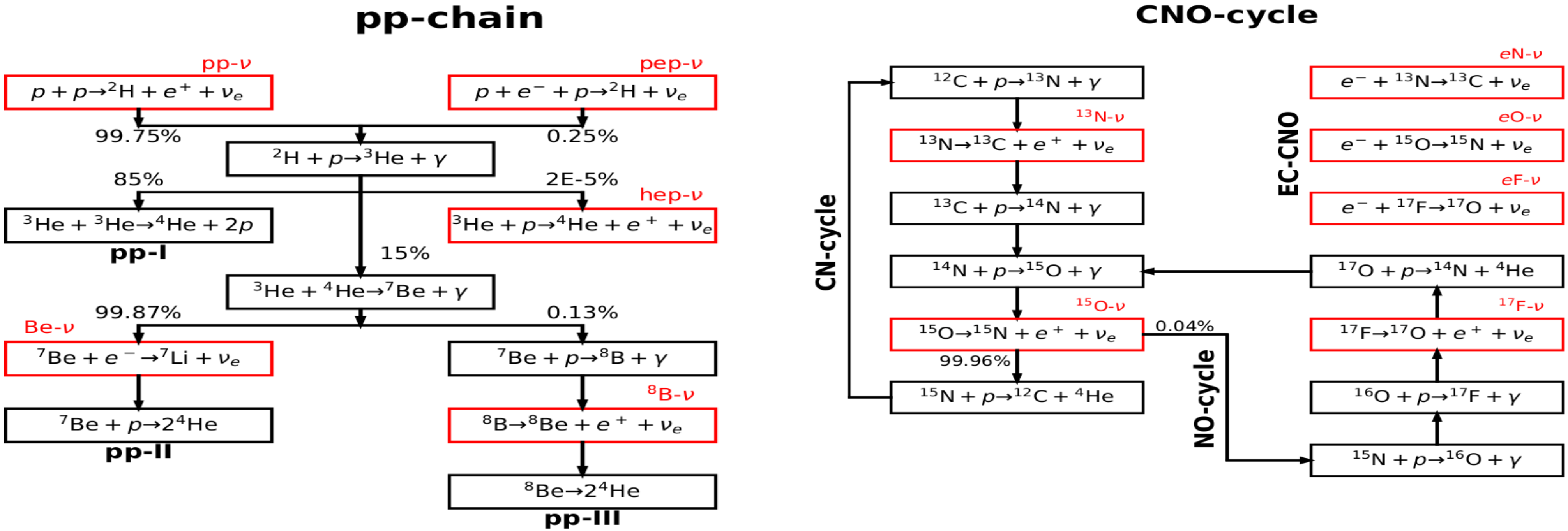


(m1= 0 ; m2=8.4 meV ; m3=50 meV)

SOLAR NEUTRINOS

Solar Energy produced by fusion:

$$4\,p+2\,e^- \rightarrow {}^4He+2\nu_e+27\ MeV$$



pp-chain

pp-ν
$p+p\rightarrow{}^2H+e^++\nu_e$

pep-ν
$p+e^-+p\rightarrow{}^2H+\nu_e$

99.75%

0.25%

$^2H+p\rightarrow{}^3He+\gamma$

85%

2E-5%

$^3He+{}^3He\rightarrow{}^4He+2p$
pp-I

hep-ν
$^3He+p\rightarrow{}^4He+e^++\nu_e$

15%

$^3He+{}^4He\rightarrow{}^7Be+\gamma$

99.87%

0.13%

Be-ν
$^7Be+e^-\rightarrow{}^7Li+\nu_e$

$^7Be+p\rightarrow2\,{}^4He$
pp-II

$^7Be+p\rightarrow{}^8B+\gamma$

^8B-ν
$^8B\rightarrow{}^8Be+e^++\nu_e$

$^8Be\rightarrow2\,{}^4He$
pp-III

CNO-cycle

CN-cycle

$^{12}C+p\rightarrow{}^{13}N+\gamma$

^{13}N-ν
$^{13}N\rightarrow{}^{13}C+e^++\nu_e$

$^{13}C+p\rightarrow{}^{14}N+\gamma$

$^{14}N+p\rightarrow{}^{15}O+\gamma$

^{15}O-ν
$^{15}O\rightarrow{}^{15}N+e^++\nu_e$

99.96%

$^{15}N+p\rightarrow{}^{12}C+{}^4He$

0.04%

NO-cycle

$^{15}N+p\rightarrow{}^{16}O+\gamma$

$^{16}O+p\rightarrow{}^{17}F+\gamma$

^{17}F-ν
$^{17}F\rightarrow{}^{17}O+e^++\nu_e$

$^{17}O+p\rightarrow{}^{14}N+{}^4He$

EC-CNO

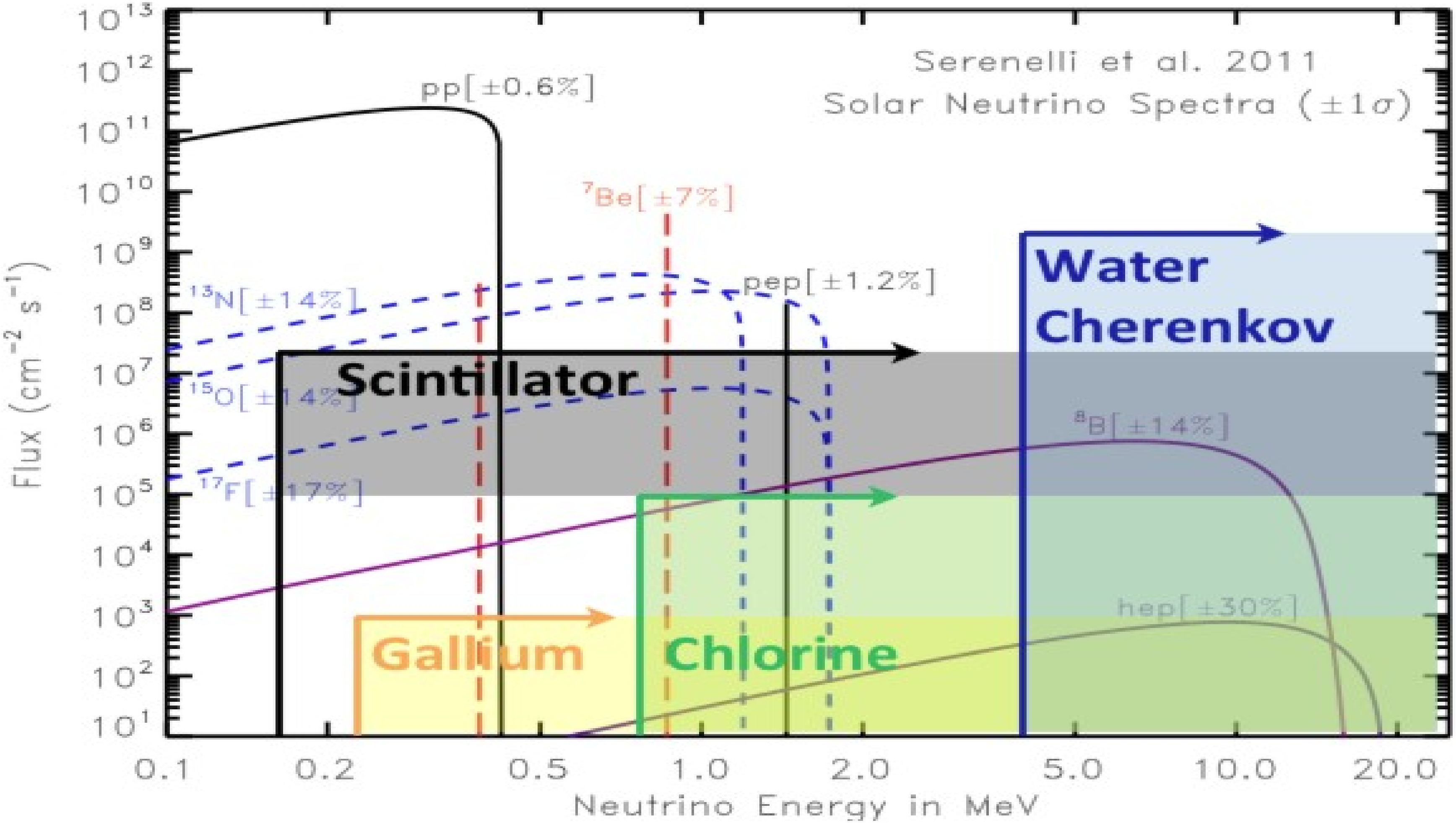
eN-ν
$e^-+{}^{13}N\rightarrow{}^{13}C+\nu_e$

eO-ν
$e^-+{}^{15}O\rightarrow{}^{15}N+\nu_e$

eF-ν
$e^-+{}^{17}F\rightarrow{}^{17}O+\nu_e$

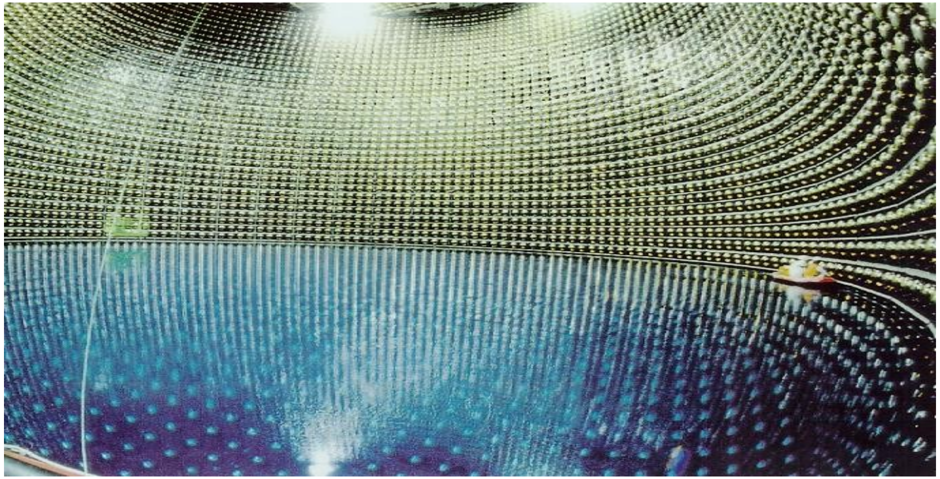
energy flux on Earth: $\phi_E\simeq1.5\ kW/m^2$ ⇒ **neutrino flux:** $\phi_\nu\simeq\dfrac{2\times\phi_E}{27\ MeV}\simeq6\times10^{10}\dfrac{\nu_e}{cm^2\,s}$

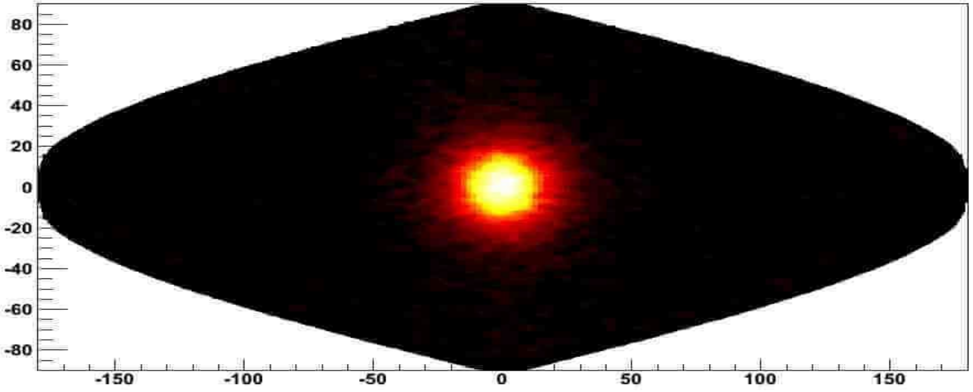
SOLAR NEUTRINO SPECTRA



~3% of solar energy emitted in ν_e with E_ν~0.1-14 MeV

Super Kamiokande



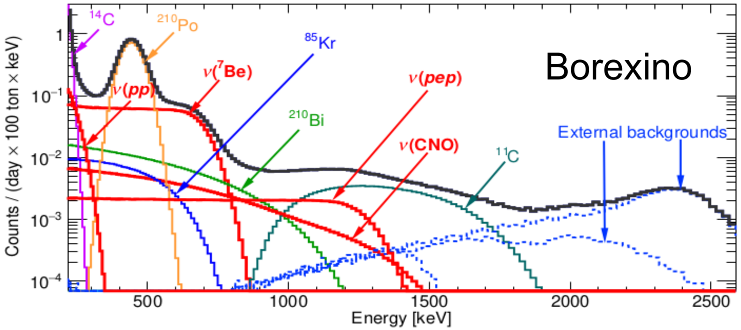


first image of a neutrino source

Cherenkov in H_2O

$$\nu_e + e^- \rightarrow \nu_e + e^-$$

(and some sensitivity to $\nu_{\mu,\tau}$)



scintillators (Borexino, KamLAND ..)
lower threshold but no directionality

SNO heavy water, smaller volume than SK

solar neutrinos also observed radiochemically (with Cl & Ga),
but just counted a month later → no direction nor original energy

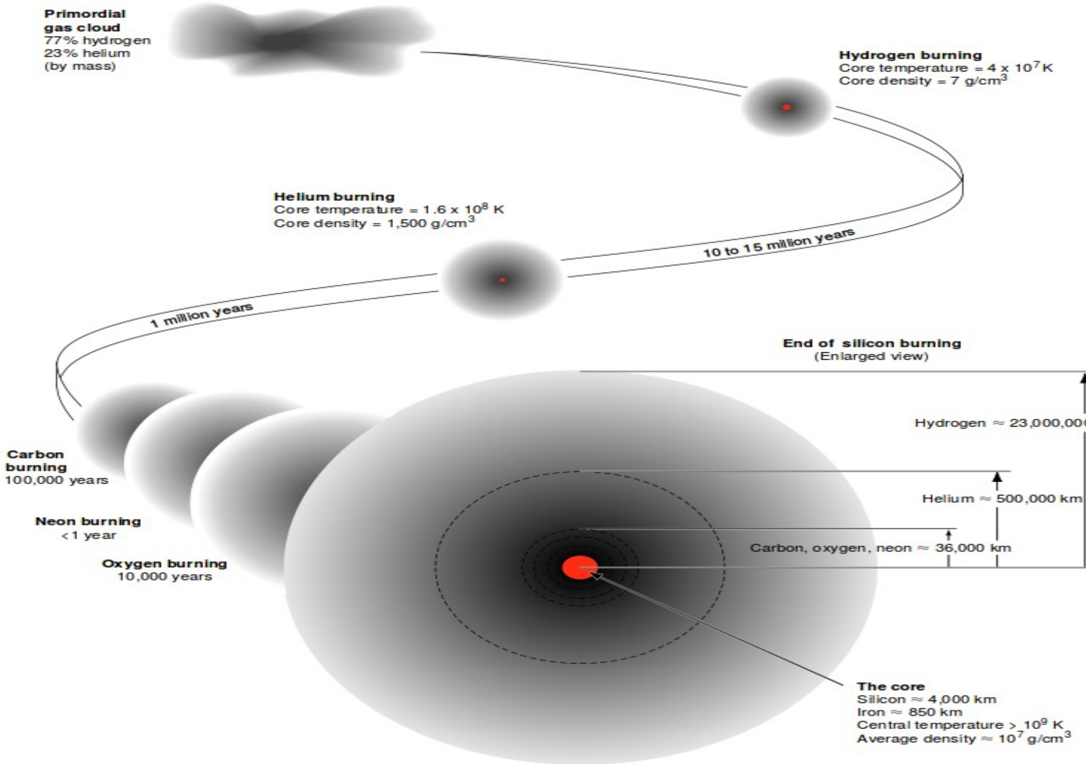
Supernova Neutrinos

The life of stars:
gravity against thermal pressure
→ need to burn fuel

Stars with $M > 8M_{sun}$ burn
H → He → C,O → Ne → Si → Fe

but Fe burning is endothermic
→ contracts until e degeneracy
pressure prevents collapse

but when $M_{Fe} \approx M_{Ch} \approx 1.4\ M_{sol}$
⇒ collapse to n-star (R = 10 km)
releasing $E_b \approx GM^2_{sun}/R \approx 3\text{x}10^{53}$ erg



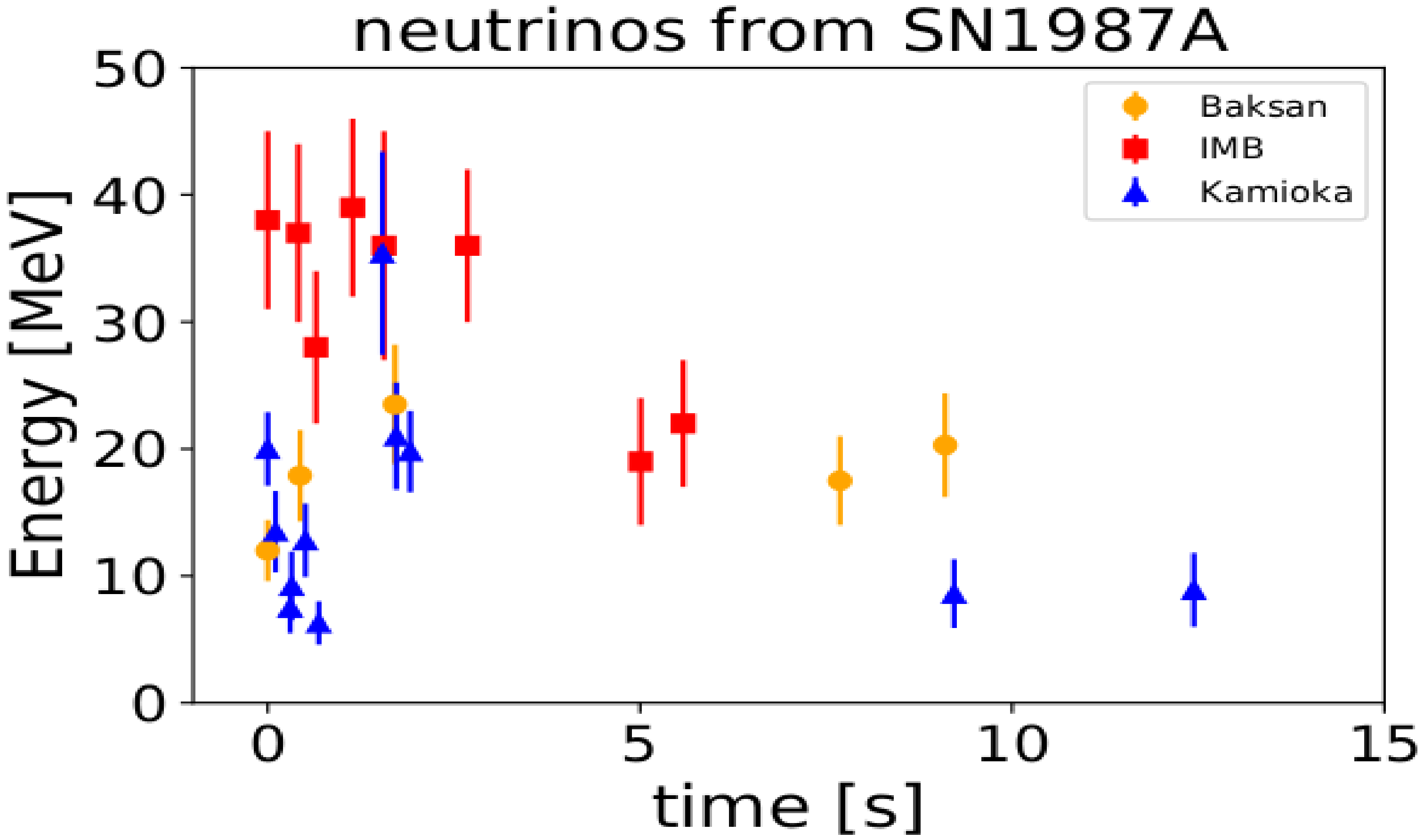
SUPERNOVA explosion → 99% emitted as MeV neutrinos in ~ 10 s !

1% in kinetic energy of expanding envelope, 0.01% in light over few months

hypernovas may produce long GRBs, accelerating CRs in the jets → UHE ν
short GRBs (< 2 sec) from neutron star binaries can also produce UHE ν

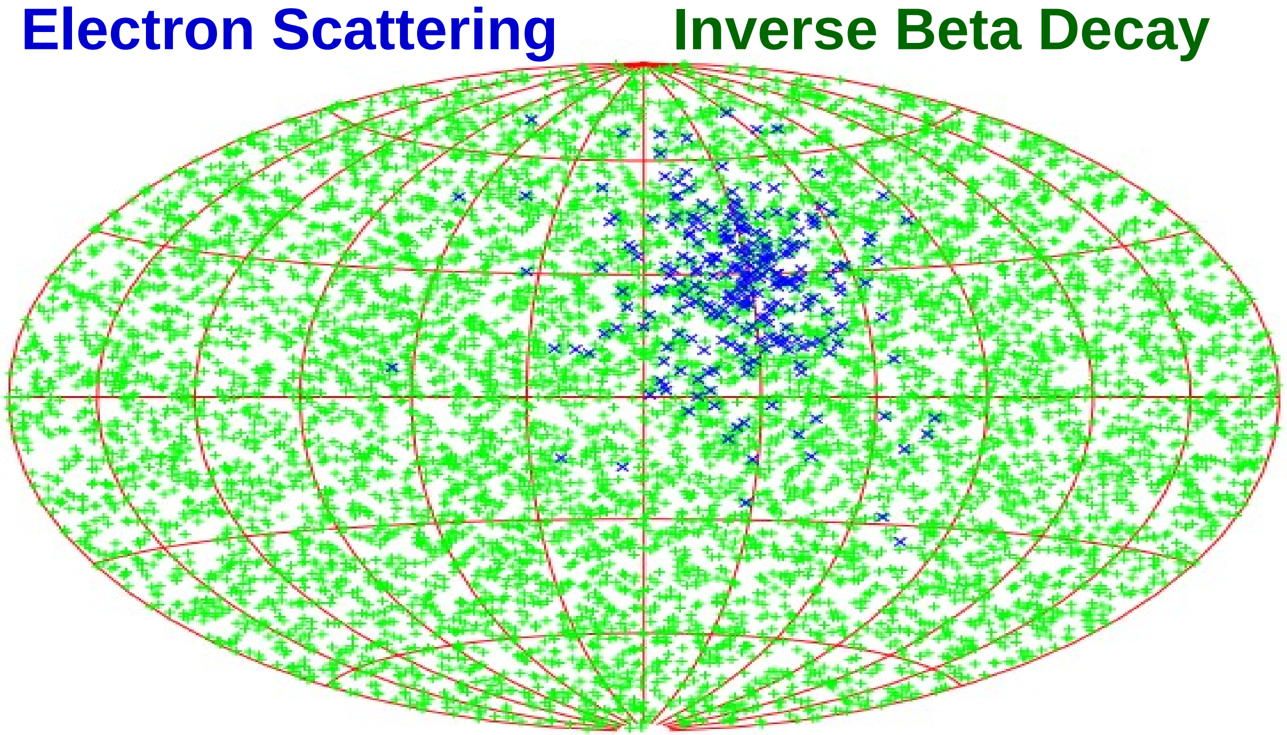
No Galactic SN seen since the invention of the telescope :(
although about 1 to 3 per century expected, but obscured by gas

SN 1987A was seen in the nearby LMC in light and in neutrinos !



most (all?) IBD of $\bar{\nu}_e$ → isotropic, no picture :(

future Galactic supernova (d~10 kpc) at SuperKamiokande:



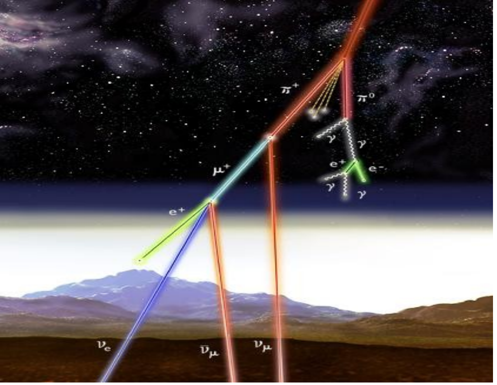
~6000 events
expected in SK

pointing may reach 2-3 deg with SK Gd
it happens few hours before light is emitted → early warning

http://snews.bnl.gov

High energy atmospheric neutrinos

(from weak decays of hadrons in showers produced by CR-air interactions)

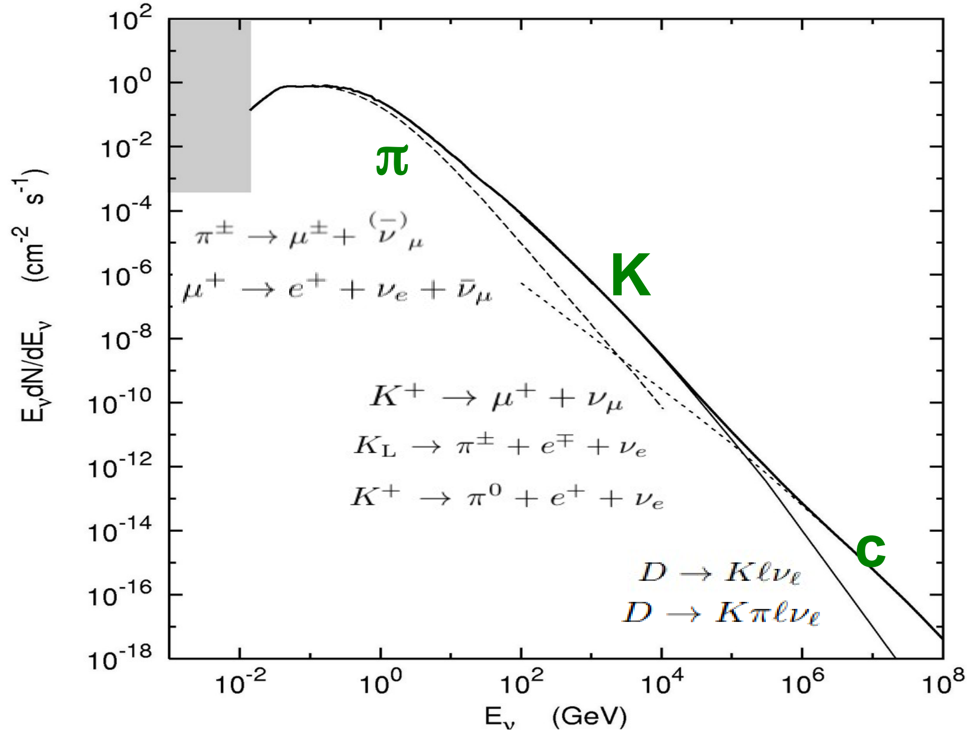


meson decay length: $L = \gamma c \tau \;,\; \gamma = E/m$

$$L_\pi \simeq 6\ km\,(E_\pi/100\ GeV)$$
$$L_K \simeq 7.5\ km\,(E_K/TeV)$$
$$L_D \simeq 2\ km\,(E_D/10\ PeV)$$

interaction length $\lambda_\pi = 120\ g/cm^2$

attenuation length: $L^{att} = \dfrac{1.2\ km}{\rho/10^{-3}\ g/cc} \simeq 5\ km$ **(h~10 km)**



at low energies, atmospheric νs mainly from pion decays

but above 100 GeV pions are stopped before decay → kaons become the main source

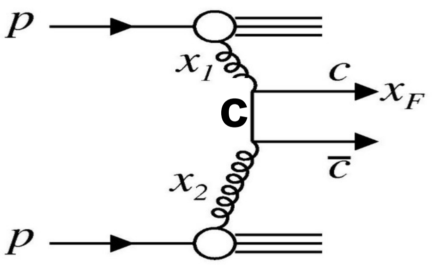
and above ~100 TeV kaons suppressed → prompt charm decays dominate

Prompt charm production

Enberg et al. /0808.0418

For E > 200 TeV → ν mostly from c decays

(D, Λ_c,...)



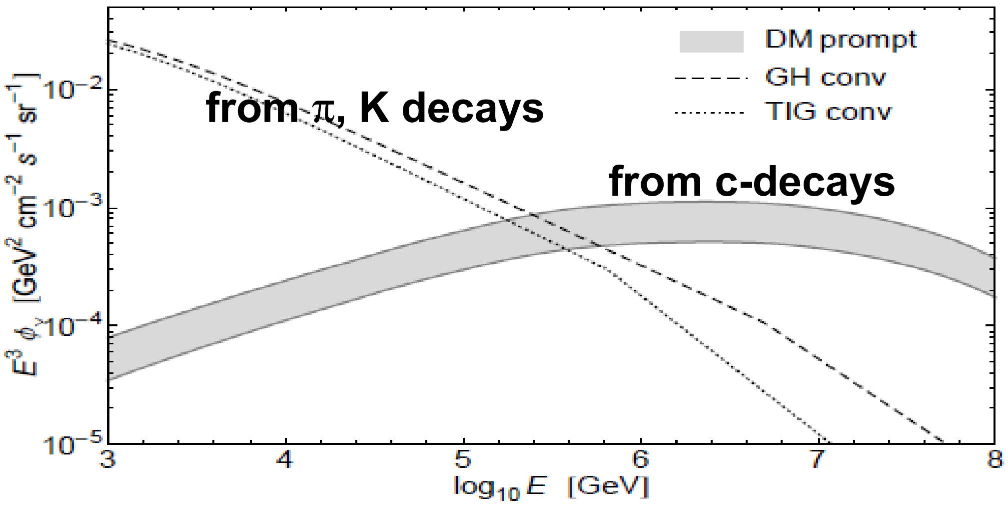
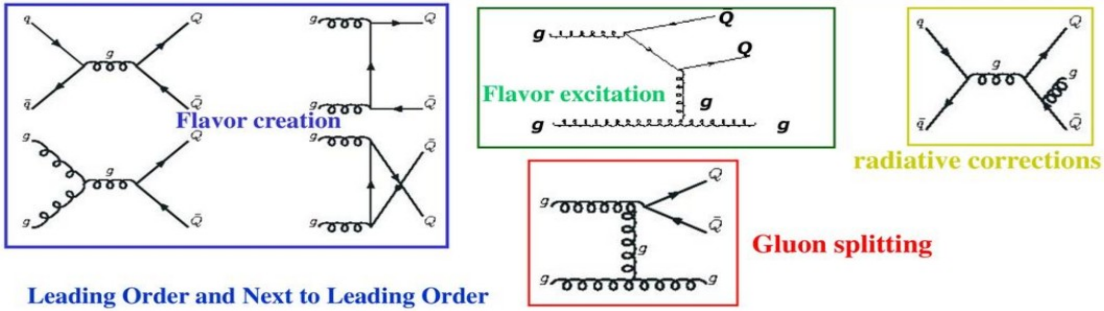


FIG. 5: Prompt and conventional $\nu_\mu + \bar{\nu}_\mu$ fluxes in the vertical

sample gluon density distribution at tiny momentum fractions ($x_2 < 10^{-5}$ for $E > 10^{15}$ eV) → need to extrapolate from measured values

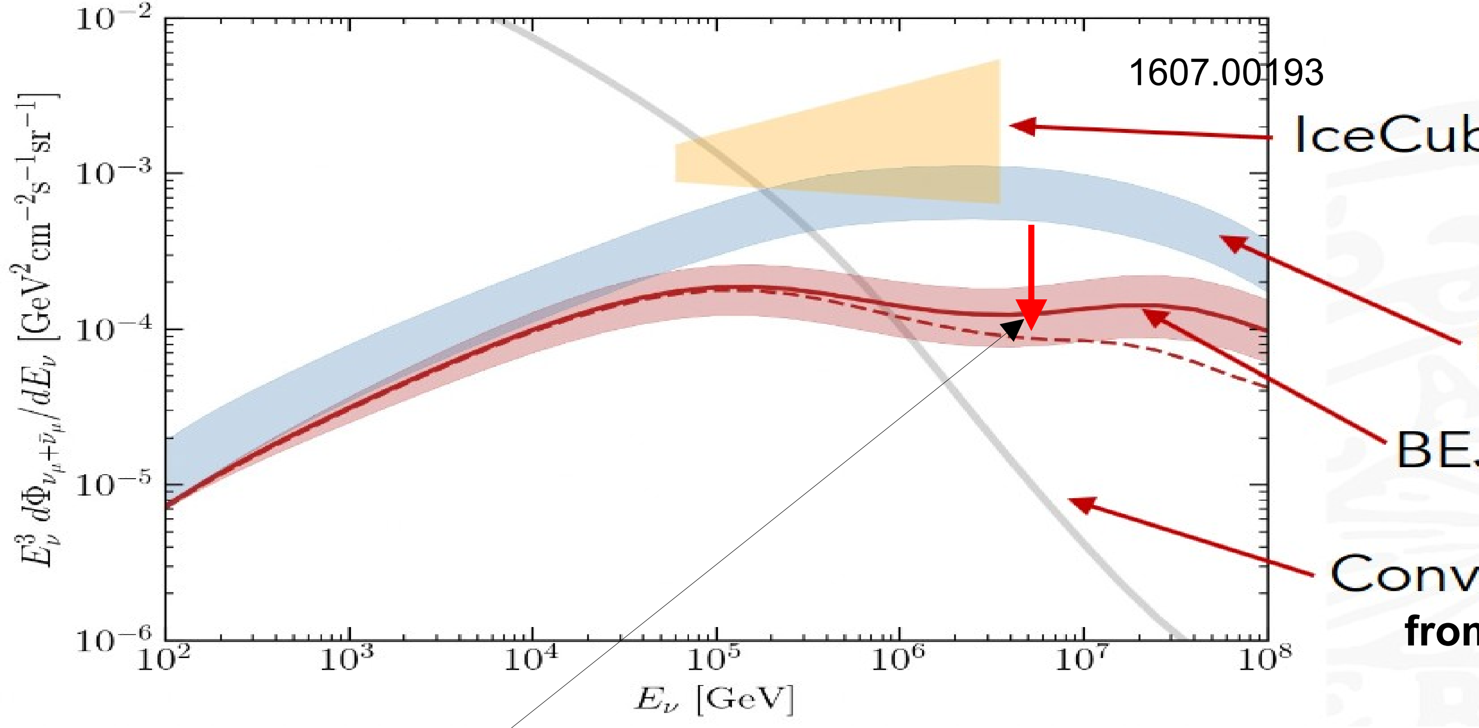
also requires to include
large NLO processes

→ significant uncertainties



Leading Order and Next to Leading Order

Prompt neutrino fluxes



1607.00193

IceCube 7.5 yr

ERS

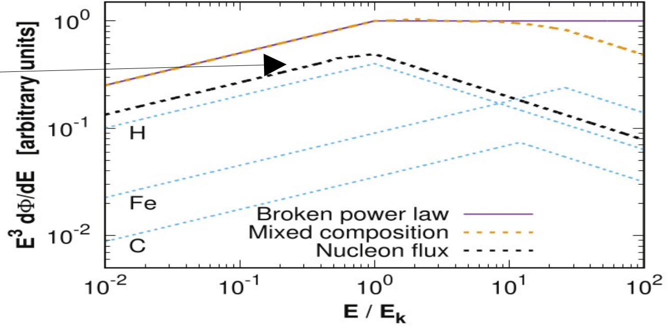
BEJRSS

Conventional

from π, K decays

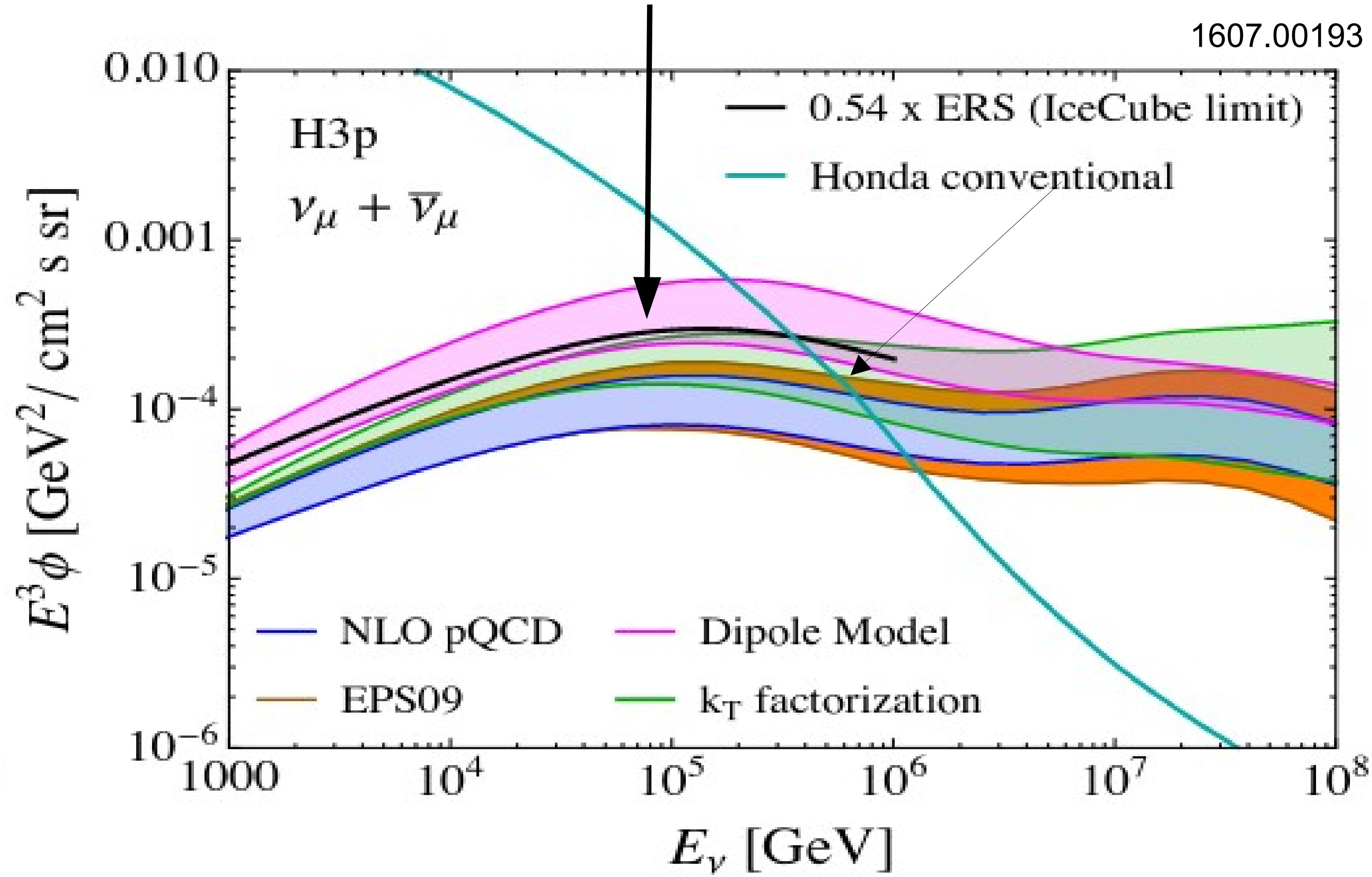
what is relevant is the flux of nucelons
not just the total CR fluxes
(ERS assumed all CRs where H)

Candia ER 0306632



IceCube bounds

1607.00193



Note that:

Probability for pion to decay before interacting ~ $\lambda_{int}/\lambda_{dec}$ ~ E^{-1}
→ conventional atmospheric flux ~ CR flux / E ~ $E^{-3.7}$

Prompt flux ~ CR flux ~ $E^{-2.7}$
(and steeper above 100 TeV due to knee)

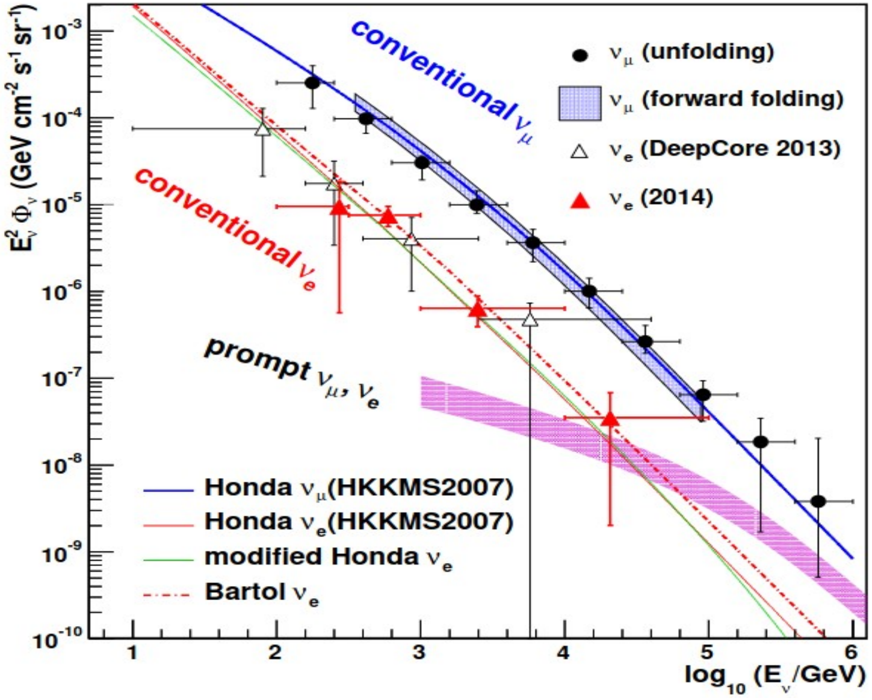
ν_e conventional fluxes from K decays
~ ν_μ fluxes/30

while ν_e ~ ν_μ for prompt

➞ ν_e fluxes cross at ~ 30 TeV

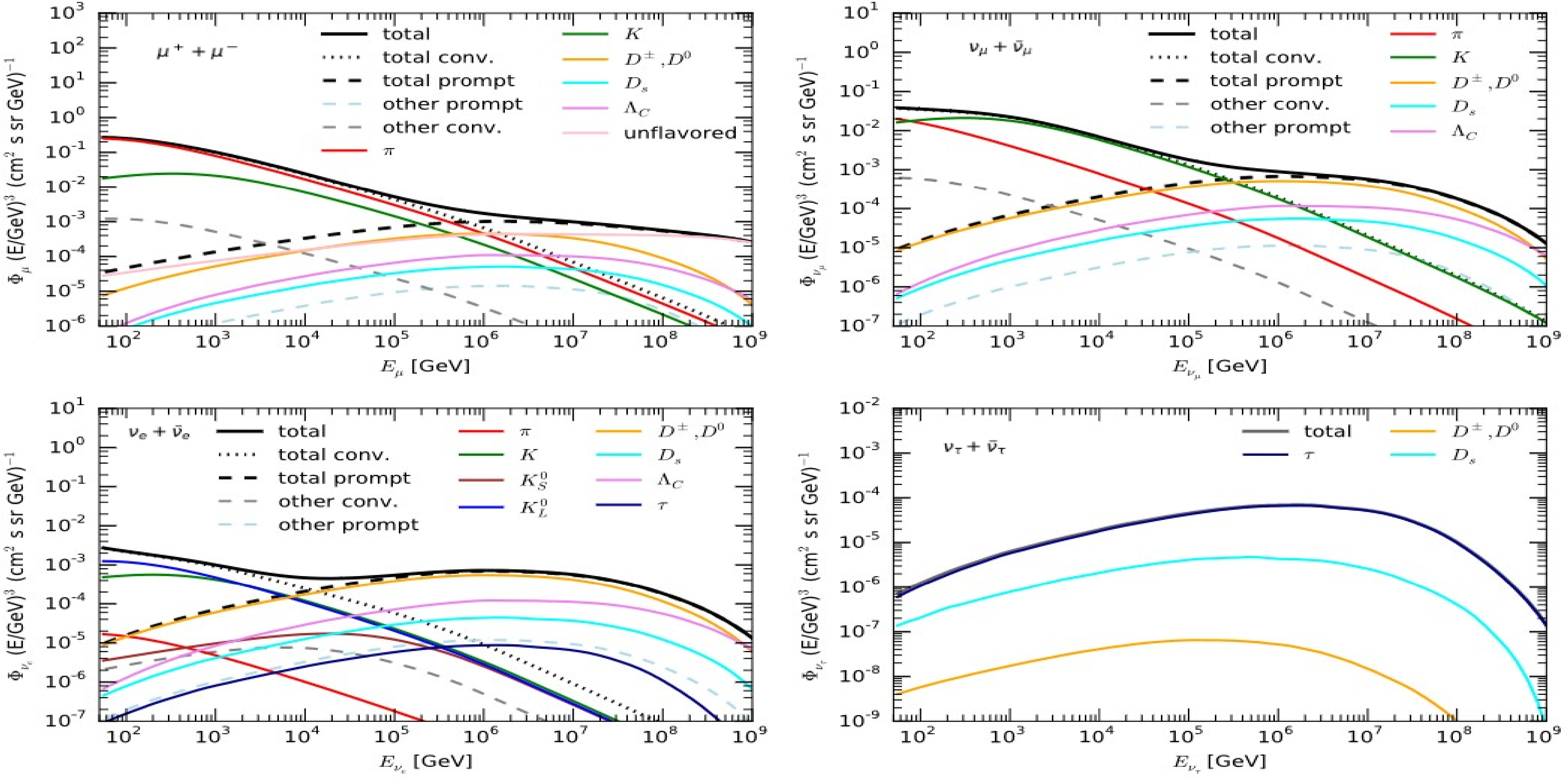
➞ ν_μ fluxes cross at > 500 TeV

1504.03753



astrophysical sources have less dense targets → π decay without interaction
→ astrophysical fluxes ~ $E^{-\gamma}$, with γ ~ 2 to 2.4 ?
They may become dominant above few tens or hundreds of TeV

ATMOSPHERIC MUON & NEUTRINO FLUXES

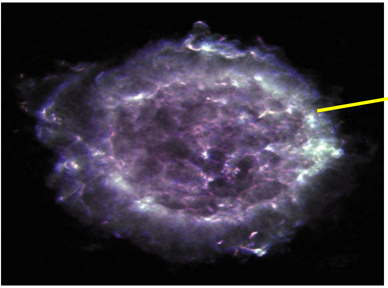


Fedynitch et al. 1806.04140

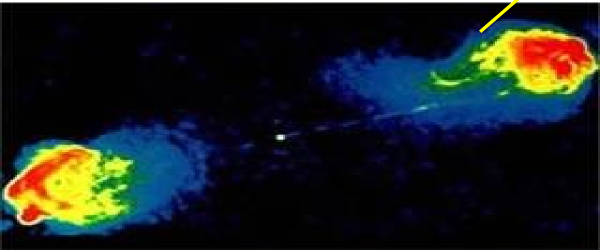
Examples of powerful astrophysical objects [potential CR accelerators]

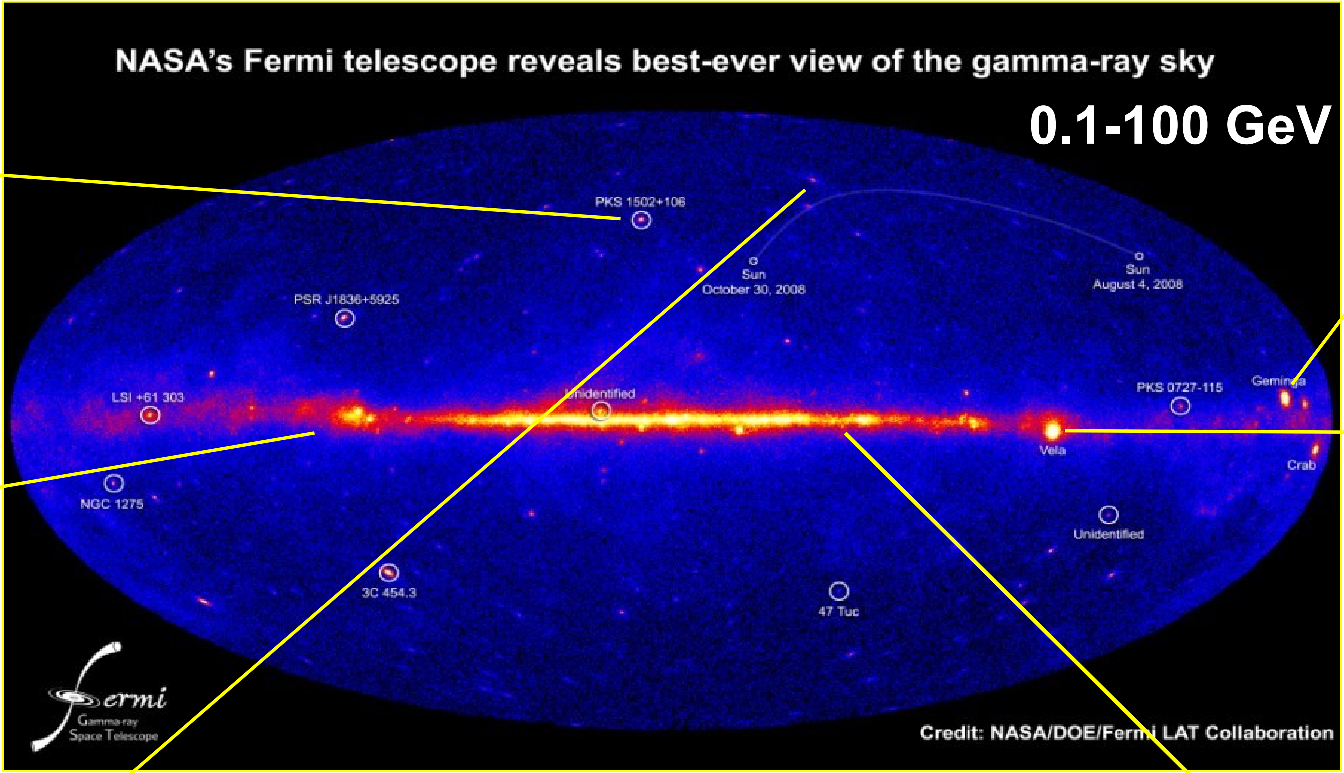
AGN

SNR



radio Galaxy





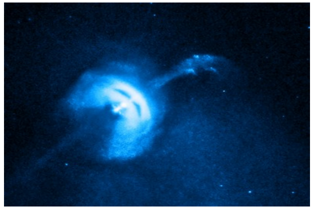
NASA's Fermi telescope reveals best-ever view of the gamma-ray sky

Credit: NASA/DOE/Fermi LAT Collaboration

colliding galaxies

Pulsar

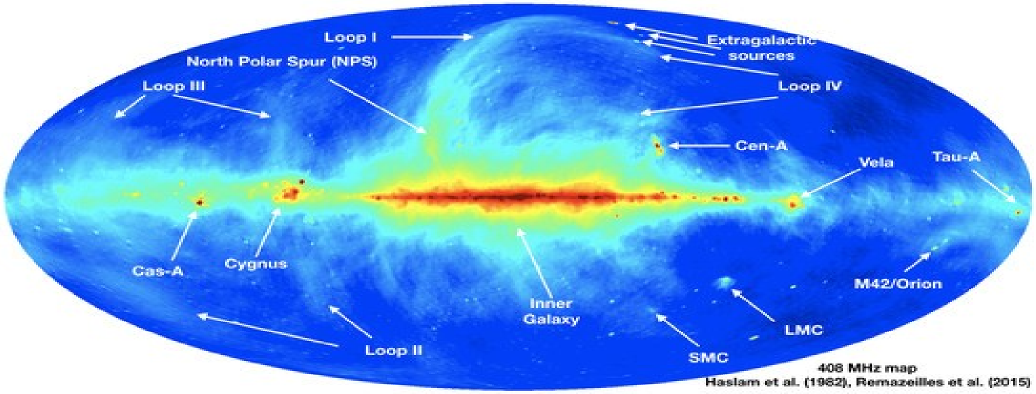
PWN



GRB

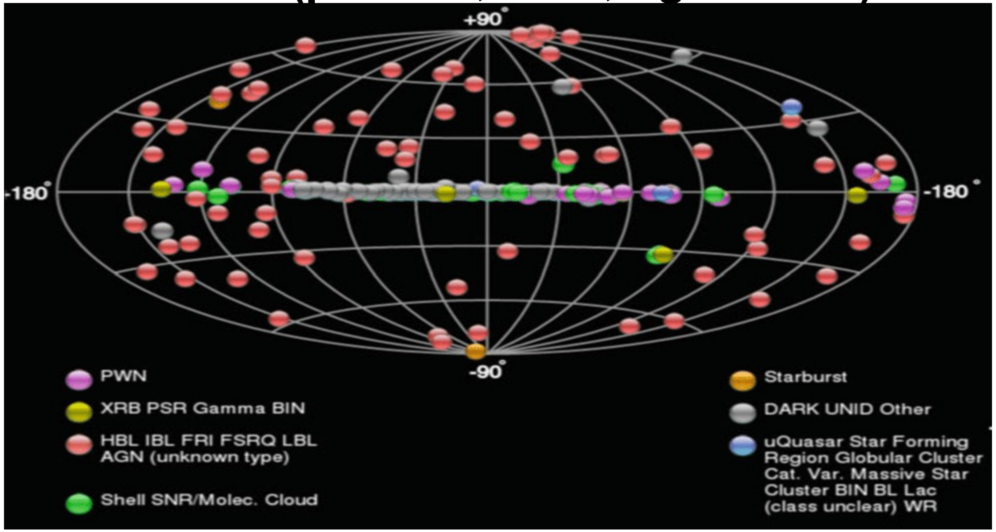
diffuse emission

Radio maps:
Synchrotron emission
(accelerated e, SNR, pulsars,
radiogalaxies, ...)



408 MHz map
Haslam et al. (1982), Remazeilles et al. (2015)

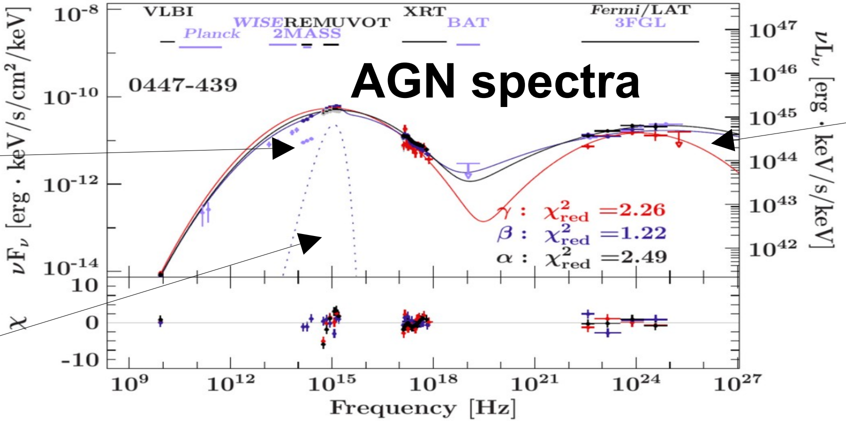
TeVCAT (IACT, HAWC, LHAASO)
E>100 GeV (pulsars, SNR, xg AGNs..)



Synchrotron from e in jet

thermal from accretion disk (opt-UV)

AGN spectra



igure 1.5: Broadband spectral energy distribution of PKS 0447-439. The model includes both peaks and an additional blackbody for present thermal excess. (Krauß et al., 2016)

ICompton on synchrotron γ or on external radiation

and/or

hadronic γ from π^0 decays produced by interactions of accelerated CRs → ν from associated charged pion decays

Neutrino production mechanisms

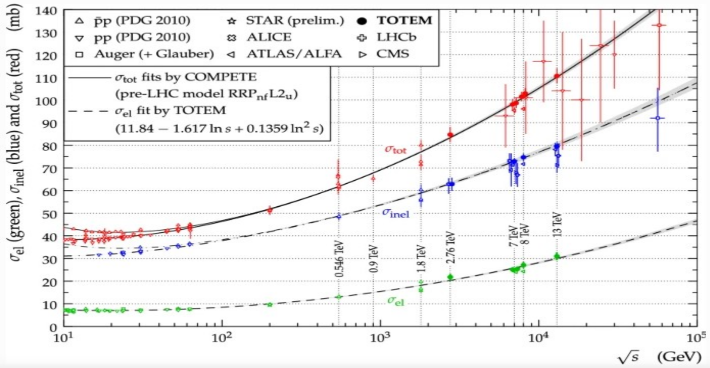
pp scenarios (gas targets)

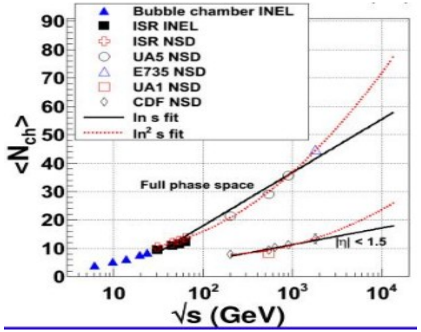
$$p + p \rightarrow \frac{N_\pi}{3}(\pi^+ + \pi^0 + \pi^-) + X$$

$$\pi^\pm \rightarrow \mu^\pm + \overset{(-)}{\nu}_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^0 \rightarrow \gamma + \gamma \qquad E_\pi \simeq 2\,E_\gamma \simeq 4\,E_\nu$$

Large π multiplicities → $\langle E_\nu \rangle \sim E_p/50$





low threshold, smooth rise, large multiplicities

pγ scenarios (radiation targets)

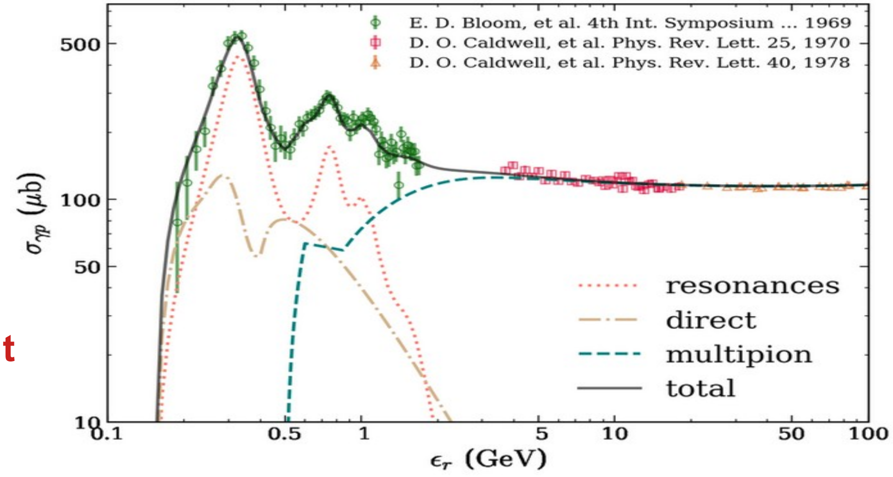
e.g.

$$p + \gamma \rightarrow \Delta^+ \rightarrow n + \pi^+ \qquad E_\nu \simeq E_\pi/4 \simeq E_p/20$$

threshold at: $E'_p > \frac{m_\Delta^2 - m_p^2}{4\varepsilon'_\gamma} = \left(\frac{100\ \mathrm{eV}}{\varepsilon'_\gamma}\right) \times 1.6\ \mathrm{PeV}$

prove it

In blazars or GRB jets, observed E is boosted $E_\nu \simeq \Gamma\, E'_\nu$



pp scenarios (SNR, AGN lobes & cores, CR reservoirs: SBG, galaxy clusters, ...)

ν emissivity:

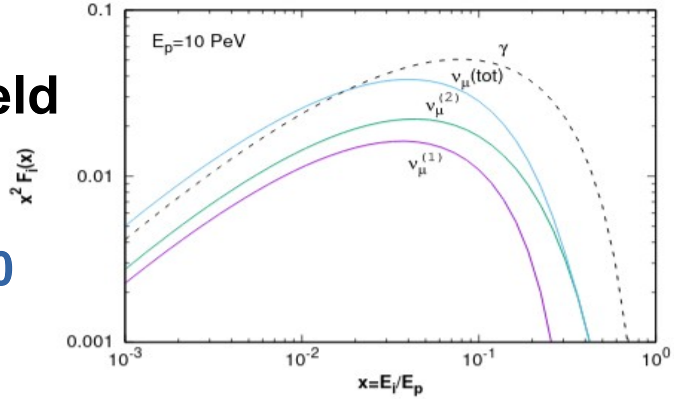
$$\frac{\mathrm{d}q_{\nu_i}}{\mathrm{d}E_\nu} = N_\mathrm{N} \int_{E_\nu}^{\infty} \frac{\mathrm{d}E_p}{E_p} \sigma_{pp} F_{\nu_i}(x_\nu, E_p) \frac{\mathrm{d}q_p}{\mathrm{d}E_p}$$

CR spectrum

ν yield

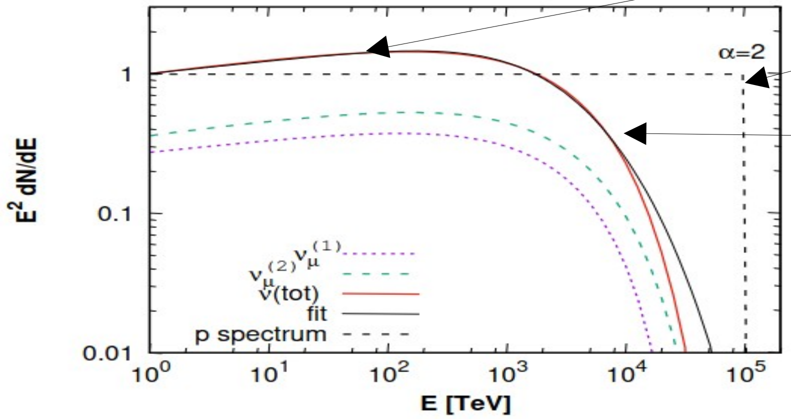
column density

Kelner et al 06



Neutrino energy distribution much broader than just $E_p/20$ (corresponding to $E_\nu \sim E_\pi/4 \sim 0.2\ E_p/4$)

The neutrino spectrum approximately follows CR spectrum (scaling)
→ almost power-law down to low energies (just slightly harder)



assuming CR proton spectrum E^{-2} with sharp cutoff

neutrino cutoff shape much softer (actually depends on CR cutoff shape)

ER&Vissani 2011.12769

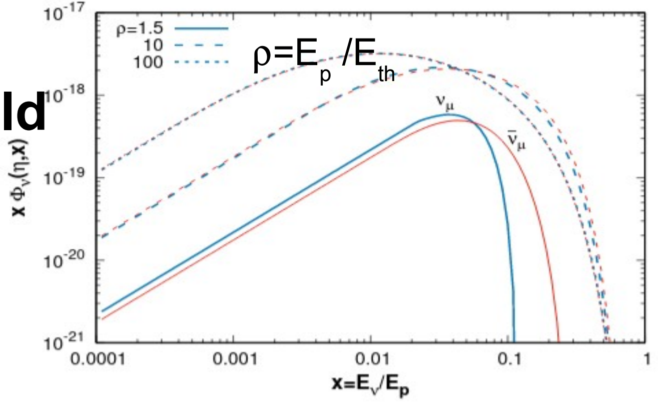
pγ scenarios (AGN jets&cores, GRBs, ...)

$$\frac{\mathrm{d}q_i}{\mathrm{d}E_i'}(E_i') = \int \frac{\mathrm{d}E_p'}{E_p'}\,\mathrm{d}\varepsilon'\,\frac{\mathrm{d}q_p}{\mathrm{d}E_p'}(E_p')\,\frac{\mathrm{d}n_{\mathrm{ph}}}{\mathrm{d}\varepsilon'}(\varepsilon')\,\Phi_i(\eta, x_i)$$

photon density

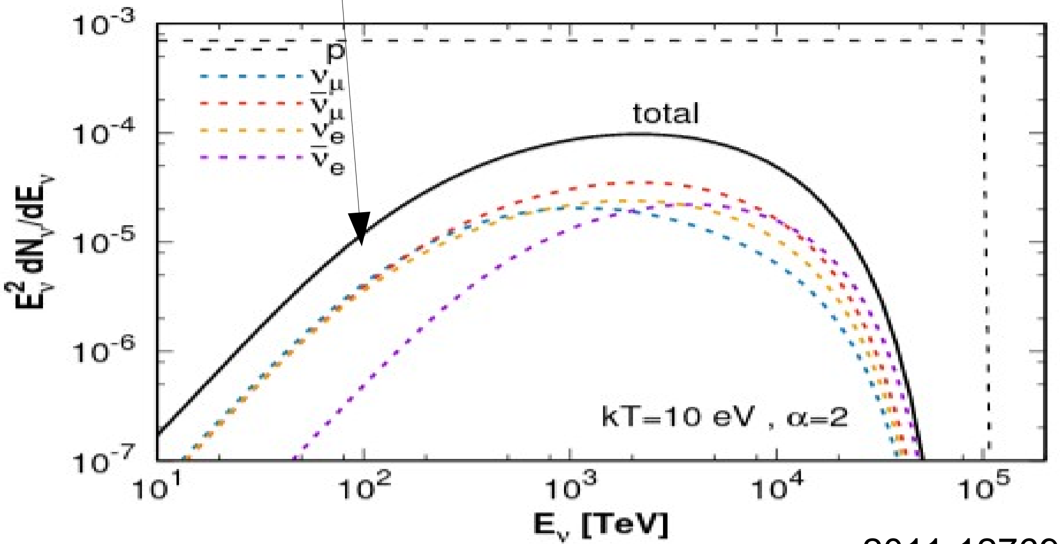
ν yield

Aharonian et al. 08



$(\eta \equiv 4\epsilon' E'_p/m_p^2)$

the neutrino spectrum depends on both the photon and CR spectra
strongly suppressed below threshold of Δ production



2011.12769

relation between neutrino and photon fluxes

$\pi^\pm \to \mu^\pm + \overset{(-)}{\nu}_\mu$ $\mu^+ \to e^+ + \nu_e + \bar{\nu}_\mu$ $\pi^0 \to \gamma + \gamma$ $E_\pi \simeq 2E_\gamma \simeq 4E_\nu$

in hadronic processes, neutrino and photon fluxes intimately related

$$\frac{1}{3}\sum_\alpha q_{\nu_\alpha}(E_\nu) \simeq q_{\pi^\pm}(4E_\nu)\frac{dE_\pi}{dE_\nu} \simeq 4K_\pi q_{\pi^0}(4E_\nu) \simeq 2K_\pi q_\gamma(2E_\nu)\frac{dE_\gamma}{dE_\pi} \simeq K_\pi q_\gamma(2E_\nu)$$

$$K_\pi \equiv \frac{q_{\pi^\pm}}{q_{\pi^0}}$$

q_i(E) is differential source generation rate of species i

similarly:

$$\frac{1}{3}\sum_\alpha [E_\nu^2 q_{\nu_\alpha}(E_\nu)] \simeq \frac{K_\pi}{4}[E_\gamma^2 q_\gamma(E_\gamma)]_{E_\gamma = 2E_\nu}$$

prove it

pp production:

$$p + p \to \frac{N_\pi}{3}(\pi^+ + \pi^0 + \pi^-) + X$$

$$K_\pi \simeq 2$$

pγ production:

$$p + \gamma \to \Delta \to \pi^+ + n$$

$$p + \gamma \to \Delta \to \pi^0 + p$$

$$BR(\Delta \to \pi^0 + p) = 2/3$$

$$K_\pi = \frac{1}{2}(if\ \Delta\ resonance\ dominates)$$

→ **prove it using that**

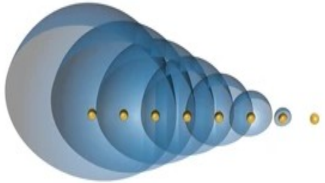
(Δ^{++}, Δ^+, Δ^0, Δ^-) isospin=3/2
(π^+, π^0, π^-) I=1
(p, n) I=1/2

but if multipion production dominates, K_π → 2

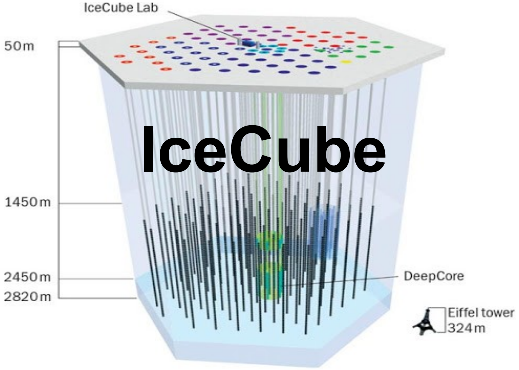
if γ hadronic and source transparent, γ / ν depends on production mechanism

NEUTRINO TELESCOPES (5 GeV to 10 PeV and beyond)

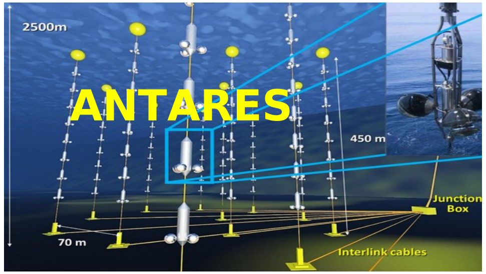
observe Cherenkov light from relativistic charged particles

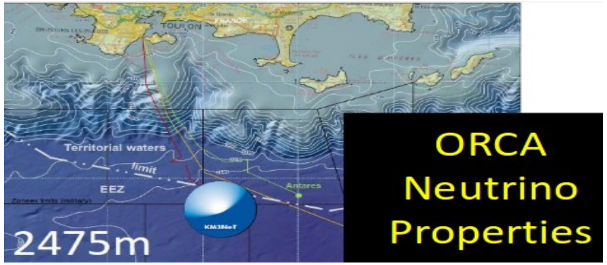


(DUMAND †1995, AMANDA 1996-2005)



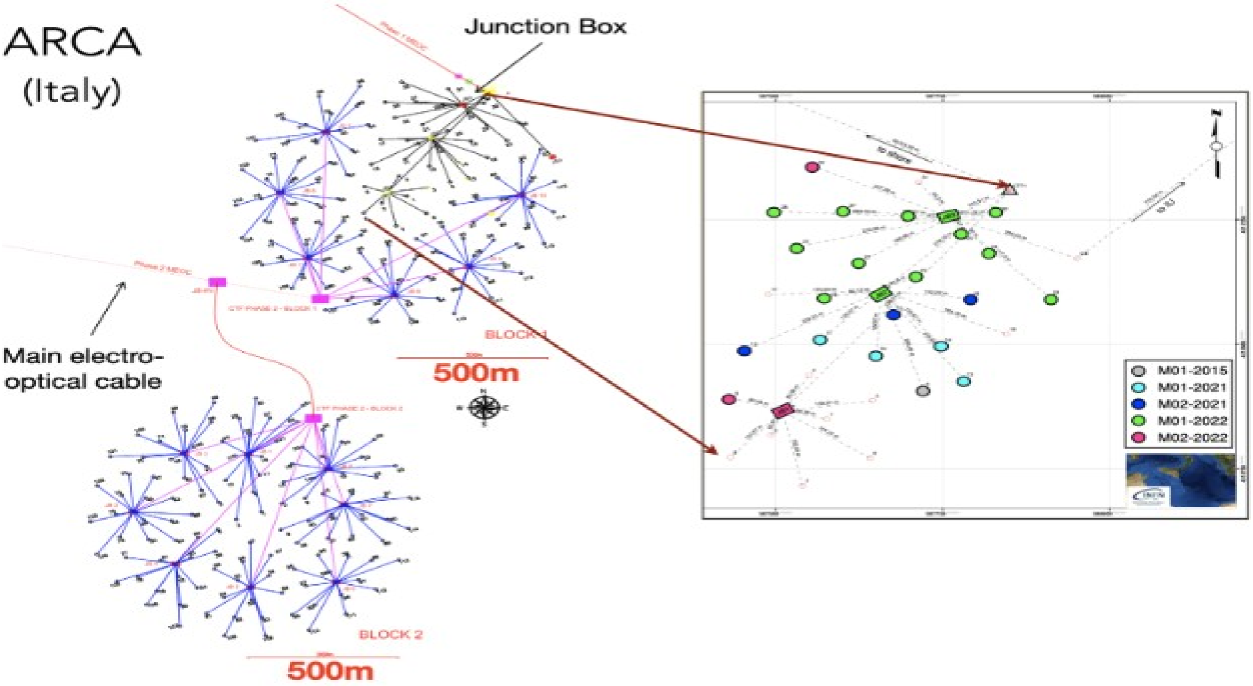
km^3 detector at South Pole,
completed by 2011,
looking at northern ν sky
and to southern sky above 100 TeV

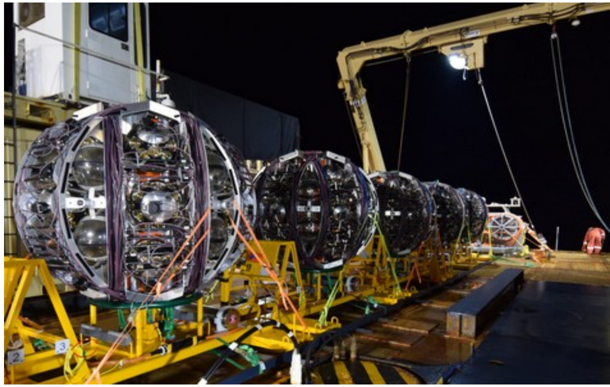




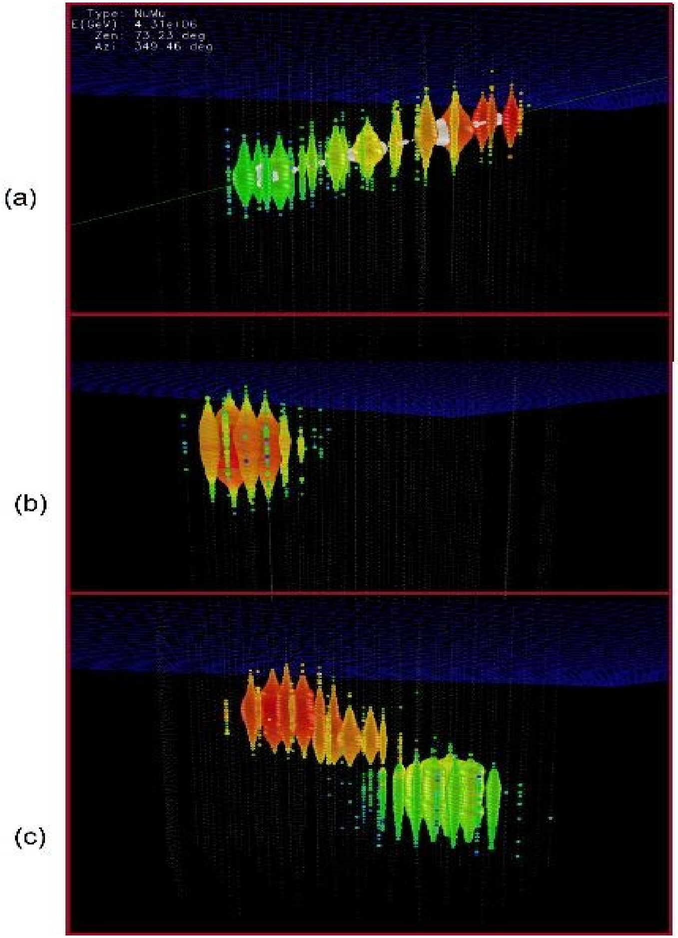
km^3 detector in Mediterranean
looking at southern neutrino sky
and northern sky above 100 TeV
KM3NeT: ORCA & ARCA
also GVD in lake Baikal

ARCA deployment





One may even distinguish neutrino flavors



muon neutrino (track)

good angular resolution: <1-2 deg
poor E resolution (factor ~2)
muon can be produced outside detector

electron neutrino (cascade, also from NC)

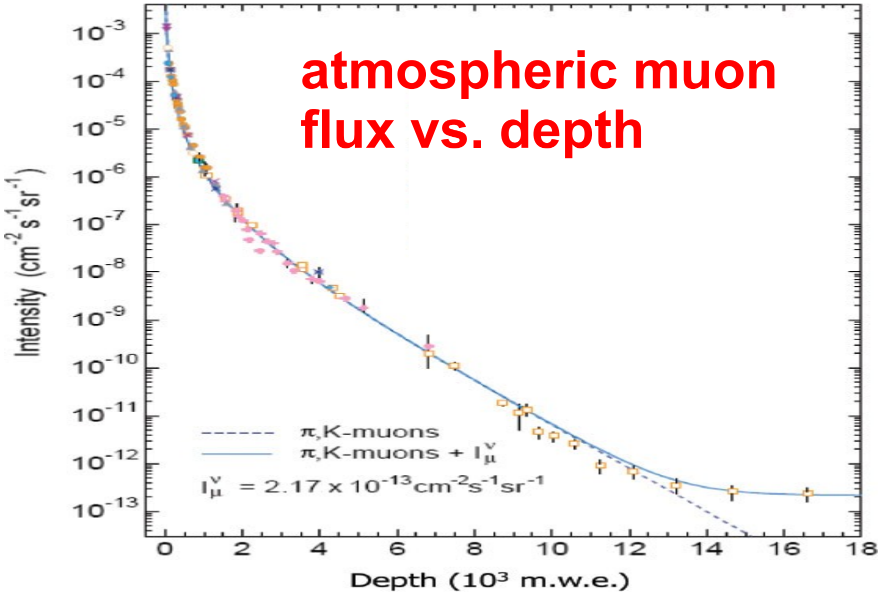
7-15 deg angular resolution (at IC)
15% E resolution
NC showers have only fraction of E_ν

tau neutrino (double bang)

$$\gamma c \tau \simeq \frac{E}{PeV} 50\ m$$

(seen as double pulse cascade for E< PeV)

atmospheric muon flux vs. depth

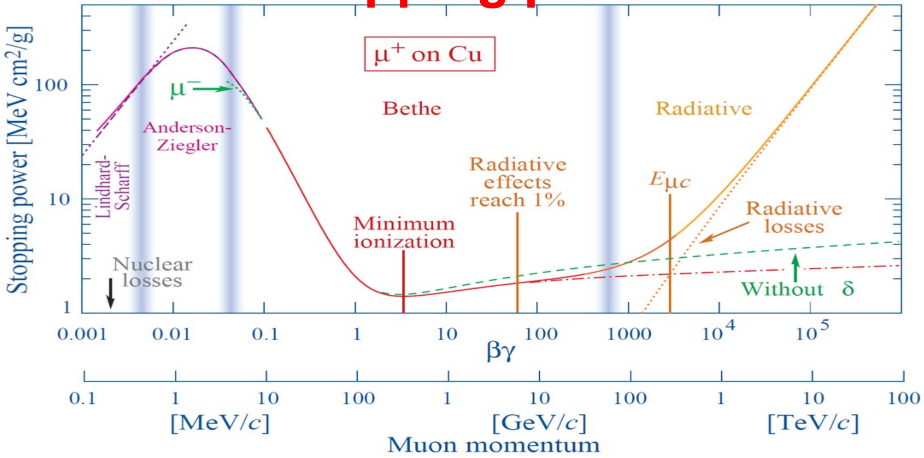


need to be underground and better look downward

(at 2km depth, Rate at IC~10^3 Hz)

check it

muon stopping power vs. E



for $E_\mu > 0.1\,GeV$: $$\frac{dE_\mu}{dX} \simeq -\alpha - \beta E_\mu$$

$$\alpha \simeq 2\,MeV\,cm^2/g \qquad \beta \simeq 4\times 10^{-6}\,cm^2/g$$

muon range from E_μ to E_{th}:

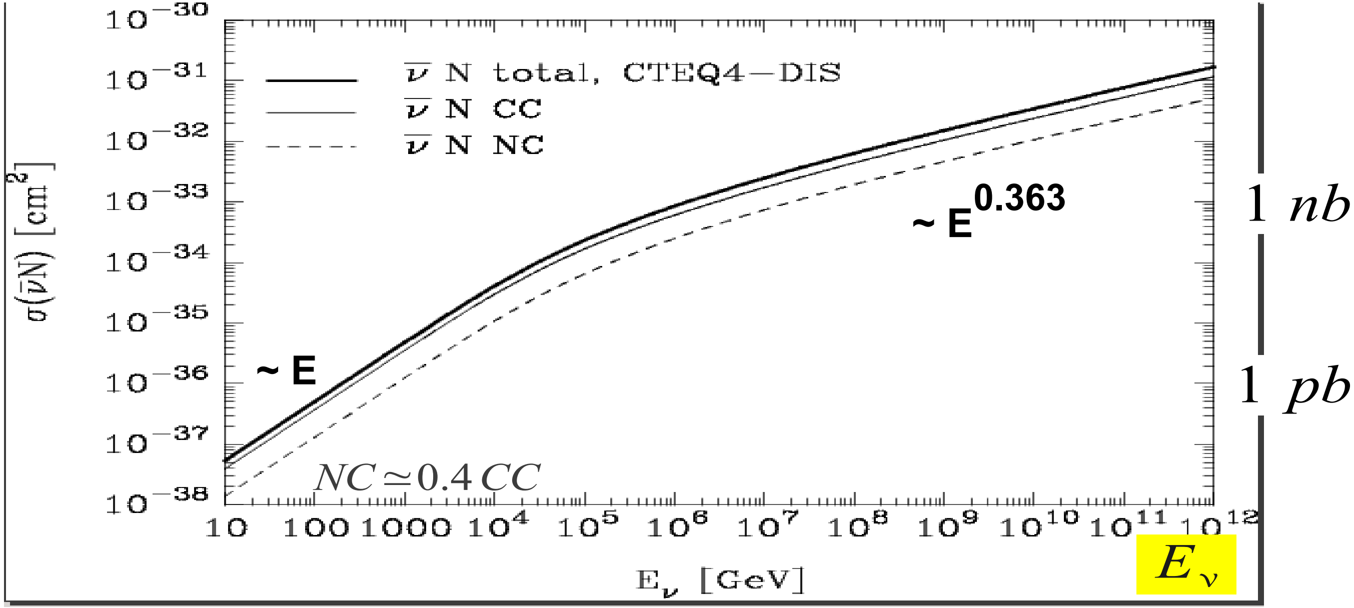
$$d(E_\mu, E_{th}) \simeq D \ln \frac{(1+E_\mu/\epsilon)}{(1+E_{th}/\epsilon)}$$

prove it

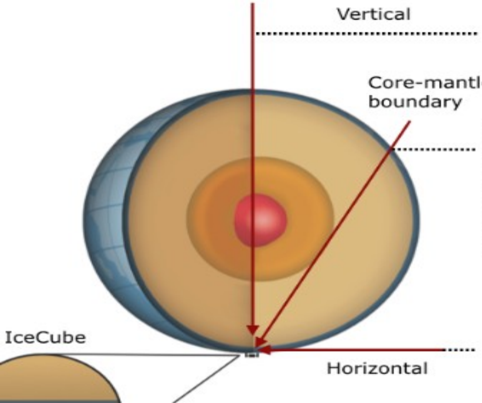
$$D \equiv \frac{1}{(\rho\beta)} \simeq \frac{2.5\,km}{\rho/\rho_{ice}} \qquad \epsilon \equiv \frac{\alpha}{\beta} \simeq 0.5\,TeV$$

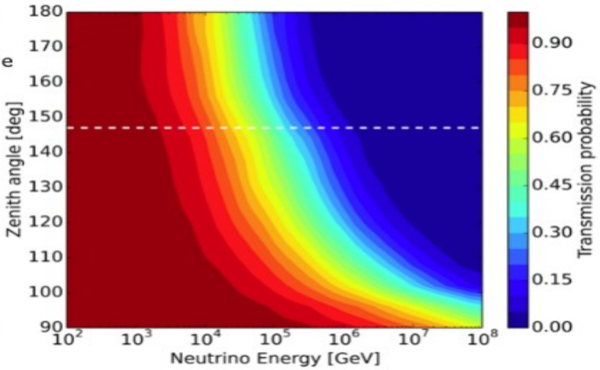
for E > TeV, muons reach detector from several km distance (while e are not MIP)

neutrinos detected via deep inelastic ν nucleon interactions



cross section grows with E ! but Earth becomes opaque for E > 100 TeV

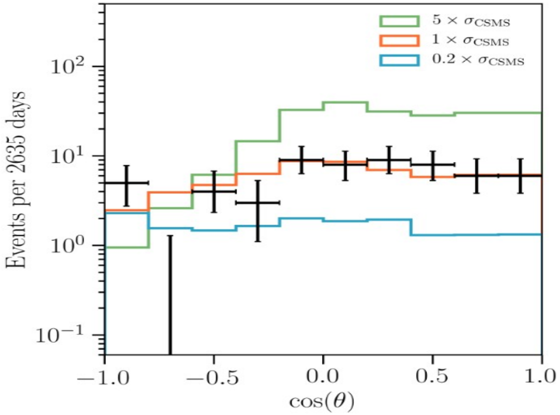




$$attenuation = \exp\left(-\bar{n}\,\sigma\,L\right)$$

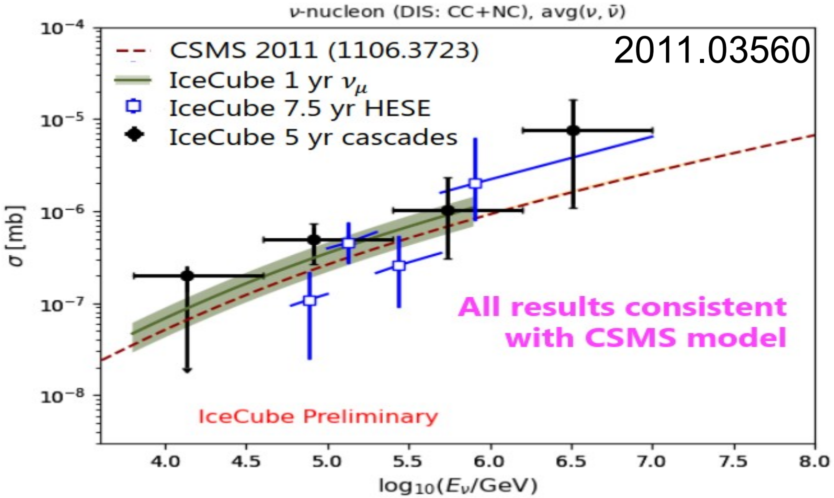
$$\bar{n}\,\sigma\,L \simeq \frac{\bar{\rho}}{5\,g/cm^3}\,\frac{\sigma}{300\,pb}\,\frac{L}{10^4\,km}$$

→ **need to look above horizon at the highest energies**



60 HESE events above 60 TeV

attenuation has been used to measure νN cross section beyond reach of accelerators

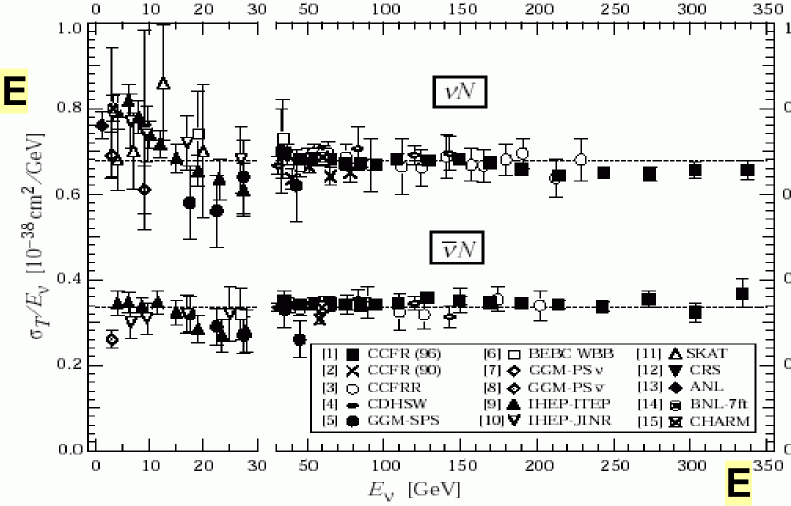


2011.03560

All results consistent with CSMS model

accelerator results

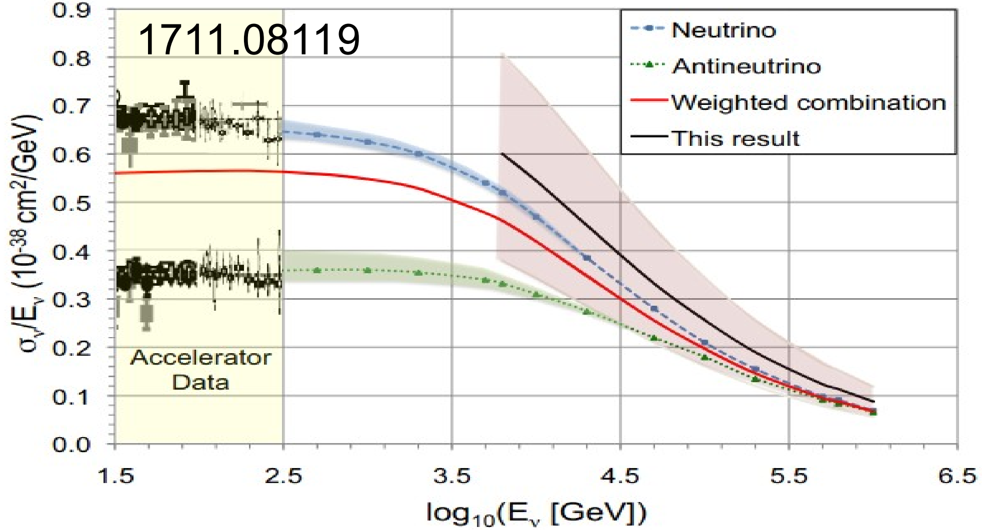
σ / E



E

Figure 39.10: σ_T/E_ν, for the muon neutrino and anti-neutrino charged-current total cross section as a function of neutrino energy. The error bars include both statistical and systematic errors. The straight lines are the averaged values over all energies as measured by the experiments in Refs. [1–4]: $= 0.677 \pm 0.014$ (0.334 ± 0.008) $\times 10^{-38}$ cm^2/GeV. Note the change in the energy scale at 30 GeV. (Courtesy W. Seligman and M.H. Shaevitz, Columbia University, 2001.)

IceCube results



1711.08119

(10784 up-going mus above 6 TeV)

LHC will fill the gap (2022-2025)

High-energy neutrino measurements with FASERν Yosuke Takubo

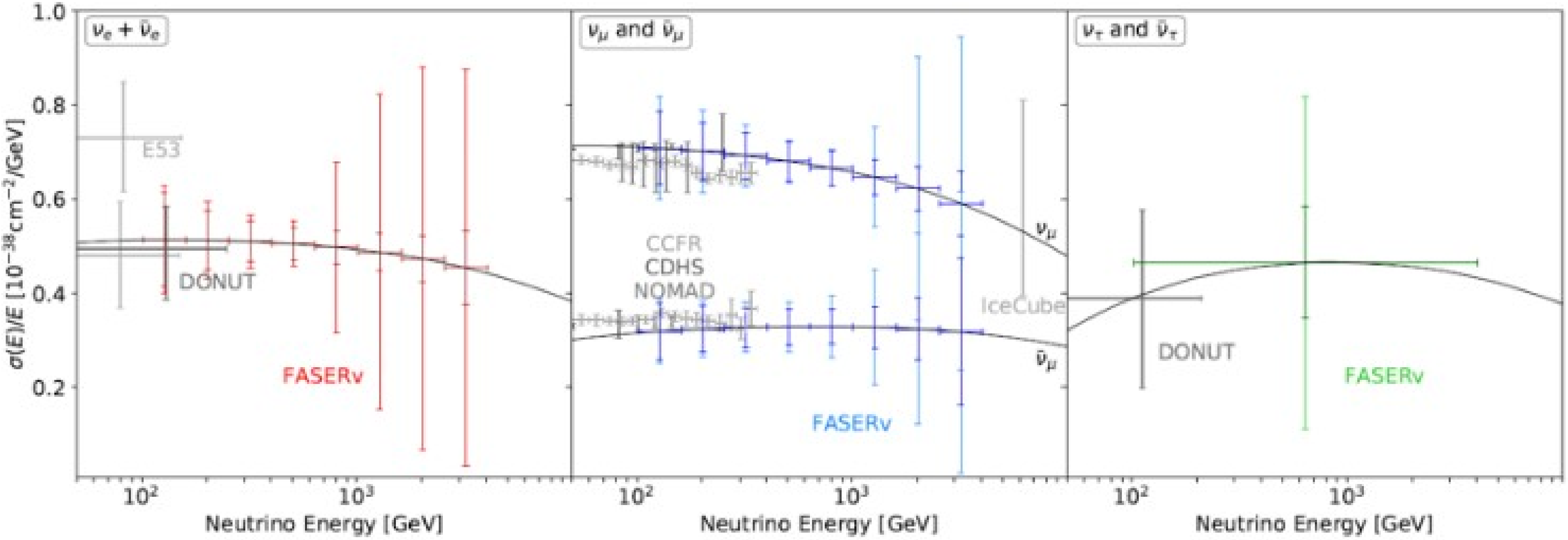
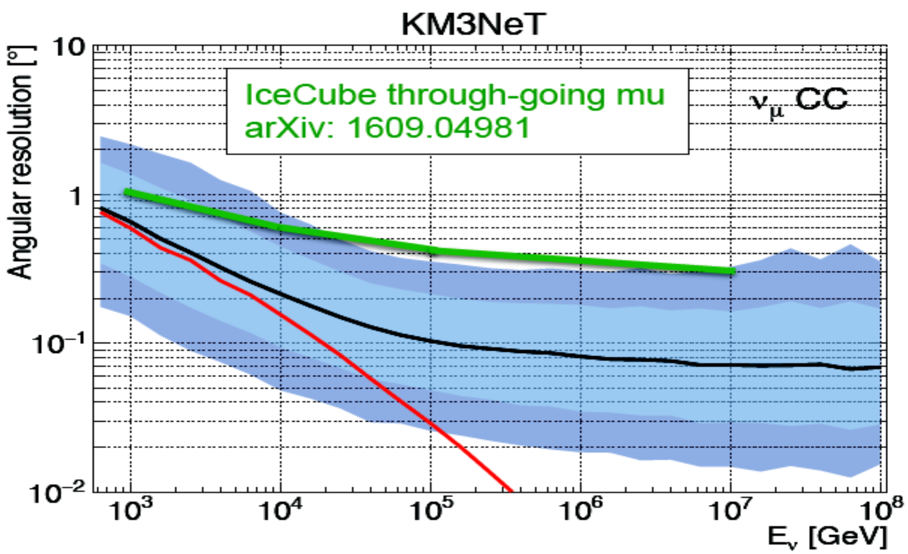


Figure 3: The expected sensitivity to ν-nucleaon CC cross-section for ν_e (left), ν_μ (middle) and ν_τ (right) with 150 fb^{-1} of data-taking at FASERν in LHC Run 3.

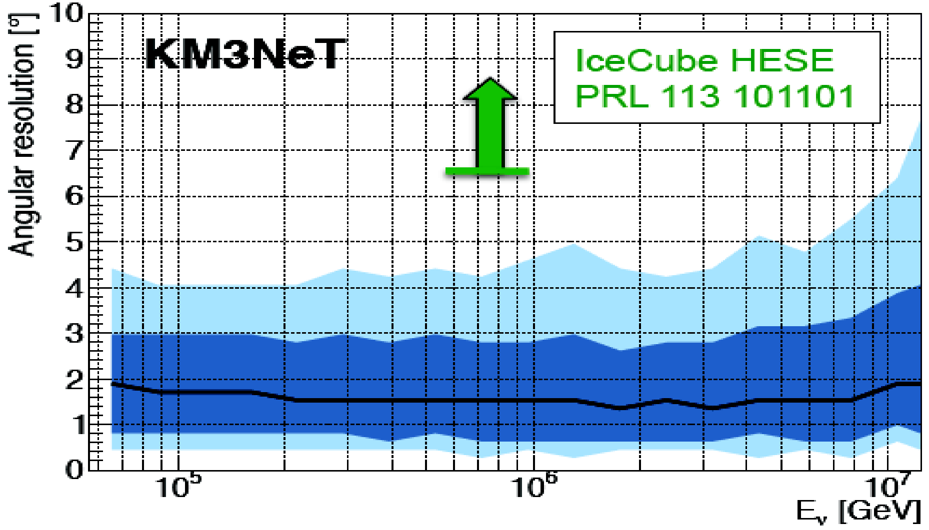
PoS(ICHEP2022)556

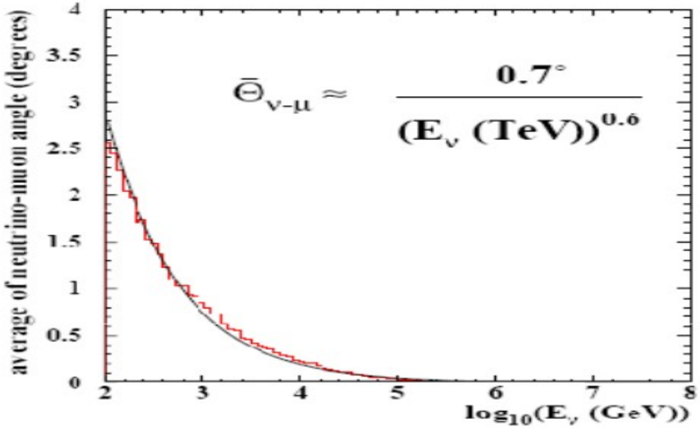
angular resolution

tracks



showers

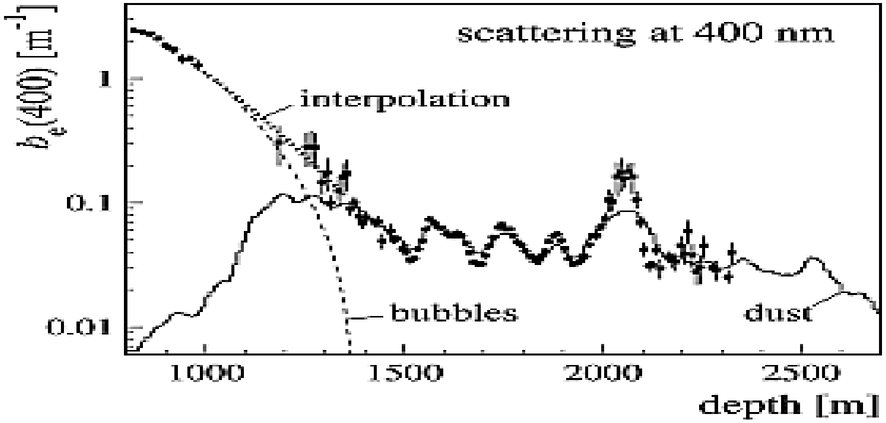




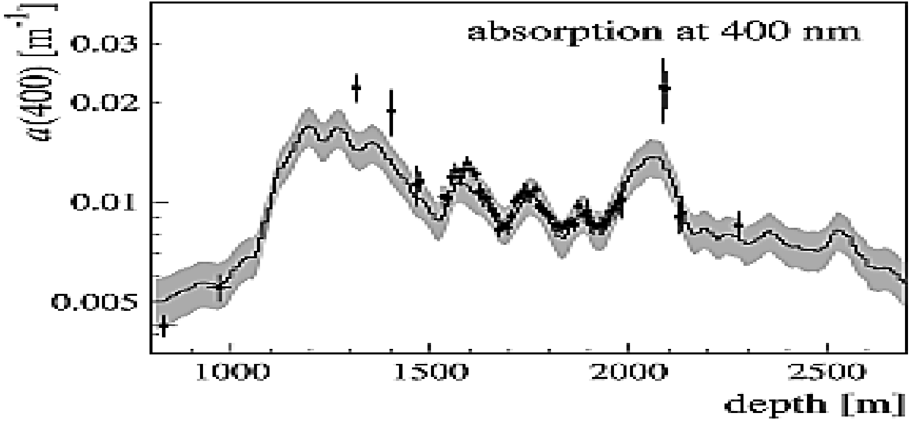
resolution	in sea-water	(in ice)
tracks	~ 0.1°	(> 0.5°)
showers	~ 2°	(> 6°)

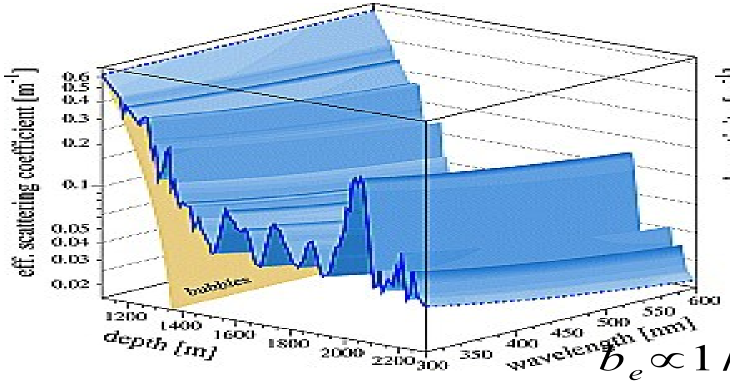
ICE SCATTERING AND ATTENUATION

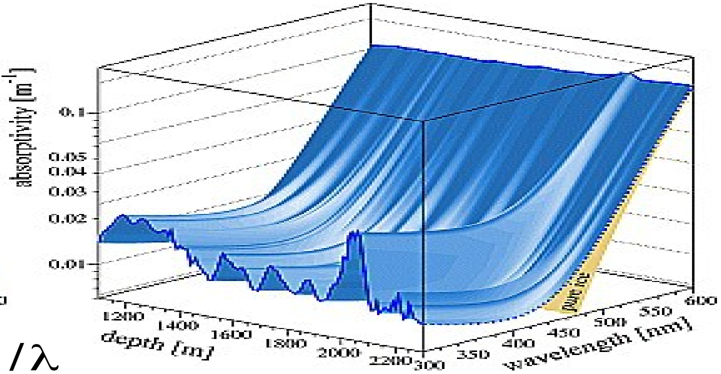
$b_e = 1/\lambda_e$



$a = 1/\lambda_a$







$b_e \propto 1/\lambda$

Effective scattering length for isotropization at 400 nm $\lambda_e \sim 20-30\,m$

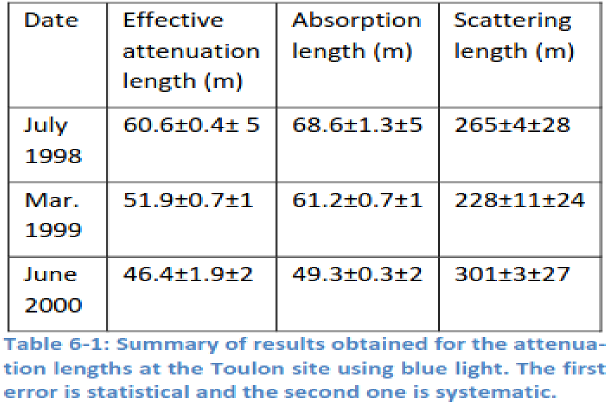
while $\lambda_a \sim 100\,m$

Ackerman et al, J Geophys Res 2006

absorption/scattering in sea water

Toulon

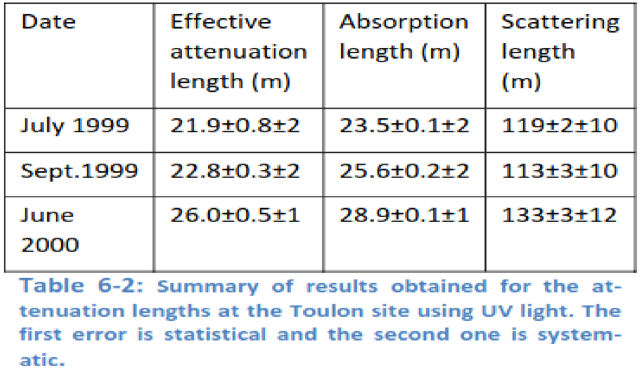
blue



Date	Effective attenuation length (m)	Absorption length (m)	Scattering length (m)
July 1998	60.6±0.4± 5	68.6±1.3±5	265±4±28
Mar. 1999	51.9±0.7±1	61.2±0.7±1	228±11±24
June 2000	46.4±1.9±2	49.3±0.3±2	301±3±27

Table 6-1: Summary of results obtained for the attenuation lengths at the Toulon site using blue light. The first error is statistical and the second one is systematic.

UV



Date	Effective attenuation length (m)	Absorption length (m)	Scattering length (m)
July 1999	21.9±0.8±2	23.5±0.1±2	119±2±10
Sept.1999	22.8±0.3±2	25.6±0.2±2	113±3±10
June 2000	26.0±0.5±1	28.9±0.1±1	133±3±12

Table 6-2: Summary of results obtained for the attenuation lengths at the Toulon site using UV light. The first error is statistical and the second one is systematic.

CapoPassero

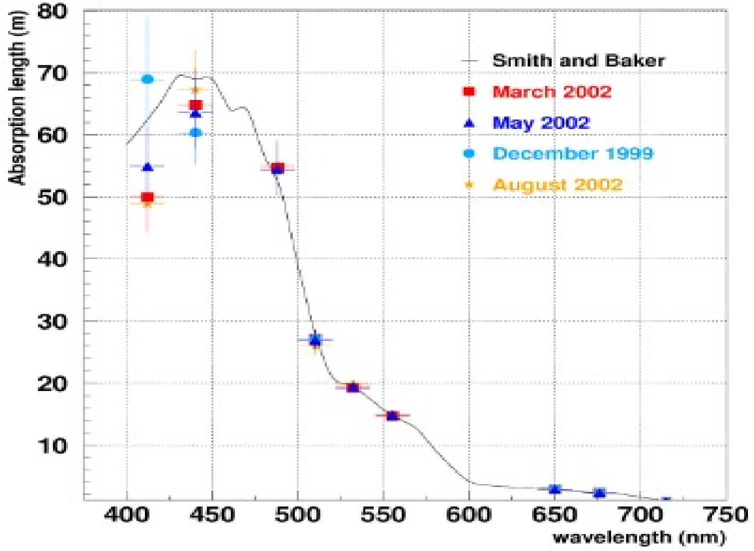
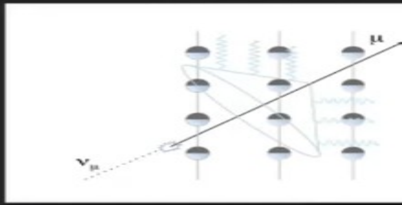


Figure 6-2: Average absorption length as a function of wavelength, for four seasons at the Capo Passero site.

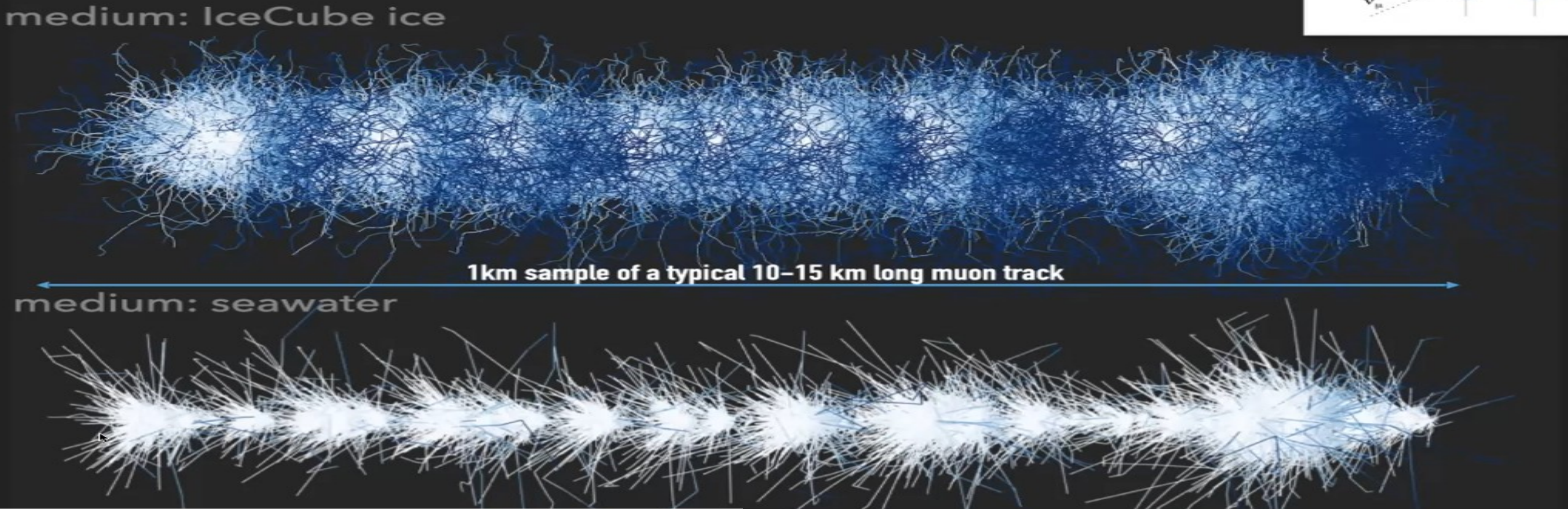
Km3NeT CDR

Scattering is not an issue → better angular resolution in sea water but absorption strong → cannot separate PMTs too much

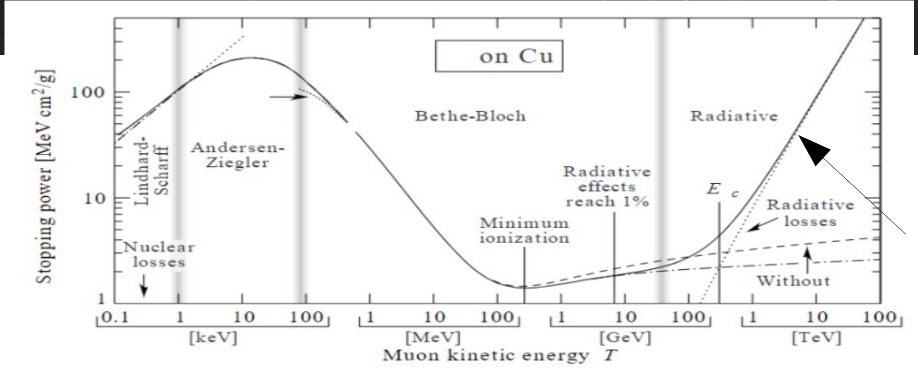
HORIZONTAL HIGH ENERGY MUONS: THE SIGNATURE



1 PeV horizontal muon



K. Krings



In regime of catastrophic stochastic E losses

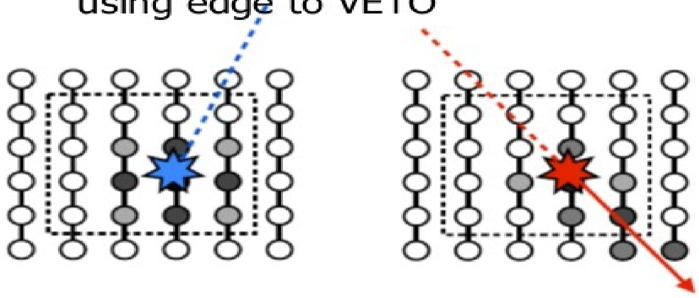
At IceCube: downgoing muons ~ 10^3 Hz, atmo ν ~ 10^{-3} Hz, astrophysical ~ 10^{-5} Hz

(→ need to look for upgoing, or veto downgoing muons, and focus on high E)

suppress atm. μ background

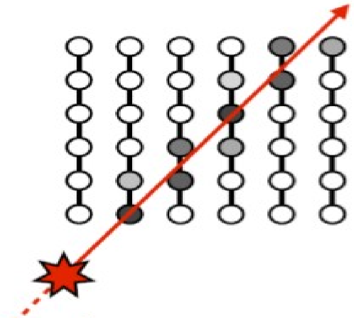
“starting” events

using edge to VETO



upgoing tracks

using Earth as filter



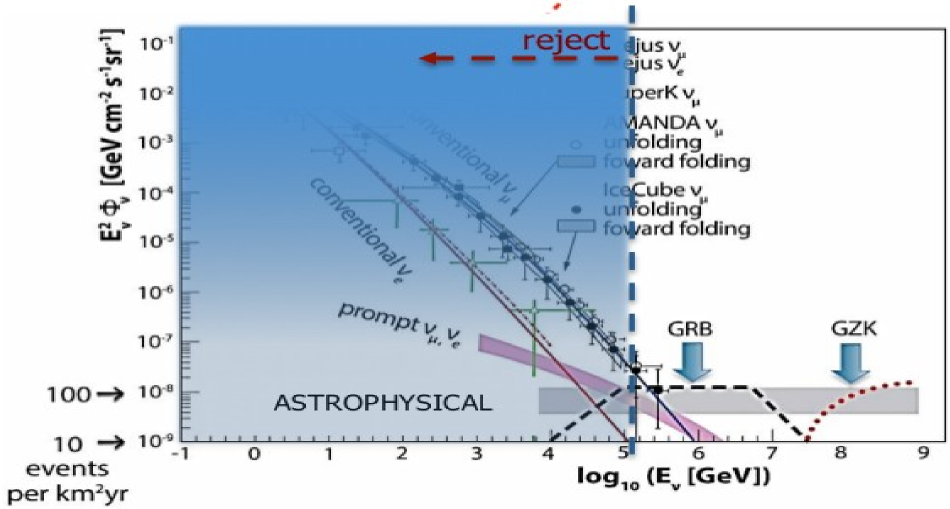
suppress atm. ν background

using ENERGY

diffuse searches

SPATIAL TEMPORAL CORRELATIONS

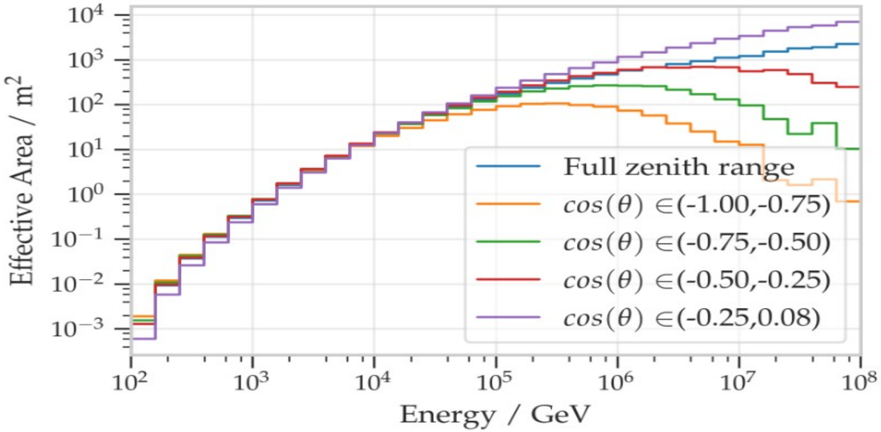
point sources



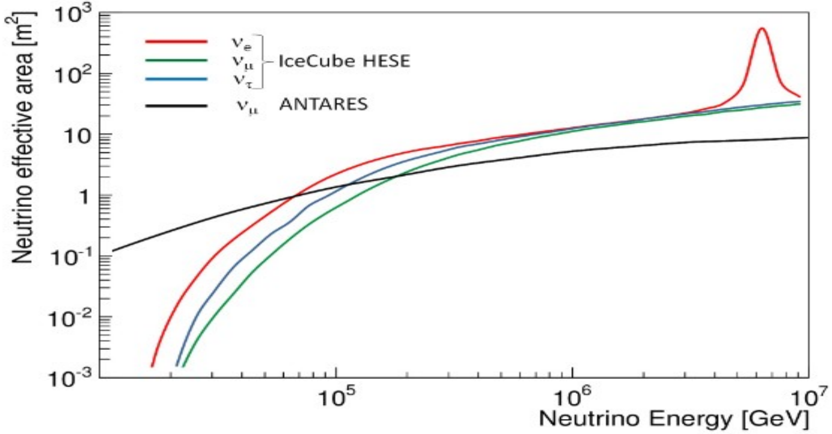
Effective area of detector:

$$N_{events} = A_{eff}\,Fluence \qquad ; \; Fluence = \int dt\,Flux$$

IC tracks



IC showers & Antares tracks



depends on cross section, Earth attenuation, fiducial volume, …

A_{eff} ~ 1 m^2 at TeV, 100 m^2 at 100 TeV (tracks)

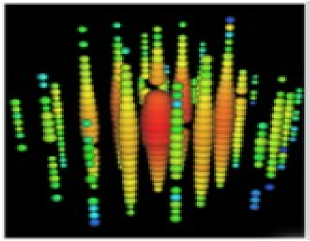
~ 10 m^2 for cascades at PeV

it is like catching water with a strainer

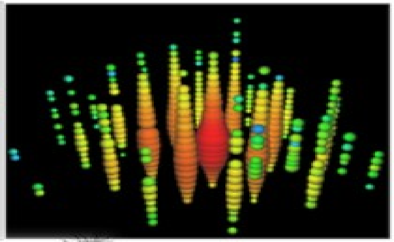
Note that typical astro flux is:

$$E_\nu^2 \Phi_\nu \sim 10^{-8}\,GeV/(cm^2\,s\,sr) \rightarrow d\Phi/d\,lnE \sim 3(TeV/E_\nu)/(m^2\,yr\,sr)$$

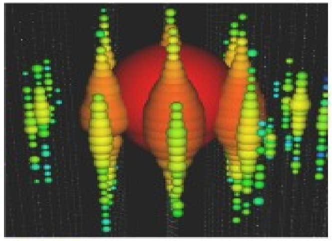
Using the High Energy Starting Events (HESE), IceCube observed PeV neutrinos measuring ~ a dozen per year of astrophysical neutrinos with E > 60 TeV



"Bert"
1.04 PeV
Aug. 2011



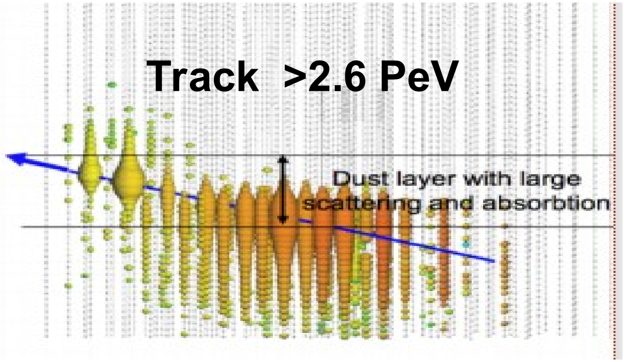
"Ernie"
1.14 PeV
Jan. 2012



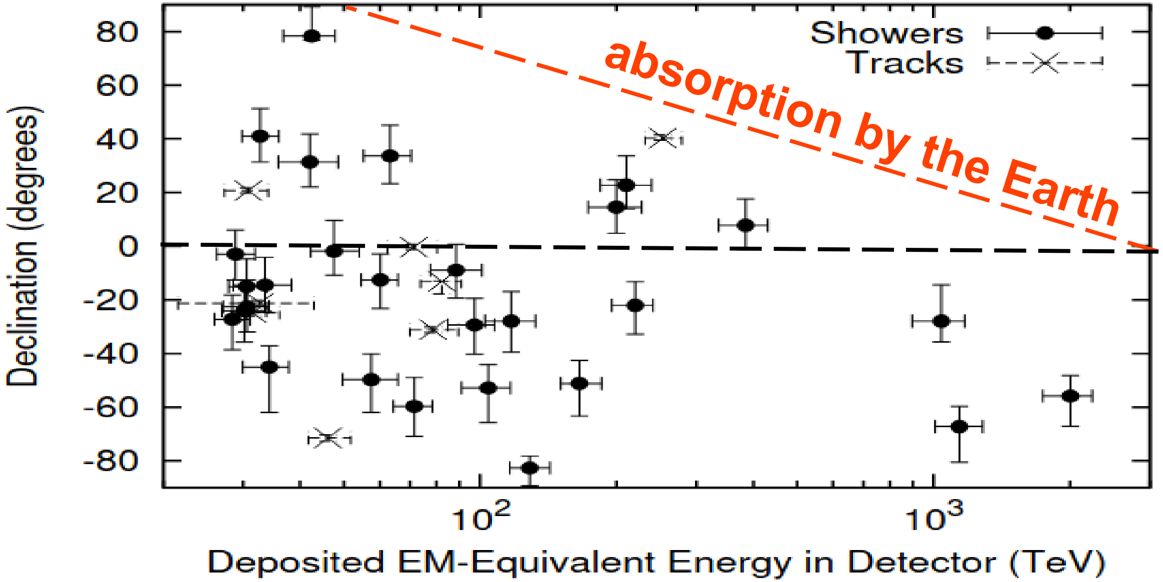
"Big Bird"
2 PeV
Dec. 2012

(Science 2013)
1405.5303

color: time
size: E deposit



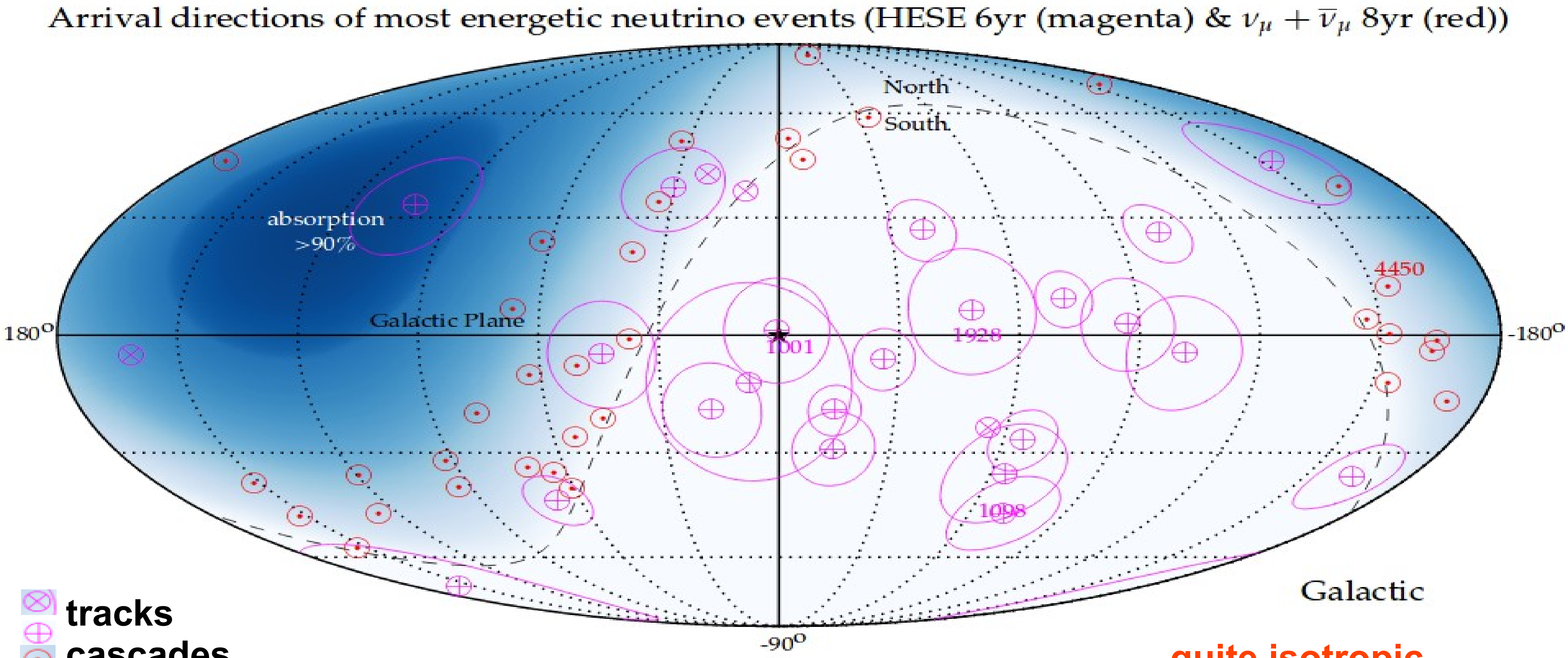
Track >2.6 PeV



upgoing

downgoing

Map of astrophysical neutrino arrival directions



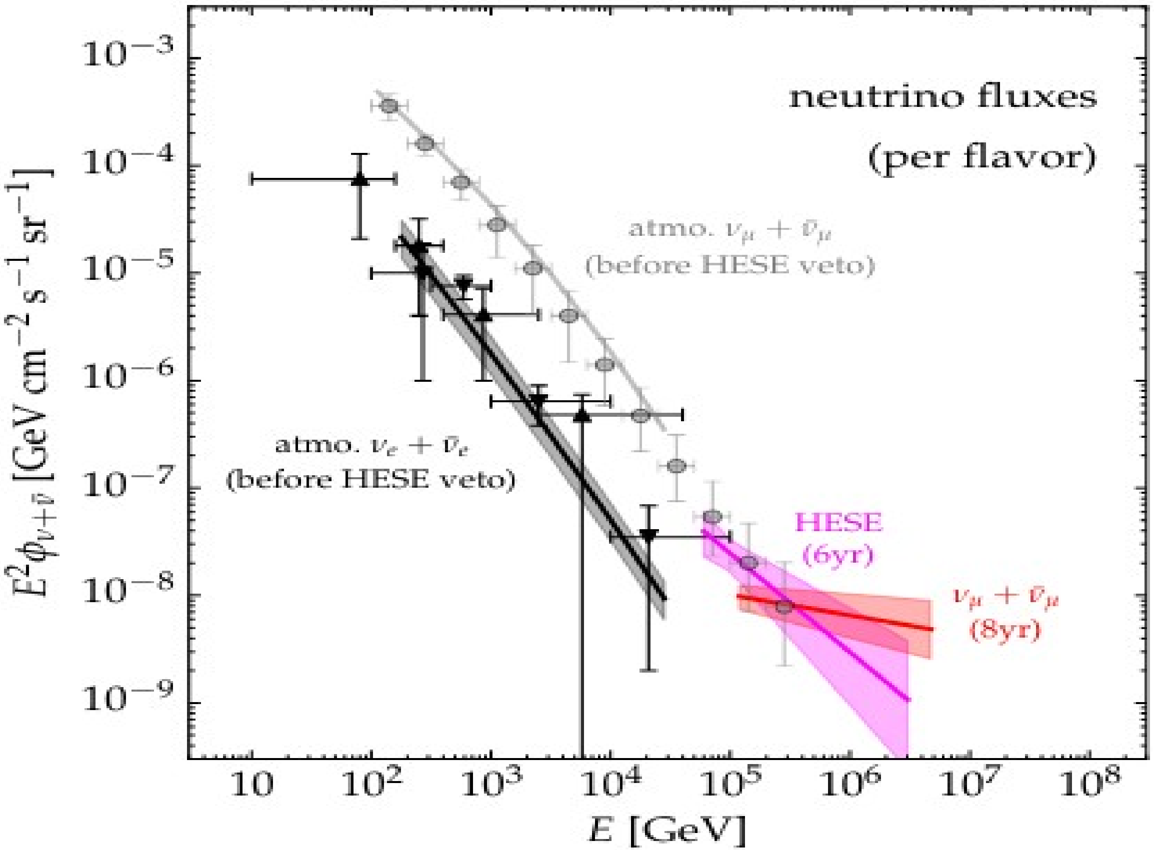
⊗ tracks
⊕ cascades
⊙ upgoing tracks

quite isotropic

upgoing tracks with E_μ > 200 TeV, HESE with E > 100 TeV

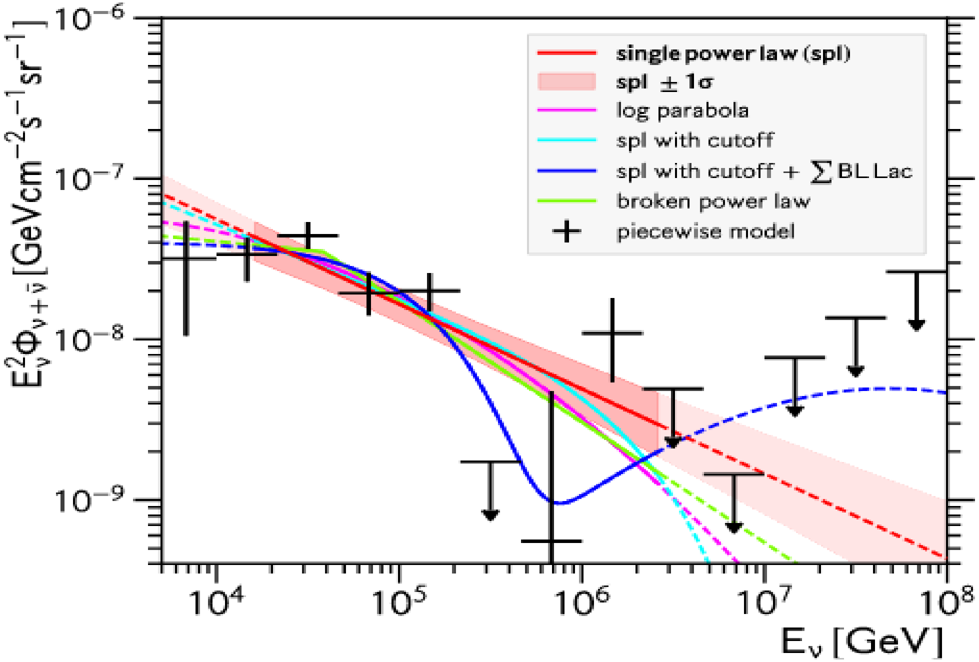
1805.11112

Spectrum of HESE & throughgoing muons from ν_μ CC



CASCADE EVENTS

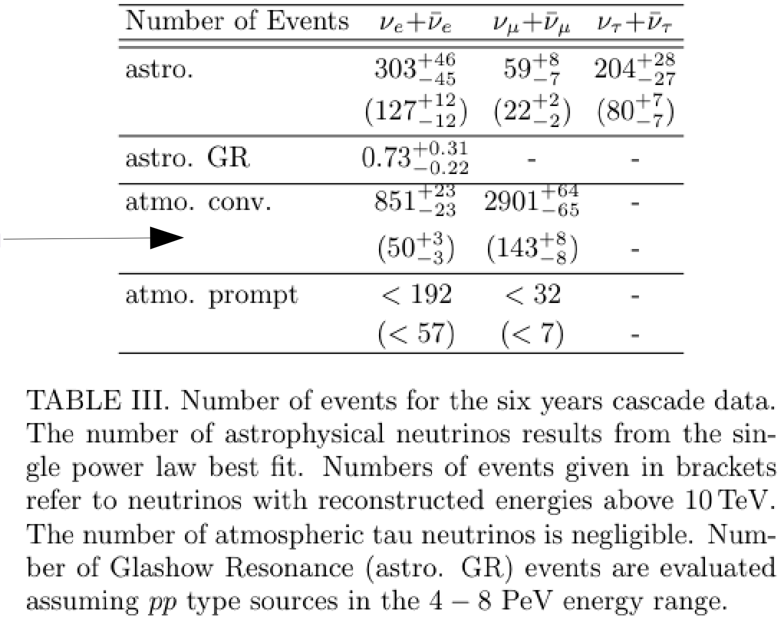
From ν_e and ν_τ CC + NC from all flavors



sensitive energy range

from 16 TeV to 2.6 PeV

small atmosph backg

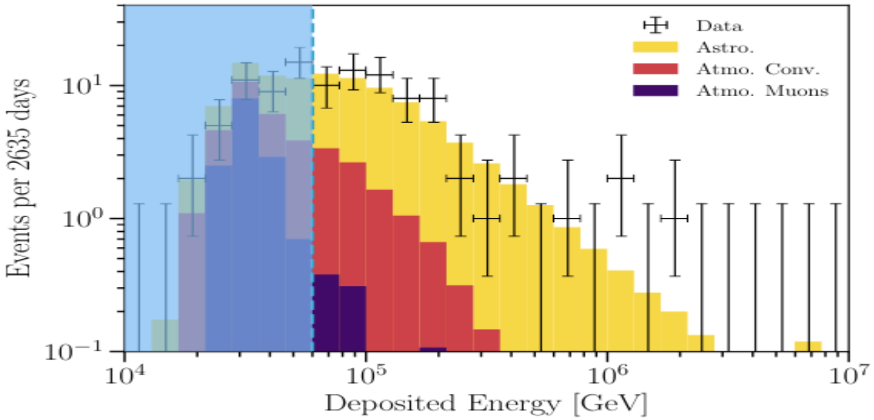


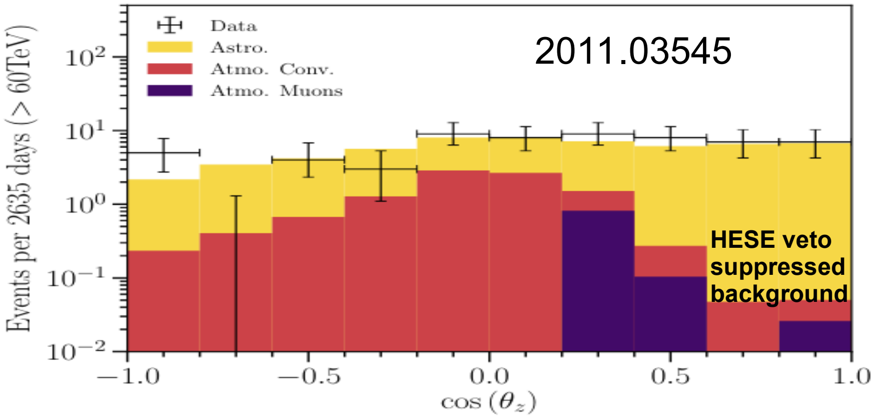
Number of Events	$\nu_e+\bar{\nu}_e$	$\nu_\mu+\bar{\nu}_\mu$	$\nu_\tau+\bar{\nu}_\tau$
astro.	303^{+46}_{-45} (127^{+12}_{-12})	59^{+8}_{-7} (22^{+2}_{-2})	204^{+28}_{-27} (80^{+7}_{-7})
astro. GR	$0.73^{+0.31}_{-0.22}$	-	-
atmo. conv.	851^{+23}_{-23} (50^{+3}_{-3})	2901^{+64}_{-65} (143^{+8}_{-8})	- -
atmo. prompt	< 192 (< 57)	< 32 (< 7)	- -

TABLE III. Number of events for the six years cascade data. The number of astrophysical neutrinos results from the single power law best fit. Numbers of events given in brackets refer to neutrinos with reconstructed energies above 10 TeV. The number of atmospheric tau neutrinos is negligible. Number of Glashow Resonance (astro. GR) events are evaluated assuming *pp* type sources in the 4 – 8 PeV energy range.

2001.09520

Latest update

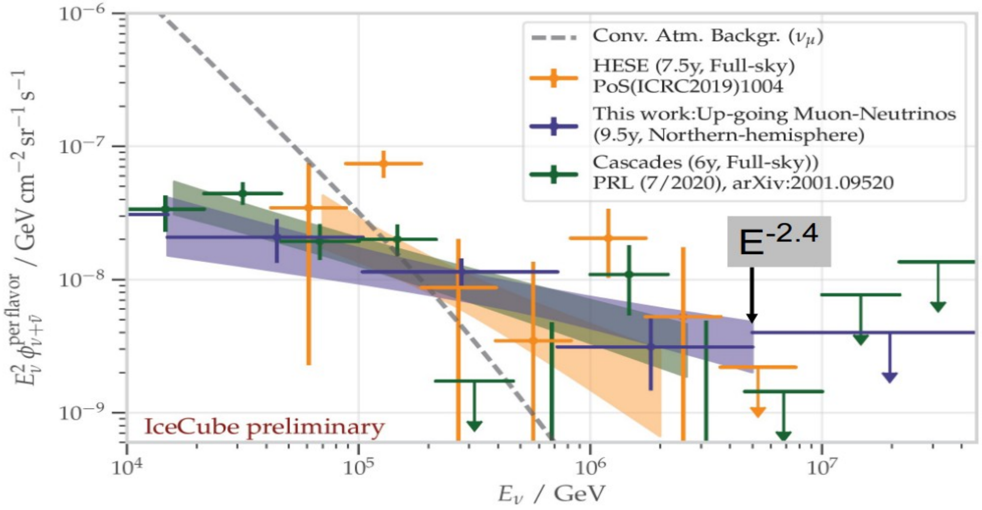




2011.03545

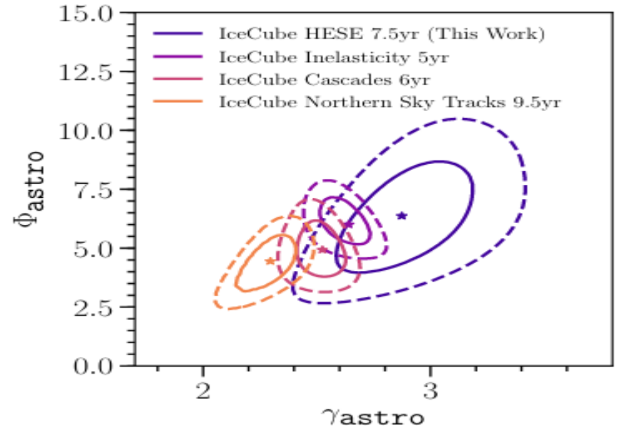
HESE veto suppressed background

harder than atmospheric background & isotropic

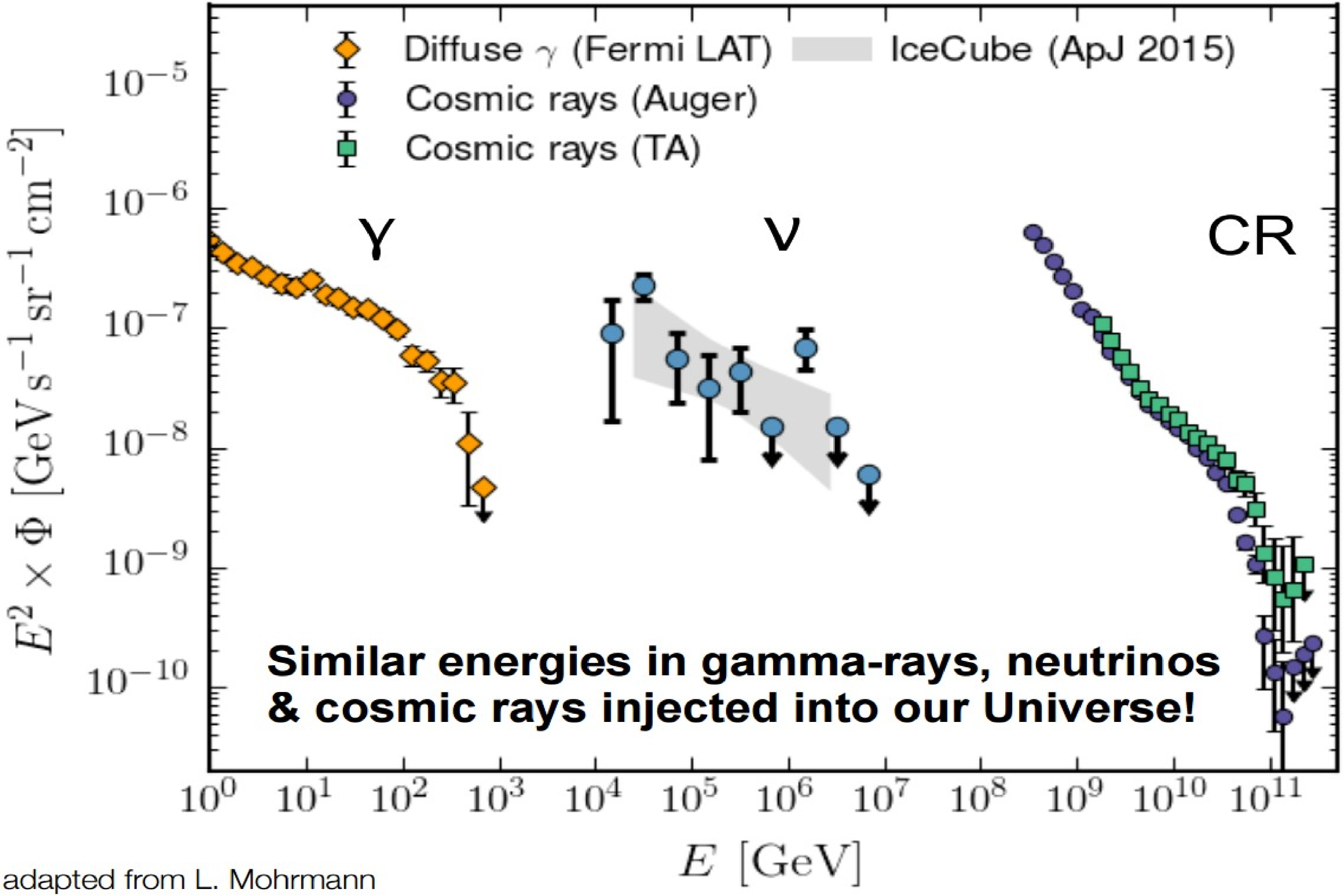


$E^{-2.4}$

$$\frac{d\Phi_{6\nu}}{dE} = \Phi_{\text{astro}}\left(\frac{E_\nu}{100\,\text{TeV}}\right)^{-\gamma_{\text{astro}}} \cdot 10^{-18}\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$



some tension, but is it a single power-law?
are fluxes in the north (tracks) equal to the south (seen with cascades)?

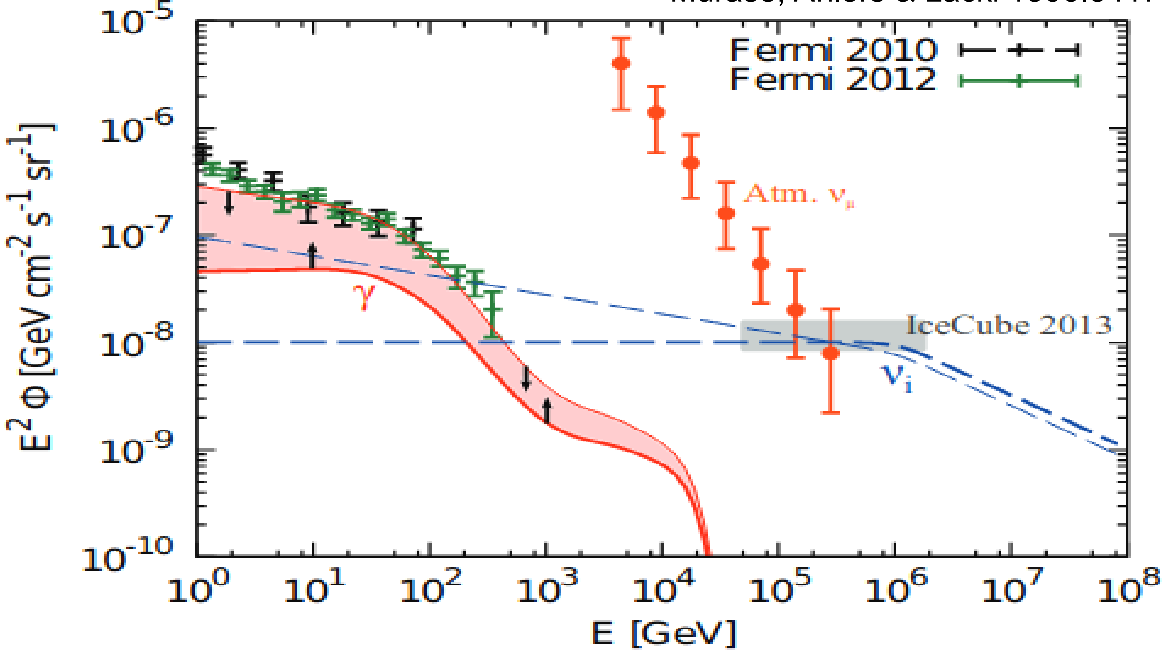


Similar energies in gamma-rays, neutrinos & cosmic rays injected into our Universe!

g. adapted from L. Mohrmann

photons from associated neutral pion decays cascade down below PeV by interactions with CMB and EBL radiation backgrounds

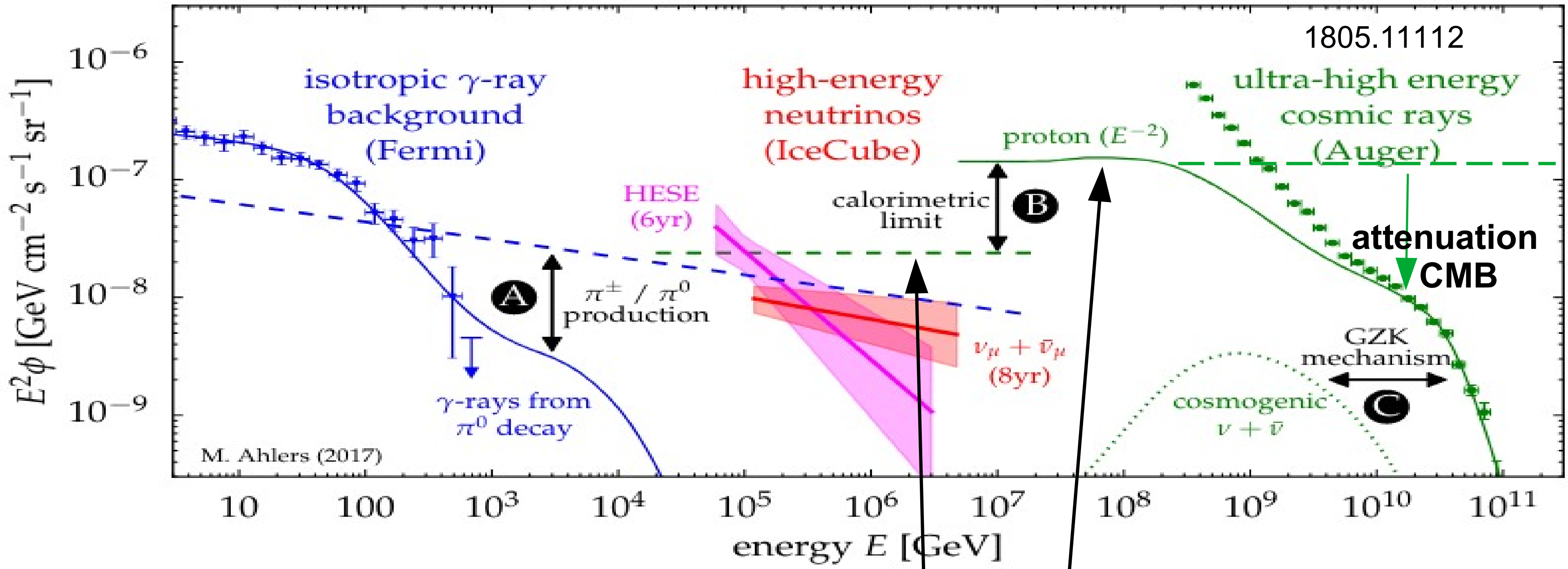
Murase, Ahlers & Lacki 1306.3417



typically the neutrino spectrum below 500 TeV cannot be softer than ~$E^{-2.2}$ to not overshoot gamma background bounds

→ suggest sources opaque to VHE photons (hidden sources)

and/or astrophysical fluxes strongly suppressed below 100 TeV (pγ scenarios?)



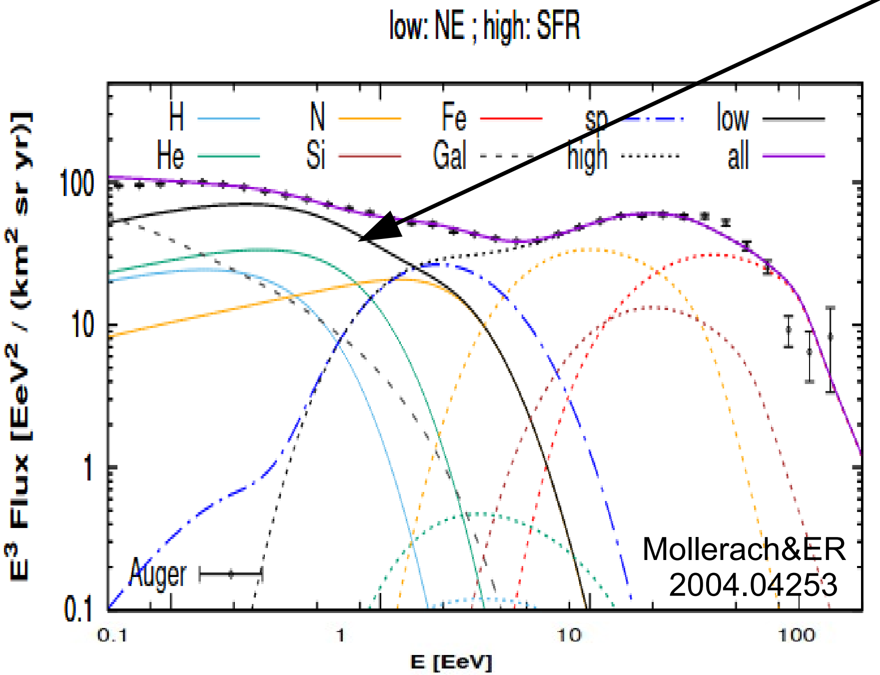
Waxman-Bahcall ‘bound’, or reference flux (1999):
if extragalactic UHECRs were protons with E^{-2} spectrum
and significantly converted to pions at PeV energies,
the maximum ν flux would be ~ $E^2\,\Phi \sim 3.10^{-8}$ GeV/cm^2 s sr (all flavors)

observed flux near WB would suggest sources almost opaque to CRs

Waxman-Bahcall flux revisited:

- now we know that UHECRs are not dominantly protons above 5 EeV

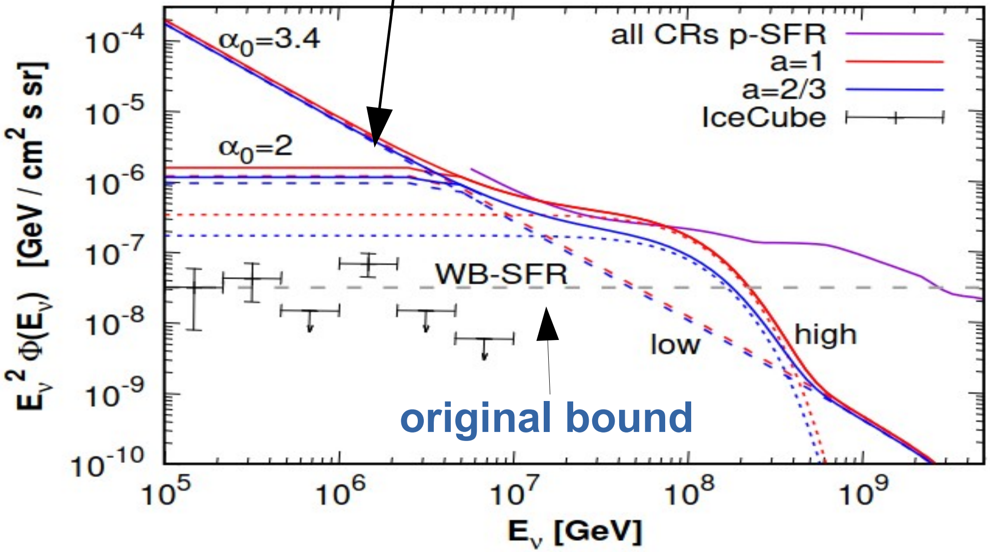
- below 5 EeV CRs are likely extragalactic and from different sources



Mollerach&ER 2004.04253

Upper-bounds in realistic scenarios

ER 2105.12506

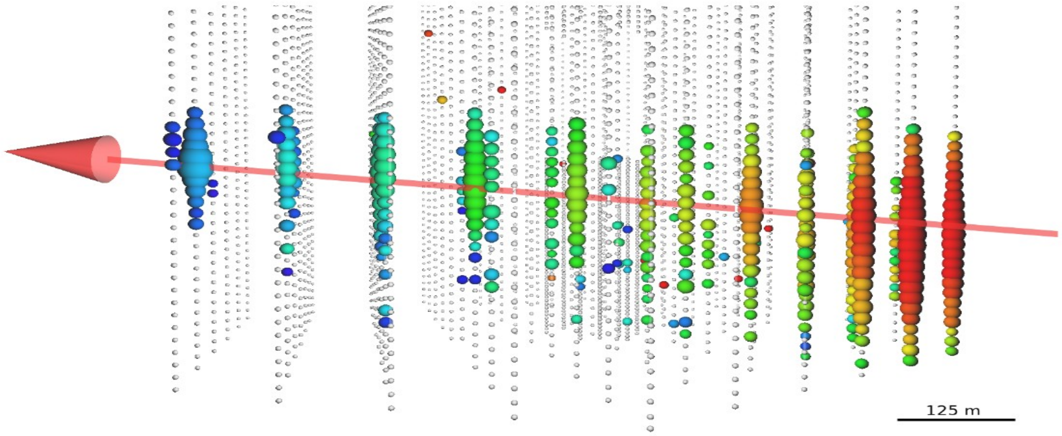


original bound

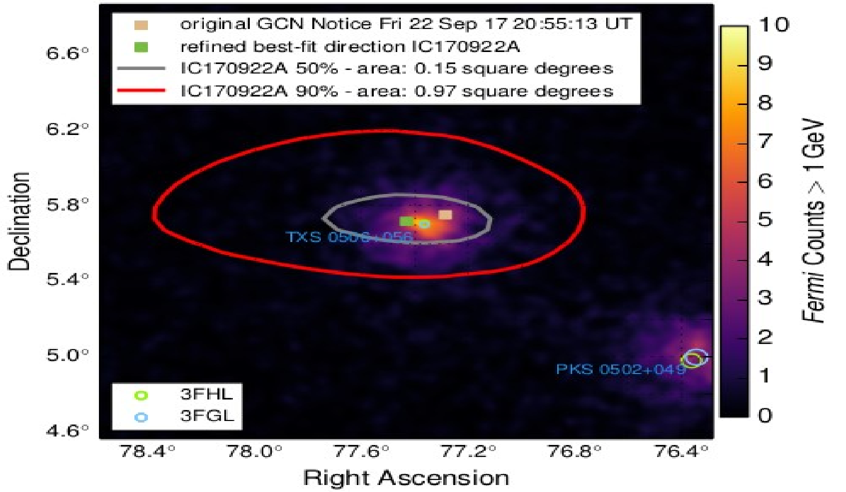
realistic scenarios would only require that less than few% of CRs interact at the sources

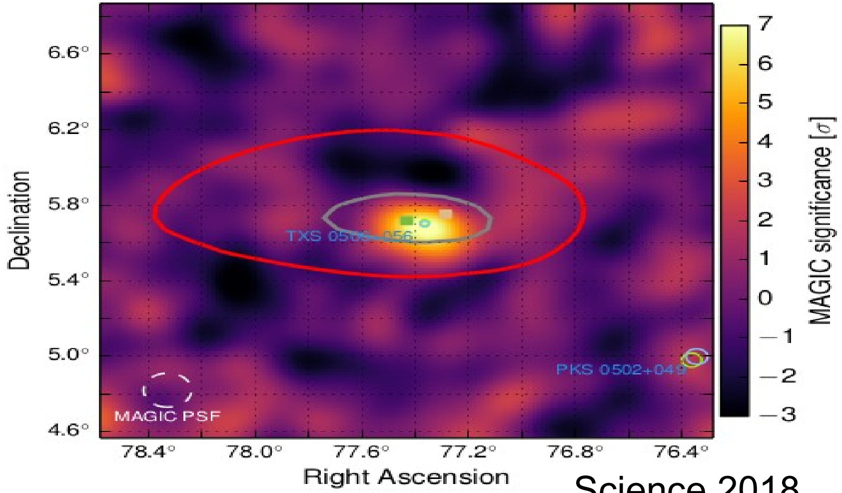
the PeV sources can be thin to CRs and still produce observed ν fluxes

IN 2018 ICECUBE OBSERVED 300 TeV NEUTRINO FROM BLAZAR TXS 0506+056 (first neutrino clearly associated to a high-energy extragalactic source)



ure 1: Event display for neutrino event IceCube-170922A. The time at which a DOM



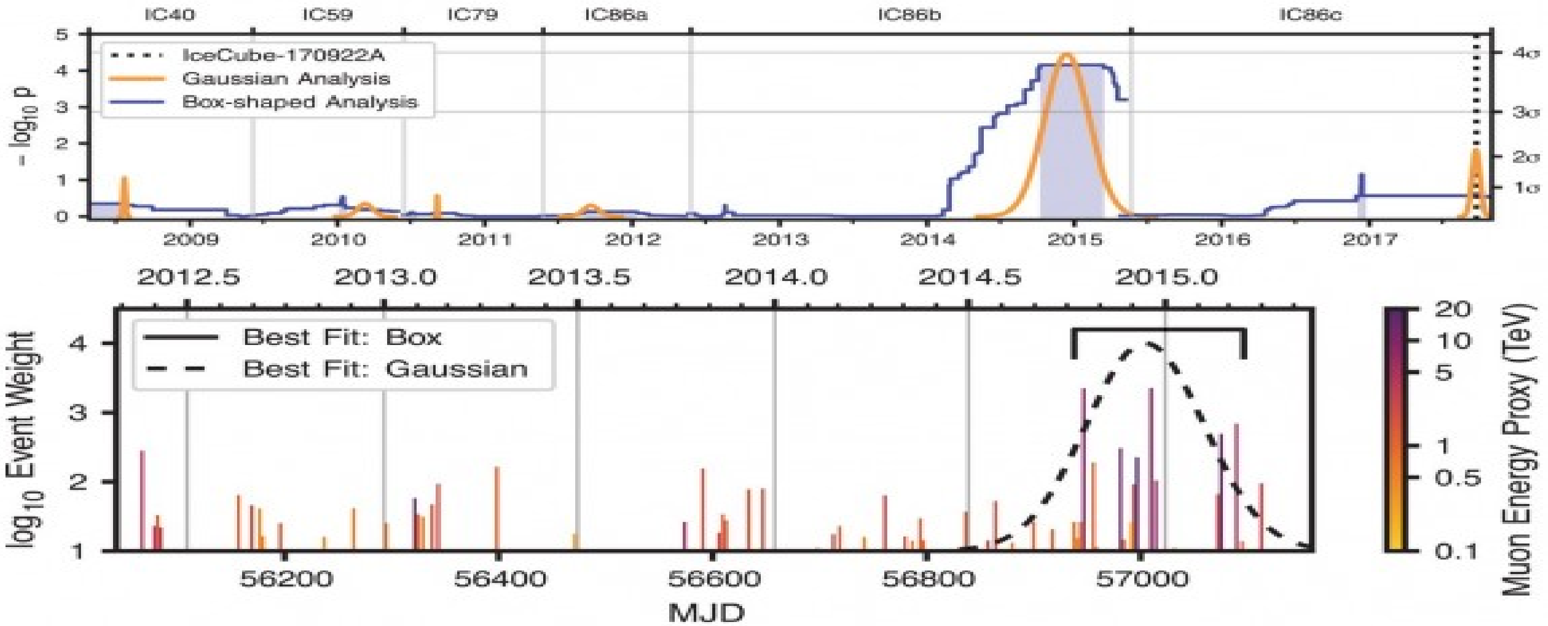


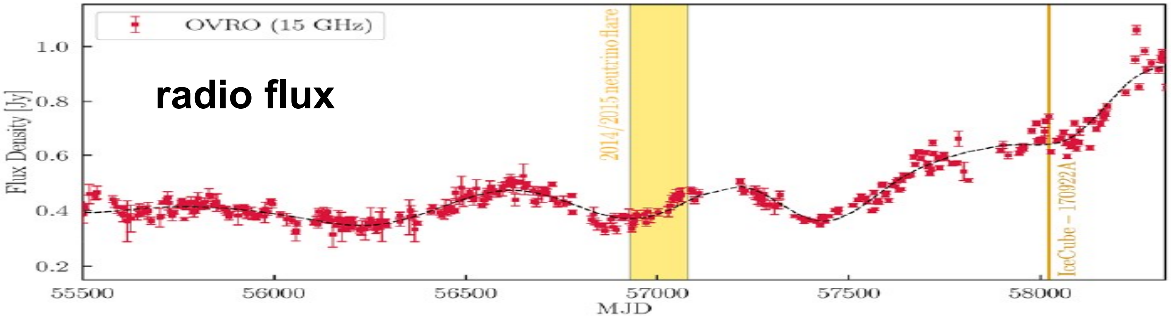
IceCube event direction coincides with Blazar TXS 0506+056, that was in a state of increased activity (Fermi, Magic)

source redshift $z = 0.33$ (> 1.7 Gpc!)

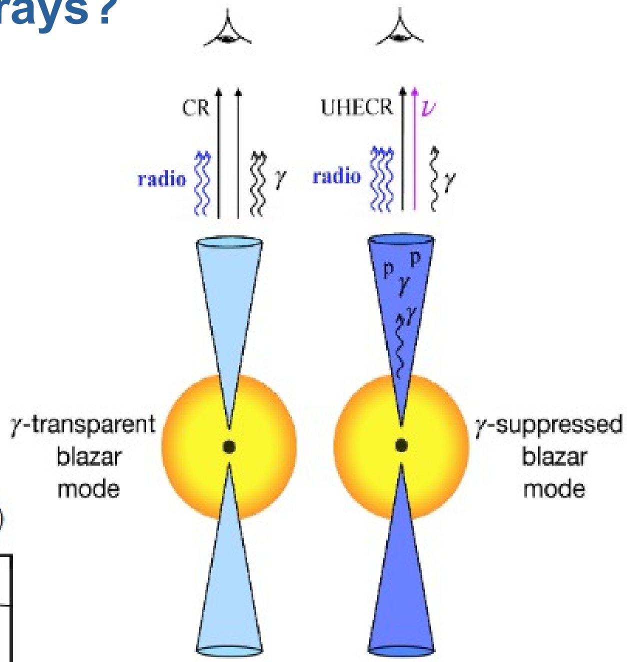
Science 2018

searching in archival data in the TXS direction:
→ ~1-20 TeV flare lasting 160 days near end 2014 (13+-5 events)

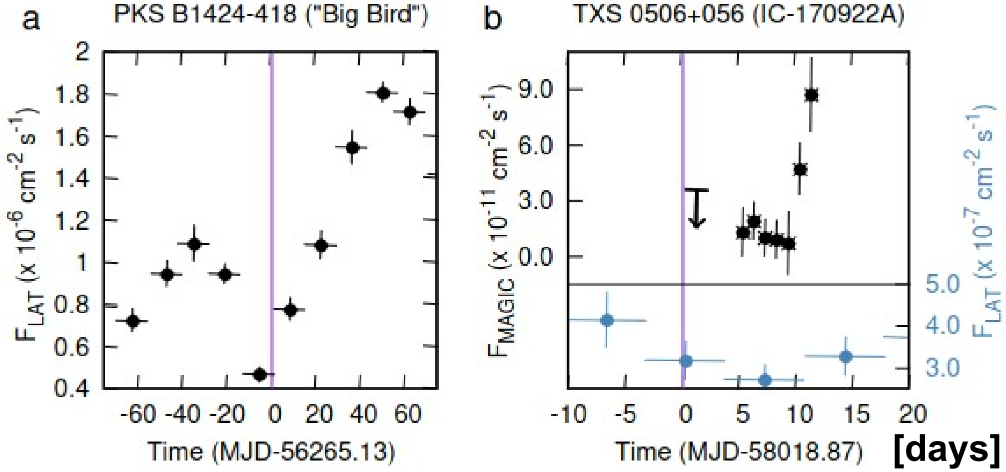



radio flux

remarkably, the energetic neutrino in TXS (and other less significant blazar candidates) appeared during brief periods of reduced gamma flux: the enhanced target that produced the neutrinos also attenuated the gamma rays?

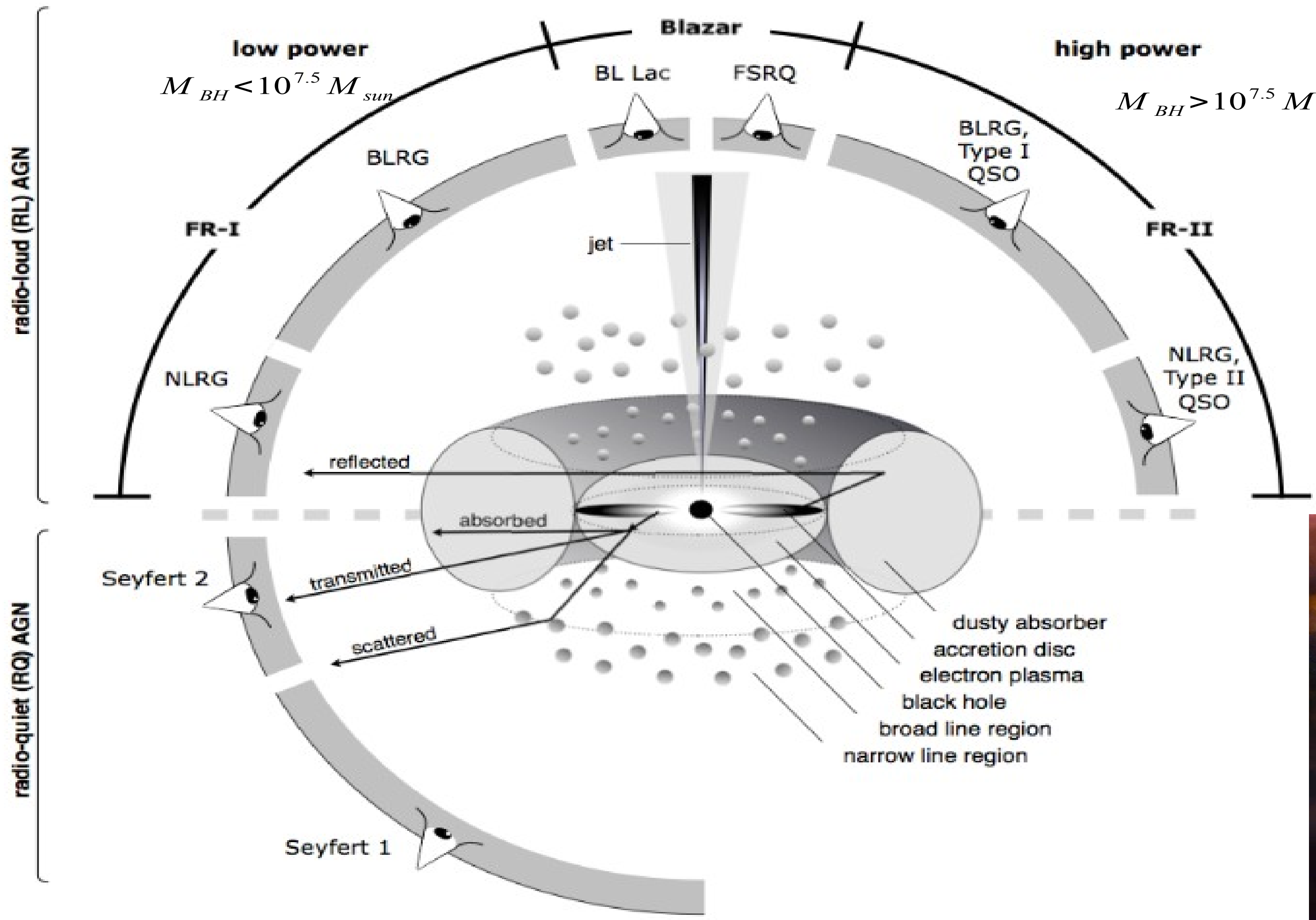


$$\tau_{\gamma\gamma} \simeq \frac{\sigma_{\gamma\gamma}}{\kappa_{p\gamma}\sigma_{p\gamma}}\,\tau_{p\gamma} \simeq 10^3\,\tau_{p\gamma}$$



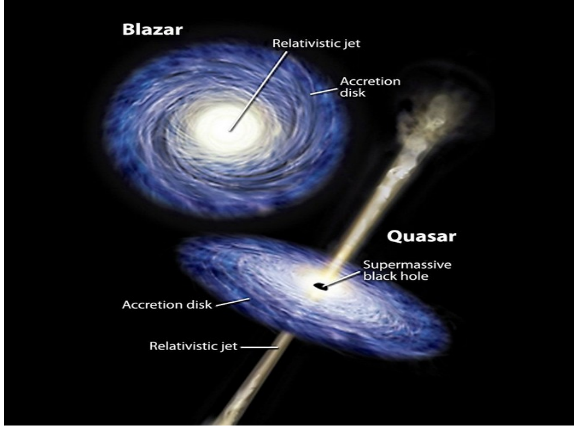
Kun et al 2009.09792

AGN Grand Unification



$M_{BH} < 10^{7.5} M_{sun}$

$M_{BH} > 10^{7.5} M_{sun}$

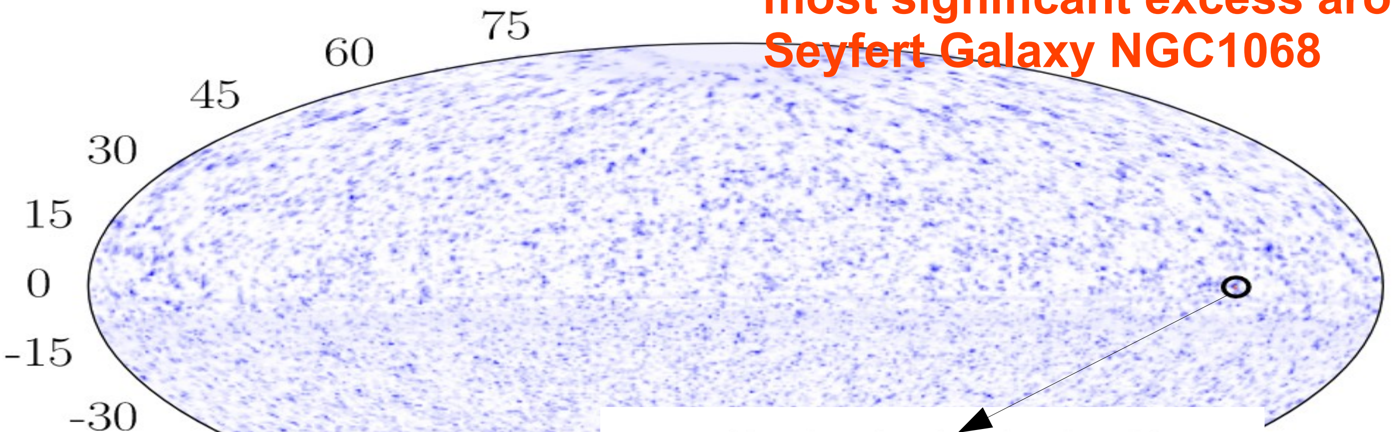


FR: Fanaroff Riley

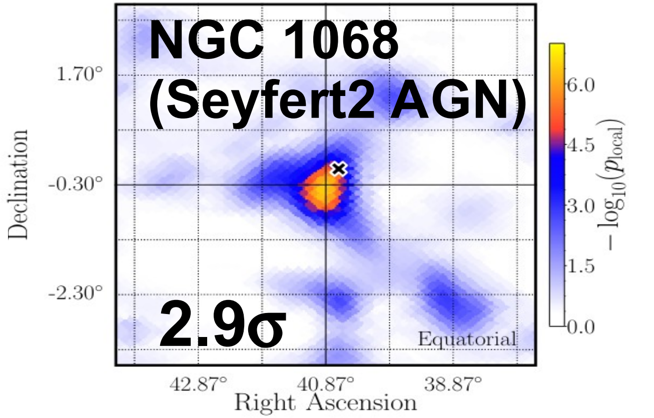
IceCube SEARCH FOR POINT SOURCES WITH MUON TRACKS

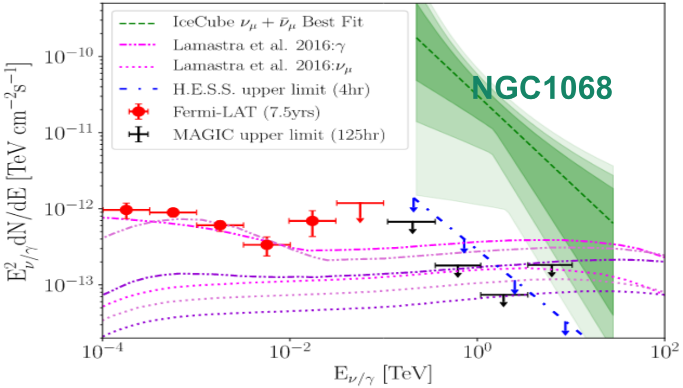
(angular resolution < 1°)

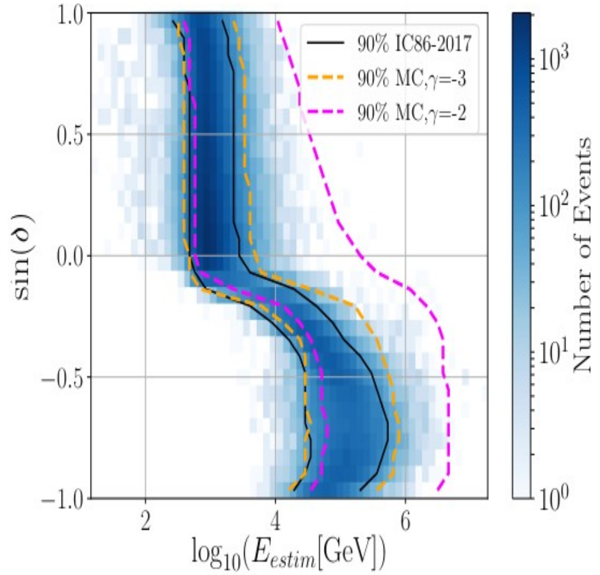
most significant excess around Seyfert Galaxy NGC1068



(about 130k events per yr)







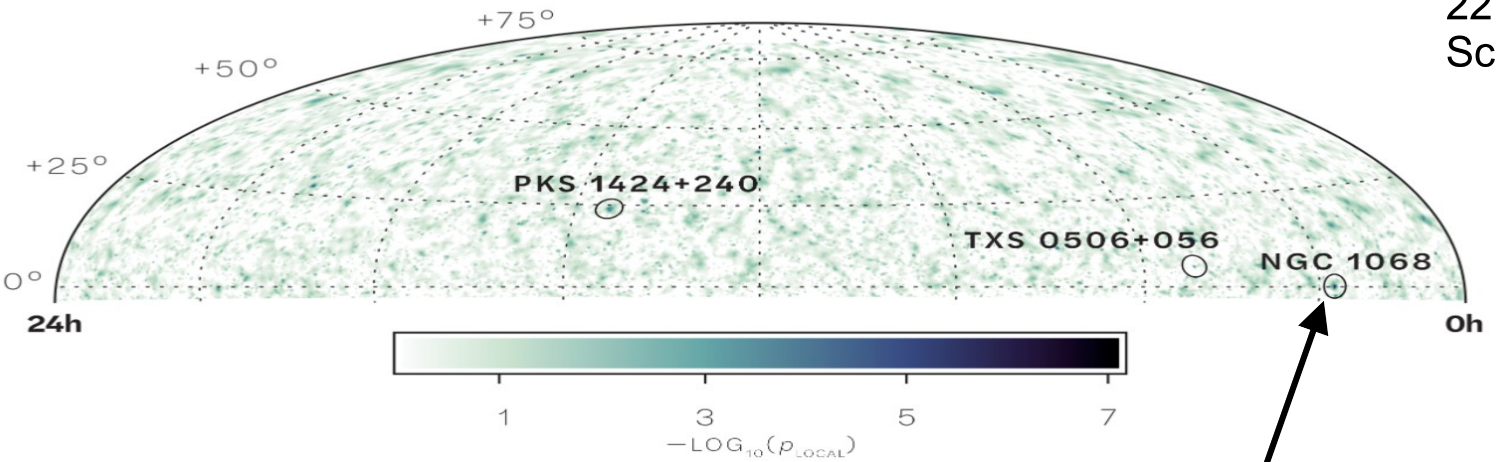
for upgoing, E > 1 TeV, backg from atmo neutrinos

for downgoing, E > 100 TeV, backg from atmo muons

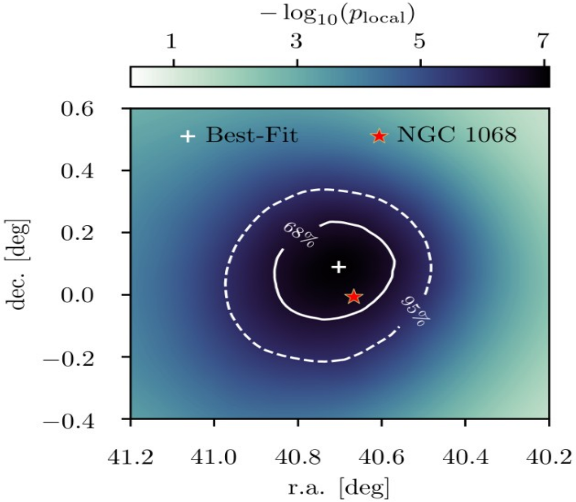
1910.08488,

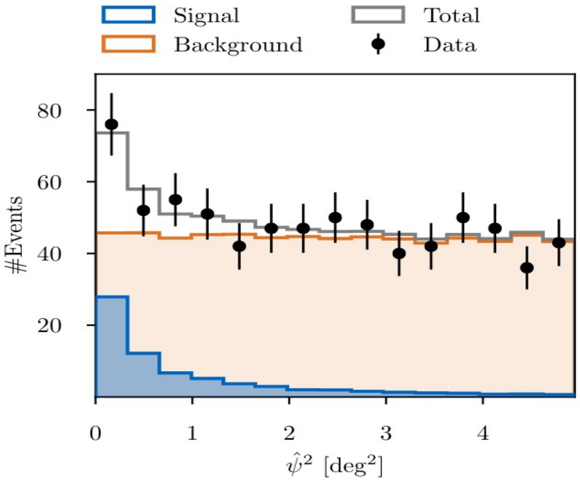
NGC 1068 latest results

2211.09972
Science 22



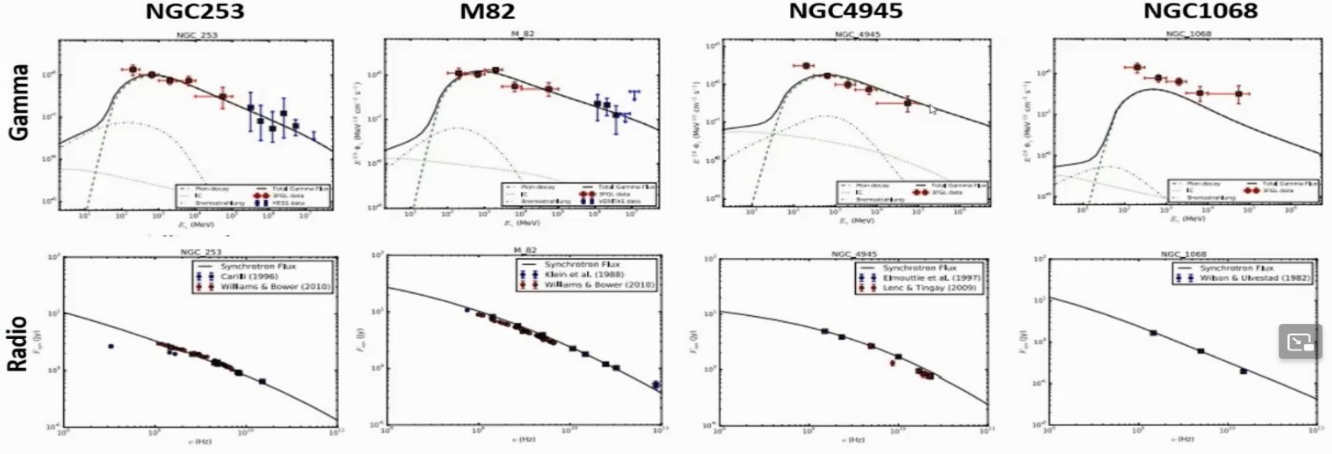
79+-20 excess neutrinos,
4.2σ in catalog search





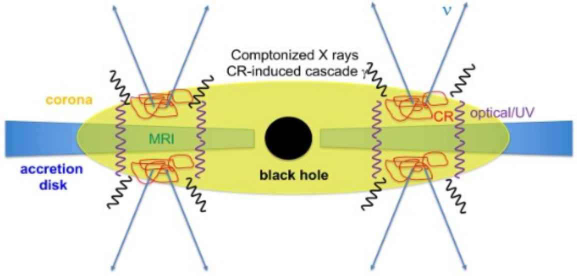
emission consistent with being steady

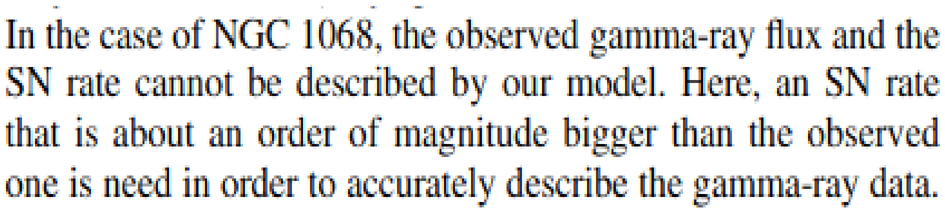
SBG γ emission from radio inferred e & p



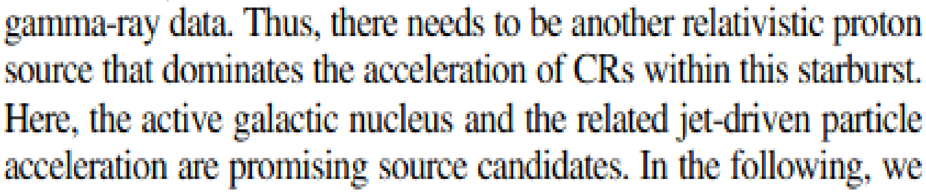
Eichmann & JBT, ApJ (2016)

falls short for NGC 1068
extra emission from corona?



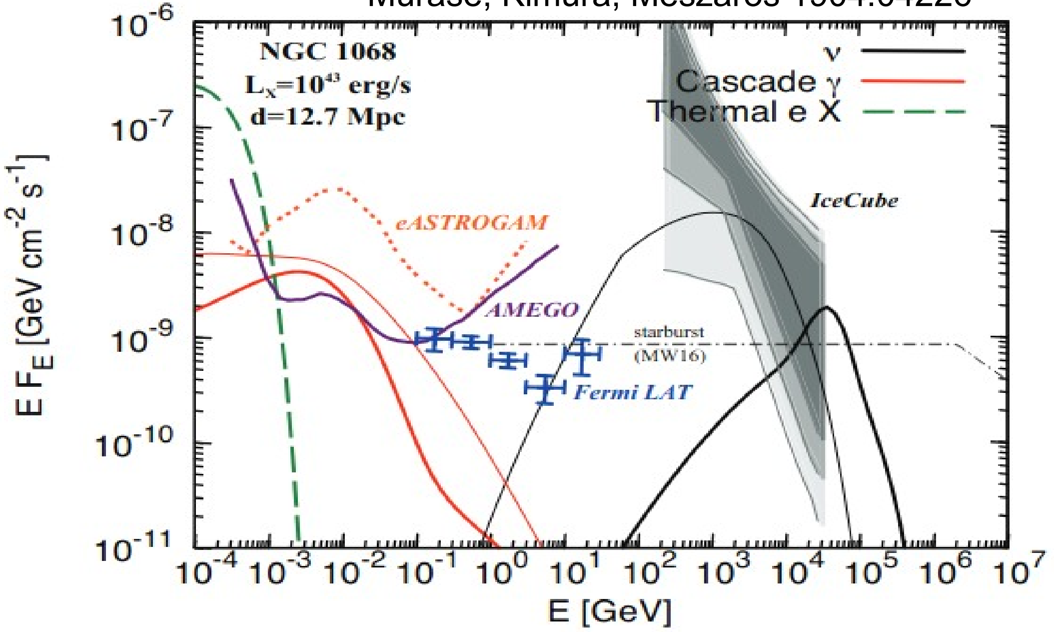


In the case of NGC 1068, the observed gamma-ray flux and the SN rate cannot be described by our model. Here, an SN rate that is about an order of magnitude bigger than the observed one is need in order to accurately describe the gamma-ray data.



gamma-ray data. Thus, there needs to be another relativistic proton source that dominates the acceleration of CRs within this starburst. Here, the active galactic nucleus and the related jet-driven particle acceleration are promising source candidates. In the following, we

Murase, Kimura, Meszaros 1904.04226

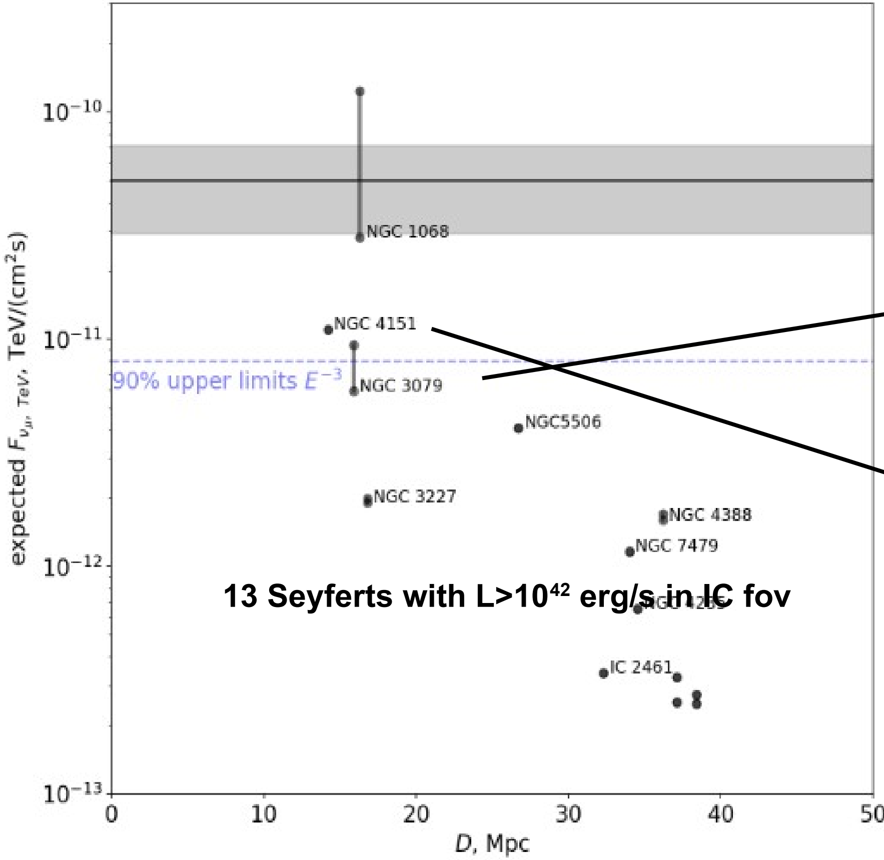


Are all Seyfert TeV neutrino emitters?

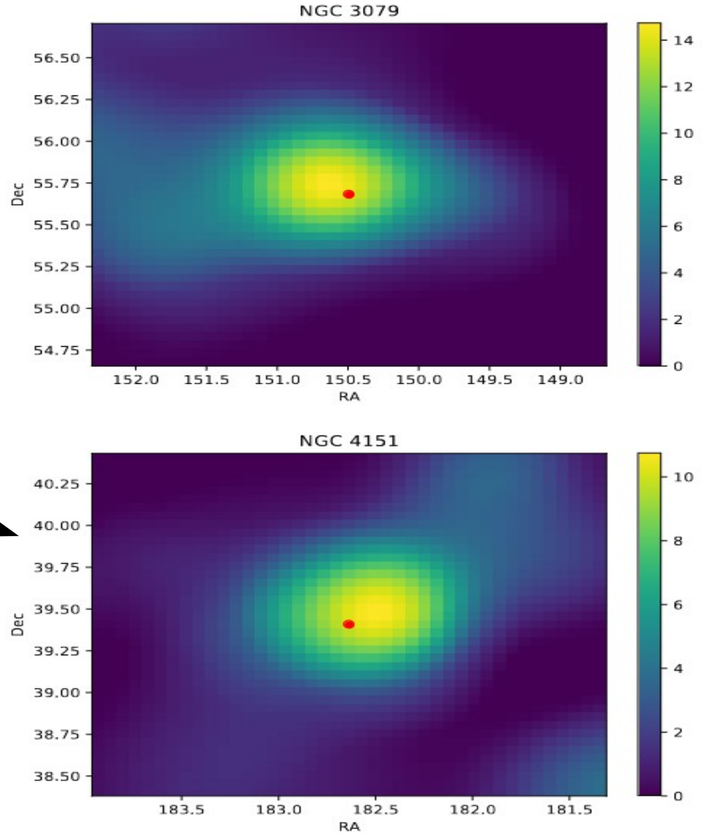
Neronov, Savchenko, Semikoz, 2306.09018

neutrino flux expected from observed Xrays

observed in IceCube muon tracks



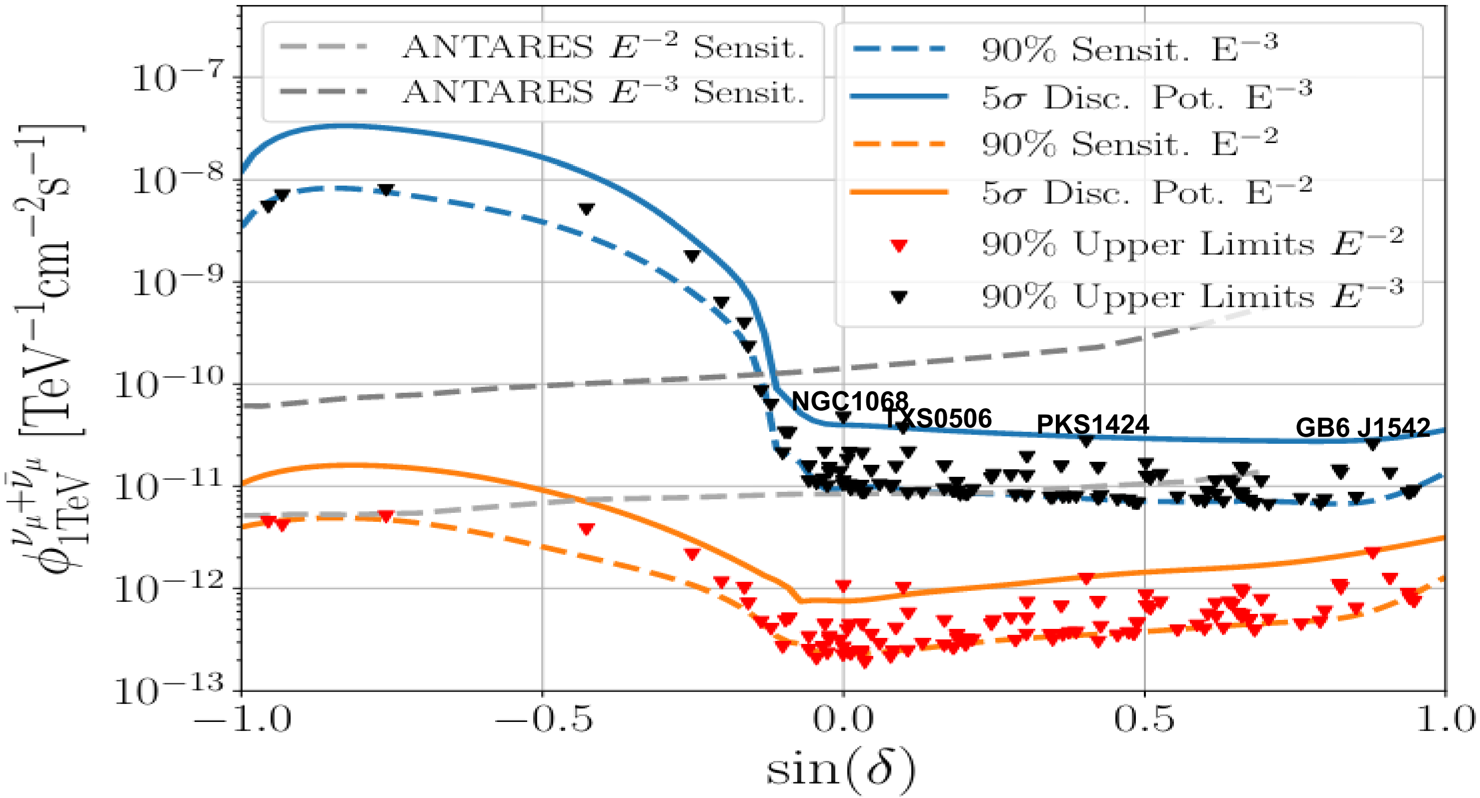
13 Seyferts with L>10^{42} erg/s in IC fov



probably yes

FLUX BOUNDS FOR LIST OF 110 PRESELECTED GAMMA SOURCES

(from 4FGL: BLLac, FSRQ, starburst gal + few galactic sources from TeVCAT)



1910.08488

(1 Seyfert+3 blazars)

TXS 0506 blazar at 1.7Gpc distance, NGC 1068 Seyfert at ~14 Mpc
→ populations with very different luminosities and source densities

some hints of correlations with TDE? 2005.05340

there are also stringent bounds on contribution from GRBs (<1%)

2205.11410,
2302.05459

THE GLASHOW RESONANCE

Interaction of $\bar{\nu}_e$ with electrons in ice

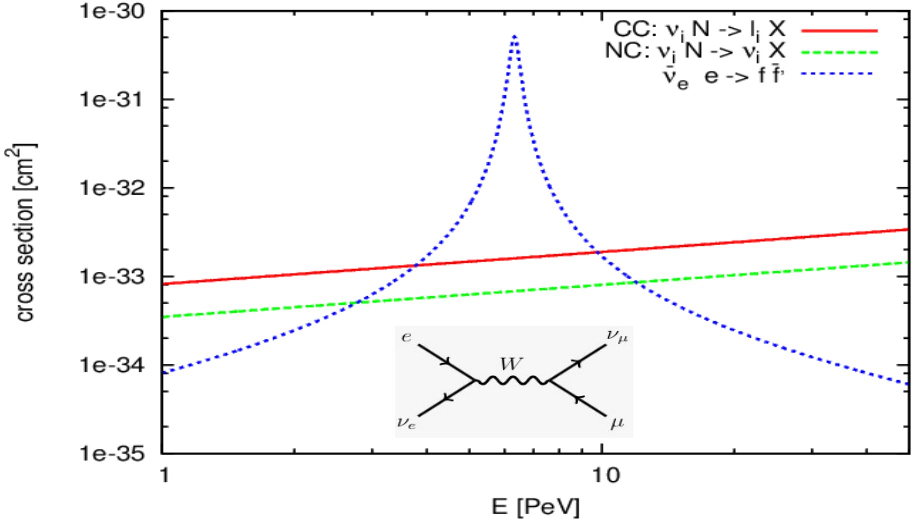
$$\bar{\nu}_e e \rightarrow W \rightarrow \bar{f}\, f'$$

resonant for:

$$E = \frac{M_W^2}{2 m_e} = 6.3\, PeV$$

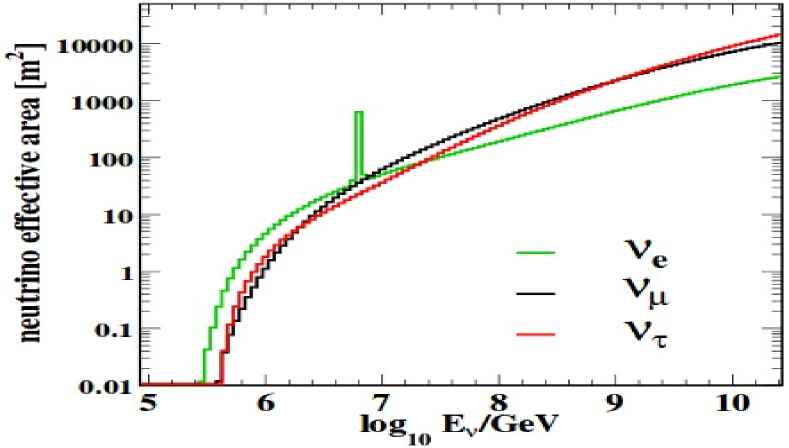
at the peak,

$$\sigma(\bar{\nu}_e e \rightarrow all) \simeq 350\, \sigma^{CC}(\nu_i N \rightarrow l_i X)$$

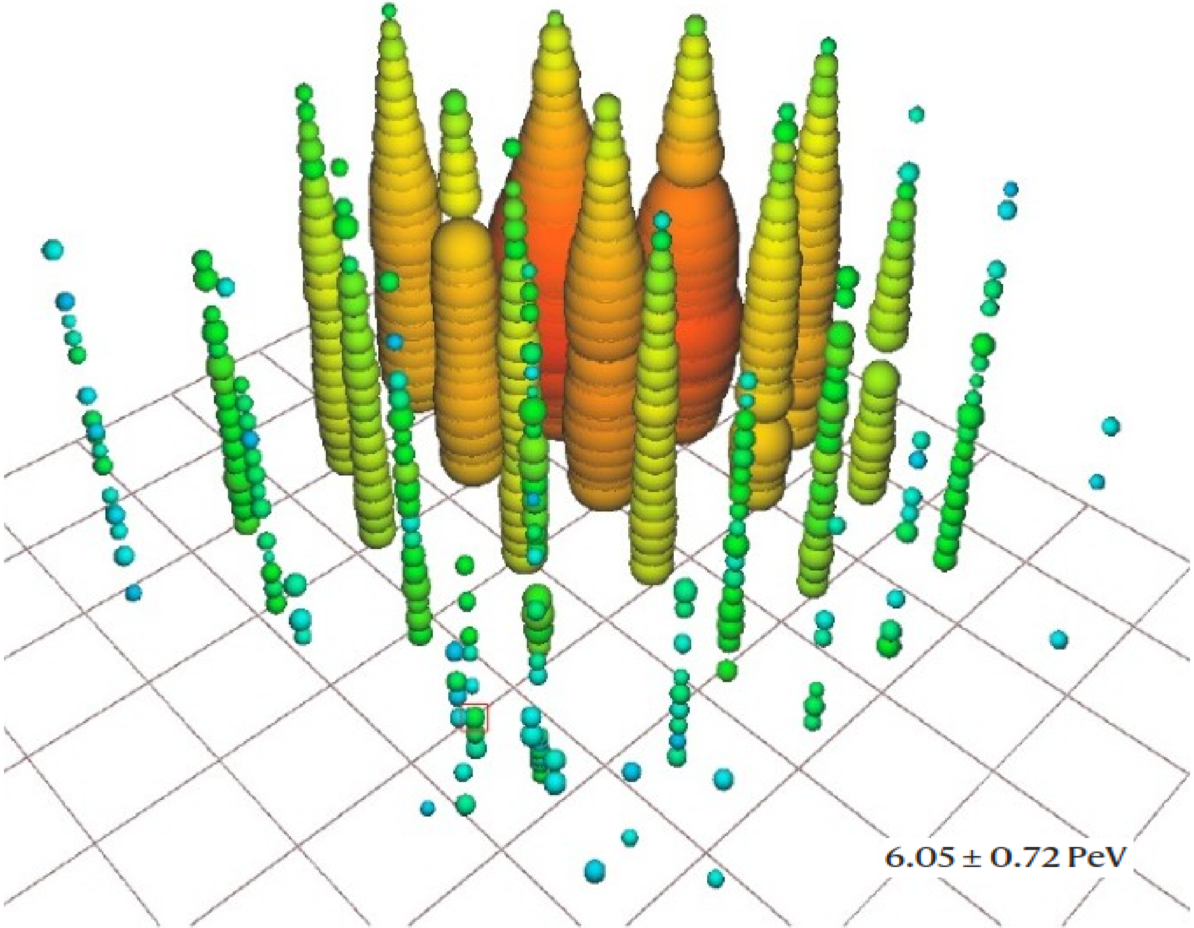


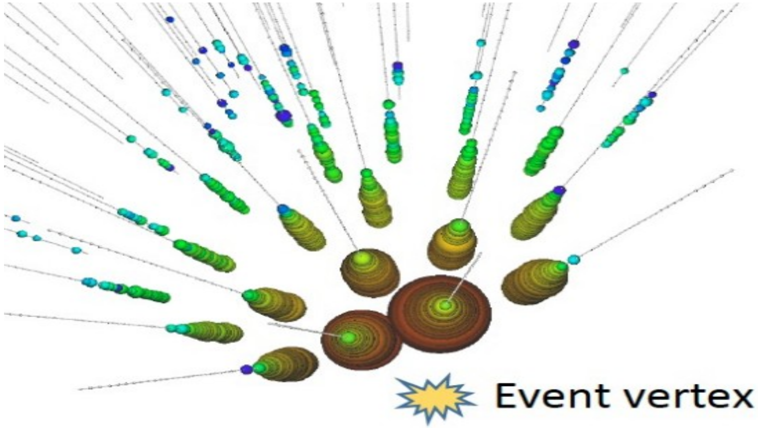
but peak narrow (0.17 PeV),
electron antineutrino flavor not dominant, $n_e/n_N = 5/9$

→ overall contribution to the IceCube rates from W resonance is similar to the CC+NC ones within 2.5 PeV of the resonance



one W-resonance candidate has been observed!

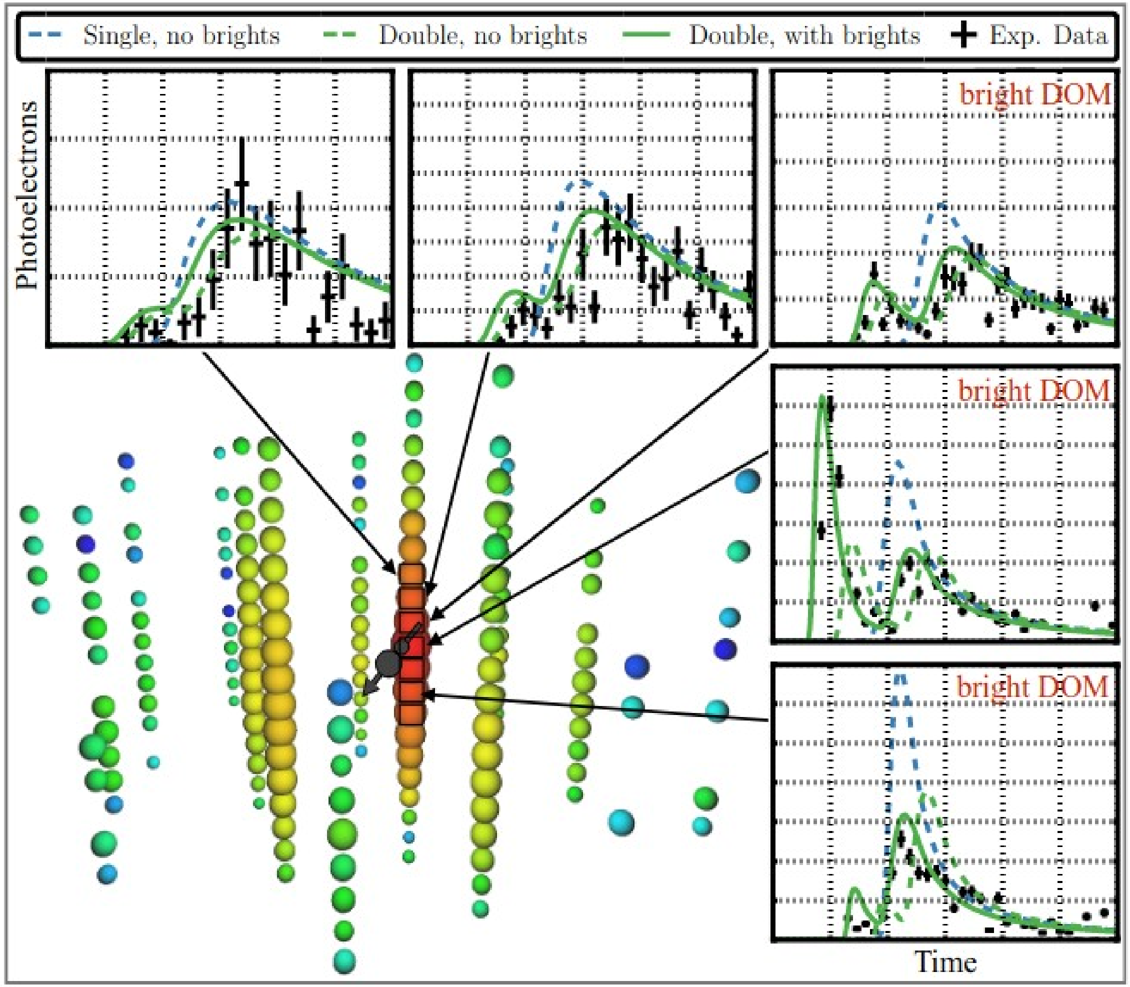




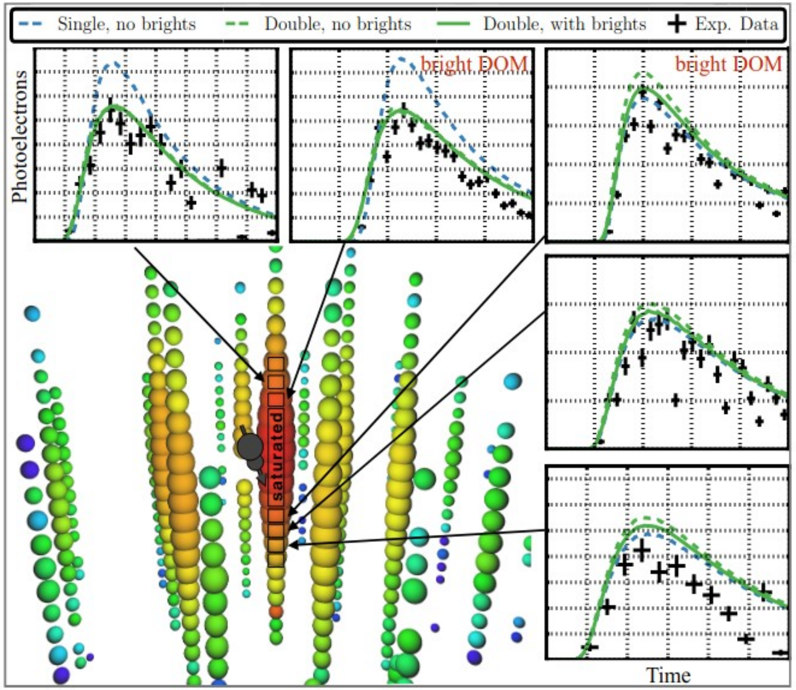
Nature 591 (2021) 7849

two tau neutrino candidates have been observed !

2011.03561

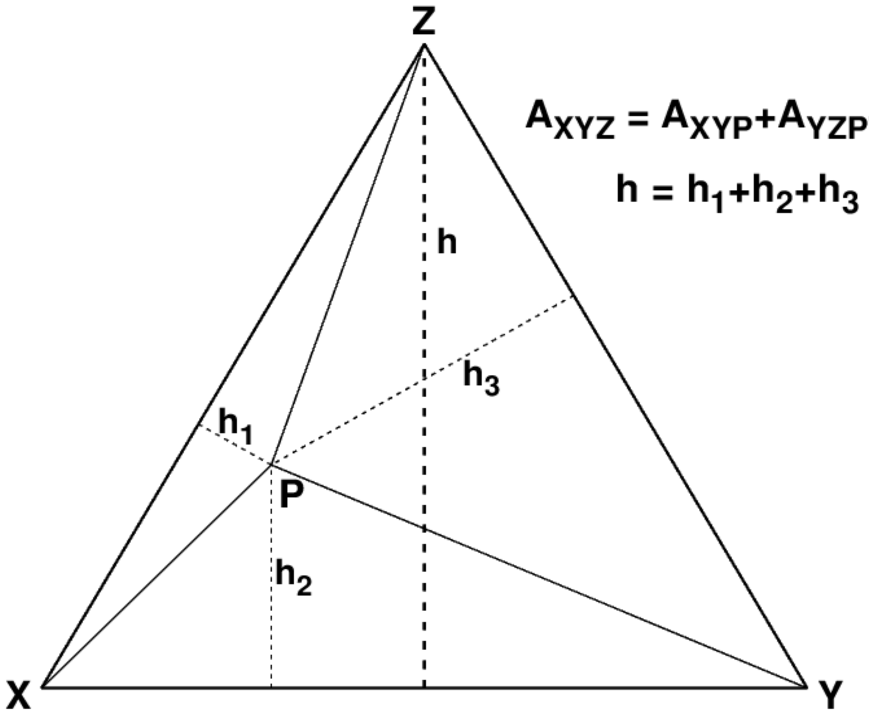


Event #1	Event #2
> 1.5 PeV	> 65 TeV



double pulse

FLAVOR TRIANGLE & VIVIANI'S THEOREM



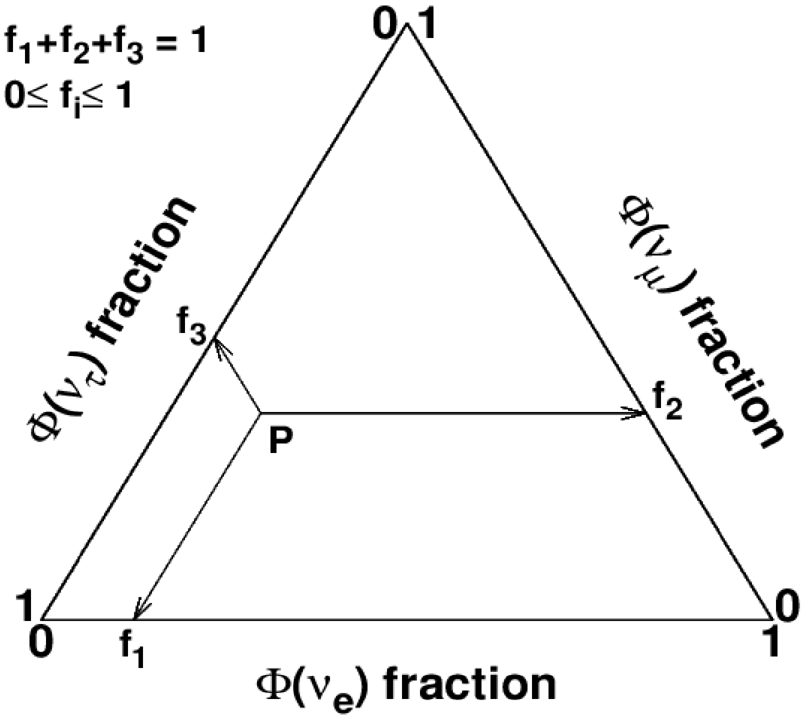
$A_{XYZ} = A_{XYP}+A_{YZP}+A_{ZXP}$

$h = h_1+h_2+h_3$

$f_i = h_i/h$

$f_1+f_2+f_3 = 1$

$0 \leq f_i \leq 1$



Flavor oscillations of astrophysical neutrinos

Incoherent flavor conversions

(Pakvasa et al 2008)

$$P_{\alpha\beta}=\sum_i |U_{\alpha i}|^2 |U_{\beta i}|^2$$

(after traveling from cosmological distances oscillations get averaged

$$<\sin^2(\Delta m^2)x/4E)>\simeq 1/2$$

what arrives is an incoherent superposition of mass eigenstates

π^--decays: $(\nu_e:\nu_\mu:\nu_\tau)=(1:1:0)\rightarrow 2\times(0.40:0.31:0.29)$

$(\bar{\nu}_e:\bar{\nu}_\mu:\bar{\nu}_\tau)=(0:1:0)\rightarrow(0.24:0.39:0.37)$

[similarly for π^+ **decays]**

(IceCube measures neutrinos+antineutrinos)

$\nu+\bar{\nu}\rightarrow(0.335:0.339:0.326)$

μ dumps: $(\nu_e:\nu_\mu:\nu_\tau)=(0:1:0)\rightarrow(0.24:0.39:0.37)$

[if μ get damped by synchrotron emission before decay]

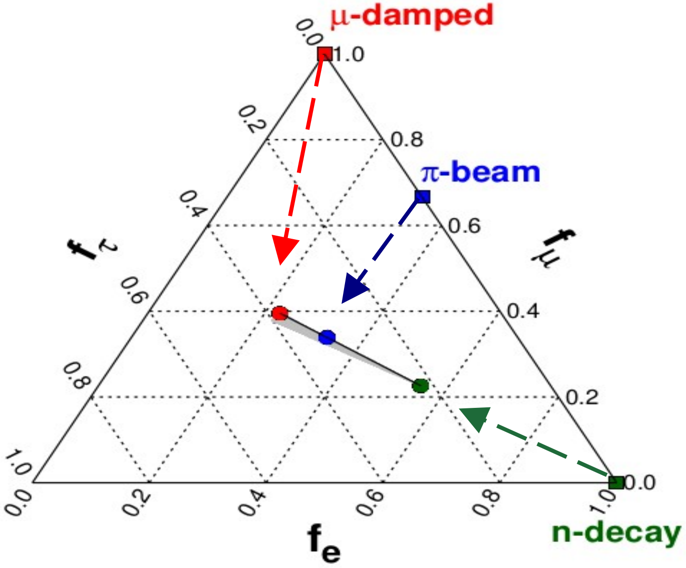
(Kashti&Waxman 05)

n-decays: $(\nu_e:\nu_\mu:\nu_\tau)=(0:0:0)\rightarrow(0:0:0)$

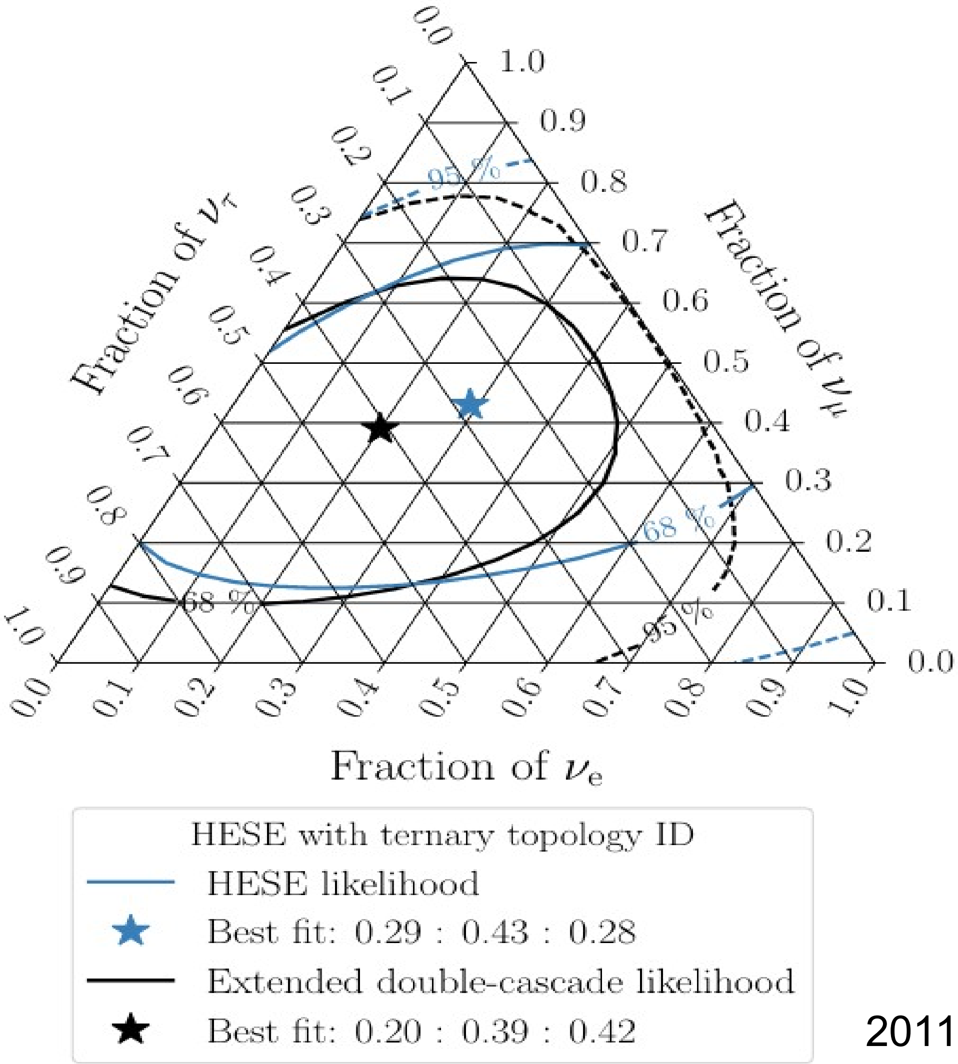
$(\bar{\nu}_e:\bar{\nu}_\mu:\bar{\nu}_\tau)=(1:0:0)\rightarrow(0.55:0.24:0.21)$

(strong nuclear photodisintegrations)

(for NH)



Results from IceCube

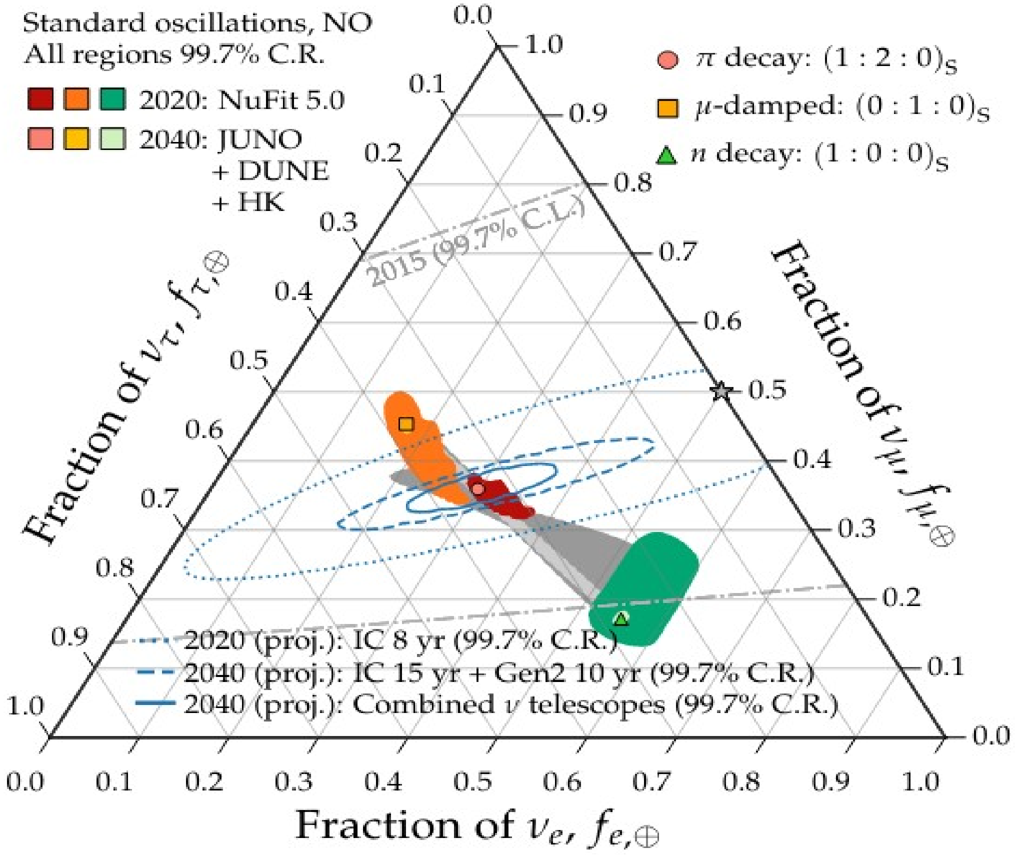


cascade / track ratio

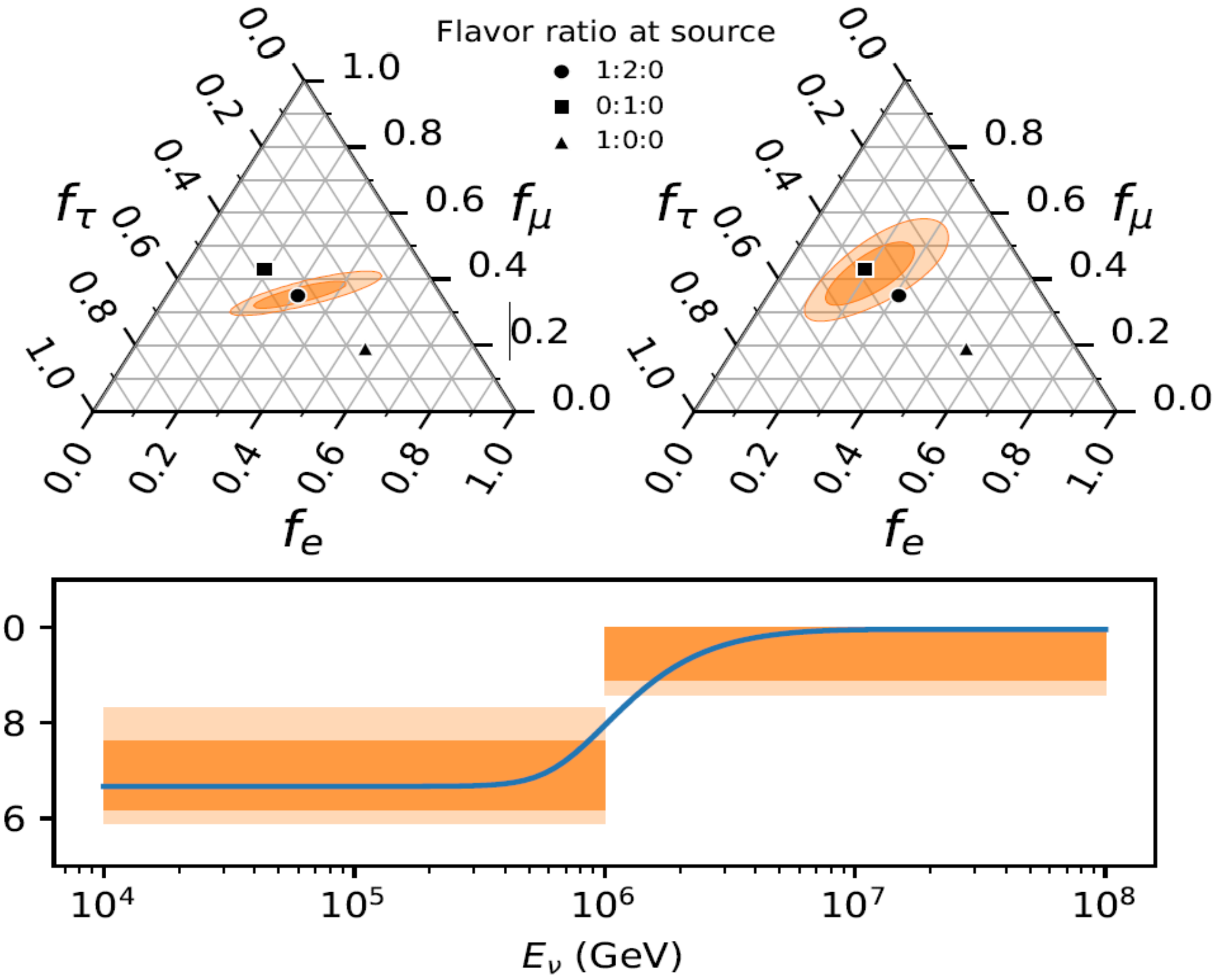
tau neutrinos, ...

2011.03561

IN 20 YEARS FROM NOW...



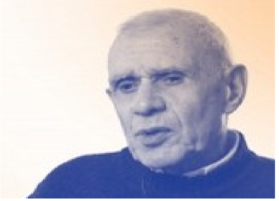
Song et al. 2012.12893



transition to muon damped sources observable with Gen2

Ultra-high energy neutrinos from interactions with CMB

(Berezinsky & Zatsepin)



UHECRs can be attenuated by background photons as they travel (cosmogenic ν) besides eventually interacting at the sources (astrophysical ν)

Threshold:

$$p\,\gamma \to \pi^+\, n$$

$$s=(p_p+p_\gamma)^2>(m_p+m_\pi)^2 \Rightarrow E_p>\frac{m_\pi(2m_p+m_\pi)}{4E_\gamma}\simeq\frac{70\,EeV}{E_\gamma/10^{-3}\,eV}$$

10^{20} eV for CMB photons,
10^{17} eV for optical photons

ν energies:

$$p\,\gamma \to \pi^+\, n$$

$$\pi^+\to\mu^+\,\nu_\mu\to e^+\,\bar{\nu}_\mu\,\nu_\mu\,\nu_e \longrightarrow E_{\bar{\nu}_\mu}\simeq E_{\nu_\mu}\simeq E_{\nu_e}\simeq E_\pi/4\simeq E_p/20$$

$$n\to p\,e\,\bar{\nu}_e \longrightarrow E_{\bar{\nu}_e}\simeq\frac{m_n-m_p-m_e}{2\,m_n}E_n\simeq 4\times10^{-4}E_n$$

Redshift (production at 0<z<4) :

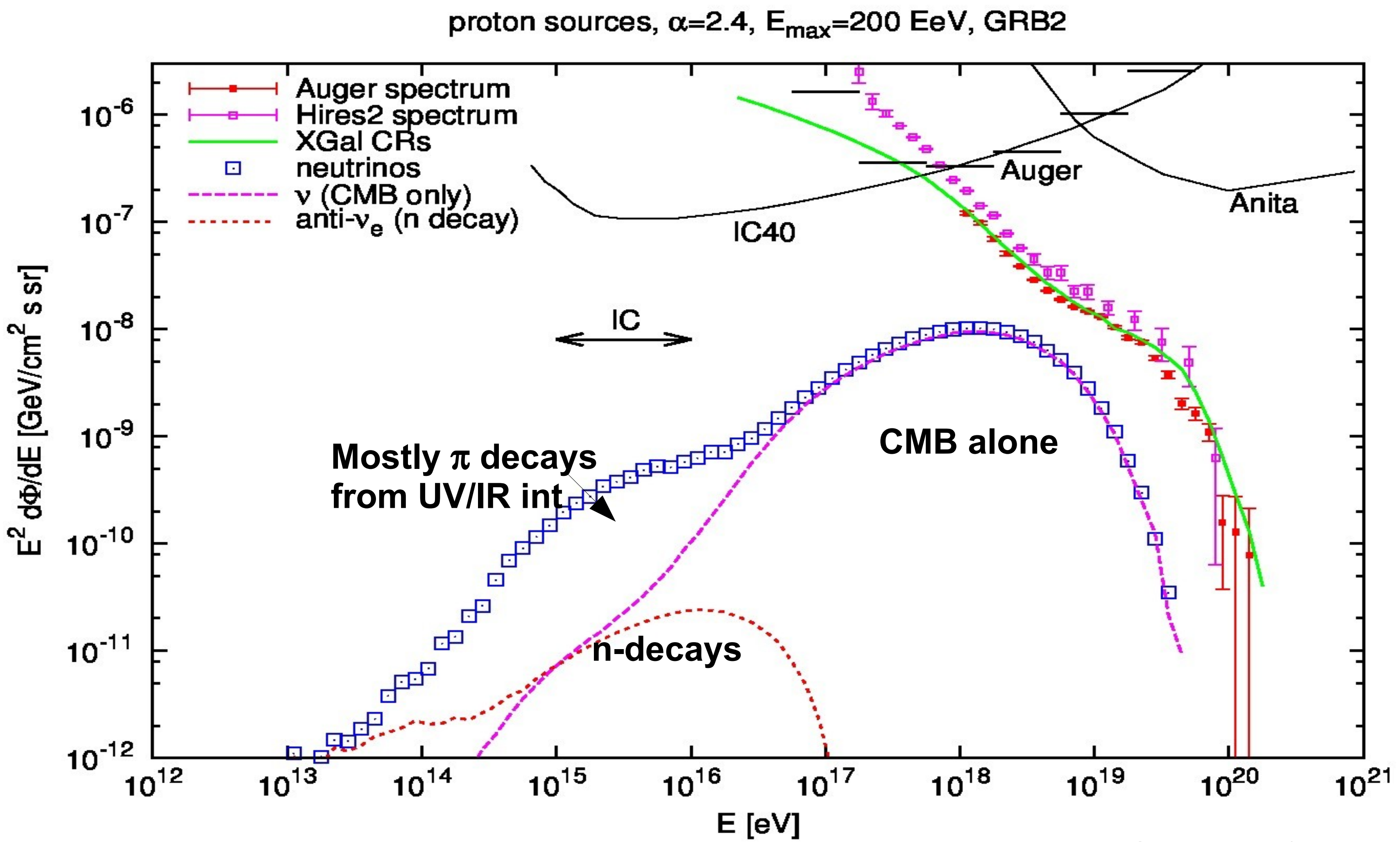
T_{CMB}=(1+z) 2.7 K → redshifted threshold

Redshifted ν energy $E_\nu^{\pi-dec}\simeq\frac{E_p}{20(1+z)}$

$$E_\nu^{\pi-dec}\simeq\frac{5\,EeV}{(1+z)(E_\gamma/10^{-3}\,eV)}$$

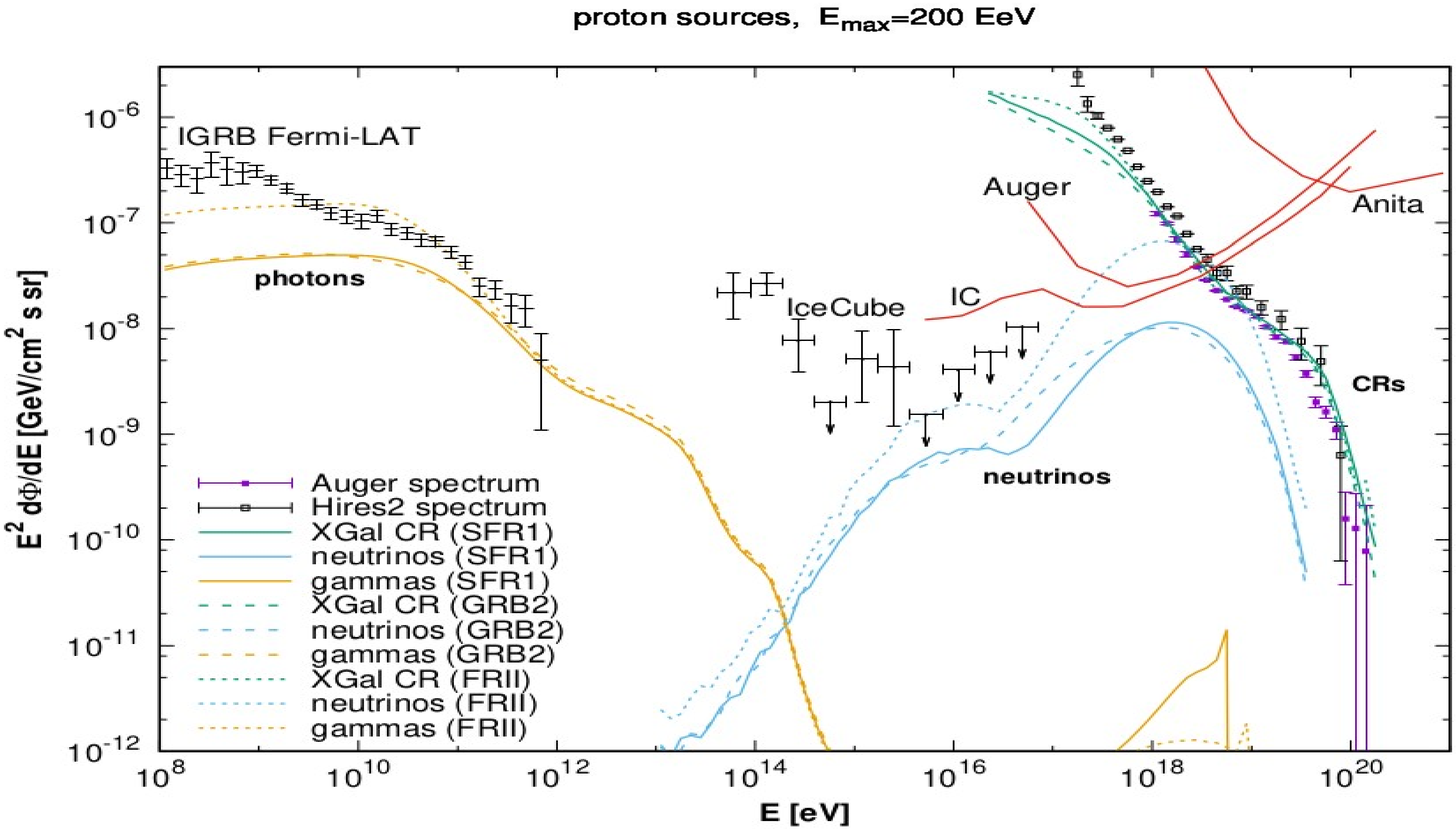
EeV ν from interactions with CMB photons
PeV ν from interactions with UV/O/IR photons

Cosmogenic neutrinos from UHECR proton sources



ER, Sigl, vVliet & Mollerach 1209.4033

ν and γ for different CR source evolutions & cascade bound

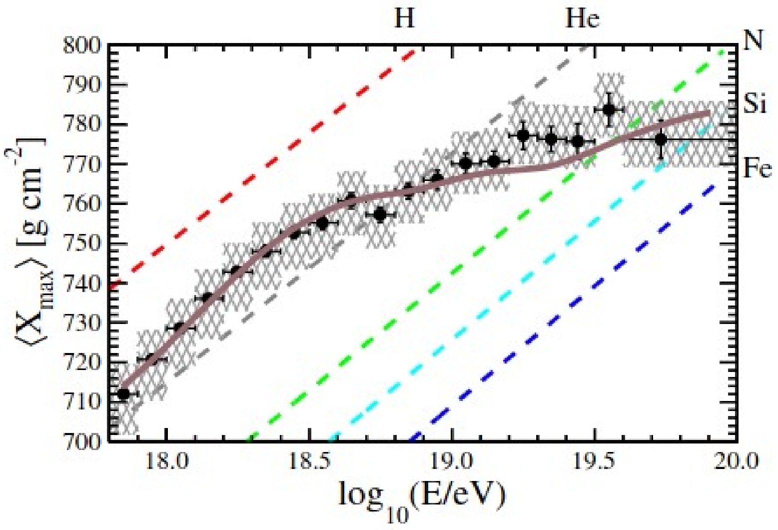


very strong evolution in tension with γ flux

ER, Sigl, vVliet & Mollerach 1209.4033

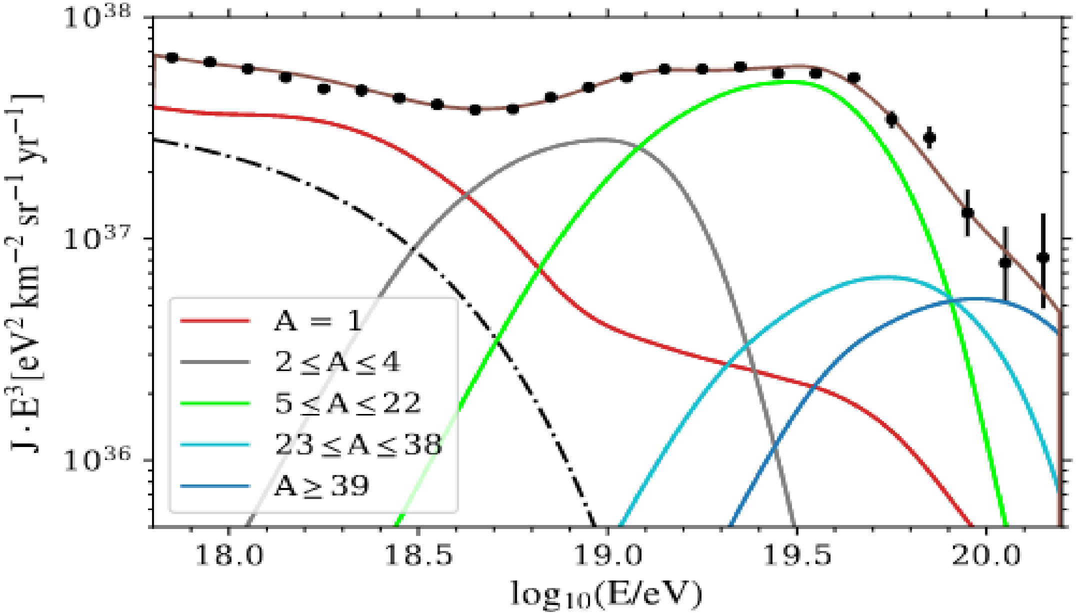
but the Auger Observatory established that above the ankle (>5 EeV) CRs become increasingly heavier

2211.02857



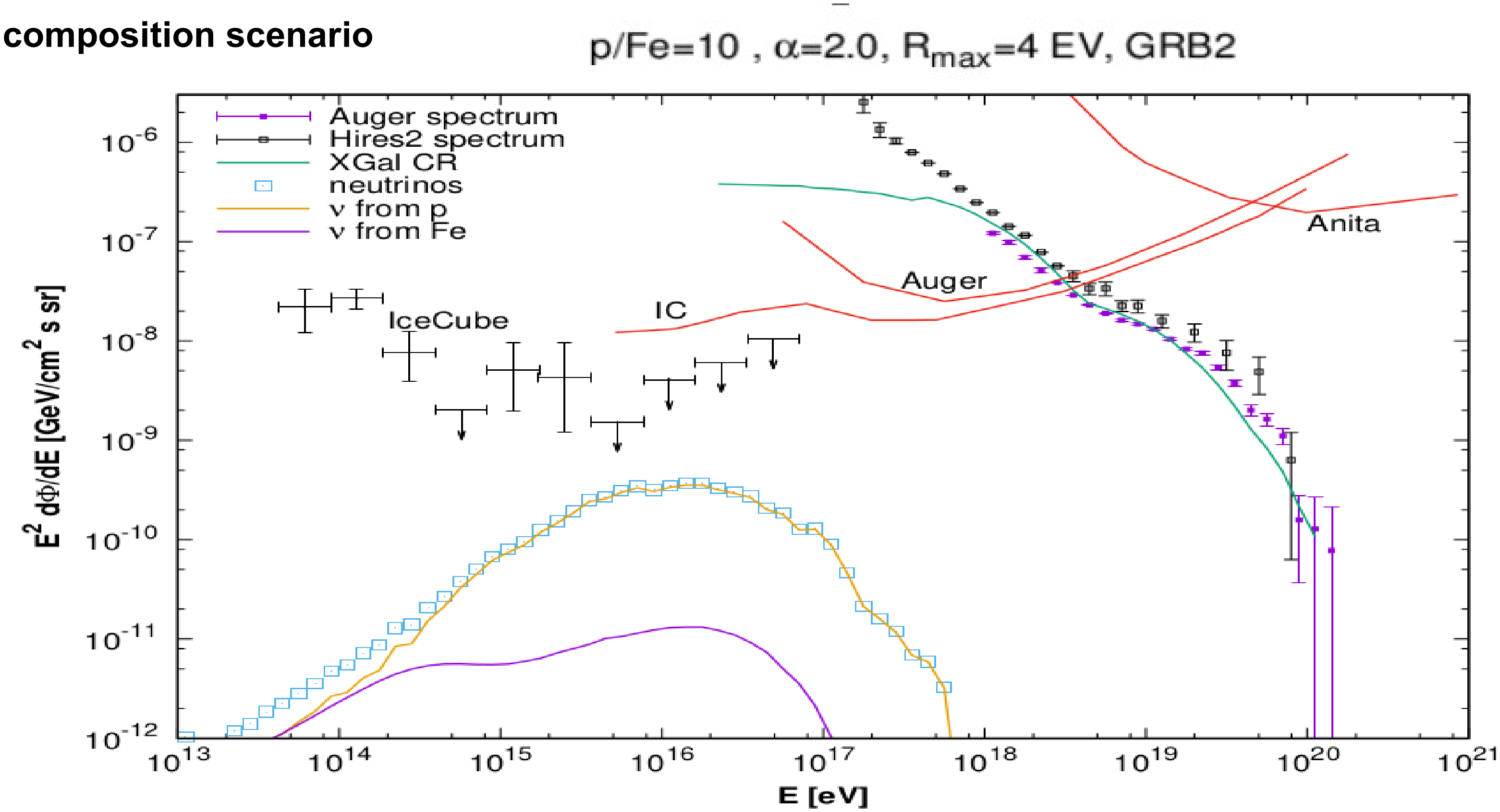
depth of shower maxima vs. E

modeled composition



scenario with mixed composition with low rigidity cutoff (E/Z< 4 EeV)

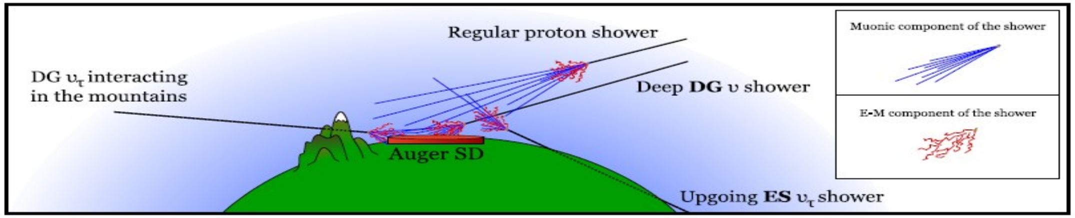
mixed composition scenario



p component below ankle interacting with EBL leads to PeV ν fluxes (~10% of IC)

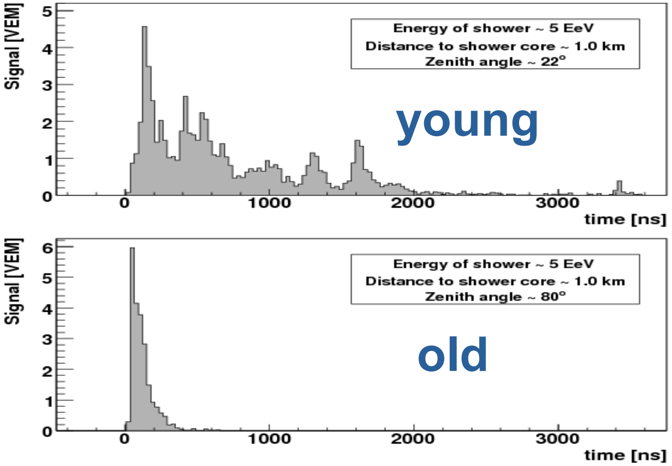
due to low cutoff no pions from CMB → no EeV ν (disappointing model)

NEUTRINO DETECTION IN AUGER

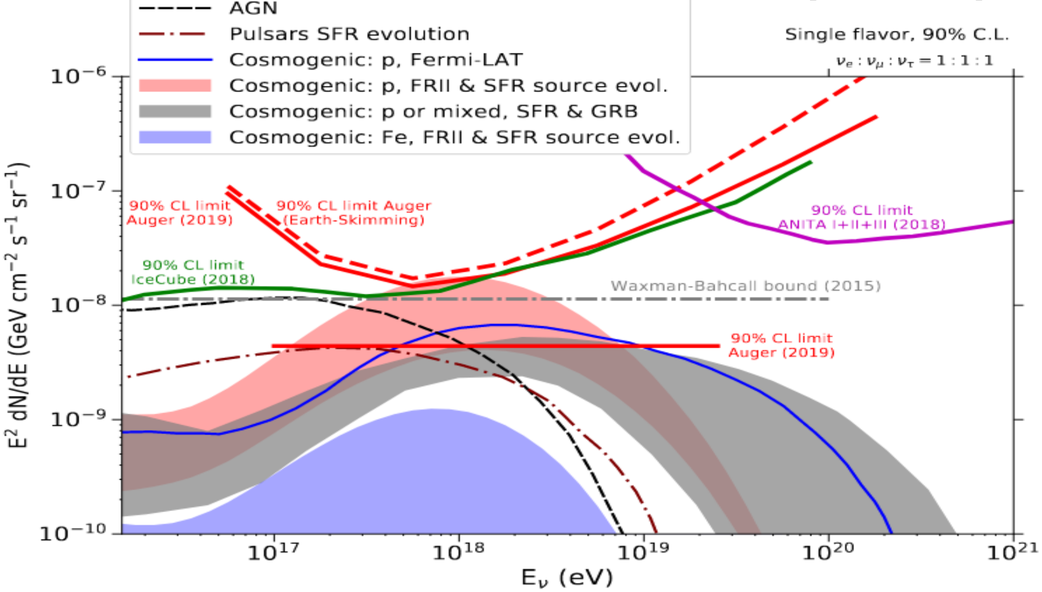


Only neutrinos can produce young horizontal showers

signal vs. time in WCD



[ICRC 2019]

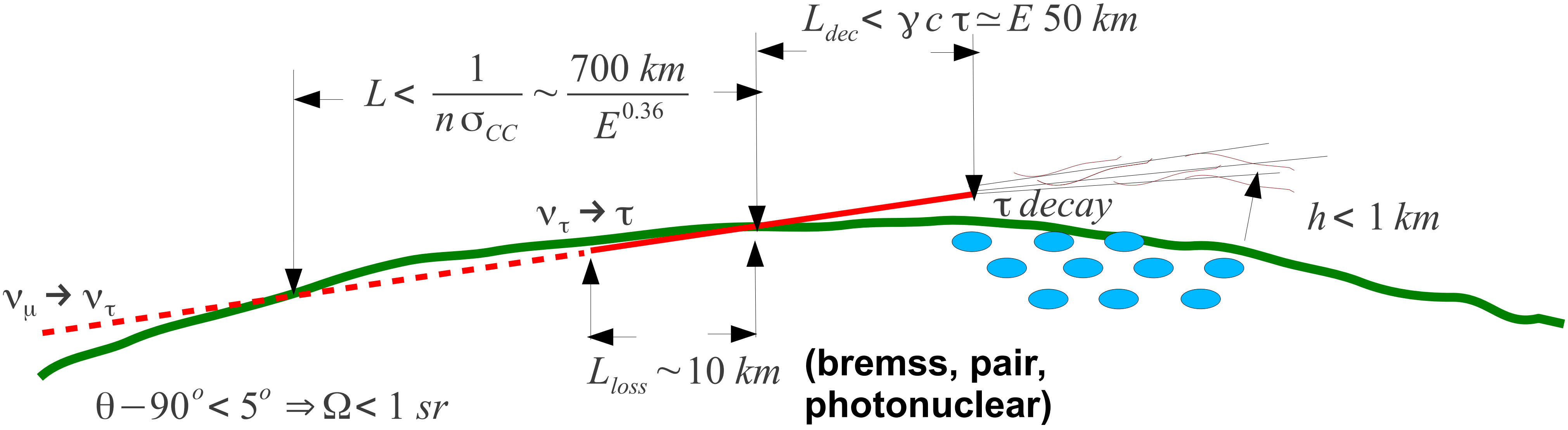


0 events observed → bounds scale linearly with exposure

Up-going Earth-skimming ν_τ showers

Fargion 2000,
Bertou et al '01
Feng et al. '02

$$\sigma_{CC} \simeq 10^{-32}\, cm^2\, E^{0.36} \qquad (E\,[EeV])$$



$$L_{dec} < \gamma c \tau \simeq E\, 50\, km$$

$$L < \frac{1}{n\sigma_{CC}} \sim \frac{700\, km}{E^{0.36}}$$

$\nu_\tau \rightarrow \tau$

τ decay

$h < 1\, km$

$\nu_\mu \rightarrow \nu_\tau$

$L_{loss} \sim 10\, km$ **(bremss, pair, photonuclear)**

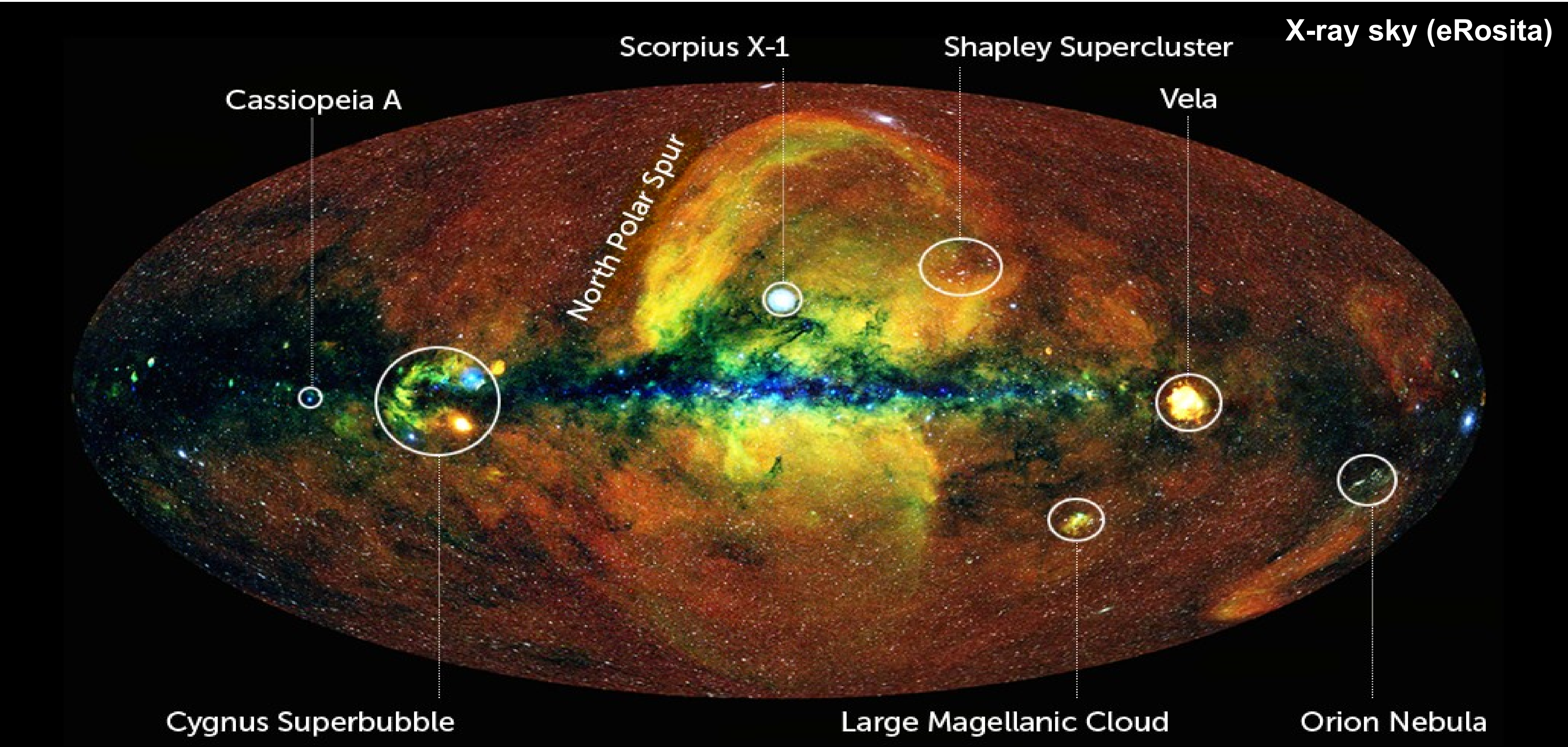
$\theta - 90^o < 5^o \Rightarrow \Omega < 1\, sr$

probability of interacting in the last 10 km ~ 0.01

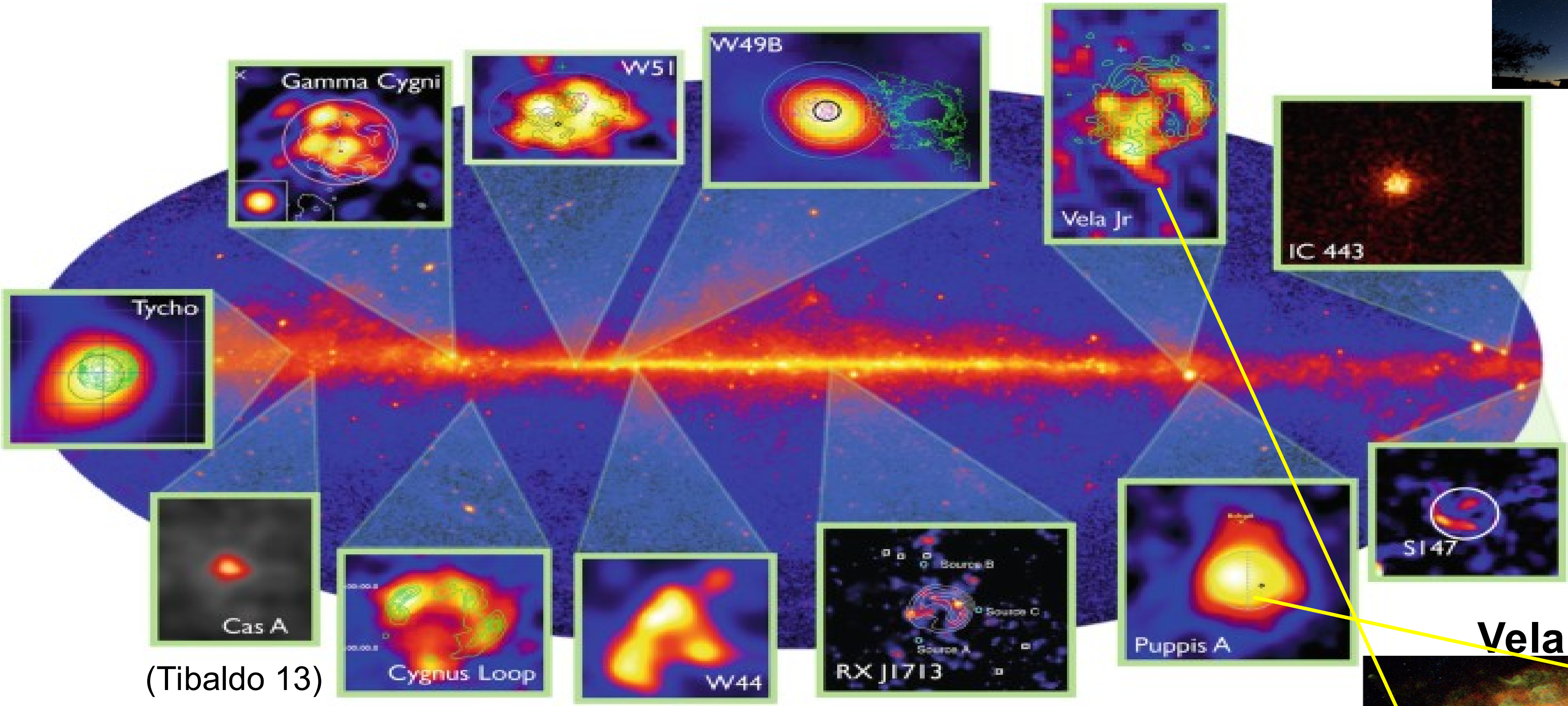
→ effective exposure ~ 0.1 km^2 sr (while ~ 10^4 km^2 sr for UHECR)

(bounds also include some downgoing θ > 70^o)

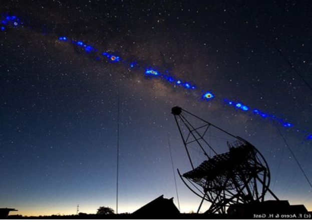
GALACTIC SOURCES



Galactic TeV γ sources



(Tibaldo 13)

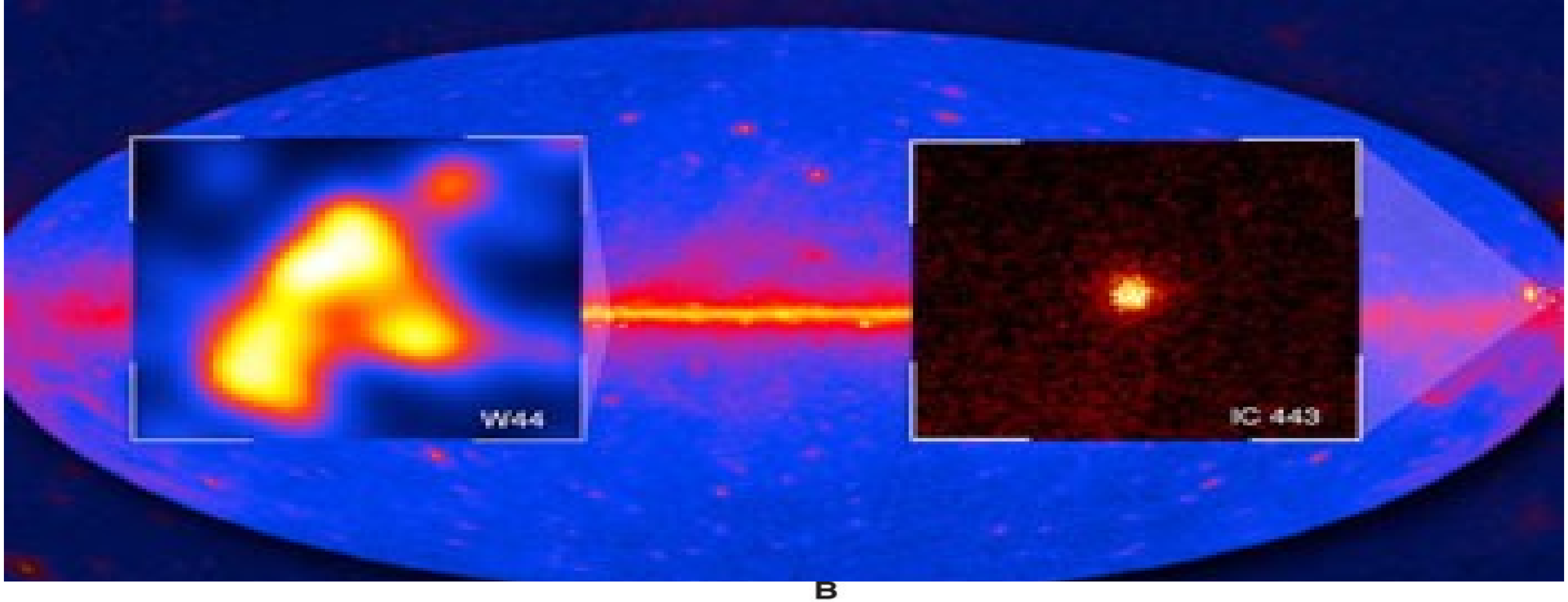


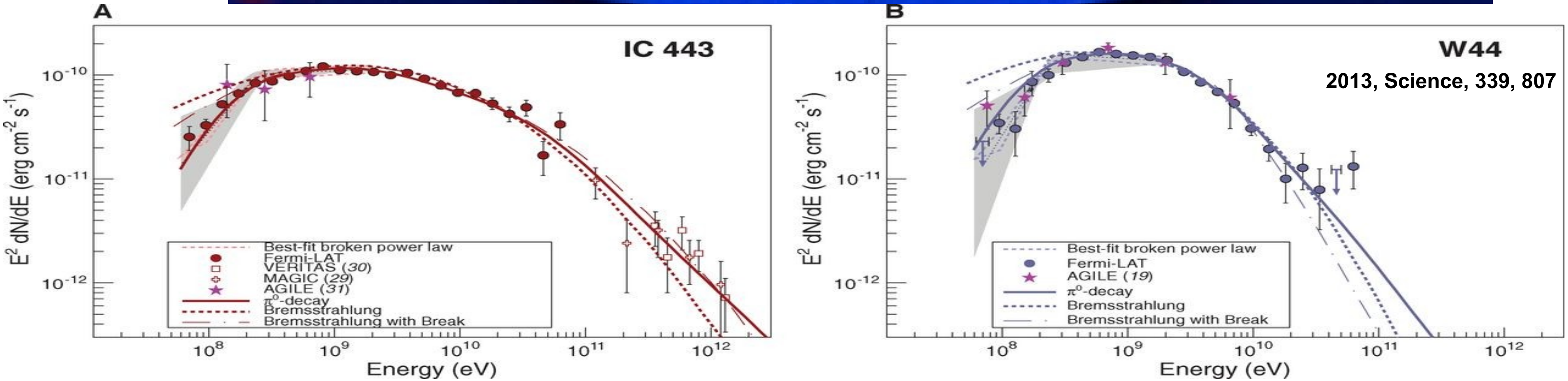
IACT

Vela in X rays

A supernova remnant called Vela (center, reddish green) is one of the most prominent X-ray sources in the sky. The supernova exploded about 12,000 years ago, about 800 light-years away, and overlaps with two other known supernova remnants: Vela Junior (faint purple ring at bottom left) and Puppis A (blue cloud at top right). All three explosions left behind neutron stars, but only the stars at the centers of Vela and Vela Junior are visible to eROSITA.

several show evidence of pion bump → hadronic acceleration (Agile, Fermi)



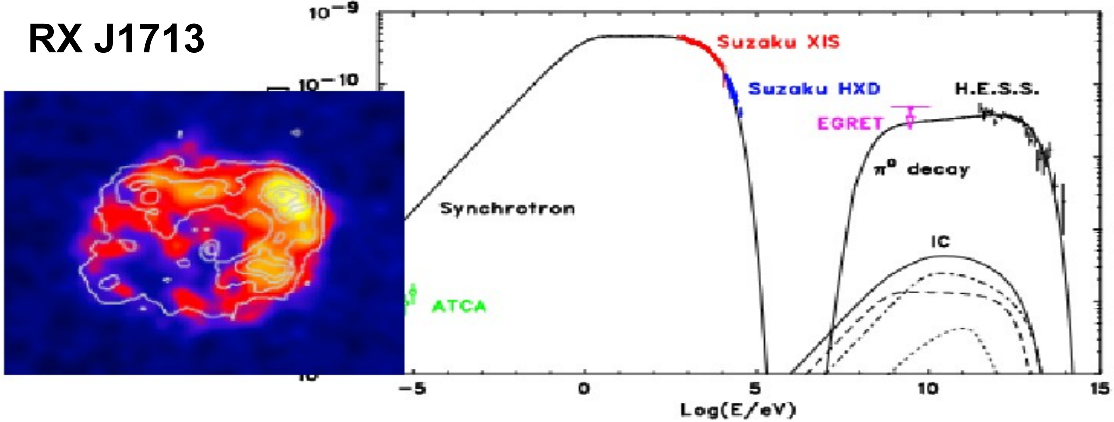


2013, Science, 339, 807

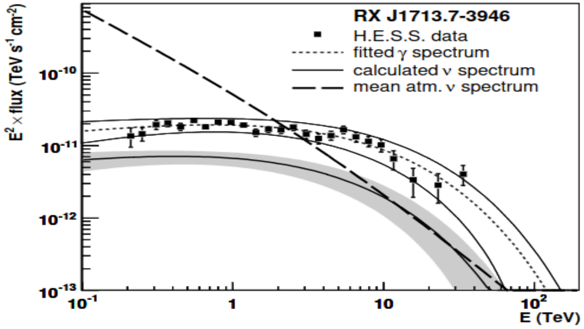
FERMI found SN remnants with clear signals of gammas from pion decays (low E supp.)
Proton acceleration in Supernovae to beyond 10 TeV proved, associated ν flux expected

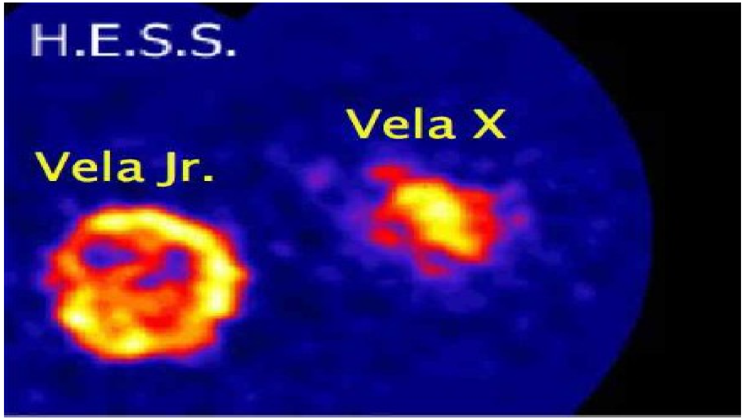
SNR in TeV γ (HESS), 1 kpc, 1600yr ?

RX J1713

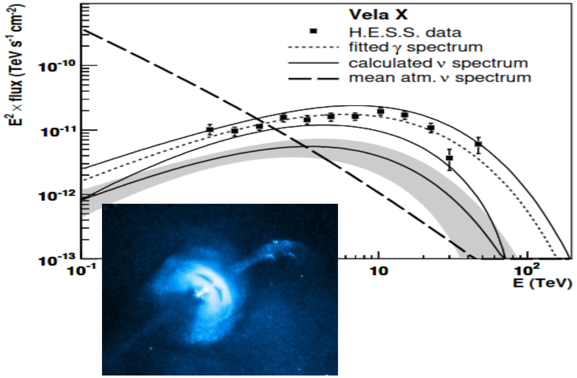


Kappes et al. 0607286



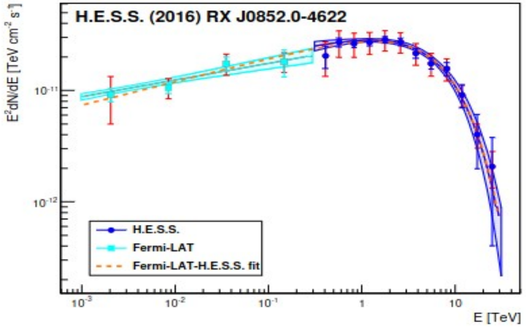


Vela X PWN



Vissani & Aharonian 1112.3911

Vela Jr SNR

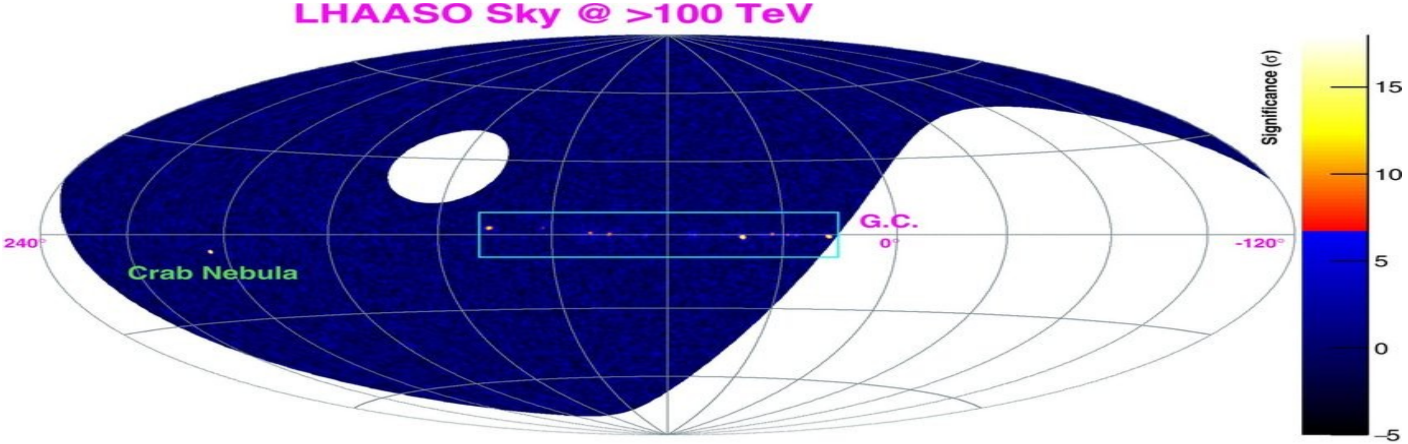


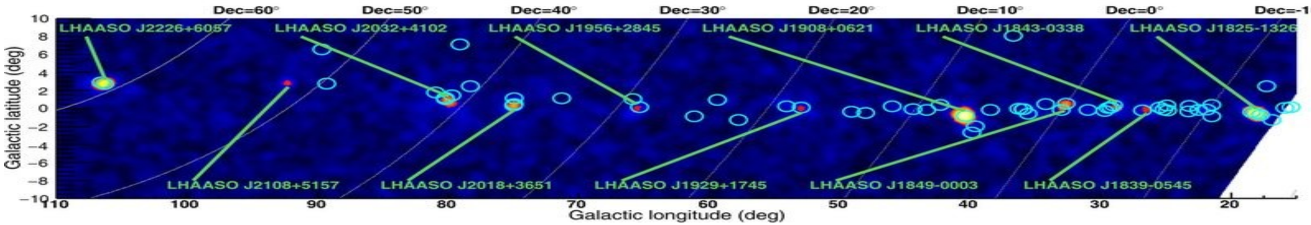
expect few events per km² yr above TeV if hadronic

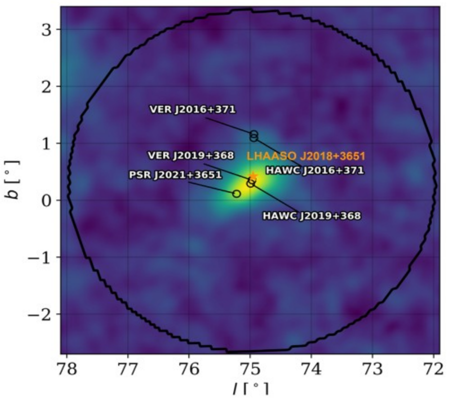
these sources are in southern hemisphere → good targets for KM3NeT
IceCube can see e.g. Cygnus region, Crab, CasA

Ultrahigh-energy photons up to 1.4 petaelectronvolts from 12 γ-ray Galactic sources

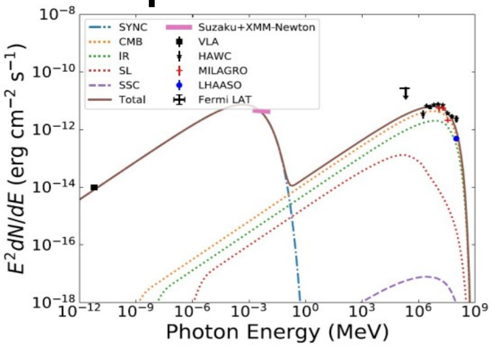
Nature 2021

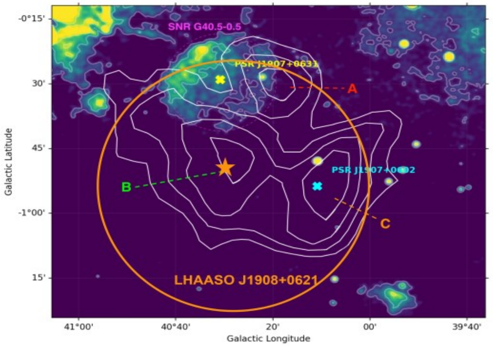




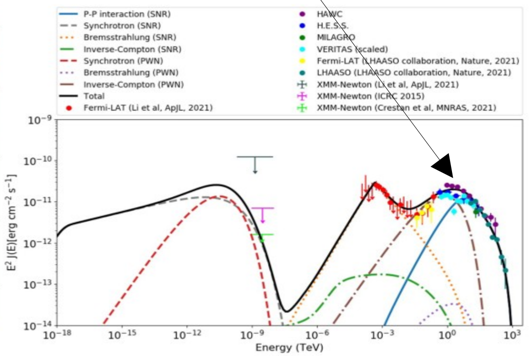


leptonic





hadronic

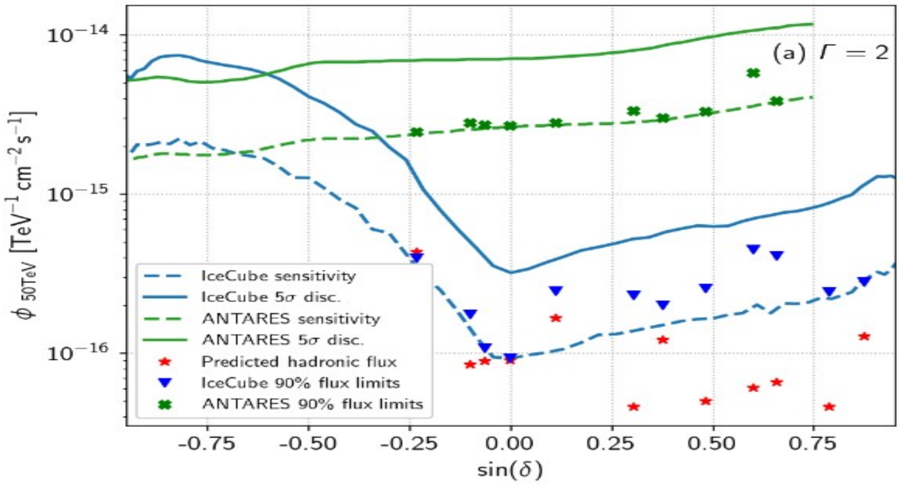


Searches for Neutrinos from LHAASO ultra-high-energy γ-ray sources using the IceCube Observatory

2211.14184

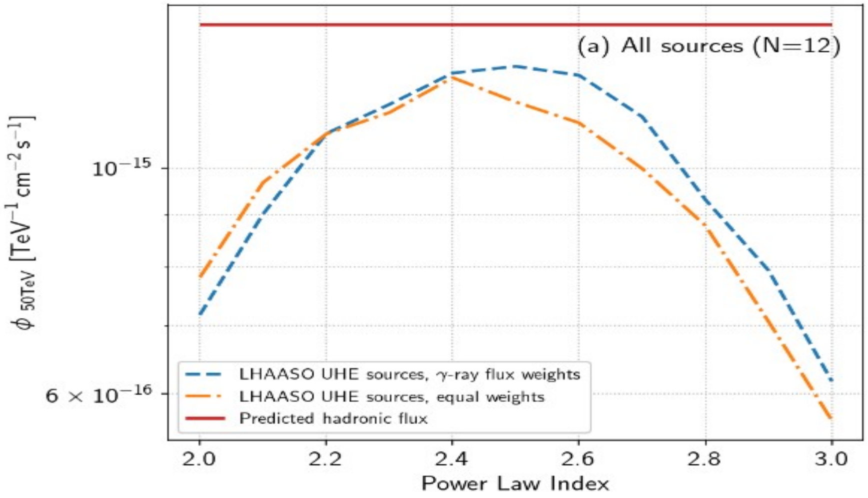
no excess observed → 90%CL bound on source fluxes

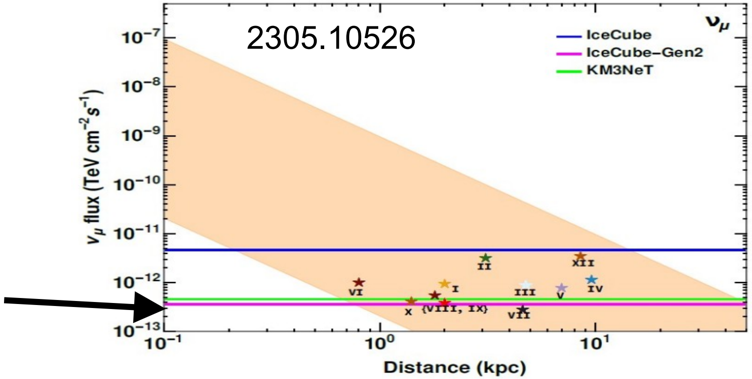
individual sources



$$\frac{dN_{\nu_\mu+\nu_{\bar{\mu}}}}{dE_\nu} = \phi_{90\%} \cdot \left(\frac{E_\nu}{50\mathrm{TeV}}\right)^{-2} \times 10^{-16}\ \mathrm{TeV}^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$$

stacked search



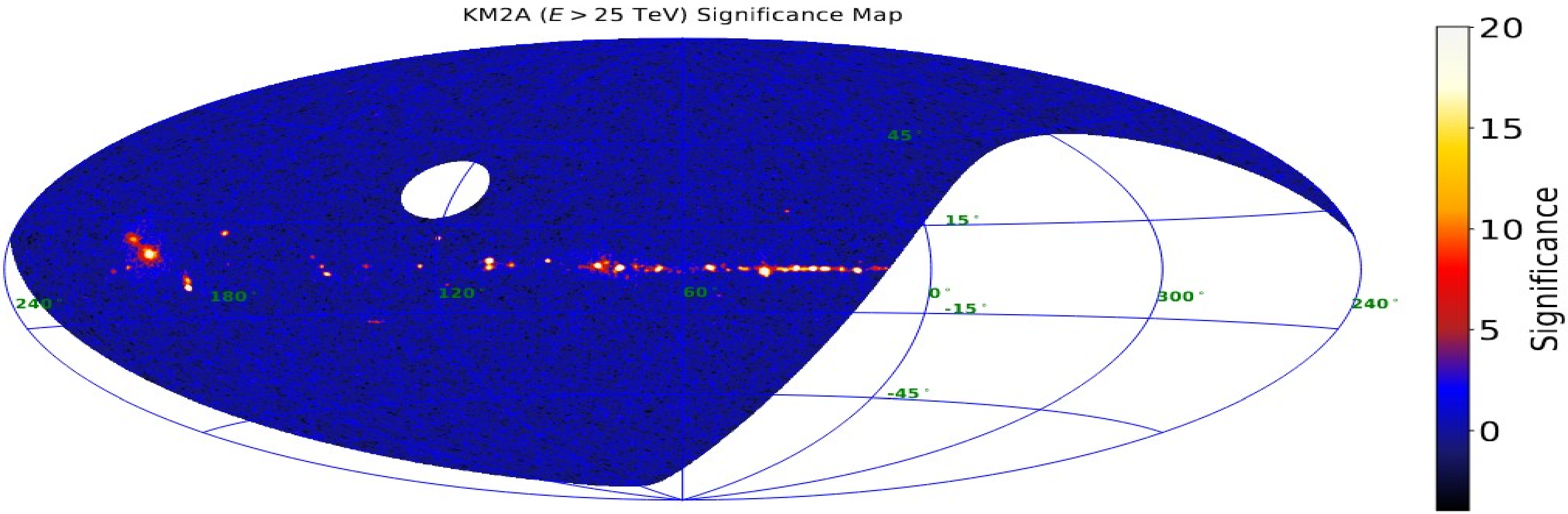

2305.10526

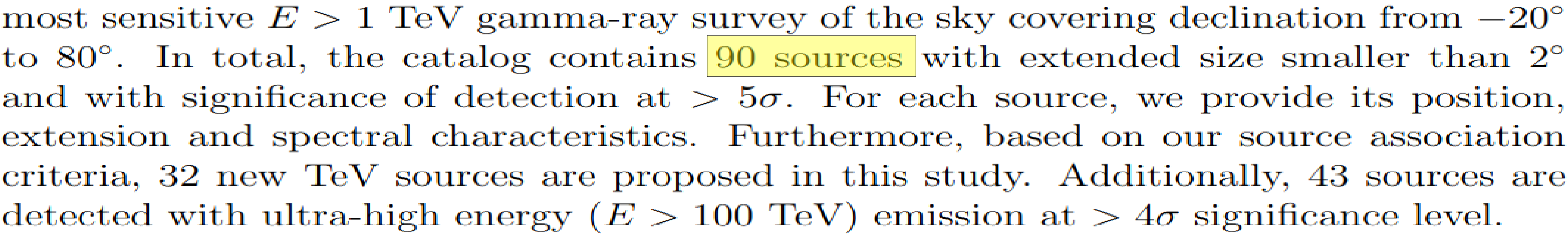
for Crab, hadronic contribution < 59% of total
LHAASO J2226+6057 < 47% ,
but for others expectations below bounds
→ need larger detectors & better angular resolution

UPDATE

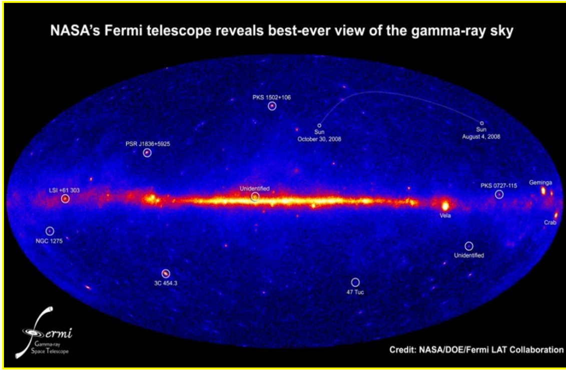
2305.17030

The First LHAASO Catalog of Gamma-Ray Sources

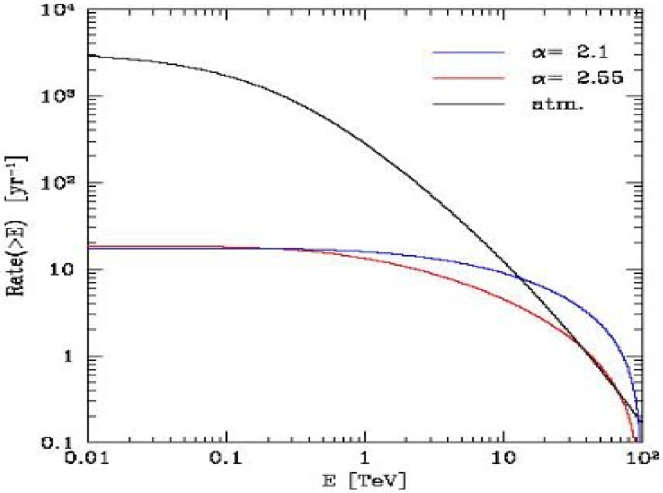



most sensitive $E > 1$ TeV gamma-ray survey of the sky covering declination from $-20°$ to $80°$. In total, the catalog contains 90 sources with extended size smaller than $2°$ and with significance of detection at $> 5\sigma$. For each source, we provide its position, extension and spectral characteristics. Furthermore, based on our source association criteria, 32 new TeV sources are proposed in this study. Additionally, 43 sources are detected with ultra-high energy ($E > 100$ TeV) emission at $> 4\sigma$ significance level.

diffuse neutrino flux from Galaxy



observed γ rays are from π^0 decays produced in CR - gas interactions
→ expect neutrinos from associated charged pion decays

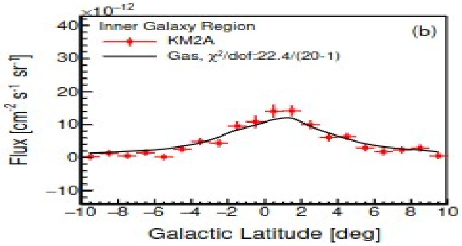


KM3NeT sensitivity

(depends on slope of CR spectrum)

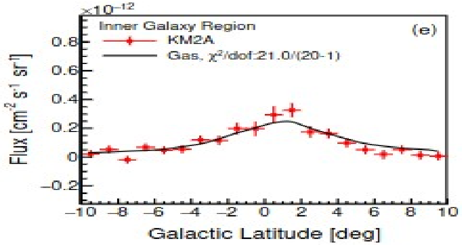
should be observable in the future with muon tracks

a 2σ excess observed with Antares



10-63 TeV

recently LHAASO observed difuse γ emission from the Galaxy in 10 TeV – 1 PeV range 2305.05372

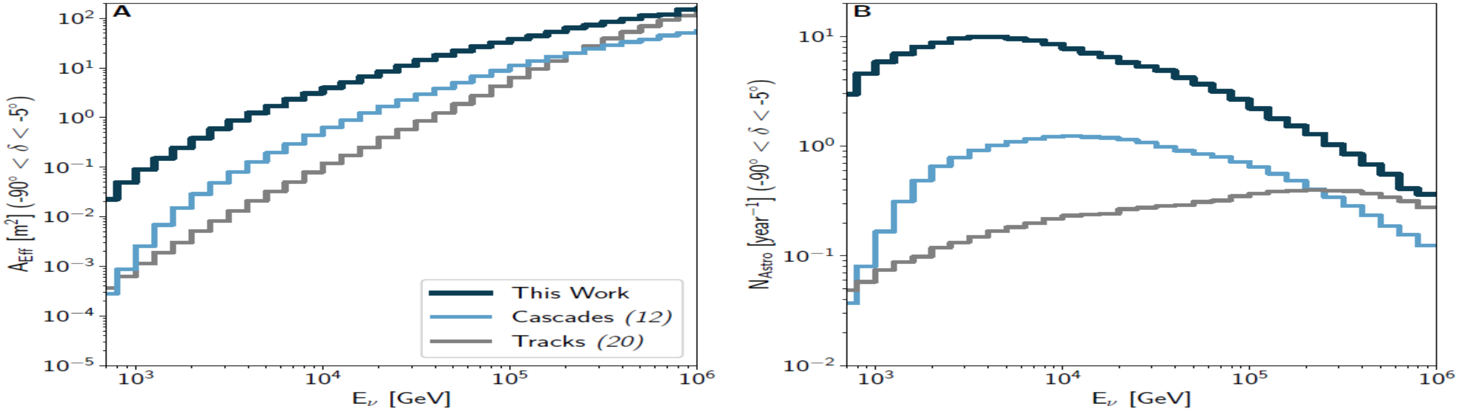


63-1000 TeV

see also Tibet AS array result 2104.05181

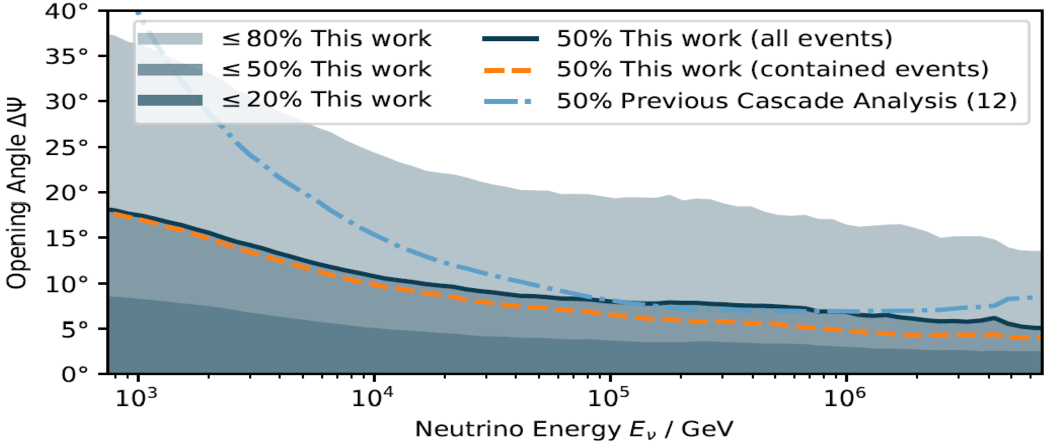
last week's results from IceCube (Science)

new analysis using cascades & improved reconstruction with machine learning



30x more events

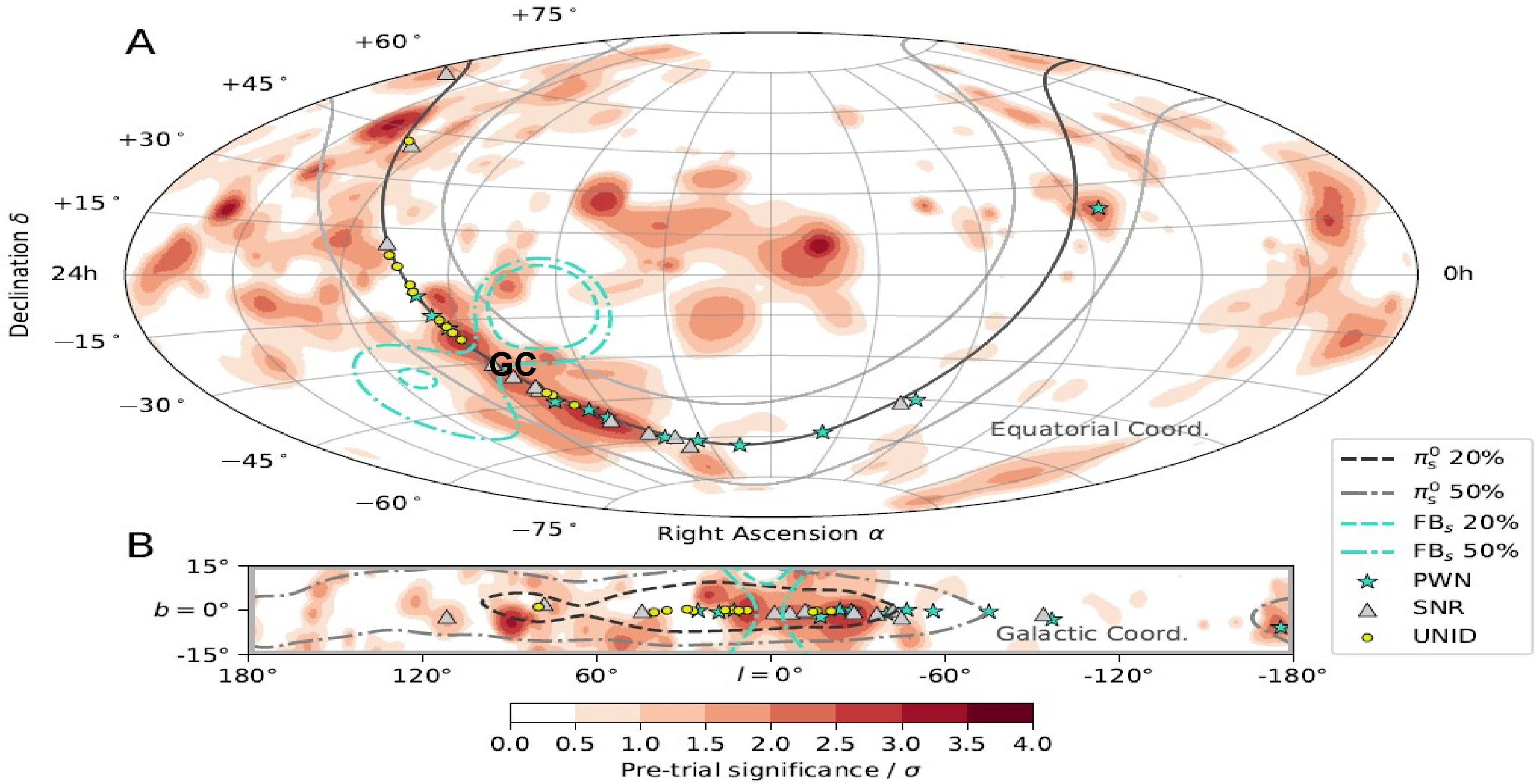
E > 0.5 TeV



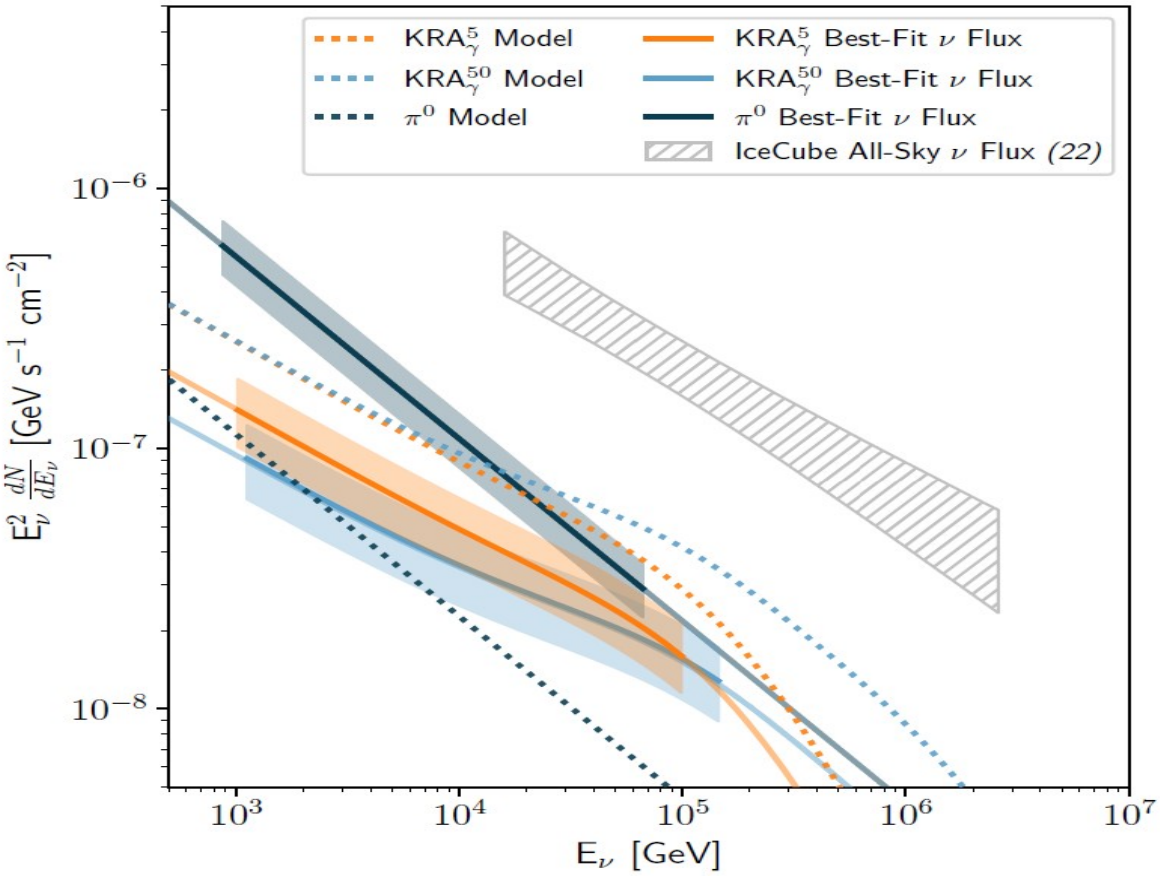
angular resolution still reasonable to detect diffuse signal from Galactic plane

59600 events, with about 7% being astrophysical (87% atmospheric, 6% tracks)

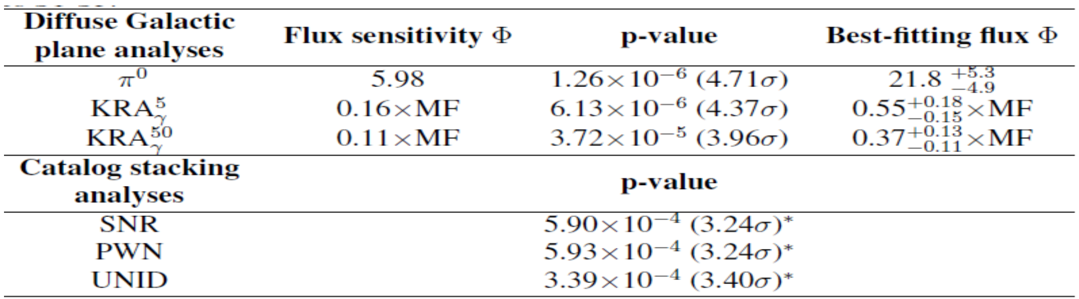
cascades allow IC to look also to southern sky (where GC lies) where tracks are overwhelmed by atmospheric muons



comparing with diffuse emission templates → 4.5σ excess observed

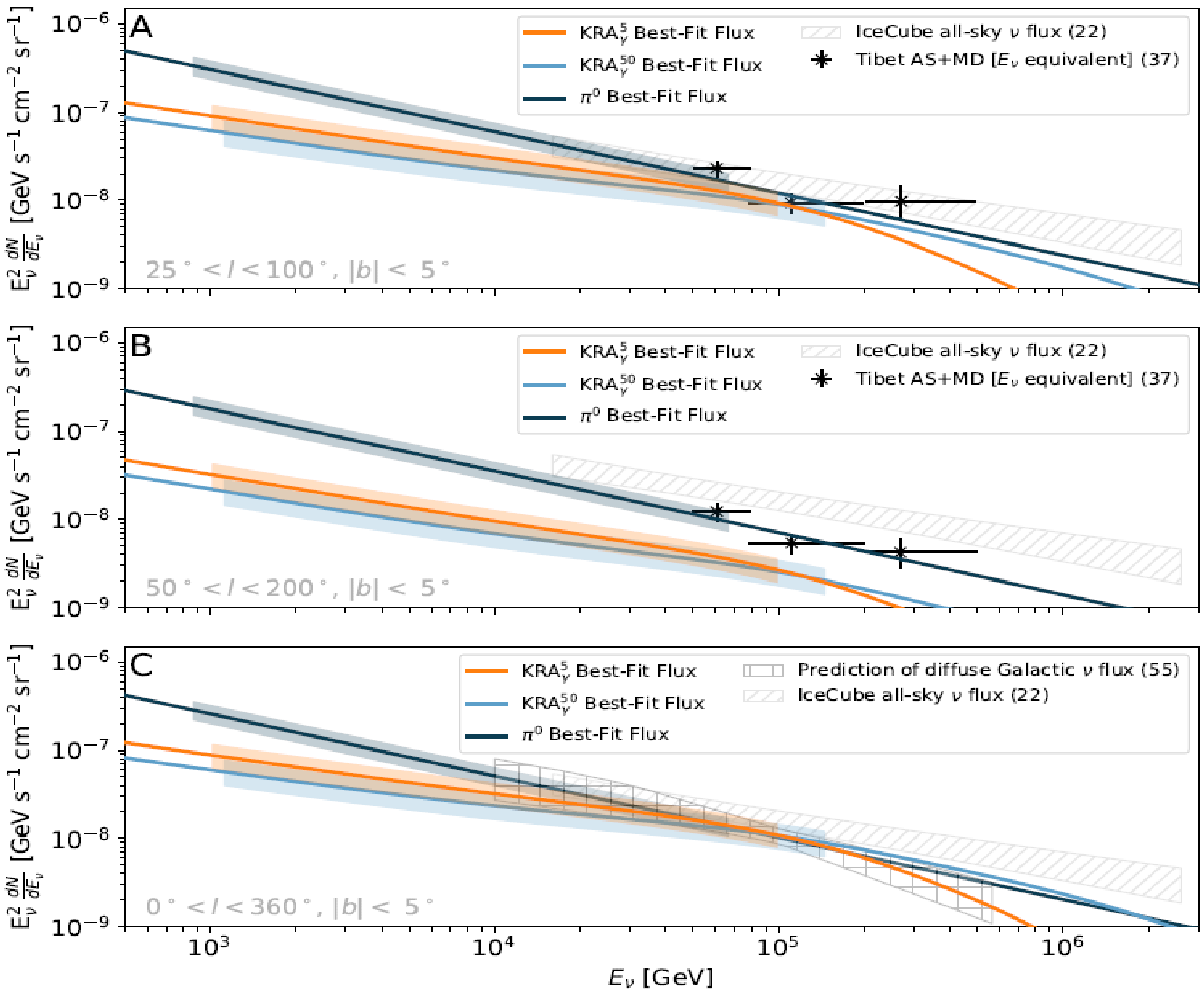


6 to 13% of astrophysical neutrinos come from the Galaxy at 30 TeV

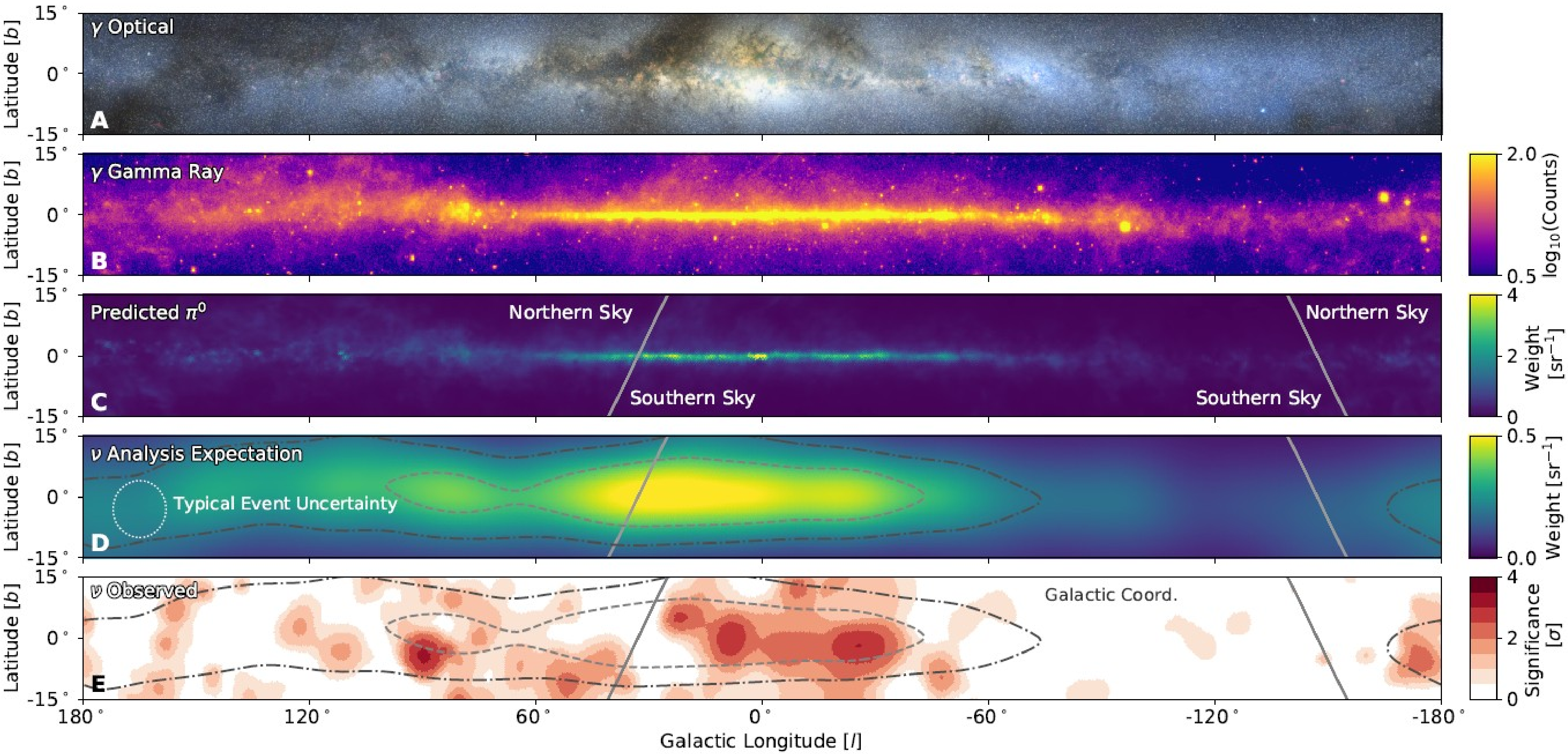


Diffuse Galactic plane analyses	Flux sensitivity Φ	p-value	Best-fitting flux Φ
π^0	5.98	1.26×10^{-6} (4.71σ)	$21.8^{+5.3}_{-4.9}$
KRA$_\gamma^5$	$0.16\times$MF	6.13×10^{-6} (4.37σ)	$0.55^{+0.18}_{-0.15}\times$MF
KRA$_\gamma^{50}$	$0.11\times$MF	3.72×10^{-5} (3.96σ)	$0.37^{+0.13}_{-0.11}\times$MF
Catalog stacking analyses		**p-value**	
SNR		5.90×10^{-4} (3.24σ)*	
PWN		5.93×10^{-4} (3.24σ)*	
UNID		3.39×10^{-4} (3.40σ)*	

flux in the Galactic plane



the multimessenger picture starting to get completed



the Galactic contribution may also alleviate the tension between fluxes measured with cascades and tracks

Palladino&Vissani 1601.06678

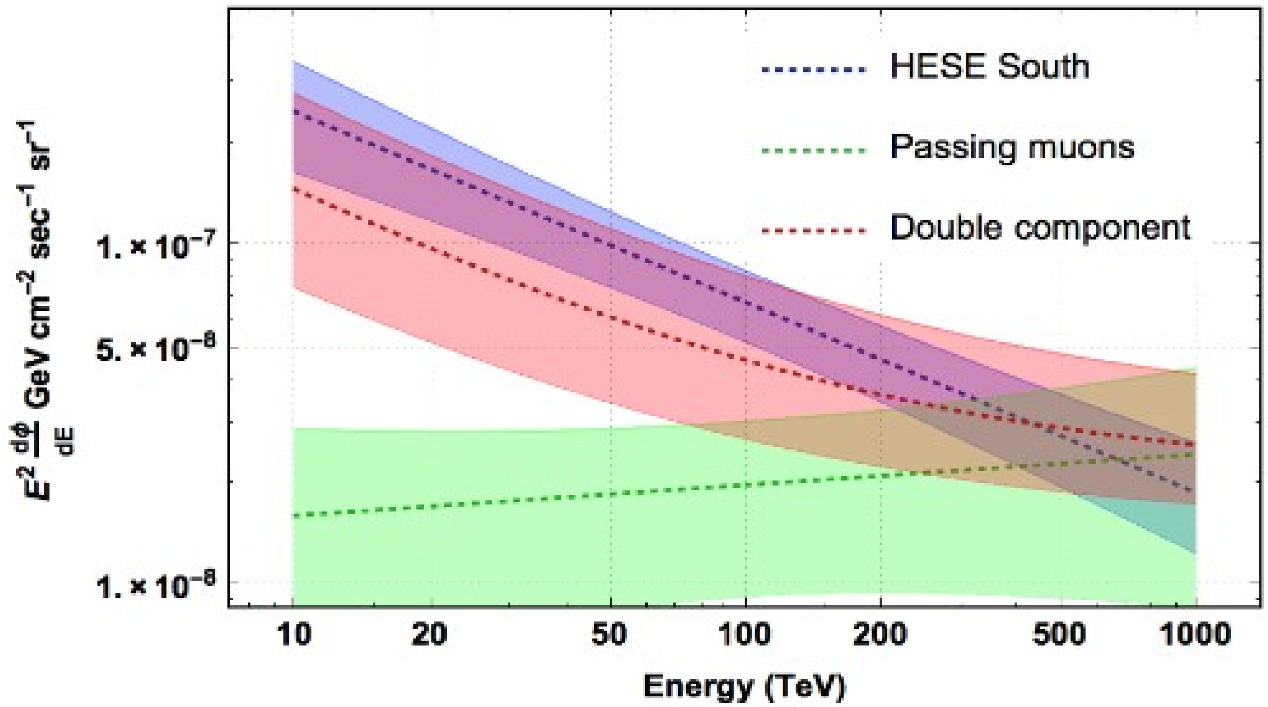
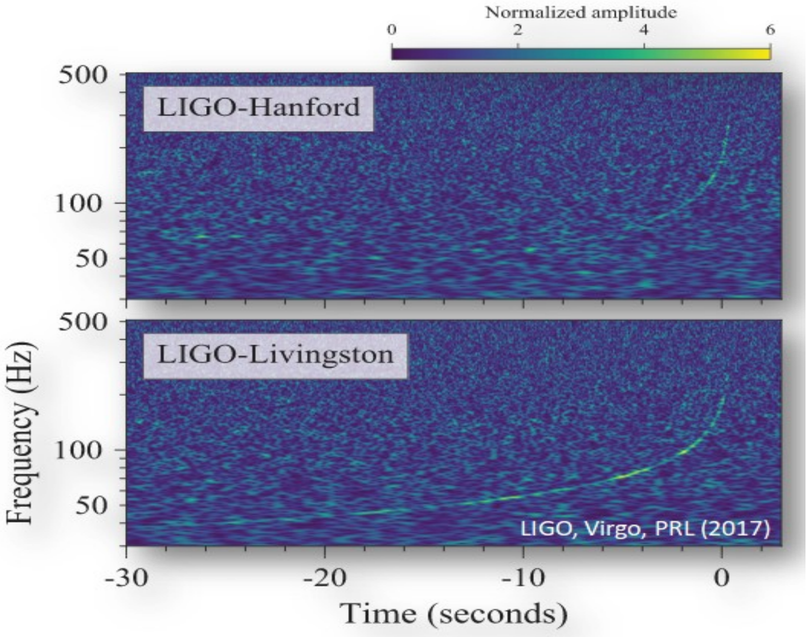
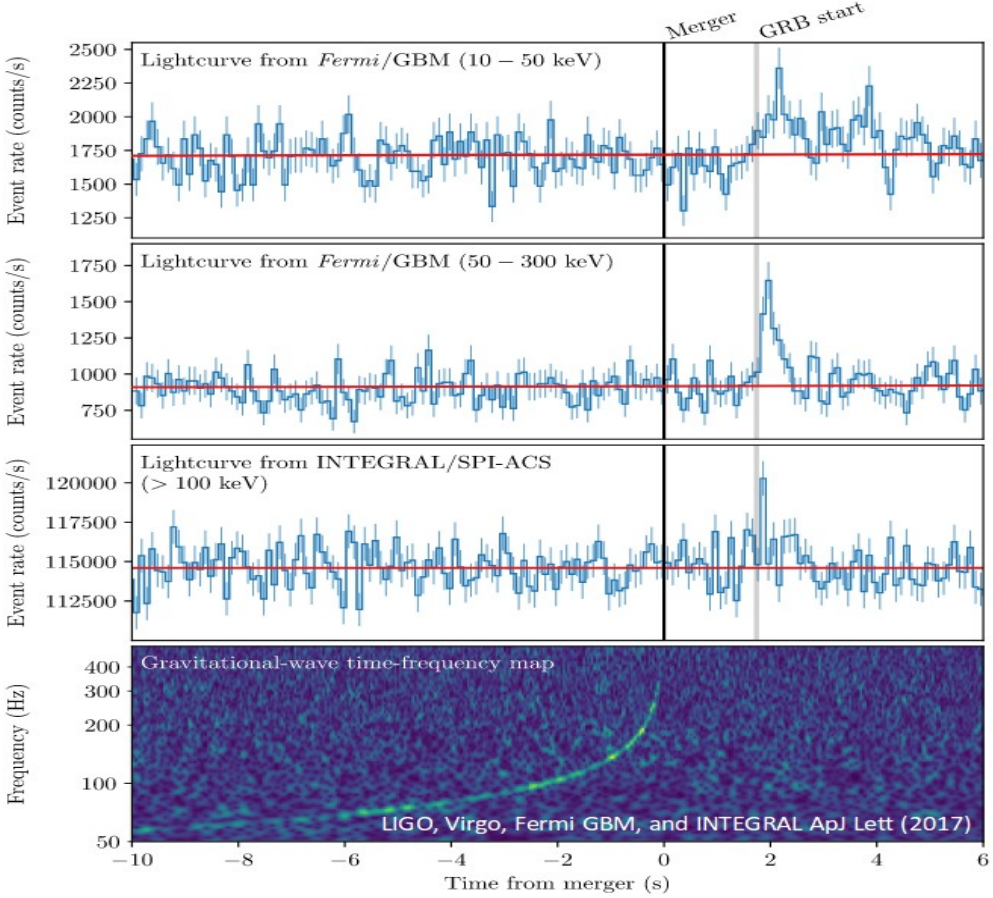


Figure 3: *Comparison between the fluxes measured by IceCube from the Northern sky and Southern sky with the two-components flux.*

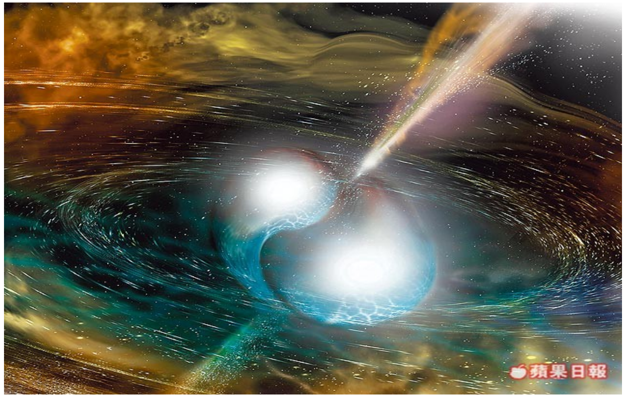
IN 2017 LIGO/VIRGO OBSERVED BINARY NEUTRON STAR MERGER



LIGO, Virgo, PRL (2017)



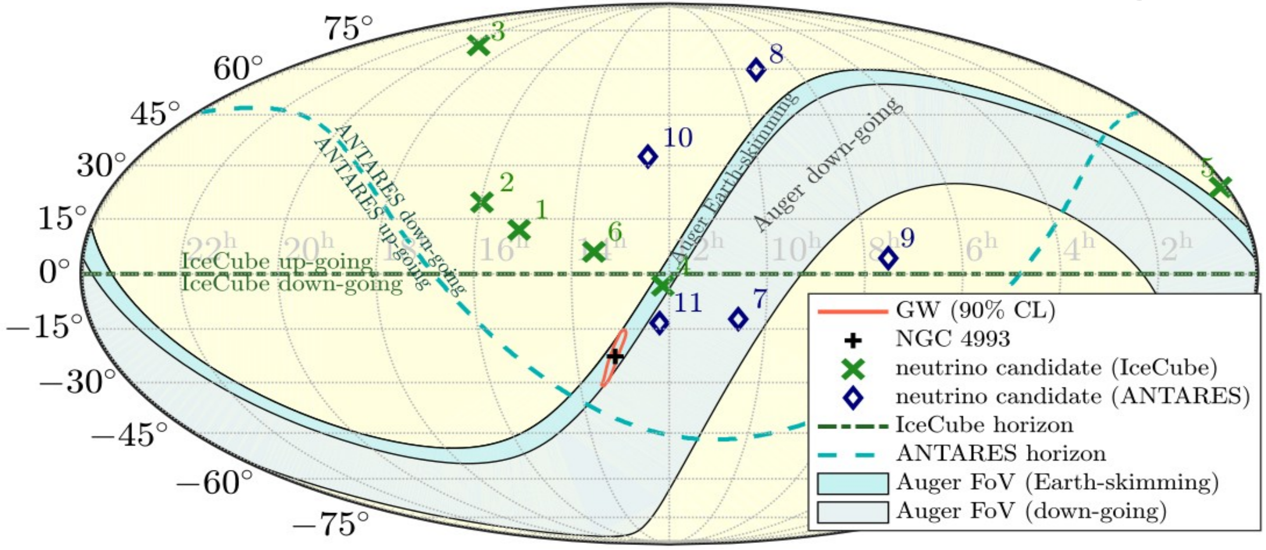
LIGO, Virgo, Fermi GBM, and INTEGRAL ApJ Lett (2017)



also seen in gamma rays, and then optical, radio, X-rays , …
Gravitational waves: the new messenger

IYSICAL JOURNAL LETTERS, 850:L35 (18pp), 2017 December 1

NEUTRINOS FROM BINARY MERGERS



Neutrinos searched in Auger, IceCube and Antares data, but nothing observed → flux upperbounds

still waiting for simultaneous GW, gamma and neutrino observation

(CRs, being charged, arrive much later)

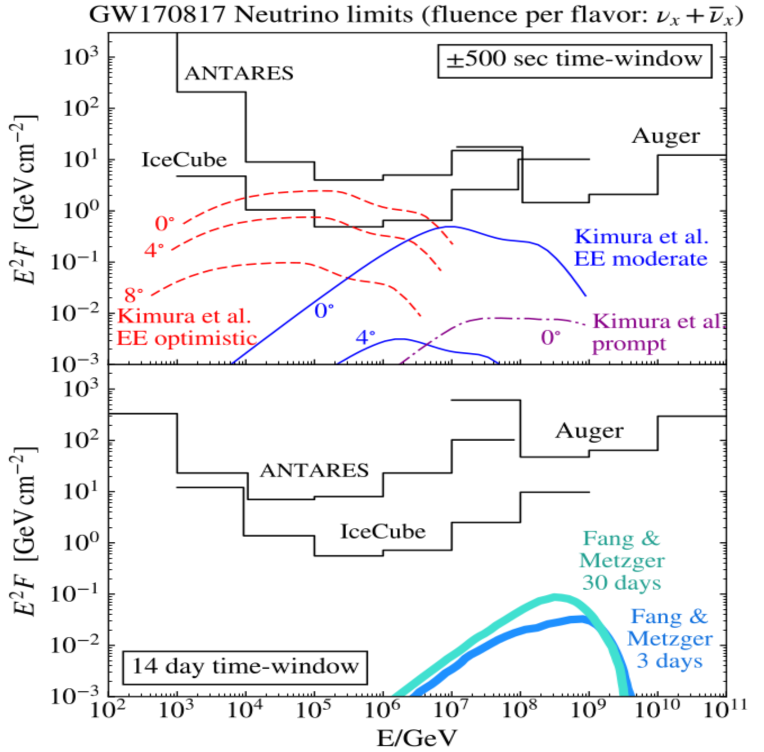
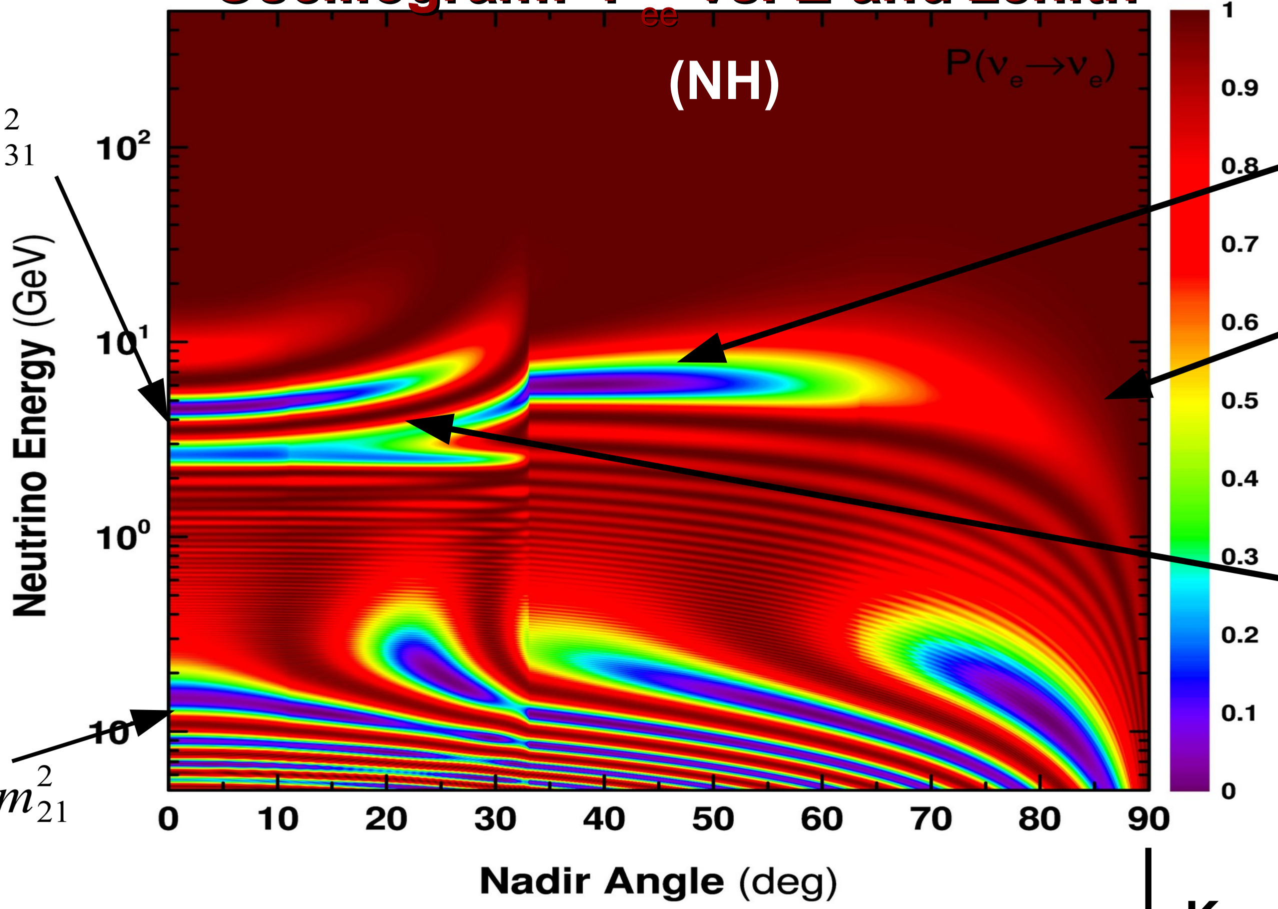


Figure 2. Upper limits (at 90% confidence level) on the neutrino spectral fluence from GW170817 during a ±500 s window centered on the GW trigger time (top panel), and a 14 day window following the GW trigger (bottom

oscillations of atmospheric neutrinos (DeepCore, ORCA, HyperK,...)

Oscillogram: P_{ee} vs. E and zenith



Δm^2_{31}

Δm^2_{21}

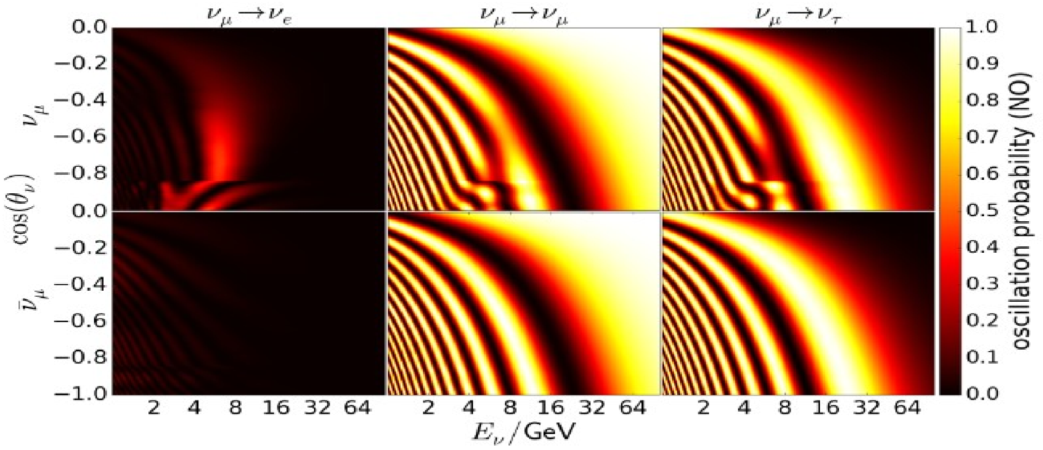
magic baseline

present LBL experiments
(T2K, MINOS, NOvA)

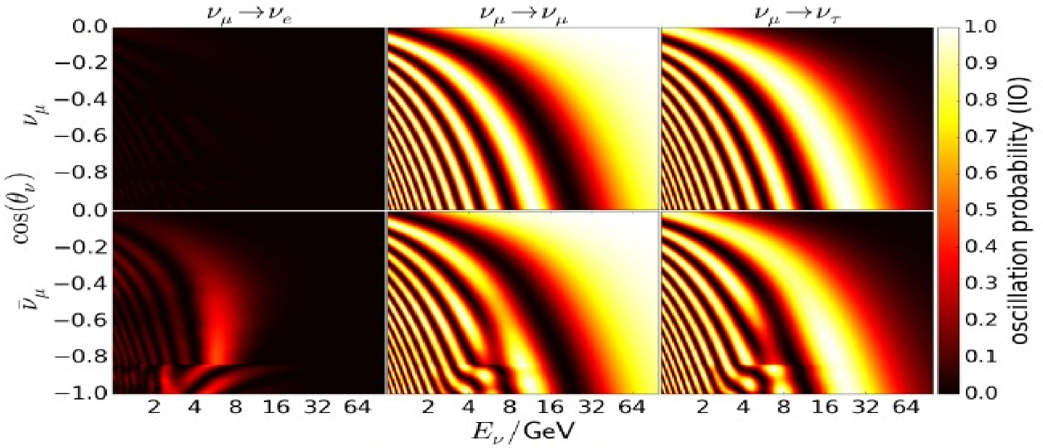
Parametric resonance
in the core

KamLAND

can use atmospheric neutrinos from different directions and energies



(a) Normal Ordering



(b) Inverted Ordering

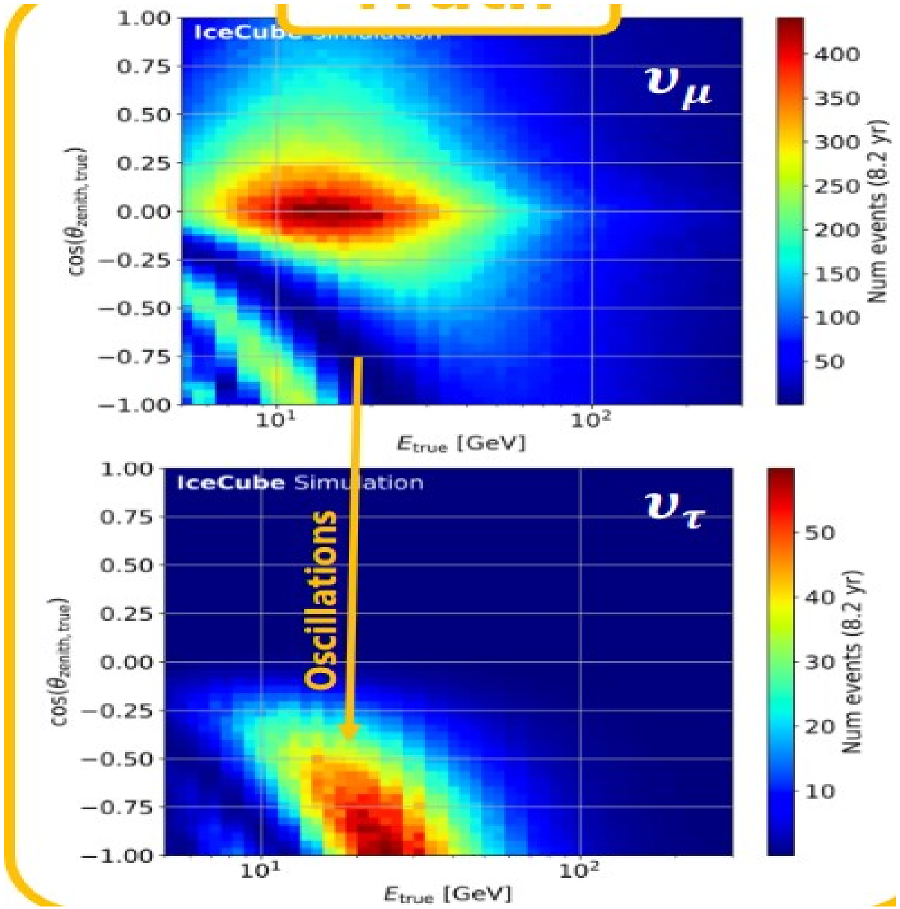
1902.07771

for IO the plots for E > GeV are approximately exchanged
→ could determine hierarchy with atmospheric nus with E < 10 GeV
(SK and DeepCore favor NO)

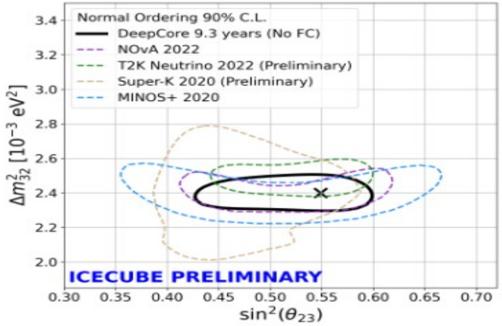
Note that: $\sigma^{CC}(\nu N) \simeq 2\,\sigma^{CC}(\bar{\nu} N)$

→ asymmetry is observable
(also neutrino flux not identical to antineutrino flux)

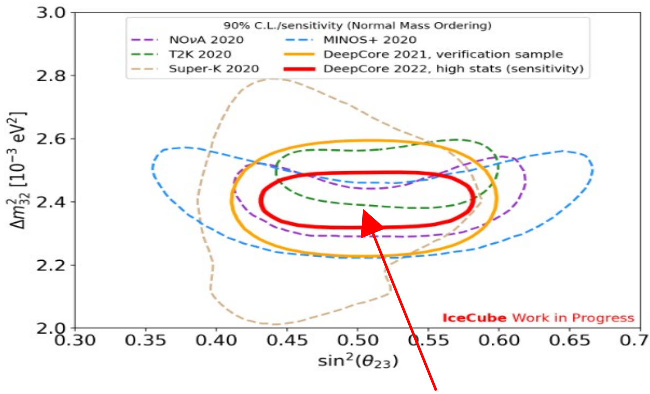
future: IC upgrade, ORCA and INO (magnetized → μ^+/μ^-)



2305.16514



Deep-Core studying ν_μ disappearance



Deep-Core studying ν_τ appearance
(as excess of upgoing cascades)
→ will improve mass-mix constraints

similar L/E as LBL experiments probing Δm^2_{31}= 2.5E-3 eV^2:
L/E ~ 10^4 km/20 GeV or 10^3 km/2 GeV
but one in DIS regime, the other in the resonant QE regime

A=(IO-NO)/NO

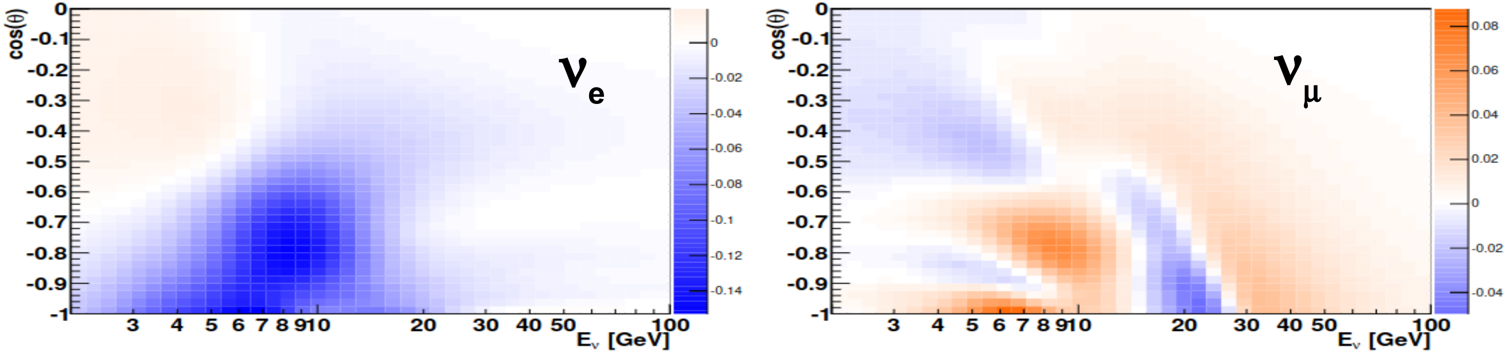
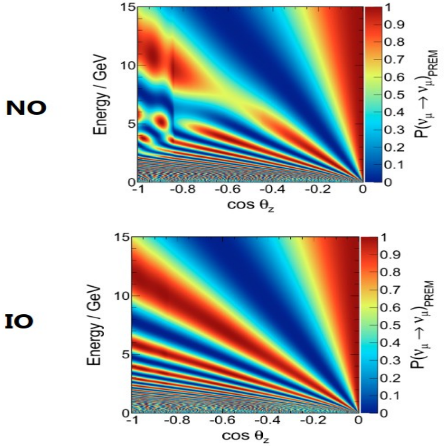
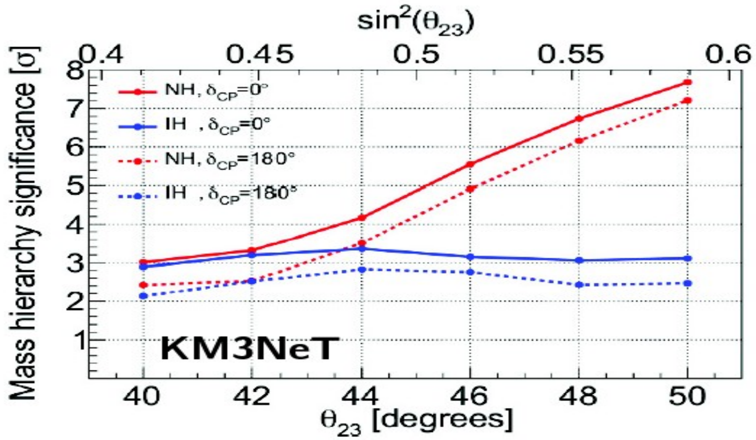


Figure 53: Asymmetry (as defined by Eq. 19) between the number of $\nu + \bar{\nu}$ CC interactions expected in case of NH and IH, expressed as a function of the energy and the cosine of the zenith angle. The right (left) plot applies to muon (electron) neutrinos. A smearing of 25% is applied on the energy. On the angle,



IC upgrade & ORCA will determine mass hierarchy from matter effects induced nu-antinu differences

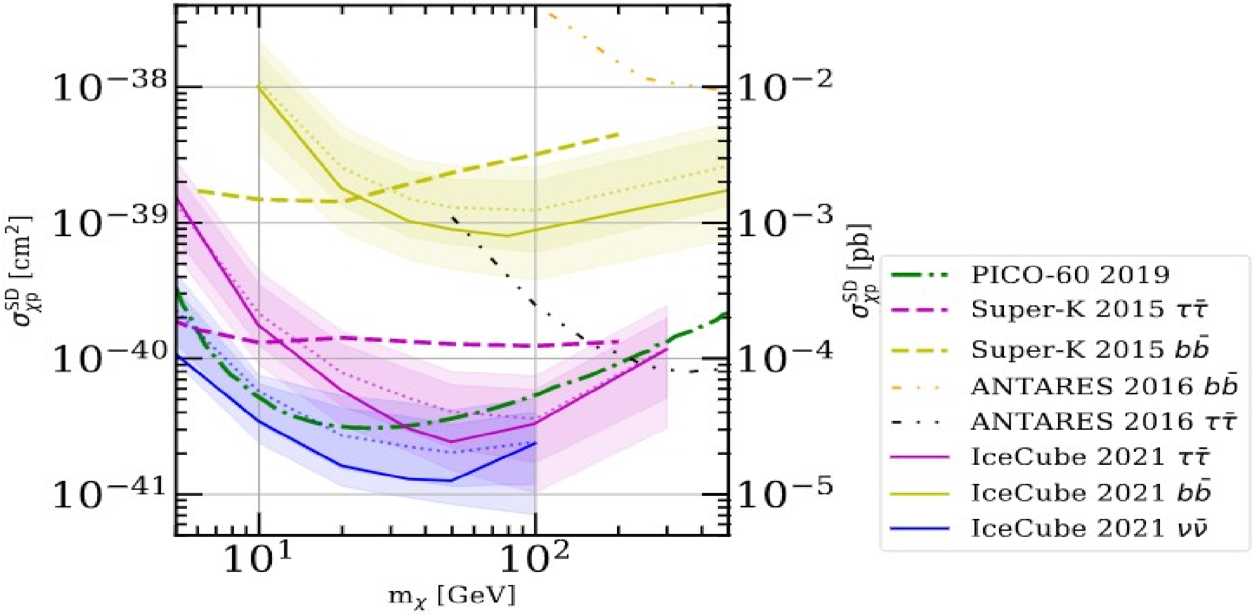


sensitivity on νMO depends on θ_{23} octant and CP phase

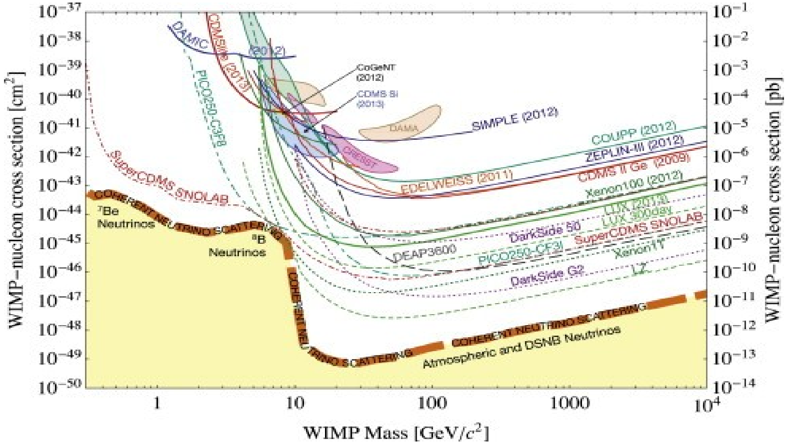
GeV neutrinos from WIMP annihilation in the Sun

Spin-dependent WIMP nucleon xsect determines WIMP capture in Sun

spin-independent scattering in direct DM search

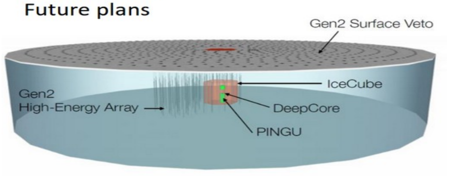


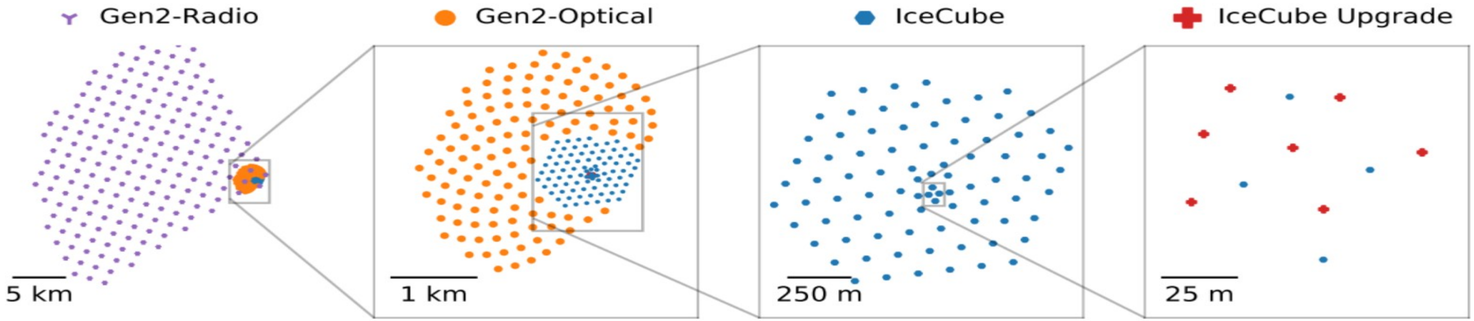
2111.09970

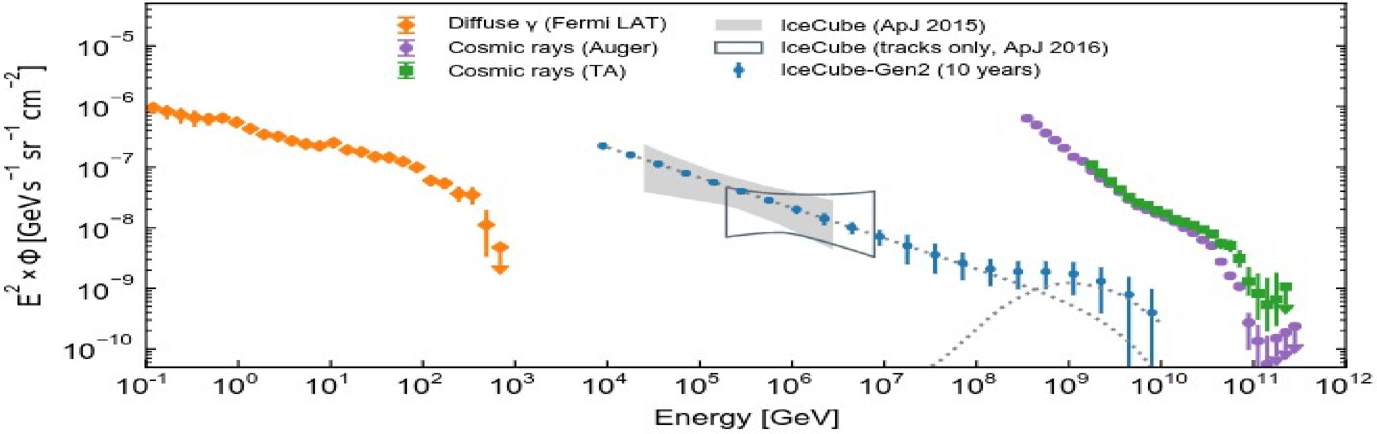


the future

ICECUBE_Gen2
Future plans







old

new

history & future of WCD:

Kamiokande (3 kt; >7 MeV) ; SKamioka (50 kt, >5 MeV) ; HyperK (300 kt)

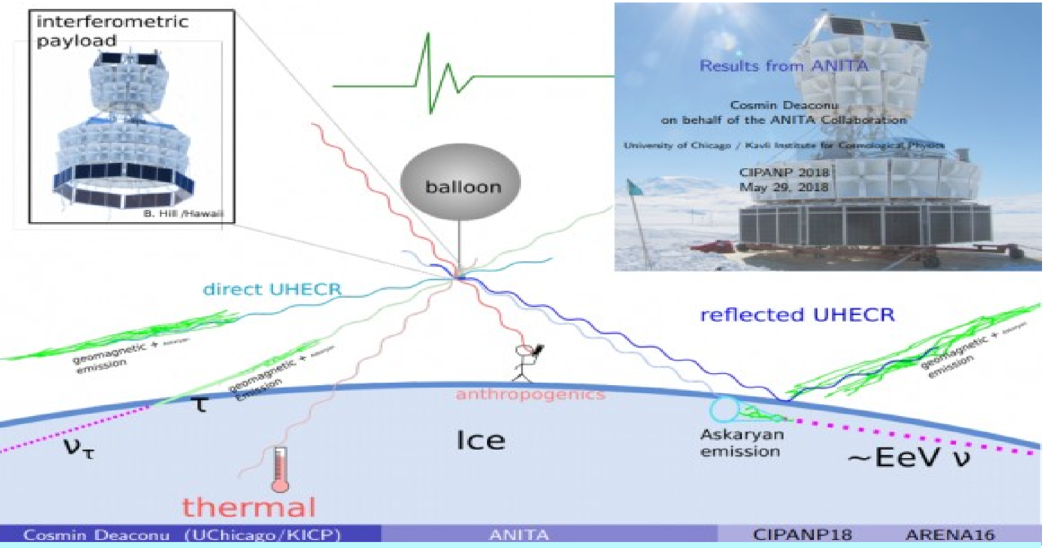
Amanda (Mt) ; Antares (10 Mt) ; IceCube (1 Gt, >100 GeV)

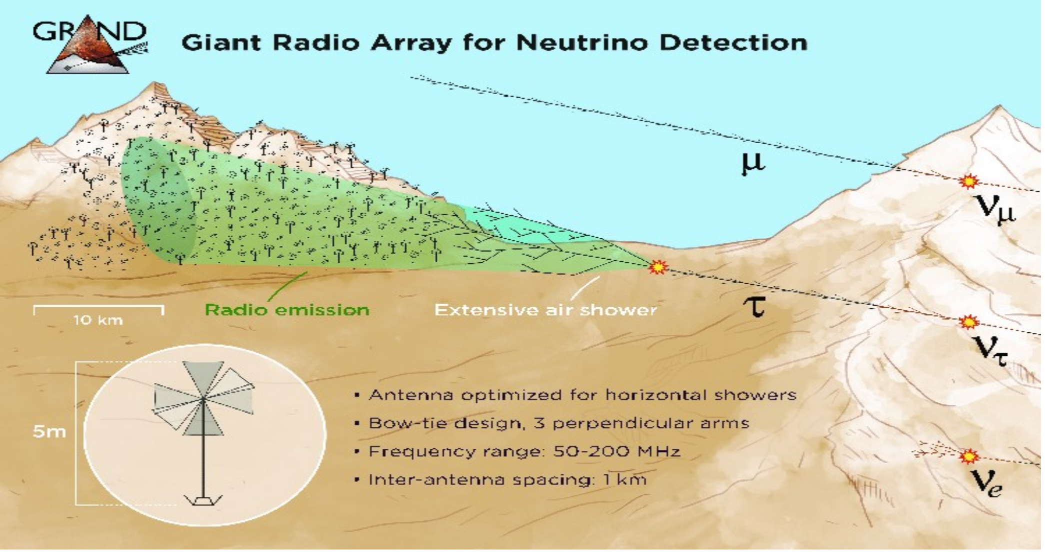
DeepCore (20 Mt, E>10 GeV) ; ORCA (4 Mt, E>5 GeV)

GVD (1Gt) ; ARCA (1.2 Gt, >100 GeV) ; Gen2 (8 Gt, >1 TeV)

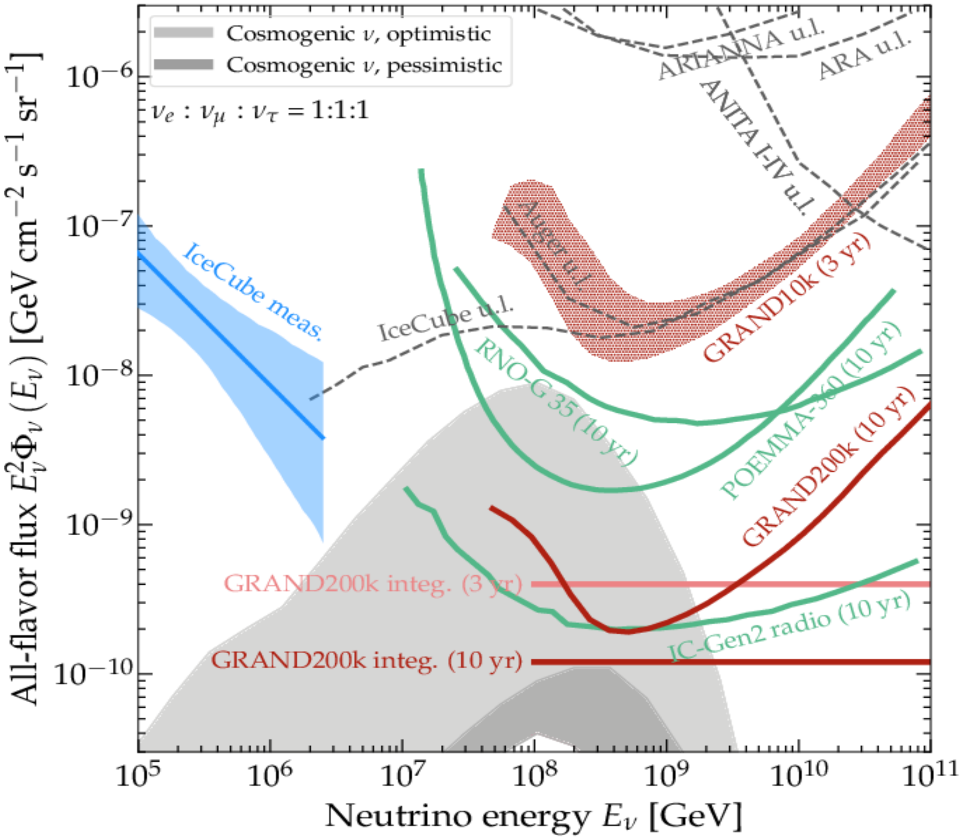
P-ONE (3 Gt) ; TRIDENT (>10 Gt)

radio to chase cosmogenic neutrinos





- Antenna optimized for horizontal showers
- Bow-tie design, 3 perpendicular arms
- Frequency range: 50-200 MHz
- Inter-antenna spacing: 1 km



CONCLUSIONS

Detection of astrophysical ν produced a revolution

We are at the dawn of the era of high-energy neutrino astronomy

- there is now a 300 TeV neutrino from TXS & hints from other blazar sources
  also the Seyfert NGC1068 has been detected

- will provide clues on the sources of UHECRs, both Xgalactic and Galactic

- contribute to multimessenger astronomy

Also particle physics insights:

- measurement of cross section beyond accelerators & charm production

- W resonance neutrinos , tau neutrino observations

- flavor studies will constrain source mechanism

- searching for cosmogenic neutrinos, neutrinos from WIMP annihilations,
  neutrino oscillations: mass ordering and mixings, …..

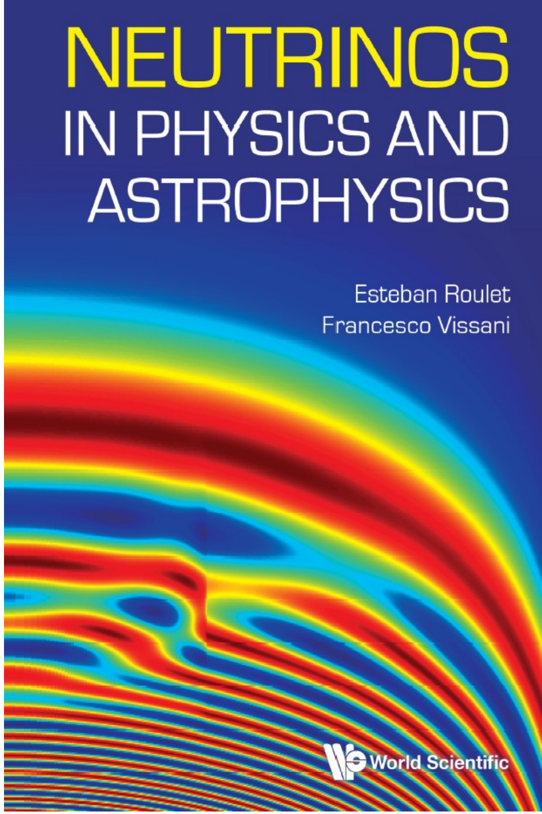
the coming years will certainly be very exciting

Some books about neutrinos:

- **Physics of Neutrinos:**
  Fukugita and Yanagida (2003)

- **Probes of Multimessenger Astrophysics,**
  Maurizio Spurio (2018)

- **Neutrinos in Physics and Astrophysics:**
  Roulet & Vissani (2022)



Check also:

https://pdg.lbl.gov/2022/reviews/rpp2022-rev-neutrino-mixing.pdf

http://www.nu.to.infn.it Neutrino Unbound page
(including links to experiments & recent conferences and schools)