High-energy astrophysical neutrinos: Open questions and prospects

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The key goals of High Energy ν astronomy

- Identify the sources of (ultra) high energy (HE) cosmic rays

  UHE : $>10^{19}$ eV

  p(A) + γ(p) → $\pi^{\pm}$ → $e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu + \bar{\nu}_\mu$; $E_\nu \approx E_{p(n)}/20$

  ν's, unlike p & A, point to their sources

- Provide unique constraints on models of HE astrophysical sources

- Possibly: Study ν/fundamental physics

  π decay → $\nu_e:\nu_\mu:\nu_\tau = 1:2:0$ (propagation)→ $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$

Required detector size

- Identify the sources of (ultra) high energy (HE) cosmic rays

  $p(A) + \gamma(p) \rightarrow \pi^{\pm} \rightarrow e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu + \bar{\nu}_\mu \quad ; \quad E_\nu \approx E_{p(n)}/20$

  $Q_{UHE}[10^{19} - 10^{20}\text{eV}] \approx 10^{44}\ \text{erg}/(\text{Mpc}^3\ \text{yr})$ [EW 95]

  Q_{UHE} comparable to $Q[\sim 10\ \text{GeV}]$

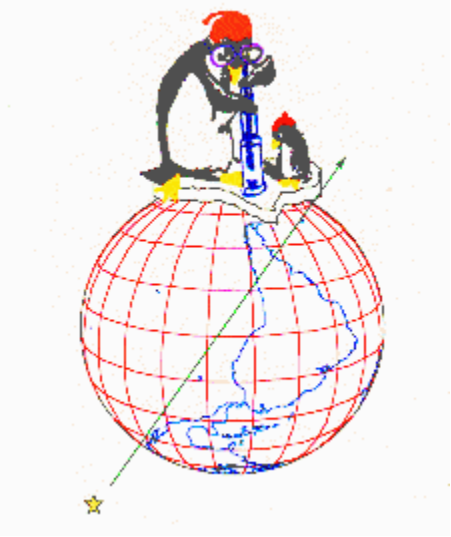
  Full loss to pion production:

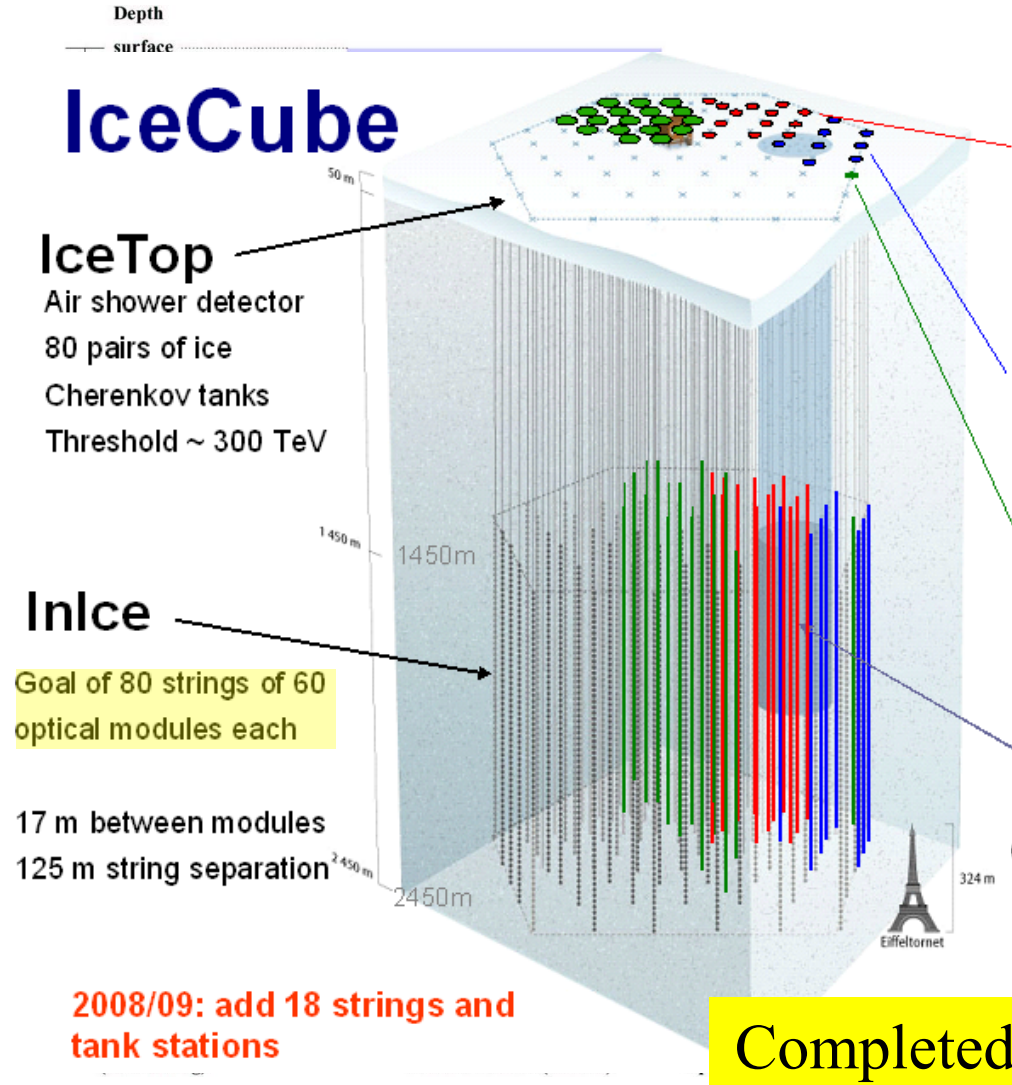
  $E_\nu^2 d\dot{N}_\nu/dE_\nu = 3.4 \text{ x } 10^{-8}\ \text{GeV}/(\text{cm}^2\ \text{sr s})$ [EW & Bahcall 99]

- Expected signal overwhelmed by atmospheric ν's below ~10 TeV,
  Minimal detector size: 1 Gton (1 km^3 water) at ~100 TeV,
  10^3 Gton at ~ 10^{18} eV.

- Intensity similar to the cosmic ray bound expected at:
  ~ 10^{18} eV - IF UHE are p's, due to pγ with CMB [GZK ν's];
  Below ~1000 TeV – IF CR production follows star-formation. [Loeb & EW 06]
  SFR dominated by starbursts, which are "calorimeters" up to $E \sim 1Z$ PeV.

AMANDA & IceCube





IceCube

IceTop

Air shower detector
80 pairs of ice
Cherenkov tanks
Threshold ~ 300 TeV

InIce

Goal of 80 strings of 60 optical modules each

17 m between modules
125 m string separation

2006-2007:
13 strings deployed

2007-2008
18 strings deployed

2005-2006: 8 strings

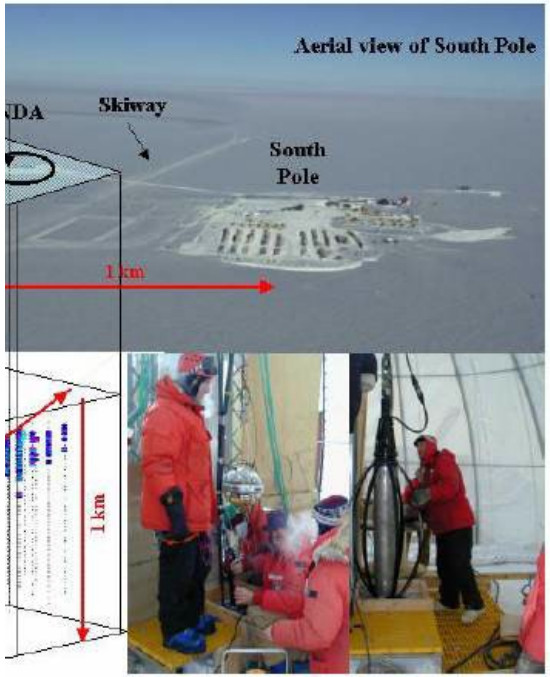
2004-2005 : 1 string

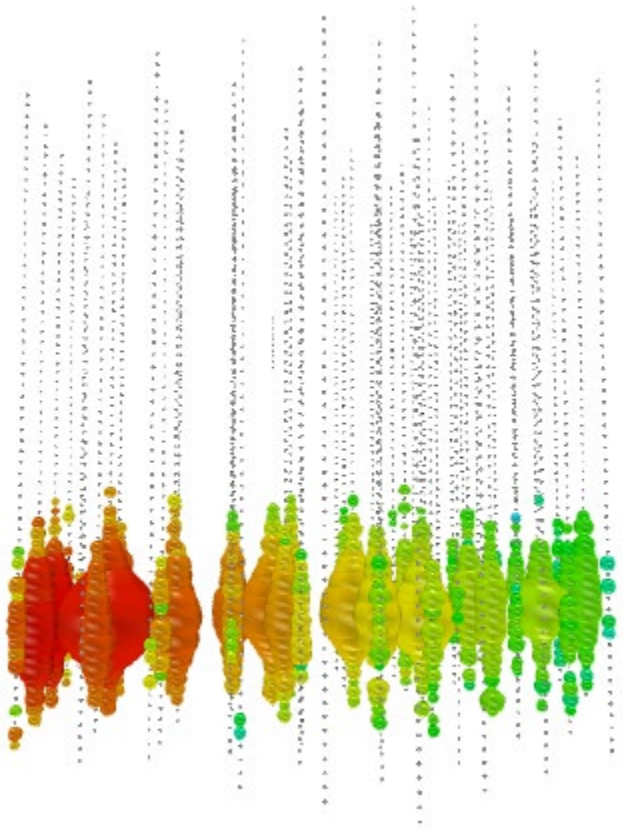
AMANDA-II
19 strings
677 modules

Current configuration:
40 strings,
40 IceTop stations
plus AMANDA

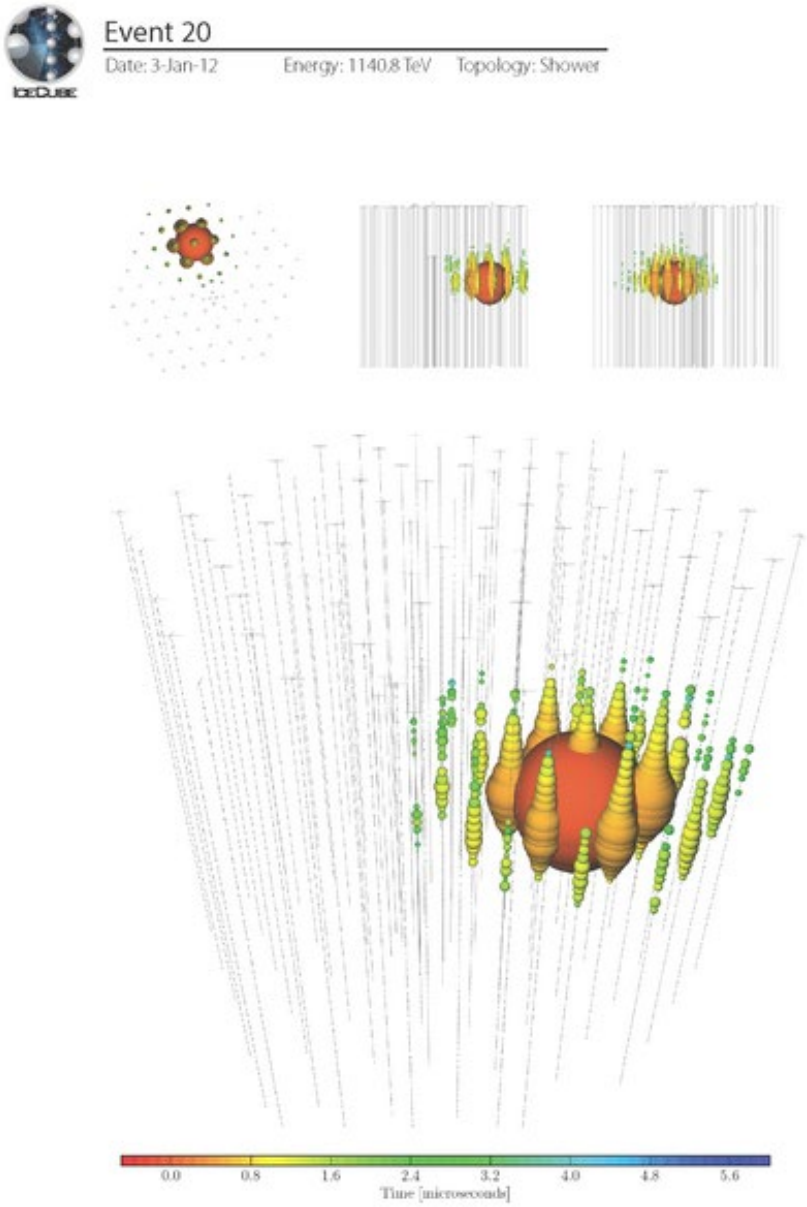
2008/09: add 18 strings and tank stations

Completed Dec 2010





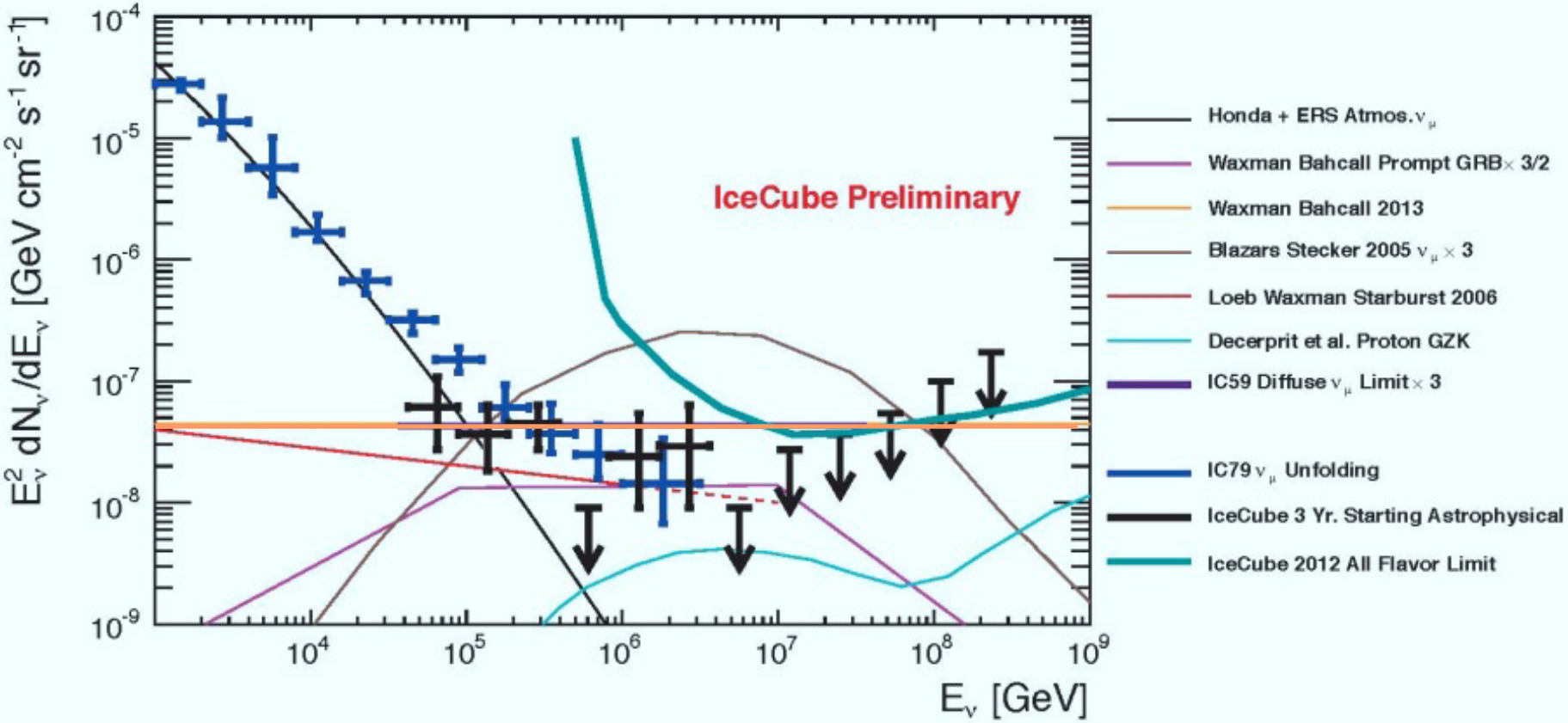
400TeV



1100TeV

IceCube: 37 events at 50Tev-2PeV

~6σ above atmo. bgnd. [02Sep14 PRL]



$E^2\Phi_\nu = (2.85 \pm 0.9) \times 10^{-8}$ GeV/cm^{2}sr s $= E^2\Phi_{WB} = 3.4 \times 10^{-8}$ GeV/cm^{2}sr s (2PeV cutoff?).

Consistent with Isotropy (extra-Galactic origin),

$\nu_e:\nu_\mu:\nu_\tau = 1:1:1$ (π deacy + cosmological prop.).

IceCube's extra-Galactic ν's: What we have learned

50 TeV - 1 PeV

- The energy production rate densities in the local universe in ~ 100 TeV ν's and in $>10^{10}$ GeV CRs are similar:

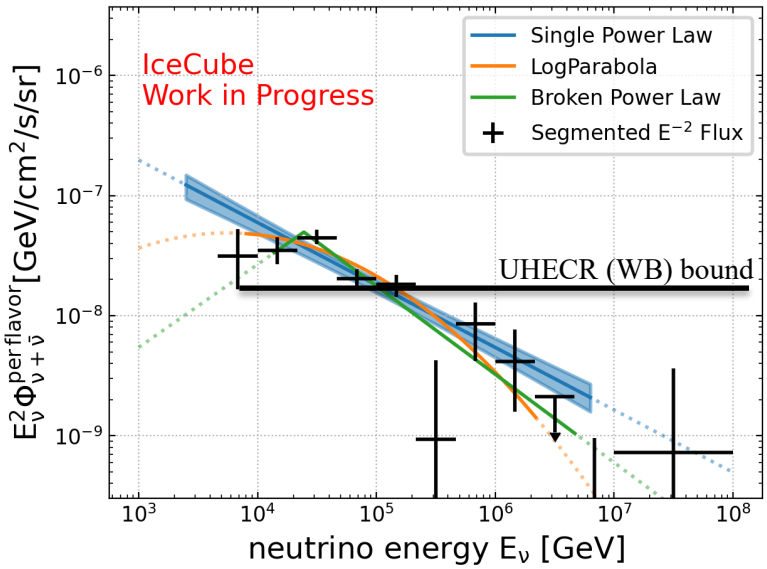
  $\sim 10^{44}$erg/Mpc^{3}yr ($\Phi_\nu \approx \Phi_{WB}$)

→ The sources may be related, but no direct evidence, and the sources are not identified.

- A lower limit on steady source density:

  $n_s > 10^{-7}$/Mpc^3, $L_\nu < 10^{42.5}$ erg/s.

IC 23, ν flux per flavor



10 - 30 TeV

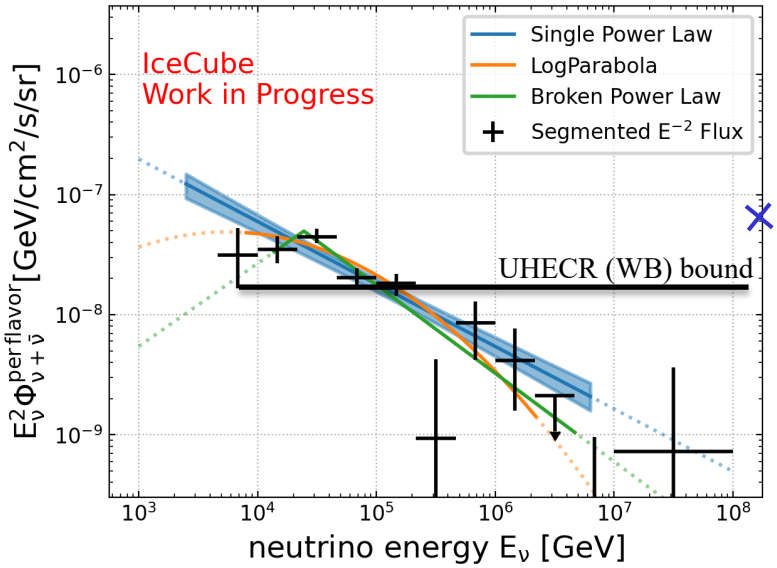
- $\Phi_\nu \approx 2\Phi_{WB}$ and is in tension with the 100 GeV γ background, as $\Phi_\gamma(100\text{GeV}) \approx \Phi_\nu$ is expected after EM cascades on the IR background.

→ Suggests the existence of "hidden sources", from which ν's escape but γ's don't.

[** Initial ~4σ detection of a Galactic disk component (<10% of the flux).]

KM3NeT very high energy event

IC 23, ν flux per flavor



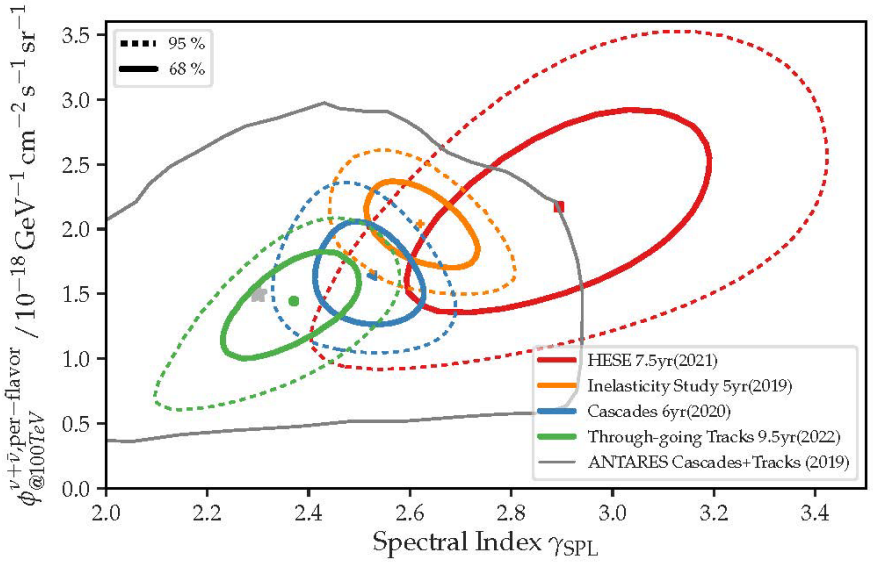
Most likely a “lucky” 1:100 event

Extra-Galactic ν's: What we are missing

10 TeV – 10 PeV

- The spectrum measurement is crude.
- The flavor ratio measurement (consistent with 1:1:1) is crude.

IC & ANTARES, spectral index



10^8 – 10^{10} GeV

- A flux measurement (10^{-9}GeV/cm^{2}s sr) will constrain the UHE CR composition.

Sources

- The sources have not been identified.
- A ~3σ association, including a 300TeV ν – a Blazar (TXS 0506+056)
  - Models challenged by X- and γ- ray observations [e.g. Murase 18] .
  - Blazars do not dominate the background [e.g. IC 17].
- A ~4σ association, <10 TeV – an AGN (Seyfert)/Starburst galaxy (NGC1068)
  (2 lower significance associations [Neronov et al. 24])
  - A hidden γ-ray source, $L_\nu >\sim 30\ L_\gamma$ (1 GeV – 1 TeV)

Source Candidate: I. Blazars

Blazars are not the dominant HE ν sources

- Blazar number density << 10^{-7}/Mpc^3
- Stacking analyses limit their contribution to <~10% [e.g. IC 17, 25]

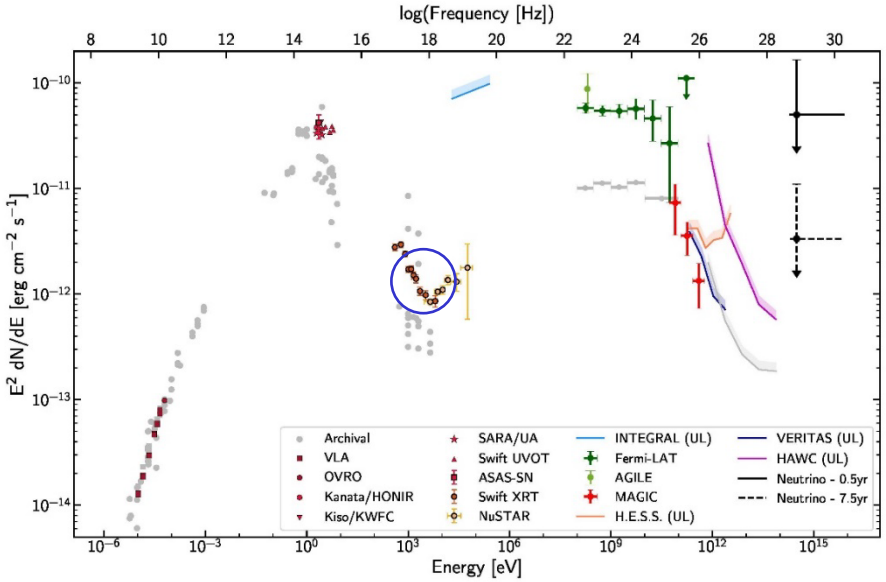
- And what about the ~3σ association, 300TeV ν with TXS 0506+056 Blazar flare?

The association with TXS 0506+056 is likely a coincidence

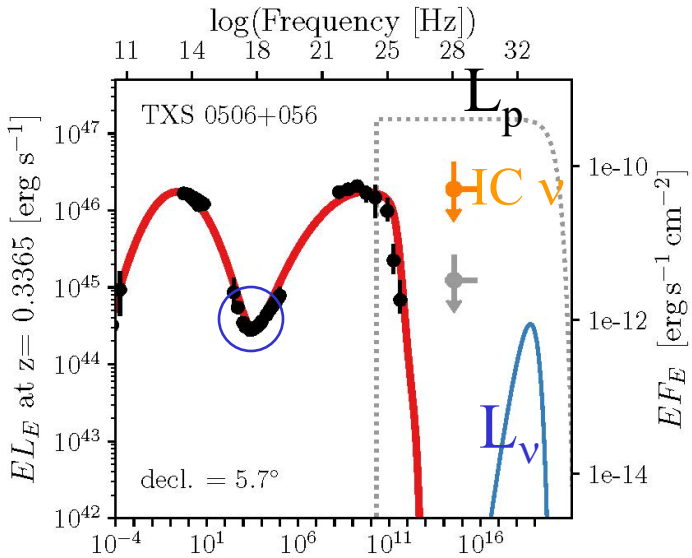
- The escape of high-energy γ's limits the density of target photons for pγ, implying $L_\nu << L_p$ and requiring
  $L_p > 10^4 L_\gamma$ to account for the ν detection.

- SWIFT XRT measurements set the most stringent limit on L_p, $L_p << 10^4 L_\gamma$

- ν's may be produced by a mechanism independent of that of observed photon production.
  This is difficult to support/rule out by observations.



[Multi messenger 18]



[Oikonomou et al. 19]

Source Candidate: II. AGN Seyfert/Starburst

NGC1068 Seyfert/Starburst association challenges: I. Physics - $L_{CR} \sim L_{Eddington}$

- $L_\nu \sim 100\, L_\gamma$ is much larger than $L_\nu \sim L_\gamma$ predicted for Starbursts.
  New models suggested, associated with the AGN (Seyfert) activity.
- Models postulate ν production at the ~10 R_s vicinity of the BH, to obtain efficient ν production and strong suppression of 100GeV photon emission by pair production with UV photons. [Das et al. 24, Padovani et al. 24, Lemoine & Rieger 24, Inoue et al. 24]

- 100 TeV p + ~1 keV γ → ~5 TeV ν
  100 TeV p + ~10 eV γ → $e^{\pm}$

$$\frac{L_\pi}{L_\pm} \approx \frac{L_X}{L_{UV}} \approx 10^{-1.5}$$

since (dE/E x σ / ε_γ) similar for pion & for pair production

→ $$L_{CR}(\sim 100\ \mathrm{TeV}) \approx 2\, L_\nu \frac{L_{UV}}{L_X} \approx 10^{44}\mathrm{erg/s} \approx 0.1\, L_{\mathrm{Eddington}}$$

$$L_{CR}(1\mathrm{GeV}-100\mathrm{TeV}) \approx L_{\mathrm{Eddington}}$$

- This would imply a modification of our basic understanding of AGN physics.

NGC1068 association challenges: II. Statistics

- If the ν luminosity of NGC1068 were typical for Seyferts, the resulting ν luminosity would exceed the observed one by a factor >100:

$$3 \times 10^{42}\mathrm{erg/s} \times (10^{-4}\ \mathrm{Mpc}^{-3}) = 10^{46}\mathrm{erg/Mpc^3yr}.$$

→ NGC1068 must be a "rare Seyfert"- e.g.:
Estimated large intrinsic hard X-ray luminosity corresponding to ~ $10^{-5}\ \mathrm{Mpc}^{-3}$, reducing the discrepancy to a factor >10.

- However,
Stacking analysis of SWIFT-BAT hard X-ray AGN show no ν signal [IC 25]
(limiting their contribution to <10%).

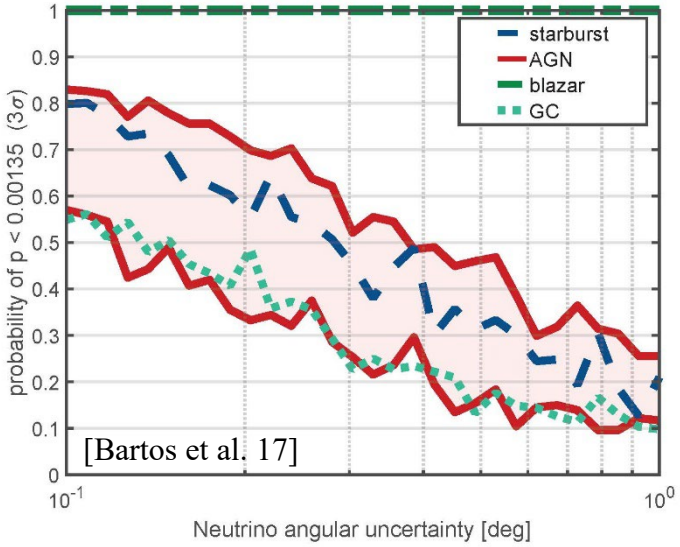
We do not have an observational identification of the sources that dominate the HE ν flux

Identifying >10 TeV steady sources: (10 km^2 x 10 yr) required, beyond 2040

- ~1 atmospheric ν_μ per 1 squared degree.
- Source density >10^{-7}/Mpc^3, source number >10^6.
- 1% of astrophysical ν's, i.e. <~10, originate at d<100 Mpc.

→ Association with sources by correlation with catalogs is difficult.

- (10 km^2+ $\Delta\theta$ <0.5 deg) X 10yr
  + complete source catalog to 200 Mpc
  required for a 3σ association with nearby sources.



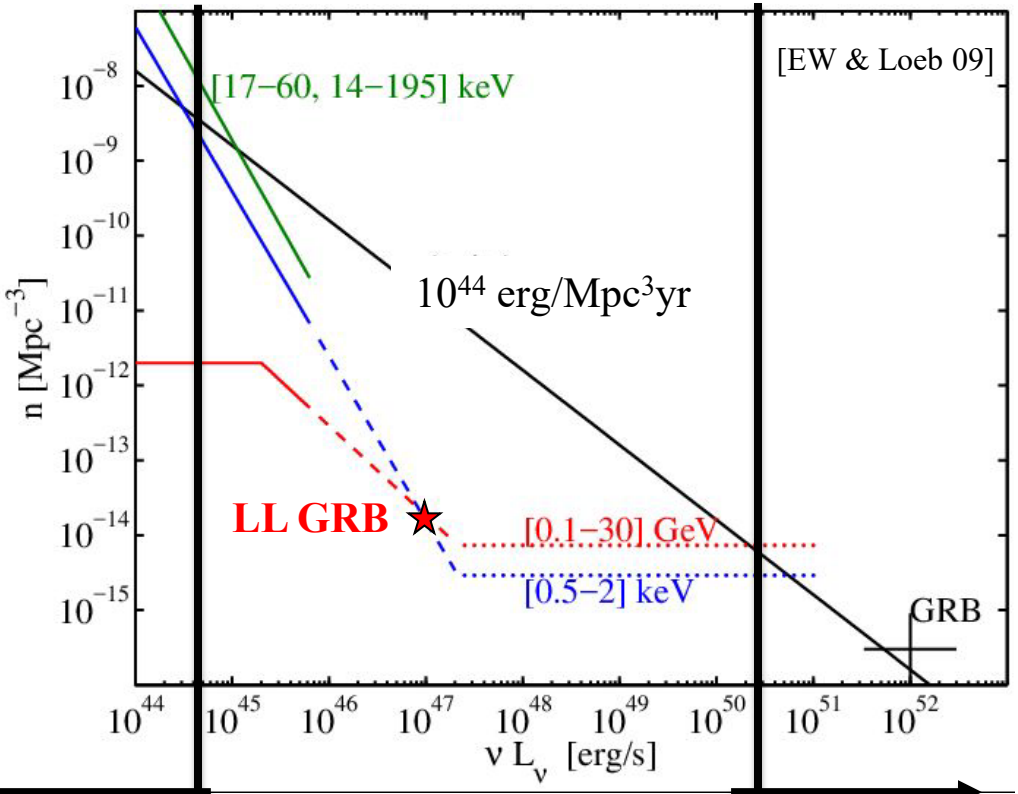
Probability for a 3σ detection, for 10 yrs IceCubeGen2, and complete catalogs to 0.2 Gpc

Near-term main hope: transient sources

Coincident ν/EM transient detection increases the significance of an angular association for transient duration $\Delta t \lesssim$ days $\ll$ T ~ 1yr.

Identifying >10 TeV transient sources: Which X/γ–ray flares are viable candidates?

The number density of active X/γ-ray flares



$L_\gamma < 10^{45}$erg/s

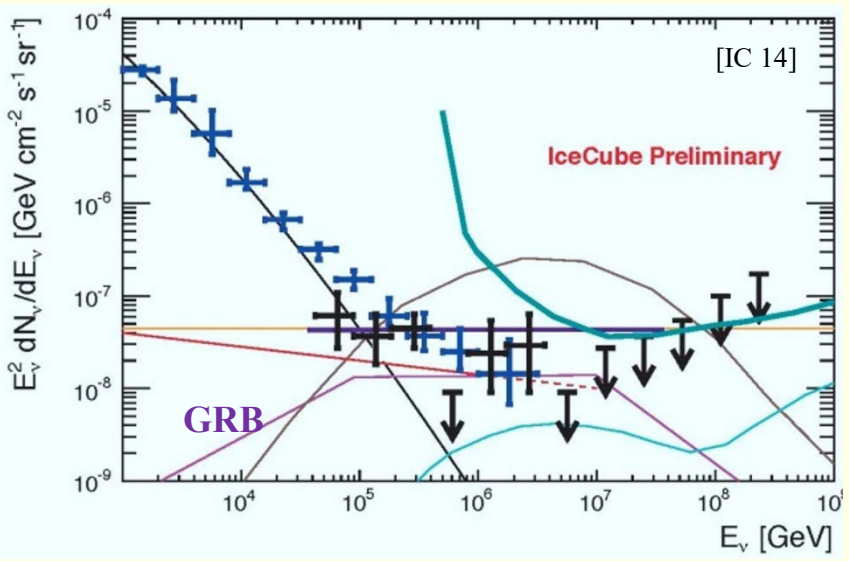
$L_\gamma > 10^{50}$erg/s

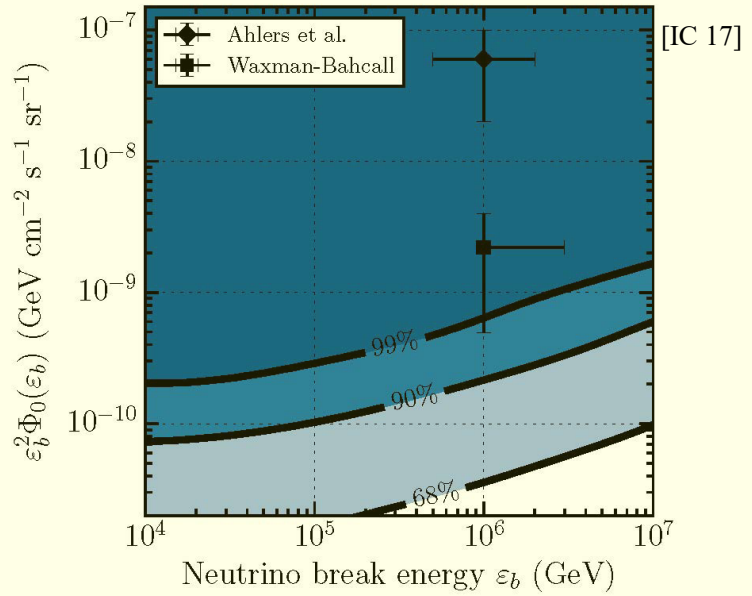
<~1% of the flux

Prompt GRB ν's: <1% of the flux

- Stacking analysis finds no ν signal in association with lGRB
- Largely based on SWIFT-BAT localizations

- LLGRBs/Chocked GRBs have been suggested to dominate IceCube's signal
  [e.g. Senno, Murase, and Mészáros 16]





Identifying >10 TeV, $L_\gamma < 10^{45}$erg/s transient sources: A challenge to X/γ–ray observations

- A handful of events per year- requires detection of d>1Gpc sources.

- $L_\gamma < 10^{45}$erg/s (assuming $L_\nu \leq L_\gamma$) → required sensitivity:

  $f_\gamma < \frac{10^{44}\,\mathrm{erg/s}}{4\pi(1\mathrm{Gpc})^2} = 10^{-12}$ erg/cm^{2}s

- May be possible with SWIFT-XRT (~1keV; 0.1 sq. deg FOV; ~10^{-13} erg/cm^{2}s @ 3hr), and with EP-FXT (~1keV; 1 sq. deg FOV; ~10^{-13} erg/cm^{2}s @ 10^3s).
  Challenging for NuSTAR and SVOM.

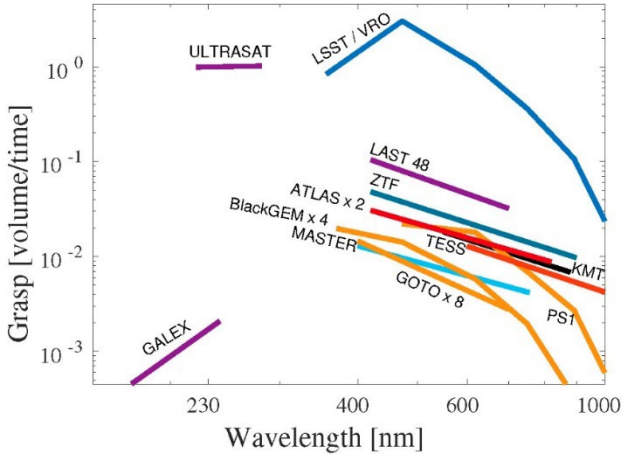
Well below the sensitivity of
BAT/GBM (~1MeV), Fermi LAT (~1GeV), HESS, MAGIC, LHAASO (sub-TeV).
Marginal for CTA/LST (sub-TeV).

Identifying >10 TeV transient sources: UV/Optical surveys open new opportunities

- Many candidate sources are expected to be UV bright.
  - Supernovae:
    Jet-driven explosions,
    (LL GRBs),
    Ejecta – Circumstellar Medium interaction,
  - Tidal disruption events.

- The ULTRASAT UV space telescope will enable a systematic detection and detailed study of these fast transients, and possibly coincident ν/EM detections.

Transient detection volume accessible to leading surveys

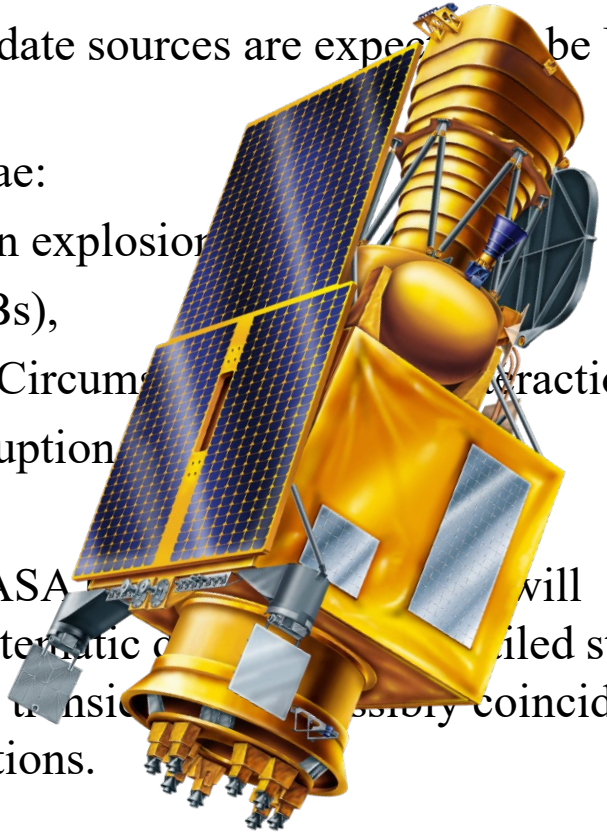


A handful of ν-γ associations for the nearest, yet quite distant – 0.5 Gpc, sources, will not enable a systematic detection and study of the transient sources.

Sensitive, wide FOV UV/Optical surveys are key for systematic study and understanding.

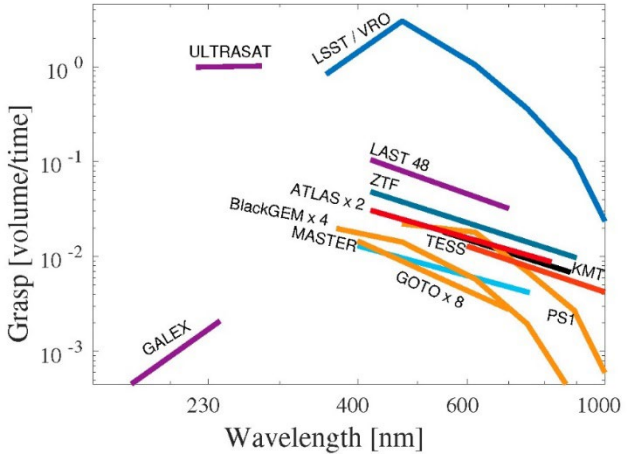
Identifying >10 TeV transient sources: UV/Optical surveys open new opportunities

- Many candidate sources are expe[c]ted to be UV bright.
  - Supernovae:
    Jet-driven explosion (LL GRBs),
    Ejecta – Circumstellar interaction,
  - Tidal disruption
- The ULTRASAT will enable a systematic detailed study of these fast transients and possibly coincident ν/EM detections.



ULTRASAT

Transient detection volume accessible to leading surveys



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Sensitive, wide FOV UV/Optical surveys are key for systematic study and understanding.

Summary

- HE ν astronomy has the potential to
  - Provide unique constraints on models of HE astrophysical sources, and
  - Identify the sources of (very) HE cosmic-rays.
- Fulfilling the potential relies on the EM identification of the neutrino sources.

- M_{eff}~10 Gton @ $10^5 - 10^8$GeV (IceCube Gen2 + KM3NeT/ GVD/ P1/ TRIDENT/ HUNT) is required to
  - Detect multiple events from few nearby sources (eg starbursts),
  - Possibly detect luminous transients (GRB/TDE-jet) contributing ~1% of the flux,
  - Obtain accurate ν spectrum, angular distribution and flavor content.

- EM follow-up observations may identify hour-day long transient sources, e.g. SN CSM breakouts.
  Crucial for a systematic study of the sources.
  EM detector requirements: FOV > 1deg^2, Sensitivity better than 10^{-13} erg/cm^{2}s.
  - May be possible at X-ray (XRT, EP-FXT), marginal at sub-TeV (CTA).
  - UV/O (ULTRASAT) surveys are key for systematic study.

- 10^8 – 10^{10} GeV: A flux measurement (10^{-9}GeV/cm^{2}s sr) will constrain the UHE CR composition (Radio: ANITA/ARA/ICGen2/ARIANNA/RNO-G/PUEO/GRAND/BEACON).