

High-energy astrophysical neutrinos

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High Energy ν astronomy: Goals, Status

- Key Goals:
 - Identify the sources of (ultra) high energy cosmic rays, $>10^{19}$ eV
 $p(A) + \gamma(p) \rightarrow \pi^\pm \rightarrow e^\pm + \nu_e(\bar{\nu}_e) + \nu_\mu + \bar{\nu}_\mu$; $E_\nu \approx E_{p(n)}/20$
 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 $\rightarrow \nu_e:\nu_\mu:\nu_\tau = 1:2:0$ (propagation) $\rightarrow \nu_e:\nu_\mu:\nu_\tau = 1:1:1$
- This talk- status overview:
 - Key observational results and their limitations
 - Theoretical implications
 - Open questions
 - Way forward

Observations: I. Key results

Flux & Spectrum

- 50 TeV – 1 PeV, all flavor
 $E^2\Phi_\nu \approx 4 \times 10^{-8} \text{ GeV}/(\text{cm}^2 \text{s sr}).$
- Possible suppression at $E > 1 \text{ PeV}$.
- 10 – 30 TeV : Flux enhanced by $\times 2\text{-}3$.

Flavor ratio

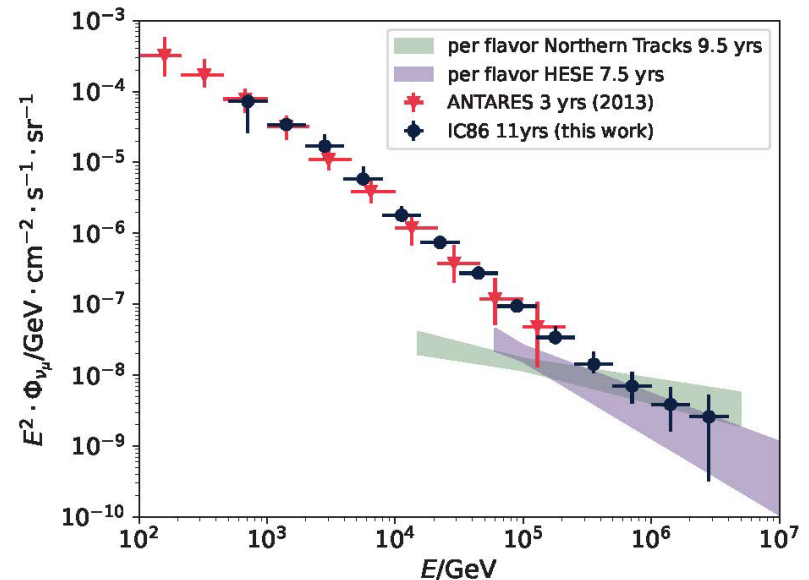
- Consistent with $\nu_e:\nu_\mu:\nu_\tau = 1:1:1$

Angular distribution

- Consistent with Isotropy.
- ** Initial $\sim 4\sigma$ detection of a Galactic disk component ($<10\%$ of the flux).
- The flux is most likely dominated by XG sources.
- A lower limit on steady source density:

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

IC 25, ν flux per flavor



Observations: II. Limitations

Flux & Spectrum

- 10 TeV – 1 PeV spectrum measurement is crude.
- No flux measurement at $10^8 - 10^{10}$ GeV.
A flux measurement (10^{-9} GeV/cm²s sr) will constrain the UHE CR composition.

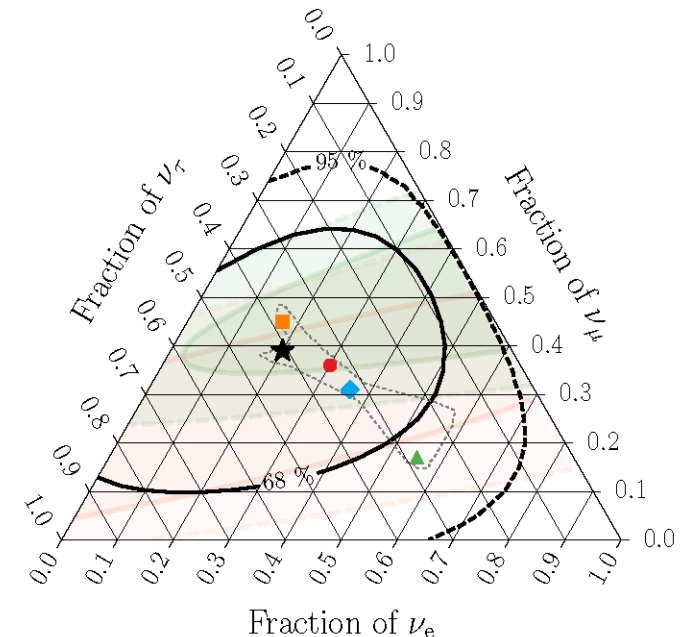
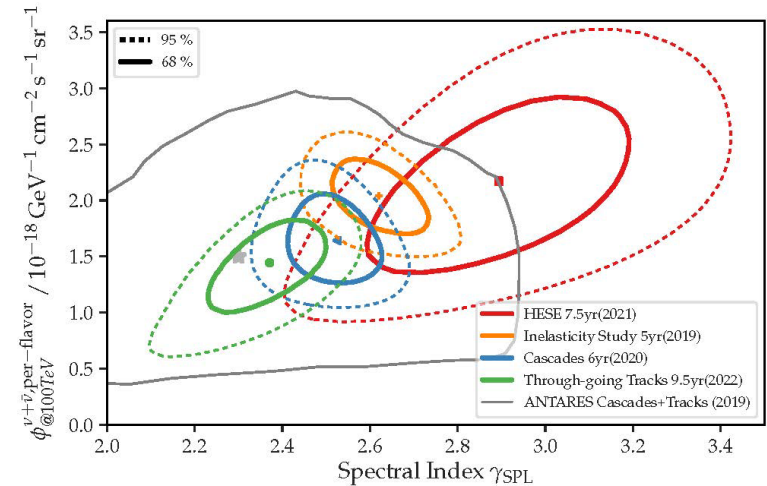
Flavor ratio

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

Sources

- The sources dominating the flux have not been identified.

IC & ANTARES, spectral index



Implications: I. 50 TeV – 1 PeV

- $\Phi_\nu \approx \Phi_{\text{WB}} \rightarrow$

$$E_\nu^2 \dot{n}_\nu(z=0, 100 \text{ TeV}) \approx 2 \times 10^{43} \frac{\text{erg}}{\text{Mpc}^3 \text{yr}}$$

$$\approx 0.5 E_{\text{CR}}^2 \dot{n}_{\text{CR}}(10^{10.5} \text{ GeV})$$

$$\approx 0.1 E_{\text{CR}}^2 \dot{n}_{\text{CR}}(10 \text{ GeV}).$$

- The sources may be related, but no direct evidence.
- Two classes of models.

- $\Phi_\nu \approx \Phi_{\text{WB}}$ is a coincidence,

$$E_{\text{CR}}^2 \dot{n}_{\text{CR}}(1 \text{ A PeV}) \gg E_{\text{CR}}^2 \dot{n}_{\text{CR}}(10^{10} \text{ GeV}),$$

a small fraction of 1 A PeV CR energy converted to ν 's:

$$E_\nu^2 \dot{n}_\nu = f_\nu E_{\text{CR}}^2 \dot{n}_{\text{CR}}(1 \text{ A PeV}), \quad f_\nu \ll 1.$$

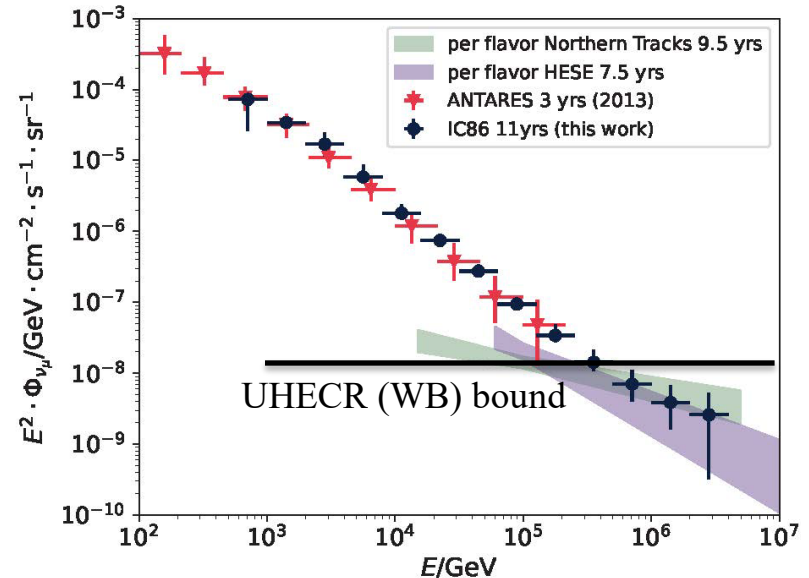
- $\Phi_\nu \approx \Phi_{\text{WB}}$ is not a coincidence, the sources are related,

$$E_{\text{CR}}^2 \dot{n}_{\text{CR}}(1 \text{ A PeV}) \approx E_{\text{CR}}^2 \dot{n}_{\text{CR}}(10^{10} \text{ GeV}),$$

and the sources reside in calorimetric environments for <1 PeV rigidity:

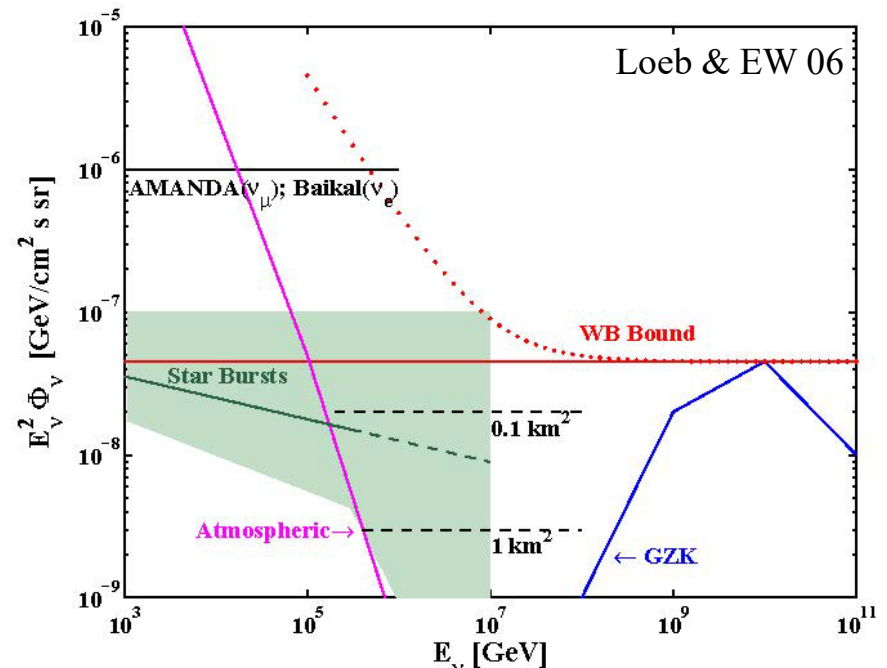
$$E_{\text{CR}}^2 \dot{n}_{\text{CR}}(1 \text{ A PeV}) \approx E_{\text{CR}}^2 \dot{n}_{\text{CR}}(10^{10} \text{ GeV}), \quad f_\nu \approx 1.$$

IC 25, ν flux per flavor



A plausible explanation

- Much of cosmic star formation occurred in transient starburst episodes ($z \sim 1-2$).
 - $L_{\text{CR}} \propto \text{SFR}$ (MW – starbursts)
 - Starbursts are hadronic calorimeters for $E > \sim 1 \text{ A PeV}$ (large B , Σ)
- The WB bound was predicted to be saturated at $E < 1 \text{ PeV}$.
- The predictions relies on known sources, with no large/small free parameters.
- Main uncertainty: $z \sim 1.5$ galaxy properties.
- The ν 's are produced in the ISM, not at the source.



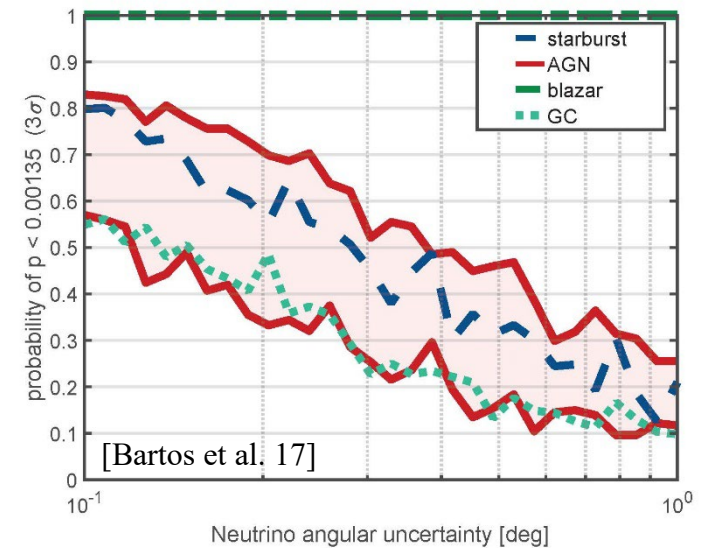
Implications: II. 10 – 30 TeV

- $\Phi_\nu \approx 2\Phi_{\text{WB}}$ 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 [Murase, Ahlers, Lacki 13].
- Suggests the existence of “hidden sources” at < 30 TeV, from which ν ’s escape but γ ’s don’t.

The challenge of identifying steady ν sources: (10 km² x 10 yr) required

- $\frac{N_\nu(<z)}{N_\nu} \approx \frac{1}{3}z$ for $z \ll 1$,
 $\rightarrow N(\text{track}, >50\text{TeV}, <300\text{Mpc}) \approx 10$.
- The number of events from the nearest source

$$N_{\text{near}} \approx 0.3 \left(\frac{n_s}{10^{-5} \text{Mpc}^{-3}} \right)^{-1/3}$$
 (proper stacking increases S/N by $\times \sqrt{3}$).
 $\rightarrow$ A 10 km² detector is required for a detection of a handful of events from nearby sources.



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

Candidate source detections

- A $\sim 3\sigma$ association, including a 300 TeV ν – a Blazar (TXS 0506+056)
 - Models challenged by X- and γ - ray observations [e.g. Murase 18, Oikonomou et al. 19].
 - Blazars do not dominate the background [e.g. IC 17].
- A $\sim 4\sigma$ association, <10 TeV – an obscured AGN (Seyfert, NGC1068) @ 10 Mpc (2 lower significance associations [Neronov et al. 24]).
It may also be a “hidden” gamma-ray source.

NGC1068 association: I. Statistics challenges

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

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

→ If the association is real, we are lucky to have a nearby 100 times brighter than a typical source.

** The 4.2σ significance of the association did not increase with $\sim 50\%$ exposure increase (decreased to 4.0σ , while it should have increased to 5σ).

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

NGC1068 association: II. Physics challenges,

$$L_{CR} \sim L_{Eddington} \sim 10L_X$$

- $L_\nu \sim 100 L_\gamma$ is much larger than $L_\nu \sim L_\gamma$ predicted for Starbursts.
New models suggested, emission associated with the AGN (Seyfert) activity.
 - Models postulate ν production at the $\sim 10 R_s$ 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]
 - $100 \text{ TeV } p + \sim 1 \text{ keV } \gamma \rightarrow \sim 5 \text{ TeV } \nu$
 $100 \text{ TeV } p + \sim 10 \text{ eV } \gamma \rightarrow e^\pm$
$$\frac{L_\pi}{L_\pm} \approx \frac{L_X}{L_{UV}} \approx 10^{-1.5}$$

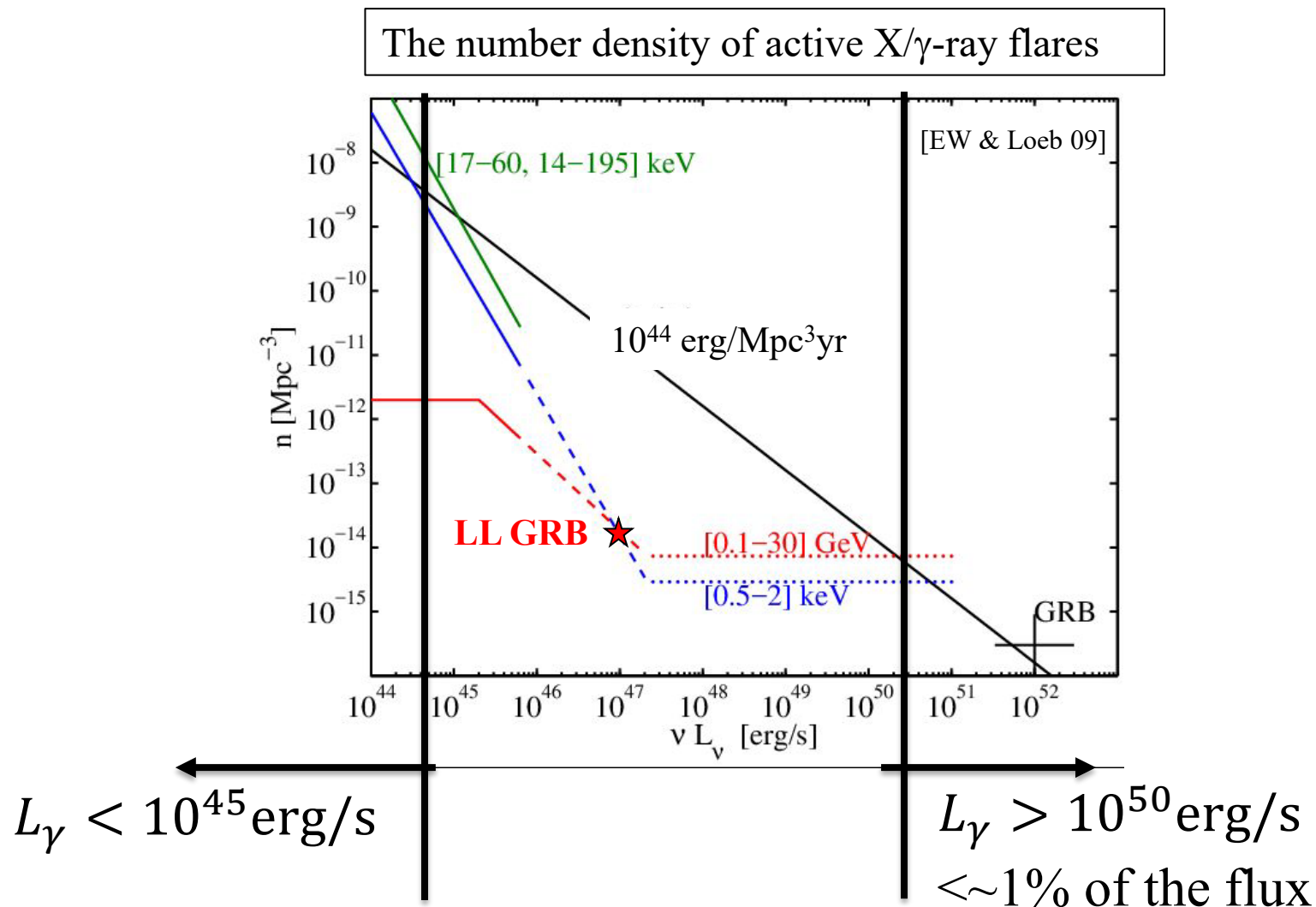
since $(dE/E \times \sigma / \epsilon_\gamma)$ similar for pion & for pair production.
- $L_{CR}(\sim 100 \text{ TeV}) \approx 2 L_\nu \frac{L_{UV}}{L_X} \approx 10^{44} \text{ erg/s} \approx 0.1 L_{Eddington}$
- $$L_{CR}(1\text{GeV} - 100\text{TeV}) \approx L_{Eddington} \approx 10L_X$$
- This would imply a modification of our basic understanding of AGN physics.
(Cutting off the CR spect. at 30TeV and the UV at 30eV requires fine-tuning, limits ν 's to $< \sim 1 \text{ TeV}$, and requires $L_{CR} \sim L_X$).

Near-term main hope: transient sources

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

Identifying >10 TeV transient sources:

Which X/ γ -ray flares are viable candidates?



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

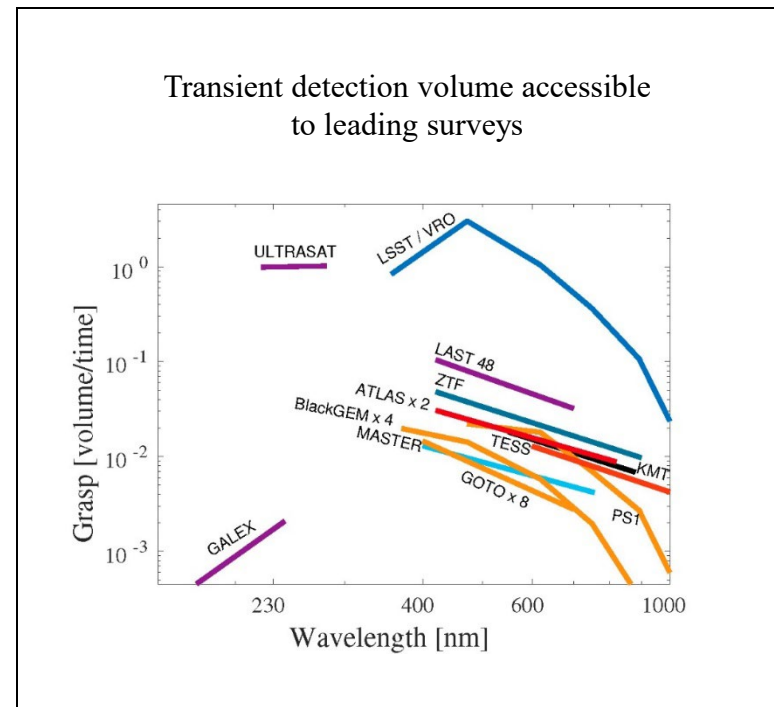
- A handful of events per year- requires detection of $d > 1$ Gpc sources.
- $L_\gamma < 10^{45}$ erg/s (assuming $L_\nu \leq L_\gamma$) $\rightarrow$ required sensitivity:
$$f_\gamma < \frac{10^{44} \text{ erg/s}}{4\pi(1\text{Gpc})^2} = 10^{-12} \text{ erg/cm}^2\text{s}$$
- May be possible with SWIFT-XRT (~ 1 keV; 0.1 sq. deg FOV; $\sim 10^{-13}$ erg/cm²s @ 3hr), and with EP-FXT (~ 1 keV; 1 sq. deg FOV; $\sim 10^{-13}$ erg/cm²s @ 10³s).
Challenging for NuSTAR and SVOM.

Well below the sensitivity of

BAT/GBM (~ 1 MeV), Fermi LAT (~ 1 GeV), 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.



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.

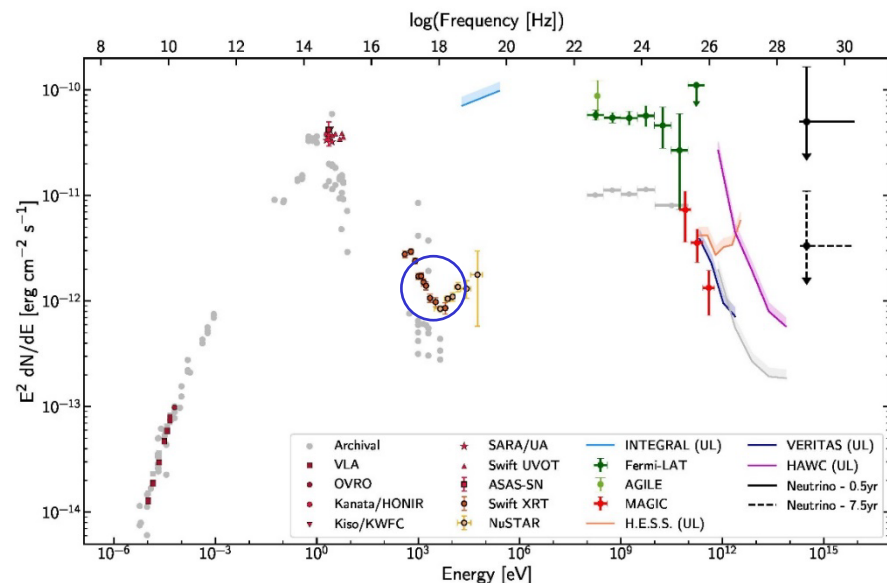
Summary

- 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.
- $M_{\text{eff}} \sim 10 \text{ Gton} @ 10^5 - 10^8 \text{ GeV}$ (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 $\sim 1\%$ 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: $\text{FOV} > 1 \text{ deg}^2$, Sensitivity better than $10^{-13} \text{ erg/cm}^2\text{s}$.
 - May be possible at X-ray (XRT, EP-FXT), marginal at sub-TeV (CTA).
 - UV/O (ULTRASAT) surveys are key for systematic study.
- $10^8 - 10^{10} \text{ GeV}$: A flux measurement ($10^{-9} \text{ GeV/cm}^2\text{s sr}$) will constrain the UHE CR composition (Radio: ANITA/ARA/ICGen2/ARIANNA/RNO-G/PUEO/GRAND/BEACON).

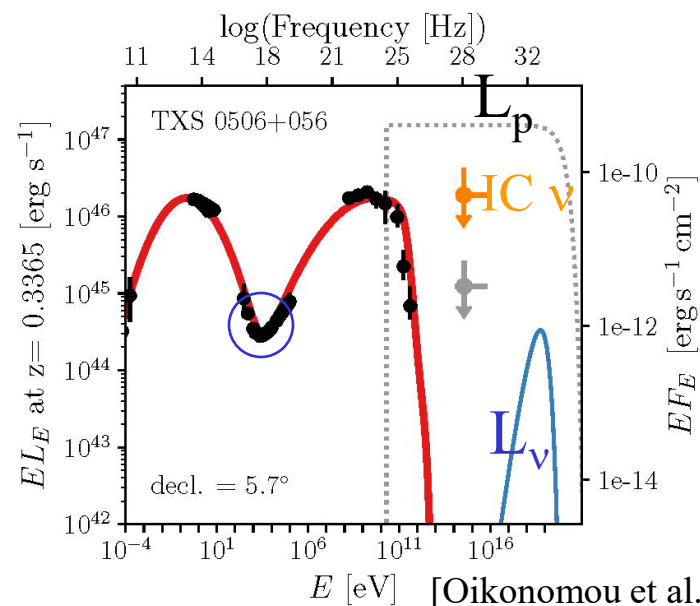
Backup Slides

The association with TXS 0506+056 is likely a coincidence

- The escape of high-energy γ 's limits the density of target photons for $p\gamma$, implying $L_v \ll L_p$ 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 , $L_p \ll 10^4 L_\gamma$
- 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]

Star forming galaxies: candidate CR calorimeters

- Starbursts: $(n, B, \text{SFR}) / (n, B, \text{SFR})_{\text{MW}} \sim 100\text{-}1000$; $\text{SFR} \sim 100 M_{\text{sun}}/\text{yr}$.
- Radio, IR & γ -ray (GeV-TeV) observations
→ Starbursts are calorimeters for E/Z reaching (at least) 10TeV.
- Theoretical estimates of $f(p \rightarrow \pi)$:
Scaling from the MW → $f=1$ to $E > 1\text{PeV}$ for $\Sigma_{\text{disk}} > 0.03 \text{ g/cm}^2 \equiv \text{"starburst"}$.
- Most of the stars in the universe were formed in galaxies with high SFR.
If $Q_{\text{CR}} \sim \text{SFR}$ Then $\Phi_{\nu}(\epsilon_{\nu} < 1\text{PeV}) \sim \Phi_{\text{WB}}$ [Loeb & EW 06; He 13; Liu 14; Senno et al. 15] .
- Main contribution: $z=1\text{--}2$ star-forming galaxies.
Main Uncertainty: Fraction of stars formed in calorimetric environments.
CO observations of $z=1.5$ 'average' galaxies [e.g. Daddi et al 10]:
 $\text{SFR} \sim 100 M_{\text{sun}}/\text{yr}$, molecular disks with $\Sigma \sim 0.1 \text{ g/cm}^2$,
supportive but with large uncertainties.