Extra-Galactic ~~& Galactic~~ High Energy ν Astronomy: Key open questions

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Sep 2024

The key goals of High Energy ν astronomy

- Identify the sources of (very) high energy (HE) cosmic-rays,
- Provide unique constraints on models of HE astrophysical sources,
- Possibly: Study ν/fundamental physics.

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

50 TeV - 1 PeV

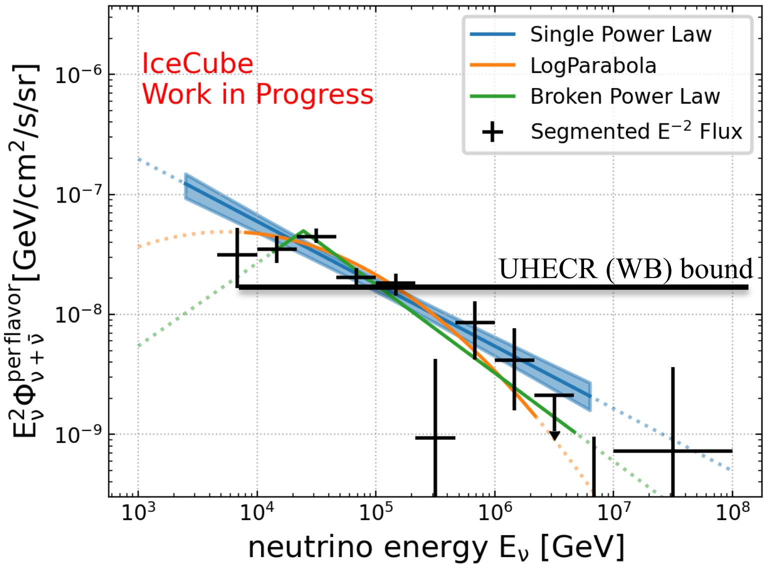
- The energy production rate densities in the local universe in ~ 100 TeV ν's and in $>10^{10}$ GeV CRs are similar:

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

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

- Flux dominated by many weak sources: $n_s > 10^{-7}$/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.

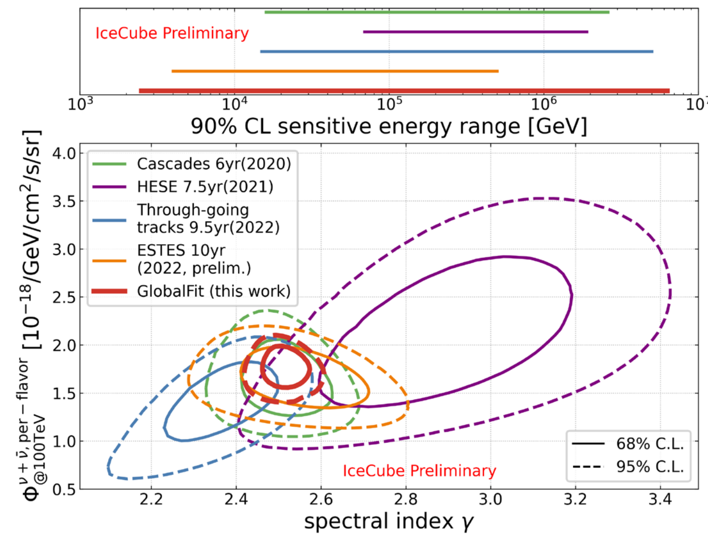
→ Suggests the existence of "hidden sources", from which ν's escape but γ's don't.

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 23, 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.
- One 3σ association, including a 300TeV ν – a Blazar (TXS 0506+056)
  - Models challenged by X- and γ- ray observations [e.g. Murase 18] .
  - Blazars cannot dominate the background [see Grrappa's talk, cf. Buson's talk].
- One 4σ association, <10 TeV – an AGN (Syefert)/Starburst galaxy (NGC1068)
  - A hidden γ-ray source, L_ν >~ 30 L_γ (1 GeV – 1 TeV)

NGC1068 association challenges: I. Physics $L_{CR} \sim L_{Eddington}$

- 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]

- 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

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

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

- This would imply a modification of our basic understanding of AGN physics (and, Acceleration mechanism not known).

NGC1068 association challenges: II. Statistics
NGC1068 must be an exceptional ν source

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

$$2 \times 10^{42}\text{erg/s} \times (10^{-4}\ \text{Mpc}^{-3}) = 6 \times 10^{45}\text{erg/Mpc}^3\text{yr}$$

- The average cosmic ν luminosity within a 10Mpc sphere is

$$10^{44}\text{erg/Mpc}^3\text{yr x (10 Mpc sphere)} = 10^{40}\text{erg/s} .$$

The inferred ν luminosity of NGC1068 is 2×10^{42}erg/s

→ NGC1068 is exceptionally (100 times) brighter than typical
(not exceptionally close at ~10 Mpc for source density >~ 10^{-4} Mpc^{-3})

ν's from Supernova driven shocks: Alternative "γ-ray hidden" sources of >~10 TeV ν's

- Collisionless SN shocks driven into the circum/inter stellar medium (CSM/ISM) are likely CR accelerators
- CR-CSM/ISM pp interaction is a likely source of ν's

[e.g. Murase et al. 11; Petropoulou et al. 17; Sarmah et al. 22]

- For typical CSM wind/ISM
  - ν emission over months-years
  - Low ν luminosity, small contribution to the ν background
  - Accompanied by HE γ-rays (low pair production optical depth)

- Much larger ν luminosity may be produced if the progenitor star is surrounded by a compact optically thick CSM

[Katz, Sapir & EW 11, Li 19]

Evidence for the prevalence of optically thick CSM at ~$10^{14.5}$ cm around Type II SN progenitors

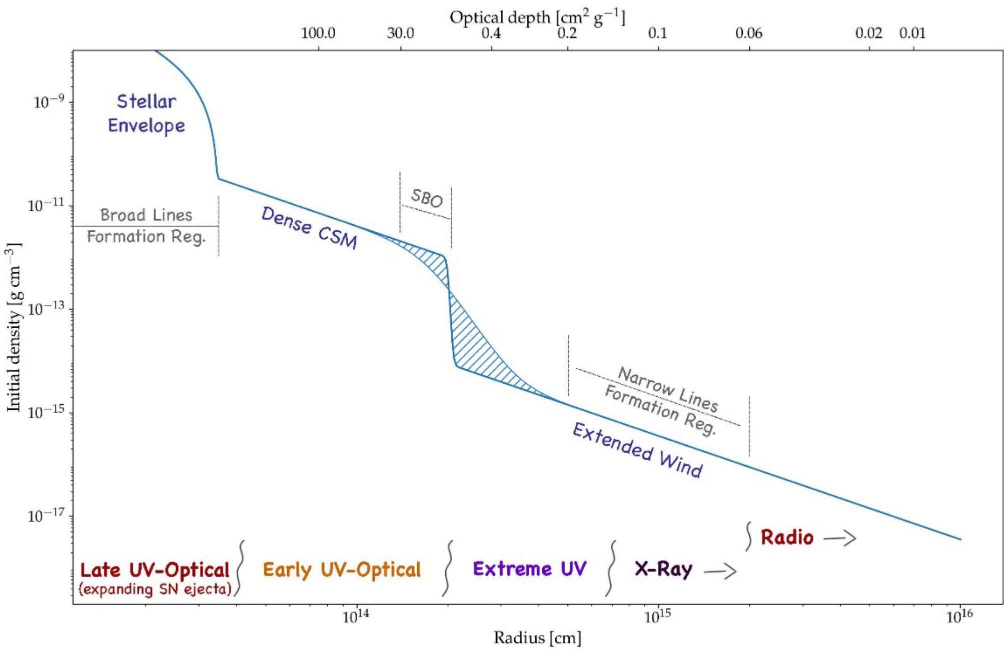
- Most type IIn SN progenitors show >10^{47}erg precursors, ~1yr preceding SN
  Unbinding ~0.1-1 solar mass, ejected to ~(100km/s x 1 yr =) $10^{14.5}$ cm

  [Strotjohannet al. 21]
- 50% of regular type II SNe show a slow, ~3-d, rise of the light-curve to large, ~$10^{43.5}$erg/s, UV luminosity –
  A SN shock breaking through an optically thick CSM,
  ~ 0.1 solar mass out to ~(10,000km/s x 3-d) = $10^{14.5}$ cm

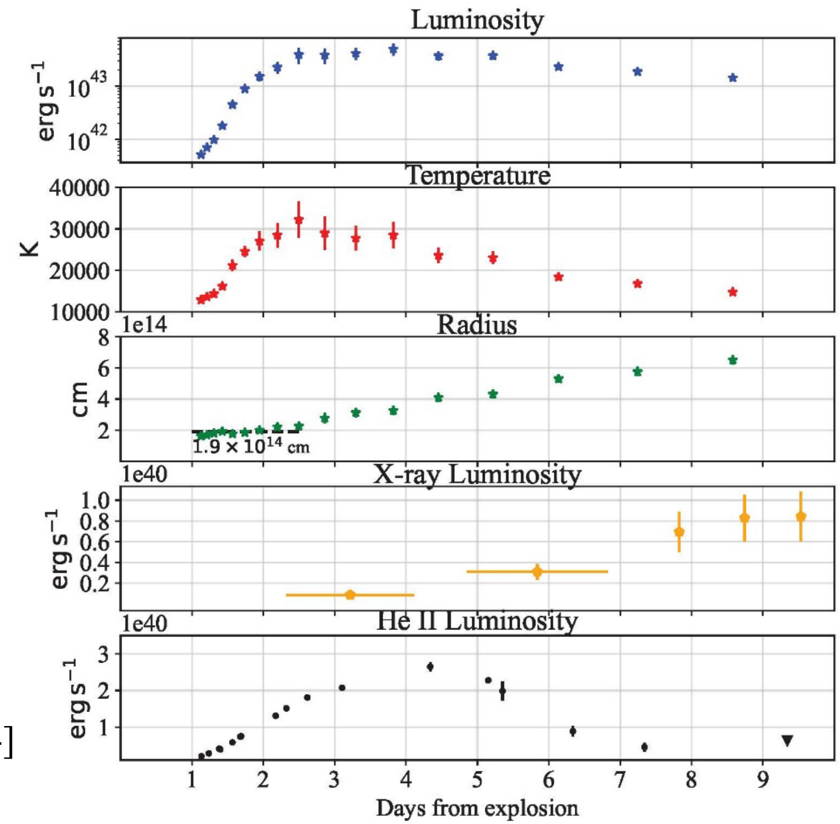
  [Irani et al. 24]
- >50% of regular type II SNe show narrow lines of ionized species, disappearing after ~2-3 days –
  Emission from ~0.1 solar mass CSM excited by the shock UV luminosity,
  disappearing after shock crossing at ~(10,000km/s x 3-d) = $10^{14.5}$ cm

  [Bruch et al. 23]

SN 2023ixf, 6.4 Mpc



[Zimmerman et al. 24]



ν's from SN shock breakouts through compact optically thick CSM

- ν's produced by pp collisions during and shortly after the transition of the SN shock from being radiation-mediated to collisionless

$$L_{br,\,UV} \sim 10^{43.5}\ \mathrm{erg/s}, \quad L_{br,\,\nu} \sim 0.05\, L_{br,\,UV}, \quad \Delta t \sim 3\mathrm{d}$$

- Significant contribution to the >~10 TeV ν background if ~0.1 solar-mass ejection is prevalent on a year time scale preceding explosion

$$0.05 \times 10^{43.5}\ \mathrm{erg/s} \times 3\mathrm{d} \times (10^{-4}\ /\mathrm{Mpc}^3\ \mathrm{yr}) = 5 \times 10^{43}\ \mathrm{erg/Mpc}^3\ \mathrm{yr}$$

- The pair production optical depth at >100GeV is > 10^4, due to the compact size and large UV luminosity

- The rate of SNe producing >1 (ν induced μ) events in a 1 km^2 detector is <~1/10yr (SN 2023ixf – 0.2 ν induced μ). A single association will be significant at 99.9% CL.

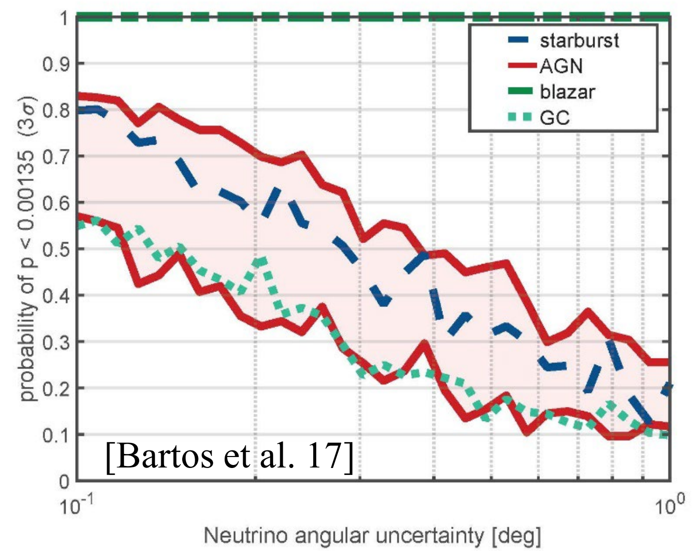
[EW et al. 24]

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.

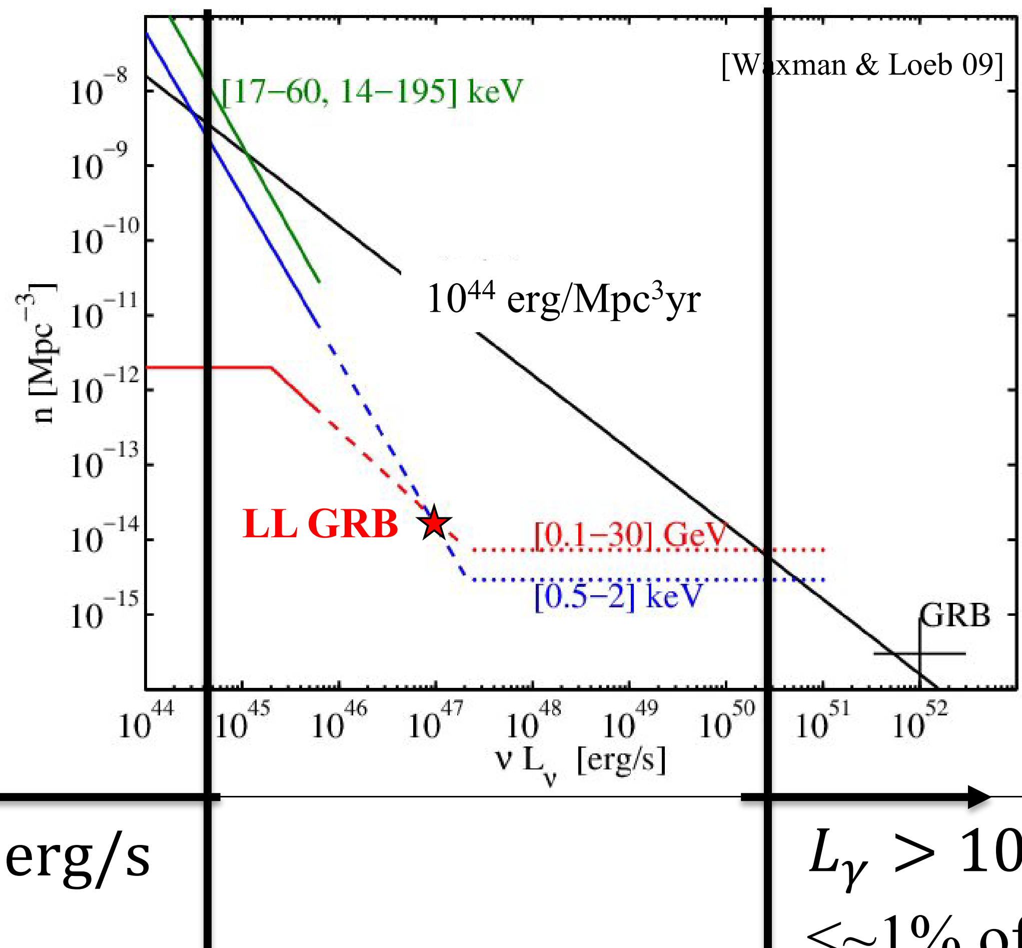
- (10 km^2+ $\Delta\theta$ <0.5 deg) X 10yr
  + complete source catalog to 200 Mpc
  required for a 3σ association with nearby sources.



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

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

Identifying >10 TeV transient sources: Unlikely with X/γ–ray observations

- Coincident ν/EM transient detection increases the significance of an angular association for transient duration Δt ~ days << T ~ 1yr.

- A handful of events per year- d>1Gpc sources.
  $L_\gamma < 10^{45}$erg/s (assuming $L_\nu \leq L_\gamma$).

→ The required sensitivity:

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

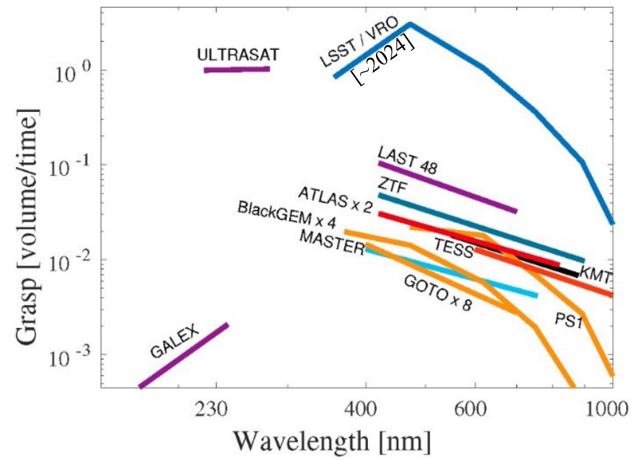
- May be possible with XRT (~1keV; 0.1 sq. deg FOV).
  Well below the sensitivity of
  BAT/GBM (~1MeV), Fermi LAT (~1GeV), HESS, MAGIC, LHAASO (sub-TeV).
  Marginal for CTA/LST (sub-TeV).

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.

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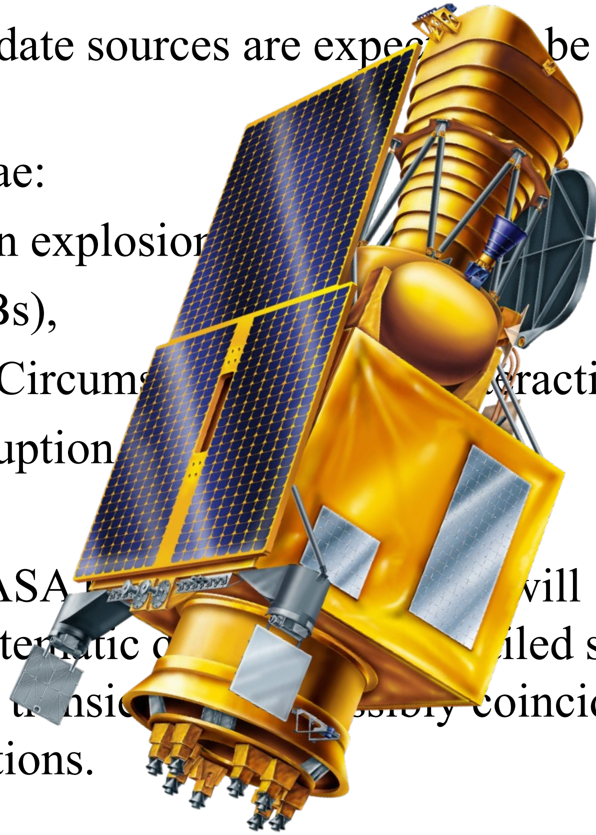

ULTRASAT

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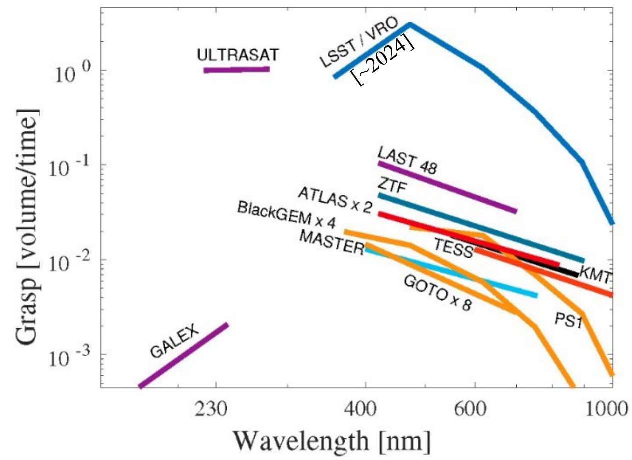

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Summary

- 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) 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), 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).