Electro-magnetic transient surveys: A key to progress in High Energy ν astronomy

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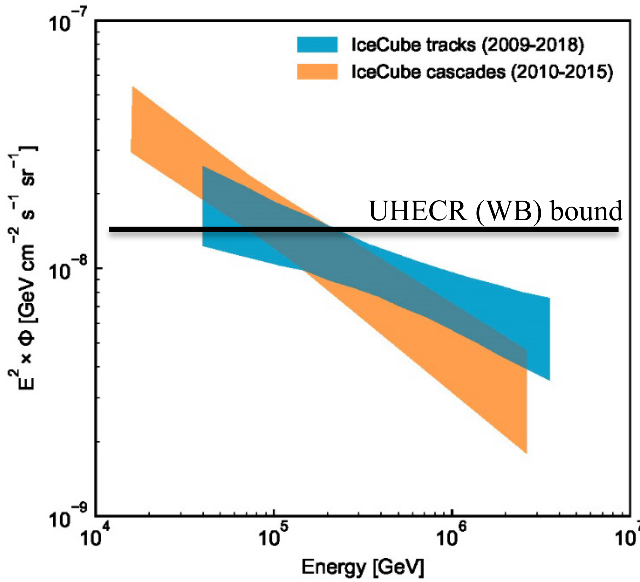
IceCube's extra-Galactic ν's: What we have learned

~ 50 TeV – ~ 3 PeV

- The energy production rate density in the local universe in ~ 100 TeV ν's and in >10^{10} GeV CRs is similar: ~10^{44}erg/Mpc^{3}yr ($\Phi \approx \Phi_{WB}$):
  Suggests that
  - ν's and HE CRs produced by the same sources;
  - HE CR sources reside in "calorimetric" environments, most likely star-forming galaxies, where 1(E/Z) PeV CRs lose all their energy to pion
- No "point sources" (multiple event sources) identified.
  Flux dominated by many weak sources: $n_s > 10^{-7}$/Mpc^3, $L_\nu < 10^{42.5}$ erg/s.

ν flux per flavor



~ 20 TeV

- $\Phi \approx 2\Phi_{WB}$ and is in tension with the 100 GeV γ background.
  Suggests the existence of "hidden sources", from which only (mainly) ν's escape.

The key goals of HE ν astronomy

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

The detection of high energy (HE) extra-Galactic neutrinos by IceCube demonstrates the potential for achieving these goals.

Fulfilling the potential relies on the electromagnetic identification of the neutrino sources.

Extra-Galactic ν‘s: What we are missing

<u>10 TeV – 10 PeV</u>

- The sources have not been identified.
  - Indication (<3σ) for an association with one blazar, and one SFR/AGN galaxy. Blazar association- Buson’s talk- some caveats & inconsistencies remaining.
  - Blazars may contribute to, but cannot dominate, the flux.

- The spectrum measurement is crude.
  - A single power-law or multiple “breaks”?

- The flavor ratio measurement is crude.
  - Consistent with 1:1:1.

<u>10^8 – 10^{10} GeV</u>

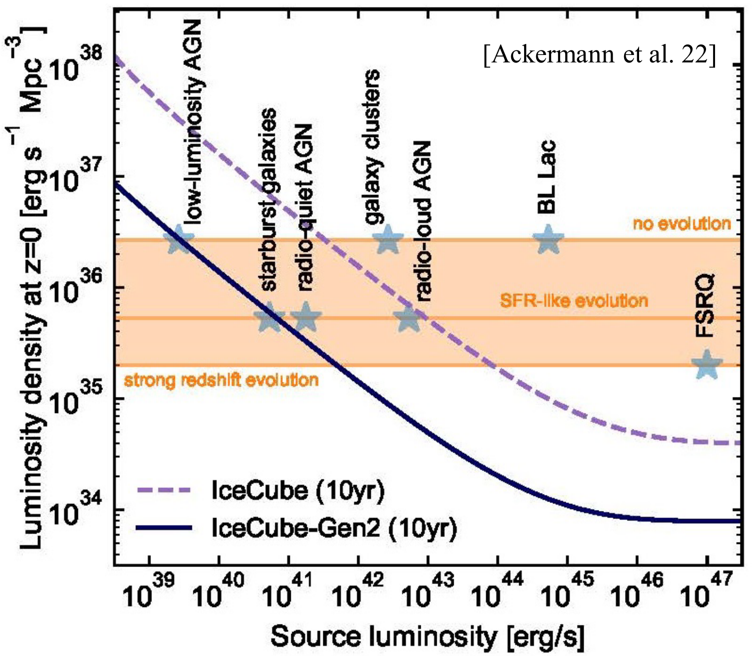
- A flux measurement (10^{-9}GeV/cm^{2}s sr) will constrain the UHE CR composition.

Identifying the sources: An order of magnitude increase in the detected ν number is required

- Measured flux implies a (z=0) luminosity density $n_s L_\nu \approx 10^{43.5}\text{erg/Mpc}^3\text{yr}=10^{36}\text{erg/Mpc}^3\text{s}$.
- $N(\text{multiple tracks})=1\left(\frac{\zeta}{3}\right)^{-\frac{3}{2}}\left(\frac{n_s}{10^{-7}\text{Mpc}^{-3}}\right)^{-\frac{1}{2}}\left(\frac{A}{1\text{km}^2}\right)^{\frac{3}{2}}$

  $\Rightarrow n_s > \frac{10^{-7}}{\text{Mpc}^3}\left(\frac{A}{1\text{km}^2}\right)^3, \; L_\nu < 10^{42.5}\text{erg/s},$

  $N(\text{all sky})>10^6$.
- Rare bright sources (eg “blazars”)- Ruled out as the dominant sources.



An order of mag increase in sensitivity is required to detect multiple events from nearby sources with $n_s \sim 10^{-5}/\text{Mpc}^3$ (eg starbursts).

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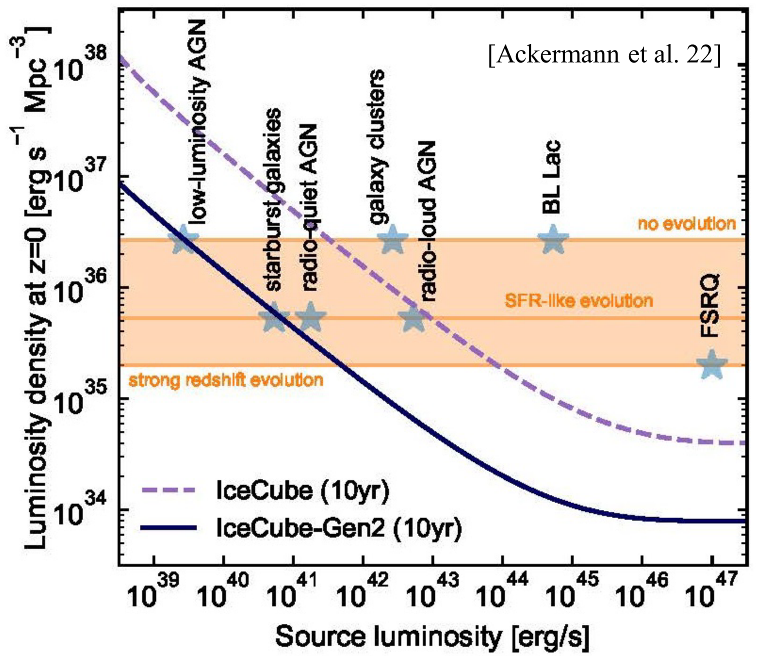

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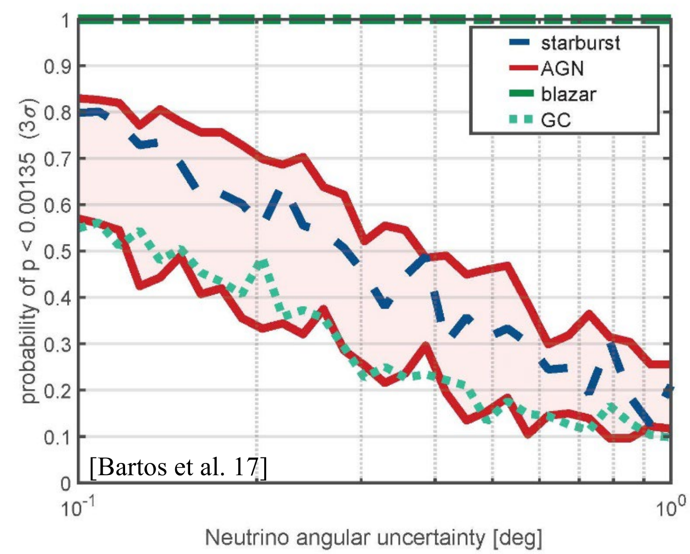
Can we make progress towards source identification before this is achieved (in ~2040)?

Source identification by angular correlation with EM source catalogs: Unlikely.

- ν track direction uncertainty ~ 1 deg,
  50% of ν's produced beyond $z \approx 1$, $d_L \approx 5$ Gpc,
  >>1 sources/deg^2.

- Can we look only at nearby sources, with lower angular sky density?
  - ≈5% of ν's produced by sources at d<0.5 Gpc
    → Only a handful of track events from d<0.5 Gpc sources.
  - Catalogs are highly incomplete already at 0.2 Gpc.



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

Can the sources be identified by temporal correlation with X/γ–ray flares?

- Coincident transient ν/EM detection increases the significance of an angular association, for transient duration $\Delta t \ll T \sim 1$yr.
  (Δt~ months- minor improvement.)

- The absence of neutrino point sources:

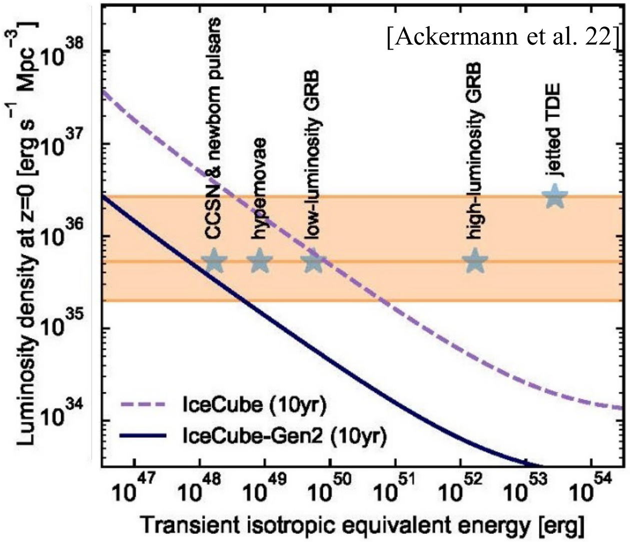
$$\dot{n}_s = \frac{n_s}{T} > \frac{10^{-7}}{\mathrm{Mpc^3 yr}}, \quad E_\nu = L_\nu T < 10^{50}\mathrm{erg}.$$

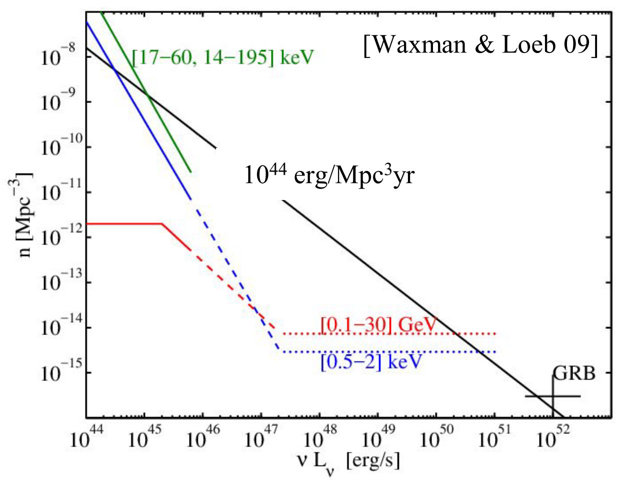
The number of active X/γ–ray flares:

$L_\gamma < 10^{45}\mathrm{erg/s}$ (assuming $L_\nu \le L_\gamma$).

The required sensitivity:

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





The number density of active X/γ-ray flares

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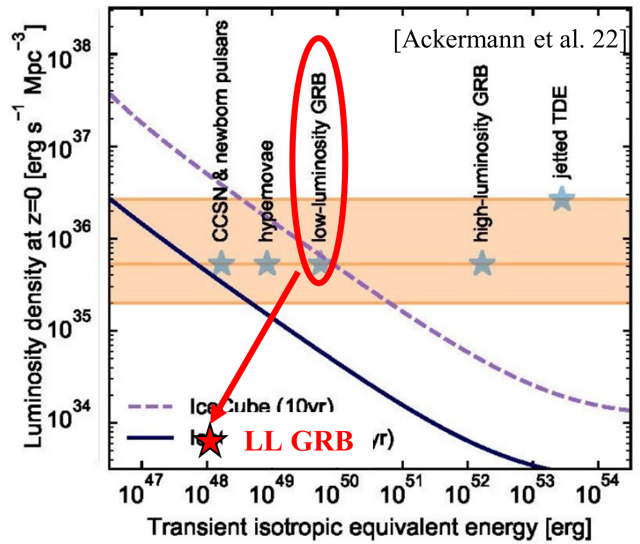
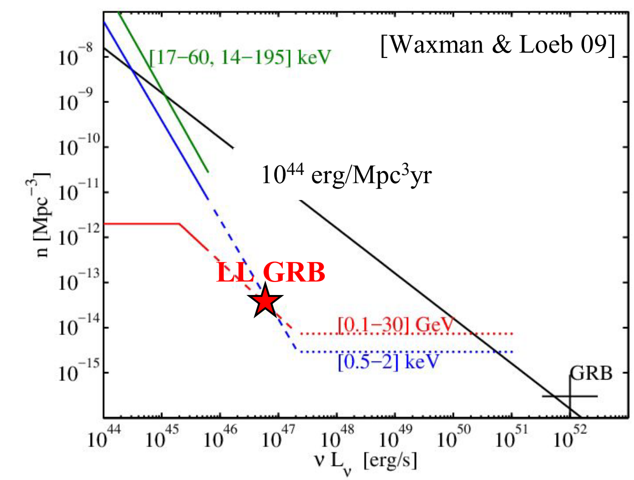
For LL GRBs to produce the observed ν flux, they need to produced 100 times more energy in ν's than in γ's.
This is not supported by any observation.





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- $\Delta t < 1$ min – Requires very wide FOV EM detectors for simultaneous observations.
  - BAT/GBM ~1MeV sensitivity ~ $10^{-8.5}$ erg/cm^{2}s, corresponding to 10^{48}erg/s at 1 Gpc.
    → Far from required sensitivity.
  - Fermi LAT ~1GeV sensitivity ~ 10^{-12} erg/cm^{2}s for 1yr integration.
    LHAASO sub TeV ($\tau_{\gamma\gamma}$=1 for 0.3 TeV @ 1Gpc) sensitivity ~ 10^{-11} erg/cm^{2}s for 1yr integration.
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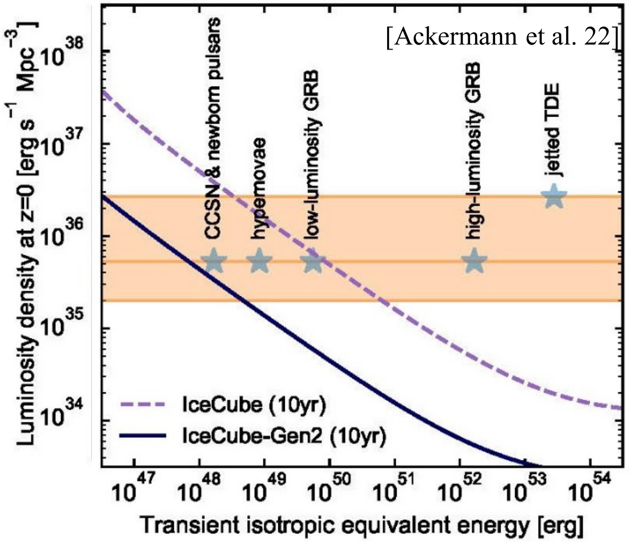

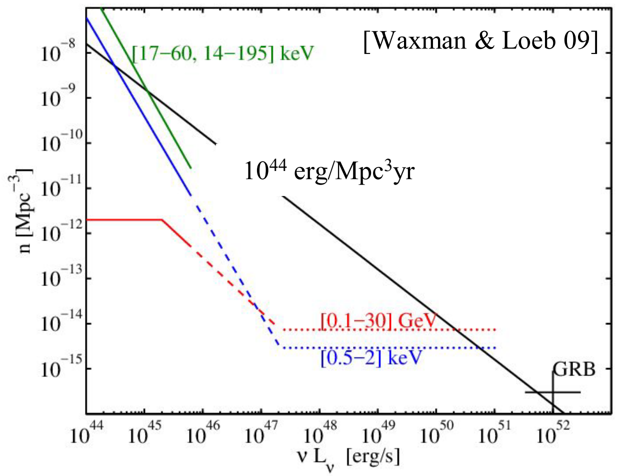

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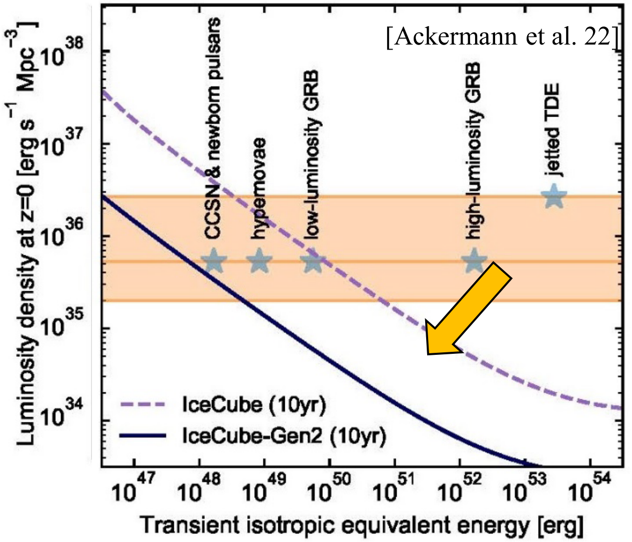
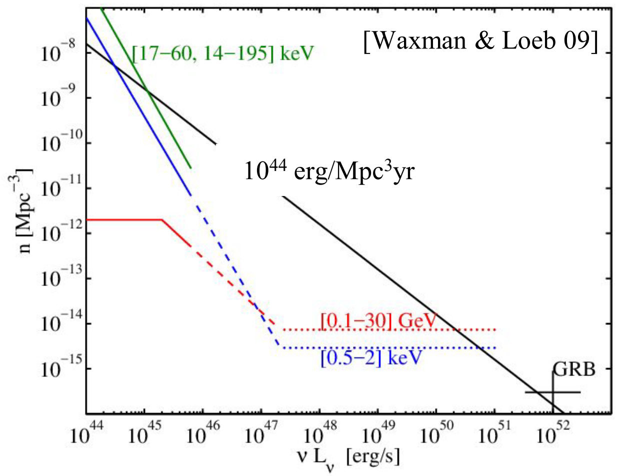
- Very bright transients, GRBs/TDE-jets, may be detectable. However, they contribute up to ~1% of the flux, i.e., up to ~1 ν.





The number density of active X/γ-ray flares

Can the sources be identified by temporal correlation with X/γ–ray flares? Possibly in X-rays, if bright.

- The required sensitivity:

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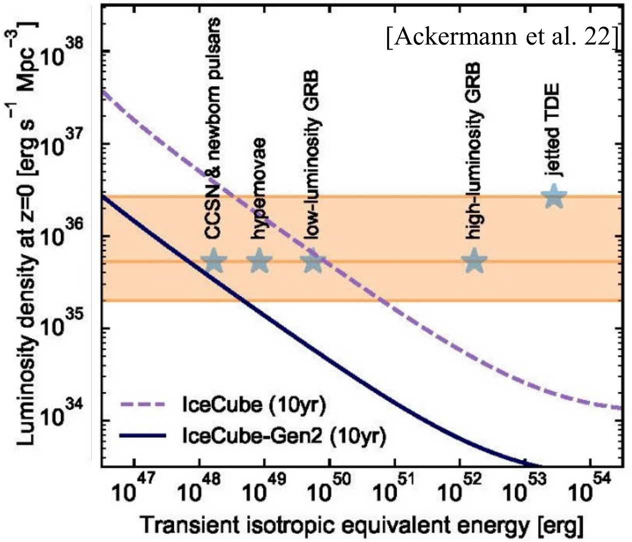
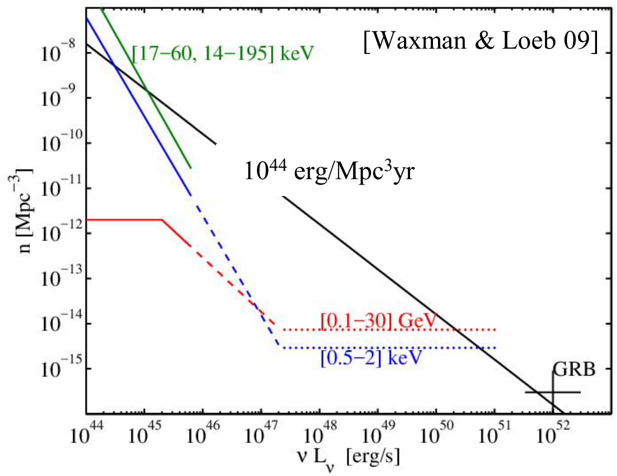
- $\Delta t \sim 1$ hr -1 d: Allows slewing ~1deg FOV detectors.

  - XRT ~1keV 3hr sensitivity ~ 10^{-13} erg/cm^{2}s,
    → A few transients may be detected, if bright enough.
    (NuStar FOV 10').

  - CTA (sub-TeV) 50 hr sensitivity ~ 10^{-12} erg/cm^{2}s,
    → Marginal.
    (HESS/MAGIC less sensitive).





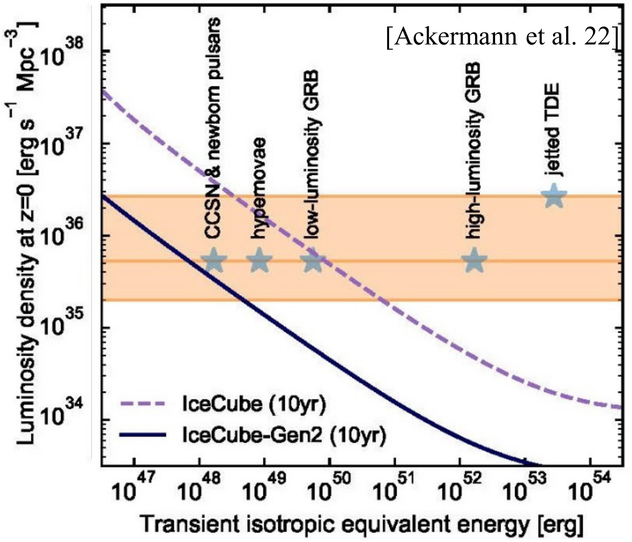
The number density of active X/γ-ray flares

Can UV/Optical transient surveys help identify the sources? Possibly.

- $\Delta t < 1$ min – Requires very wide FOV EM detectors.
  Not sensitive enough.

- $\Delta t \sim 1$ hr -1 d: Allows slewing.
  Requirements:
  - FOV > 1 deg^2,
  - Sensitivity much better than 10^{-13} erg/cm^{2}s.

  SWIFT UVOT – 0.1 deg^2, 5×10^{-15} erg/cm^{2}s (10^4s).



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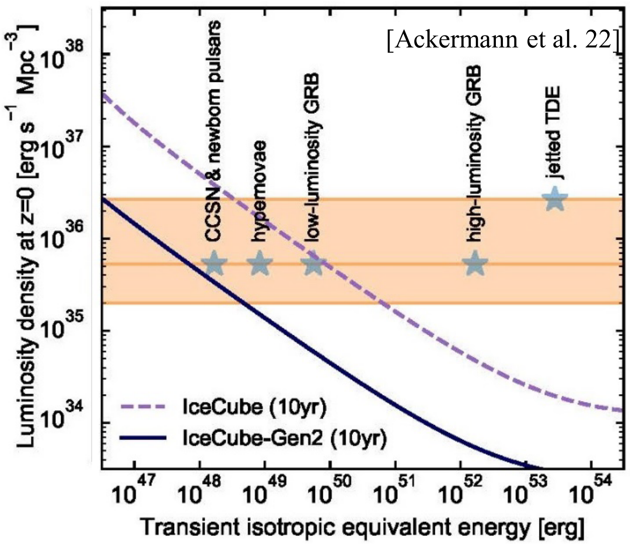


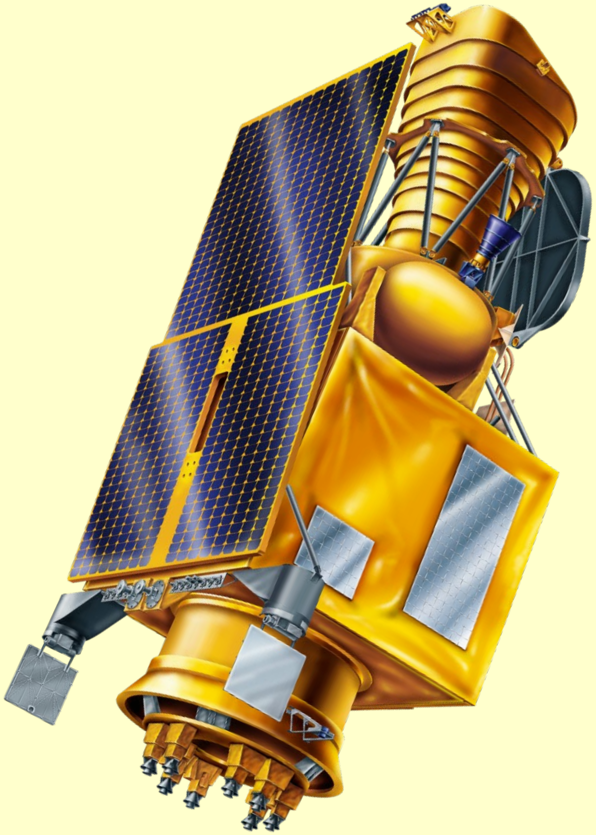
- Many candidate sources are expected to be UV bright.
  - Supernovae: Jet driven explosions,
    (LL GRBs),
    Ejecta – Circumstellar Medium interaction,
  - Tidal disruption events.

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.

ULTRASAT: A Wide-Field UV Space Telescope

Revolutionize our understanding of the hot transient Universe



PI	E. Waxman (WIS)
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Deputy PI	A. Gal-Yam (WIS)
Camera PI	D. Berge (DESY)
Project Scientist	Y. Shvartzvald (WIS)
Science Lead	E. Ofek (WIS)
Payload Lead	S. Ben-Ami (WIS)
Technology Lead	O. Lapid (WIS)

Funding partners
ISA
WIS
NASA
DESY

Industry partners
IAI
Elop
Tower

The study of Transient Cosmic Phenomena is taking Center Stage

An exciting frontier, many fundamental open questions

Sources	**Open questions**
Gravitational Wave sources NS-NS/BH mergers	- Physics of the sources of gravitational waves - Where did the heavy elements, Fe – U, form? - Current H_0
Supernovae	- How do massive stars explode and affect their environment?
Tidal disruption of stars (TDE) by super-massive black holes (SMBH)	- What is the SMBH "demographics"? - How do they affect their environment? - How is mass accreted onto BH?
…	…

Why now?

Technology enables telescopes with very large fields of view,

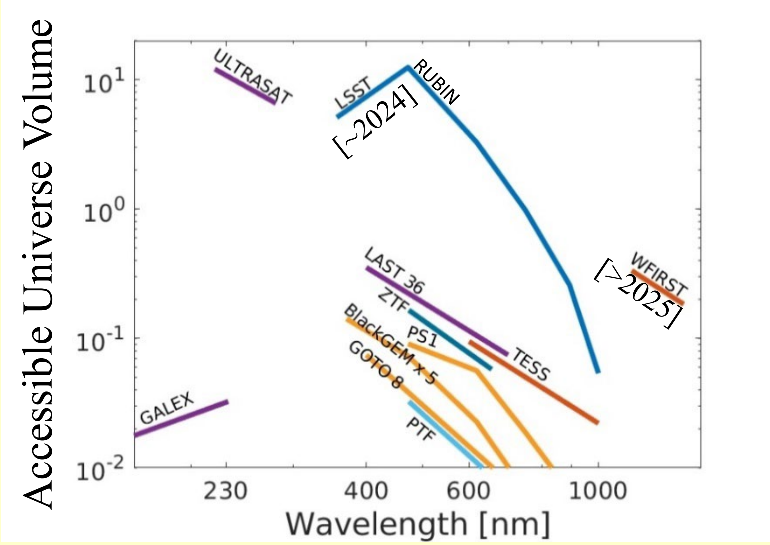
Crucial for “catching” transient events.

ULTRASAT's uniqueness

Key Properties

- Very large, 200 deg^2, field of view.
- High UV (230-290nm) sensitivity:
  1.5 x 10^{-3} ph/cm^2 s (900s, 5σ)
  [m = 22.4],
  3 x 10^{-15} erg/cm^2 s (10^4s).

Transient detection rates of leading surveys



Key Capabilities

- Monitor an unprecedentedly large volume of the Universe.
- New window in wavelength (NUV) and in cadence (minutes - months).
- Real-time alerts to ground/space-based telescopes (GEO orbit), initiate world-wide follow-ups.
- ToO: Instantaneous >50% of the sky in <15 min for >3 hr.

ULTRASAT: Key Science Goals

<u>EM counterparts to GW sources</u>

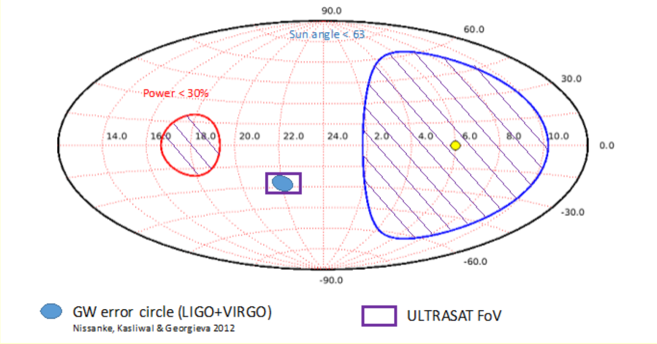
Starting (late) 2025: GW detectors will identify ~10 NS-NS events/yr, ~100 deg^2 error box.

- Fast localization of NS-NS/BH mergers: Rapid, <15min, access to >50% of sky, Cover GW error box in a single image.
- Localize mergers to their host galaxies.
- Provide UV light curves to measure ejecta properties.

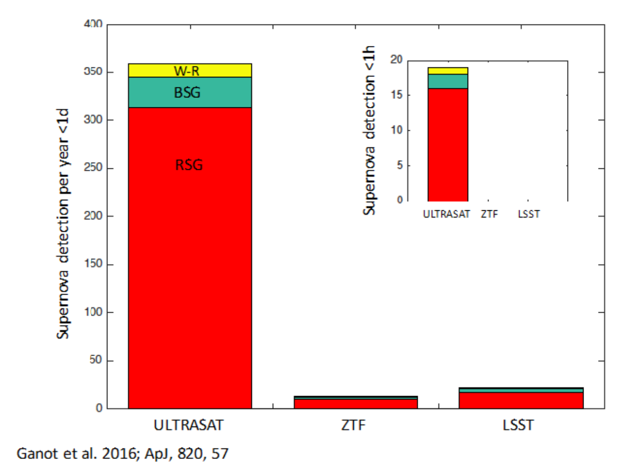
<u>Deaths of massive stars</u>

- High quality early high cadence UV data, Rapid alerts for follow-ups, 100's of SNe including rare types.
- Measure properties of supernova progenitors.
- Map progenitors to supernova types.
- Reveal pre-explosion evolution and mass loss.

ULTRSAT's ToO access



Rates of early detections of SNe



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Be in space by 2025

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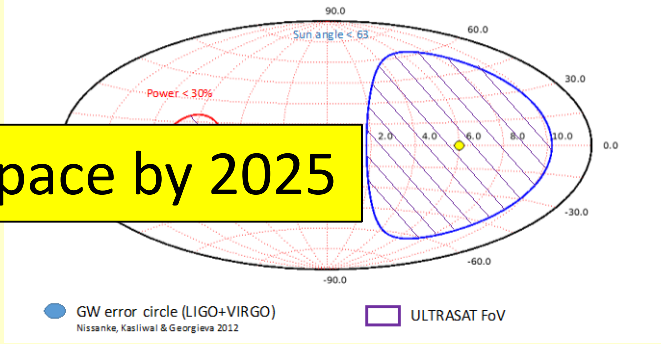

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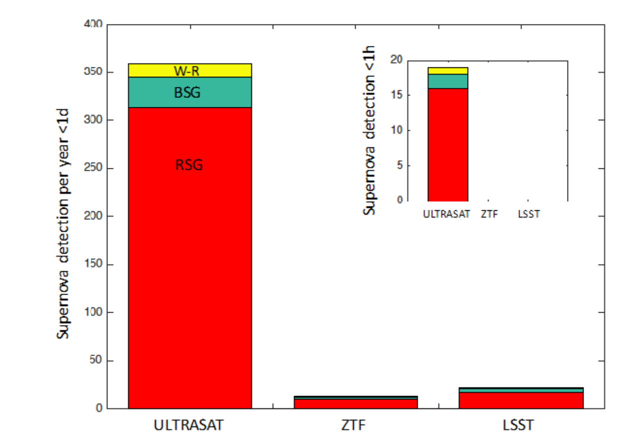


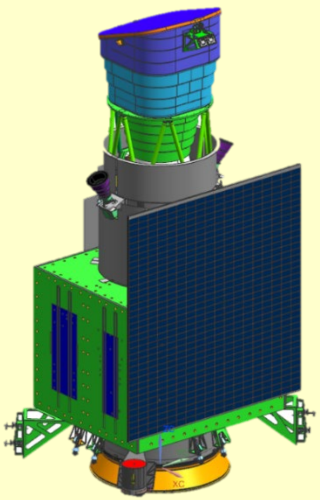
Ganot et al. 2016; ApJ, 820, 57

ULTRASAT: A broad science impact

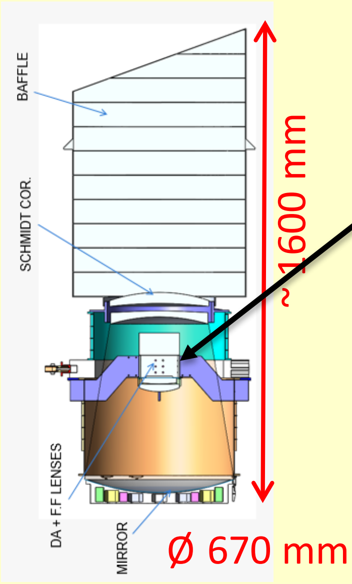
Source Type		# Events per 3 yr mission	Science Impact
Supernovae			
	Shock break-out and Early (shock cooling) of core collapse SNe	>40 >500	Understand the explosive death of massive stars
	Superluminous SNe	>250	Early evolution, shock cooling emission
	Type Ia SNe	>40	Discriminate between SD and DD progenitors
Compact Object Transients			
	Emission from Gravitational Wave events: NS-NS and NS-BH	~25	Constrain the physics of the sources of gravitational waves
	Cataclysmic variables	>25	Accretion and outburst physics
	Tidal disruption of stars by black holes	>250	Accretion physics, black hole demographics
Quasars and Active Galactic Nuclei			
	Continuous UV lightcurves	>7500	Accretion physics, BLR Reverberation mapping
Stars			
	M star flares	$>4\times10^5$	Planet habitability, magnetospheres
	RR Lyrae	>1000	Pulsation physics
	Nonradial hot pulsators, e.g., α Cyg, δ Scuti, SX Phe, β Cep etc. types	>250	Asteroseismology
	Eclipsing binaries	>400	Chromosphere and eclipse mapping
Galaxies and Clusters			
	All Sky Survey – galaxies	$>10^8$	Galaxy Evolution, star formation rate

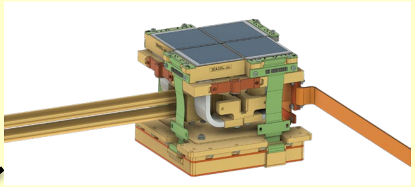
ULTRASAT: Implementation & Collaboration

Spacecraft: IAI



Telescope: Elop/Elbit





Focal Plane Array
DESY/Helmholtz
(Germany)

Sensor: Tower
(Israel)

Hosted launch to GTO: NASA
(MoU negotiations near final stage)

Launch Q2/3 2025
>3.5 year science mission (6 year fuel)

Dimentions: 1.5 x 1.7 x 3.4 (m^3)
Power: 500 W
Mass: 500 + 630 (Prop) kg

ULTRASAT: Status & Timeline

- The program is on track.
- Full teams have been assigned and are working.
- Major risks identified and managed:
  - Challenging time line,
  - Complex Interfaces,
  - Contamination prevention and control.
- Mission cost (including launch) approx. $110M.

Mile Stone	ARO + Month	Time
Kick off	0 (23 September 2019)	“Q4” 2019
SRR	3	Q1 2020
SDR	6	Q2 2020
PDR	17	Q1 2021
CDR	27	Q4 2021/ Q1 2022
Supply of FPA (“camera”)	46	Q3 2023
Supply of Telescope	56	Q2 2024
Satellite ready	66	Q1 2025
Launch	67 -	Q2/3 2025

ULTRASAT: Science Collaboration

- 13 Science Working Groups - WG members receive real time data access.
  Open to all (and already including most) Israeli astronomers.

- NASA Launch contribution- MoU negotiations at final stage,
  Science return: US PIs (NASA funded) will join WG's,
  NASA project scientist: J. Rhoads.

- DESY Camera contribution-
  Science return: 3 DESY PIs in WG's.

- Rubin (LSST) collaboration- advanced negotiations.

ULTRASAT: Science impact

- Revolutionize our view of the hot transient Universe:

  - Discovery volume 300 X GALEX,

  - Continuous min-mon cadence at 22.4mag in a new window (NUV),

  - Real-time alerts to ground/space-based telescopes.

- A broad impact:

  GW sources, SNe, variable and flare stars, AGN, TDEs, compact objects, galaxies.

- Groundbreaking science with an affordable satellite mission.

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,
  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), UV/O.
  - Very challenging at sub-TeV (CTA).

- $10^8 - 10^{10}$ GeV: A flux measurement (10^{-9}GeV/cm^{2}s sr) will constrain the UHE CR composition (Radio).

Backup Slides

Science goal: Planet habitability

- UV flares and Coronal Mass ejections around prime candidate stars for terrestrial planet searches (M-dwarfs/young Solar analogues)
  - Severely limit habitability,
  - May allow prebiotic chemistry,
  - May produce false positive biomarker signatures (O_3 from photo-dissociation of H_2O & CO_2).

- Flares dominate UV output. Flare rates unknown.

- ULTRASAT will monitor ~10^6 stars
  - Determine NUV flare frequency and luminosity distribution as functions of both spectral subclass and stellar rotation period,
  - Determine best habitable planet candidates (e.g., from TESS) for expensive spectroscopic bio-marker searches, e.g. by JWST (extended).

ULTRASAT: Mission profile

- ALL SKY SURVEY
  - 3hr/day during the first 6 months
  - 7x deeper than state-of-the art (GALEX) (23 AB limiting mag @ $|b|>30°$)

- LONG STARES
  - 2 directions near the Ecliptic poles, minimize Galactic extinction and zodiac bgnd
  - Real-time data download and analysis
  - Alerts within 15min of observations
  - 10% of time lower cadence (8000 sq. deg., 4day)- see Eran's talk

- Targets of Opportunity (ToO's)
  - Instantaneous >50% of the sky in <15 min for >3 h
  - No limit on ToO number, except for max 75 with negative power balance (~25%)
  - Continuous transmission to the ground

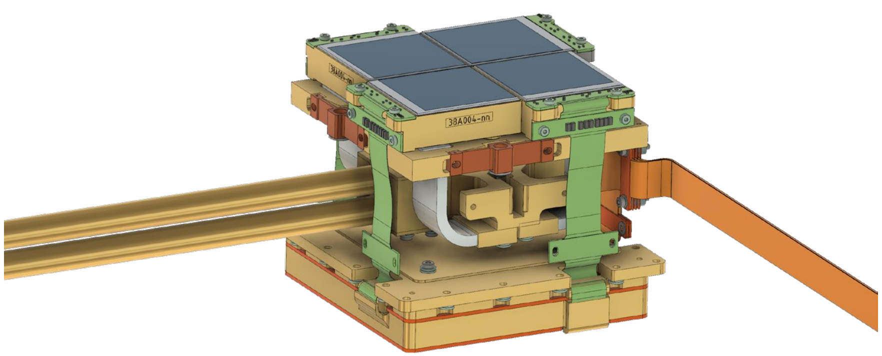
Focal Plane array: Main characteristics

- BSI CMOS from Tower Semiconductors

  (4 tiles aligned to < 50 μm)
- High UV QE using

  high-K dielectric coating,

  optimized anti-reflection coating
- AnalogValue electronics design, Ramon Space support for space qualified design (e.g., radiation hardness)

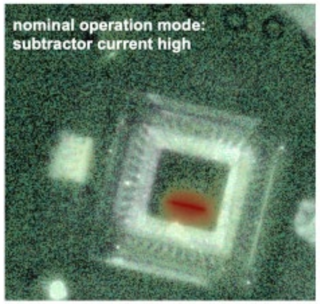


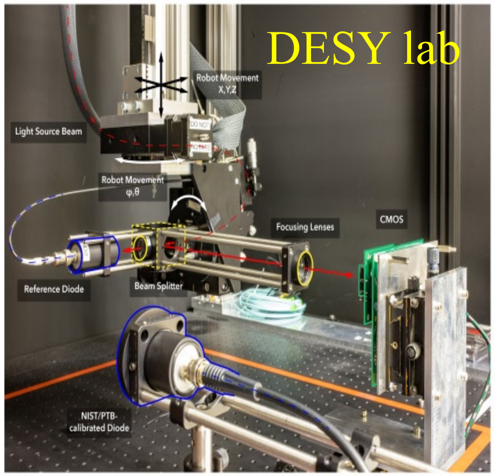
Sensor main Specs.

Photosensitive surface	90x90 mm
Pixel size	9.5 μm
Operation waveband	230-290nm
Mean QE in Operation band	>70%
Operation temperature	200±5 °K
Dark current @ 200 °K	<0.03 e^-/sec
Readout mode	Rolling shutter
Readout time	<25 sec
Readout noise @ High-gain	<3.5 e^-/pixel
Electronic cross-Talk	<0.01%
Pixel sampling scheme	HDR capability
Low-gain Well capacity	140-155 Ke^-
High-gain Well capacity	16-21 Ke^-
Bits per Pixel – total (data only)	14 (13)

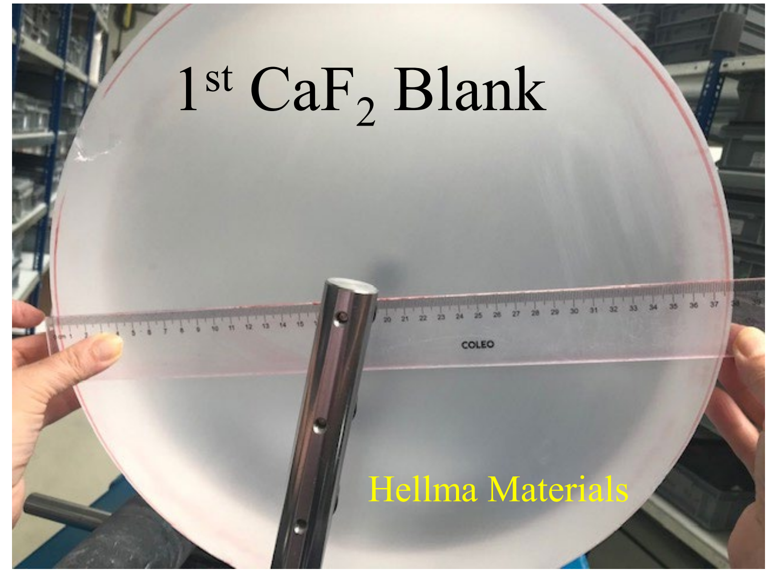
Long lead items (LLI)

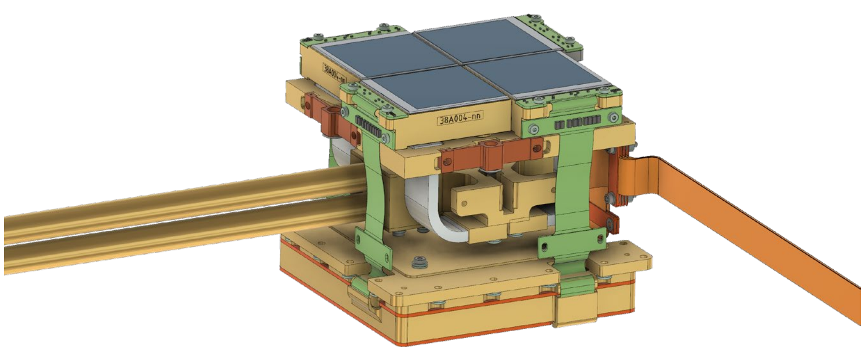
CMOS detectors produced by Tower, being tested in Germany





First lens blanck





Key technology challenges

- CMOS sensor - UV QE>60% (Tower).
- UV optics performance across a wide FOV (WIS/Elop).