CTAと
マルチメッセンジャー天文学
CTA and Multi-messenger Astronomy

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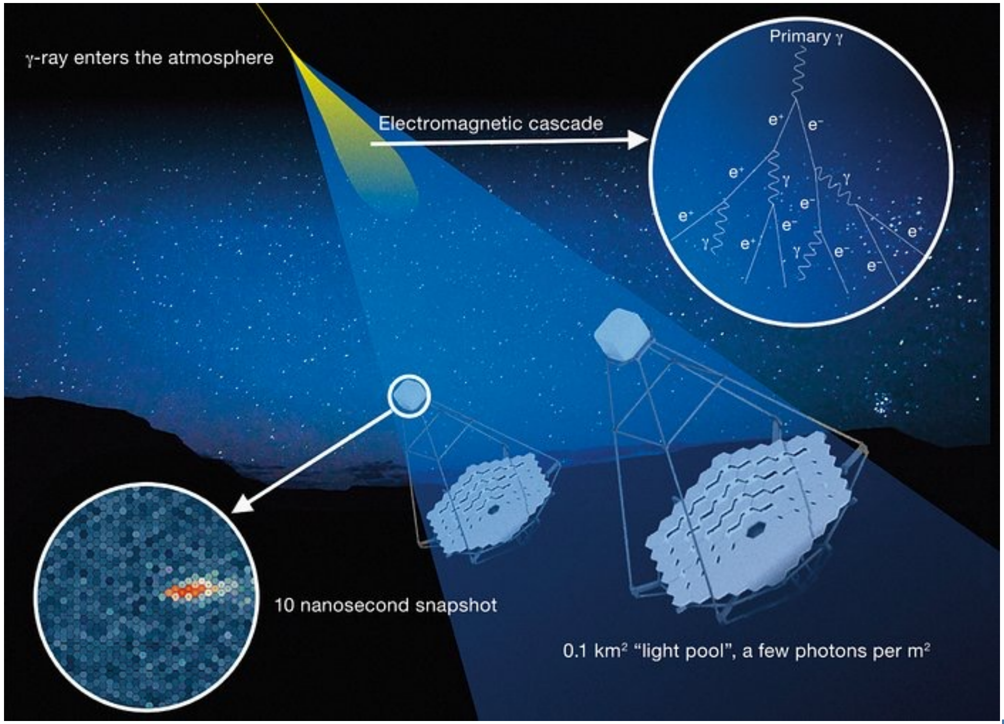
(ICRR)

2023/Nov/1st

研究会「マルチメッセンジャー天文学の展開」
@柏キャンパス図書館

Cherenkov Telescope Array

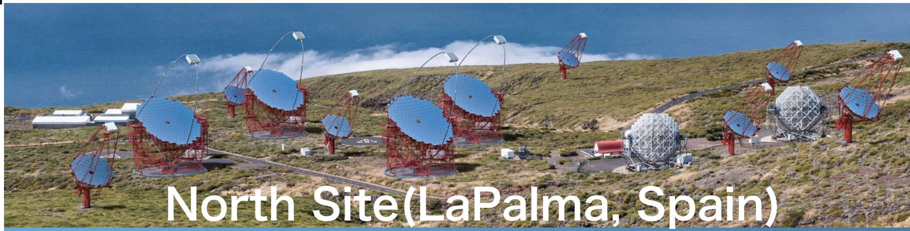


❑ Imanging Atmospheric Cherenkov Telescope (IACT)

Imaging EM-cascades initiated by high energy gamma-rays inside the atmosphere with Cherenkov photons.

From obtained images, rejecting hadronic background and estimating energy and direction of primary gamma-rays.

By observing the same cascade with multiple IACTs, the senstivity improves dramatically.

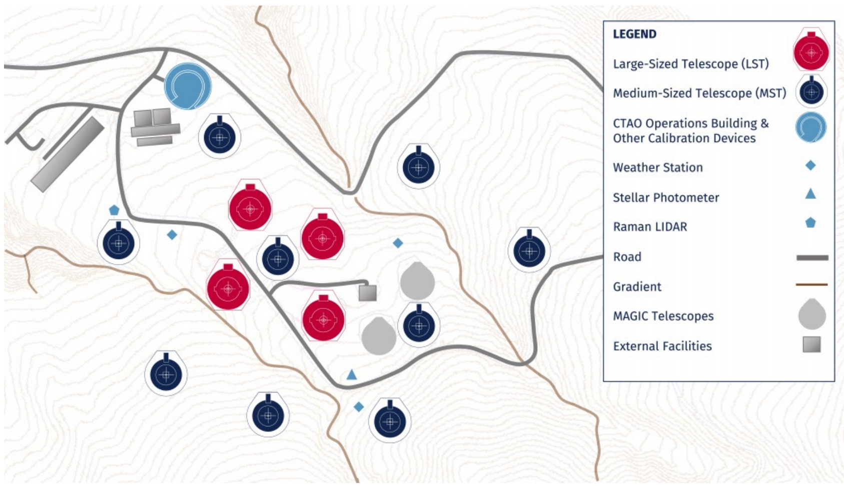


❑ Cherenkov Telescope Array (CTA)

- Deploying tens of IACTs ~km^2 area.
- 3 different sizes of telescopes
- One array in each hemisiphere.

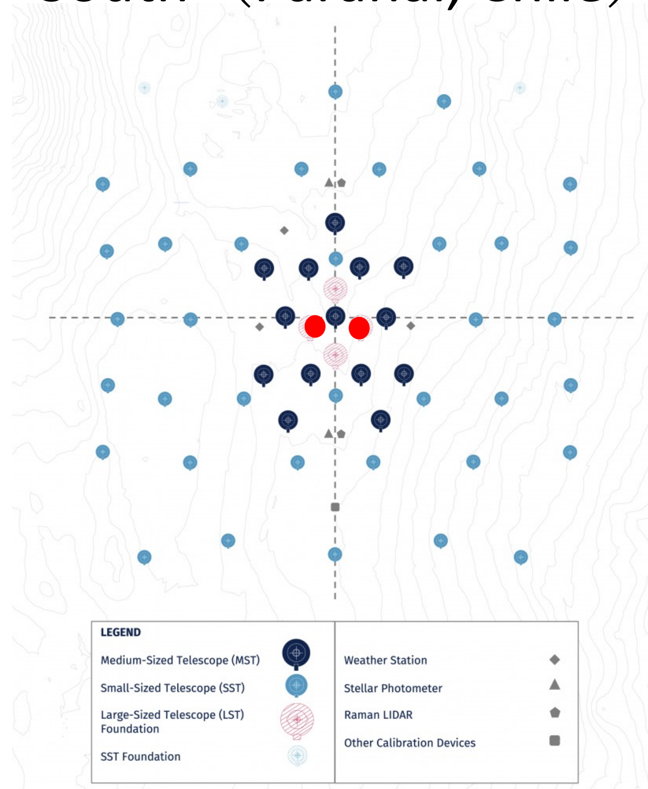
Alpha Configuration (1st Stage)

- North（La Palma, Spain）



LST 4 tel
MST 9 tel

- South（Paranal, Chile）



LST 2 tel
MST 14 tel
SST 42 tel

	Diameter [m]	#tel (N)	#tel (S)	Energy [TeV]	FoV [deg]
LST	23	4	2(4)	0.02 - 3	4.5
MST	9.7/11.5	9(15)	14(25)	0.08 - 50	7.5
SST	4.3	0	42(70)	1 - 300	10.5

2016～ North Construction
2022～ South Construction
2028年　North Complete
2028年　South Complete
Operation ＞20 years

3

CTA Consortium

25か国, >1500名

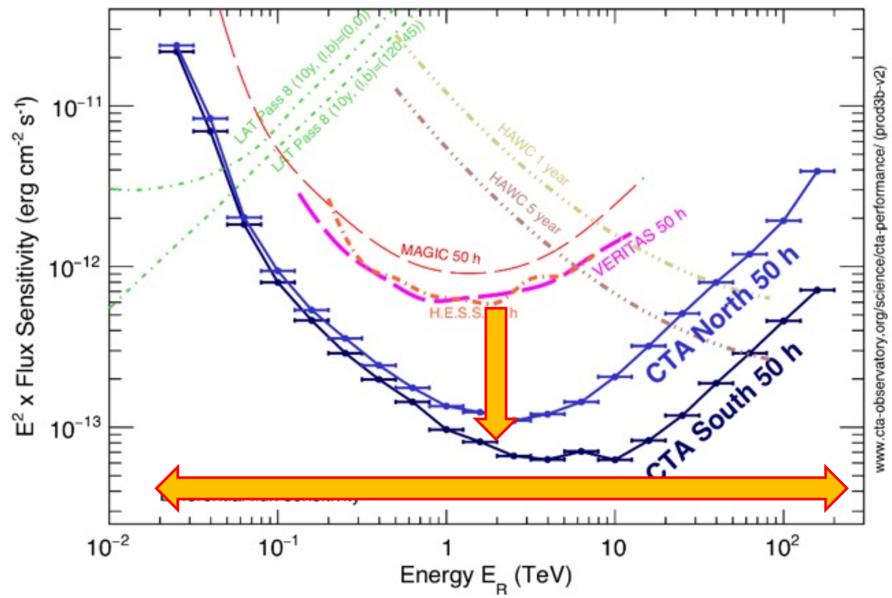
CTA-Japan 122名

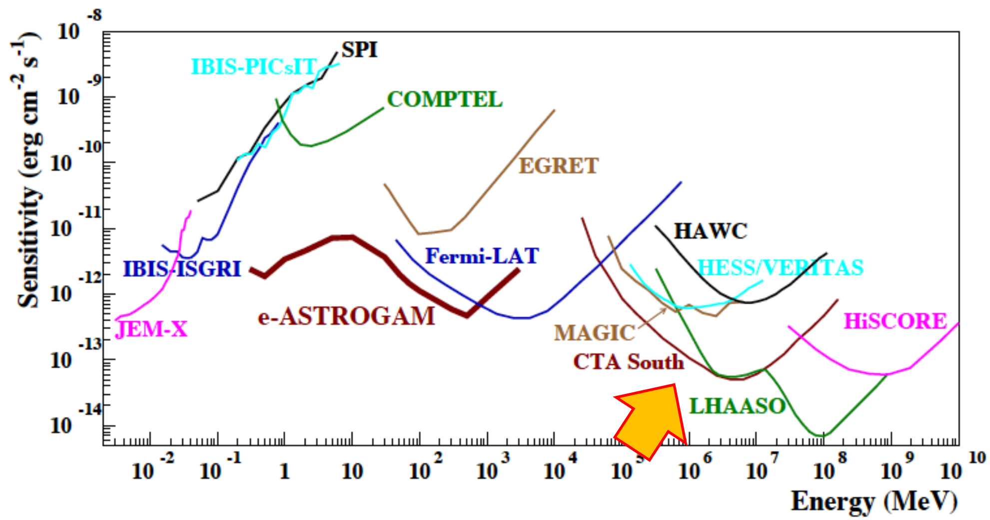
21機関

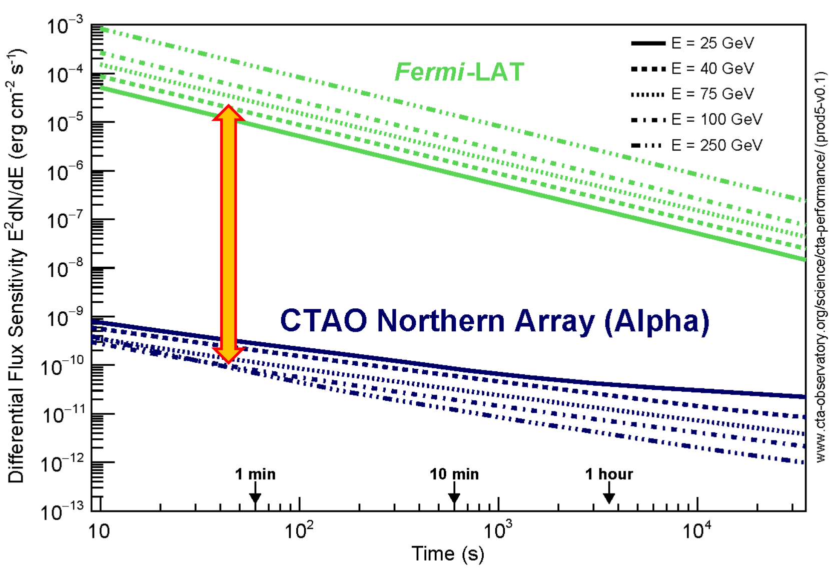
青山大　大林花織, 佐藤優理, 田中周太,
　　　　山崎了, 吉田篤正
茨城大　片桐秀明, 柳田昭平, 吉田龍生
大阪大　井上芳幸, 松本浩典, Ellis
Owen,
北里大　村石浩
京大基研 井岡邦仁, 石崎渉
京大理　川中宣太, 鶴剛, 寺内健太,
　　　　李兆衡
熊本大　高橋慶太郎
KEK素核研　田中真伸
甲南大　井上剛志, 鈴木寛大, 田中孝明,
　　　　千川道幸, 溝手雅也, 山本常夏
国立天文台　郡和範
埼玉大　勝田哲, 立石大, 寺田幸功
東海大　阿部和希, 櫛田淳子, 佐々誠司,
　　　　高橋菜月, 西嶋恭司

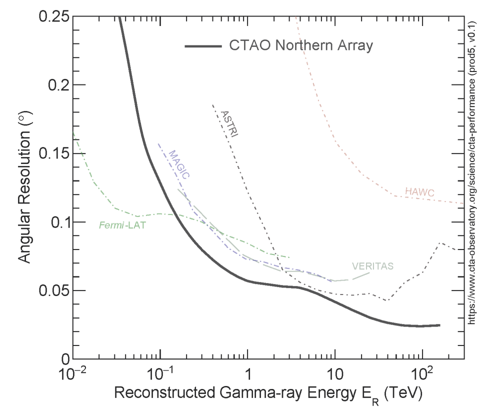
東大　浅野勝晃, 阿部正太郎, 粟井恭輔, 稲田知大, 猪目祐介, 笛吹一樹,
宇宙線研　大石理子, 大岡秀行, 大谷恵生,岡知彦, 加賀谷美佳, 金森翔太郎,
窪秀利, Xiaohong Cui, 小林志鳳, Albert K. H. Kong,
齋藤隆之, 櫻井駿介, 佐野栄俊, Timur Dzhatdoev, Marcel Strzys,
高田順平, 武石隆治, Thomas P. H. Tam, K. S. Cheng,,
Wenwu Tian, 手嶋政廣, 野崎誠也, 野田浩司,
バクスター・ジョシュア・稜, 橋山和明, Daniela Hadasch,
林克洋, 林航平, 廣島渚, 広谷幸一, David C. Y. Hui, 深見哲志,
藤田裕, Ievgen Vovk, Pratik Majumdar,
Daniel Mazin, 村瀬孔大, 吉越貴紀
東大理　大平豊, 戸谷友則, 馬場彩
東北大　當真賢二
徳島大　折戸玲子
名大理　立原研悟, 早川貴敬, 福井康雄, 山本宏昭
名大ISEE　奥村曉, 高橋光成, 田島宏康, バン・ソンヒョン
広大先理工 今澤遼, 榧木大修, 木坂将大, 須田祐介, 高橋弘充, 深沢泰司
広大宇宙科学センター 水野恒史
宮崎大　森浩二
山形大　郡司修一, 坂本貫太, 門叶冬樹, 中森健之
山梨学院大 内藤統也, 原敏
理研　井上進, Donald Warren, 榊直人, 澤田真理, 辻直美,
Maxim Barkov, Gilles Ferrand, Haoning He, 長瀧重博
立教大　内山泰伸, 林田将明
早稲田大　片岡淳

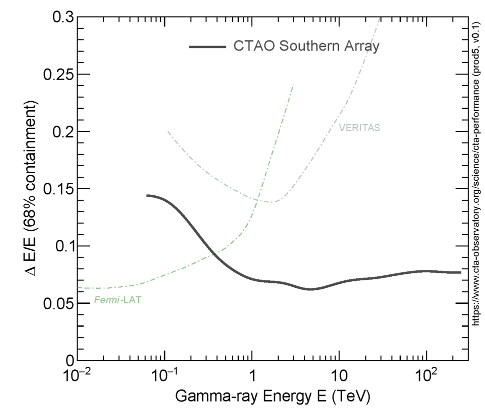
CTA Performance





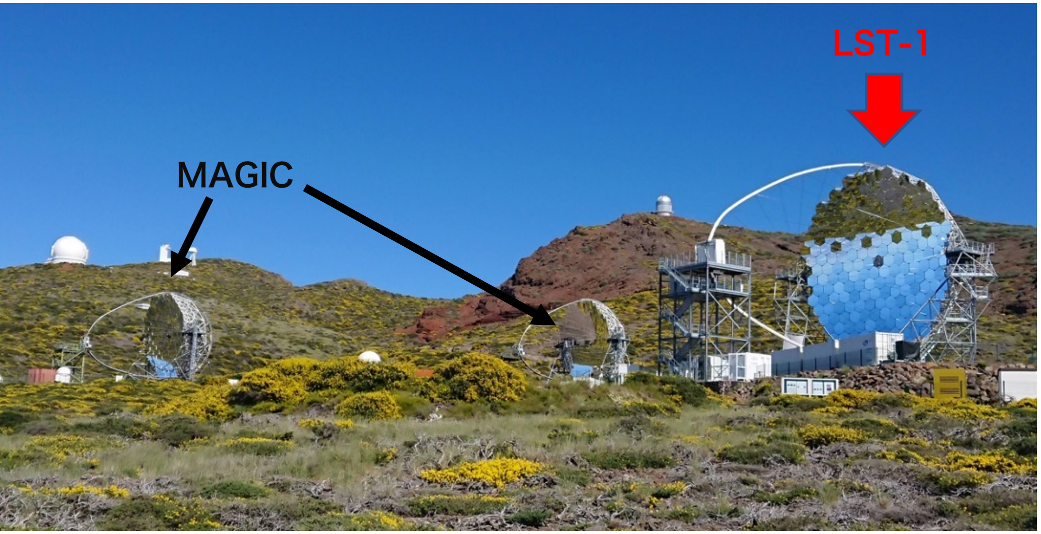


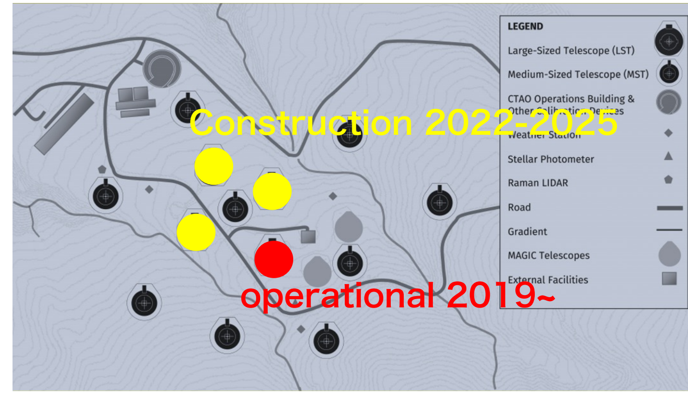


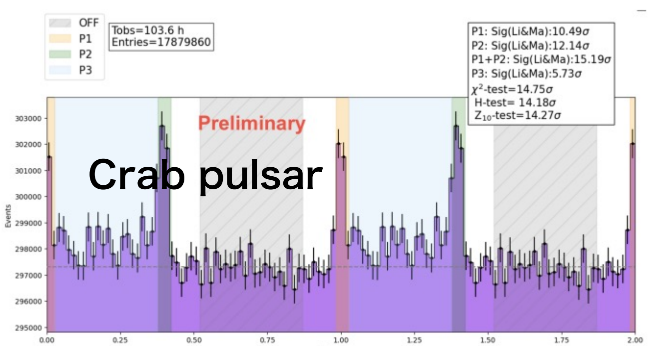


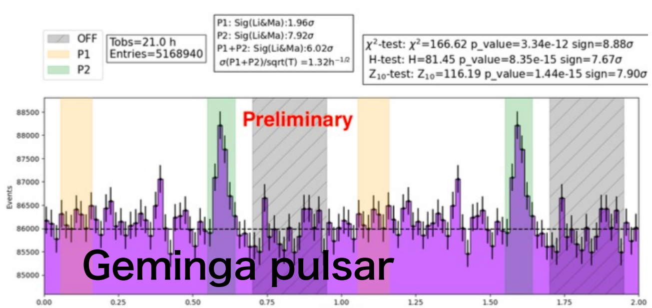
	30 GeV	300 GeV	3 TeV	30 TeV
Angular res.	0.25 deg	0.08度	0.05度	0.03度
Energy res.	20%	10%	7%	8%

CTA North Status

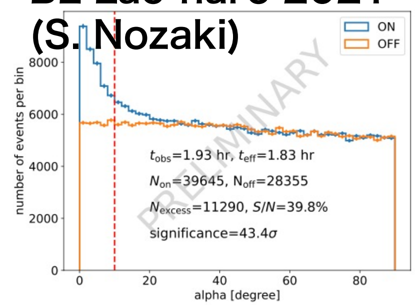


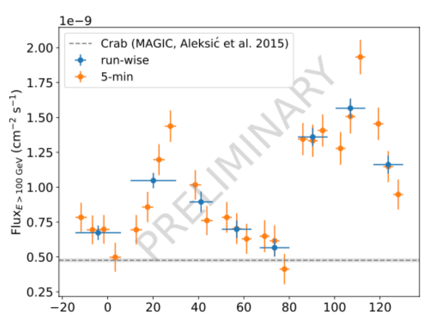




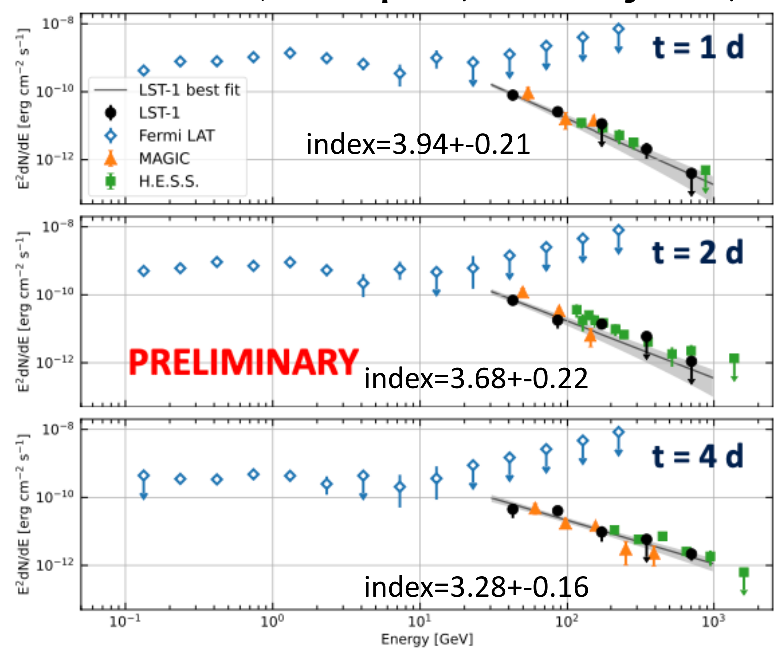


BL Lac flare 2021 (S. Nozaki)





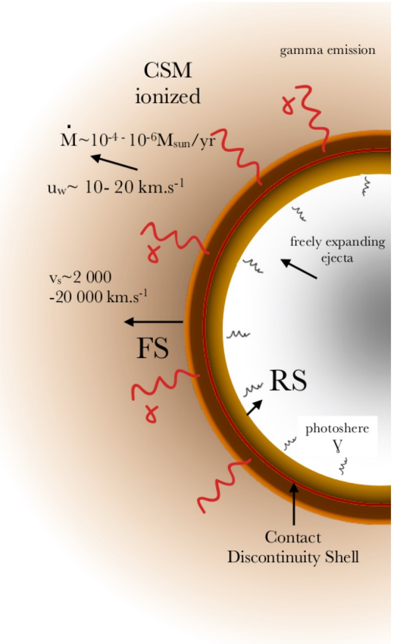
Nova, RS Oph. (Y. Kobayashi)

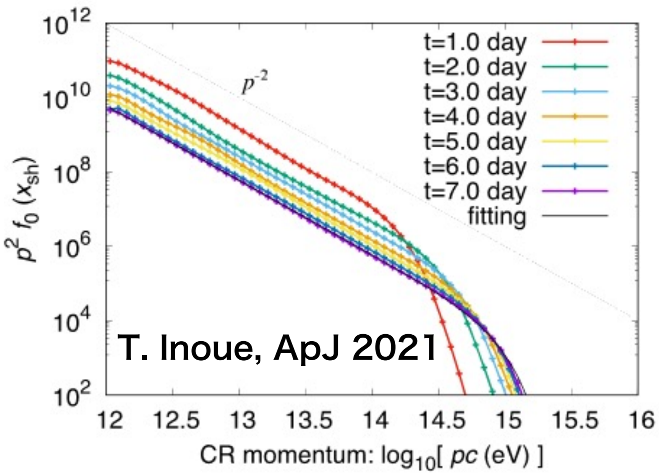


CTA and multi-messenger

Target	Physics	messenger
Type II Supernovae	Supernova Mechanism	γ, LowE-ν
Supernova Reminants	(hadron) CR acceleration	γ, ν
Pulsar Halo	CR propagation	γ, electron
Galactic Diffuse, Center	CR accel. & propagation.	γ, ν
Blazars	Jet physics, origin of UHECR	γ, ν, UHECR
Seyfart Galaxies	AGN structure	γ, ν
Neutron Star merger	Short GRB mechanism	γ, GW,
Low Lominosity GRB	GRB mechanism and diffuse ν	γ, ν

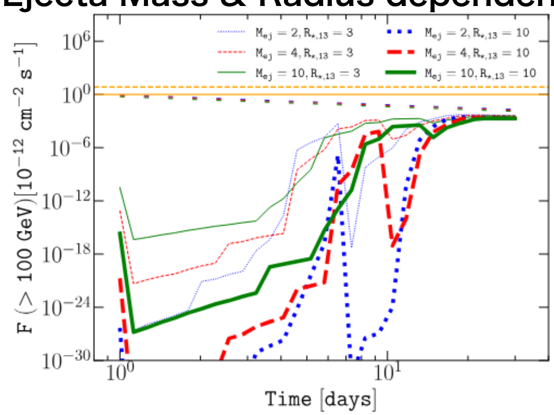
Type II Supernovae



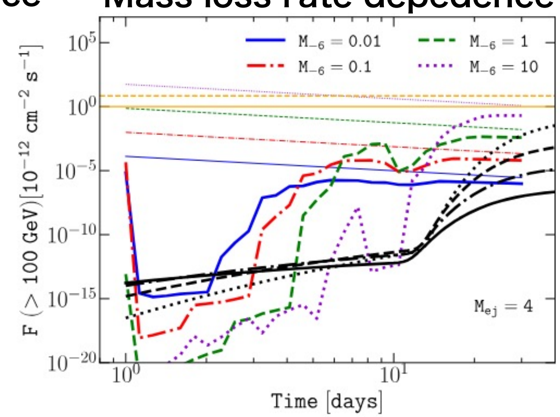


$$E_{\rm max} \simeq 0.4 \times 10^{14}\,{\rm eV}\,\xi_B \left(\frac{B}{0.03\,{\rm G}}\right) \times \left(\frac{v_{\rm sh}}{10^4\,{\rm km\,s^{-1}}}\right)^2 \left(\frac{t}{10\,{\rm day}}\right).$$

Ejecta Mass & Radius dependence



Mass loss rate depedence



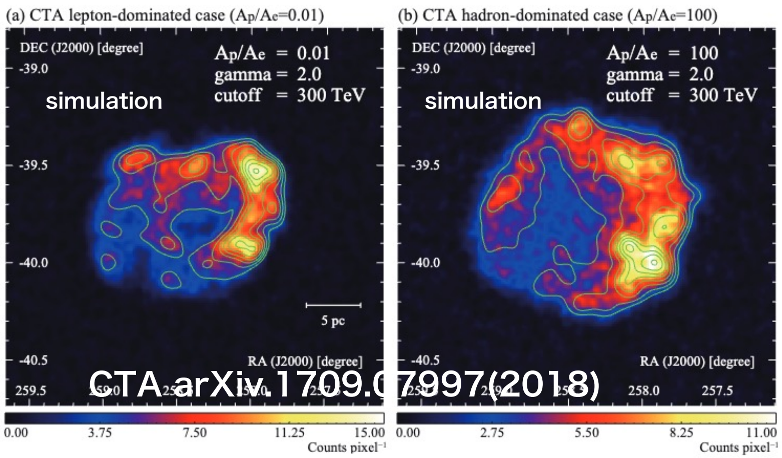
P. Cristofari, MNRAS 2021

- Core collapse explosion inside the dense material released by Red Supergiant.
- Shock is formed and efficient acceleration up to 100 TeV within several days.
- TeV gamma-rays are initially absorbed inside the photosphere, and become visible after several days.
- Flux and light curve depend on explosion energy, Ejecta mass, mass loss rate, Radius of the progenitor etc.
- CTA can detect them up to LMC/SMC distances (~50 kpcs)
- Combined with SK/HK observation of supernova neutrino one can study the SN mechanism.

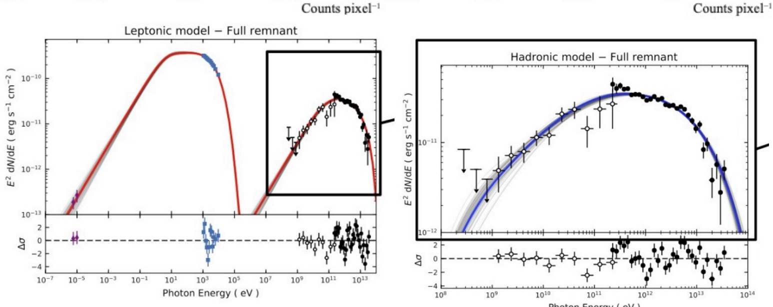
Supernova Remnants

RX J1713, CTA KSP

Leptonic   Hadronic

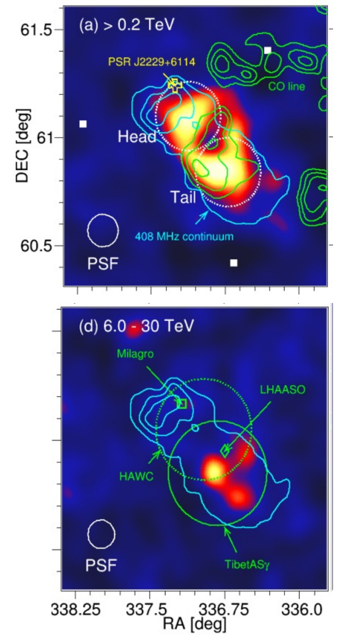


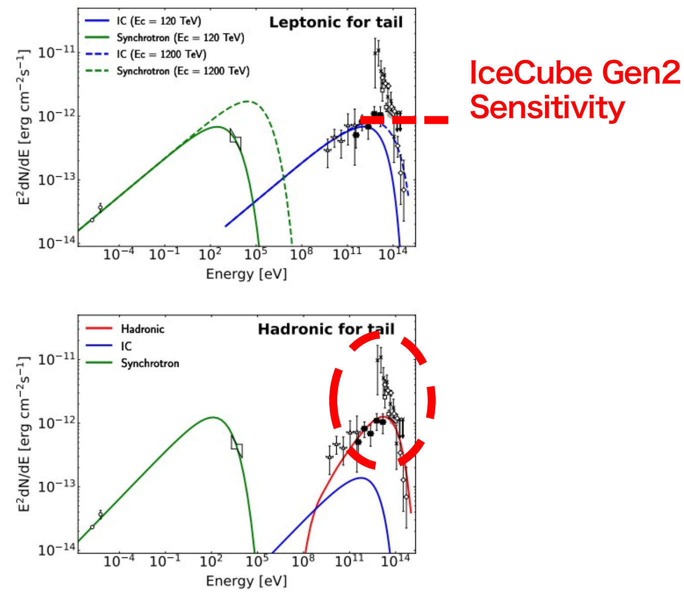
CTA arXiv.1709.07997(2018)



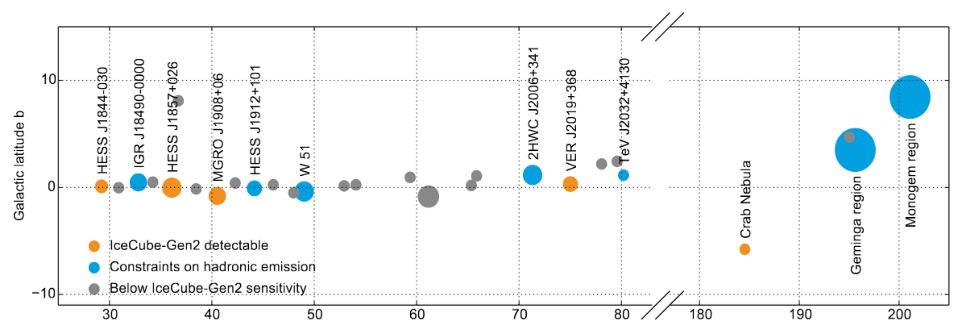
HESS A&A (2018)

G106.3, Best PeVatron candidate





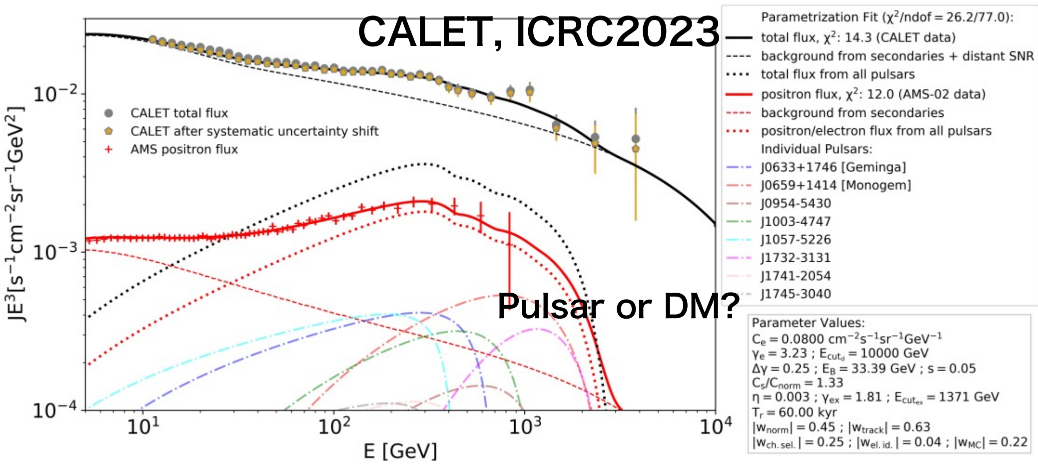
MAGIC A&A 2023



Ice Cube: arXiv:2008.04323 (2022)

Definite proof of Proton acceleration requires pi-0 cutoff or Neutrino detection.

Pulsar Halo and positron excess



CALET, ICRC2023

Pulsar or DM?

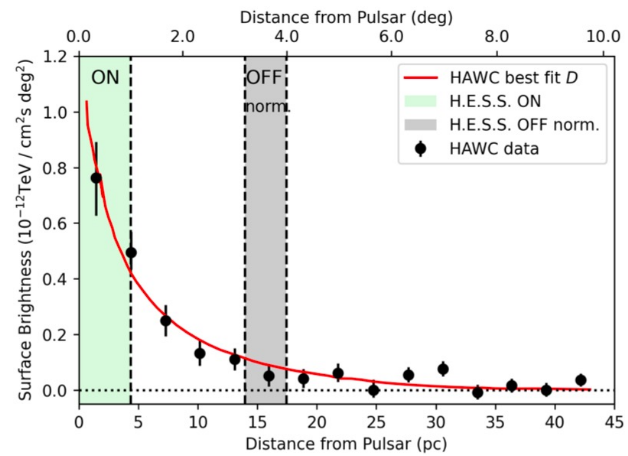
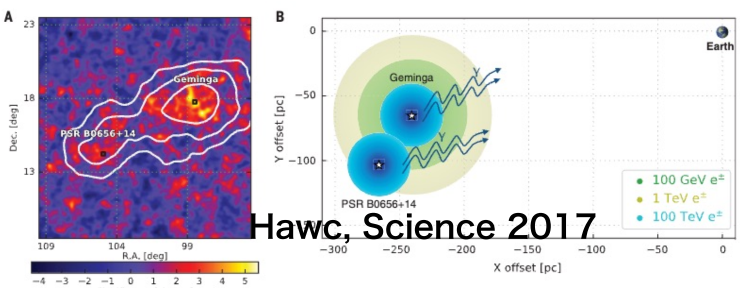
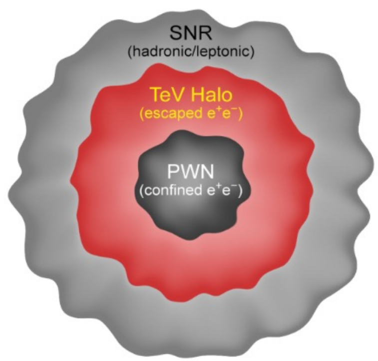


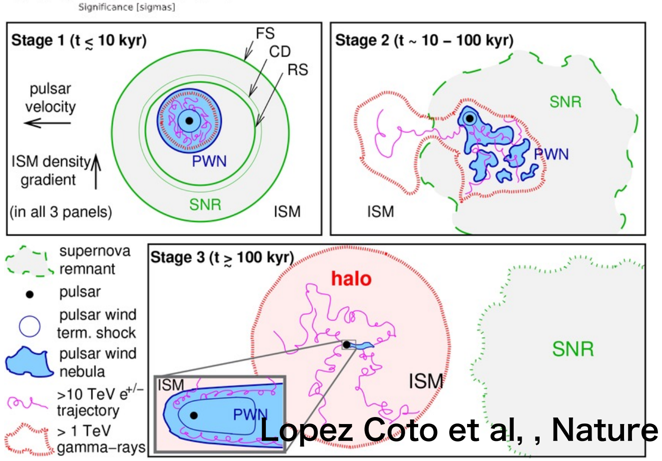
Fig. 1. Surface brightness profile of emission around the Geminga pulsar measured with HAWC (Abeysekara et al. 2017a). Shaded regions indicate the parts of the emission profile that are used as ON (radius $\theta \lesssim 1.0°$) and OFF normalisation (radius $\theta \gtrsim 3.2°$) regions to estimate the background level and evaluate the significance in the analysis of the 2019 H.E.S.S. dataset. The region shown for normalisation of the OFF counts is only accessible with the 2019 dataset, due to the wider pointing strategy used.



Hawc, Science 2017



Sudoh et al., 2019, Phys RevD.

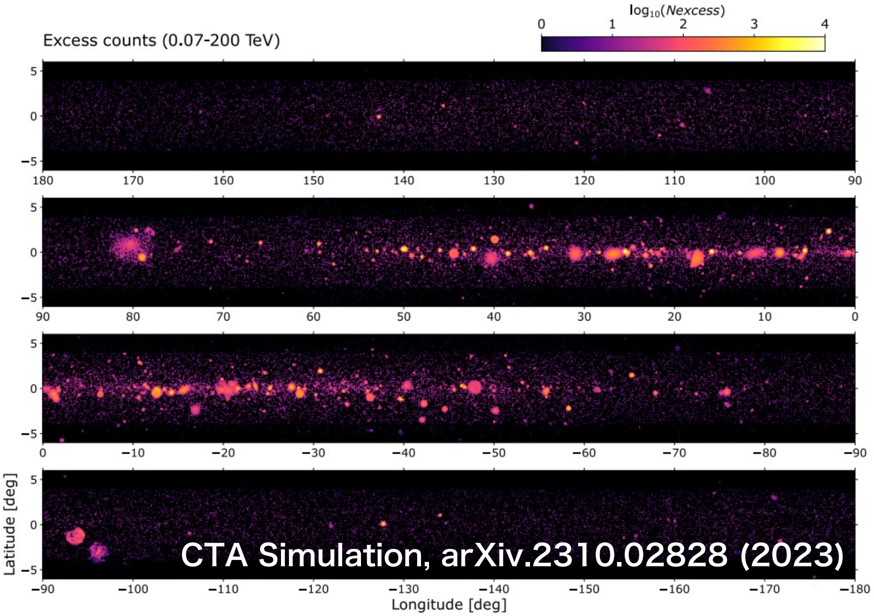


Lopez Coto et al, , Nature Astronomy 2022

Still not clear how TeV Halo is created and how the diffusion is supressed.
To understand better we need

- Energy dependent morphology with high ang. resolution
- Energy spectrum
- More sources (so far ~7)
    - 10 times more with CTA

Galactic Plane and Diffuse



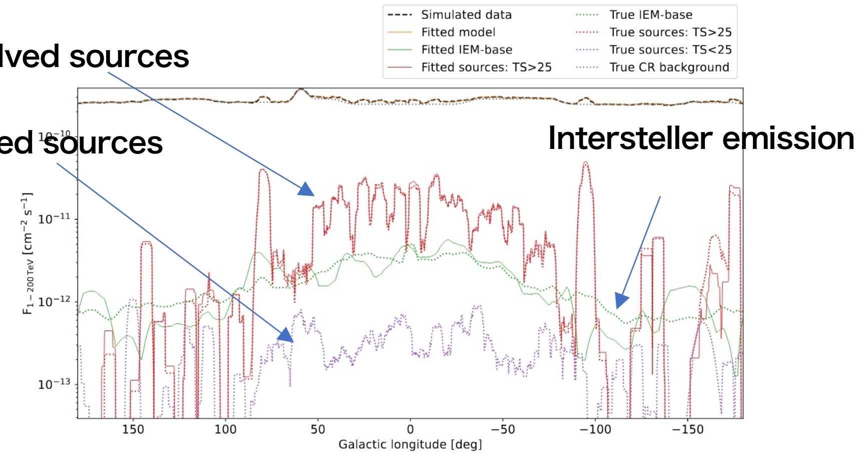
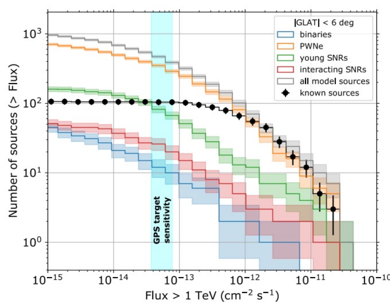
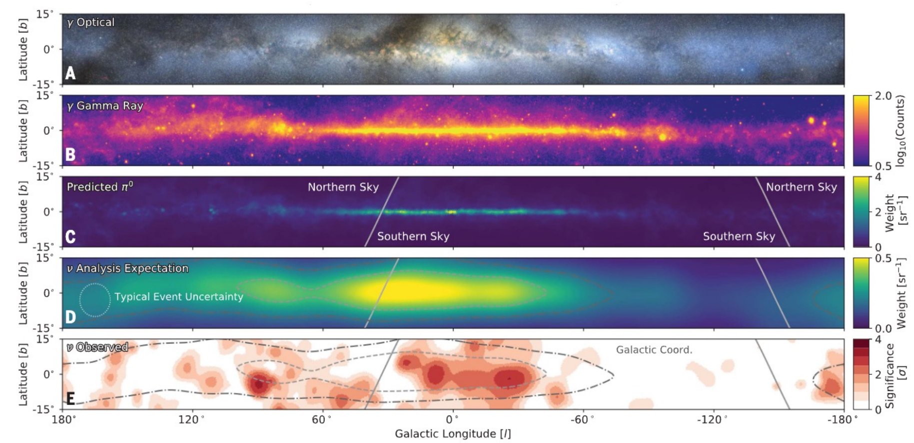


Figure 15. Flux distribution in Galactic longitude from different source and background components. Fluxes are integrated over latitudes of ±6° and over a 6° sliding window in longitude for the 1-200 TeV energy range. The fitted models are displayed as solid lines and the simulated models as dotted lines.

Region	STP (h)	LTP (h)	Total (h)
SOUTH			
300°-60°, Inner region	300	480	780
240°-300°, Vela, Carina		180	180
210°-240°		60	60
NORTH			
60°-150°, Cygnus, Perseus	180	270	450
150°-210°, anticentre		150	150

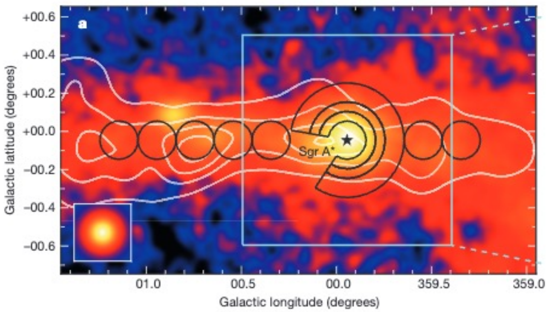


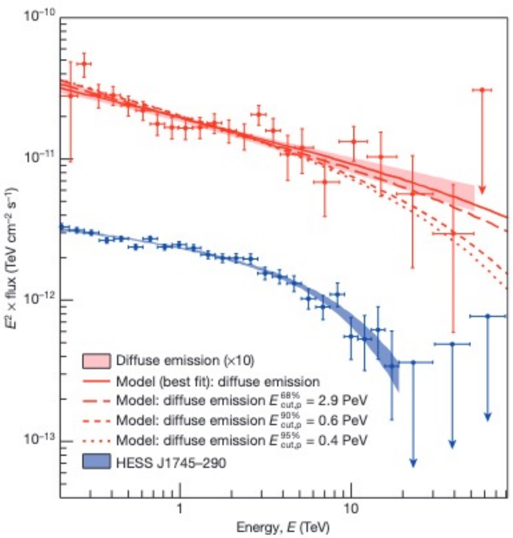


Detailed Cosmic Ray Propagation study with gamma and neutrino

IceCube, Science 380 (2023)

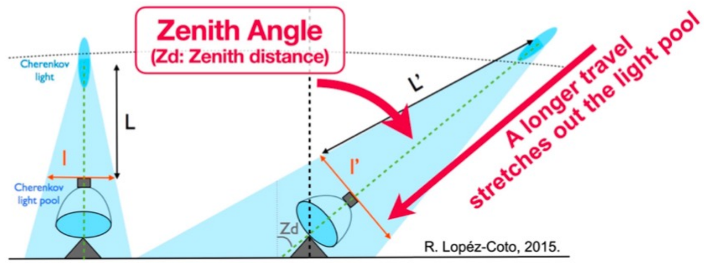
Galactic Center



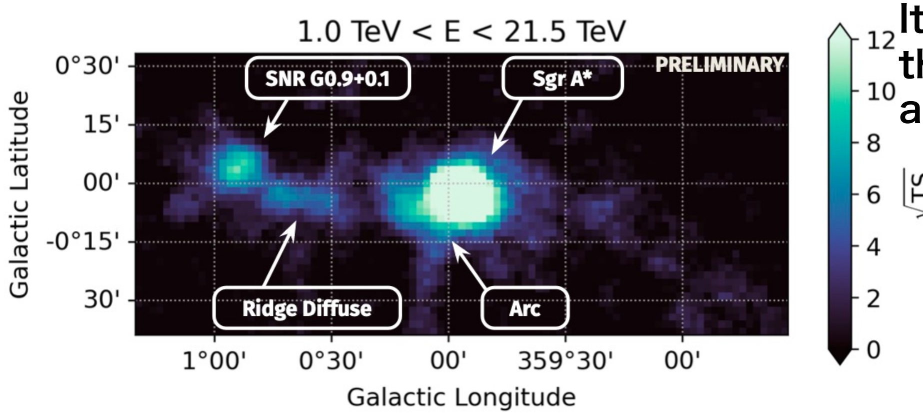


HESS, Nature 2016

LST-1 is located at 28° N latitude:
the Galactic Center in the southern sky requires LZA observations (≳ 58°)

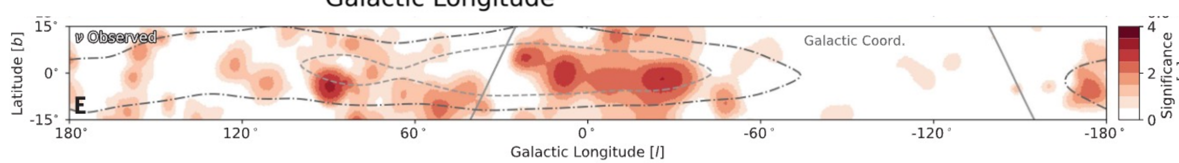


The first LST-1 sky map highlights prominent signals, and illustrates successful extended-source observations.



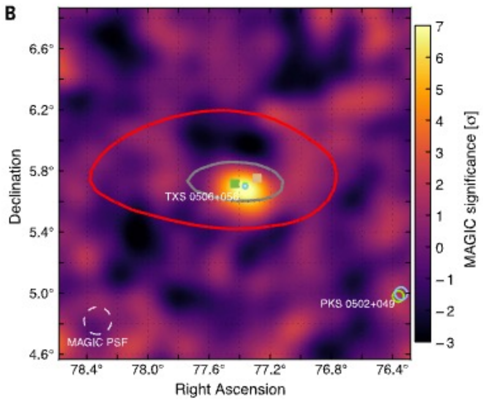
LST-north is a good detector for GC.
It will come earlier than the south array.

LST1 mono,
by S. Abe (ICRR)
JPS 2023 Autumn.

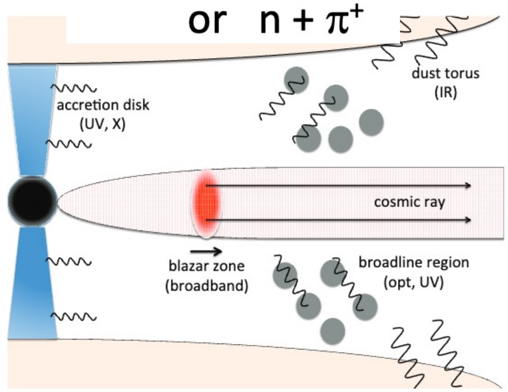


Blazars

TXS 0506+056

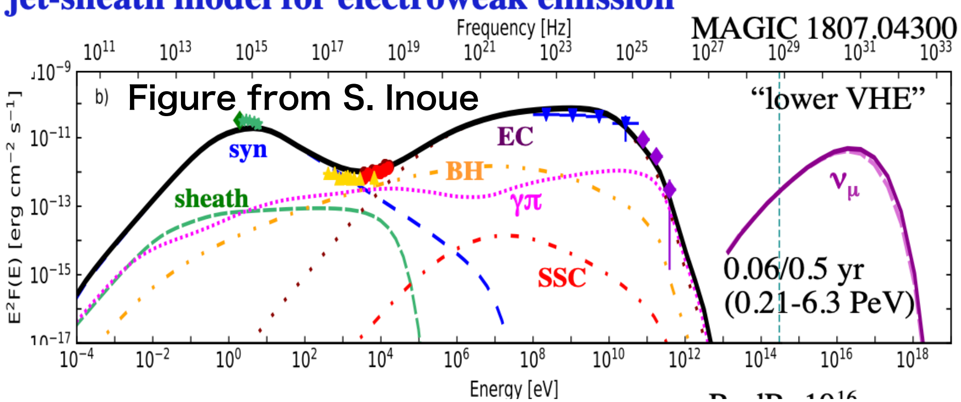


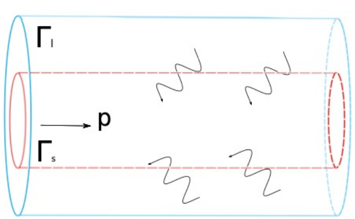
• $p + \gamma \rightarrow p + \pi^0$ or $n + \pi^+$



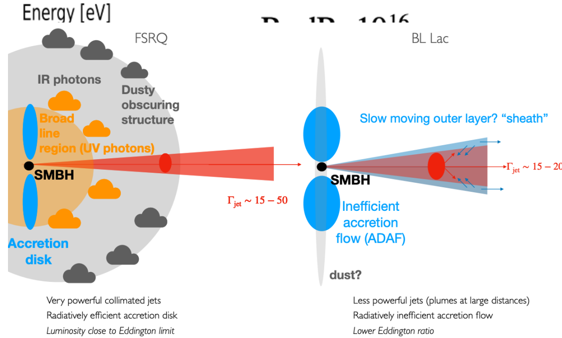
- TXS 0506 is the only objects which showed possible TeV gamma-neu correlation
  - A 290 TeV neutrino event during flaring activity in 2017, with ~3σ.
  - In addition, 3.5σ neutrino excess between 2014 and 2015.
- nu: p-gamma interaction
- gamma: leptonic EC
- Why only TXS0506?
  - ~80 blazars with TeV detections.
  - TXS0506 is BLLac, and not particularly famous.
  - We need more statistics/sources.

jet-sheath model for electroweak emission

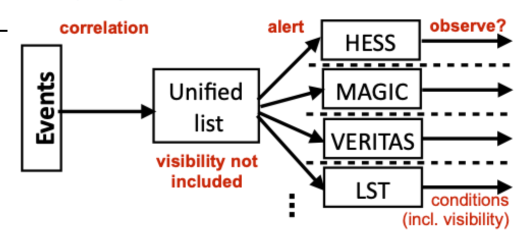




Tavecchio+ 14, 15
Righi & Tavecchio 17

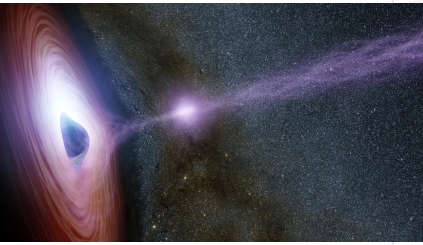


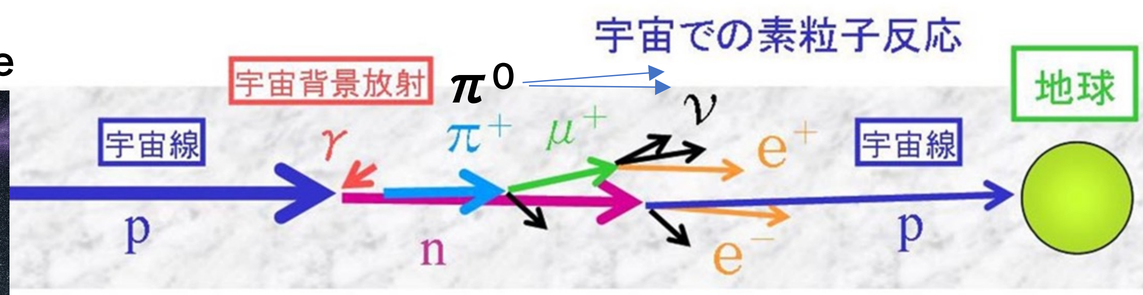
"GFU (Gamma follow-up program)" is being coordinated by K. Noda et al.
- Giving list of intereting sources/nu event conditions to IceCube and ask them to alert.



Blazars as UHECR source

From TA web site





GZK 限界の起源（宇宙線と宇宙背景放射の反応）

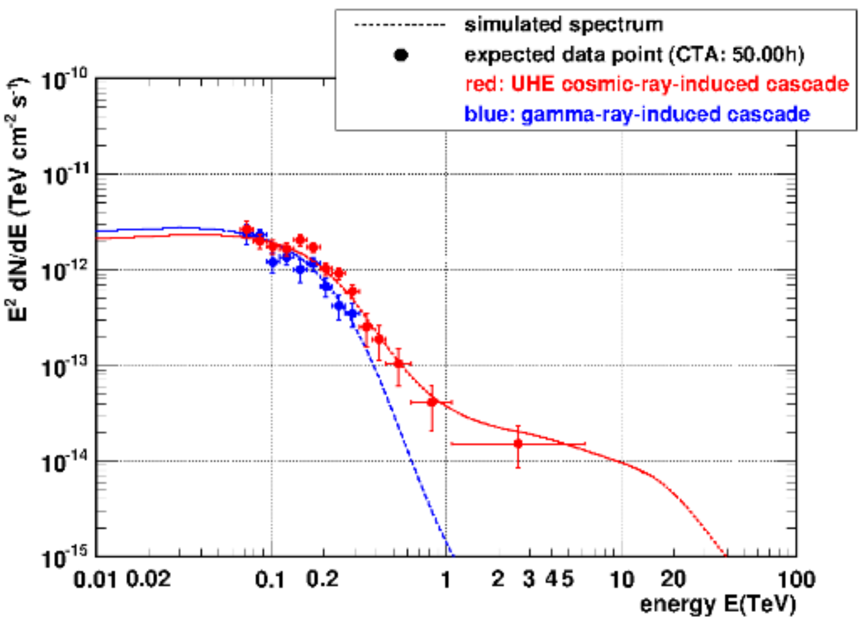
B << 10^{-10} G

$\Theta_{jet} > \theta_{def}$

Blazar

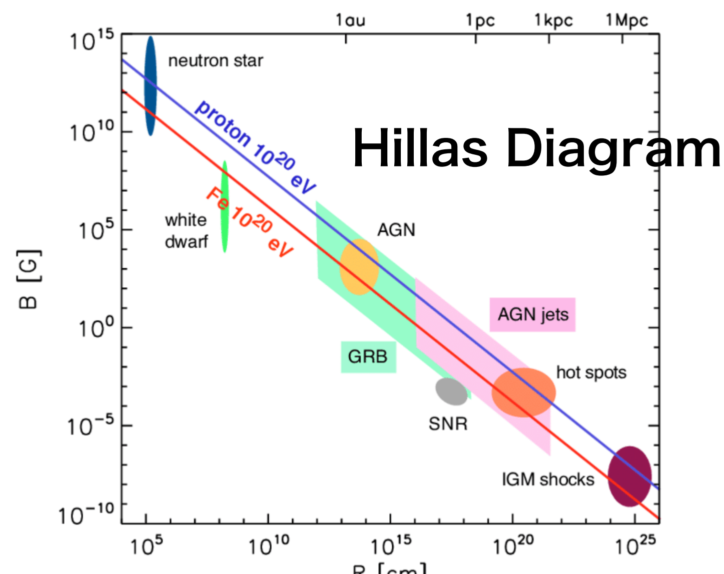
~100 Mpcs

~3 Gpcs



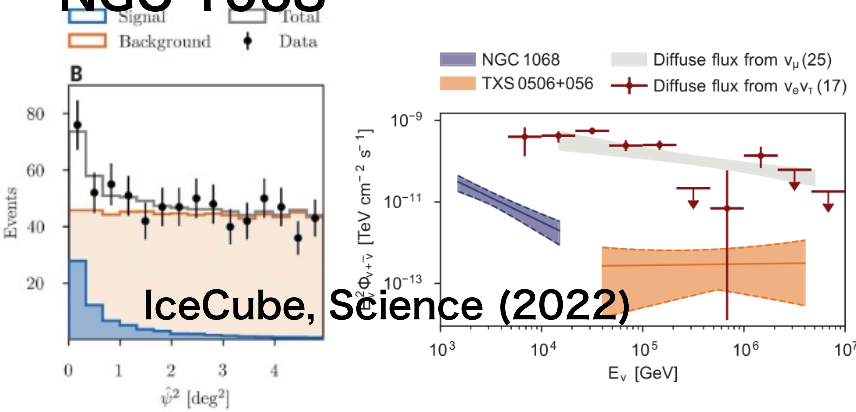
blazar KUV00311-1938
Z=0.5-1.34

Essey et al., Astropart. Phys (2010)
Takami et al., ApJ (2013)

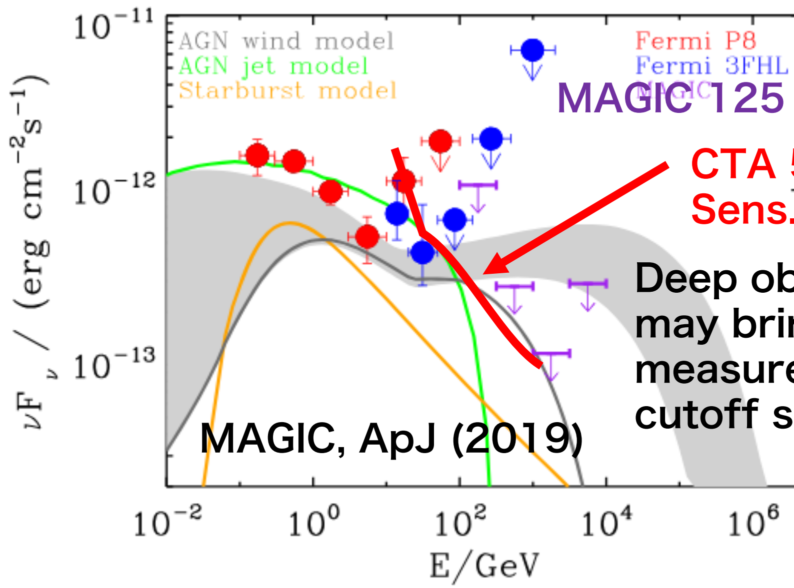


Seyfert Galaxies

NGC 1068



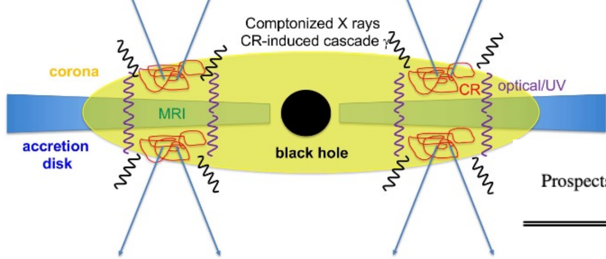
IceCube, Science (2022)



MAGIC, ApJ (2019)

Deep observation may bring the measurement of cutoff spectrum

Corona model



$p + p\ (N) \rightarrow p + p\ (N) + \pi^0$

or $p + n\ (N') + \pi^+$

$p + \gamma \rightarrow p + \pi^0$

or $n + \pi^+$

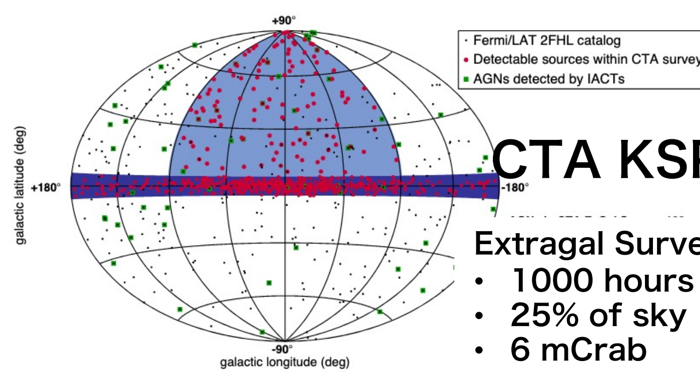
More candidates

Table 3
Prospects for Observations of Bright nearby Seyfert Galaxies in 10 yr of IceCube Operations

Source	Stochastic (High CR Pressure)	Stochastic (Modest CR Pressure)	Magnetic Reconnection
	p-value		
NGC 1068	10^{-6}	0.09	1.8×10^{-4}
NGC 1275	0.03	0.3	0.1
CGCG 164-019	0.04	0.3	0.1
UGC 11910	0.1	0.4	0.09
Cen A	0.5	0.2	0.2
Circinus Galaxy	0.5	0.3	0.3
NGC 7582	0.5	0.5	0.1
ESO 138-1	0.5	0.5	0.09
NGC 424	0.5	0.5	0.5
NGC 4945	0.5	0.5	0.5

Keirandish et al., ApJ (2021)

Non-bias search needed?



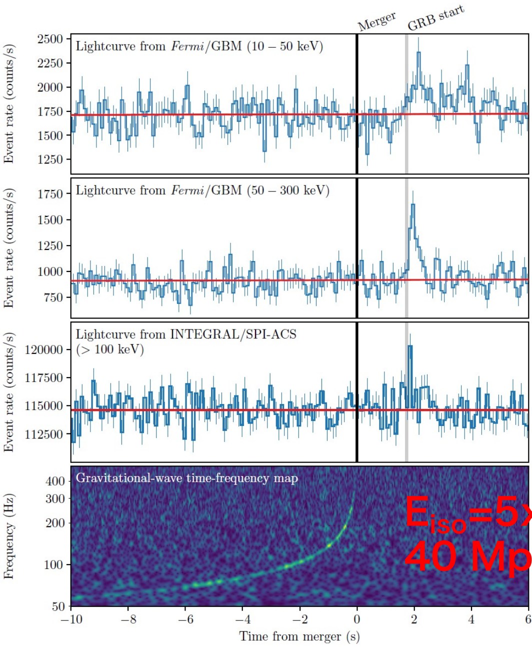
CTA KSP

Extragal Survey

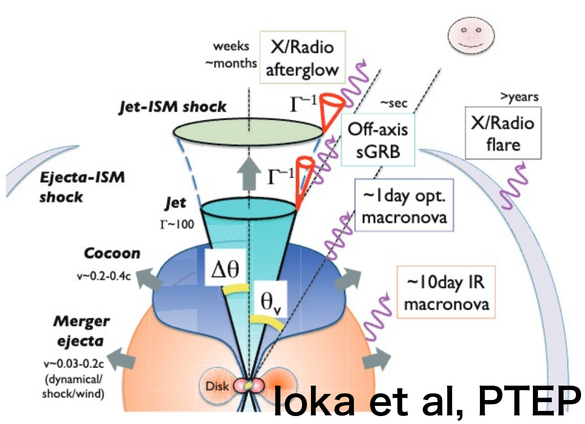
- 1000 hours
- 25% of sky
- 6 mCrab

Neutron Star Merger/Short GRB

GRB 170817A/GW170817



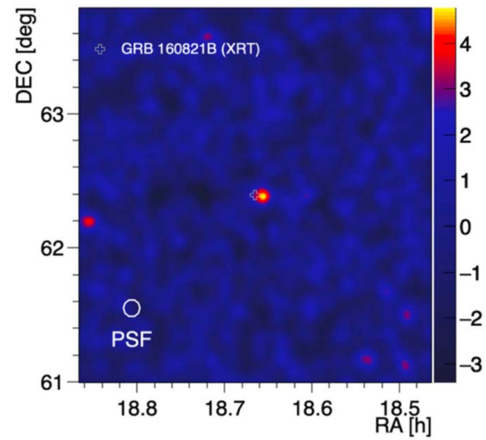
E_{iso}=5x10^{46} erg
40 Mpc



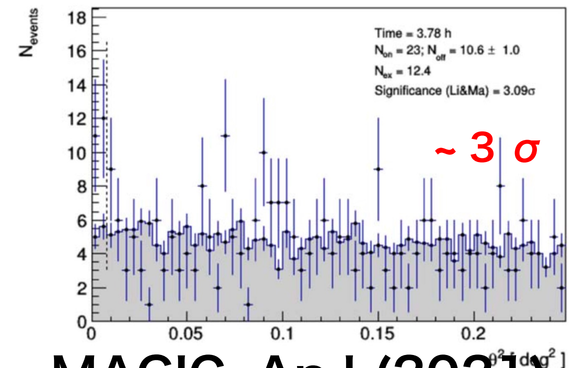
Ioka et al, PTEP 2015

Fig. 1 Schematic figure of our unified picture.

GRB 160821B



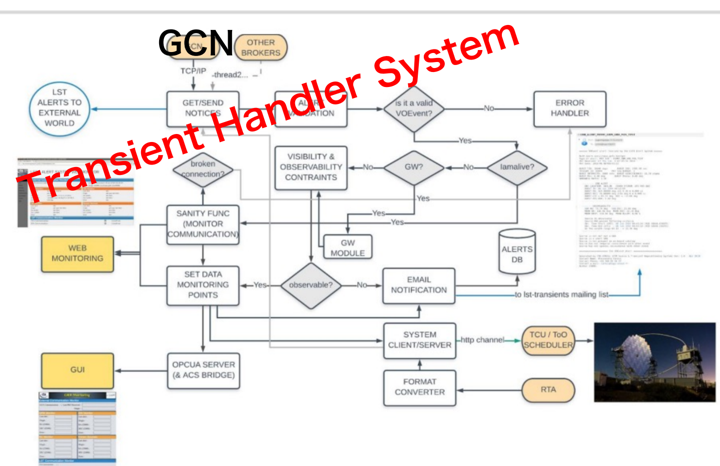
E_{iso}=1.2x10^{50} erg
Z=0.16



MAGIC, ApJ (2021)

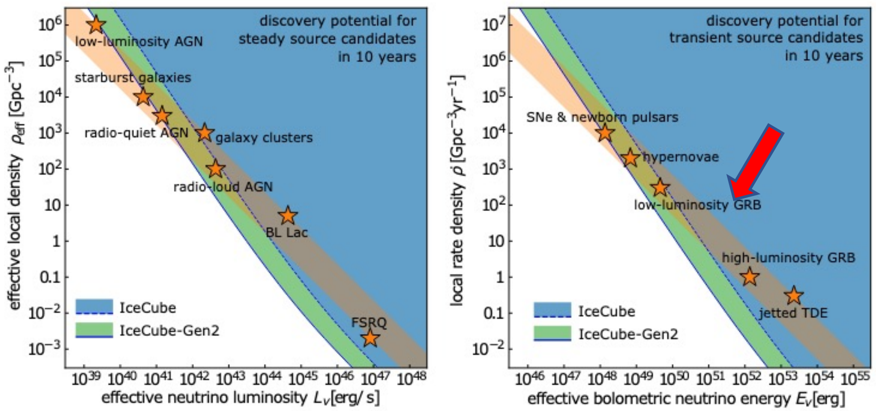
t= 24s to t=4 h
Under moon

TH workflow



Follow-up observation of neutron star merger is one of the top priorities.

Low Luminosity GRB



IceCube 2008.04323 (2020)

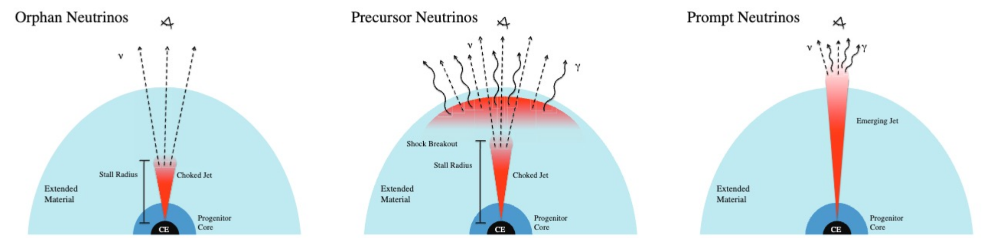
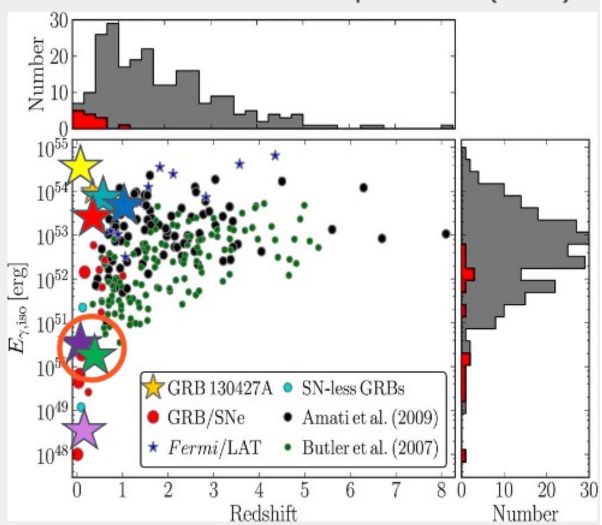


FIG. 1: **Left panel:** The choked jet model for jet-driven SNe. Orphan neutrinos are expected since electromagnetic emission from the jet is hidden, and such objects may be observed as hypernovae. **Middle panel:** The shock breakout model for LL GRBs, where transrelativistic shocks are driven by choked jets. A precursor neutrino signal is expected since the gamma-ray emission from the shock breakout occurs significantly after the jet stalls (e.g., [26]). **Right panel:** The emerging jet model for GRBs and LL GRBs. Both neutrinos and gamma-rays are produced by the successful jet, and both messengers can be observed as prompt emission.

★GRB190829A
- E_{iso} = 1.8 × 10^{50} erg
- Redshift z = 0.078
- H.E.S.S. detected VHE emission
- Very low radiation efficiency of prompt emission (0.12 %)
  cf.) Salafia et al. (2022)

★GRB201015A
- E_{iso} = 1.1 × 10^{50} erg
- Redshift z = 0.426
- MAGIC observed and reported a hint of signal
- MAGIC paper in prep. (K. Terauchi)

D. Xu et al. ApJ 776 98 (2013)



★ GRB180720B (z = 0.65) ★ GRB190114C (z = 0.42)
★ GRB201216C (z = 1.1) ★ GRB221009A (z = 0.15)
★ GRB190829A (z = 0.078) ★ GRB160821B (z = 0.16; short)

From K. Terauchi, ASJ meeting

- LL GRBs are good canndidate for diffuse nu
- Can be explained by choked jet model . (Senno et al., Phys Rev D. 2016)
- Can be explained by off-axis (Sato et al 2021, MNRAS).
- Out of 6 TeV GRBs, 2 are LL GRBs.
- We need more samples with CTA to understand the mechanism.

Summary

Target	Physics	messenger
Type II Supernovae	Supernova Mechanism	γ, LowE-ν
Supernova Reminants	(hadron) CR acceleration	γ, ν
Pulsar Halo	CR propagation	γ, electron
Galactic Diffuse, Center	CR accel. & propagation.	γ, ν
Blazars	Jet physics, origin of UHECR	γ, ν, UHECR
Seyfart Galaxies	AGN structure	γ, ν
Neutron Star merger	Short GRB mechanism	γ, GW,
Low Lominosity GRB	GRB mechanism and diffuse ν	γ, ν

- With CTA and other messengers, one can study many different topics (much more than this table).