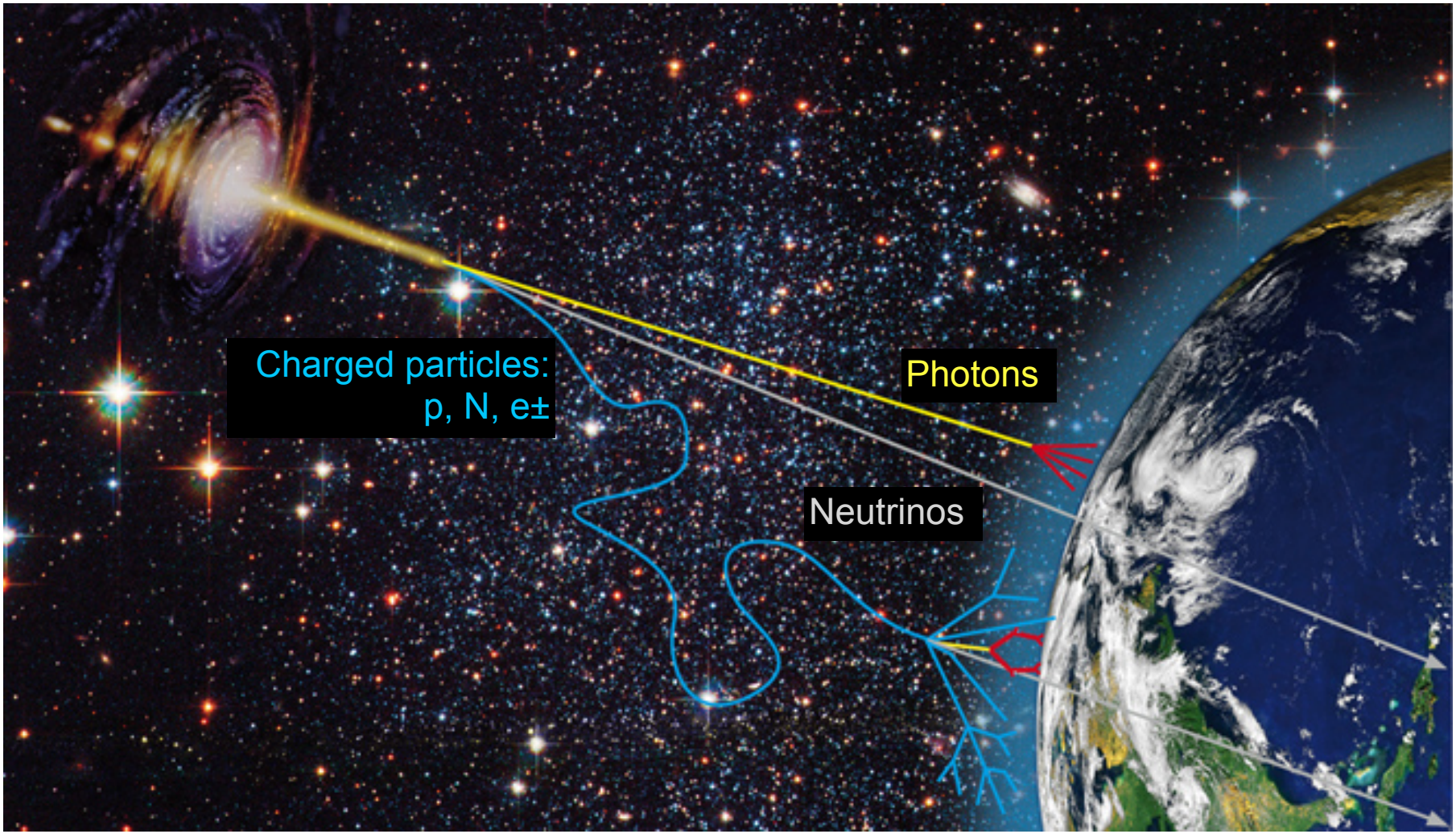
高エネルギーガンマ線によるIceCube ニュートリノ事象の追観測

天文学会2018秋季大会@兵庫県立大学
企画セッション“高エネルギー宇宙ニュートリノから展開するマルチメッセンジャー天文学”
2018年9月18日

林田　将明 (甲南大学)

マルチメッセンジャー観測：光子(ガンマ線）

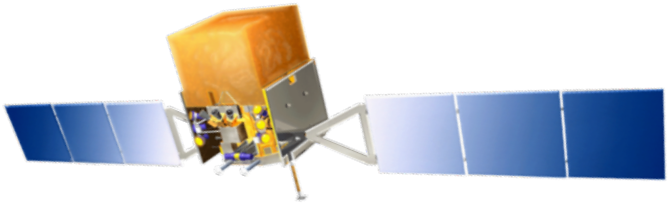


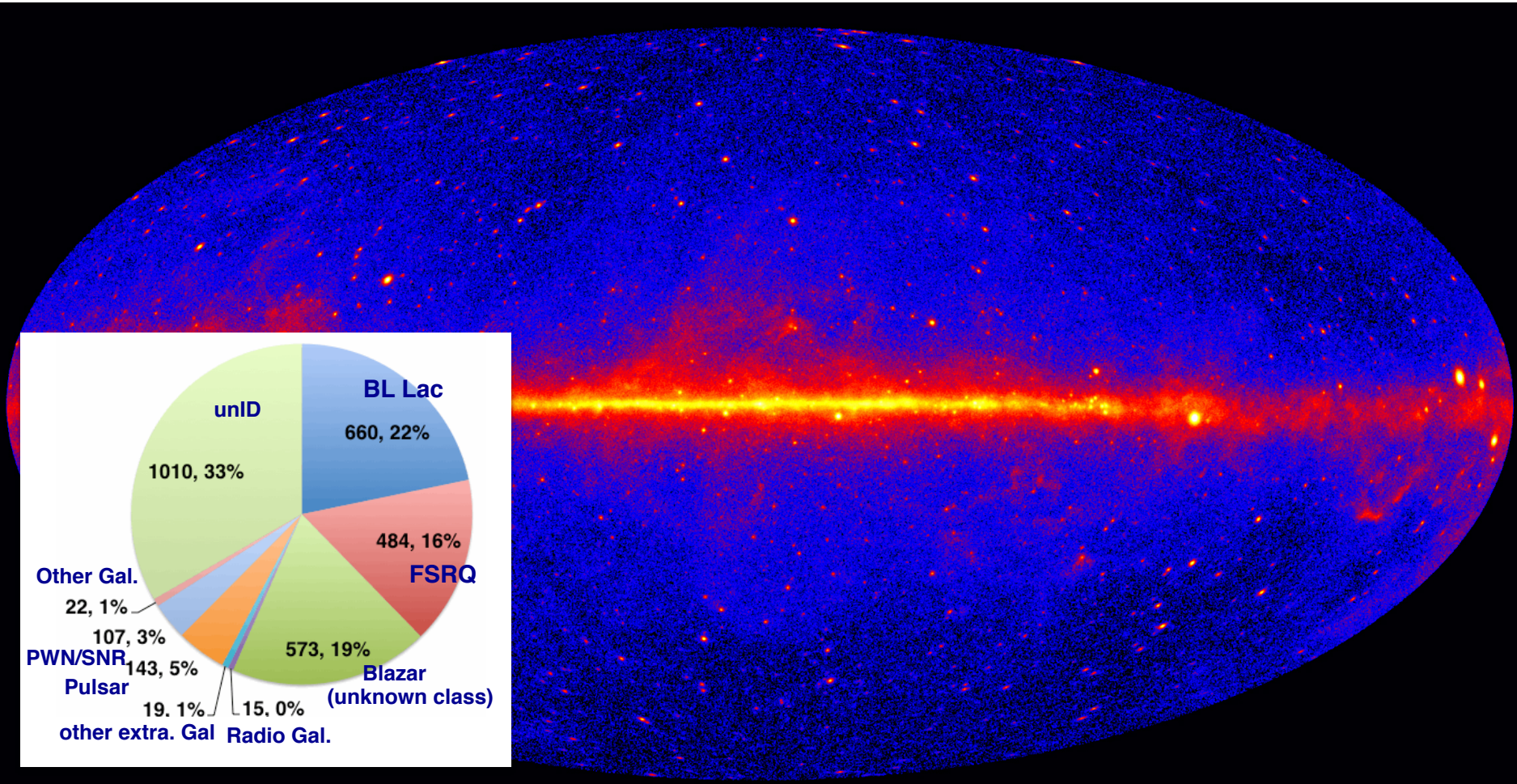
Outline

1. イントロダクション: ガンマ線観測
   - これまでのガンマ線によるフォローアップ観測
2. IceCube-170922A/TXS0506+056
   - 高エネルギーガンマ線による観測
   - 2014/2015 “neutrino flare” 時のガンマ線
3. 考察
   - なぜTXS0506+056なのか？
     - ブレーザーが主なニュートリノ起源天体か？
   - ブレーザー以外の候補天体

Gamma-ray sky (>100 MeV)

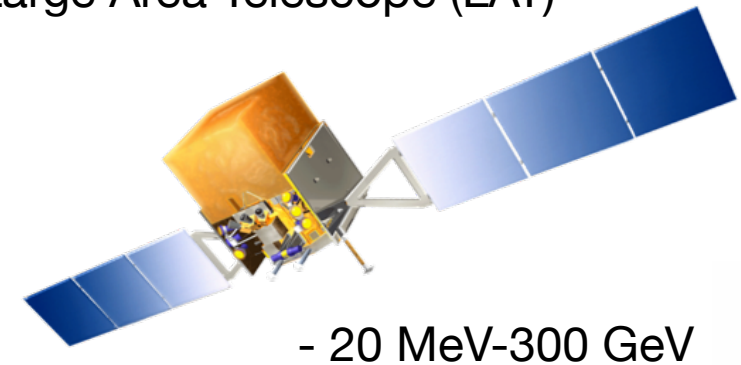
Fermi-LAT (Satellite)





Fermi Gamma-ray Space Telescope

Large Area Telescope (LAT)

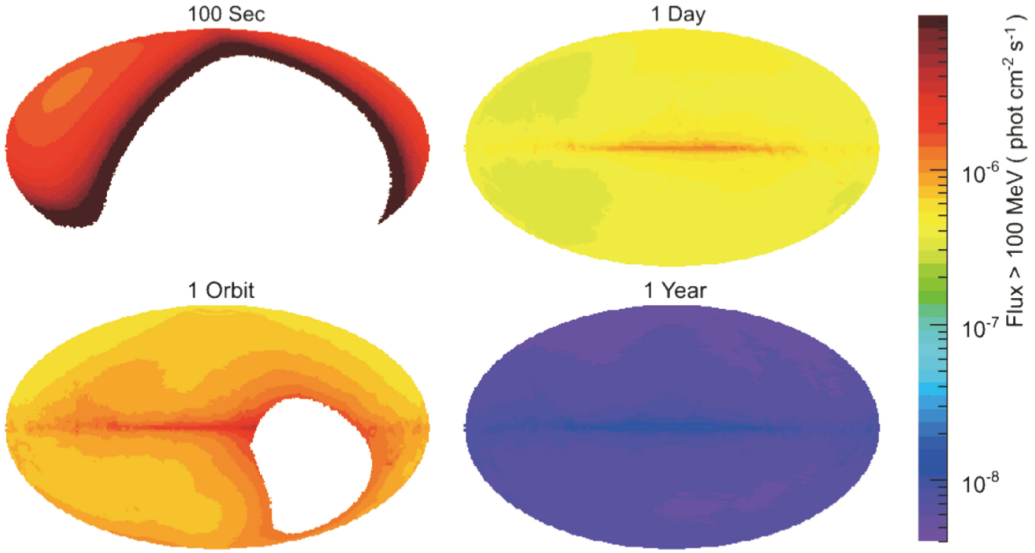


- 20 MeV-300 GeV

- 2008年6月11日打ち上げ→今年10周年を迎えた
- 検出器に大きな問題はなく観測中
- 全天サーベイ観測にて運用

2.4strの広視野により、
3時間（2軌道）で全天
のサーベイ観測可能

All-sky survey-mode observation

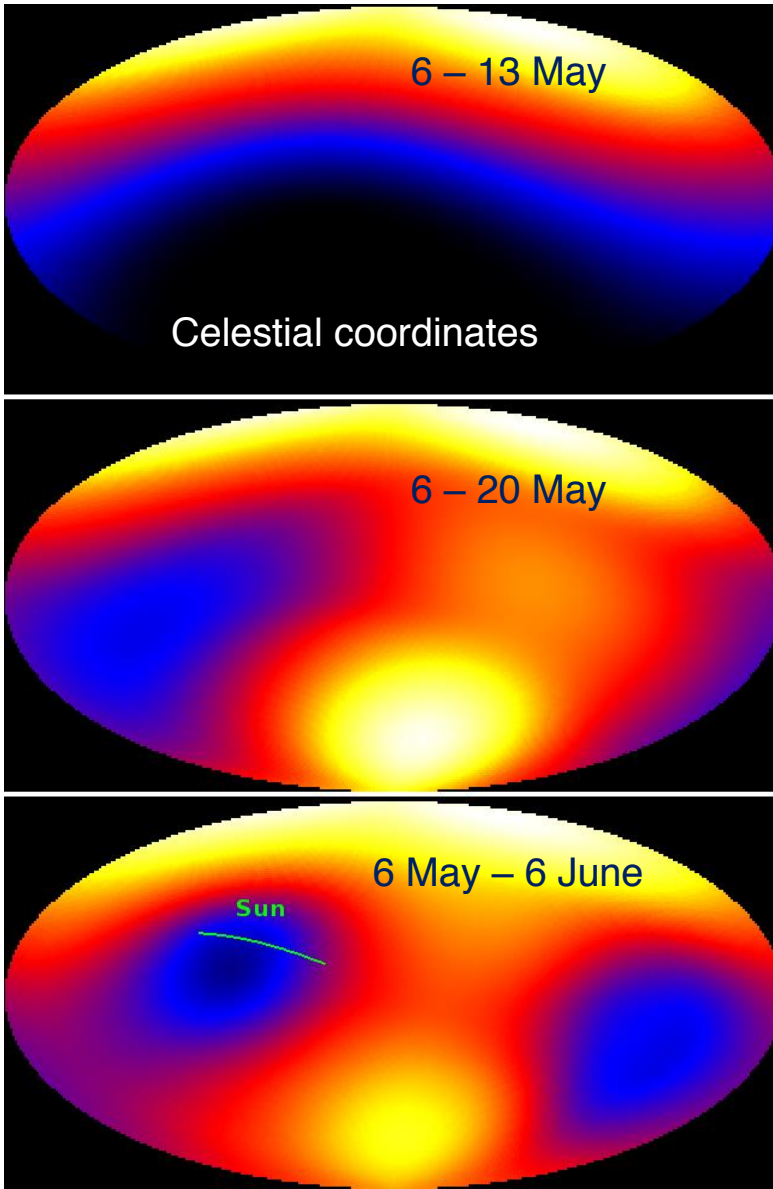


→変動/突発天体を毎日観測できる優れた性能

現状の観測モード

Current *Fermi* operations

- The orbit's inclination is 25.6°
- The LAT can stay at the same rocking angle for one week (top)
- … but not for two weeks (center)
- Over one month (bottom), exposure minima (20 – 25% of maximum) correspond to the Sun and antiSun.
- Average over one year broadly similar to previous survey mode
- Working to improve sky coverage over daily time scale

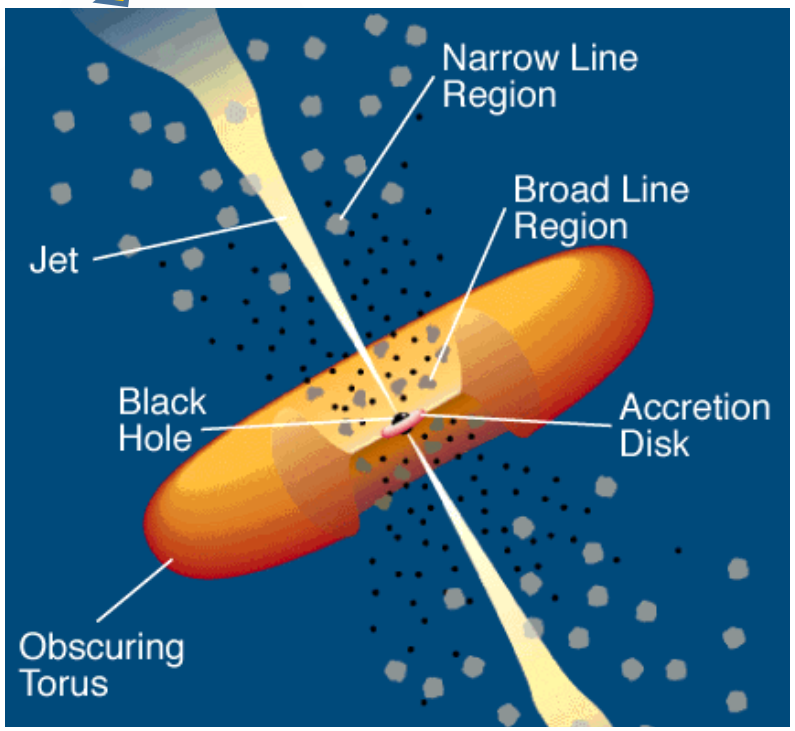


Blazars: Active Galactic Nucleus Jets

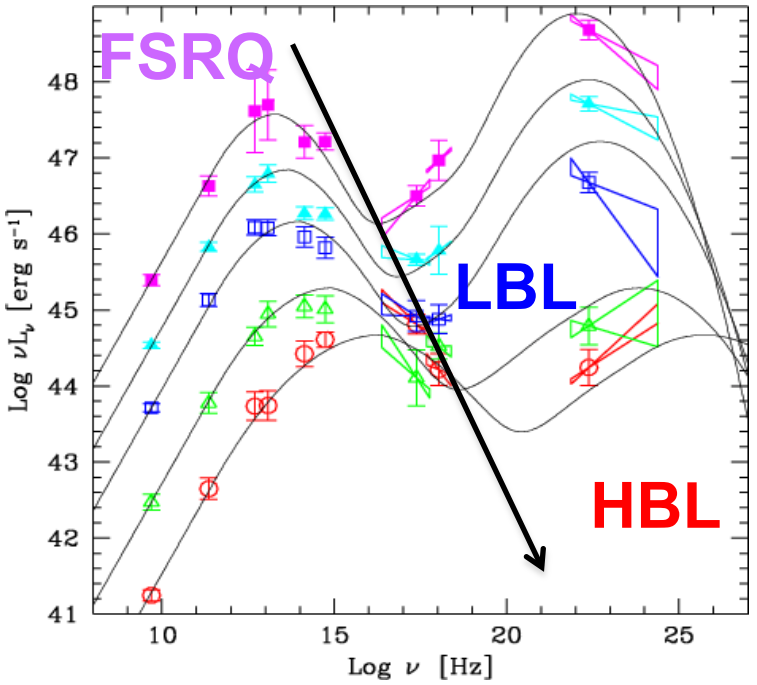
- Flat Spectrum Radio Quasar: luminous disk
- BL Lac type : low luminous disk (almost **no optical line**

Observer

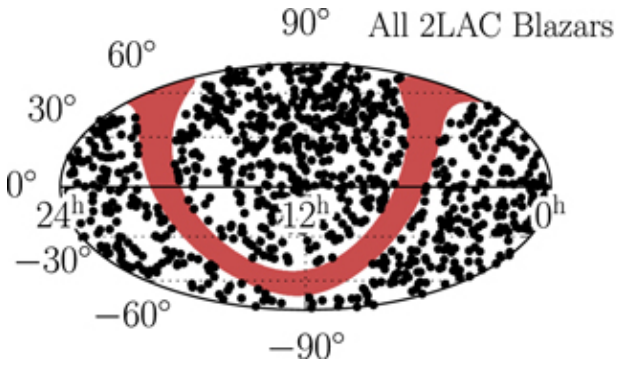
Blazar



Blazar sequence (?)

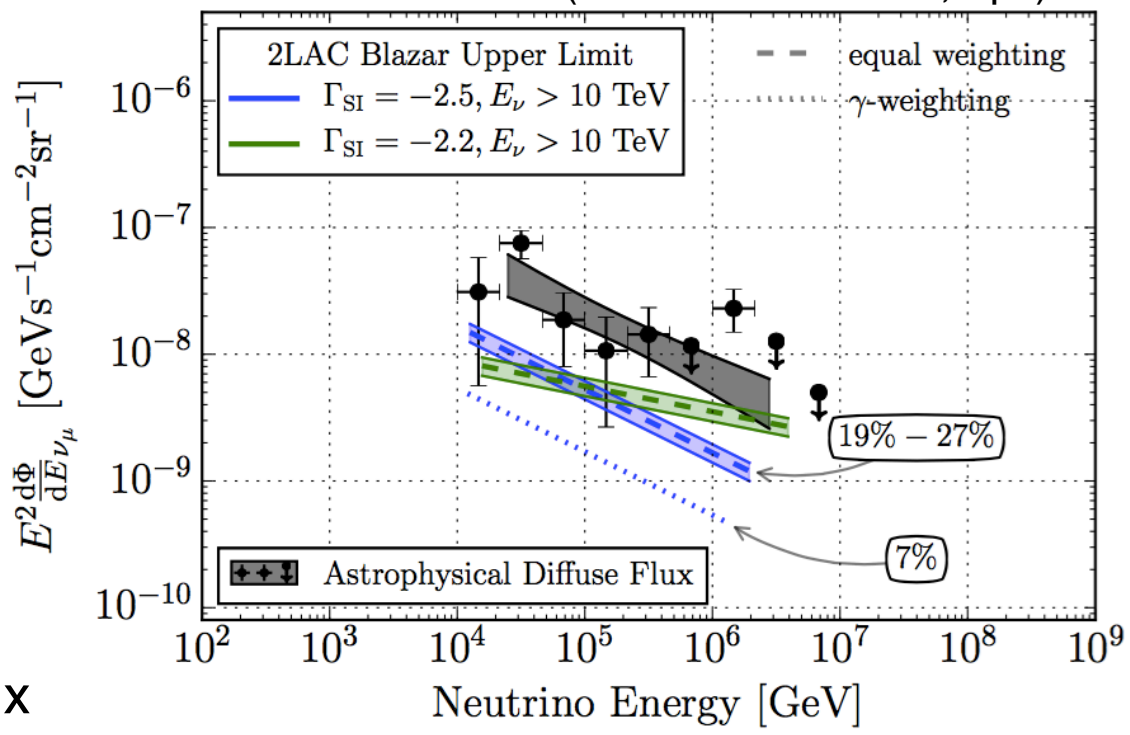


LAT blazars and IceCube event correlations



(2LAC = 2nd LAT AGN catalog)
[862 srcs, |b| > 10 deg]

(IceCube Coll. 2017, ApJ)



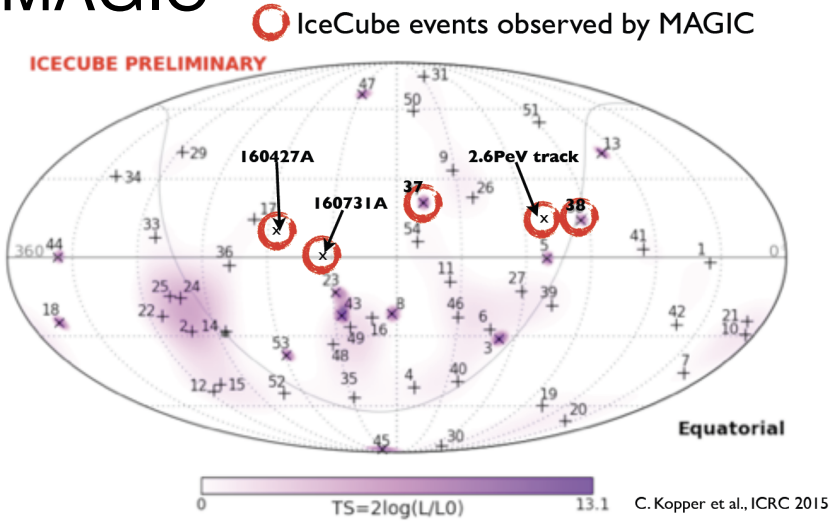
no spatial
correlation between
2LAC source and IC events

- < 27% of the IC neutrino flux

ガンマ線ブレーザー(の定常放射)はニュートリノ起源の主要な天体、とは言えなそうだ。

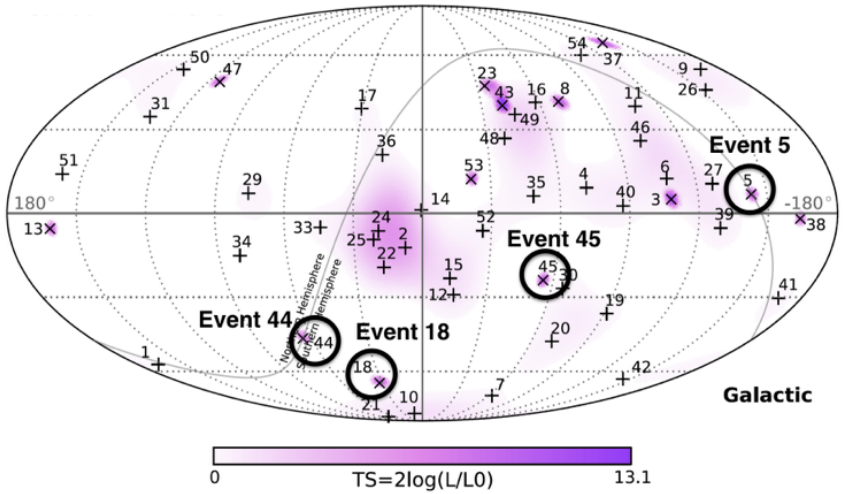
Observations for Archival ν events by IACTs (>100 GeV)

MAGIC

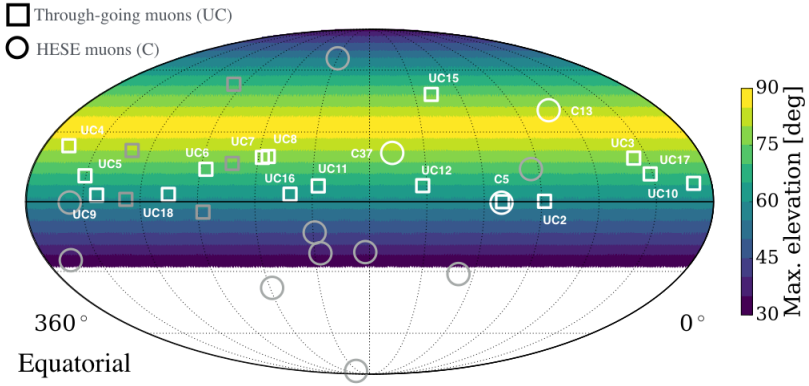


C. Kopper et al., ICRC 2015

H.E.S.S.



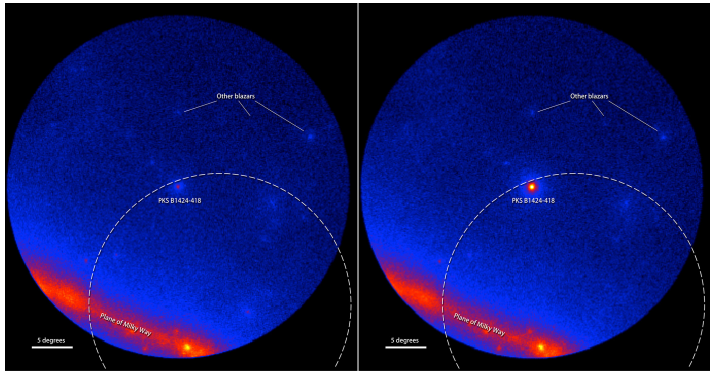
VERITAS



どれも対応ガンマ線源の発見には至らず。

Possible association of PeV neutrino with high fluence blazar PKS 1424-418 (z=1.522)

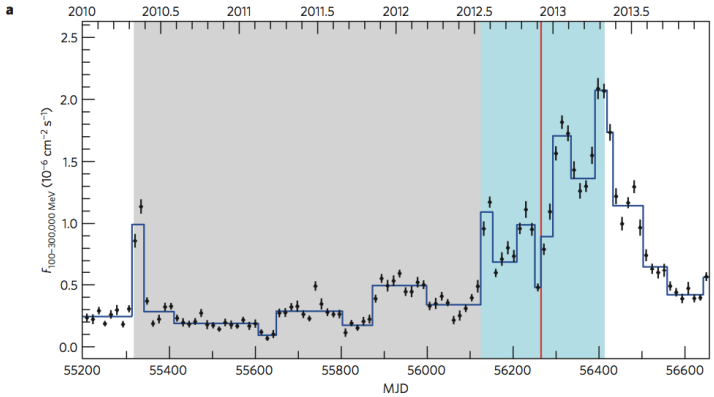
4 December 2011: ~2 PeV



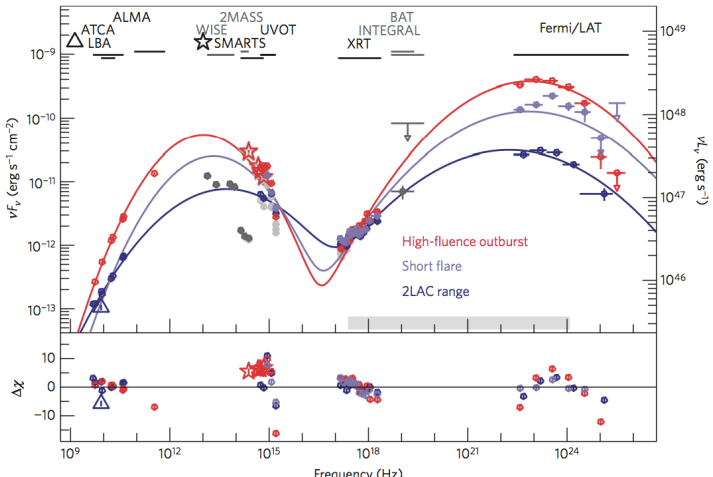
- Cascade event of error radius of ~10 deg (17 γ-ray blazars inside)
- ~5% chance probability

Table 1 | Maximum-possible number of petaelectronvolt-neutrino events in 36 months (988 days live-time) of IceCube data for the 17 2LAC γ-ray blazars in the field of the 2 PeV IceCube event based on 2LAC catalogue γ-ray spectra and contemporaneous X-ray data.

2FGL name	Common name	F_γ (erg cm^{-2} s^{-1})	$N^{max}_{\nu,PeV}$
2FGL J1230.2-5258	PMN J1229-5303	$(2.4^{+1.5}_{-1.5})\times10^{-11}$	0.14
2FGL J1234.0-5733	PMN J1234-5736	$(1.1^{+0.4}_{-0.4})\times10^{-11}$	0.06
2FGL J1303.5-4622	PMN J1303-4621	$(1.9^{+0.6}_{-0.6})\times10^{-11}$	0.11
2FGL J1303.8-5537	PMN J1303-5540	$(1.04^{+0.11}_{-0.11})\times10^{-10}$	0.38
2FGL J1304.3-4353	1RXS 130421.2-435308	$(2.11^{+0.25}_{-0.25})\times10^{-11}$	0.12
2FGL J1307.5-4300	1RXS 130737.8-425940	$(8.4^{+1.7}_{-1.7})\times10^{-12}$	0.05
2FGL J1307.6-6704	PKS B 1304-668	$(1.54^{+0.15}_{-0.15})\times10^{-10}$	0.89
2FGL J1314.5-5330	PMN J1315-5334	$(8.1^{+0.9}_{-0.9})\times10^{-11}$	0.47
2FGL J1326.7-5254	PMN J1326-5256	$(1.04^{+0.21}_{-0.18})\times10^{-10}$	0.59
2FGL J1329.2-5608	PMN J1329-5608	$(1.38^{+0.36}_{-0.29})\times10^{-10}$	0.93
2FGL J1330.1-7002	PKS B 1326-697	$(1.53^{+0.11}_{-0.11})\times10^{-10}$	0.89
2FGL J1352.6-4413	PKS B 1349-439	$(5.4^{+1.0}_{-1.0})\times10^{-11}$	0.32
2FGL J1400.6-5601	PMN J1400-5605	$(6.9^{+0.8}_{-0.8})\times10^{-11}$	0.40
2FGL J1407.5-4257	CGRaBS J1407-4302	$(1.6^{+0.5}_{-0.5})\times10^{-11}$	0.09
2FGL J1428.0-4206*	PKS B1424-418*	$(2.04^{+0.17}_{-0.16})\times10^{-10}$*	1.57*
2FGL J1508.5-4957	PMN J1508-4953	$(7.6^{+3.0}_{-2.3})\times10^{-11}$	0.55
2FGL J1514.6-4751	PMN J1514-4748	$(5.6^{+0.6}_{-0.6})\times10^{-11}$	0.32
Sum (2LAC)			7.9

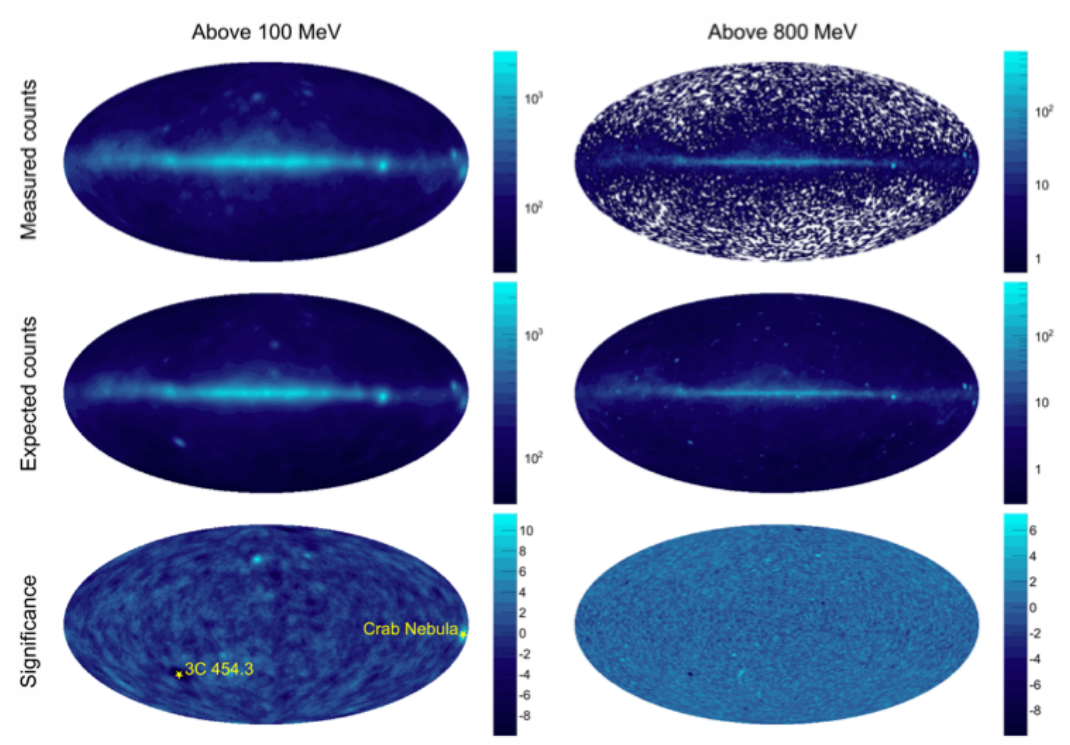


Kadler+16

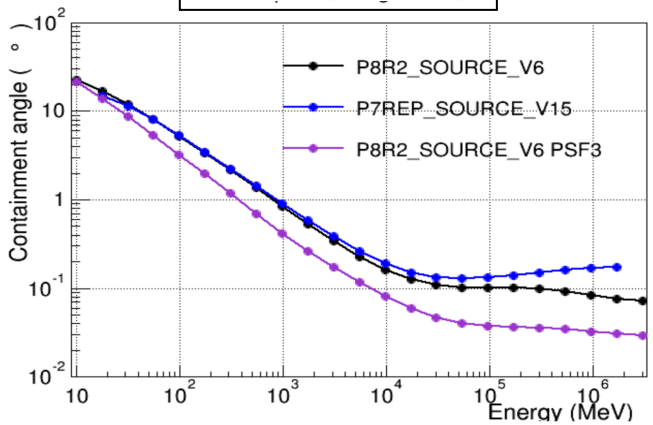


Fermi All sky Variability Analysis (FAVA)

- 一週間ビン
- E>100 MeV, E>800 MeV
- 一定領域内の検出光子数と、平均値とを比較
  - aperture photometry (↔ max. likelihood fit for the standard analysis.)
- カニ星雲のフレアを発見

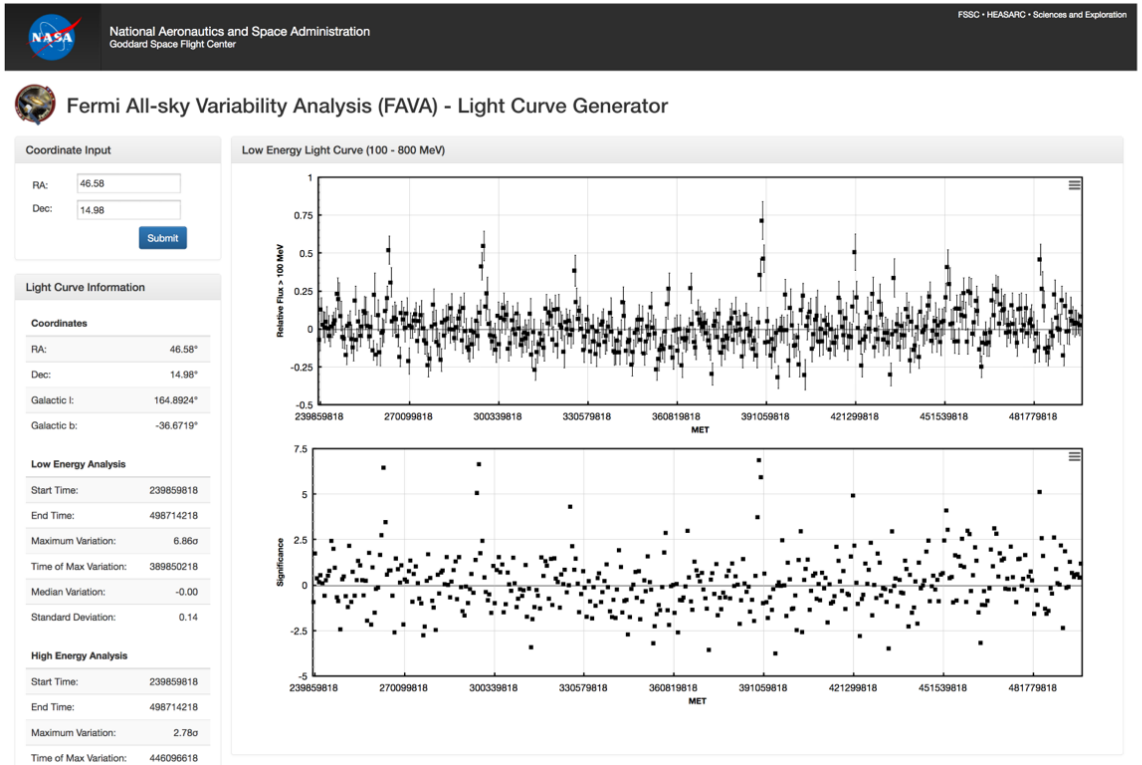


PSF (68 %)



$$N^{exp}(\phi,\theta) = \sum_{E:j=1..12} \sum_{\alpha:i=1..4} N^{tot}_{i,j}(\phi,\theta) \times \frac{\epsilon^{week}_{i,j}(\phi,\theta)}{\epsilon^{tot}_{i,j}(\phi,\theta)},$$

FAVA webpage



- https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/LightCurve.php
- Automatic production of light curve at any locations (RA, Dec)

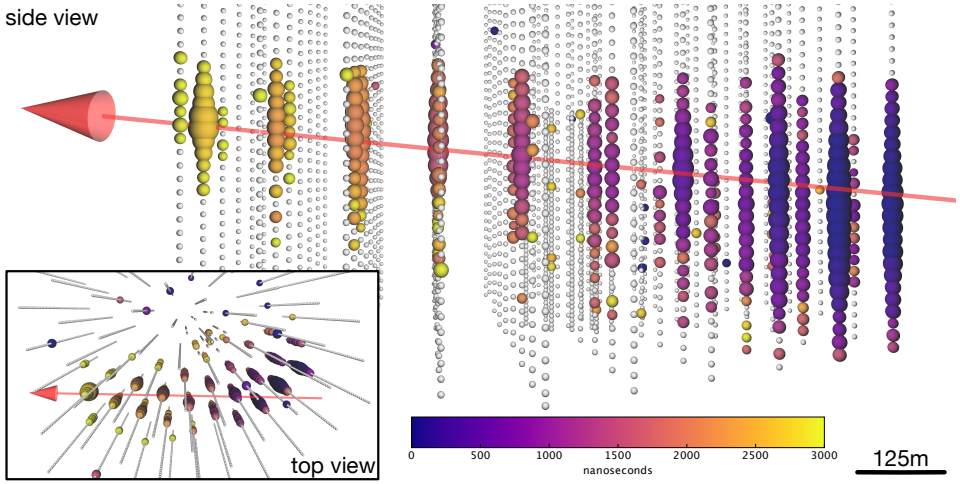
論文には、この結果ではなく、標準解析
(max. likelihood fit)した結果を用いたほうがよいです！！

IceCube-170922A

(IceCube, Fermi-LAT, MAGIC++Coll. 2018 Science, aat1378)

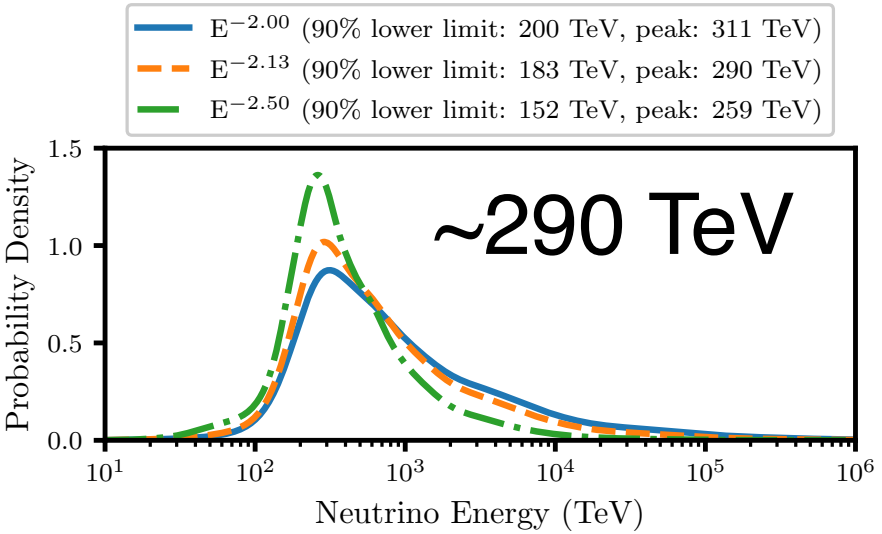
EHE alert: 2017/9/22 20:54:30 UTC

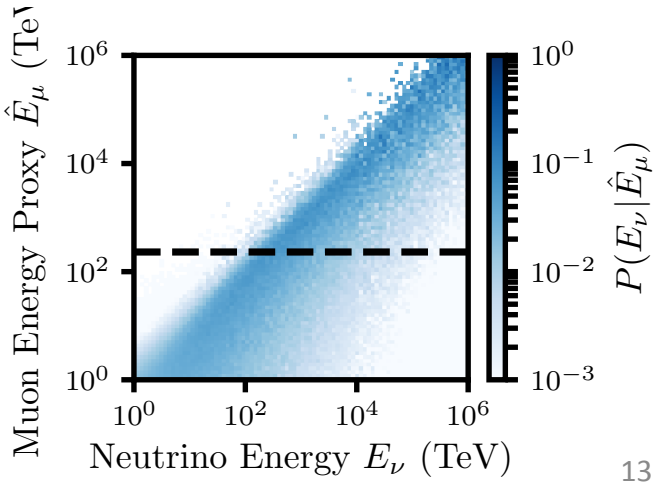
IceCube event
(ν_μ :muon track)



singleness: 56.5 %

energy estimation



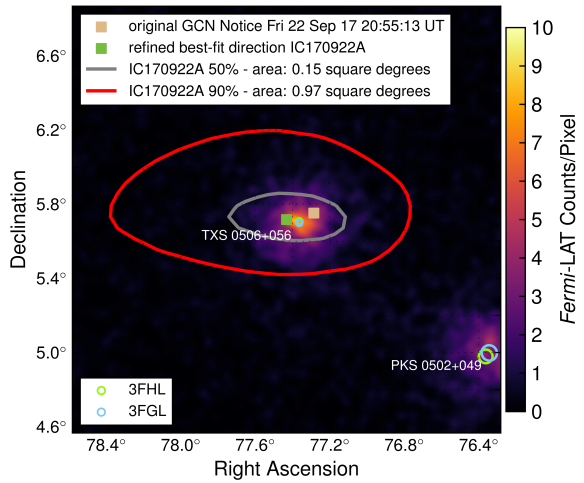


GCN CIRCULAR #21916

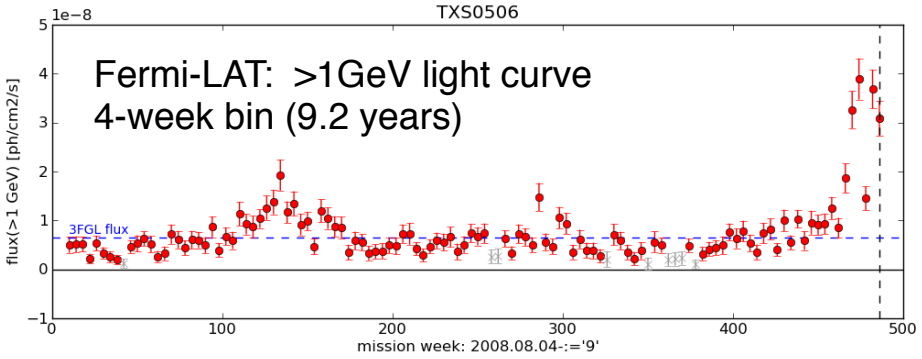
RA: 77.43 deg (-0.80/+1.30 deg)
Dec: 5.72 deg (-0.40/+0.70 deg)
(J2000: 90% error)

HE gamma-ray data by Fermi-LAT

BL Lac TXS 0506+056 (z=0.3365)



IceCube170922A



Tanaka ,Y, et al. ATel#10791

[Previous | Next | ADS]

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942

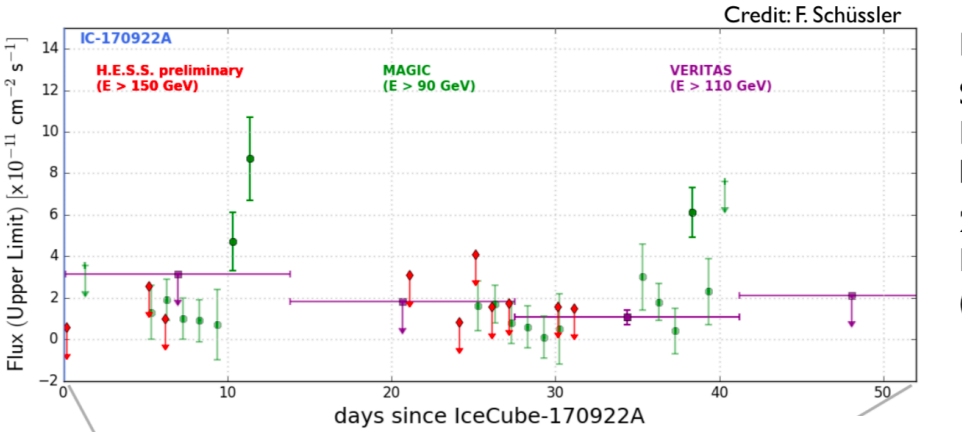
Tweet Recommend 3

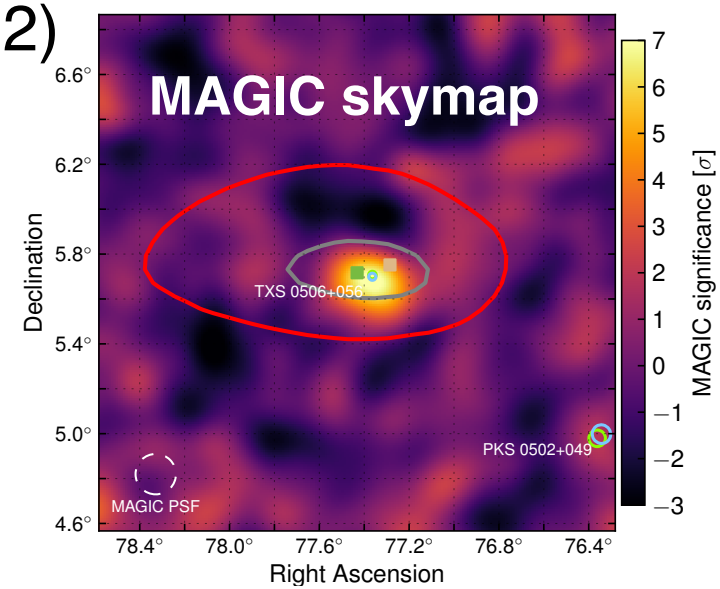
We searched for Fermi-LAT sources inside the extremely high-energy (EHE) IceCube-170922A neutrino event error region (https://gcn.gsfc.nasa.gov/gcn3/21916.gcn3, see also ATels 10773, 10787) with all-sky survey data from the Large Area Telescope (LAT), on board the Fermi Gamma-ray Space Telescope. We found that one Fermi-LAT source, TXS 0506+056 (3FGL J0509.4+0541 and also included in the 3FHL catalog, Ajello et al., arXiv:1702.00664, as 3FHL J0509.4+0542), is located inside the IceCube error region. The FAVA (Fermi All-sky Variability Analysis) light curve at energies above 800 MeV shows a flaring state recently (https://fermi.gsfc.nasa.gov/ssc/data/access/lat/FAVA/SourceReport.php?week=477&flare=27). Indeed, the LAT 0.1--300 GeV flux during 2018 September 15 to 27 was (3.6+/-0.5)E-7 photons cm-2 s-1 (errors are statistical only), increased by a factor of ~6 compared to the 3FGL flux, with nearly the same power-law index of 2.0+/-0.1. We strongly encourage multiwavelength observations of this source. We also encourage optical spectroscopy for this source, because the redshift is still unknown. According to NED, the R-band magnitude is reported as 15.1 (Healey et al. 2008, ApJS 175, 97). Radio observations show that this blazar has had increasing flux during the past year: http://www.astro.caltech.edu/ovroblazars/data.php?page=data_query, http://www.physics.purdue.edu/astro/MOJAVE/sourcepages/0506+056.shtml.

Because Fermi operates in an all-sky scanning mode, regular gamma-ray monitoring of this source region will continue. For this source the Fermi-LAT contact person is Yasuyuki T. Tanaka (ytanaka@astro.hiroshima-u.ac.jp). The Fermi-LAT is a pair conversion telescope designed to cover the energy band from 20 MeV to greater than 300 GeV. It is the product of an international collaboration between NASA and DOE in the U.S. and many scientific institutions across France, Italy, Japan and Sweden.

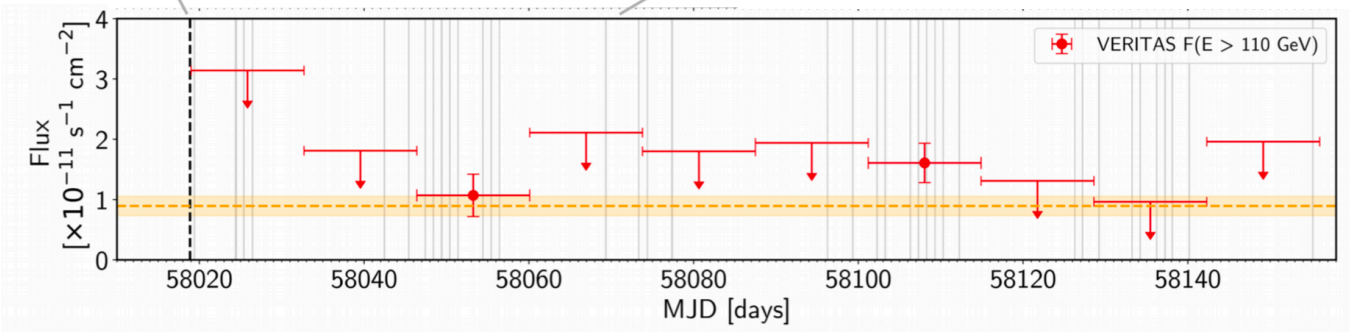
VHE γ-ray observations

MAGIC (>90 GeV): 41hr (Sep 24 – Nov 2)
2 flares, day-scale variability





H.E.S.S.: 13 h (Sep 22 – Oct 24)
no detection

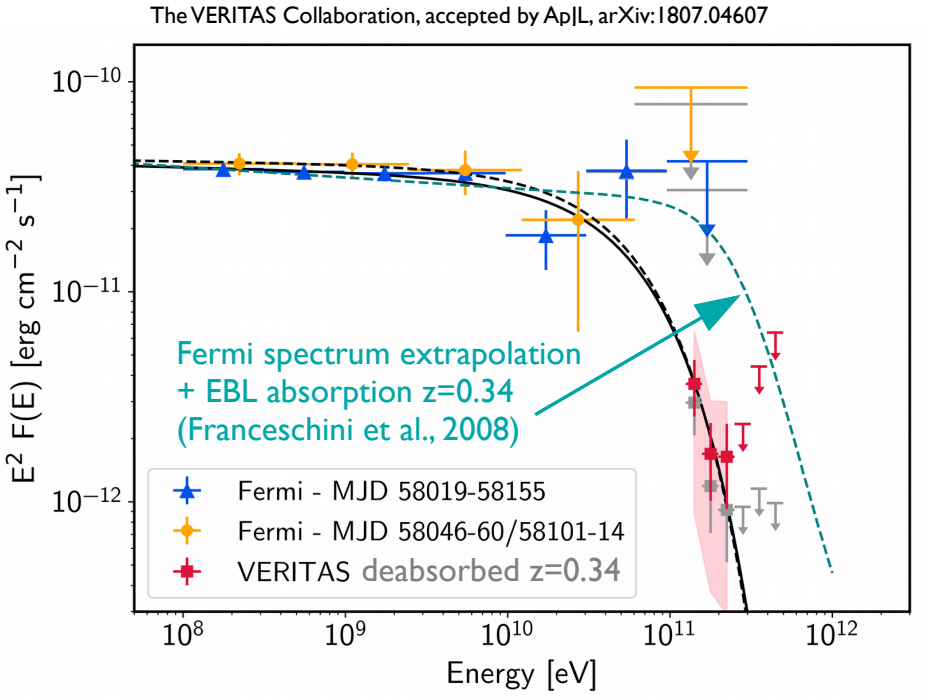


VERITAS (>110 GeV): 35h (Sep 23 – Feb 6), 5.8σ

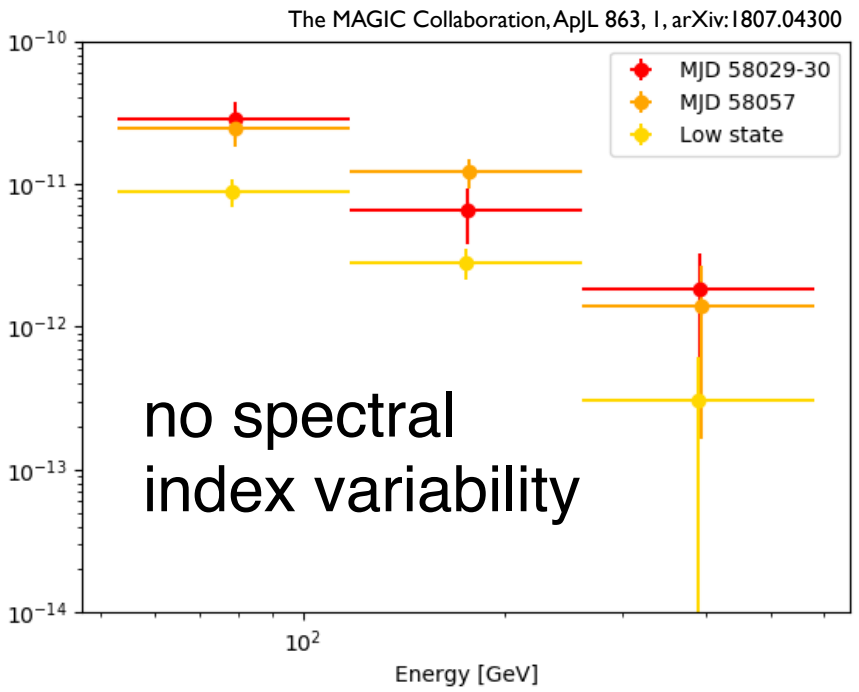
[10]

VHE γ-ray spectra

VERITAS



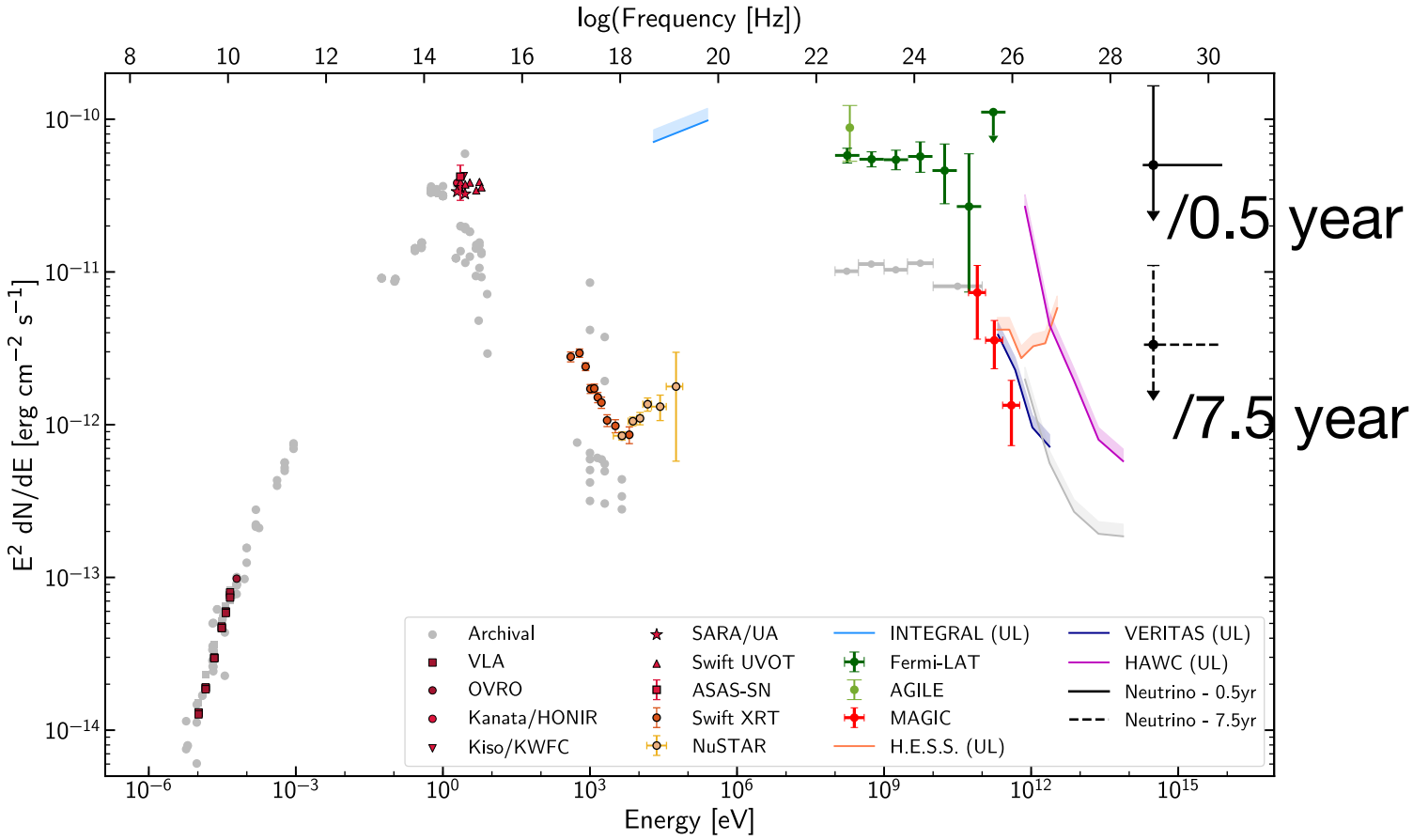
MAGIC



- *VHE spectrum index ~ 4.0 (while Fermi-LAT: ~2.0)*
- *significant curvature apart from EBL effect*

Broad Band SED

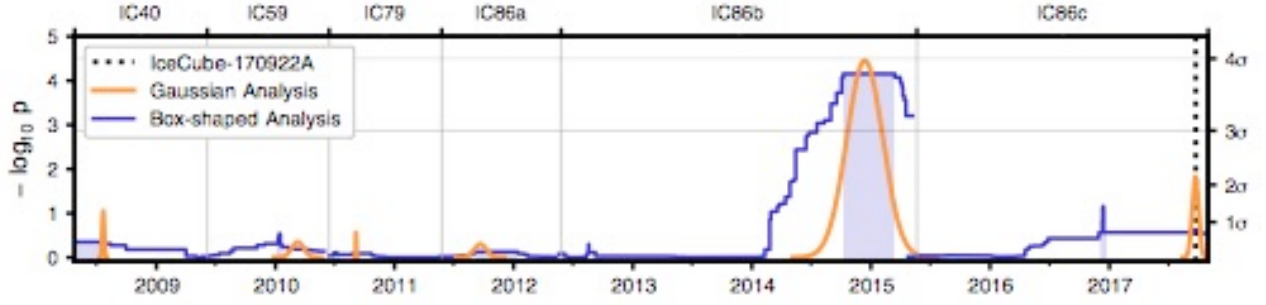
(color points: obtained within 14 days of the IC170922A event)

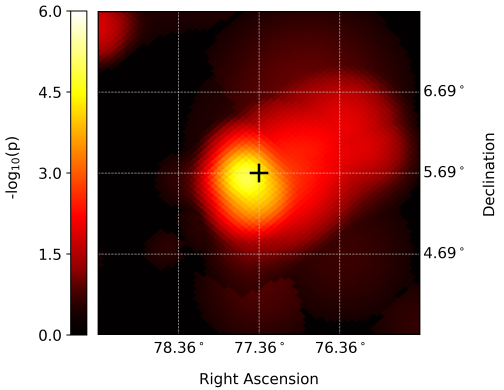


In the past IceCube data for TXS 0506+056

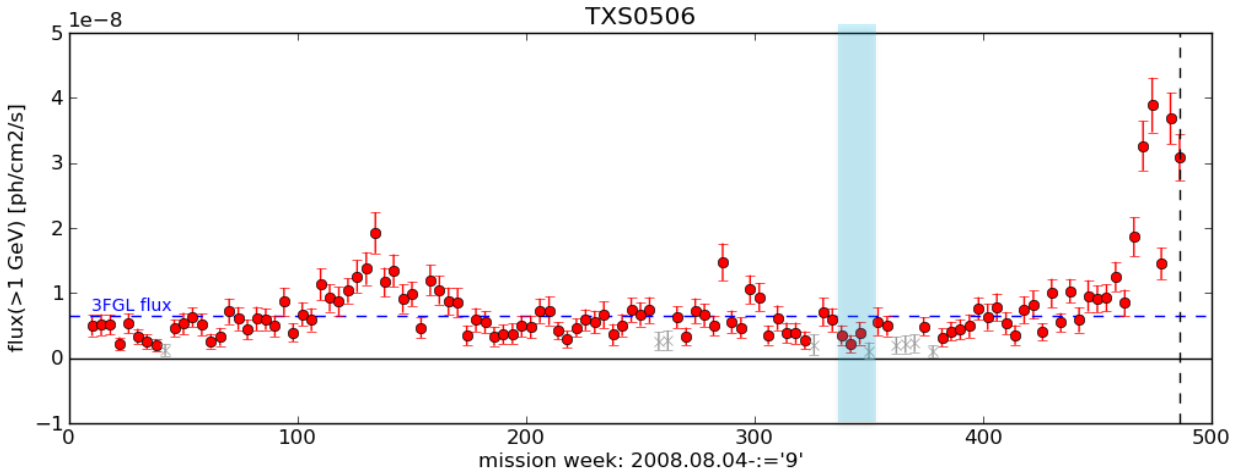
(IceCube Coll. 2018 Science aat2890)

April 2008 to October 2017





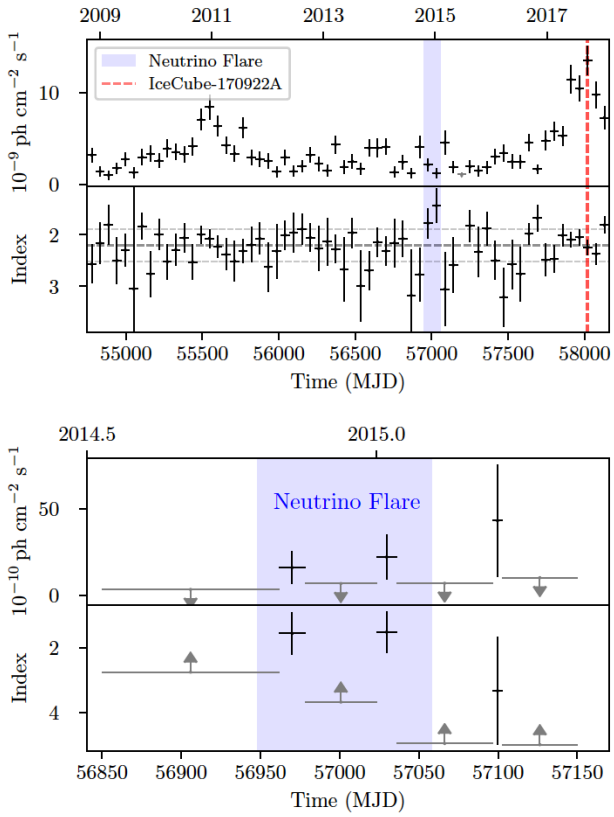
excess:3.5σ



Detailed look of the Gamma-ray band

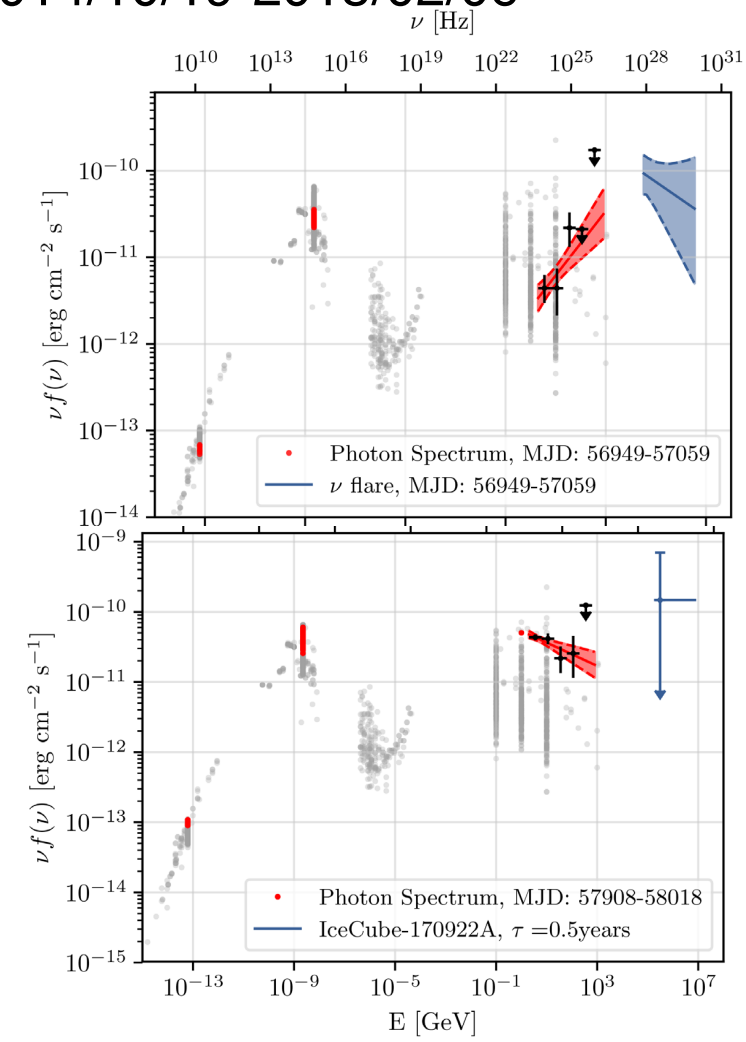
(Padovani+18 MNRAS, 480)

TXS 0506+056
Gamma-ray (> 2GeV)



Low flux, but hard state
(ただし <2 σ)

2014/10/19-2015/02/06



2017/06/04-2015/09/22

ジェットはニュートリノ起源天体か？

- ν とγフレアの同期：3 σ (post-trial)
  - ただし1事象
- νフレアもあった
  - ただしγ では暗い (冪は硬い?)

- なぜTXS 0506+056なのか？
  - なぜもっと明るい天体 (例：3C 279, Mkn421)ではないのか？

ジェットはニュートリノ起源天体か？

- 3FGLと3FHLから銀河系外天体全て
  （含、未同定l銀緯l>5deg) → **2257天体**
- 期間：**9.2年** (2008/8月-2017/10月)、**> 1GeV**

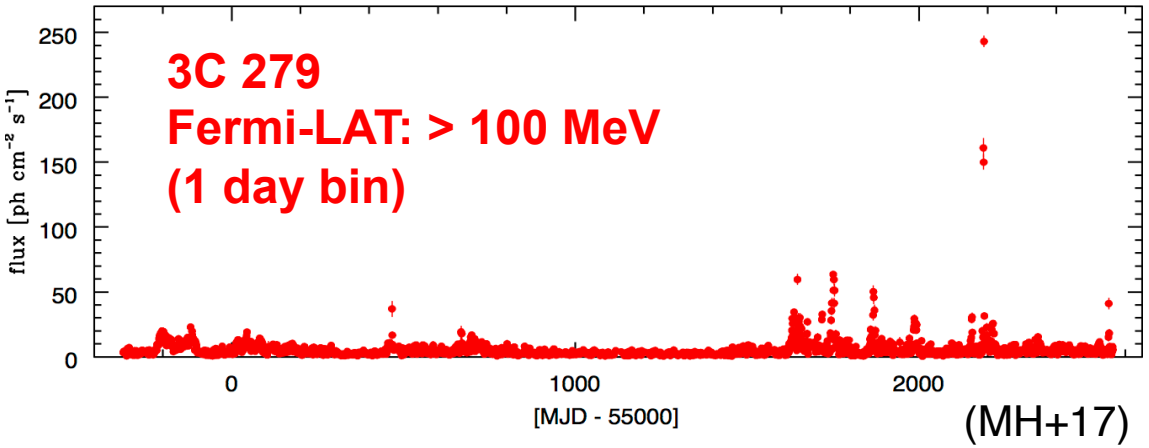
TXS 0506+056 (**LBL**, z=0.3365)

- (RA, Dec) = (05h09m25.964 +05°41’35”.33)

<比較対象>

3C 279 (**FSRQ**, z=0.536): sub-TeV検出あり

- (RA, Dec) = (12h56m11.166s -05°47’21”.52)
- 分スケールの変動

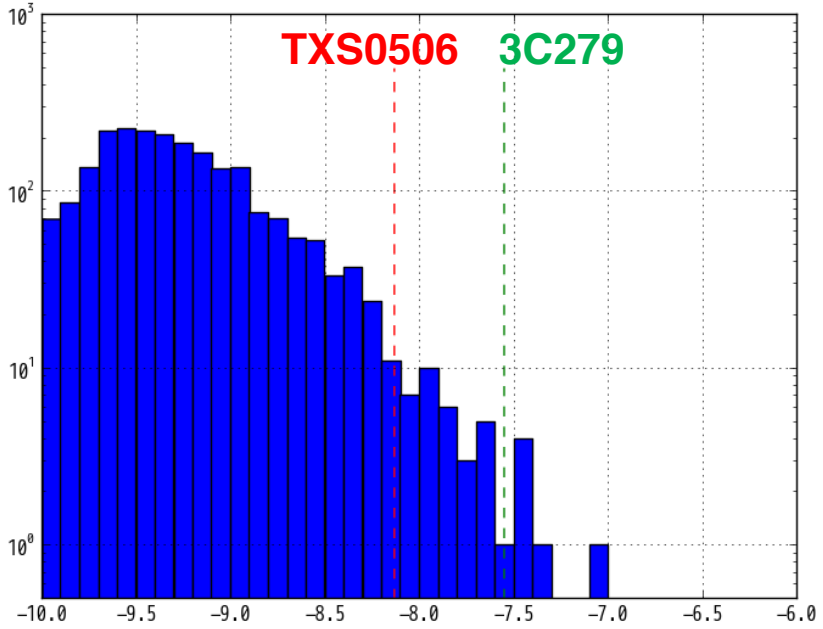


(MH+17)

ジェットはニュートリノ起源天体か？

- 3FGLと3FHLから銀河系外天体全て
  （含、未同定l銀緯l>5deg) → **2257天体**
- 期間：**9.2年** (2008/8月-2017/10月)の**平均flux > 1GeV**

Flux > 1 GeV (9.2年平均）



TXS0506: 44番目/2257

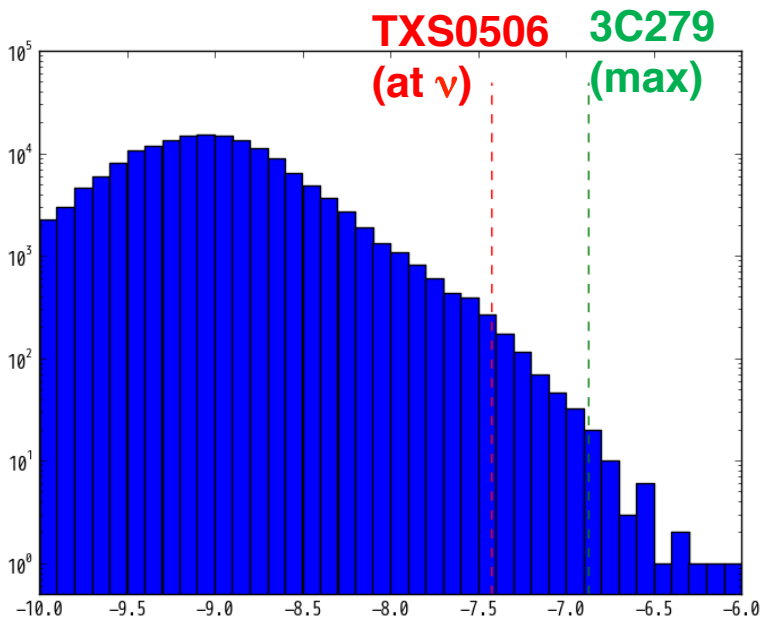
3C279： 7番目/2257

Highest: 3C454.3

ブレーザーガンマ線フレアの頻度

- 3FGLと3FHLから銀河系外天体全て
  （含、未同定|銀緯|>5deg) → **2257天体**
- 期間：**9.2年** (2008/8月-2017/10月), **28日bin, > 1GeV**

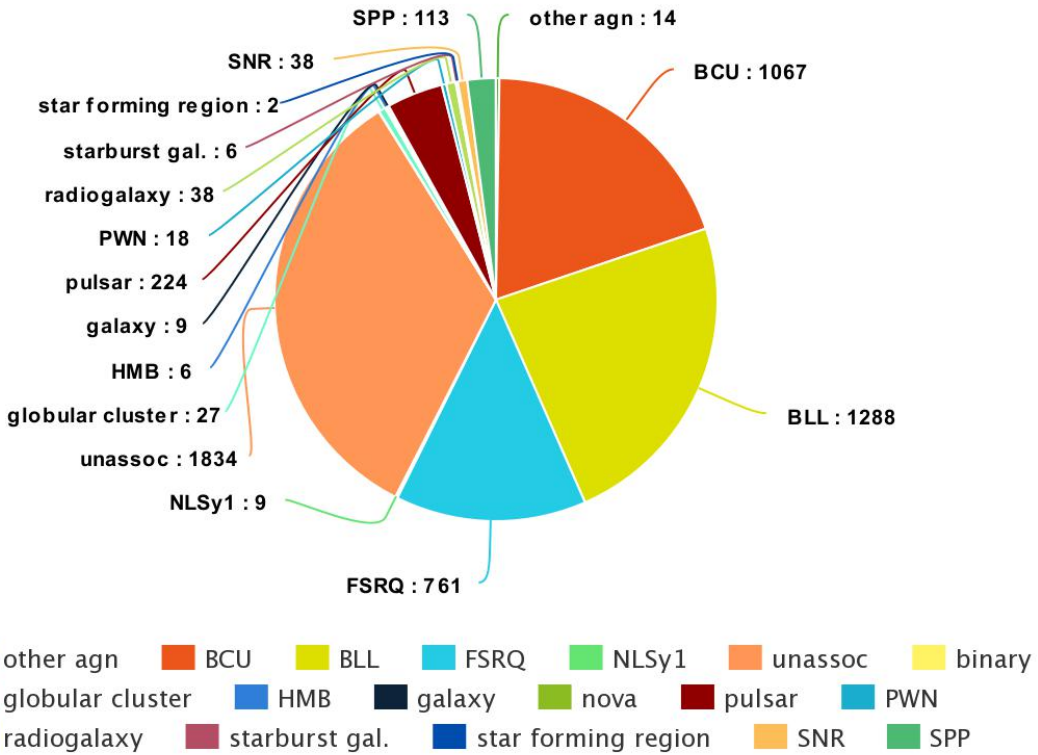
Flux > 1 GeV (28日bin)



TXS0506 at IC170922A
0.20 % (全天体、全ビンの中で)

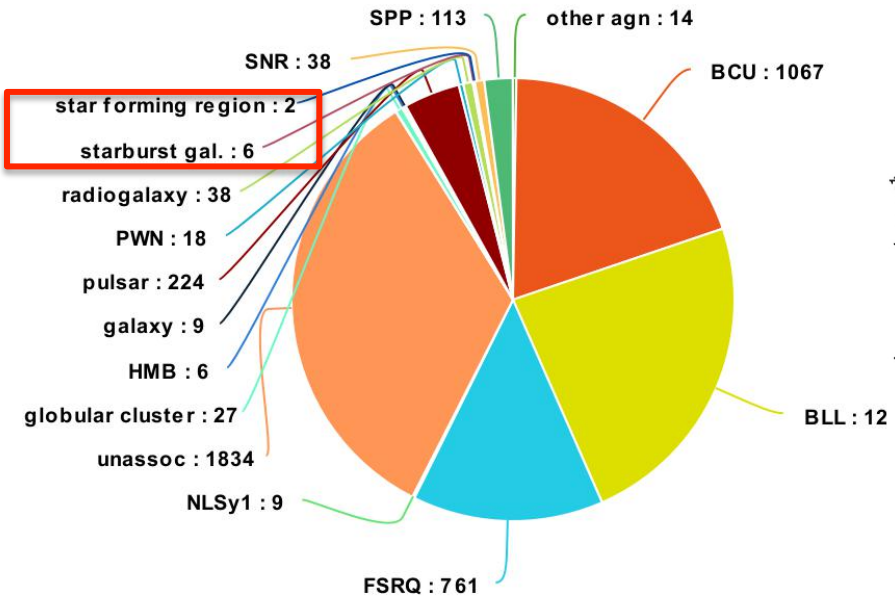
4th Fermi catalog (preliminary: FL8Y)

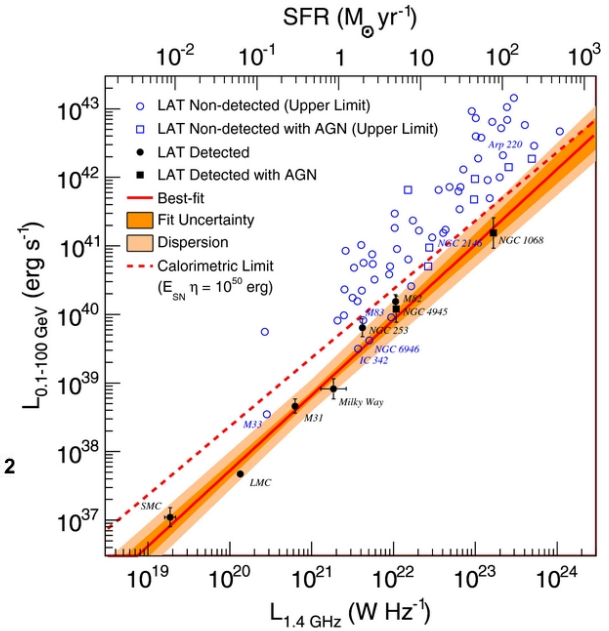
3FGL	vs	FL8Y (pre-4FGL)
4 years (Pass7)	Data	8 years (Pass8), 2.3x(acceptance)
100 MeV – 300 GeV	Energy	100 MeV – 1 TeV
3033	No. of sources	~5500



4th Fermi catalog (preliminary: FL8Y)

3FGL	vs	FL8Y (pre-4FGL)
4 years (Pass7)	Data	8 years (Pass8), 2.3x(acceptance)
100 MeV – 300 GeV	Energy	100 MeV – 1 TeV
3033	No. of sources	~5500

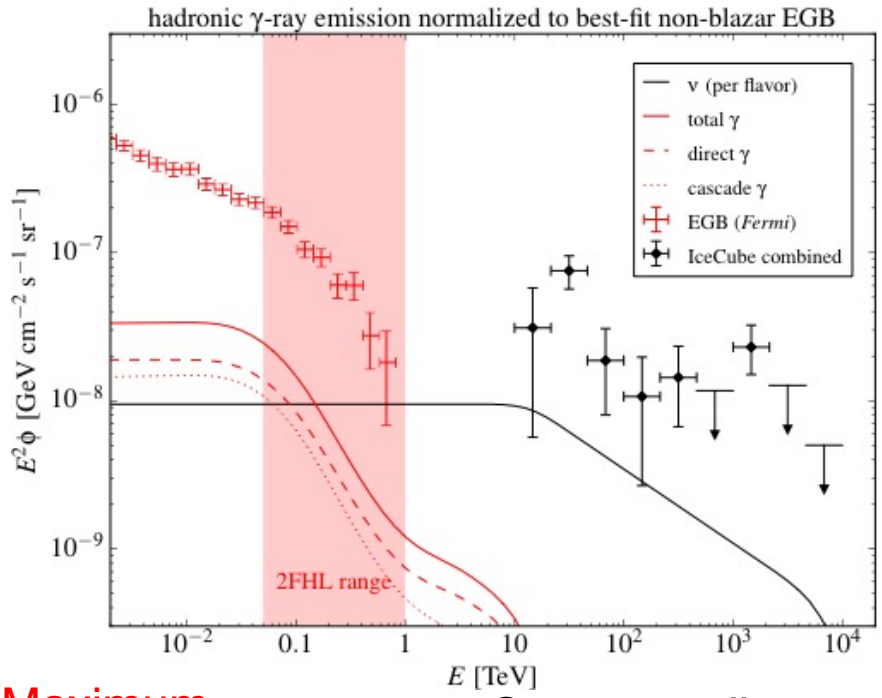




(Ackermann+12)

star-forming galaxies

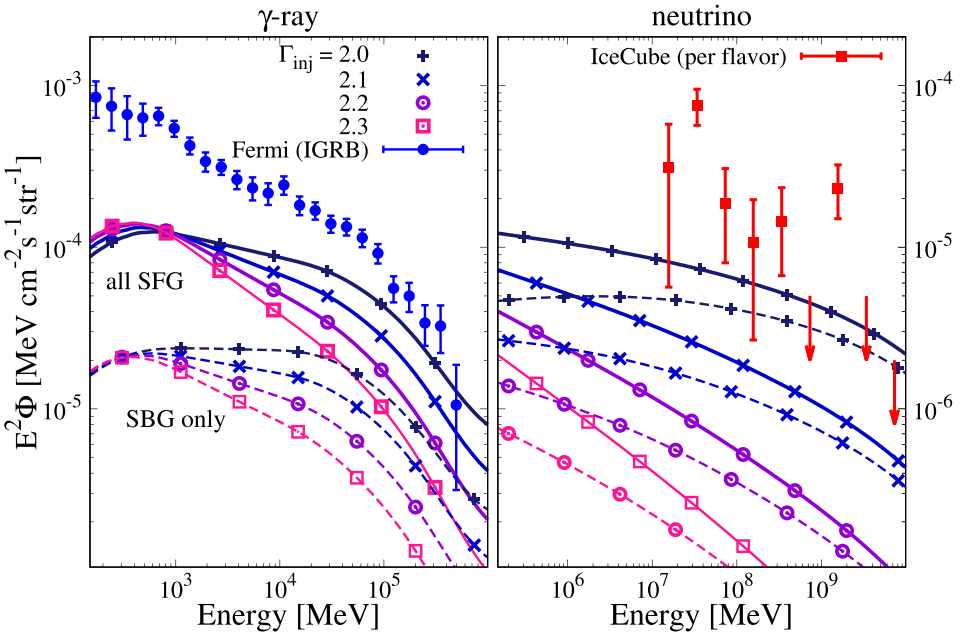
(Bechtol+17, ApJ)



Maximum non-blazar γ-ray spectrum (17%)

Corresponding neutrino spectrum

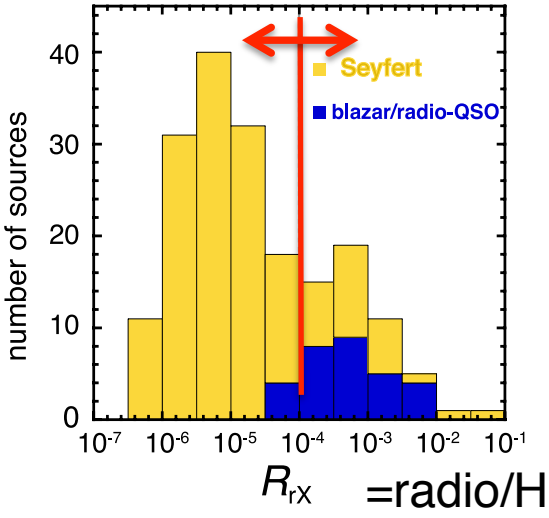
(Sudou+18, PASJ)



背景ガンマ線放射とニュートリノフラックスを同時に満たすように説明するのは難しい

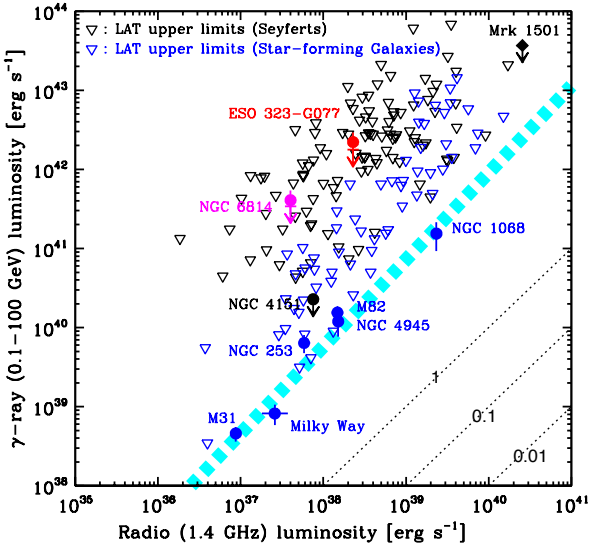
Radio-quiet AGNs

1. Hard-X-ray bright Seyferts: 120

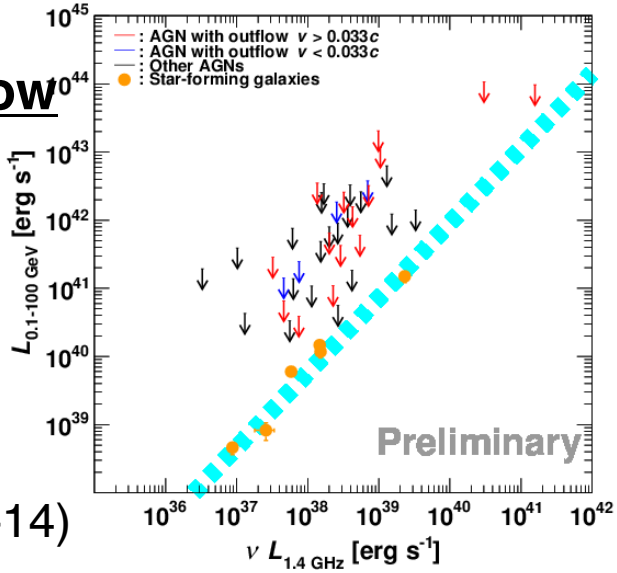


4-year data

(Ackermann+12)



2. Radio-quiet AGNs with Ultra Fast Outflow
candidate (42, 19 with UFO)
6-year data
(Tomono, MH, Inoue,S, ICRC15)

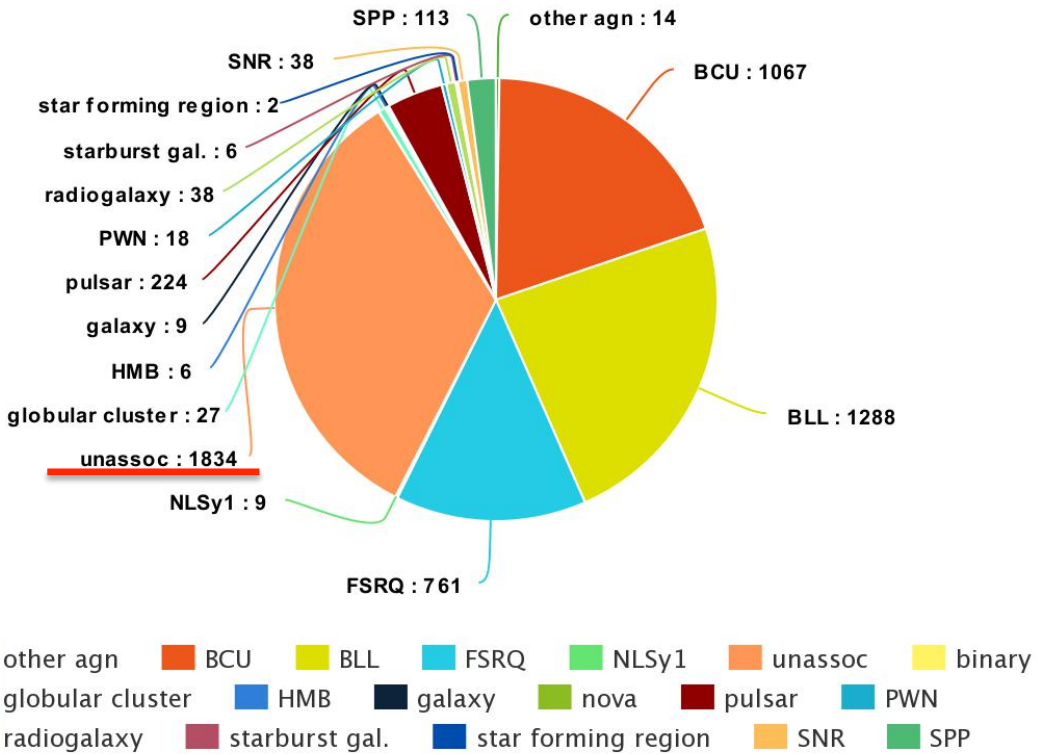


1,2共に未検出！！

c.f. 降積流(RIAF)からのニュートリノ放射 (Kimura+14)

4th Fermi catalog (preliminary: FL8Y)

3FGL	vs	FL8Y (pre-4FGL)
4 years (Pass7)	Data	8 years (Pass8), 2.3x(acceptance)
100 MeV – 300 GeV	Energy	100 MeV – 1 TeV
3033	No. of sources	~5500



ガンマ線未同定天体

- 主にブレーザーかパルサーだと言われているが、、
  - 突発天体からの年スケールの遅延放射？
  - gamma-ray emission from NS merger??

Takami+14, PRD

PHYSICAL REVIEW D **89,** 063006 (2014)

High-energy radiation from remnants of neutron star binary mergers

Hajime Takami*
Theory Center, Institute for Particle and Nuclear Studies, KEK, 1-1, Oho, Tsukuba 305-0801, Japan

Koutarou Kyutoku†
[2]*Department of Physics, University of Wisconsin-Milwaukee, P.O. Box 413, Milwaukee, Wisconsin 53201, USA*

Kunihito Ioka‡

Murase+18, ApJ

THE ASTROPHYSICAL JOURNAL, 854:60 (13pp), 2018 February 10

https://doi.org/10.3847/1538-4357/aaa48a

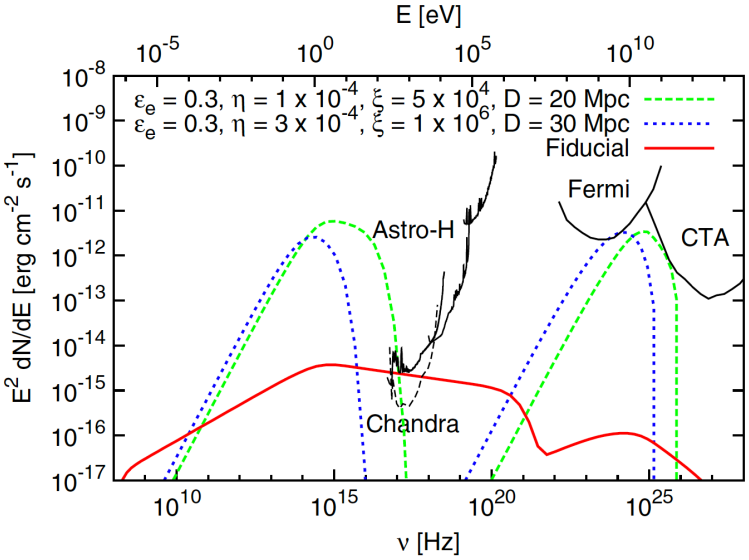
Double Neutron Star Mergers and Short Gamma-ray Bursts: Long-lasting High-energy Signatures and Remnant Dichotomy

Kohta Murase[1,2,3,4], Michael W. Toomey[1], Ke Fang[5], Foteini Oikonomou[1,2,3,6], Shigeo S. Kimura[1,2,3], Kenta Hotokezaka[7], Kazumi Kashiyama[8], Kunihito Ioka[4], and Peter Mészáros[1,2,3]

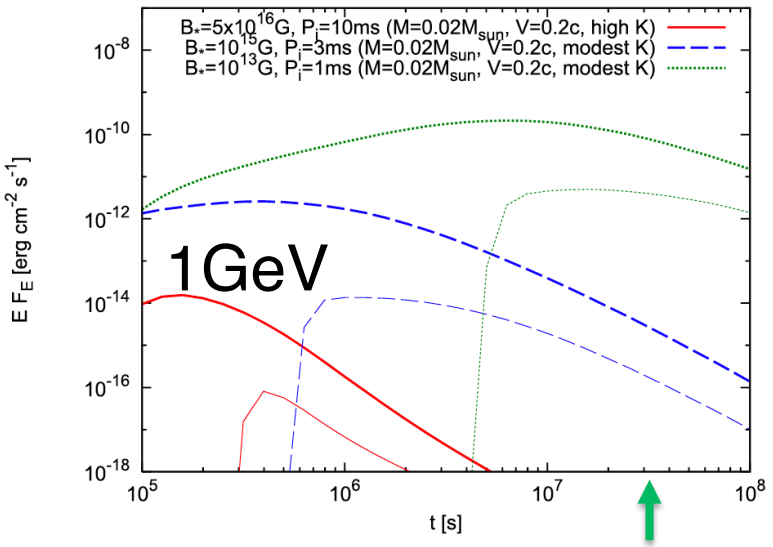
ガンマ線未同定天体

- 主にブレーザーかパルサーだと言われているが、、
  - 突発天体からの年スケールの遅延放射？
  - gamma-ray emission from NS merger??

Takami+14, PRD



Murase+18, ApJ



年

$$t_{\rm dec} = \frac{R_{\rm dec}}{\beta c} = 5 M_{-2}^{1/3} n_0^{-1/3} \beta_{0.3}^{-1} \ {\rm yr},$$

ニュートリノも出る (Kimira+18, PRD)

まとめ

- ブレーザーは一番数の多い高エネルギーガンマ線天体
- ブレーザー定常放射とν事象に（全体的な）位置相関は無い

IceCube170922A/TXS0506+056

- 通常の~5倍の明るさ (>1GeV)、>100 GeV放射検出
- Top 0.2% (>1GeV, 28日平均。全天体、9.2年中）
- 2014/2015のnフレア時、γ強度は低い（冪は硬い？）
- |赤緯|<10度のBL Lac天体では一番明るい
  - 実は、FSRQよりBL Lacの方がより好ましいν生成環境の可能性は？

ブレーザー以外の起源天体の可能性

- スターバースト銀河 ❌ (背景ガンマ線放射と両立せず）
- ジェット以外のAGN ❌? (ガンマ線放射は未検出）
- 未同定天体。NS mergerの可能性はある????
- ガンマ線 (100 MeV)で光らず、(sub-)PeV νだけ出せる機構はあるか？