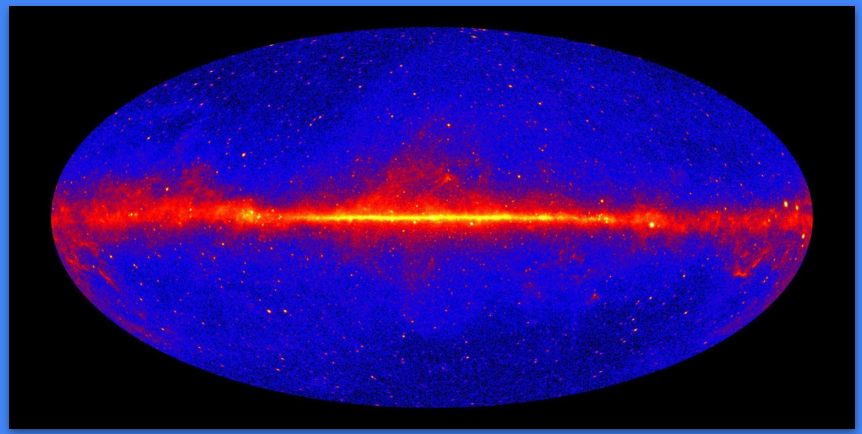
Recent Results of Fermi: Its Role in the Era of Multimessenger/Multiwavelength Astrophysics

T. Mizuno (Hiroshima Univ.) on behalf of the Fermi-LAT Collaboration

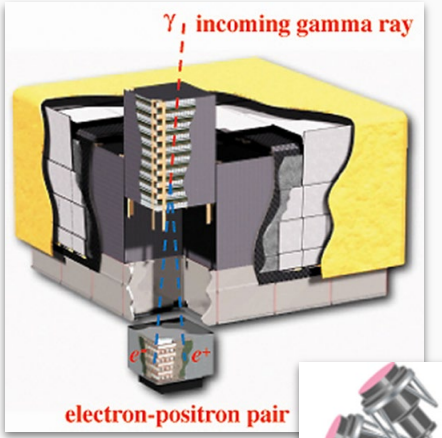
@Kyoto Symposium (Physics of the Two Infinities), 2023 Mar. 27



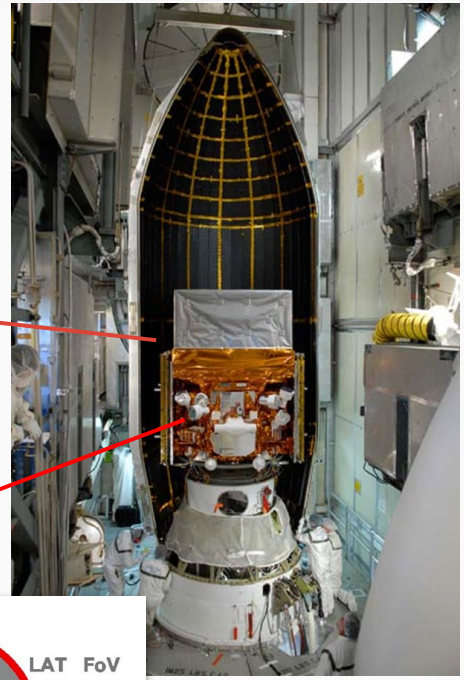
Fermi Mission

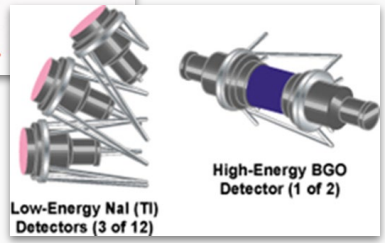
Fermi Gamma-ray Space Telescope:

- International space mission, launched in 2008
- LAT+GBM (TM is a LAT member)

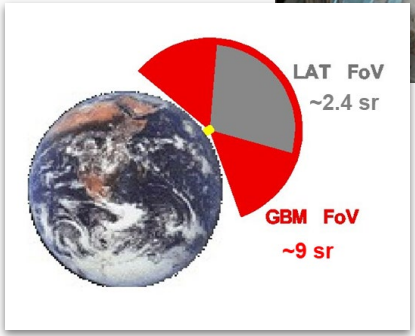


LAT (Large Area Telescope) (Atwood+09 for details)
20 MeV to > 300 GeV
Field of view (FOV): 2.4 sr
Gamma-ray sky survey (imaging & spectroscopy)
occasionally autonomous repoint request (ARR) triggered by GBM





GBM (Gamma-ray Burst Monitor)
8 keV to 30 MeV
FOV: 9 sr
Monitoring transient sources (spectroscopy)

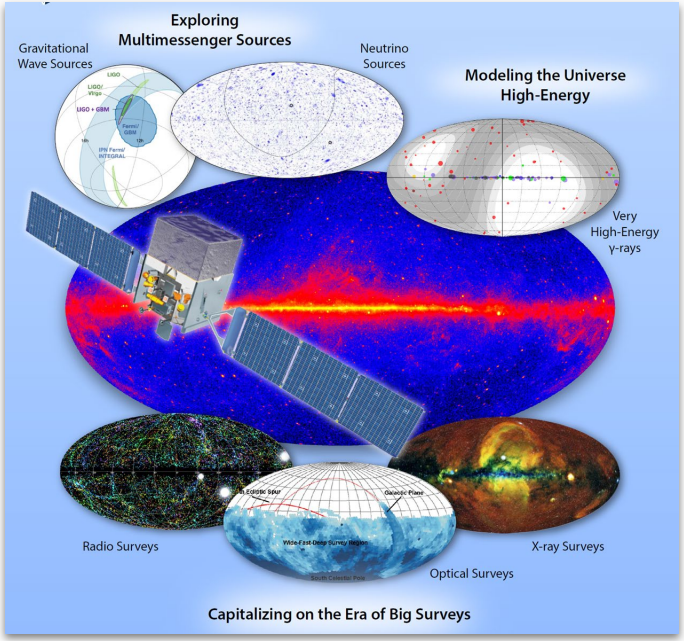


Role of Fermi in Today's Astrophysics

NASA Astrophysics Advisory Committee panel report says

"Fermi provides unique access to the gamma-ray portion of the electromagnetic spectrum and the largest simultaneous filed-of-view of any space telescope. Its data give us a time-domain view of the entire gamma-ray sky and are a crucial asset for gravitational-wave and multi-messenger astrophysics"

(2022 NASA senior review proposal)



Fermi plays a key role in today's astrophysics by providing

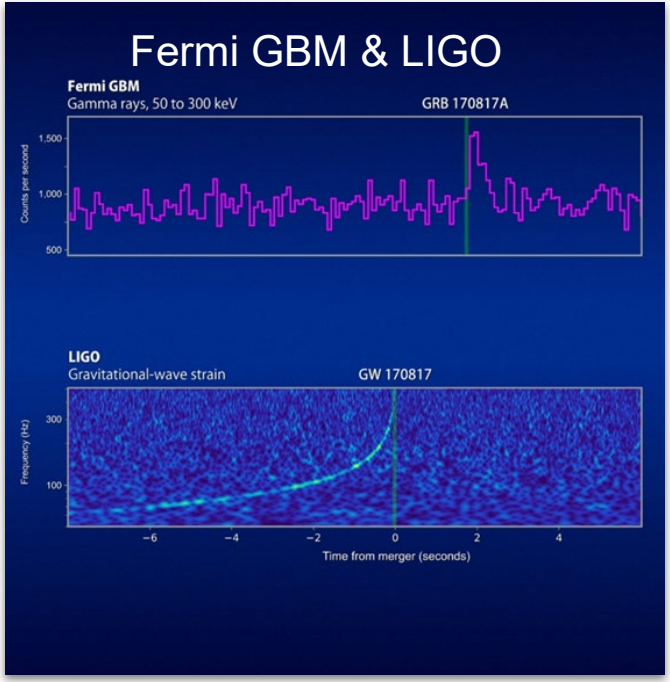
- Crucial data for multimessenger (MM) astrophysics
- Useful catalogs of various source classes
- Crucial data for multiwavelength (MW) astrophysics

(see also Hadasch's talk (Day1) and Tibaldo's talk (Day 2))

MM Astrophysics (1): GW170817

GW170817 (neutron star (NS) merger) = GRB 170817A (short gamma-ray burst; sGRB)

- Positional & temporal association



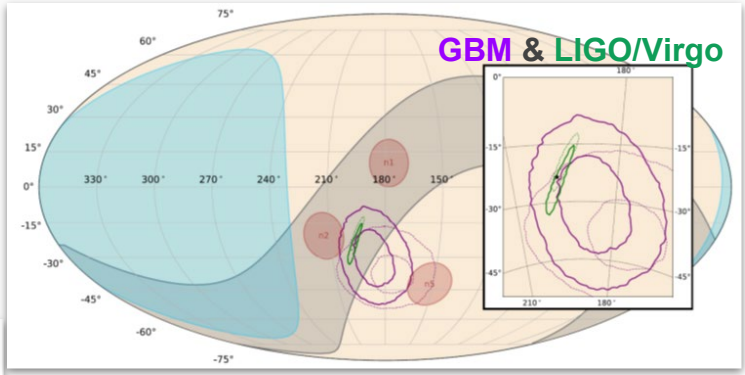
https://fermi.gsfc.nasa.gov/fermi10/fridays/01122018.html

MM Astrophysics (1): GW170817 (Cont'd)

GW170817 (NS merger) = sGRB

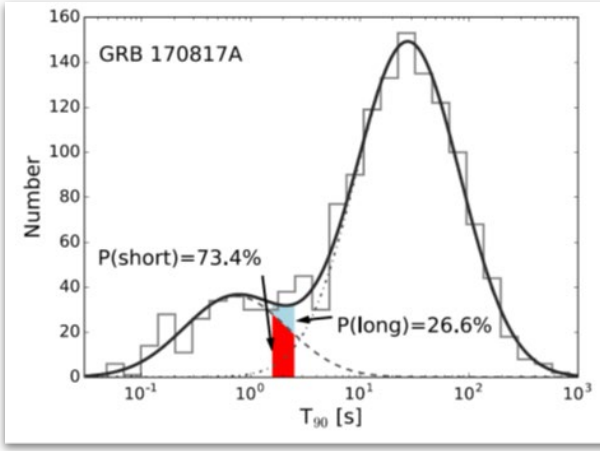
- T_{90} ~2.0 s
- E_{peak} ~200 keV
- (probability to be a short-hard class ~70%)

localization

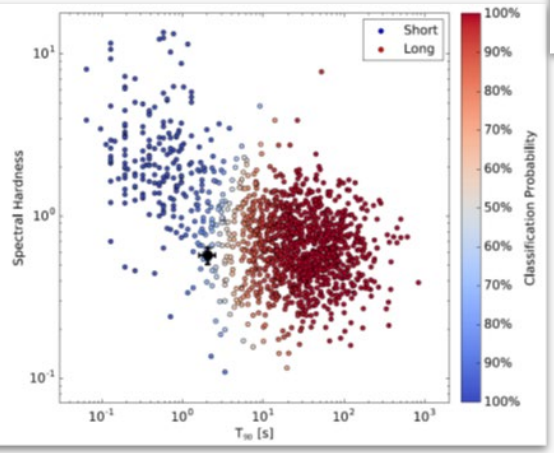


(Goldstein+17)

duration (T_{90})



T_{90} vs. spectral hardness



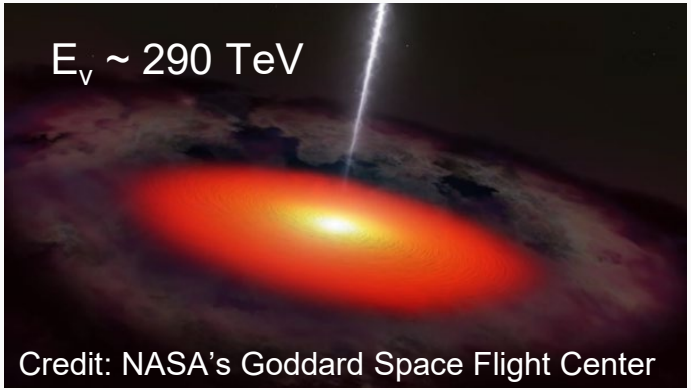
LAT was off at t_0 due to South Atlantic Anomaly (Ajello+18)

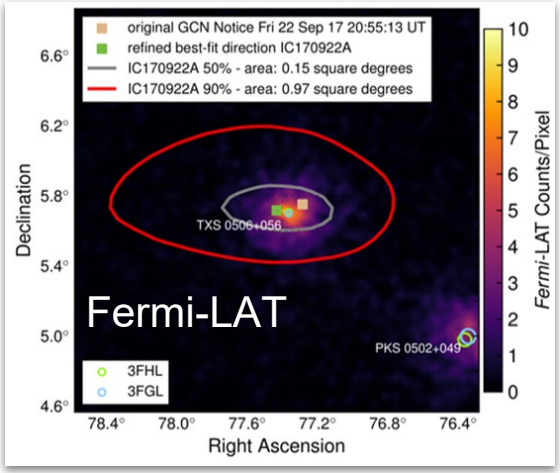
~5% of GBM-sGRBs were detected by LAT (within FOV or ARR); next GW/GBM events in O4 are anticipated

MM Astrophysics (2): IceCube-170922A

IceCube-170922A (high energy (HE) ν events) from TXS 0506+056 (blazar)

- Positional & temporal association





(Analysis led by Y. Tanaka@Hiroshima; Atel#10791)

(Aasten+18)

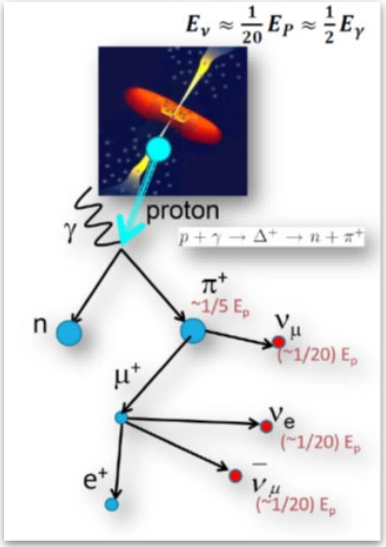
9 yrs

1.5 months

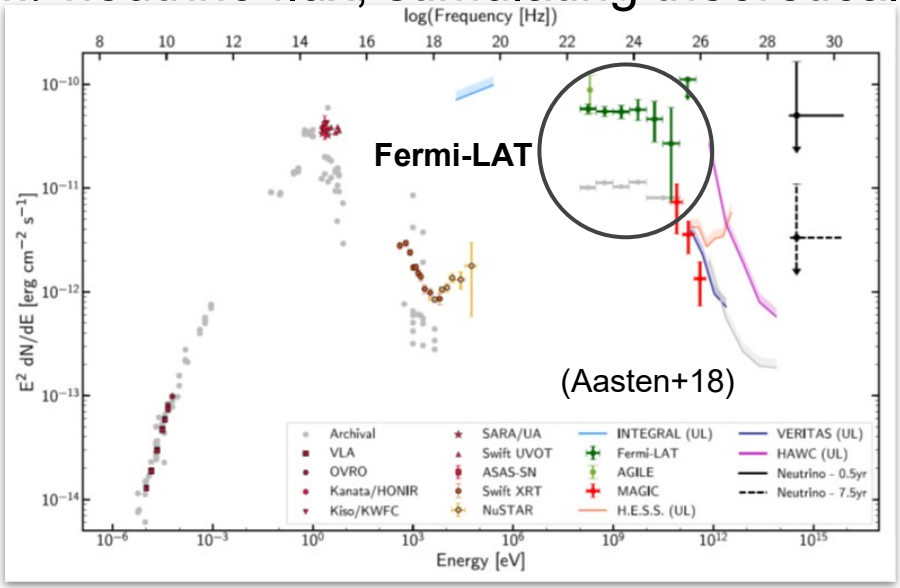
MM Astrophysics (2): IceCube-170922A (Cont'd)

HE ν events; cosmic-ray (CR) p+γ interaction (E_ν ~ 290 TeV, E_p ~ 3 PeV)

MW data shows rather typical (leptonic) blazar spectrum; difficult to draw a direct connection w/ neutrino flux, stimulating theoretical works



$$p + \gamma \rightarrow \pi^{\pm} X \rightarrow \mu^{\pm} \nu_\mu \rightarrow e^{\pm} \nu_e \nu_\mu$$



(e.g., Ansoldi+18, Keivani+18)

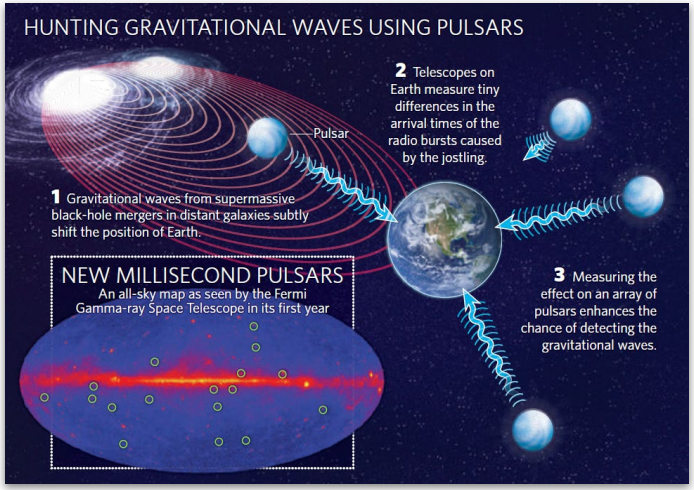
MM Astrophysics (3): Pulsars and GW

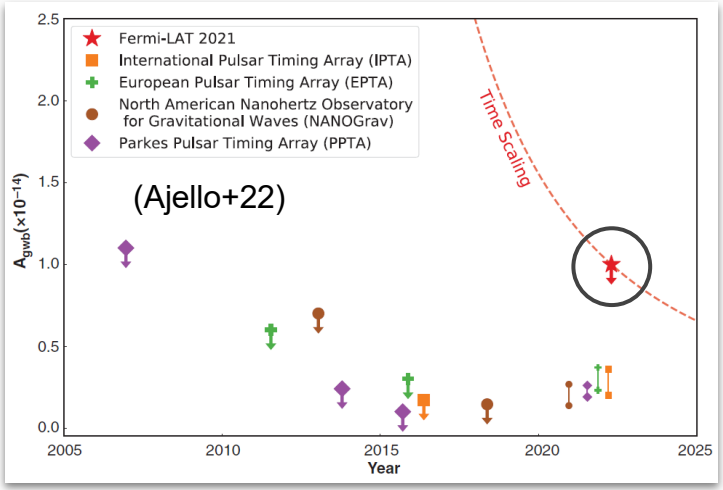
Coalescing binary supermassive black holes in merging galaxies fill the universe with long GWs (@nanohertz) => pulsar timing array (PTA) in radio

Gamma-ray is independent to and complementary with radio PTAs; free from effects of ionized interstellar medium (dispersion measure)

- 12.5 yrs data & 35 millisec. pulsars (MSPs); results already 30% as good as radio PTAs

(Nature, 2010)





MM Astrophysics (3): Pulsars and GW (Cont'd)

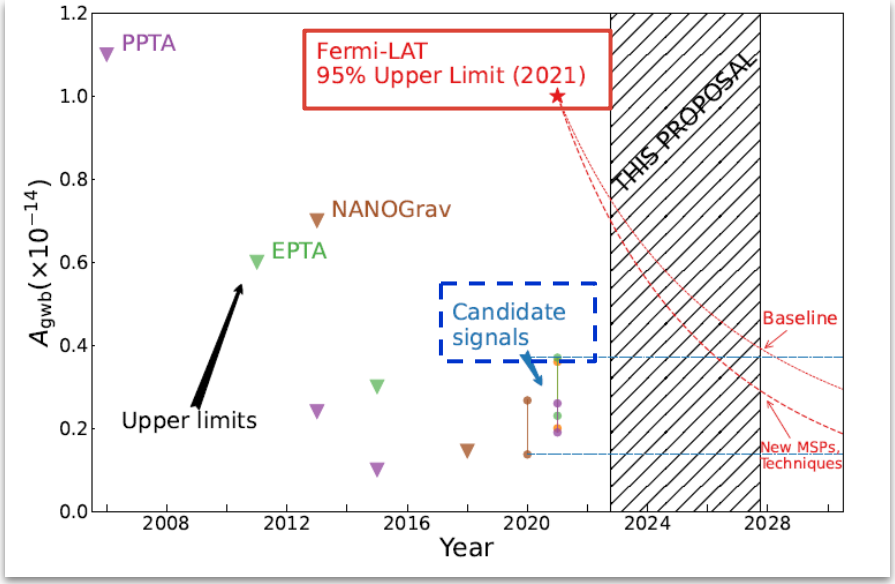
Gamma-ray is independent to and complementary with radio PTAs; free from effects of ionized interstellar medium

- 12.5 yrs data & 35 MSPs; results already 30% as good as radio PTAs

The LAT constraints improve as $t^{-13/6}$

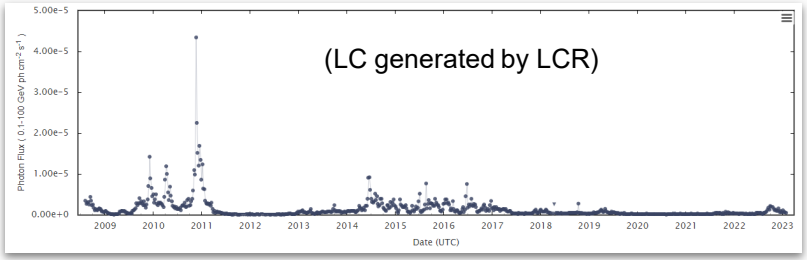
- Over the next ~5 yrs Fermi-LAT will confirm or refute the candidate signal from radio PTAs

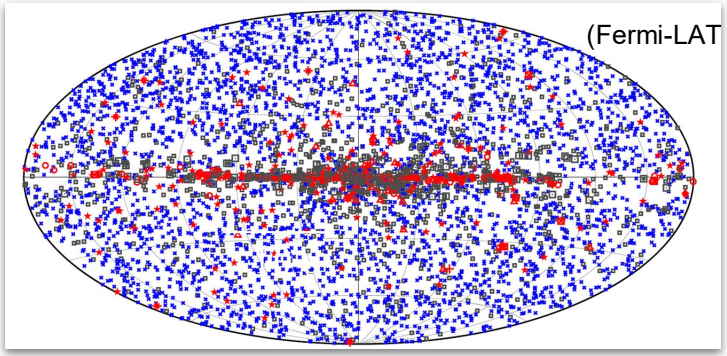
(2022 NASA senior review proposal)



Useful Catalog and Resources

- Fourth Fermi-LAT Source Catalog: Fermi-LAT Collaboration 2020, ApJS 247, 33
  - Main catalog that contains >6000 γ-ray sources
- Light Curve Repository: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository
  - Useful web-based service that provides automated time-series analysis
- First Fermi-LAT Long-term Transient Source Catalog; Fermi-LAT Collaboration 2021, ApJS 256, 14
- First Fermi-LAT Solar Flare Catalog; Fermi-LAT Collaboration 2021, ApJS 252, 13
- Second Fermi-LAT Flaring Source Catalog; Fermi-LAT Collaboration 2017, ApJ 846, 34
- Fourth Fermi-LAT AGN Catalog; Fermi-LAT Collaboration 2022, ApJS 263, 24
- Second Fermi-LAT GRB Catalog; Fermi-LAT Collaboration 2019, ApJ 878, 32
- Third Fermi-LAT Hard Source Catalog; Fermi-LAT Collaboration 2017, ApJS 232, 18
- First Fermi-LAT Supernova Remnant Catalog; Fermi-LAT Collaboration 2016, ApJS 224, 8
- Second Fermi-LAT Pulsar Catalog, Fermi-LAT Collaboration 2013,ApJS 208, 17



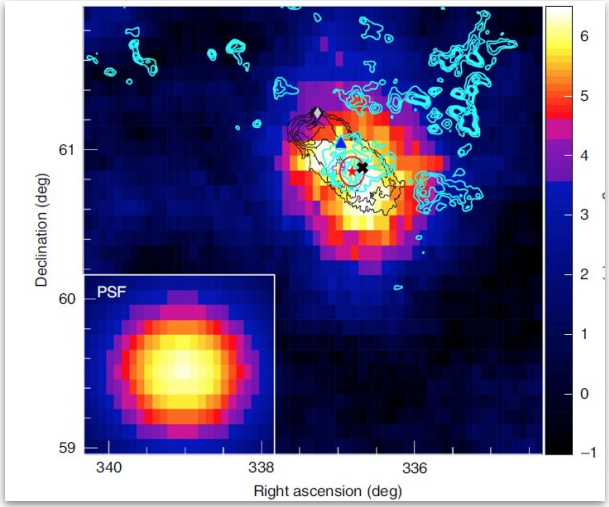


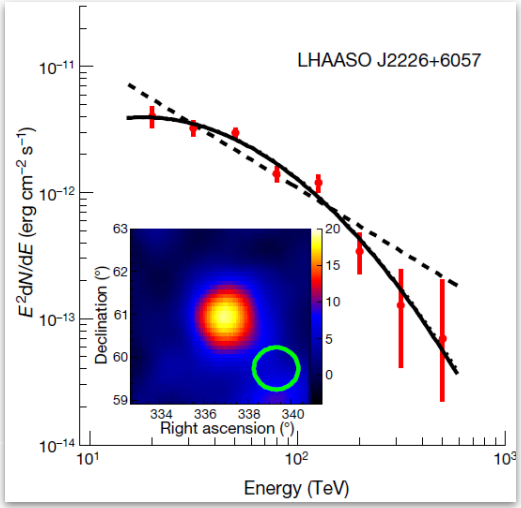
MW Astrophysics (1): SNR G106.3+2.7

- Supernova remnants (SNRs) are believed to be the main source of Galactic CRs up to knee (~3 PeV)
- Tibet ASγ discovered γ-rays above 100 TeV toward G106.3+2.7, with position deviates from pulsar but close to molecular cloud (“PeVatron”)
- LHAASO reported E_{max} = 0.57 PeV

GeV data is crucial to investigate the source nature, but contamination from nearby pulsar (PSR) is severe (Xin+19)

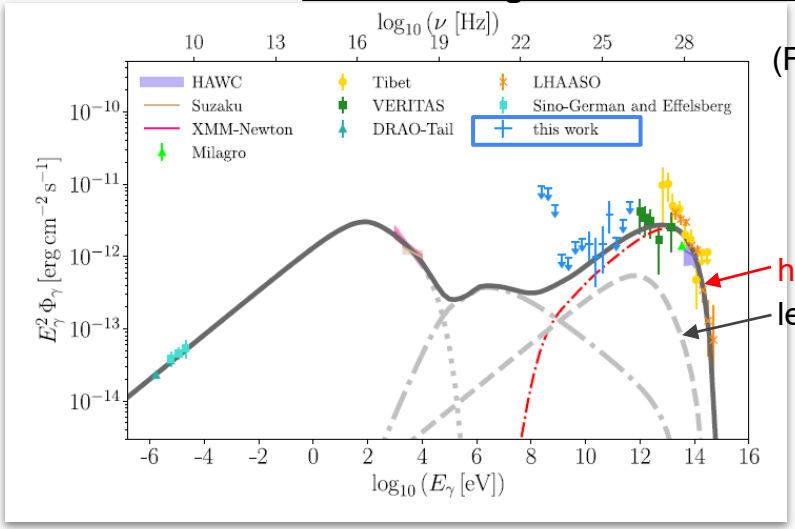
(Amenomori+21, Cao+21)



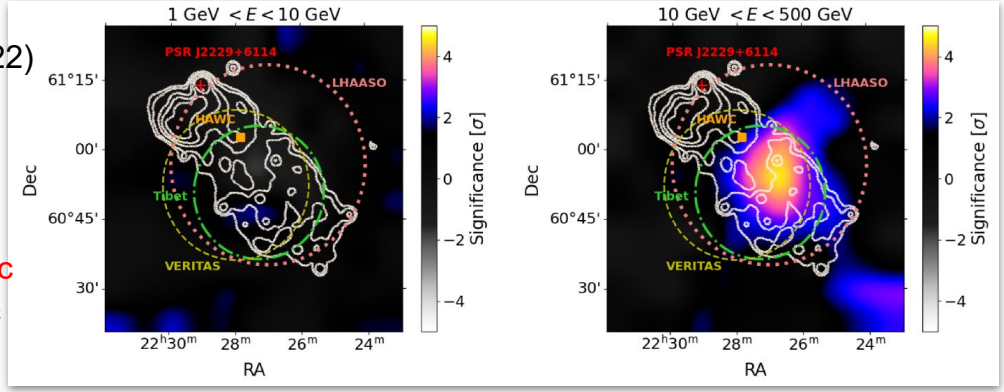


MW Astrophysics (1): SNR G106.3+2.7 (Cont'd)

- Dedicated analysis by Fang+22 by removing >95% PSR contamination w/ phase-cut
  - No emission btw. 1-10 GeV, significant emission above 10 GeV from the SNR
  - GeV-TeV spectrum too hard to explain by single electron population (α_e=2.4 by radio and X-ray). Instead, e+p scenario well explain the MW spectrum, firmly establishing the source to be PeVatron



(Fang+22)



α_p=1.7, $E_{p,max}$=0.8 PeV, B~10 uG

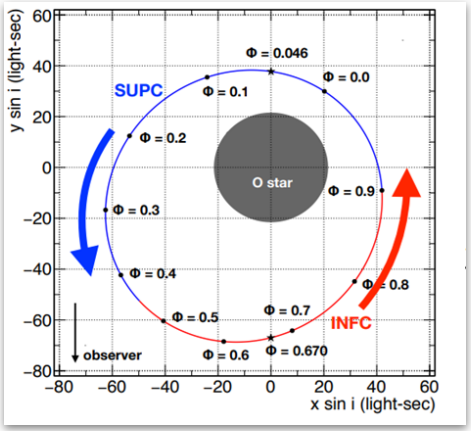
W_p=3.3x10^{48} erg, W_e=5.3x10^{47} erg

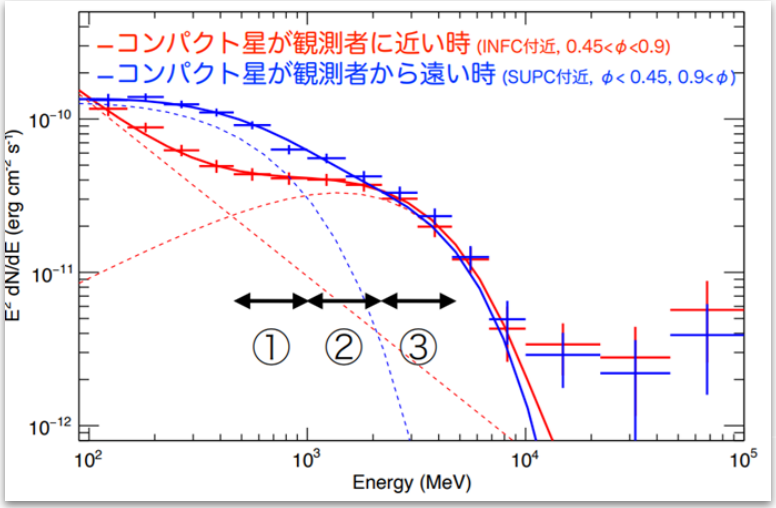
(plausible for CR acceleration by SNR)

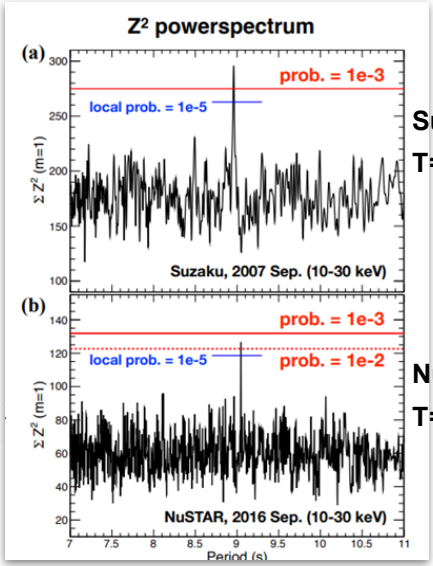
MW Astrophysics (2): LS 5039

- Famous gamma-ray binary, whose GeV flux anti-correlates to X-ray/TeV
- Compact star unknown, acceleration and emission mechanism unsettled
- New Fermi data revealed two components in GeV (stable in HE)
- Suzaku and NuSTAR revealed a sign of pulsation of P~9 s

(Yoneda+20
Yoneda, TM+21)







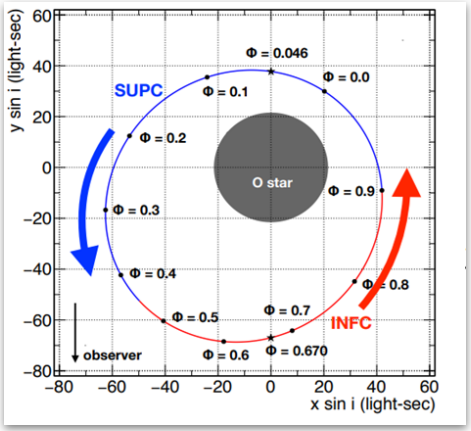
Suzaku (2007)
T=8.96+/-0.01

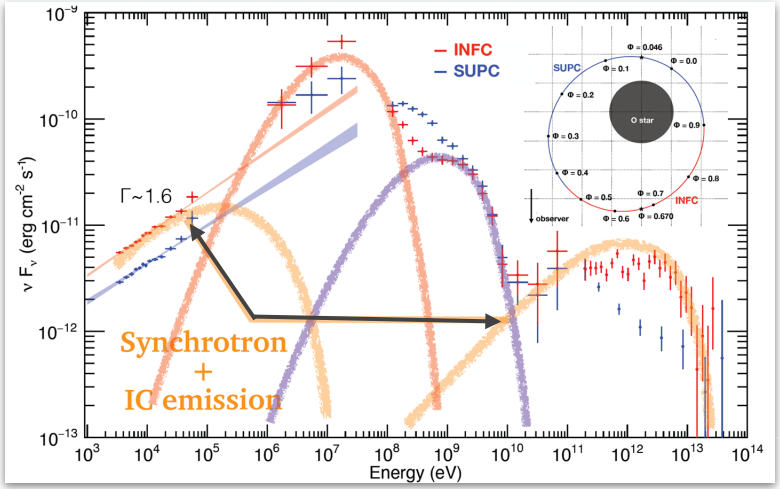
NuSTAR (2016)
T=9.05+/-0.01

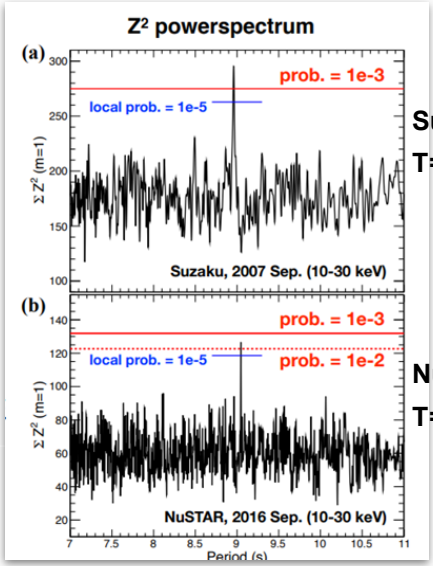
MW Astrophysics (2): LS 5039 (Cont'd)

- Two component in GeV (at least 4 components in SED)
- A sign of pulsation of P~9s
  - NS binary, but spin down luminosity is too small to explain L_{bol} (particularly MeV/GeV)
- Magnetic reconnection in Magnetar + O star suggested
  - New hypothesis : Magnetar found in a binary system for the first time

(Yoneda+20
Yoneda, TM+21)







Suzaku (2007)
T=8.96+/-0.01

NuSTAR (2016)
T=9.05+/-0.01

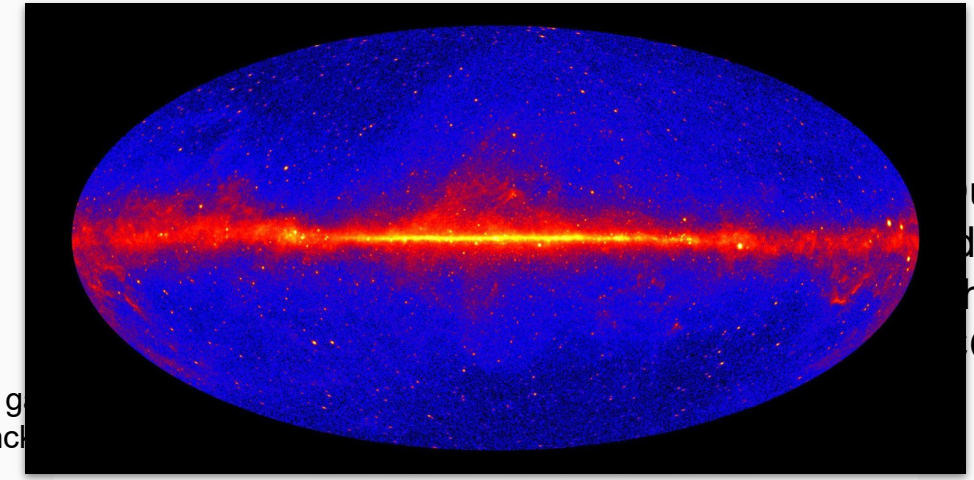
MW Astrophysics (3): Diffuse γ-rays to study ISM gas and CRs

Diffuse γ-ray is produced by interaction of CRs and interstellar medium (ISM), telling us gas and CRs in the interstellar space

- (Simplest) Way: Use HI and CO lines to trace HI and H_2 gas, then use γ-ray to obtain I_{CR} ($\propto I_\gamma / N_H$)

Issue: Significant amount of gas not properly traced by HI/CO lines

(e.g., Grenier+05, Planck Collab. 2011)



Dark g
(Planck

ust and γ-ray have been used to trace
dark gas", but they cannot distinguish gas
hases (presumably optically thick HI and
O-dark H_2)

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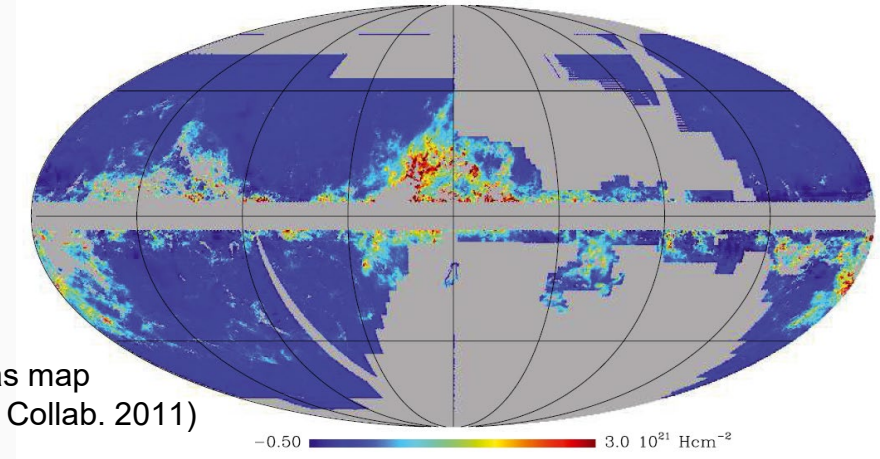


Dark gas map
(Planck Collab. 2011)

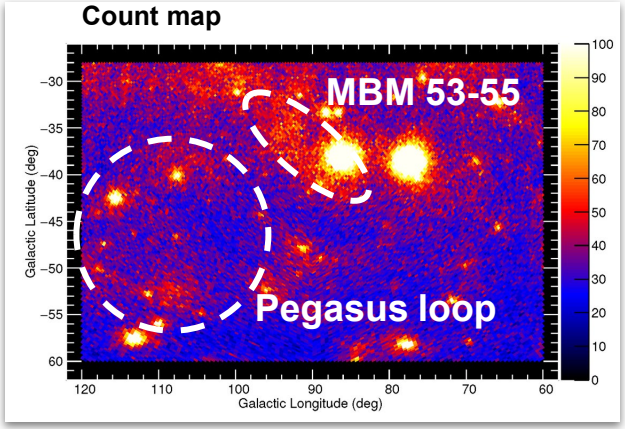
Dust and γ-ray have been used to trace "dark gas", but they cannot distinguish gas phases (presumably optically thick HI and CO-dark H_2)

MW Astrophysics (3): MBM 53-55 Clouds and Pegasus loop

Dust and γ-ray cannot distinguish phases of "dark gas", preventing accurate measure of gas and CRs

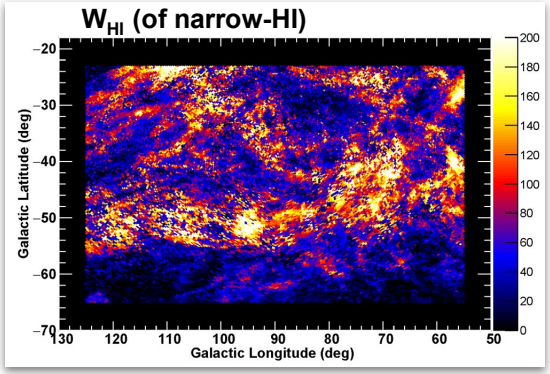
Dust & HI correlation revealed that narrow-line HI gas is associated with dark gas and broad-line HI gas with optically thin HI (Kalberla+20)

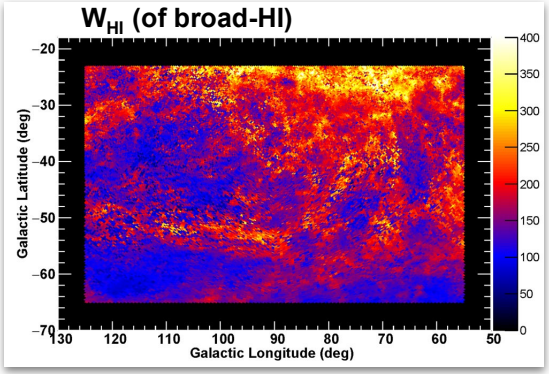
(3C454.3's contamination reduced; LCR)



(Mizuno+22)

Mizuno+22 applied HI-line-profile based analysis (for the first time) to γ-ray data of MBM 53-55 clouds and Pegasus loop



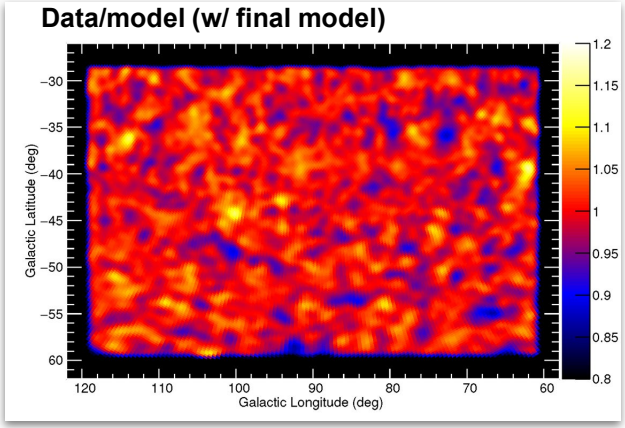


MW Astrophysics (3): MBM 53-55 Clouds and Pegasus loop (Cont'd)

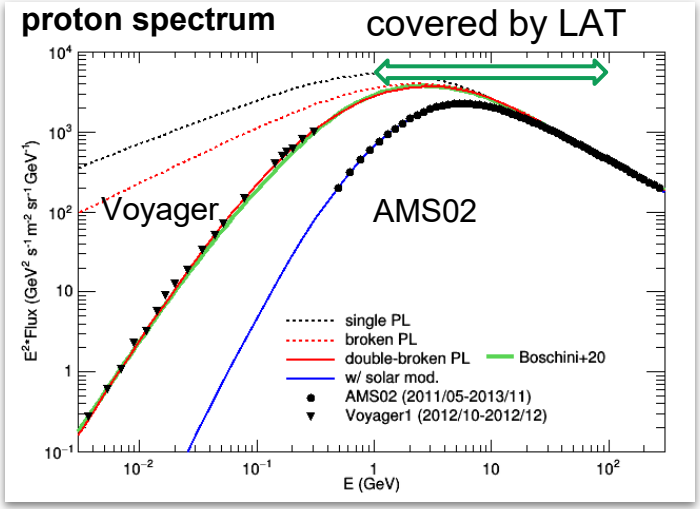
We applied HI-line-profile based analysis (w/ aid by dust emission)

- Succeeded in distinguishing gas phases and reproducing γ-ray data

Also modelled interstellar CR spectrum (by PL of momentum w/ breaks) using γ-ray data + CR data (AMS02, Voyager)



(Mizuno+22)



R_{br1}~7 GV (agrees with a break in B/C ratio); <u>independent proof of a break in interstellar D</u> (diffusion coefficient)

Summary

Fermi is an international space mission, surveying GeV gamma-ray sky (LAT) and monitoring keV/MeV gamma-ray sky (GBM). It plays a key role in today's astrophysics

- MM: GW event (GW170817) counterpart, HE ν event (IC-170922A) counterpart, GW background@nanoheltz, etc.
- Useful catalogs/resources: Source catalog, Light curve repository, etc.
- MW: PeVatron (synergy w/ TeV), New class of gamma-ray binary (w/ X-ray), Interstellar medium and CRs (w/ radio), etc.

(More examples in Hadasch's talk (Day1) and Tibaldo's talk (Day 2))

Thank you for your attention

References (Also see p.17)

- Atwood et al. 2009, ApJ 687, 1071
- Goldstein et al. 2017, ApJL 848, 14
- Ajello et al. 2018, ApJ 861, 85
- Aasten et al. 2018, Science 361, 146
- Ansoldi et al. 2018, ApJL 863, 10; Keivani et al. 2018, ApJ 864, 84
- Ajello et al. 2022, Science 376, 521
- Buson et al. 2022, ApJL 933, 43
- Xin et al. 2019, ApJ 885, 106; Amenomori et al. 2021, Nature Astronomy 5, 460, Cao et al. 2021, Nature 594, 33
- Fang et al. 2022, PRL 129, 071101
- Yoneda et al. 2021, ApJ 917, 90
- Grenier et al. 2005, Science 307, 1292; Planck Collab. 2011, A&A 536, 24
- Kalberla et al. 2020, A&A 639, 26
- Mizuno et al. 2022, ApJ 935, 97

Backup Slide

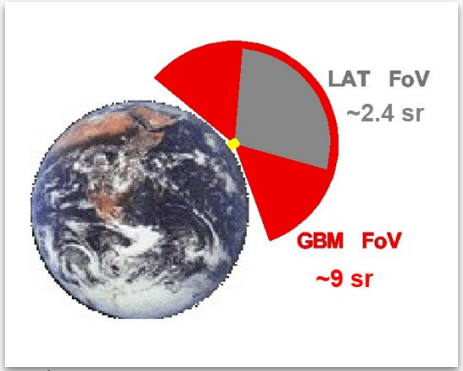
Fermi Mission (Cont'd)

International space mission, launched in 2008

- Low-earth circular orbit, 565 km altitude
- Operated for > 14 yrs, with no significant degradation of scientific performance

Observation modes of LAT

- Primary mode = sky survey
  - Scan entire sky every 3 hrs
- Autonomous Repoint Request (ARR)
  - Pointed observation following detection of bright hard-spectrum gamma-ray burst
- Target of Opportunity
  - 1 d to few weeks in duration for flaring sources



Fermi-LAT Collaboration
NASA/DOE & ~400 scientific members
(Japanese consortium contributes to both data analysis and operation; see backup)

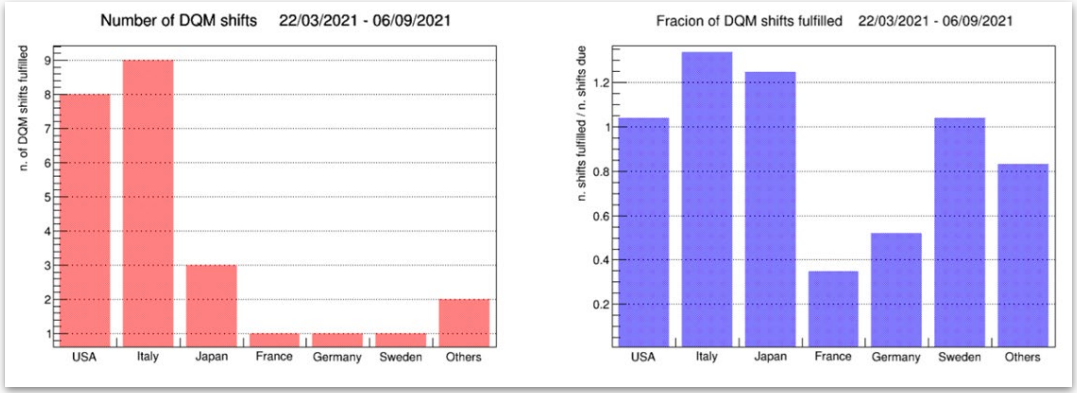
DQM (Data Quality Monitoring)

Monitor quality of instruments and data of Fermi-LAT

1 shift = 1 week. All work can be done via Web browser by reviewing 15 runs each day

Shifter checks monitor plots (light curves and hit maps) of each run. He/she flags the run as good (if everything is OK) or makes a report (if a possible issue is identified)

Important contribution to assure the quality of data (distributed to community). Japanese group takes 4-5 shifts every year. (22 shifts in FY2016-2020)



DQM (Cont'd)

Shifter checks monitor plots and makes a report if a possible issue is identified

Important contribution to <u>assure the quality of data</u>

In this example, shifter (student in Japan) identified a drop of rate associated with solar flare, and GTI is defined

Re: [DATAMON] Errors and Warning in run 651822272ã (M4.7 solar flare)

maldera@to.infn.it via the list datamonlist@glast2.stanford.edu via astro.hiroshima-u.ac.jp Aug 30, 2021, 8:32 PM (5 days ago)

to datamonlist

Dear all,

thanks for reporting these alarms.

They are due to a M4.7 solar flare,
started at 05:39:00, ended at 6:23:00, and peaked at 6:11;
https://www.lmsal.com/solarsoft/latest_events_archive/events_summary/2021/08/28/gev_20210828_0539/index.html

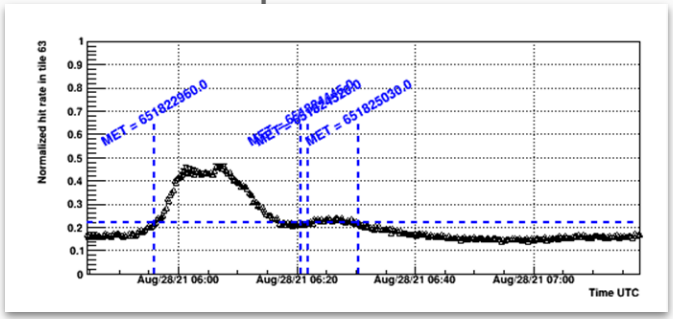
The solar flare panel shows a dip in the normalized events rate, suggesting the need of a BTI.
Since the flare peak is few minutes after the rocking angle change(that can give some problems in the normalized rate), I recreated the same plots for events with zenithTheta<100deg, obtaining a similar result (plot attached).
Therefore I created a bad time interval from 5:58 to 6.17 (19 minutes).

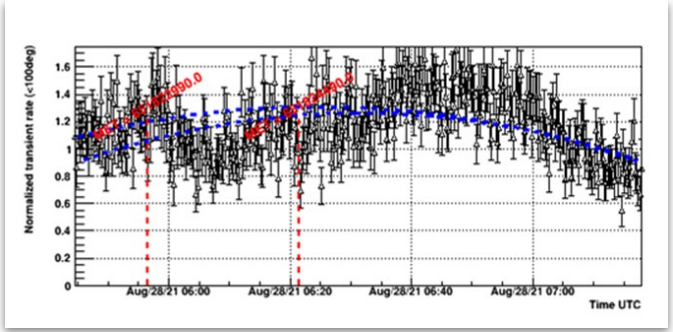
Simone

ps: I also changed the run status to good (the "bad" part will be filtered out by the cut on the bad time intervals)

Il 30/08/21 04:32, matake@astro.hiroshima-u.ac.jp via the list ha scritto:

> Dear all,
>
> This run has errors and warnings on active tile 48-63 and these values are larger than the upper limit of the threshold.
> Thus I'll mark Quality and ACD of this run as "Good with bad parts".
> Feel free to change it if needed.
>
> Best regards
> Hiroto Matake

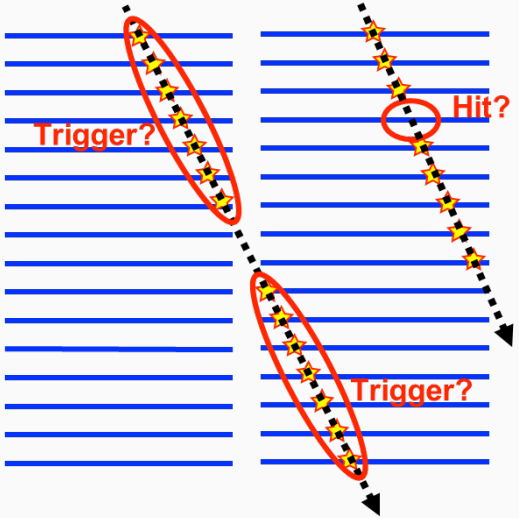


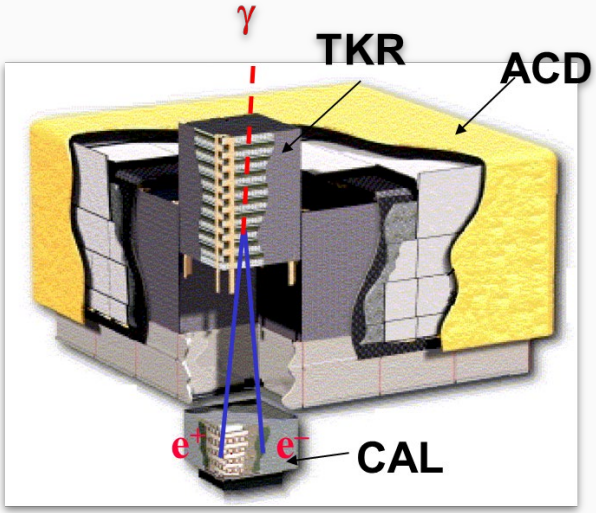


Tracker Monitoring: Efficiencies

Fermi-LAT consists of three subsystems, Tracker (direction measurement), CAL (energy meas.) and ACD (background rejection)

Experts monitor the instrument to assure stable performance. Nagoya group is responsible for TKR and monitors efficiencies and noise occupancies

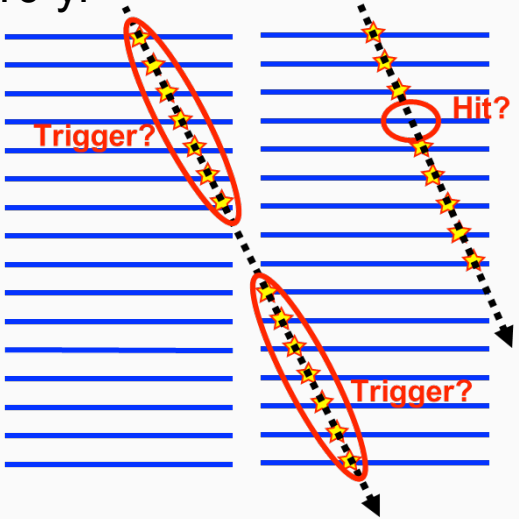


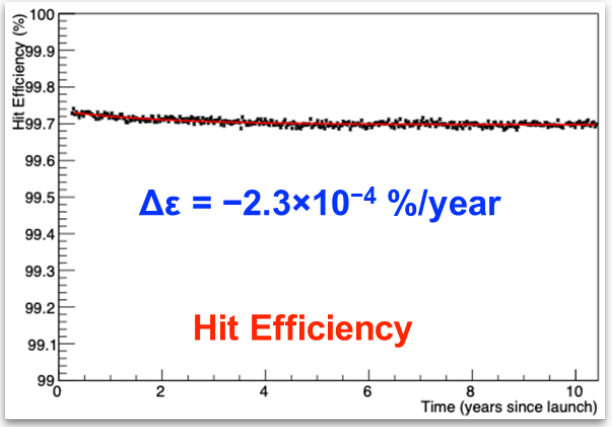


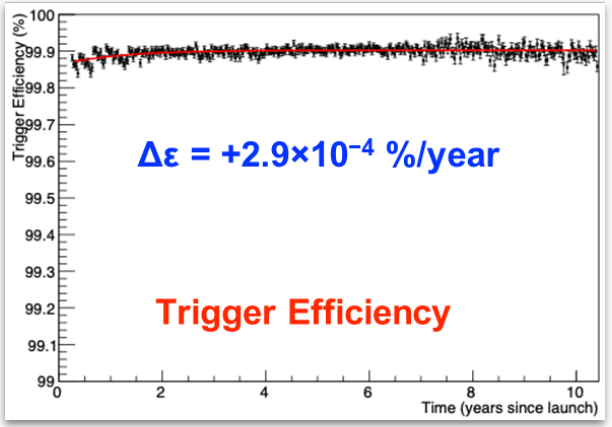
Tracker Monitoring: Efficiencies (Cont'd)

Experts monitor the instrument to assure stable performance (Nagoya group is responsible for TKR)

Hit & Trigger efficiencies have been stable over 10 yr







4th Fermi-LAT Source Catalog (4FGL)

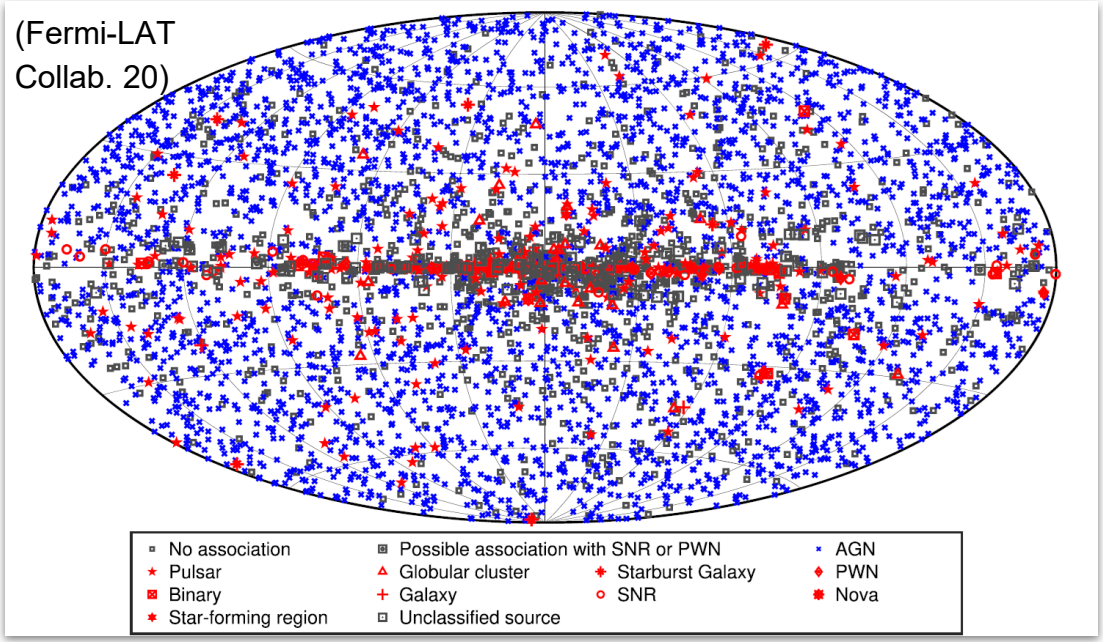
- (Fermi-LAT provides useful catalogs/resources of various types)
- 4FGL-DR3 contains 6659 γ-ray sources

Useful when writing a proposal, paper of your source

Includes new γ-ray source classes (non-AGN galaxies, globular clusters, high-mass binaries, novae)

Some source classes are more populated than expected (MSPs, radio quiet pulsars, high-z AGNs)

~30% of sources unassociated

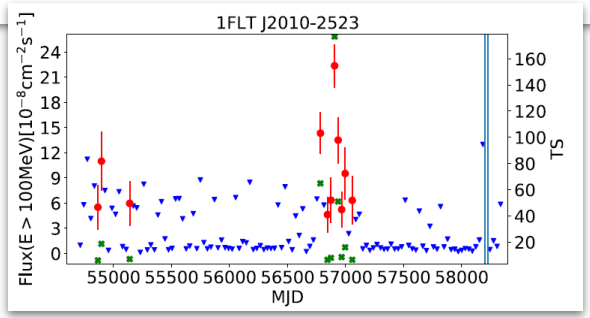


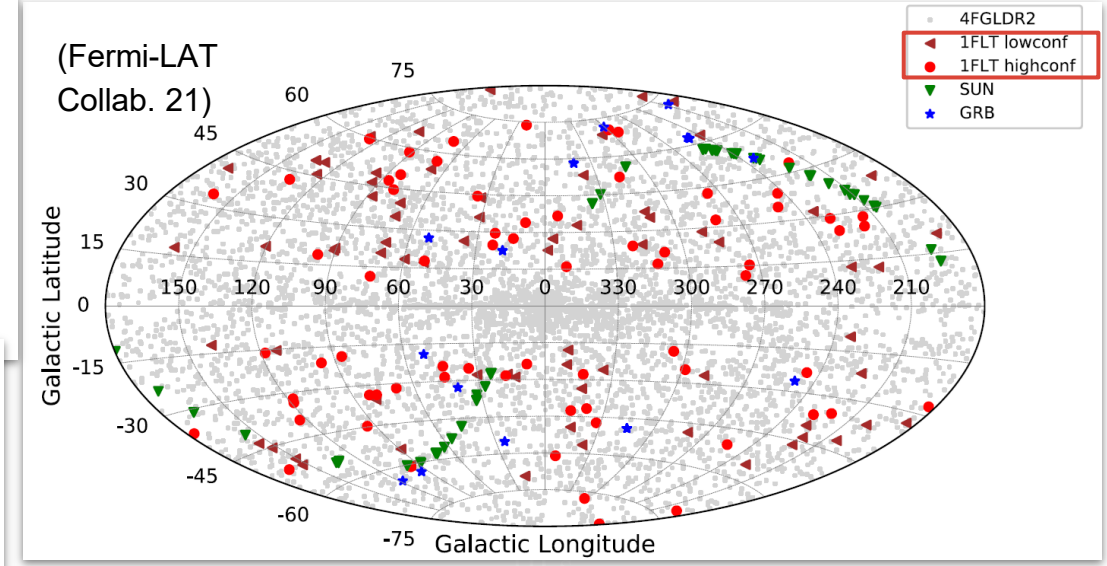
Long-term Transient Sources Catalog (1FLT)

- (Fermi-LAT provides useful catalogs/resources of various types)
- 1FLT lists 142 new transient in monthly timescale, not in 4FGL
  - ~100 are confidently associated with AGNs

Census of 1FLT Sources

Class	Class Description	Number
FSRQ	Flat-spectrum radio quasar	24
BLL	BL Lacertae object	1
CSS	Compact steep-spectrum radio source	1
SSRQ	Steep-spectrum radio quasar	1
RG	Radio galaxy	3
BCU	Blazars of uncertain type	70
AGN	Active galactic nuclei of other type	2
UNASS	Unassociated	40





Long-term Transient Sources Catalog (1FLT) (Cont'd)

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Census of 1FLT Sources

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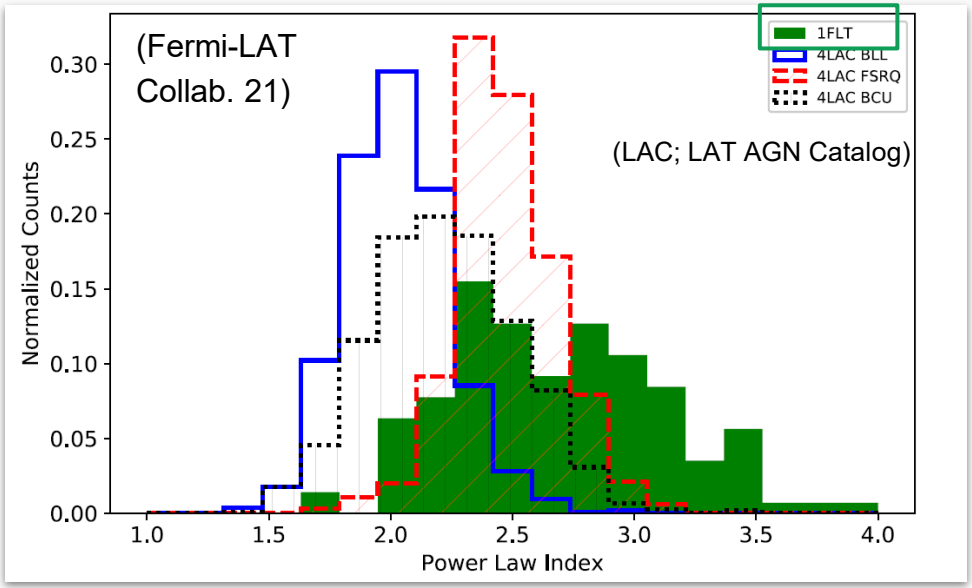


More FSRQ found; BL Lacs less variable, FSRQ's activity mainly seen in flaring events

Spectrum softer than 4LAC; soft sources less distinguishable over long integration

Fermi Light Curve Repository (LCR)

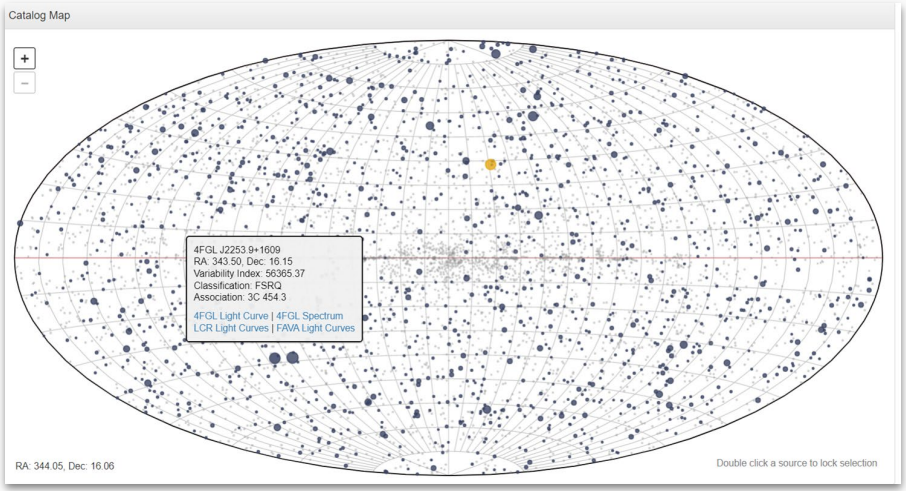
- (Fermi-LAT provides useful catalogs/resources of various types)
- Fermi LCR provides an automated time-series analysis

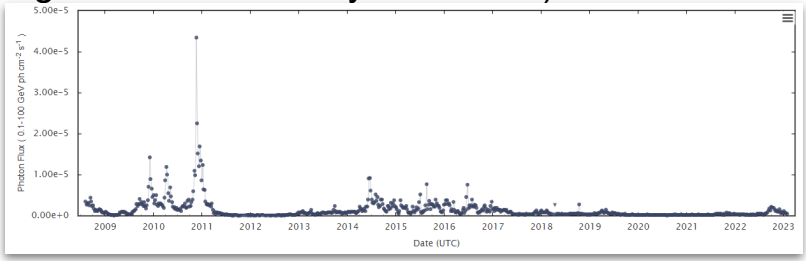
Provides LCs (resolutions of 3 day, 1 week and 1 month) for many 4FGL sources

Energy flux and photon flux

LCs derived from Maximum likelihood analysis

(you may also use LCR to find good-time-interval for reducing contamination to your source)



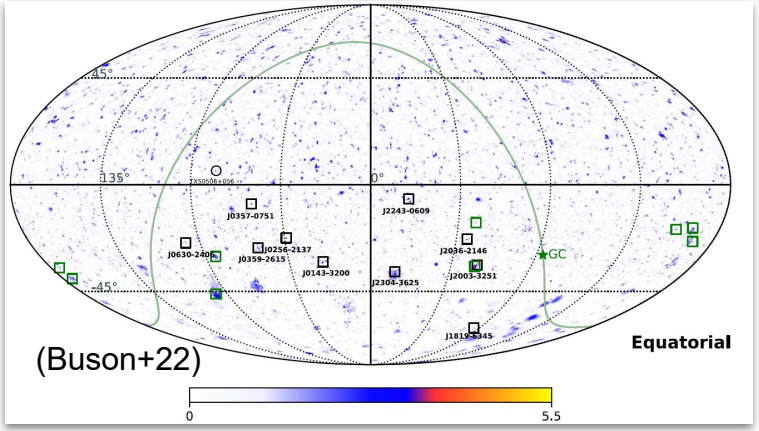


MM Astrophysics (4): neutrino - gamma ray connection

Association of neutrino with flaring blazar TXS 0506+056 sparked interest to identify further counterparts

- No other counterpart has been identified unambiguously (positional & temporal)
  - Simultaneous observations ongoing to expand the populations (e.g., possible association ob IC211208A with gamma-ray flare of PKS 0735+17)
- 10 IceCube hotspots located in the southern sky are likely originated from blazars in 5BZCat (well-defined sample of blazars)

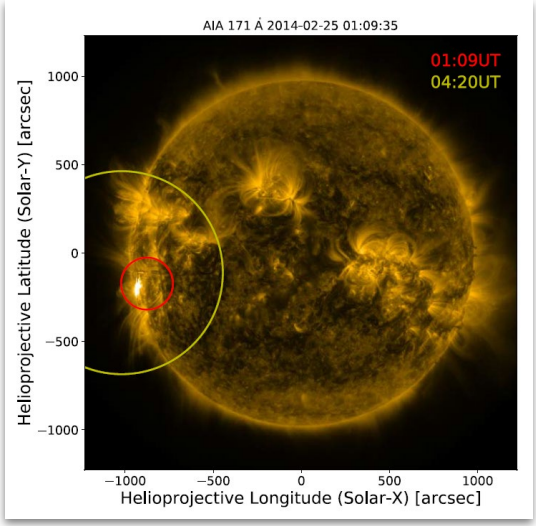
Only 1 out of 10 was reported as gamma-ray emitter in 2nd LAT AGN (active galactic nucleus) catalog, suggesting different emission sites for neutrino and gamma



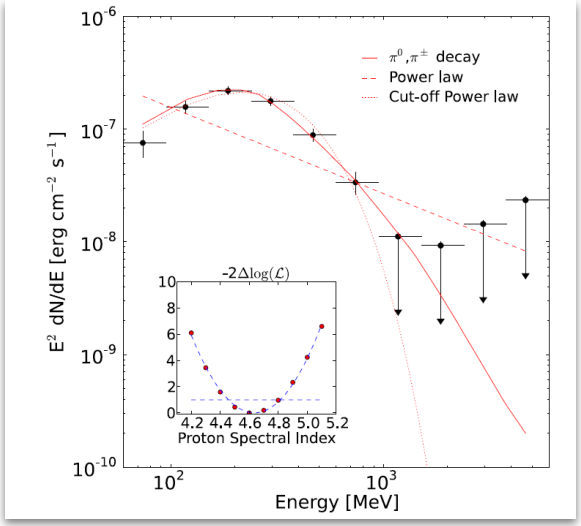
(Buson+22)

First Solar Flare Catalog

- (Fermi-LAT provides useful catalogs/resources of various types)
- Fermi-LAT detected 45 solar flares (FLSF; E>60 MeV)
  - 3 from behind the limb
  - All but three flares are associated with coronal mass ejection
  - Emission due to decay of pions produced by >300 MeV protons



(Fermi-LAT Collab. 21)

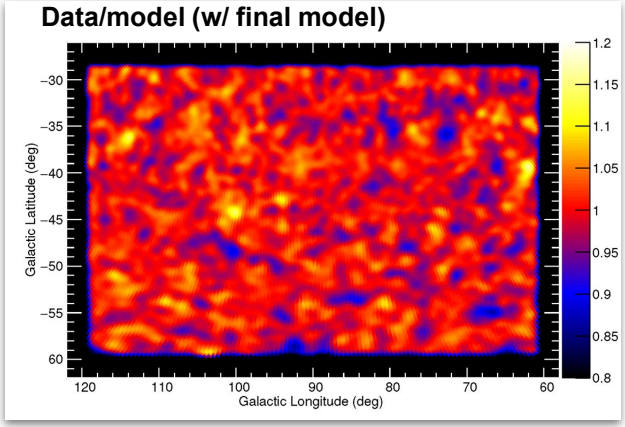


MW Astrophysics (3): MBM 53-55 Clouds and Pegasus loop (Cont'd)

We applied HI-line-profile based analysis

- γ-ray/W_{HI} is higher in narrow HI, establishing it to be thick HI
- Residual remains, very likely CO-dark H_2 (modeled using dust emission)

Also modelled interstellar CR spectrum (by PL of momentum w/ two breaks) using γ-ray data + CR data (AMS02, Voyager)



(Mizuno+22)