The Case for Extended Science Operations of the Fermi Large Area Telescope

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Fermi Large Area Telescope (LAT) PI
and
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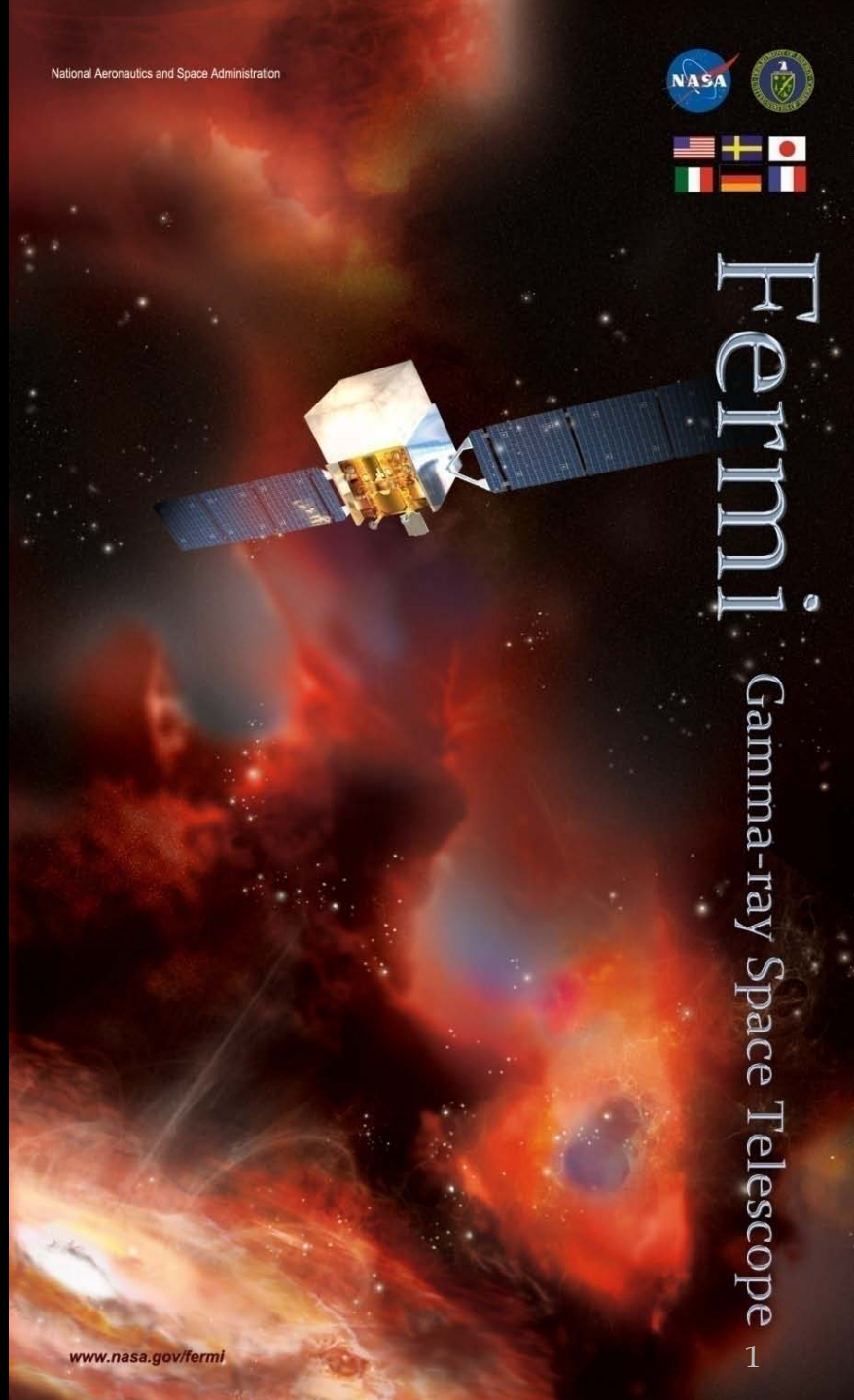
Fermi LAT International Finance Committee
November 4-5, 2011



The IFC would like to hear a summary of the LAT-related components of the science case for extending the Fermi GST mission in advance of the NASA senior review.

action item from May 2011 IFC meeting

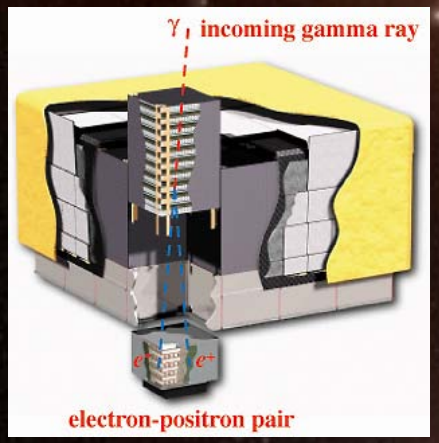
Outline

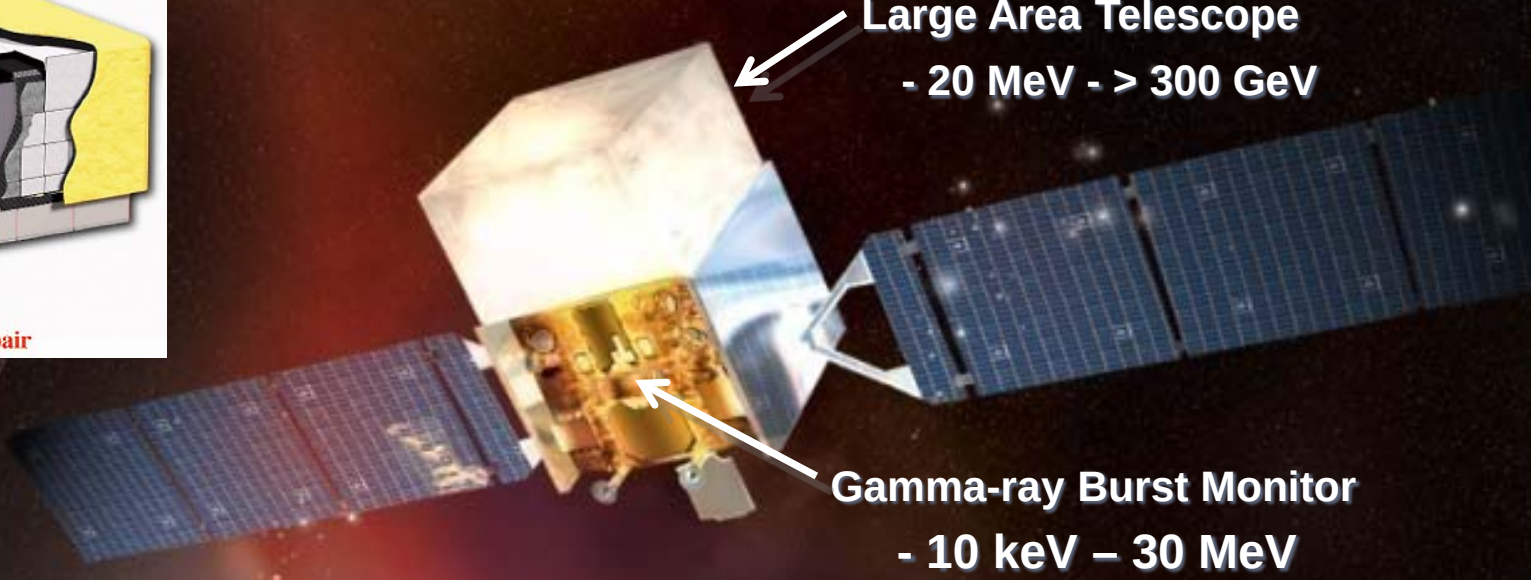
- LAT Highlights and Discoveries from 3 years of operation:
  - significance
  - what can be gained with extended mission

- details of impact of extended mission in subsequent talks:
  - extragalactic science: AGNs and other galaxies; isotropic ©-ray background
  - Galactic science: pulsars, binary sources, supernovae remnants, galactic transients/novae
  - dark matter and new physics
  - gamma-ray bursts

- Pass 8: realizing the full potential of the LAT

Fermi Gamma-ray Space Telescope





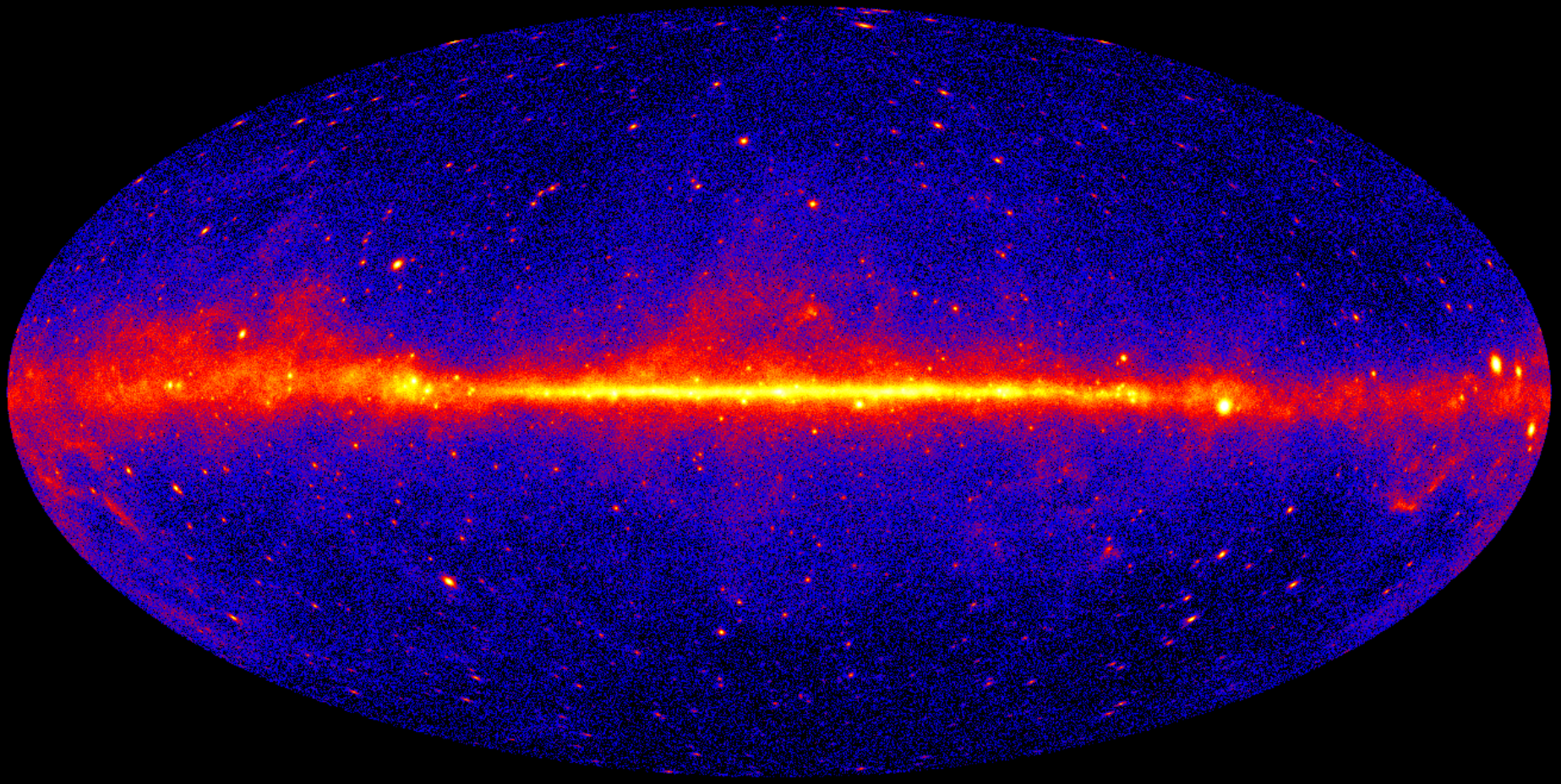
The LAT is a unique resource providing

- broad energy coverage, overlap with ACTs
- large FoV: all-sky coverage every 3 hours – transients

Multiwavelength observations have been key to several LAT scientific breakthroughs and will continue to be important during extended operations

Fermi's Restless Universe

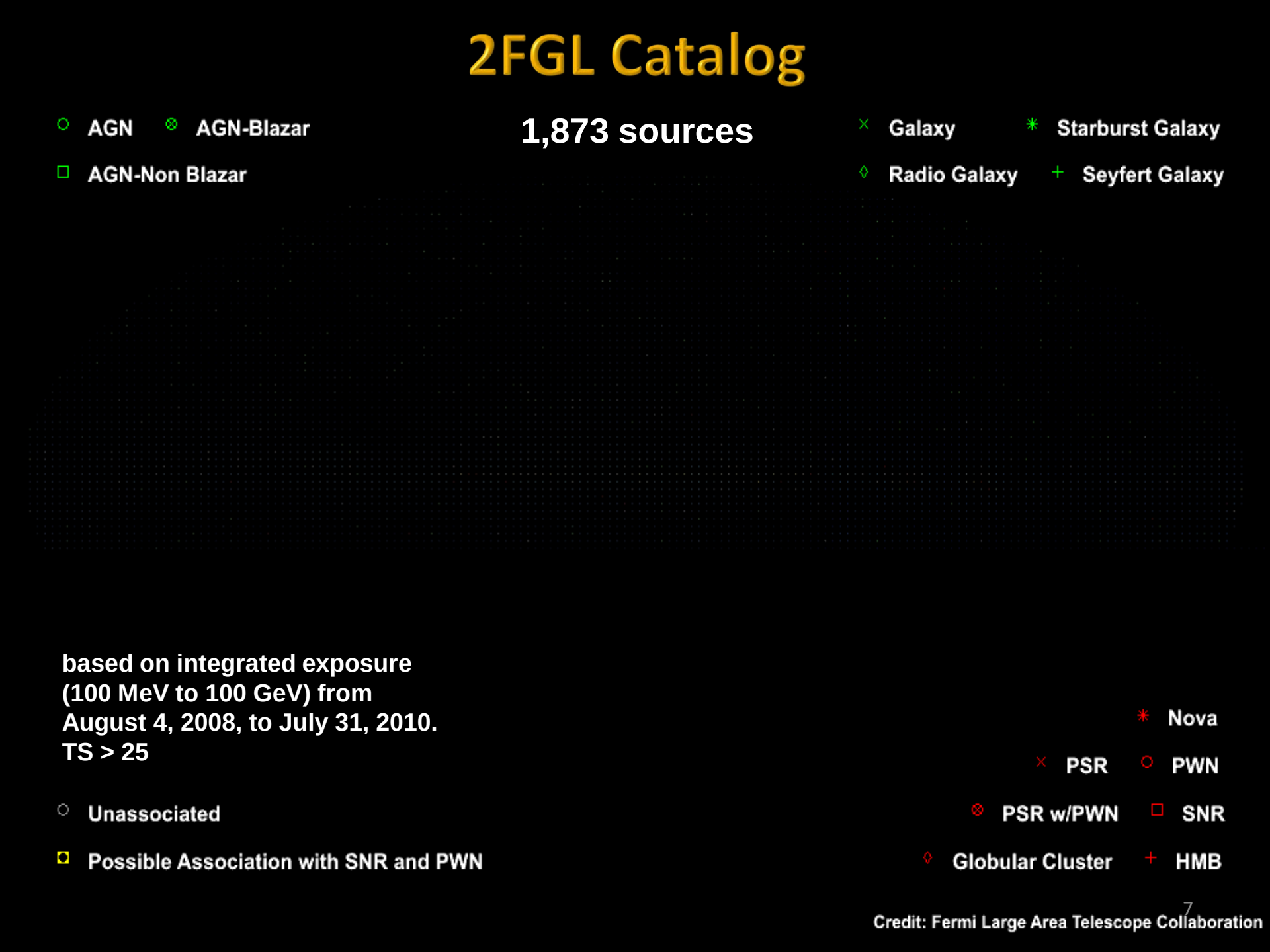
all-sky projection



E > 1 GeV

24 months

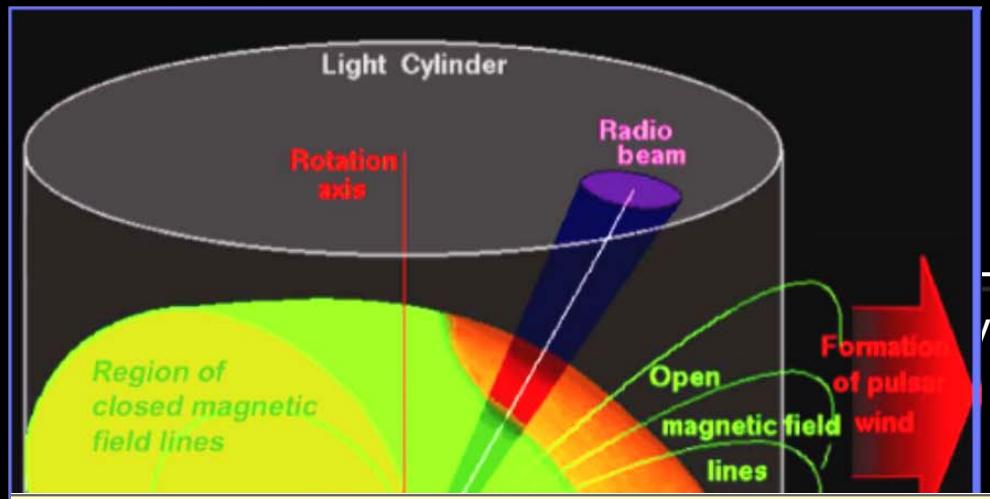
2FGL Catalog



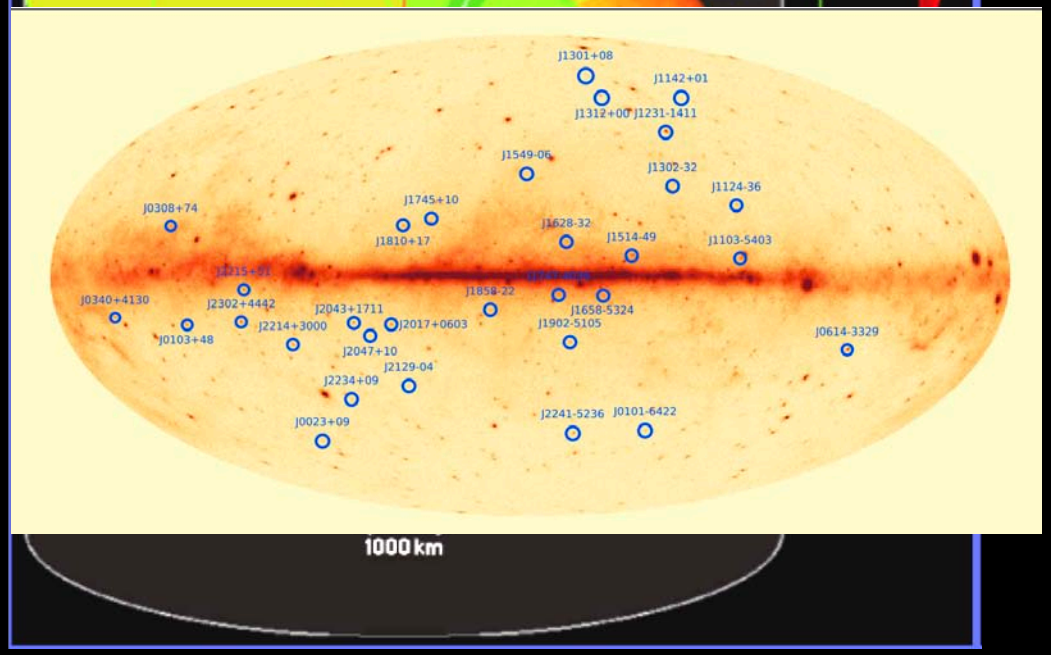
Credit: Fermi Large Area Telescope Collaboration

LAT discoveries & highlights

significance



7-fold increase in number of sources compared to EGRET 3EG catalog; includes several new source classes



largely settled long debate about ©-ray emission location; advanced understanding of pulsar evolution & overall energy budget

MSPs established as ©-ray emitters; large increase in supply of clocks for pulsar timing arrays for gravitational radiation detection; contributes to census of nearby MSPs

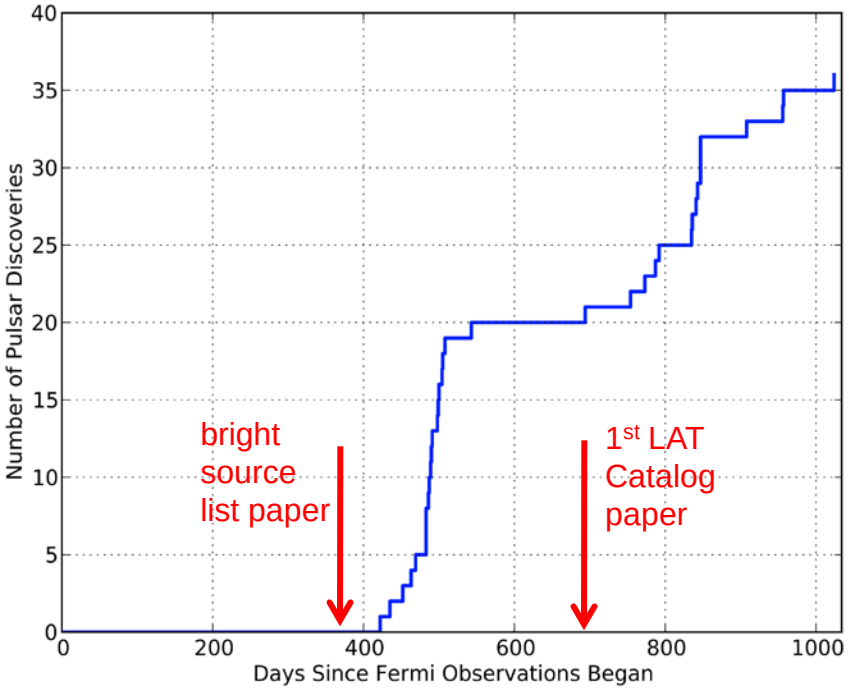
©-rays from neutron stars interacting strongly with companion star; link in evolution of MSPs

LAT discoveries & highlights

impact of extended operation

1,873 ©-ray sources; - 31% unidentified or unassociated

refine positions & monitor for variability, facilitating identifications & possible detections of new source classes

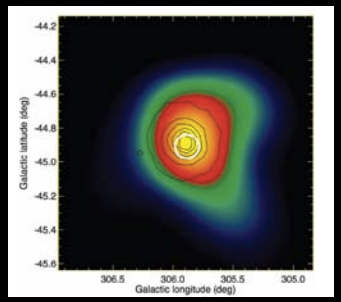


larger sample, allowing accurate determination of ©-ray beaming fraction & dependence on spin period, age, etc.

MSP discoveries will keep growing ~ linear with time (©-ray intensity uncorrelated with radio; radio searches driven by area of error box: $A \sim 1/t$)

larger sample of these rare but significant systems; orbital modulation?

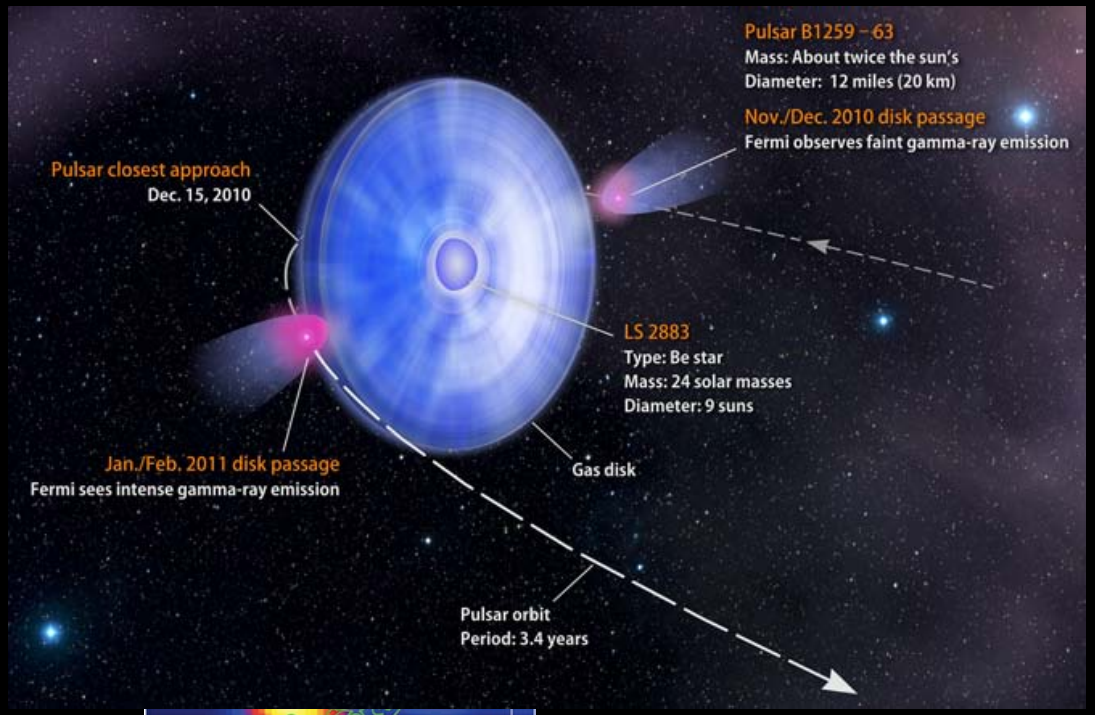
LAT discoveries & highlights



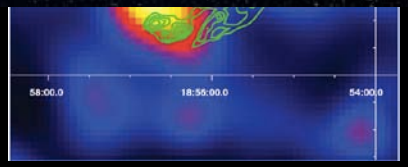
high-energy emission from globular clusters

significance

provides reliable, independent method to assess population of MSPs in globular clusters



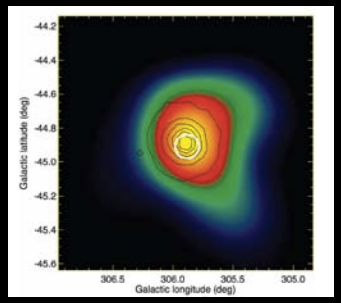
due to spectral-temporal behavior, conclude that GeV and TeV emissions have different (unknown) origins; compact objects either NS or BH



SNRs generally believed to be primary source of cosmic-rays up to knee; LAT detections dominated by middle-aged SNRs interacting with nearby molecular clouds; most measured spectra consistent with hadronic origin, but not all (e.g., RX J1713.7-3946)

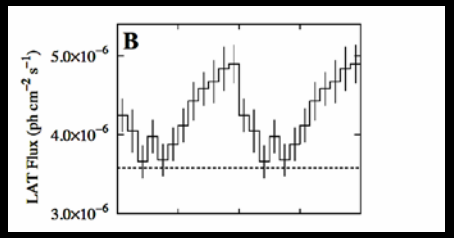
LAT discoveries & highlights

impact of extended operation

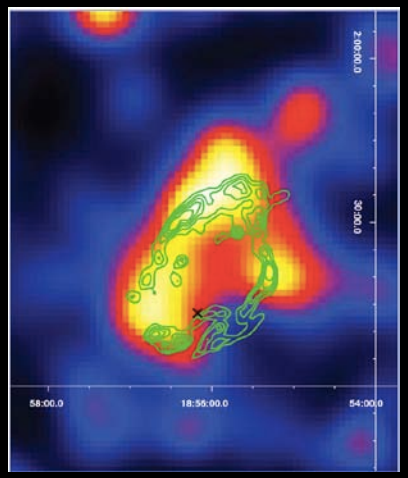


high-energy emission from globular clusters

obtain larger sample of these rare systems



©-ray binaries, including the first binary system discovered with ©-ray observations

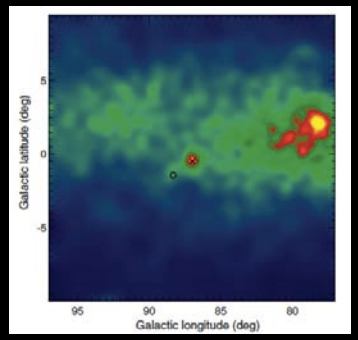


©-ray (>1 GeV) emission from more than a dozen Supernovae Remnants (SNRs)

increase sample SNRs; determine e^--p ratio in sample of SNRs by differentiating IC and □^{O}-decay spectra; study CR escape from remnants via observation of GeV emission from nearby molecular clouds

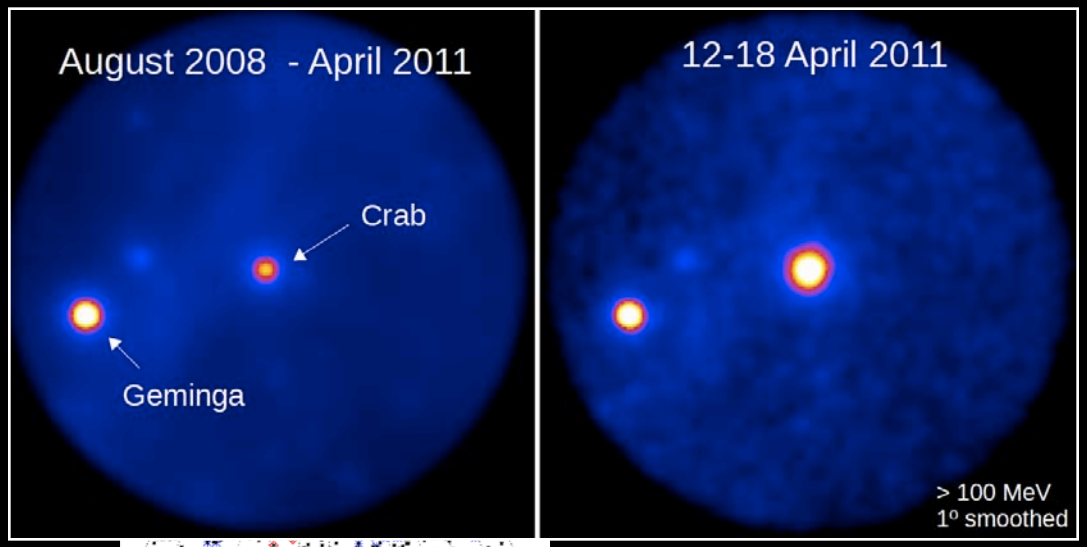
LAT discoveries & highlights

significance

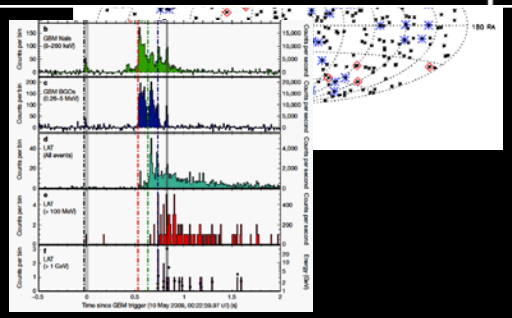


©-ray emission from nova V407 Cygni

unexpected discovery of ©-rays from a symbiotic binary nova; 1st detection of high-energy emission from a white dwarf



giant flares challenge diffusive shock theories of particle acceleration & emission in pulsar winds & SNRs



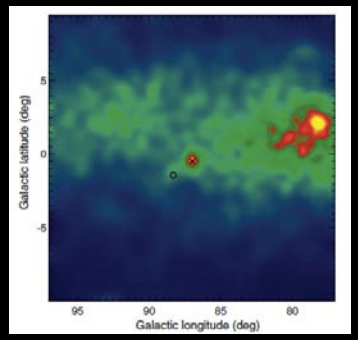
long and short duration ©-ray bursts

most relativistic outflows ($\wp$ ~1000) ever observed; some LAT bursts are also most energetic;

robust constraints placed on violations of Lorentz invariance implied by some descriptions of quantum gravity

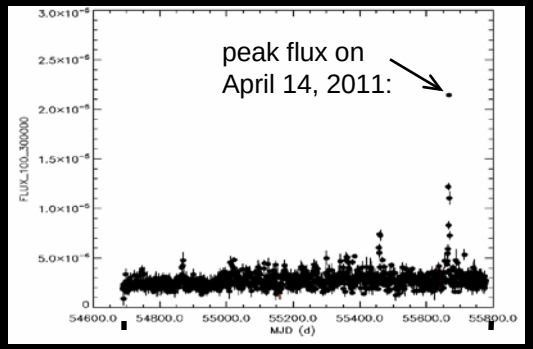
LAT discoveries & highlights

impact of extended operation



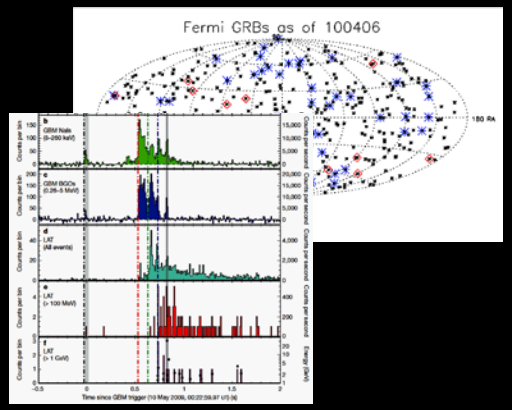
©-ray emission from nova V407 Cygni

continue providing all-sky ©-ray transient alert capability, crucial to multiwavelength studies of galactic and extragalactic transients



high-energy emission from both long and short duration ©-ray bursts

be on lookout for flares in other sources such as SNR0540-69, the Crab's “twin” in LMC

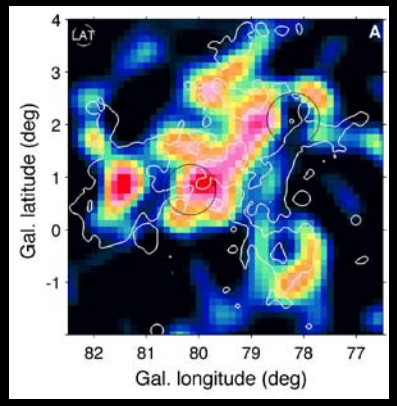


high-energy emission from both long and short duration ©-ray bursts

larger sample of both long and short high-energy bursts facilitating systematic studies of burst evolution and mechanisms of prompt and delayed emission

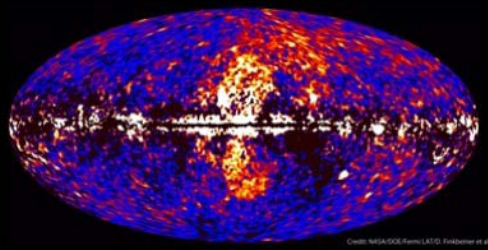
LAT discoveries & highlights

significance



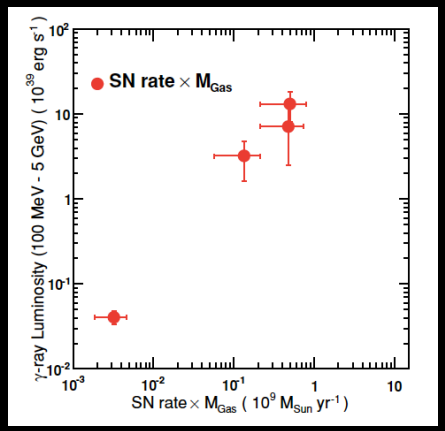
cocoon of freshly accelerated cosmic-rays in the Cygnus superbubble

observational evidence for the long advocated hypothesis that massive-star clusters host cosmic-ray factories



©-ray emitting bubbles extending 25,000 light-years north and south of the galactic center

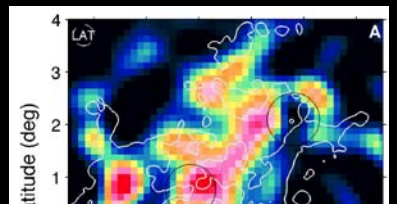
indication of "historic" activity in the Galactic center region possibly associated with starburst activity or injection of high-energy cosmic rays from GC black hole activity.



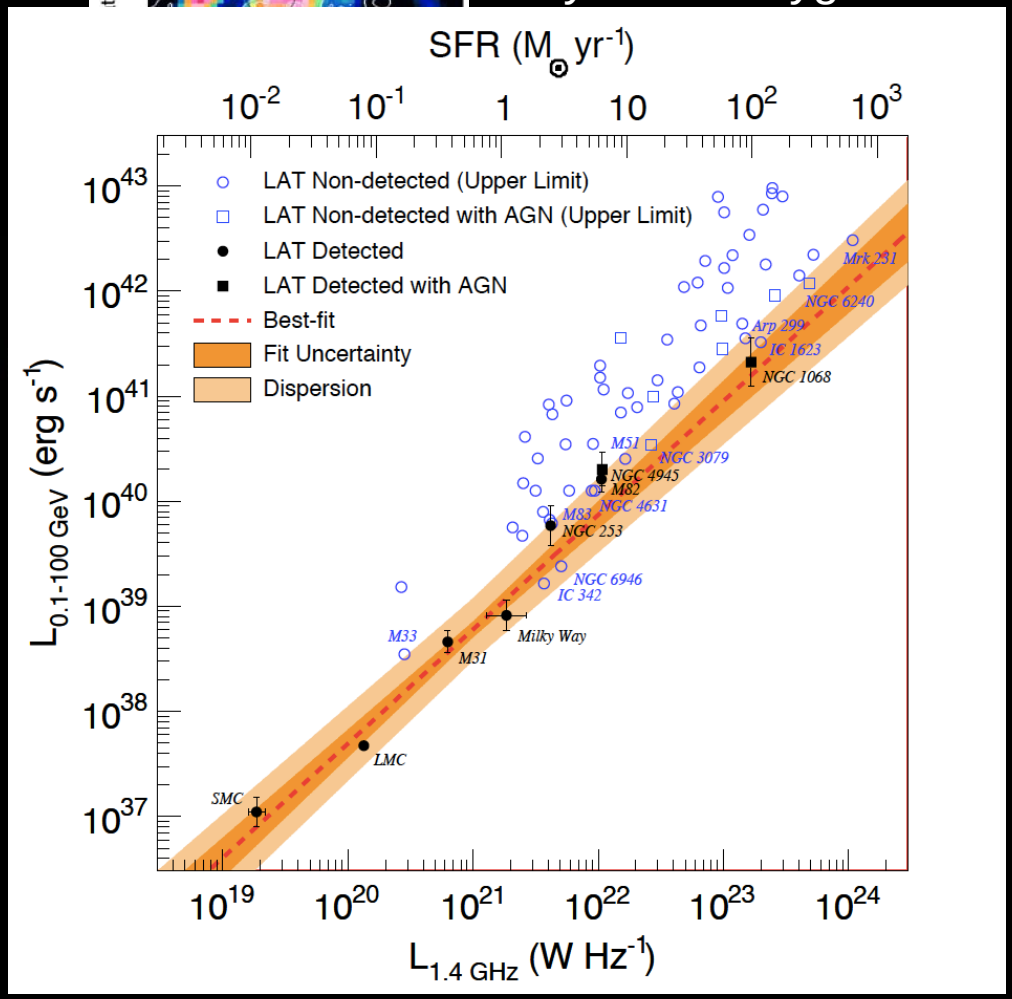
GeV emission from starburst galaxies and nearby normal galaxies

view cosmic-ray production "from outside looking in" & study link between CR production & star formation; begin to understand contribution of these new ©-ray source classes to isotropic "diffuse" background

LAT discoveries & highlights



cocoon of freshly accelerated cosmic-rays in the Cygnus



impact of extended operation

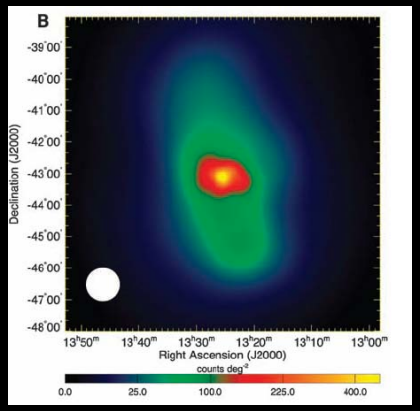
determine if CRs from single accelerator or from distributed acceleration process; search for other cocoons in stellar superclusters & OB associations

with deeper exposure, trace structure to Galactic plane, search for fainter remnants of earlier activity, & extend spectral coverage

detect more members of these poorly sampled source classes; important for accurate accounting of contributions to isotropic diffuse ©-ray background and for study of cosmic-ray production

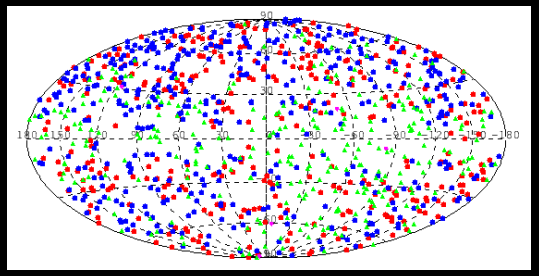
LAT discoveries & highlights

significance



resolved images of high-energy emission from radio galaxy Centaurus A

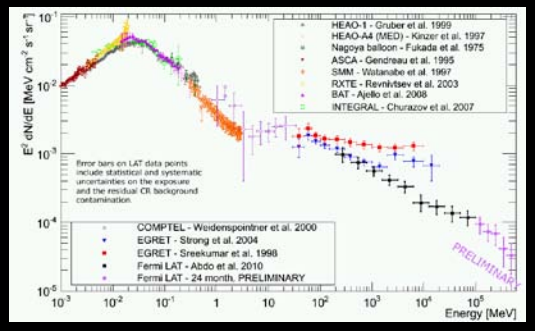
demonstrates need for particle acceleration within 100's kpc-scale lobes; constrain B field and particle energy density in lobes



detection of nearly 1,000 blazar AGNs

constrain blazar luminosity function & determine contribution of blazars to isotropic diffuse bkgd ≤ 30%;

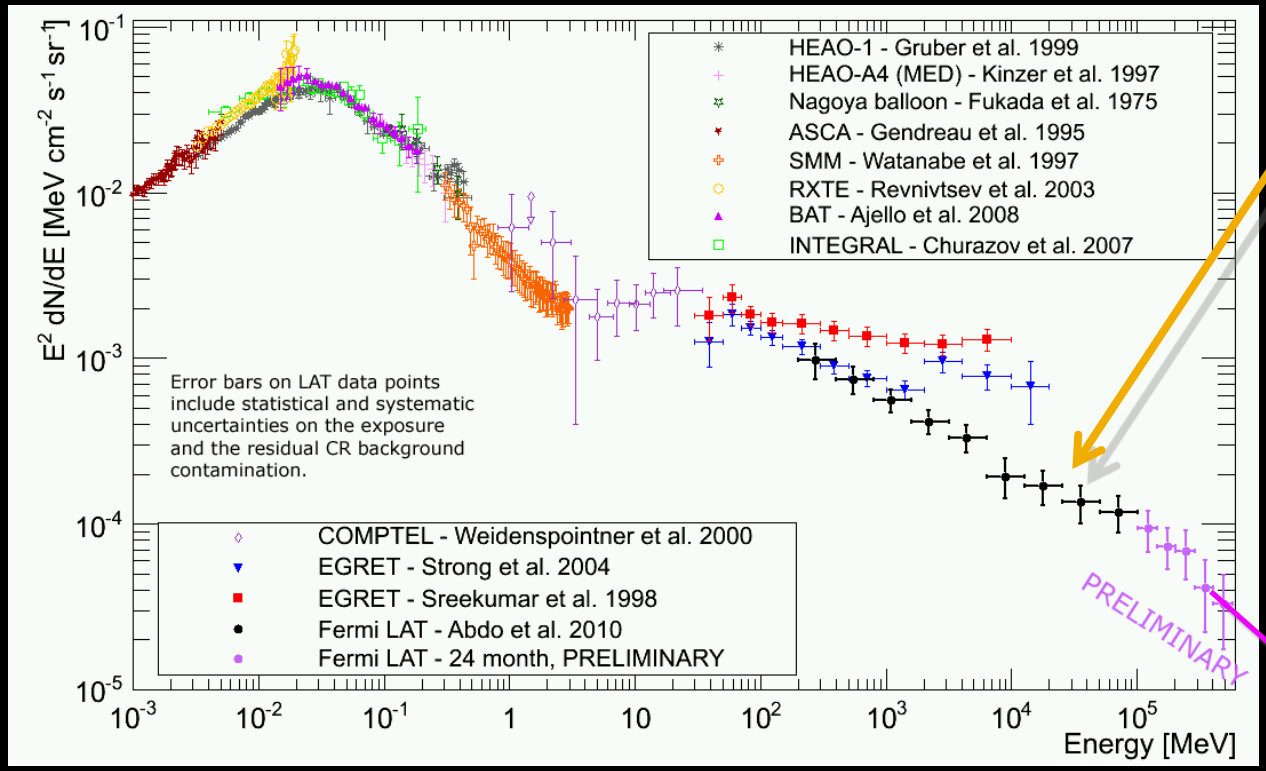
establish lower limit of ~3 x 10^{-16} gauss for intergalactic magnetic field; constraints on extragalactic background light (EBL).



measurement of spectrum of high-energy isotropic radiation to more than 100 GeV

constraints on ©-ray production by dark matter annihilation, photo-pion production by extragalactic ultrahigh energy cosmic-rays

A key science question that connects to many areas of LAT science

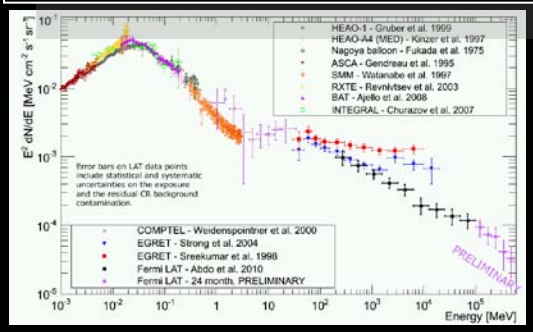


point sources & truly diffuse component

- need accurate accounting of point source contributions

- extend spectral measurement to above 1 TeV; new discovery space

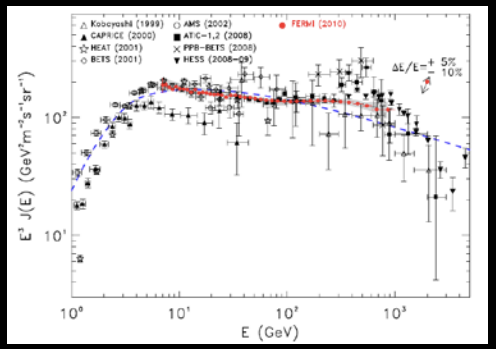
?



measurement of spectrum of high-energy isotropic radiation to more than 100 GeV

extend measurement to >1 TeV & thereby look for pileup or cutoff due to EBL absorption of distant sources & look for dark matter decay signatures

LAT discoveries & highlights

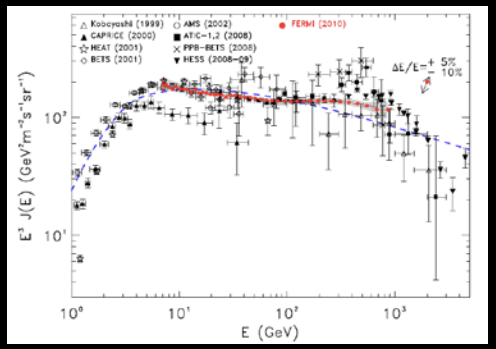


measurement of e^+e^- spectrum to 1 TeV

significance

most *precise* measurement of e^+e^- spectrum from 7 GeV to 1 TeV

LAT discoveries & highlights



measurement of e^+e^- spectrum to 1 TeV

impact of extended operation

extend measurement to at least 2 TeV

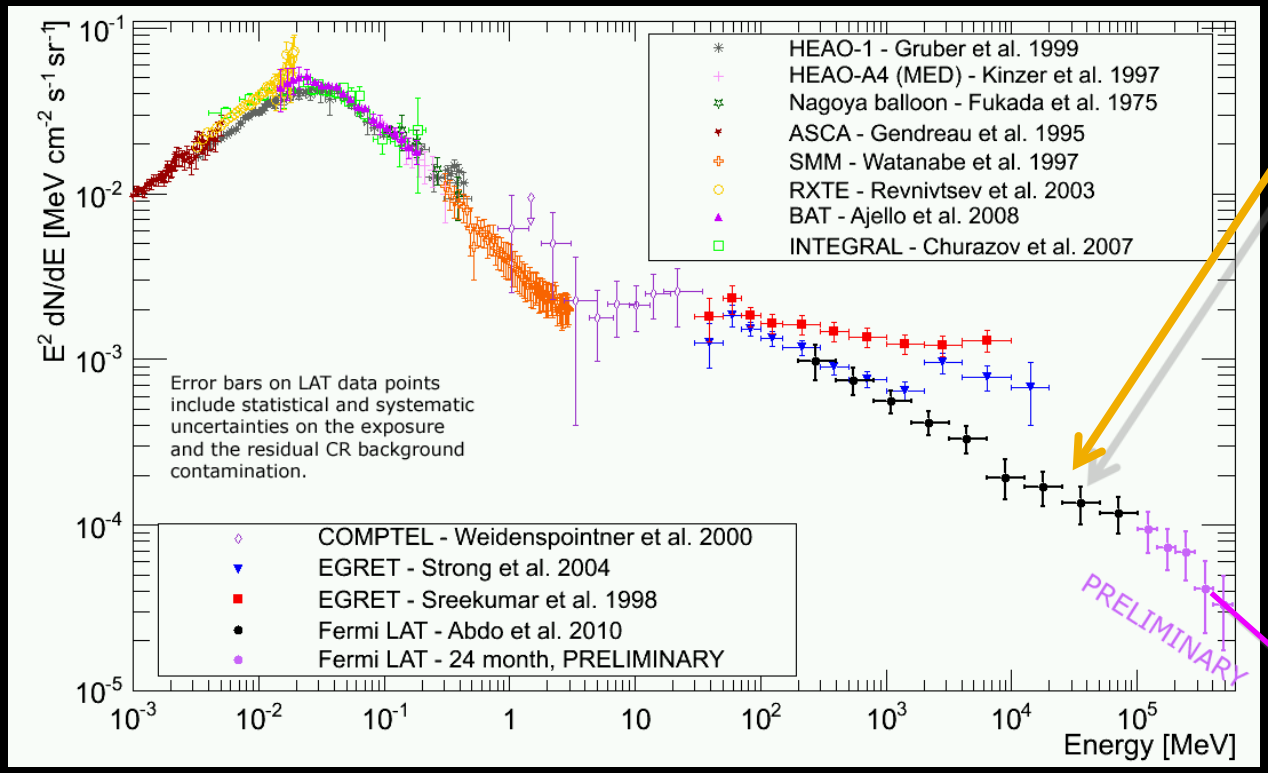
Summary

- In the next 5 years, with LAT we can expect to (a partial list):
  - discover new ©-ray source classes by pursuing identification of 2FGL unidentified sources, and better characterize cosmic evolution of poorly-sampled source classes
  - Complete the accounting of contributions to high-energy isotropic ©-ray background; make first measurements of spectrum above 100 GeV
  - more than double number of millisecond pulsar discoveries (in the field), thus enhancing capabilities of radio pulsar timing arrays (e.g. NANOGrav) for gravitational radiation detection
  - continue to provide all-sky transient alert capability, crucial for multiwavelength studies of transients ranging from extragalactic high-energy GRBs (~1 per 2 months) to rare galactic transients such as novae (V407 Cygni) and flaring SNRs (Crab)
- at the lowest and highest energies all the above will be significantly enhanced by implementation of Pass 8 analysis

Backup slides

What is the origin(s) of isotropic diffuse radiation?

A key science question that connects to many areas of LAT science

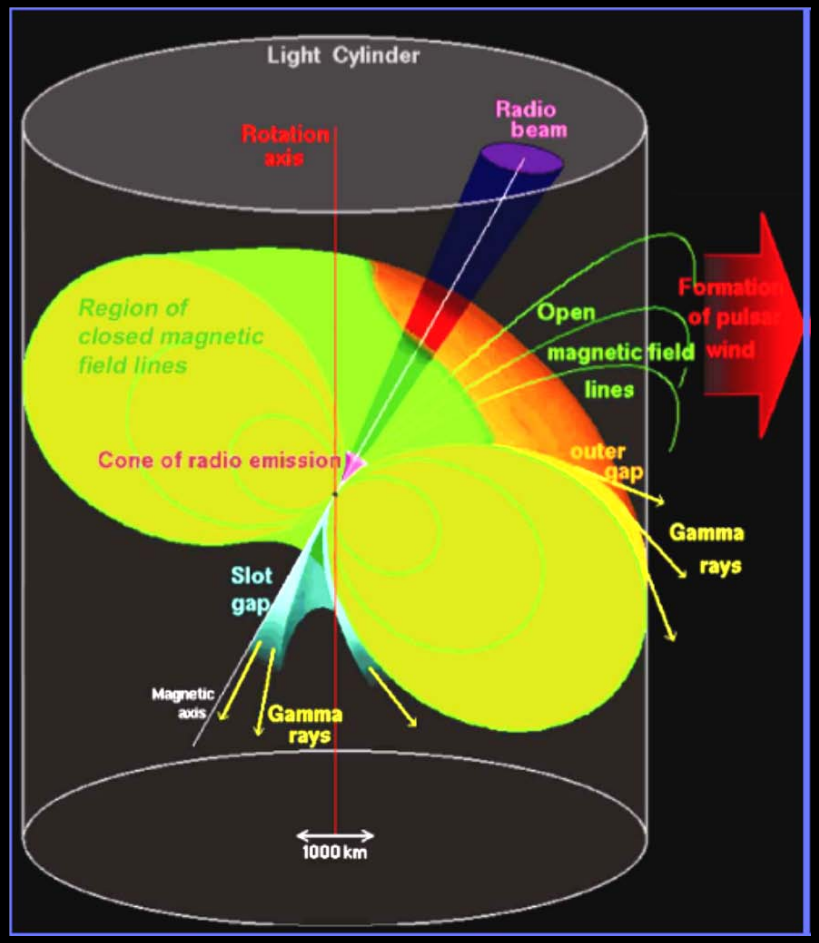


point sources & truly diffuse component

- need accurate accounting of point source contributions

- extend spectral measurement to above 1 TeV; new discovery space

gamma-ray pulsars

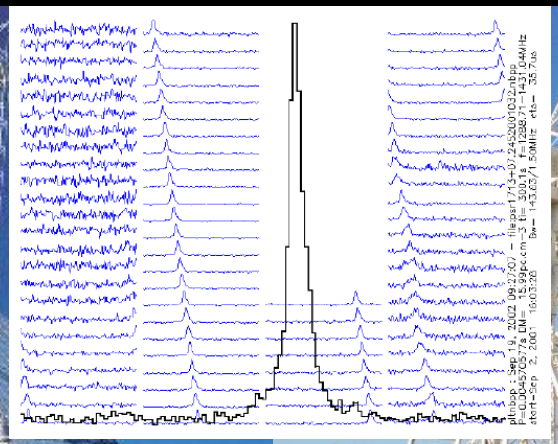


- Detection of gamma-ray Pulsars Through Blind Frequency Searches
- Detection of Population of gamma-ray Millisecond Pulsars
- Detection of High-Energy gamma-ray Emission from the Globular Cluster 47 Tucanae

more than 100 gamma-ray pulsars detected to date

Radio support for Fermi has been massive and of tremendous value! (here: just a few)

Parkes (Australia)



Jodrell Bank (England)

Urumqi (China)

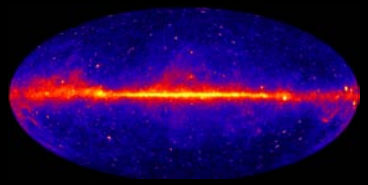
Greenbank (USA)

Nançay (France)

Fermi and the Radio Pulsar Community: A Productive Symbiotic Relationship

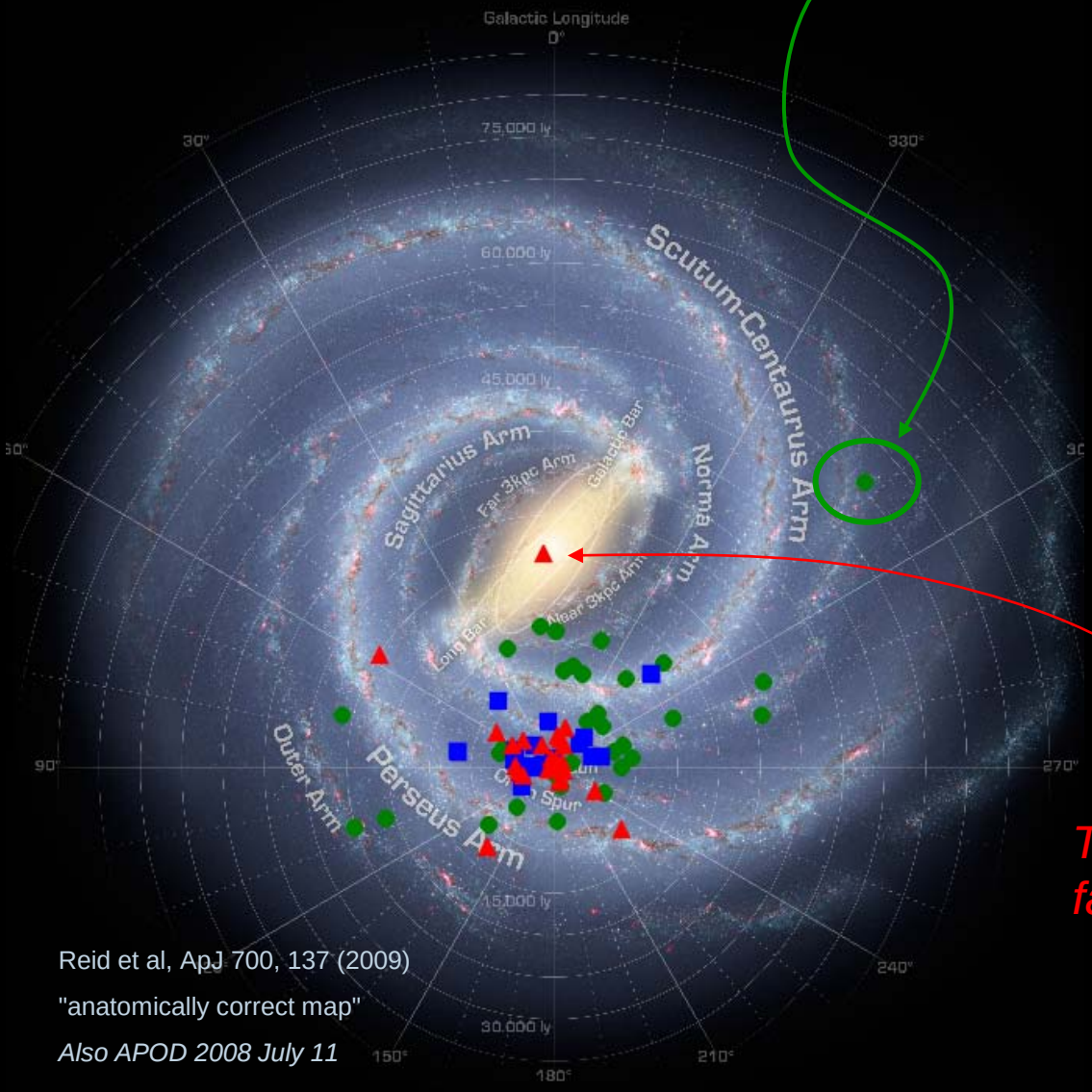
Radio Pulsar Community

Fermi LAT



Timing models for >700 pulsars	→	Discovered gamma-ray pulsations from 57 radio pulsars (38 young, 19 MSP)
Radio detection of 4, deep upper limits for rest (really "radio quiet")	←	38 LAT blind search pulsar positions and timing
New radio MSP in GC NGC 6652	←	Gamma-ray globular cluster detections (indicating that they harbor MSPs)
VLBA astrometry for distance measurements	→	Accurate efficiency and energetics
35 new MSPs discovered!	←	UNASSOC source positions
	→	LAT pulsations found from 19 so far!

gamma-ray pulsars seen from above



Reid et al, ApJ 700, 137 (2009)

"anatomically correct map"

Also APOD 2008 July 11

Example: PSR J1410-6132

Parkes radio rotation ephemeris

Period = 50 ms
$\dot{E} = 10^{37}$ erg/s

HESS TeV PWN overlaps.

The NE2001 DM distance of 15.6 kpc needs cross-checks.

This MSP in globular cluster is far above the galactic plane.

Globular Clusters

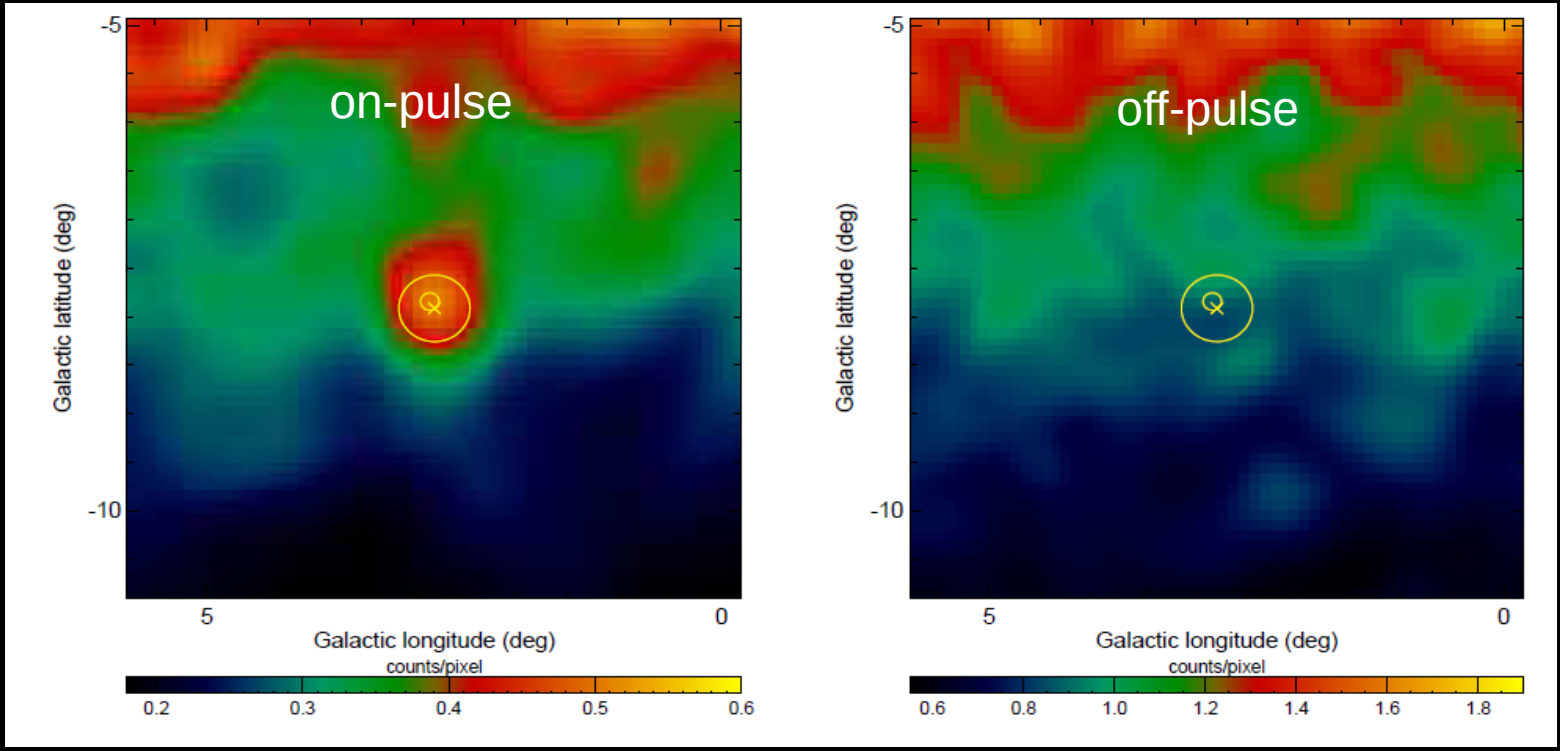
47 Tuc

- half of known MSPs are in Globular clusters.
- pulsar-like gamma-ray spectra seen for 8 GC's; used to constrain the number of MSPs therein Abdo, A. A. et al. 2010, A&A, 524, A75

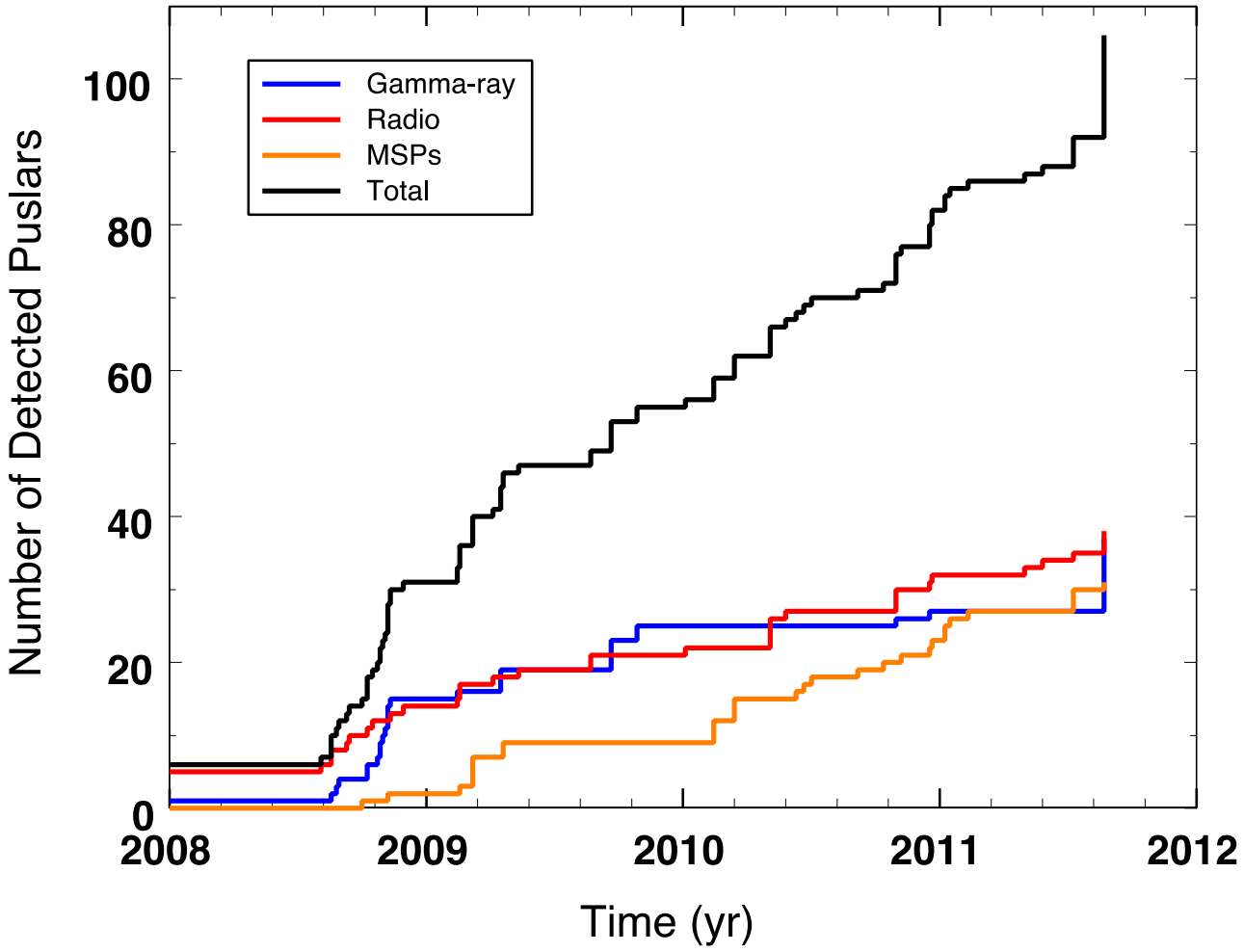
NEW: *gamma-ray pulsations seen from PSR J1823-3021A in NGC6624 !*

P. Freire et al, Science accepted

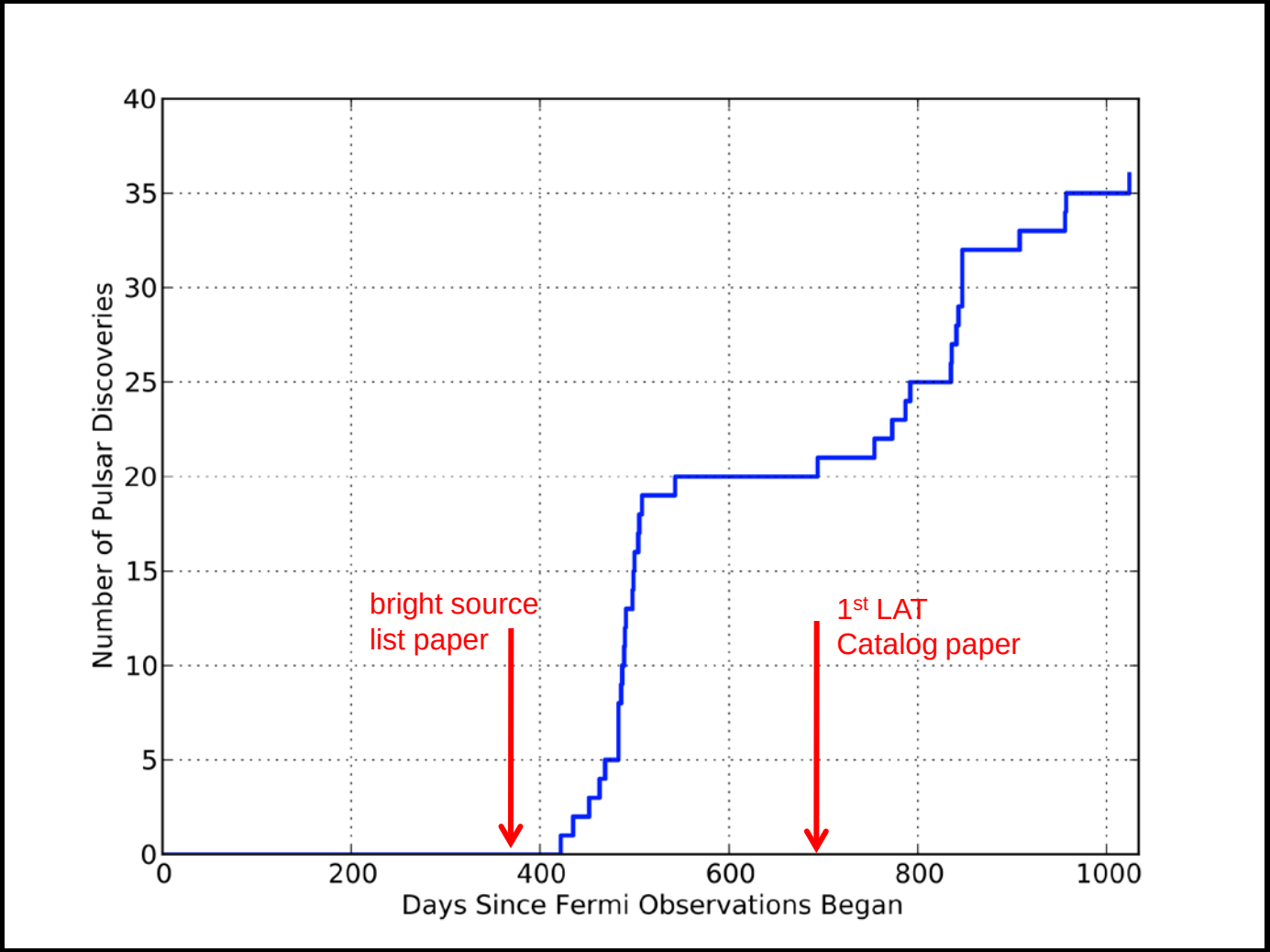
No off-pulse GeV emission! All gamma-ray luminosity of the GC from one MSP.

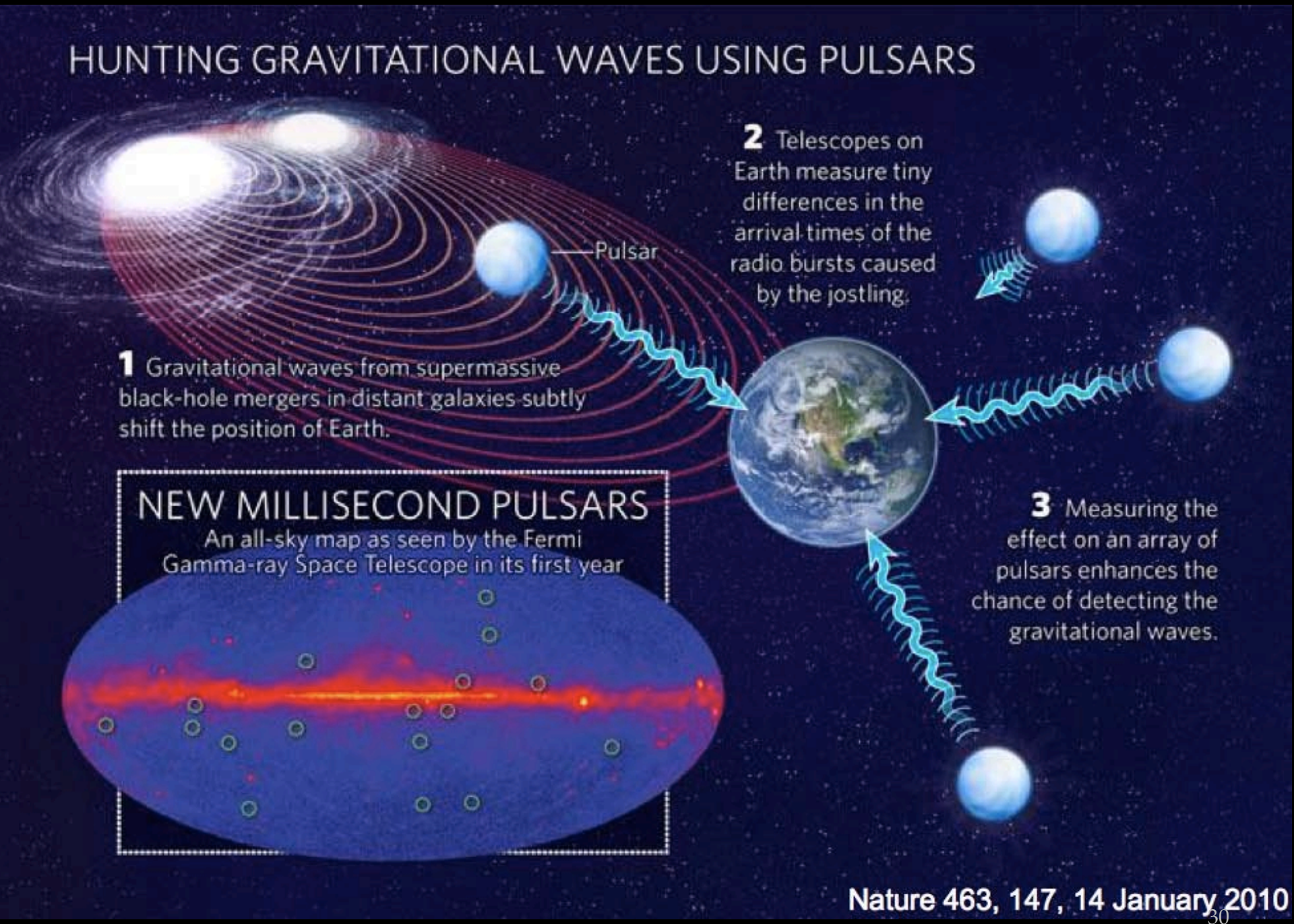


pulsar detections

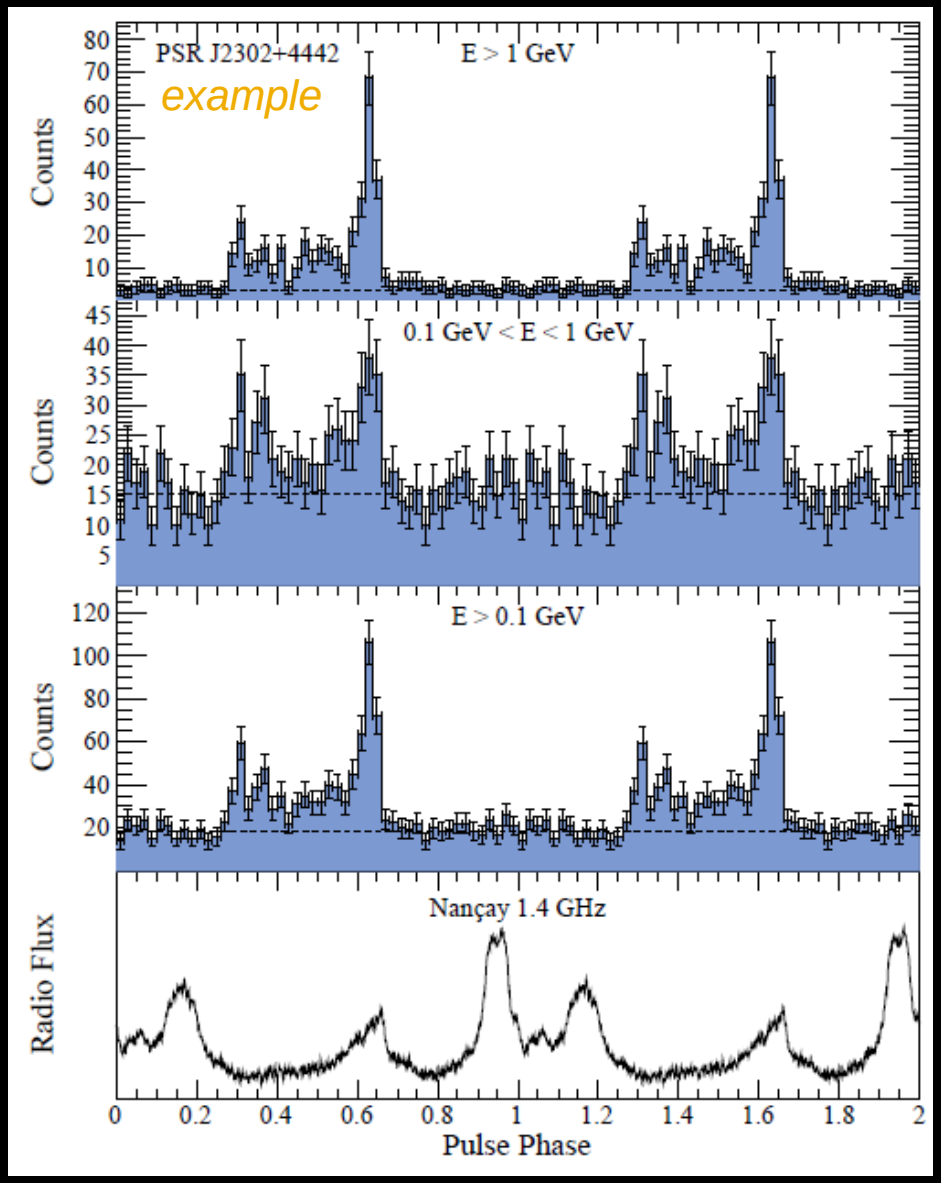


Radio MSP discoveries in LAT Unid error boxes




HUNTING GRAVITATIONAL WAVES USING PULSARS
Pulsar
1 Gravitational waves from supermassive black-hole mergers in distant galaxies subtly shift the position of Earth.
2 Telescopes on Earth measure tiny differences in the arrival times of the radio bursts caused by the jostling.
3 Measuring the effect on an array of pulsars enhances the chance of detecting the gravitational waves.
NEW MILLISECOND PULSARS
An all-sky map as seen by the Fermi Gamma-ray Space Telescope in its first year
Nature 463, 147, 14 January 2010

©-pulsations from new radio MSPs



Take away message:

Radio and ©-ray fluxes uncorrelated.

As *Fermi* mission continues, new *Fermi* sources are weaker and weaker.

But they can still point to undiscovered radio-bright pulsars!

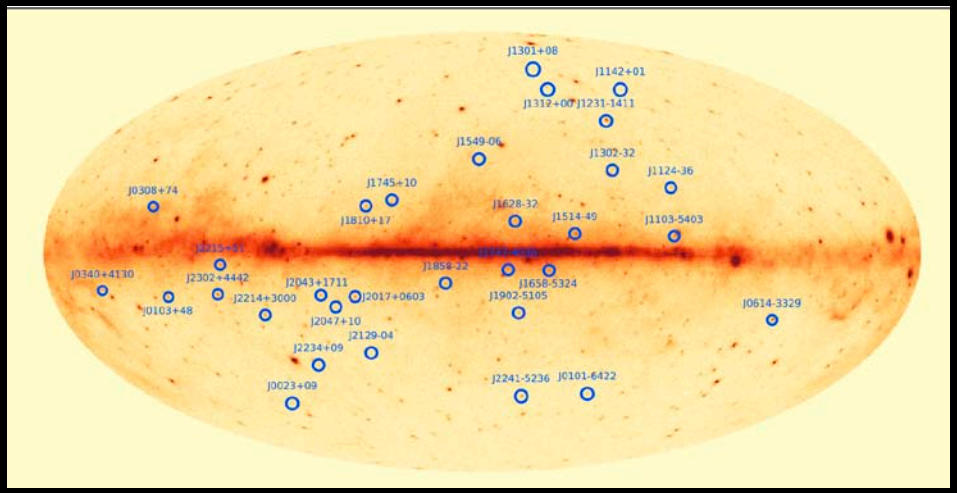
Therefore, *Fermi*-directed radio searches will continue to bear fruit.

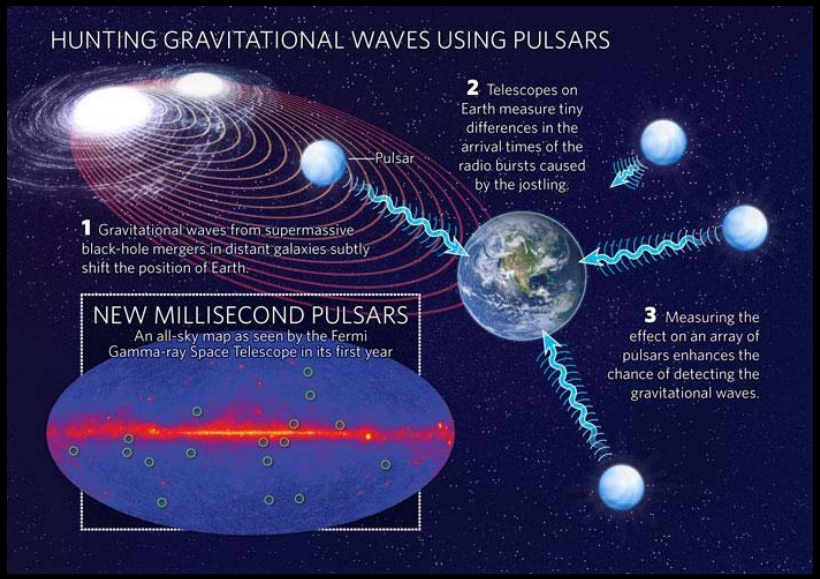
IMPORTANT SPIN-OFF: new very stable MSPs for gravity wave searches.

Cognard, I. et al. 2011, ApJ, 732, 47

Exciting Results: Present and Future

- went from 6 to **88** known gamma-ray pulsars
  - gamma-rays dominate pulsar energy budgets
  - gamma-ray profiles constrain emission region geometry
- LAT is an efficient finder of MSPs
  - 50% increase in number of known MSPs!
  - At least **7** new black widow binaries (much larger proportion than in radio surveys… why?) Only ~4 known outside the globular cluster system previously





Future Promise

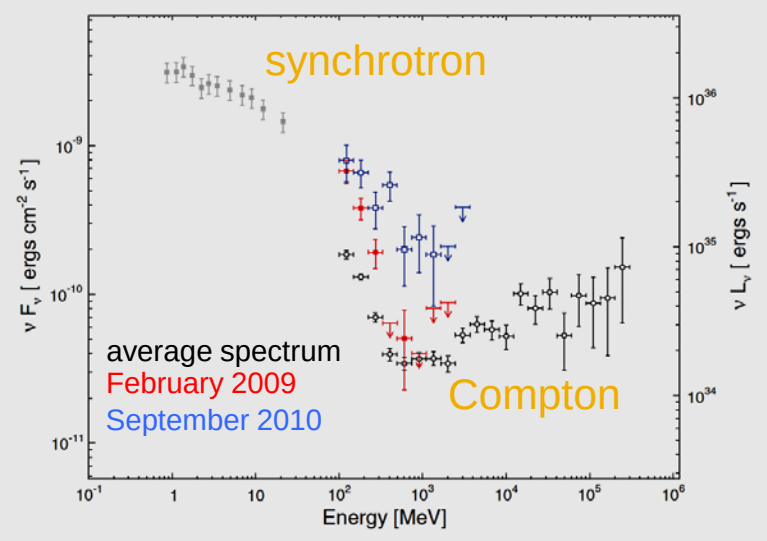
- MORE pulsar discoveries – radio fluxes don't correlate with gamma-ray, so new faint LAT sources may point to bright radio pulsars
- Look for shock emission from black widow systems – orbital modulation?
- Population studies will constrain Galactic MSP population
- Pulsar timing arrays could detect nanoHertz gravitational waves

©-ray flares from the Crab Nebula

Science **331,** 817 (2010); also seen by AGILE

1st reports of variability of high-energy gamma-ray emission from Crab nebula

Spectral energy distribution (25 months)

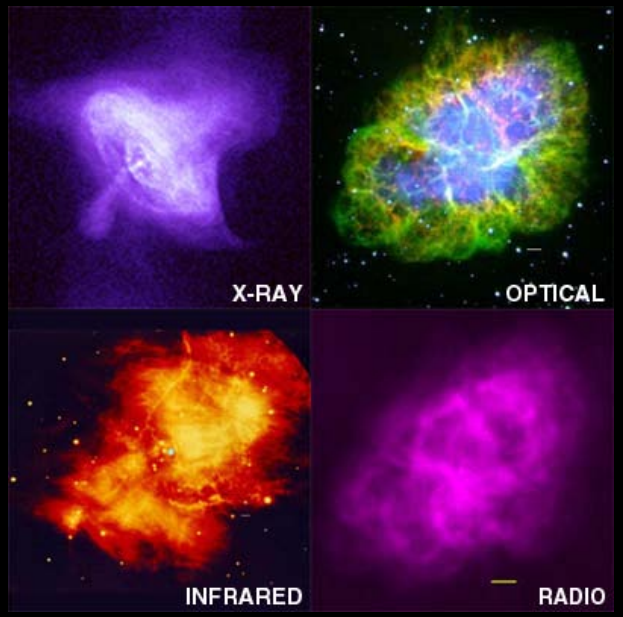


flare time scales (4 days) imply compact flaring region:

$L < Dct < 1.4 \times 10^{-2}$ pc

(1.5 arcsec)

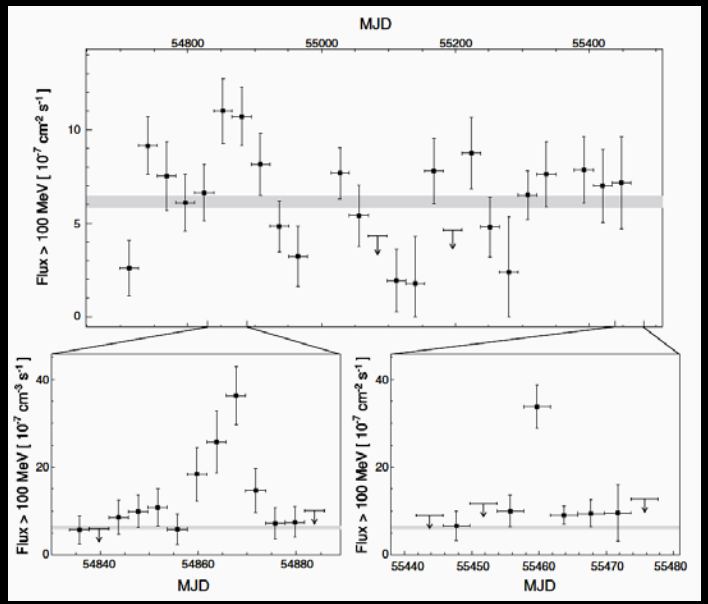
Structures this small only found in inner part of nebula, close to pulsar wind termination shock, base of the jet, or the pulsar.



spectrum and short flare time scales imply **emission is synchrotron radiation** (electron cooling timescales for IC emission & bremsstrahlung ≥ 10^7 yr.)

detection of synchrotron photons up to ≥ 1 GeV implies electrons accelerated to ≥ 1 PeV in the nebula.

efficiency of synchrotron losses requires a strong electric field to compensate; severe difficulties for diffusive shock acceleration mechanism.



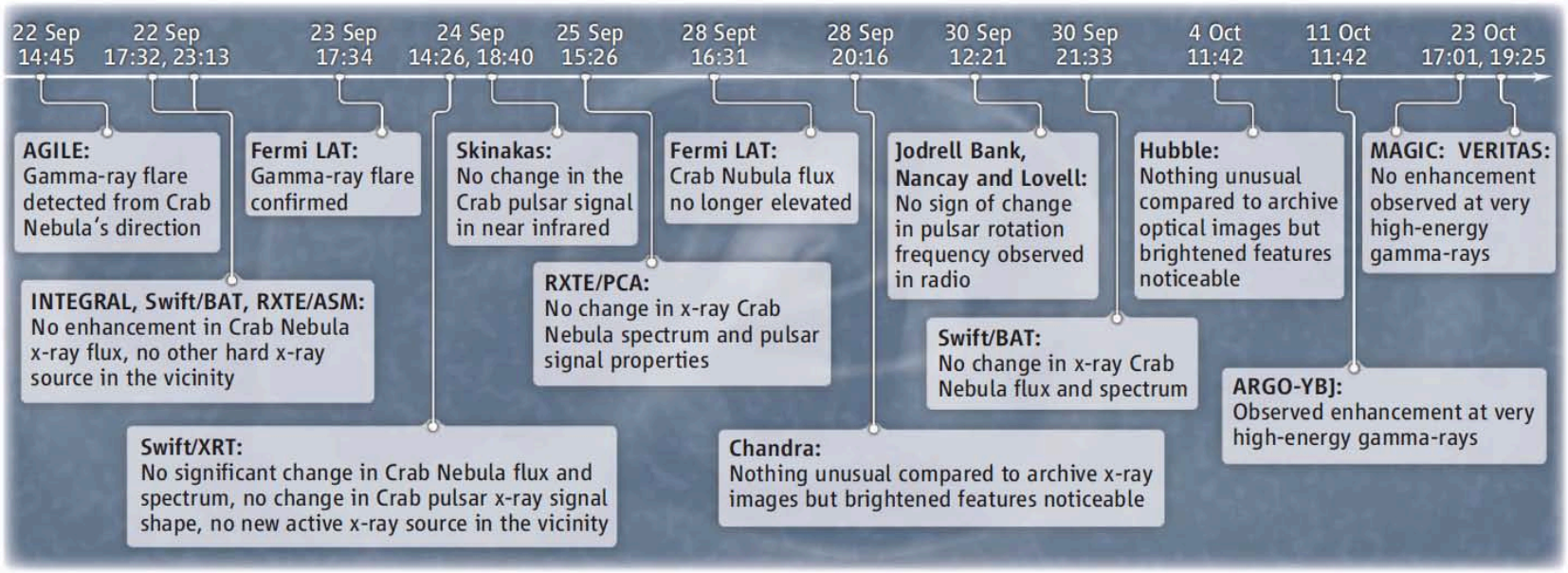
Crab flare: coordination of multiwavelength real-time observations

ASTRONOMY

Astronomy in the Time Domain

Coordination between various instruments provides a real-time aspect to observing transient astrophysical events.

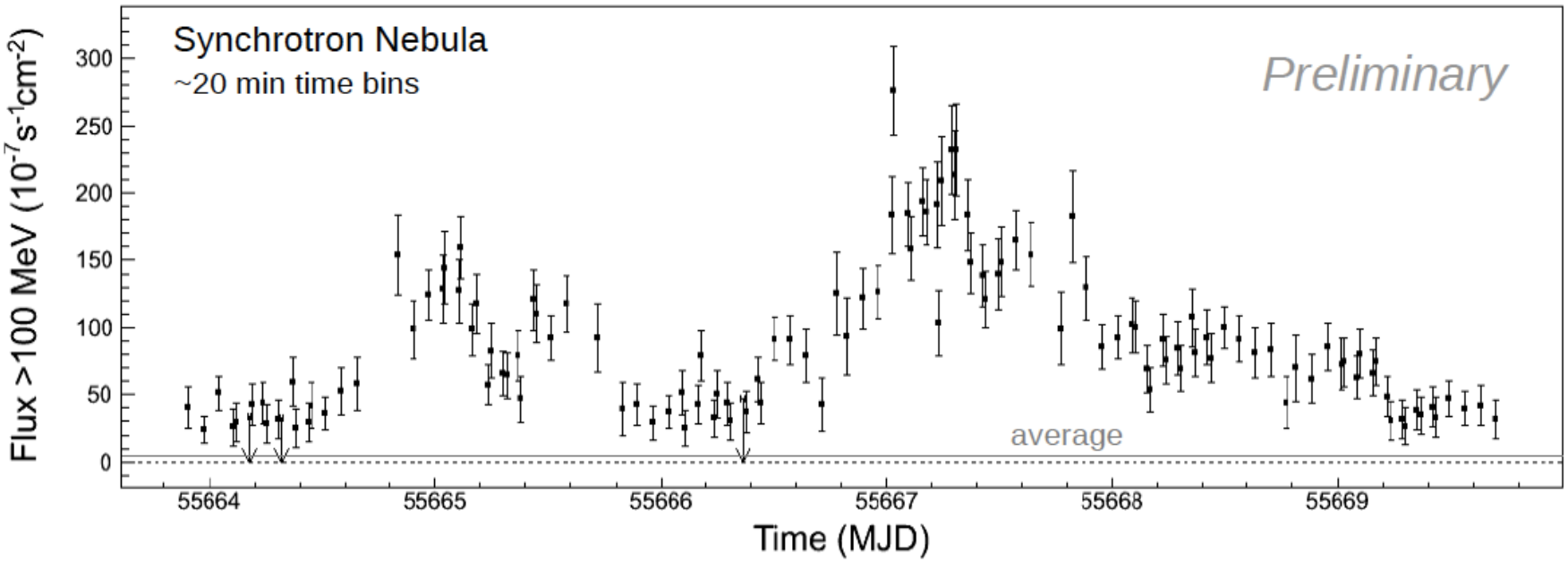
Elisa Bernardini



A time line of events. Timetable of the *Astronomer's Telegram* releases on the recent Crab Nebula flare in universal time, within 1 month after discovery on 22 September 2010. Corresponding telegram IDs are: 2855, 2856, 2858, 2861, 2866, 2867, 2868, 2872, 2879, 2882, 2889, 2893, 2903, 2921, 2967, 2968.

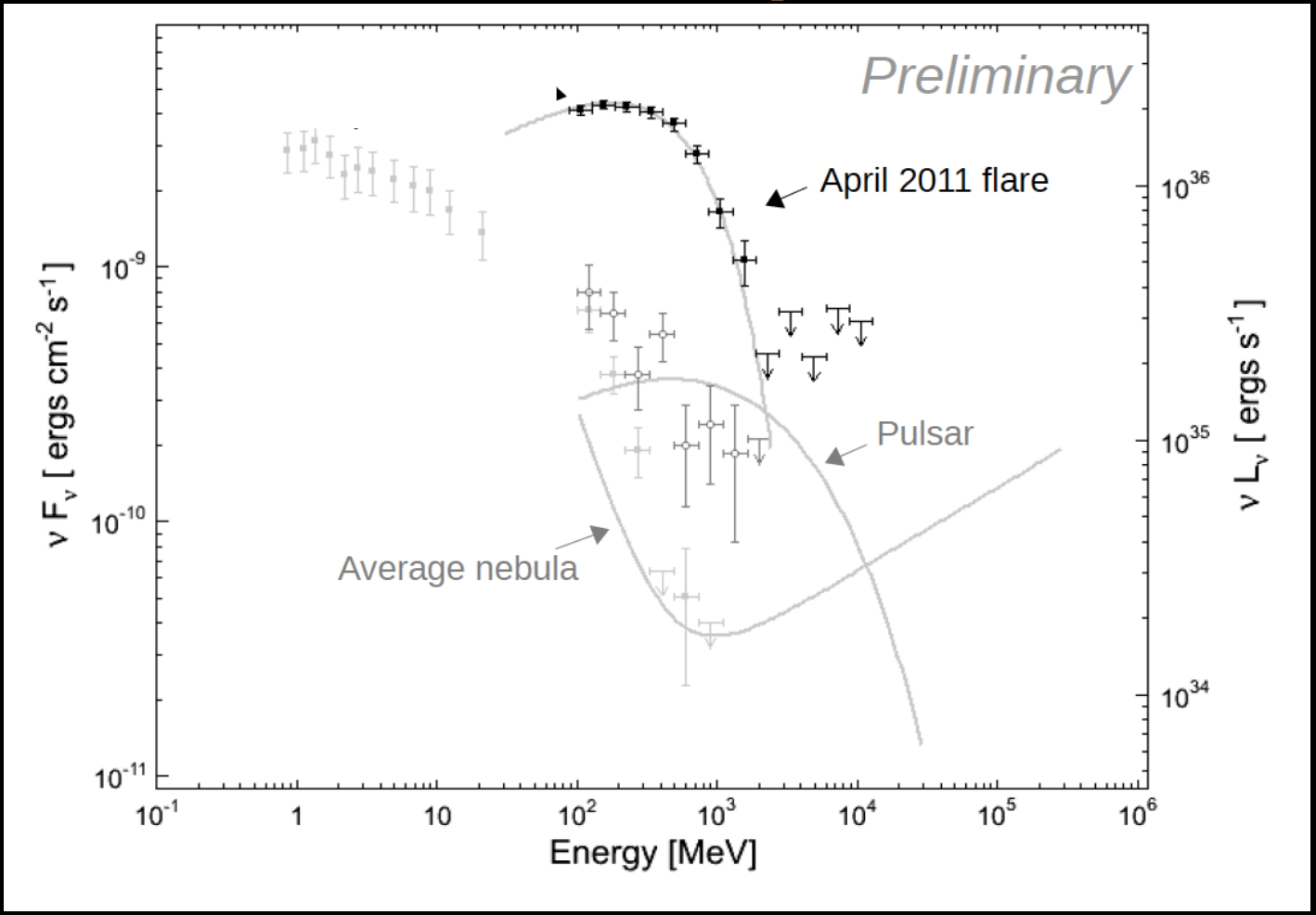
reported in Science, 331, 686 (2011)

latest Crab flare



Fast variability (~1h)

Crab flare spectrum



New spectral component of power law of index 1.6 and exponential cutoff at 580 MeV (Pulsar like, but no sign of pulsation in flare photons)

R. Buehler, Fermi Symposium 2011

Fermi GRB detections as of 2011-08-01

~682 GBM GRB (since Aug 2008)

32 LAT GRB (9 LAT LLE-only GRB)

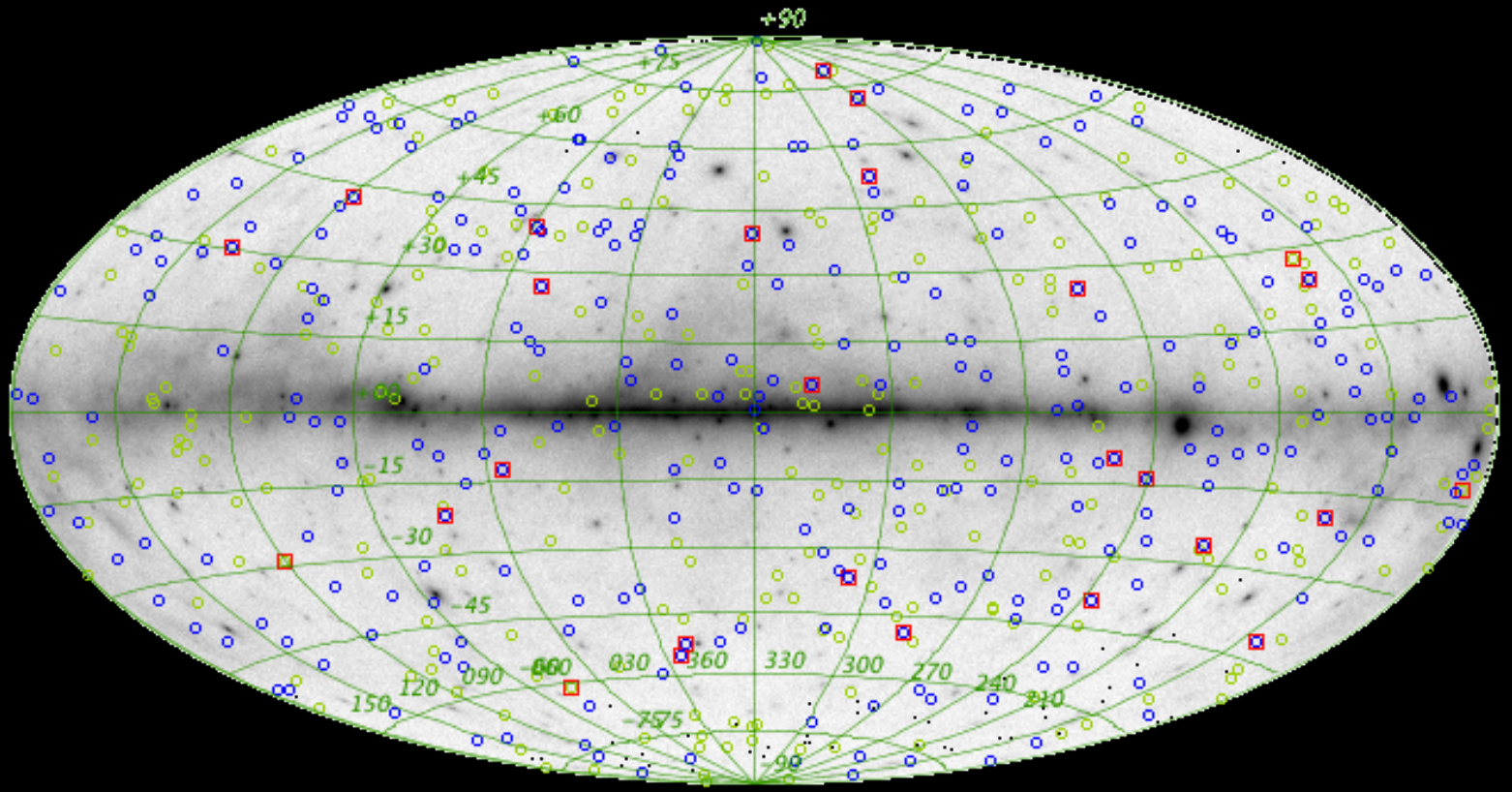
Circles:

In Field-of-view of LAT (<70˚): 345

Out of the FOV

Squares:

LAT detections



PRELIMINARY

LAT GRBs, a summary

the Brightest and Most Distant Sources Seen by Fermi

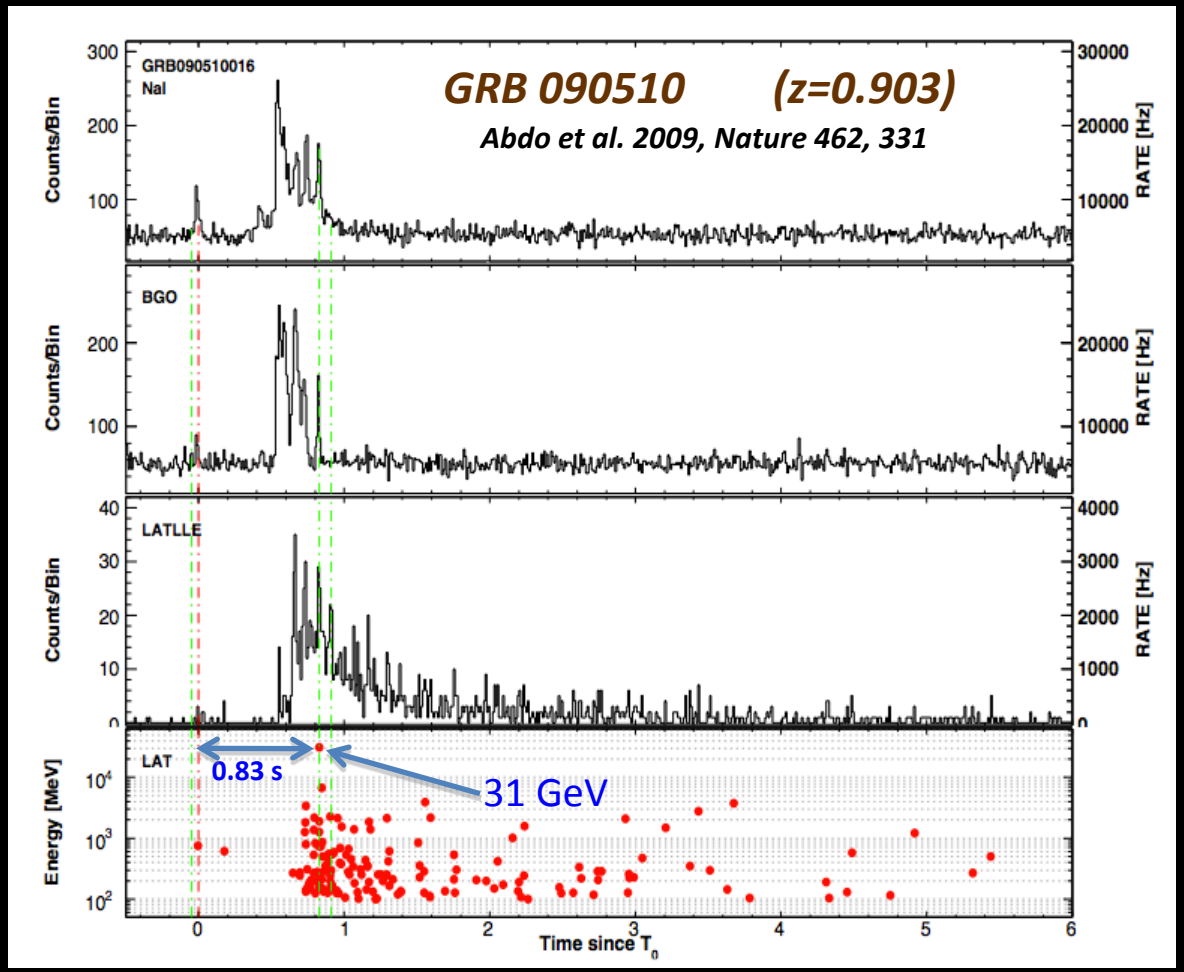
GRB Name	GBM T90	N Pred. Events (>100MeV, Trans.)	HE Delayed Onset?	Long Lived HE Emission?	Maximum Energy (GeV)	Arrival time of the highest events (seconds since trigger)	Redshift
GRB080825C	Long	10	√	√	0.6	28.3	-
GRB080916C	Long	188	√	√	13.2	16.5	4.35
GRB081006	Long	13	√	√	0.8	1.8	-
GRB081024B	Short	11	√	√	3.1	0.6	-
GRB081207	Long	LLE	-	-	-	-	-
GRB090217	Long	17	√	√	1.2	179.1	-
GRB090227B	Short	3	-	-	0.0	0.0	-
GRB090323	Long	30	√	√	7.5	195.4	3.57
GRB090328	Long	50	√	√	24.5	261.7	0.736
GRB090510	Short	186	√	√	31.3	0.8	0.903
GRB090531B	Short	LLE	-	-	1.6	115.2	-
GRB090626	Long	LLE	√	√	2.1	111.6	-
GRB090902B	Long	314	√	√	33.4	81.8	1.822
GRB090926	Long	249	√	√	19.6	24.8	2.106
GRB091003	Long	3231	√	√	2.8	6.5	0.897
GRB091031	Long	15	√	√	1.2	79.8	-
GRB100116A	Long	14	-	√	13.1	296.4	-
GRB100225A	Long	LLE	-	-	-	-	-
GRB100325A	Long	6	-	√	1.9	71.4	-
GRB100414A	Long	27	√	√	4.7	288.3	1.368
GRB100724B	Long	22	-	-	0.2	61.8	-
GRB100728A	Long	4	-	-	0.1	81.2	-
GRB100728A	Long	LLE	-	-	0.1	81.2	-
GRB101014A	Long	LLE	-	-	-	-	-
GRB101123A	Long	LLE	-	-	-	-	-
GRB110120A	Long	5	-	-	1.8	72.5	-
GRB110328B	Long	LLE	-	-	1.6	514.7	-
GRB110428A	Long	17	√	√	2.6	14.8	-
GRB110529A	Short	LLE	-	-	-	-	-
GRB110625A	Long	12	-	√	2.4	272.4	-
GRB110721A	Long	29	-	√	1.7	0.7	0.38
GRB110731A	Long	65	√	√	3.4	436.0	2.83

PRELIMINARY

- ~30 GRB have been seen by LAT above 100 MeV;
- **Both long (>2 sec) and short (<2 sec) bursts have been seen;**
- Some bursts are only visible in LAT Low Energy events;
- **Most of the bursts show high-energy emission afterglow and delayed high-energy onset;**
- Constraint: lower limit of bulk Lorentz factor of the colliding shells: ~1000;
- **Some bursts have an extra spectral component (a different mechanism at high energy?);**

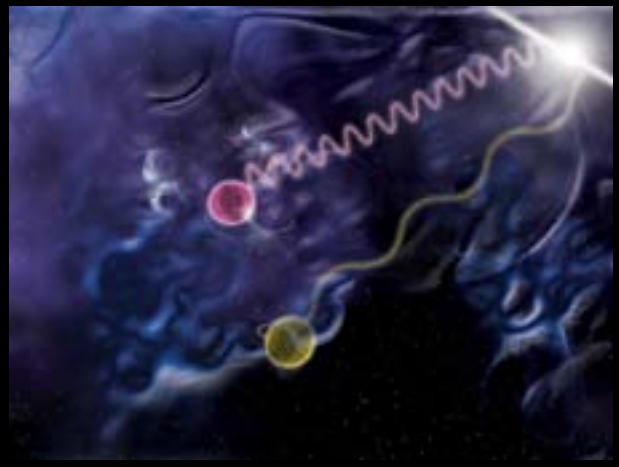
- These short, distant and bright flashes can be used as tools to <u>probe basic physics…</u>

limits on Lorentz invariance violation



Constraints on the quantum gravity mass scale (M_{QG}) by direct measurement of photon arrival times, testing energy dependent dispersion of the speed of light.

For linear dispersion:
$M_{QG,1}/M_{Planck} > 1.19$



Extragalactic Background Light

$\tau\alpha\upsilon_{\gamma\gamma} = 1$

Extrinsic gamma-gamma absorption by UV background light

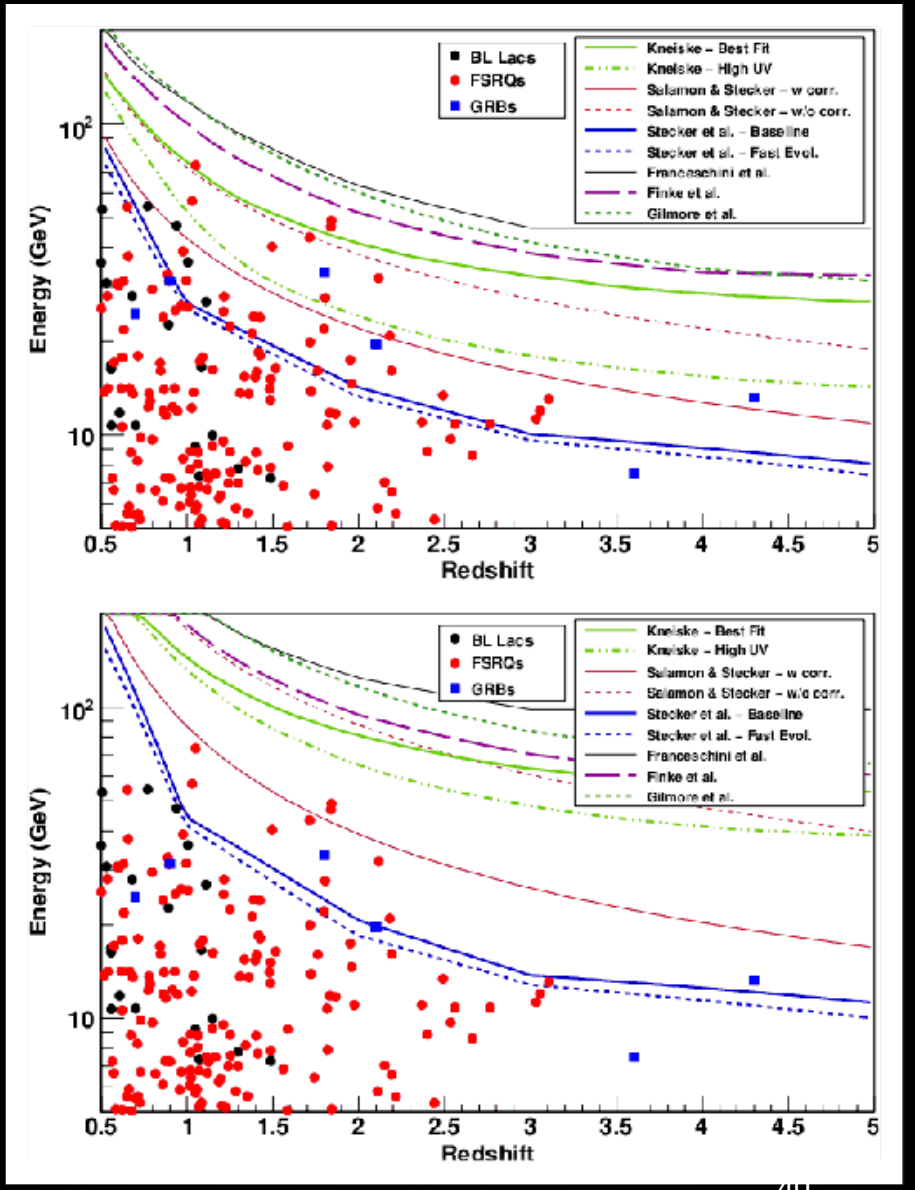
Combined study of AGN and GRB of known redshift

Highest photon energies consistent w/ sources

$\tau\alpha\upsilon_{\gamma\gamma} = 3$

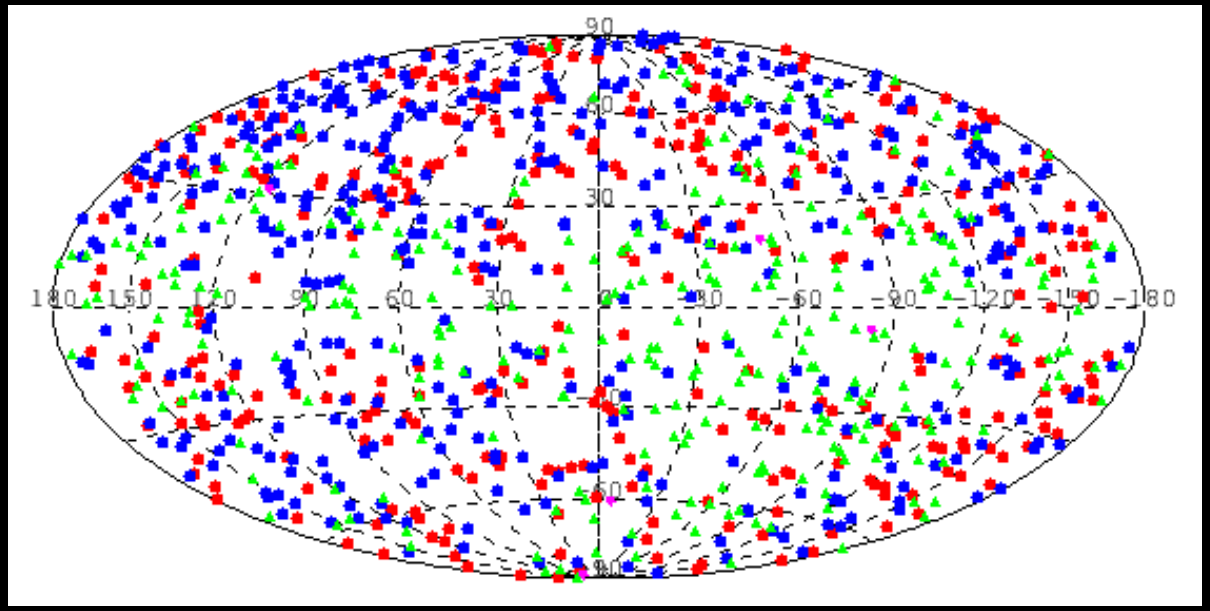
« baseline » model from Stecker et al. ruled out at ~3.6σ, using only GRBs

Abdo, A. A. et al. 2010, ApJ, 723, 1082

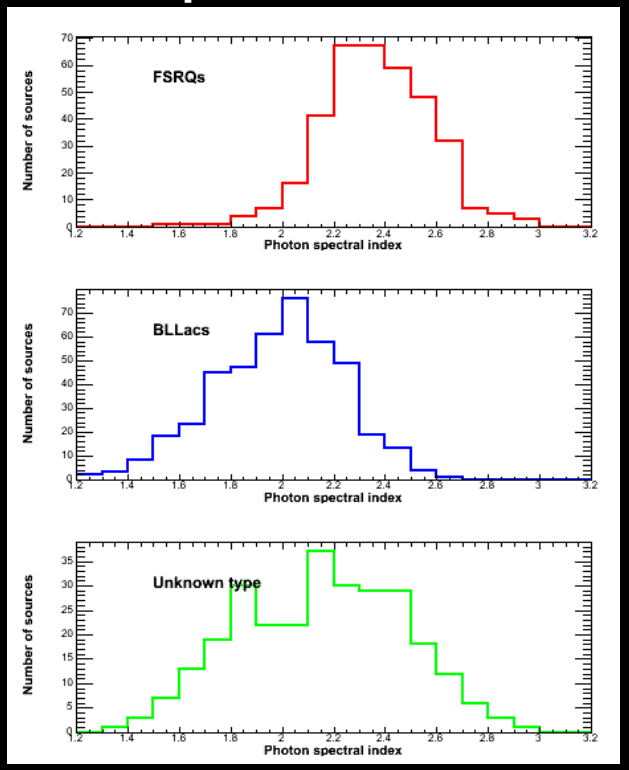


2LAC: 2nd LAT AGN Catalog

1,016 sources



Spectral Index



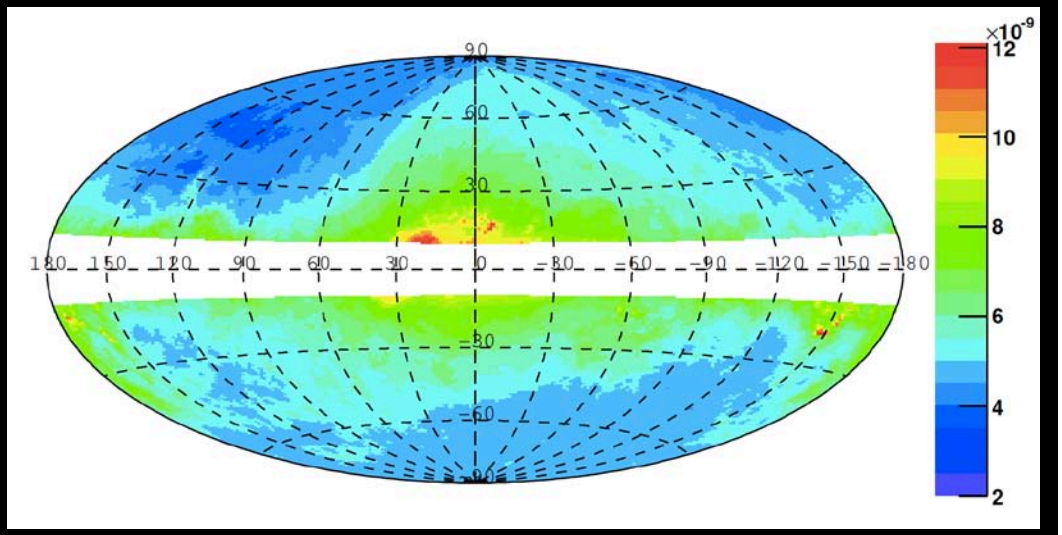
FSRQs:360
BL Lacs:423
Other AGN (including radio and starburst): 30
Unknown: 203

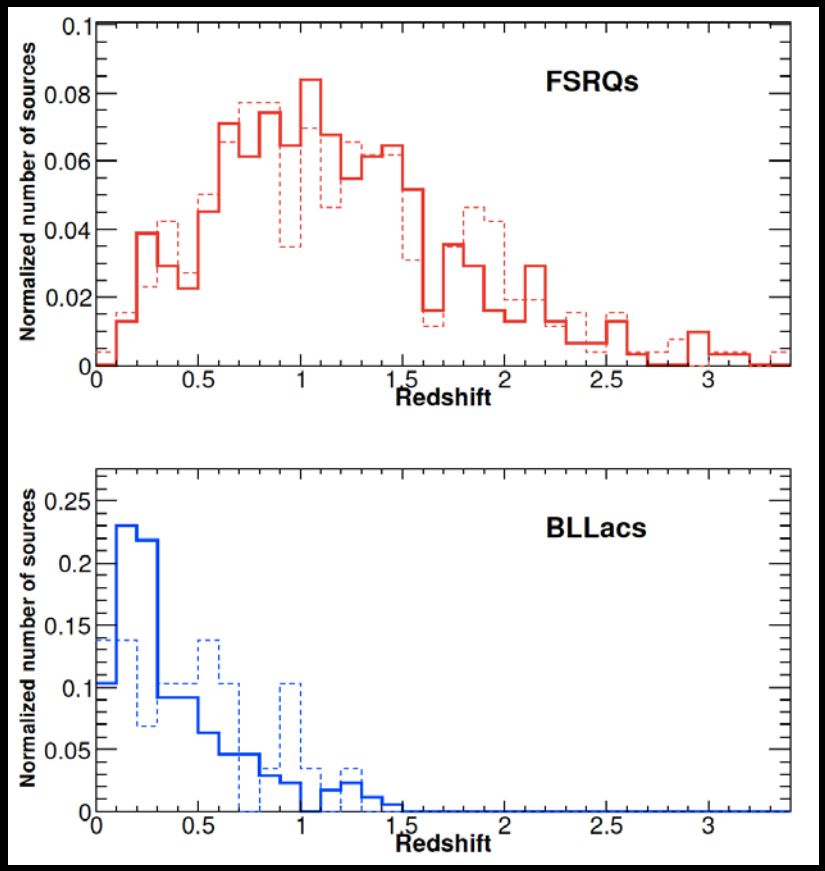
Look for spatial association between 2FGL sources and known AGN

Less sensitivity near galactic plane (foreground confusion & survey bias)

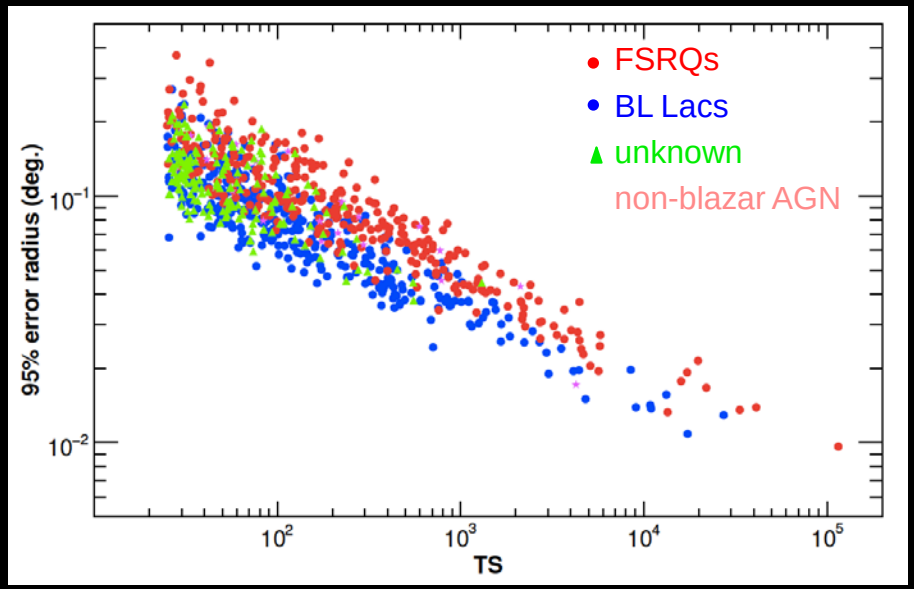
2LAC: 2nd LAT AGN Catalog

2LAC is significance (not flux) limited:



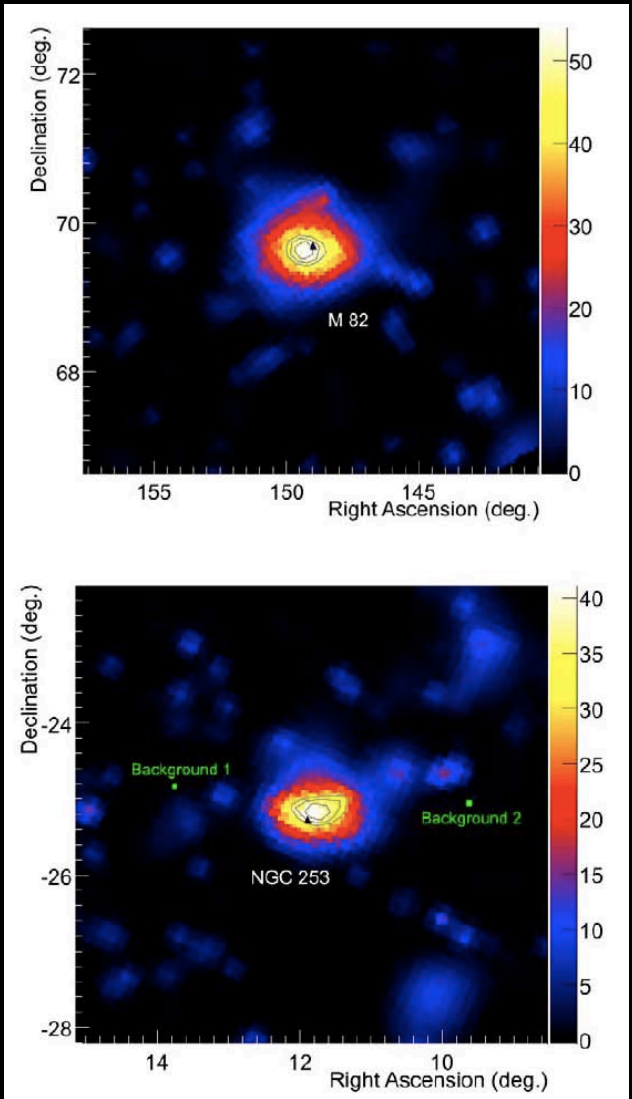


redshift distribution



95% containment radius

Starburst galaxies



"Detection of Gamma-Ray Emission from the Starburst Galaxies M82 and NGC 253 with the Large Area Telescope on Fermi" *Ap. J.* **710** 133 (2010)

First GeV (and TeV) detections of starburst galaxies

New laboratories for studying cosmic-rays on galactic scales; from the outside looking in