フェルミ衛星による
最近の成果と
MeVガンマ線観測への期待

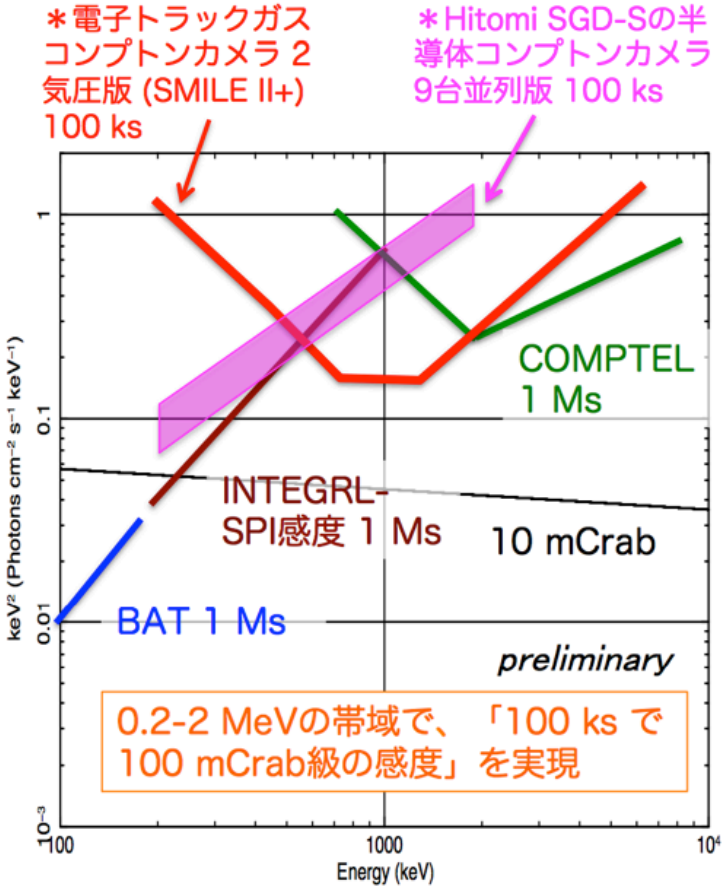
田中康之 (広島大学宇宙科学センター)

2 :現状技術で実現可能な感度@100 ks (2020-25年頃)

2-1 計算した感度
- 有効積分時間は100 ksとする。
- 感度は統計3σ。連続成分に対し、dE/E = 0.5 で計算。精度は factor 2程度。

2-2 結果
- 100 ks 気球で、現状の衛星(INTEGRAL-SPIなど)の ~1 Ms 感度が実現。
- 検出器の改良で、2倍、10倍を目指す。

この5-10年は「工夫」の時代
- 視野の大小でBGDの大小→感度の小大。
- 見る天体で観測効率が。天の北極や南極付近なら観測効率が25% → 100 %になるかも。あるいは４つの天体を、赤経方向に90degずつ離してリストできる？
- 狙うエネルギー帯域を絞ることも有効。



- 感度ギャップの0.1-100 MeVの中で、高エネルギー側での帯域を考えると、フェルミで明るいsteady sourceがターゲットになるだろう
- 今回は、フェルミで検出している天体のなかから、明るいGeVガンマ線ソースを抽出した (定常、トランジェント天体の両方を含む)

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- 系外 GeV bright sources
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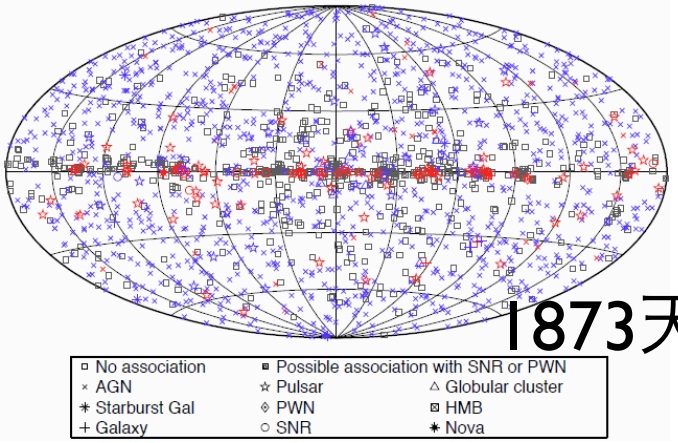
  - ✓ 3C 273 (almost steady, hard X-ray brightest)
- 太陽フレア、Terrestrial Gamma-ray Flash (TGF)
- Summary

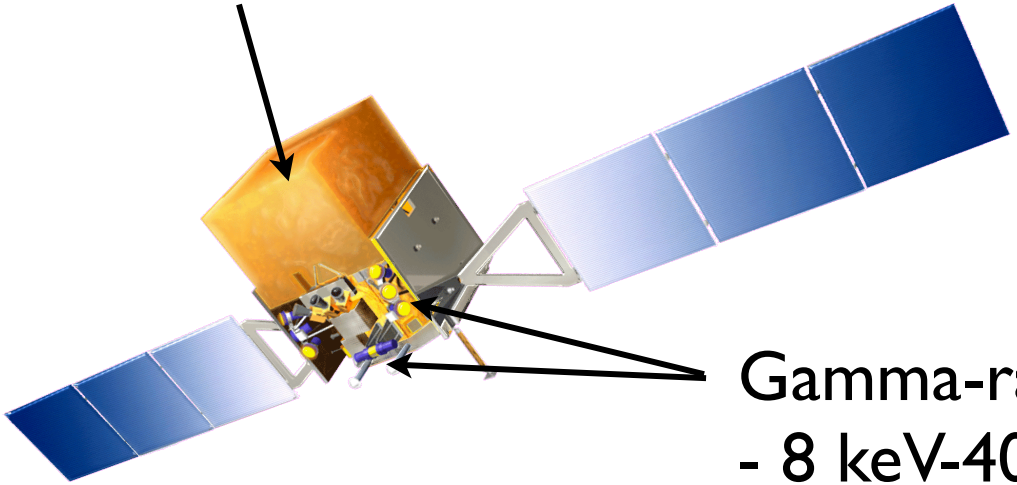
フェルミガンマ線宇宙望遠鏡

- 2008年6月11日打ち上げ
- 現在も順調に観測を継続中 (全天サーベイモード)



1873天体

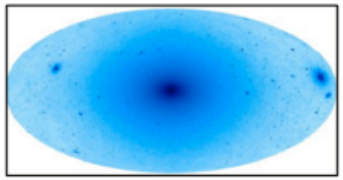
Large Area Telescope (LAT)
- 20 MeV-300 GeV
- 2.4 strの広い視野を生かして、3時間毎に全天をスキャン

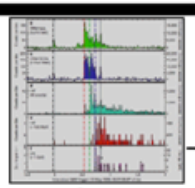


Gamma-ray Burst Monitor (GBM)
- 8 keV-40 MeV
- 全天を監視

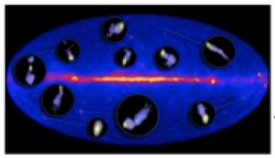
Fermi Science Menu

Dark Matter searches

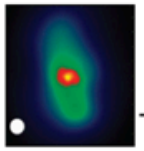




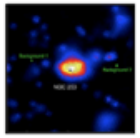
GRBs



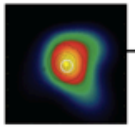
Blazars



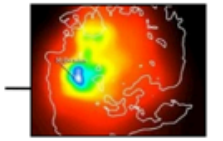
Radio Galaxies



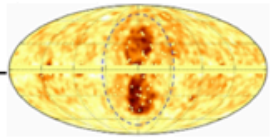
Starburst Galaxies



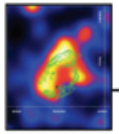
Globular Clusters



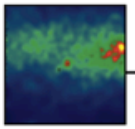
LMC & SMC



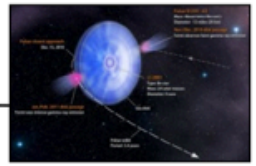
Fermi Bubbles



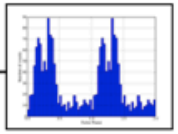
SNRs & PWN



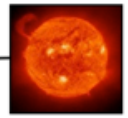
Novae



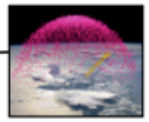
γ-ray Binaries



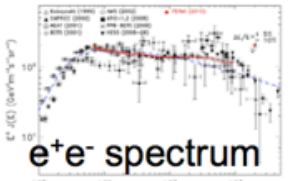
Pulsars: isolated, binaries, & MSPs



Sun: flares & CR interactions



Terrestrial γ-ray Flashes



e^+e^- spectrum

Unidentified Sources

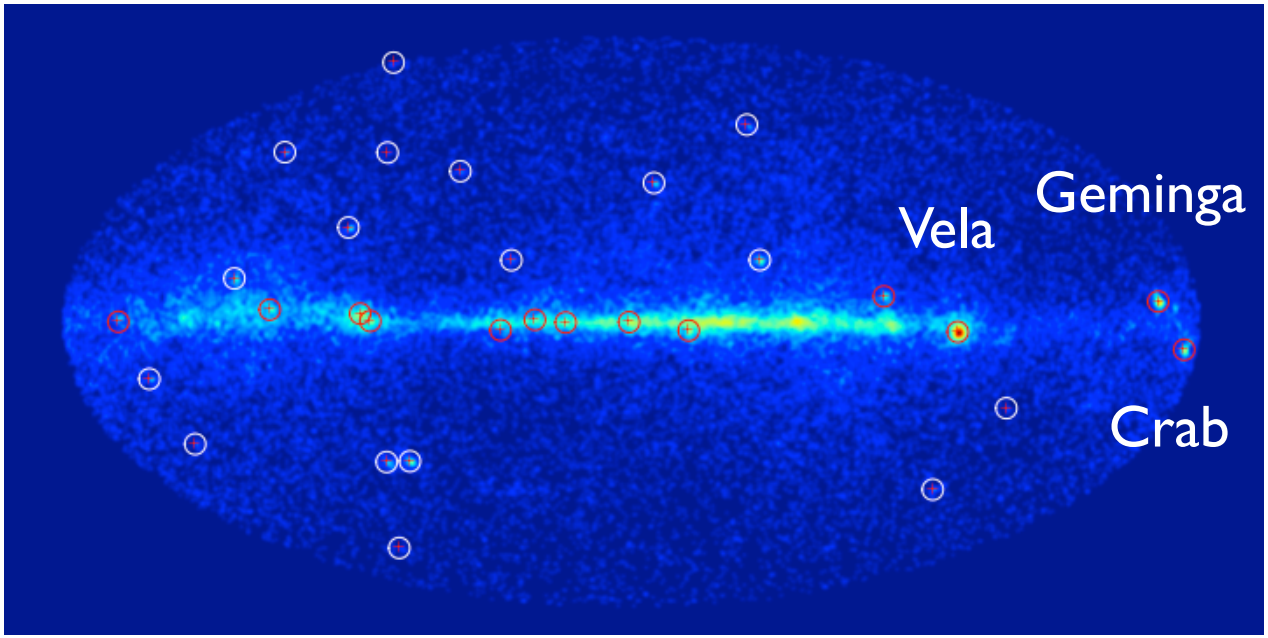
Galactic

Extragalactic

Bright Fermi sources

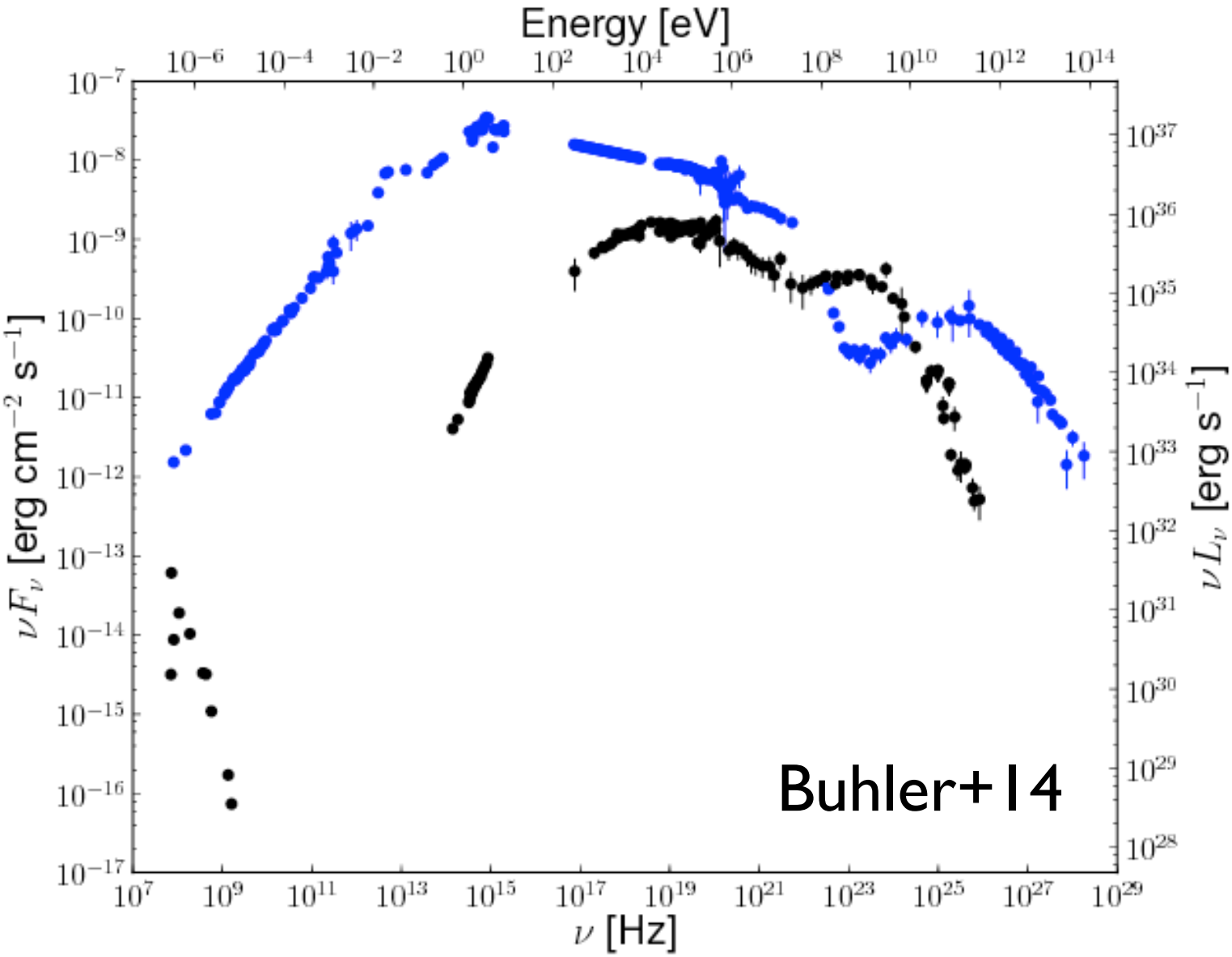
- 1日積分で検出されるソース。典型的には1.0×10^{-6} photons/cm2/s (E>100 MeV)以上のフラックス

- Galactic sources
  - ✓ Vela, Geminga, Crab pulsars
  - ✓ Gamma-ray binary (Cyg X-3, PSR 1259-63, LS 61-303,,,
  - ✓ Supernova Remnants
- Extragalactic sources
  - ✓ Blazars
  - ✓ GRBs
- Solar flares



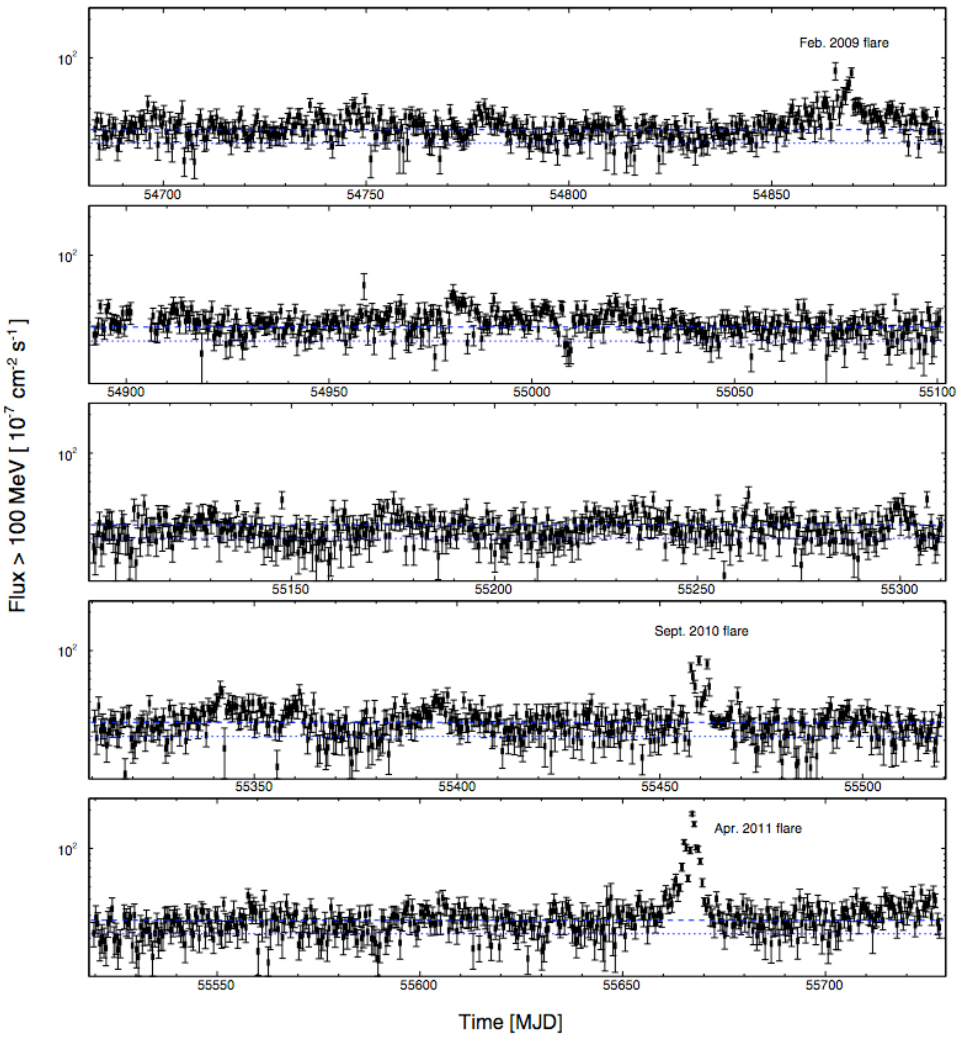
系外天体はすべてブレーザー

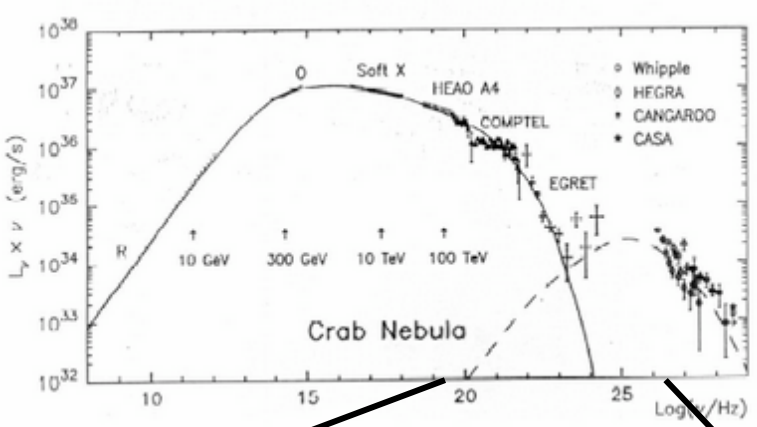
SEDs of Crab nebula and pulsar

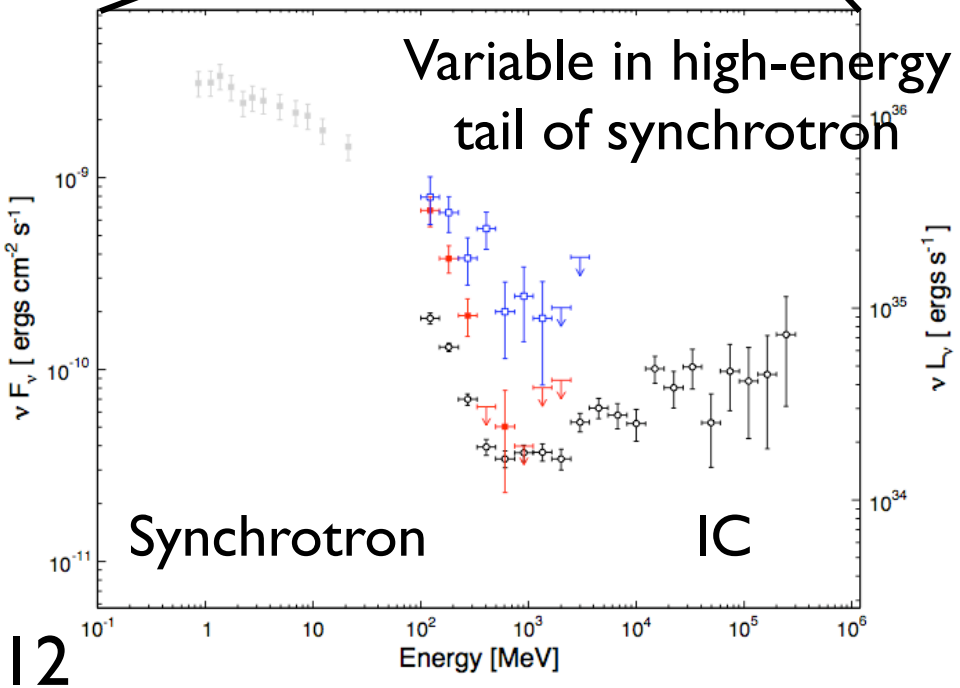


Crab nebula flare

LAT light curve (E>100 MeV)

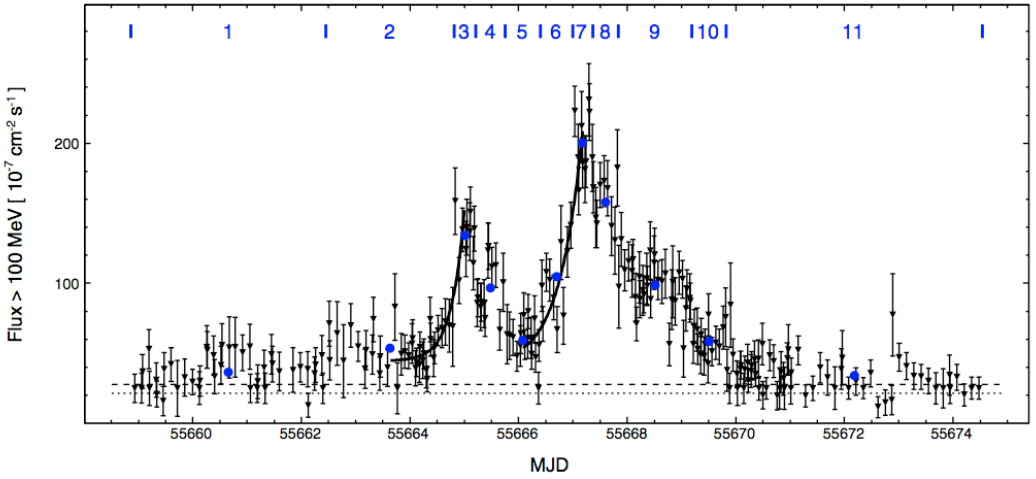


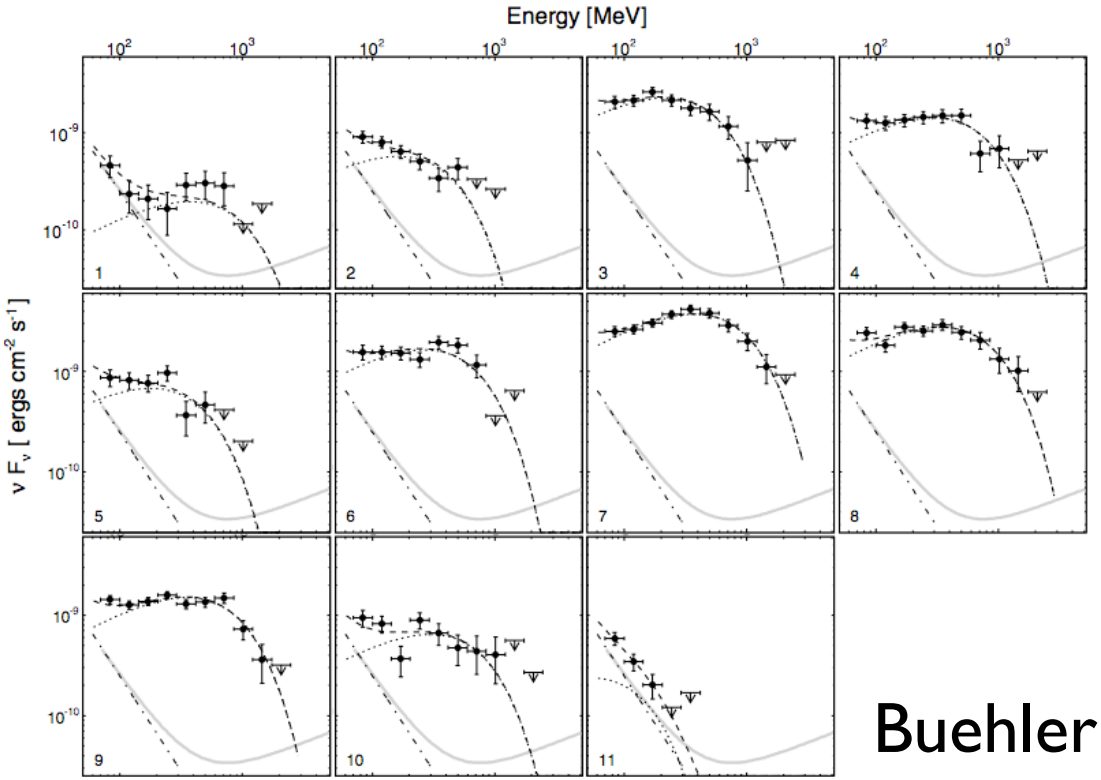




Abdo+11, Buehler+12

Giant flare in 2011 April





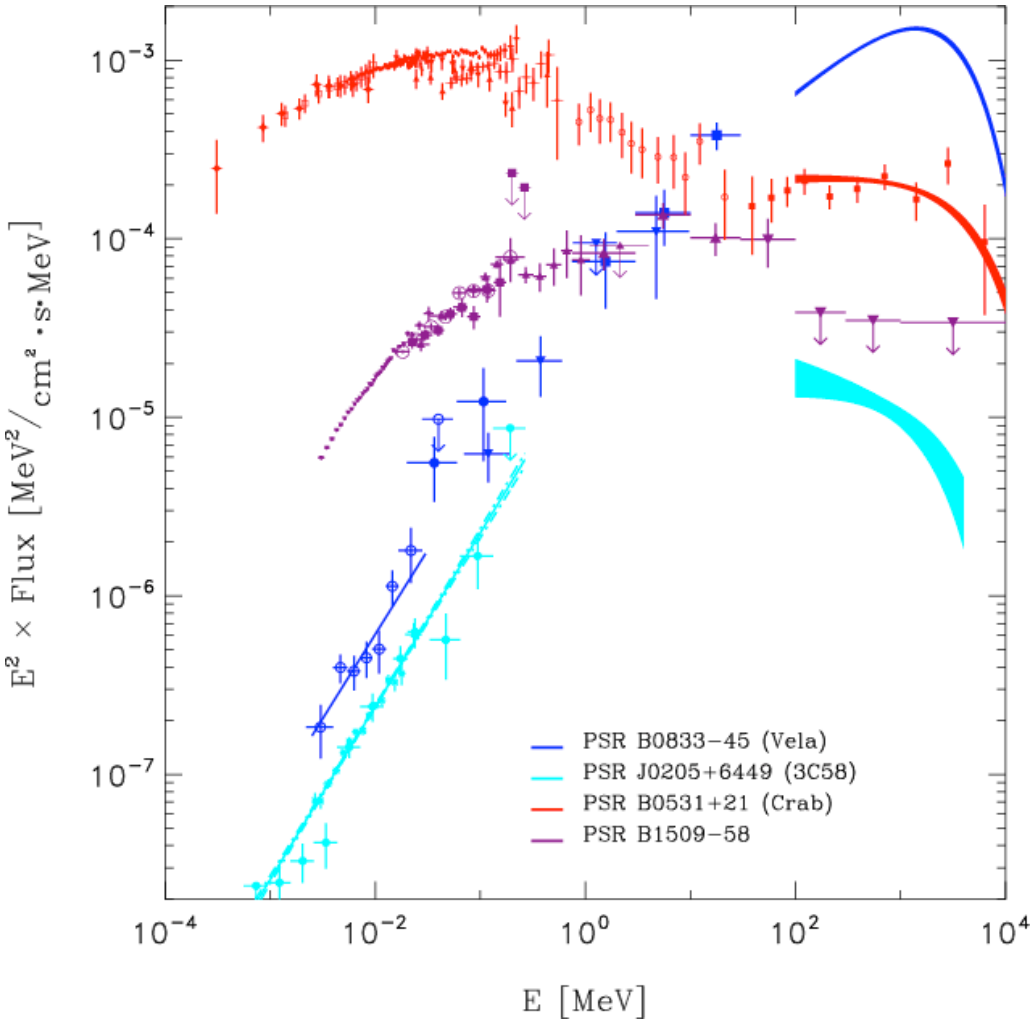
Doubling timescale of ~8 hour (Compact emission region of $L<ct_d \sim 2.8 \times 10^{-4}$ pc)

Isotropic peak luminosity is 4×10^{36} erg/s (~1% of total spin-down power)

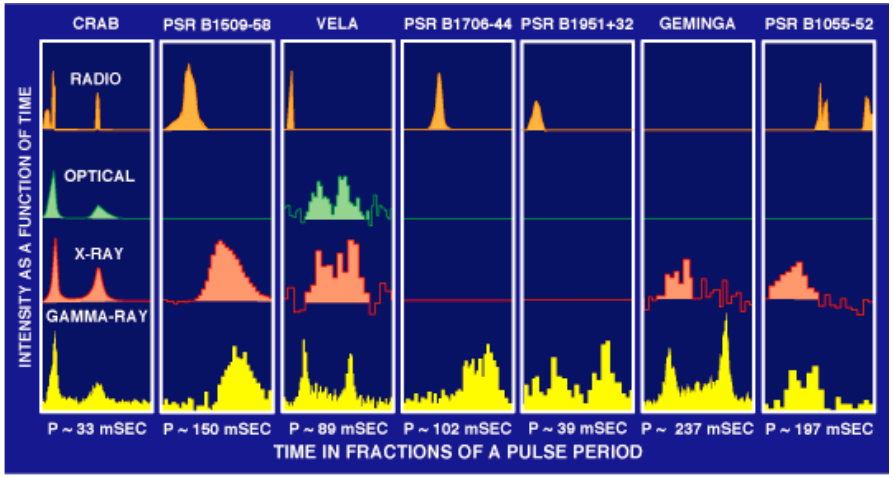
Cutoff Energy is above 400 MeV (this is above theoretical upper limit of cutoff energy of ~200 MeV)

Buehler+12, 田中孝+12(物理学会誌)

Vela pulsar (P=89.3 ms)



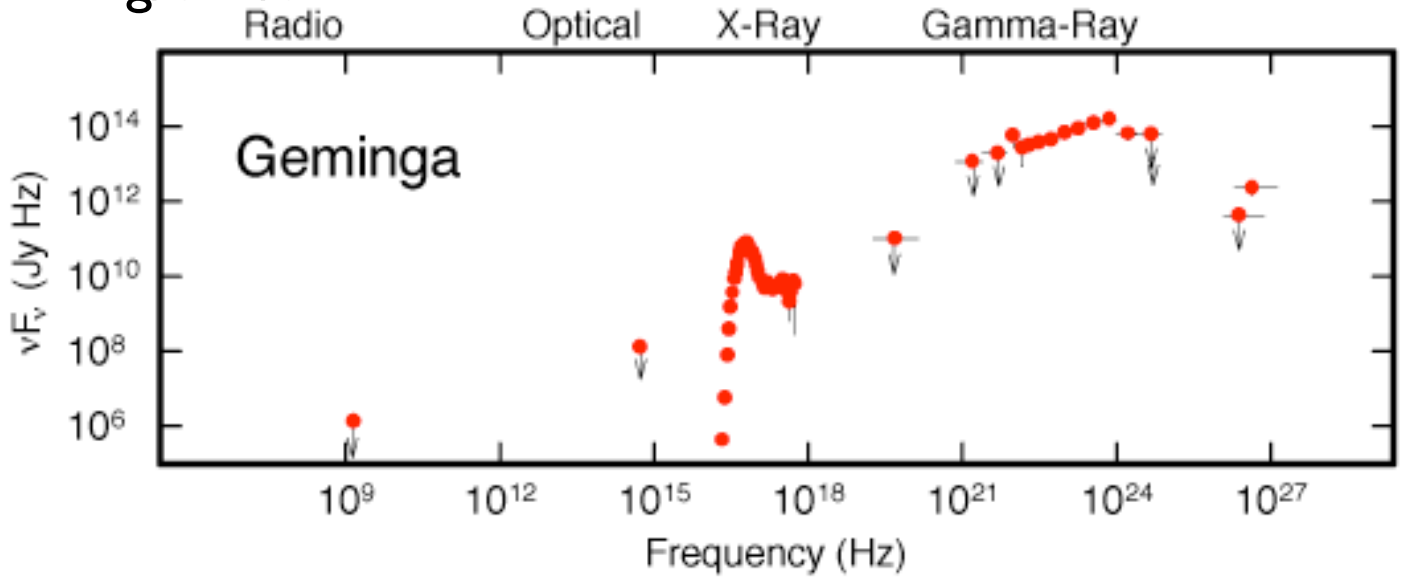
- GeV帯域で最も明るいパルサー
- MeV帯域ではCrabの1/3程度のフラックス
- MeVではまずPulse profileの測定と多波長との比較など



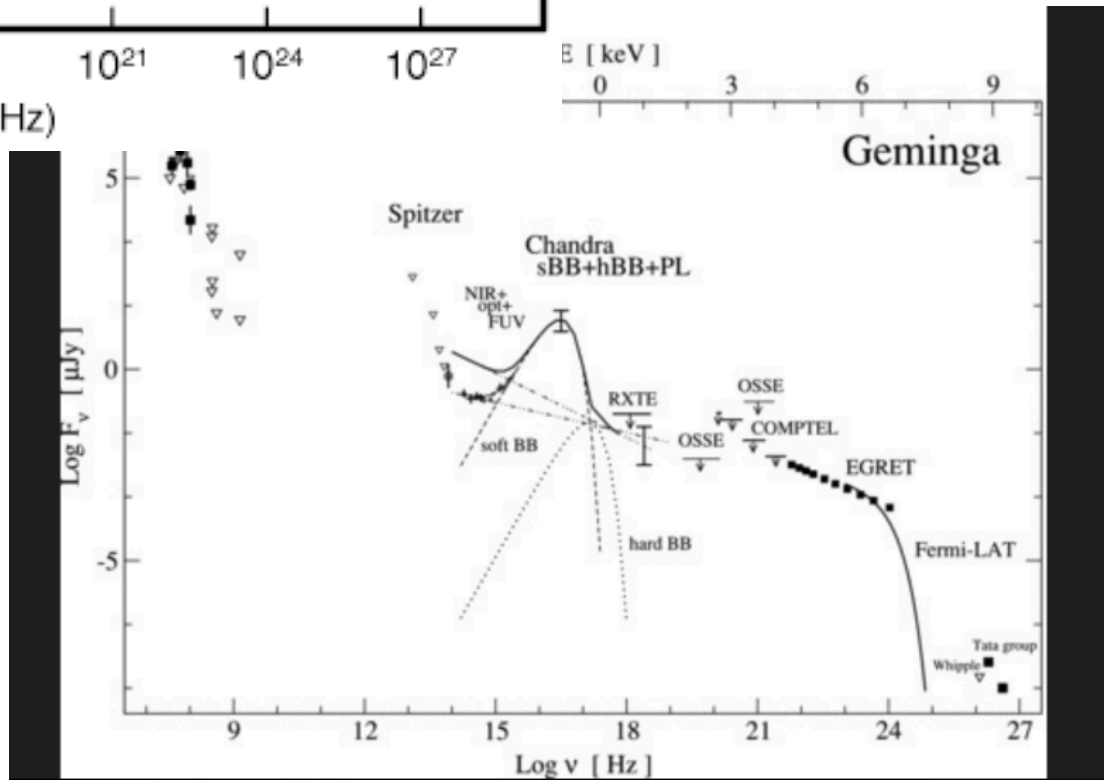
Heasarc webpage

Geminga (P=237.1 ms)

10^{-23} erg/cm^2/s

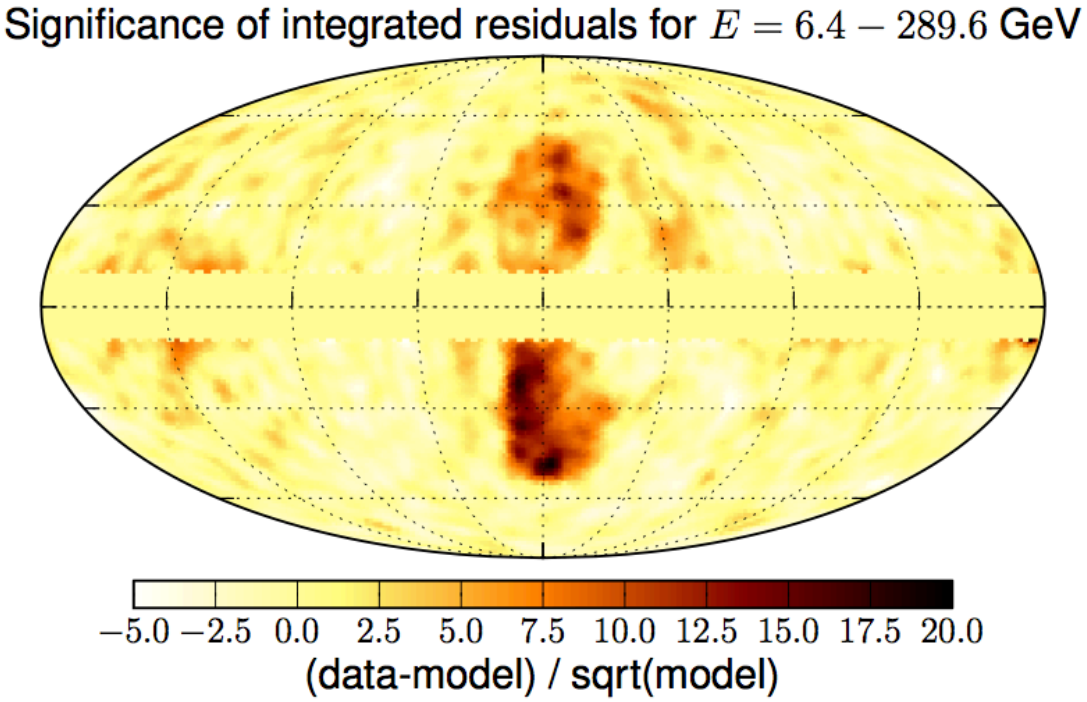


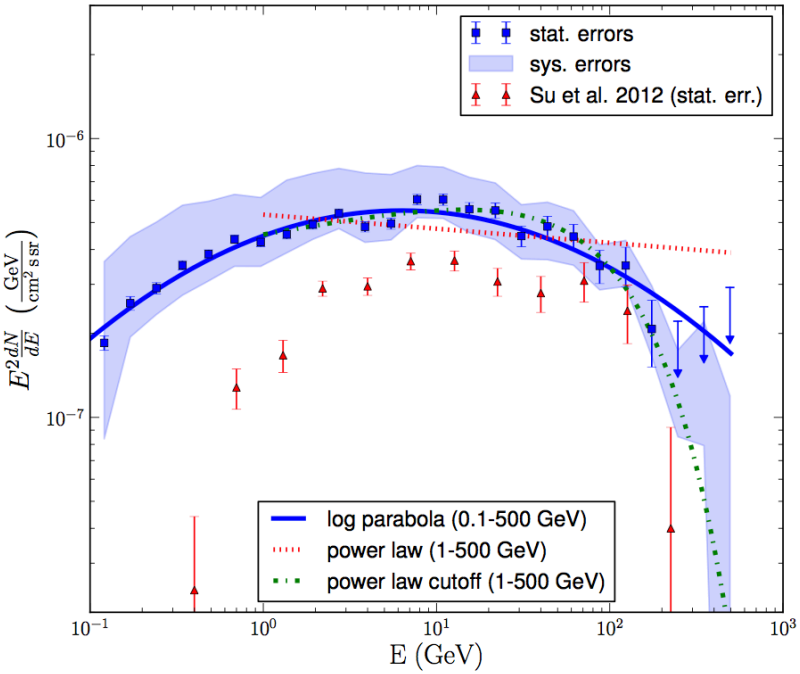
Danilenko+11

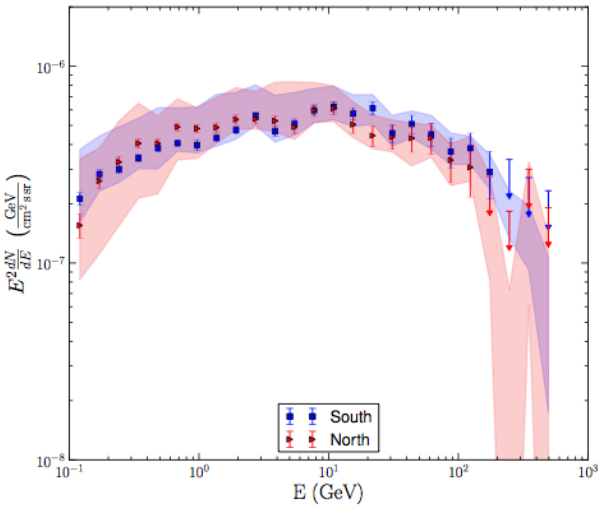


- COMPTEL and OSSE UL
- MeV帯域では~10^{-11} erg/cm2/sと暗い

Fermi bubble





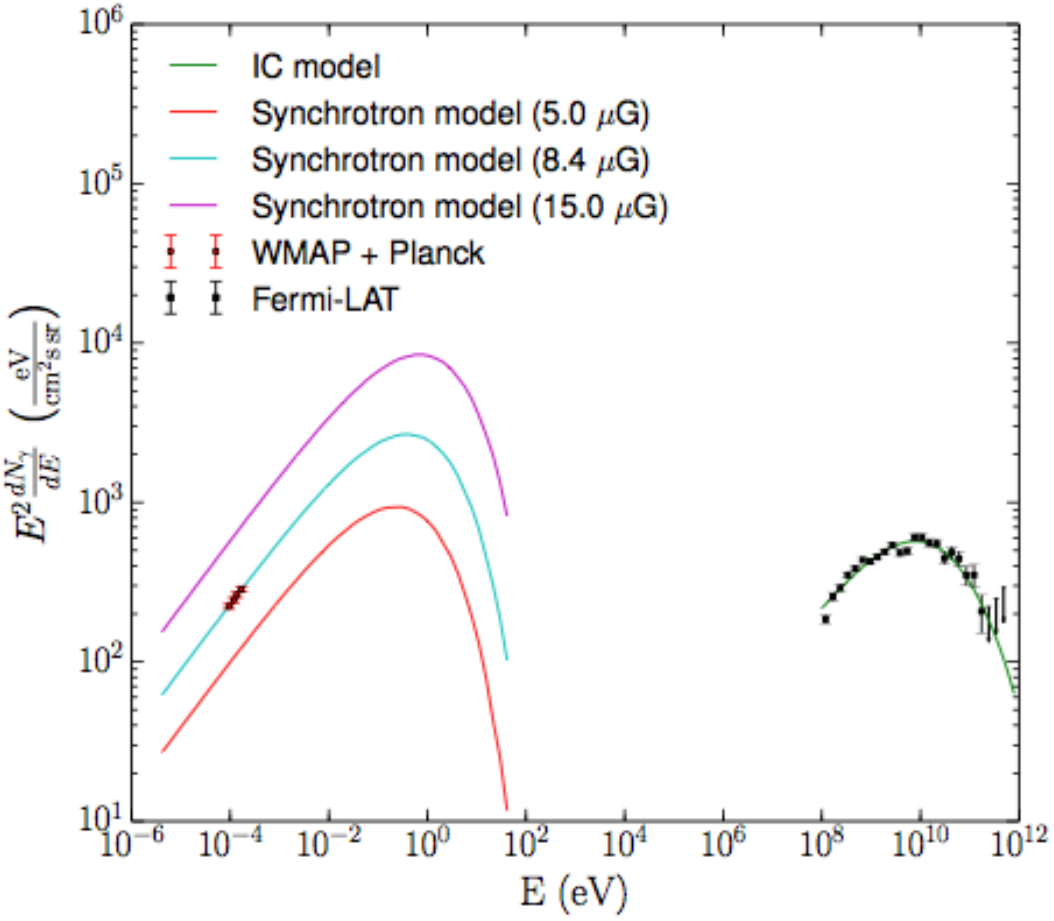


Ackermann+14

Cutoff PL with index=1.87
Ecut=113±20±50 GeV

- 南北のローブはほぼ同じスペクトルを示す

SED modeling



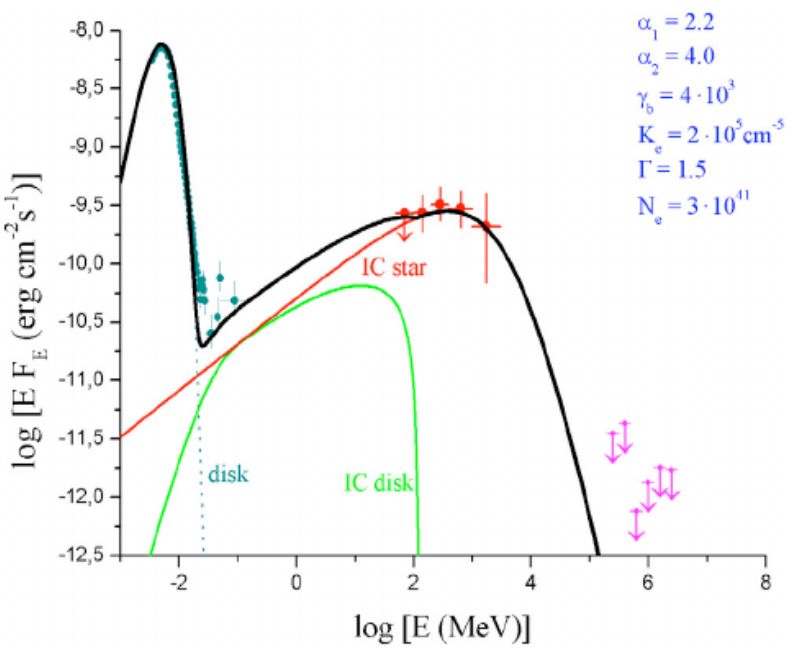
Ackermann+14

- WMAP haze+Fermiのデータについて Syn+SSCモデリング
- 磁場は8 uG
- Hadronicでは合わないらしい
- MeVではそれほど明るくないだろう

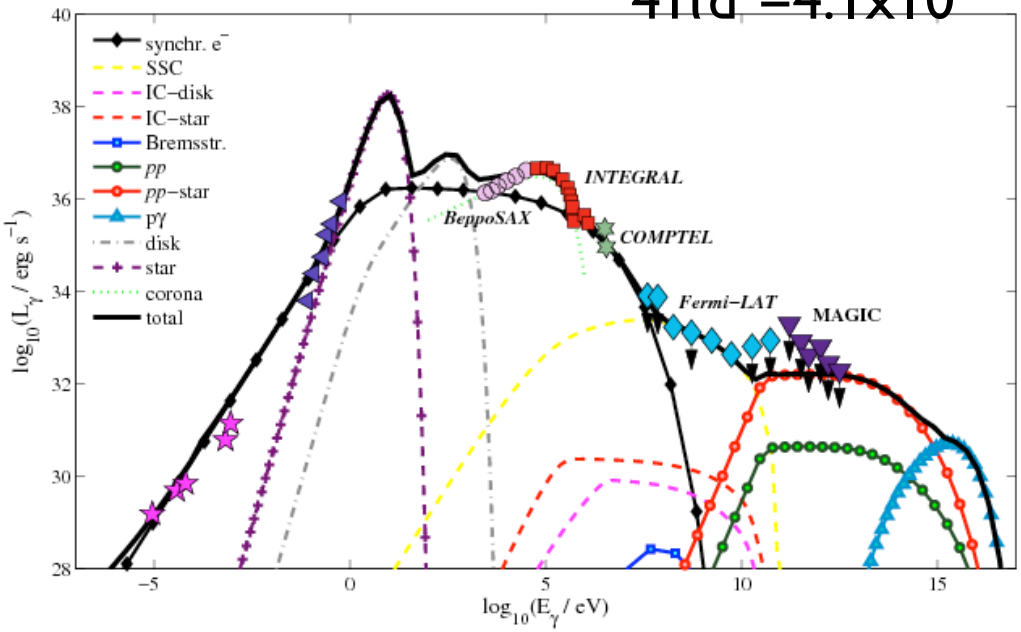
Cyg X-3 and X-1 in LAT band

d=1.9 kpc

$4\pi d^2=4.1\times10^{44}$



2E-11



- Cyg X-3: Bright (1-day exposure で検出) but rate events (1 per year)
- Cyg X-1: Faint but steady (low hard stateなら)
- 偏光測定による放射機構の決定 (SSCだとdisk/coronaよりも高い偏光度)
- ジェット成分の検出はSEDモデリングによる物理量の推定やジェットパワーの見積もりに必須
- 1 MeVでは同じぐらいのフラックス: ~10^{-10} erg/cm^2/s

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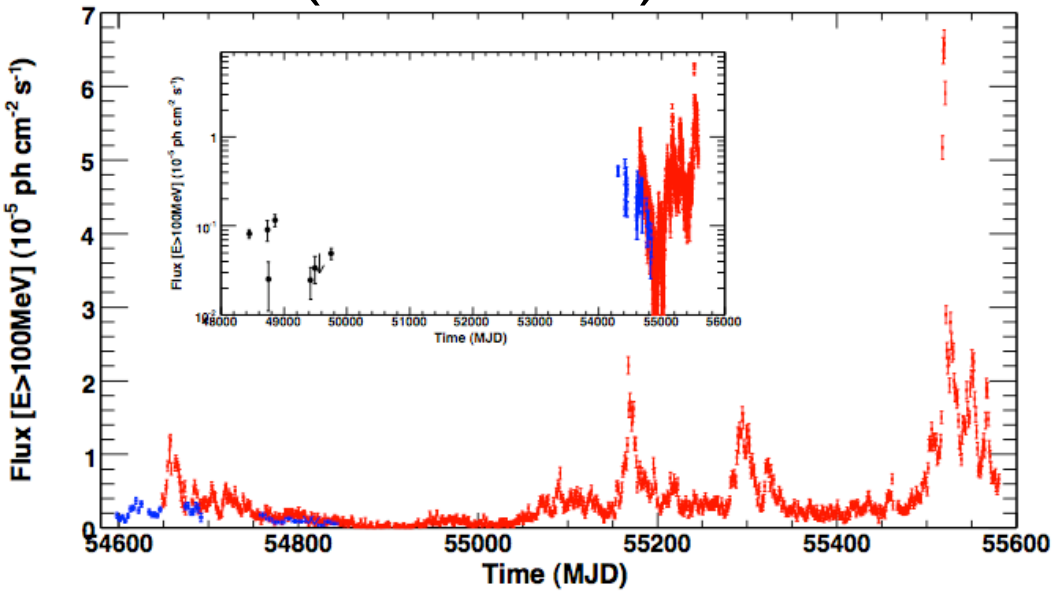
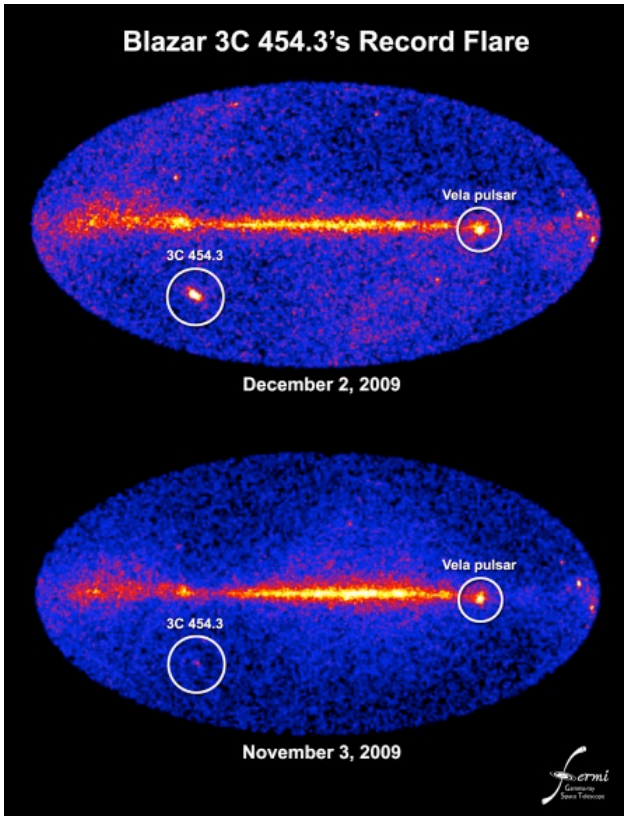
Blazar flare

3C 454.3 (Abdo+11)





- 毎日のようにフレアが検出されている (FSRQ, BL lac, NLSy1)
- ここ最近は、(i) フレアが初めて検出された天体、 (ii) フレアが既に検出されている天体については、フラックスが極めて高いなど特異なフレアの場合、にのみAtelが出される
- LAT monitored source list light curve, Fermi sky blogも参照下さい

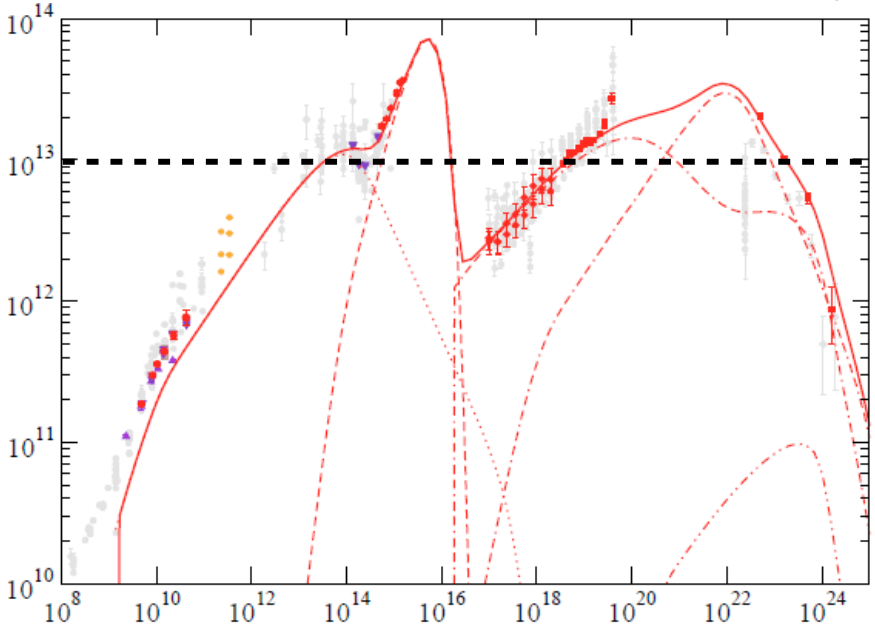
3C 273 and 3C 454.3

3C 273 (almost steady)

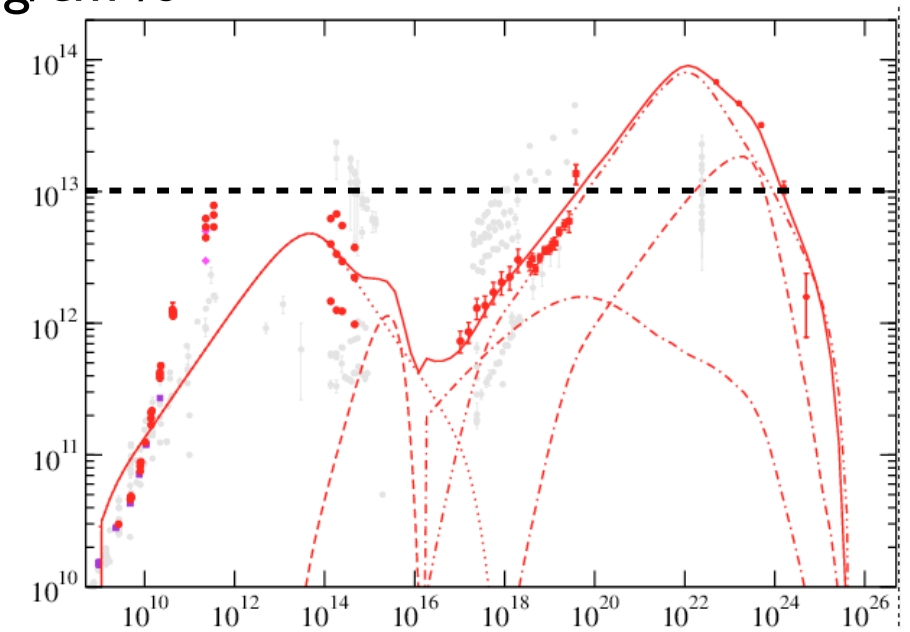
Jy Hz

10^{-23} erg/cm^2/s

3C 454.3 (highly variable)



Hz



Hz

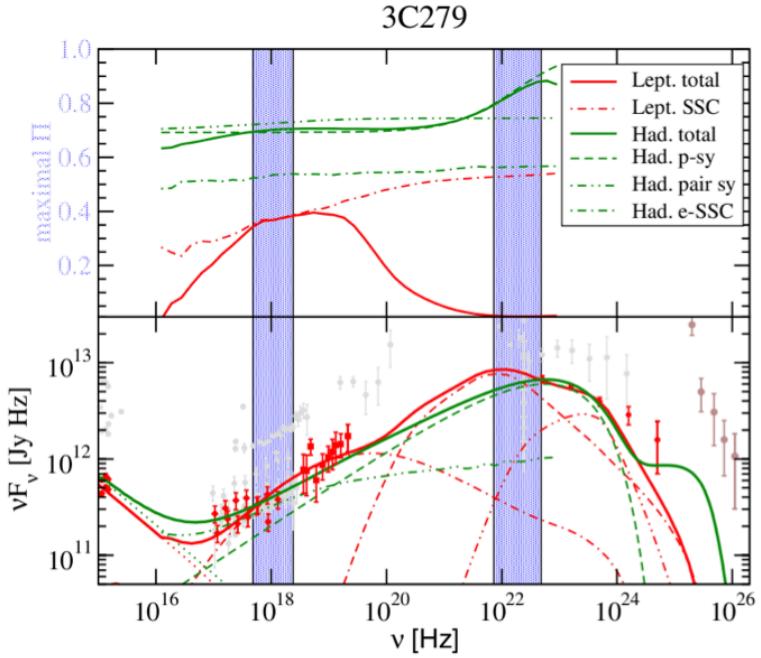
- 3C 273はほぼ定常で、hard X~gammaで最も明るい
- 3C 454.3などのflaring FSRQもおそらくdetectableなぐらい明るくなりそう

http://homepage.uibk.ac.at/~c705282/FSRQ_modeling.html by Aneta Reimer

どんなサイエンスが明らかになるか

- MeV帯域でのフラックス測定によるSEDモデリングの精密化
  - ✓ hard X-GeVガンマ線は滑らかにつながりそうなので、これまでの結果とそれほど変わらないだろう
- 偏光測定による放射機構の決定
  - ✓ ECなら偏光度小さく、SSCなら偏光度大きい (Zhang+13)

偏光度



SSCなら最大40-50%

ECなら最大でも数%

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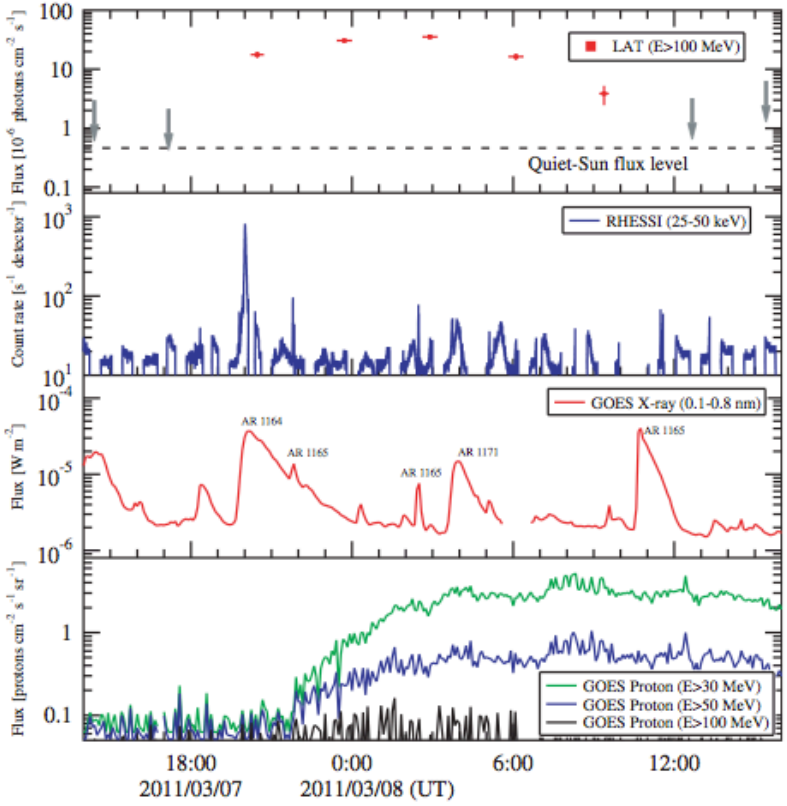
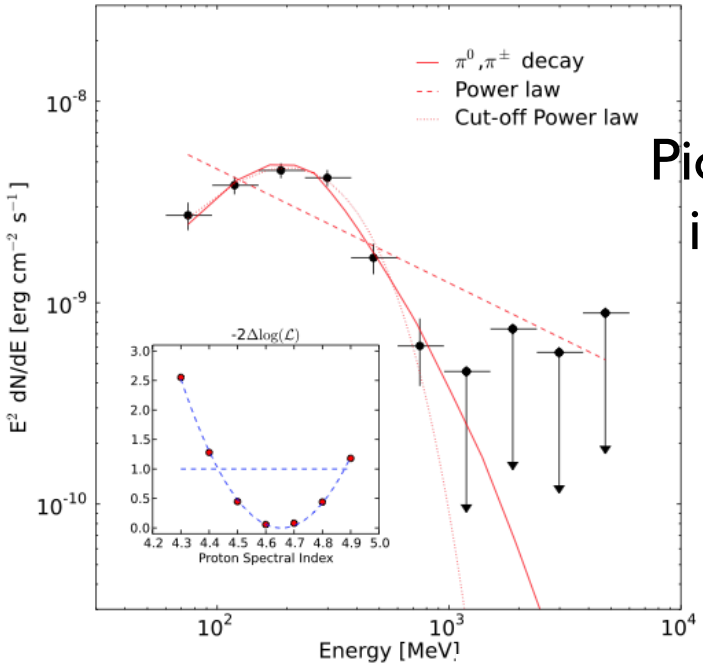
太陽フレアからの長時間ガンマ線放射

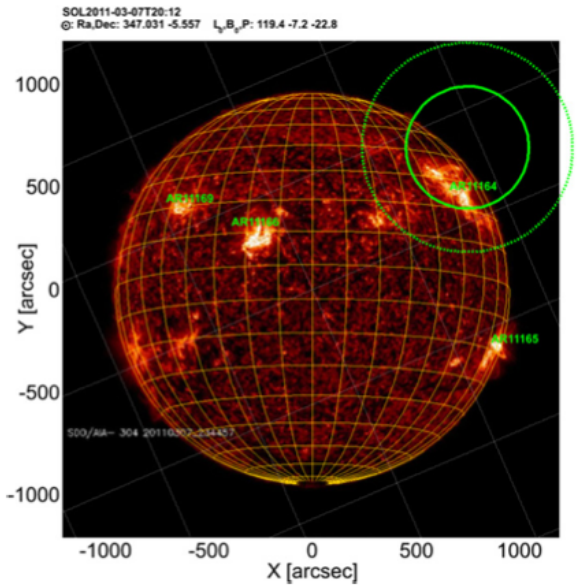
M3.7 flare on 2011 March 7





Pion-decay bump
is clearly seen

ガンマ線は付随する活動
領域から放射
→活動領域の乱流加速？



Ackermann+14

LAT event list

Table 1
Solar Flares Detected by the *Fermi* LAT from 2008 August to 2012 August

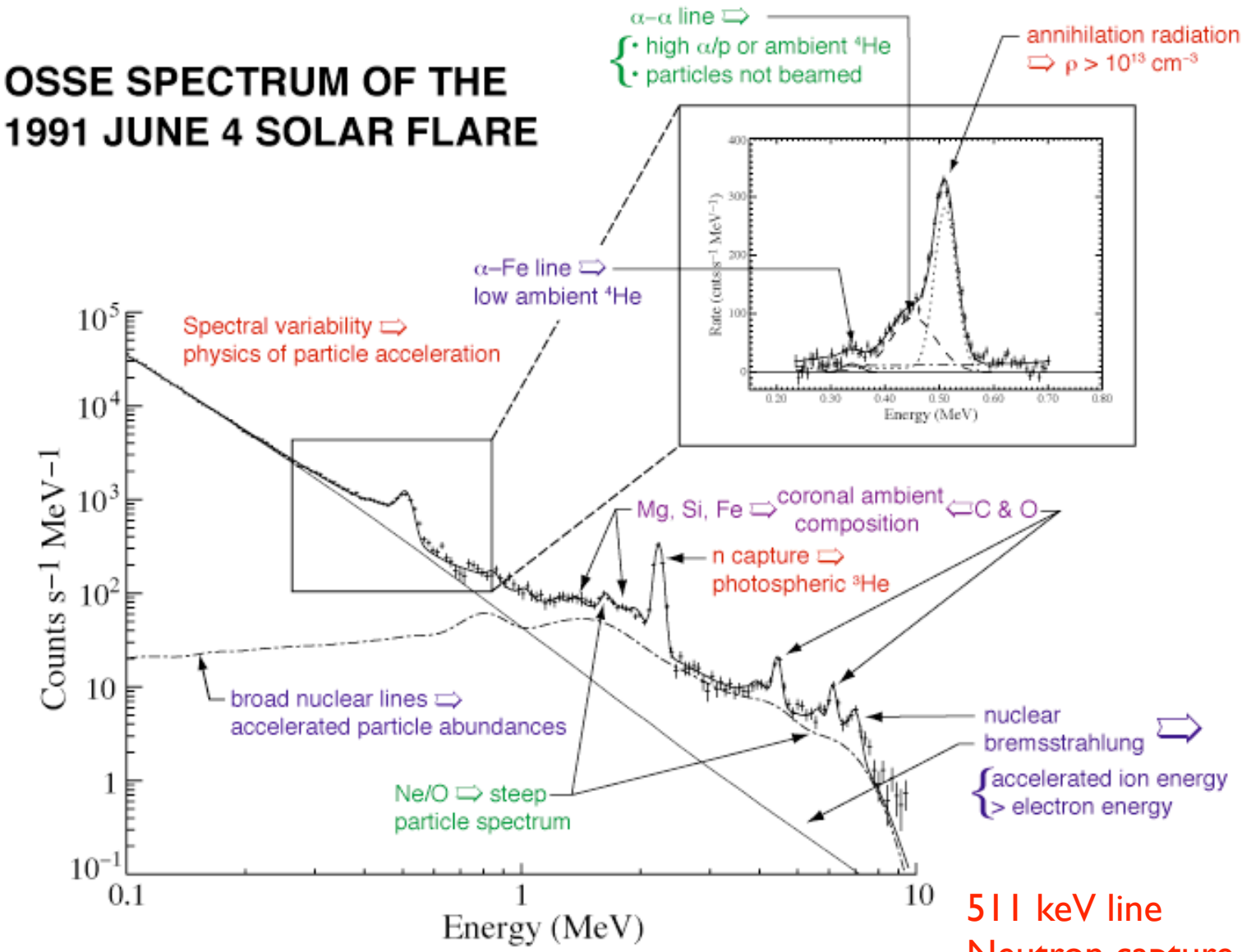
Date	*GOES* X-Ray Class, Start–End[d]	Type	Duration (hr)	CME Speed[a] (km s^{-1})	*Fermi* Time Window Start[d], Duration (minutes)	TS[b]	Flux[c]	Energy Flux[c]
2010 Jun 12	M2.0, 00:30-01:02	I	···	486	00:55, 0.8	LLE[e]	···	···
2011 Mar 7	M3.7, 19:43-20:58	I/S	10.7	2125	20:15, 25	230	1.9 ± 0.3	6.7 ± 1.0
		S			23:26, 36	520	3.5 ± 0.3	11.9 ± 1.1
2011 Mar 8		S			02:38, 35	450	3.5 ± 0.3	11.6 ± 1.1
					05:49, 35	200	1.9 ± 0.3	5.4 ± 0.7
2011 Jun 2	C2.7,9:42-9:50	I/S	0.8	976	09:43, 45	35	0.4 ± 0.2	1.4 ± 0.5
2011 Jun 7	M2.5, 06:16-06:59	S	2.2	1255	07:34, 53	570	3.6 ± 0.3	11 ± 0.9
2011 Aug 4	M9.3, 03:41-04:04	S	1.9	1315	04:59, 34	390	2.5 ± 0.3	7.9 ± 0.8
2011 Aug 9	X6.9, 07:48-08:08	I	···	1610	08:01, 3.3	LLE[e]	···	···
2011 Sep 6	X2.1, 22:12-22:24	I	0.6	575	22:17, 0.2	LLE[e]	···	···
		I/S			22:13, 35	[f]	[f]	
2011 Sep 7	X1.8, 22:32-22:44	S	2.1	792	23:36, 63	350	1.0 ± 0.1	3.5 ± 0.4
2011 Sep 24	X1.9, 09:21-09:48	I	···	1936	09:34, 0.8	LLE[e]	···	···
2012 Jan 23	M8.7, 03:38-04:34	I/S	5.7	1953	04:07, 51	180	0.8 ± 0.1	2.7 ± 0.4
		S			05:25, 69	650	2.1 ± 0.2	6.6 ± 0.5
		S			07:26, 16	69	3.7 ± 0.9	9.6 ± 2.2
		S			08:47, 35	97	2.6 ± 0.5	7.0 ± 1.3
2012 Jan 27	X1.7, 17:37-18:56	D	4.0	1930	19:45, 11	78	3.2 ± 0.8	9.6 ± 2.2
		S			21:13, 24	47	1.0 ± 0.3	2.8 ± 0.8
2012 Mar 5	X1.1, 02:30-04:43	I/S	5.3	1602	04:12, 49	69	0.5 ± 0.1	1.5 ± 0.3
		S			05:26, 71	250	0.9 ± 0.1	2.5 ± 0.3
		S			07:23, 28	39	0.8 ± 0.2	2.4 ± 0.7
2012 Mar 7	X5.4, 00:02-00:40	S	20.2	2684	00:46, 31	22000	[f]	[f]
	X1.3, 01:05–01:23	I/S		1785	00:46, 60	LLE[g]	···	···
					03:56, 32	16000	113.1 ± 2.0	400.5 ± 6.6
					07:07, 32	8900	71.9 ± 1.6	232.6 ± 4.9
					10:18, 32	1900	30.1 ± 1.5	91.9 ± 4.3
					13:29, 32	120	8.9 ± 1.9	29.9 ± 5.9
					19:51, 25	50	0.4 ± 0.1	1.7 ± 0.5
2012 Mar 9	M6.3, 03:22-04:18	D	5.7	844	05:17, 34	51	0.6 ± 0.2	2.0 ± 0.5
		S			06:52, 35	100	0.9 ± 0.2	2.8 ± 0.6
		S			08:28, 34	159	1.4 ± 0.2	4.3 ± 0.7
2012 Mar 10	M8.4, 17:15-18:30	D	4.3	1379	21:05, 30	43	0.4 ± 0.1	1.0 ± 0.3
2012 May 17	M5.1, 01:25-02:14	I/S	1.2	1582	02:18, 22	45	1.0 ± 0.3	3.4 ± 0.9
2012 Jun 3	M3.3, 17:48-17:57	I	0.2	605	17:52, 0.6	LLE[e]	···	···
		I/S			17:40, 23	300	3.2 ± 0.4	10.6 ± 1.2
2012 Jul 6	X1.1,23:15-23:49	I/S	0.9	892	23:19, 52	930	3.5 ± 0.2	10.4 ± 0.7

Notes.
[a] CME data are available at the following url: http://cdaw.gsfc.nasa.gov/CME_list/.
[b] The significance of the detection in terms of σ is roughly $\sqrt{TS}$.
[c] Flux and energy flux are calculated between 100 MeV and 10 GeV and have units of $\times 10^{-5}$ photons cm^{-2} s^{-1} and $\times 10^{-9}$ erg cm^{-2} s^{-1}, respectively.

- 打ち上げから4年で同様のイベントが計18発
- Mクラスフレアでも多数検出
- 高速CMEが付随していることが多い

Ackermann+14

太陽フレアMeVスペクトル



https://heasarc.gsfc.nasa.gov/docs/cgro/epo/posters/Greatest_Hits/OSSE_June_4.html

511 keV line
Neutron capture line by proton: 2.2 MeV
12C deexcitation line: 4.4 MeV
16O deexcitation line: 6.1 MeV

Nuclear Emission Processes

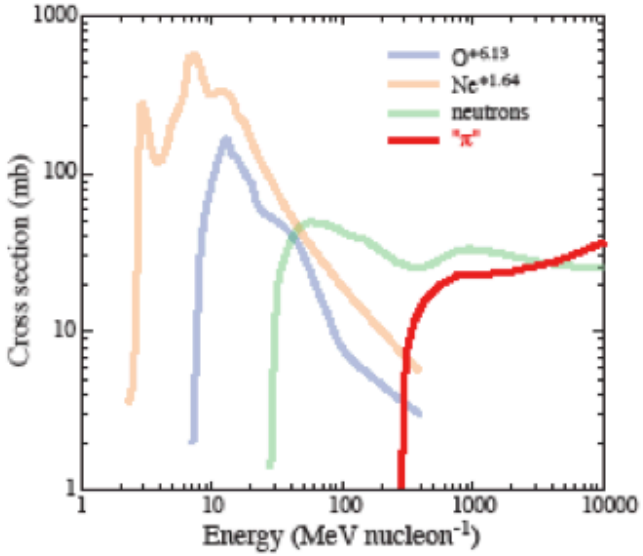
γ-ray lines

$$\left.\begin{matrix} p \\ \alpha \end{matrix}\right\} + {}^{12}C \rightarrow {}^{12}C^{*4.439}$$

$$\left.\begin{matrix} p \\ \alpha \end{matrix}\right\} + {}^{16}O \rightarrow {}^{12}C^{*4.439} + \ldots$$

$$\alpha + {}^{4}He \rightarrow {}^{7}Li^{*0.478}$$

$$\alpha + {}^{4}He \rightarrow {}^{7}Be^{*0.429}$$



neutrons

$$p + {}^{4}He \rightarrow n + \ldots$$

$$\alpha + \alpha \rightarrow n + \ldots$$

$$\left.\begin{matrix} p \\ \alpha \end{matrix}\right\} + {}^{12}C \rightarrow n + \ldots$$

} escape to Earth

capture on photospheric H $\rightarrow$ D + $\gamma_{2.223}$

positrons

$$\left.\begin{matrix} p \\ \alpha \end{matrix}\right\} + {}^{12}C \rightarrow {}^{11}C \rightarrow e^{+}$$

$$\left.\begin{matrix} p+p \\ p+\alpha \end{matrix}\right\} \rightarrow \pi^{+} \rightarrow e^{+}$$

} $\gamma_{511,\ cont.}$

pions

$$\left.\begin{matrix} p+p \\ p+\alpha \end{matrix}\right\} \rightarrow \left.\begin{matrix} \pi^{0} \\ \pi^{+,-} \end{matrix}\right\} \rightarrow \begin{matrix} \gamma \\ e^{+,-} \end{matrix} \rightarrow \gamma_{511,\ cont.}$$

Neutron capture line by proton: 2.2 MeV

^{12}C deexcitation line: 4.4 MeV

^{16}O deexcitation line: 6.1 MeV

CGROによる太陽フレアToO観測

Table 1. High-energy observations of three X-class flares in June 1991.

Rank+01

Instrument	Energy Range	9 June 1991	11 June 1991	15 June 1991
COMPTEL	0.8 to 30 MeV	several hours	several hours	several hours, w/o imp. phase
	10–100 MeV neutrons	about 1 hour	about 1 hour	several hours
BATSE-LAD	20 keV to >1 MeV	about 1 hour	about 1 hour	about 40 min
OSSE	40 keV to >150 MeV	imp. phase	about 2 hours	—
EGRET	>30 MeV	— (TASC: imp. phase)	several hours (TASC: imp. phase)	—
GAMMA-1	>50 MeV	—	—	several hours
PHEBUS	75 keV to >1 MeV	imp. phase	—	—

- All the instruments onboard CGRO observed X-class solar flares in 1991 June
- COMPTEL results are shown in Rank+01

Fermi/LATの結果と非常によく似た

Long-duration 2.2 MeV gamma-ray emission

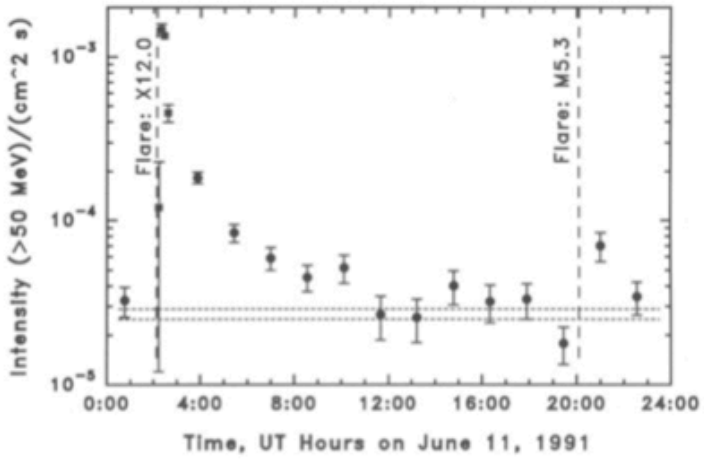


FIGURE 17. Intensities of >50 MeV photons observed by EGRET around the time of 1991 June 11 flare.

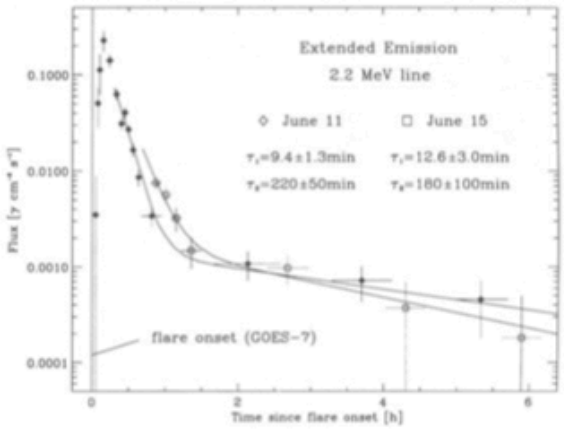
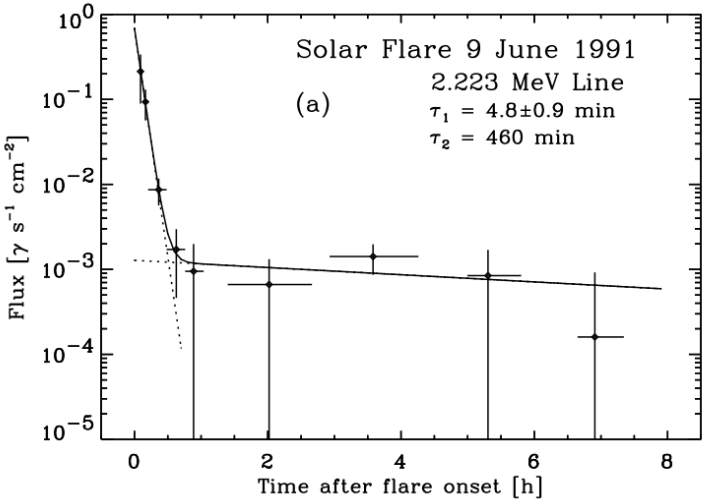
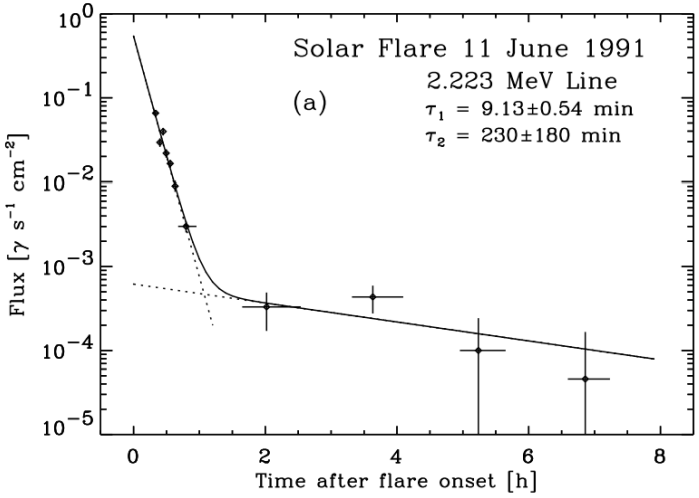


FIGURE 18. Intensities of 2.223 MeV photons observed by COMPTEL displaying the extended emission from the 1991 June 11 and 15 flares.

Time-extended >50 MeV and 2.22 MeV emission from the 1991 June 11 flare observed by CGRO EGRET and COMPTEL (Kanbach et al. 1993, Rank, Ryan, et al. 2001)

Light curve of 2.2 MeV line





Rank+01

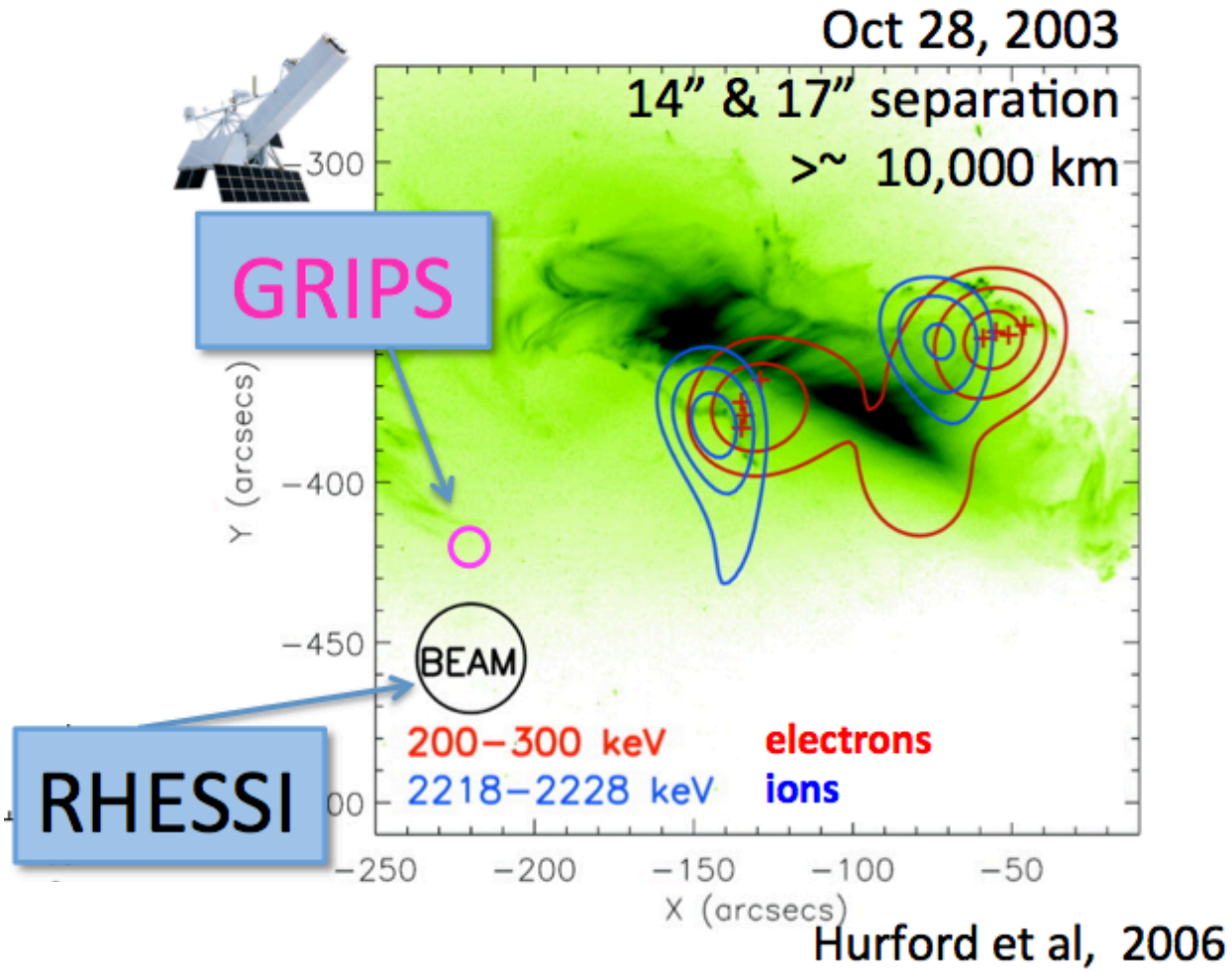
Table 2. Characteristic parameters for the extended phase.

flare	energy	τ_1^a	τ_2^a	Φ_t^b	T_t^c
9 June	2.2 MeV	4.9 ± 0.9 min	450 min	2.5×10^{-3}	30 min
	4–7 MeV	4.2 ± 2.0 min	220 ± 150 min	6.5×10^{-3}	20 min
11 June	2.2 MeV	9.13 ± 0.54 min	230 ± 180 min	9.0×10^{-4}	65 min
	4–7 MeV	10.4 ± 1.2 min	220 ± 160 min	1.0×10^{-3}	60 min
	pion decay	10.8 ± 1.4 min			
	bremsstr.	8.6 ± 1.0 min			
15 June	2.2 MeV	10.3 ± 2.0 min	180 ± 110 min	9.0×10^{-4}	75 min

[a] τ_1, τ_2: decay constants for the short and long decay phase, respectively;
[b] Φ_t: photon flux [$\gamma\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$] at which the transition occurs;
[c] T_t: time after flare onset at which the transition occurs.

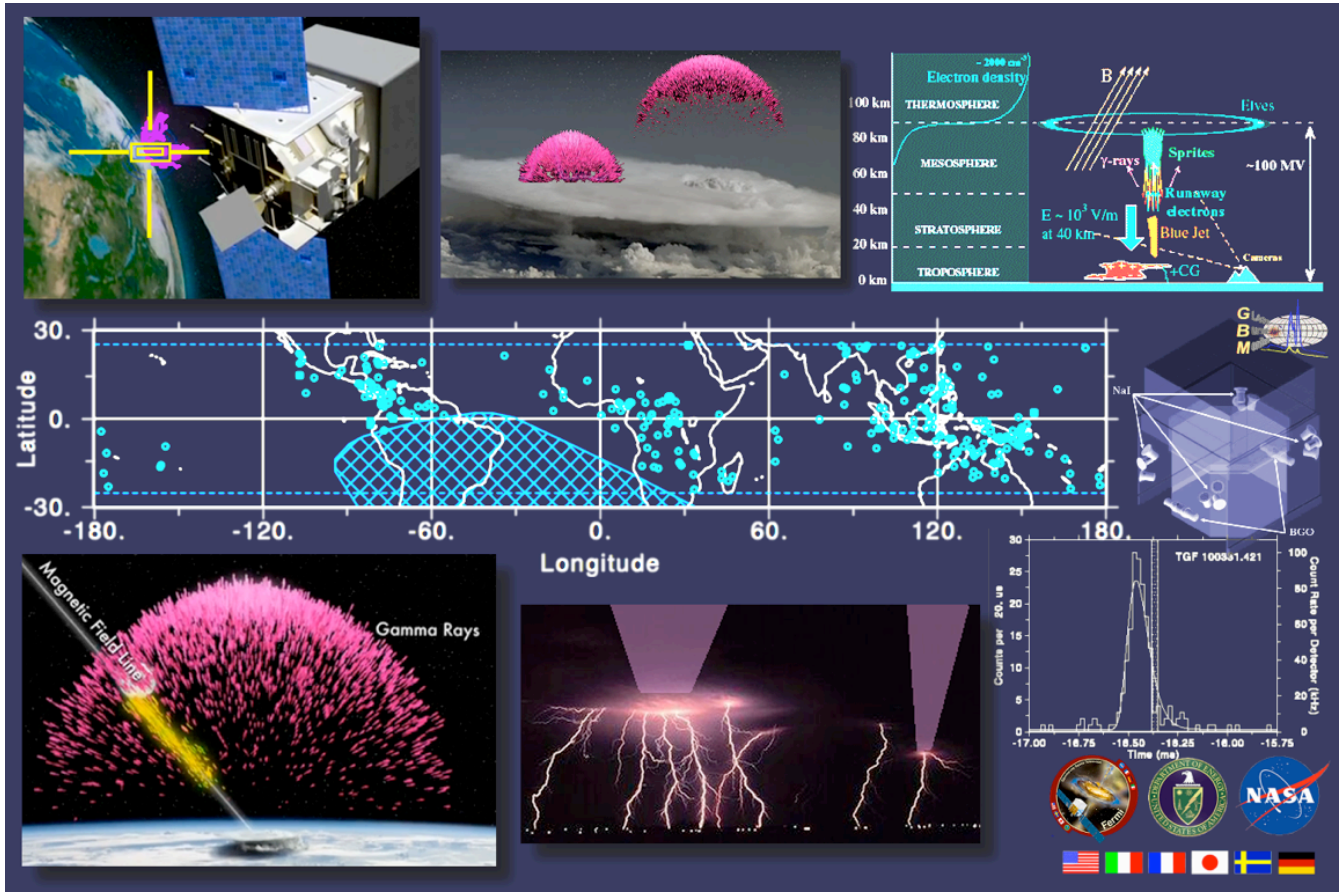
- c.f. 511 keV line flux~1.1E-3 photons/cm2/s from GC measured by Integral
- 次の太陽活動期 (2020~2025)に大きな黒点が出たら狙う？

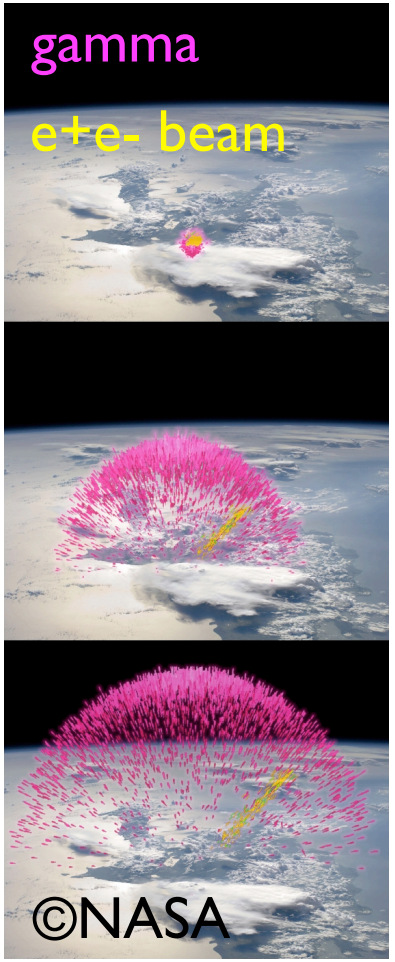
高い空間分解能が可能ならガンマ線放射領域を特定できる



- Hard Xとガンマ線が異なる場所から放射されている (Hurford+06)
- 電子とイオンで加速場所が異なる？？
- RHESSIではこの１例のみ
- RHESSIチームによってGRIPS気球実験が行われているらしい (Duncan+16)

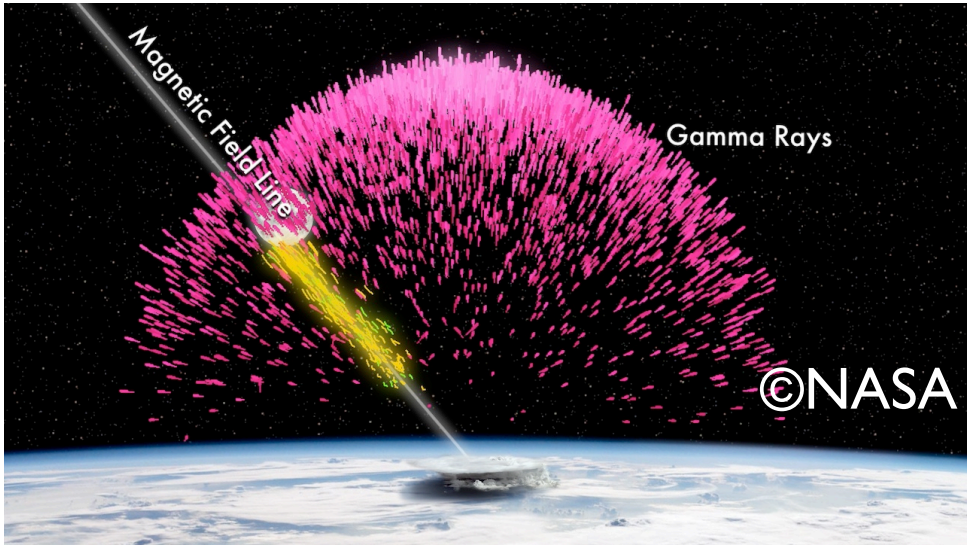
Terrestrial Gamma-ray Flash (TGF)



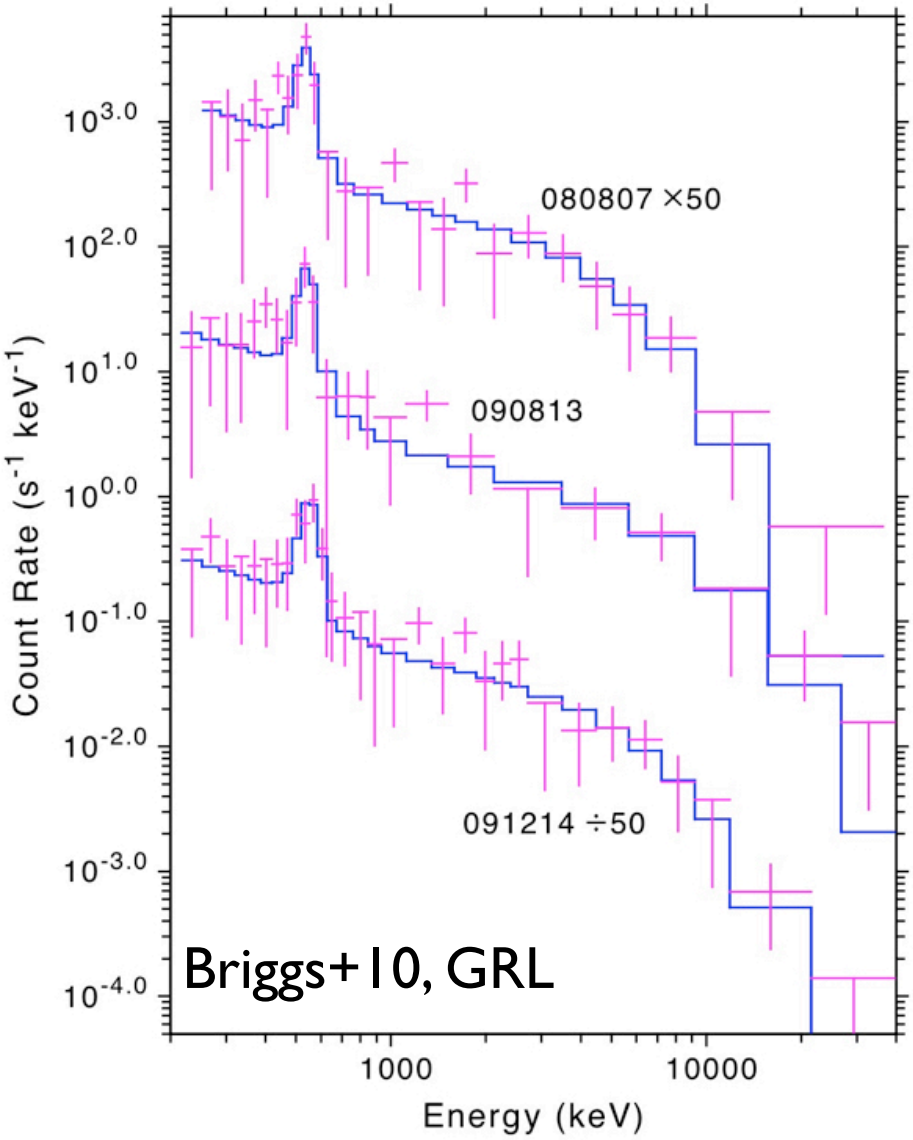


- GBMはTGFからのガンマ線を850 events per year検出
- 雷多発地域からTGFを検出->雷起源を示唆
- 雷放電によって加速された電子によるガンマ線放射

511 keV line from Positron annihilation



- 雷放電で生成された陽電子が磁場に沿って伝播し、フェルミGBMの検出器内で対消滅



Summary

- フェルミで検出している明るいMeV/GeVガンマ線源は、
  - ✓ Vela, Geminga, Crab pulsars
  - ✓ flaring blazars
- 太陽フレアMeVガンマ線観測は、ターゲットが明るくライン放射が強いので、興味深いように思われる
  - ✓ Temporary extended 2.2 MeV neutron capture line emission
  - ✓ 高角度分解能の観測はGRIPS気球実験 by Rhessi team (UCB)
- 衛星観測（小型でも？）ならTGFも頻繁に観測できるだろう