第二届GECAM研讨会

GECAM项目简介

熊少林

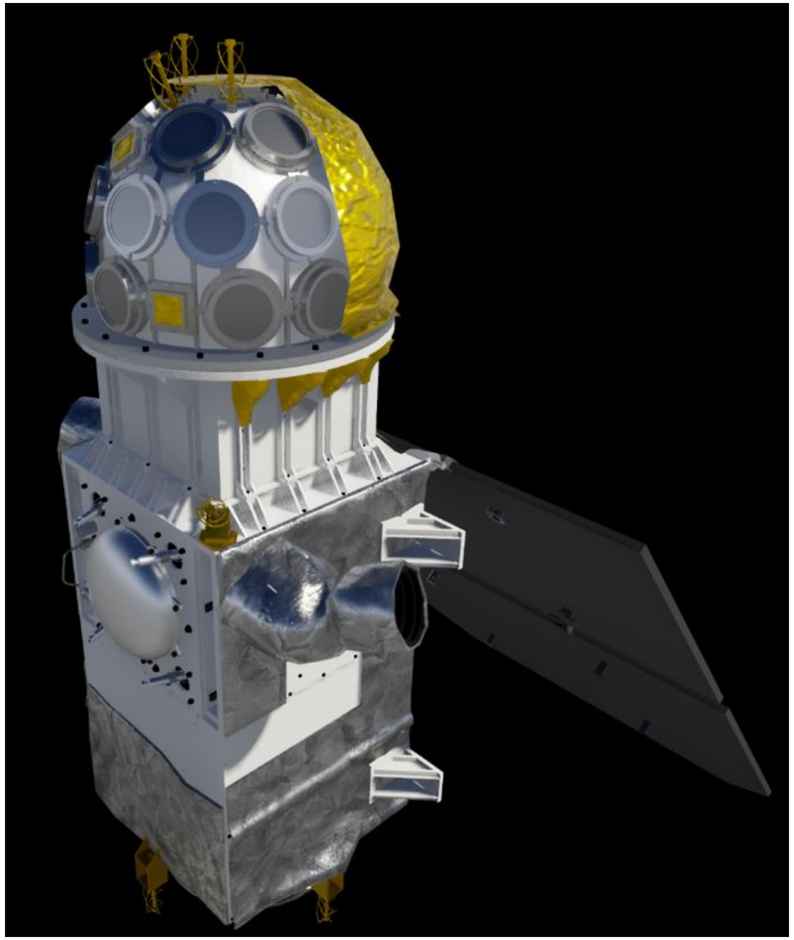
(代表GECAM团队)

中国科学院高能物理研究所

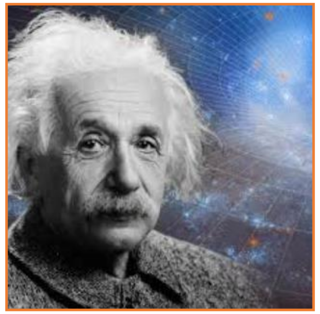
2020-10-31

报告提纲

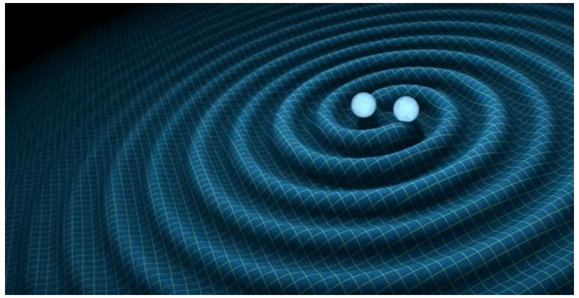
- 项目历程
- 探测性能
- 科学目标
- 联合观测
- 科学应用
- 数据政策



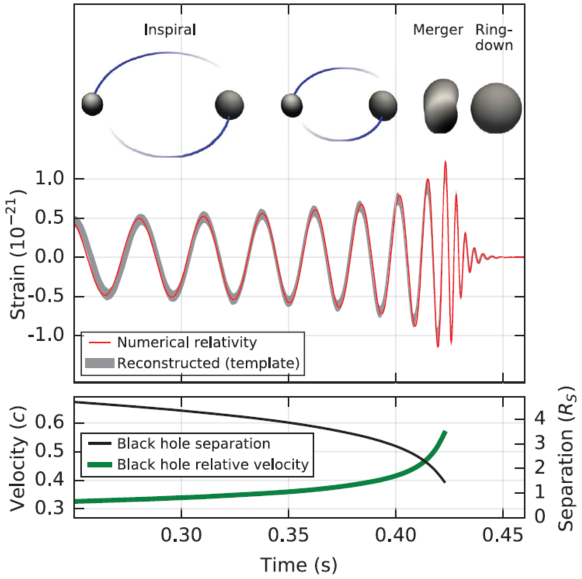
引力波天文学时代



爱因斯坦
一百年前
广义相对论
的预言



LIGO激光干涉
引力波天文台



GW150914：首个
双黑洞并合引力波

2017年度
诺贝尔物理学奖

Photo: Bryce Vickmark
Rainer Weiss
Prize share: 1/2

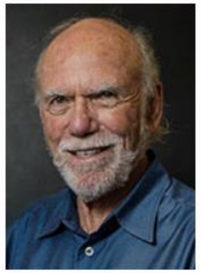
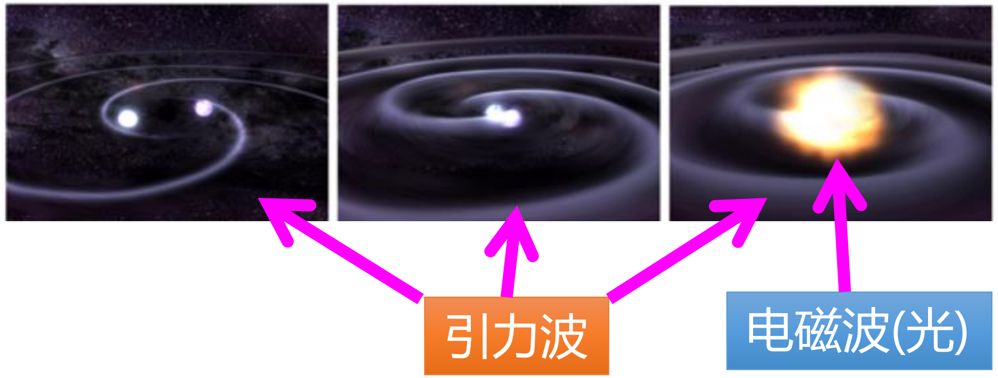
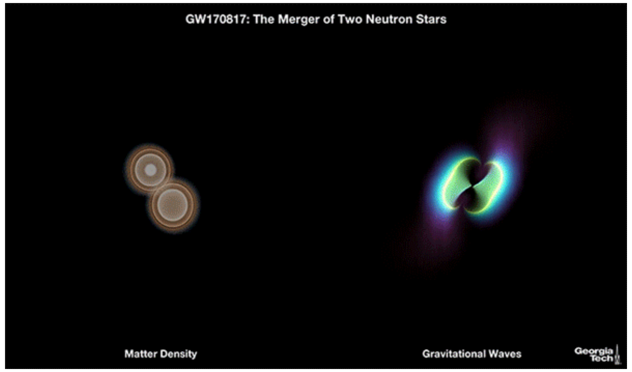


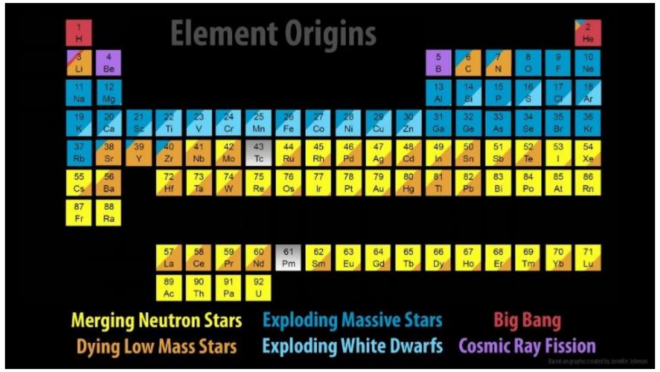
Photo: Caltech
Barry C. Barish
Prize share: 1/4

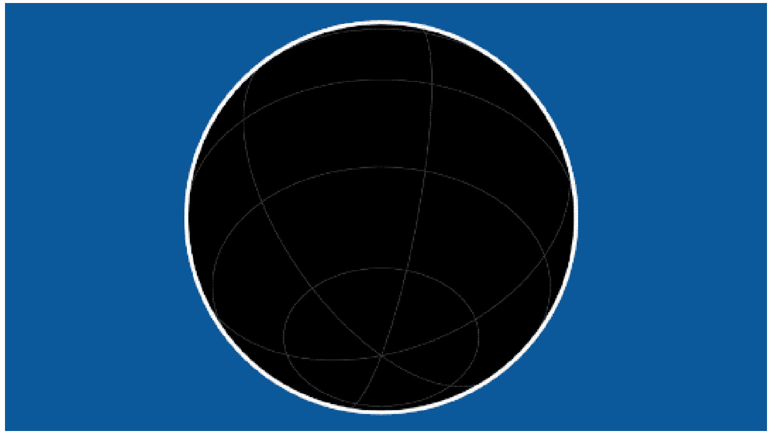
Photo: Caltech Alumni Association
Kip S. Thorne
Prize share: 1/4

引力波电磁对应体的重要意义

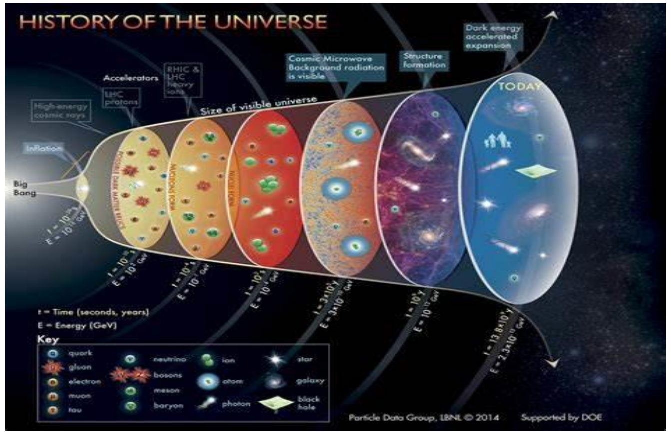








电磁对应体精确定位引力波源

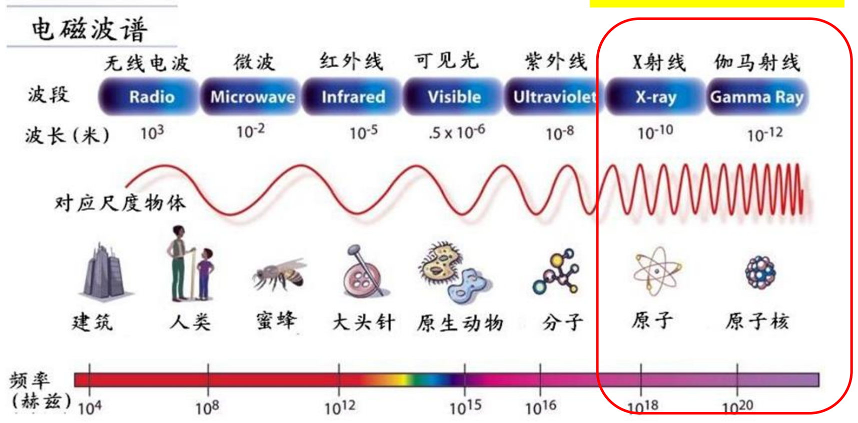


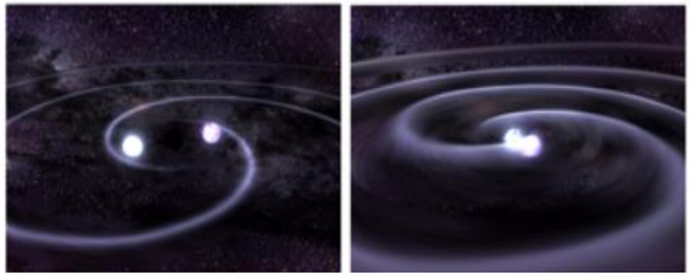
- **引力波：** 新窗口、新手段、新发现
- **电磁波：** 丰富的信息、长期积累
- **二者联合发挥重要作用**
  - 帮助证认引力波事件
  - 精确定位引力波波源
  - 研究致密天体及其并合过程
  - 破解引力波参数的简并
  - 基础物理研究
    - 引力波速度，宇宙膨胀等

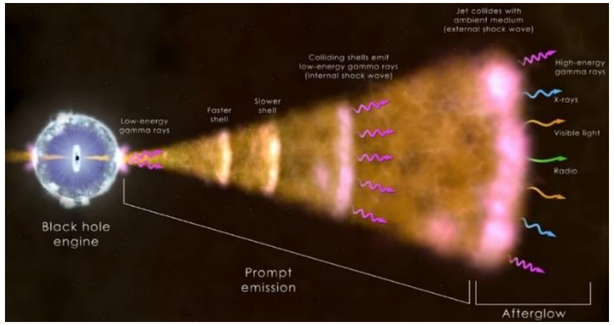
高能电磁对应体（引力波伽马暴）的特殊作用

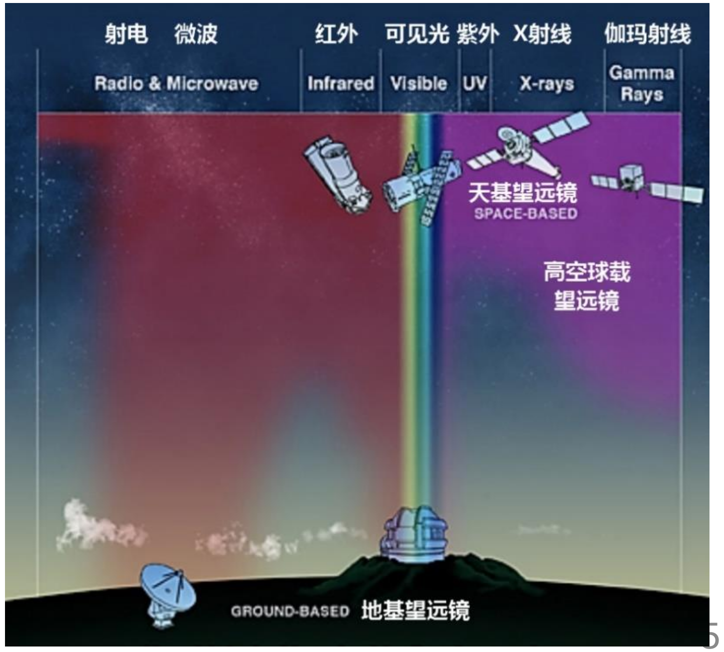
- **高能辐射光子能量高、光度大**
- **高能辐射提供触发，**引导后随观测
  - 降低光学和射电搜索范围，提高发现宿主星系的概率
- **高能段源少、跟GW信号时延短**
  - 低能段源多，望远镜转过去时间长，证认关联性难度较大
- **高能辐射转瞬即逝，**难以捕捉，数据重要

高能射线









双致密星并合引力波

高能瞬时辐射 低能余辉辐射

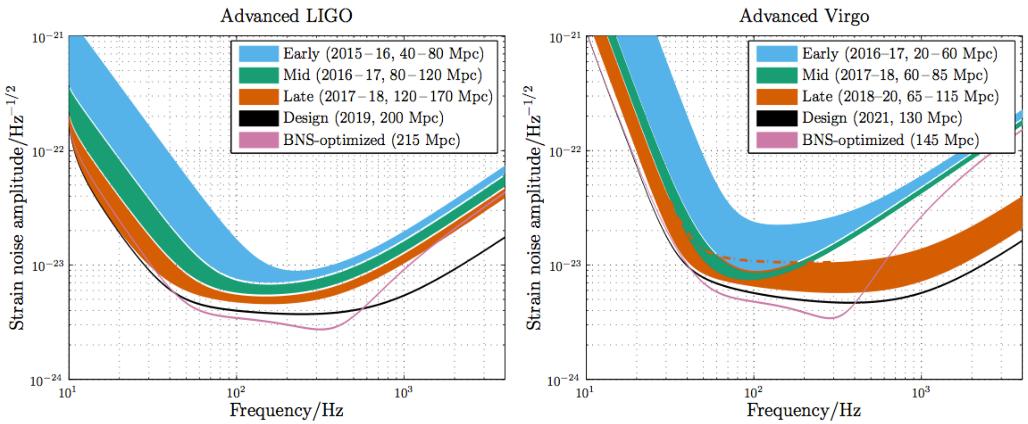
时间

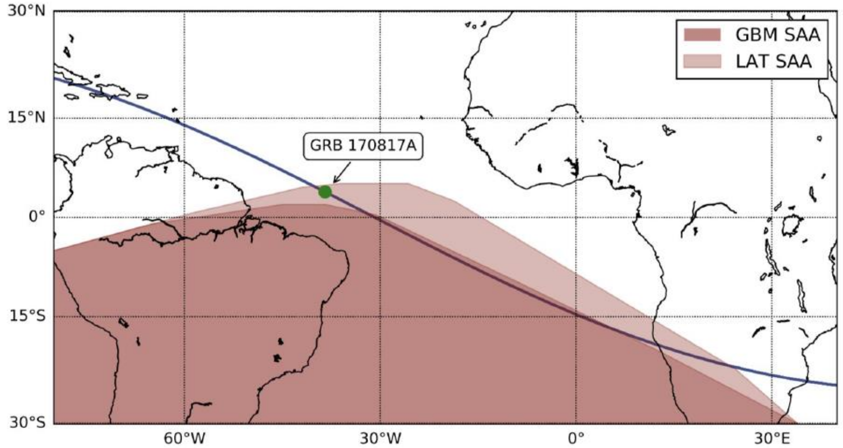
GECAM项目背景

- **2020年引力波探测器升级至设计灵敏度**
- **现有高能探测设备仍显不足**
  - Fermi/GBM, INTEGRAL/SPI-ACS, Konus-Wind, Swift/BAT, *Insight*-HXMT(慧眼)
  - **视场、灵敏度、定位能力、探测能量范围、伽马暴鉴别能力**

```
TITLE:    GCN CIRCULAR
NUMBER:   24185
SUBJECT:  LIGO/Virgo S190425z: Fermi GBM Observations
DATE:     19/04/25 15:35:23 GMT
FROM:     Cori Fletcher at USRA/NASA  <corinne.l.fletcher@nasa.gov>

C. Fletcher (USRA) reports on behalf of the Fermi-GBM Team and the
GBM-LIGO/Virgo group:

For S190425z and using the initial BAYESTAR skymap, Fermi-GBM was
observing 55.6% of the probability region at event time.
```

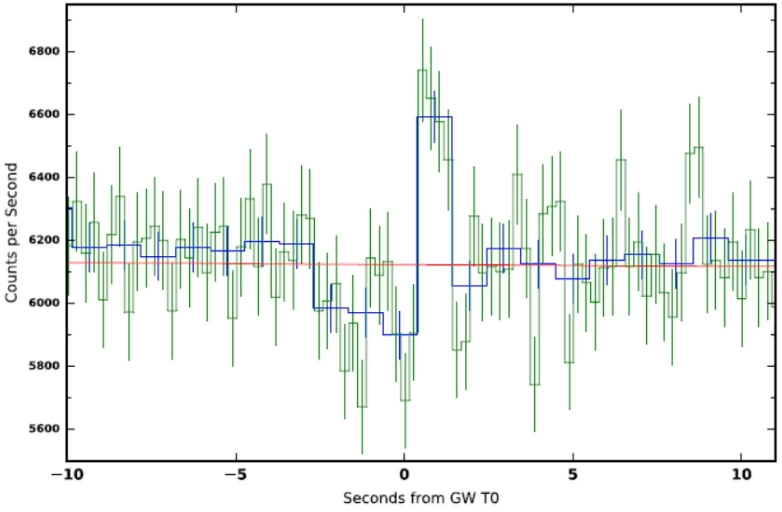
LIGO和Virgo灵敏度升级计划(2016版)



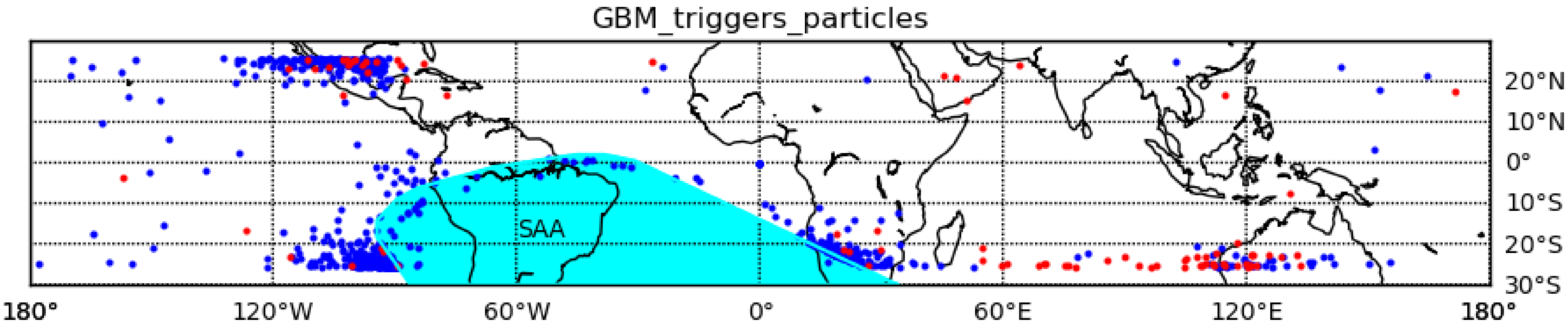



```
TITLE:    GCN CIRCULAR
NUMBER:   24065
SUBJECT:  LIGO/Virgo S190408an: Fermi GBM Observation
DATE:     19/04/08 21:00:15 GMT
FROM:     C. Michelle Hui at MSFC/Fermi-GBM  <c.m.hui@nasa.gov>

C. M. Hui (NASA/MSFC)

reports on behalf of the Fermi-GBM Team and the GBM+LIGO/Virgo Working Group:

At the time of S190408an, Fermi was passing through

the South Atlantic Anomaly from 14 minutes prior to 15 minutes after

the trigger time; therefore the GBM detectors were disabled.
```

空间粒子事件对伽马暴证认造成干扰



首个BBH疑似电磁对应体：GW150914-GBM
伽马暴？空间粒子事件？ 本底涨落？

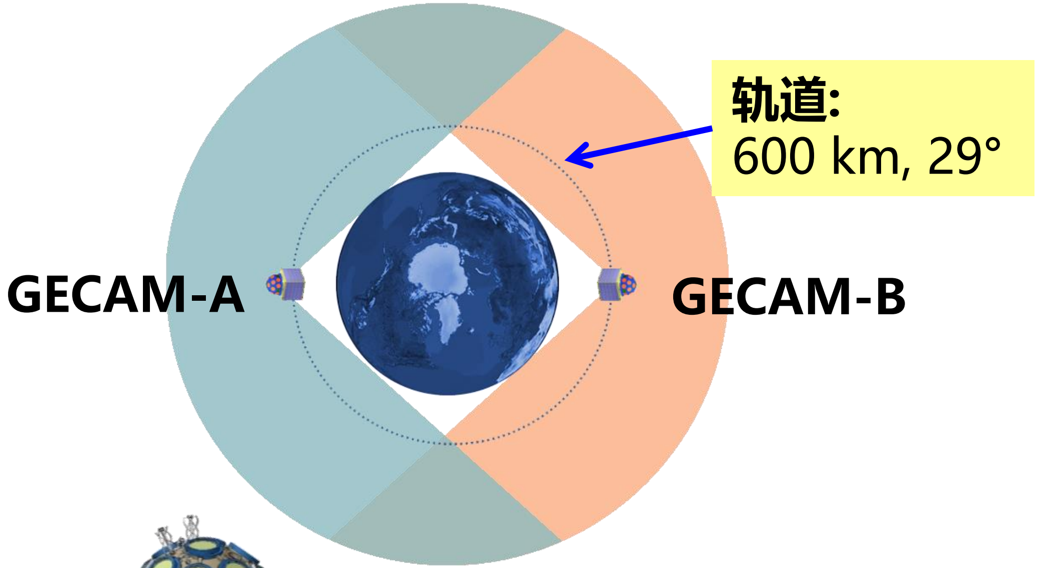


Blue dots: Local particle events   Red dots: Distant particle events

引力波暴高能电磁对应体全天监测器 (GECAM)

Gravitational wave high-energy Electromagnetic Counterpart All-sky Monitor

- **科学目标**
  - 全天监测引力波伽马暴以及新的辐射
  - 全天监测快速射电暴可能的高能辐射
  - 全时监测特殊伽马暴和磁星爆发等
- **性能指标**
  - 全天视场（100%全天）
  - 定位能力（~1度，中等亮度GRB）
  - 宽能区（6 keV-5 MeV）
  - 高灵敏度（2E-8 erg/cm2/s）
  - 伽马暴与空间粒子暴的鉴别
- **技术创新**
  - 首型空间使用的无高压紧凑宽能区伽马射线探测器
  - 新型准实时天地通讯**（延迟~几分钟）**



GECAM卫星　每颗~160 kg

Two satellites, launching in 2020, will watch for gamma rays from the violent birth of gravitational waves.

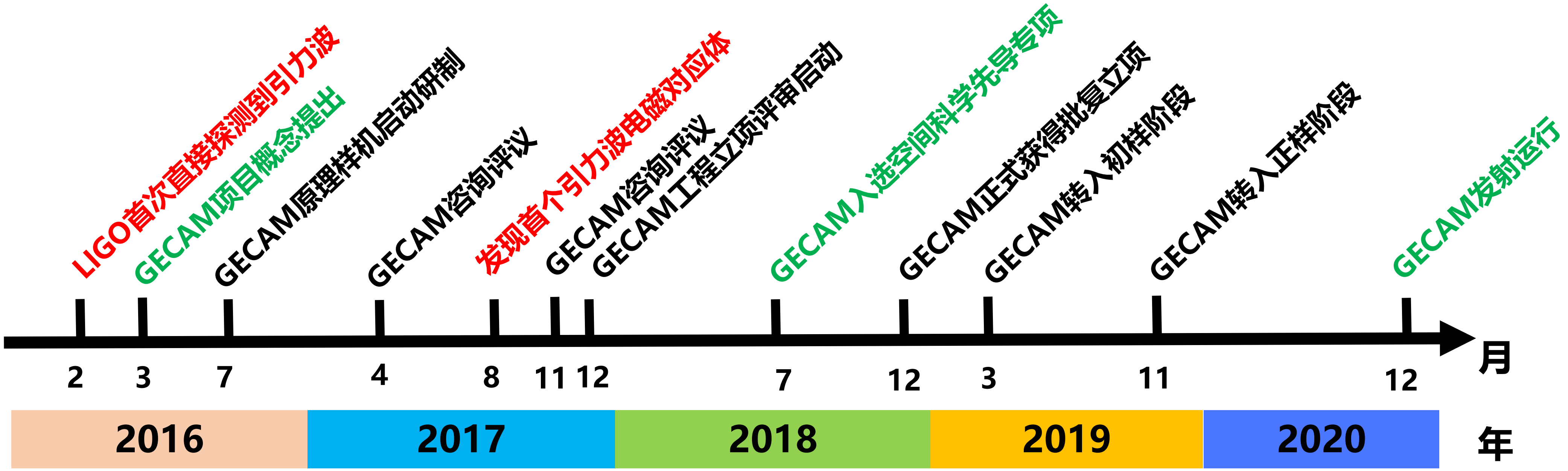
INSTITUTE OF HIGH ENERGY PHYSICS, CAS

New China space missions will watch for colliding black holes, solar blasts

By Dennis Normile | Jul. 11, 2018 , 12:45 PM

国际著名《科学》杂志报道
“空间科学（二期）”先导专项
题图为GECAM

首个机遇型空间科学卫星

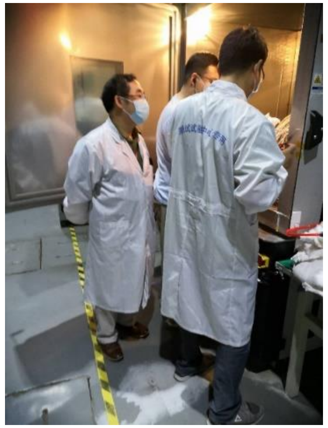


机遇型项目：重大科学机遇、周期短、成本低

战役情，尽一切努力确保工程研制质量和节点

载荷力学试验

电子学舱热真空试验



穹顶舱热真空试验

常压热循环试验


physicsworld.com

ing GECAM into orbit by the end of 2020," says Xiong, adding that they plan to deliver the assembled detectors to the satellite platform by mid-July. Once the satellites are in orbit, they will work together with ground-based detectors in the US, Europe and Japan to study gamma-ray bursts associated with gravitational waves. Physicists say that GECAM might spot several associated events each year. "GECAM will represent one of the first new 'all sky' devices that will be able to look for associated signals, wherever a gravitational wave event occurs in the sky," says Nobel laureate Barry Barish, who is a former LIGO director.

Challenges in sight

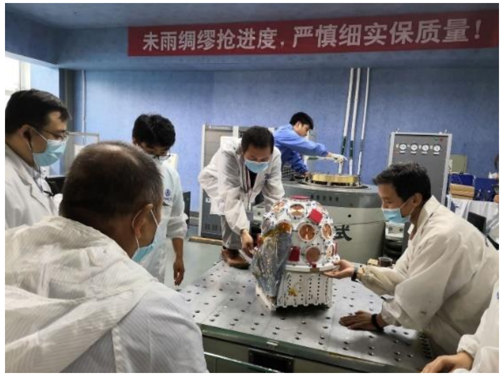
Compared to GECAM, some projects are facing financial and logistical uncertainties as they navigate longer timelines. Funding delays have already impacted some major physics research infrastructure

Under pressure Despite COVID-19, physicists in China have been working hard on the Gravitational-wave high-energy Electromagnetic

(JUNO) that is being built in southern China will aim to measure the mass hierarchies of neutrinos when it comes online by the end of 2021. Researchers expect to receive a liquid scintillator purification system from Italian partners this September, but that could now be delayed.

Physics World对GECAM战役情的报道

交付有效载荷，参加整星联试



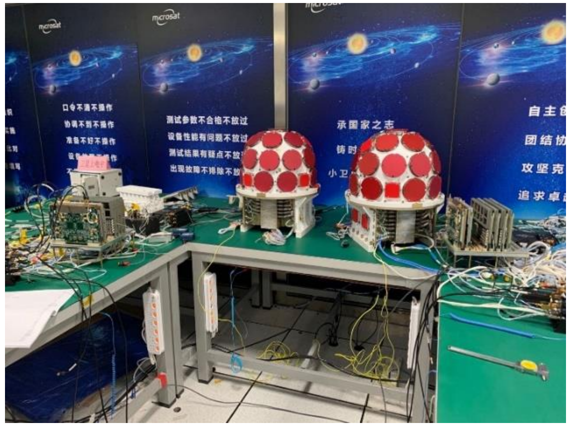
载荷力学试验


载荷交付验收测试

卫星系统铸星青年突击队

载荷测试

连夜运输



双星整星联试

整星试验

图 63 双星参试状态-X 面照片

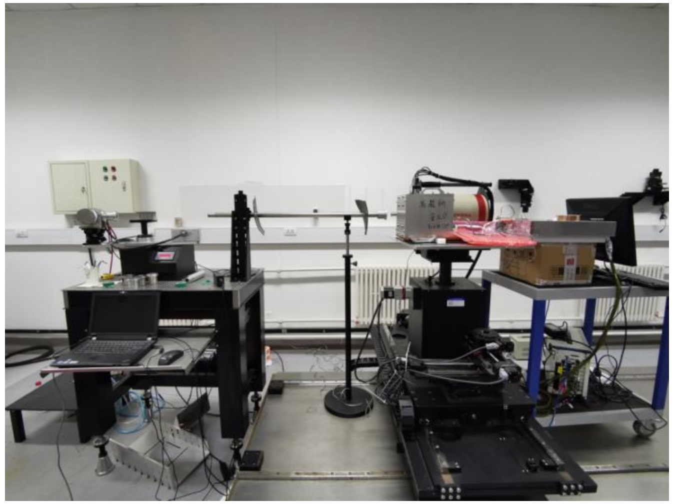
完善的地面标定

GRD探测器标定

- X射线束线能量响应标定
- 放射源能量响应标定
- 温度偏压标定
- 空间响应标定
- 死时间
- 电子能量响应
- 高计数率响应
- 相对时间精度

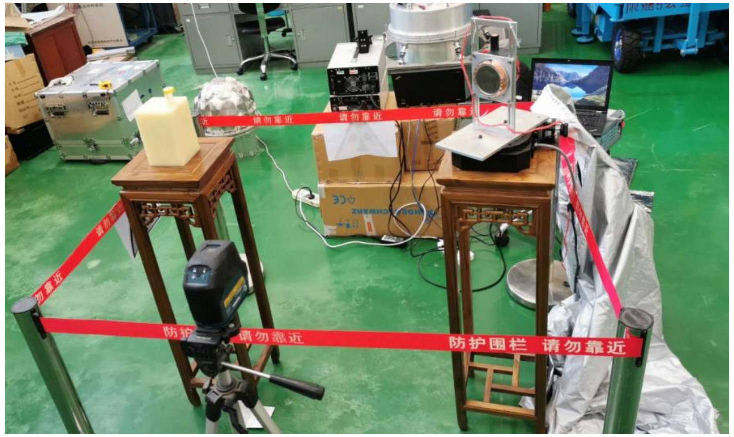
CPD探测器标定

- 电子能量响应标定
- 角度响应标定
- 温度偏压标定
- 伽马探测效率
- 死时间
- 质子能量响应
- 高计数率响应

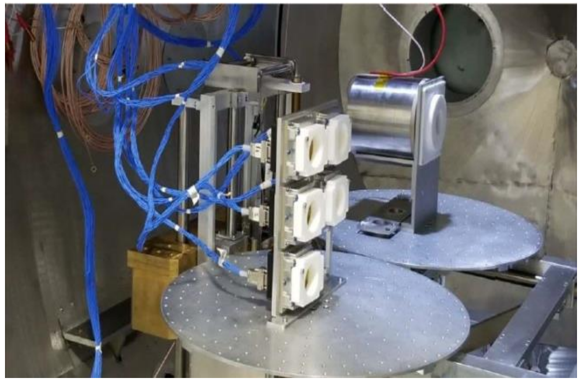


X射线束线能量响应标定

放射源能量响应标定

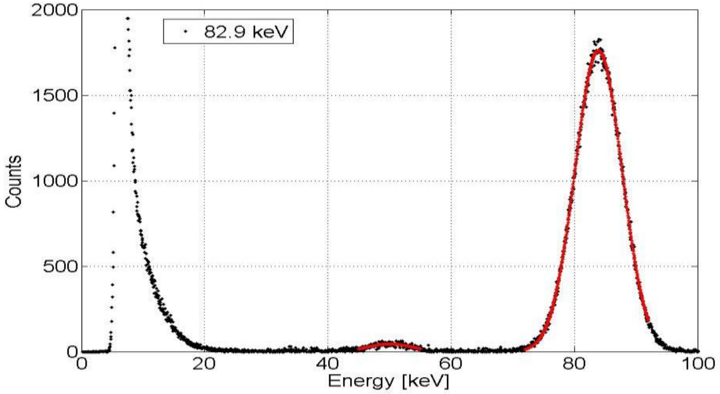


放射源角度响应标定

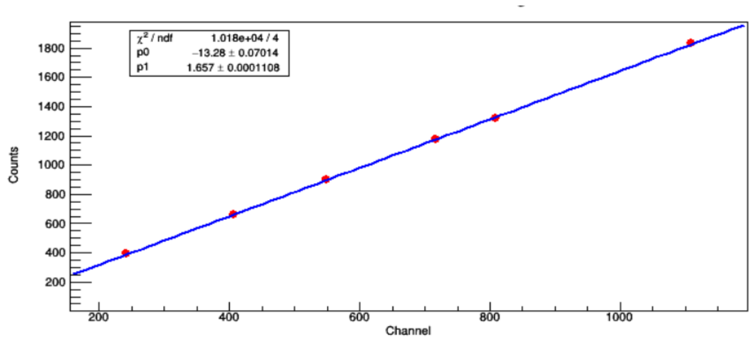


电子束标定

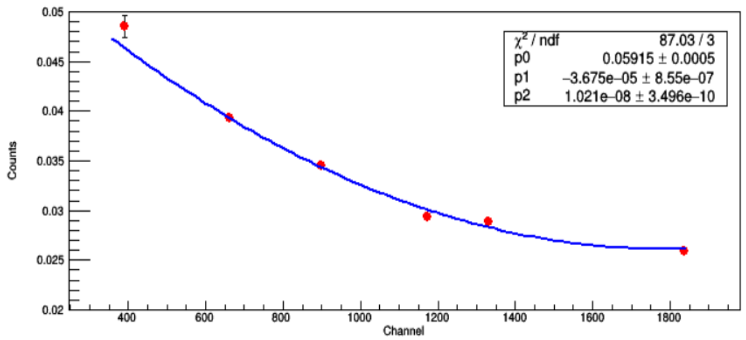
标定结果良好，论文撰写中



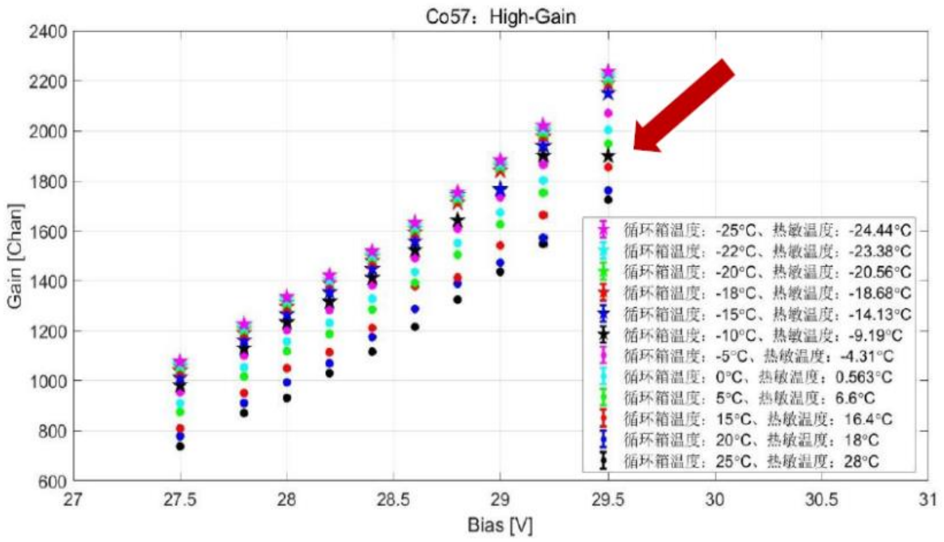
能量响应



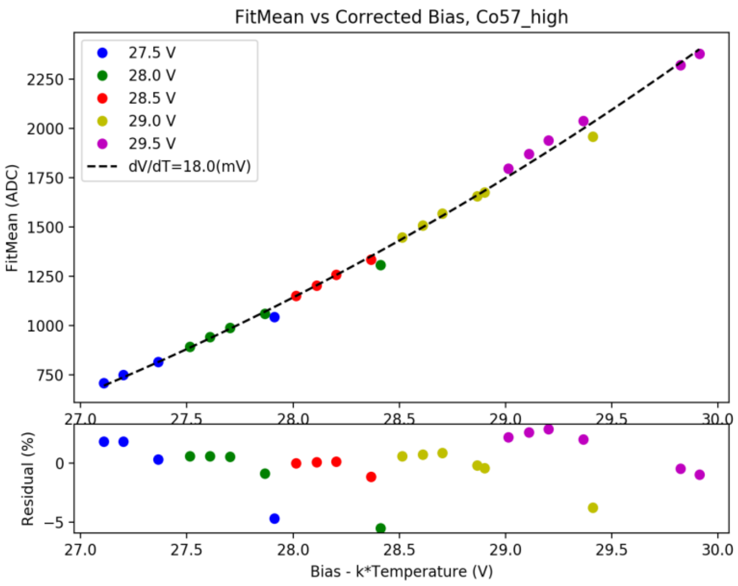
能量-能道关系（EC关系）



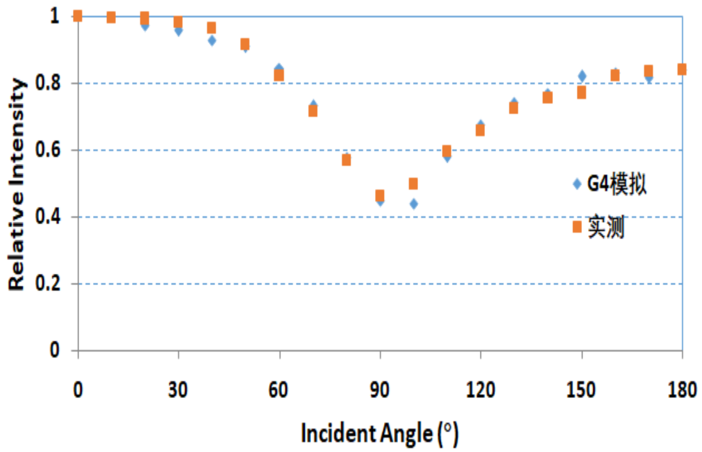
能量-能量分辨率关系



增益随温度和偏压的变化

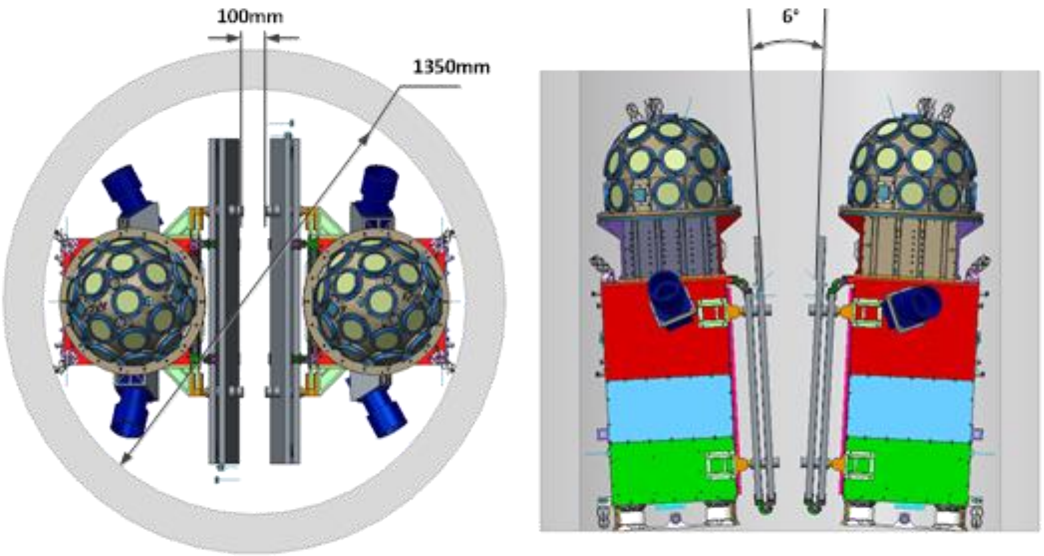


特征峰位随温度和偏压的变化



GRD探头的方向响应

计划12月发射，运行3-5年

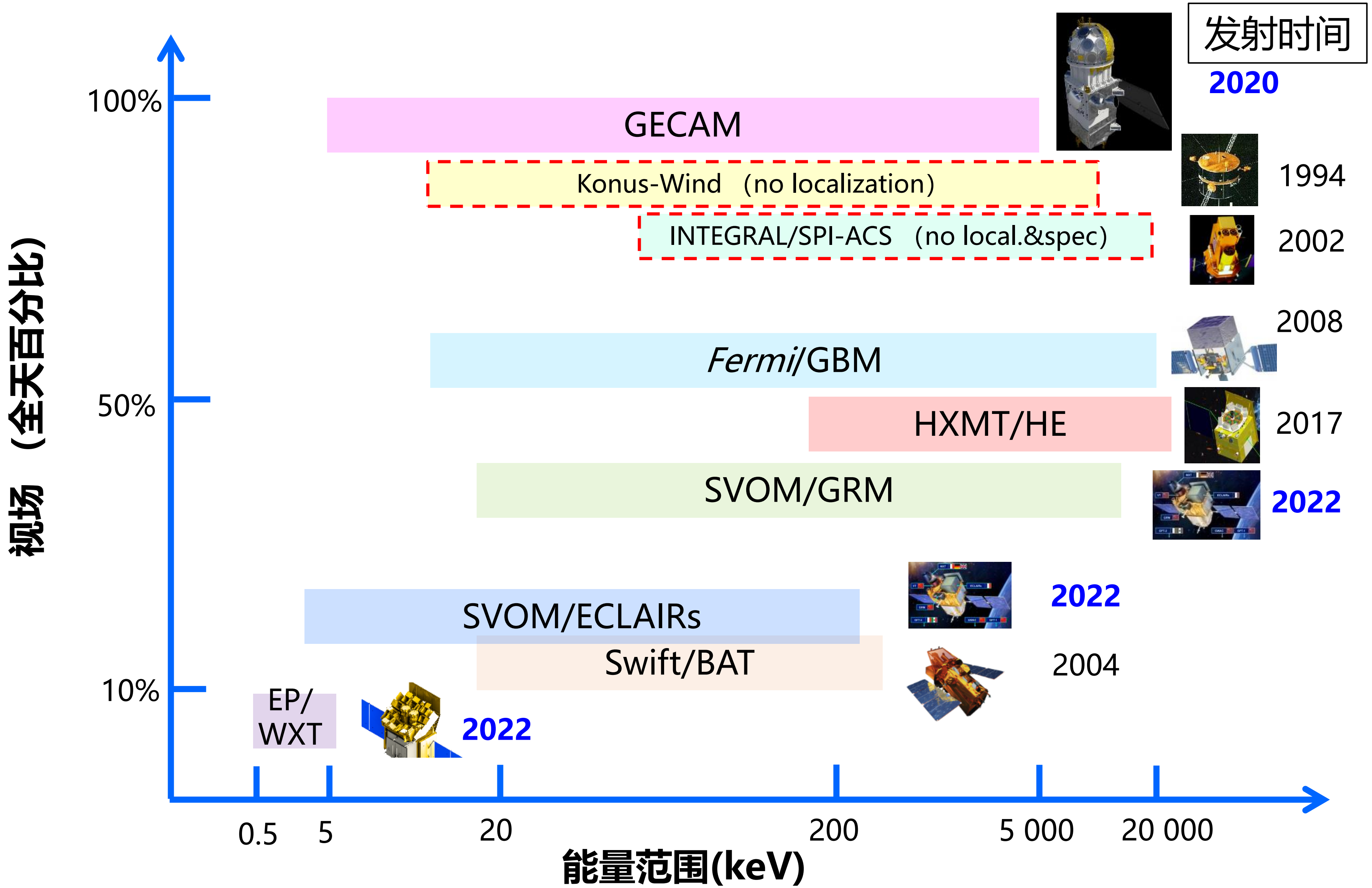


长征11一箭双星

GECAM卫星主要技术指标

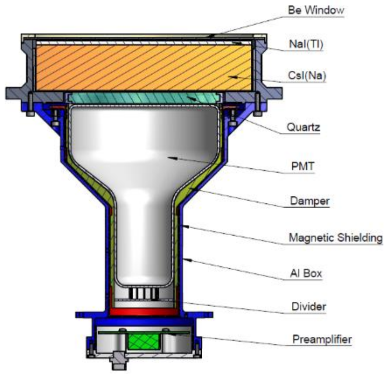
项目	指标参数	备注
轨道	600 km, 29 deg	550-600 km
发射时间与寿命	2020年12月，考核寿命3年	设计寿命 5年
伽马射线探测能量范围	8 keV – 2 MeV	实测：6 keV – 5 MeV
伽马射线探测效率	≥50%@8 keV	GRD
视场	100%全天	双星联合，GRD
暴发事件探测灵敏度	<2E-8 erg/cm^2/s (20 s, 10-1000 keV)	在标称条件下
暴发事件定位误差	< 1 deg (1-σ, 统计误差)	在标称条件下
电子探测能量范围	300 keV - 5 MeV	CPD
死时间	≤5 μs (正常事例)	GRD和CPD
绝对时间精度	~ 10 μs	使用GPS
相对时间精度	~ 0.5 μs	单颗卫星25个GRD和8个CPD之间
数传数据量	< 50 GB/天 (双星)	太阳极活跃期除外
观测警报时间延迟	< 5分钟 (50%), <60分钟（100%）	从卫星到科学应用系统的时延

GECAM与其它高能望远镜比较

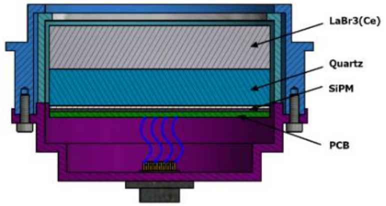


新型空间伽马射线探测器：方案+关键技术+工程化

体积小，重量轻，无需高压；能阈低，探测能量宽，增益自动调节



传统基于PMT探头



基于SiPM探头

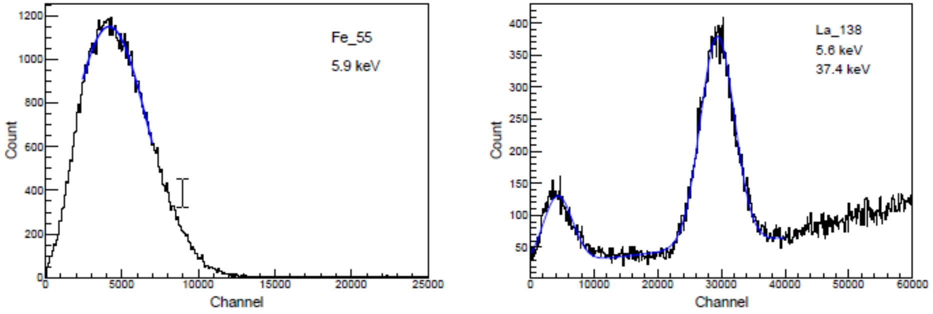
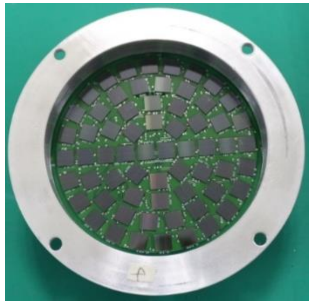
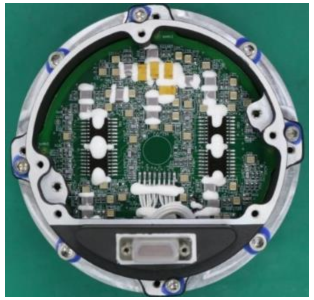
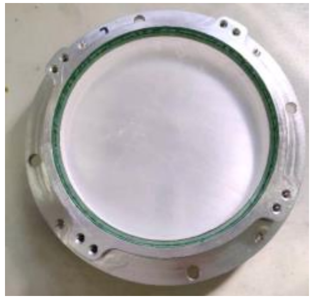


Figure 5. The spectra of ^{55}Fe and ^{138}La radioactive sources. The energy resolutions are 95.6% at 5.9 keV, 126.6% at 5.6 keV and 24.1% at 37.4 keV.





自制SiPM工程化电路



国产溴化澜晶体探头

Journal of Instrumentation

A low-energy sensitive compact gamma-ray detector based on $LaBr_3$ and SiPM for GECAM

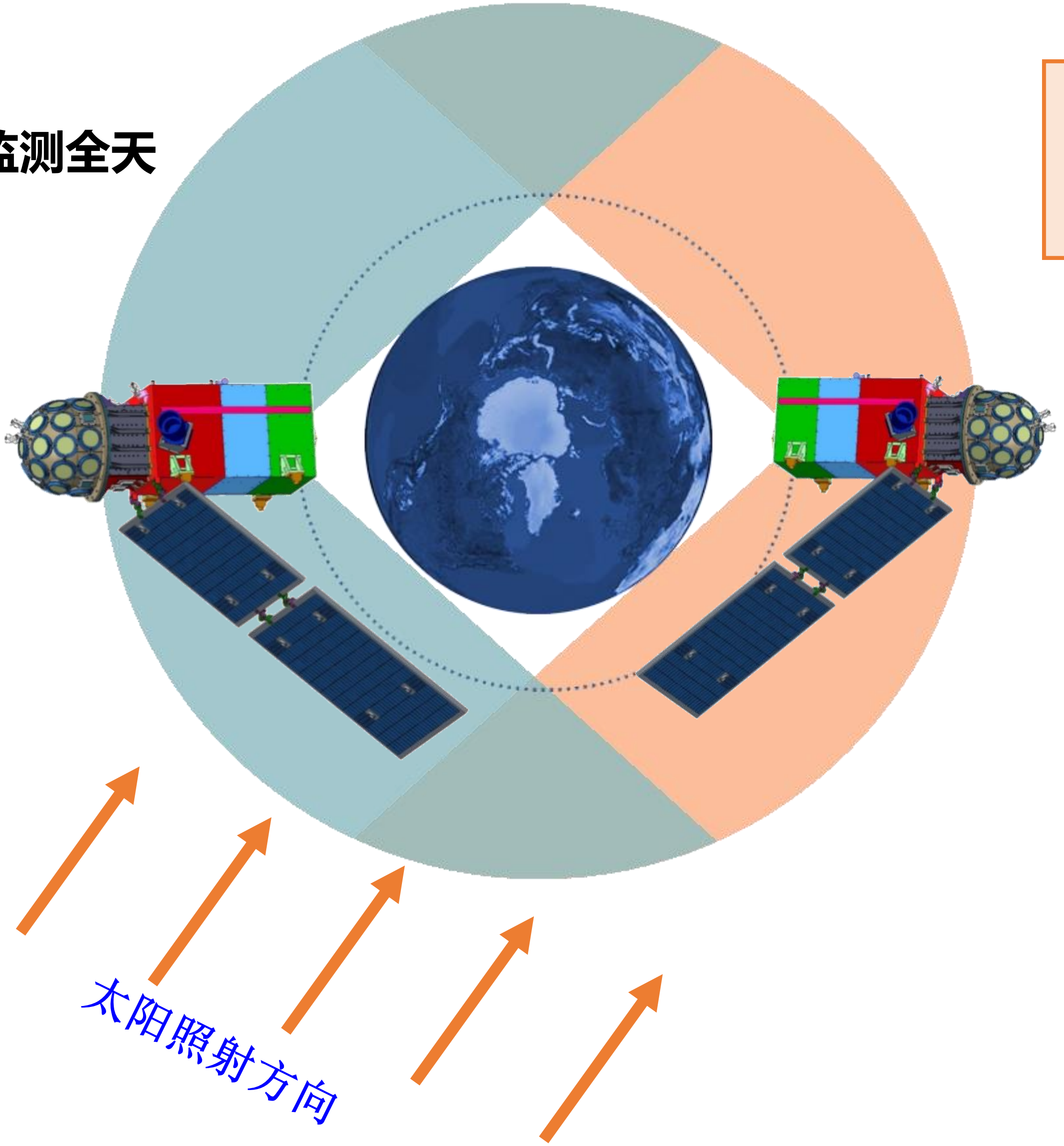
P. Lv[a,b,c], S.L. Xiong[a], X.L. Sun[a,b], J.G. Lv[a,b] and Y.G. Li[a]

Published 16 August 2018 • © 2018 IOP Publishing Ltd and Sissa Medialab

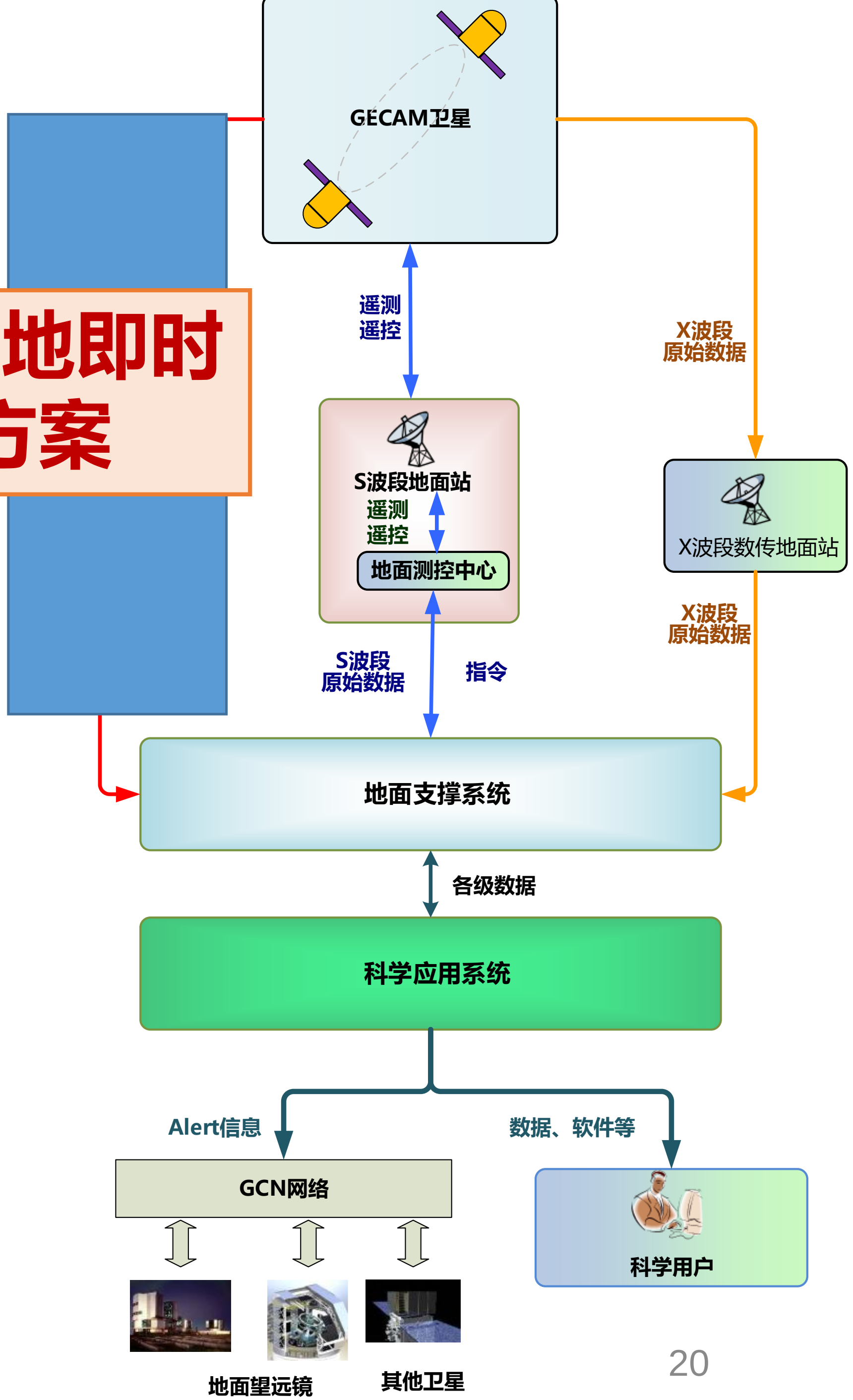
Journal of Instrumentation, Volume 13, August 2018

GECAM双星在轨运行

双星监测全天

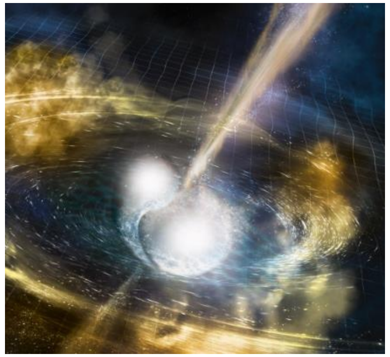
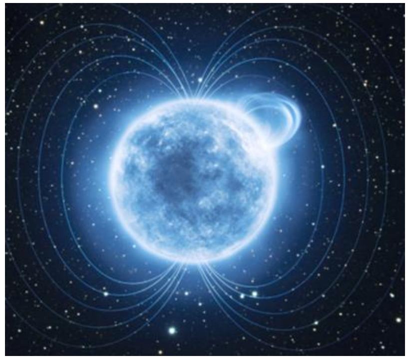
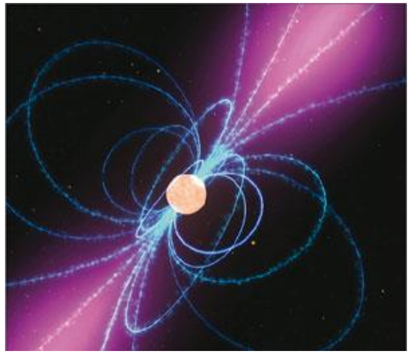


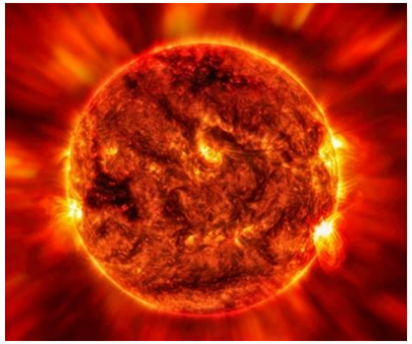
创新的星地即时通讯方案

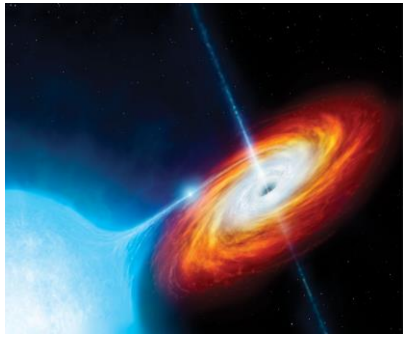
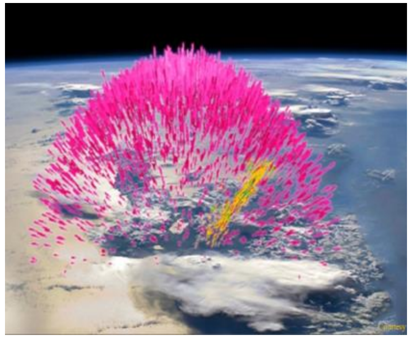


GECAM卫星科学目标

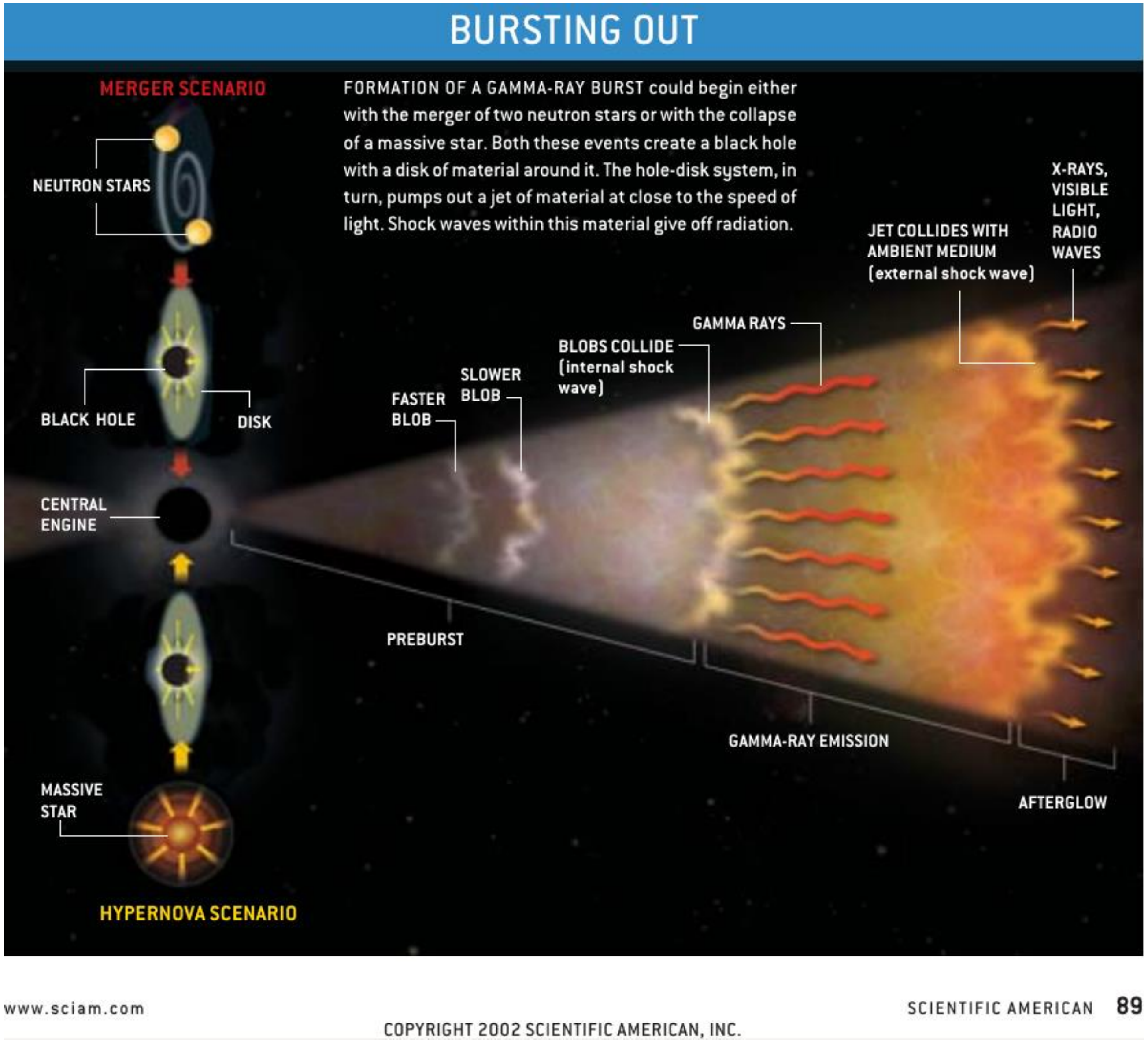
- **伽马射线暴**
  - 引力波伽马暴
  - 快速射电暴的高能辐射
  - 高能中微子的高能辐射
  - 超长暴与超软暴
- **磁星暴发**
- **黑洞潮汐瓦解恒星事件**
- **X射线双星**
- **X射线脉冲星**
- **太阳耀斑**
- **地球伽马闪/地球电子束**

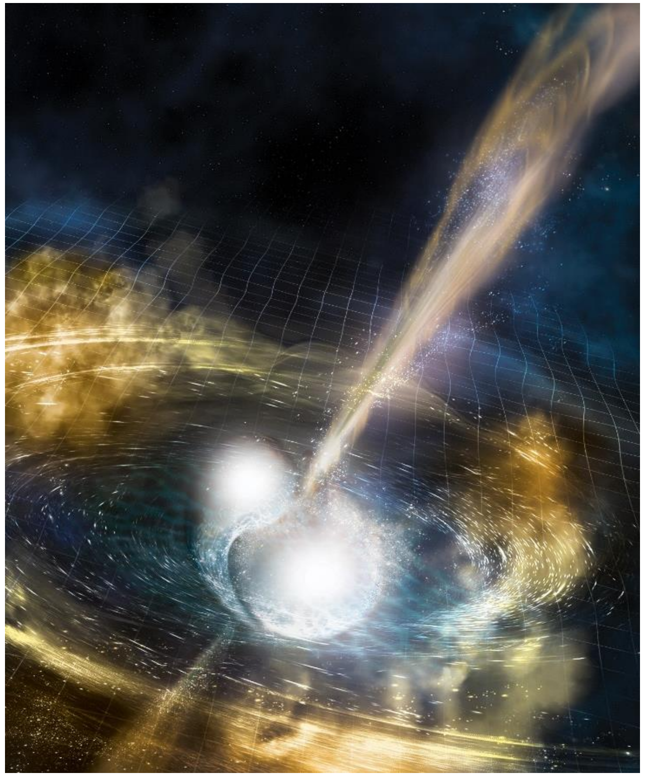



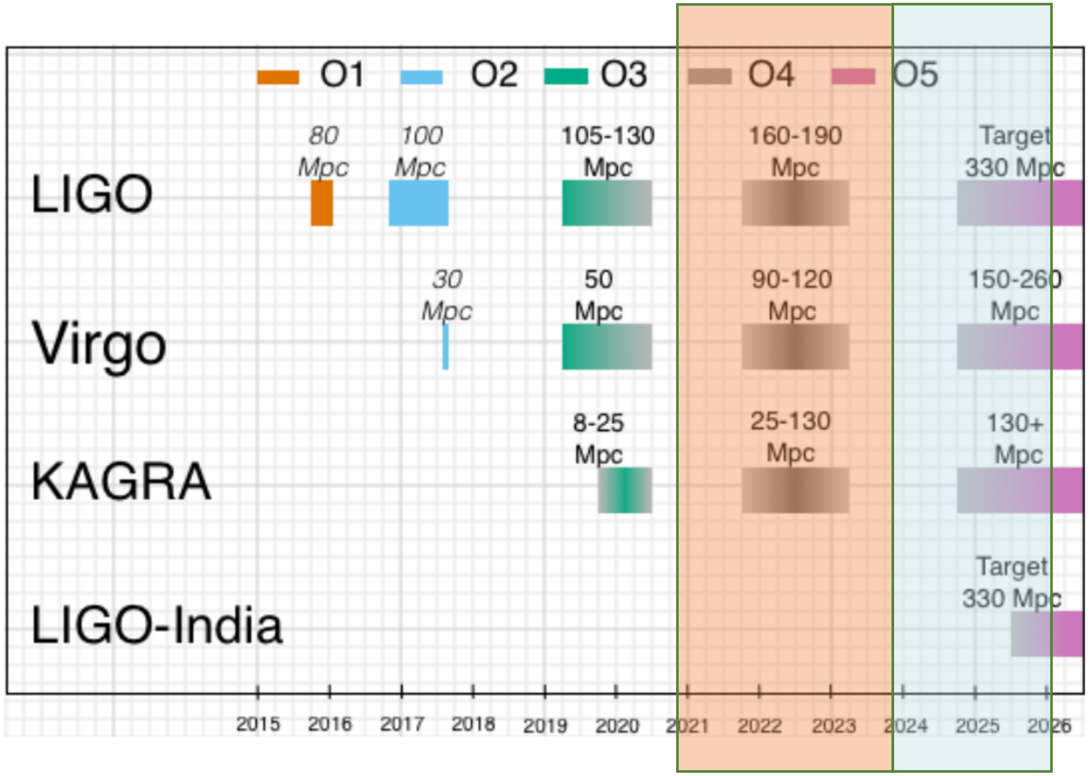
Gamma-Ray Burst (GRB)



- **Discovered** in late 1960s
- **Related Sciences**
  - star, galaxy, universe
- **Observations**
  - Prompt emission: short/long
  - Afterglow: rich features
  - Multi-messenger: GW, …
- **Open questions**
  - Progenitor
  - Central engine
  - Jet launch
  - Jet composition
  - Radiation mechanism
  - Standard candle?
  - …

全天监测引力波伽马暴

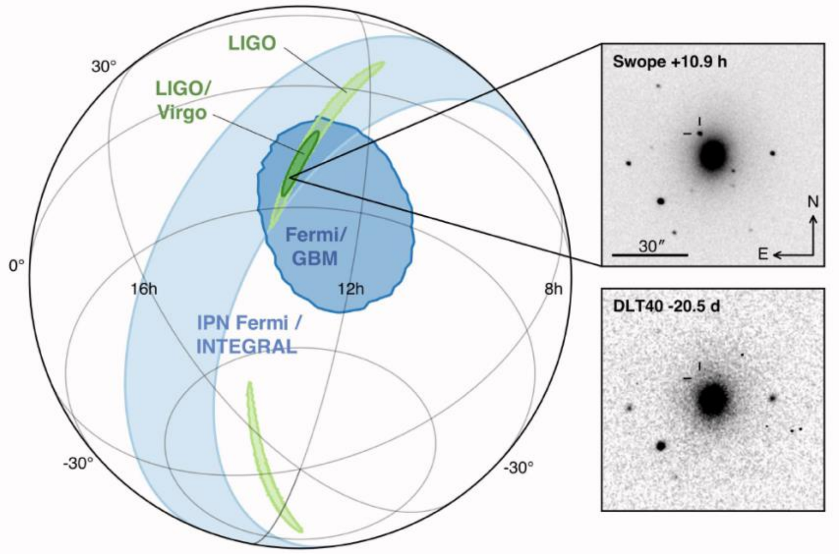




GECAM考核寿命3年，设计寿命5年

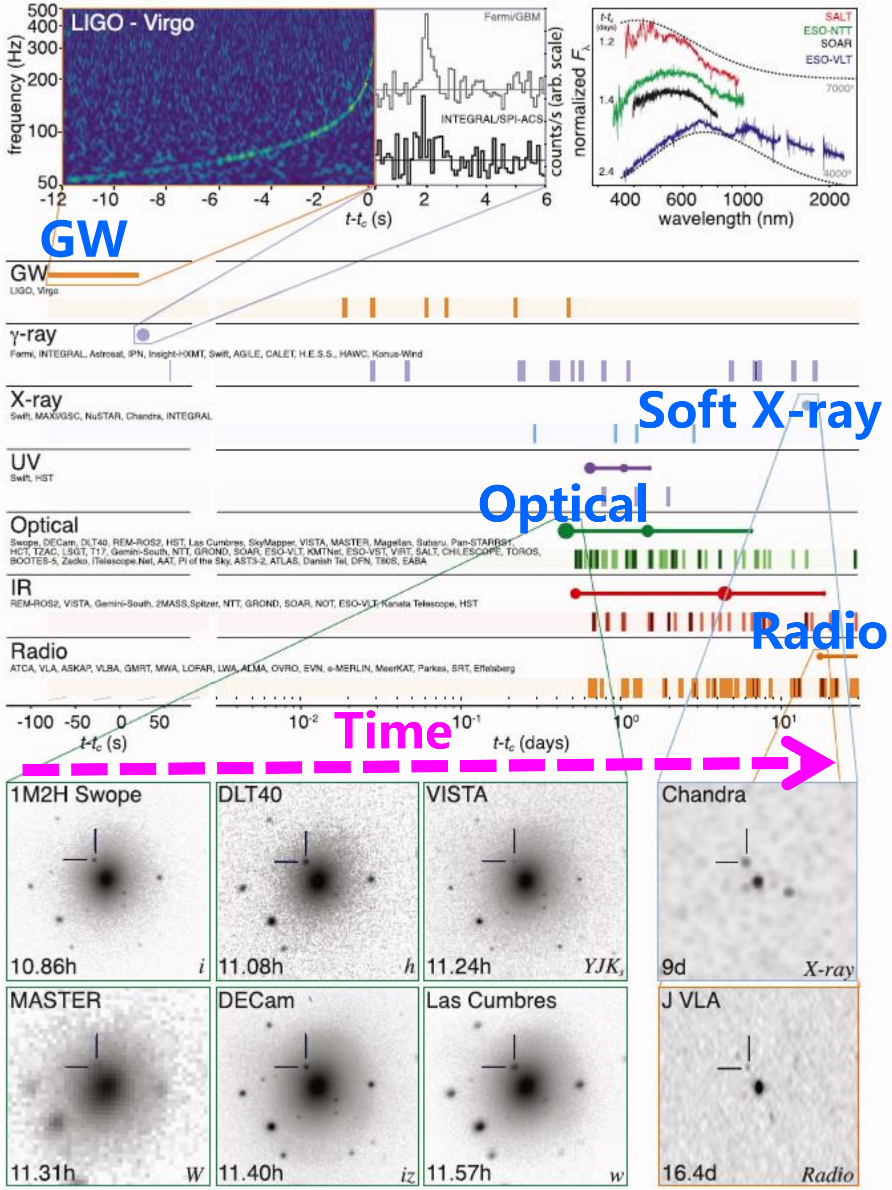
准实时提供触发警报，联合观测和后随观测

- **Early alert, even earlier than GW**
- Independent confirmation
- Reduced localization area facilitating follow-up observations
- Provide important astrophysics context



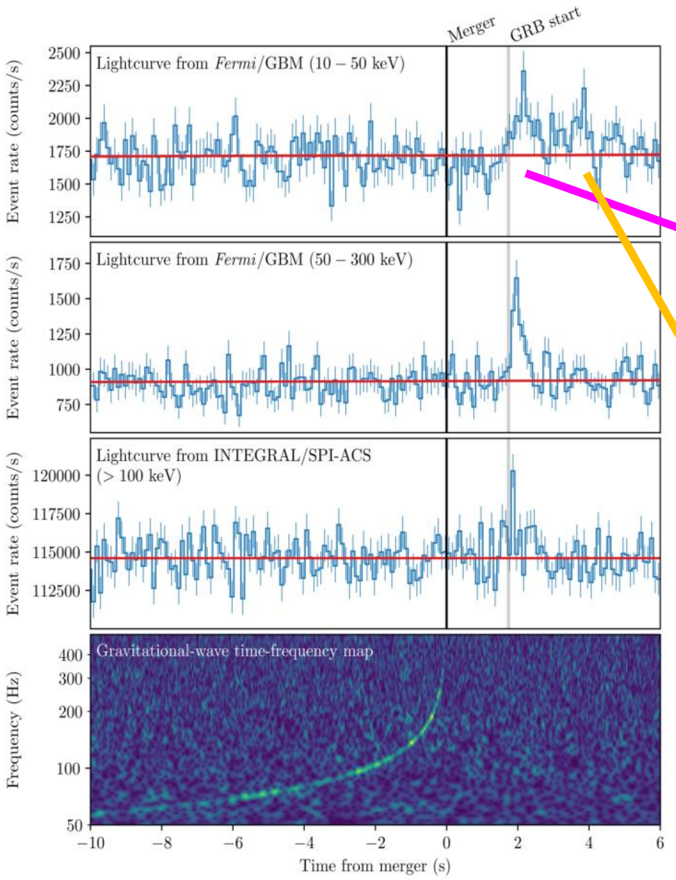
Localization is crucial for follow-up

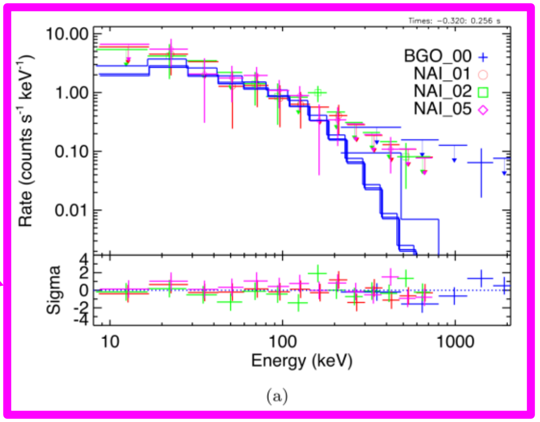
GRB170817A



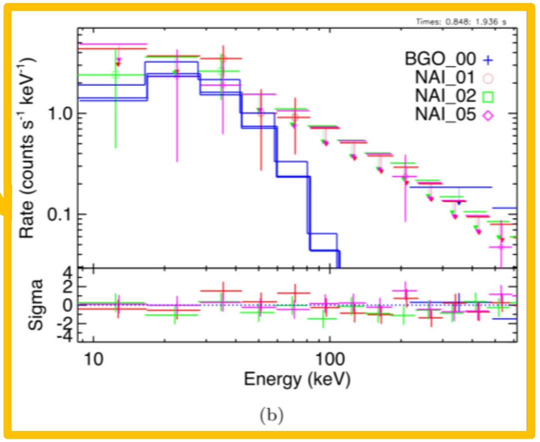
测量引力波伽马暴的时变和能谱等性质

- Delayed ~1.7 s after the GW
- Intrinsic weak, 3-4 order of magnitude weak than previously known GRBs
- hard component followed by a soft one (likely Black Body component)





First Component



Second Component

GECAM detection rate of BNS GWGRB

(Abbott+2018, Living Rev Relativ)

Epoch			2015 – 2016	2016 – 2017	2018 – 2019	2020+	2024+
Planned run duration			4 months	9 months	12 months	(per year)	(per year)
Expected burst range/Mpc		LIGO	40 – 60	60 – 75	75 – 90	105	105
		Virgo	—	20 – 40	40 – 50	40 – 70	80
		KAGRA	—	—	—	—	100
Expected BNS range/Mpc		LIGO	40 – 80	80 – 120	120 – 170	190	190
		Virgo	—	20 – 65	65 – 85	65 – 115	125
		KAGRA	—	—	—	—	140
Achieved BNS range/Mpc		LIGO	60 – 80	60 – 100	—	—	—
		Virgo	—	25 – 30	—	—	—
		KAGRA	—	—	—	—	—
Estimated BNS detections			0.05 – 1	0.2 – 4.5	1 – 50	4 – 80	11 – 180
Actual BNS detections			0	1	—	—	—
90% CR	% within	5 deg^2	< 1	1 – 5	1 – 4	3 – 7	23 – 30
		20 deg^2	< 1	7 – 14	12 – 21	14 – 22	65 – 73
	median/deg^2		460 – 530	230 – 320	120 – 180	110 – 180	9 – 12
Searched area	% within	5 deg^2	4 – 6	15 – 21	20 – 26	23 – 29	62 – 67
		20 deg^2	14 – 17	33 – 41	42 – 50	44 – 52	87 – 90

Expected GWGRB rate from BNS in 2020

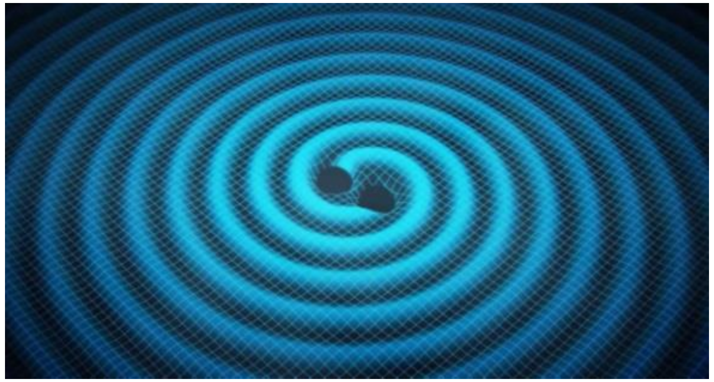
- **Fermi/GBM： 0.3-1.7/year**
- **GECAM: 2-10/year**

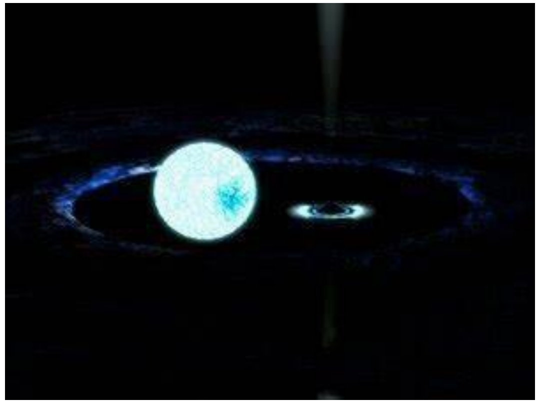
GECAM improvements over Fermi/GBM:

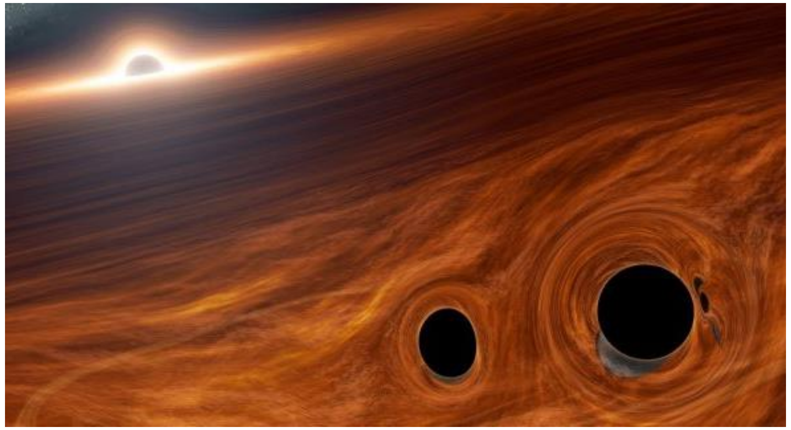
(1) FoV & duty cycle: x 2

(2) Sensitivity： x ~3 (volume)

全天监测其它类型的引力波的高能辐射







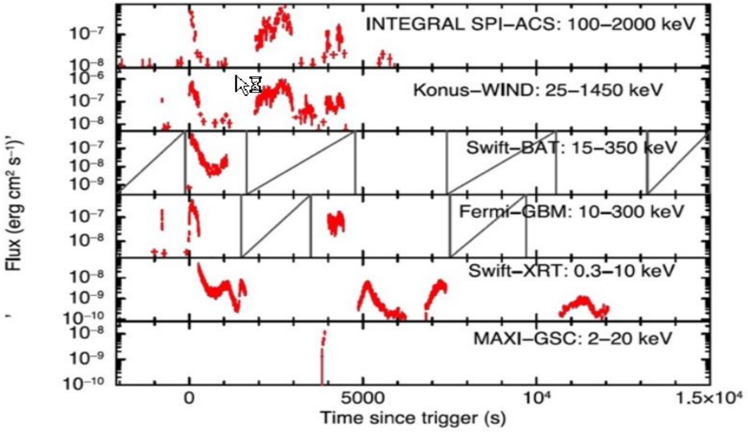
BH-BH merger
(GW150914)

BH-NS merger
(GW190814)

BH-BH merger
(GW190521)

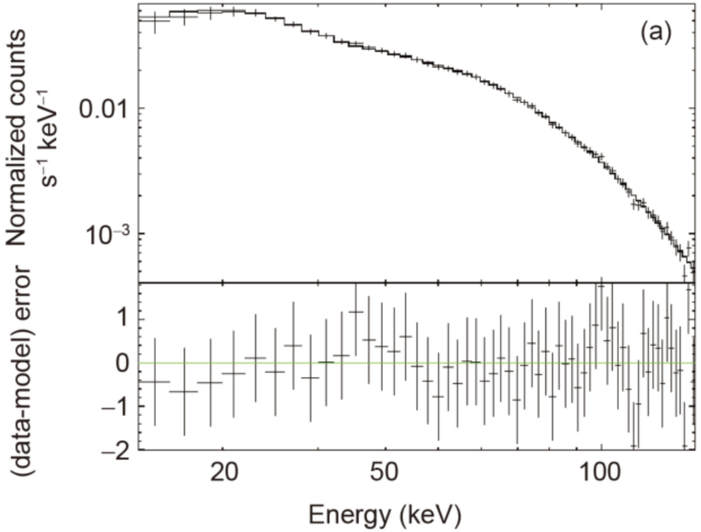
全天监测各种类型的伽马暴

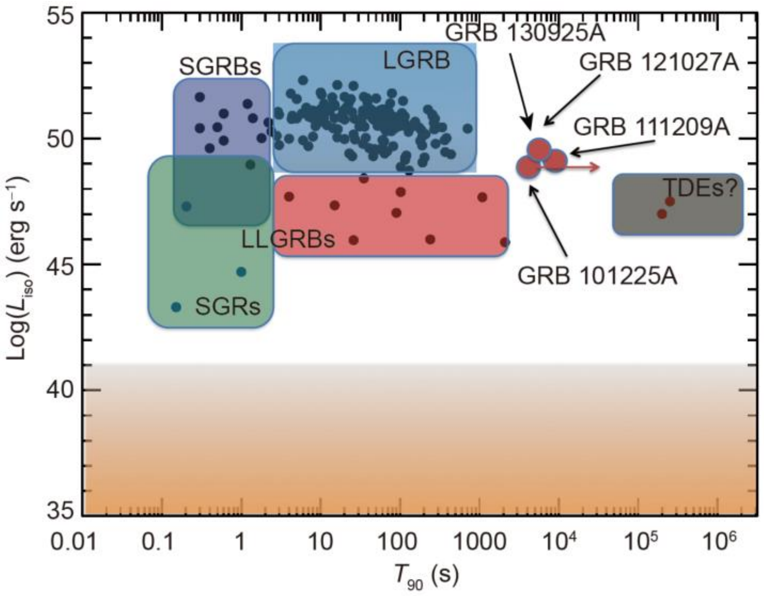
- **发布伽马暴观测预警，包括时间、定位、持续时间、能谱等信息**
- **各种类型的暴**
  - 超长，超软
- **测量伽马暴的能谱、时变**

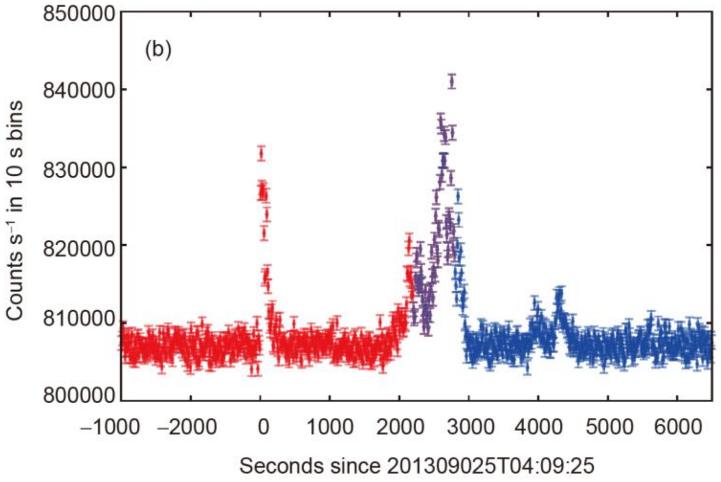


Evans et al. 2014

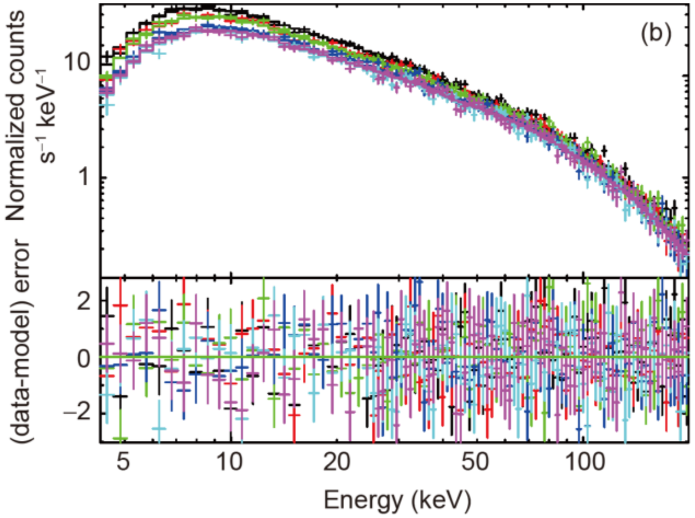
Swift/BAT





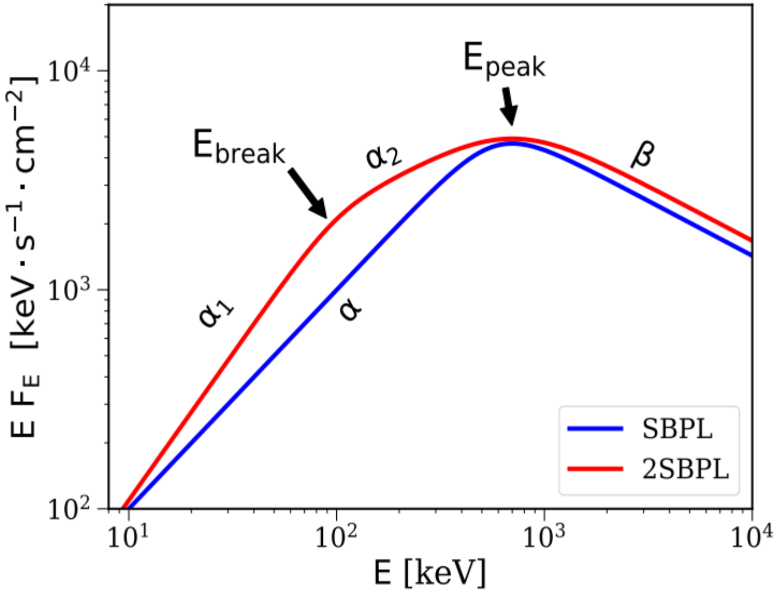


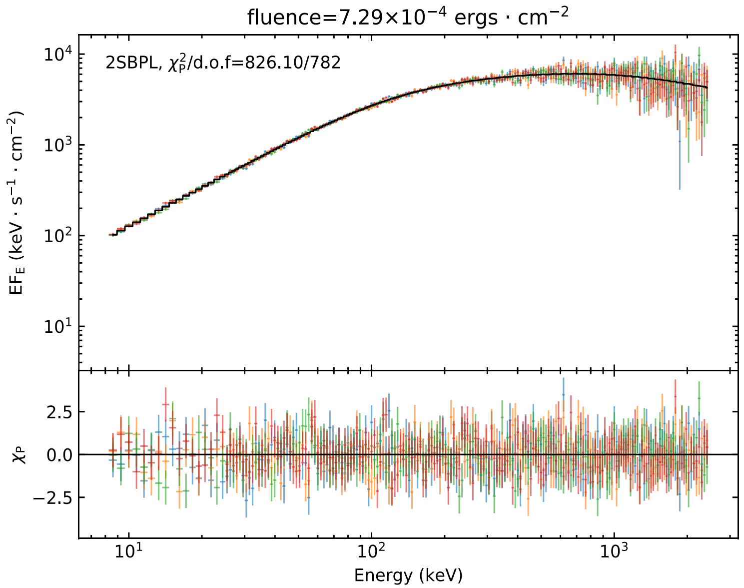
GECAM观测GRB 130925A的模拟



GECAM观测XRR 050525A的模拟

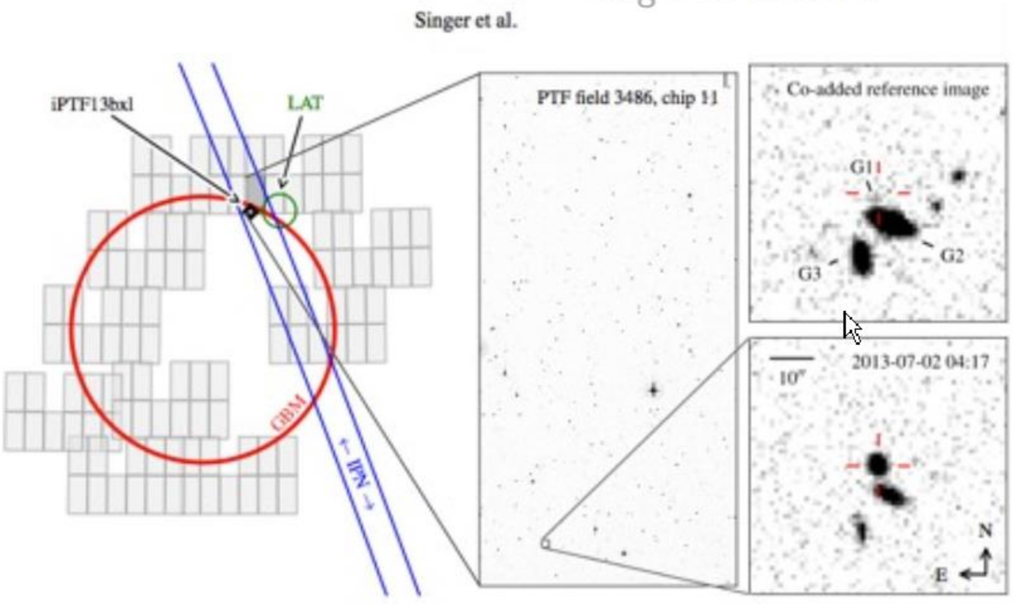
测量瞬时辐射、引导后随观测



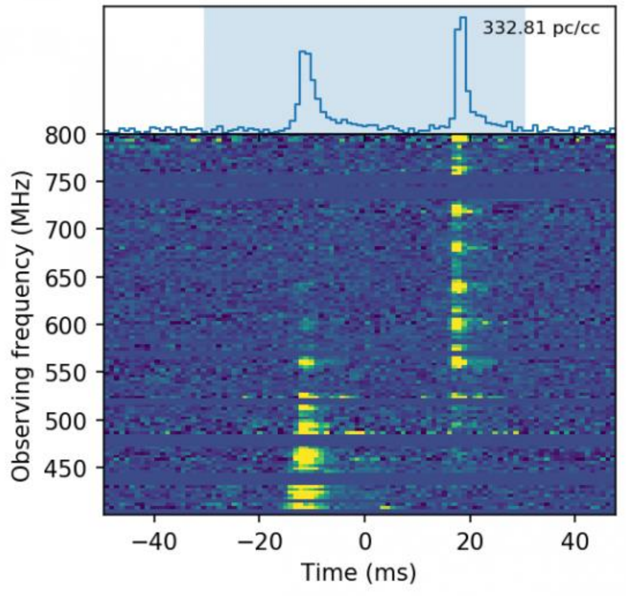


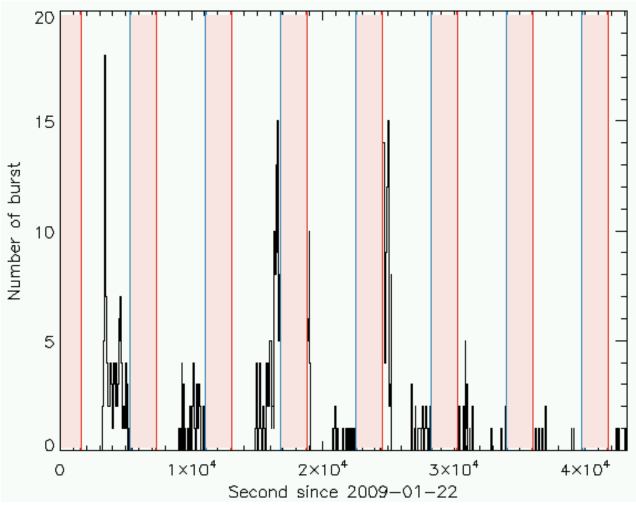
GRB 130702A - iPTF 13bxl

Singer et al. 2014

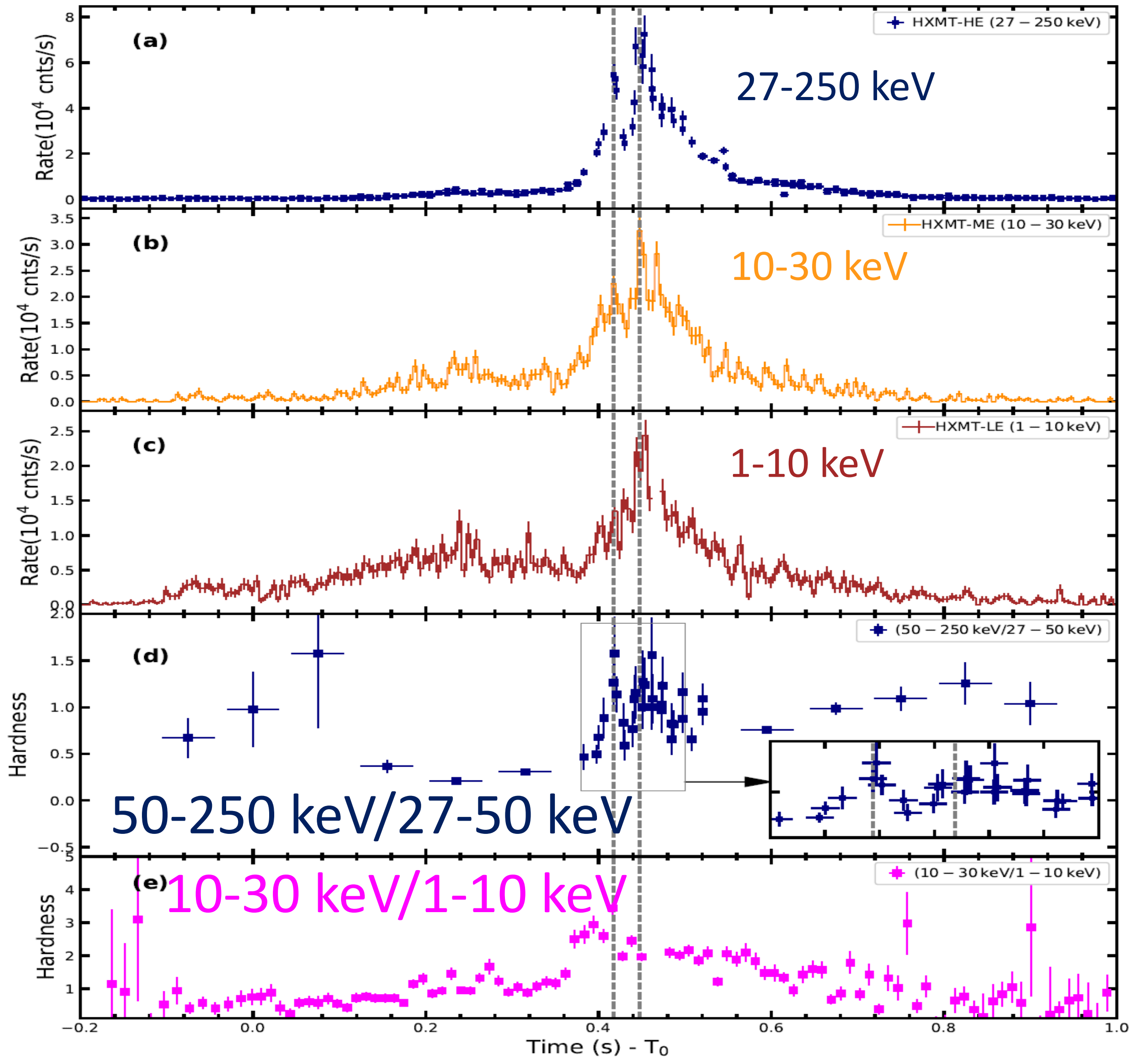


全天监测快速射电暴高能对应体和磁星暴发



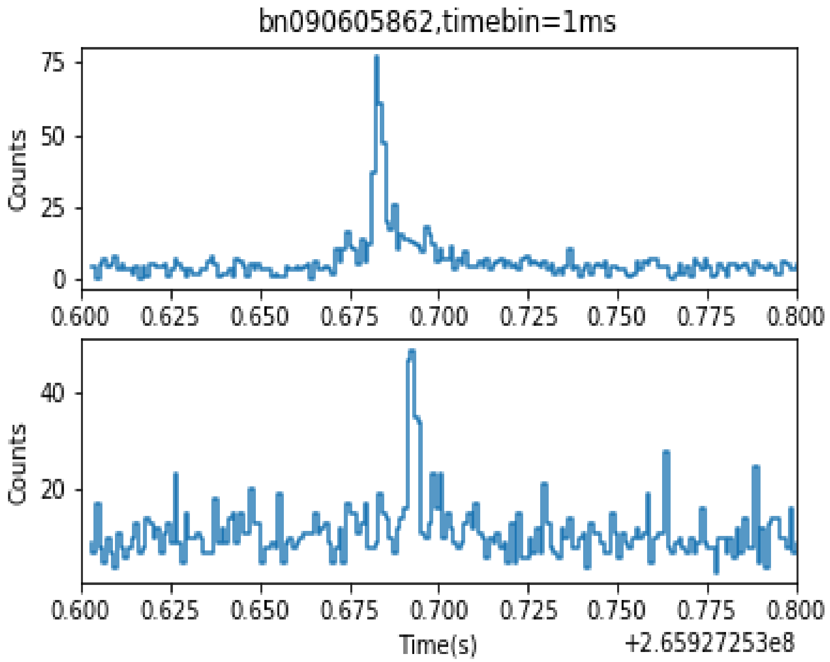


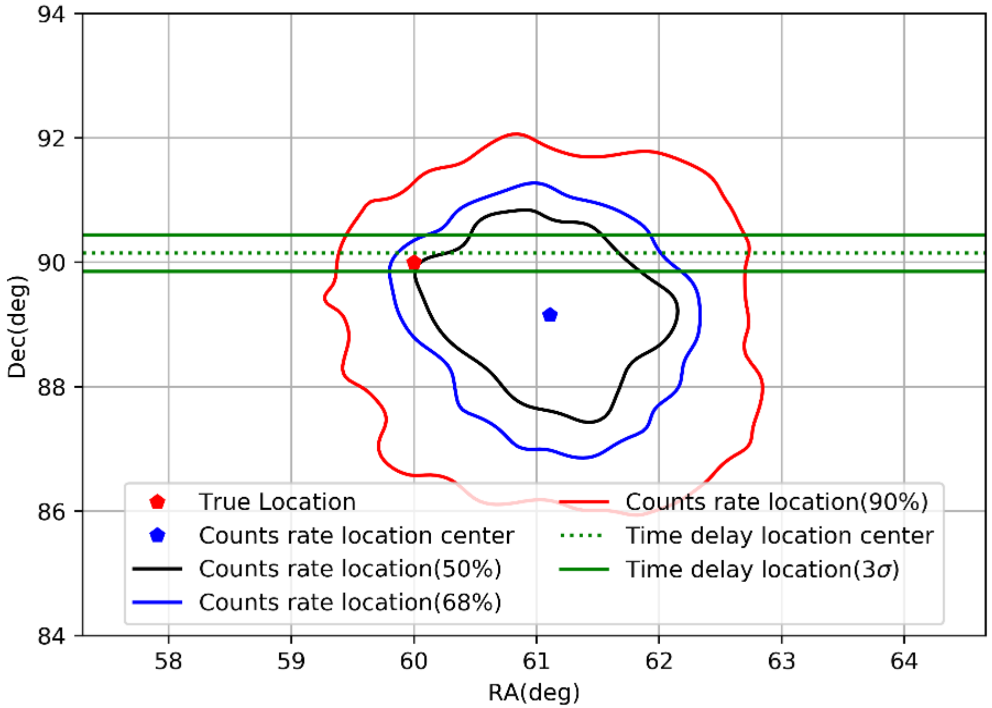
磁星爆发，阴影为GBM进入SAA区



完整监测磁星暴发，发现新磁星

GBM bn090605862

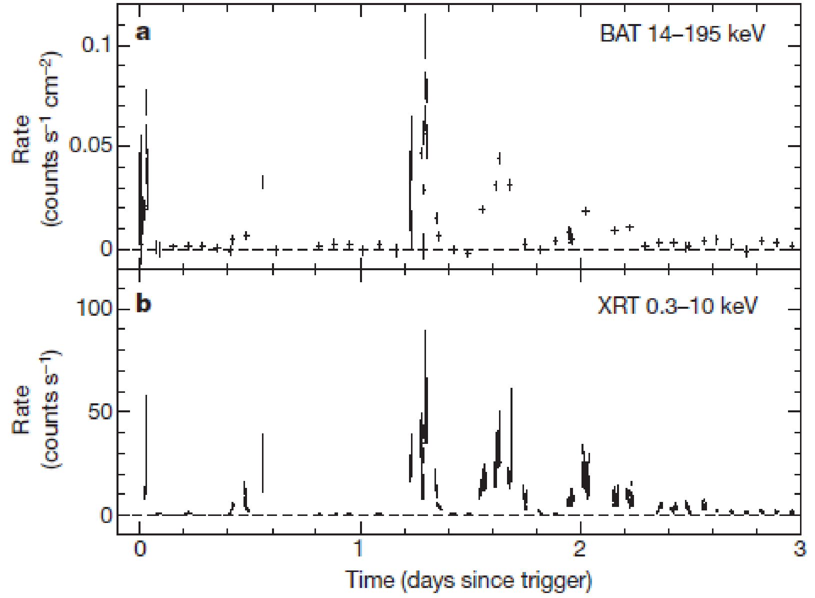


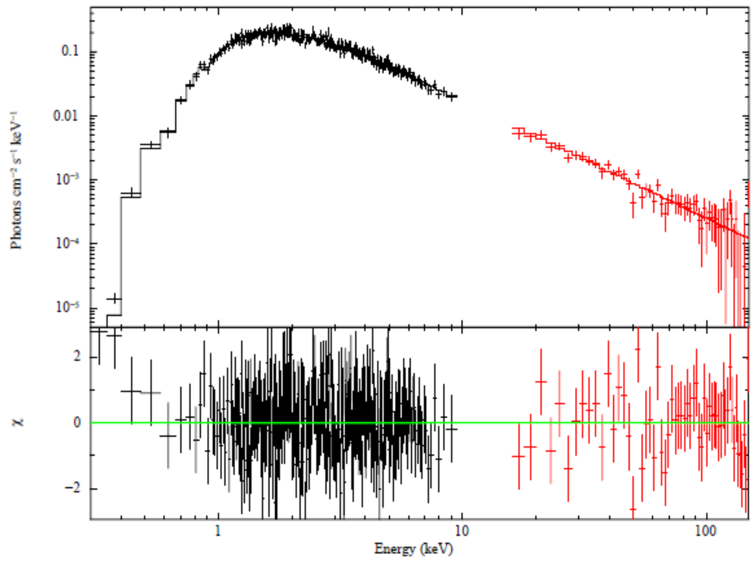


Location belt width: 0.6 deg (3-sigma)

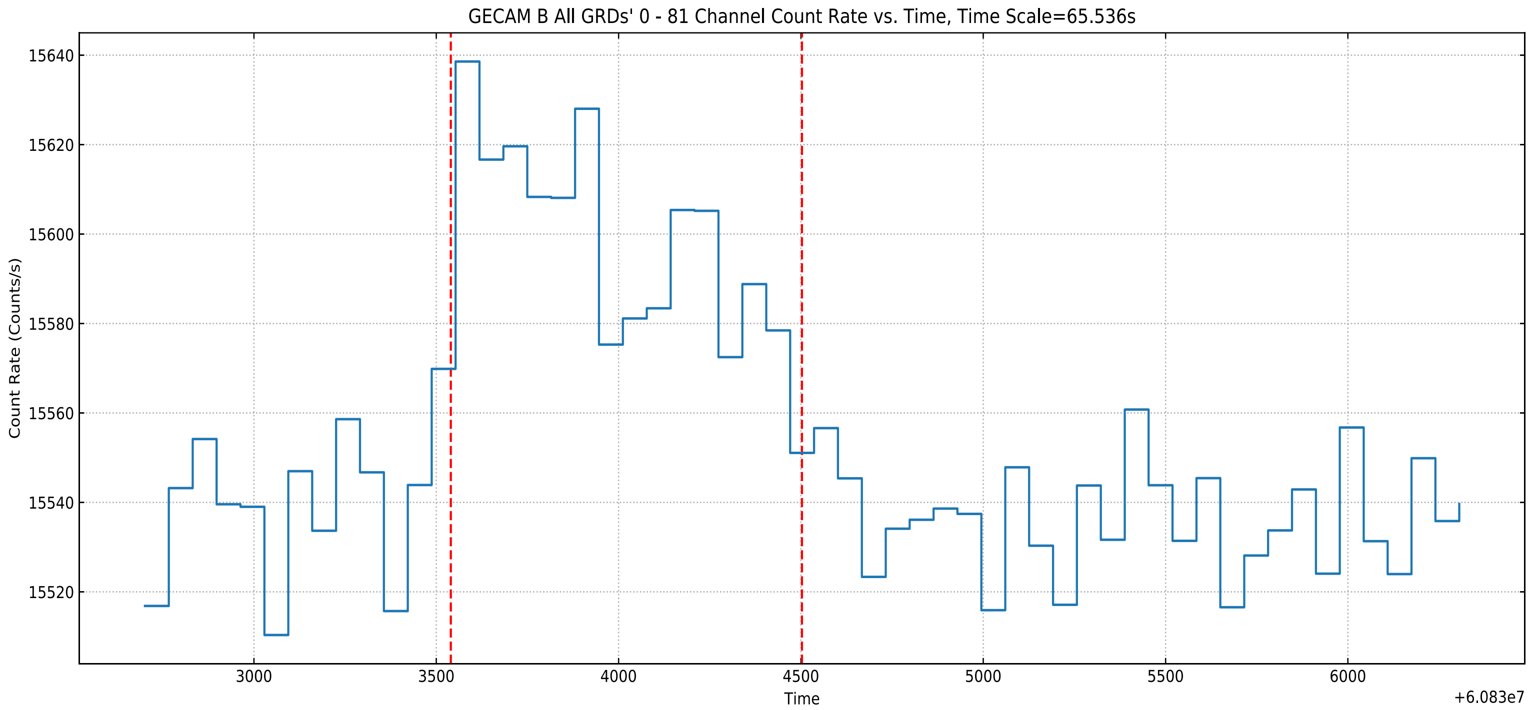
(喷流型)潮汐瓦解事件

Swift J1644+57





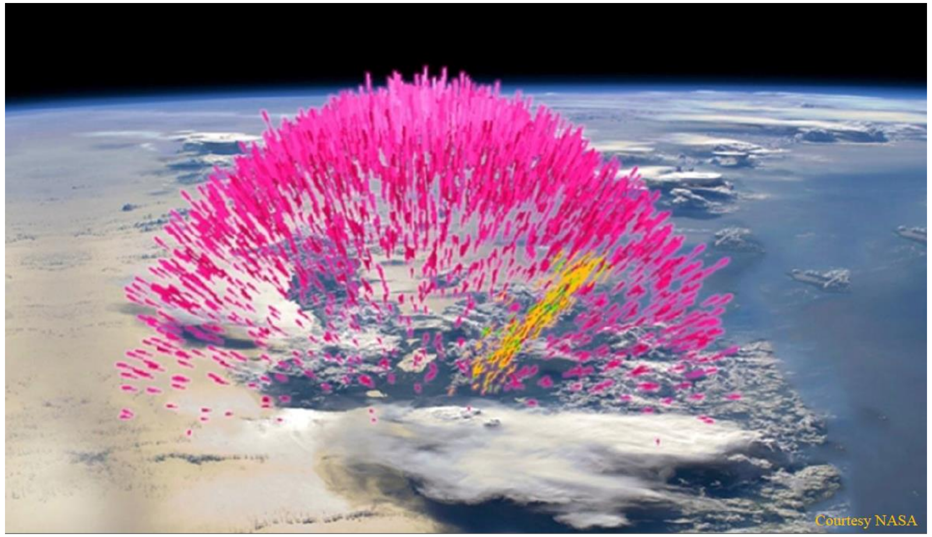
2011年3月29日的一次明亮的耀发

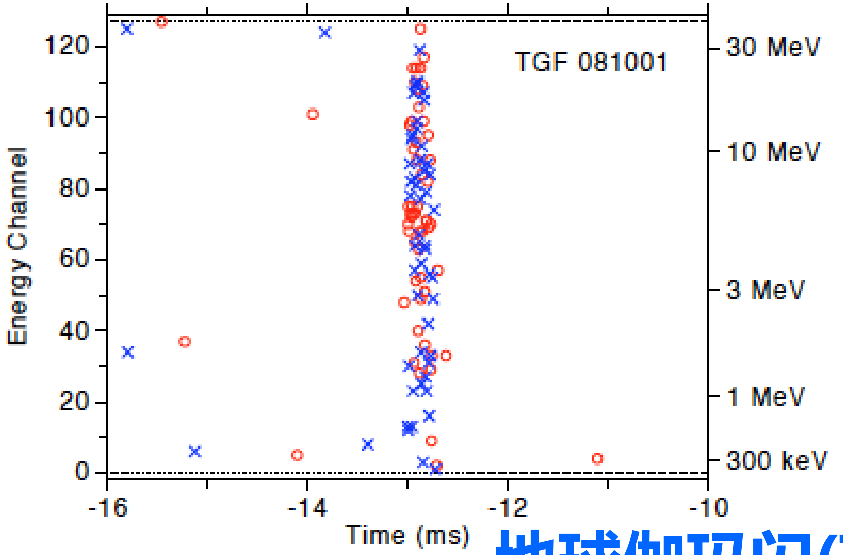


GECAM对Swift J1644+57的模拟观测光变曲线

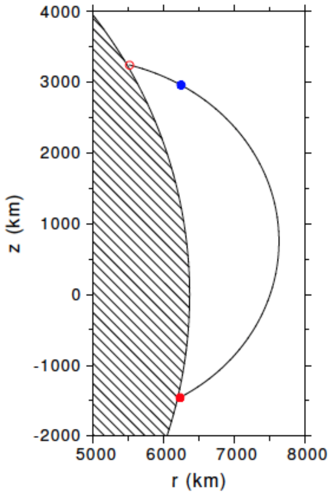
监测太阳与地球的高能辐射

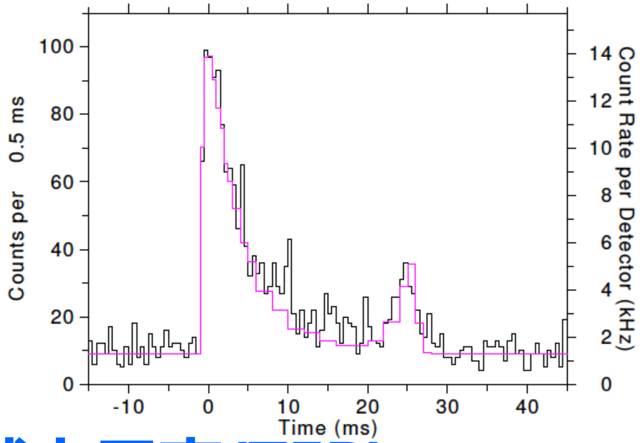
- **监测SFL宽波段辐射**
  - 热成分，非热成分
  - 不间断地监测!
- **最好的TGF/TEB探测器**
  - 两颗卫星，600km，~29度
  - GRD和CPD共同鉴别TEB
  - 有效排除宇宙线粒子的干扰





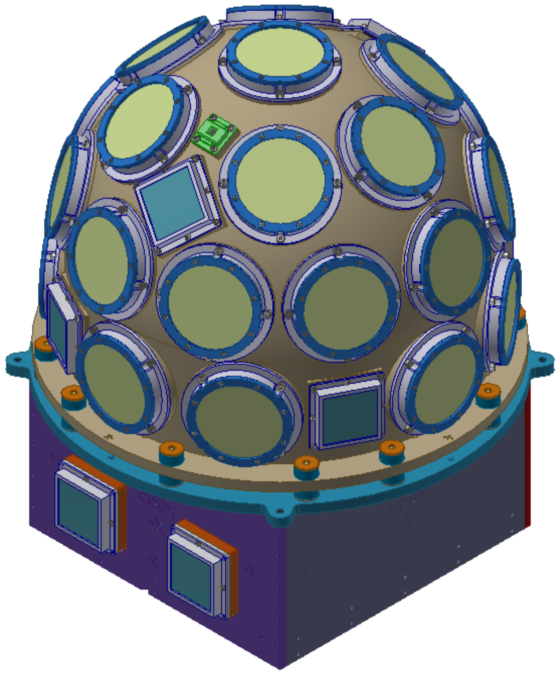
地球伽玛闪(TGF)





地球电子束(TEB)

GECAM探测器配置



For each GECAM satellite

- 25 Gamma-ray detectors (GRD, circle)
- 8 Charged particle detectors (CPD, square)

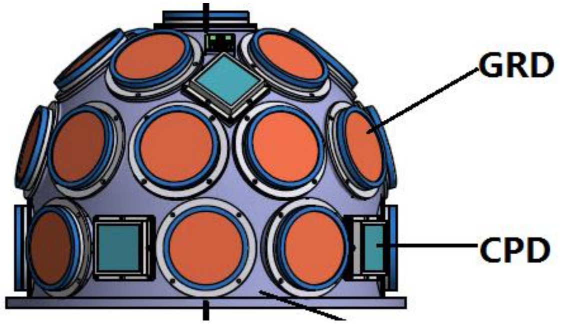
- **GRD** **($LaBr_3$+SiPM)**
  - Monitor x/gamma-ray from all-sky
  - Temporal, spectral, localization measurement for GRB
- **CPD** **(Plastic scintillator + SiPM)**
  - Monitor charged particles (e, p)
  - Identify the GRD bursts produced by charged particles in the Earth orbit (i.e. distinguish GRB and fake-GRB)

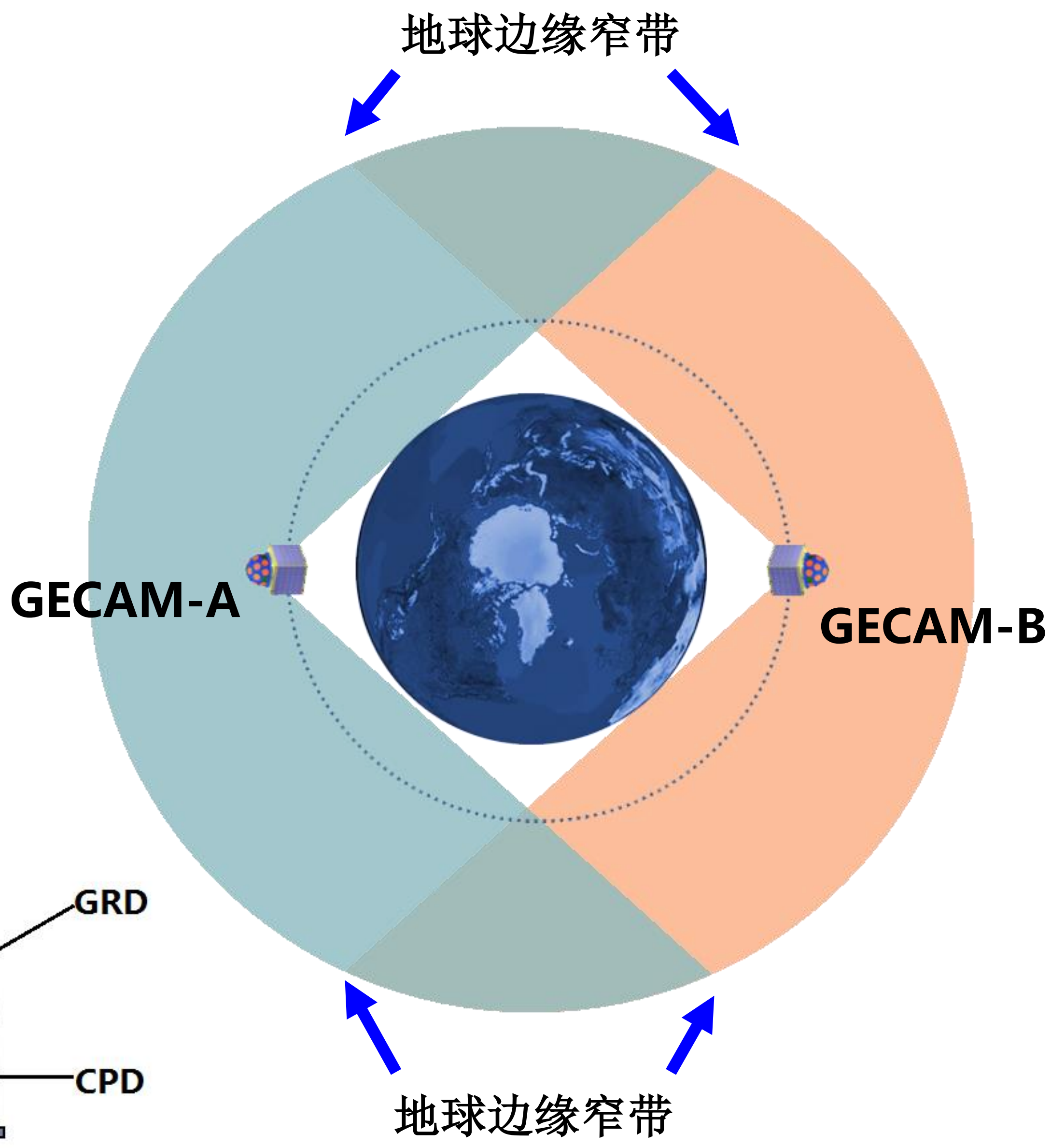
对各类源的探测方法

- **暴发搜索：各类暴发源/暂现源，监测全天**
  – 计数率突然超出本底涨落的合理范围
  – 空间粒子事件（SAA区和粒子沉降区）
- **脉冲折叠：脉冲星，周期信号，监测全天**
  – 绝对时间、卫星位置（X/Y/Z）
- **地球掩蚀：亮的持续源，地球边缘的窄带**
  – 卫星位置、地球大气模型

GRD探测器信号组成

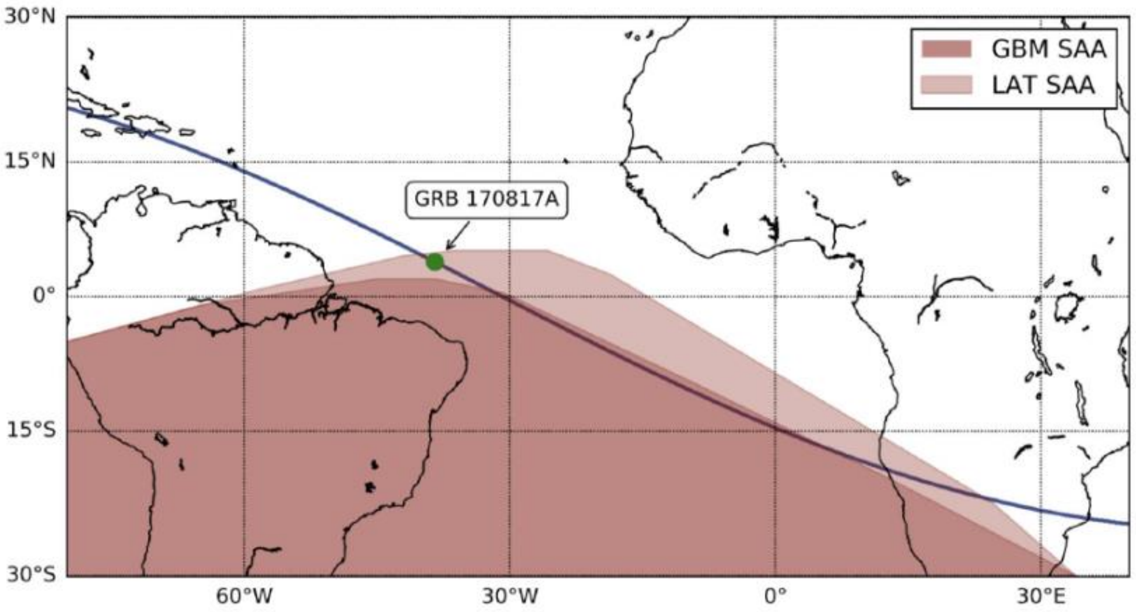
各类源：	各种本底：
伽马暴	CXB
X射线源	SAA活化
脉冲星	Particles
太阳X射线	晶体自身本底





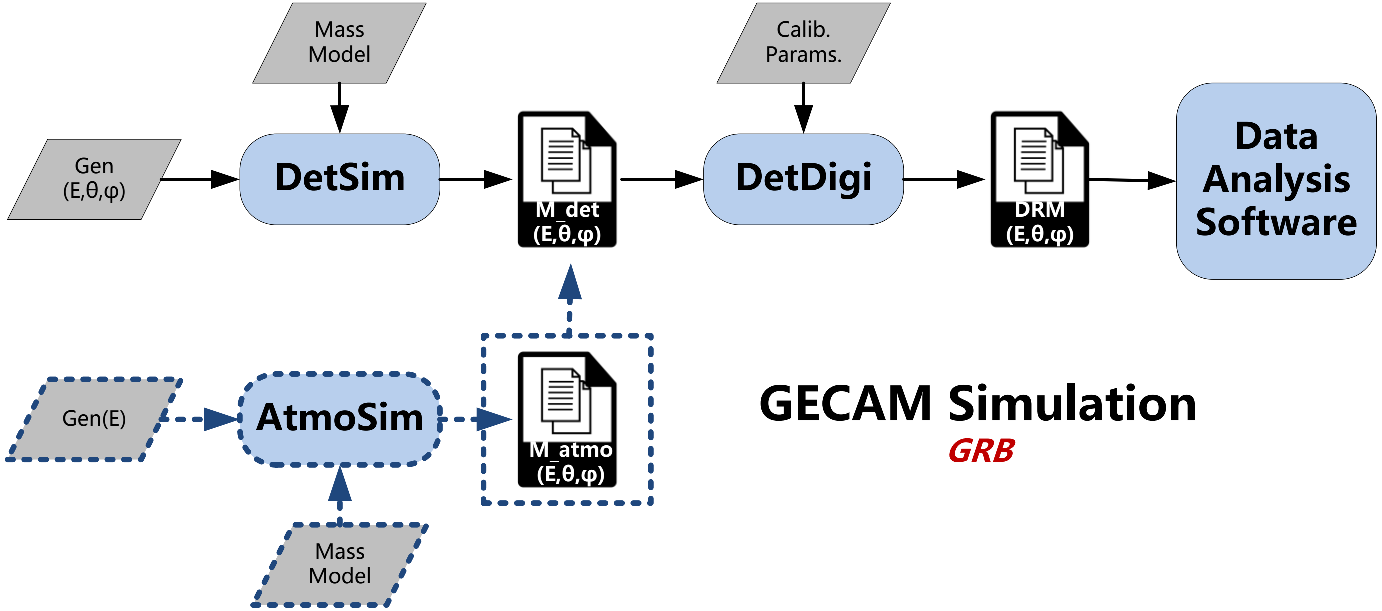
载荷观测策略：全天视场、实时触发定位

- **非SAA区**
  - 记录事例数据(EVT)和并道数据(BTIME+BSPEC)；开启在轨触发定位
- **SAA区:**
  - 尽量开机运行（虽然本底高，灵敏度降低，但仍有一定的探测能力）
  - 仅记录并道数据，不记录物理事例数据；关闭在轨触发定位功能，避免过多误触发

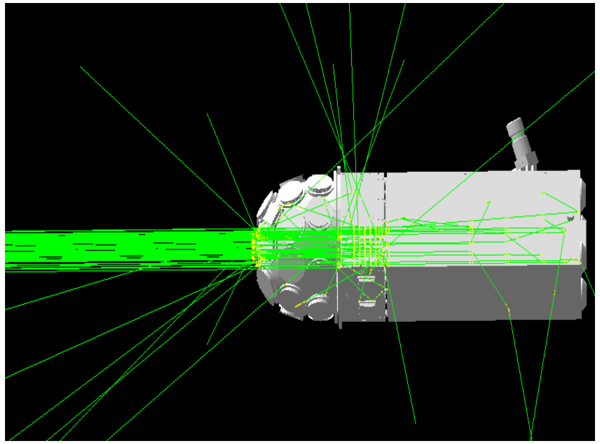


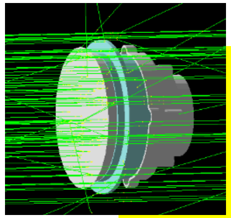
Fermi的SAA关机问题

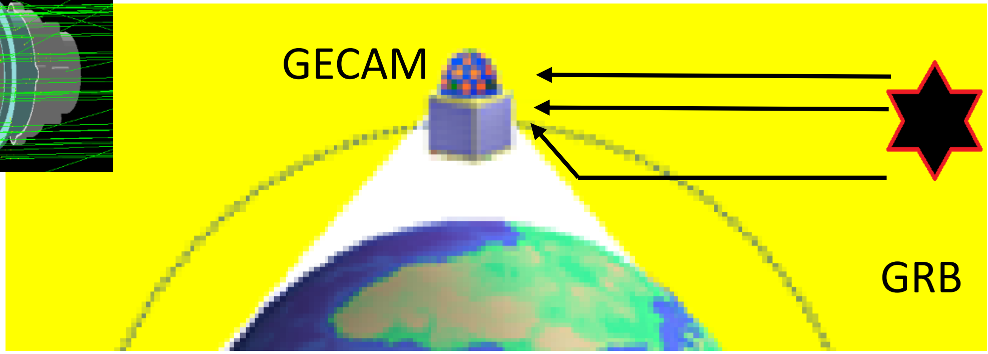
Monte Carlo simulations



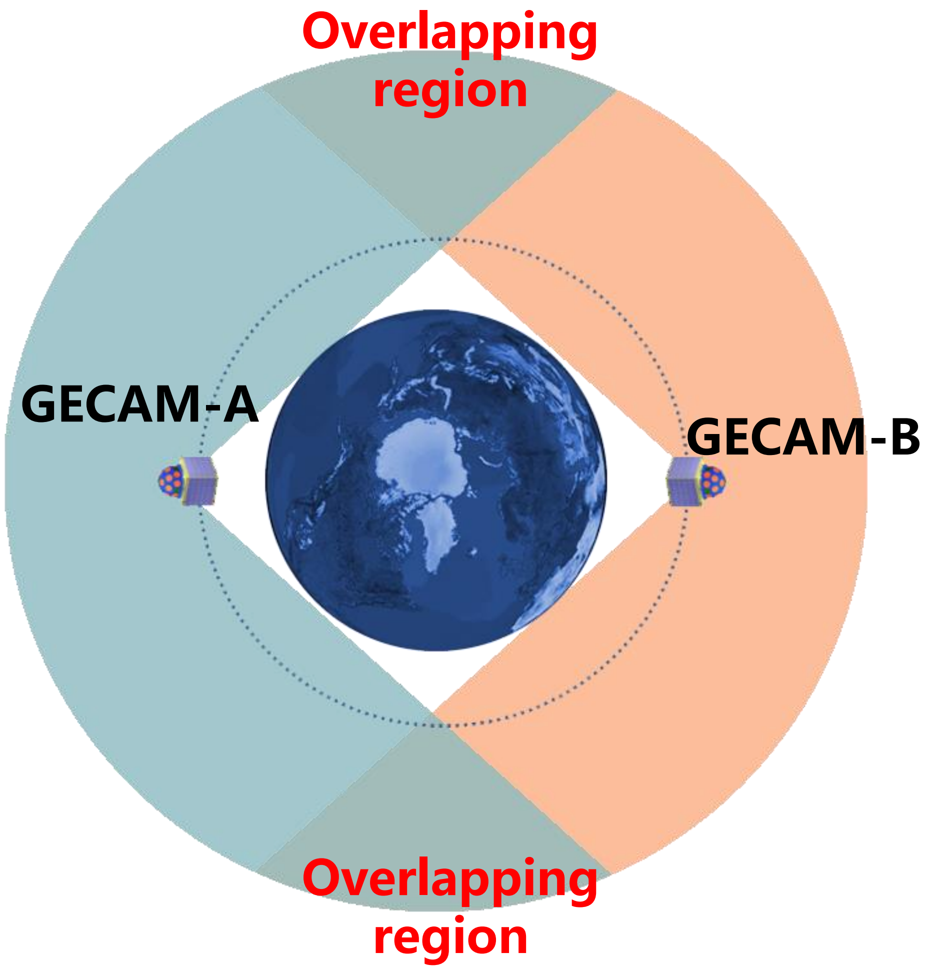
GECAM Simulation
GRB

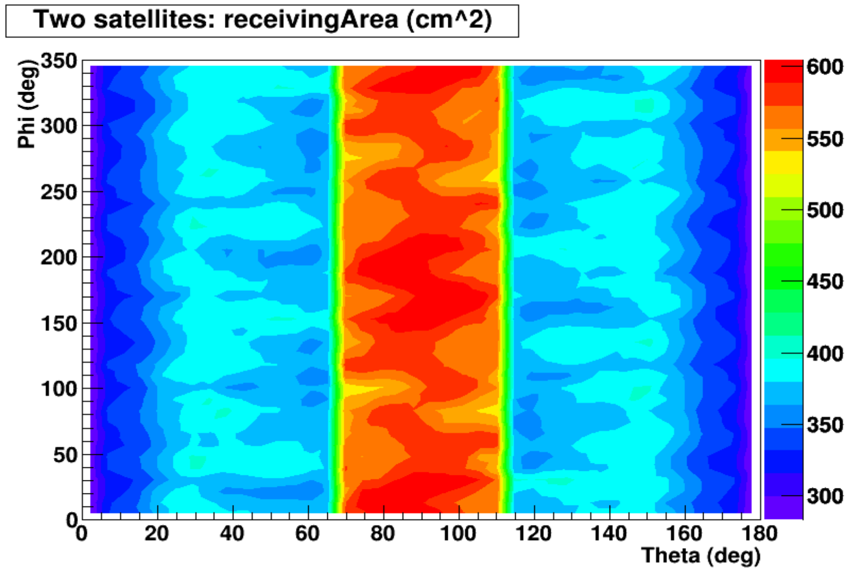


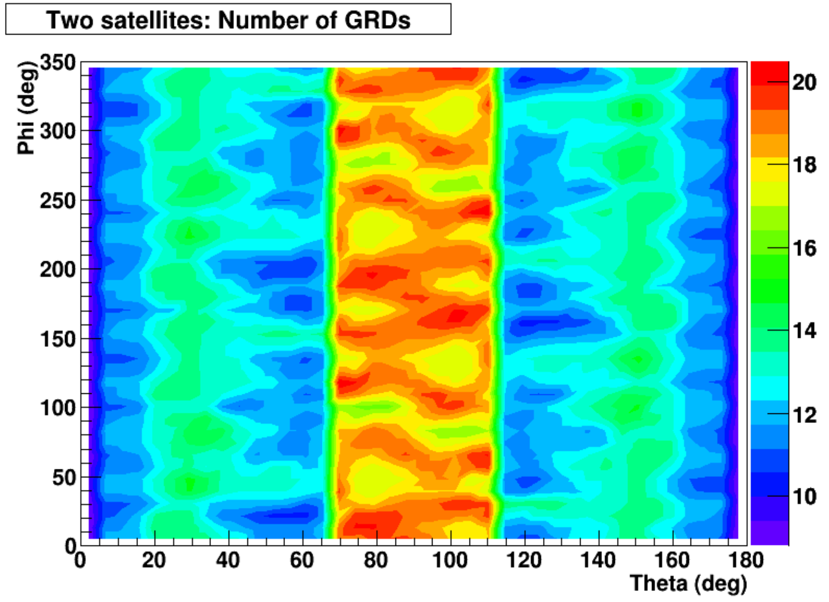




Field of View (FOV)





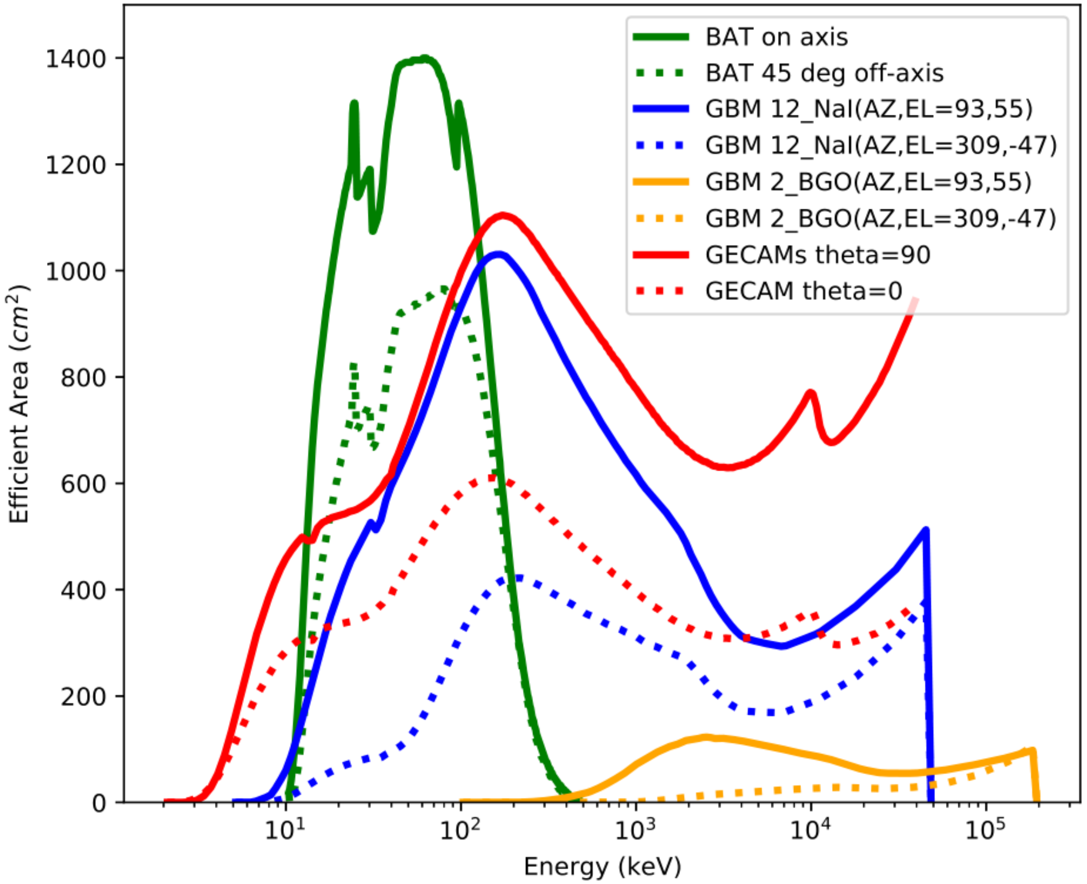


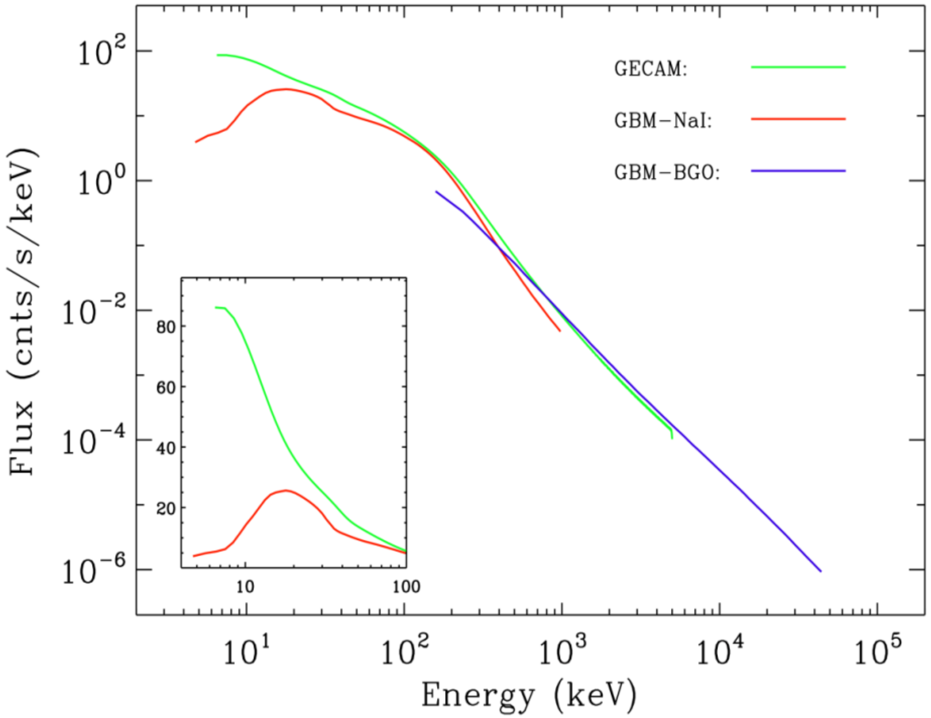
100% all-sky monitoring with
~40% GRBs detected by both satellites

Energy range and Effective Area

- **Lower energy coverage down to ~6 keV**

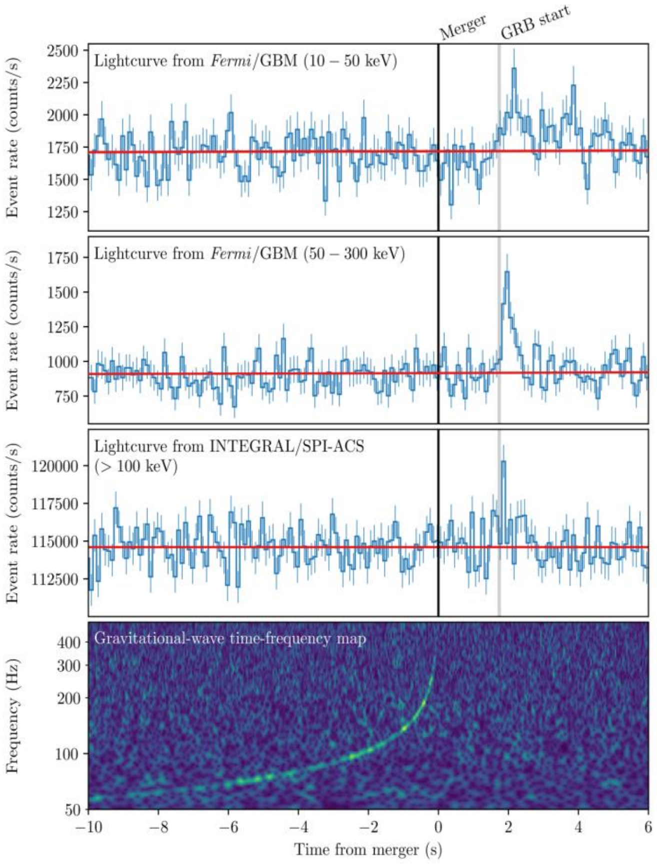
  → Very suitable for detecting GRB170817A-like GWGRB

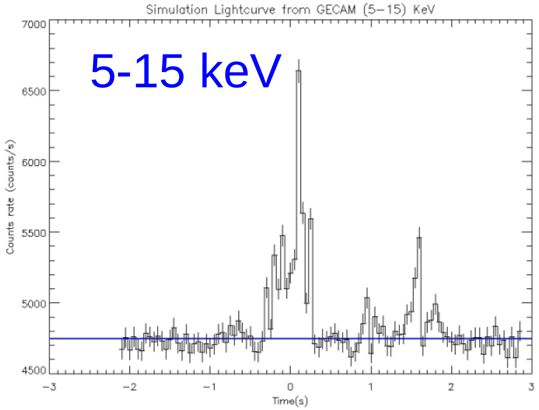


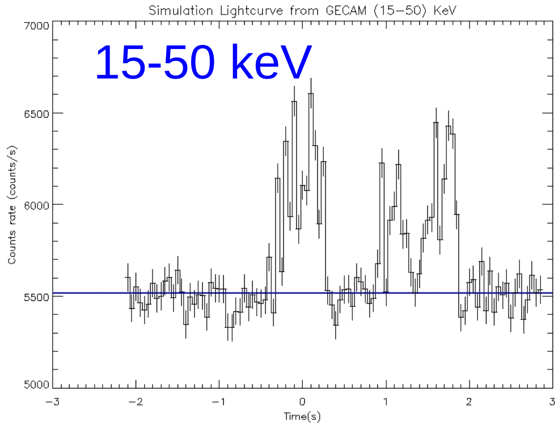


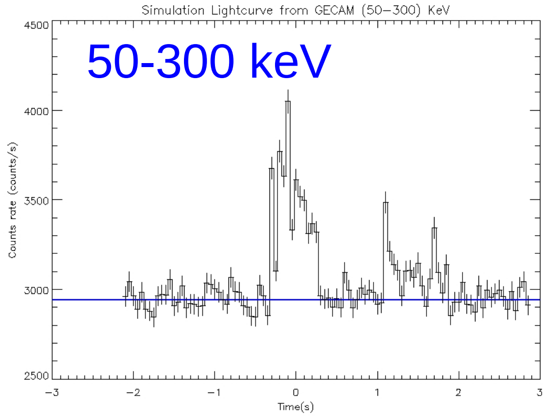
GECAM低能区探测能力占优

GECAM detection of GRB170817A (simulation)









GECAM vs. Fermi/GBM

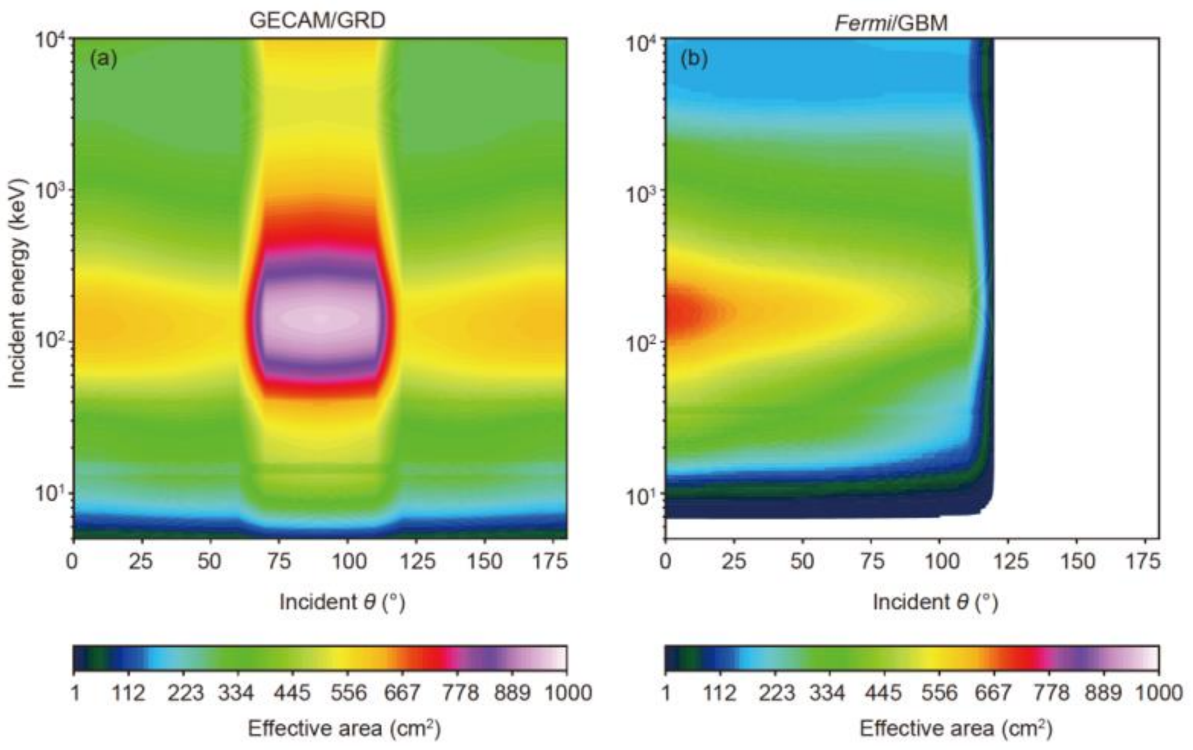
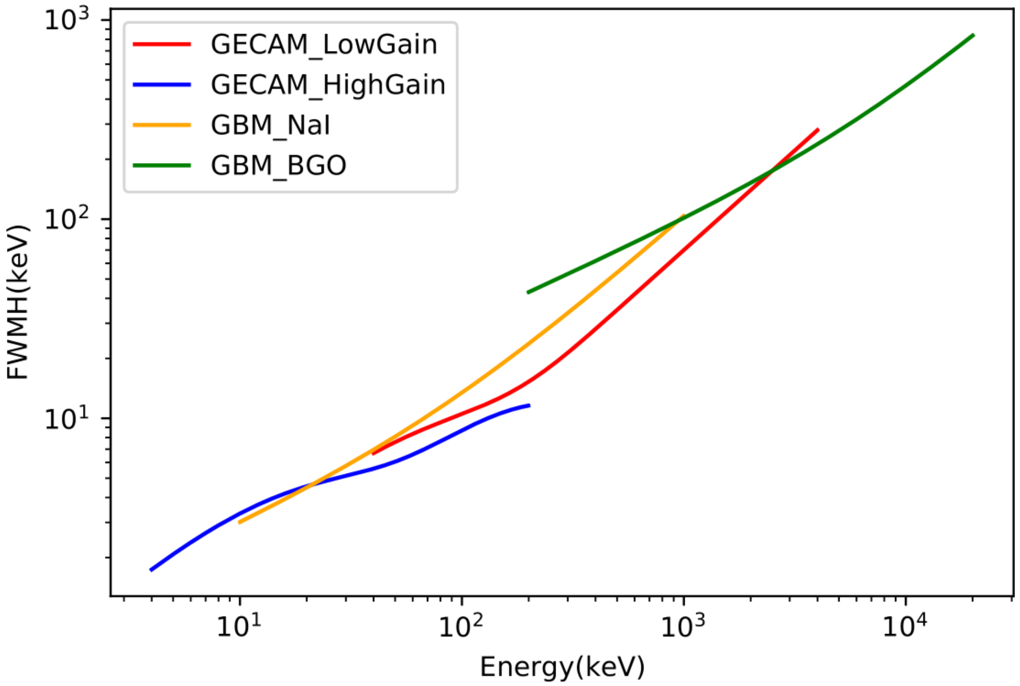
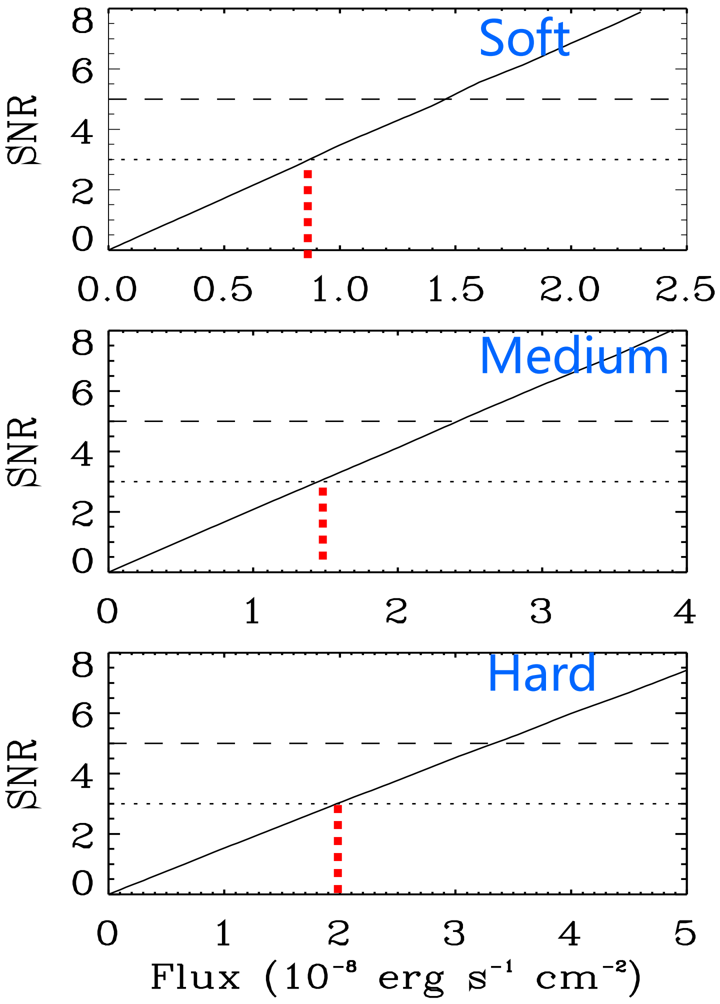


图 7 GECAM/GRD (a)和*Fermi*/GBM (b)的有效面积比较

Figure7 Comparison of effective area of GECAM/GRD (a) and *Fermi*/GBM (b).



Sensitivity

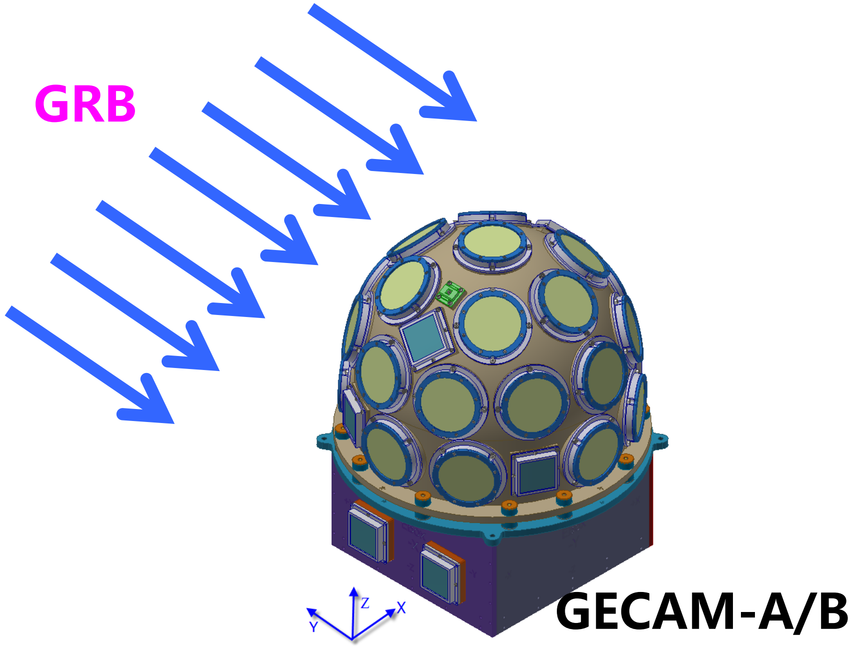


- Sensitivity: ~10^{-8} erg/cm^2/s
- Horizon for GRB 170817A: ~100 Mpc
  - Depends on:
    - Offset viewing angle
    - Spectral shape of the GWGRB
    - Incident angle to GECAM constellation
  - **Working on further improvements**

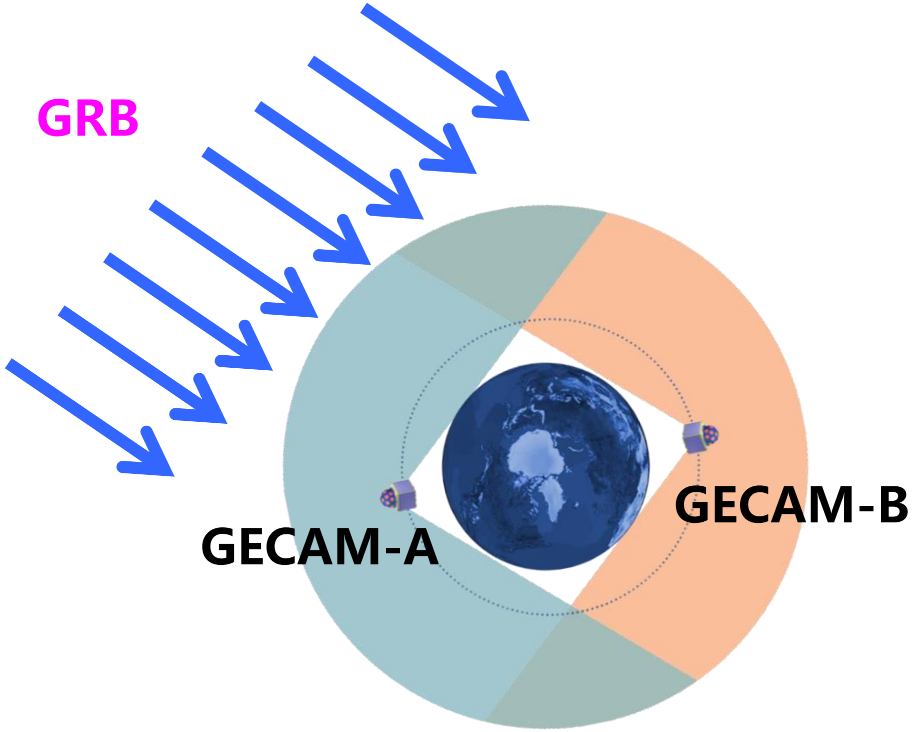
Band	α	β	Epeak (keV)
Soft	-1.9	-3.7	70
Medium	-1.0	-2.3	230
Hard	0.0	-1.5	1000

Localization

- Using the flux distribution of detectors (e.g. Fermi/GBM)
- Using the time lag between two satellites (e.g. IPN location)



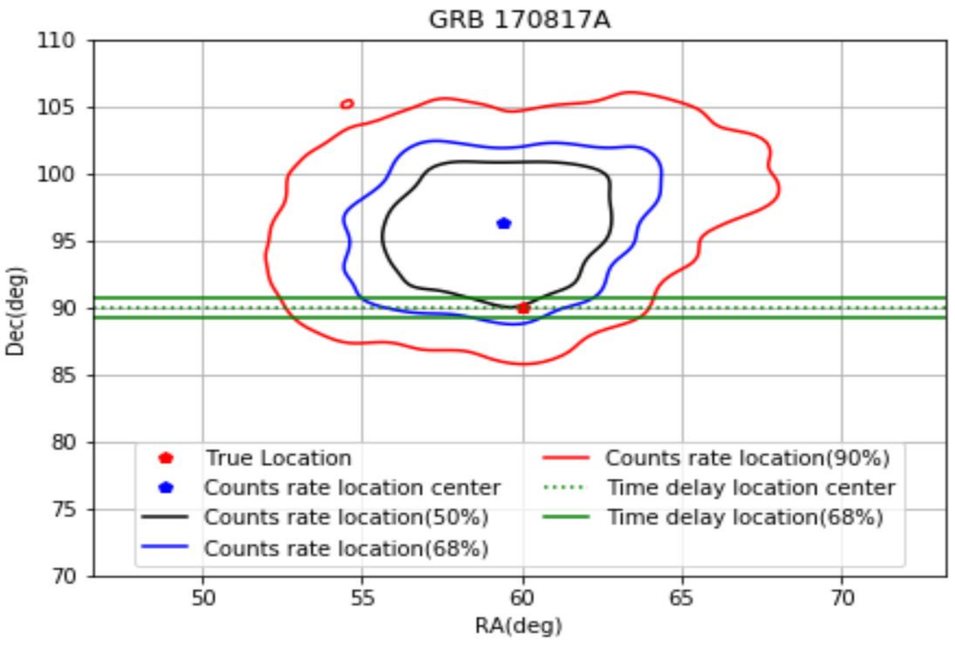
Flux distribution method



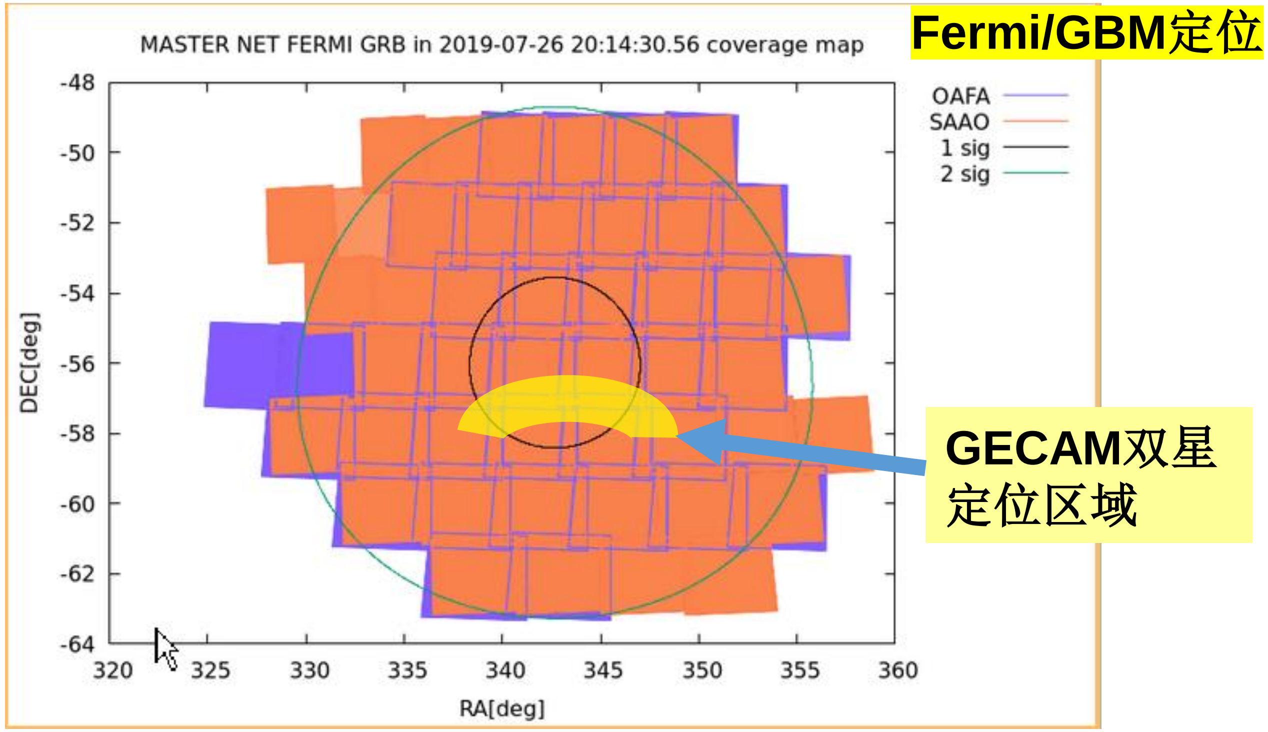
Time lag method

GECAM对短伽马暴(引力波伽马暴)的定位

短暴探测率~120个/年，其中~50个短暴具有双星联合定位



GECAM双星联合定位误差范围
比Fermi/GBM缩小一个量级以上



https://master.sai.msu.ru/site/master2/observ.php?id=1087257

GECAM的观测警报(alerts)设计

兼顾快与准

针对暴发源：伽马暴、磁星暴发、其它天体源暴发

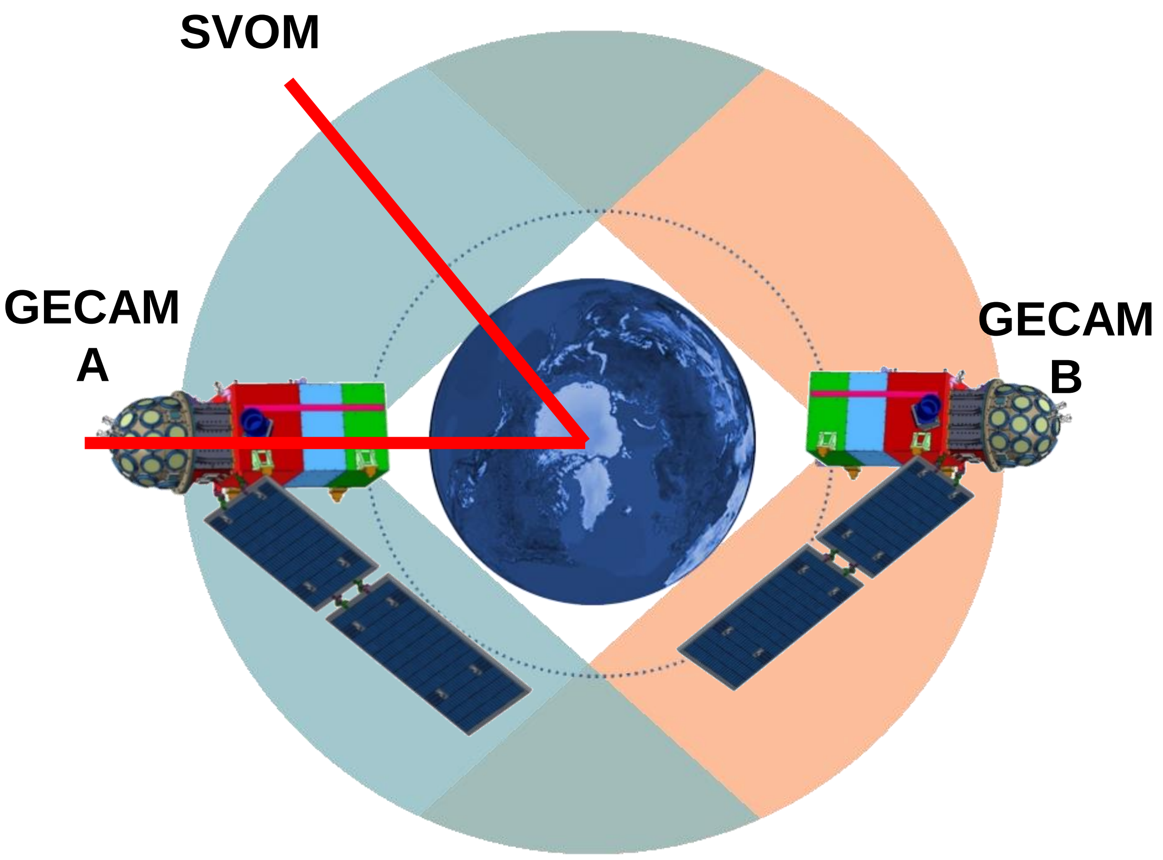
- **星上警报**
  - 触发时间、星上定位等
  - 延迟: **1-3 minutes**
- **地面自动处理短报文警报**
  - 更准确的定位、能谱、T90等
  - 延迟: **10-20 minutes**
- **地面自动处理数传数据警报**
  - 更准确的定位、能谱、T90等
  - 延迟: **~hours**
- **最终警报**
  - 双星的最终分析结果
  - 延迟: **~hours**

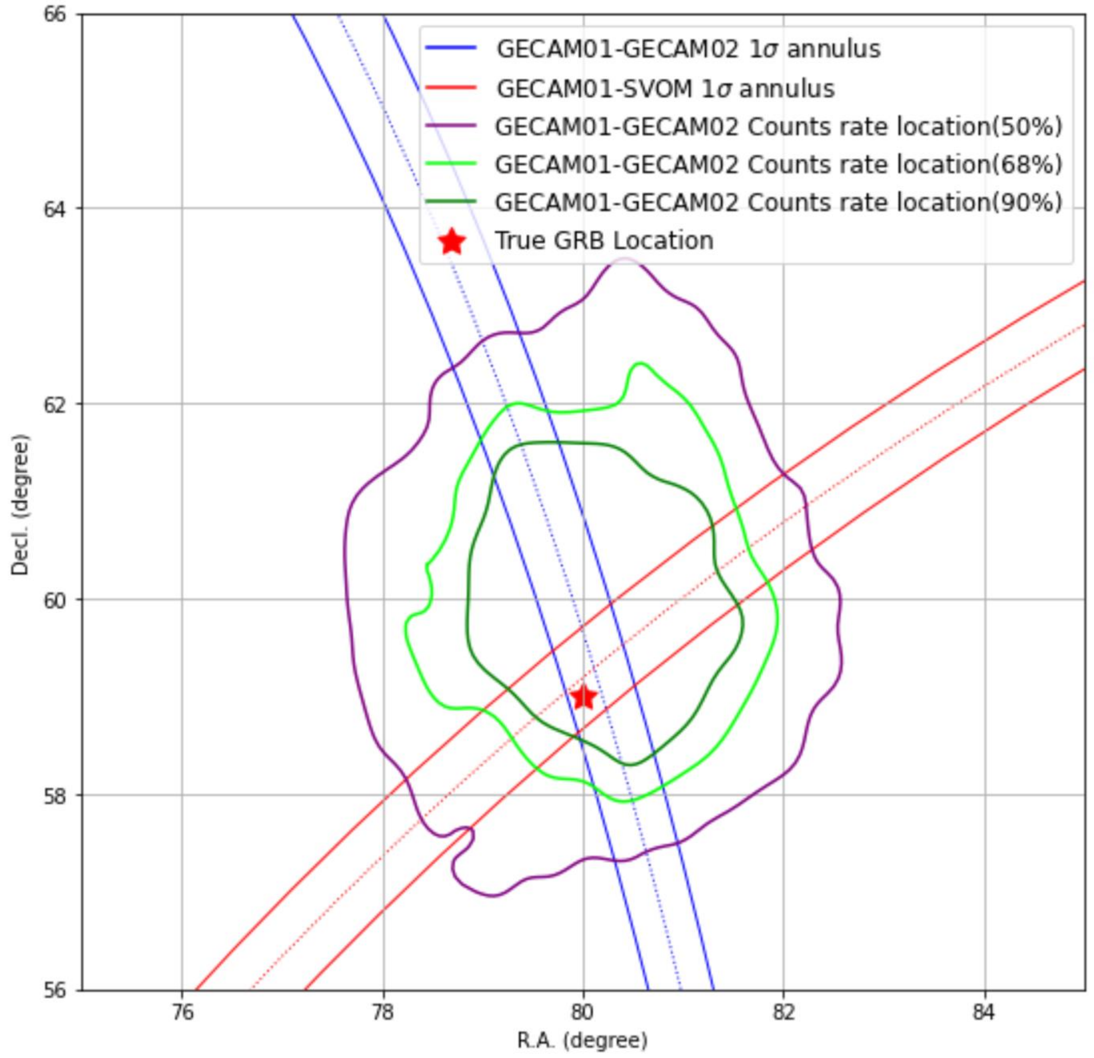
联合观测与TPS

- **多信使**
  - 引力波：LIGO，Virgo，KAGRA, …
  - 高能中微子：IceCube, …
- **空间望远镜**
  - 慧眼卫星，SVOM，EP，POLAR-2, …
  - Fermi/GBM, Swift/BAT, Konus-WIND (IPN), …
- **地面望远镜**
  - LHAASO，光学，射电…

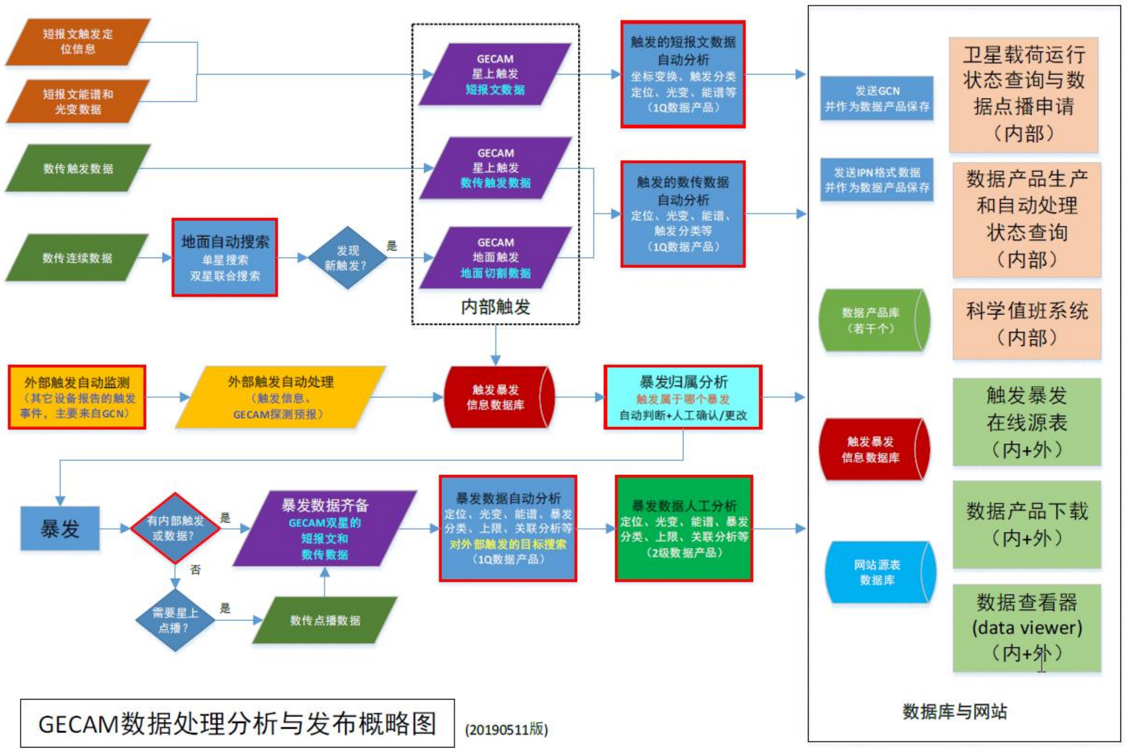
- **Time Positioning System (TPS)**
  - 基于多设备+时间延迟方法对高能暂现源定位
  - 空间高能望远镜 + GECAM双星
  - 即将上线

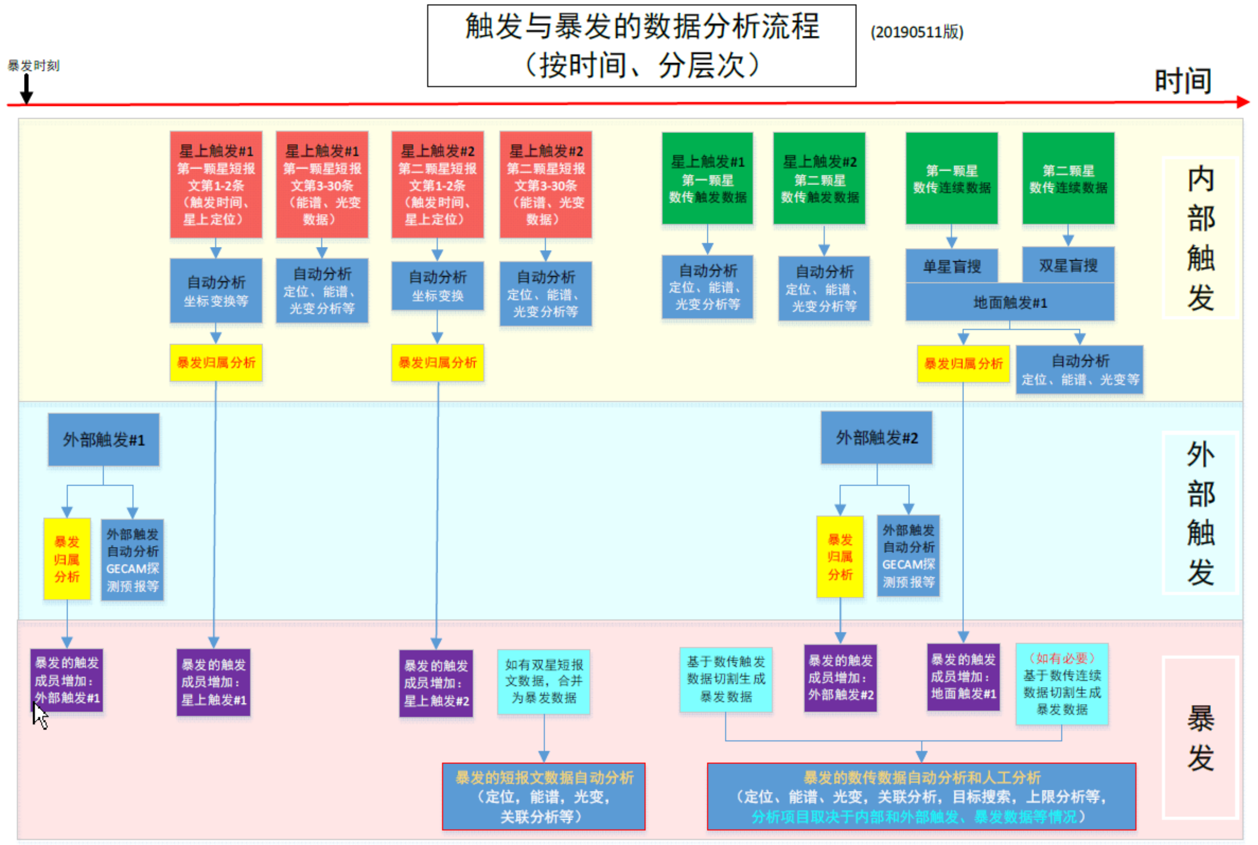
GECAM+SVOM/GRM





GECAM科学应用系统



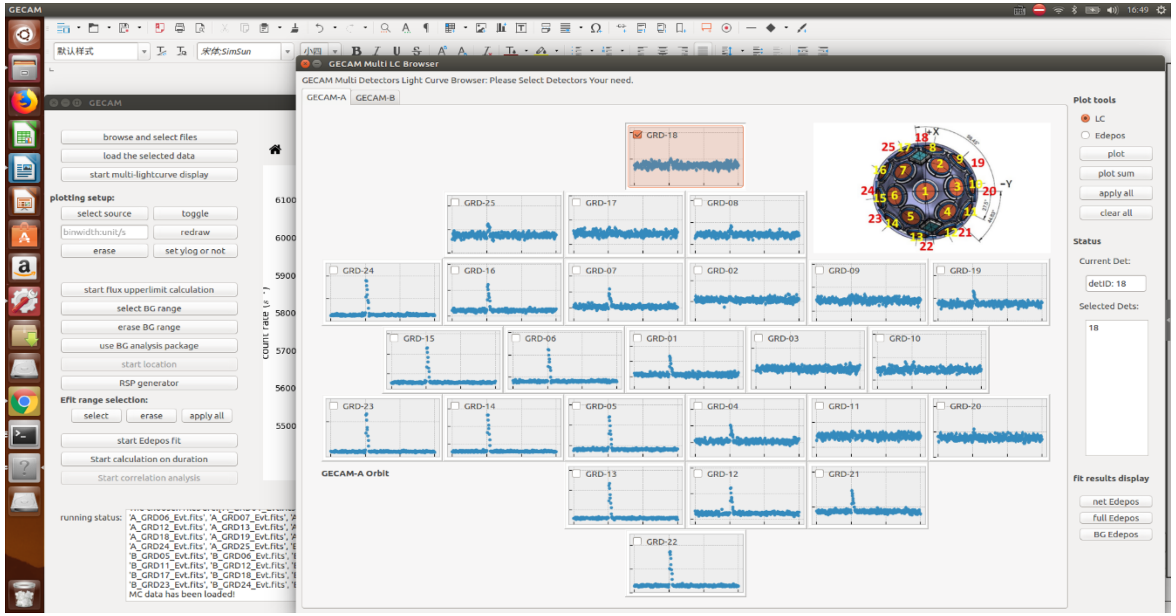


暴发/触发框架：1个暴发事件在多信使多波段多设备产生N个触发

GECAM科学应用系统

- **准实时警报数据**
  - 光变、定位、能谱等
- **事例数据**
  - 普通轨道（非SAA区）
- **并道数据**
  - 所有轨道均记录并道数据
  - 时间并道BTIME
  - 能谱并道BSPEC
- **数据分析软件**
  - 基于python的交互式分析工具
  - 命令行批量处理

GECAM主页
（建设中）



数据政策、科学合作组

- **绝大部分数据即时公开发布**
  - 天文警报数据
  - 快视数据（1Q级数据）
  - 并道数据（时间并道BTIME，能谱并道BSPEC）

- **专有期：6-12个月**
  - 事例数据

- **科学合作组**
  - 可访问专有期数据
  - 遵守合作组论文政策

总结

- **科学意义重大**
  - 引力波重大发现，宝贵机遇
- **科学目标广泛**
  - 引力波、伽马暴、磁星等
  - 快速射电暴、高能中微子等
  - 太阳耀斑、地球伽马闪等
- **综合性能领先**
  - 100%全天视场，灵敏度，定位良好
- **创新技术**
  - 首款空间溴化镧+SiPM探测器
  - 新型准实时天地通讯
- **发射运行**
  - 研制进展顺利，计划2020年12月发射
  - 在轨运行3年以上

欢迎加入GECAM科学合作组
(熊少林 xiongsl@ihep.ac.cn)