Particle Physics and Astrophysics by Cosmic Gamma-ray Observations

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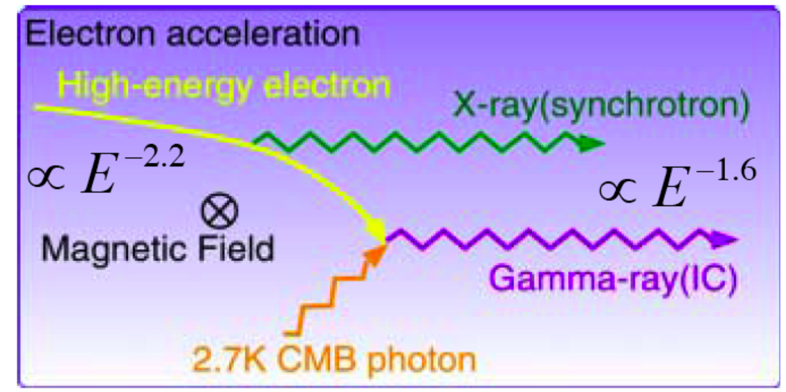
October 24–26, 2011
KMI Inauguration Conference on
“Quest for the Origin of Particles and the Universe”
Nagoya University, Japan

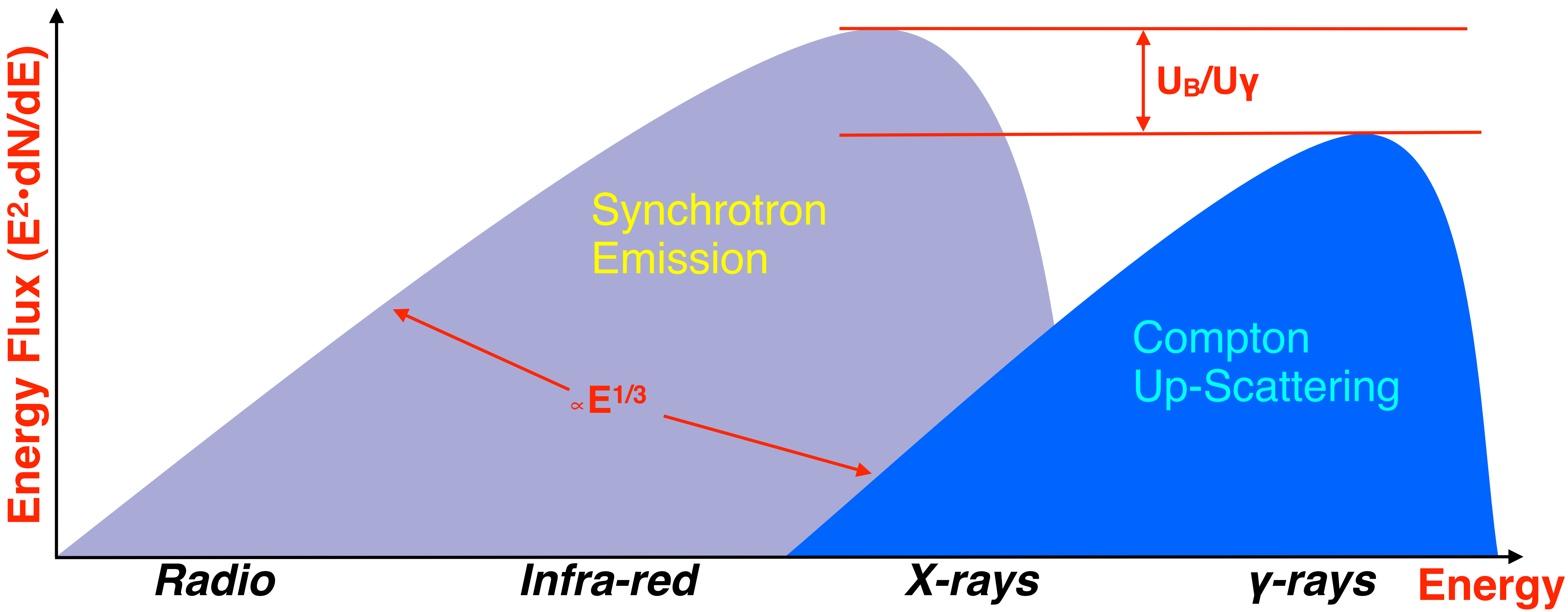
Outline

- Gamma-ray emissions in the Universe
- Cosmic gamma-ray experiments
  - Fermi Gamma-Ray Space Telescope
  - Imaging atmospheric Cherenkov telescopes
- Gamma-ray science
  - Search for WIMP dark matter
  - Search for origin of cosmic rays
  - Physics with distant gamma-ray candles
- Future prospects

Gamma-ray Emission from Electrons

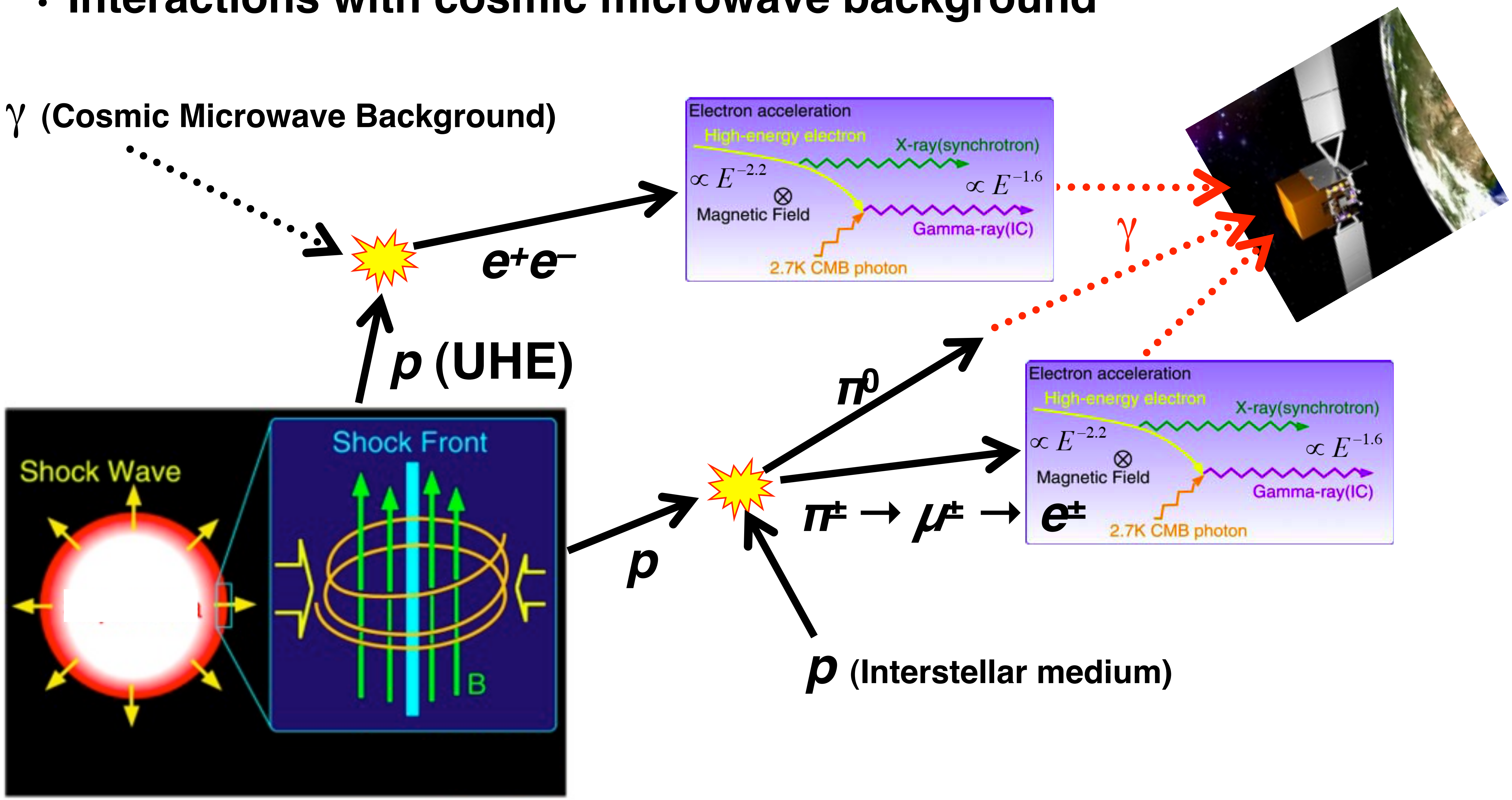
- Synchrotron radiation
- Compton up-scattering
  - CMB (Cosmic Microwave BG)
  - Synchrotron light
  - Interstellar light



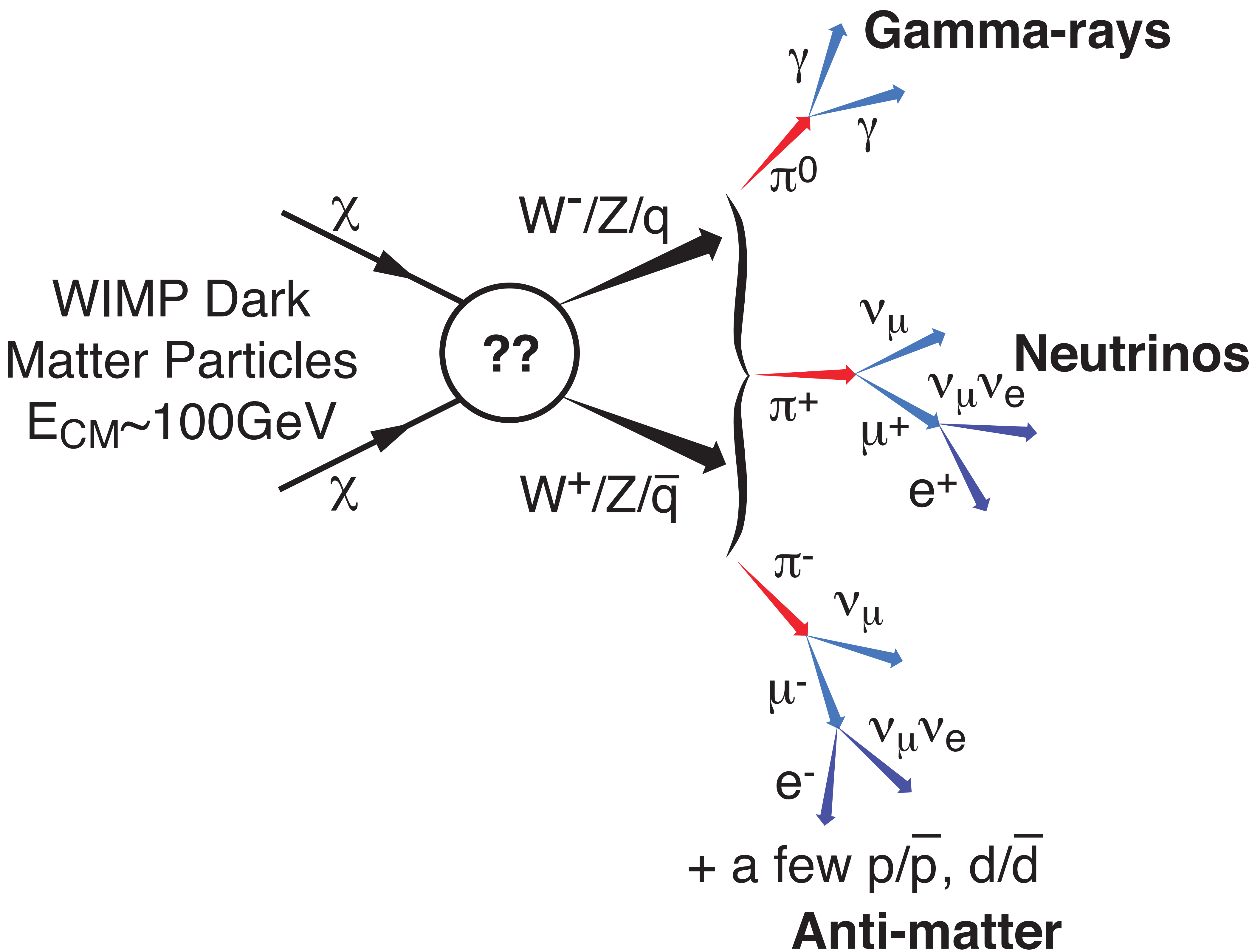


Gamma-ray Emission from Hadrons

- Nuclear interactions with interstellar medium
- Interactions with cosmic microwave background

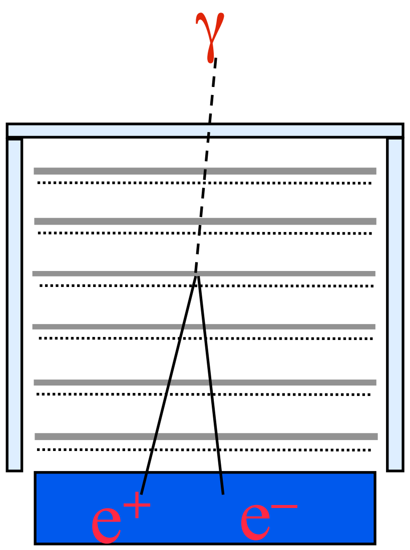


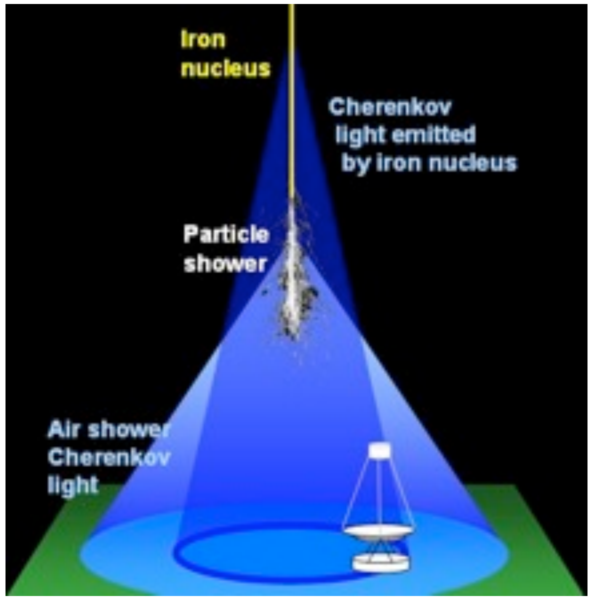
Annihilation/Decay of Massive Particles



Gamma-ray Detectors

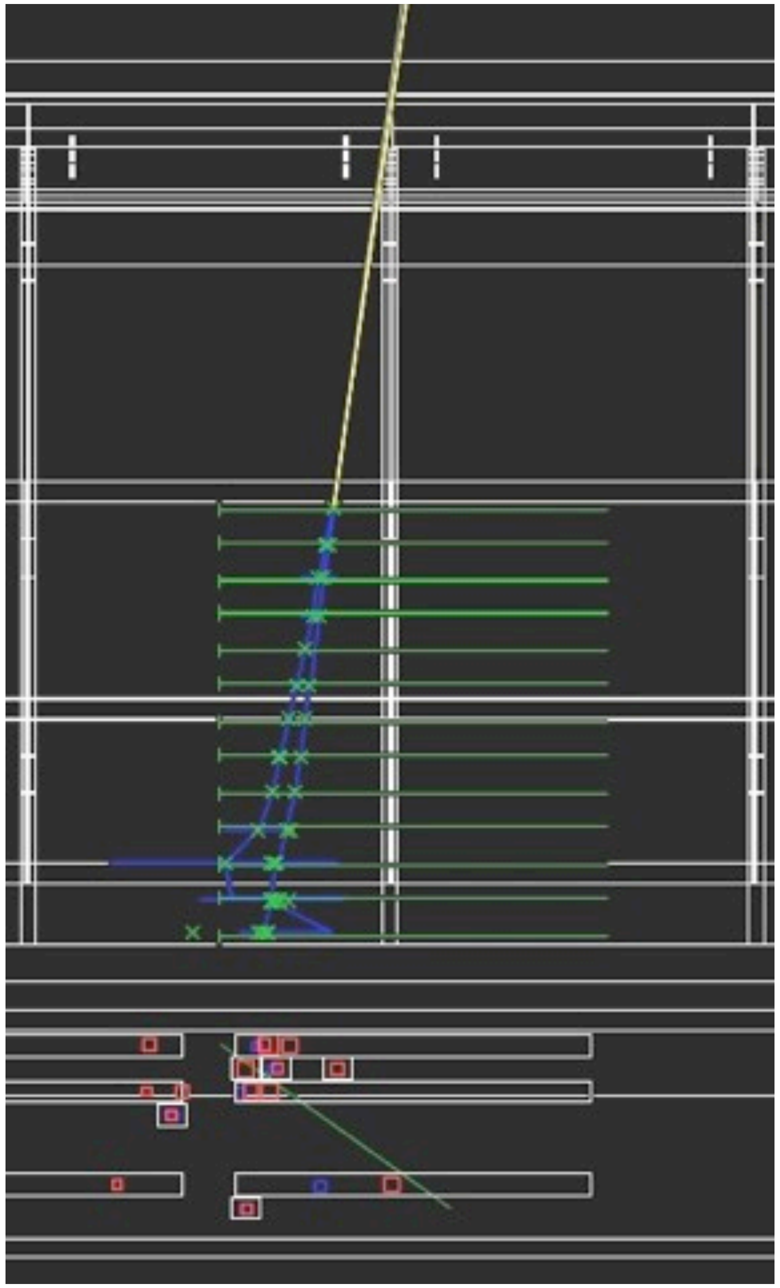
	Satellite based pair conversion	Atmospheric Cherenkov telescope
Experiments	EGRET, AGILE, Fermi	HESS, VERITAS CANGAROO, MAGIC
Energy range	0.02 – 200 GeV	0.1 – 100 TeV
Angular res.	0.04 – 10 deg	~0.1 deg
Collection area	1 m^2	10^5 m^2
Field of view	2.4 sr	10^{-2} sr
Duty cycle	~95%	<10%





Fermi (GLAST)/LAT Overview

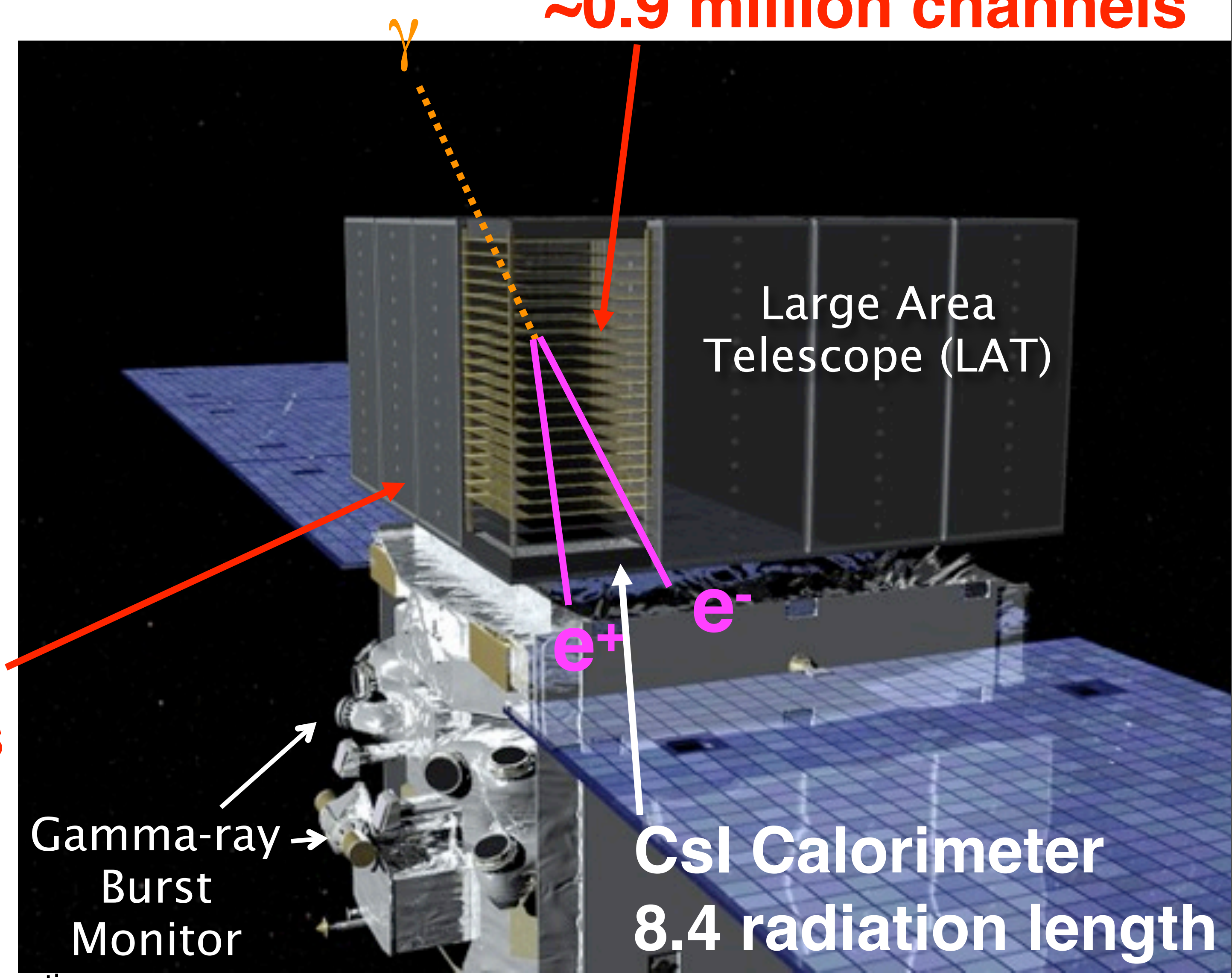
- **LAT (Large Area Telescope) on board Fermi Observatory**
- **Satellite experiment to observe cosmic gamma rays**
  - **Wide energy range: 20 MeV to >300 GeV**
  - **Large effective area: > 8000 cm^2 (~6xEGRET)**
  - **Wide field of view: > 2.4 sr (~5xEGRET)**
- **Pair-conversion telescope**
  - **"Clear" signature**
  - **Background rejection**



LAT Instrument Configuration

- **Tracker (TKR): conversion, tracking**
  - Angular resolution is dominated by scattering below ~GeV
  - Converter thickness optimization
- **Calorimeter: energy measurement**
  - 8.4 radiation length
  - Use shower development to compensate for the leakage
- **Anti-coincidence detector:**
  - Efficiency > 99.97%

Si Tracker
70 m², 228 μm pitch
~0.9 million channels



Anti-coincidence Detector
Segmented scintillator tiles
99.97% efficiency

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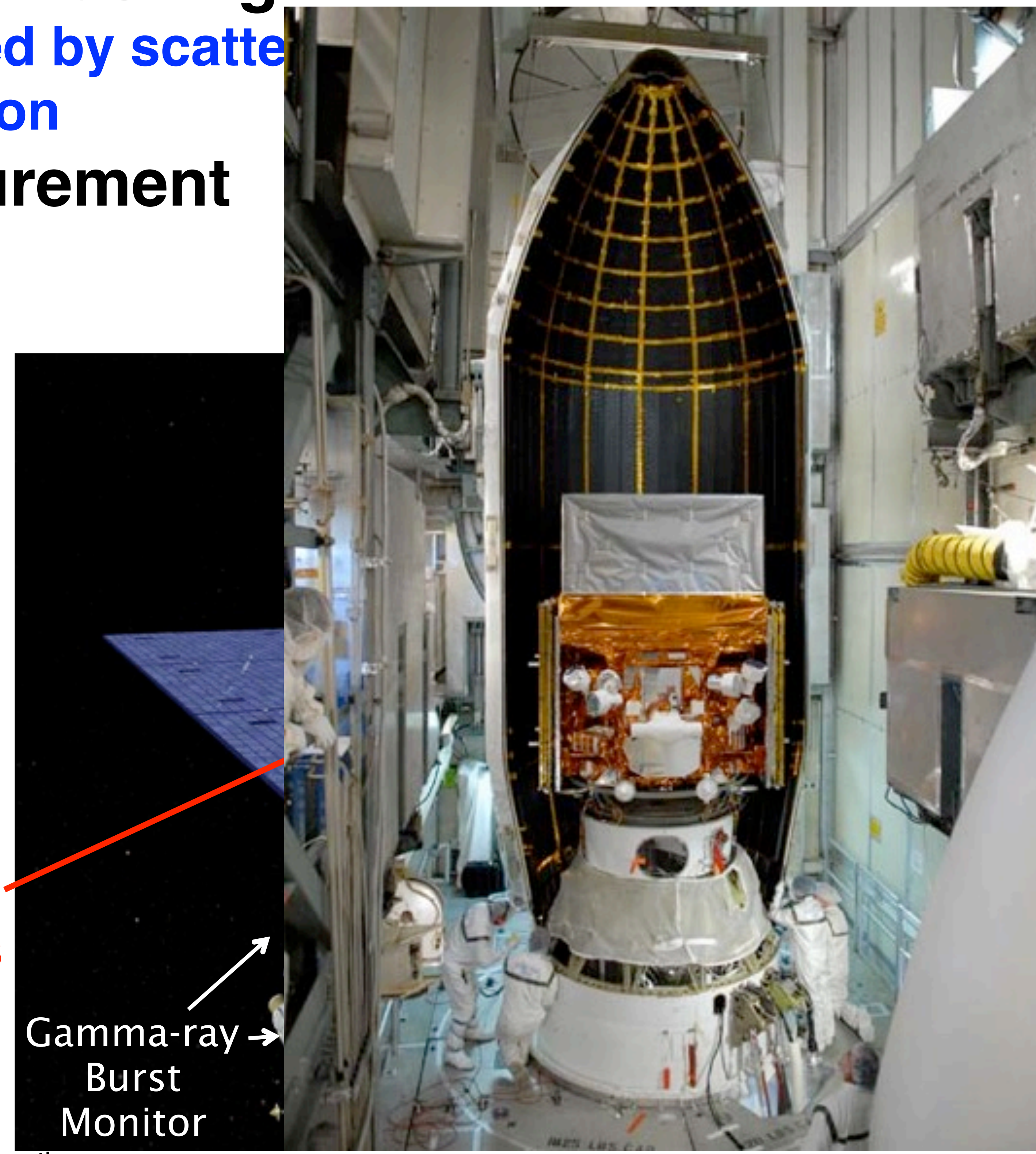

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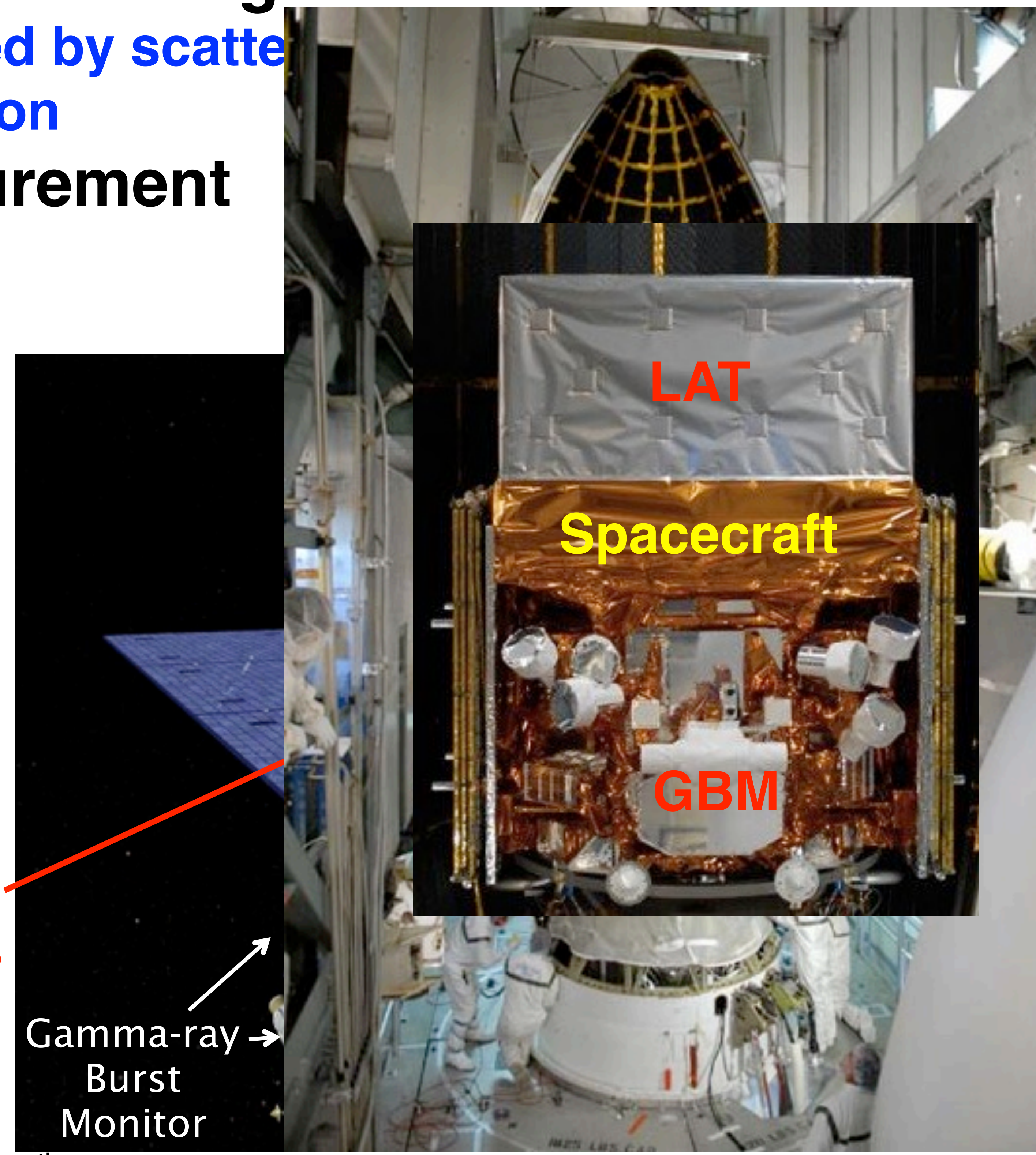

Anti-coincidence Detector
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Fermi/LAT Collaboration

Stanford University & SLAC
NASA Goddard Space Flight Center
Naval Research Laboratory
University of California at Santa Cruz
Sonoma State University
University of Washington
Purdue Univeriesty-Calumet
Ohio State University
University of Denver

~400 Scientific Members (including 96 Affiliated Scientists, plus 68 Postdocs and 105 Students)

Commissariat a l'Energie Atomique, Saclay
CNRS/IN2P3 (CENBG-Bordeaux, LLR-Ecole polytechnique, LPTA-Montpellier)

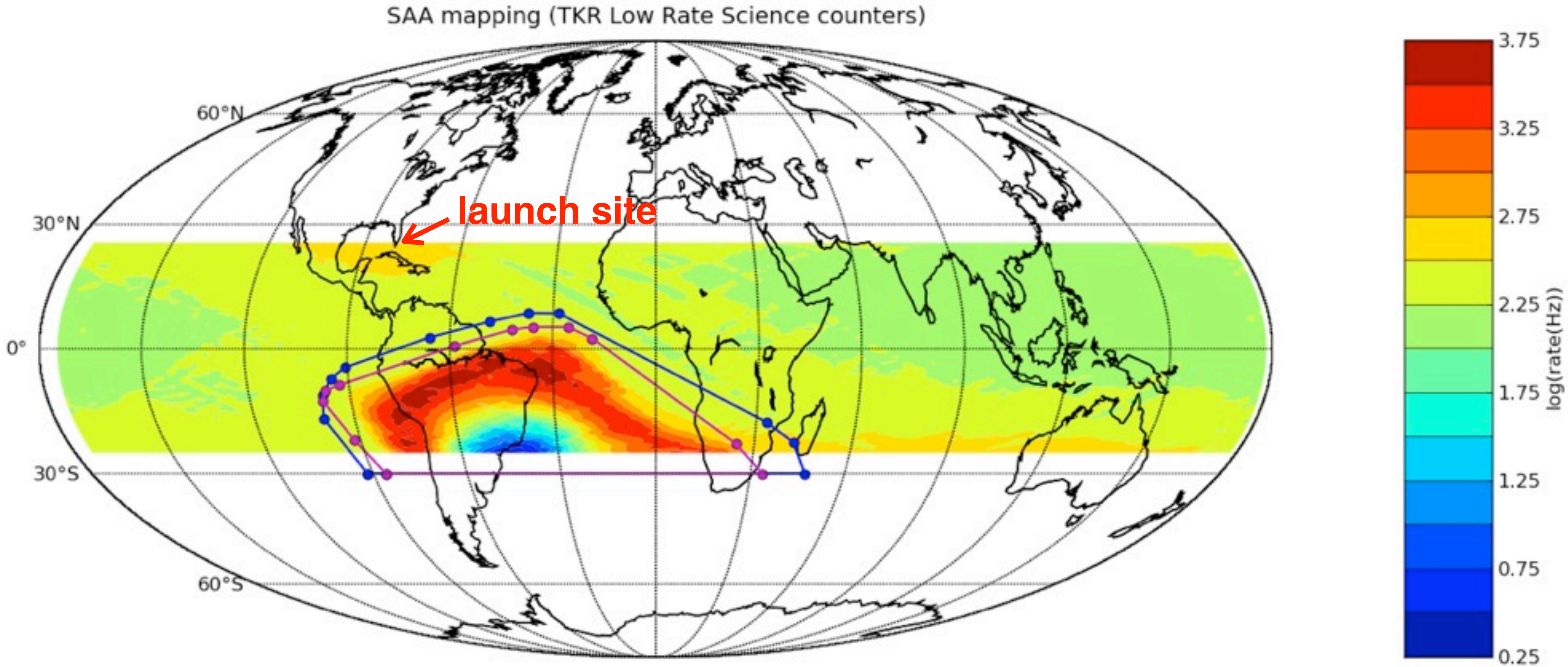
Hiroshima University
Institute of Space and Astronautical Science
Tokyo Institute of Technology
RIKEN

Instituto Nazionale di Fisica Nucleare
Agenzia Spaziale Italiana
Istituto di Astrofisica Spaziale e Fisica Cosmica

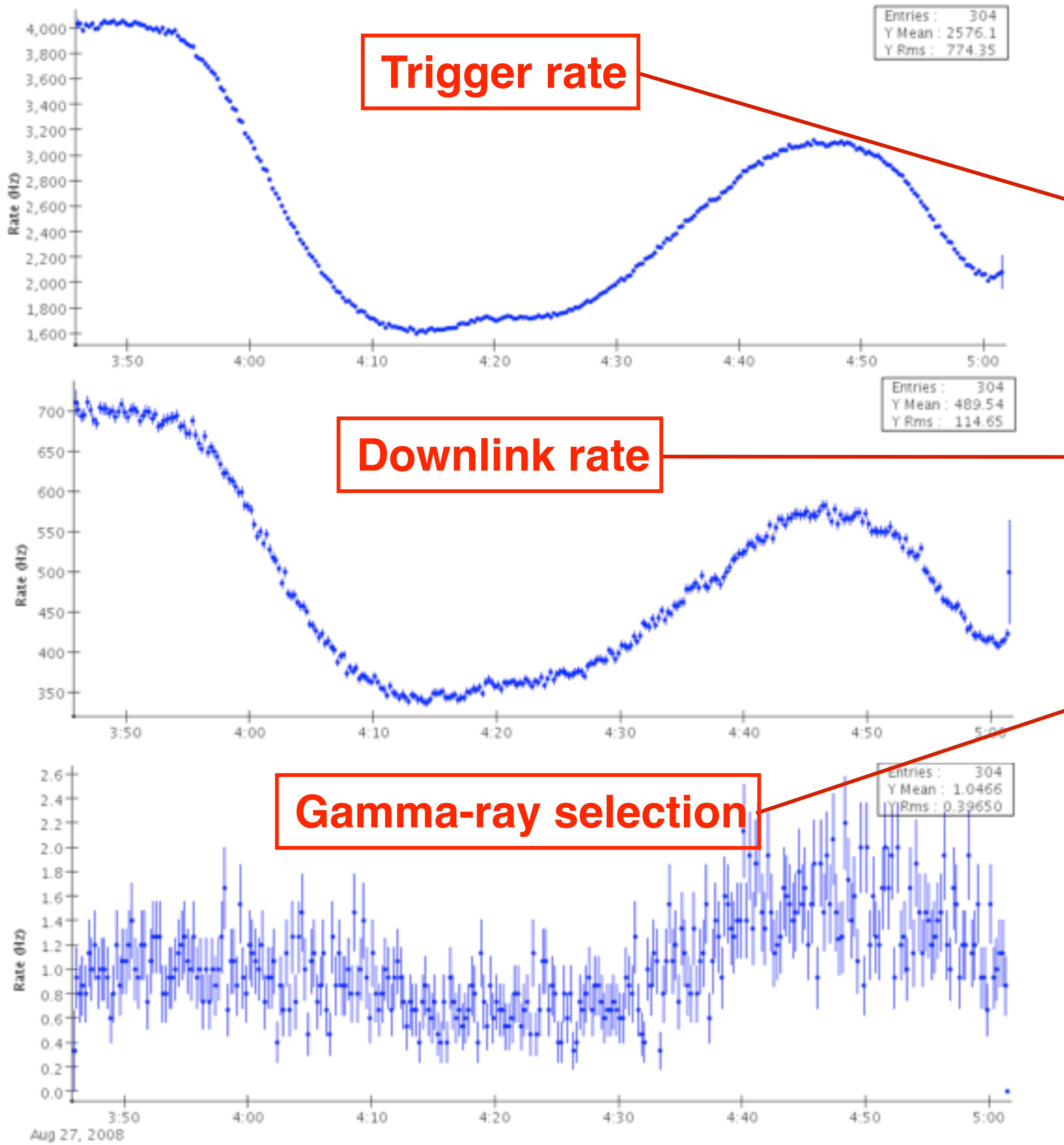
Royal Institute of Technology, Stockholm
Stockholms Universitet

Particle Background Environment

- TKR trigger rate is monitored throughout South Atlantic Anomaly
  - Trigger rate saturates above ~3.7 kHz/layer



Event Rates



- ✓ Overall trigger rate: ~1–4 kHz
  - ✓ Huge variations due to orbital effects.

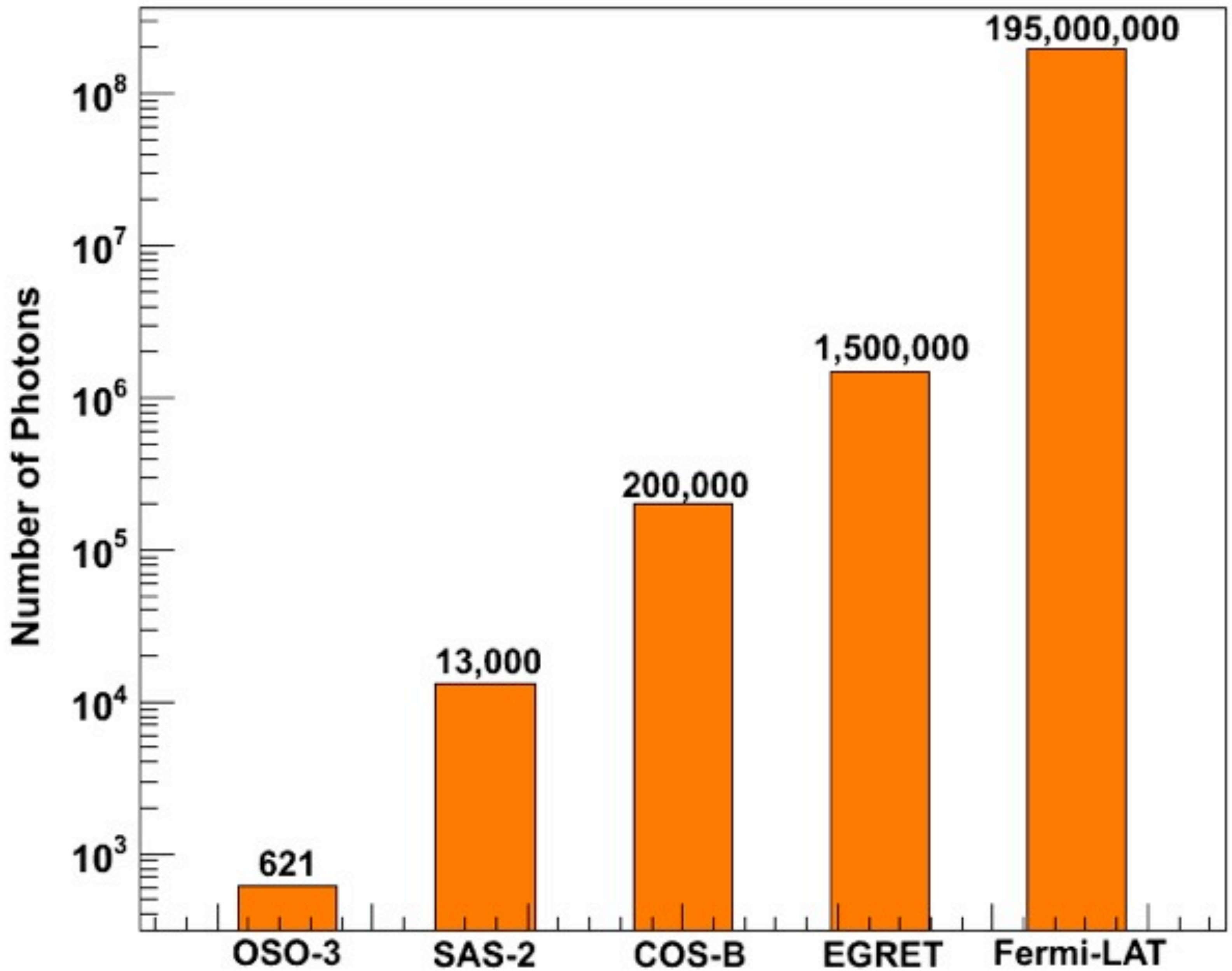
- ✓ Downlink rate: ~0.3–0.7 kHz
  - ✓ ~90% from GAMMA filter
  - ✓ ~30 Hz from minimum bias filter
  - ✓ ~5 Hz from heavy ion filter

- ✓ Rate of photons after the standard background rejection cuts for source study: ~1 Hz

- ✓ Most of the downlinked events are in fact background, final ~ 1000:1 rejection is done in ground processing.

Comparison with Previous Missions

- Number of triggers way beyond 100 billion (134×10^9; 26×10^9 downlinked)
- Number of photons in one year dwarfs previous missions
- Uptime: 99.1%
- All data public Processing time: typically 5-10 hours
- 5-year mission, no consumables



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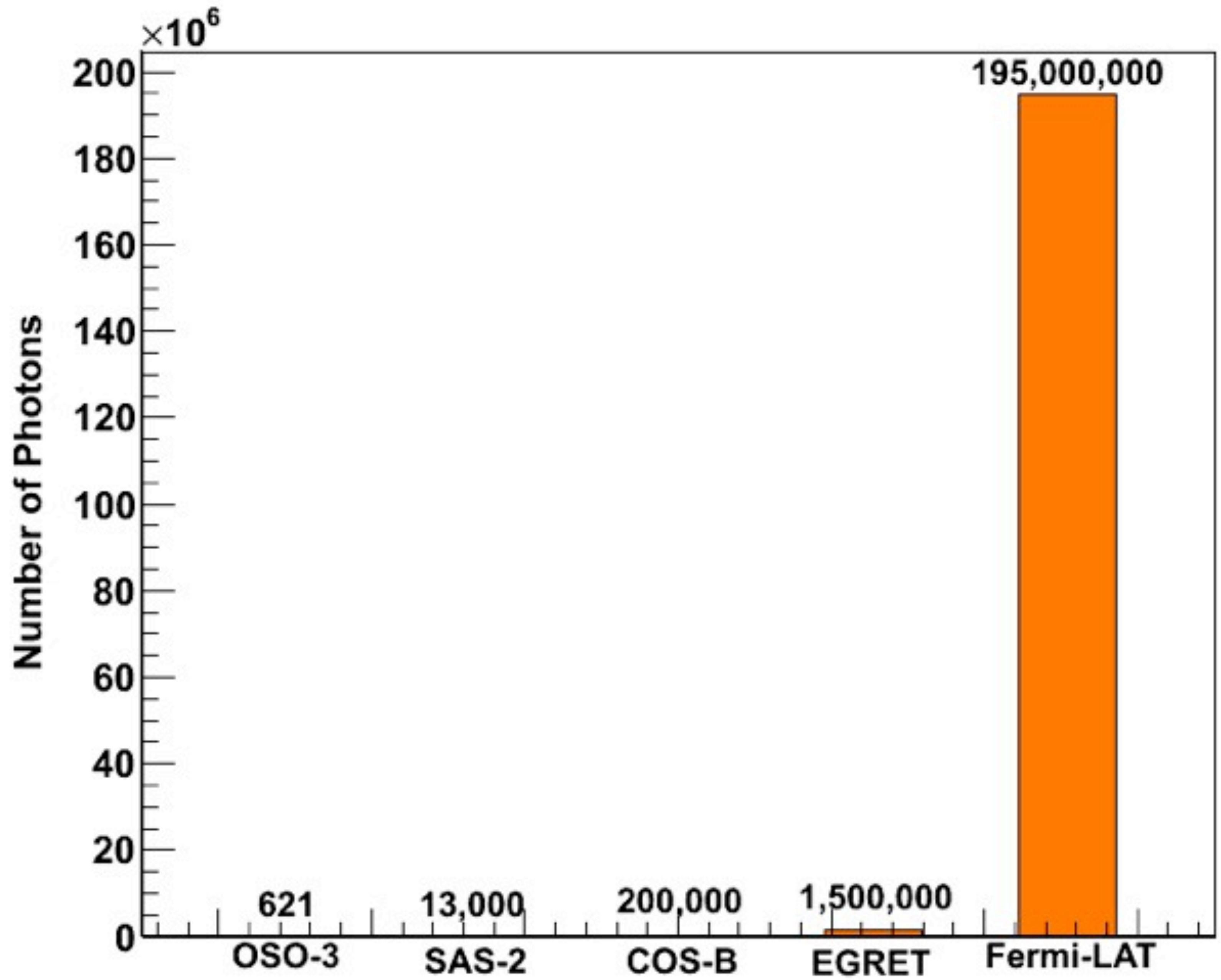
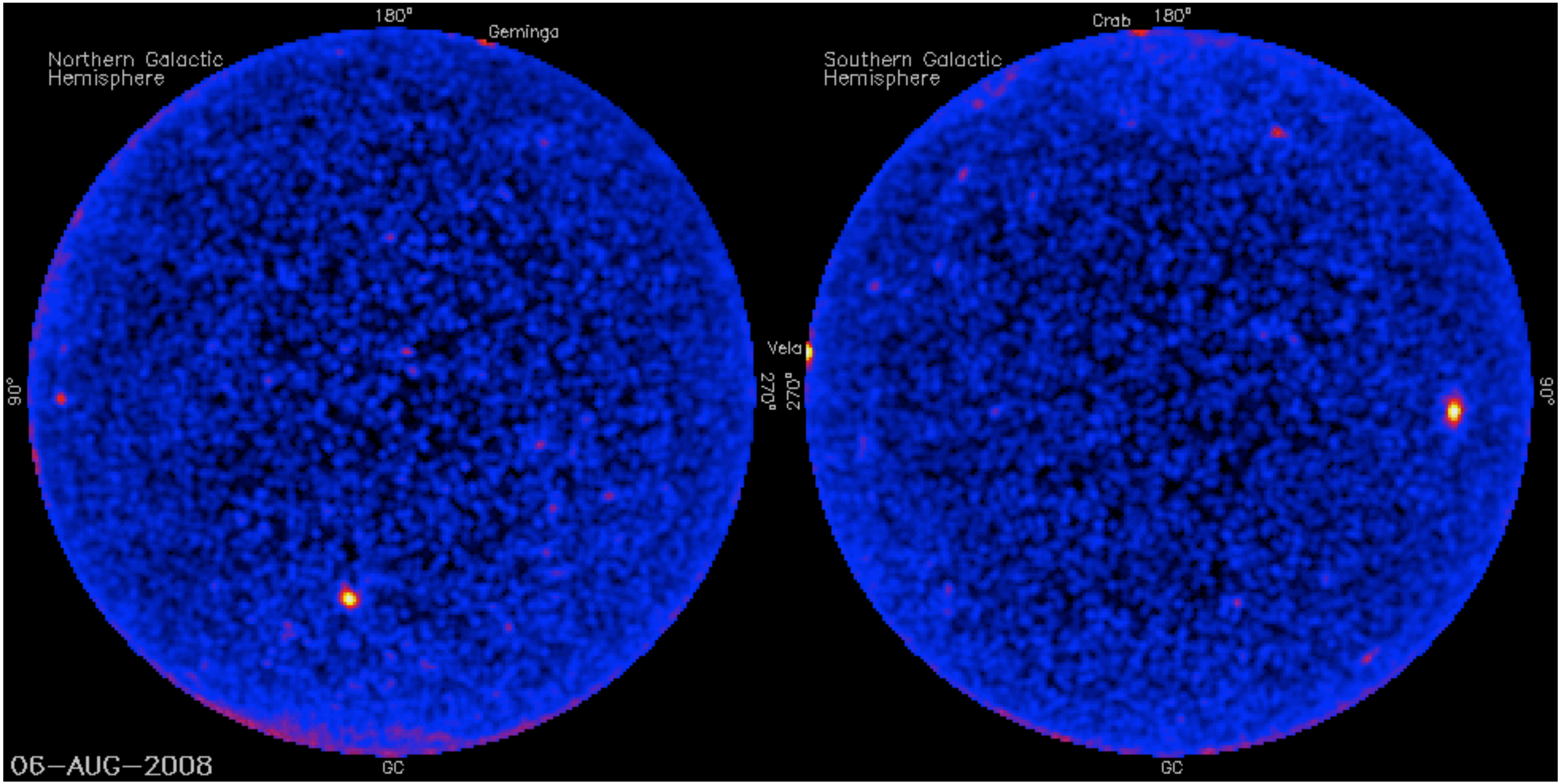
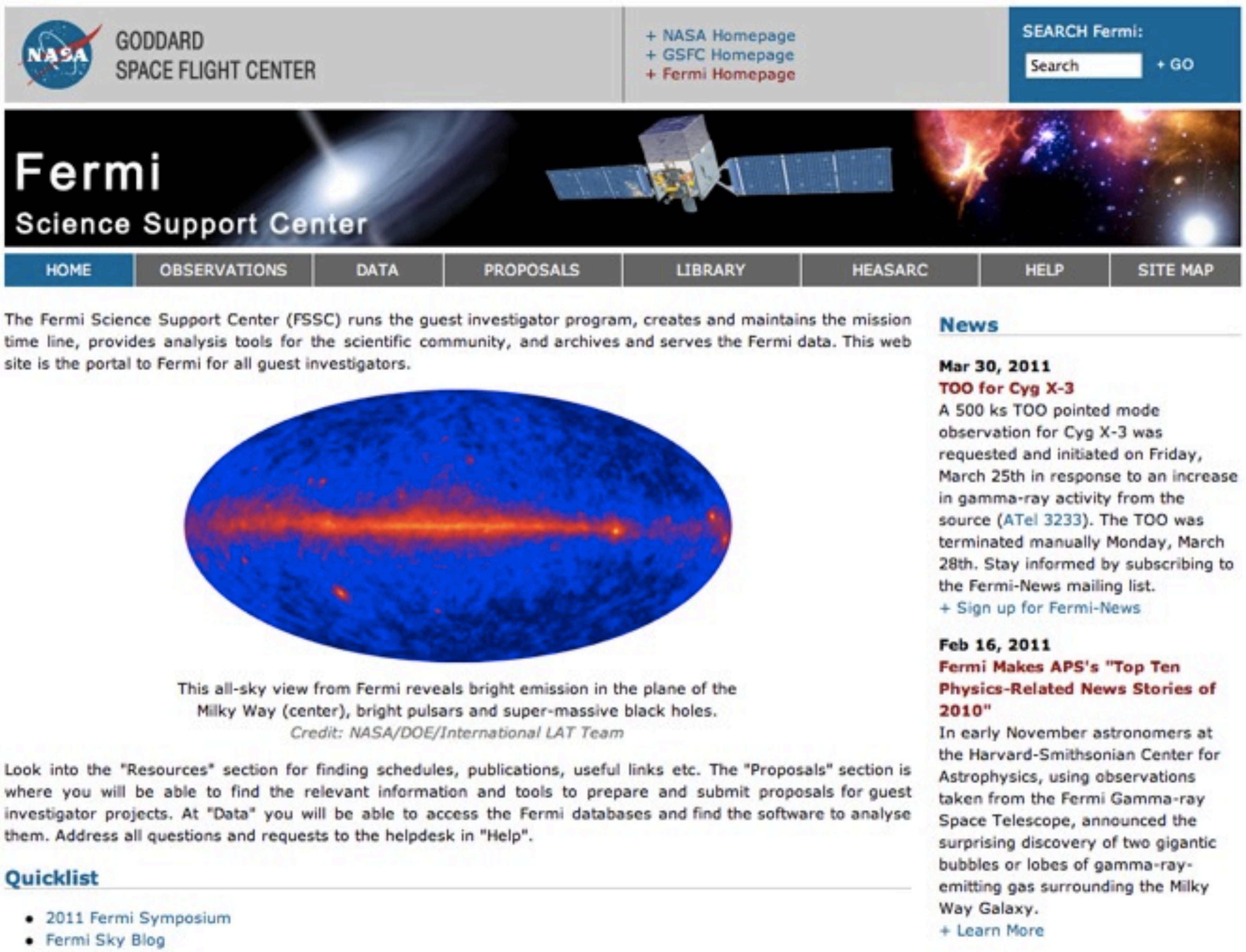


Variable Gamma-ray Sky



Fermi Science Support Center

- Fermi data have been public since 2009 August
  - data access: http://fermi.gsfc.nasa.gov/ssc/data/access/
  - analysis tool: http://fermi.gsfc.nasa.gov/ssc/data/analysis/



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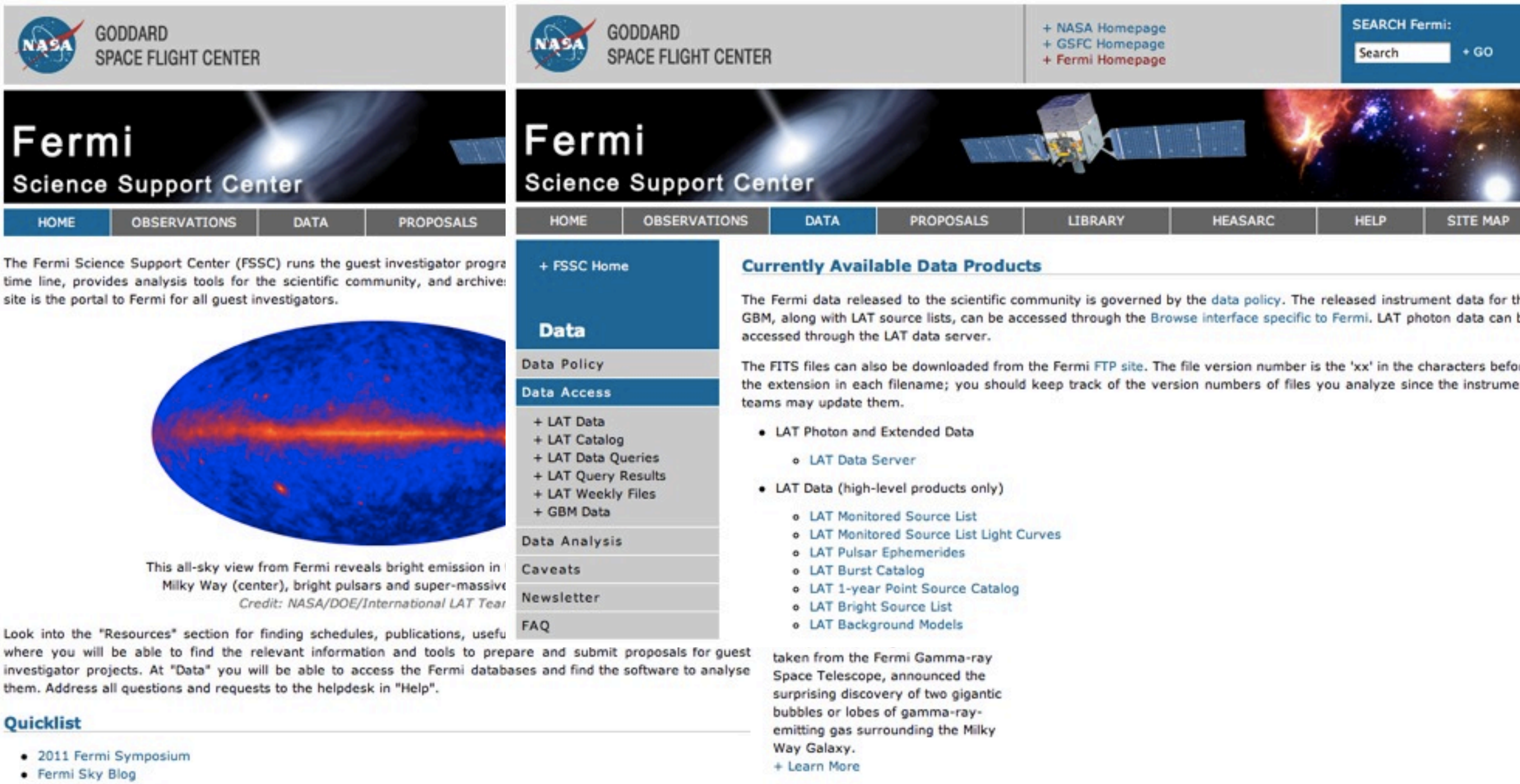
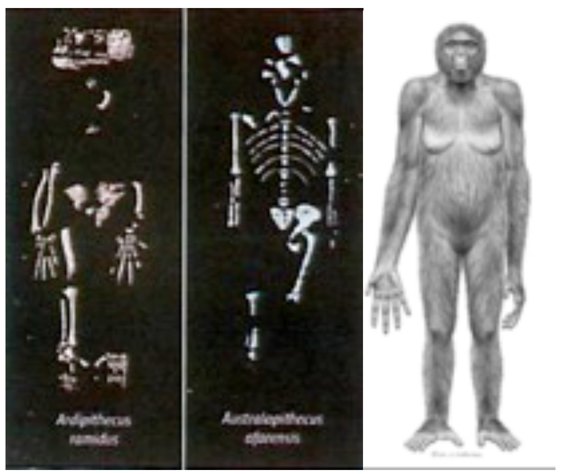


Scientific Impacts of Fermi

- **>100 publications (> 2500 citations) in 2.7 years**
- **"Breakthrough of the Year" in 2009 selected by Science magazine**

1. Ardipithecus Ramidus



2. Opening up the gamma-ray sky

- **Bruno Rossi Prize 2011 awarded to W.B. Atwood, P. Michelson and Fermi LAT Team by High-Energy Astrophysics Division of AAS**

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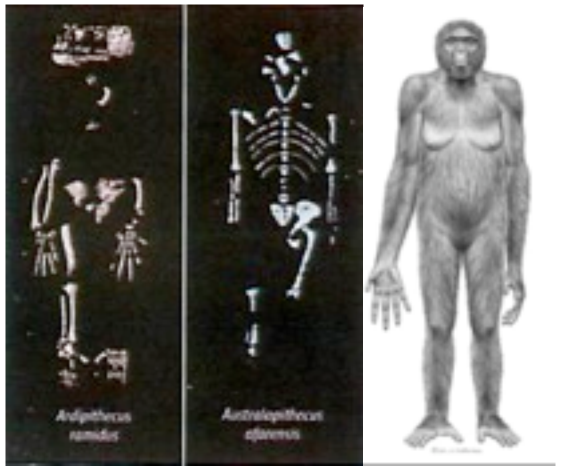


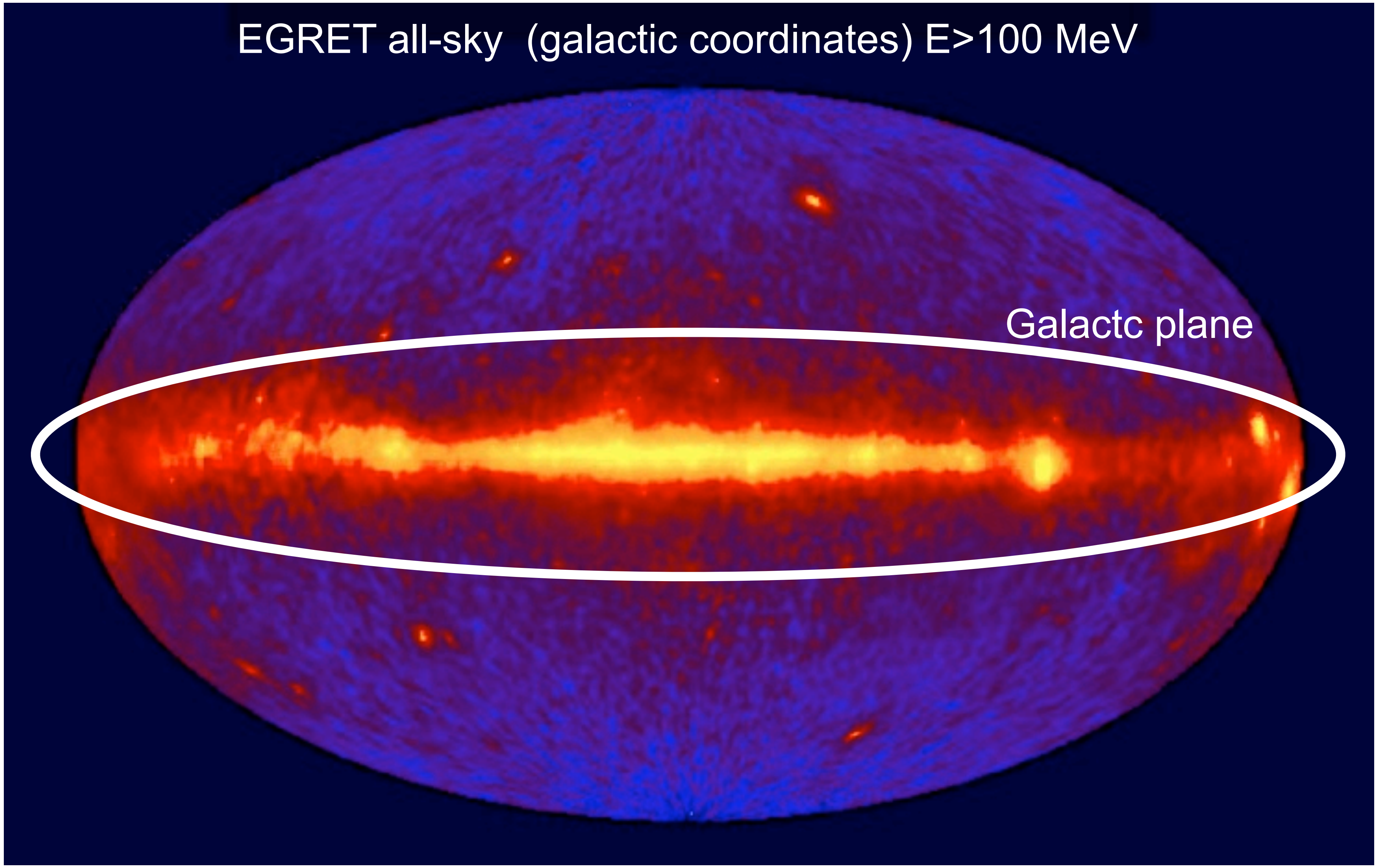
2. Opening up the gamma-ray sky

Nature: 3
Science: 10

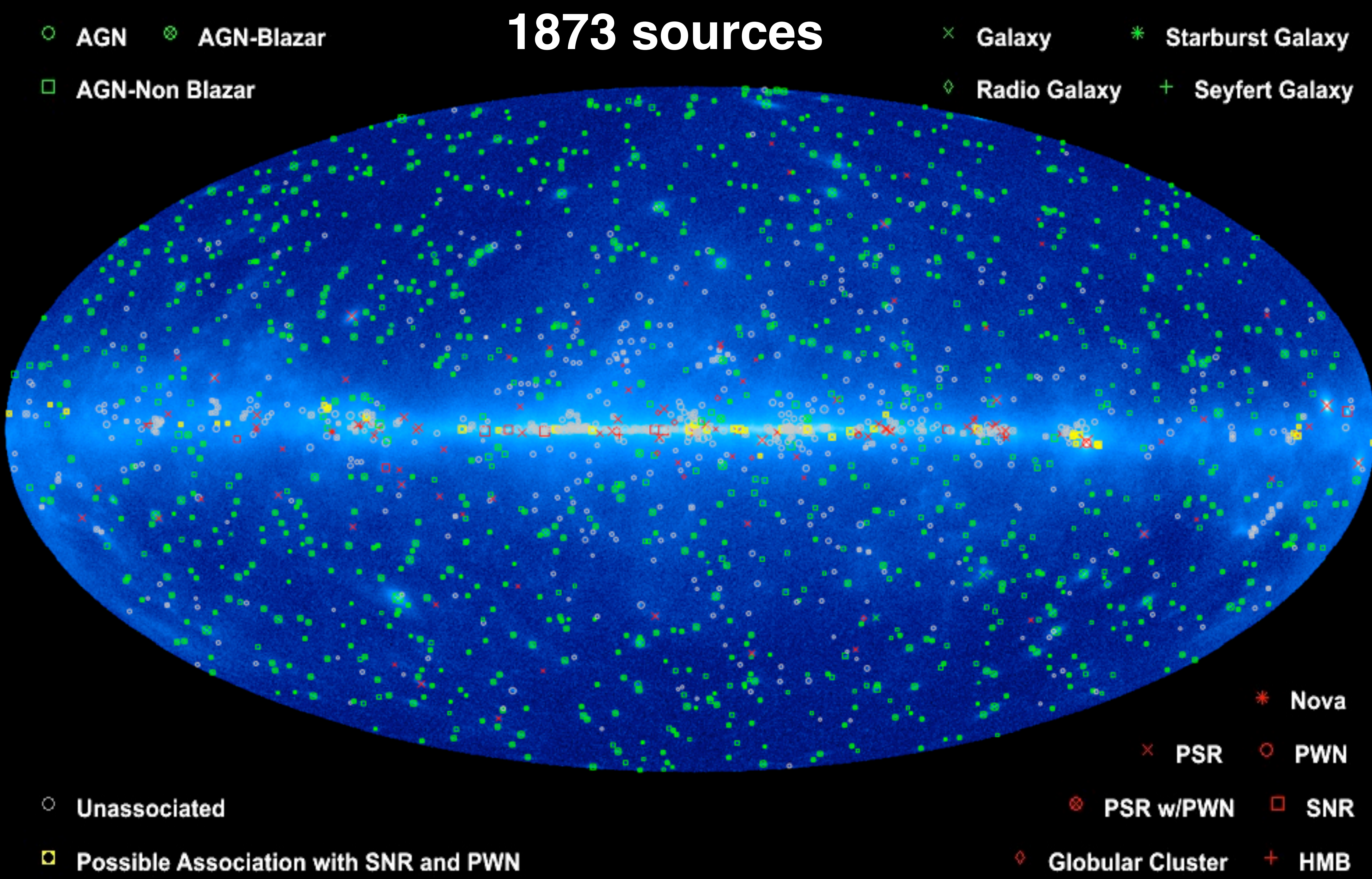
- Bruno Rossi Prize 2011 awarded to W.B. Atwood, P. Michelson and Fermi LAT Team by High-Energy Astrophysics Division of AAS

Predecessor, EGRET

- EGRET: 1991–2000
  - 271 gamma-ray sources (Hartman et al. 1999)
    - Only 38% (101 sources) have clear “identifications”



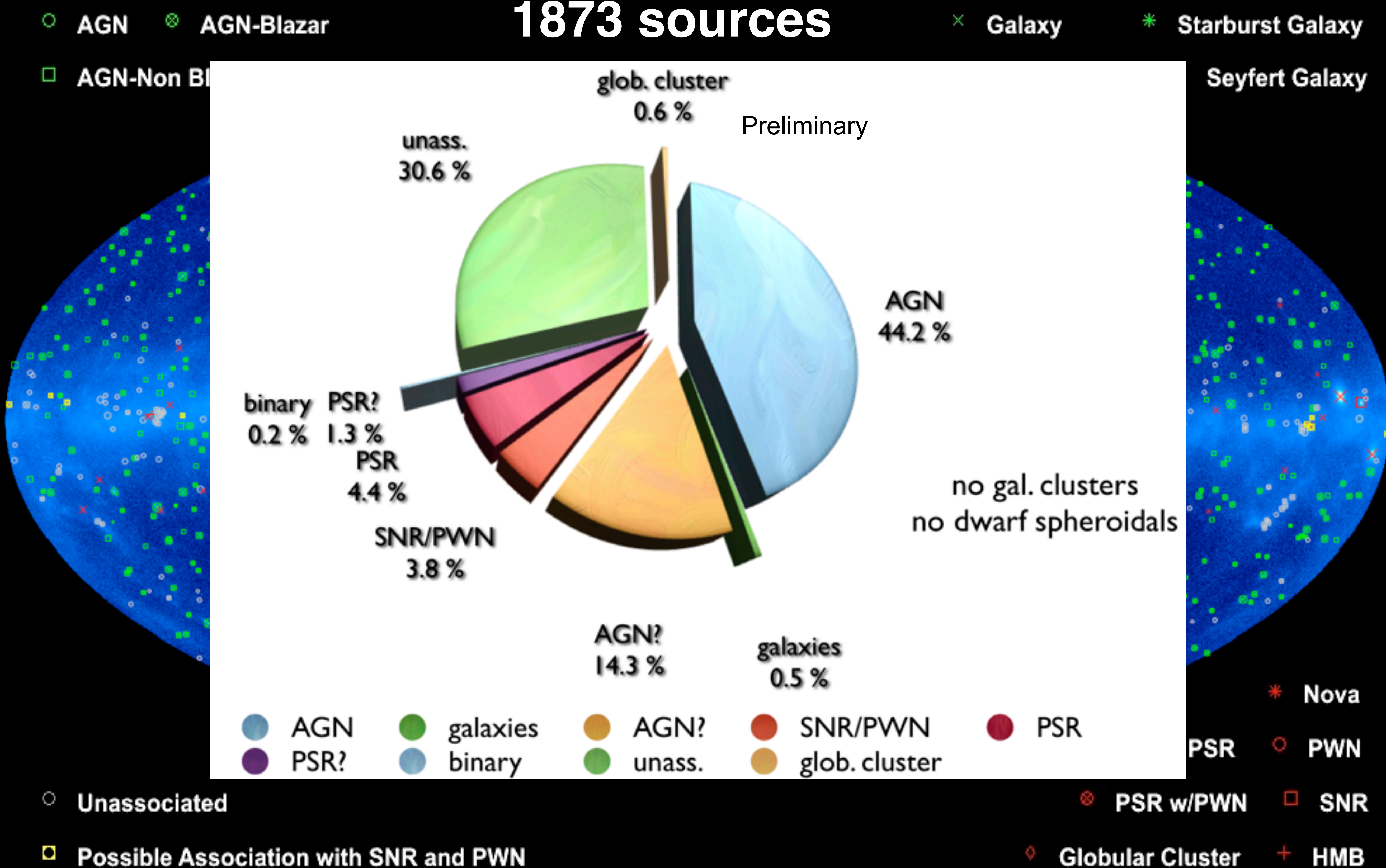
Fermi Large Area Telescope 2FGL catalog



Credit: Fermi Large Area Telescope Collaboration

Fermi Large Area Telescope 2FGL catalog

1873 sources



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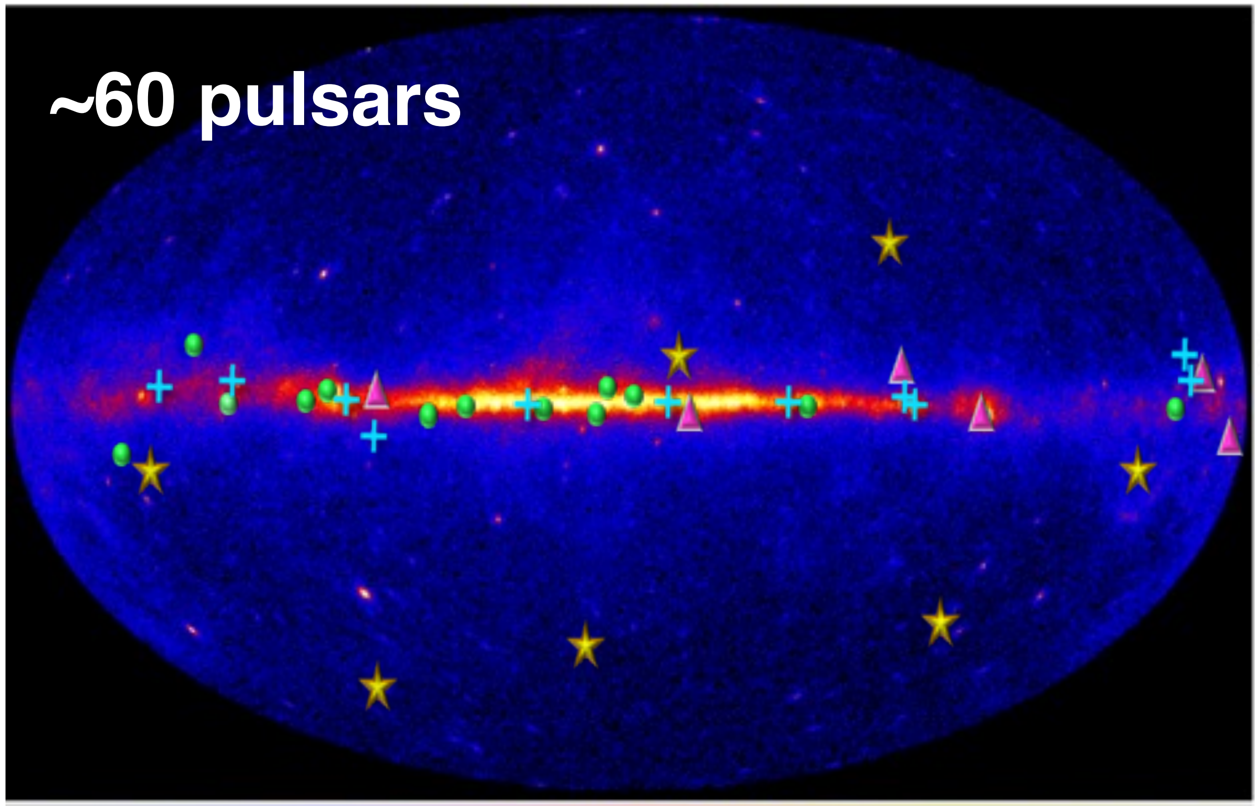
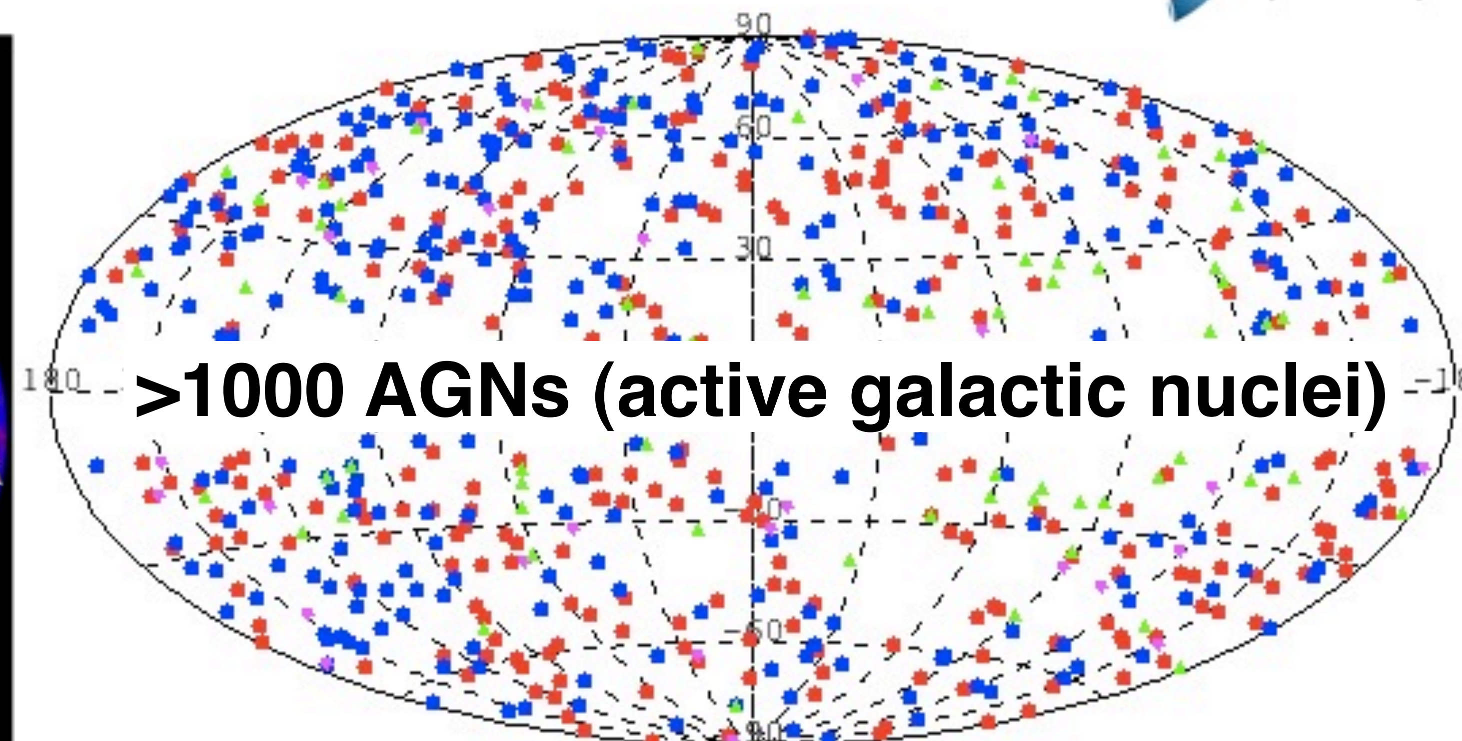
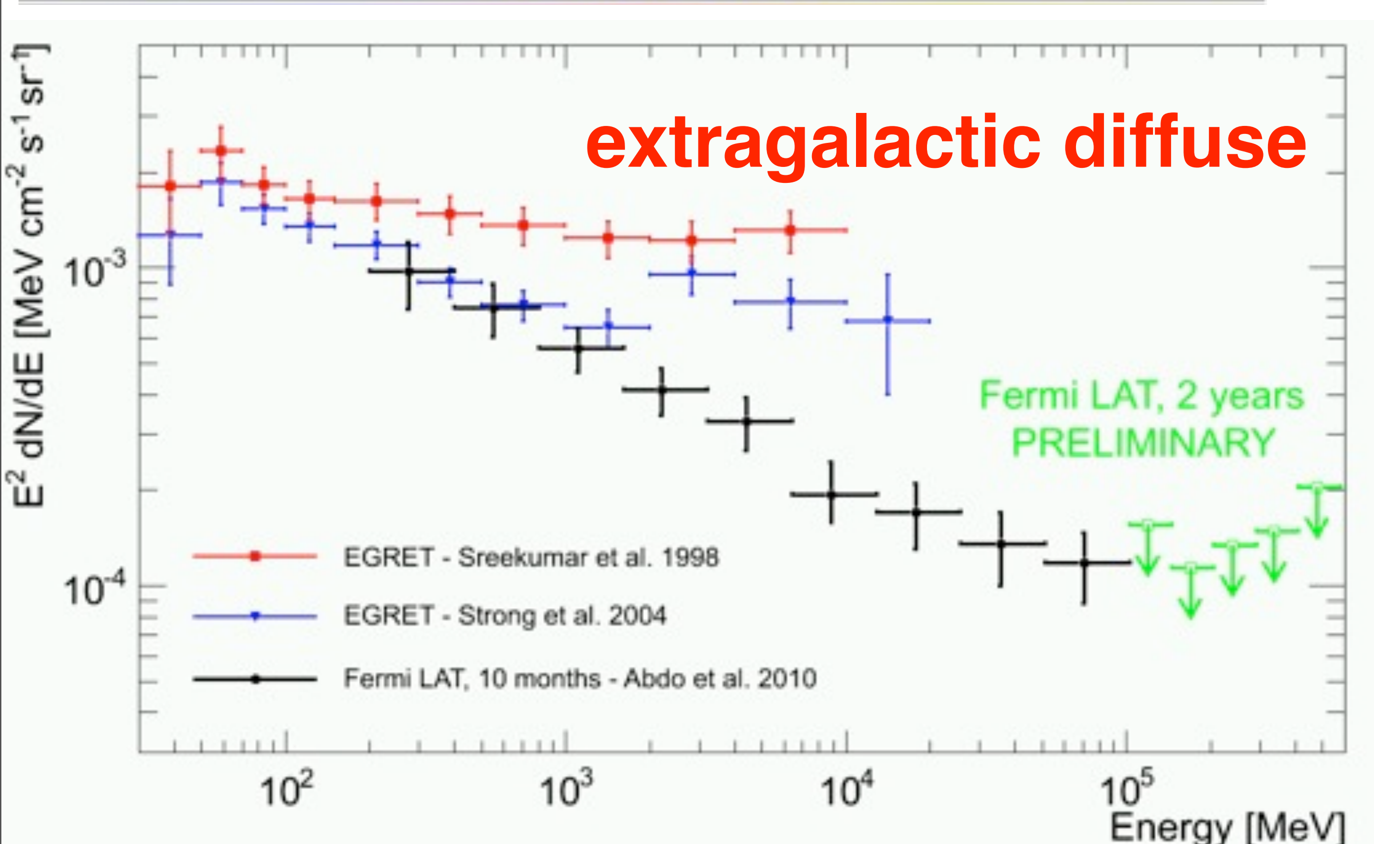
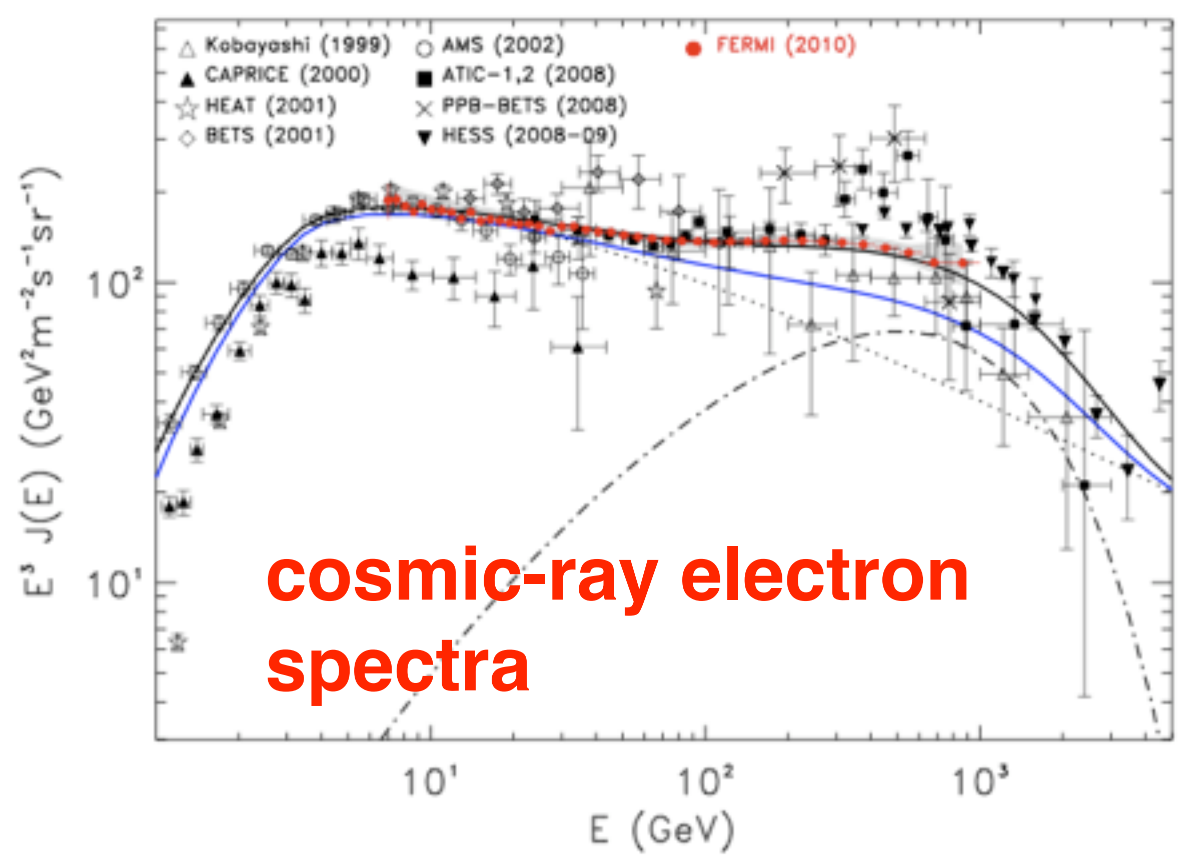
Highlights of Fermi Science









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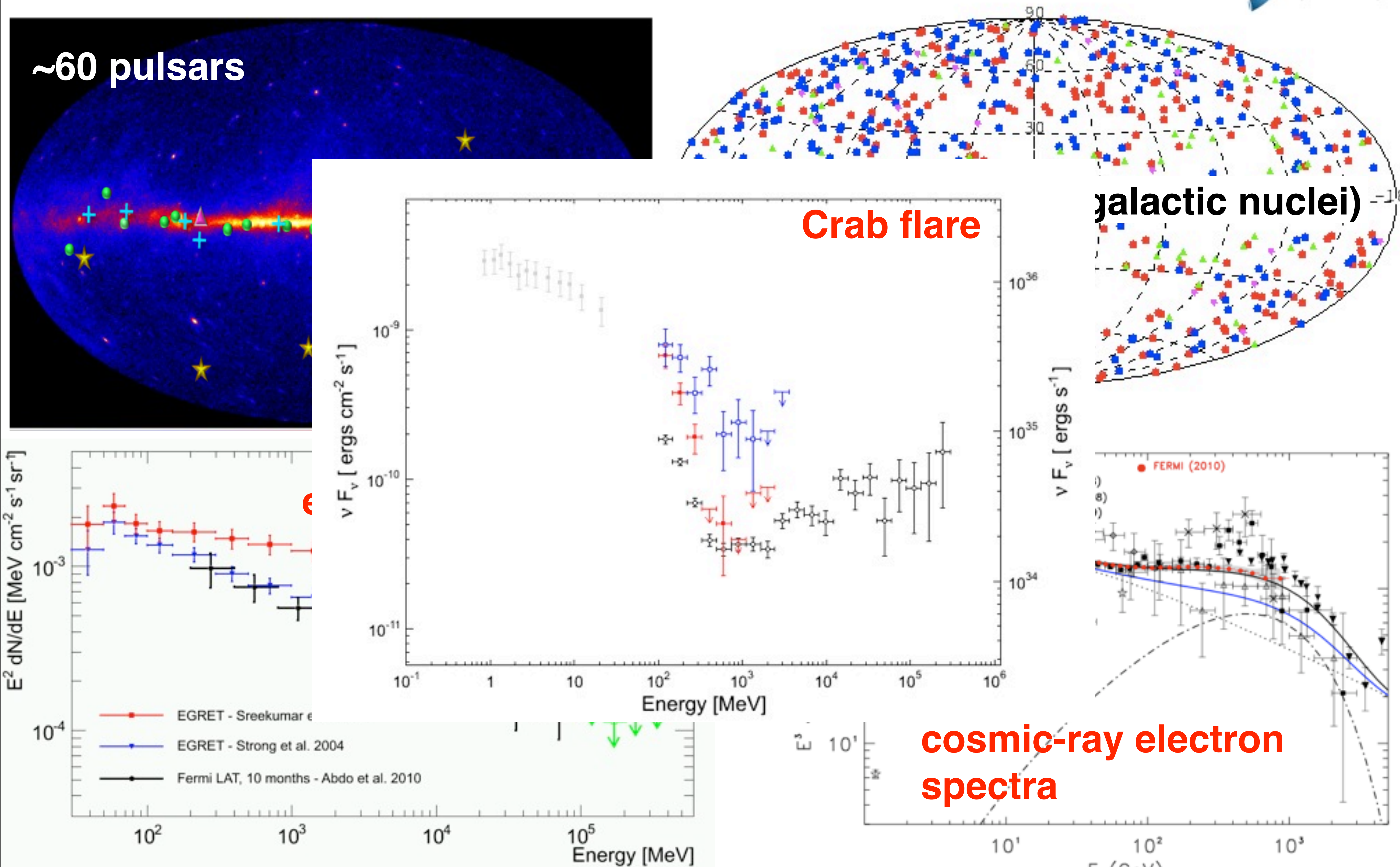
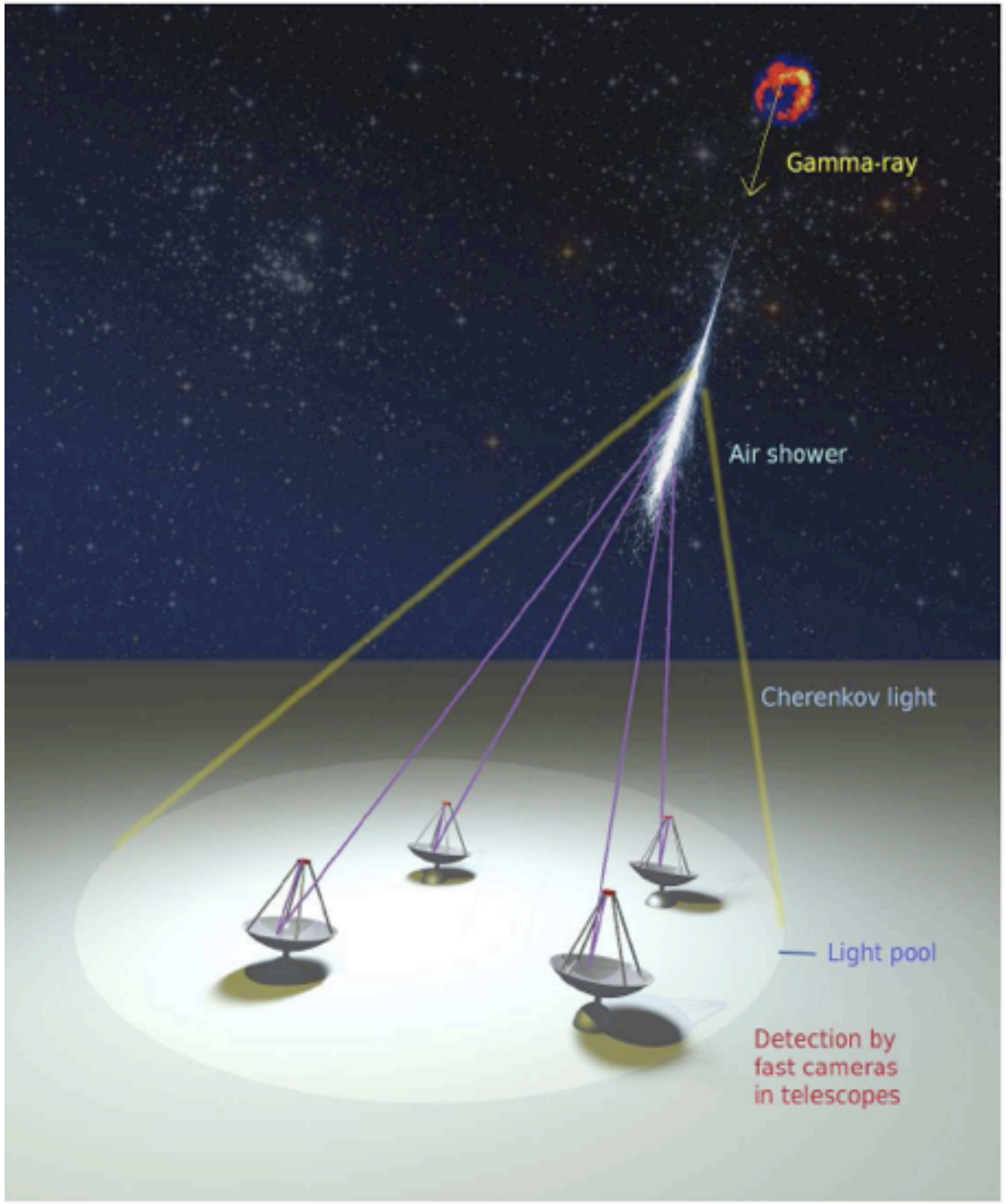
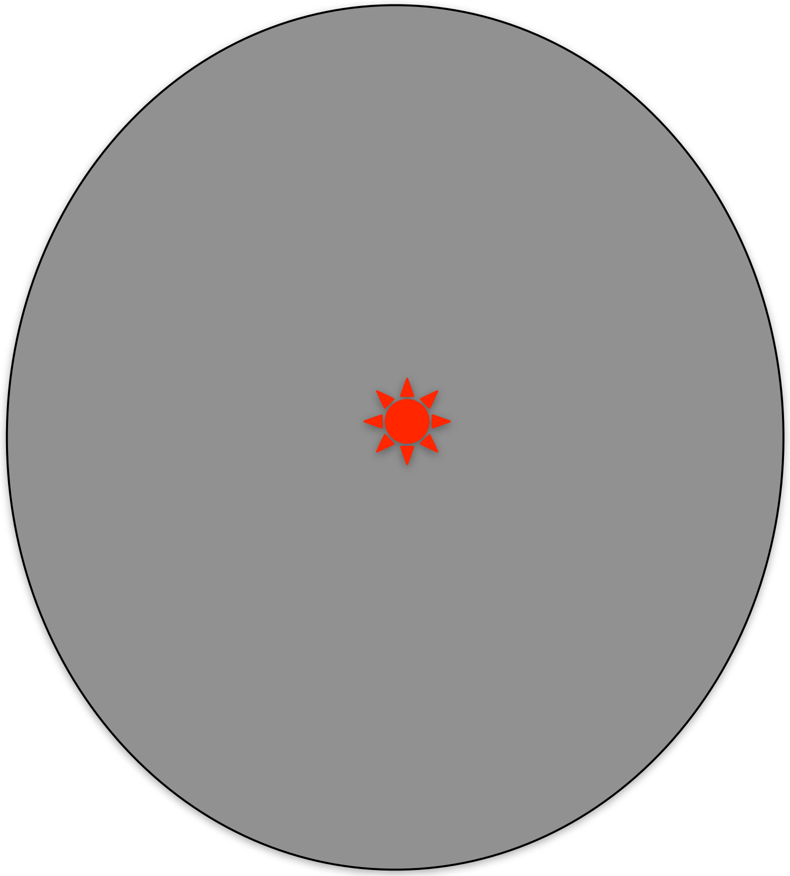


Imaging Atmospheric Cherenkov Telescope



Cherenkov Light
50photons/m² (5 pe/m²) at 1TeV



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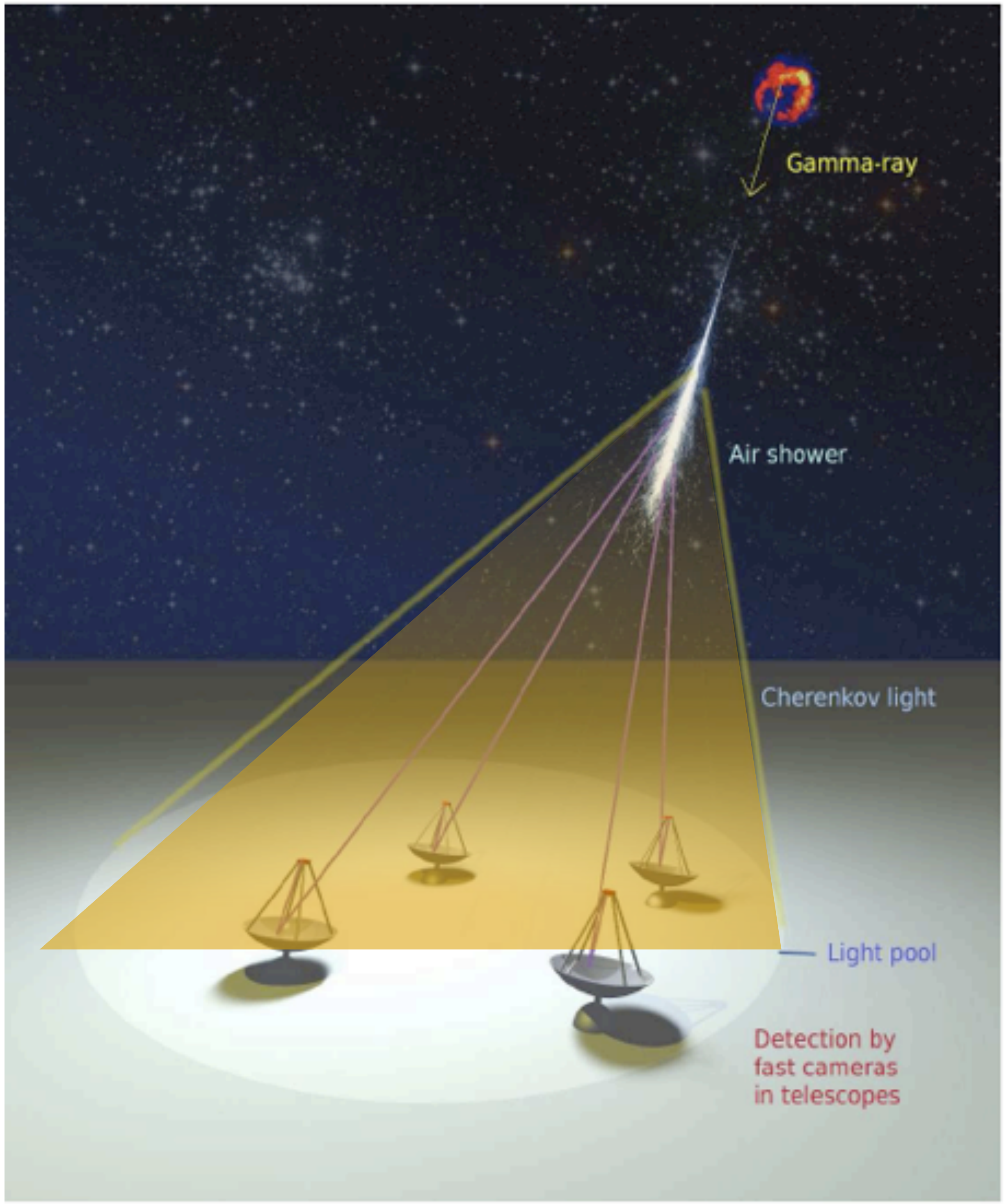

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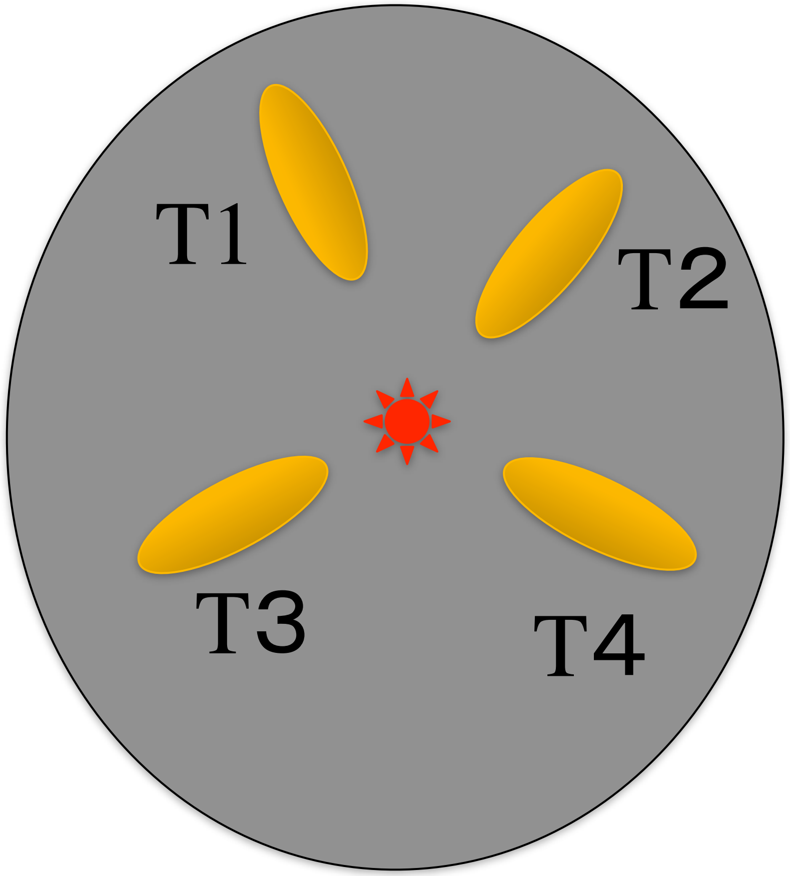

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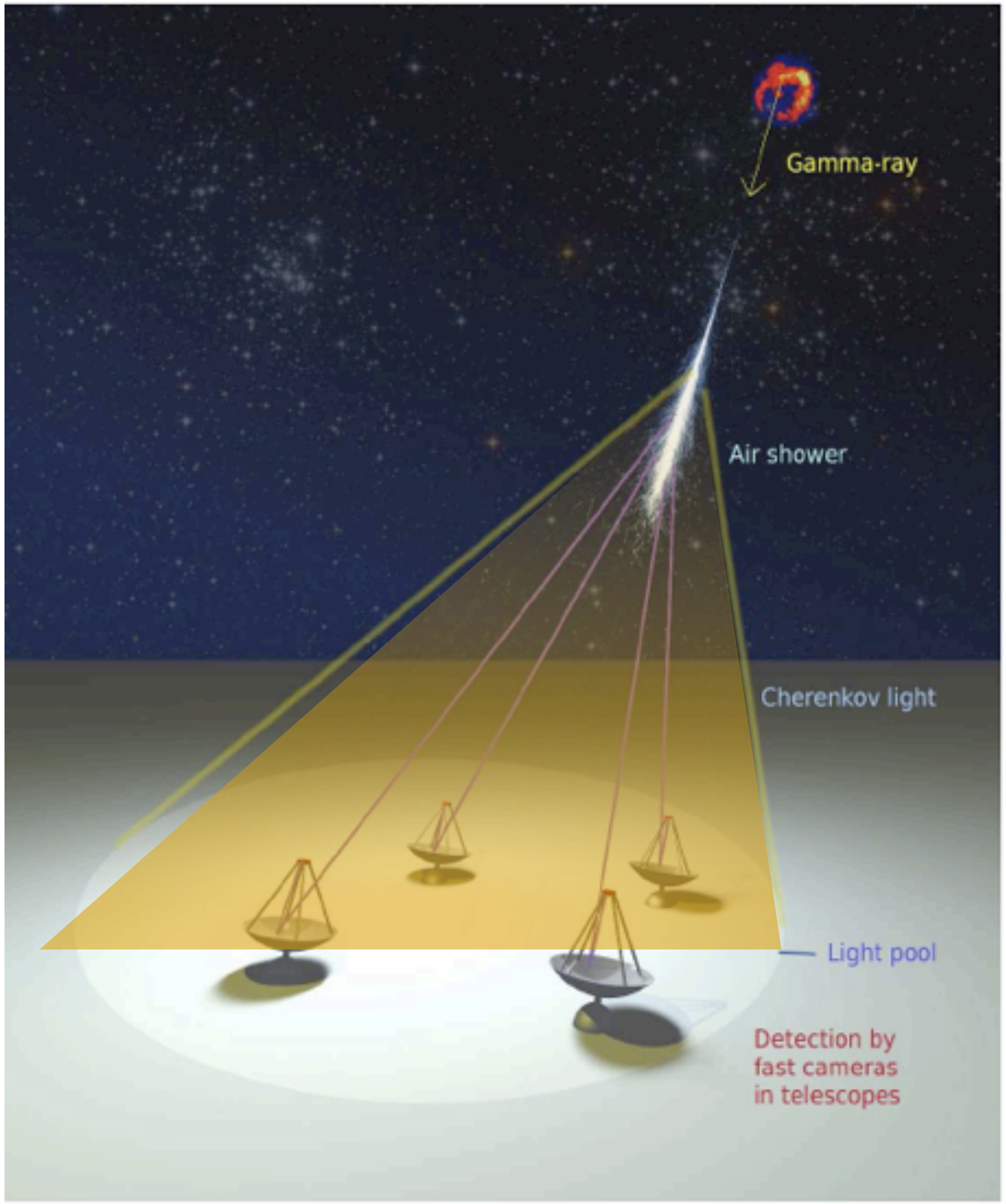

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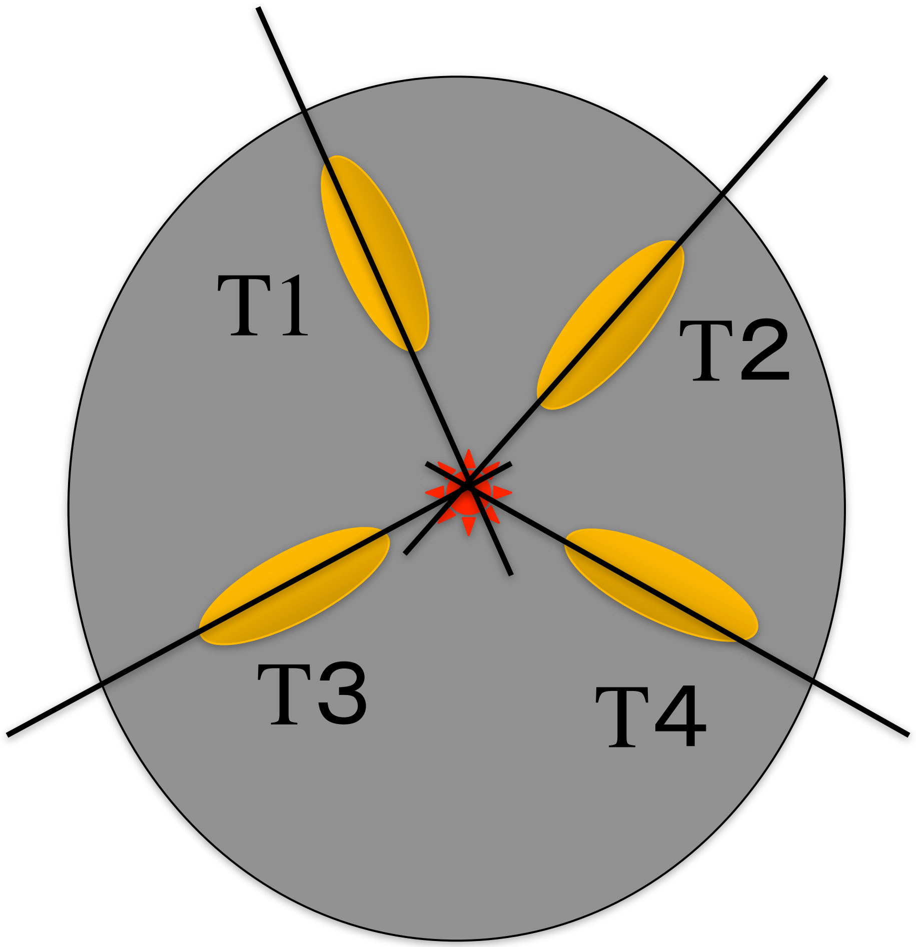

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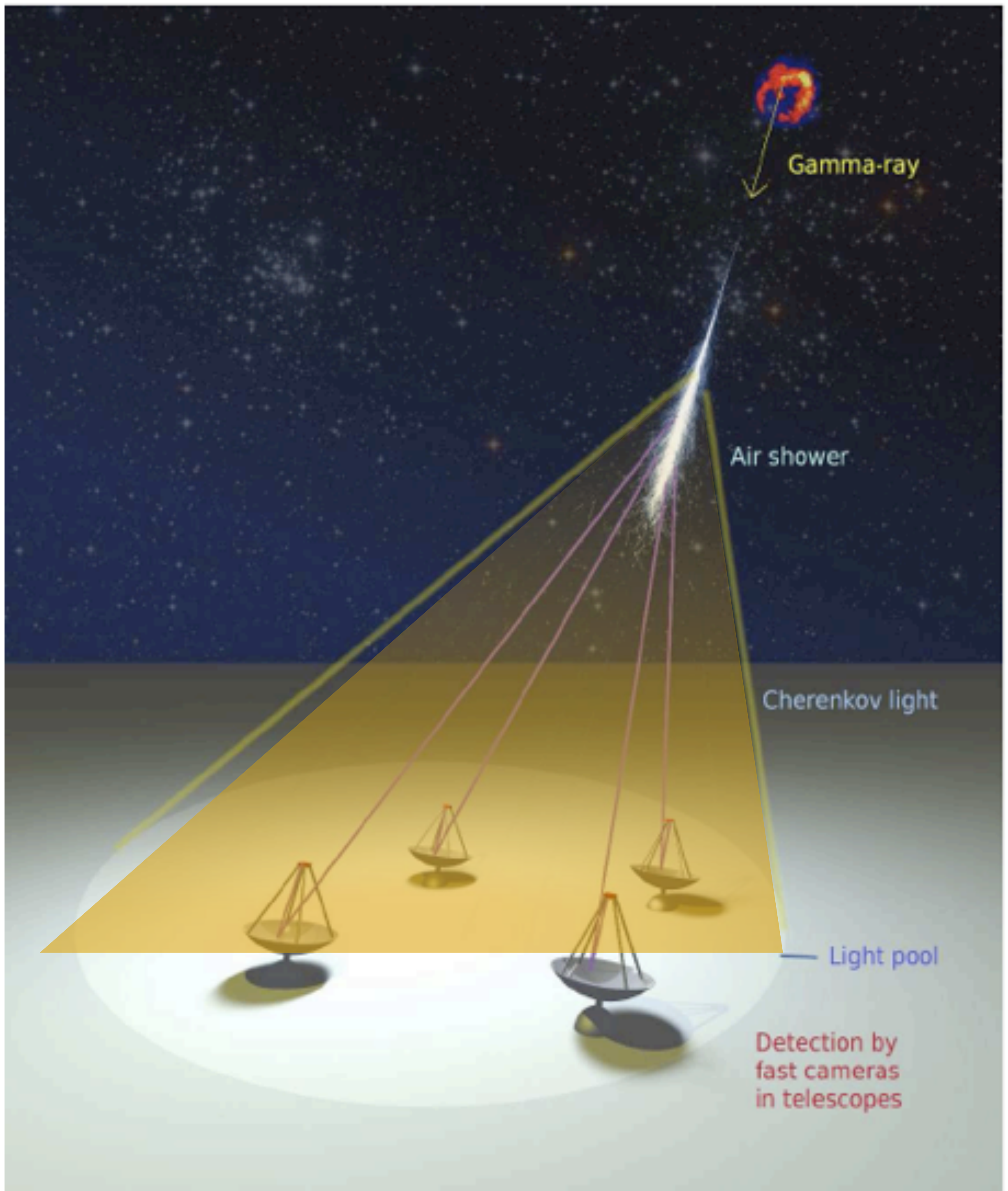

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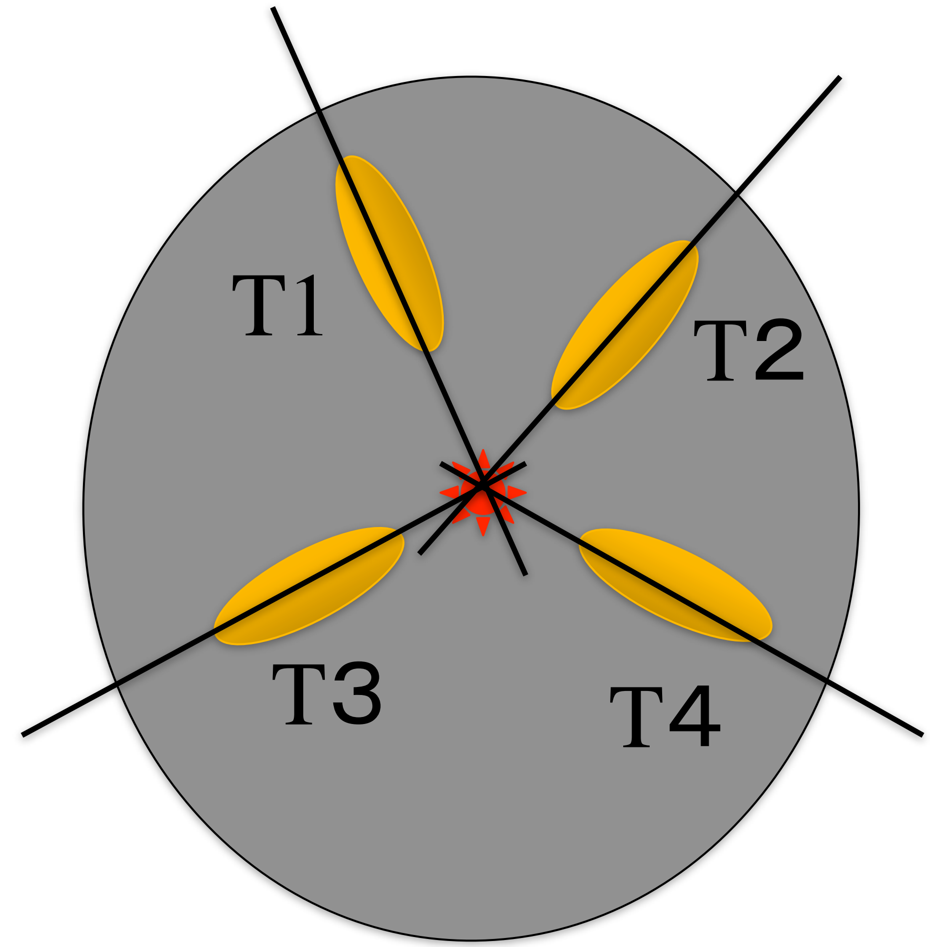
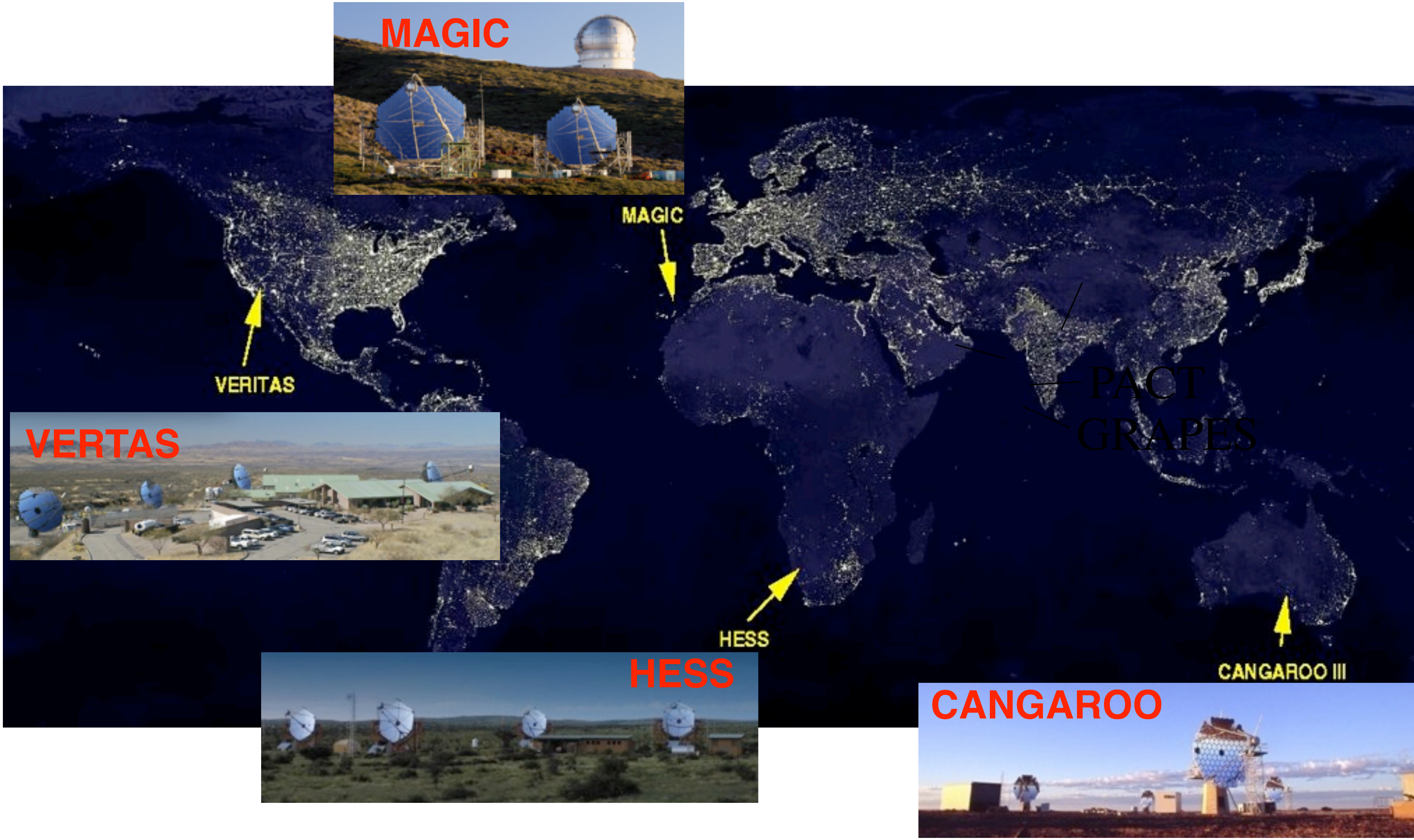


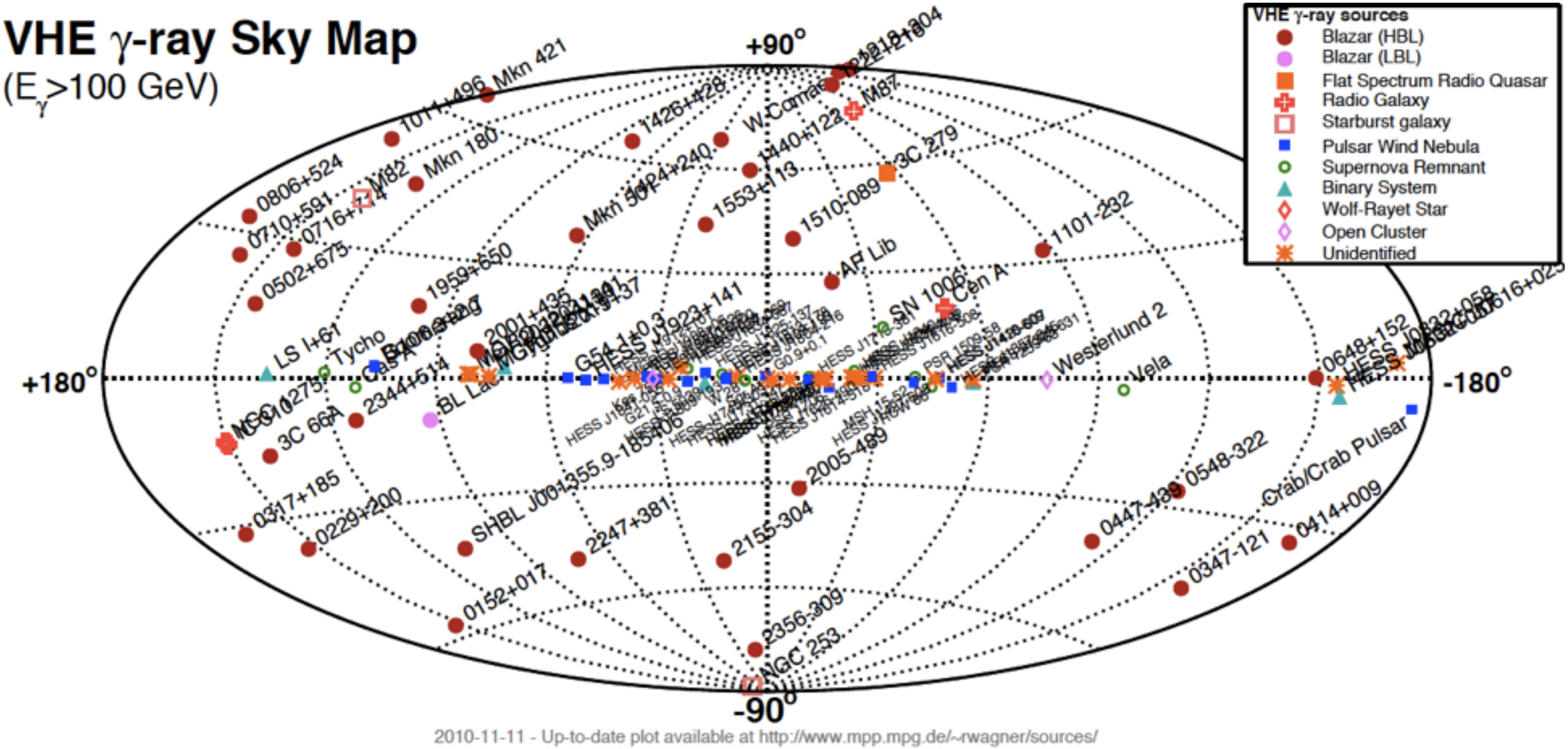
Typical parameters

Energy range 50GeV ~ 10TeV
CR rejection power >99%
Angular resolution ~0.1 degrees
Energy resolution ~20%
Detection area ~10^{5}m^2
Sensitivity ~1% Crab Flux (10^{-13} erg/cm^{2}s)

IACTs on Earth



VHE Skymap



106 sources (45 Extragalactics + 61 Galactics) in Nov 2010
Blazars, FSRQs, FR-I, Starburst galaxies
SNRs, PWNe, Pulsar, Binaries, un-IDs

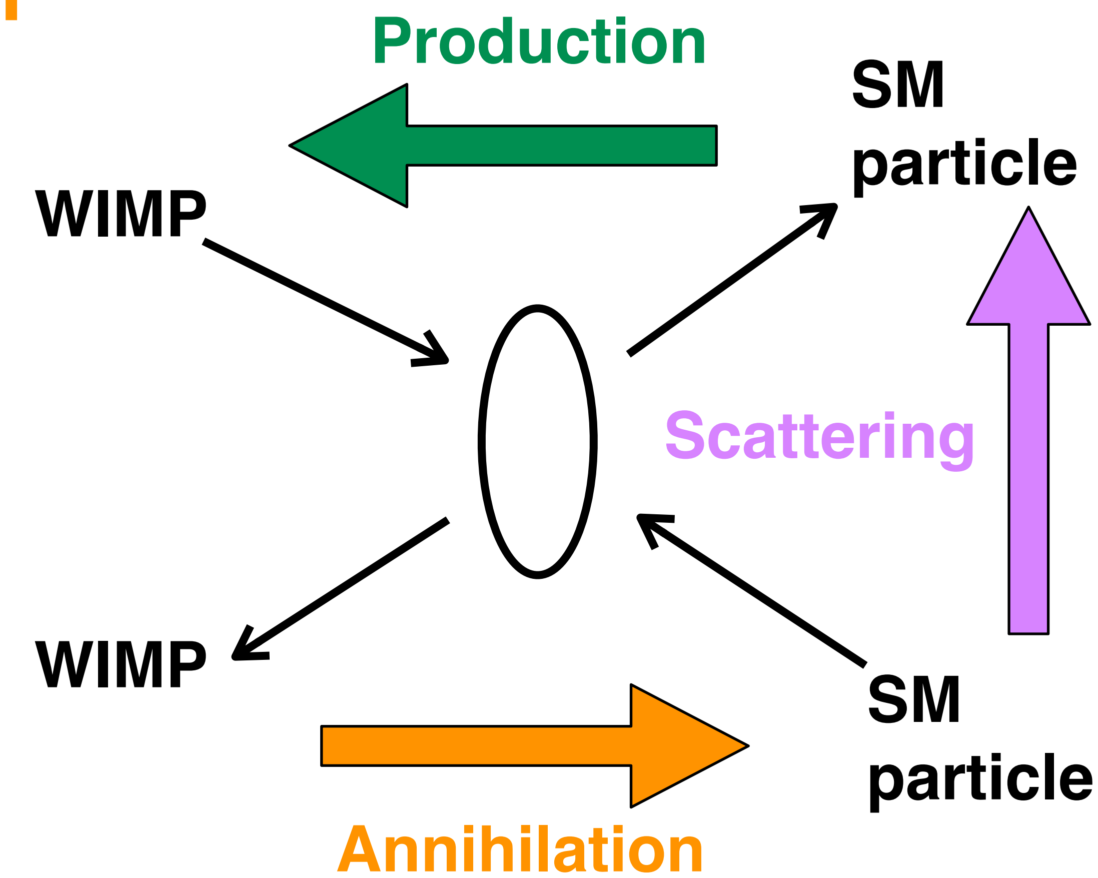
WIMP Search Approaches

- **Accelerator production**
  - **Precise measurements of DM properties: mass, cross section**
  - **UED (KK) vs SUSY**
- **Direct detection of WIMP scattering**
  - **Measurement of local WIMP density**
- **Indirect detection of WIMP annihilation**
  - **Distribution of WIMP in the Universe**

particle physics

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\varphi,\theta) = \frac{1}{4\pi}\frac{\langle\sigma_{ann} v\rangle}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f \times \int_{\Delta\Omega\ (\varphi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\varphi'))\, dl(r,\varphi')$$

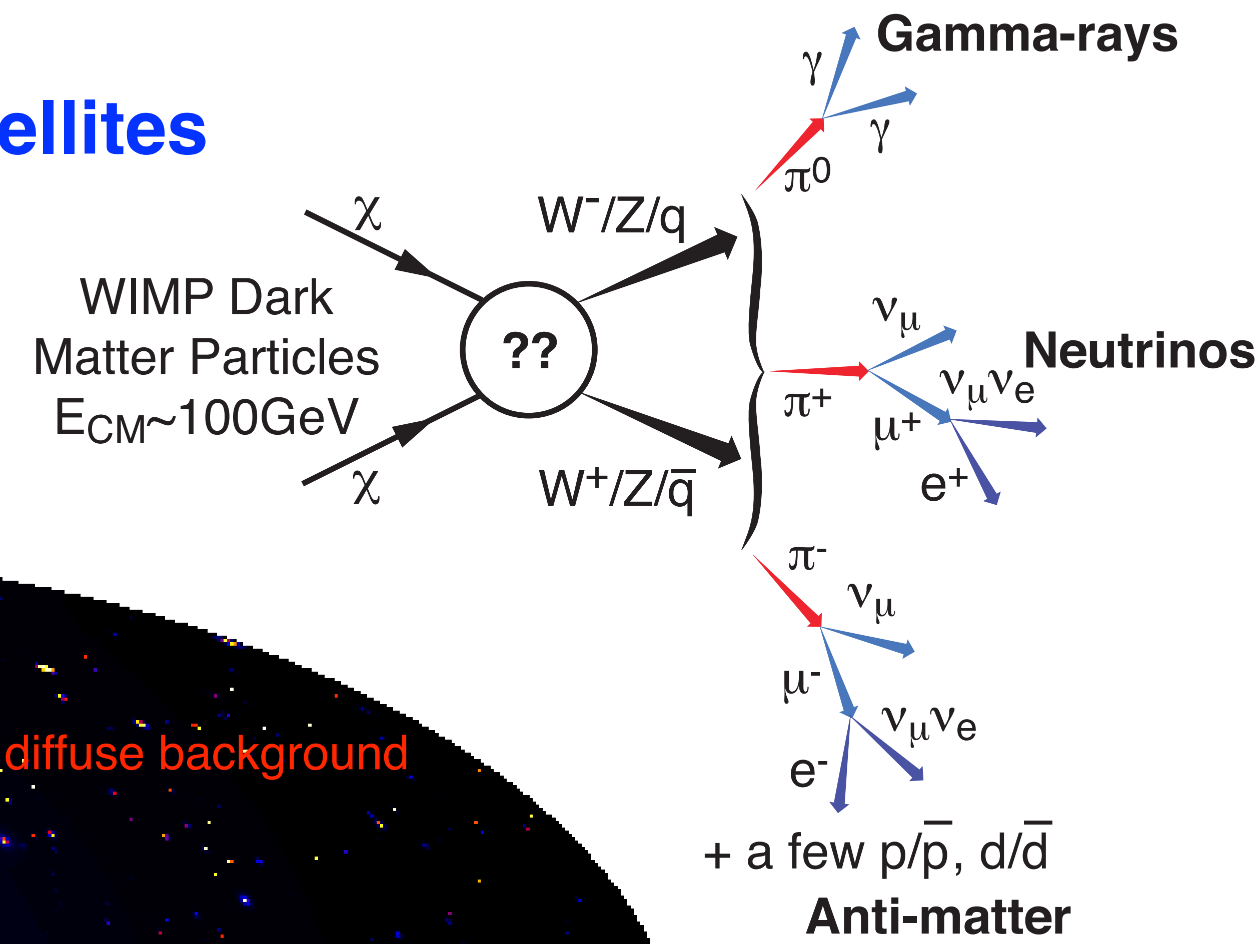
DM distribution

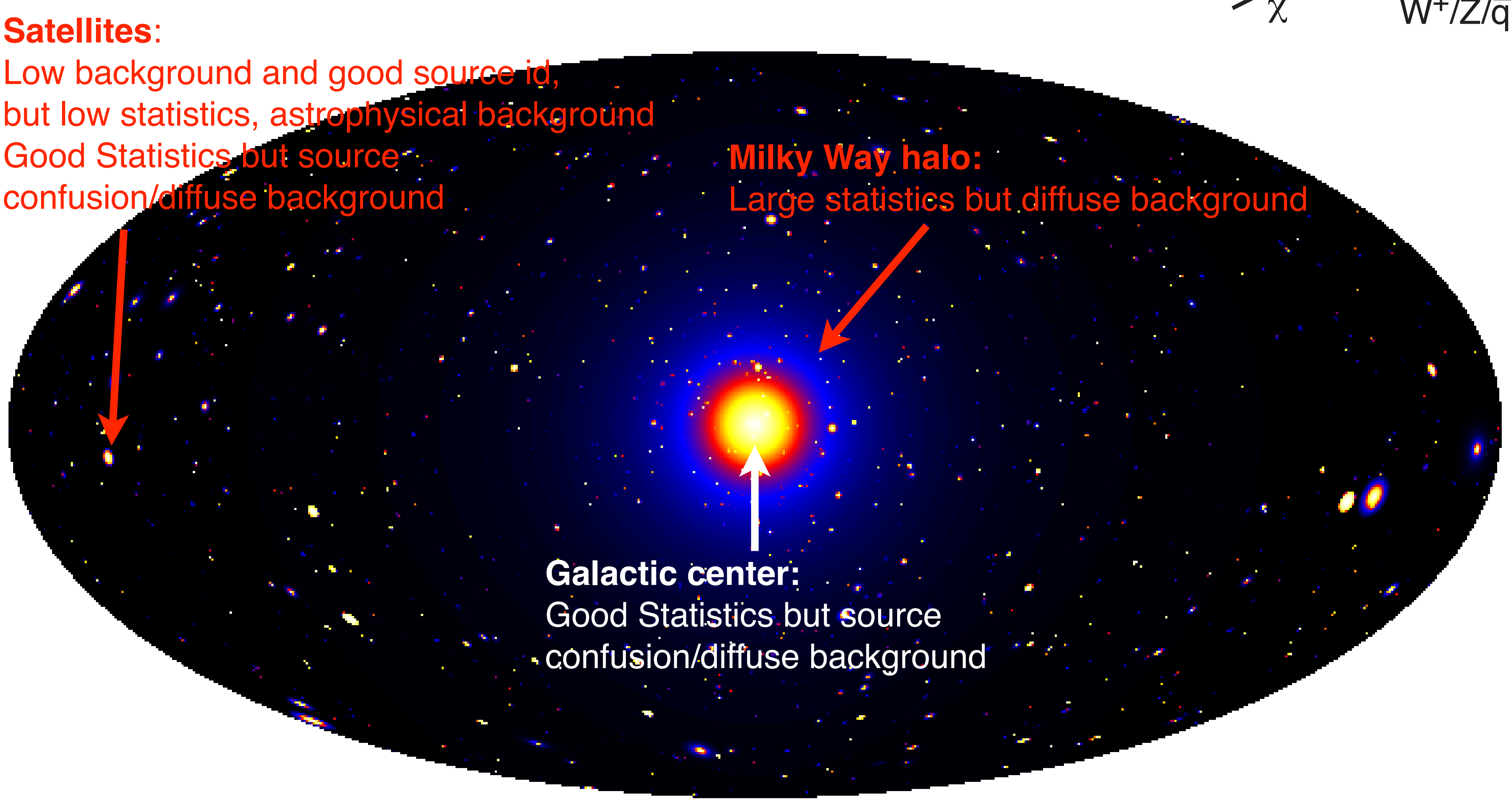


- **Those approaches are complimentary**
  - **Different model dependences and sensitivity phase space**

Search for WIMP with Gamma Ray

- Multi-pronged approaches
  - Galactic center, Milky Way halo, Satellites
  - Line emission, Continuum
  - CR electrons, Diffuse gamma-ray background





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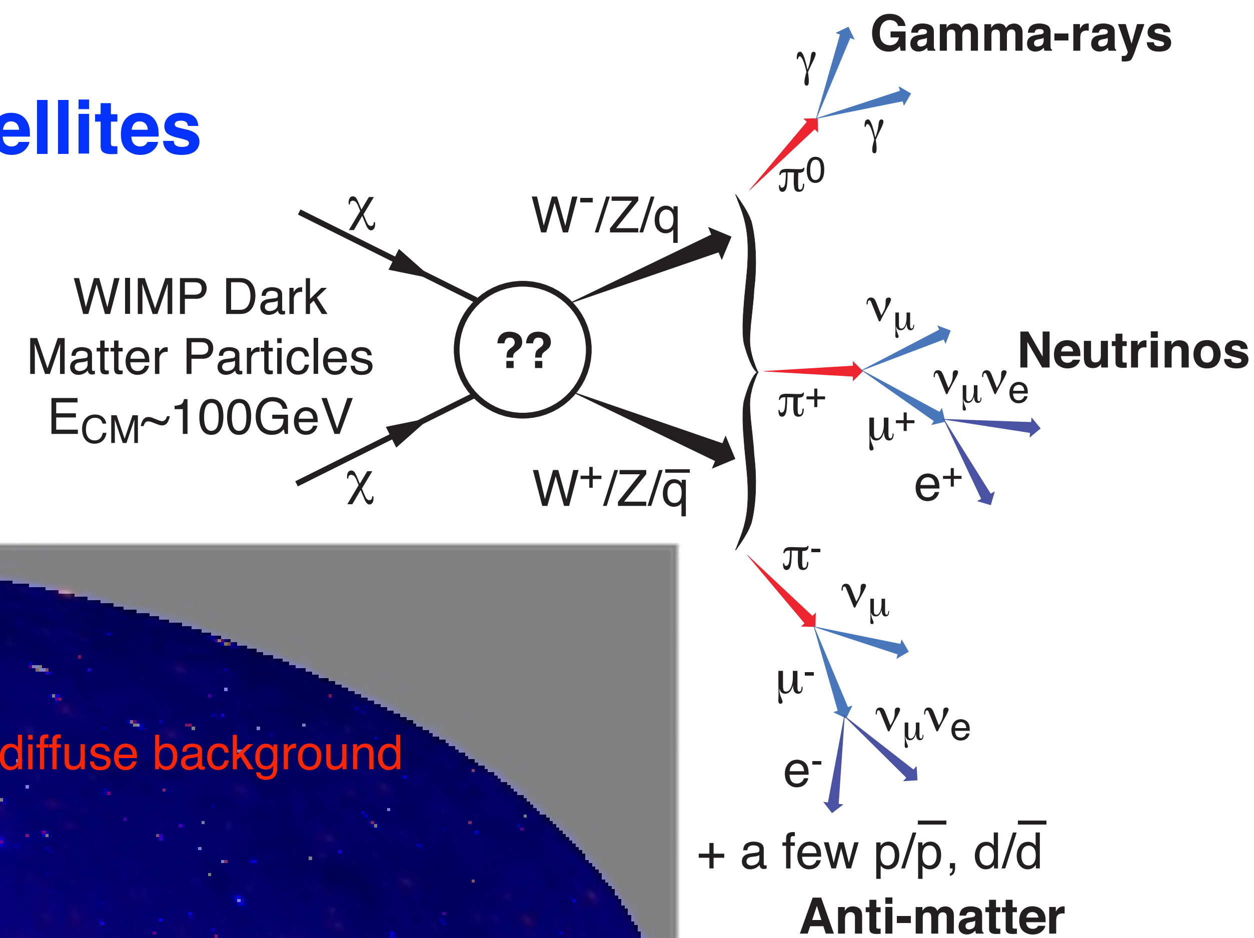
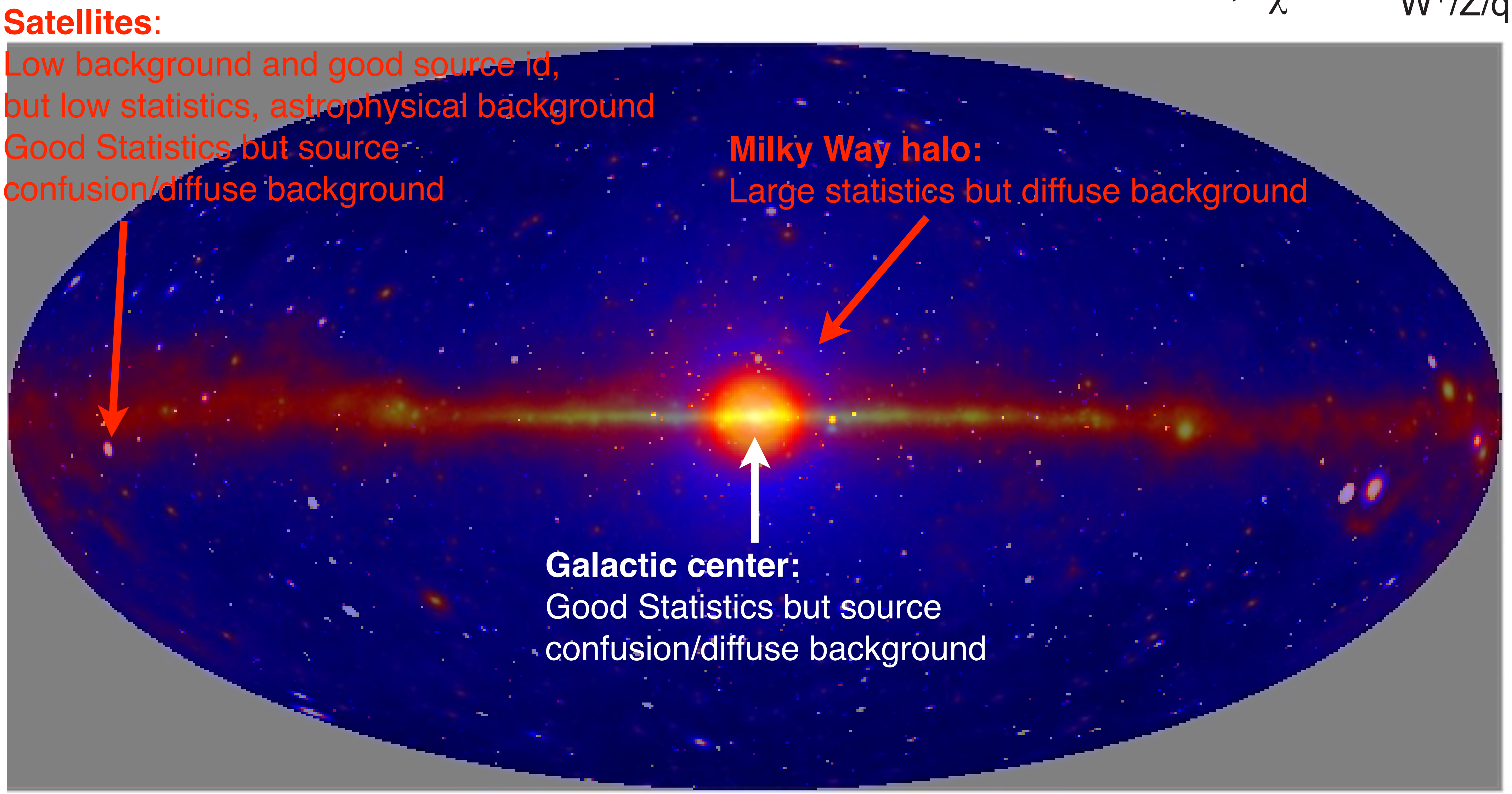
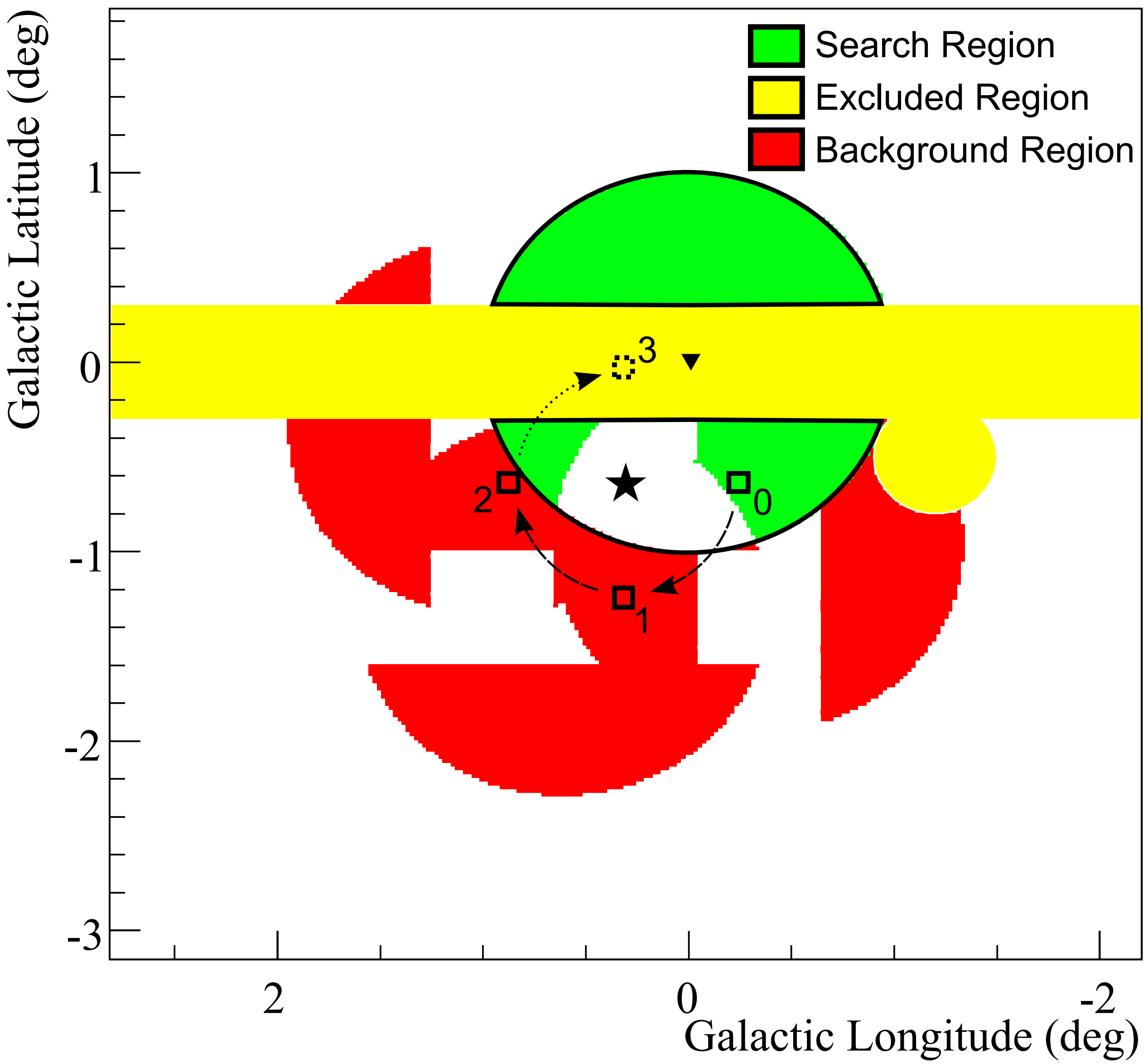
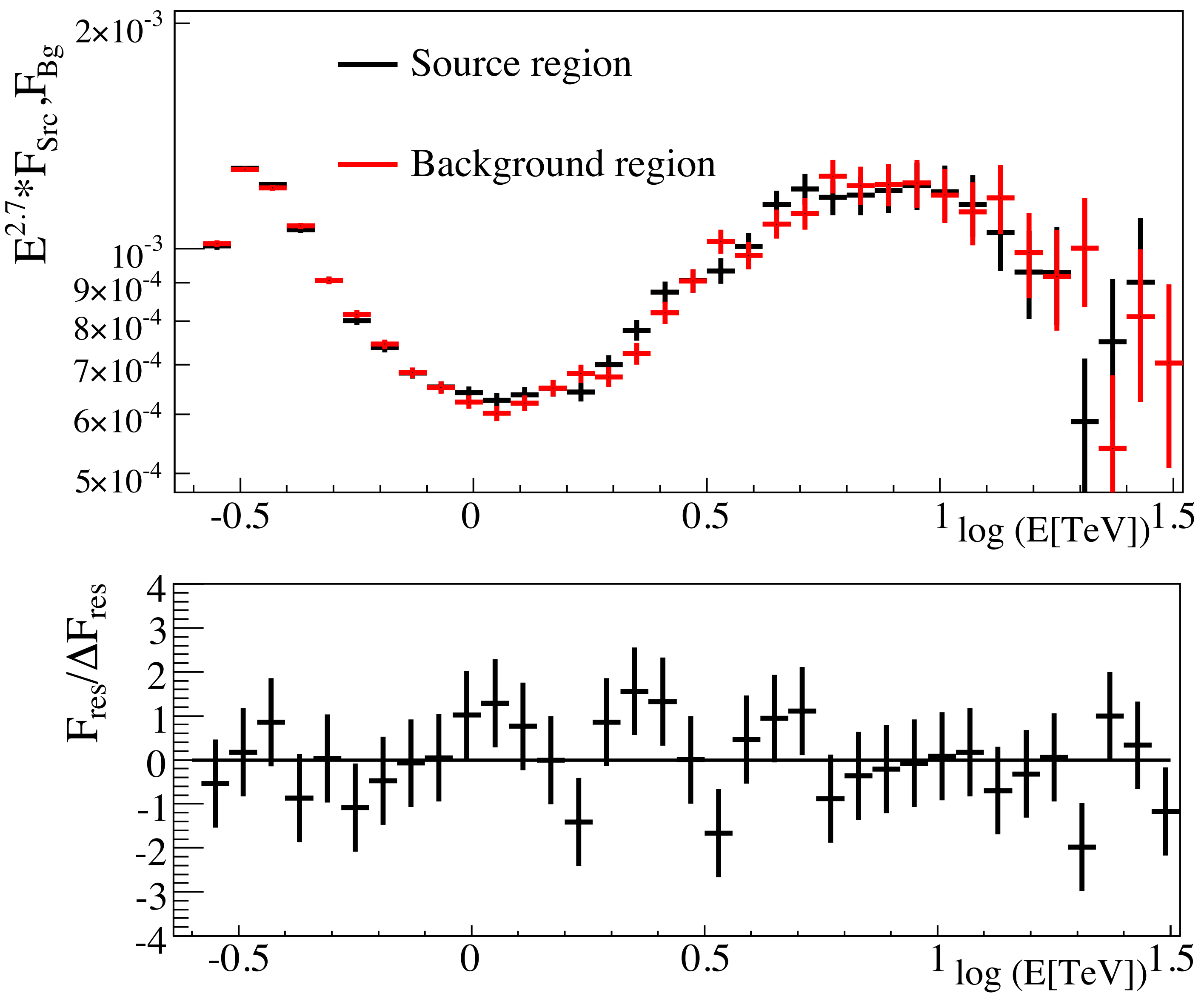




HESS WIMP Search in Galactic Center

- Galactic center is expected to have enormous amount of WIMP
  - BG in TeV band is relatively low compared with GeV band due to steep Galactic diffuse BG spectrum





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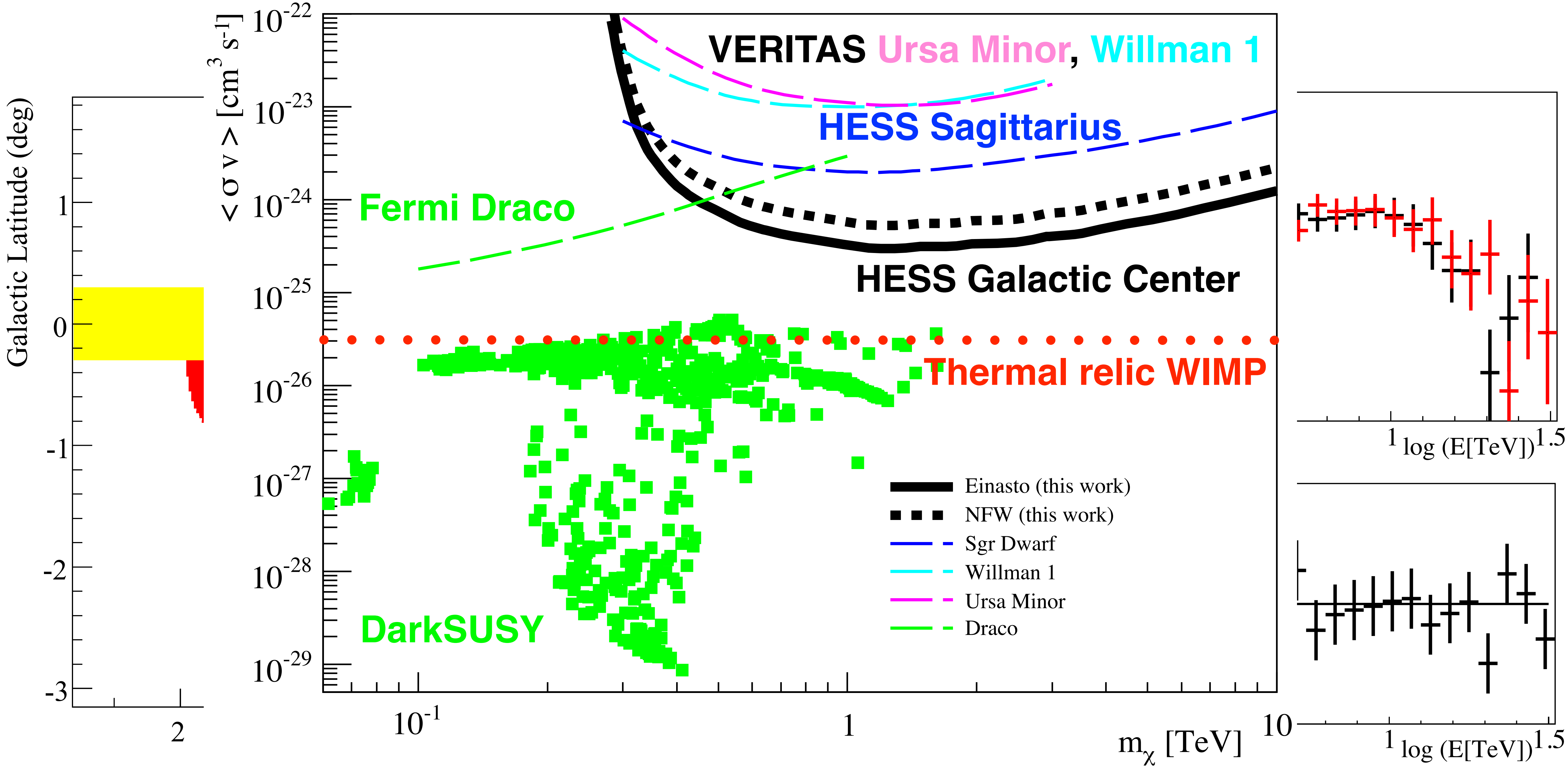

Fermi WIMP Search in Dwarf Galaxies

- 10 most promising dSph (dwarf spheroidal) based on distance, Matter/Light (M/L)
  - New DM-dominated dSph is being discovered recently

Name	Distance (kpc)	Discovered	M/L	Flux UL (E>0.1 GeV) 10^{-9} c/cm²/s
Segue 1	23±3	2007	1320±2680	1.8
Ursa Major II	30±5	2006	1722±1226	4.6
Segue 2	35	2009	650^{+1300}_{-380}	2.1
Willman 2	38±7	2004	~500	2.1
Coma Berenices	44±4	2006	448±297	1.0
Ursa Minor	66±3	1954	275±35	0.7
Sculptor	79±4	1937	158±33	4.8
Draco	76±5	1954	290±60	1.2
Sextans	86±4	1990	70±10	1.3
Fornax	138±8	1938	14.8±8.3	1.7

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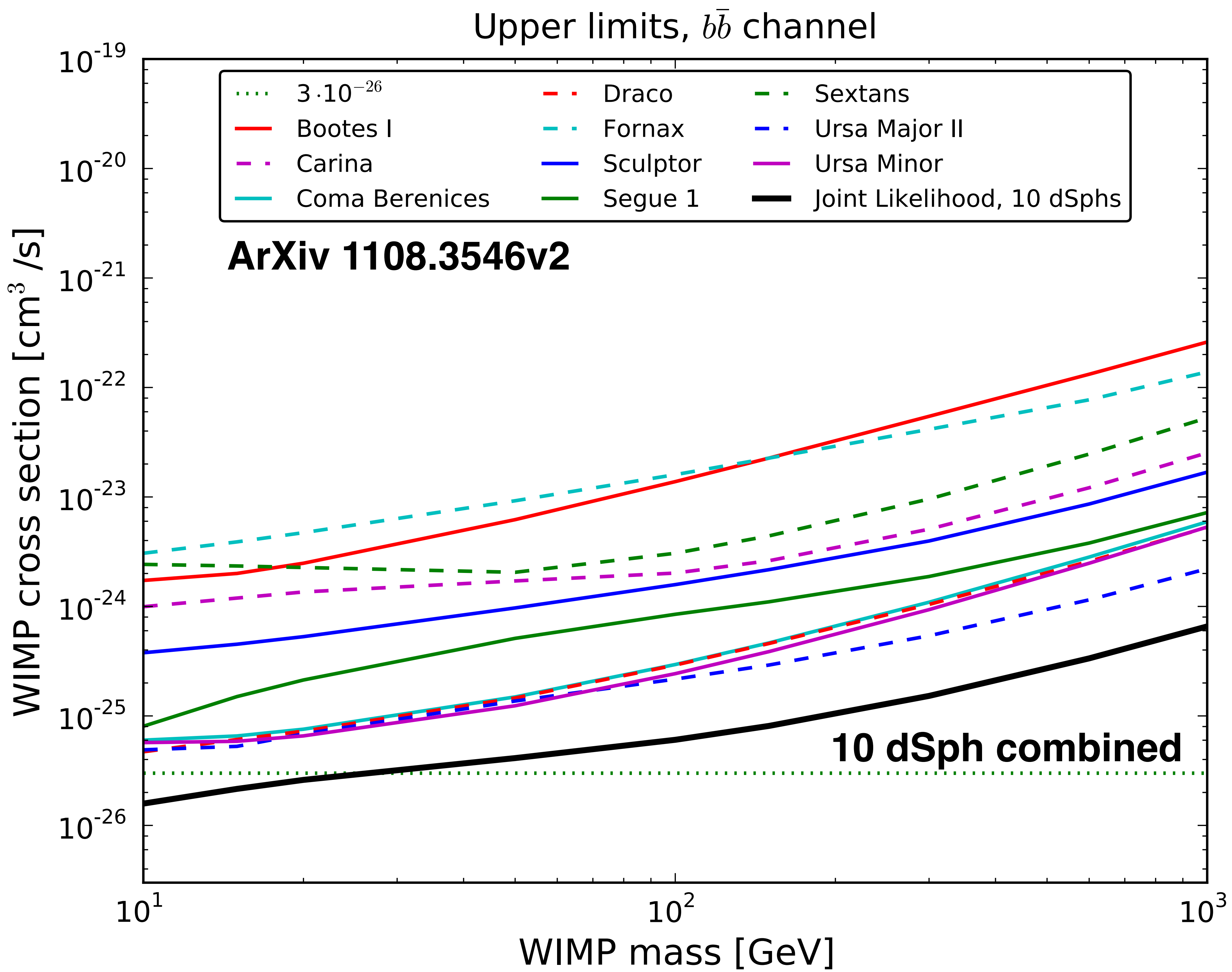

Fermi WIMP Search in Dwarf Galaxies

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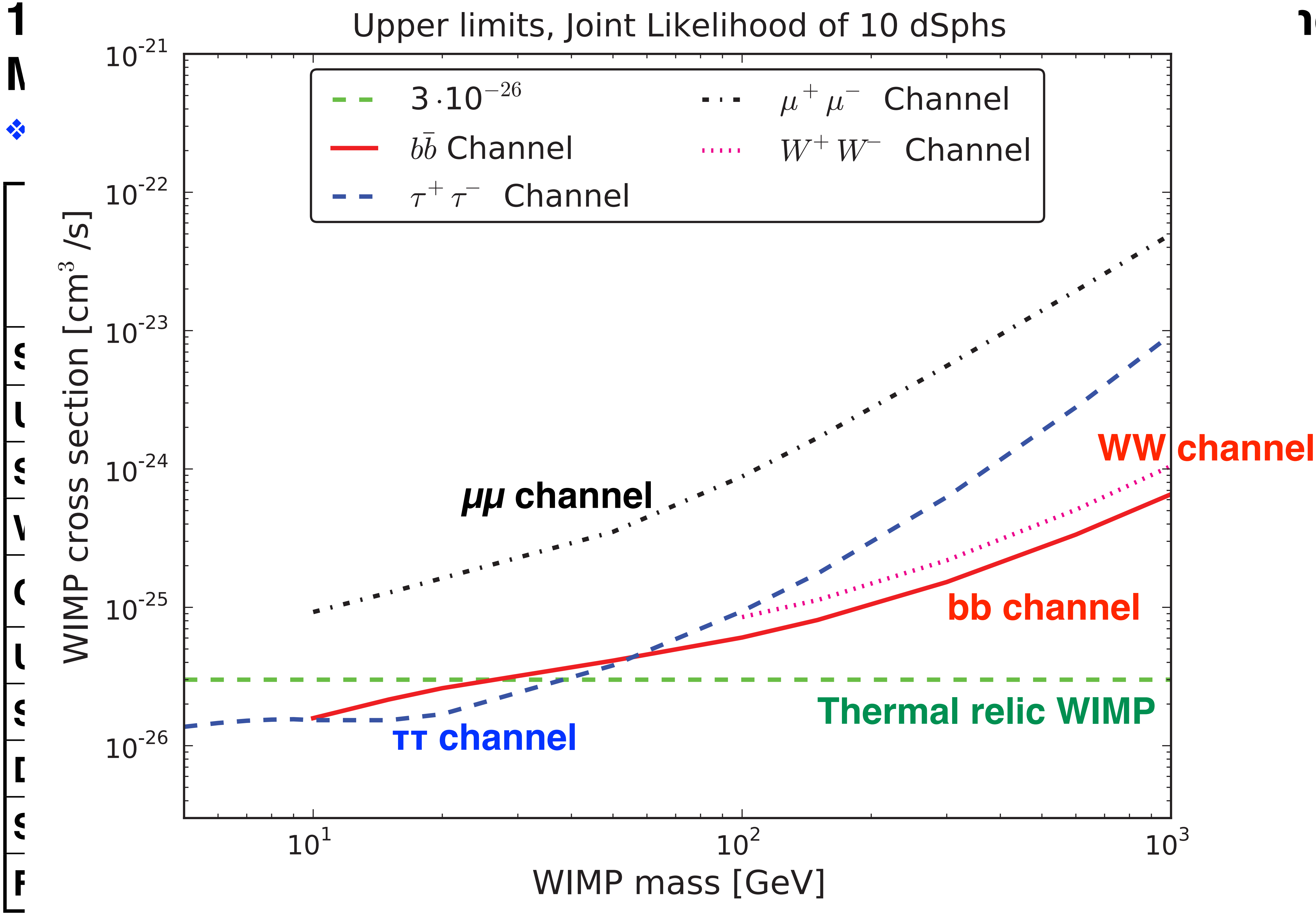
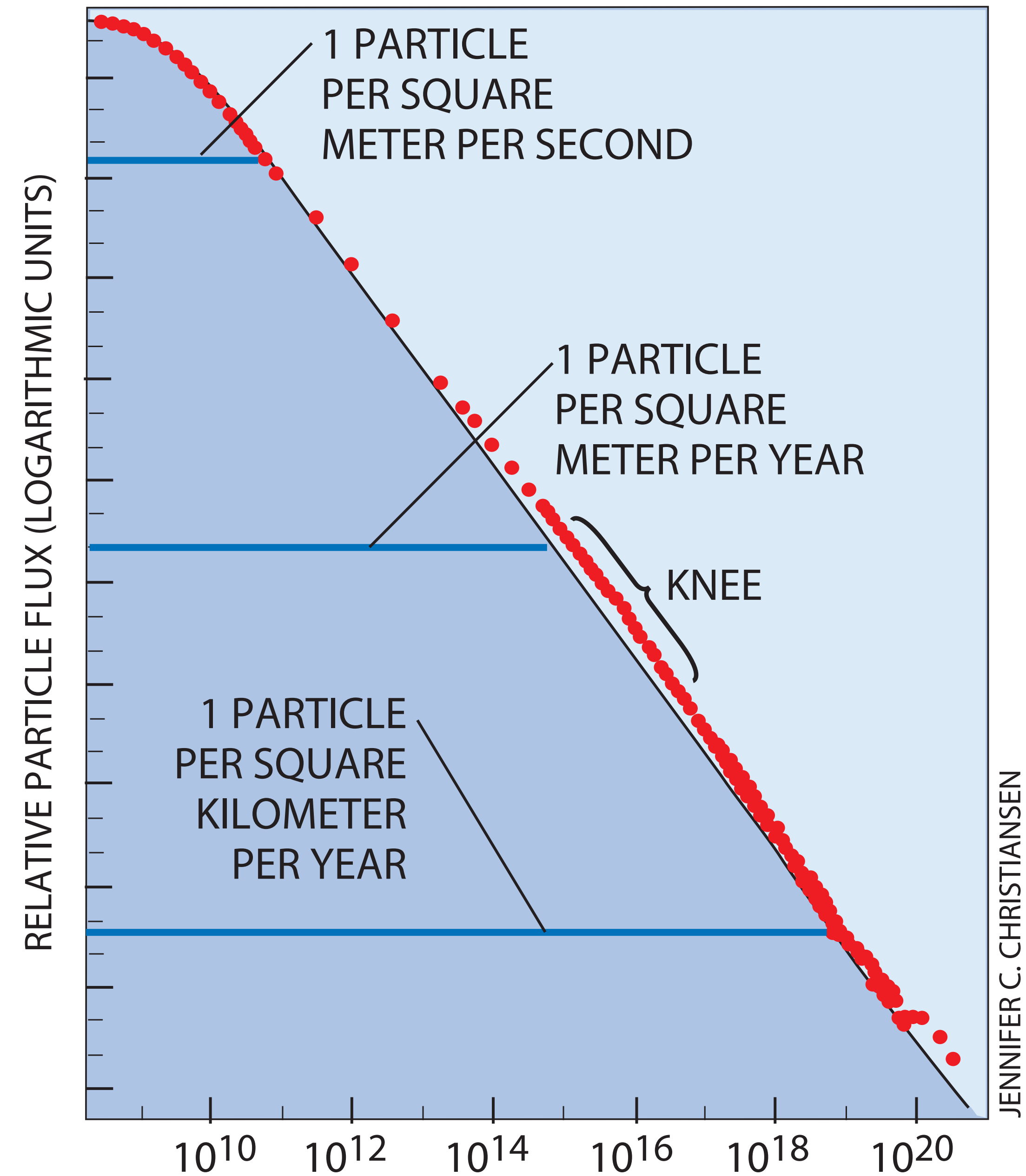


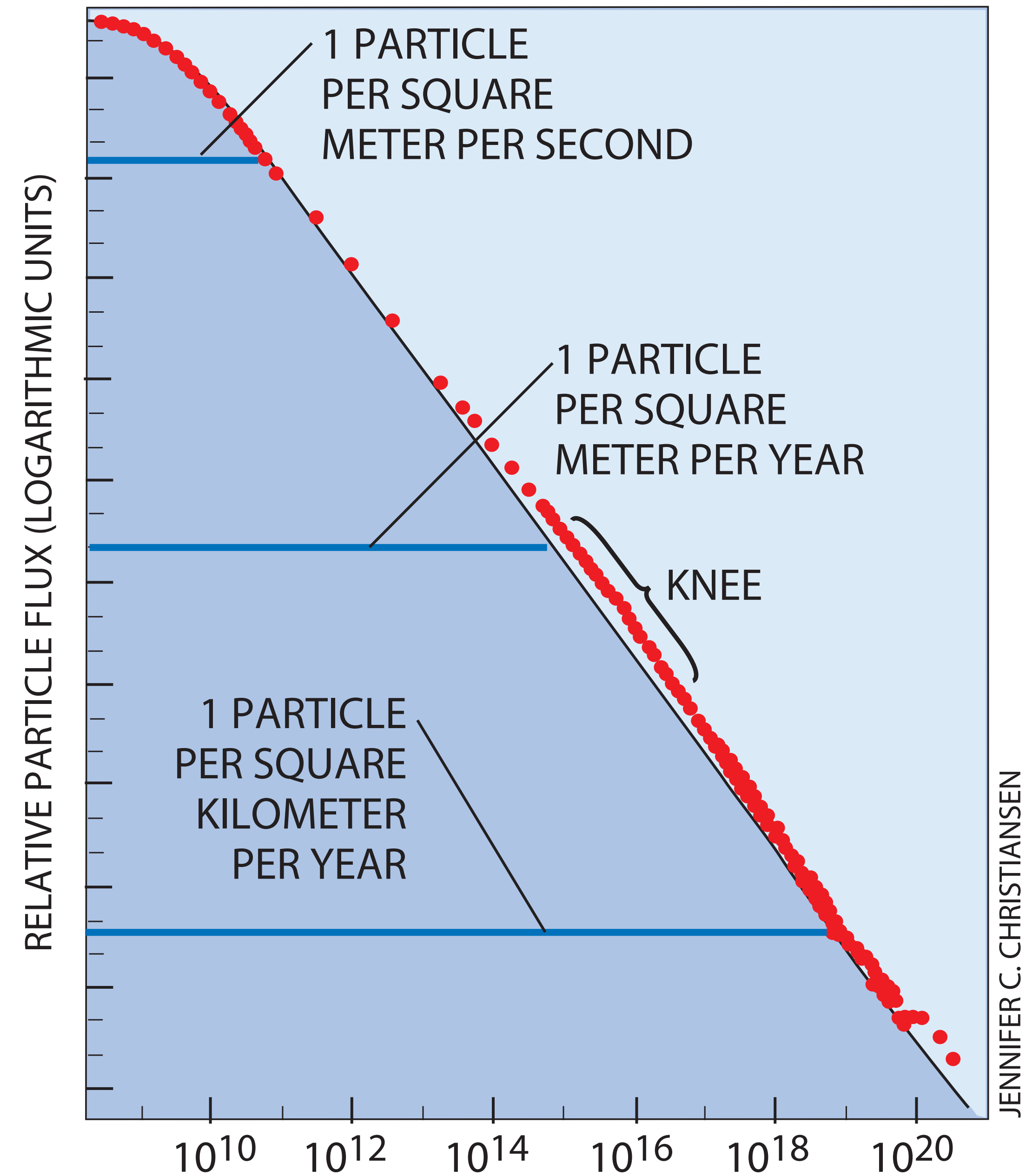
Cosmic Particle Accelerators

- **Origin of cosmic ray protons?**
  - **Galactic SNRs (Supernova Remnants) are considered as the best candidates for cosmic-rays below "Knee"**
    - **Only circumstantial evidence**
      - **Diffusive shock acceleration (Blanford&Eichler 1977)**
      - **CR energy sum consistent with SNR kinetic energy (Ginzburg&Syrovatskii 1964)**
    - **No observational evidence for hadronic acceleration**
    - **Spectral index (~2.7) is difficult to explain**
  - **Cosmic-rays above "Knee" are considered extragalactic**
    - **Gamma-ray bursts (GRB)**
    - **Active Galactic Nuclei (blazar)**
    - **Merging galaxy clusters**



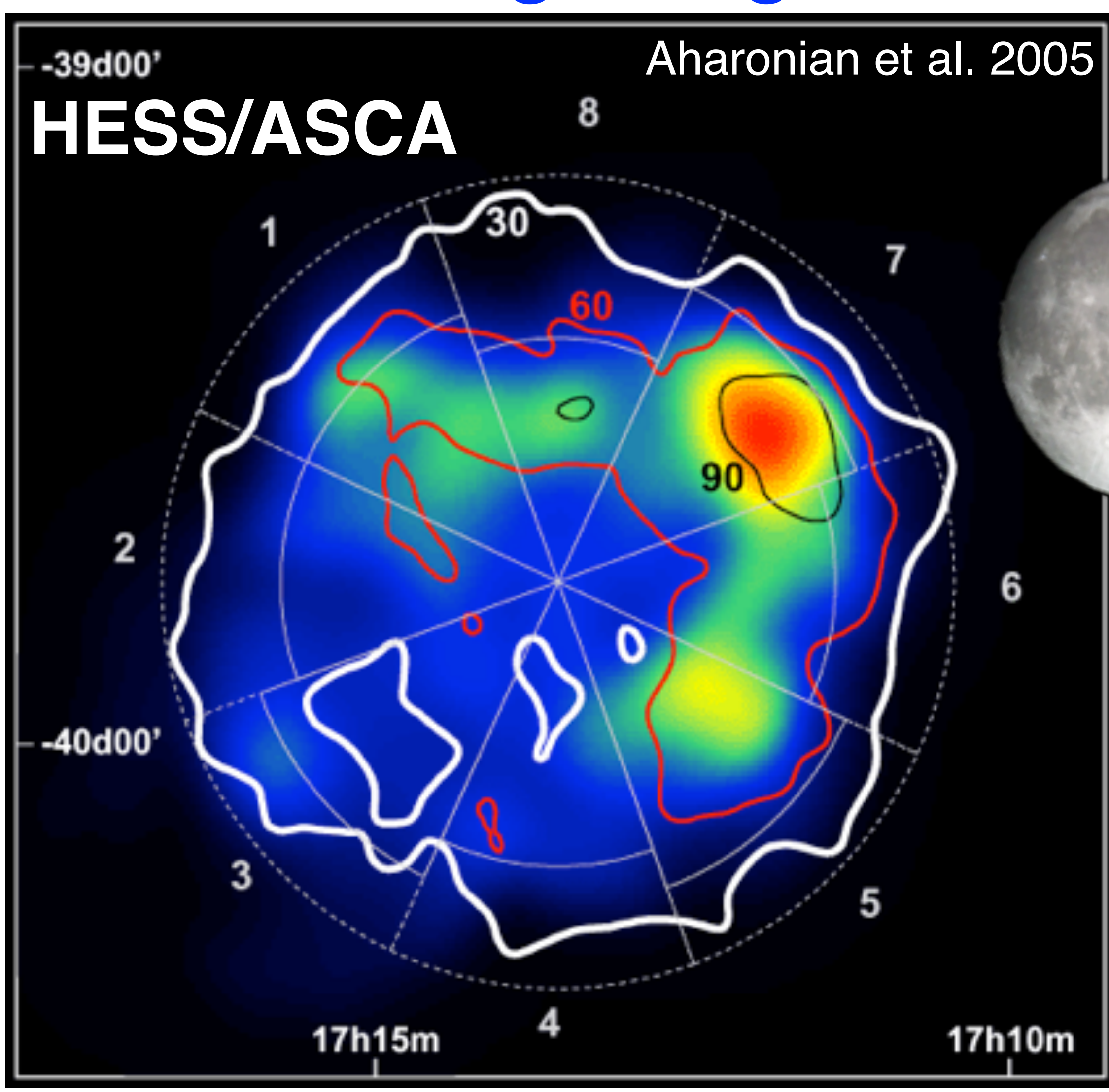
Cosmic Particle Accelerators

- Origin of cosmic ray protons?
  - **Galactic SNRs (Supernova Remnants) are considered as the best candidates for cosmic-rays below "Knee"**
    - Only circumstantial evidence
      - Diffusive shock acceleration (Blanford&Eichler 1977)
      - CR energy sum consistent with SNR kinetic energy (Ginzburg&Syrovatskii 1964)
    - No observational evidence for hadronic acceleration
    - Spectral index (~2.7) is difficult to explain
  - **Cosmic-rays above "Knee" are considered extragalactic**
    - Gamma-ray bursts (GRB)
    - Active Galactic Nuclei (blazar)
    - Merging galaxy clusters

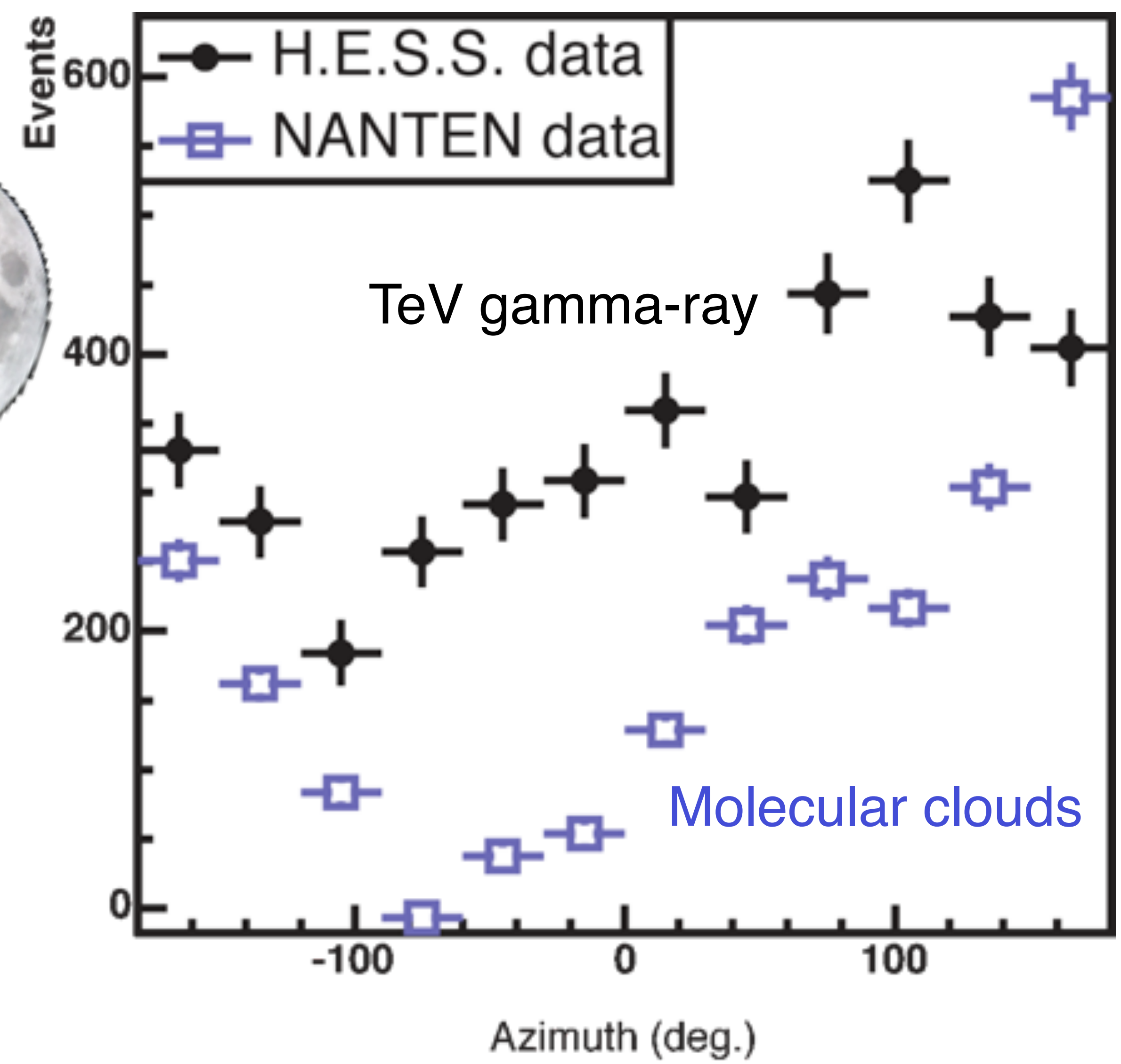


"Gold-Plated" Supernova Remnant

- HESS TeV gamma-ray observation of RX J1713.7-3946
  - Evidence for particle acceleration > 10^{14} eV
  - Morphological similarity with X-ray observation
  - Spectral feature can not conclusively distinguish leptonic or hadronic origin of gamma rays

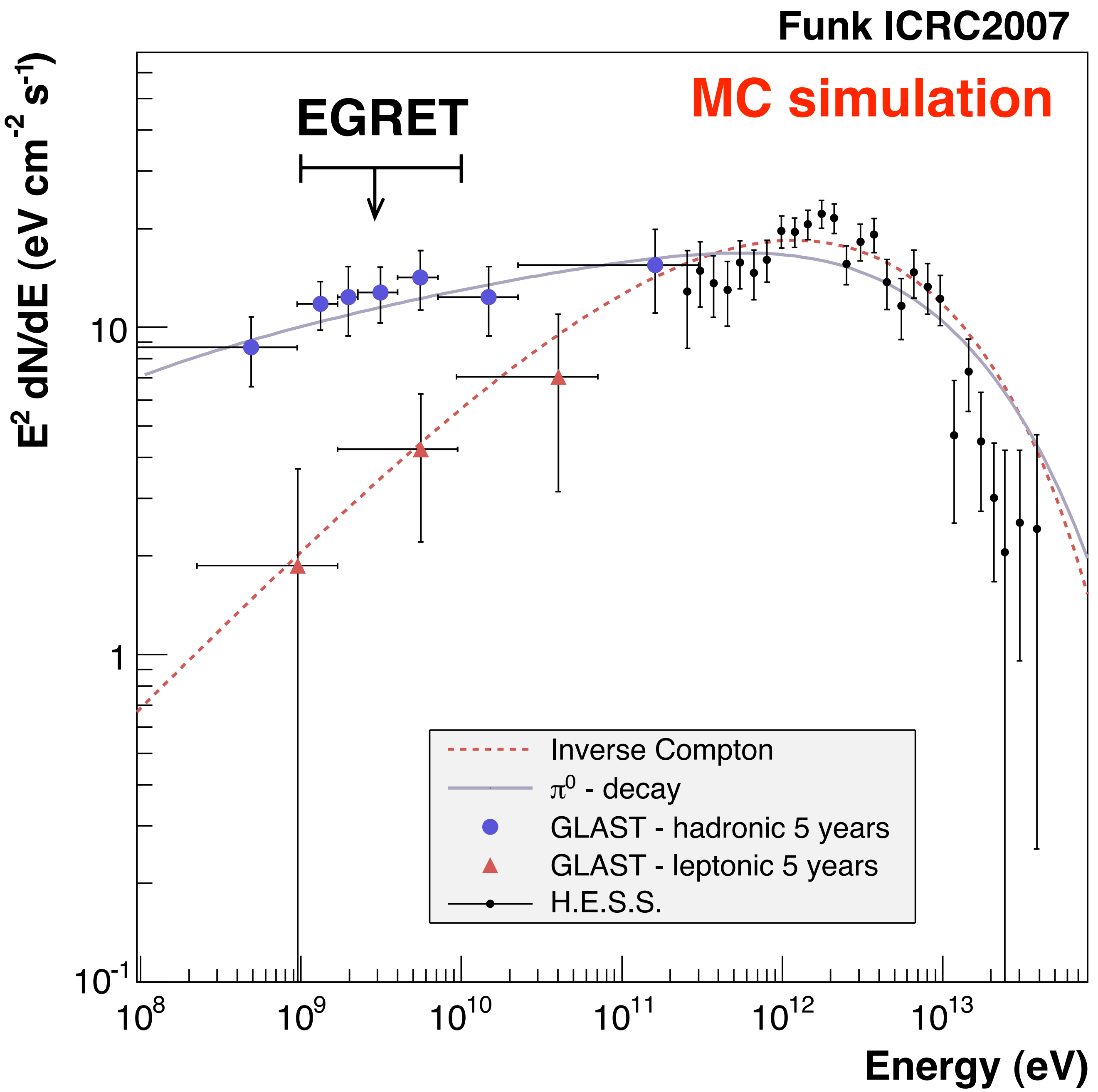


Aharonian et al. 2005



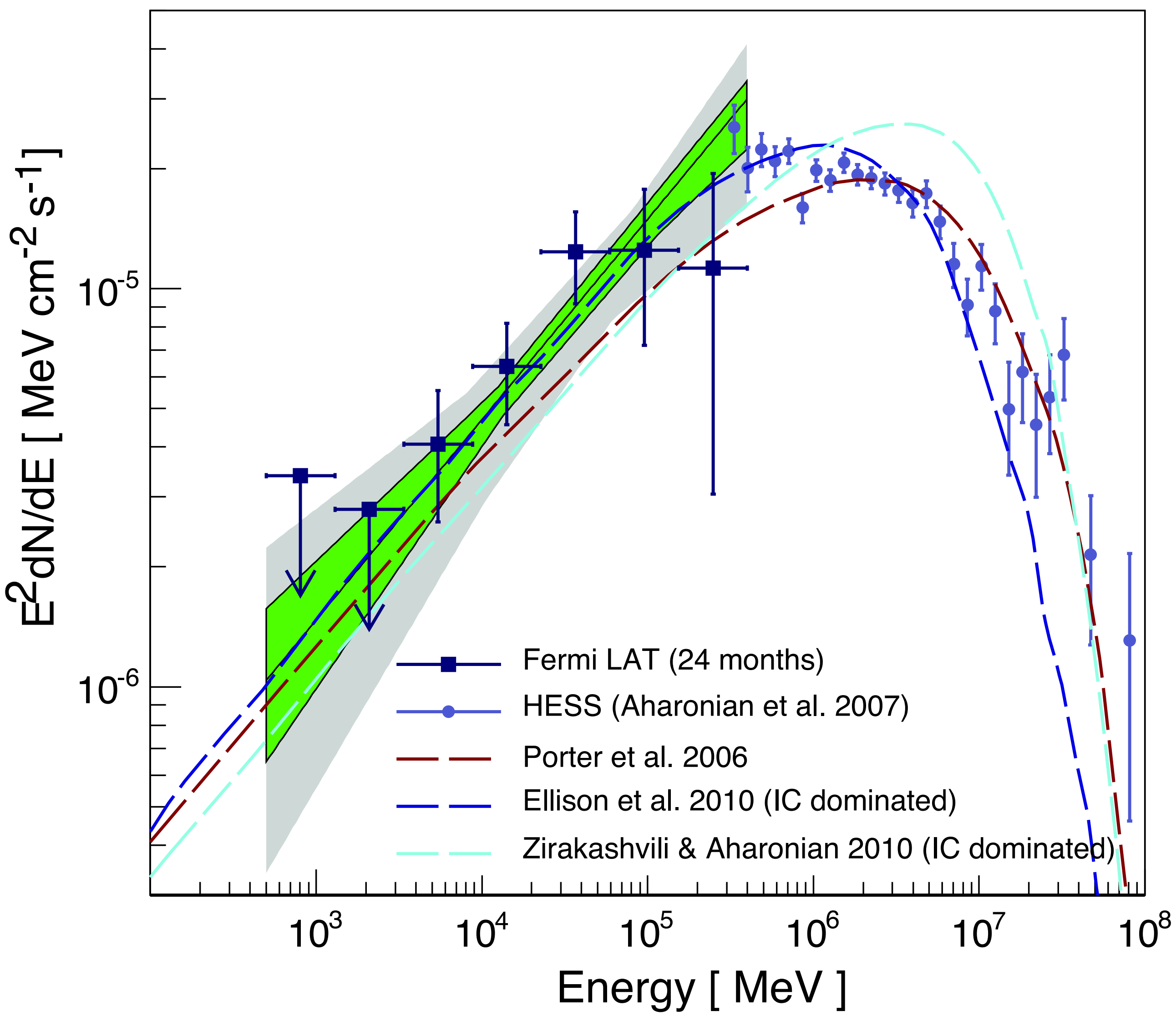
Expected Fermi Spectrum for J1713

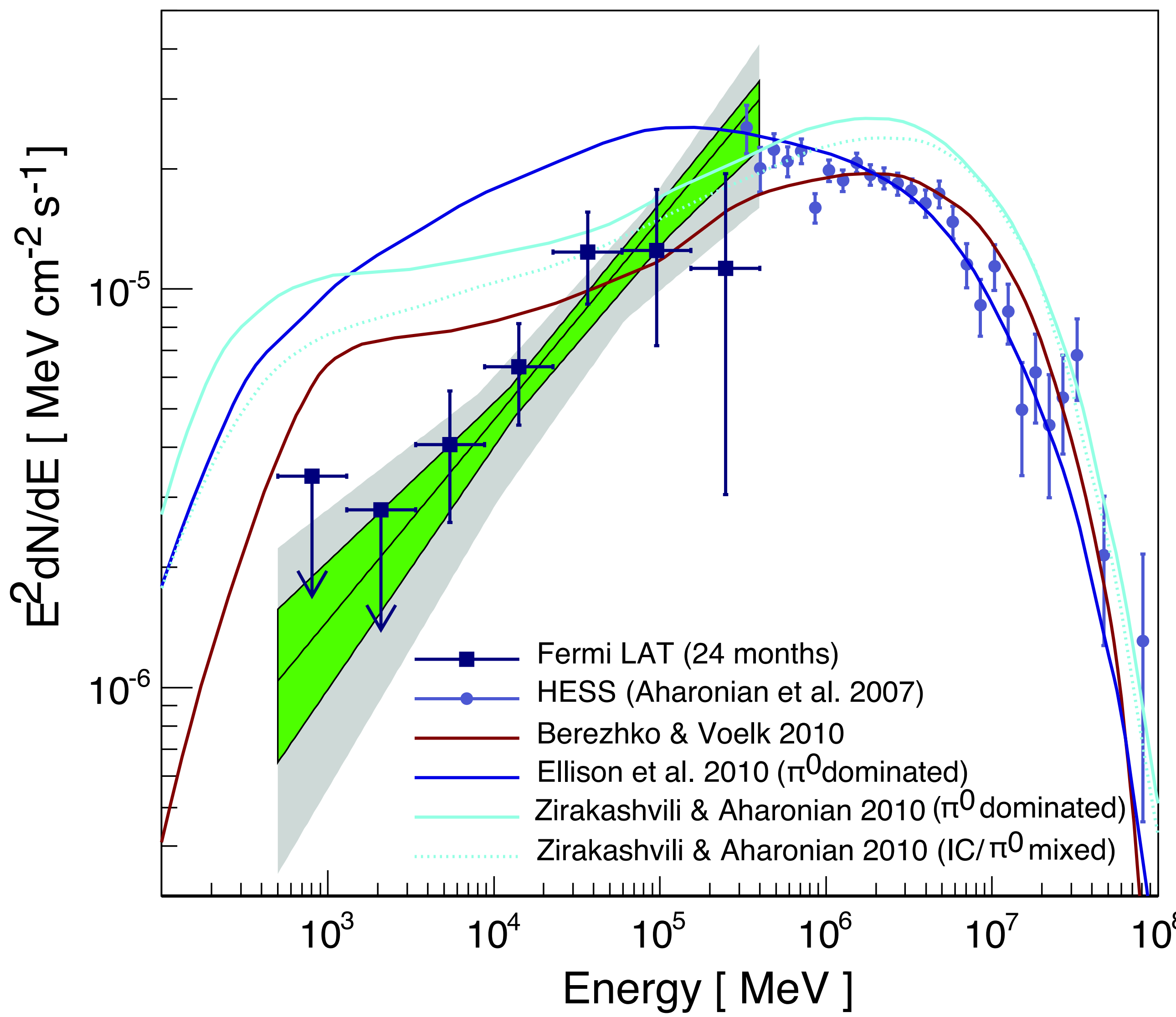
- Simulated 5-year Fermi observation of RX J1713-3946
  - Fermi is expected to positively identify hadronic contribution



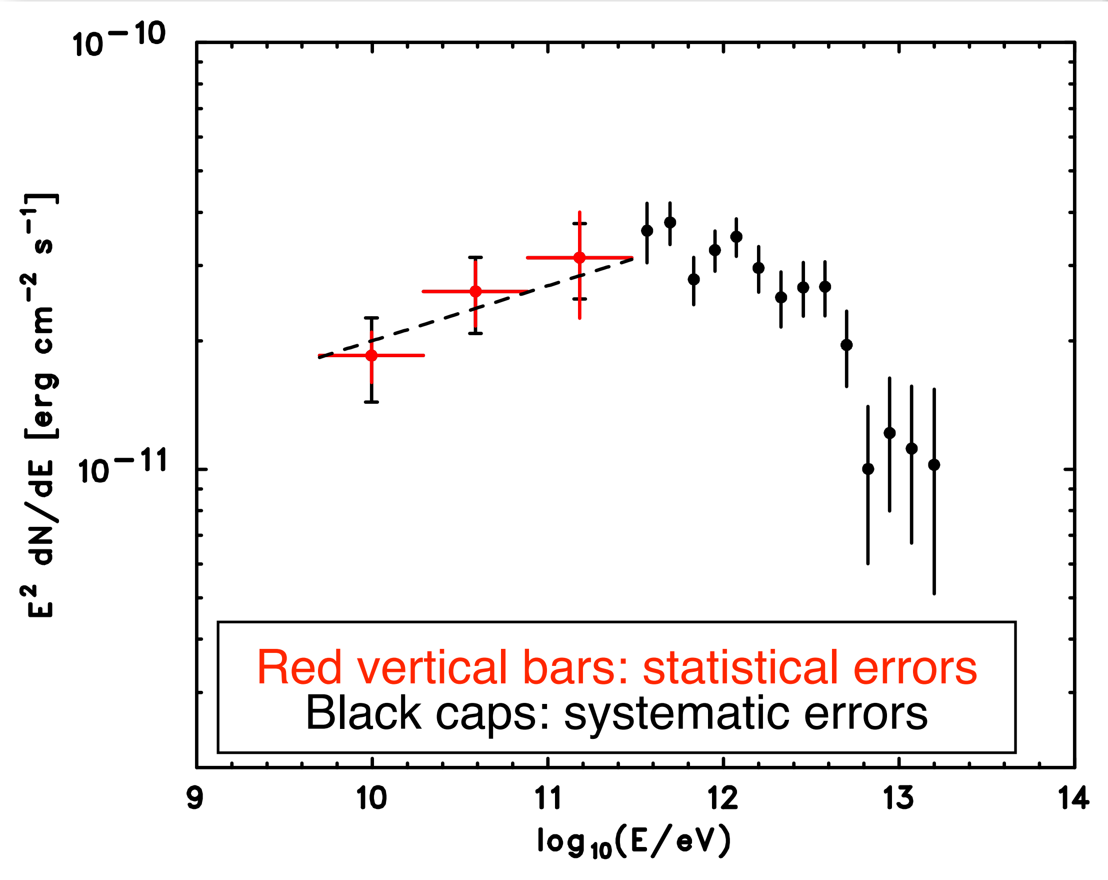
Fermi Observation of RX J1713.7-3946

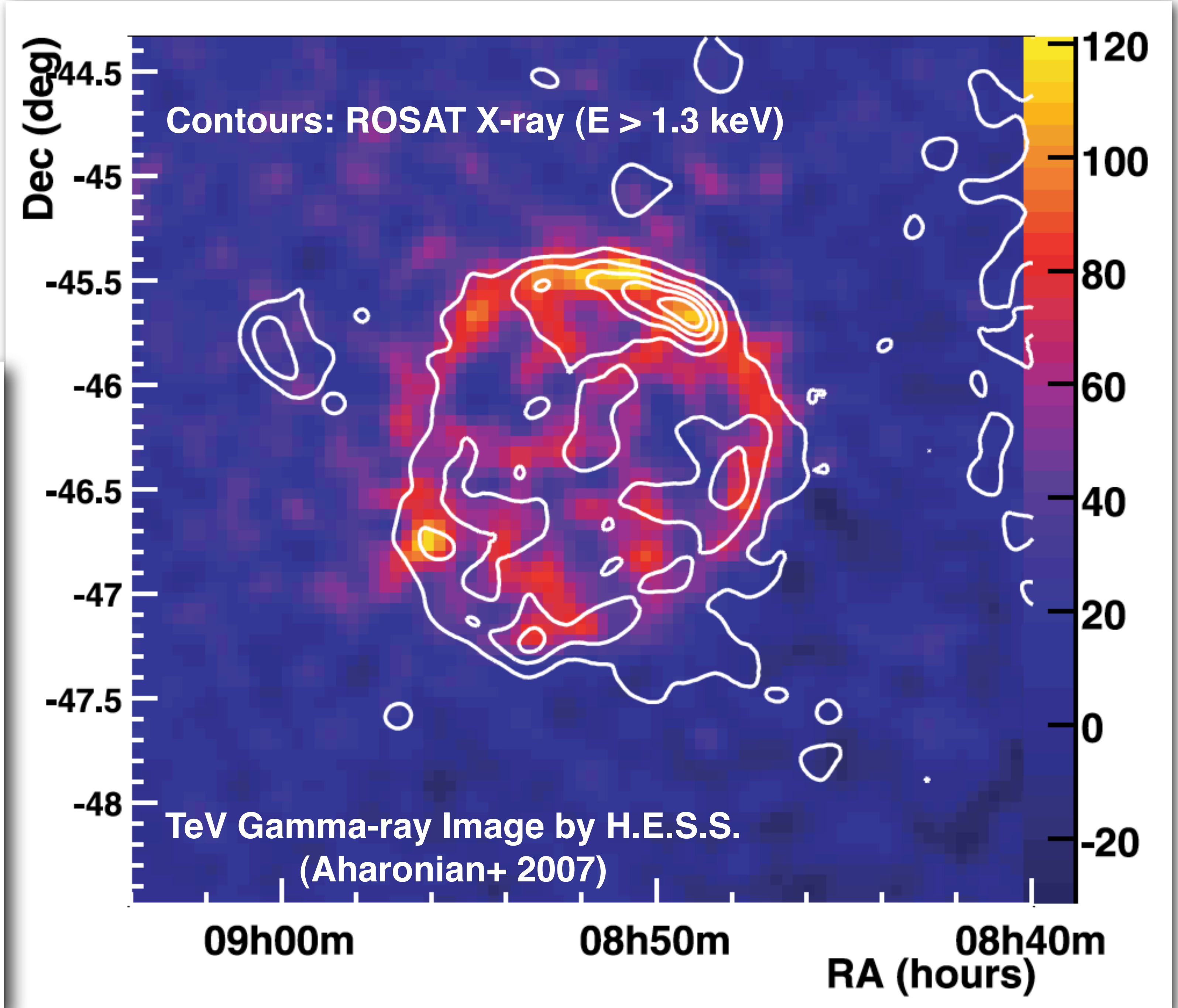
- Leptonic model may explain the Fermi spectrum better
- Requires more statistics to distinguish hadronic or leptonic nature of gamma-ray emissions





RX J0852.0–4622: Another TeV SNR





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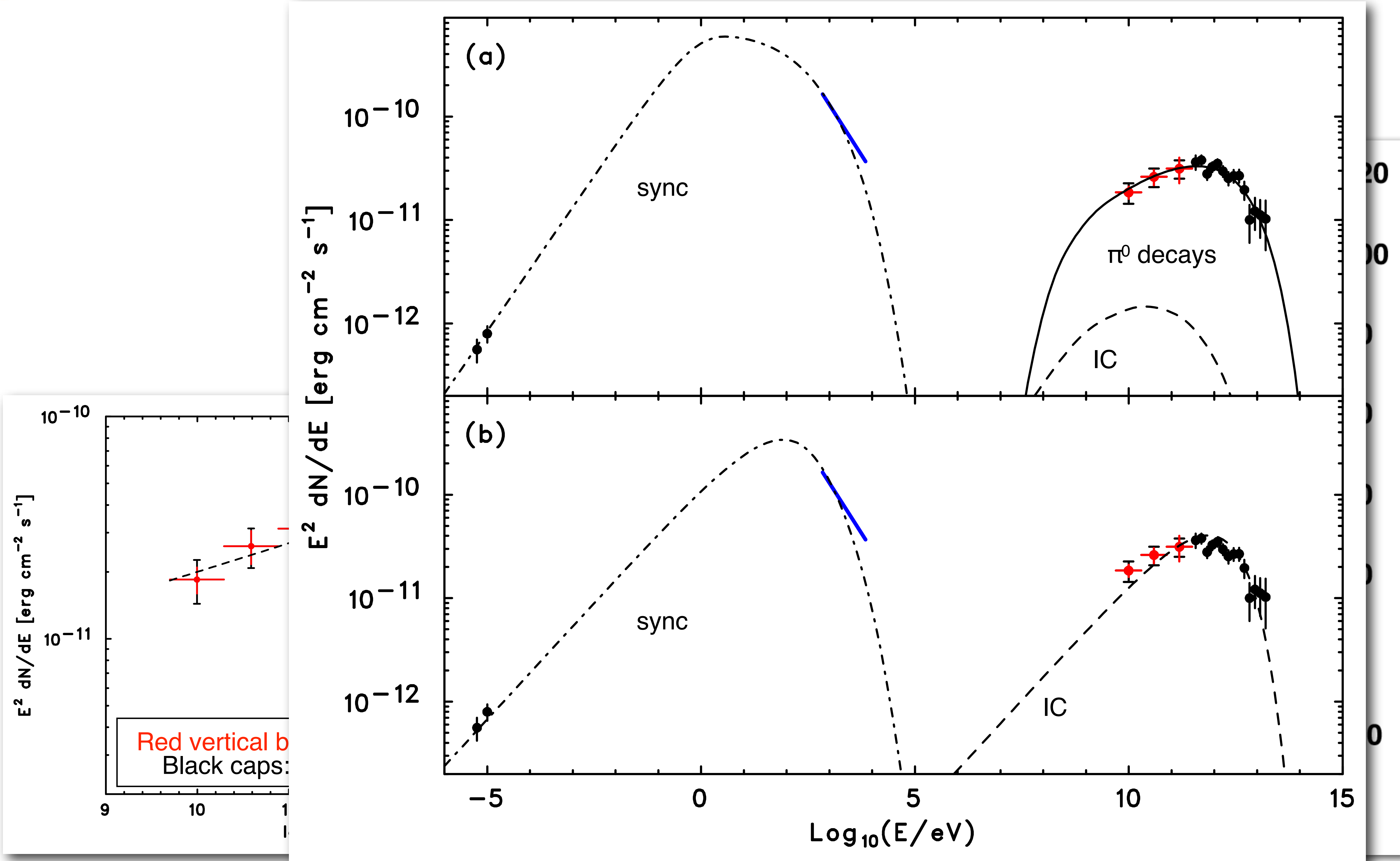
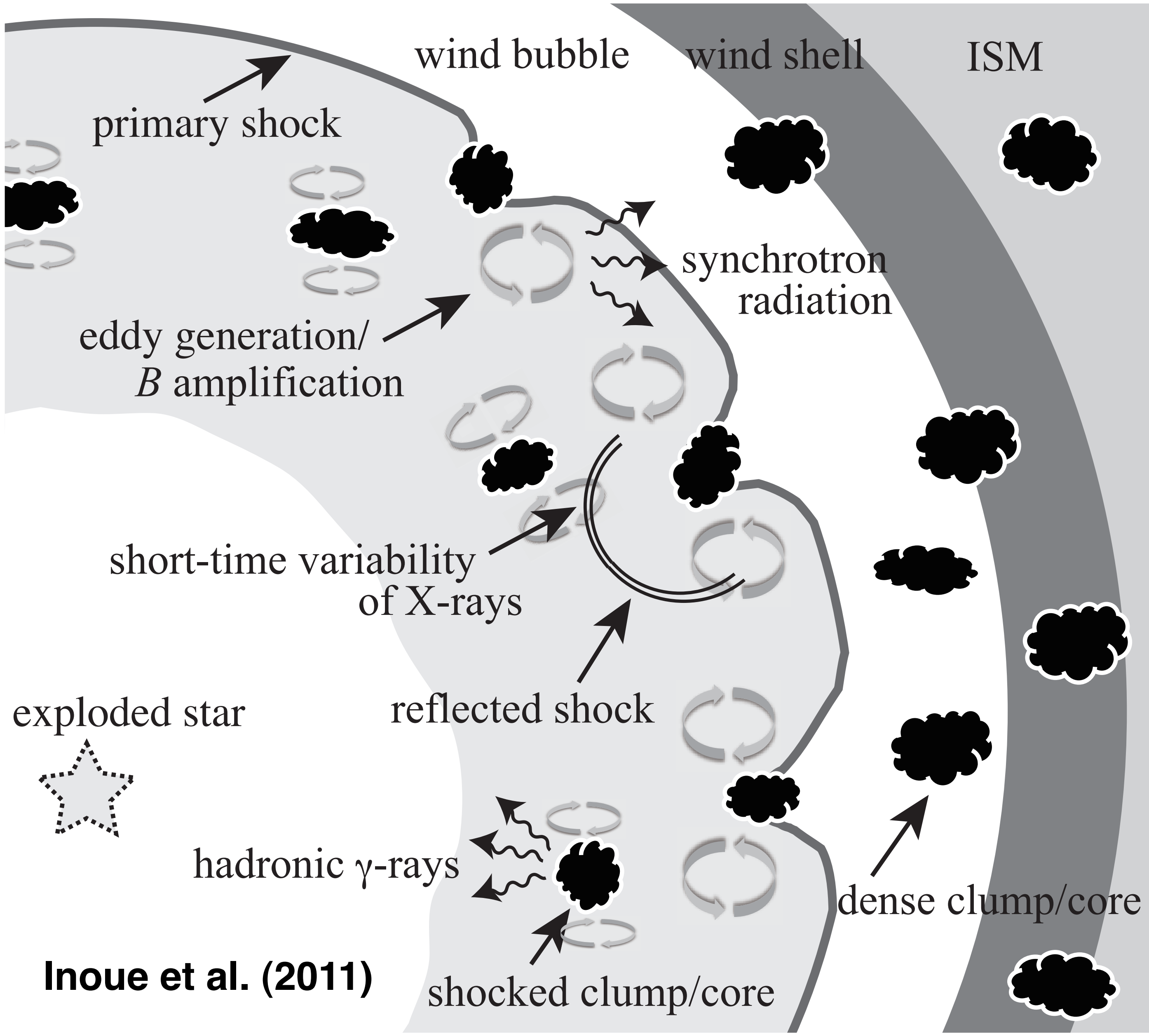


Hard Gamma-Ray Spectra

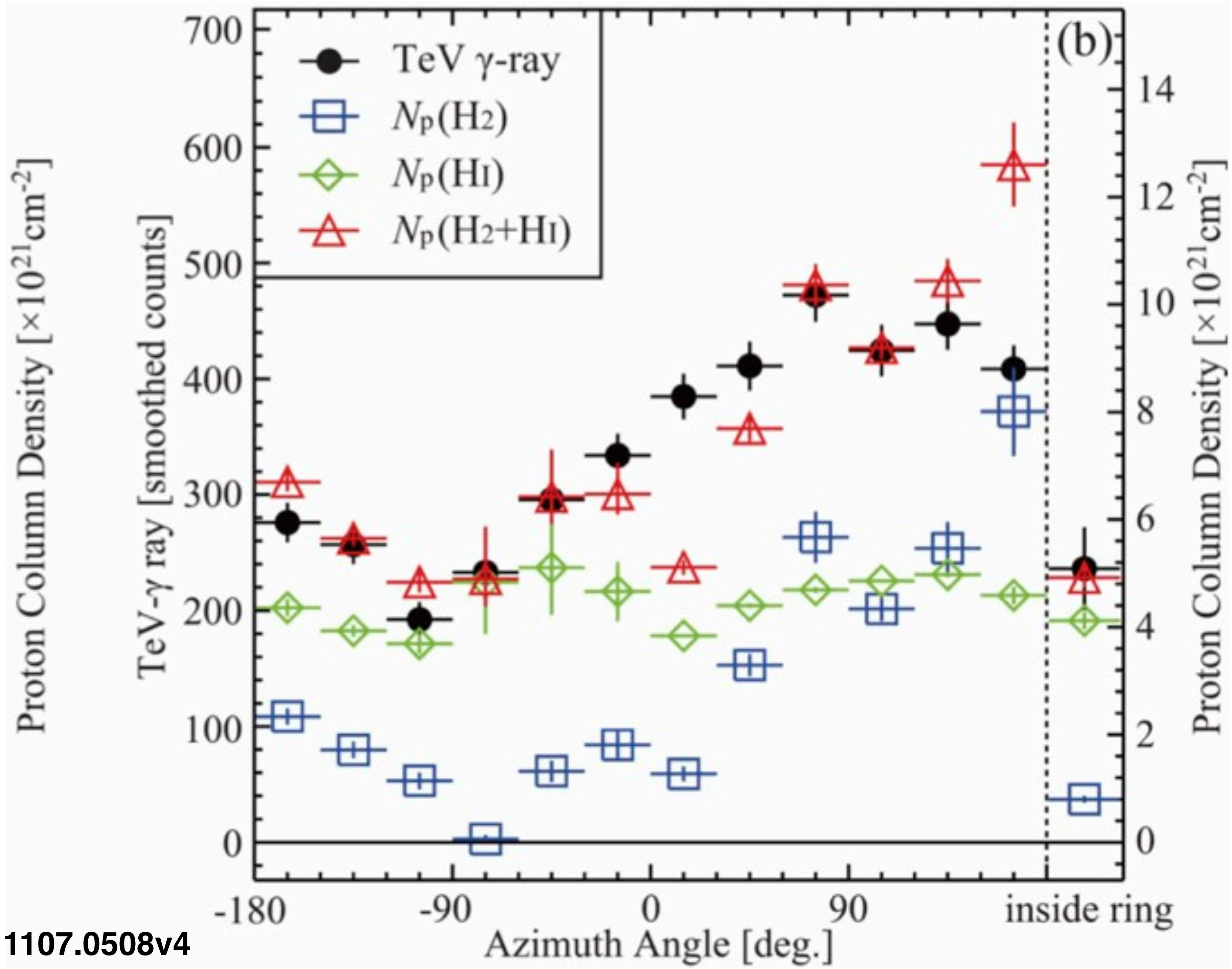
- **Hard gamma-ray can be explained by higher target density for higher energy particles**
  - **Highly inhomogeneous molecular clouds interacting with SNR**
  - **Higher energy protons can penetrate into the cloud core where target gas density is high**



Inoue et al. (2011)

Correlation with Matter Density

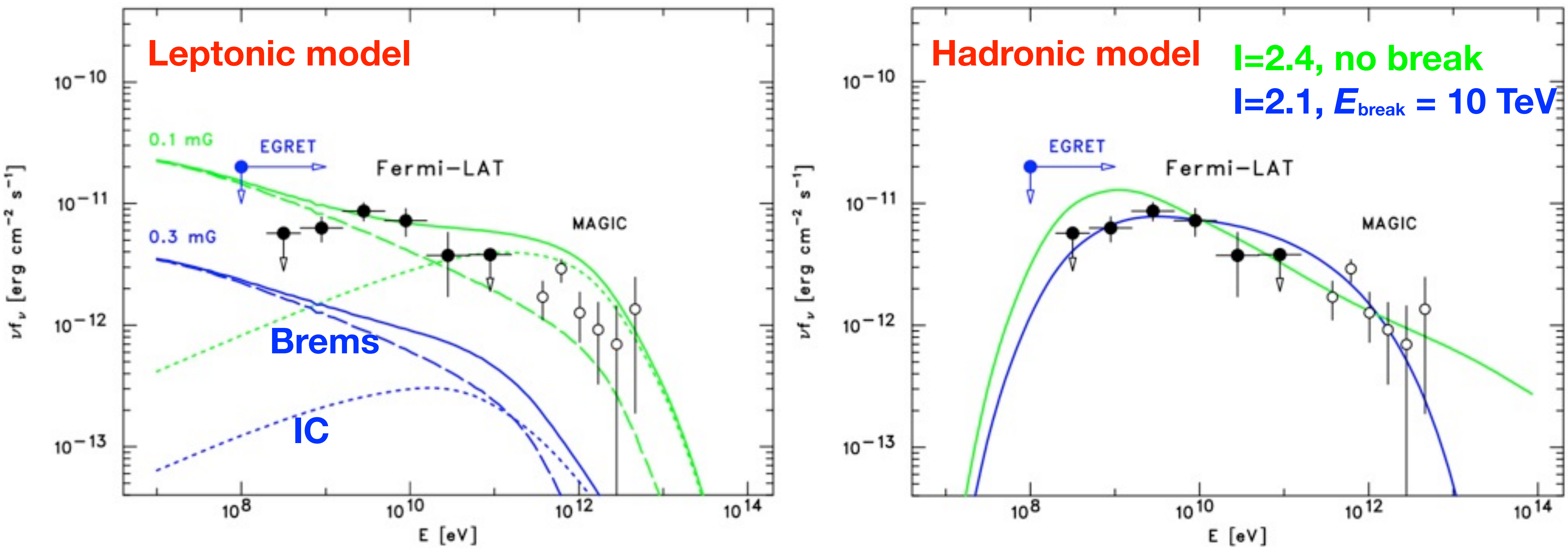
- Sum of molecular and atomic hydrogen gives good correlation with TeV gamma-ray intensity



Fukui et al. arXiv 1107.0508v4

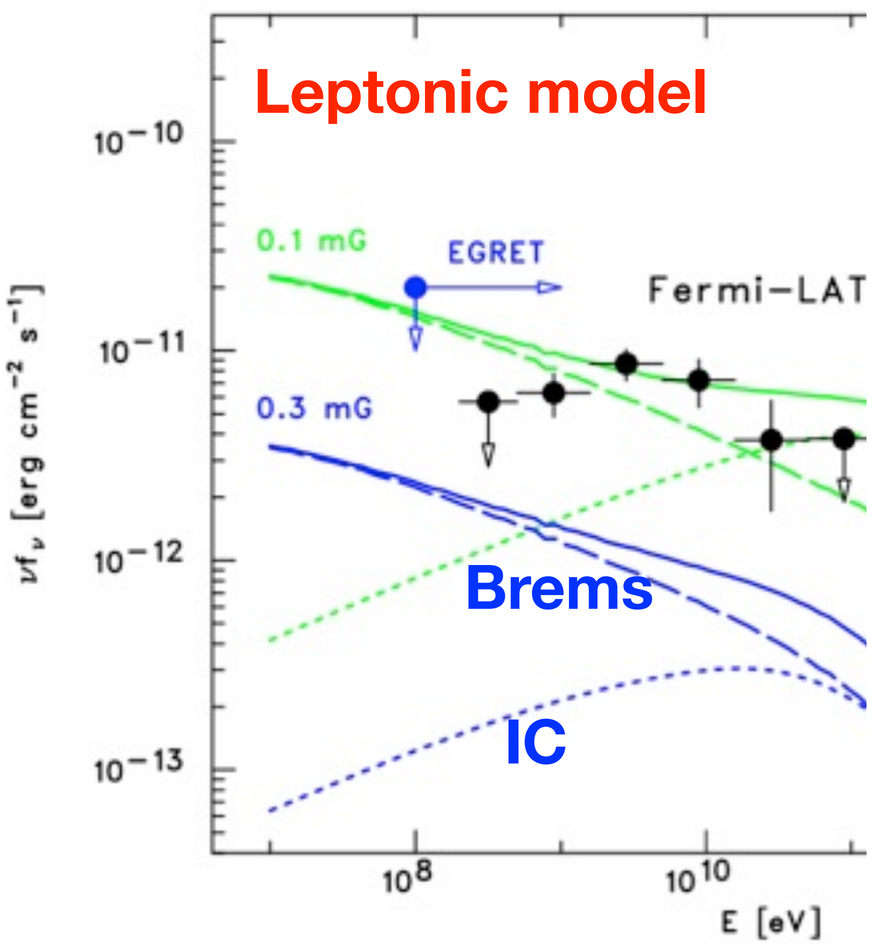
Young SNR Cassiopeia A

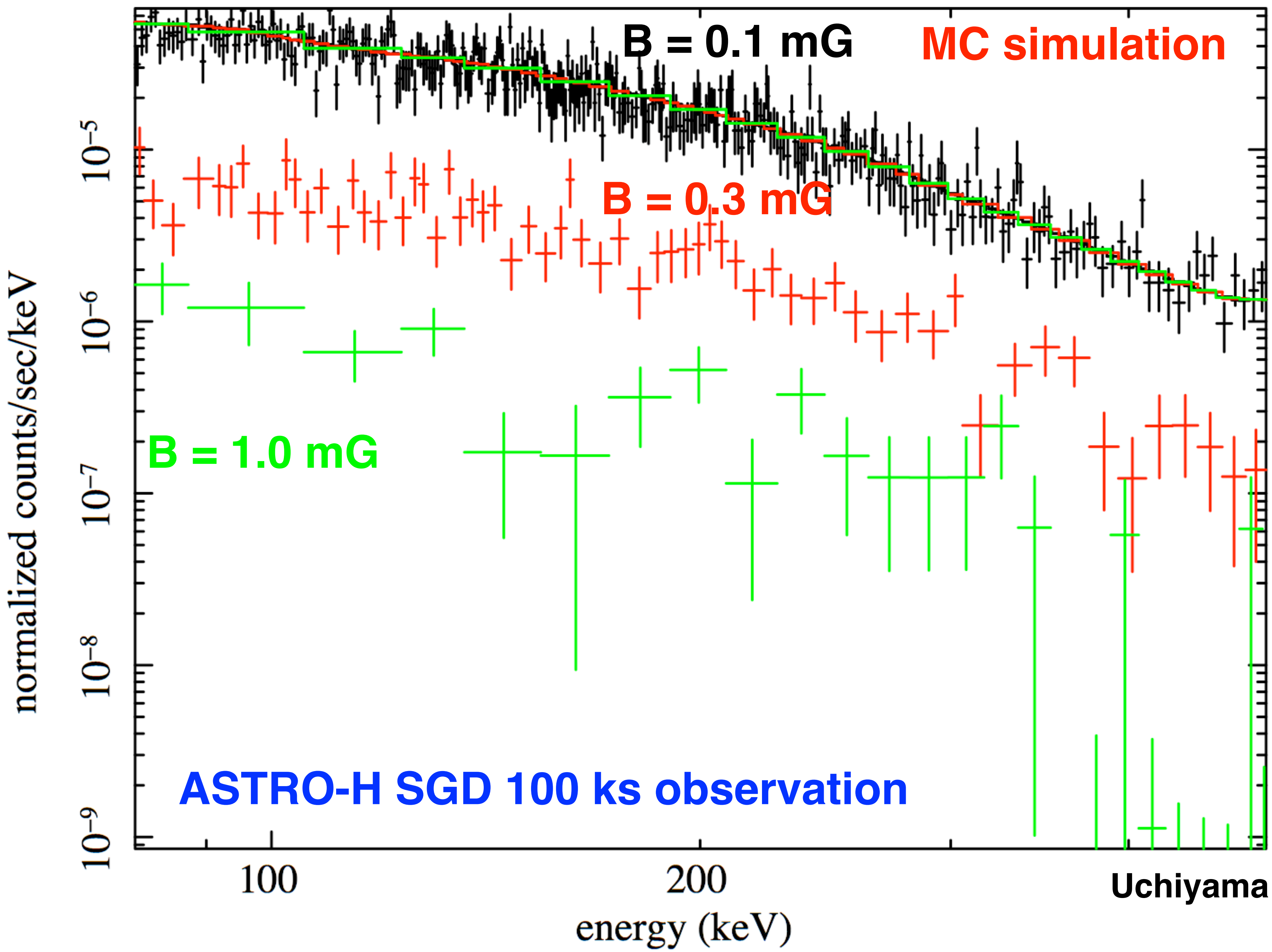
- Last SNR witnessed by human (AD 1680)
- Both leptonic and hadronic interpretation possible
  - Leptonic (Bremsstrahlung + IC)
    - B ~ 0.12 mG, $W_e \sim 1\times10^{49}$ erg
    - Not consistent with X-ray variability (B ~ 0.5 mG)
  - Hadronic (π^0 decay)
    - B > 0.12 mG, $W_p \sim 5\times10^{49}$ erg



Young SNR Cassiopeia A

- Last SNR witnessed by human (AD 1680)
- Both leptonic and hadronic interpretation possible
  - Leptonic (Bremsstr
    - B ~ 0.12 mG, W_e ~ 1
    - Not consistent with
  - Hadronic (π^0 decay)
    - B > 0.12 mG, W_p ~ 5

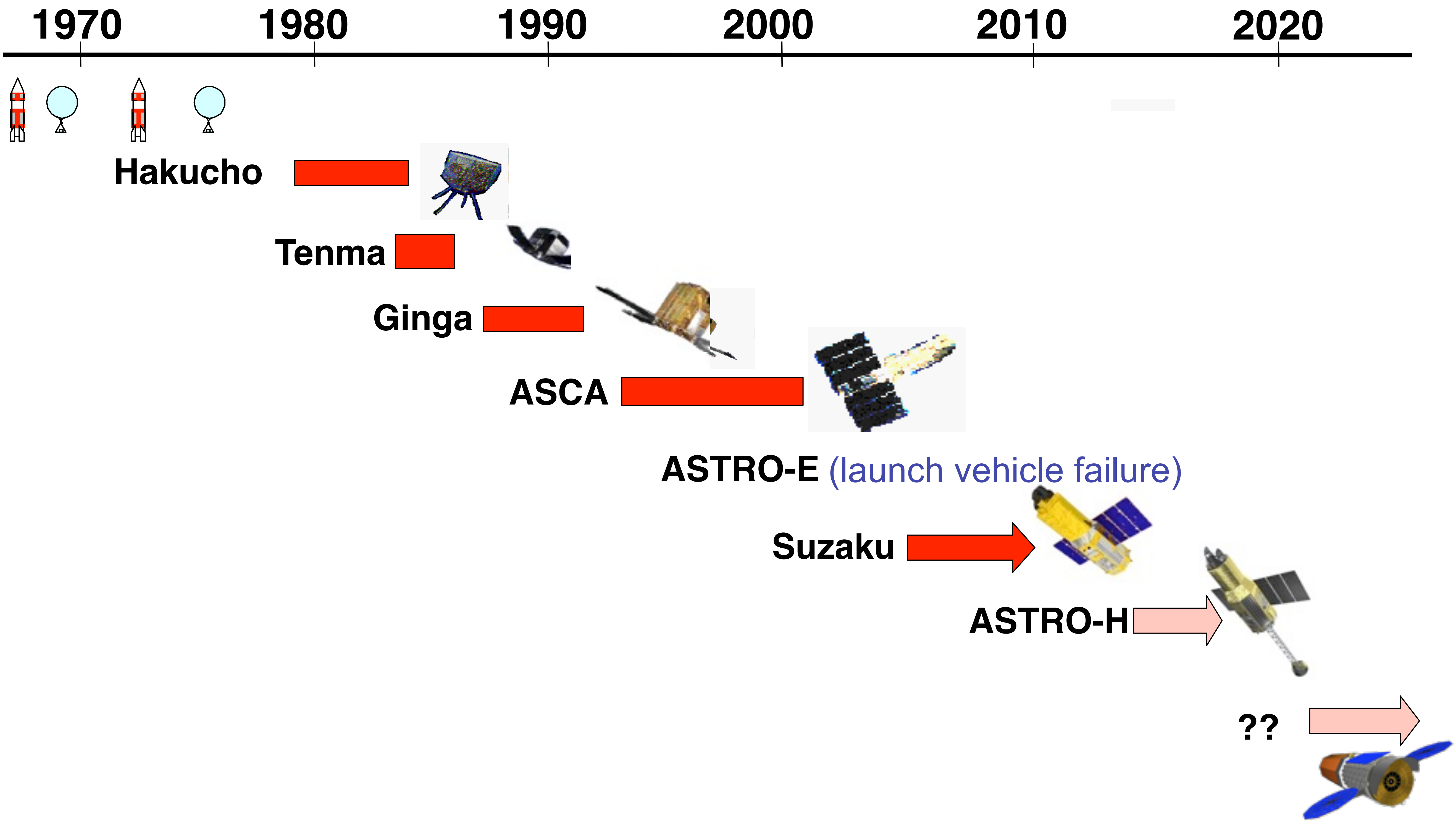




Uchiyama

JAXA ASTRO-H

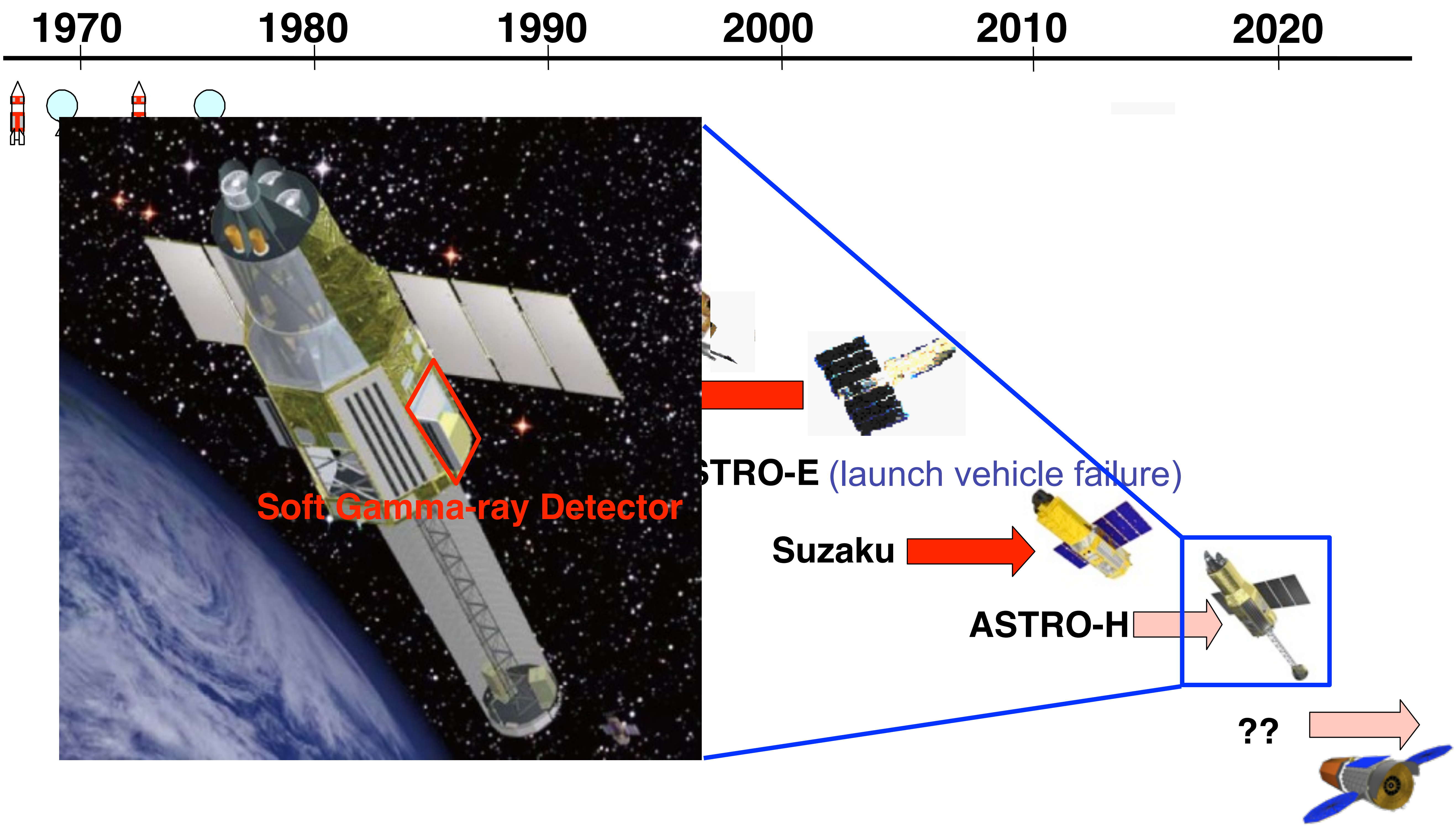
✤ History of Japanese X-ray satellite



Credit: ISAS/JAXA

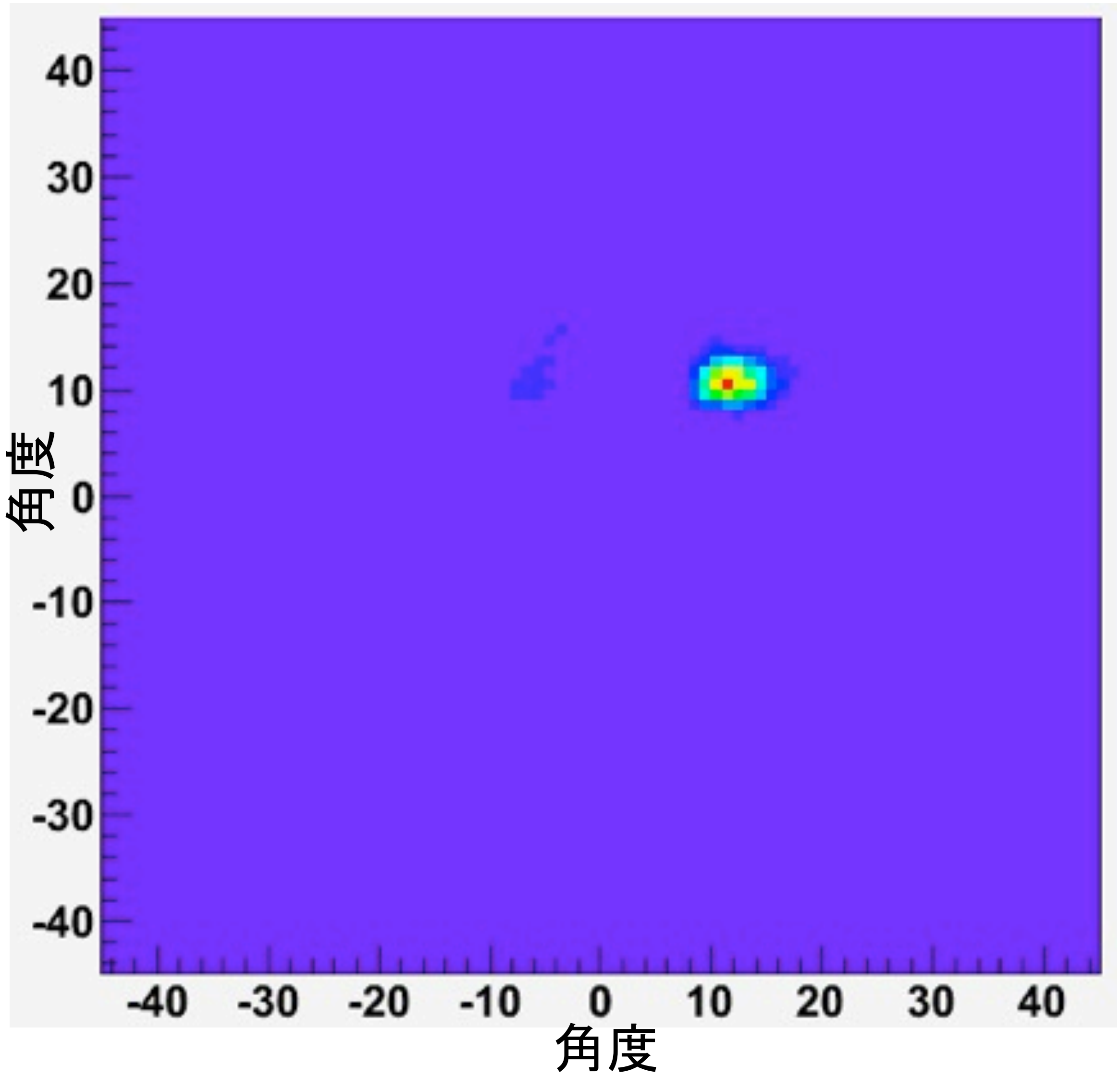
JAXA ASTRO-H

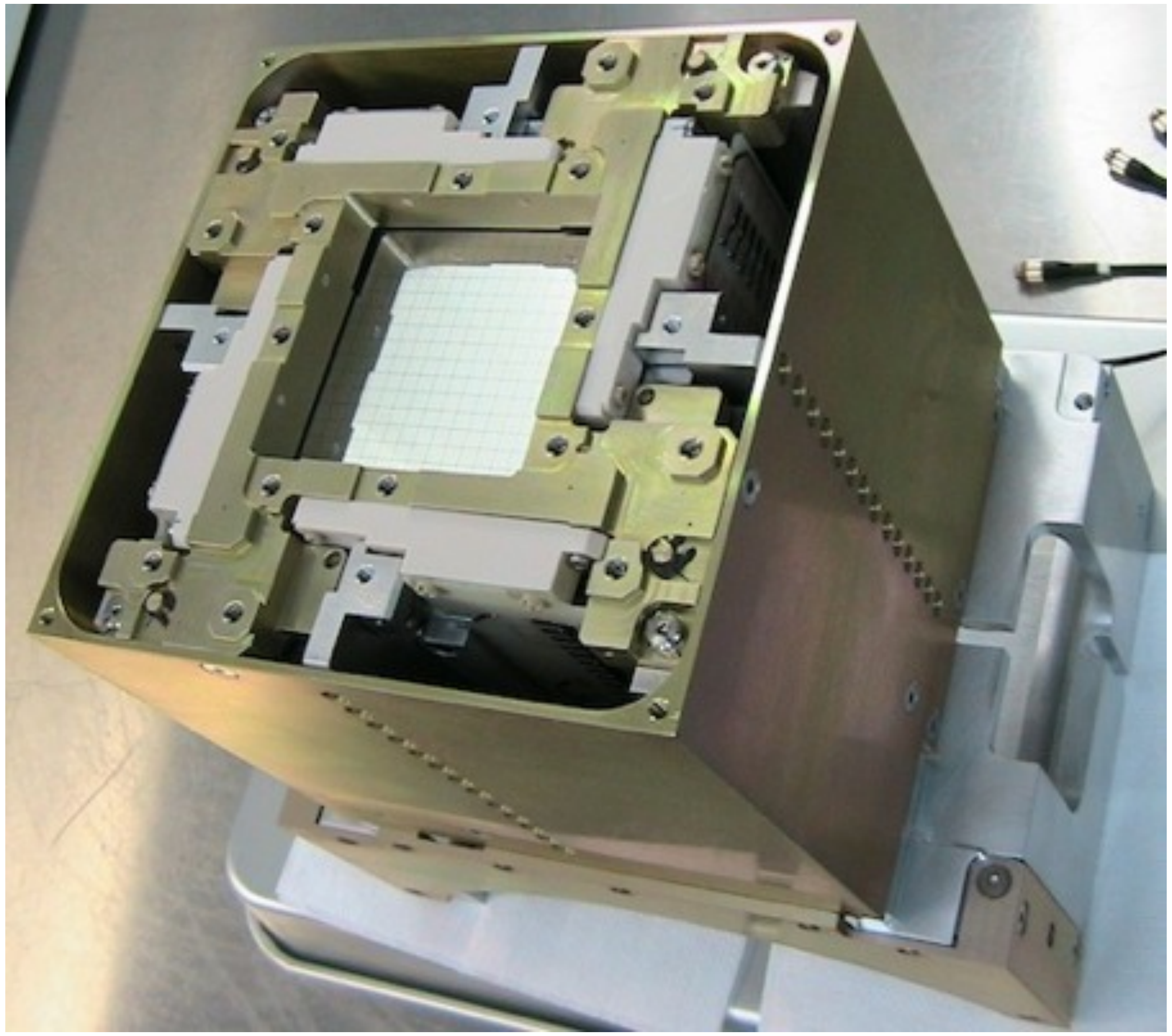
✤ **History of Japanese X-ray satellite**



ASTRO-H Soft Gamma-ray Detector

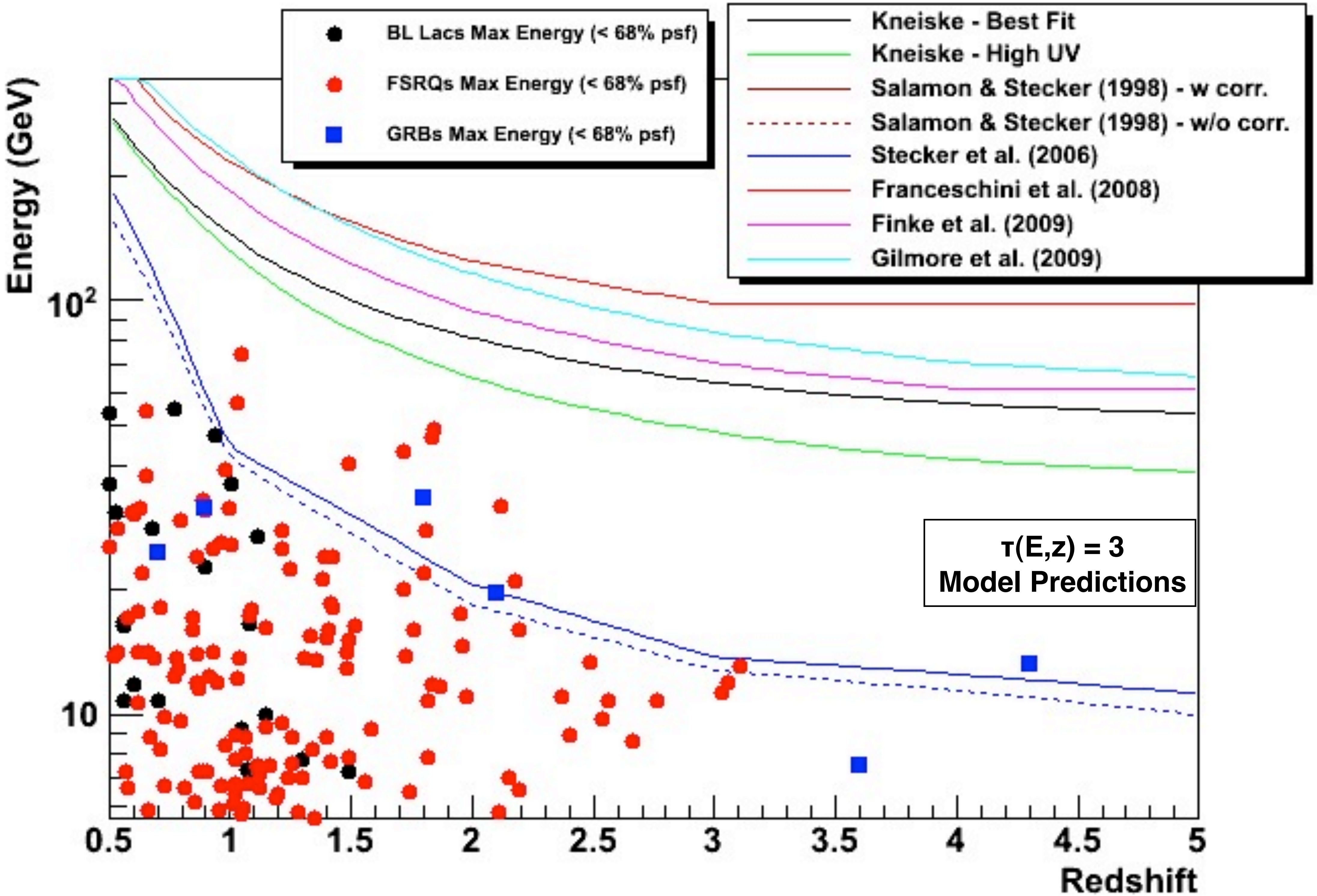
- Taking advantage of Japanese semiconductor detector technologies and space technologies
  - Silicon sensors by Hamamatsu photonics
  - Space instrument assembly (Mitsubishi Heavy Industries)
  - Localization of gamma-ray sources such as radio isotopes





AGN and GRB as Distant Candles

✤ 10–100 GeV gamma rays can probe early universe



AGN and GRB as Distant Candles

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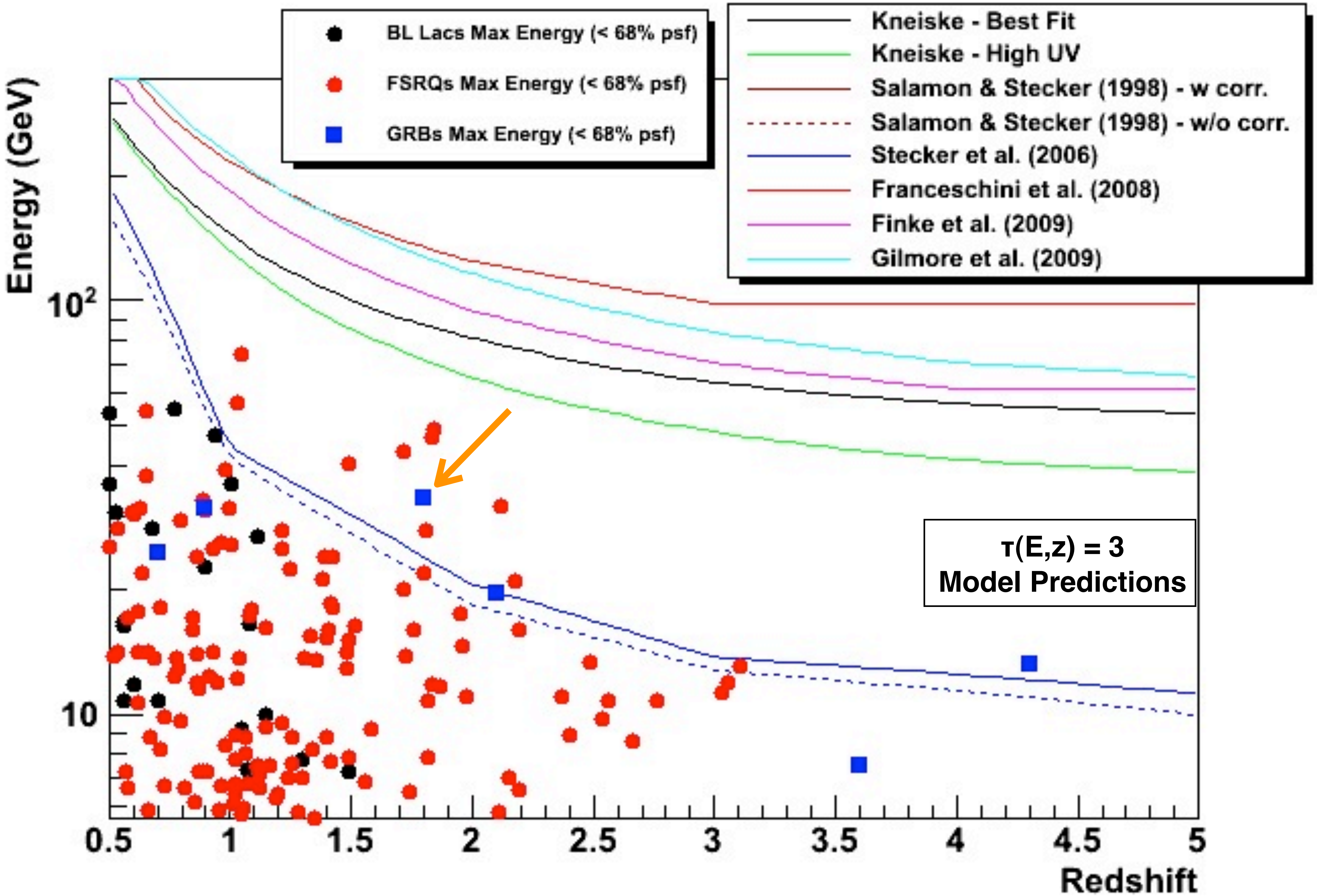


Lorentz Invariance Violation (LIV)

- Some QG models predict a violation of Lorentz Invariance at HE:

$$c^2 p_\gamma^2 = E_\gamma^2\left[1+\sum_{k=1}^{\infty} s_k\left(\frac{E_\gamma}{M_{QG,k}c^2}\right)^k\right] \Rightarrow v_\gamma^2 = \frac{\partial E_\gamma}{\partial p_\gamma} \approx c\left[1 - s_n\frac{1+n}{2}\left(\frac{E_\gamma}{M_{QG,k}c^2}\right)^n\right]$$

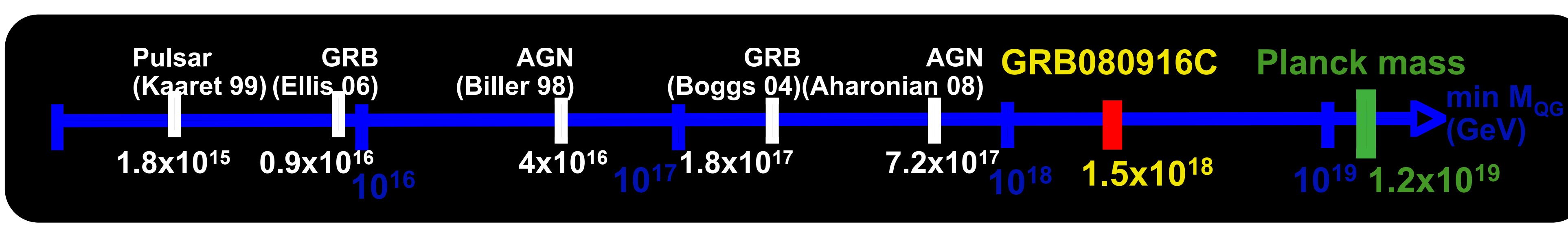
QG mass: energy scale where QG effect are expected to be significant

- Time delay between 2 photons of energies E_h and E_l emitted simultaneously:

$$\Delta t = \frac{(1+n)}{2H_0}\frac{(E_h^n - E_l^n)}{(M_{\mathrm{QG},n}c^2)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\,dz'$$

geometrical distance assuming ΛCDM

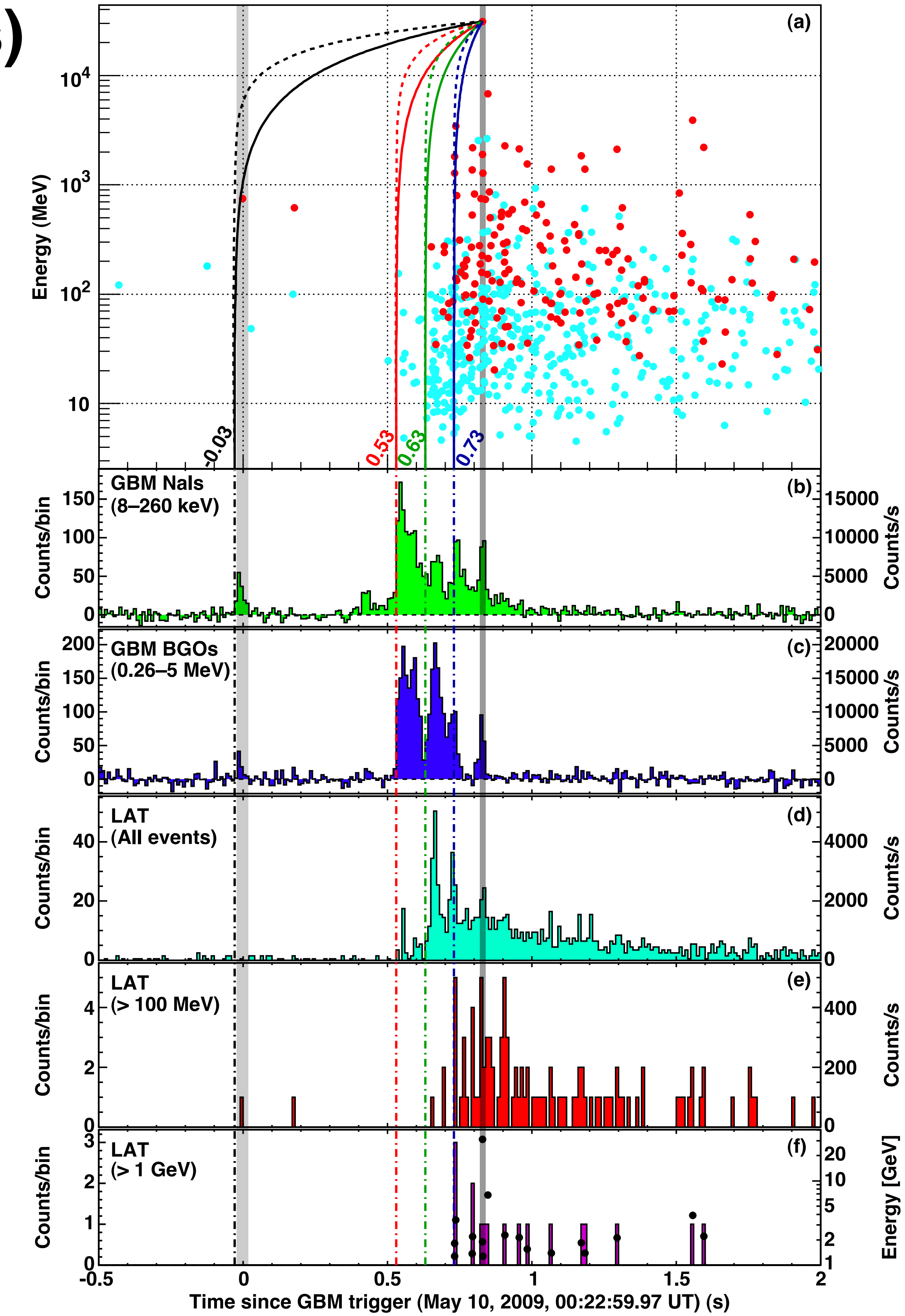
- GRB is a excellent light source due to long distance (high z) and short duration
  - Constraint using GRB 080916C: 13.2 GeV photon detected 16.5 sec after trigger



LIV Test with GRB 090510

- 30 GeV photon from z=0.9 (7.3B years)
- Quantum Gravity models predicting linear LIV are strongly disfavored

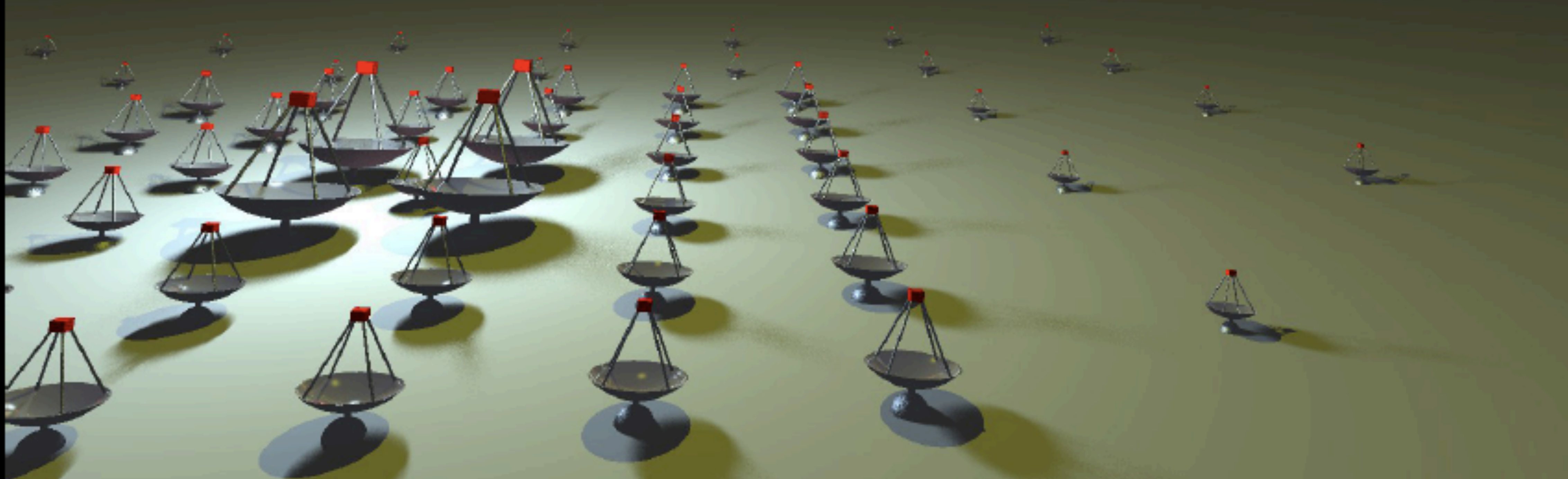
choice for t_{start}	limit on Δt (ms)	lower limit on $M_{QG,1}/M_{planck}$
start of any observed emission	< 859	> 1.19
start of main < 1 MeV emission	< 299	> 3.42
start of > 100 MeV emission	< 199	> 5.12
start of > 1 GeV emission	< 99	> 10.0
association with < 1 MeV spike	< 10	102



CTA (Cherenkov Telescope Array)

The affordable compromise

- Large collection area (x~30)
- Better angular resolution (0.03°, x~1/3)
- ~1000 of TeV gamma-ray sources
- Optimized telescope configuration
  - LST: ~23 m ϕ x 4, ~30 GeV – 1 TeV
  - MST: ~12 m ϕ x 20, ~100 GeV – 10 TeV
  - SST: 4~6 m ϕ x 40~70, ~1 TeV – 100 TeV



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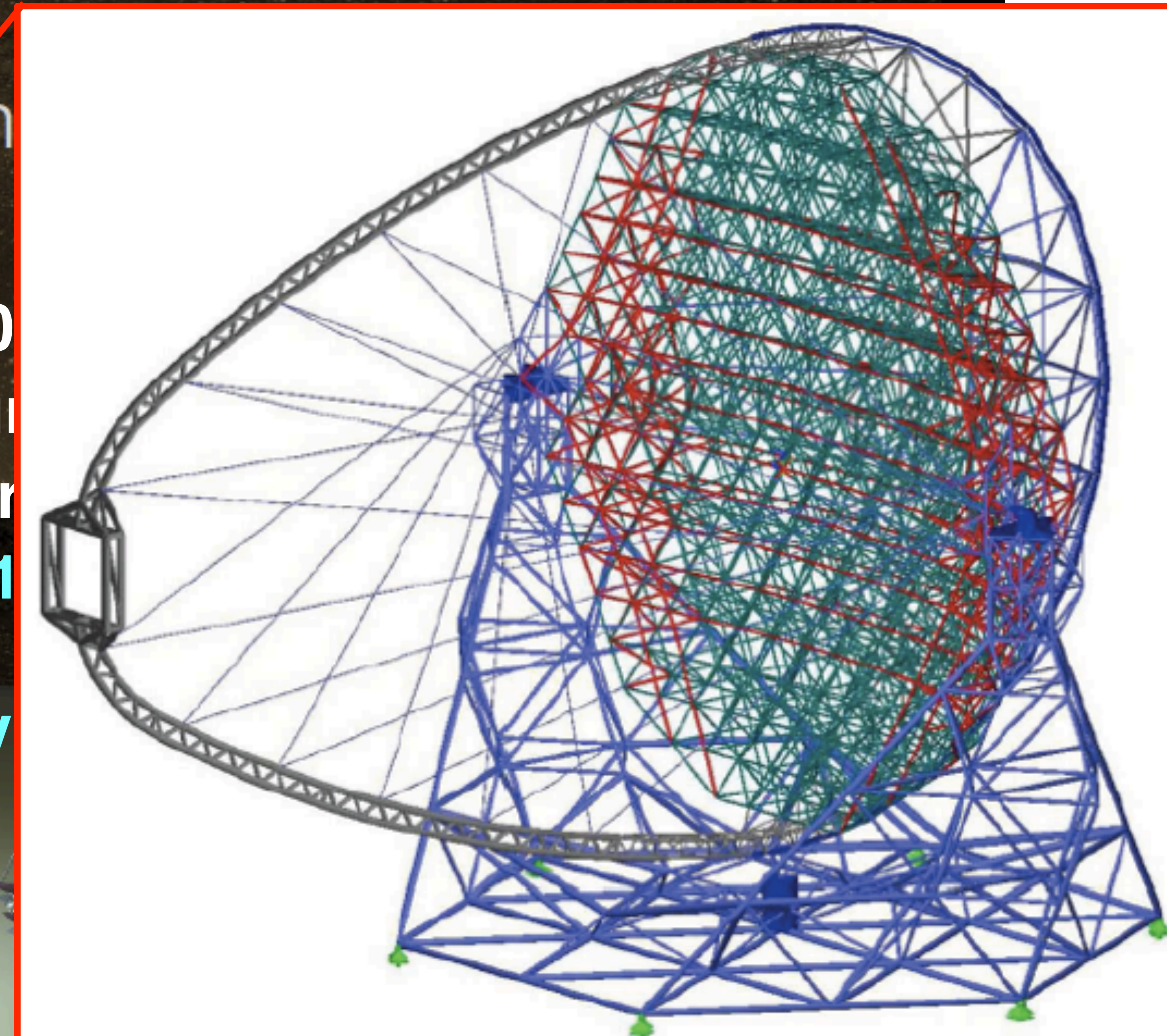

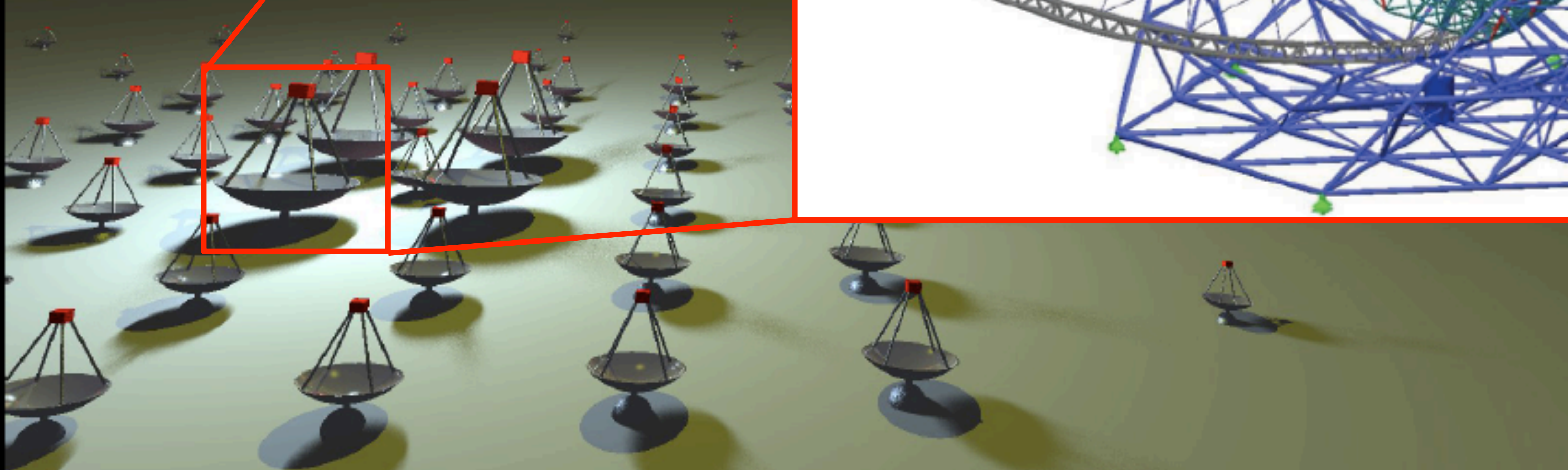

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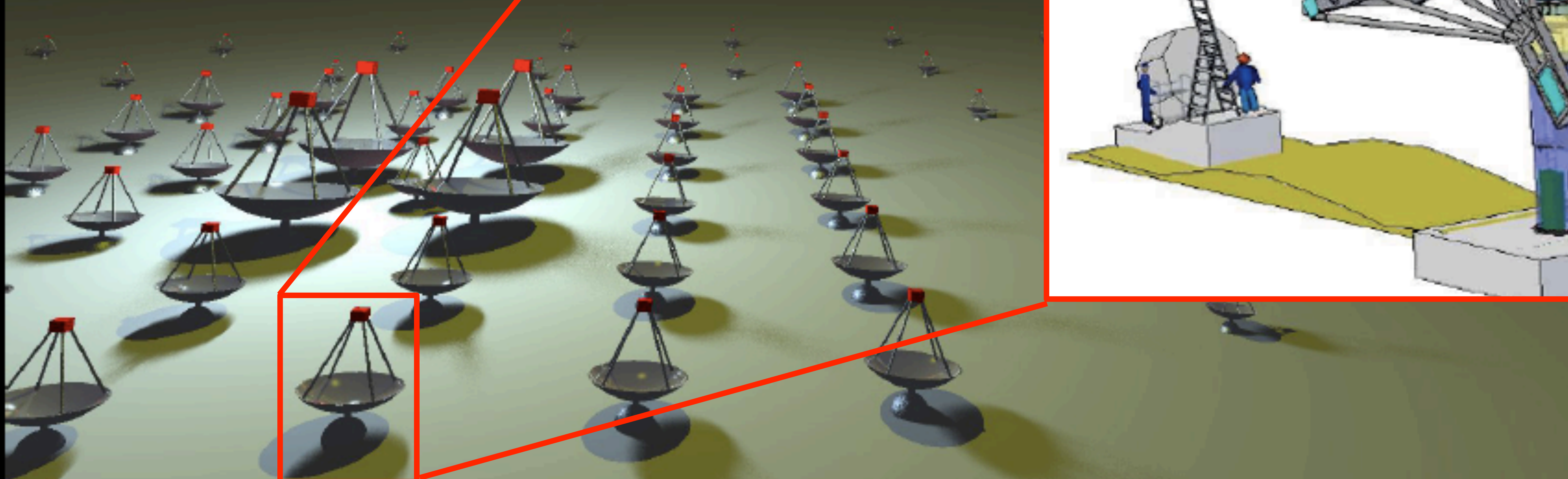

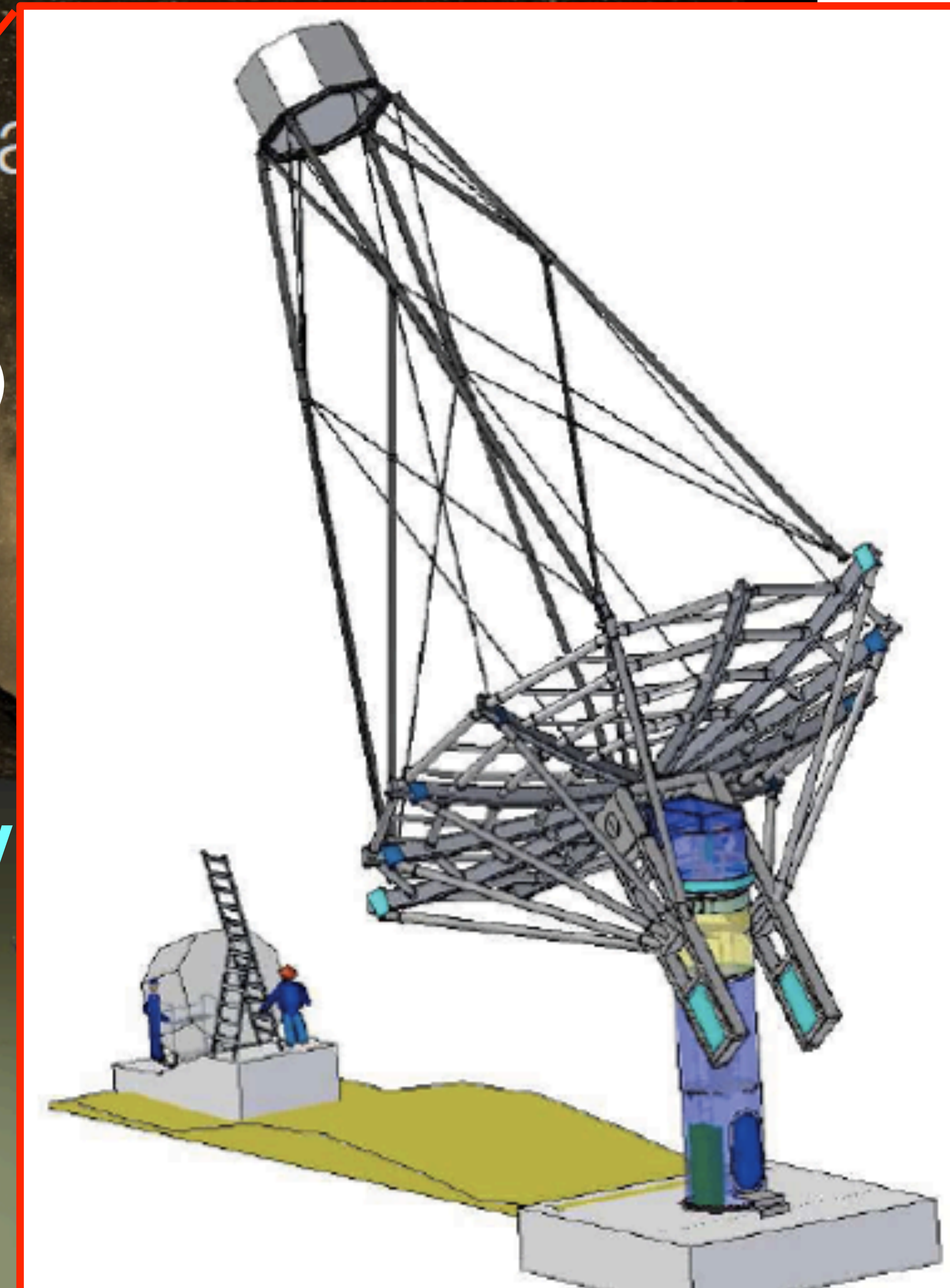

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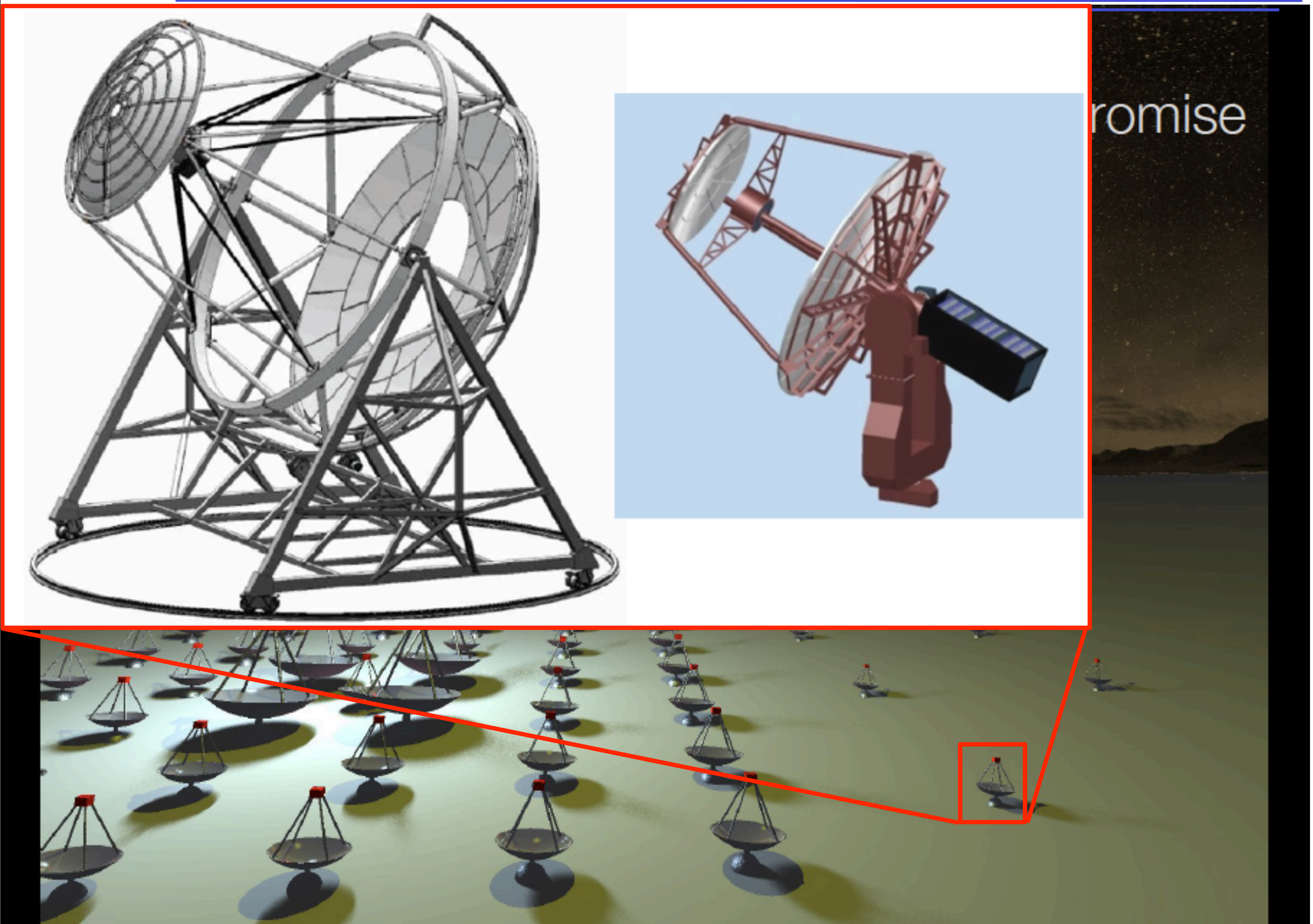

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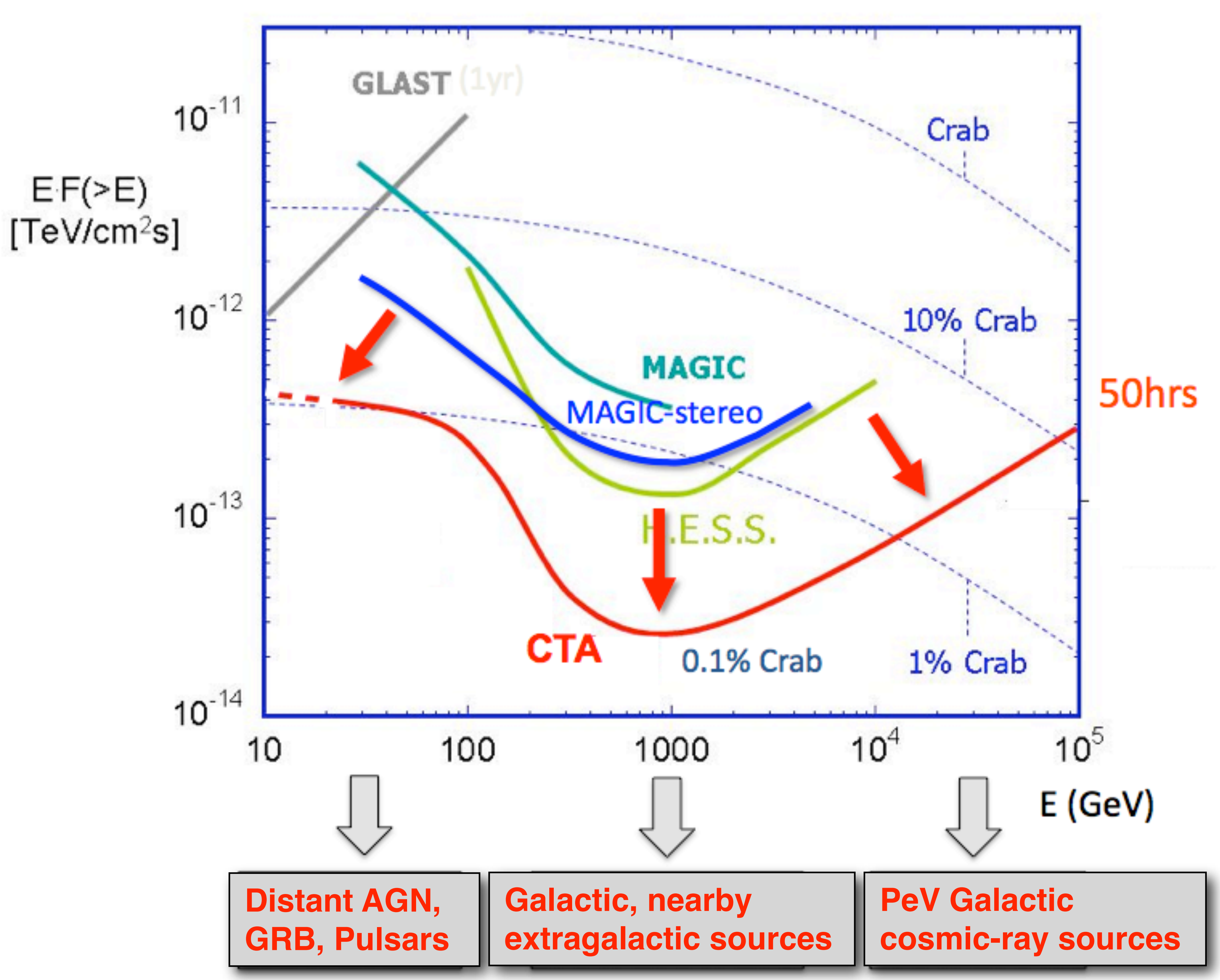
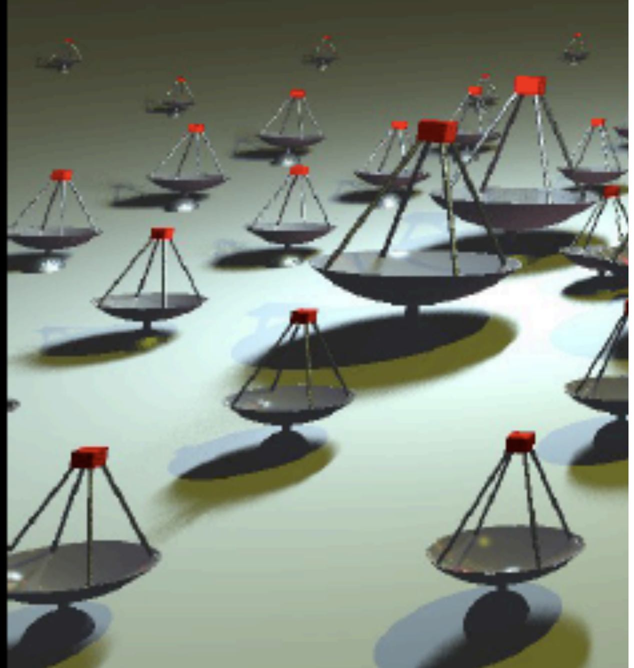
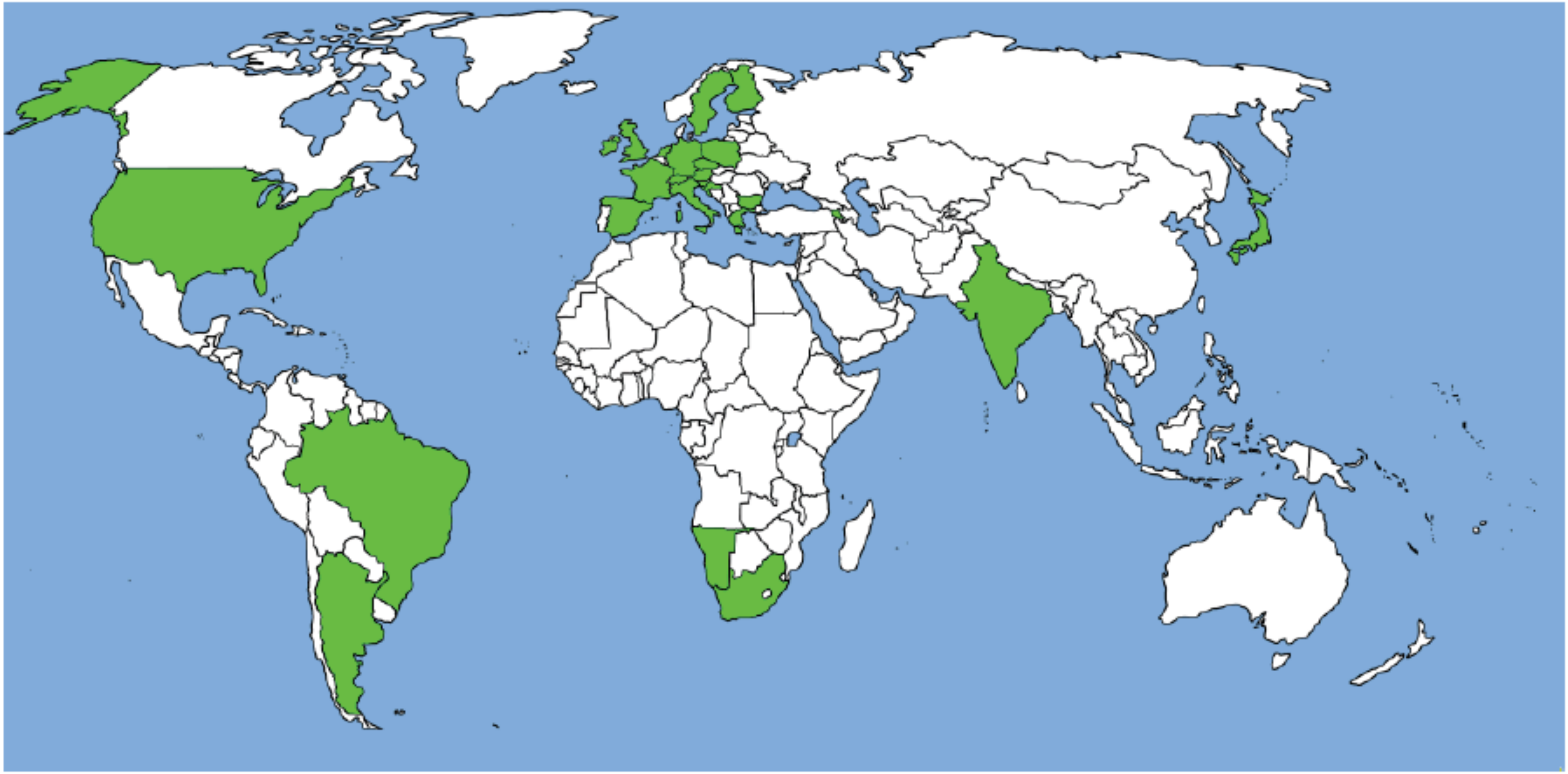




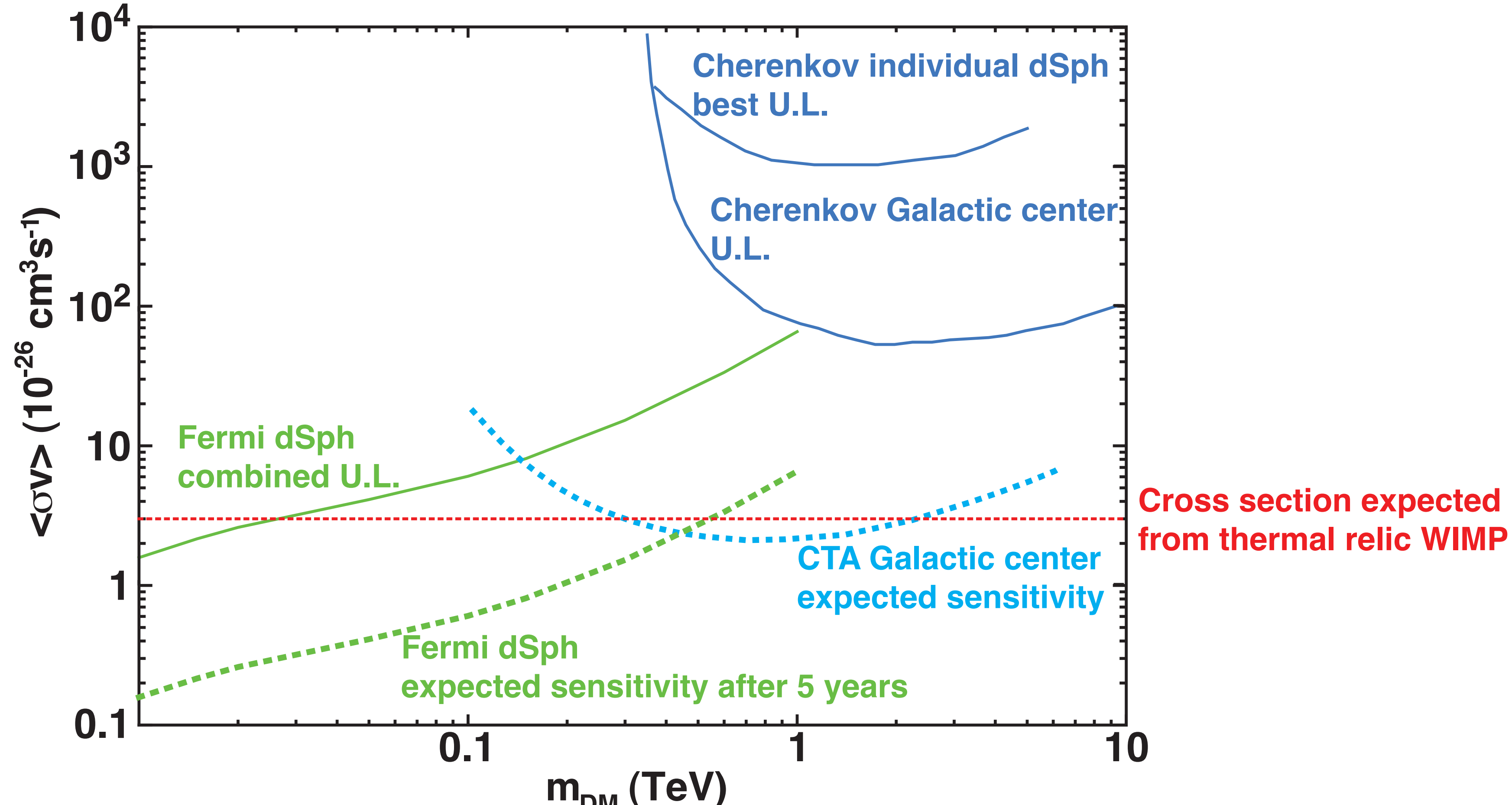
CTA Membership

- 25 countries
- 132 Institutions
- 734 Scientists



Summary and Future Prospect

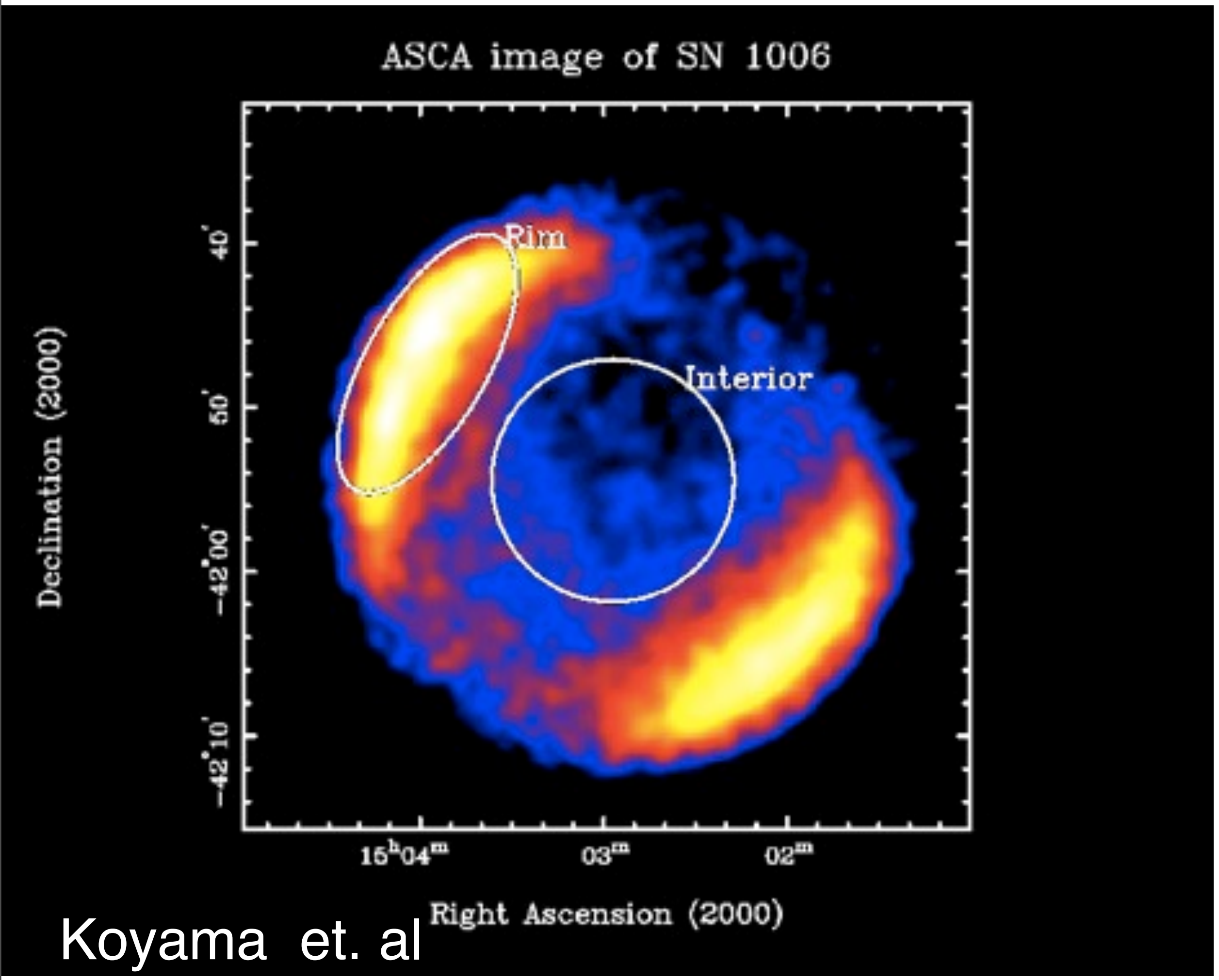
- Fermi/LAT limit on WIMP cross section is now cut into expected value from thermal relic WIMP
- Gamma-ray observations (with other waveband) are now establishing SNR as a origin of Galactic cosmic rays
- Fermi/LAT observations of distant GRBs gave very stringent constraints on LIV
- CTA is a promising project to open up TeV gamma-ray sky like Fermi

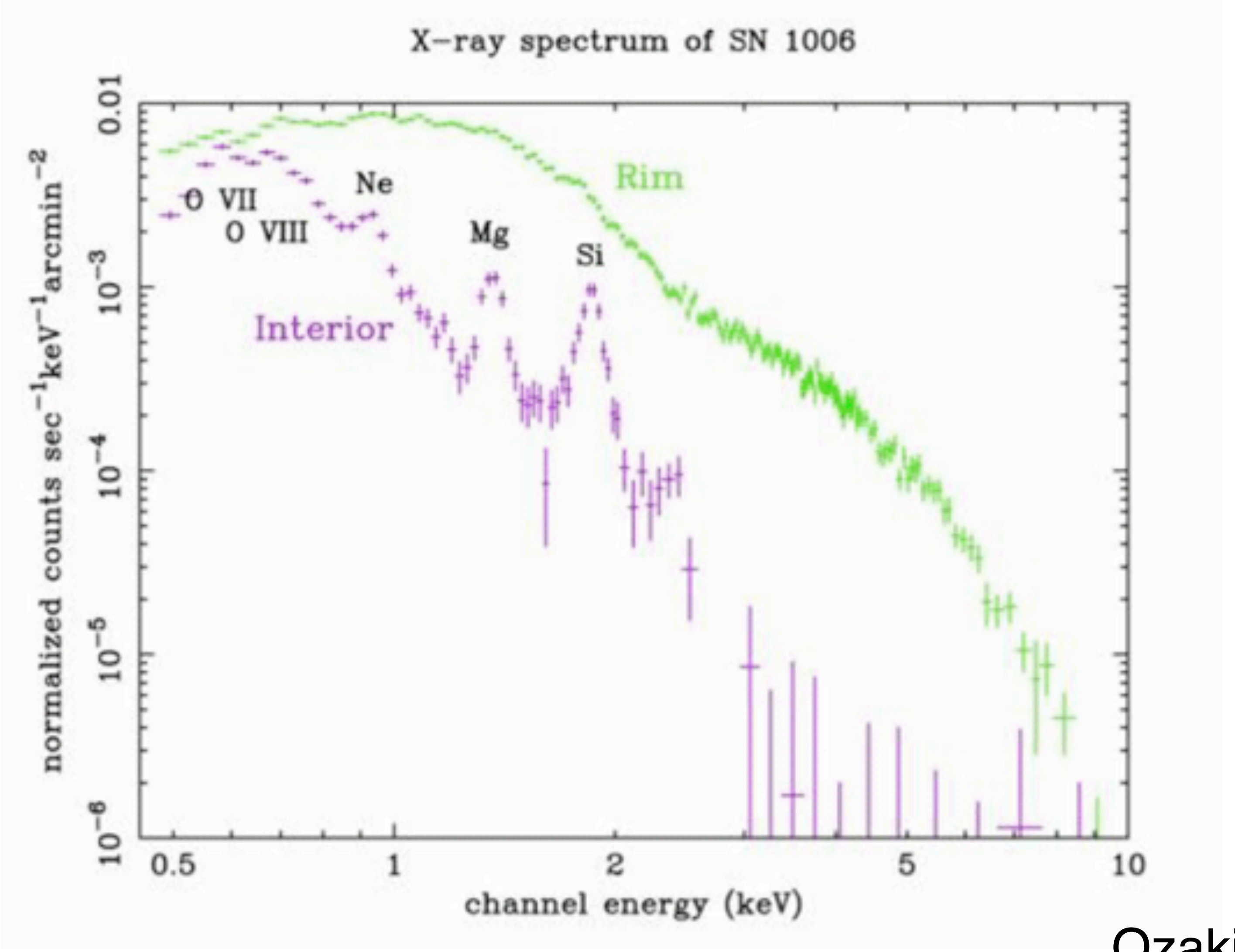


Backup

Particle Acceleration in SNR

- Young shell-type supernova: SN1006
  - Power law spectrum from rim is best described by synchrotron emission by ultra-relativistic electrons
  - First evidence of particles accelerated to > 10^{14} eV





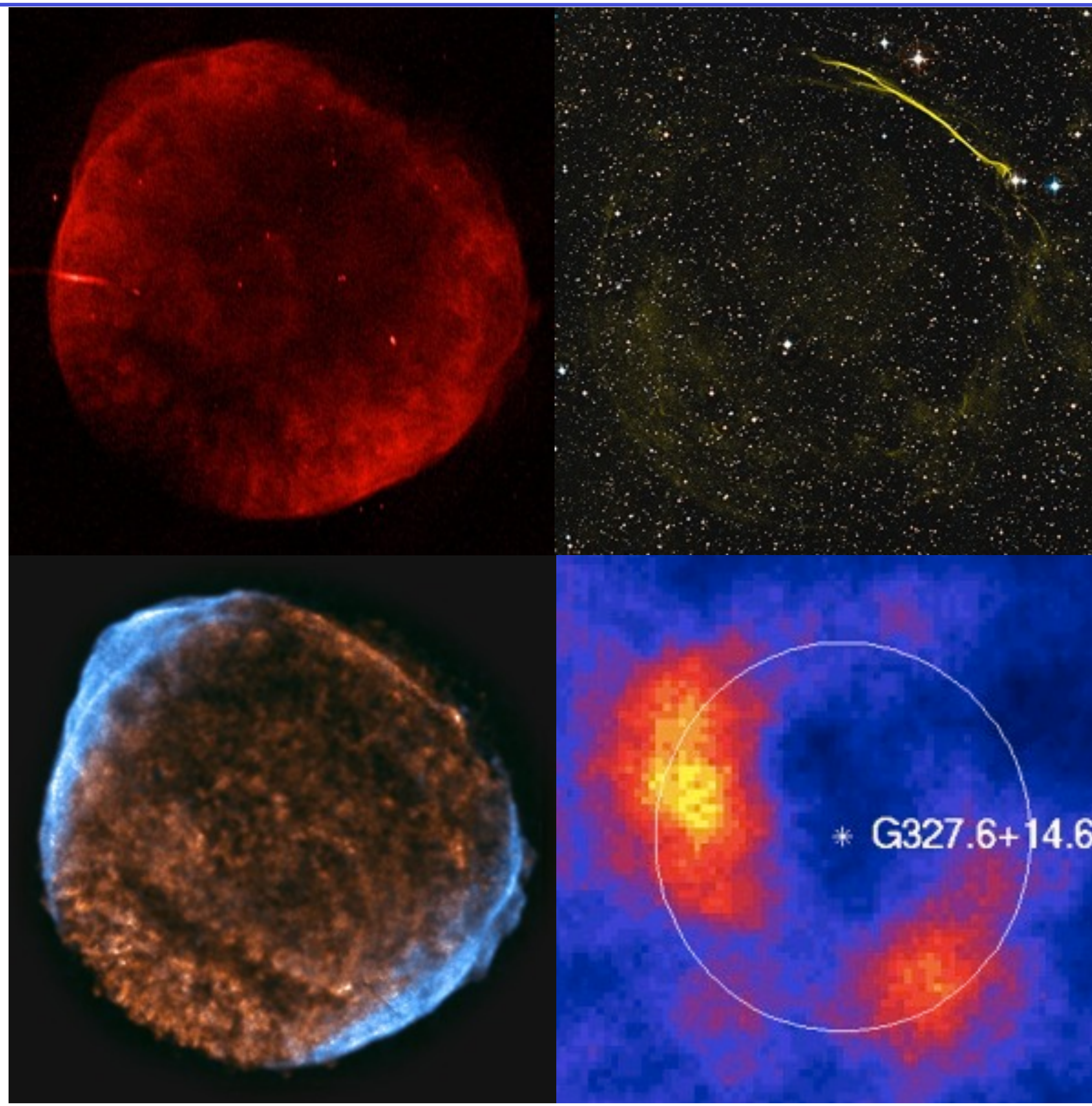
Ozaki

SNR with Multi-wavelength Observations

Radio

GeV electrons

Optical light



X-ray

High temp. plasma

TeV electrons

TeV Gamma ray

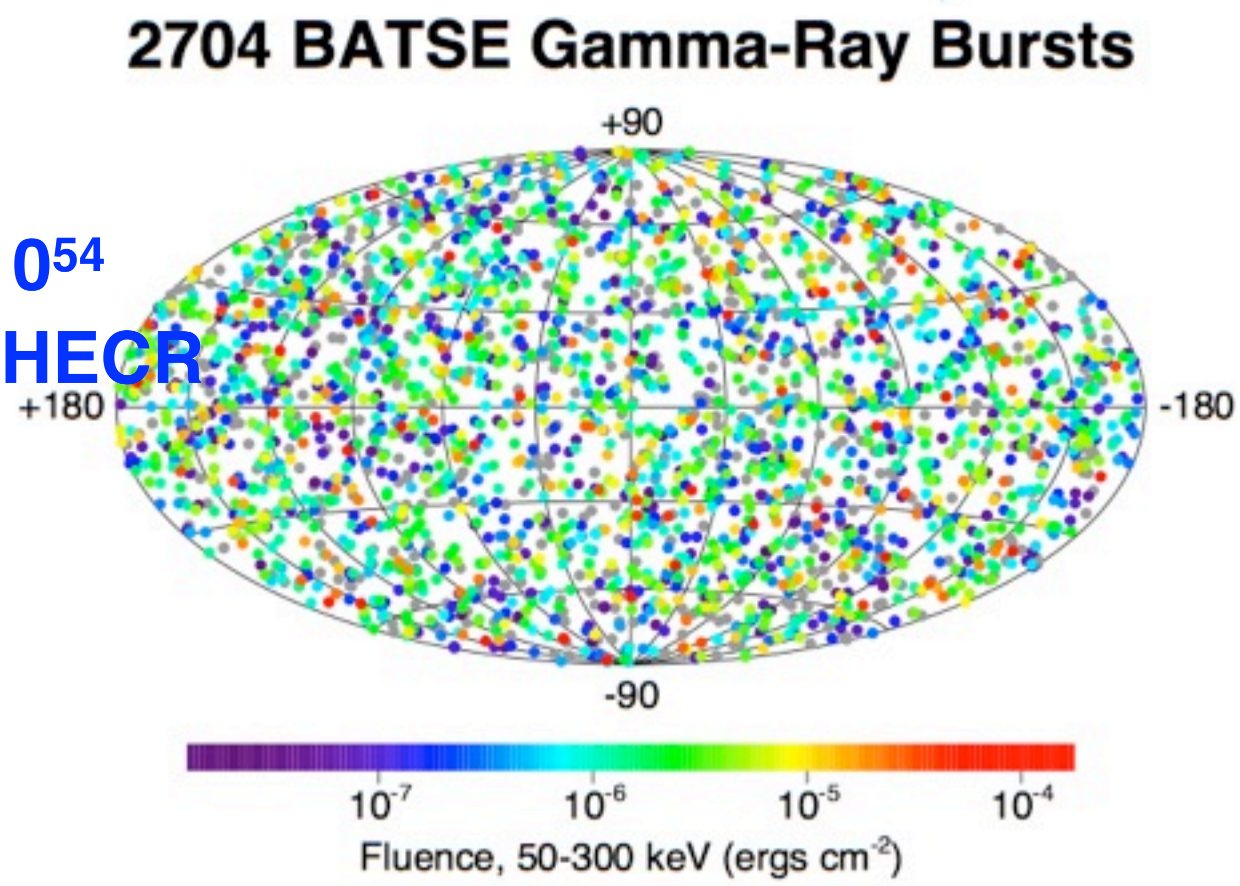
TeV electrons

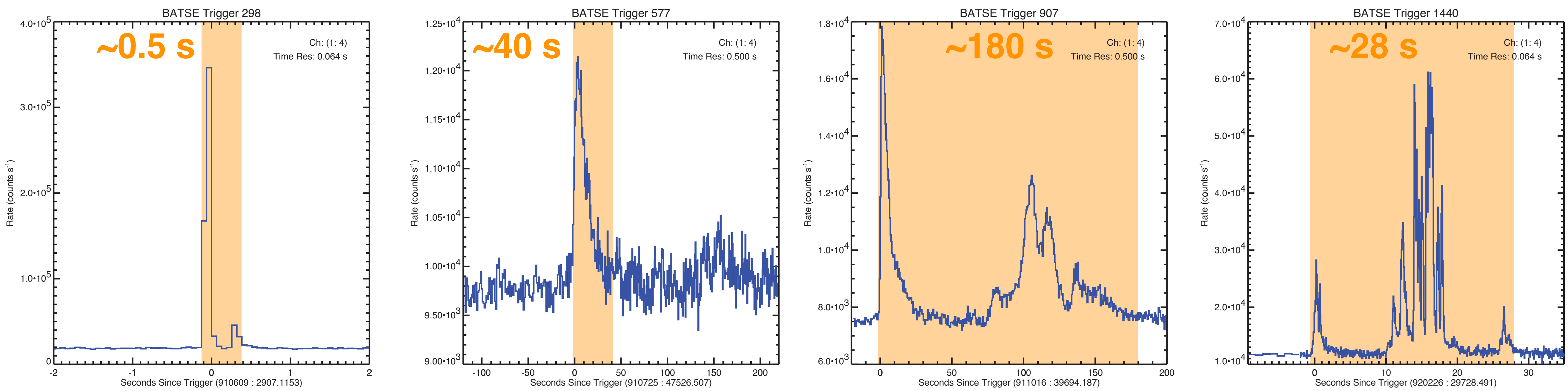
TeV hadrons

Credit: H.E.S.S., NASA/CXC/Rutgers, NRAO/AUI/NSF/GBT/VLA, Middlebury College/F.Winkler, NOAO/AURA/NSF/CTIO Schmidt & DSS

Gamma-Ray Bursts Overview (1)

- Discovered in 1967
- Cosmological origin
  - Large apparent energy release: 10^{52}~10^{54}
  - Energetics consistent with origin of UHECR
- Peak in ~MeV gamma rays
  - Band function: smoothly joined two power law
  - Synchrotron radiation of ultra-relativistic electrons in jet?





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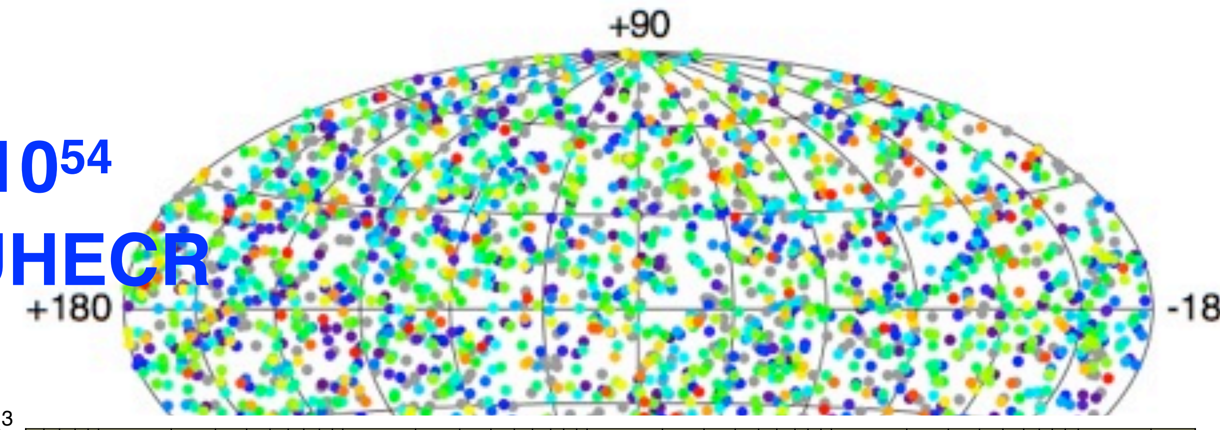
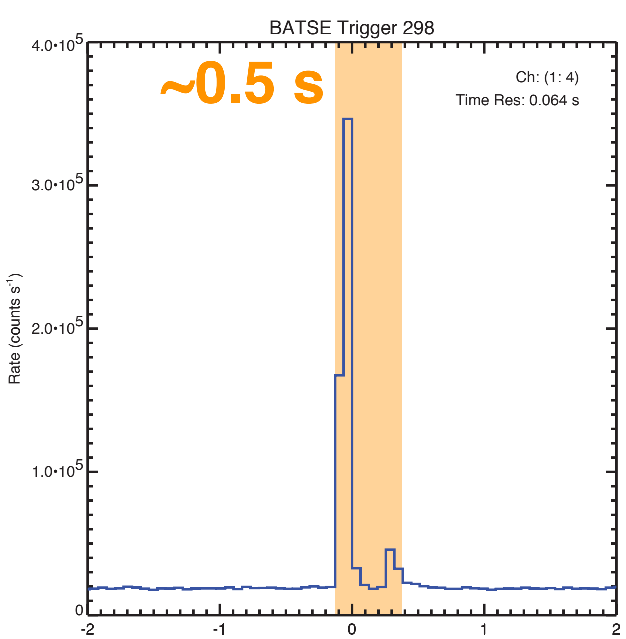
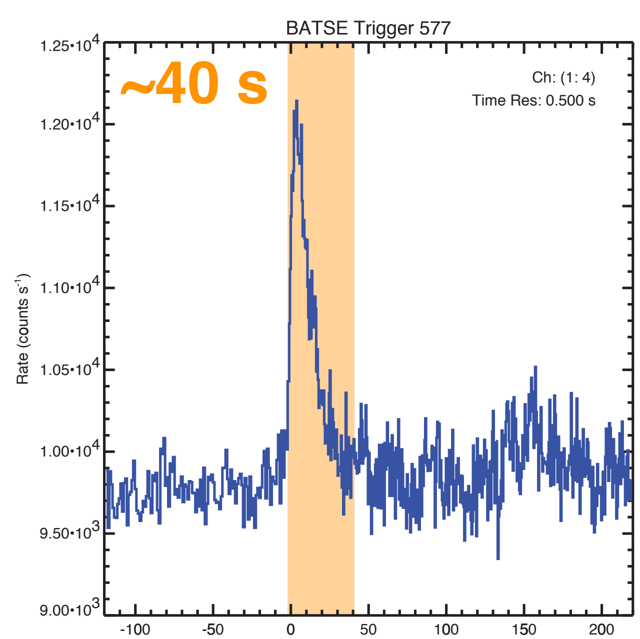
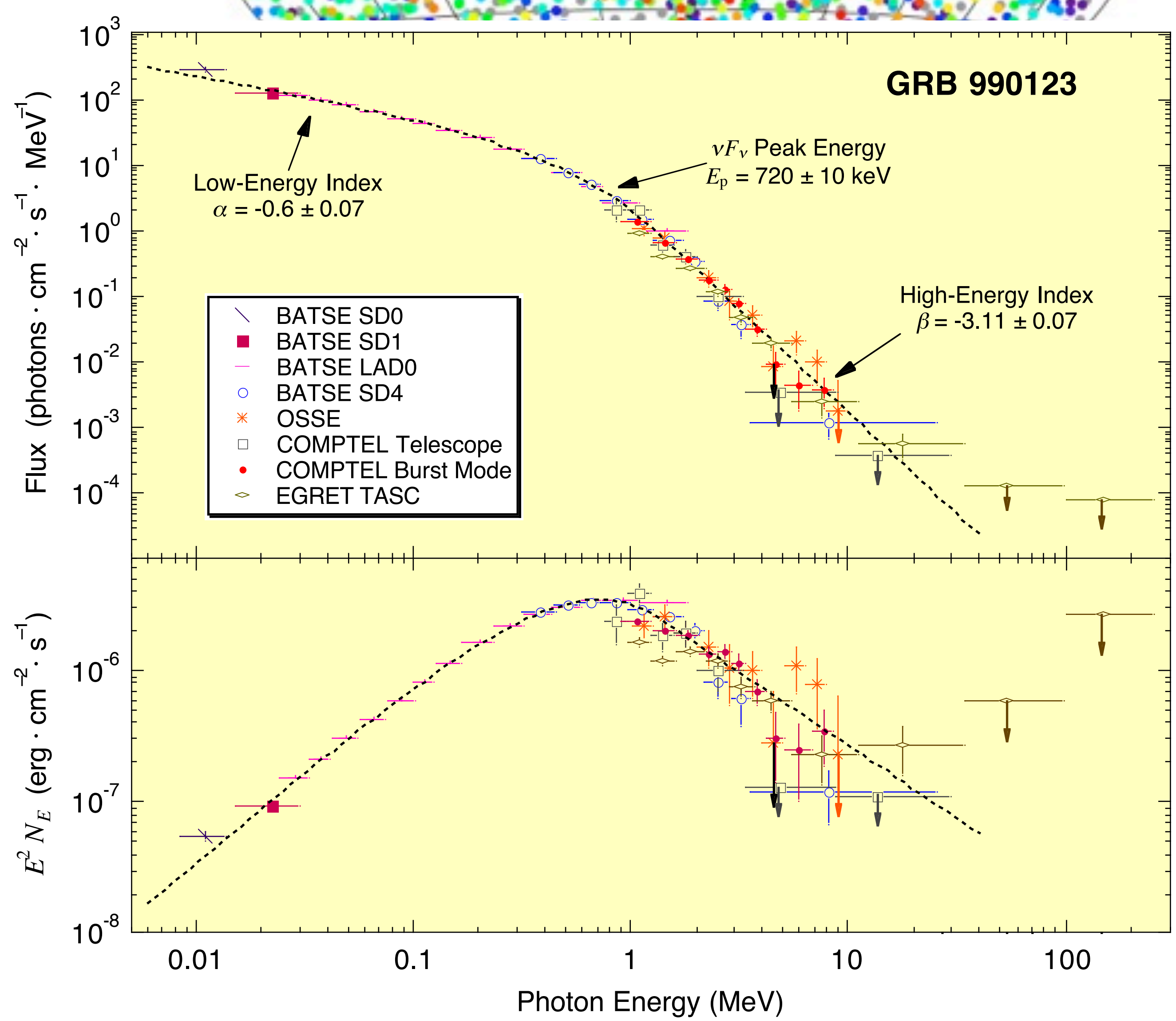
2704 BATSE Gamma-Ray Bursts



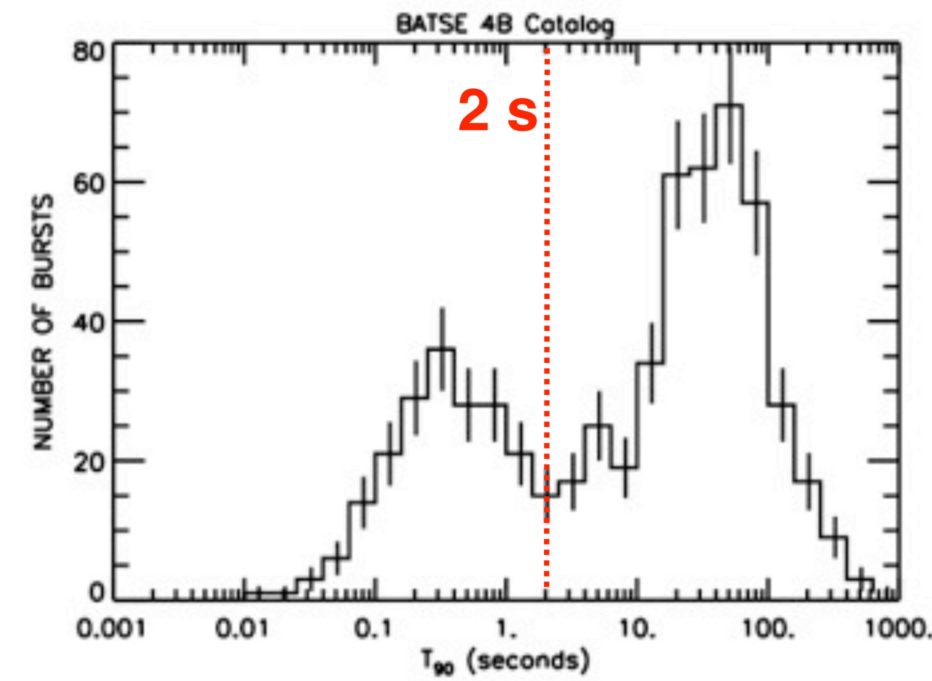


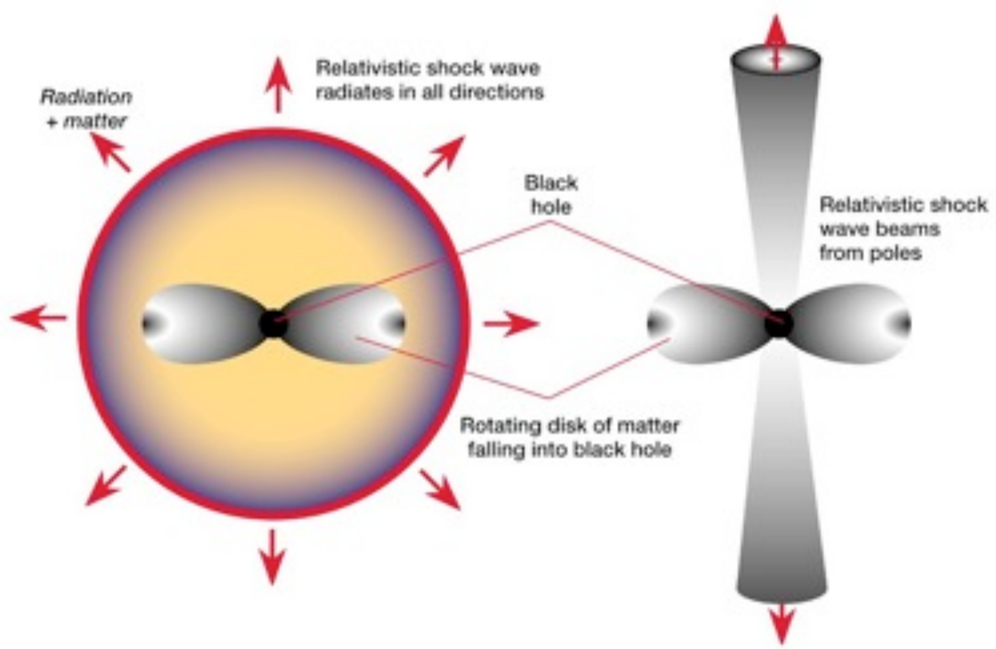


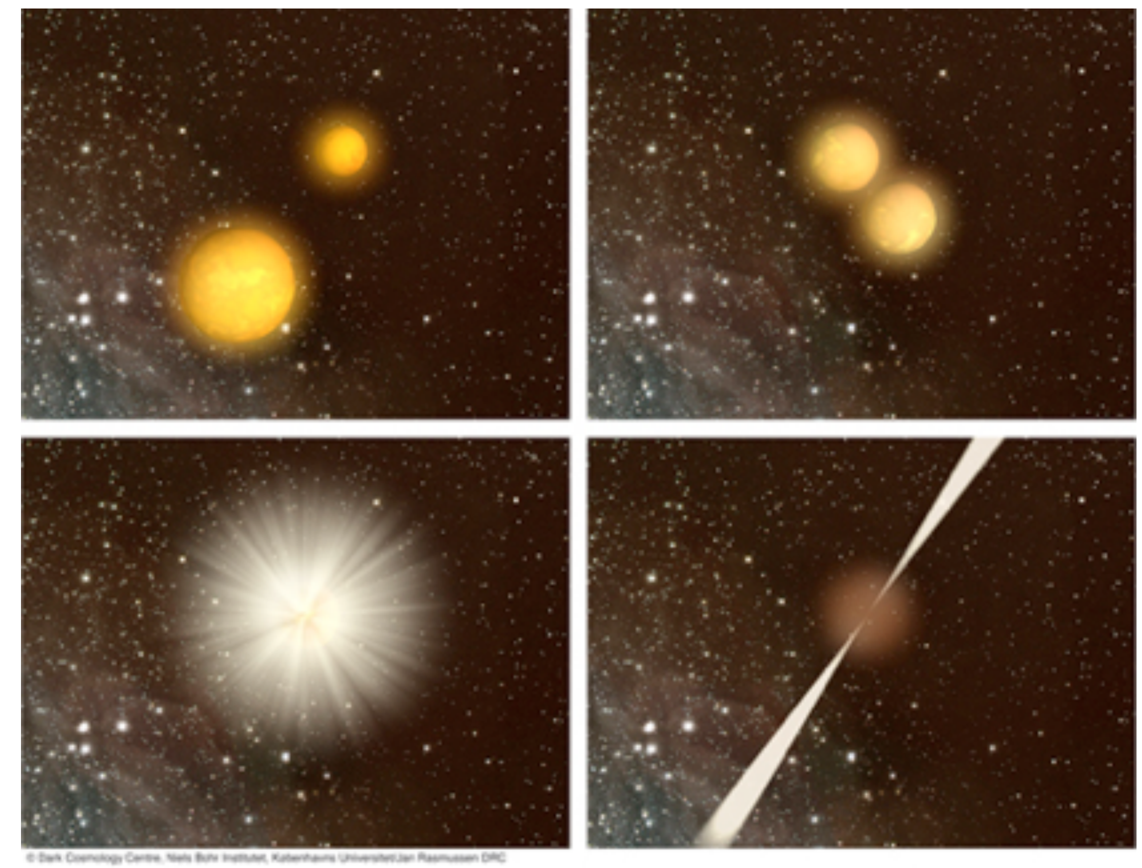


Gamma-Ray Bursts Overview (2)

- **Bimodal Duration Distribution**
  - **Short (< 2s) GRB: progenitor unknown**
    - **Merger of compact objects (NS or BH)?**
  - **Long (> 2s) GRB:**
    - **Association with supernovae**
      ⇒ Core-collapse supernovae
- **Gamma-ray emission mechanism not well understood**







The Neutron Stars Merging Scenario

ESO PR Photo 32c/05 (October 6, 2005)

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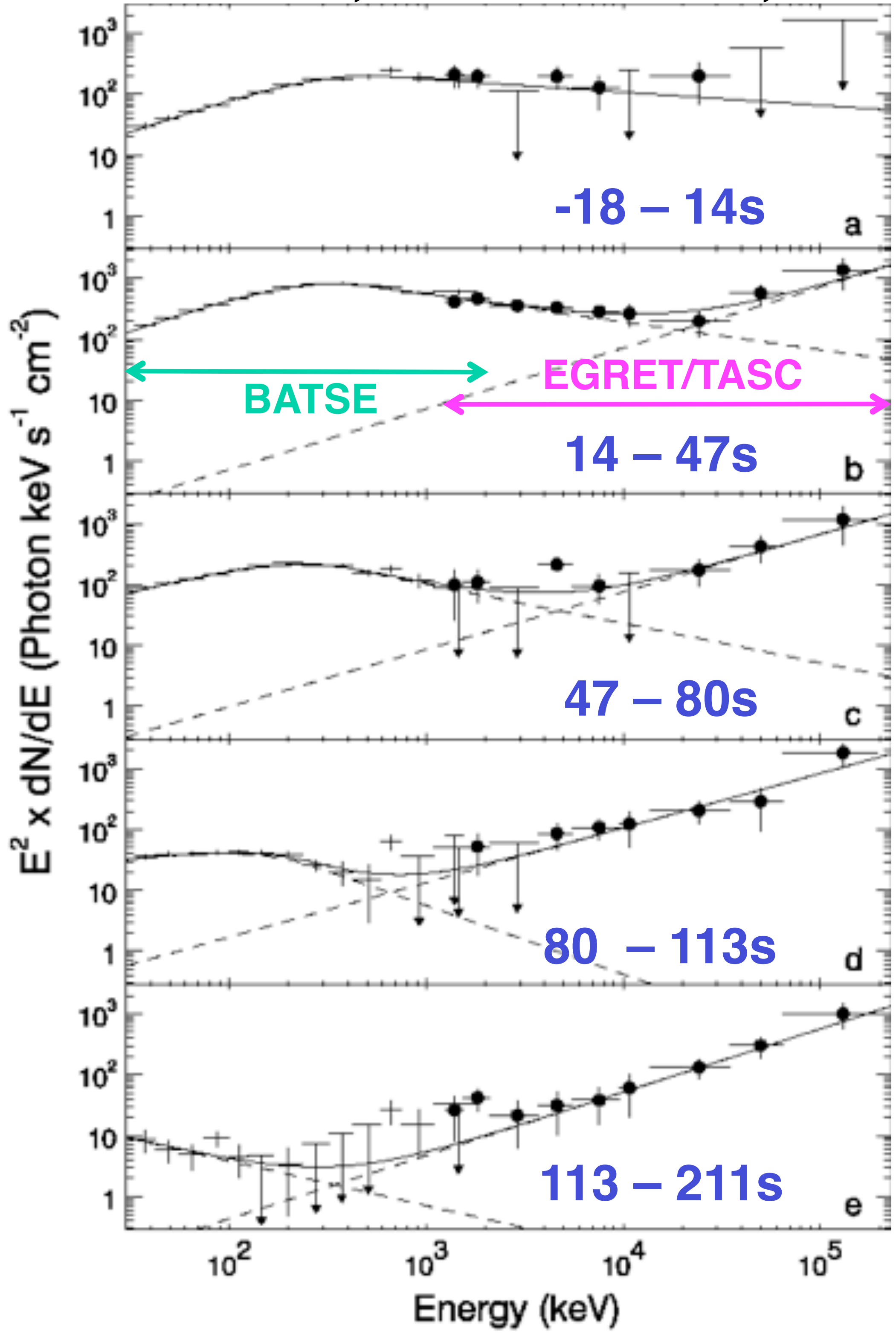
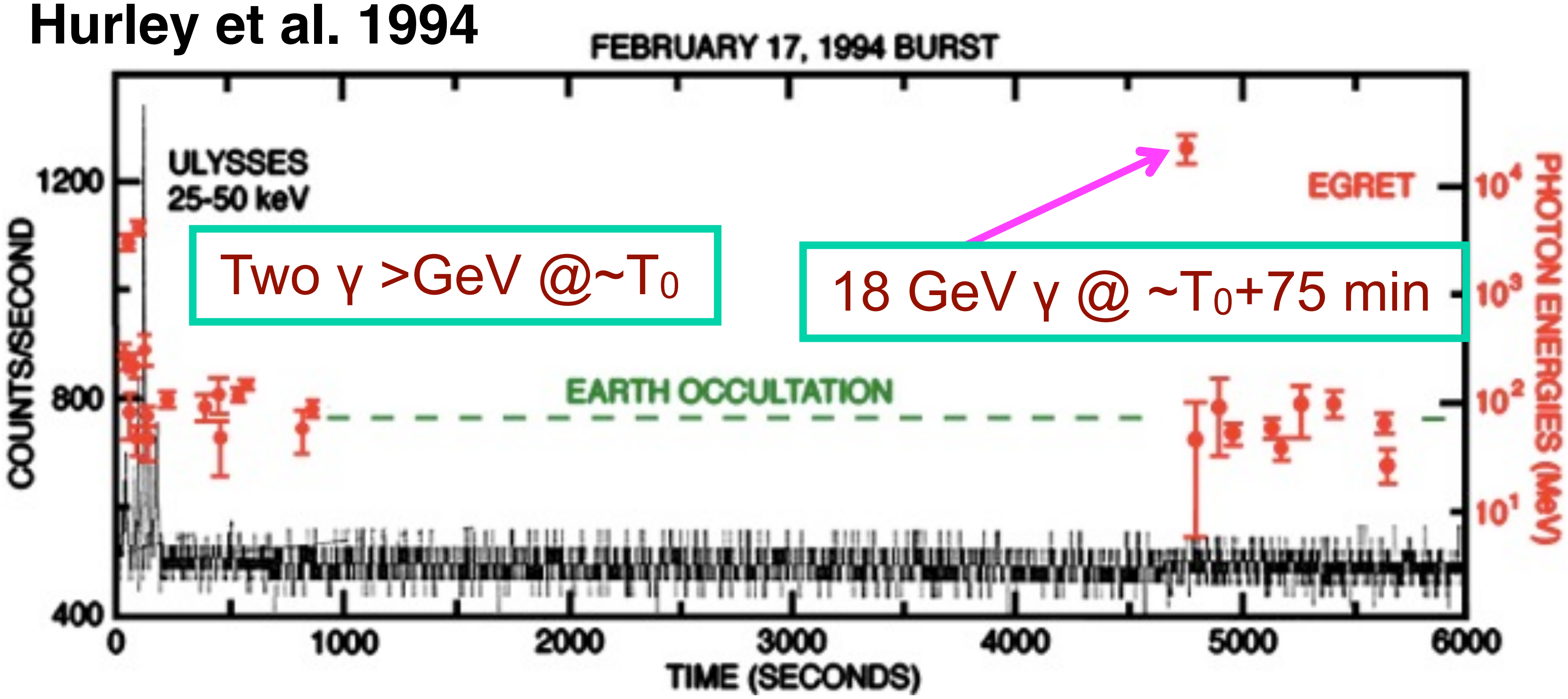
High-Energy Emissions from GRB (Past)

- EGRET observations of delayed HE gamma-ray emissions
  - It is not straightforward to explain by conventional electron synchrotron models
  - Proton acceleration? Origin of UHECR?

Gonzalez, Nature 2003 424, 749



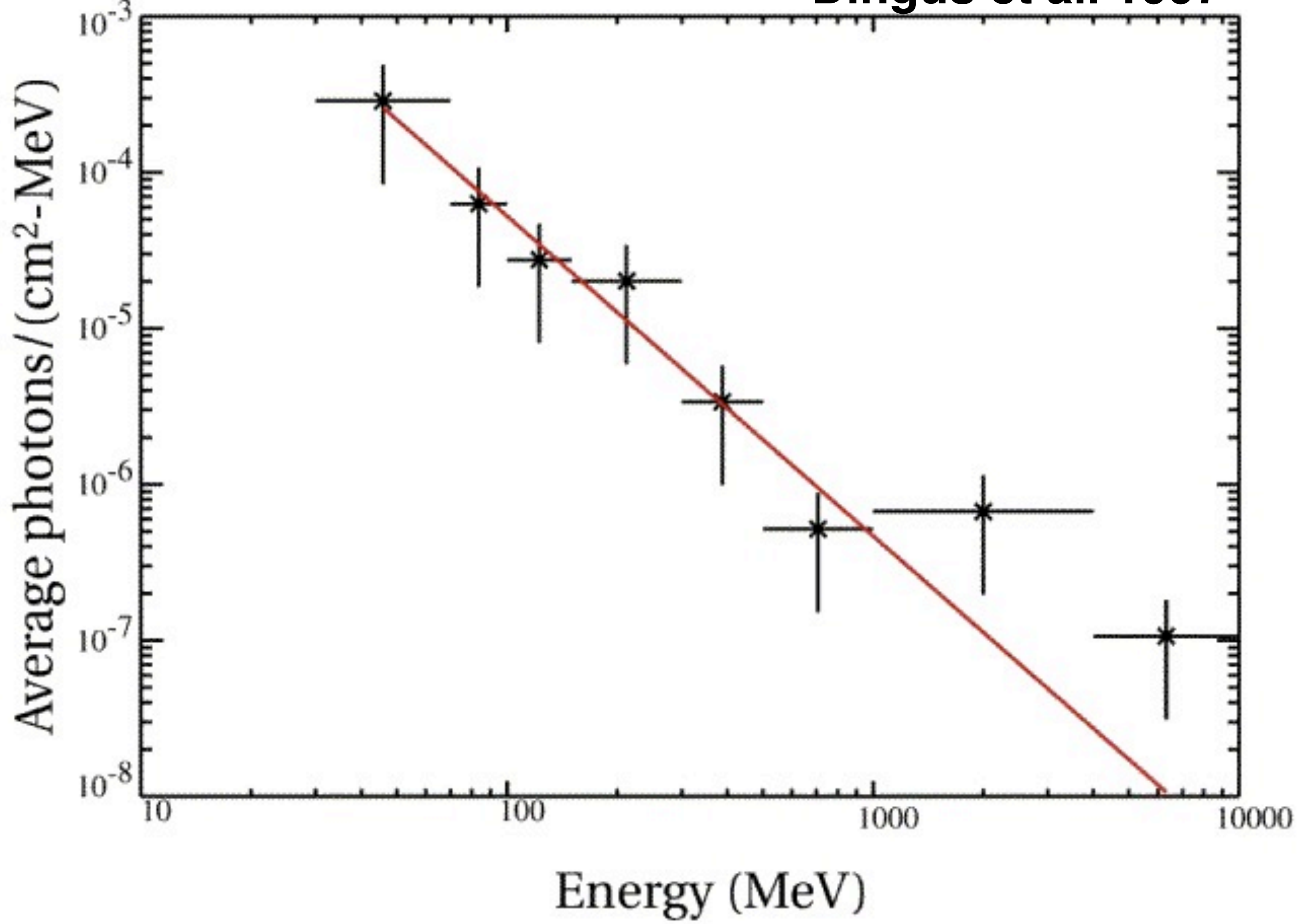
Hurley et al. 1994



EGRET High-Energy GRB Spectra

- 5 EGRET bursts with >50 MeV observations in 7 years
  - No evidence of cutoff or extra HE component in the summed spectrum

Dingus et al. 1997



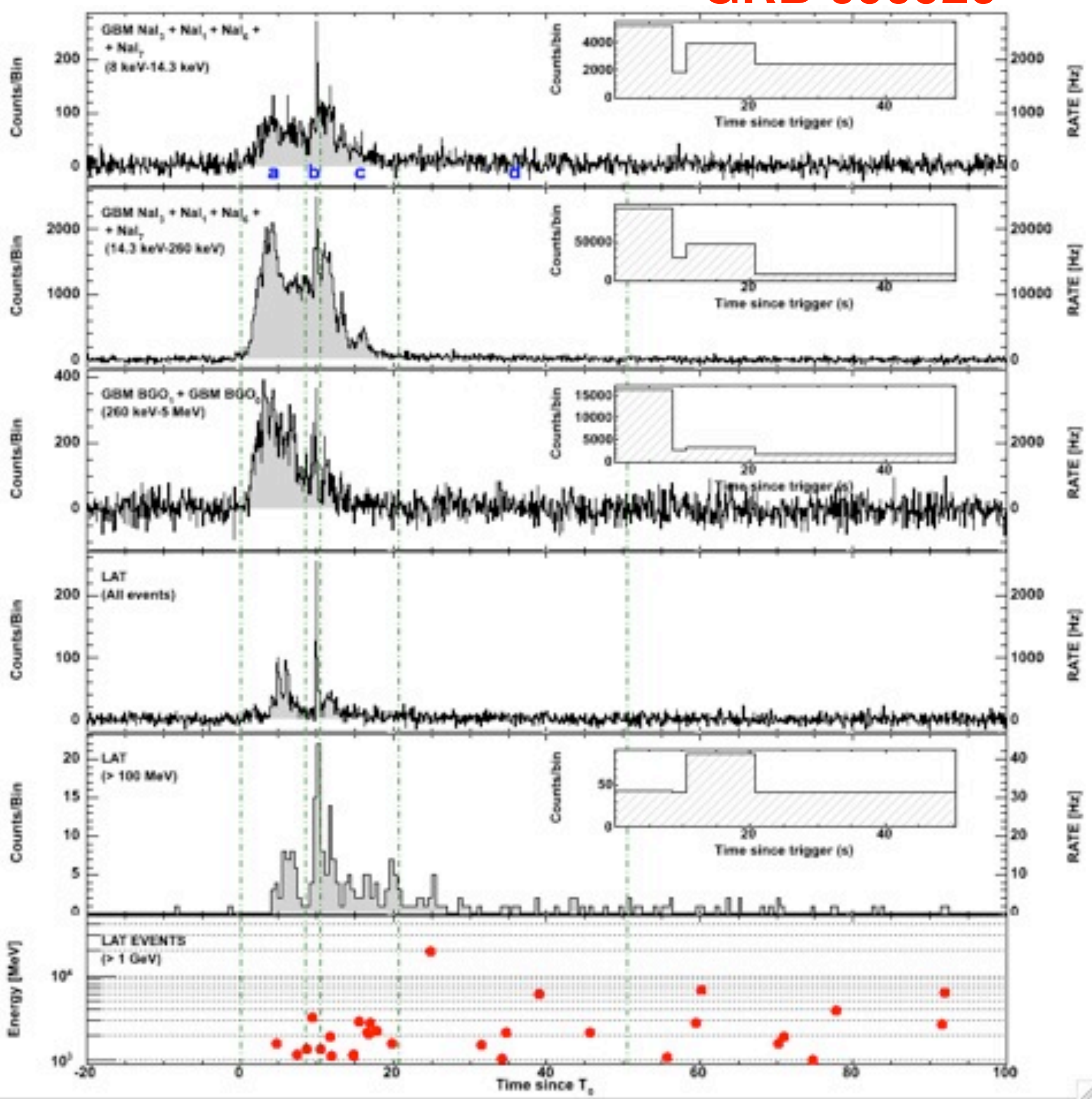
Common Features of LAT GRBs

GRB	long or short	# of events > 100 MeV	# of events > 1 GeV	Highest Energy (arrival time)	Delayed HE onset	Long-lived HE emission	Extra component	Cutoff	Redshift
080825C	long	~10	0	~0.6 GeV ($\sim T_0+28$ s)	✔	✔	?	?	
080916C	long	>100	>10	~13 GeV ($\sim T_0+17$ s)	✔	✔	hint	?	4.35
081024B	short	~10	2	~3 GeV ($\sim T_0+0.6$ s)	✔	✔	?	?	
081215A	long	—	—	—	—	—	—	—	
90217	long	~10	0	~1 GeV ($\sim T_0+15$ s)	X	X	?	?	
90323	long	~20	>0	—	—	✔	—	—	3.57
90328	long	~20	>0	—	—	✔	—	—	0.736
90510	short	>150	>20	~31 GeV ($\sim T_0+0.8$ s)	✔	✔	✔	?	0.903
90626	long	~20	>0	—	—	✔	—	—	
090902B	long	>200	>30	~33 GeV ($\sim T_0+82$ s)	✔	✔	✔	?	1.822
90926A	long	>150	>50	~20 GeV ($\sim T_0+25$ s)	✔	✔	✔	✔	2.106

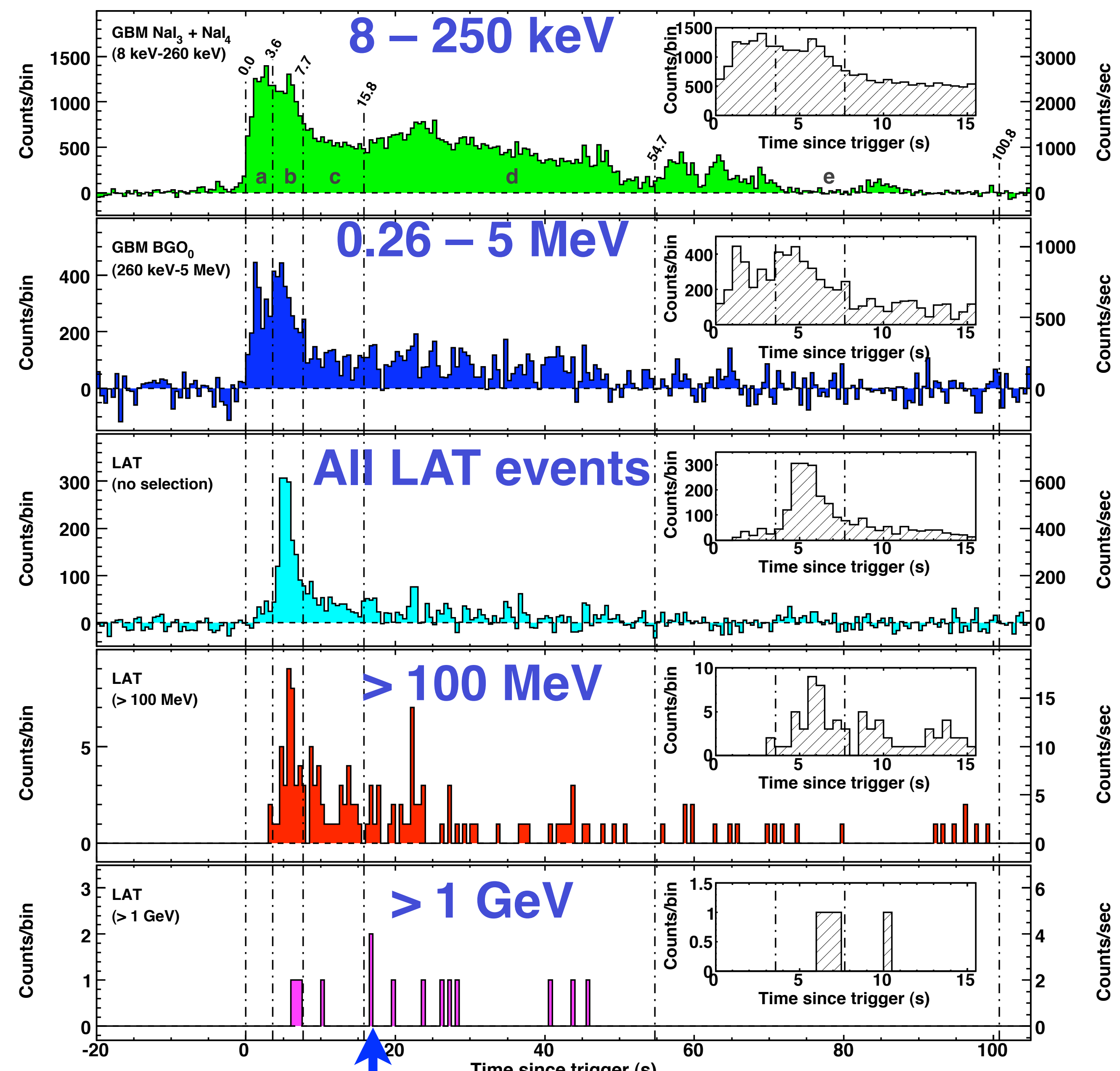
Delayed HE Gamma-ray Emission

- Opacity due to $\gamma\gamma \rightarrow e^{+}e^{-}$ in the first peak?
  - No evidence of spectral cut-off
- Late arrival of highest energy gamma rays

GRB 090926



GRB 080916C



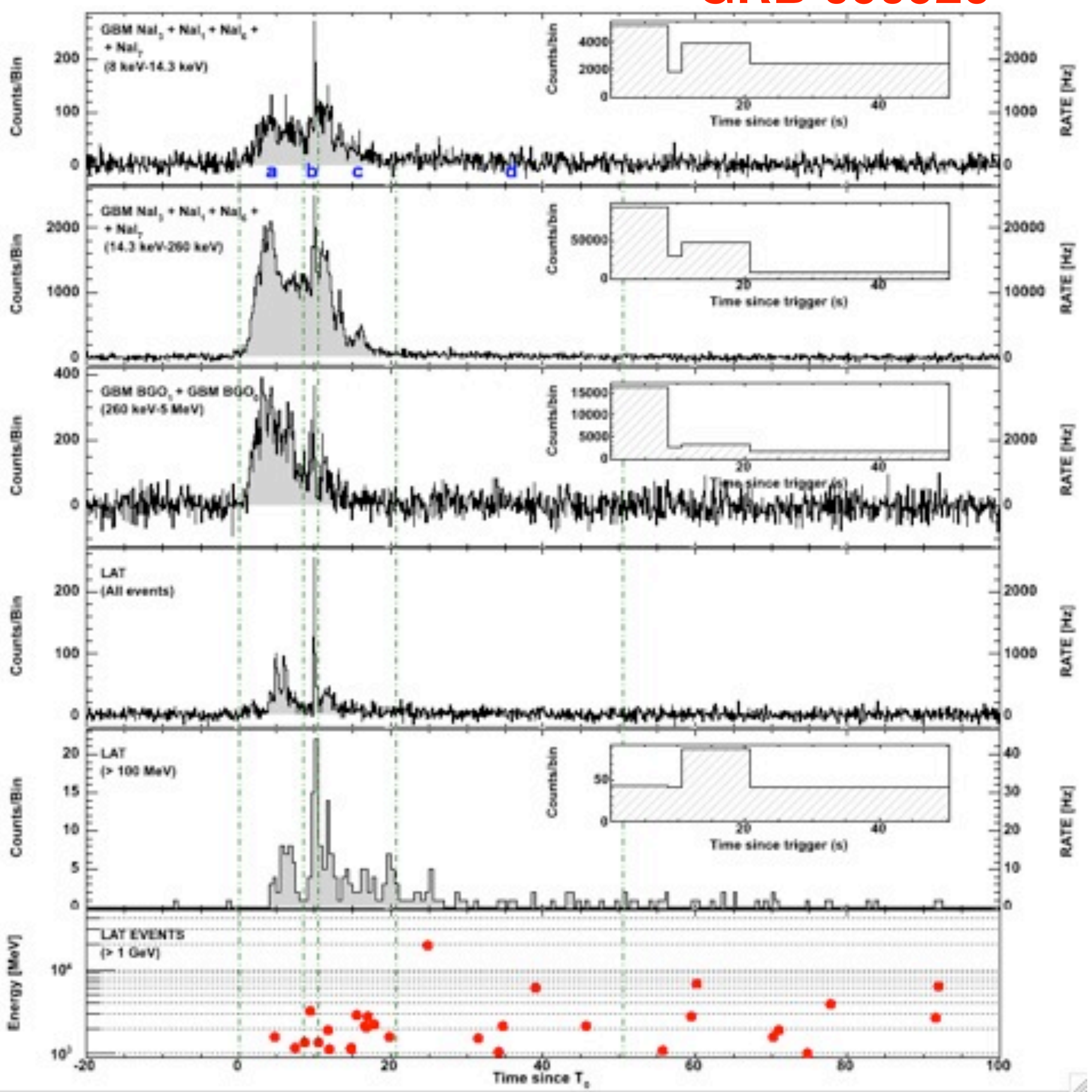
13.2 GeV photon

Science 323 1688A (2009)

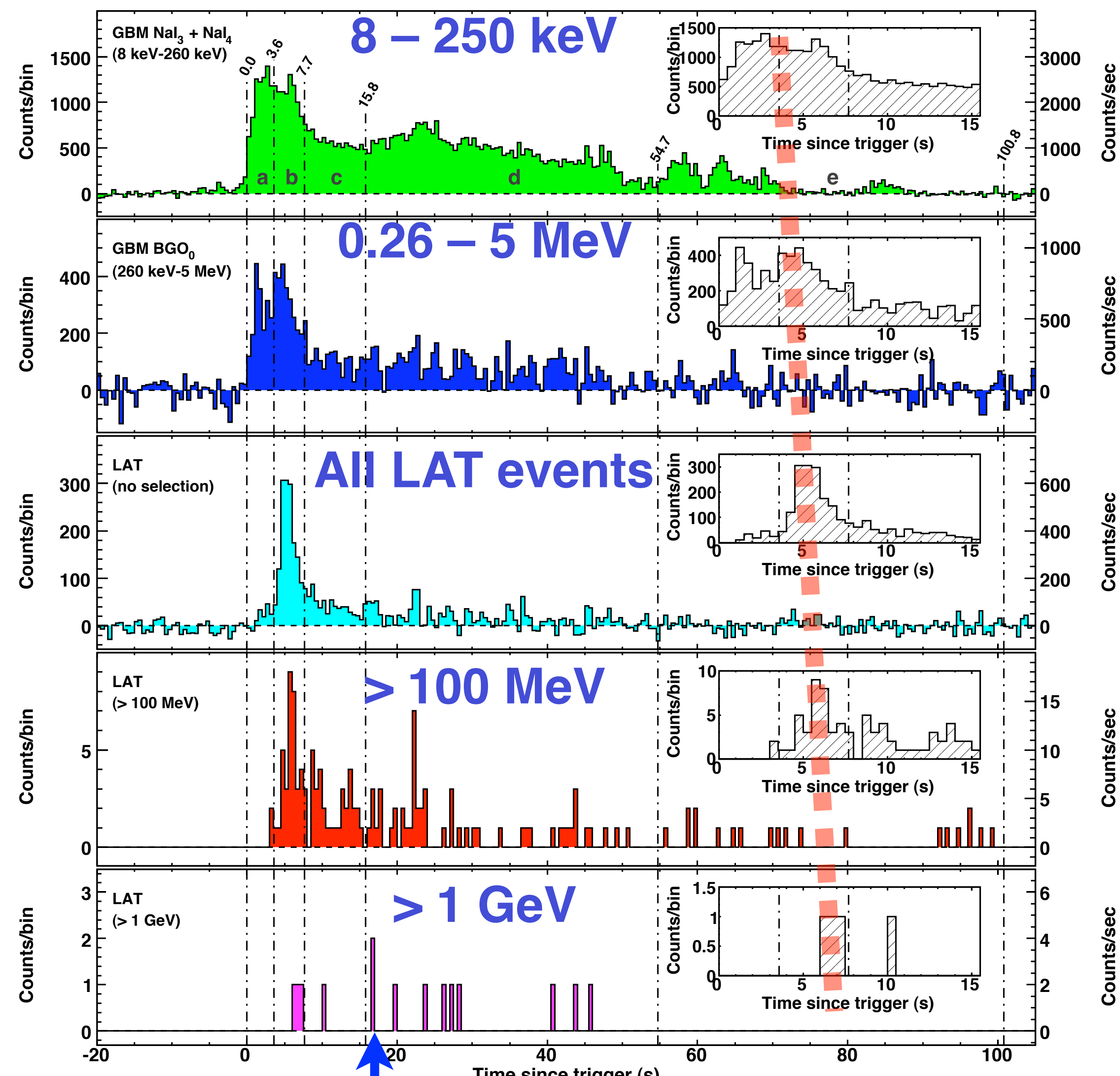
Delayed HE Gamma-ray Emission

- Opacity due to $\gamma\gamma \to e^+e^-$ in the first peak?
  - No evidence of spectral cut-off
- Late arrival of highest energy gamma rays

GRB 090926



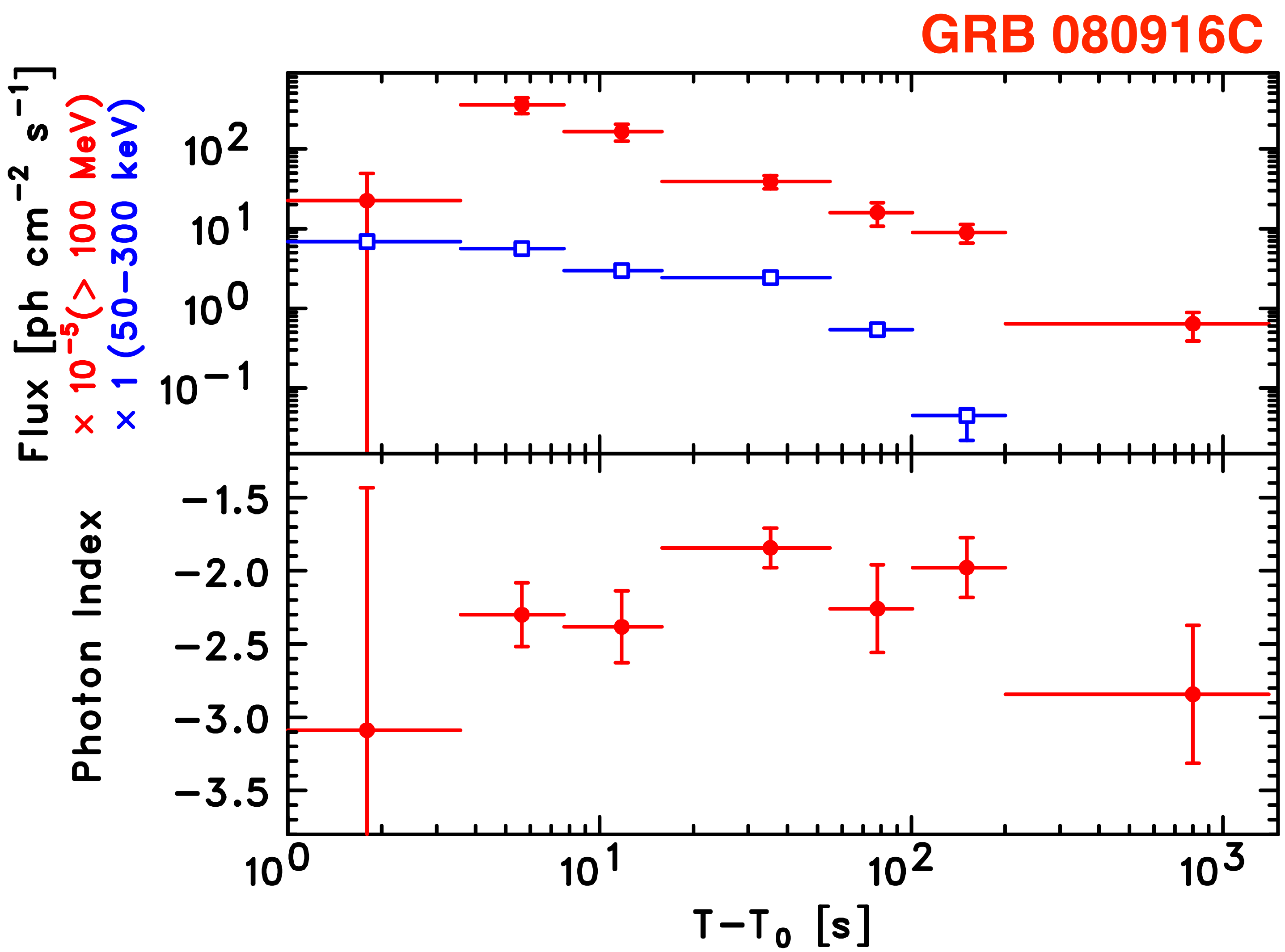
GRB 080916C

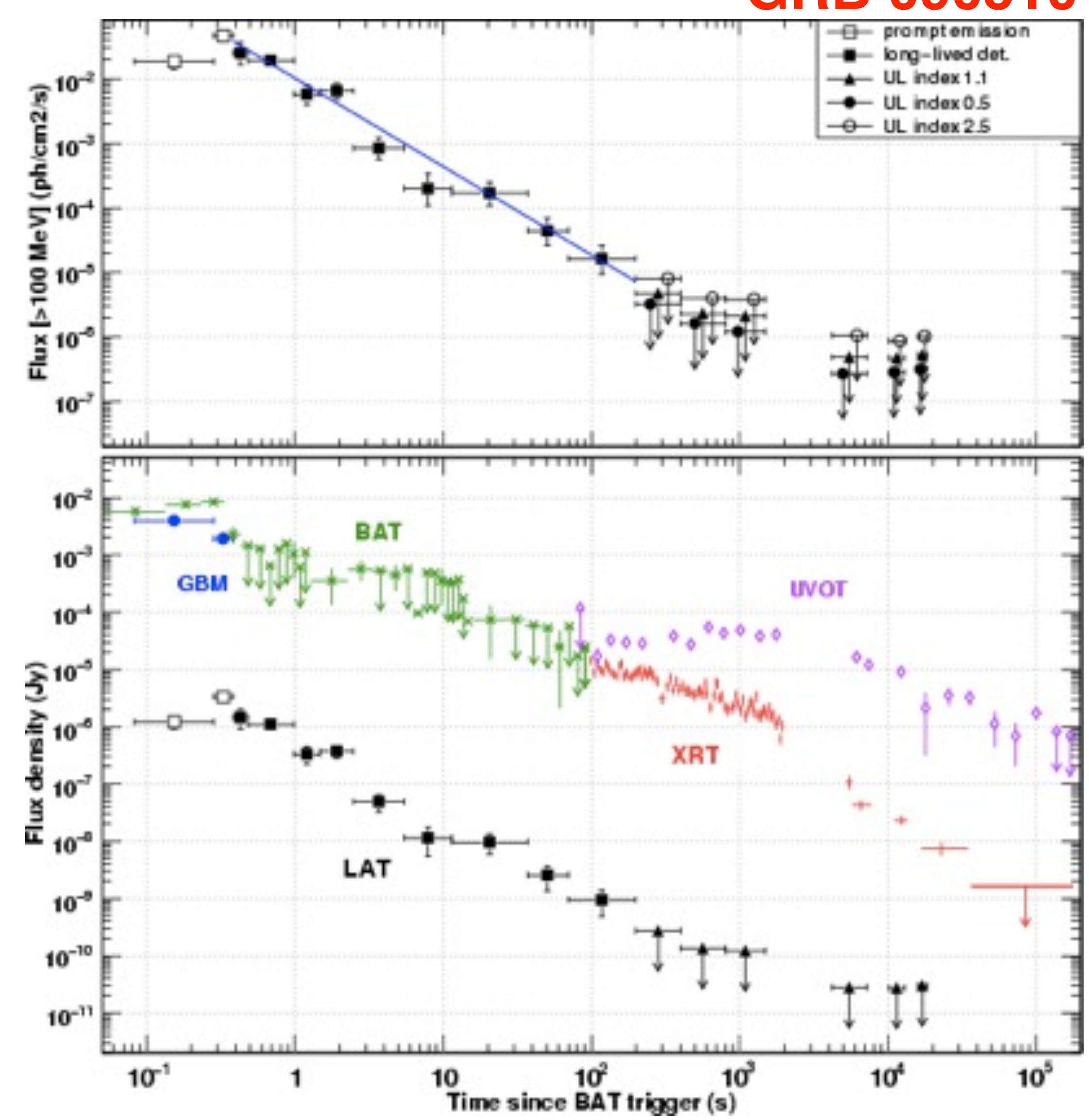


Science 323 1688A (2009)

GRB Long-Lived HE Emission

- HE (>100 MeV) emission shows different temporal behavior
  - Temporal break in LE emission while no break in HE emission
    - Indication of cascades induced by ultra-relativistic ions?
    - Angle-dependent scattering effects?



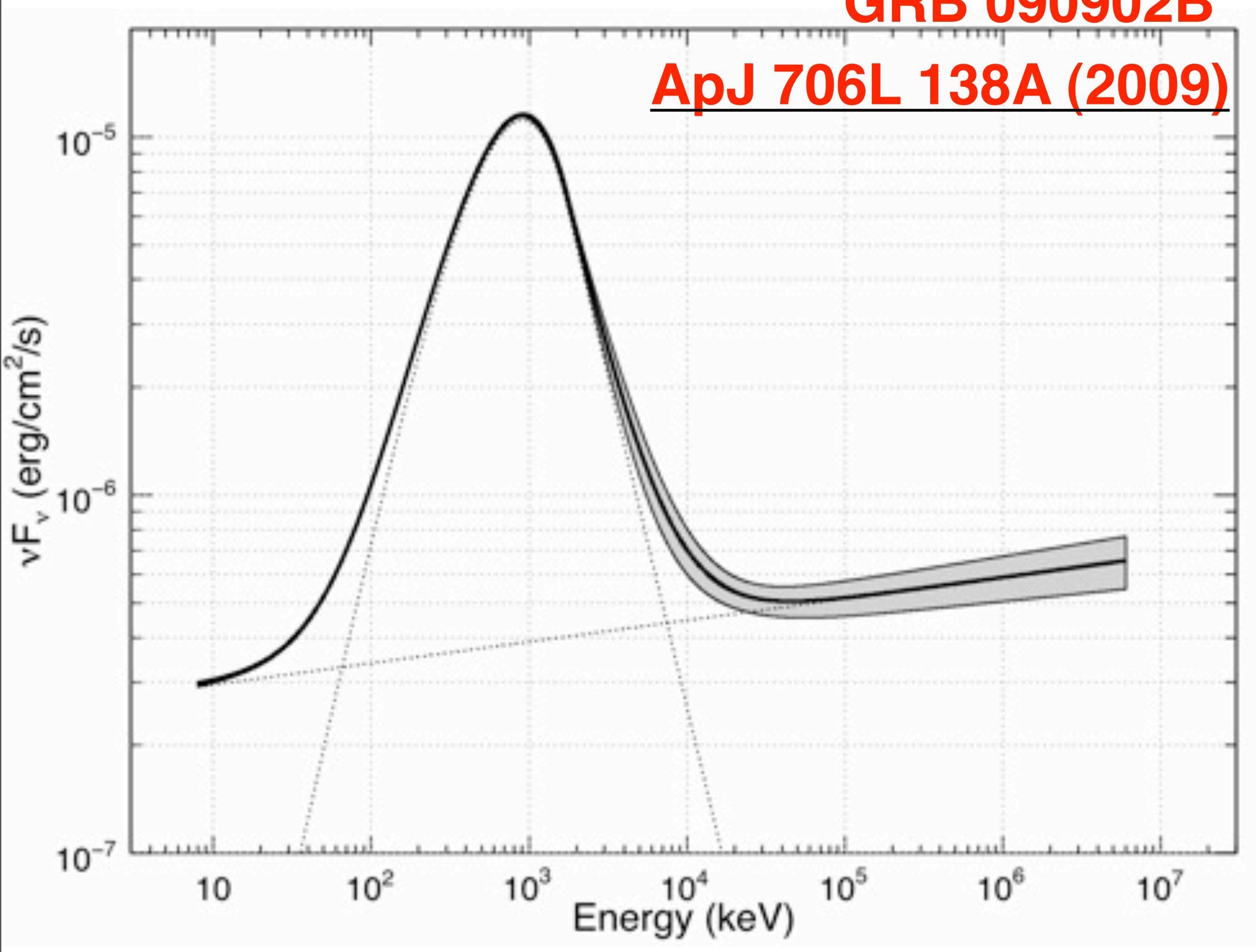


Extra Component

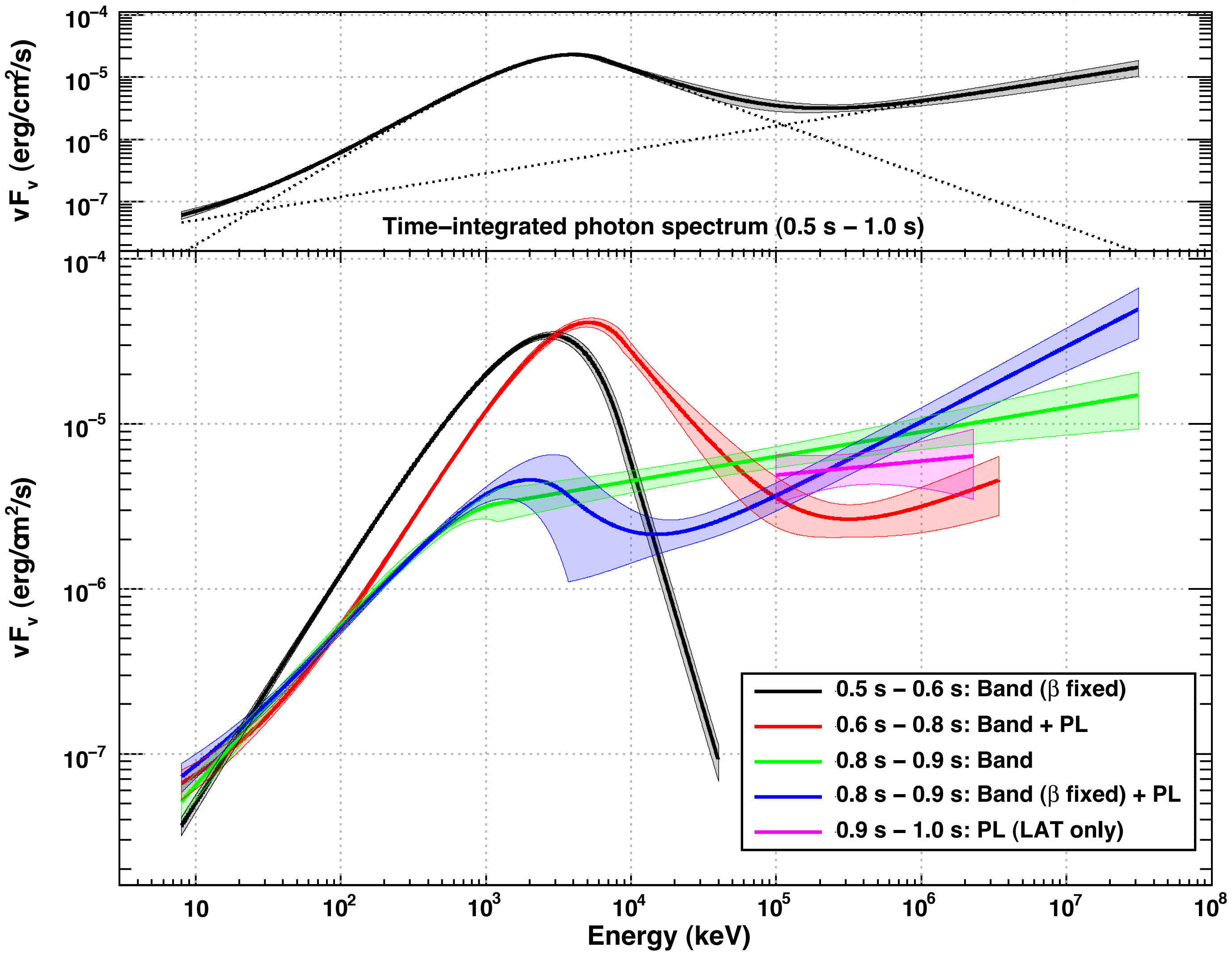
- Extra spectral component inconsistent with Band function
  - Both in low- and high-energy regions
- This is a challenge to theoretical model
  - Low energy excess difficult to explain by inverse Compton
  - Early afterglow?

GRB 090902B

ApJ 706L 138A (2009)



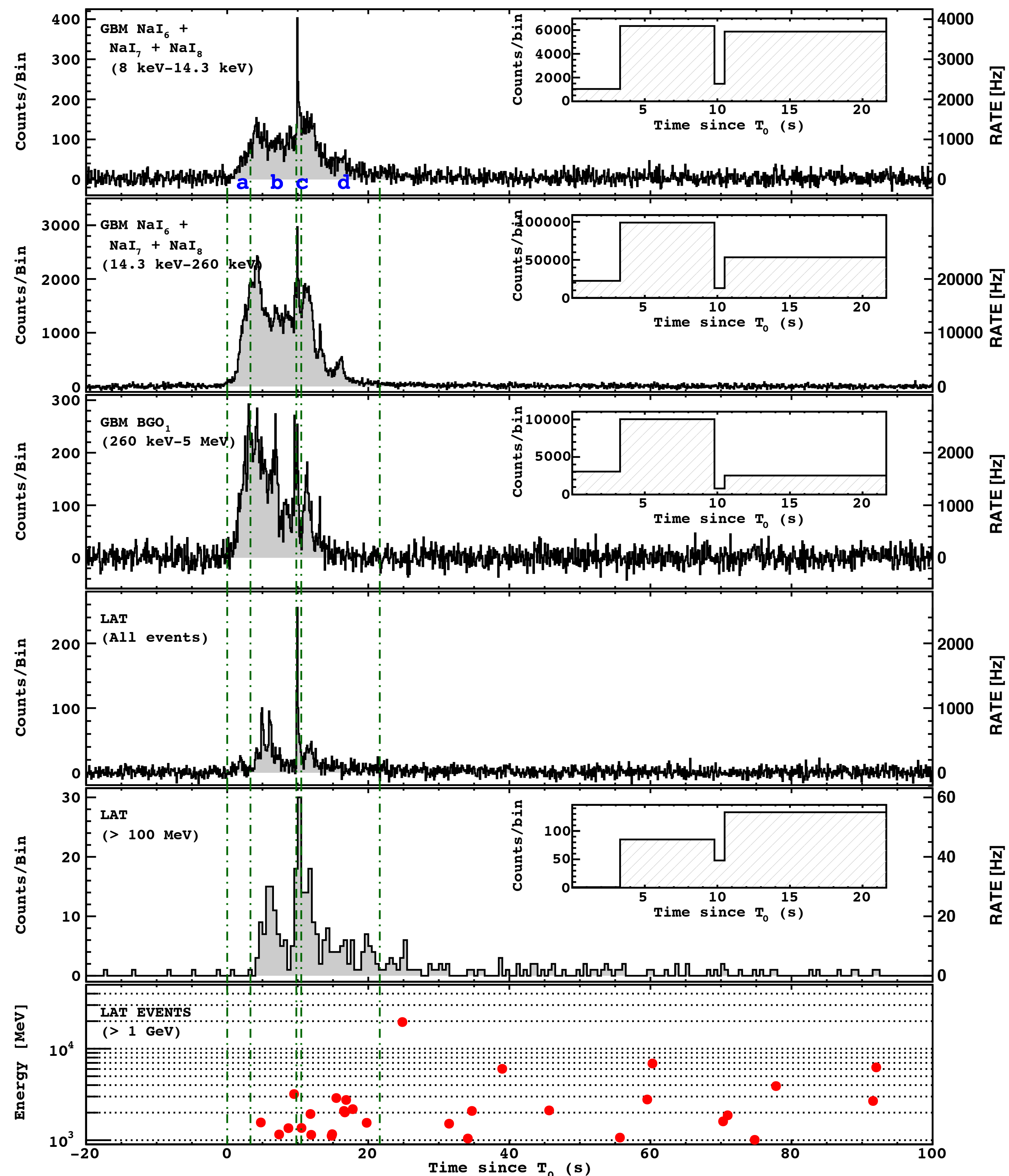
GRB 090510



Spectral cutoff - GRB 090926A

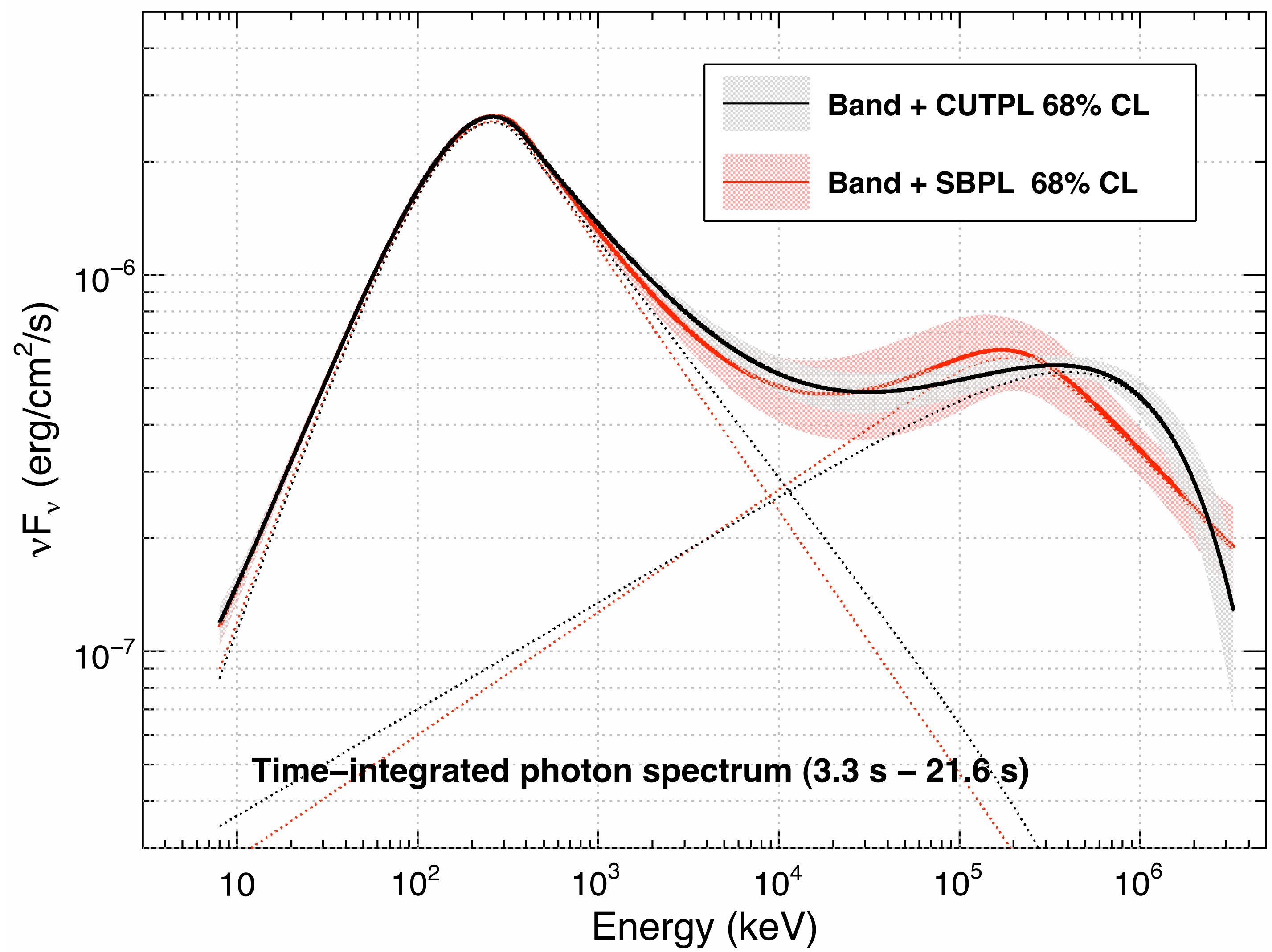
- Narrow spikes correlated in all energy band
  - Common origin

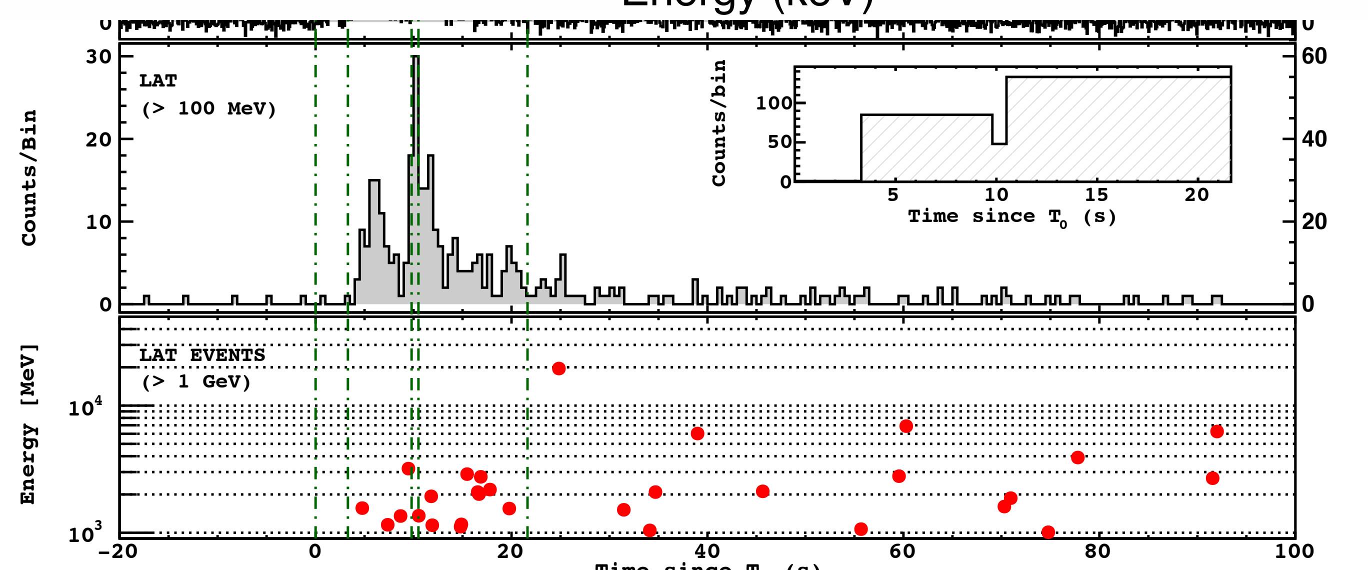
PRELIMINARY



Spectral cutoff - GRB 090926A

- Narrow spikes correlated in all energy band
  - Common origin
- Significant spectral break
  - Shape is not constrained
  - if cutoff due to γ-γ absorp.
    - 1st direct measurement of bulk Lorentz factor ($\Gamma \sim$200-700)





PRELIMINARY

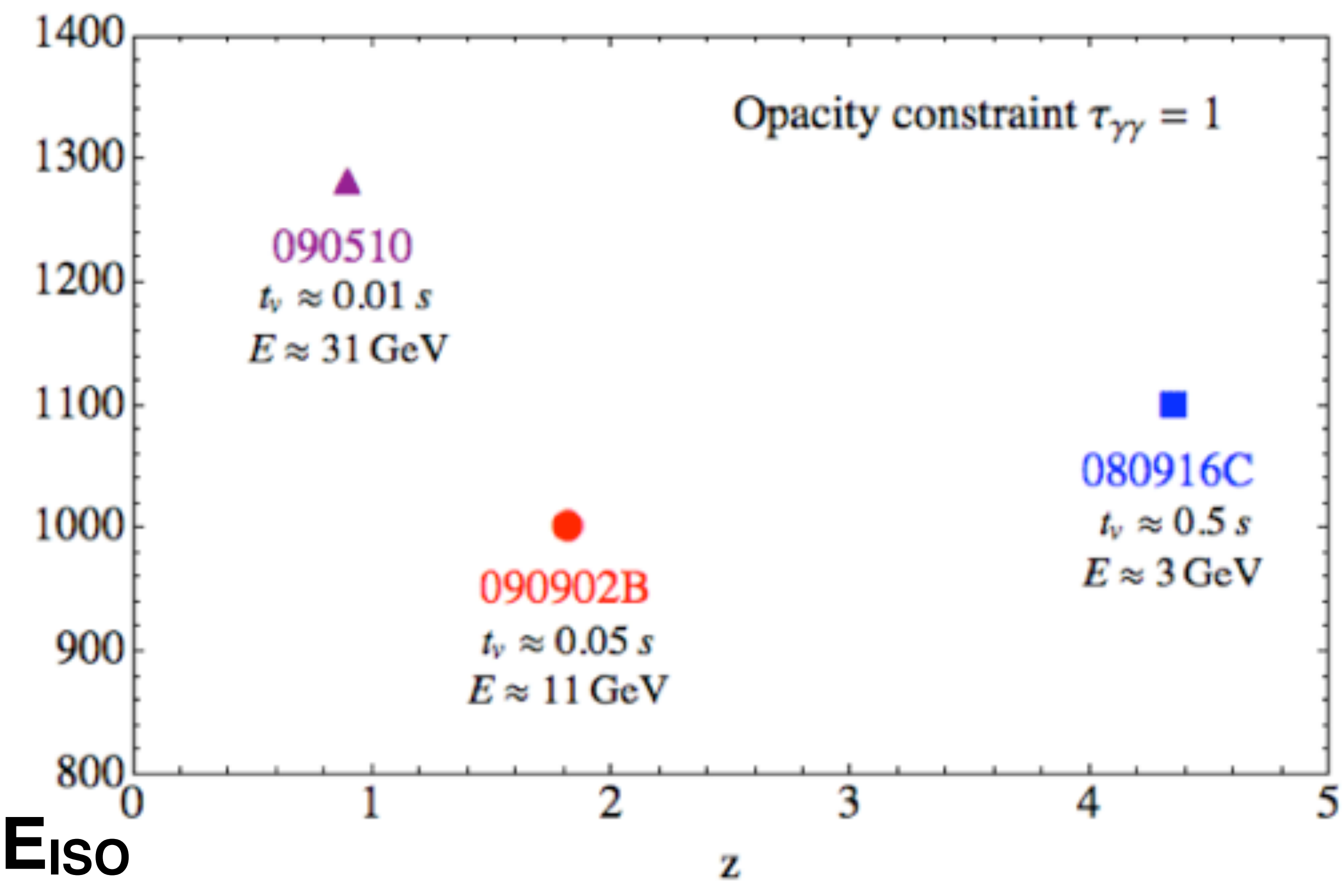
Implications on GRB Models

- Implications on GRB gamma-ray emission models
  - Internal Shock
    - Leptonic models (Synchrotron Self-Compton) Ryde 2010, Toma 2010
    - Hadronic models Asano 2009, Razzaque 2009
  - External Shock
    - Early afterglow Ghisellini 2010, Kumar & Barniol Duran 2009, Piran 2010

	Variability during prompt phase	Delayed onset	Low energy excess	Long-lived HE emission	Other features
Leptonic	✔	X	X	X	
Hadronic	X	✔	✔	✔	High B-field, large E_{ISO} (x~10)
Early afterglow	X	✔	✔	✔	High Lorenz factor

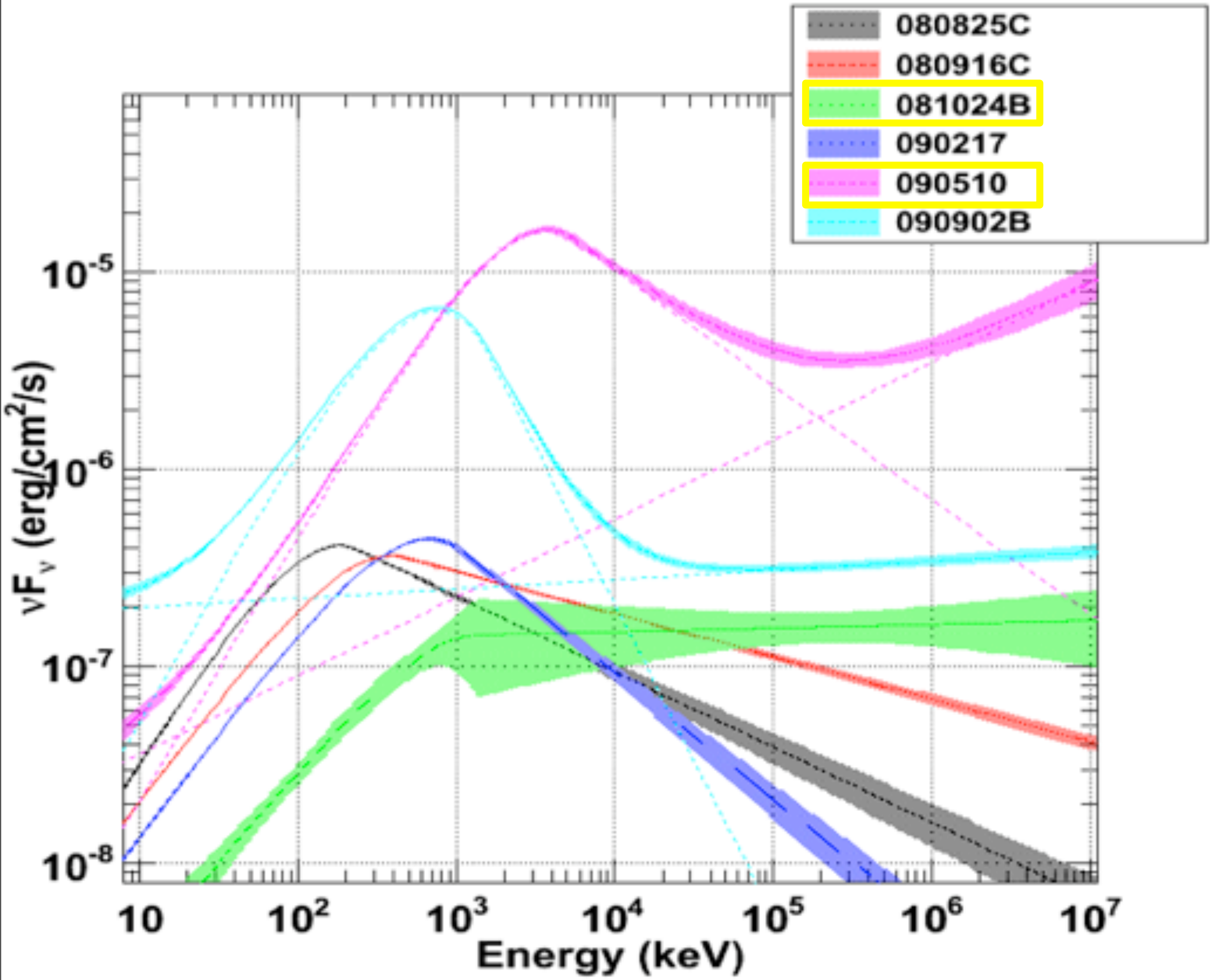
Constraints on Bulk Lorentz Factor

- Large luminosity and short variability time imply large optical depth due to $\gamma\gamma \to e^+e^-$
  - Small emission region: $R \sim c\Delta t$
  - $\tau_{\gamma\gamma}(E) \sim (11/180)\sigma_T N_{>1/E}/4\pi R^2$
    - $\tau_{\gamma\gamma}$(1 GeV) ~ $7\mathrm{x}10^{11}$ for fluence=10^6 erg/cm^2, z=1, Δt=1 s
- Relativistic motion ($\Gamma \gg 1$) can reduce optical depth
  - Lager emission region: $R \sim \Gamma^2 c\Delta t$
  - Reduced # of target photons: $N_{>1/E} \propto \Gamma^{2\beta+2}$ (note: β ~ -2.2)
    - Blue shift of energy threshold: $E_{th} \propto \Gamma$
    - Blue shift of spectrum: $N(E) = (\Gamma E)^{\beta+1}$
  - Overall reduction of optical depth: $\Gamma^{2\beta-2} \sim \Gamma^{-6.4}$
- Possible selection bias due to large E_{iso}
- Assume common emission region for all gamma rays



Long and Short GRBs

- Long & short GRBs do not show significant difference in HE spectral properties
- Short GRBs show higher energy output in HE region than long GRBs



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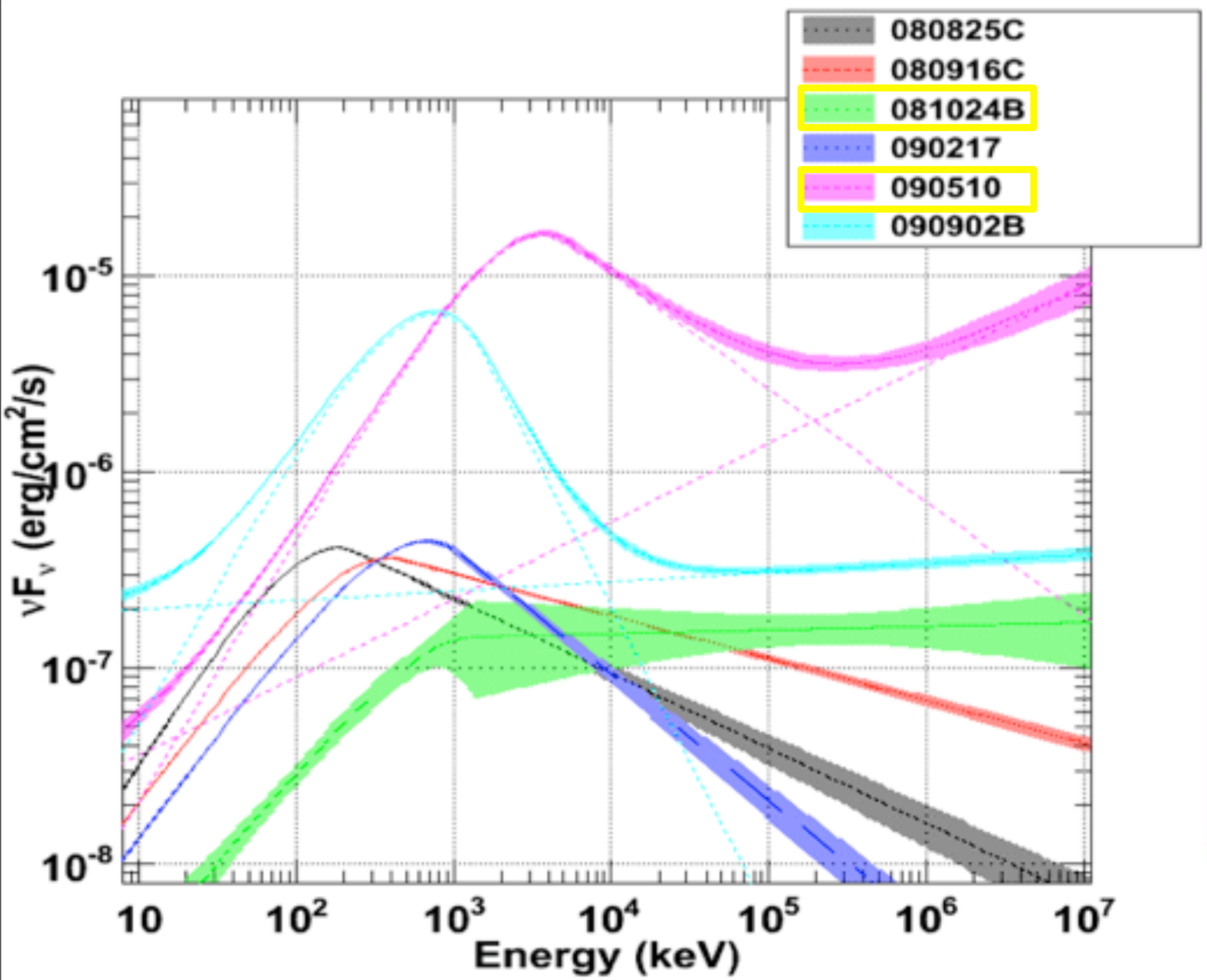
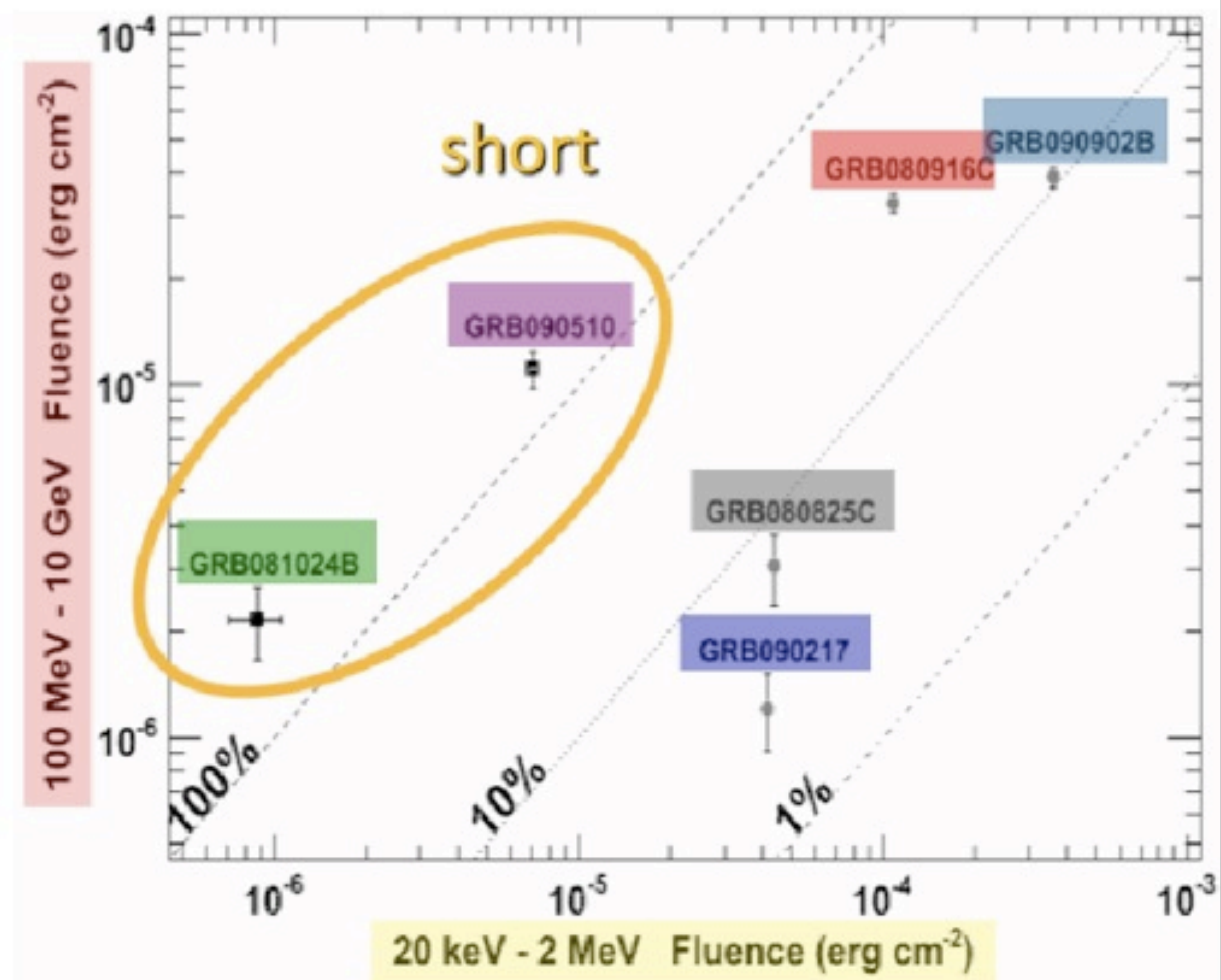
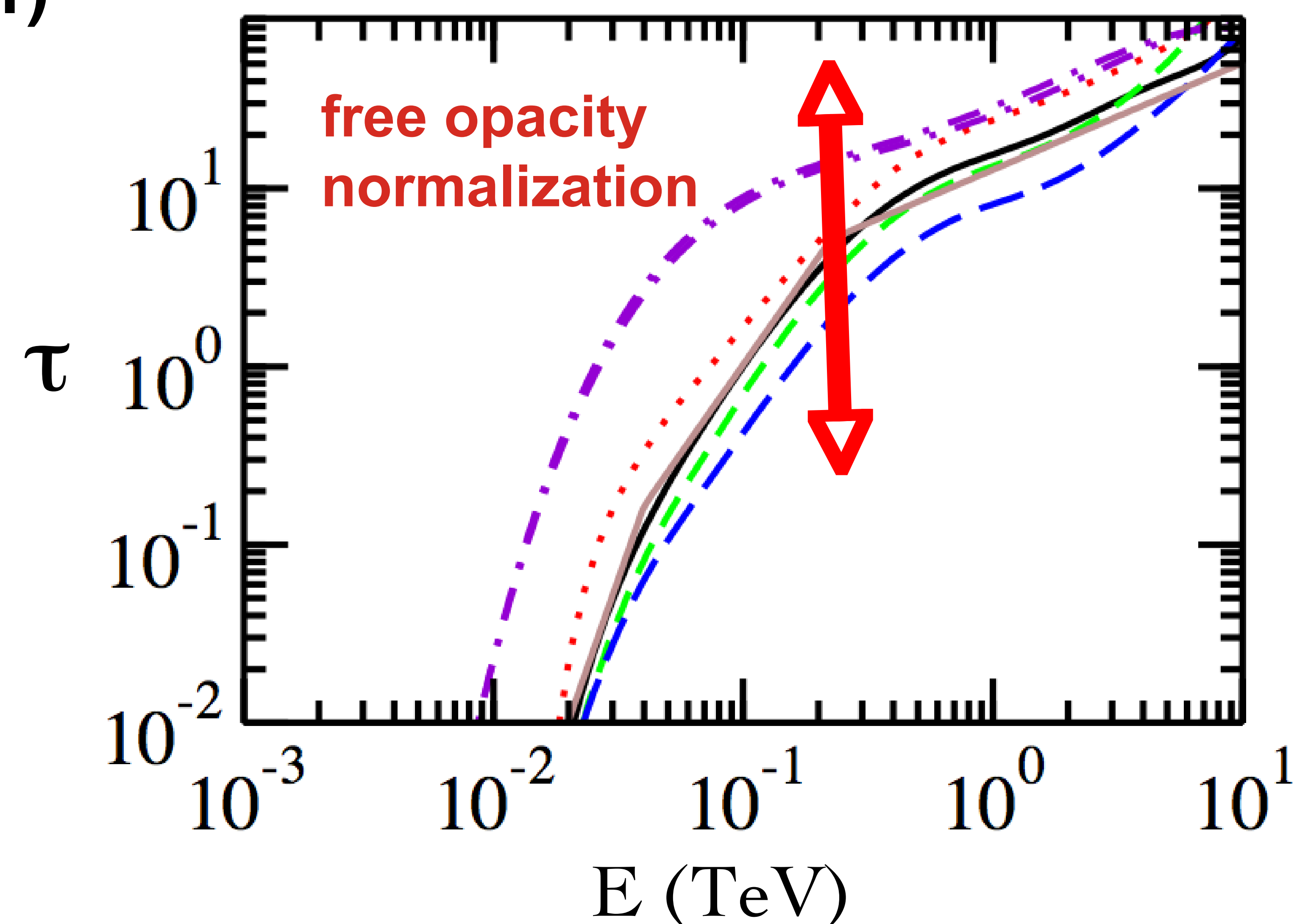




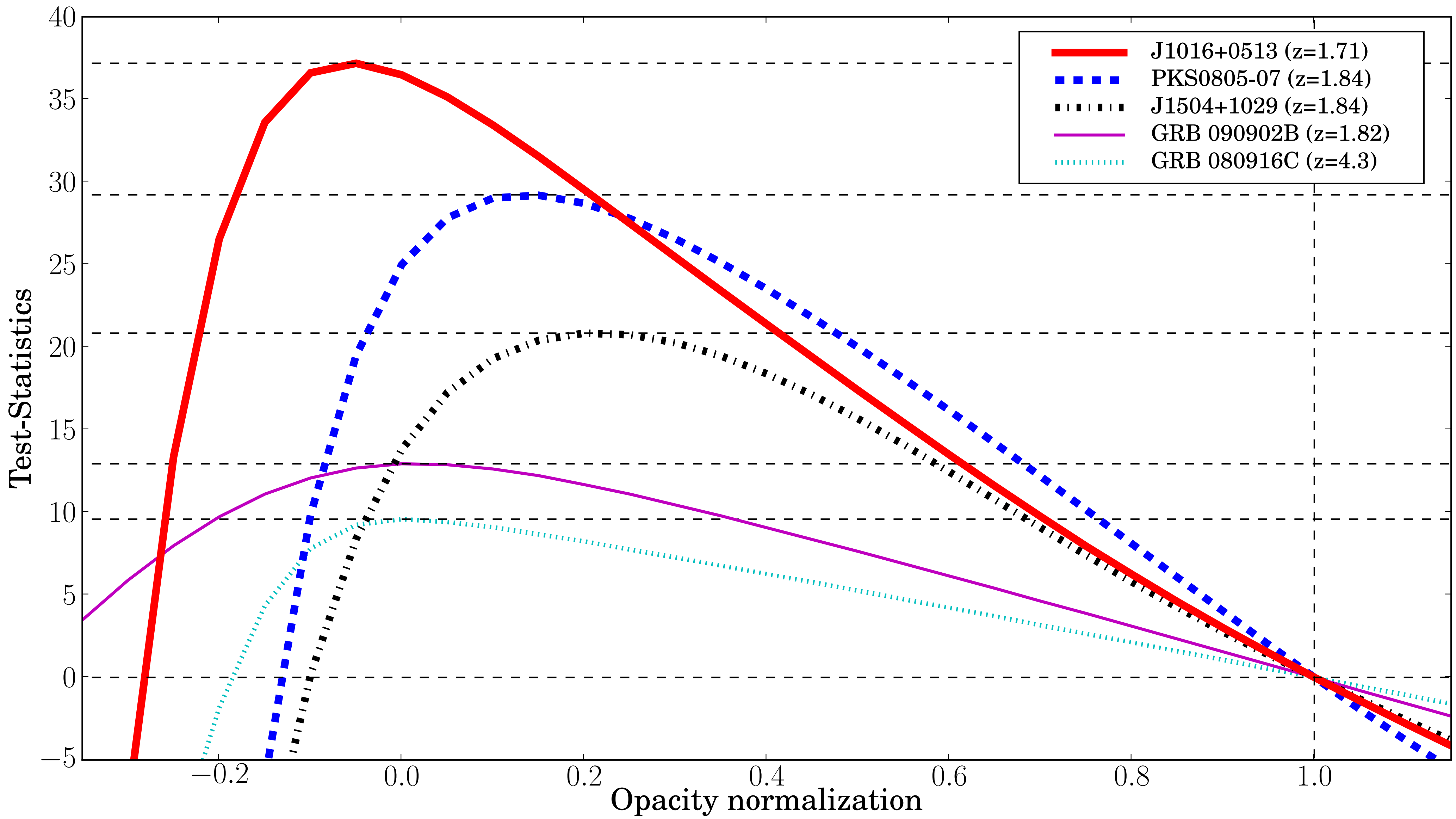
Null-Hypothesis Test with Likelihood Ratio

- Minimal assumptions: intrinsic γ-ray spectrum does not harden above ~10 GeV (conservative in case of spectral cutoff)
- Null-hypothesis (H0): [power law] + [predicted EBL]
- Alternative model (H1): EBL opacity normalization left as a free parameter
- Test-Statistics = L(H0)/L(H1)



Constraints on EBL Models

- Stecker's "baseline" and "fast evolution" models are rejected
  - > 5σ post-trial significance for 1 source (J1016+0513)
  - > 10σ significance with stacking analysis
- Other models cannot be constrained significantly



CTA Tentative Schedule