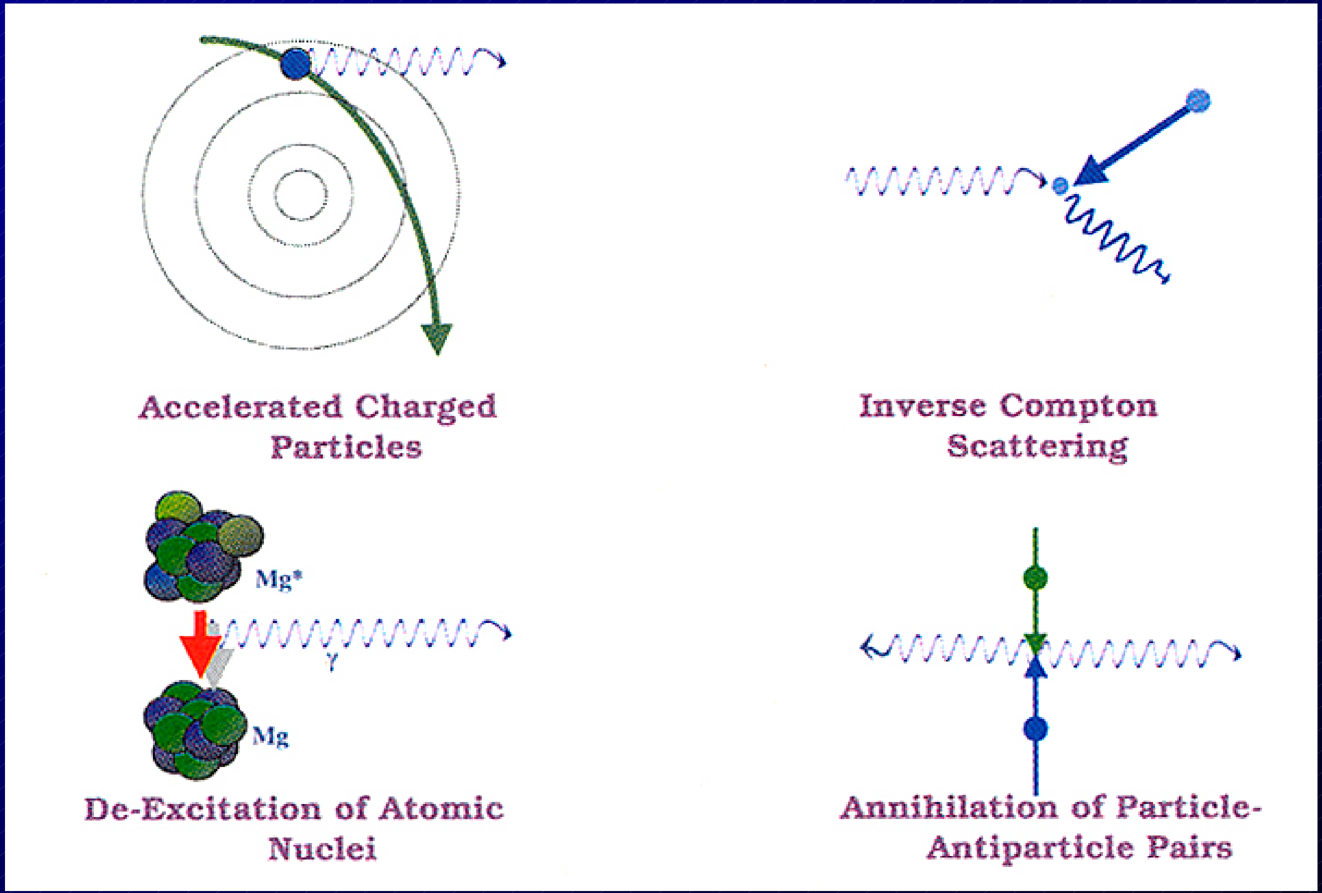
Gamma-Ray Astrophysics

Gamma-Ray Astrophysics Science Topics
Experiments in Gamma-Ray Astronomy
MPE and Gamma-Ray Astrophysics

Roland Diehl
MPE Garching

Gamma-Ray Astrophysics: Basic Processes

- Physical Source Processes at keV…GeV:



Accelerated Charged Particles

Inverse Compton Scattering

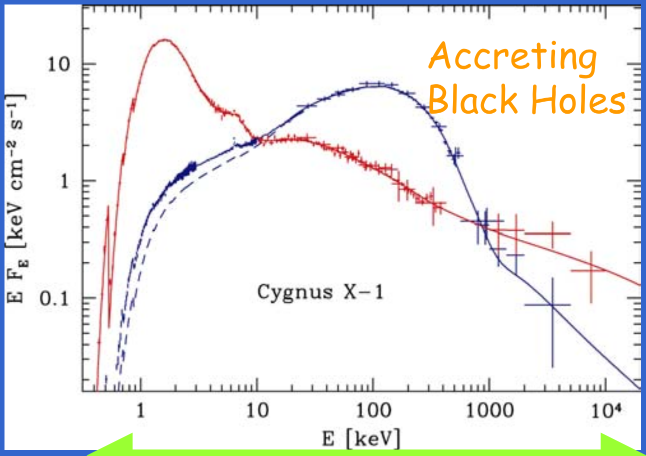
De-Excitation of Atomic Nuclei

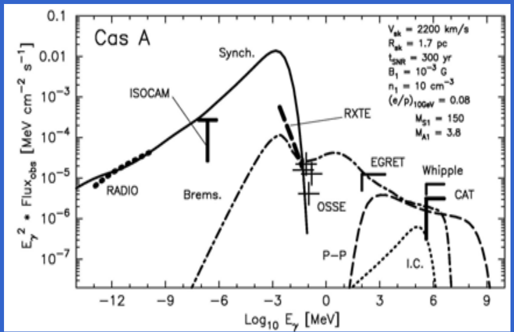
Annihilation of Particle-Antiparticle Pairs

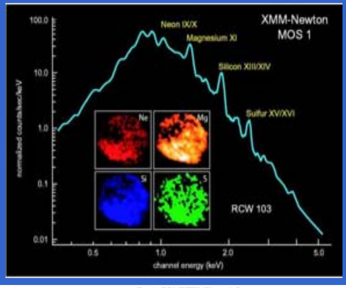
Typical Gamma-Ray Sources

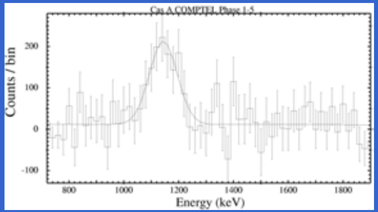
- Observational Access to Physical Processes in Gamma-Ray Sources
  - ☆ Bremsstrahlung
  - ☆ Comptonized Emission
  - ☆ Line Radiation (atomic & nuclear)

☞ Satellite-Exclusive Access: ⟷

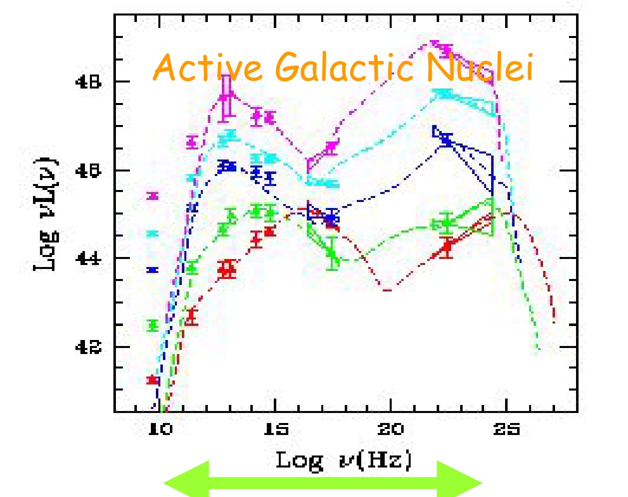








Supernova
Remnants

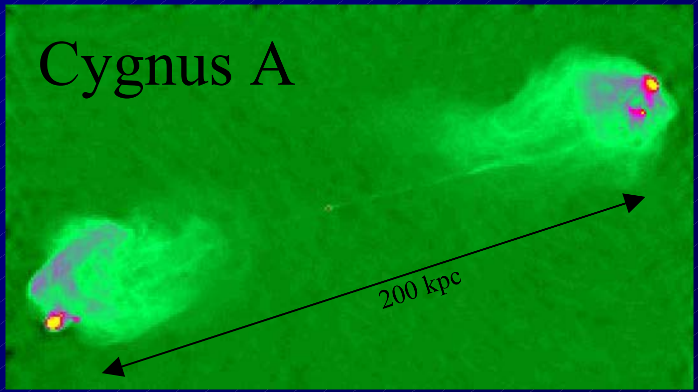


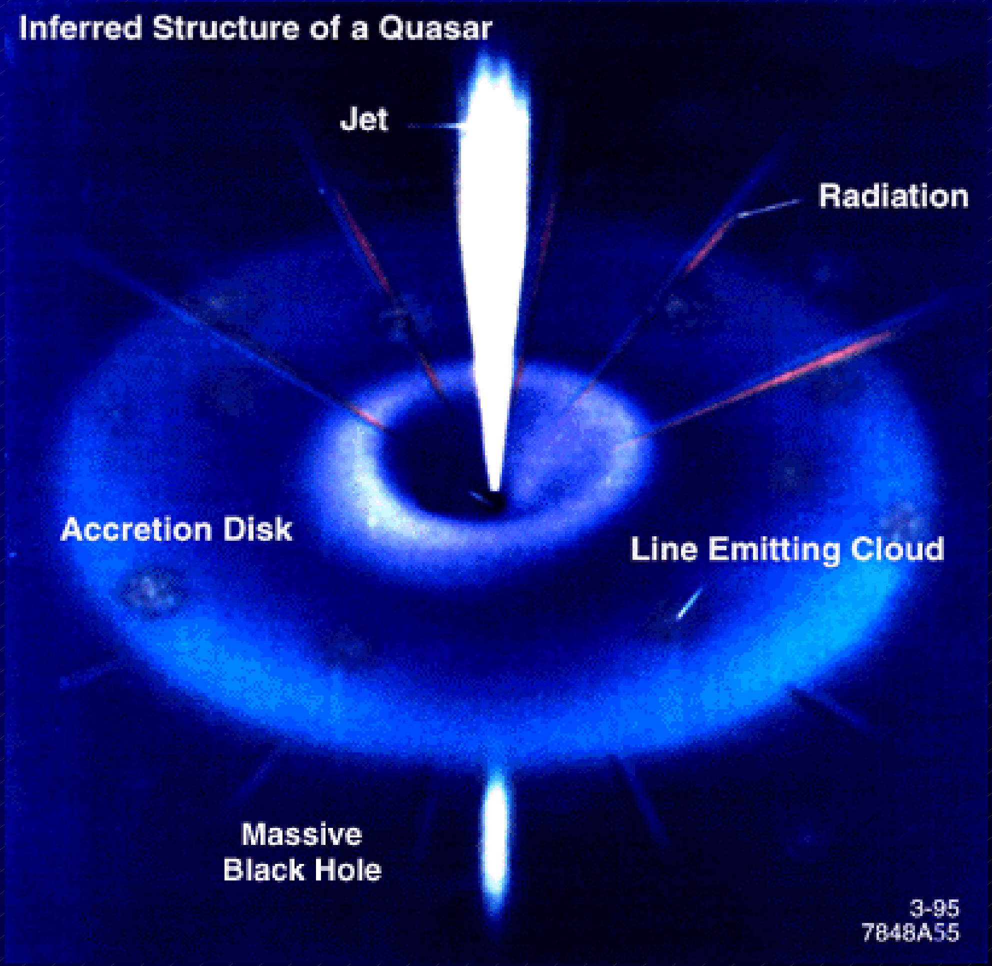
Cosmic Objects Studied in Gamma-Rays

- Active Galaxies
  - ☞ Gamma-Ray Blazars: Relativistic Plasma Jets
- Pulsars
  - ☞ 6 Gamma-Ray Pulsars
- Accreting Binaries
  - ☞ X-Ray Binaries…-> BH Candidates
- Supernovae, Novae
  - ☞ Radioactivity & Nucleosynthesis, Accelerated Particles
- Diffuse Galactic Emission, ISM
  - ☞ Cosmic Ray Sources and Propagation
  - ☞ High-Energy (nuclear) Collisions
  - ☞ Radioactivity and Galactic Nucleosynthesis

Accretion and Accelerated Plasma Jets: Quasars

- ☆ Supermassive Black Hole Accretion
  - ☞ Large-Scale Accretion Flows
  - ☞ Accretion Luminosity Interaction with Surrounding (Structured) Interstellar Matter
  - ☞ Large-Scale Plasma Jet

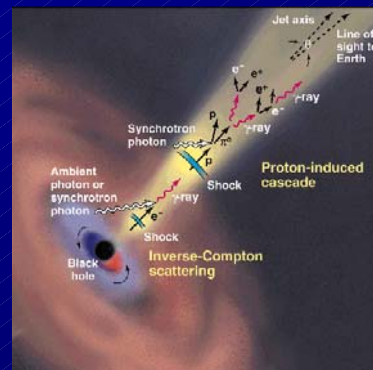


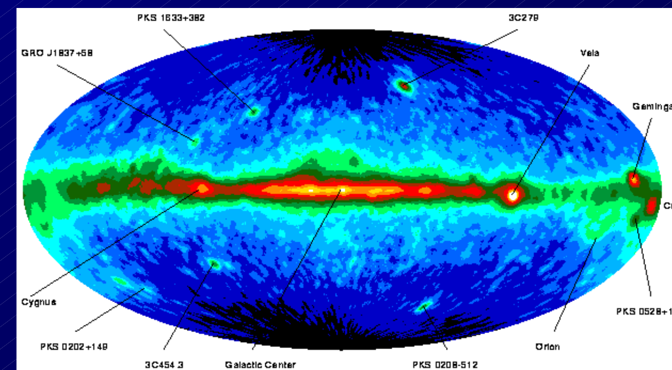


Gamma-Ray Jets from Galactic Nuclei

AGN='known' Sources of HE Plasma Jet

- ☆ …but Spectral Cutoffs at ~100 keV Energies
- ☆ AGN Classes: Viewing Angle and Source Occultation





Gamma-Ray Blazars

- ☆ Discovered with CGRO/EGRET (Hartmann et al. 1992)
- ☆ ~100 MeV Emission Dominates (10^* any other ν Band)
- ☆ Flaring / Variability
- ☆ ~100 Sources

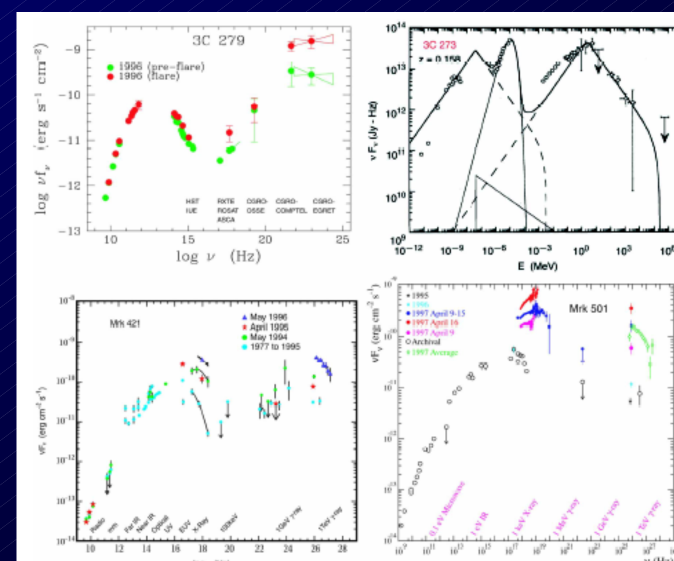
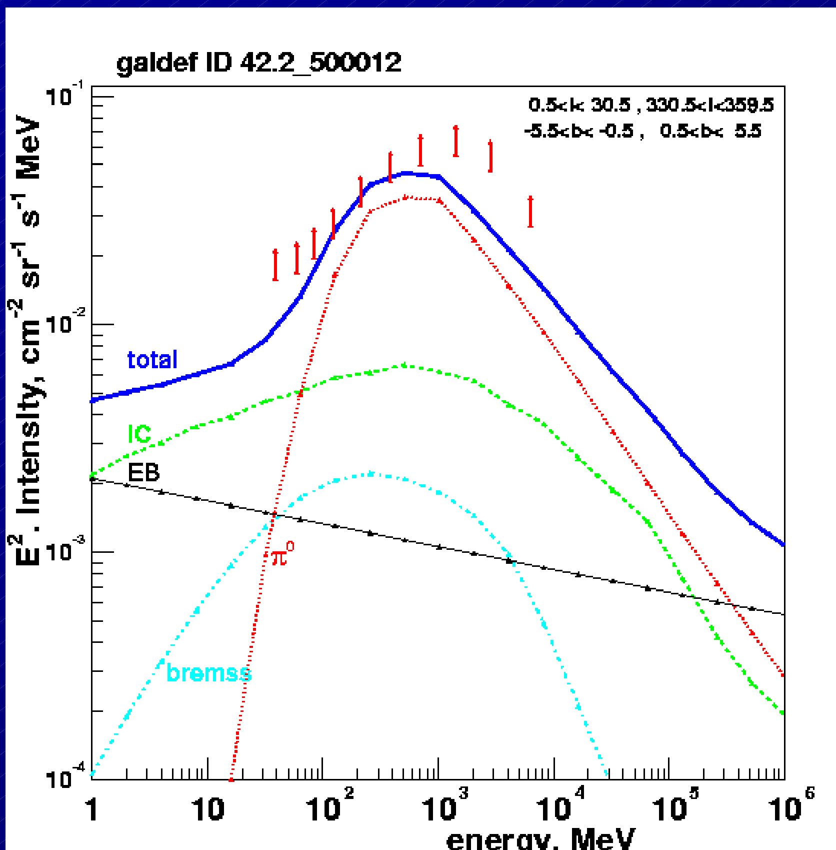


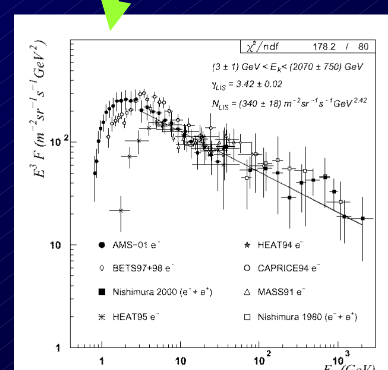
Figure 3-1 Spectral energy distributions of the quasars 3C 279 (top-left) and 3C 273 (top-right), the BL Lac object Mrk 421 (bottom-left), and the XBL Mrk 501 (bottom-right) at various epochs. Note the dominance of the gamma-ray flux in 3C 279 during the flaring state.

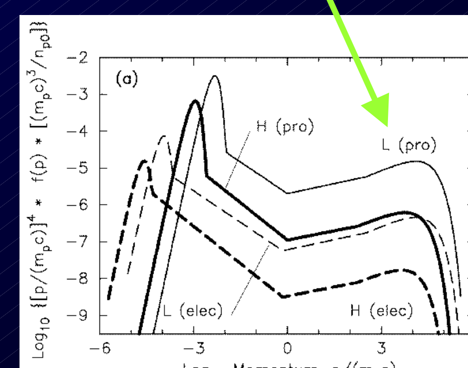
Relativistic Particles & Diffuse γ Emission



Strong, Moskalenko, Reimer 2003

- **Diffuse γ-ray Emission**
  - ☆ e^- Scattering on Starlight, CMB
  - ☆ e^- Bremsstrahlung
  - ☆ π^0 Decay (Nuclear Collisions)
- **CR e^- Spectrum Uncertain**
  - ☆ Standard -> GeV Deficit
  - ☆ Harder e^-Spectrum Helps
  - ☆ But what hardens it?
    - ☞ Nonlinear Shock Acceleration?
    - ☞ Escape from Sources?





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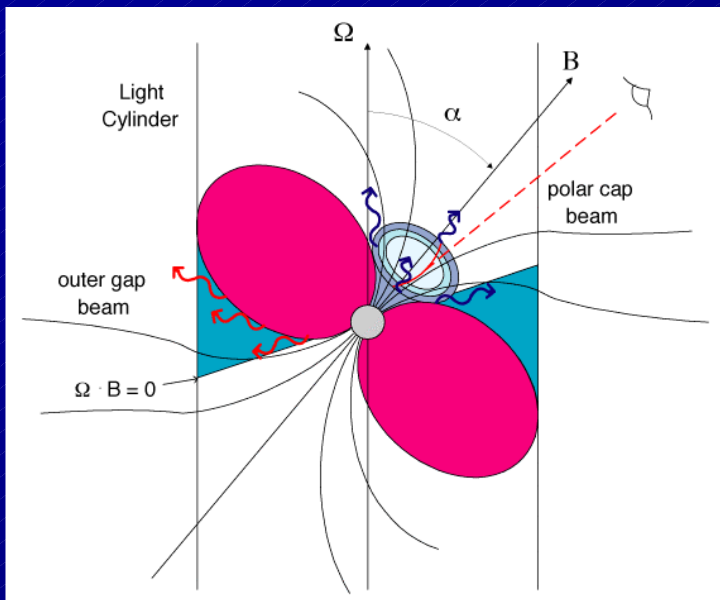
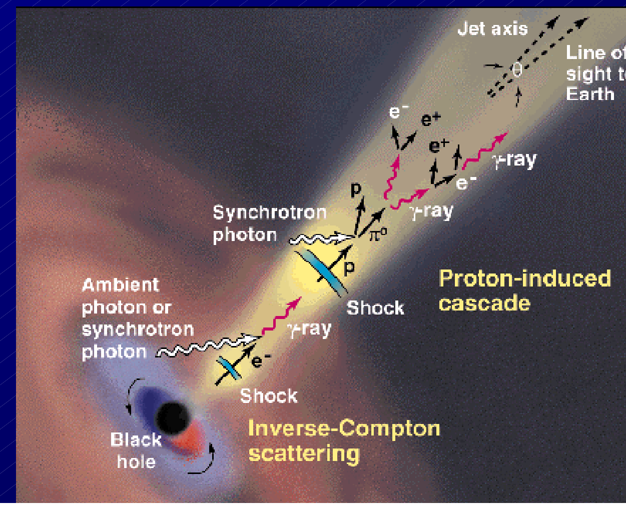
High-Energy Interactions of Cosmic Matter





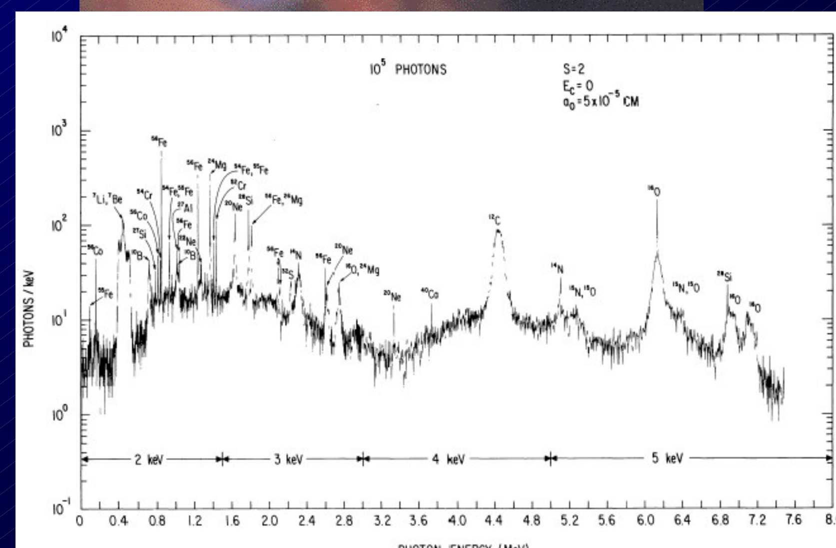
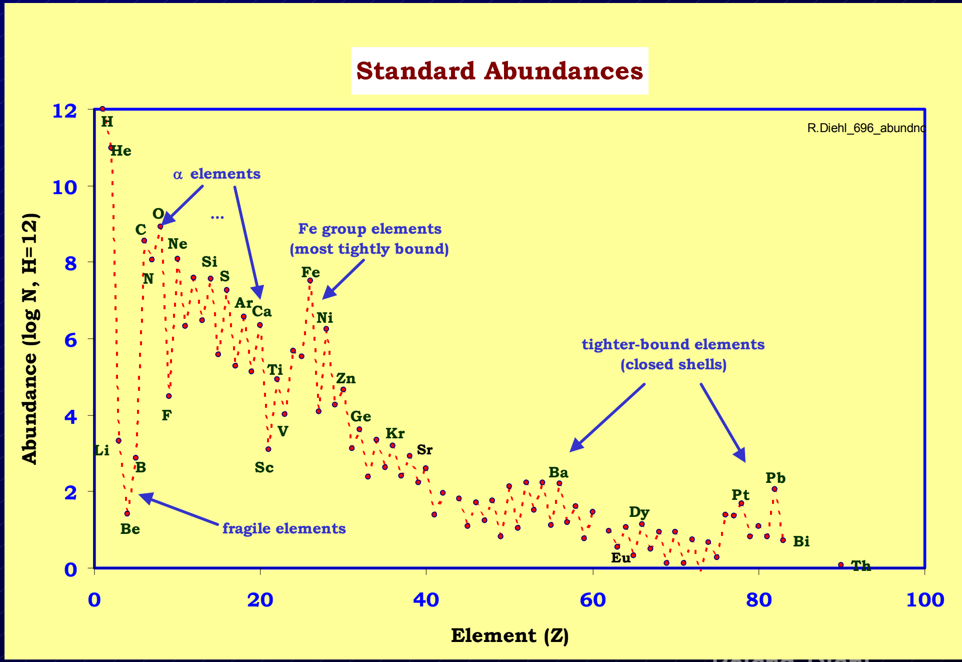


FIG. 18.—Monte Carlo simulated γ-ray spectrum for energetic particles and ambient medium having solar compositions; s and E_c are the spectral parameters of the energetic particles, and a_0 is the characteristic radius of the interstellar grain distribution.

- Relativistic Particles Interact with:
  - Electromagnetic Fields
    - Curvature Radiation
    - Synchrotron Radiation
    - Bremsstrahlung
    - Pair Creation
  - Particles, Atoms
    - Nuclear Excitation
    - Spallation

Nucleosynthesis: Understanding Abundances

- ☆ **Observed Abundances Show Characteristic Patterns**
  - ☞ Abundances Vary Much for Light Elements uf to ~ Fe-Group, are ~Similar Order of Magnitude for Elements >65
  - ☞ H and He are by far the Most Abundant Elements
  - ☞ Li, Be, B Fall in a Deep Minimum (9 Orders of Magnitude)
  - ☞ Elements C....Ca Show Exponentially-Declining Abundances
  - ☞ There is a Abundance Clear Peak Around Fe
  - ☞ There are Two Local Peaks Around Ba and Pb
- ☆ **Nuclear Processes / Reactions "Connect" Neighbouring Isotopes (Reactions –> n, p, or α capture or stripping) =>**
  - ☞ Big-Bang Nucleosynthesis Formed H and He
  - ☞ Nuclear Equilibrium Burning Formed Fe Elements
  - ☞ An "α-Process" Plays a Leading Role for Elements C...Ca
  - ☞ Elements Heavier Than Fe Formed from Fe Elements



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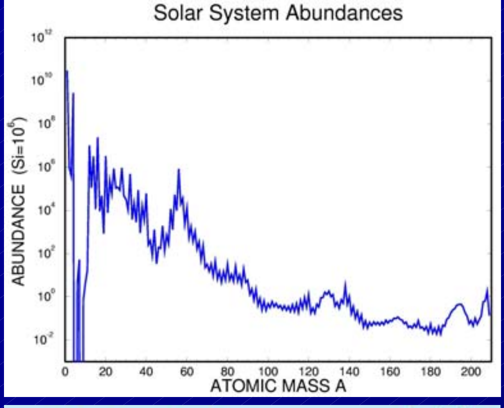
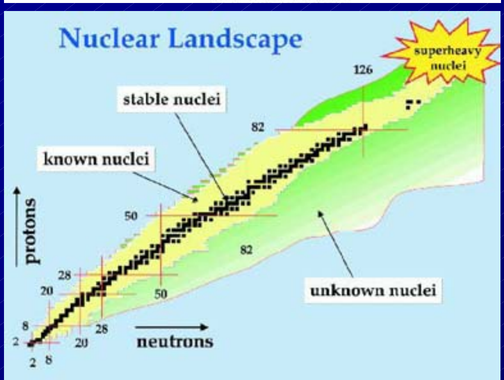
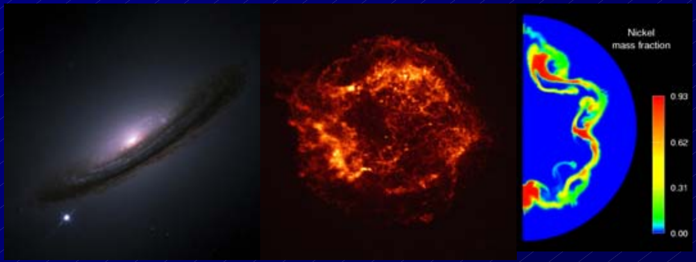
Cosmic Nucleosynthesis: The Issues





- **Nuclear Structure, Nucleon Interactions**
  - ☞ Coulomb Repulsion versus Strong Interaction
  - ☞ Collective Interactions, Clusters
- **Reaction Path far from Stability**
  - ☞ No Data from Nuclear-Physics Experiments
  - ☞ Lessons on Nuclear Physics from Astronomy
- **Cosmic Environments of Nuclear Reactions**
  - ☆ Explosive Heating & Burning Zone Dilution
  - ☆ Longterm Evolutions in Stars (Convection) and Interstellar Medium ("chemical evolution")



- **"Nuclear Astrophysics"**

Gamma-Ray Astronomy: Lines of Interest

Radioactive Isotopes

- Decay Time > Source Dilution Time
- Yields > Instrumental Sensitivities

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^*$	478
^{56}Ni	111 d	$^{56}Ni \rightarrow {}^{56}Co^* \rightarrow {}^{56}Fe^* + e^+$	158, 812; 847, 1238
^{57}Ni	390 d	$^{57}Co \rightarrow {}^{57}Fe^*$	122
^{22}Na	3.8 y	$^{22}Na \rightarrow {}^{22}Ne^* + e^+$	1275
^{44}Ti	89 y	$^{44}Ti \rightarrow {}^{44}Sc^* \rightarrow {}^{44}Ca^* + e^+$	78, 68; 1157
^{26}Al	$1.04\ 10^6$y	$^{26}Al \rightarrow {}^{26}Mg^* + e^+$	1809
^{60}Fe	$2.0\ 10^6$y	$^{60}Fe \rightarrow {}^{60}Co^* \rightarrow {}^{60}Ni^*$	59, 1173, 1332
e^+	…. 10^5y	$e^+ + e^- \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511

Nucleosynthesis Study with Gamma-Rays

Isotope	Mean Lifetime	Decay Chain	γ -Ray Energy (keV)
^{7}Be	77 d	$^{7}Be \rightarrow {}^{7}Li^{*}$	478
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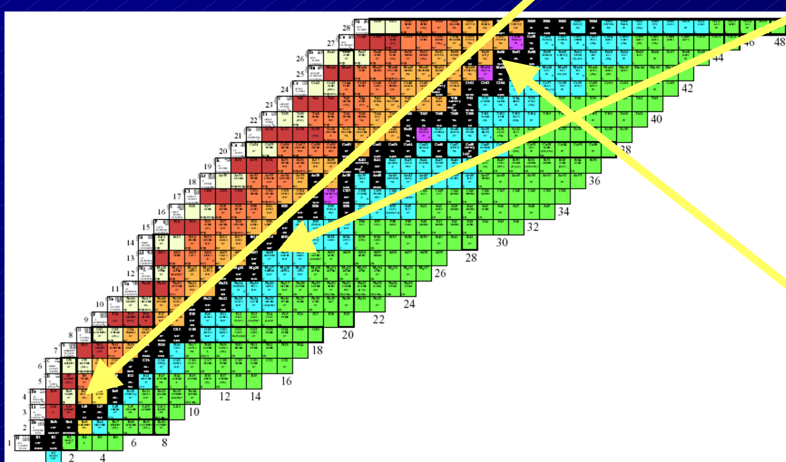
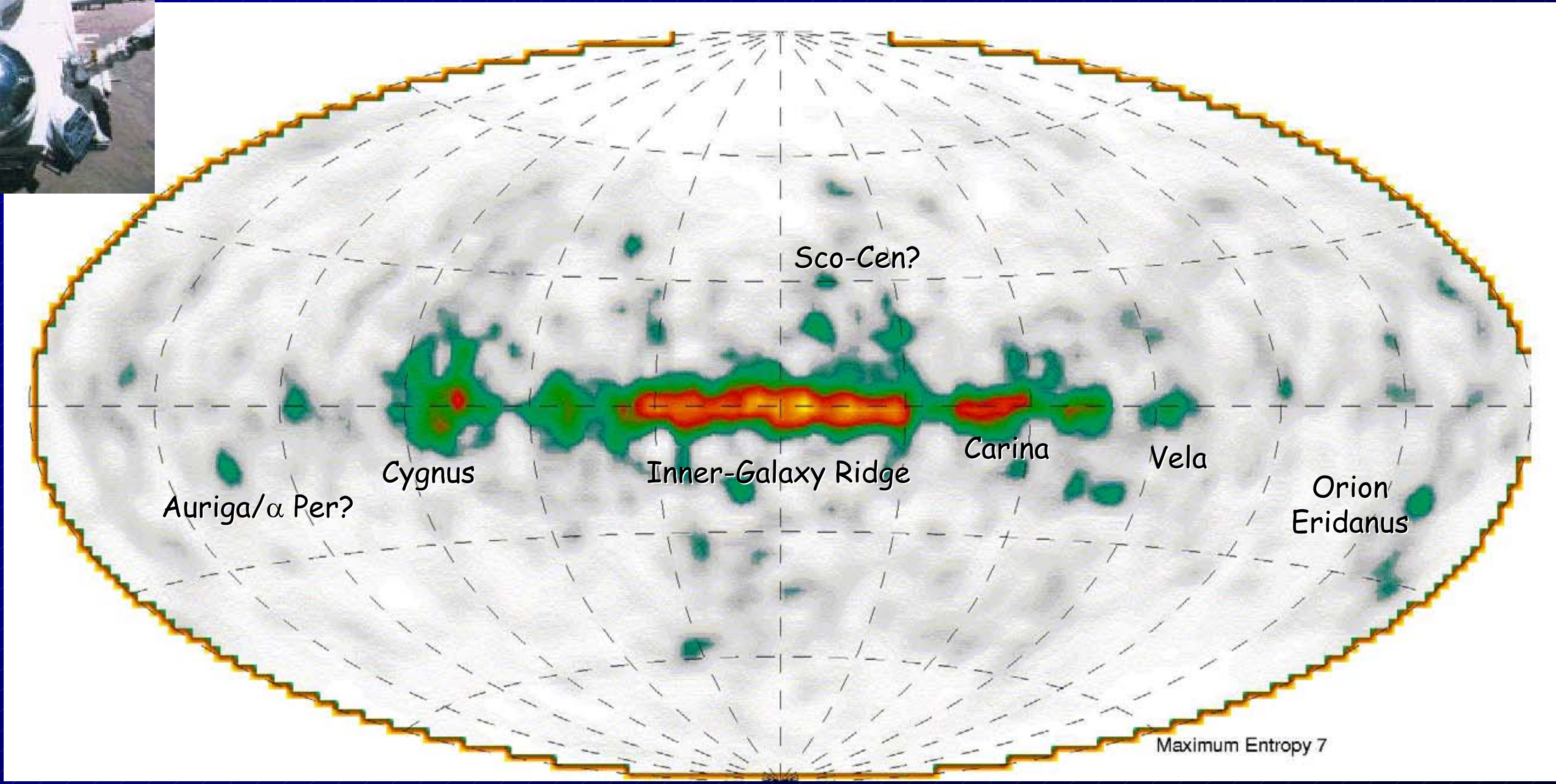
e^{+}	.... 10^{5}y	$e^{+}+e^{-} \rightarrow Ps \rightarrow \gamma\gamma$..	511, <511



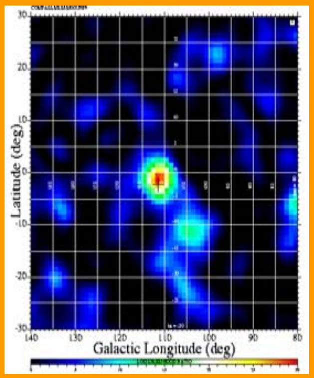
- 511 keV, ^{7}Be -> Novae
  -> p-Captures, β^{+} Decays
  -> ^{19}F Production...
- ^{26}Al -> Reaaction Path Details in Stars/SNe, ν-Process
  -> Metal/Fe Ratio, Si/Fe
- ^{44}Ti, ^{56}Ni -> Most Stable Isotopes
  $^{56}Ni/^{4}He$, Freeze-Out of NSE
  -> Metal/Fe Ratio, Heavies/Fe

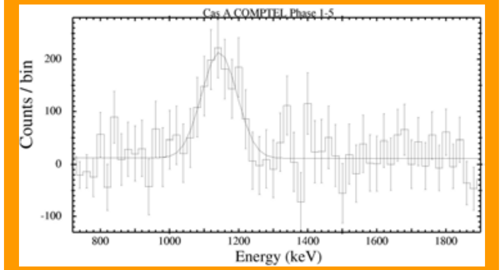
The Sky at 1809 keV: ^{26}Al

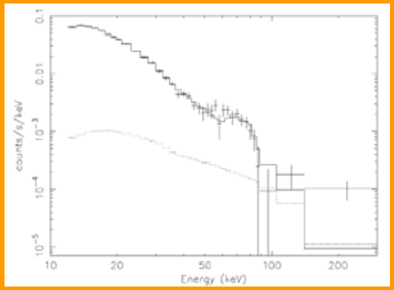


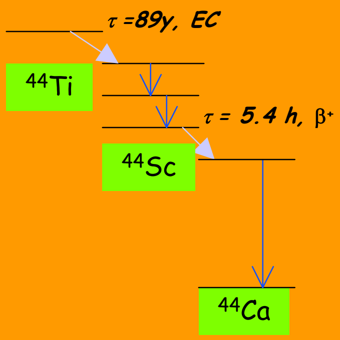
Complete CGRO Mission
(Plüschke et al. 2001)

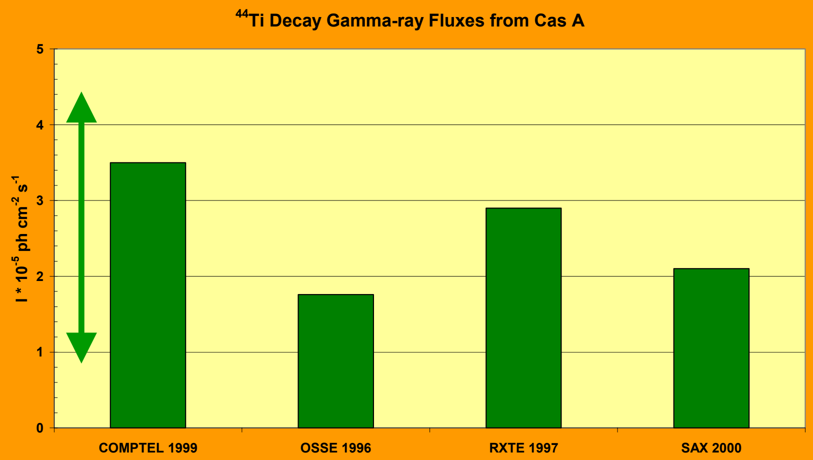
Core-Collapse Supernovae: ^{44}Ti from Cas A

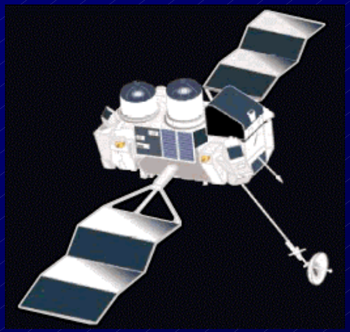


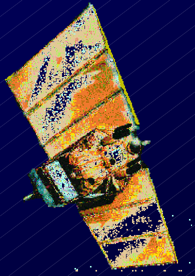












- ^{44}Ti Decay: τ~89y -> Young SNR
- Difficult γ-Ray Region (78, 68, 1157 keV) -> Uncertain Iγ

-> ^{44}Ti Ejected Mass ~0.8-2.5 10^{-4} M_o

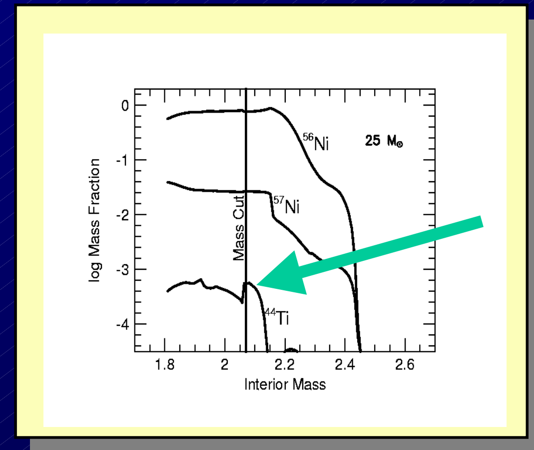
^{44}Ti Emission from cc-SNae: Open Issues

Consistency of Cas A cc-SN Model:

- ☆ ^{44}Ti Yield in Models: ~2-4 10^{-5} M_o
- ☆ ^{44}Ti Ejection Should Be Correlated to
  - High-Entropy Material -> a-Rich Freeze-Out
  - Large Explosion Energy
  - Large Mass of Ejected ^{56}Ni (Bright Supernova)

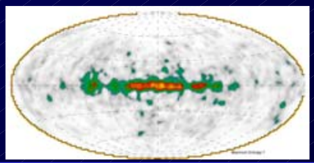
->

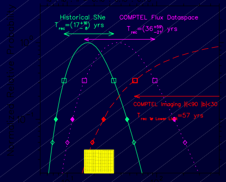
- ☆ How Peculiar a cc-SN is Cas A?
- ☆ ^{44}Ti Only From Polar Regions of Accreting Collapse?



No ^{44}Ti Sources in Inner Galaxy

- ☆ Small-Number Statistics? Observational Bias?
- ☆ Metallicity Anticorrelation?

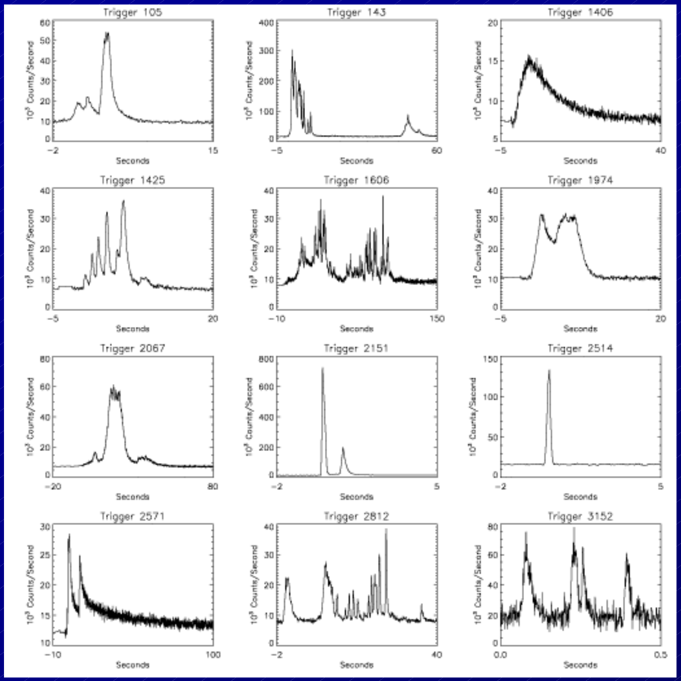


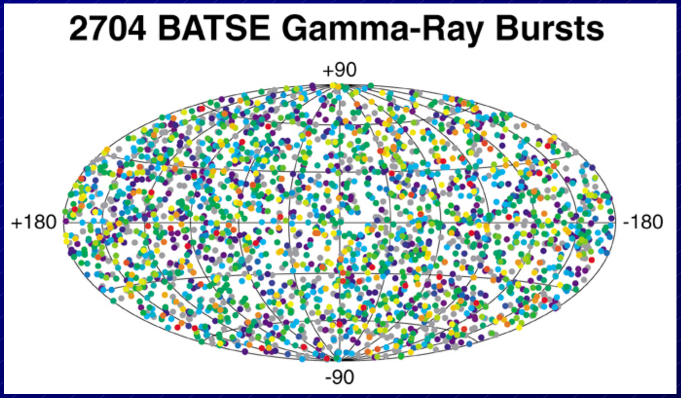


Can ^{44}Ti Sources Reveal...

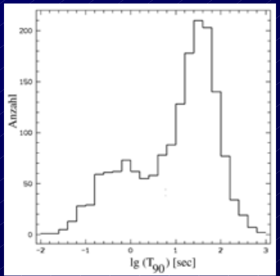
- ☆ Inner SN Velocity Profiles? Ionization-Inhibited Decay (EC)? (^{44}Ti Line Shape!)
- ☆ Asymmetric Core Collapses? Hypernovae?

Gamma-Ray Bursts

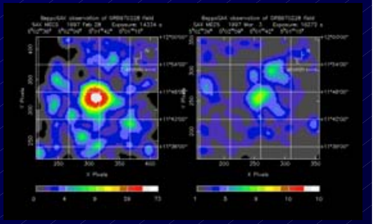


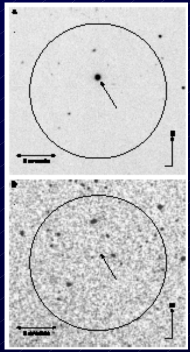


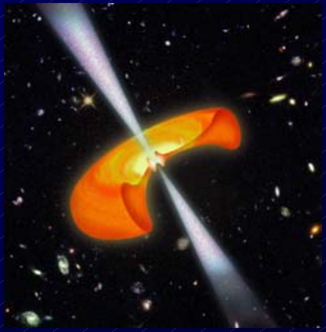
- GRB Obs ->
  - Very Energetic Flashes (>SN)
  - Isotropic but Confined
  - Time Profile Variety (short; long)

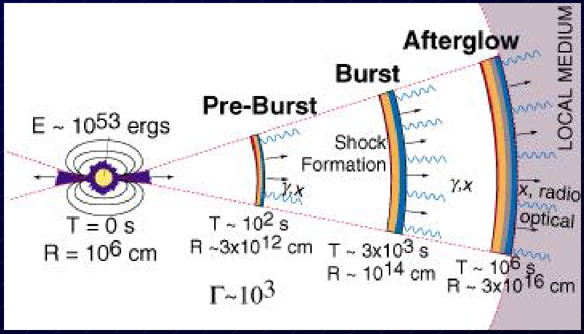


- Afterglows ->
  - Jets, ~"rSNR"
  - Massive Stars





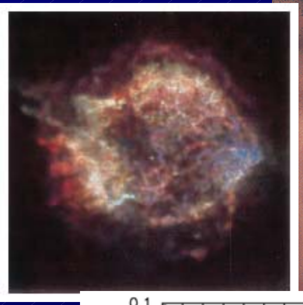


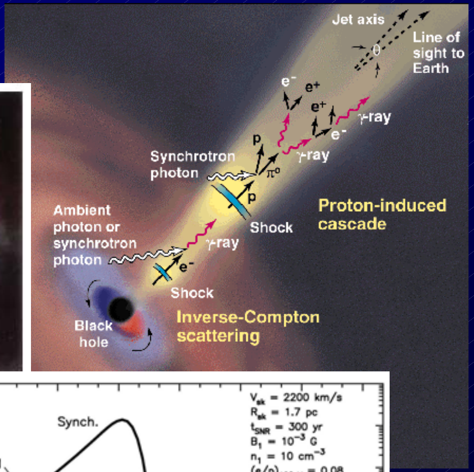


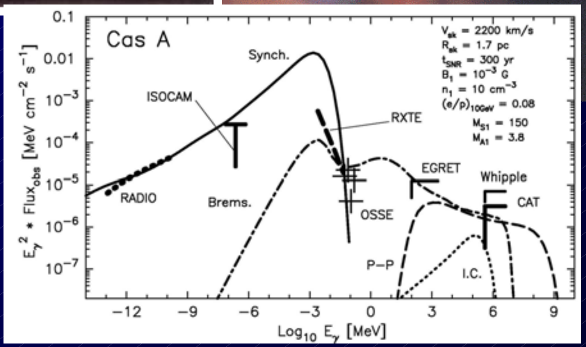
Astrophysics Topics for Space γ-Astronomy

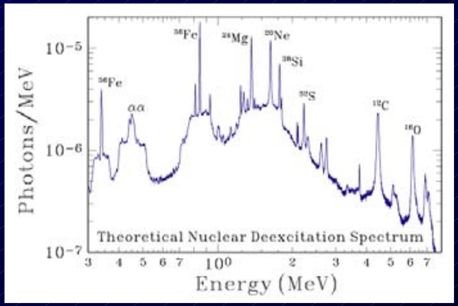
- **Relativistic Astrophysics**
  - ☆ Hot Plasma Emission
  - ☆ Non-Thermal Emission Processes
  - ☆ Acceleration of Particles

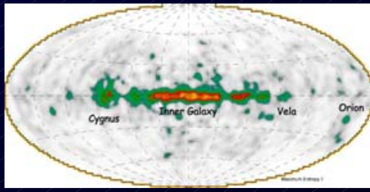
- **Nuclear Astrophysics**
  - ☆ Energetic Collisions
  - ☆ Radioactivity / Nucleosynthesis











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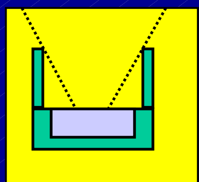
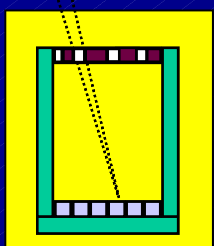
Gamma-Ray Astronomy: Instruments

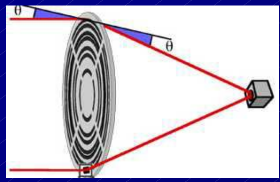
Photon Counters and Telescopes



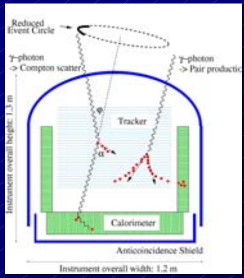
- **Simple Detector (& Collimator)**
  (e.g. HEAO-C, SMM, CGRO-OSSE)
  Spatial Resolution (=Aperture) Defined Through Shield



- **Coded Mask Telescopes**
  (Shadowing Mask & Detector Array)
  (e.g. SIGMA, INTEGRAL)
  Spatial Resolution Defined by Mask & Detector Elements Sizes



- **Focussing Telescopes**
  (Laue Lens & Detector Array)
  (CLAIRE, MAX)
  Spatial Resolution Defined by Lens Diffraction & Distance

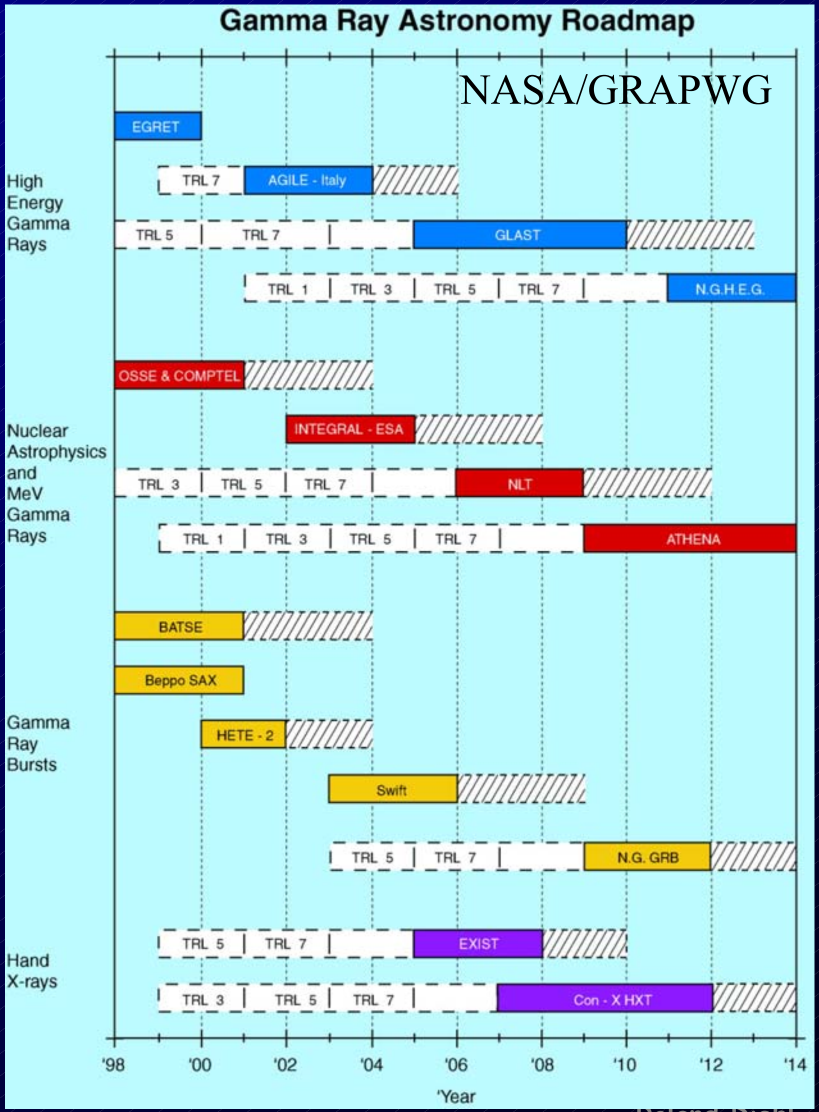


- **Compton Telescopes**
  (Coincidence-Setup of Position-Sensitive Detectors)
  (e.g. CGRO-COMPTEL, LXeGRiT, MEGA, ACS)
  Spatial Resolution Defined by Detectors' Spatial Resolution

Achieved Sensitivity: ~10^{-5} ph cm^{-2} s^{-1}, Angular Resolution ≥ deg

Satellite Astronomy with Gamma-Rays

- Different Science Targets
  -> Different Missions
  - High-Energy Gamma-Rays ~GeV
    - AGN, Gamma-Ray Blazars
    - Pulsars
    - Galactic Diffuse Emission
    - EGRET ...AGILE, GLAST
  - Medium-Energy Gamma-Rays ~MeV
    - Accreting Sources, Pulsars, AGN
    - Galactic Diffuse Emission
    - Nucleosynthesis Sources
    - COMPTEL, INTEGRAL ...MEGA, ACT
  - Low-Energy Gamma-Rays ~100keV
    - Accreting Sources
    - AGN
    - RXTE,...EXIST
  - Gamma-Ray Bursts
    - HETE-II, ...SWIFT
  - Solar Gamma-Rays
    - SMM, RHESSI



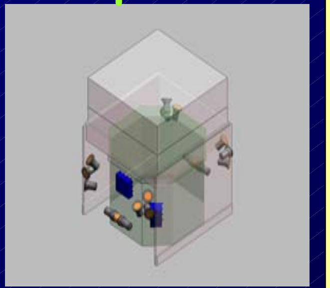
The GLAST Project

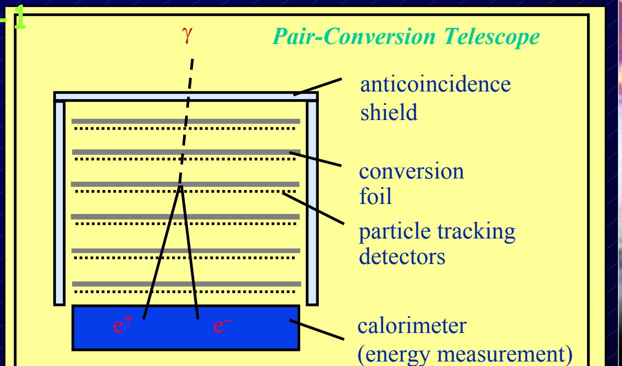
Large-Area Telescope

- 18-Plane Si Tracker, 8-Layer CsI Calorimeter
- 20 MeV-300 GeV, $\Delta E/E \sim 10\%$
- $3.5^{\circ} \ldots 0.15^{\circ}$ Resolution, 0.x' Src Location
- Sensitivity 3×10^{-9} ph $cm^{-2}s^{-1}$ (=EGRET/40)
- FoV > 2 sr

Gamma-Ray Burst Monitor

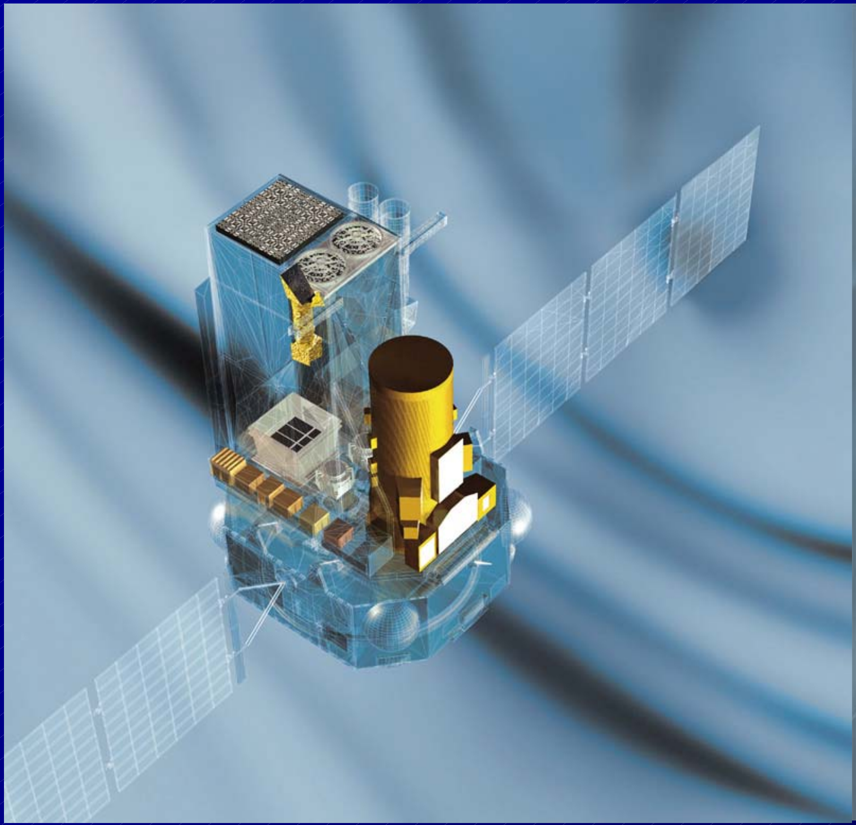
- 12 NaI, 2 BGO
  Scintillation Detectors (5”)
- 10 keV - 30 MeV
- Sensitivity 0.3 ph $cm^{-2}s^{-1}$
- FoV ~8 sr

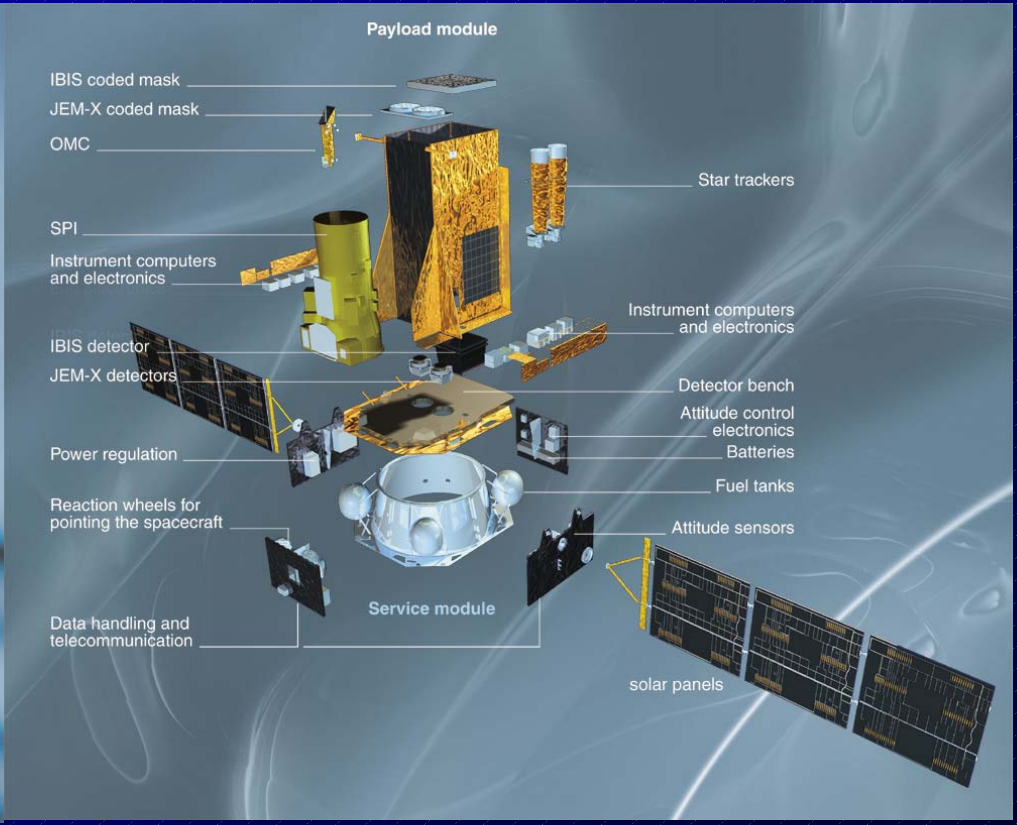




- Launch ~Sep 2006

The INTEGRAL Satellite

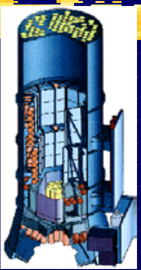




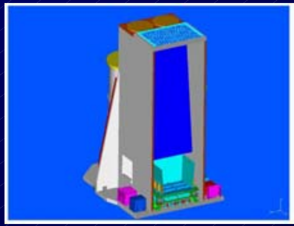
- INTErnational Gamma-Ray Astrophysics Lab
  - ☆ Spacecraft Service Module (common with XMM)
  - ☆ Two Coded-Mask Telescopes Side-by-Side
  - ☆ Monitors and Auxilliary Sensors at Periphery

INTEGRAL Scientific Payload ("Instruments")

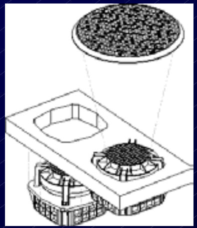
- **SPECTROMETER SPI**
  - Coded-Mask Telescope with 19-Element Ge Camera



- **IMAGER IBIS**
  - Coded-Mask Telescope with fine CdTl and CsI Camera Planes



- **X-RAY MONITOR JEM-X**
  - Coded-Mask Telescopes with Imaging Microstrip Gas Detector

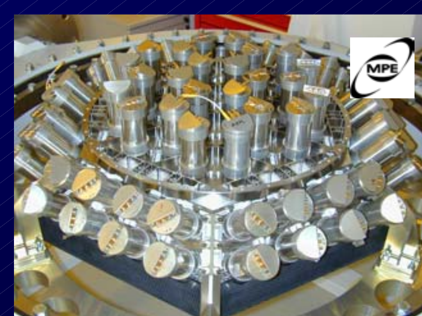


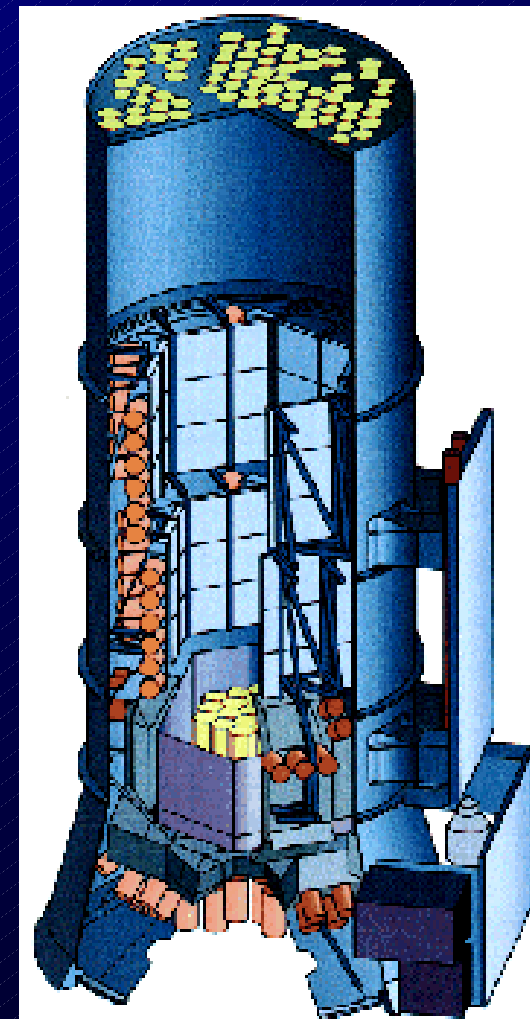
- **OPTICAL MONITORING CAMERA OMC**

- **INTEGRAL SCIENCE DATA CENTRE ISDC**

The INTEGRAL Spectrometer (SPI)

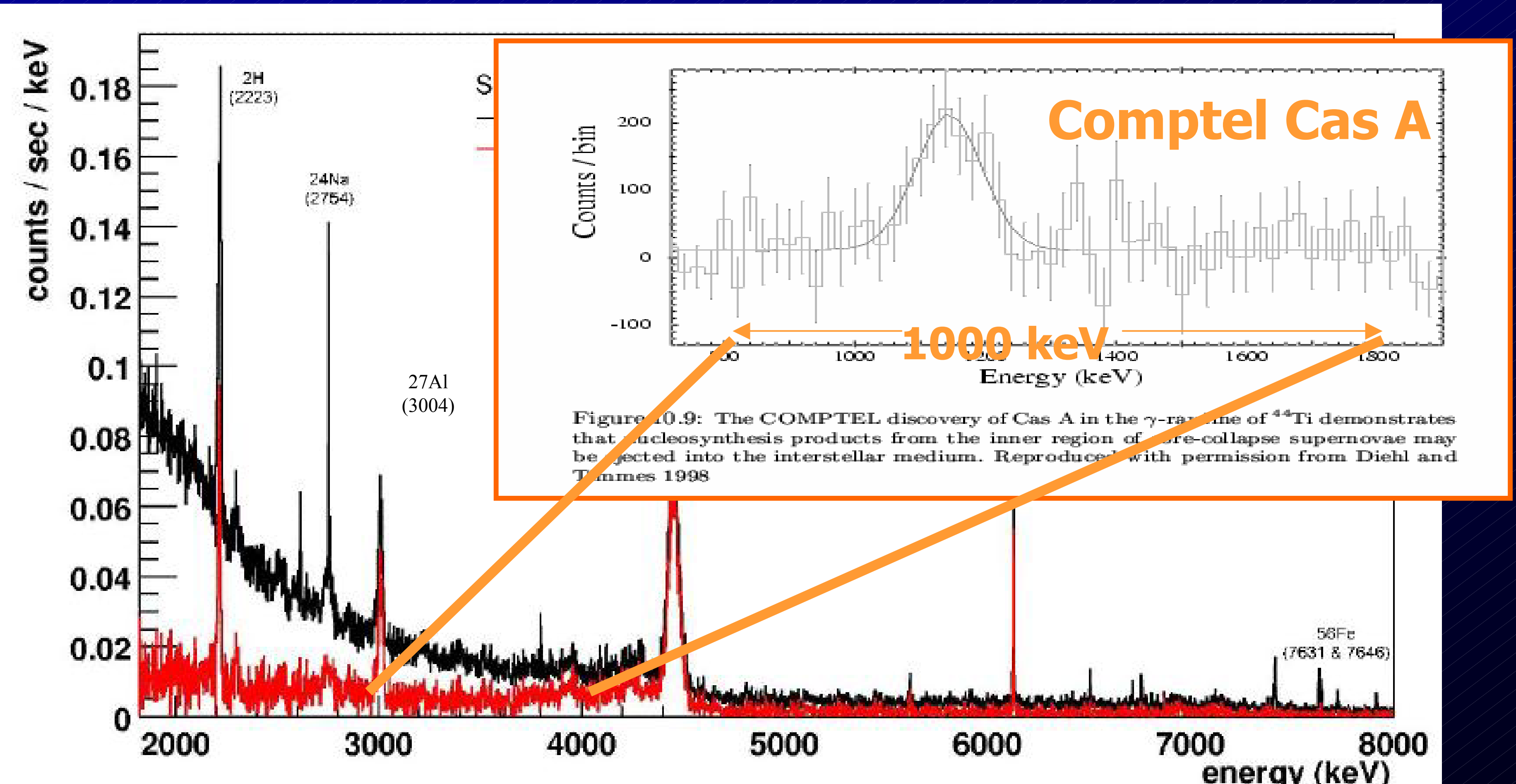
- Coded-Mask Telescope
- 19 Ge Detectors (5.5x5.5x7cm)
- BGO Anticoincidence Detector & Shield
- Stirling Cryocooler
- Energy Range 15-8000 keV
- Energy Resolution ~2.2 keV @ 662 keV
- Angular Resolution ~2 arcmin
- Field-of-View 16x16°
- Timing Resolution 52 μs





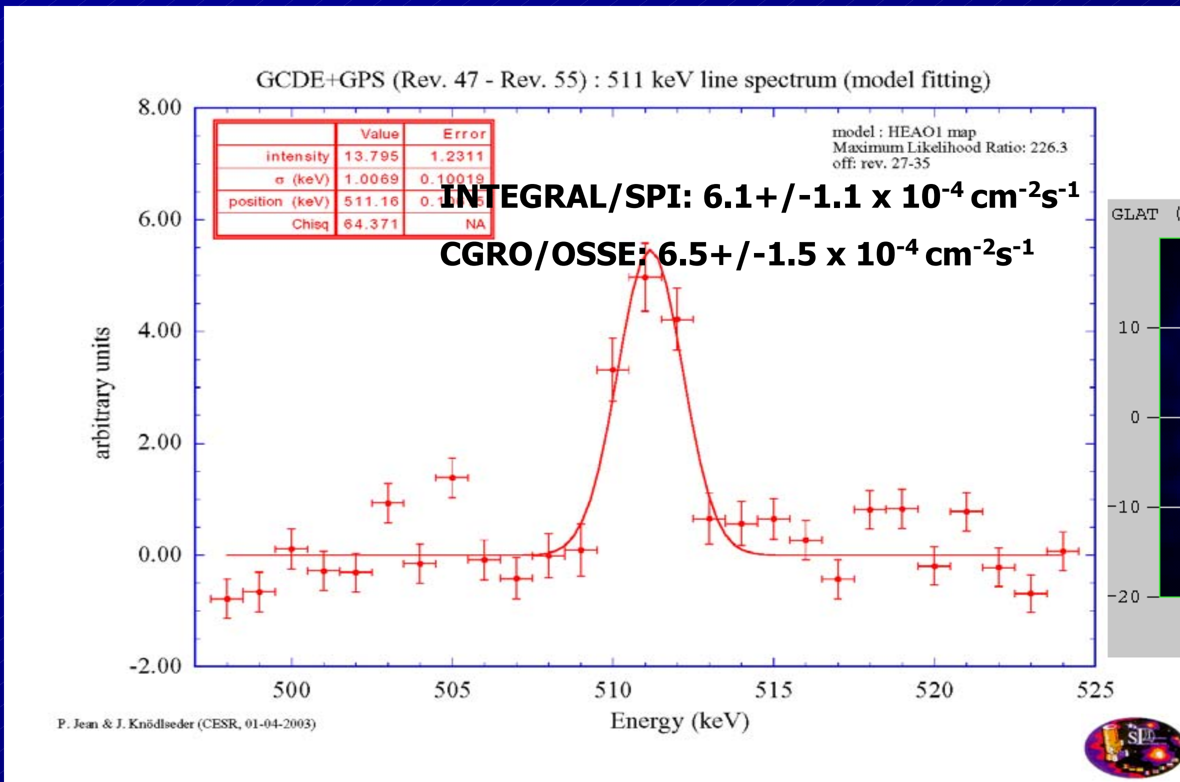
SPI: Spectroscopy in Gamma-Rays

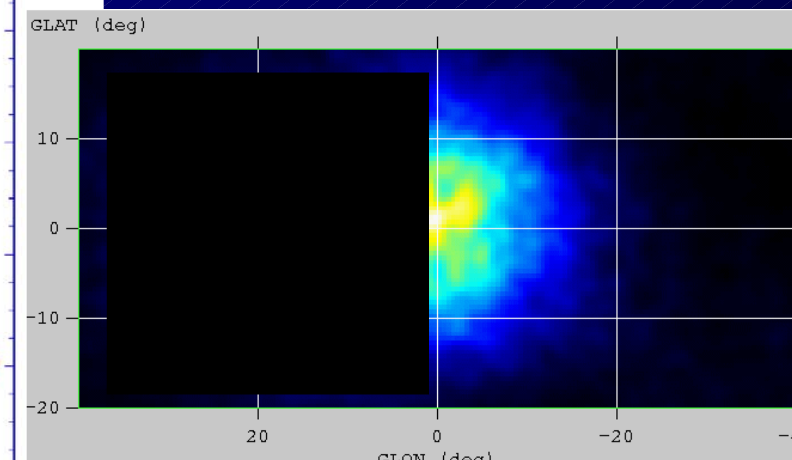
local bgd, induced by particles from solar M5 flare on 9 Nov 2002



SPI: e⁺ Annihilation in the Inner Galaxy

07/2003





Jean et al 2003
Knödlseder et al. 2003

- **Annihilation of e⁺** (from Radioactivity, Pulsars, Jet Sources…)
  - ☆ Annihilation Line at 511 keV, ~ as Expected
  - ☆ Emission Region ~Extended without Major Structure

SPI: ^{26}Al Nucleosynthesis in the Galaxy

07/2003

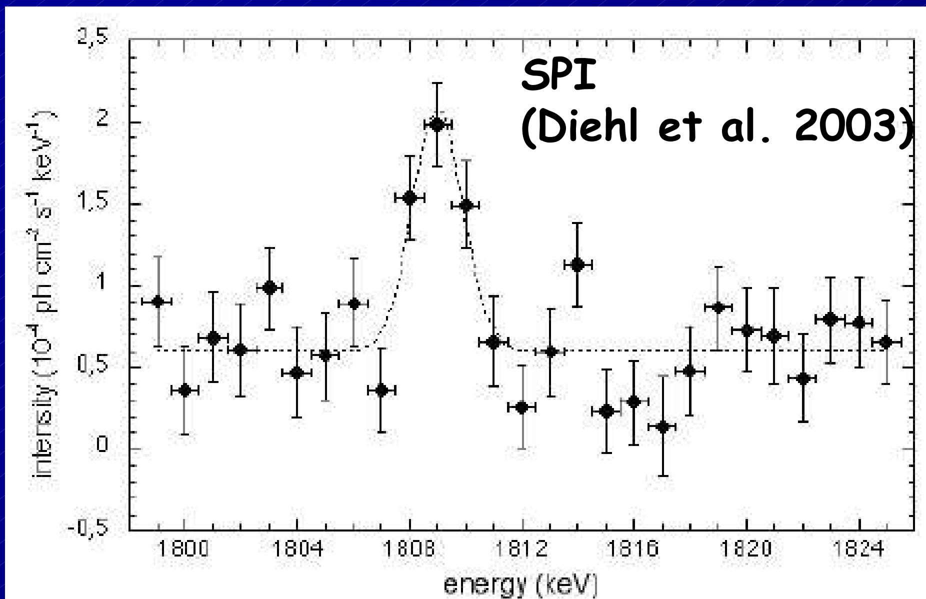
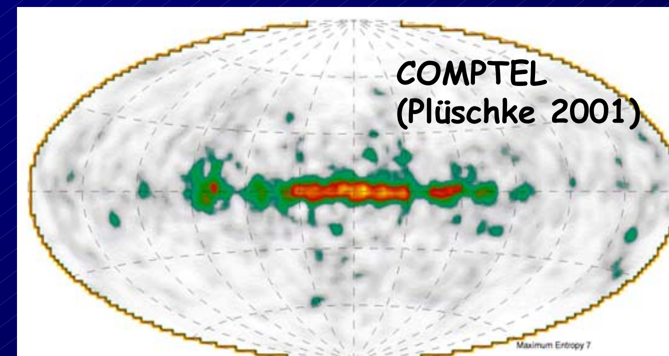
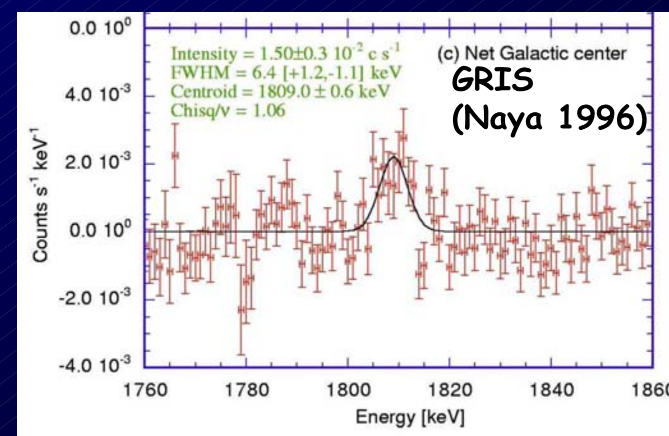


Fig. 6. Imaging analysis result from fitting a sky intensity distribution as modelled from the COMPTEL ^{26}Al skymap to each energy bin. Background was modelled from Crab observation detector ratios, and fitted in intensity to the actual measurement for each pointing, together with the sky signal.



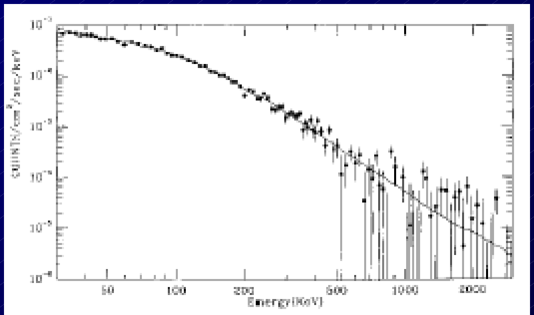


- ^{26}Al Measurement with SPI:
  - ☆ Consistent with Expectations (from COMPTEL etc.)
  - ☆ Gamma-Ray Line is Not Excessively Broadened (↯ GRIS)

Gamma-Ray Burst Instruments at MPE

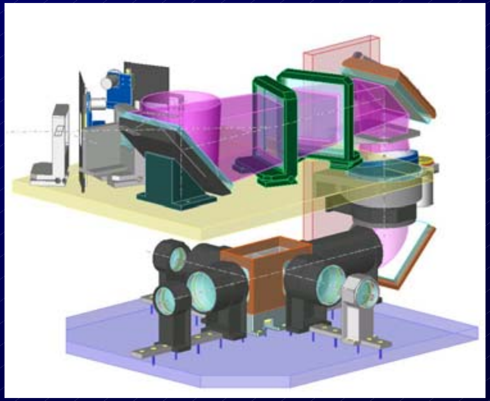
GLAST Gamma-Ray Burst Monitor "GBM"

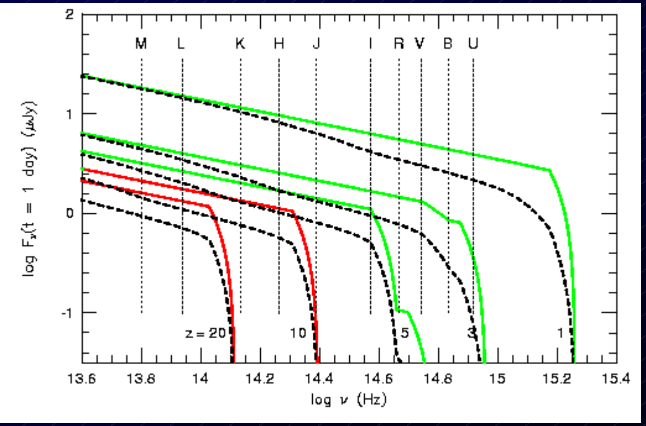
- All-Sky Survey for GRB's
- Triggering of GLAST Main Telescope
- Spectra in 10 keV-30 MeV Range
- typical spectrum->



GRB Optical/NIR Detector "GROND"

- Search for Distant GRB's: Detect Spectral Cutoff of GRB Afterglow
- Trigger Deep Studies of High-Redshift GRB
- 7-Filter Camera
  at ESO Telescope



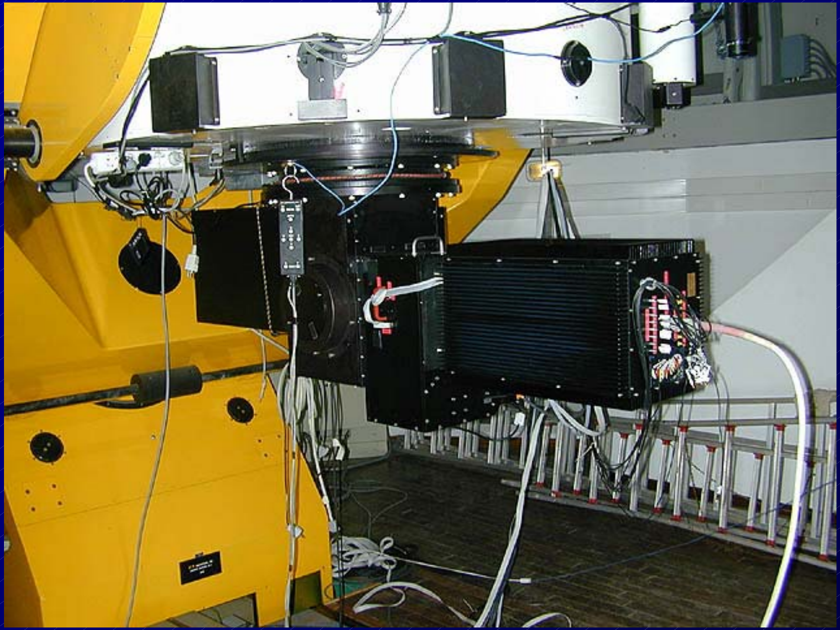


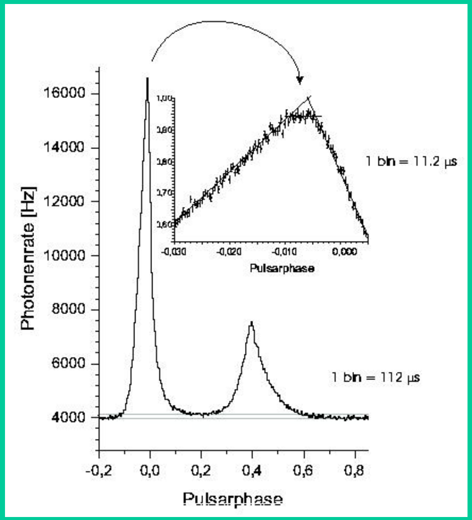
Fast-Timing Instrument at MPE

OPTIMA

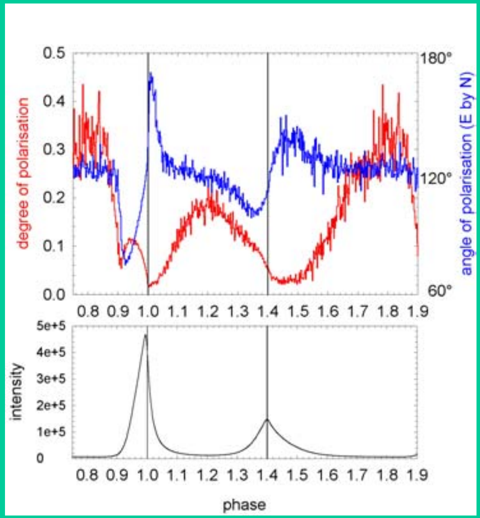
- Optical High-Resolution Timing
  for Monitoring of High-Energy Sources
- Fiber Optics Light Guide to
  Avalanche Photodiodes

- Mounted at Optical Telescopes (Skinakas, ESO)





Crab Pulsar:
Light Curve with
• Optical Peak-1
• Polarization



Gamma-Ray Astronomy at MPE

Science Areas:

- ☆ Relativistic/Nonthermal Plasma, Particle Acceleration
  - ☞ Active Galaxies, Gamma-Ray Blazars
  - ☞ Pulsars, Black-Hole Candidates (Binaries)
  - ☞ Nuclear Gamma-Ray Lines
- ☆ Nucleosynthesis Sources
  - ☞ Supernovae
  - ☞ Diffuse Galactic Line Emission
- ☆ Interstellar Medium
  - ☞ Nucleosynthesis Sources, Gamma-Ray Lines
  - ☞ Cosmic Rays and Diffuse Gamma-Ray Emission
- ☆ Identification of Unknown GeV Sources
- ☆ Gamma-Ray Bursts

MPE's Gamma-Ray Astrophysics Group

Scientists and their Projects/Research Areas

Roland Diehl	Nucleosynthesis, Gamma-Ray Lines; INTEGRAL
Jochen Greiner	Gamma-Ray Bursts, Transients; GROND
H.A. Mayer-Hasselwander	Diffuse Gamma-Ray Emission; GLAST, GROND
Gottfried Kanbach	Pulsars, Unidentified Sources, Transients; OPTIMA, MEGA
Giselher Lichti	Gamma-Ray Bursts, Supernovae, AGN; GLAST-GBM
Volker Schönfelder	Gamma-Ray Astronomy (Group Head)
Andrew Strong	Diffuse Gamma-Ray Emission, Cosmic Rays; INTEGRAL
Andreas von Kienlin	Gamma-Ray Bursts; INTEGRAL, GBM
Werner Collmar	AGN *(also MPE Computing Dept.)*
Helmut Steinle	AGN, Transients; OPTIMA *(also MPE Computing Dept.)*
Peter Kretschmar	Transients ; INTEGRAL *(at ISDC)*
Katja Pottschmidt	Transients, BH Candidates ; INTEGRAL *(at ISDC)*
+ students & guests	(various of the above)