Observational High-Energy Astrophysics
Beobachtende Hochenergie-Astrophysik

Vorlesung Physik-Departement TU München

SS 2003

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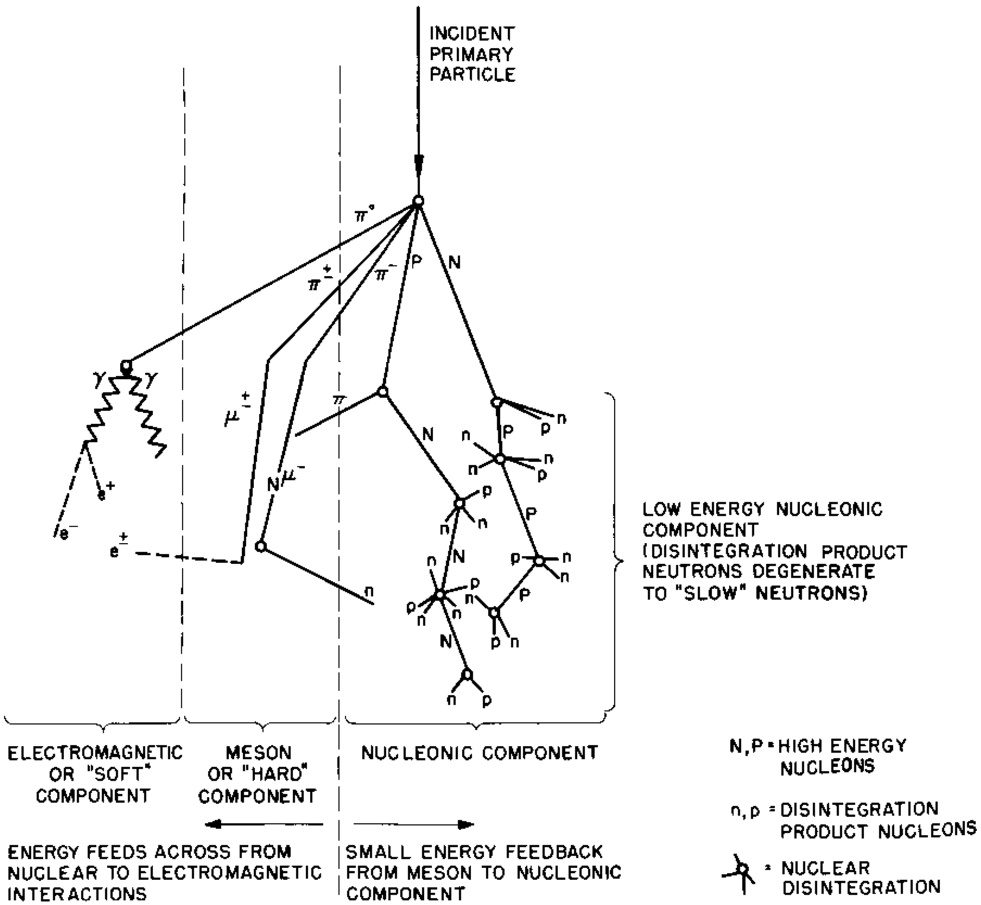
Lecture Overview

- **Theme and Sub-Topics:**
  - ☆ Astrophysical Processes and High-Energy Astronomy
    - ☞ Astronomy with Photons and Particles
    - ☞ Particle and Photon Production Processes
    - ☞ The Domain of High-Energy Radiation
  - ☆ Instrumentation for High-Energy Astronomy
    - ☞ Cosmic Ray Detectors
    - ☞ Ground-Based Telescopes for High-Energy Photons
    - ☞ Gamma-Ray Telescopes
    - ☞ X-Ray Telescopes and Spectrometers
  - ☆ Sources and Astrophysics at High Energies
    - ☞ Accreting Compact Stars & Objects
    - ☞ Exploding Stars (Novae, Supernovae)
    - ☞ High-Energy Interactions (Cosmic Rays, Jets)
    - ☞ Hot Plasma in Stellar Coronae, ISM Cavities, Galaxy Clusters

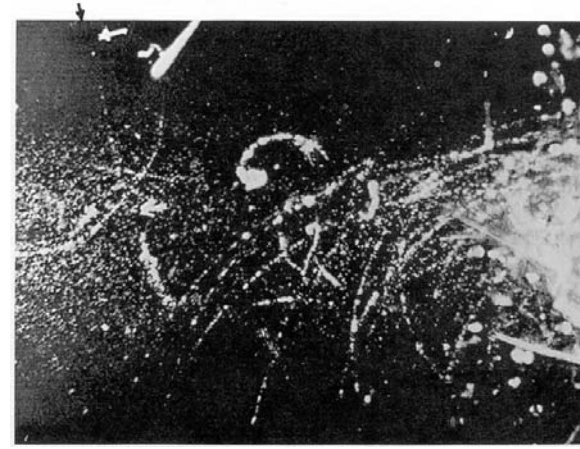
Astronomy

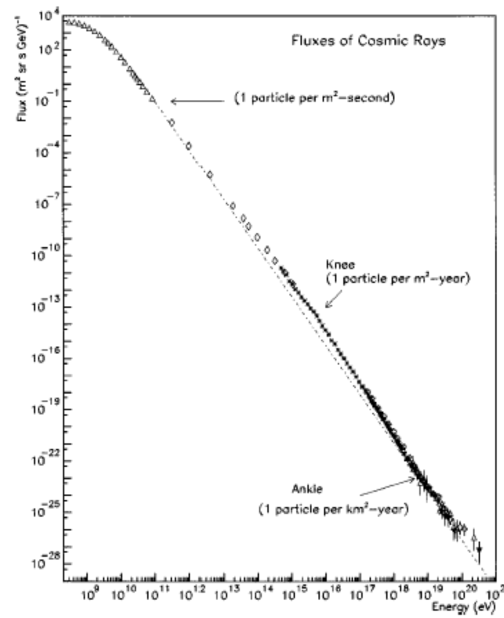
- **Measurement of Electromagnetic Radiation**
  - ☞Energy Output of Source Objects (per ν Band)
  - ☞Characteristic Source Processes
  - ☞Understanding the Object
    - Point Source / Extended Object
    - Thermal / Non-Thermal Radiation
    - Equilibrium or Transient
    - Source of Radiation, the Physical Process(es)
    - Object's Physical Parameters, Radiation Source Environment
  - ☞Understanding Cosmic Evolution
    - Object Population
    - Characteristic Epochs and Duration of Radiating Phases
    - Cycling of Matter
  - ☞Absorption, Distortion, and Occultation of Radiation
    - Interstellar Gas & Dust
    - Cosmic Photon Fields / Inverse-Compton
  - ☞Biases
    - Radiating and Dark Phases
    - Instrument Sensitivities & Resolutions
- **Measurement of Cosmic-Ray Particles**

Cosmic Rays



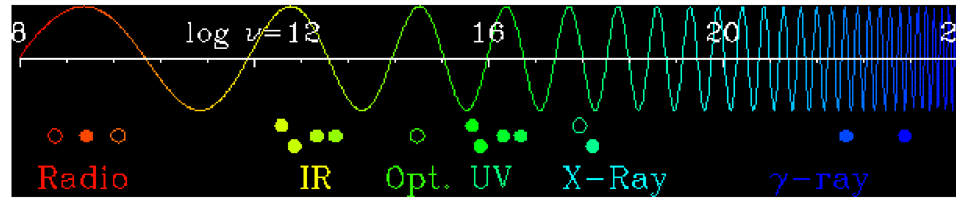
Schematic Diagram of Cosmic Ray Shower

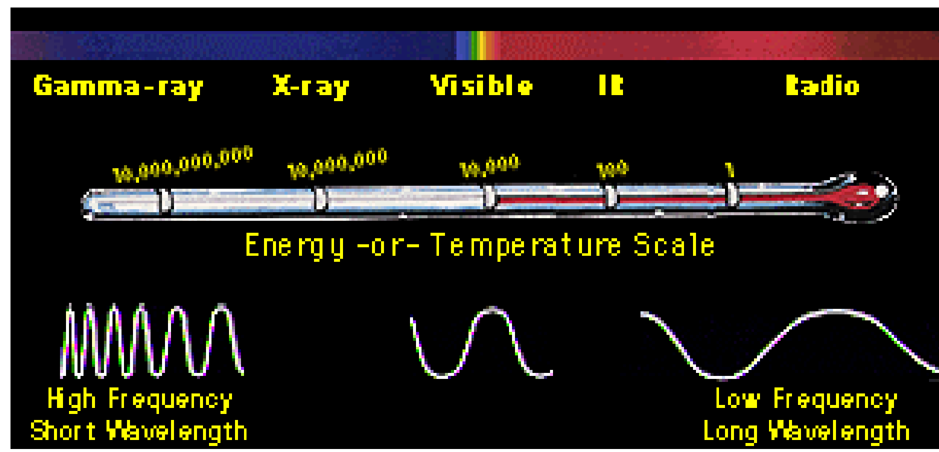




- The Discovery of Cosmic Rays ~1913 (Hess, Kohlhörster; Balloons up to 9 km) Initiates "High-Energy Astrophysics"

Electromagnetic Radiation





- Optical Astronomy
- "New Astronomies" 1930+
  - ☞Radio Astronomy >1930
  - ☞UV & X-Ray Astronomy > 1970 (IUE, Uhuru)
  - ☞Gamma-Ray Astronomy >1970 (OSOIII,SASII)
  - ☞Infrared Astronomy >1980 (IRAS)
- High-Energy Astronomy: > 100 keV … TeV

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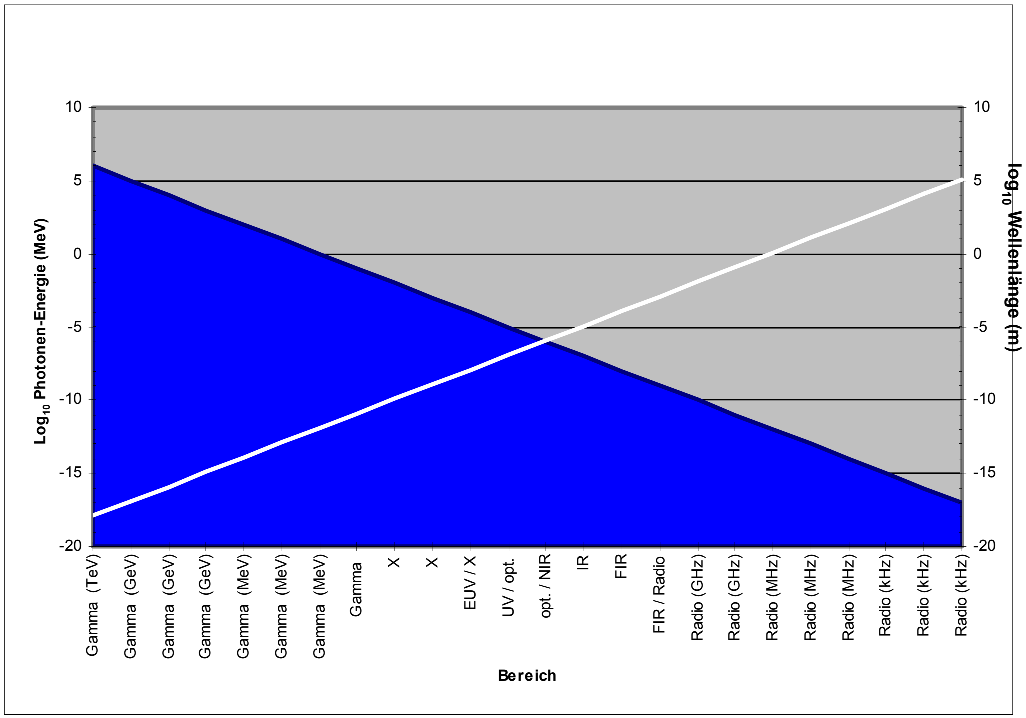
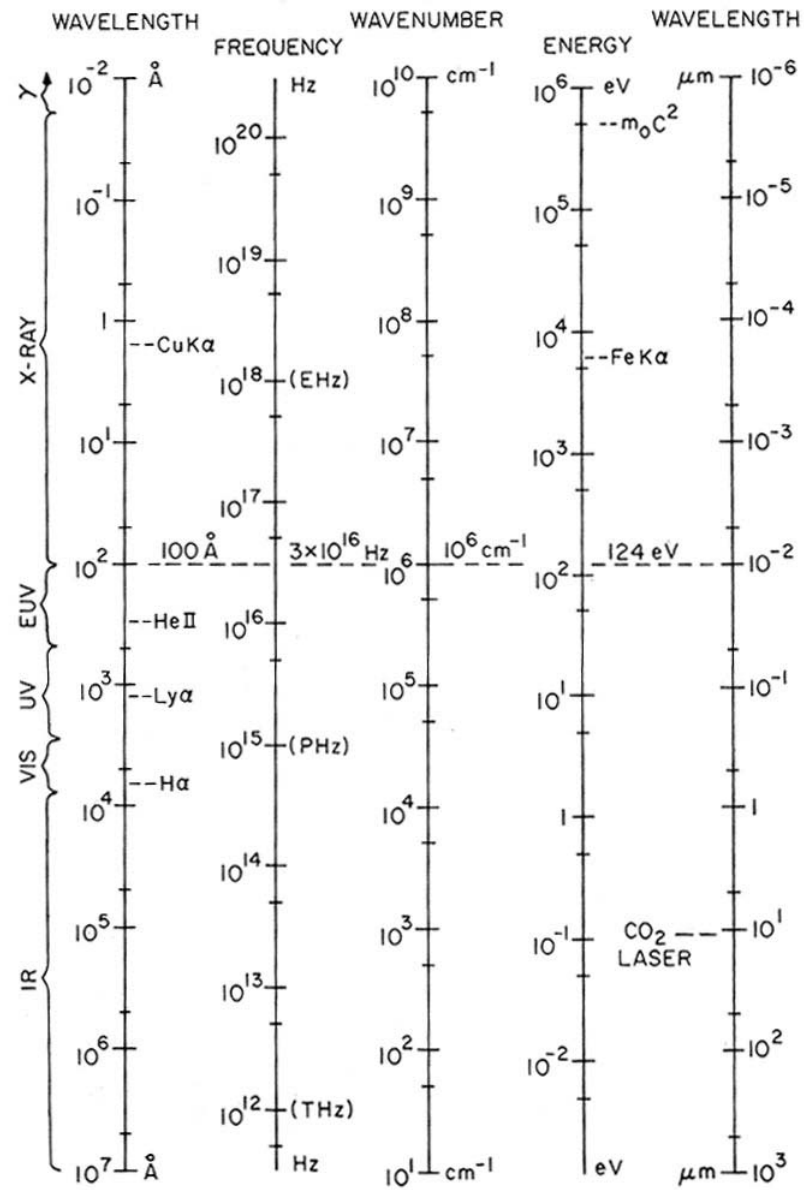
Electromagnetic Radiation: Dynamic Range

☆ **Wave/Particle Dualism**

- ☞LE: Interference, Diffraction
- ☞HE: "Knock-On" Processes





1 kiloelectron-volt = 1 keV = 10^3 eV,

1 megaelectron-volt = 1 MeV = 10^6 eV,

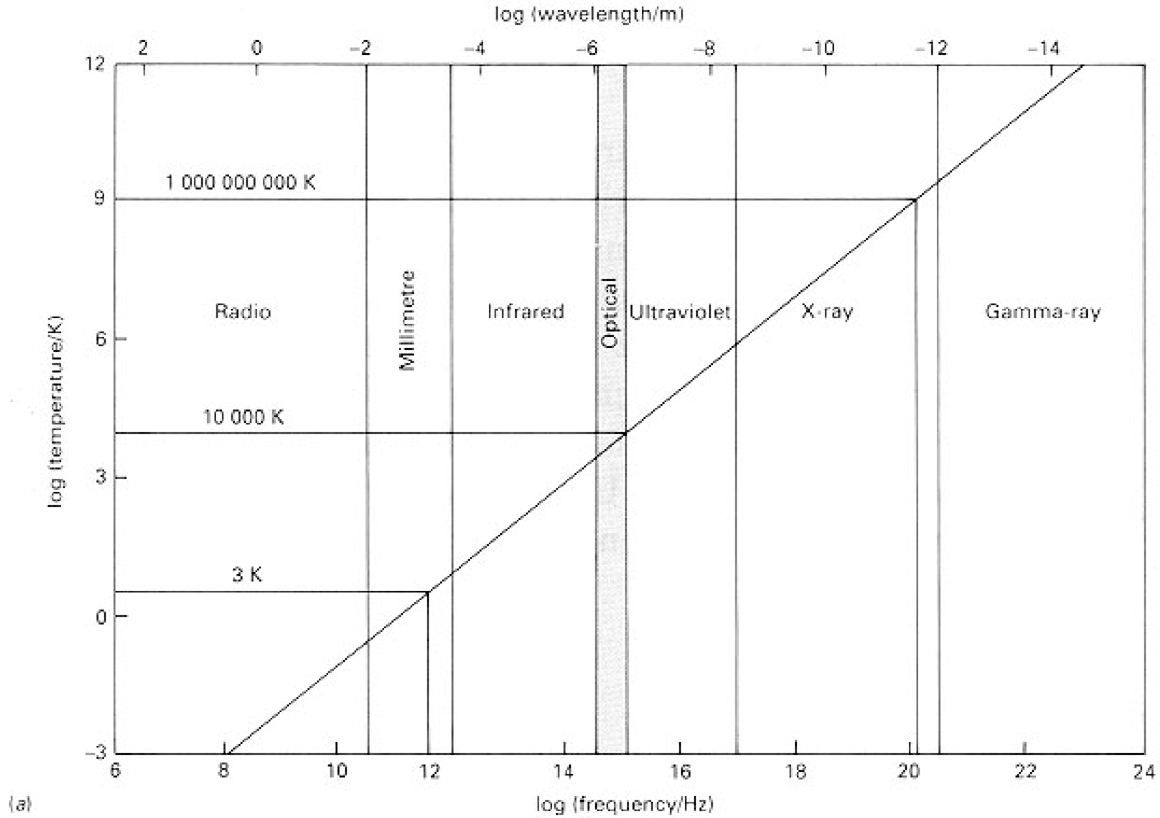
1 gigaelectron-volt = 1 GeV = 10^9 eV,

1 teraelectron-volt = 1 TeV = 10^{12} eV,

1 petaelectron-volt = 1 PeV = 10^{15} eV,

1 exaelectron-volt = 1 EeV = 10^{18} eV, etc.

Spectral Windows to Cosmic Radiation Sources



- **Thermal (Blackbody) Radiation**
  - Optical: Stars T~10.000K
  - Infrared: Dust T~30K
  - Radio: Gas T~10K
  - X-Rays: Hot Plasma T~1.000.000K
- **Non-Thermal Radiation**
  - Radio
  - X and Gamma-Rays

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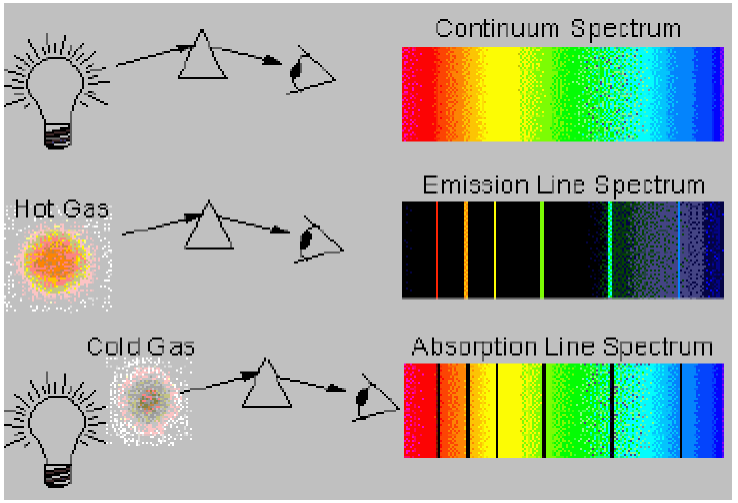
Spectral Characteristics of Cosmic Sources

- Type of Radiating Source
  - ☆ Equilibrium Radiation?
    - ☞ Thermalized Photosphere
    - ☞ LTE,
      Multi-Temperature Plasma
    - ☞ Nonthermal Processes
  - ☆ Unique Photosphere?
    - ☞ Optically Thick
    - ☞ Optically Thin
    - ☞ Superimposed
      Absorption / Emission



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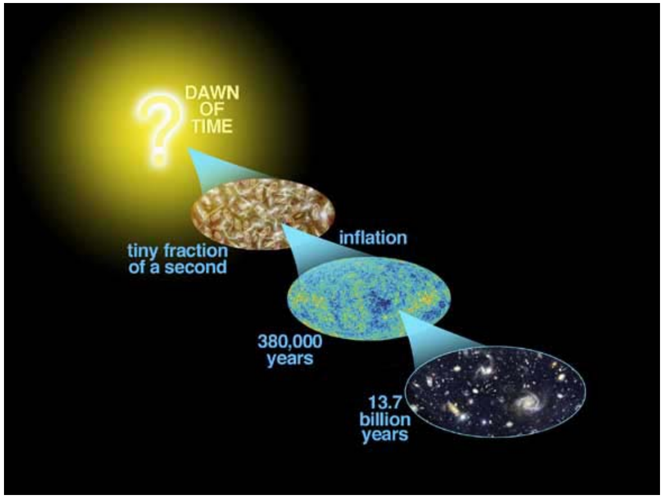
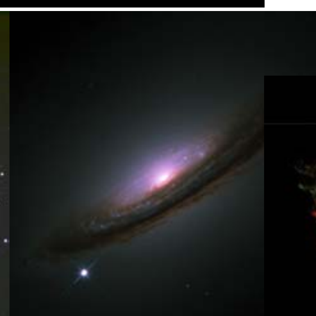
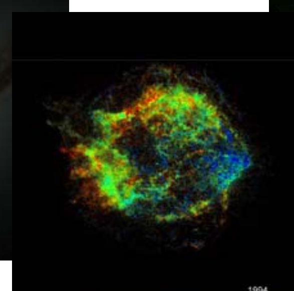
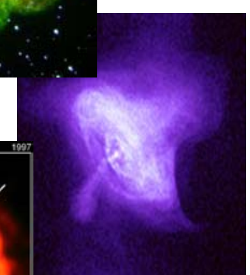
Cosmic Objects

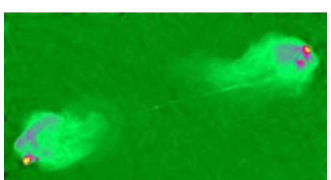


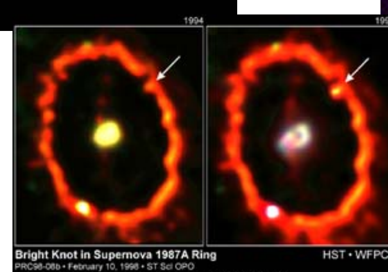
- Galaxies
- Stars
- Interstellar Gas

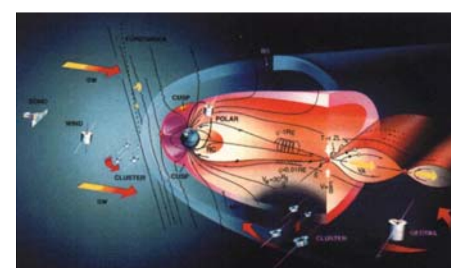












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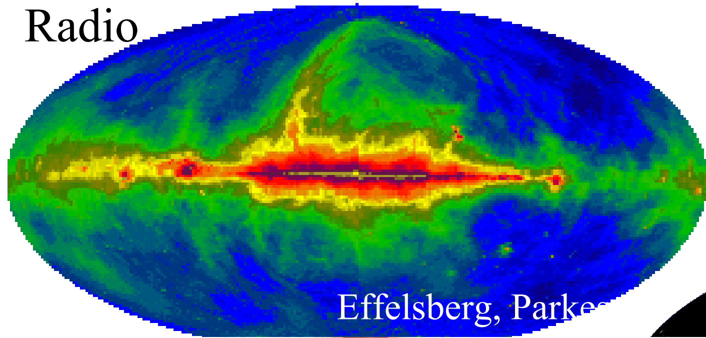
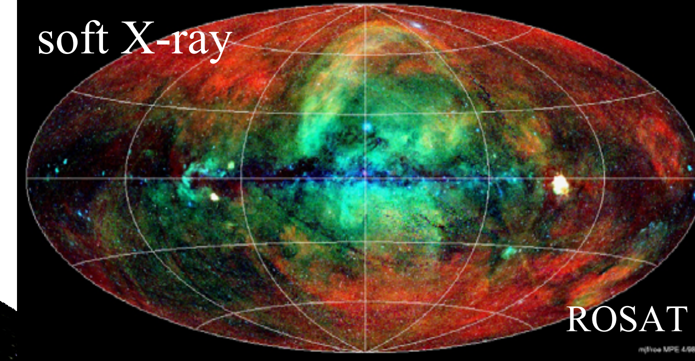
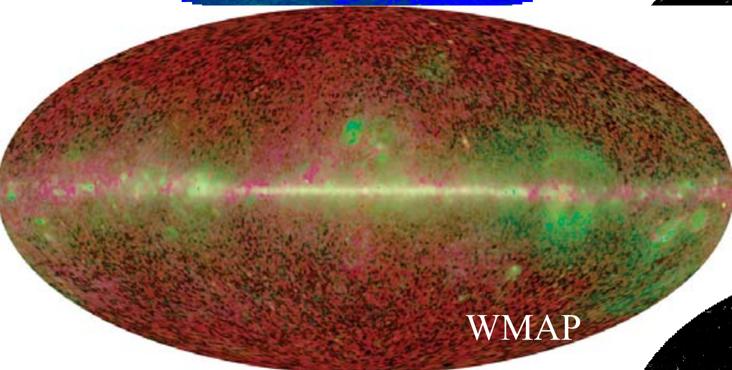
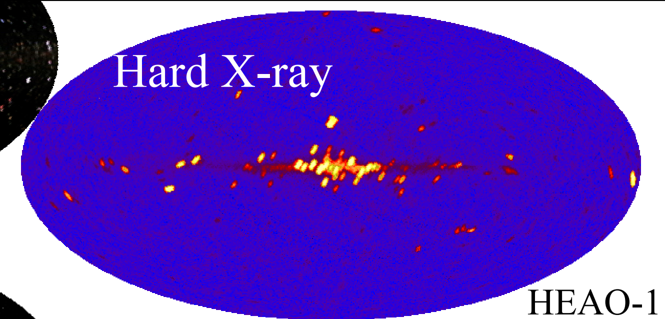
Sky Views

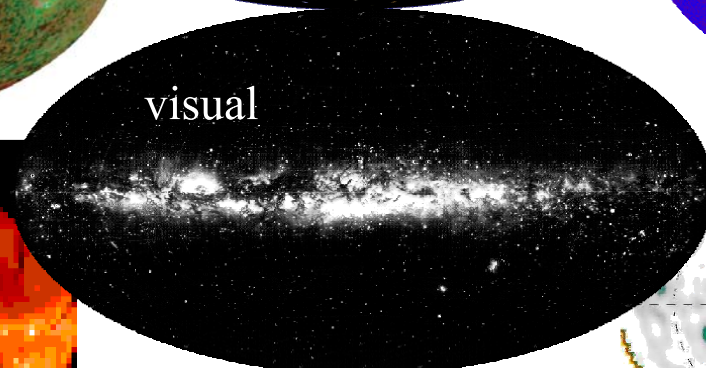

Radio
Effelsberg, Parke

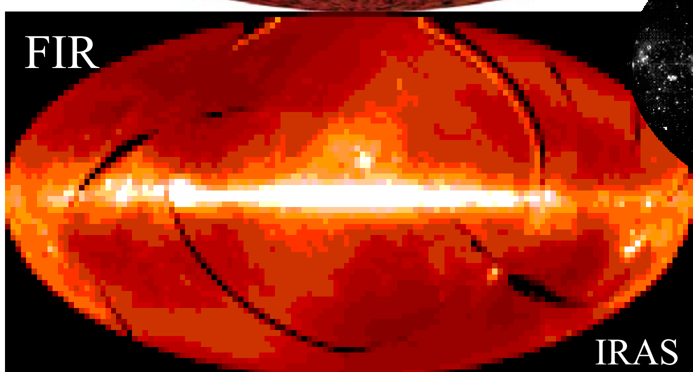

soft X-ray
ROSAT

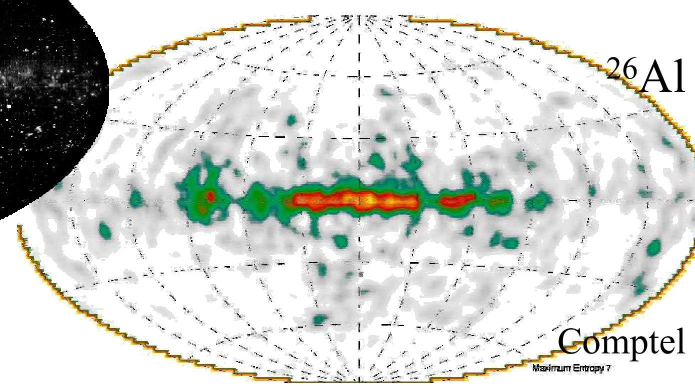

NIR
COBE/DIRBE


WMAP


Hard X-ray
HEAO-1


visual


FIR
IRAS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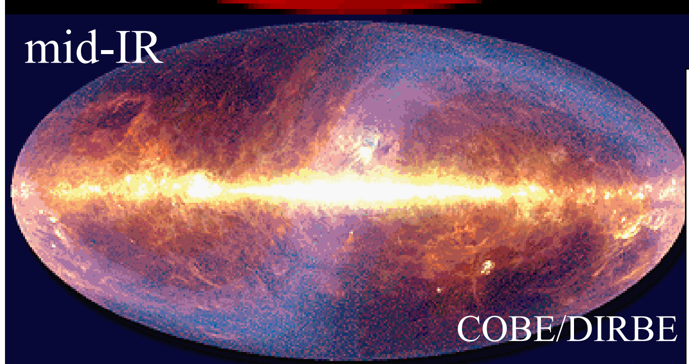
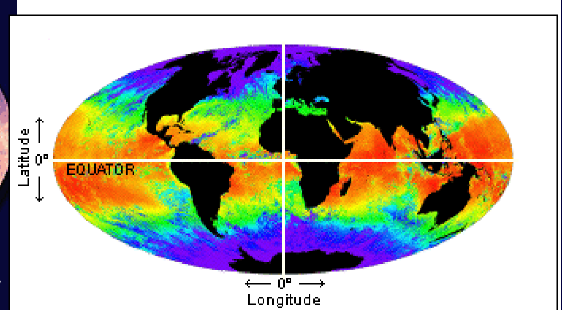
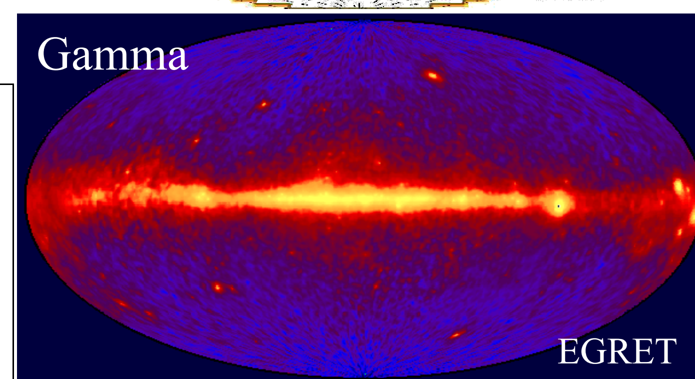
Comptel


mid-IR
COBE/DIRBE


Latitude
0°
EQUATOR
0°
Longitude


Gamma
EGRET

Blackbody Radiation

1. Planck functions (Brightness of a blackbody)

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{(\exp\frac{h\nu}{kT} - 1)} \quad \text{erg cm}^{-2}\text{sec}^{-1}\text{Hz}^{-1}\text{ster}^{-1}$$

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{(\exp\frac{hc}{\lambda kT} - 1)} \quad \text{erg cm}^{-2}\text{sec}^{-1}\text{cm}^{-1}\text{ster}^{-1}$$

$$B_{\tilde\nu}(T) = \frac{2hc^2\tilde\nu^3}{(\exp\frac{hc\tilde\nu}{kT} - 1)} \quad \text{erg cm}^{-2}\text{sec}^{-1}(\text{cm}^{-1})^{-1}\text{ster}^{-1}$$

$$B_\nu(T)\,d\nu = B_\lambda(T)\,d\lambda = B_{\tilde\nu}(T)\,d\tilde\nu$$

Rayleigh-Jean's law

$h\nu / kT \ll 1$

$$B_\nu(T) = 2\left(\frac{\nu}{c}\right)^2 kT$$

Wien's law

$h\nu / kT \gg 1$

$$B_\nu(T) = \frac{2h\nu^3}{c^2} \exp -\frac{h\nu}{kT}$$

2. Stefan-Boltzmann law

$$\text{total emittance} = \pi \int_0^\infty B_\nu(T)\,d\nu = \sigma T^4 \text{ ergs cm}^{-2}\text{sec}^{-1}$$

$$\sigma = \frac{2\pi^5 k^4}{15c^2h^3} = 5.67 \times 10^{-5} \text{ erg cm}^{-2}\text{ deg}^{-4}\text{ sec}^{-1}$$

3. Wien displacement law

Maximizing B_ν:

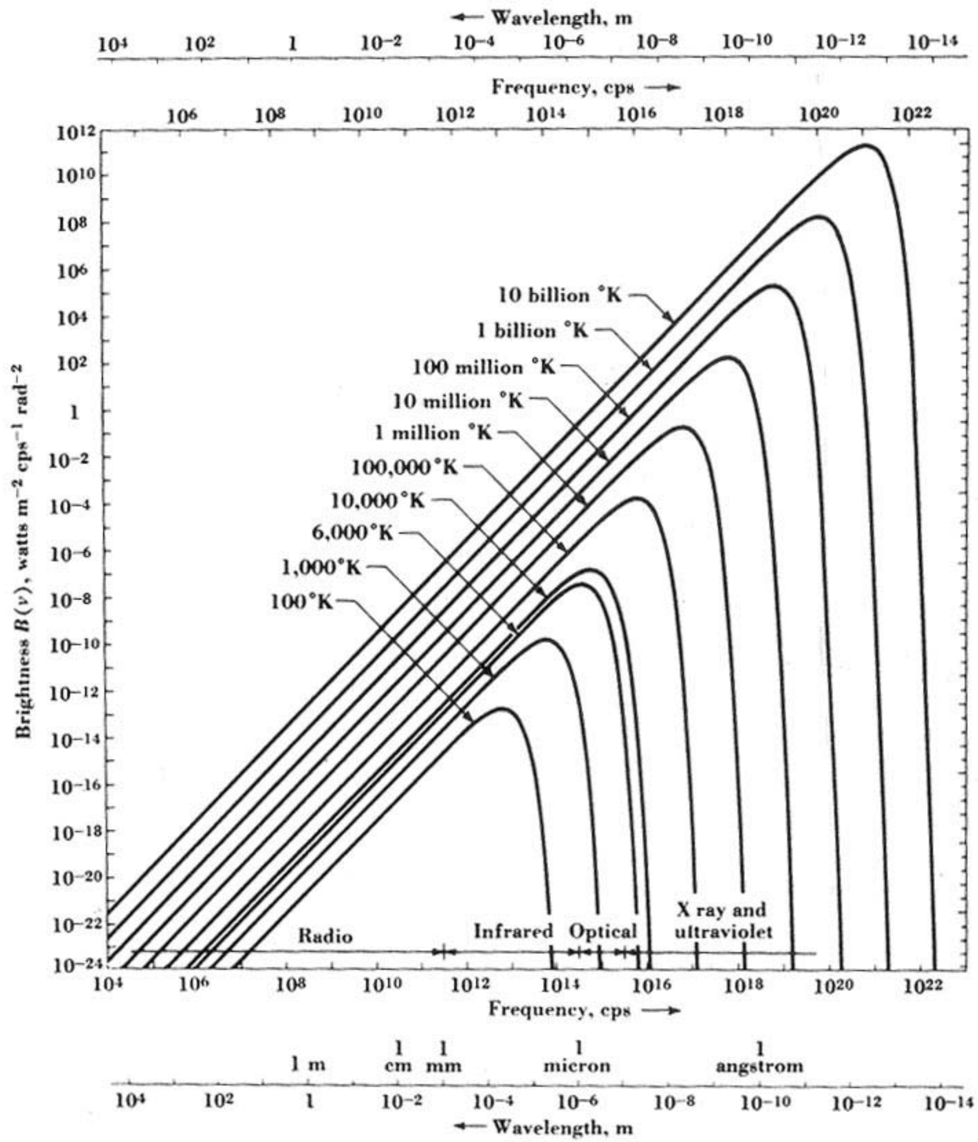
$\nu_m = 5.9 \times 10^{10}\, T$ Hz

$\lambda_m = 0.51\, T^{-1}$ cm

Maximizing B_λ:

$\nu_m = 10.3 \times 10^{10}\, T$ Hz

$\lambda_m = 0.29\, T^{-1}$ cm



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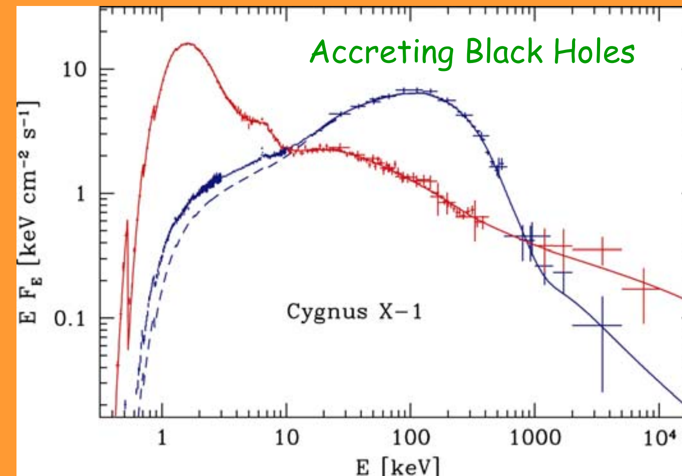
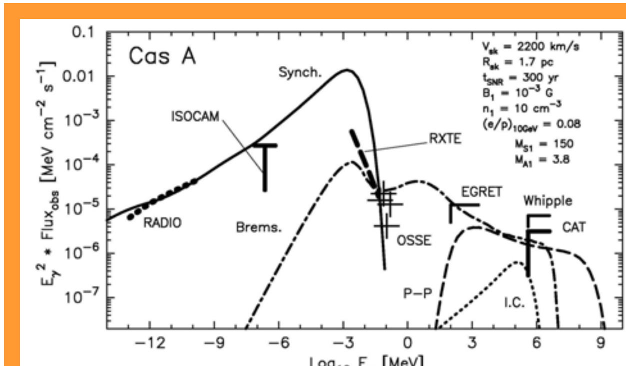
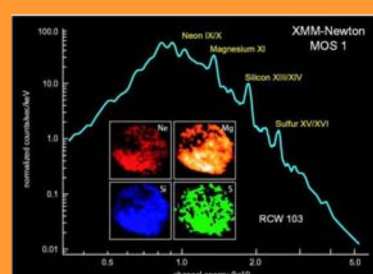
Typical-Source Energy Spectra

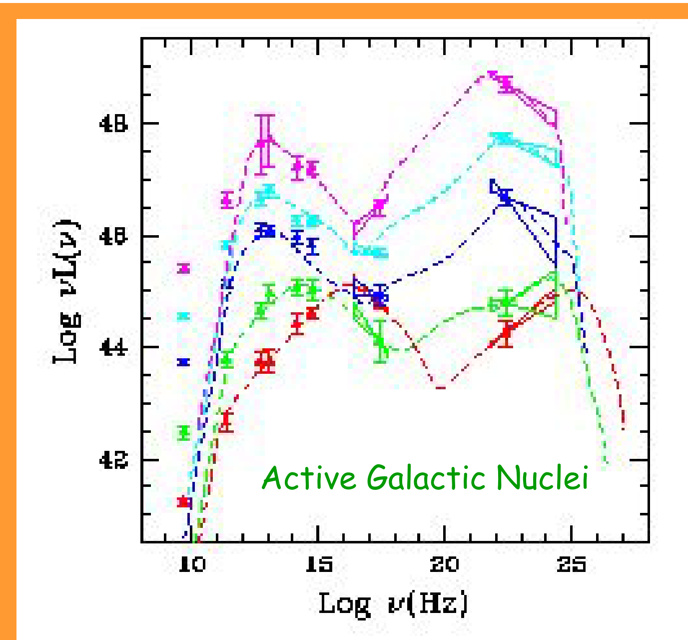
- **Thermal Components**
  - ☞ Stellar Surfaces
  - ☞ Accretion Disks
  - ☞ Plasma Bubbles
- **Non-Thermal Components**
  - ☆ Accelerated Particles
    - ☞ Synchrotron Radiation
    - ☞ Bremsstrahlung
    - ☞ ...





Supernova Remnants





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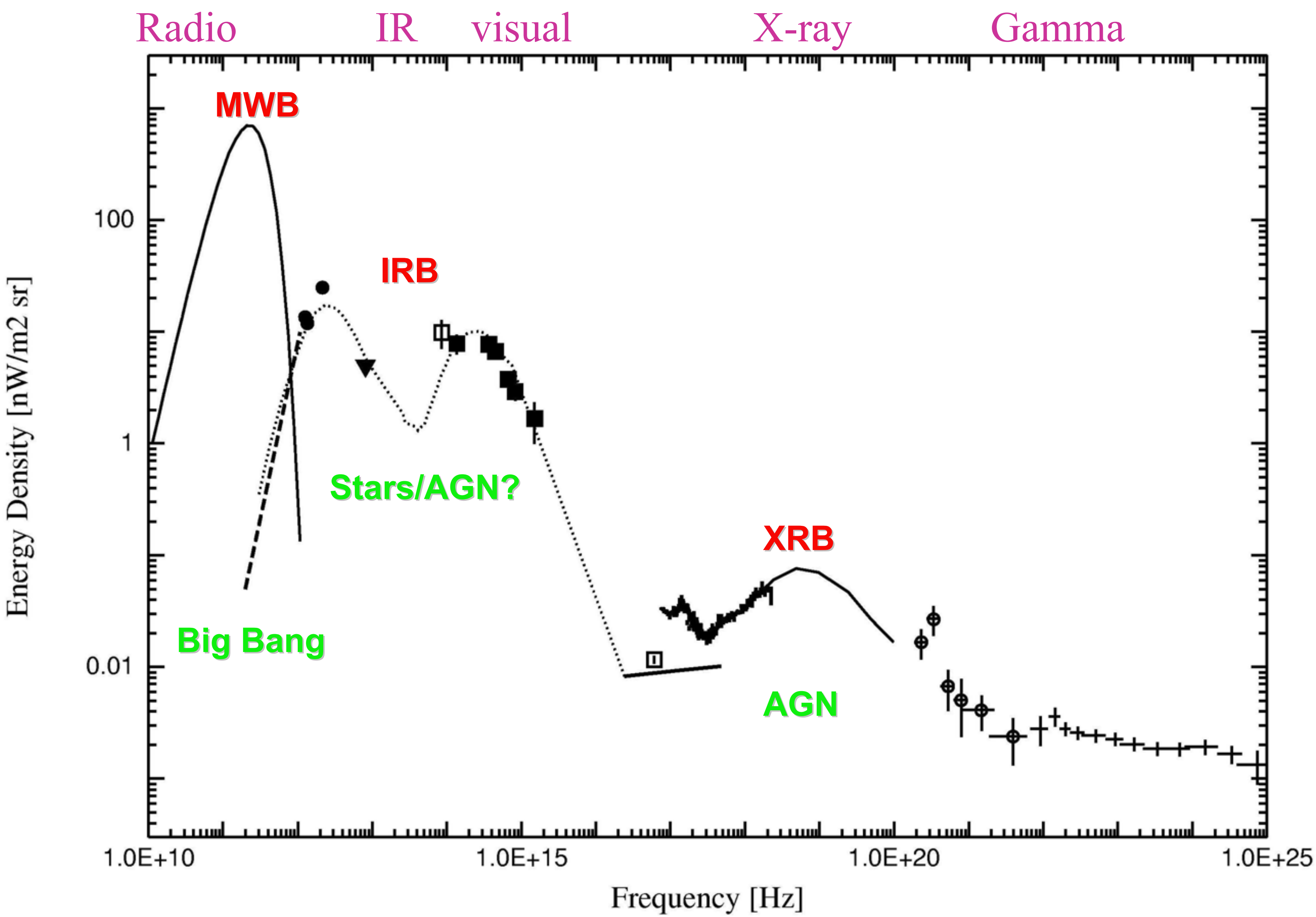
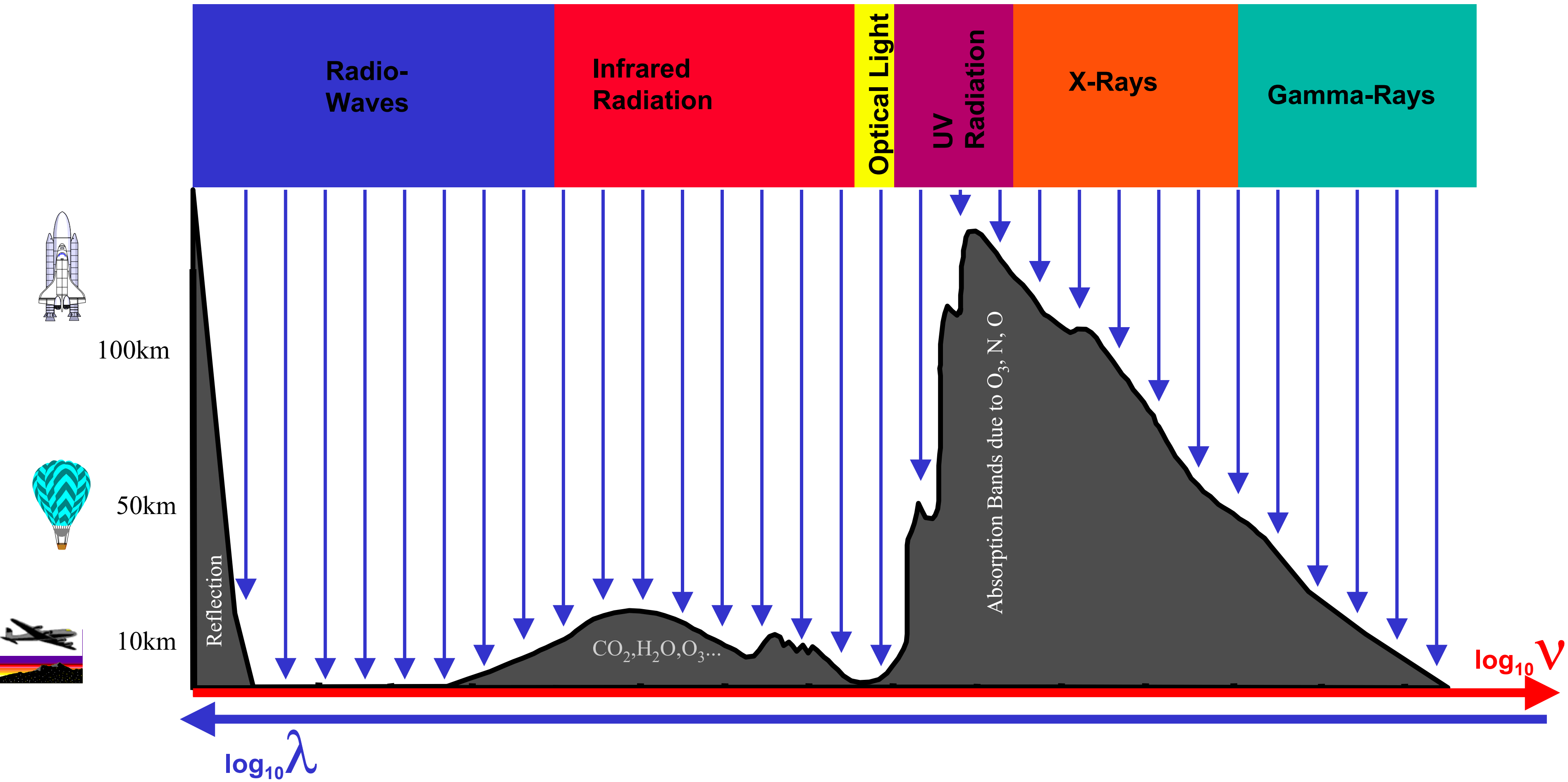
The Energy Spectrum of Diffuse Cosmic Radiation

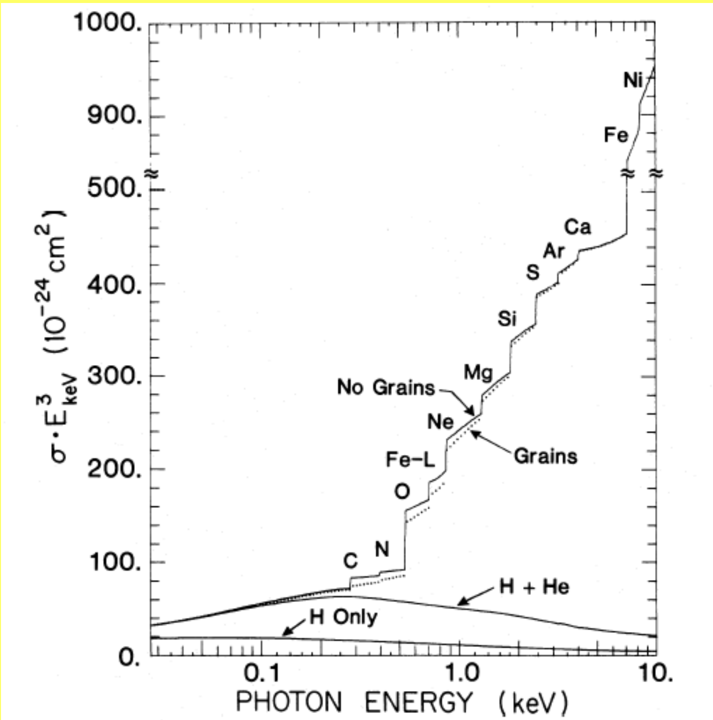


Observational Windows

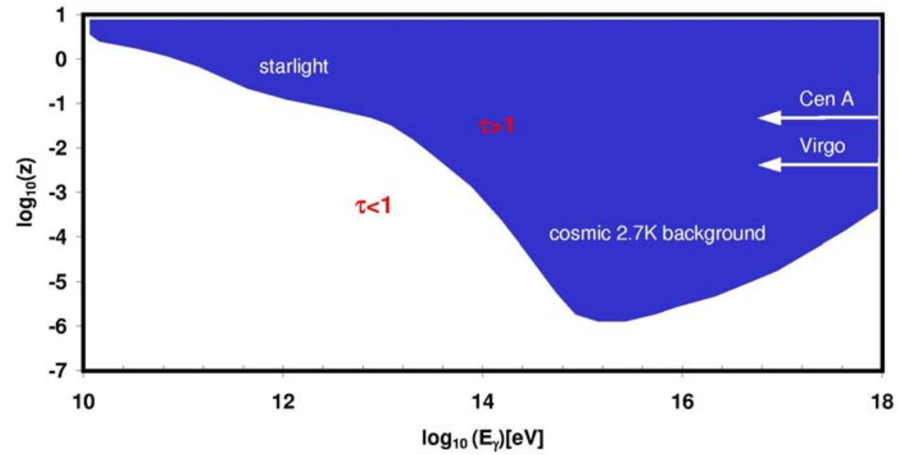


- Need a Combination of Ground-Based and Satellite Observations

Transparency of the Universe



Morrison & MacCammon ApJ 1983



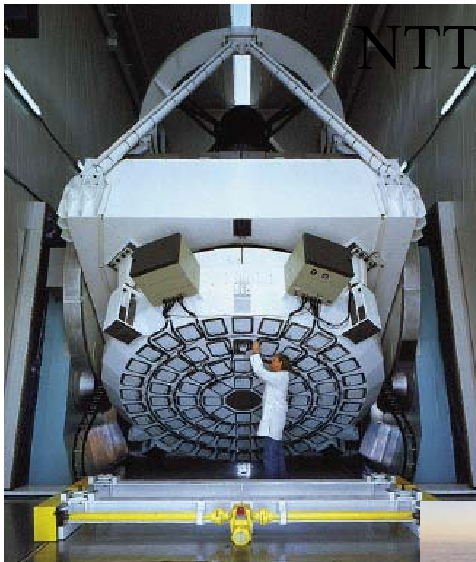
$$\tau_x = 2 \cdot 10^{-26} \left(\frac{h\nu}{1keV} \right)^{-8/3} \int N_H dl$$

- **Interaction of Photons**
  - ☆ **Absorption (Dust, Gas)**
    - ☞ Structure from
      - Dust Particles, Molecules
      - Atomic-Shell Electrons
  - ☆ **Scattering**
    - ☞ Inelastic:
      - Comptonization
      - Inverse-Compton Boosting

Astronomical Instruments

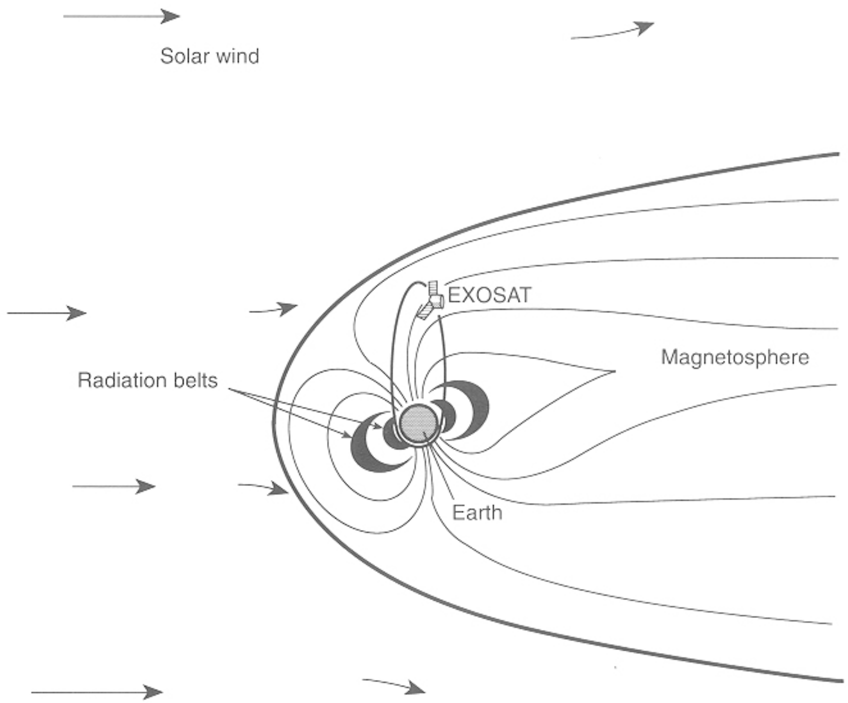
- Optical Telescopes
- Radio Telescopes
- Infrared Detector Systems
- UV Telescopes
- X-Ray Telescopes
- Gamma-Ray Detectors
- Cosmic-Ray Detectors
- Neutrino Telescopes
- Gravity Wave Detectors

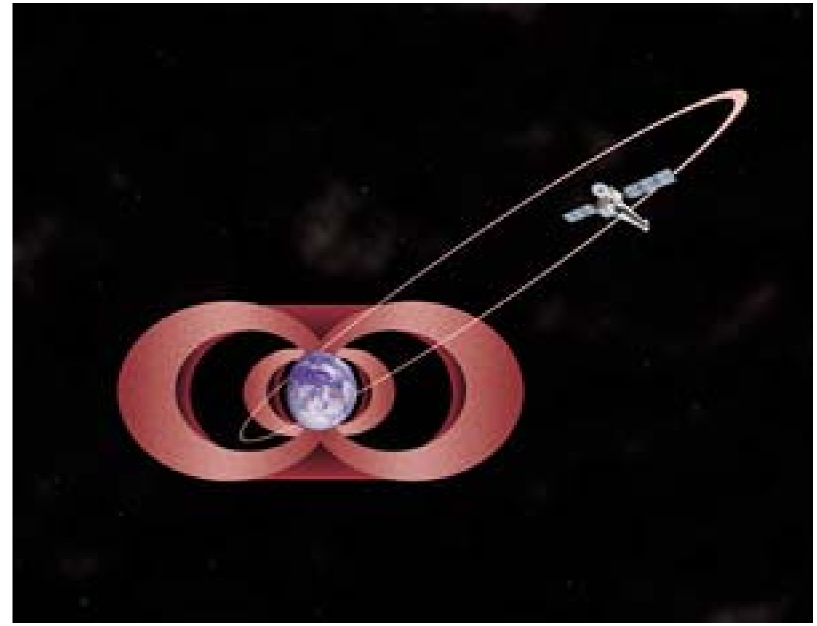
Astronomical Instruments: Ground-Based

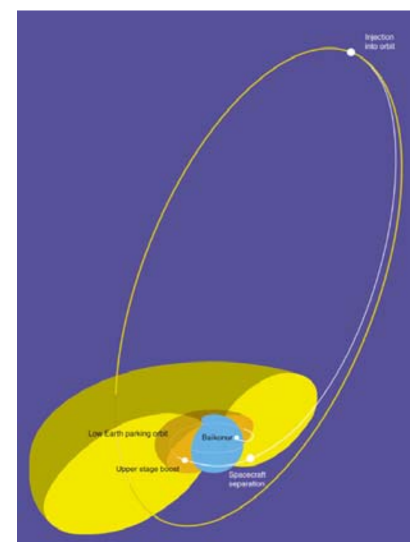


Astronomical Instruments: HE Space Missions

Satellite Orbits







- ☆ High-Earth Orbit (HEO): above radiation belts
- ☆ Low-Earth Orbit (LEO): below radiation belts
- ☆ Geostationary Orbit (GEO): partly inside radiation belts

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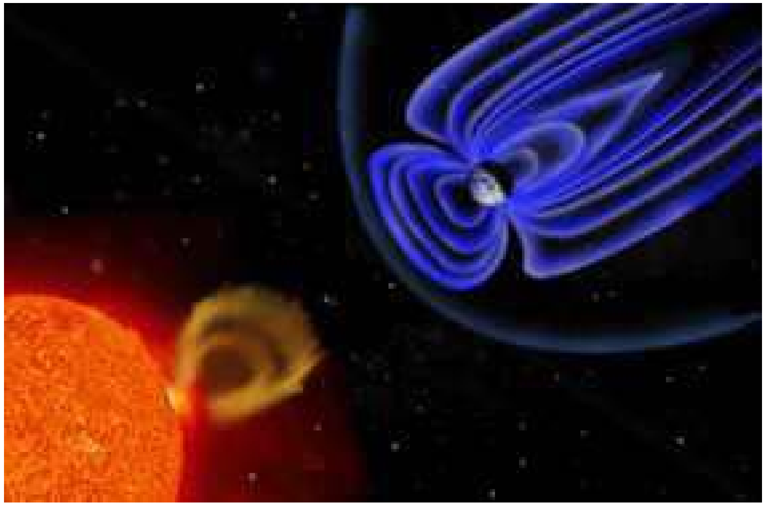
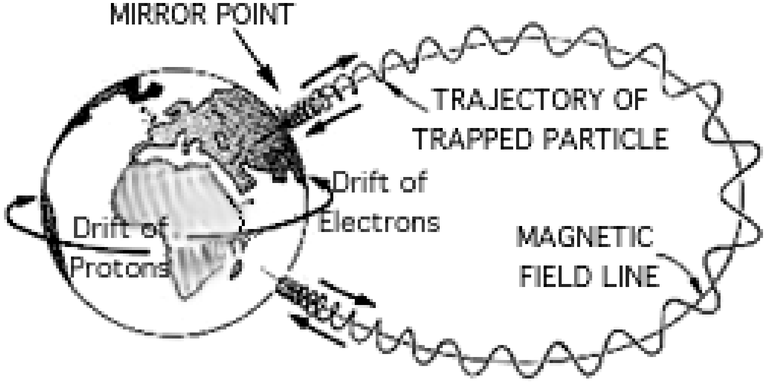
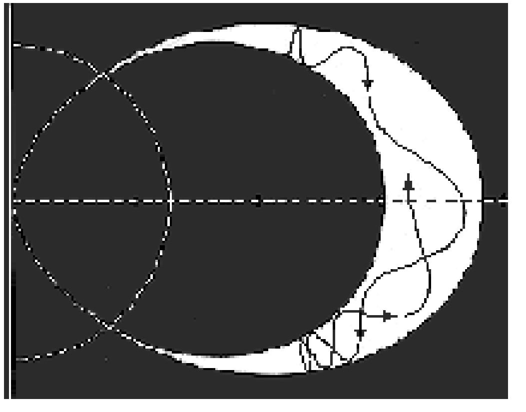
Van Allen Radiation Belts

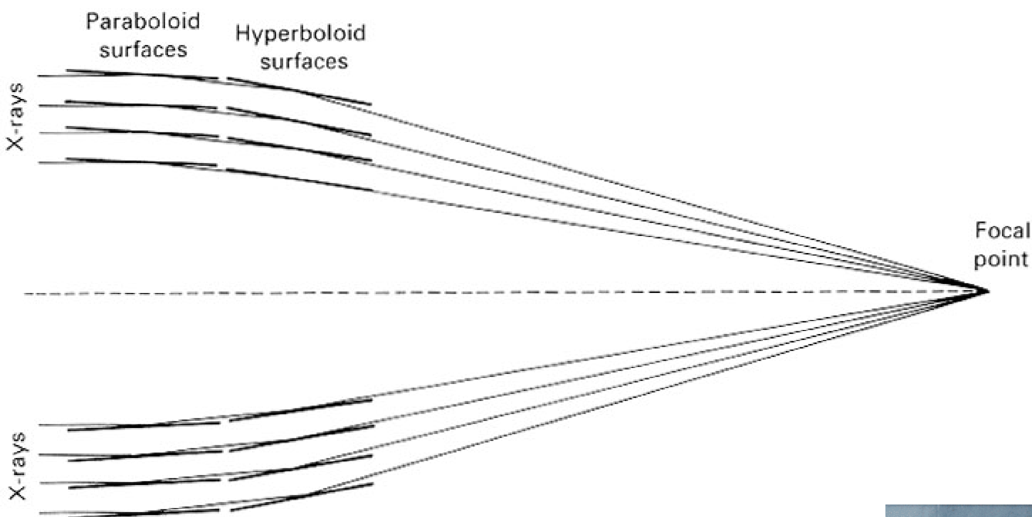






- Charged Particles are Trapped by Earth's Magnetic Field

Astronomical Instruments: X-Rays



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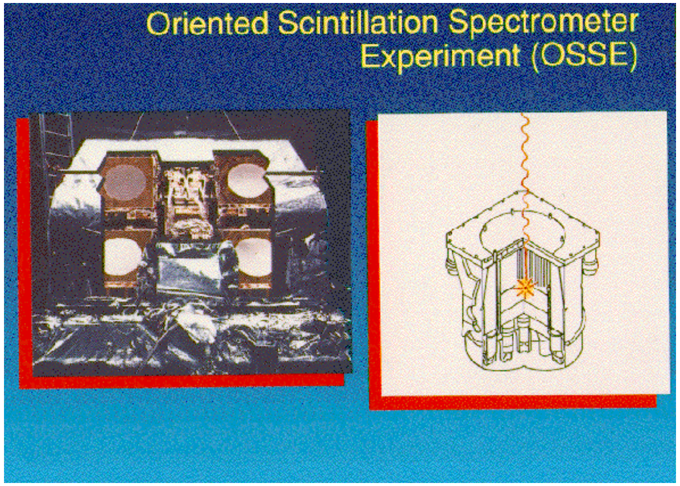
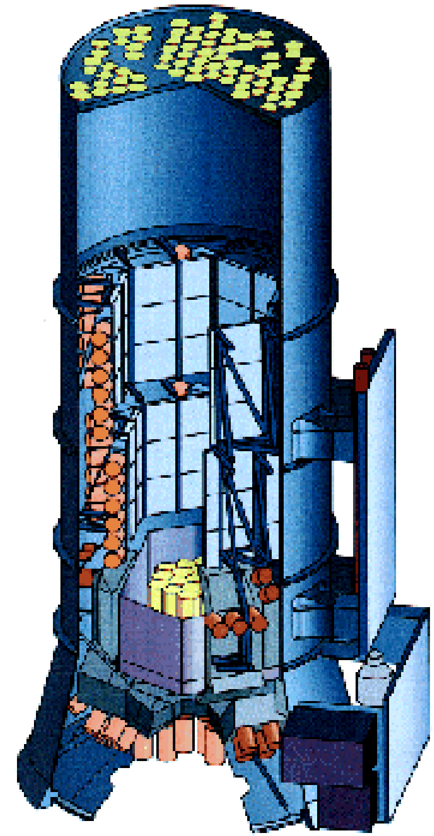
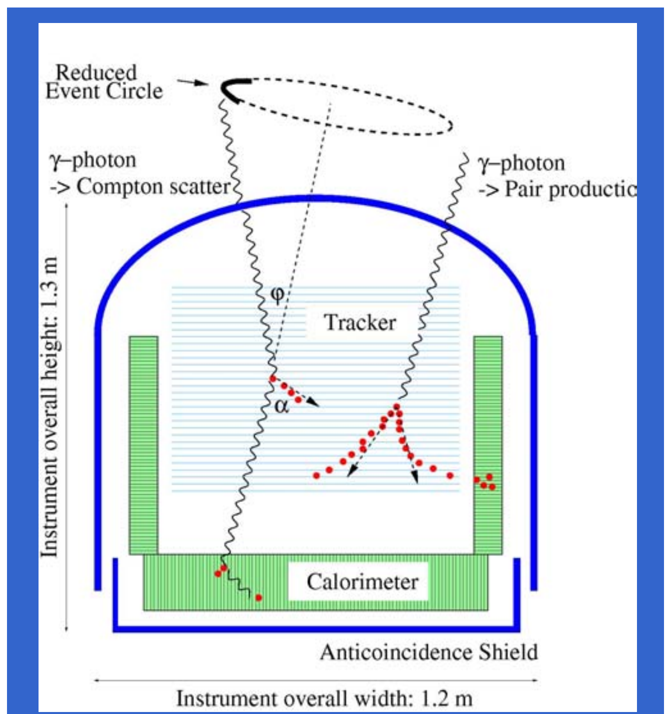
Astronomical Instruments: Gamma-Rays







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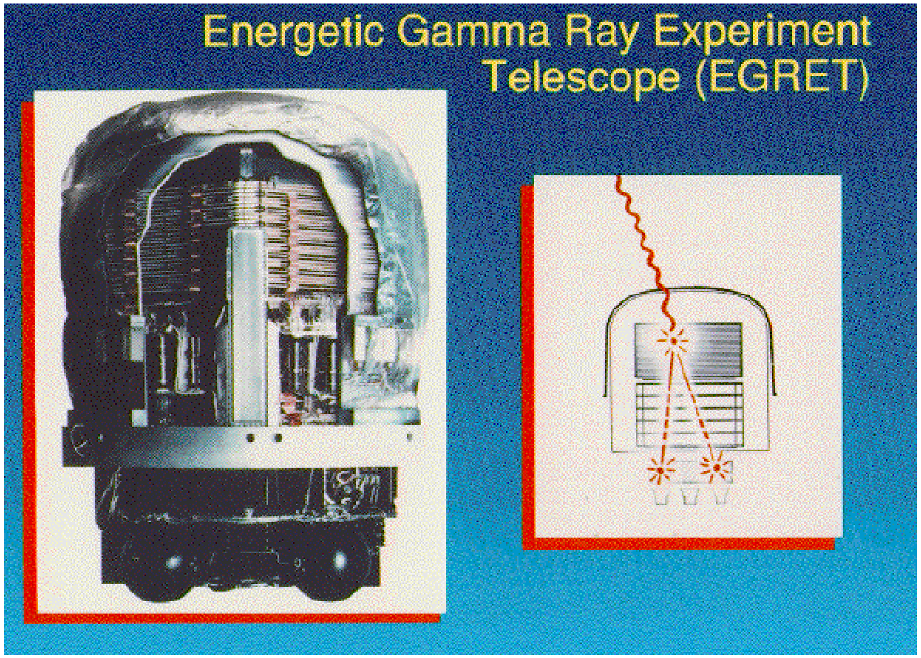
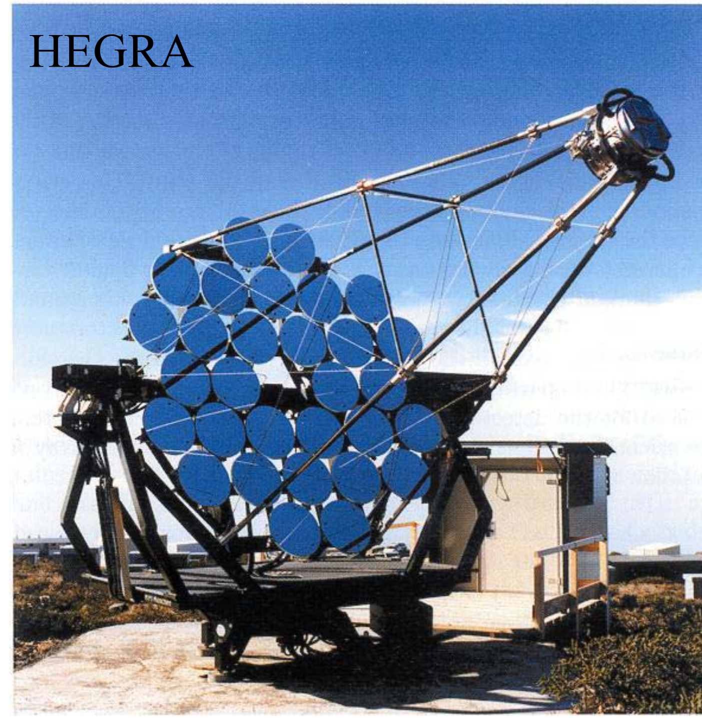
Astronomical Instruments: High-Energy Gamma-Rays & Cosmic Rays





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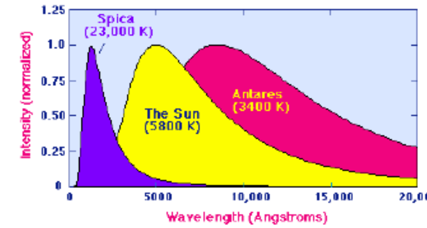
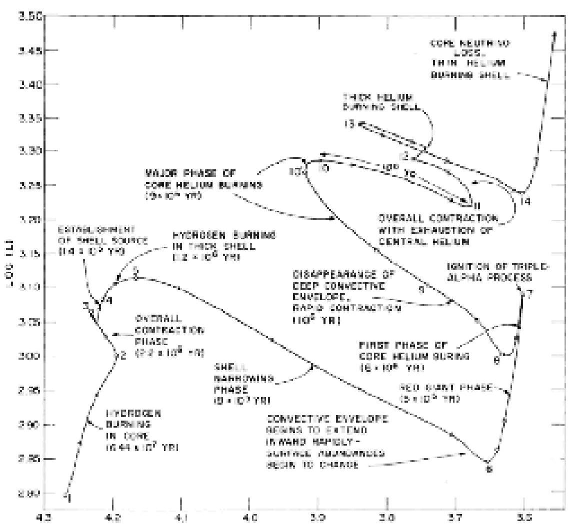
Cosmic Objects…

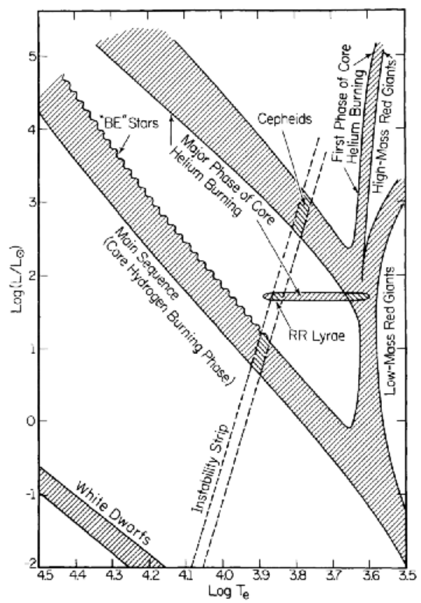
- **Stars**
  - ☞Normal Stars
  - ☞Flaring and Variable Stars
  - ☞Compact Stars (WD, NS, BH)
  - ☞Accreting Binaries
  - ☞"Exploding" Stars (SN,N; GRB?)
- **Interstellar Medium**
  - ☞Molecular Clouds, Neutral ISM
  - ☞Ionized Regions
  - ☞Supernova Remnants
- **Galaxies**
  - ☞Normal Galaxies
  - ☞Active Galaxies (Quasars, Blazars,…)
- **Large-Scale Structure of Universe**
  - ☞Galaxy Clusters
  - ☞Cosmic Microwave Background
  - ☞Dark Matter

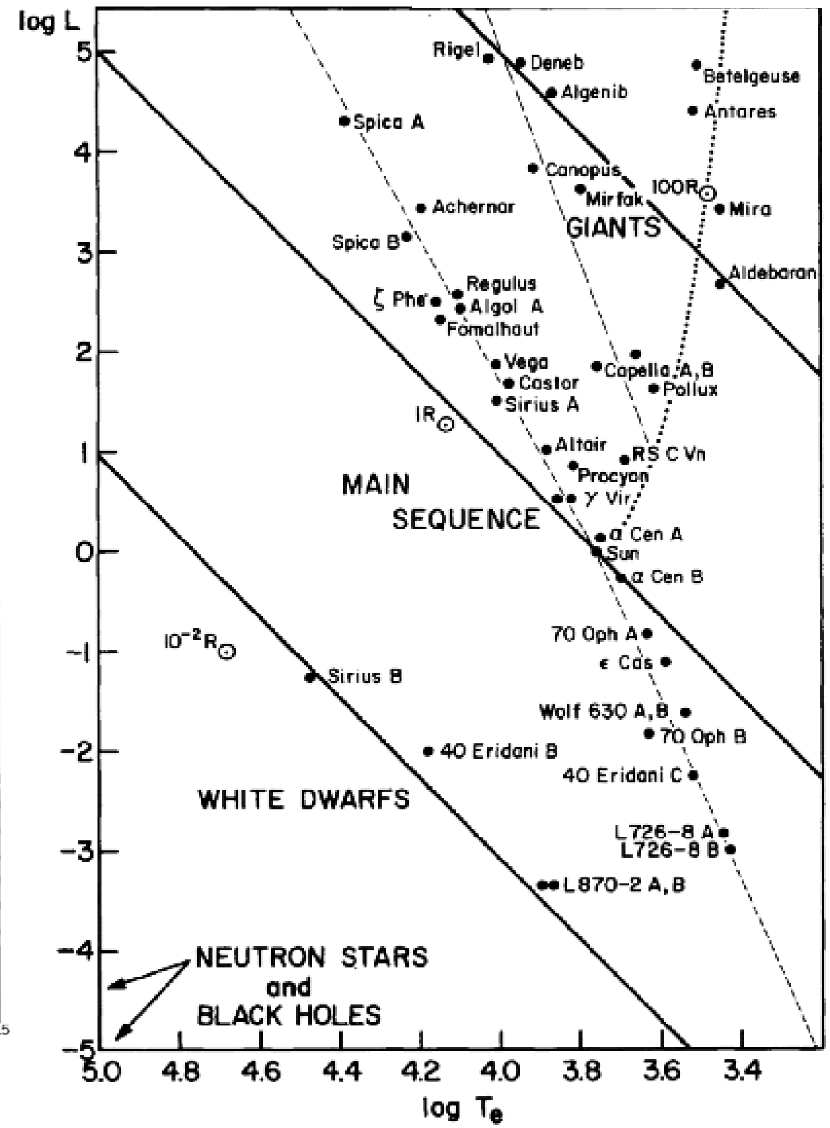
Stellar Objects: Types and Evolution



- Luminosity <-> Surface Temperature (log-log)
- Regions of Stellar States:
  - ☆ Main Sequence — H Burning Core
  - ☆ Giants — H-Exhausted Core
  - ☆ White Dwarfs — Remnant Core
- Evolution Times: $10^5 \ldots 10^{10}$y
- High-Energy Radiation:
  - ★ Coronae, Flares, Binary Interactions







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High-Energy Astrophysics Topics

☆ Relativistic Plasmas

- Stellar Coronae / Accretion onto Compact Objects / Interstellar Cavities and SNR, Intergalactic Medium / Relativistic Jets, GRB (-> Acceleration, Deceleration)

☆ Active Galactic Nuclei

- AGN, Seyfert Galaxies, Blazars, …

☞ Starbursts / Supermassive Black-Holes / Jet Physics

☆ Compact Stars

- White Dwarfs, Neutron Stars, Black Holes

☞ Equation of State, Density, Size; Rotation, Magnetic Fields; Binary Interactions

☞ Accretion / Matter Transfer Processes

☆ Nucleosynthesis

- Stars / Novae, Supernovae / Interstellar Space, Spallation / Compact-Star Regions, X-Ray Bursts, GRB

☞ Cosmic Chemical Evolution / Nuclear Reactions Regimes

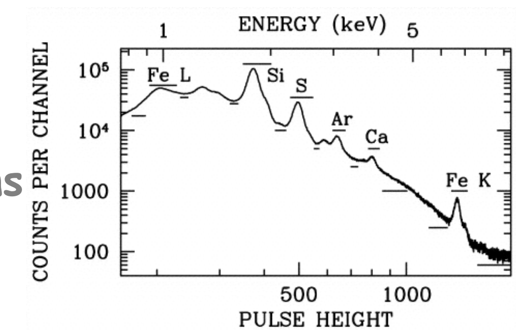
☆ Cosmic Radiation

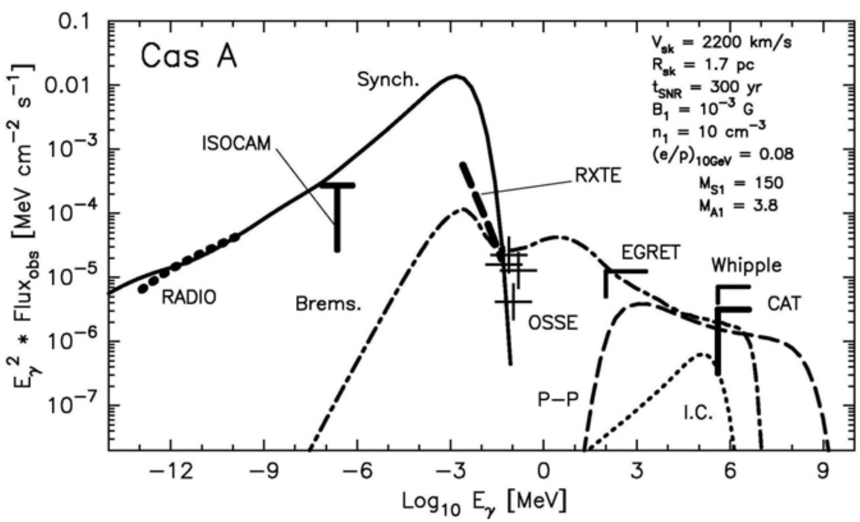
☞ Sources, Acceleration Processes

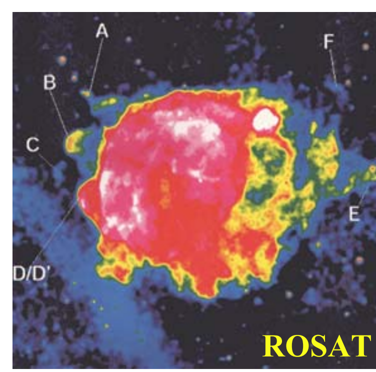
☞ Transport in Interstellar (and intergalactic) Space

Hot Plasma

- T >> 6000K
  - Matter Ionized: Ions and Electrons
  - Processes:
    - Coulomb Scatterings
    - Bremsstrahlung / Free-Free Radiation
    - Recombinations / Ionizations
    - Comptonization / Compton Scattering
  - Thermal and Non-Thermal Particle Populations (->Radiation Components)



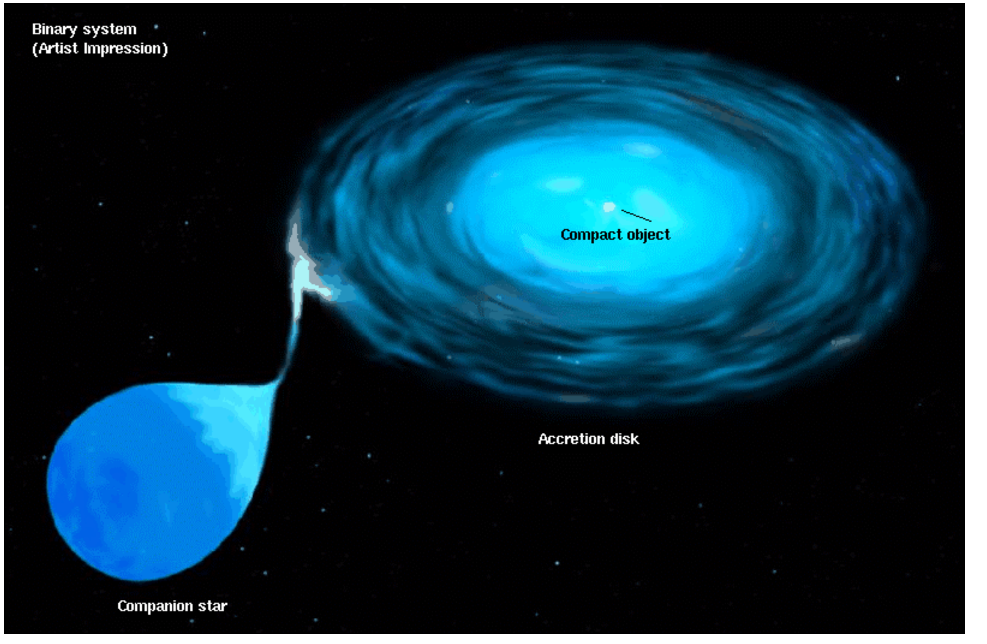


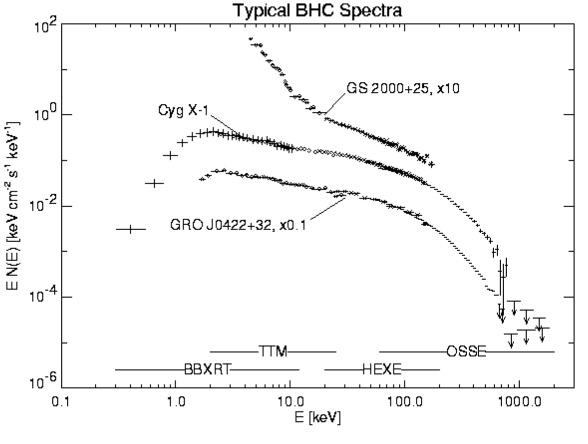


Accretion onto Compact Objects

- ☆ Angular Momentum of Matter Flow from Companion -> Accretion Disk
- ☆ Accretion Flow Dynamics -> Luminosity / Spectral "States", Instabilities
- ☆ Radiation Sources:
  - Accretion Disk
  - Corona
  - Compact-Star Surface

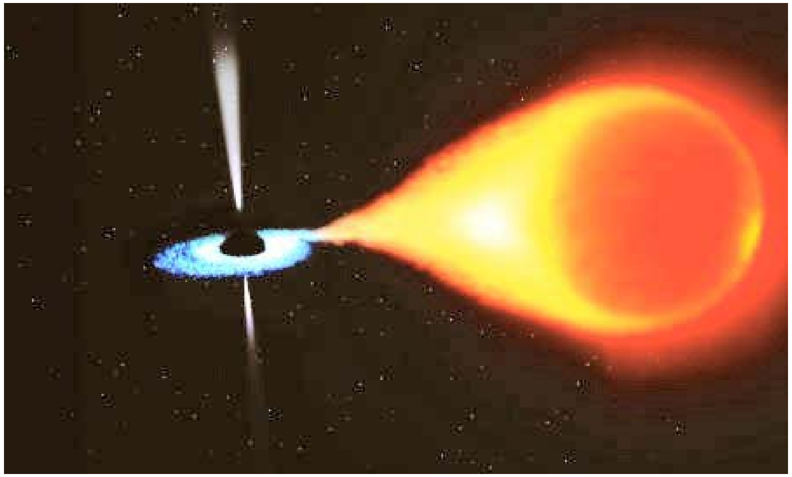
☞ Scattering, Absorption





(Cyg X-1: Wilms et al., 1996, ; GRO J0422+32, GS2000+25: Sunyaev et al., 1993, Kroeger [priv. comm.])

Plasma Jets from Accreting Compact Stars



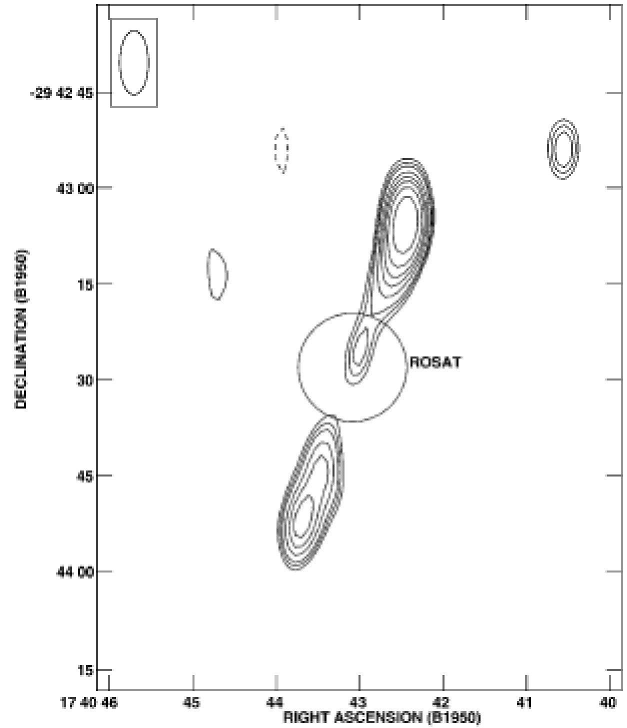
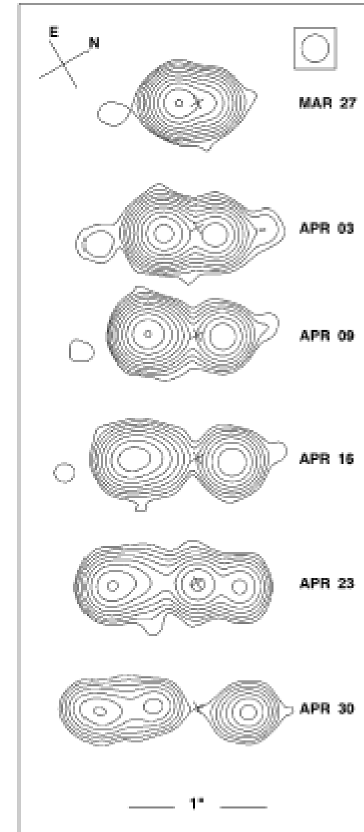


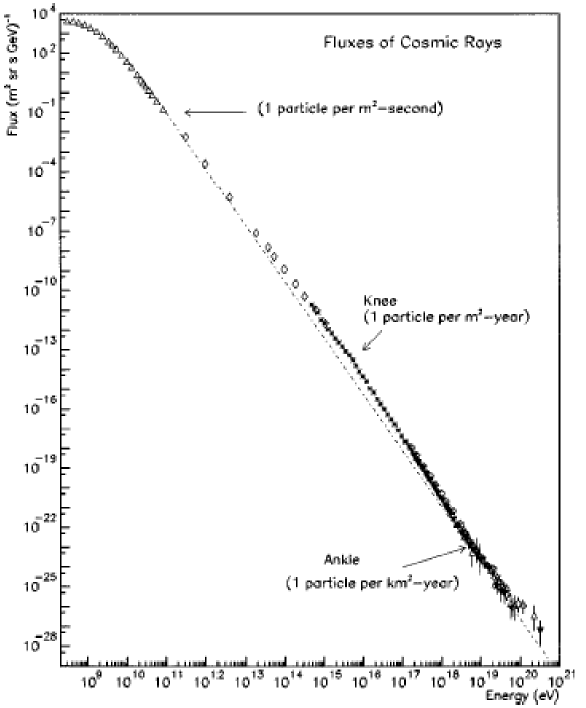
Figure 1 Contour map of the 6-cm emission from the radio counterpart of 1E1 740.7-2942, as observed with the Very Large Array (Mirabel et al 1992; Rodriguez & Mirabel 1999c). The error circle of the ROSAT position (Heindl et al 1995), that includes the core source, is also shown. At a distance of 8 kpc the length of the jet structure would be ~5 pc. The half power contour of the beam is shown in the top left corner. Contours are −4, 4, 5, 6, 8, 10, 12, 15, and 20 times 28 μJy beam^{-1}.



- “Micro-Quasars” from Jets of Accreting Stellar-Mass Sized Compact Objects
- X-Ray and Radio/γ Emission from Hot Plasma & Relativistic Particles
- “Superluminal” Plasma Blobs Traced in Radio Emission

Acceleration of Particles

- Accelerating Environments
  - ☆ Electrostatic Fields
    - ☞Pulsars
  - ☆ Magnetic Fields
    - ☞Near Compact Stars -> … ~10^{13}G
    - ☞In Stellar Environments & SNae -> … ~ G
    - ☞Galactic and Intergalactic Space -> … ~μG
    - ☞Turbulent Magnetic Fields in Shocked Gas
      - Jets (AGN, … , GRB?)
      - SNR
- Processes
  - ☆ Fermi II
    - ☞Scattering on "Magnetic Mirrors", e.g., Interstellar Clouds at Random Motion
  - ☆ Fermi I
    - ☞Scattering on Magnetic-Field Turbulences on Both Sides of Shocked-Gas Region



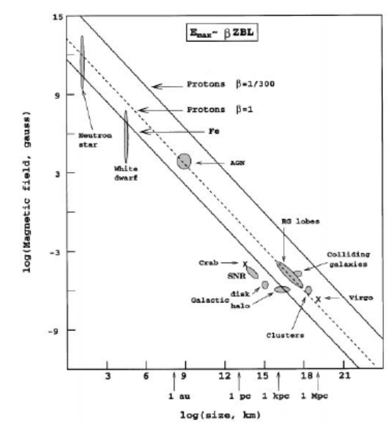


FIG. 3. Modified Hillas plot (Hillas, 1984). Size and magnetic field of possible sites of acceleration. Objects below the dashed line cannot accelerate protons to 10^{20} eV.

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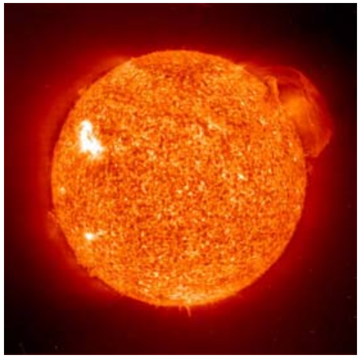
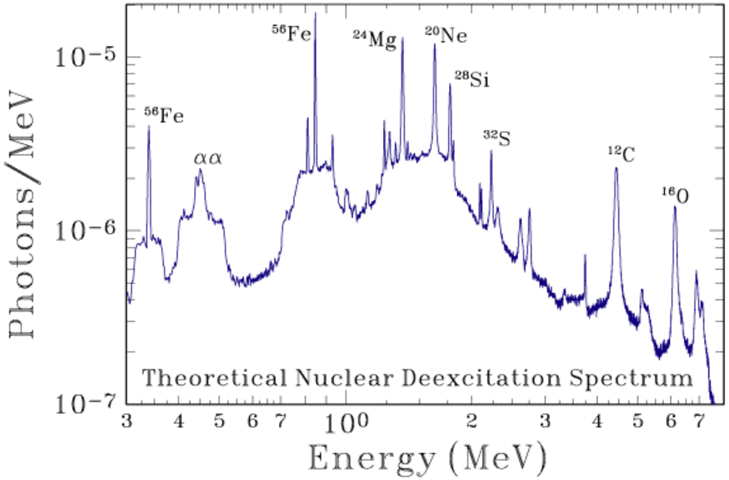
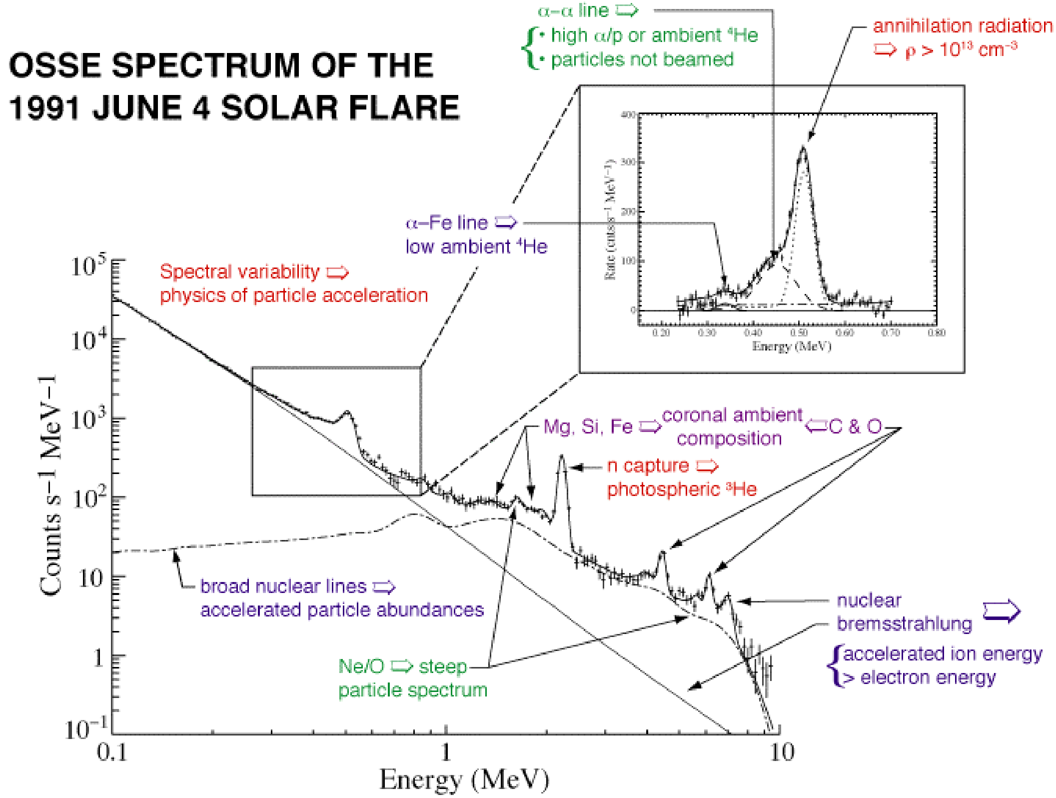
Solar Flares: Laboratories for Particle Acceleration



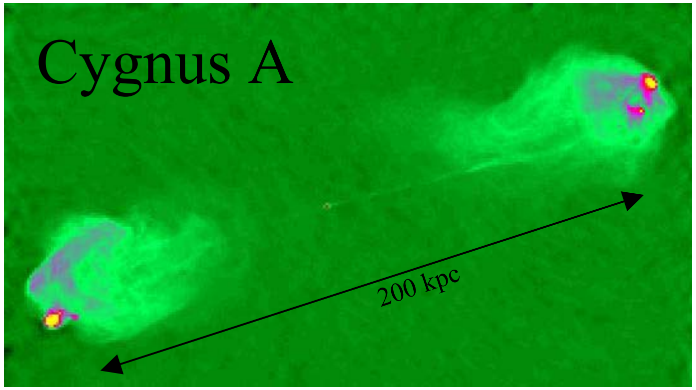


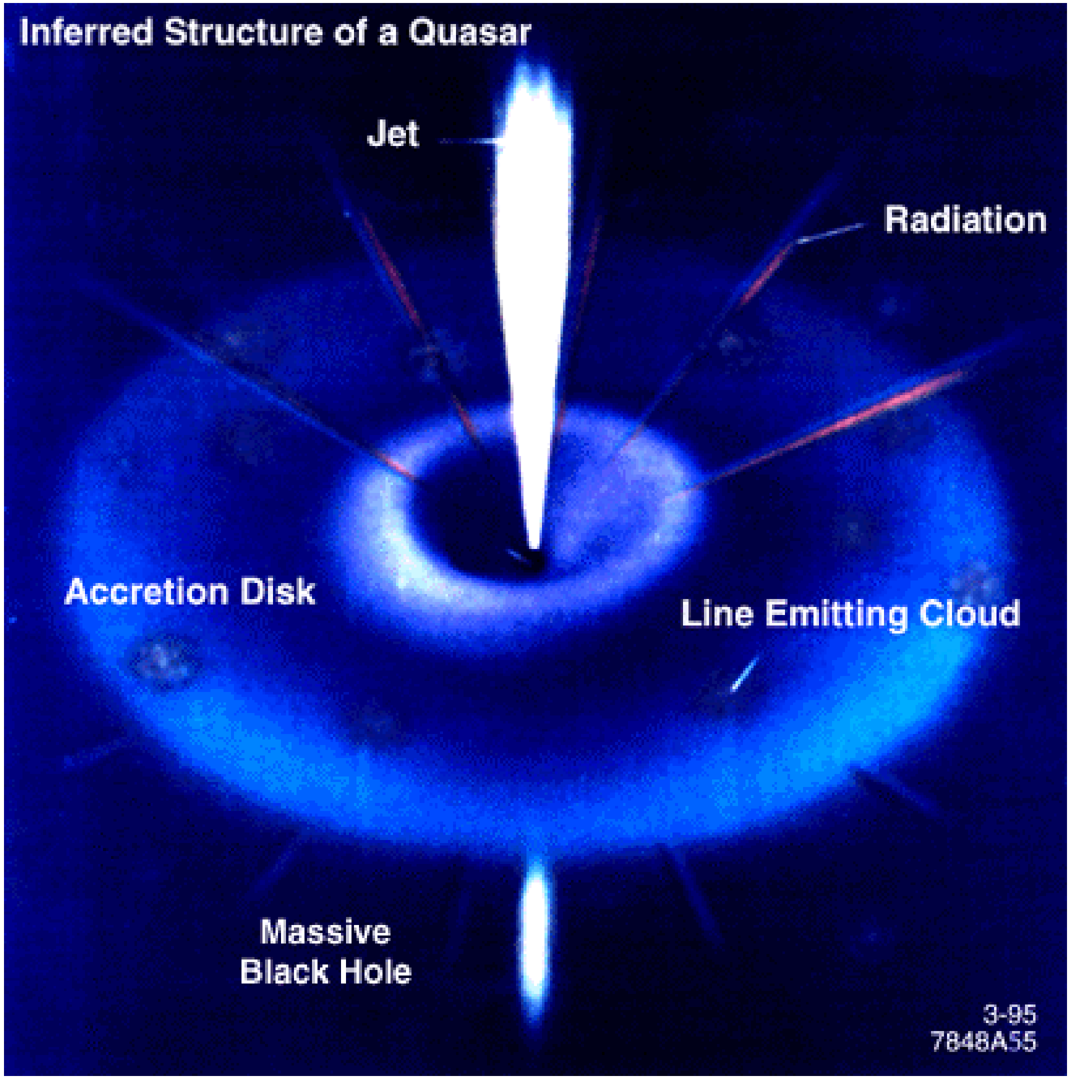


- Particle Acceleration from Magnetic-Field Reconfigurations
- Interactions of Energetic Parcticles with Solar Matter

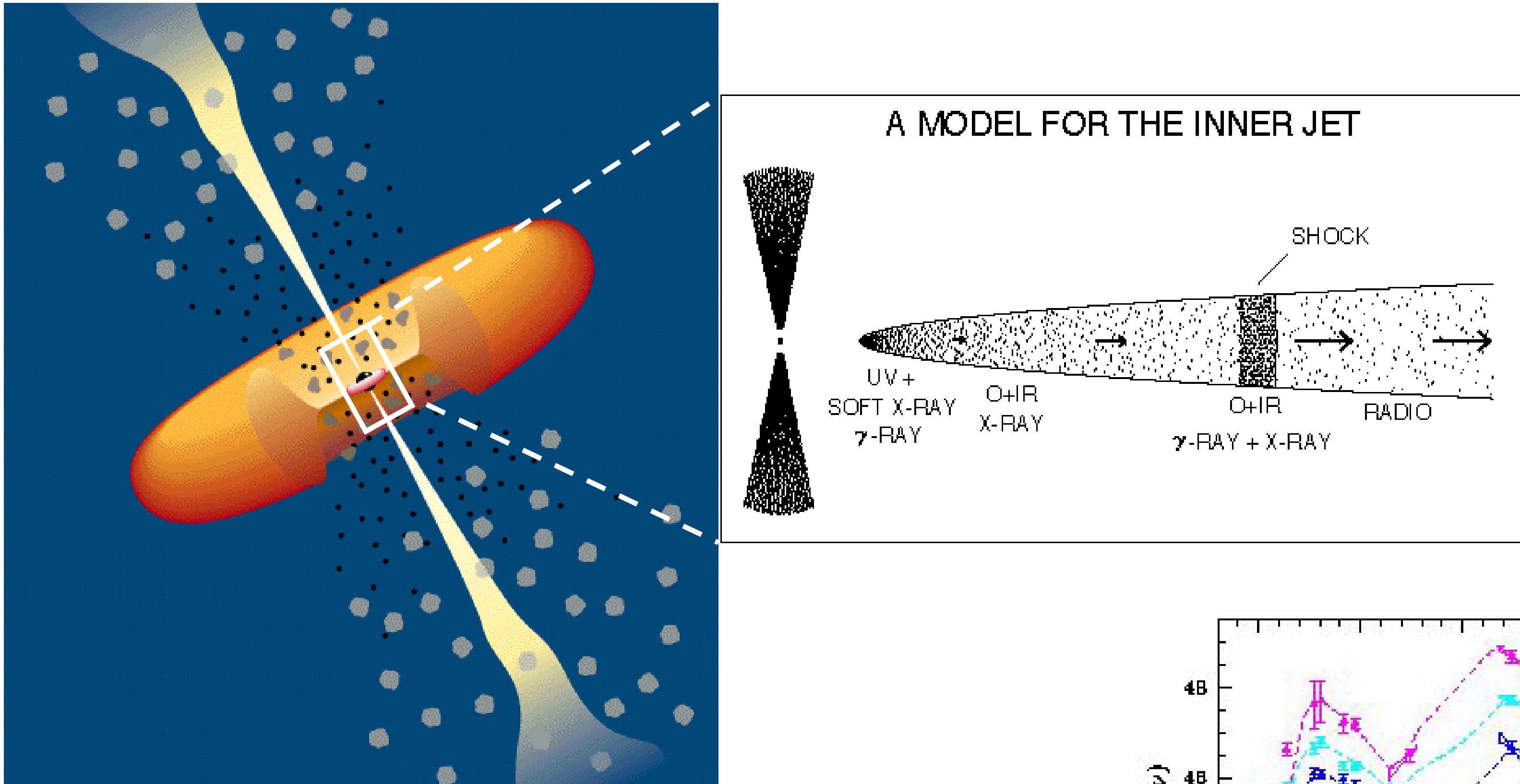
Accretion and Accelerated Plasma Jets: Quasars

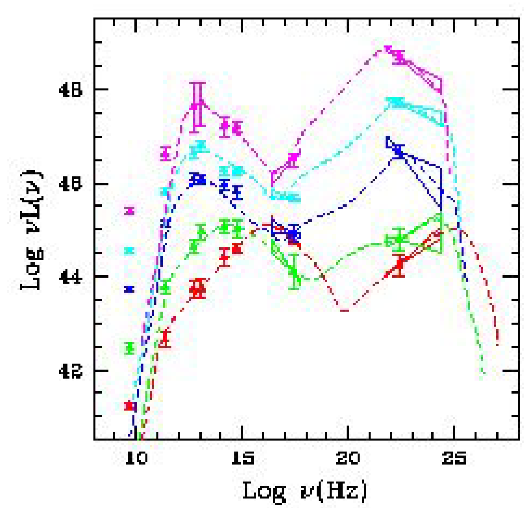
- ☆ Supermassive Black Hole Accretion
  - ☞ Large-Scale Accretion Flows
  - ☞ Accretion Luminosity Interaction with Surrounding (Structured) Interstellar Matter
  - ☞ Large-Scale Plasma Jet





Active Galactic Nuclei Radiation Phenomena





- *AGN: Central Region Outshines Galactic Starlight by Orders of Magnitude*
- *Seyfert Galaxies:= active galactic nucleus seen from the side / through absorbing matter*
- *Blazar:= active galactic nucleus where we view almost along the axis of one of the jets*

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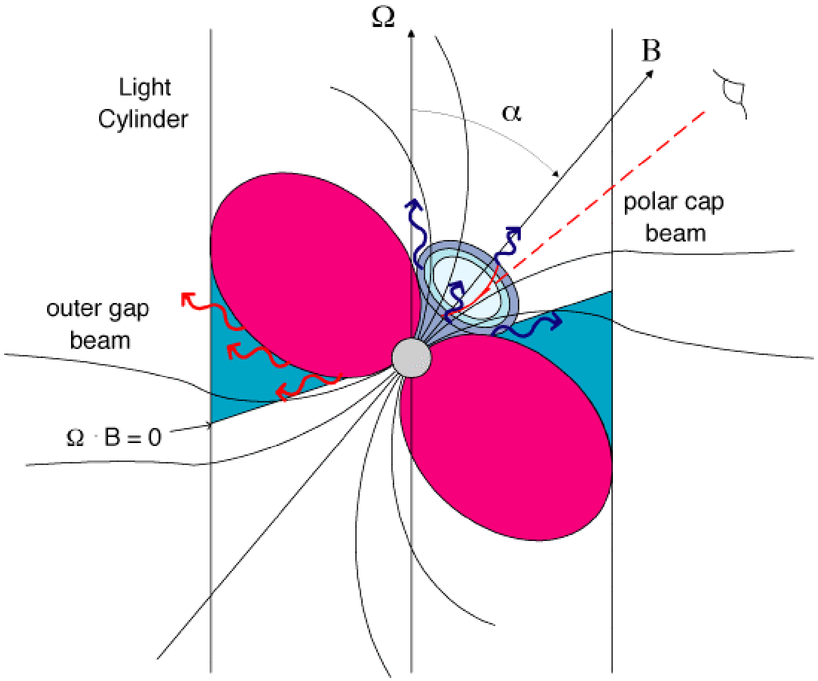
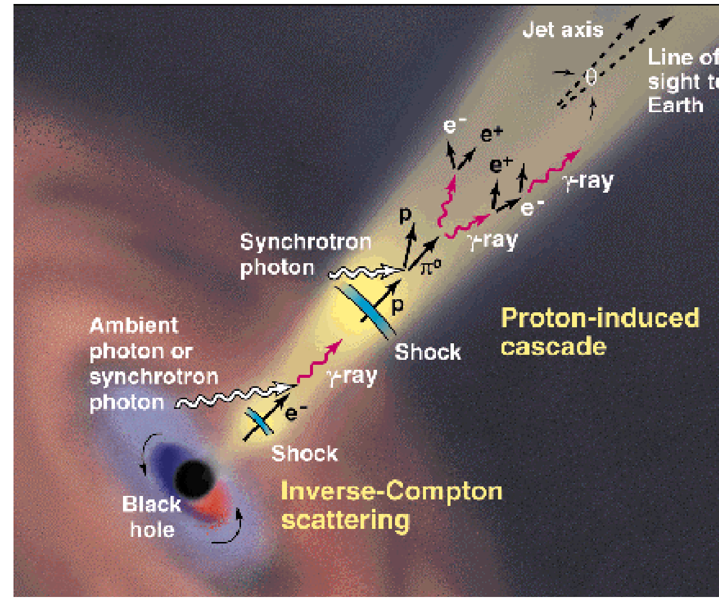
High-Energy Interactions of Cosmic Matter





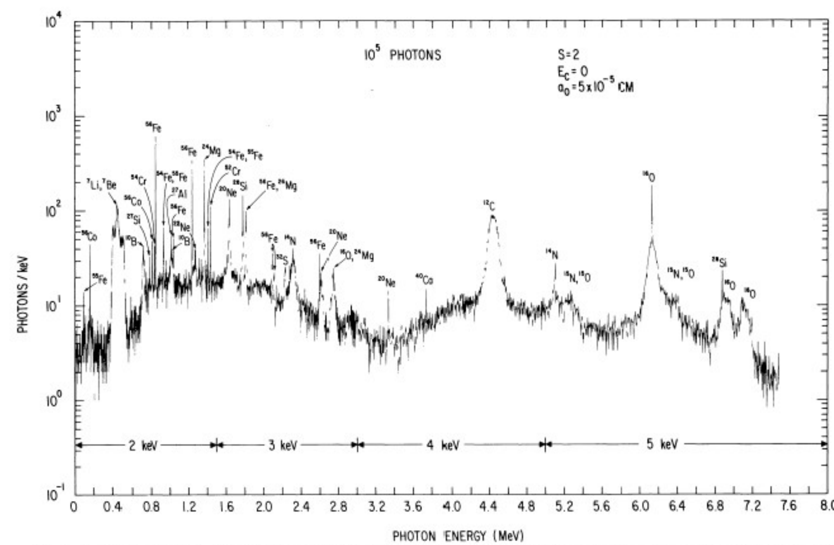


FIG. 18.—Monte Carlo simulated γ-ray spectrum for energetic particles and ambient medium having solar compositions; s and E_c are the spectral parameters of the energetic particles, and a_0 is the characteristic radius of the interstellar grain distribution.

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

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Nucleosynthesis: Understanding Abundances

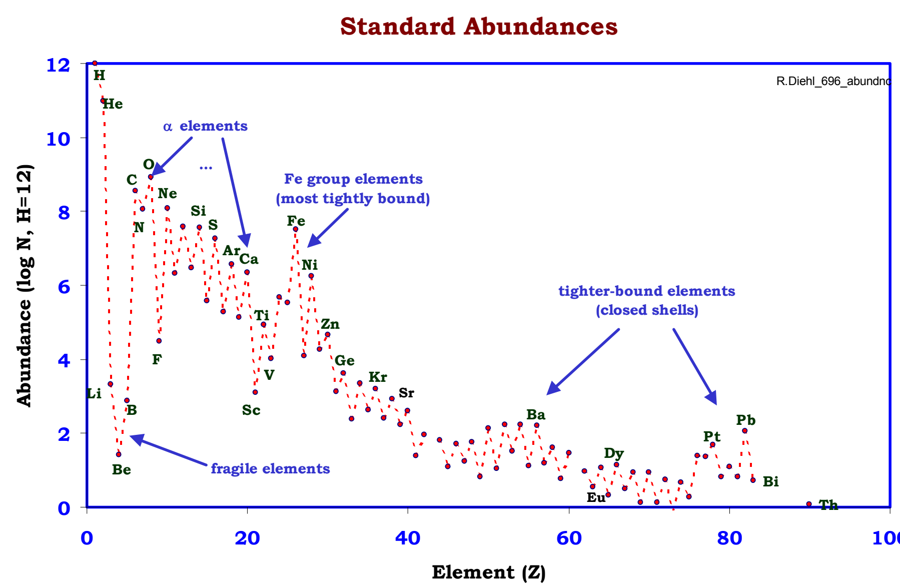
☆ Observed Abundances Show Characteristic Patterns

- ☞ 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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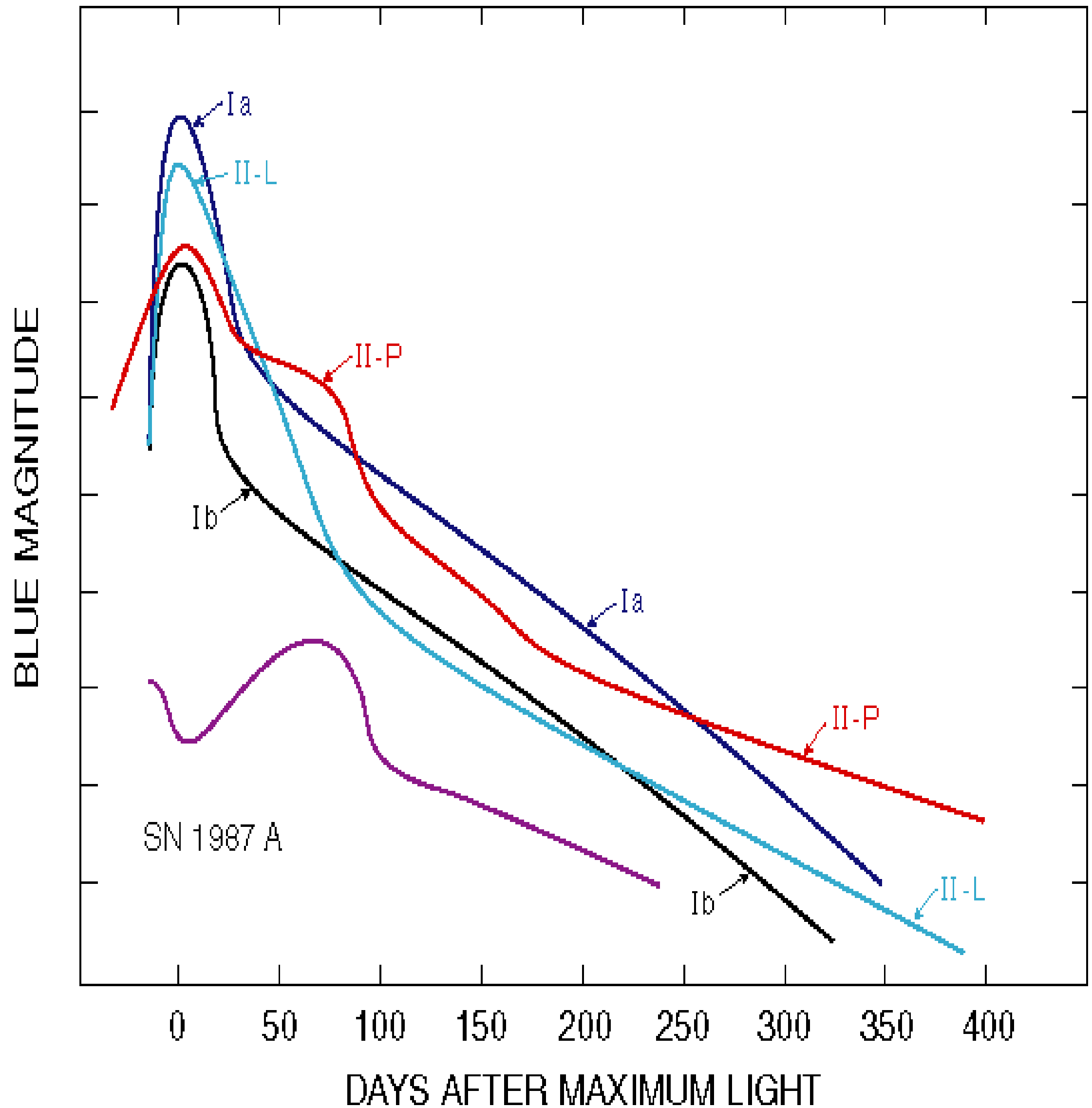
Supernovae

- Explosion of a Star
- Nuclear Energy Release
  - ☆ Radioactive By-Products of Explosive Nucleosynthesis
  - ☆ Progressive Transparency of Exploding Star
  - ☆ Thermonuclear Supernovae (Type Ia)
  - ☆ Gravitational Collapse



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Supernovae and Supernova Remnants

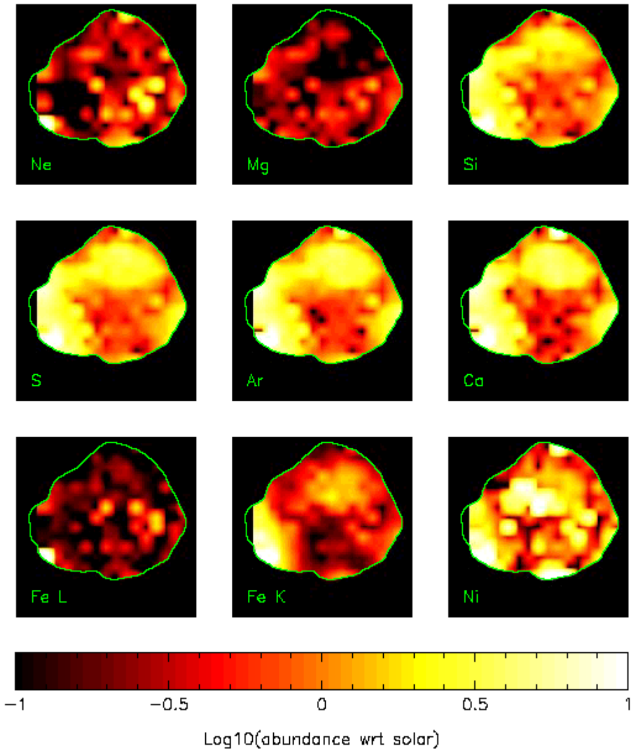


Fig. 5. Abundance maps for the elements included in the spectral fitting. All are plotted on the logarithmic scale indicated by the bar at the bottom.

Cas A / XMM

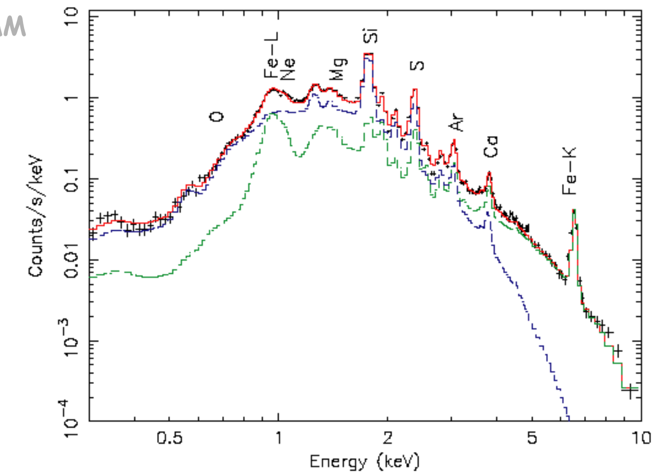
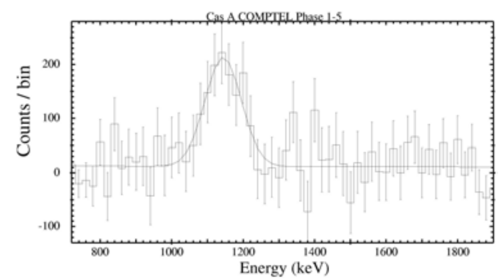


Fig. 2. An example of a spectral fit within a single 20″ × 20″ pixel – cool component in blue, hot component in green and full model in red.



Cas A ^{44}Ti (τ~89y) / COMPTEL

- Prompt SN Light from Radioactivity
- SN Debris Reflects Nucleosynthesis (and Collapsing-Star Structure)
- Interaction of Blast Wave with ISM Results in Shocked Gas & Recombination Radiation

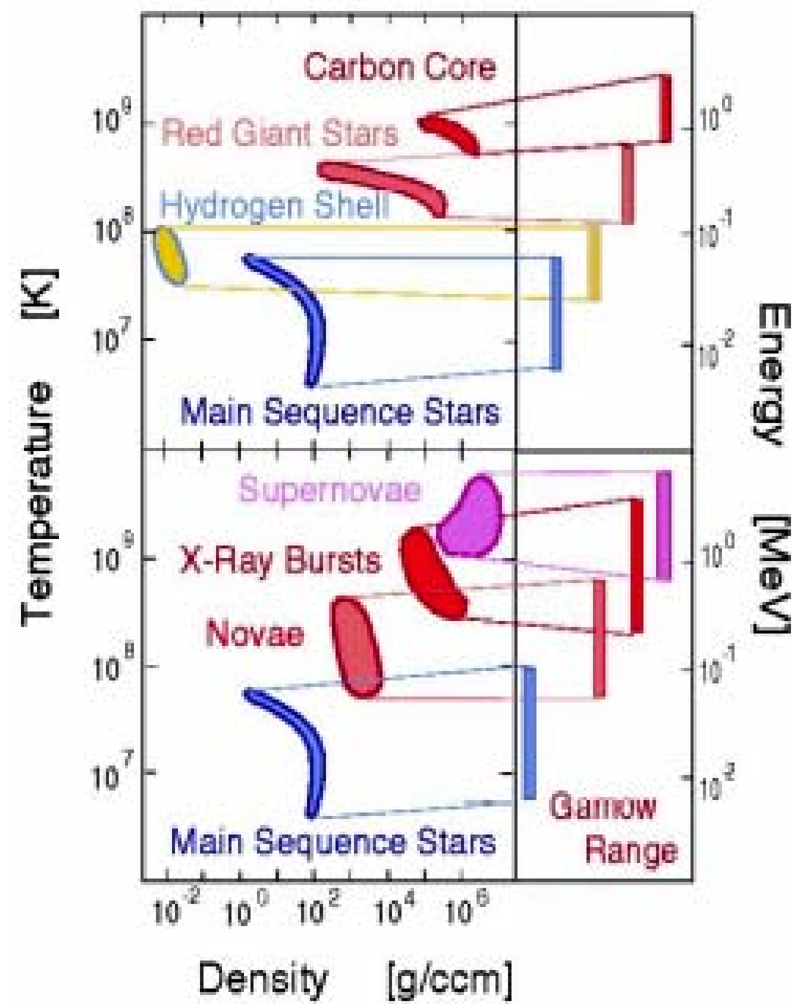
Cosmic Nucleosynthesis Environments

Nuclear Burning Requirements:

- $E_{nuclear-burning} = \langle \sigma v \rangle * Q \geq$ Local Cooling Rate

=>

Dense & Hot Environments



for a Stellar Mass Range of 1-30 M_o:

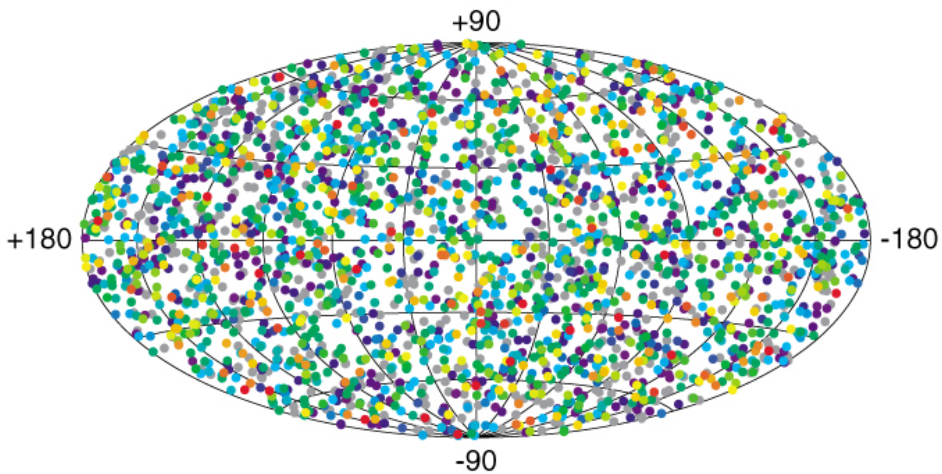
- Nuclear Burning in Stellar Cores and Shells (top)
- Nuclear Burning in Explosive Sites (bottom)
- Gamov Windows (righthand side)

Gamma-Ray Bursts

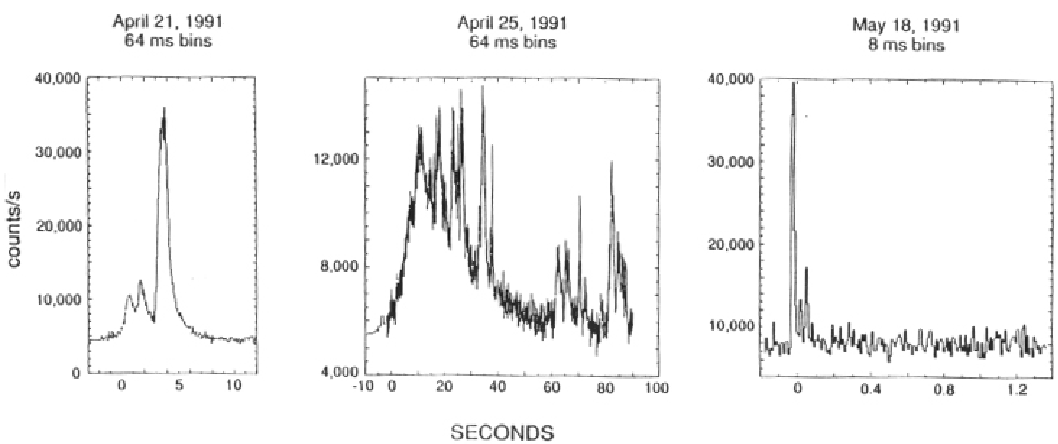
prompt

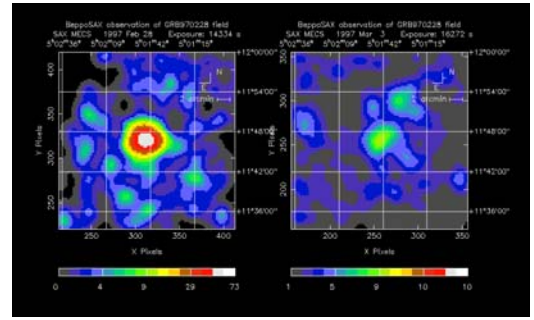
afterglow

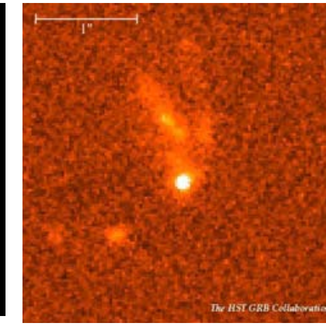
2704 BATSE Gamma-Ray Bursts



BATSE—GRO
3 Types of Gamma-Ray Bursts
50-300 keV







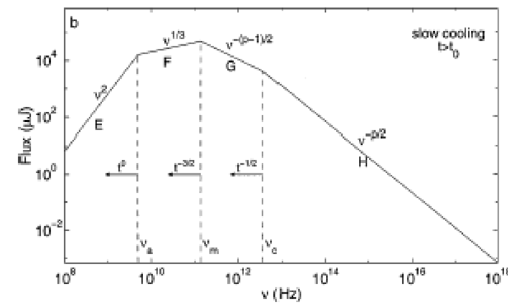
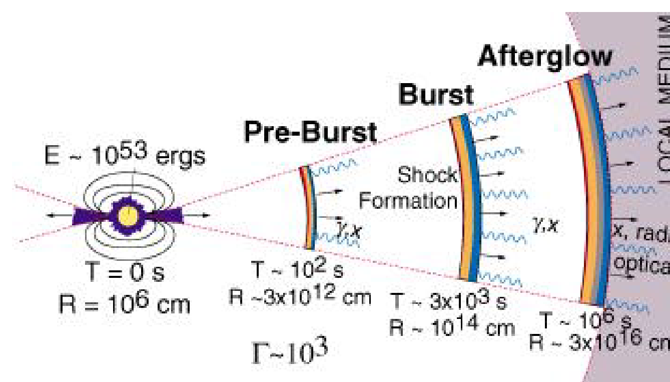


Figure 3 The piecewise power-law schematic shape of blast wave synchrotron spectra for later afterglow evolution (Sari et al 1998). The characteristic break frequencies and their time evolution are indicated, as is the spectral slope in each regime. This can be directly compared with the observed spectrum of GRB 970508 (Figure 12).



The Cosmic Cycling of Matter