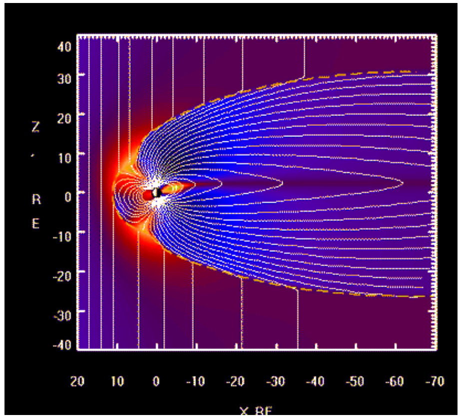
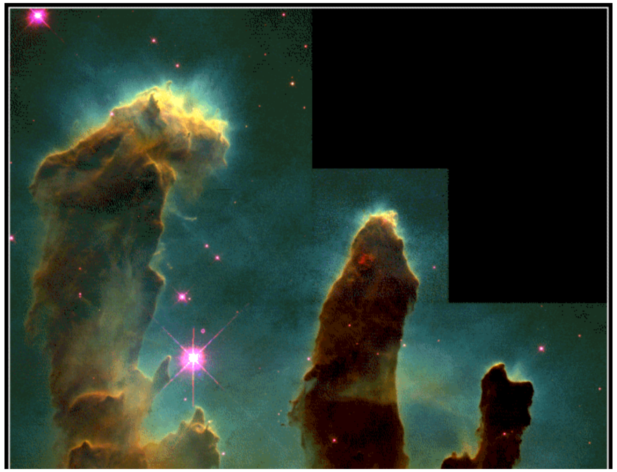
High-energy astrophysics (in a nutshell)

Xavier Barcons
Instituto de Física de Cantabria (CSIC-UC)

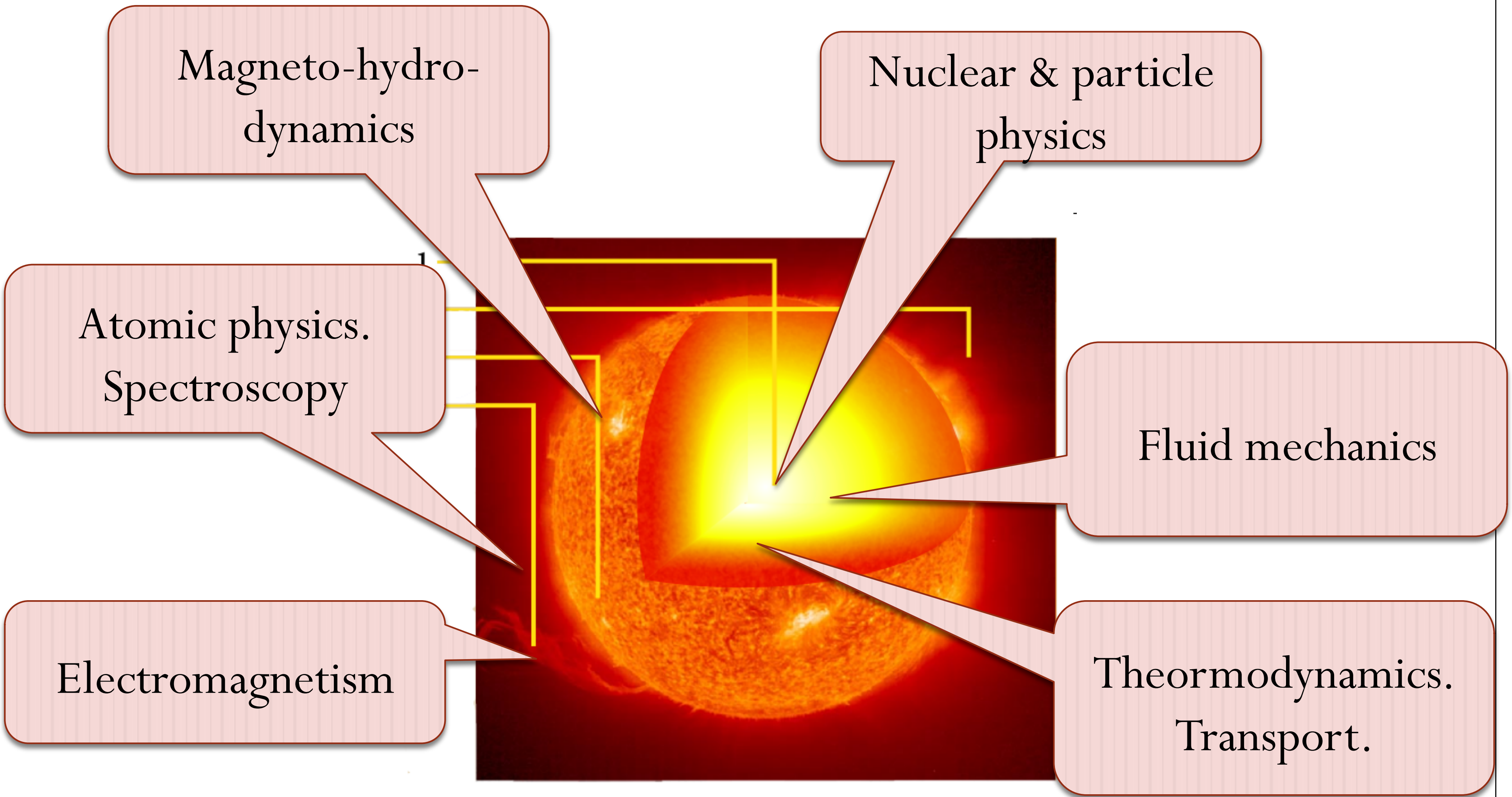
What is Astronomy?

- **Astronomy:** Study and understand celestial bodies. Includes:
  - Astrophysics
  - Astrobiology
  - Cosmology
  - Other (you name it)
- **Possibly, the most ancient science**
- **Huge societal and cultural impact**
- **Encompasses**:
  - Astronomical observations (from ground and space)
  - "In-situ" exploration
  - Theory, computing, etc.
- **Not an experimental science**





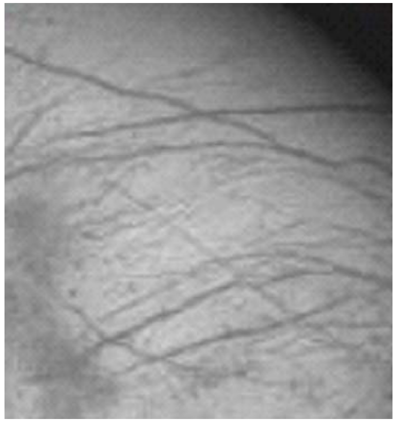
A multi-disciplinary science

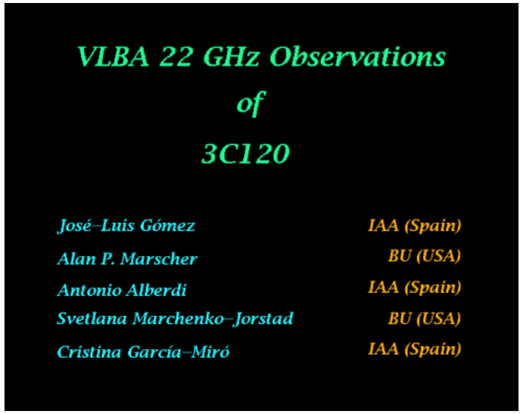


Very multi-disciplinary

Chemistry

Mathematics

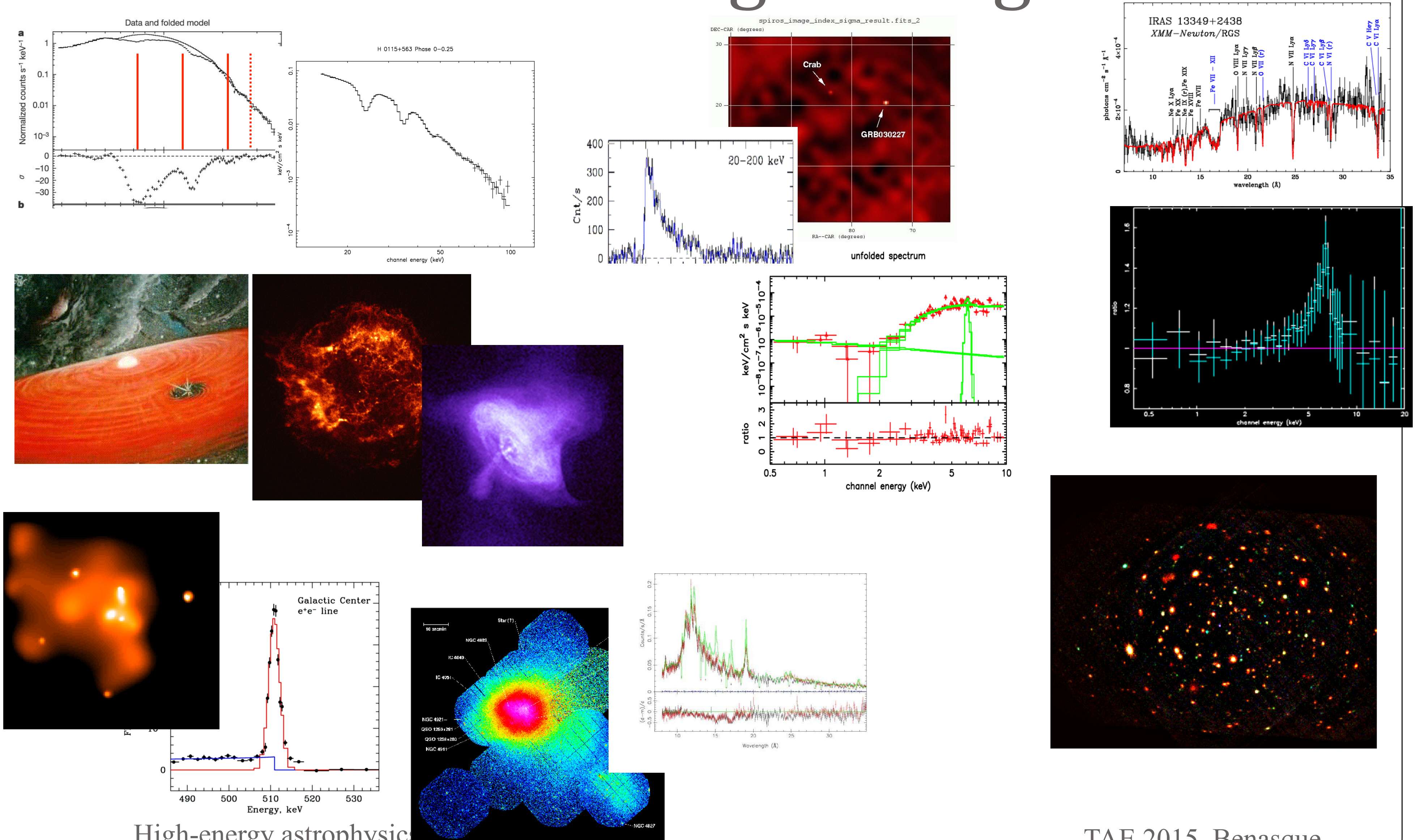




Biology

Physics

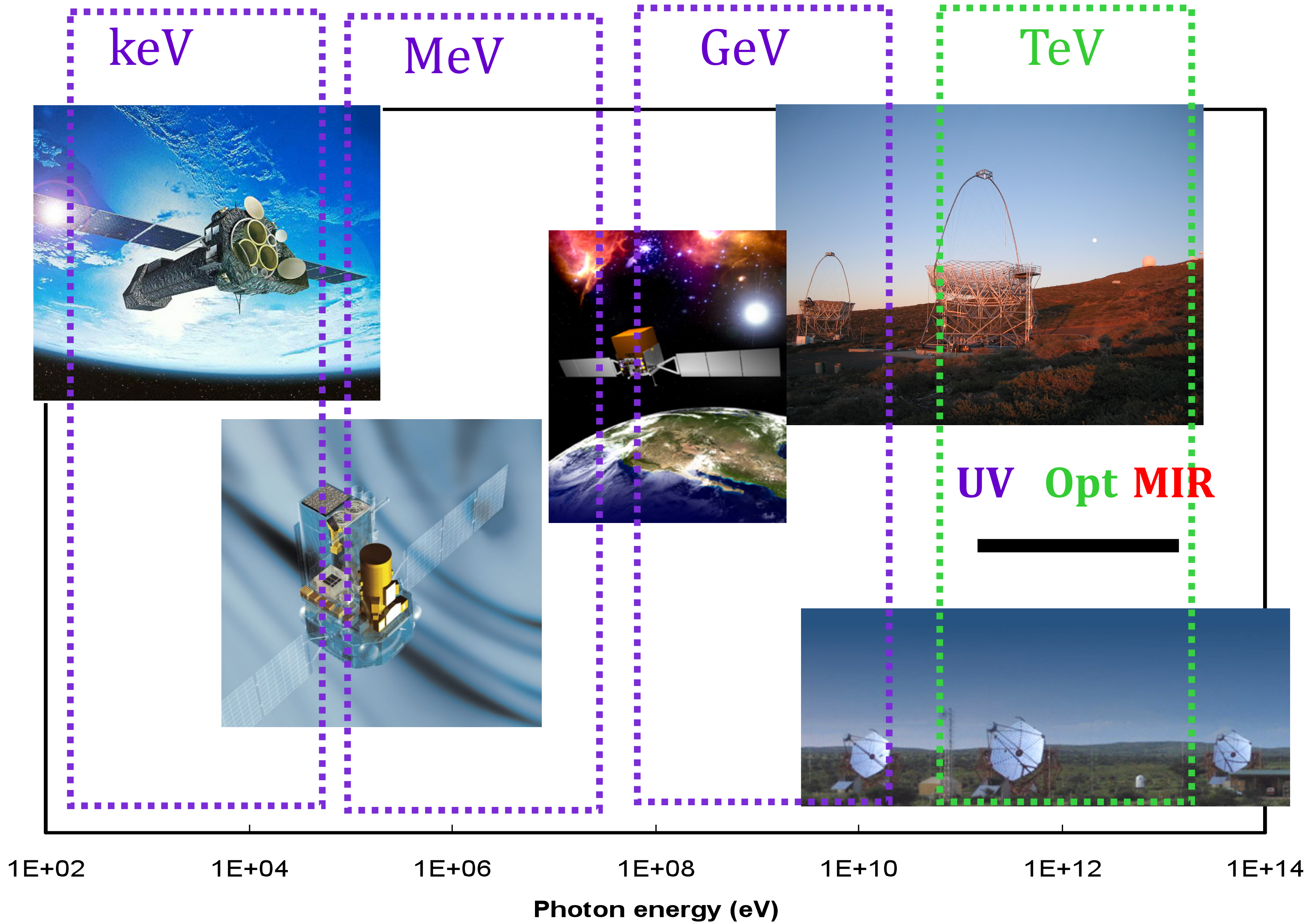
What do we see at high-energies?



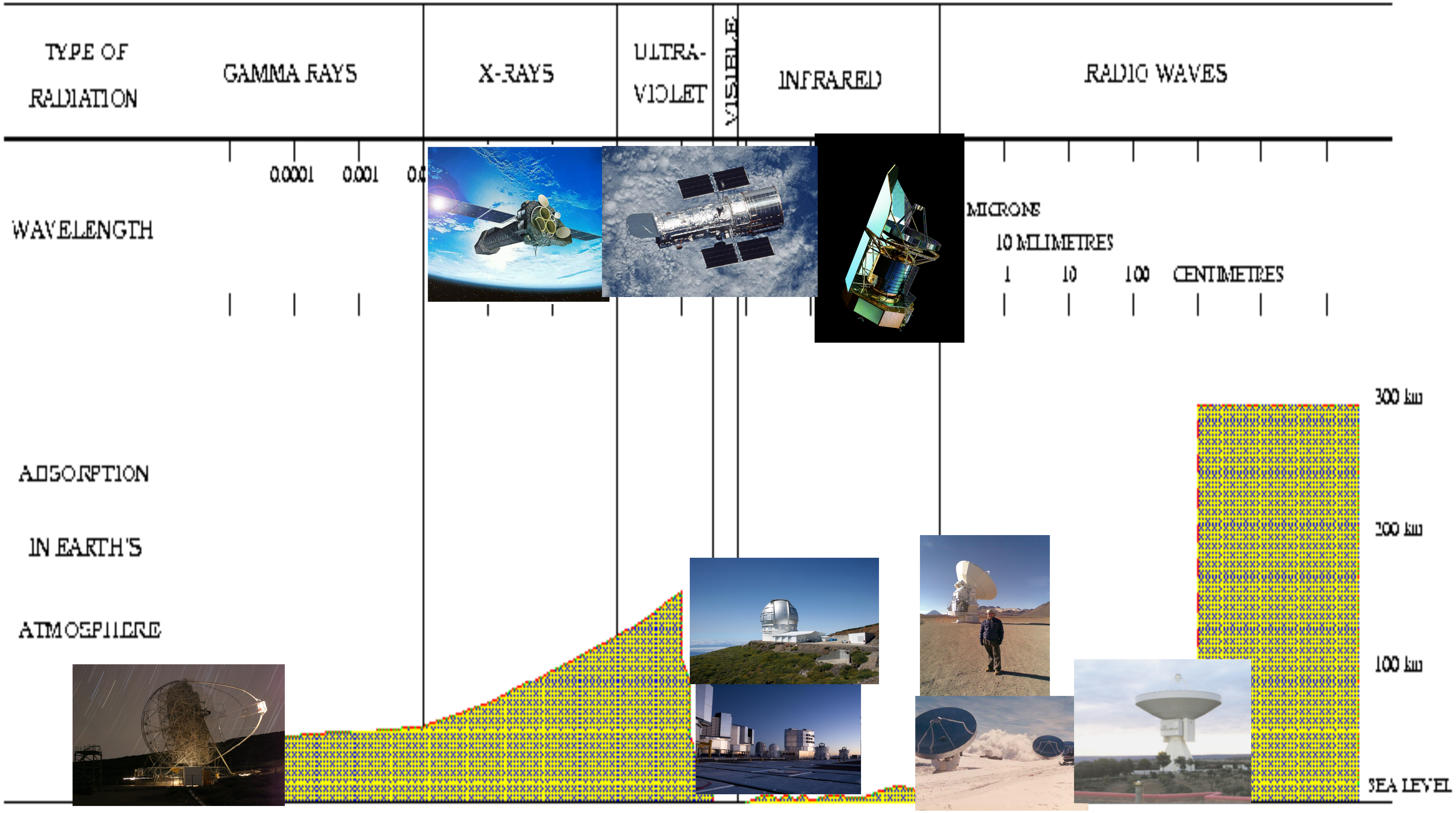
Contents

- Introduction
- Physical processes in High-Energy Astrophysics
- Technologies in High-Energy Astrophysics

From X-rays to VHE γ-rays

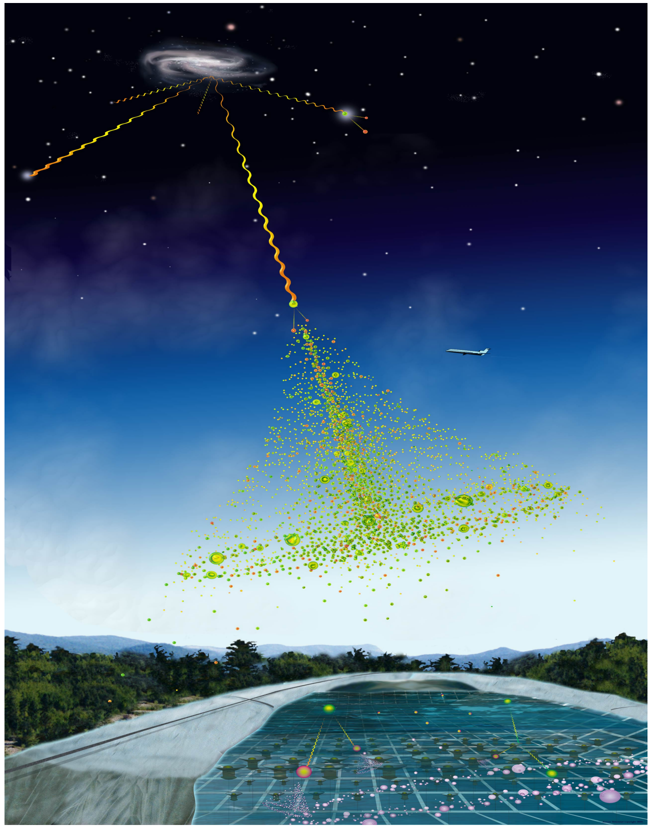


Earth’s atmosphere

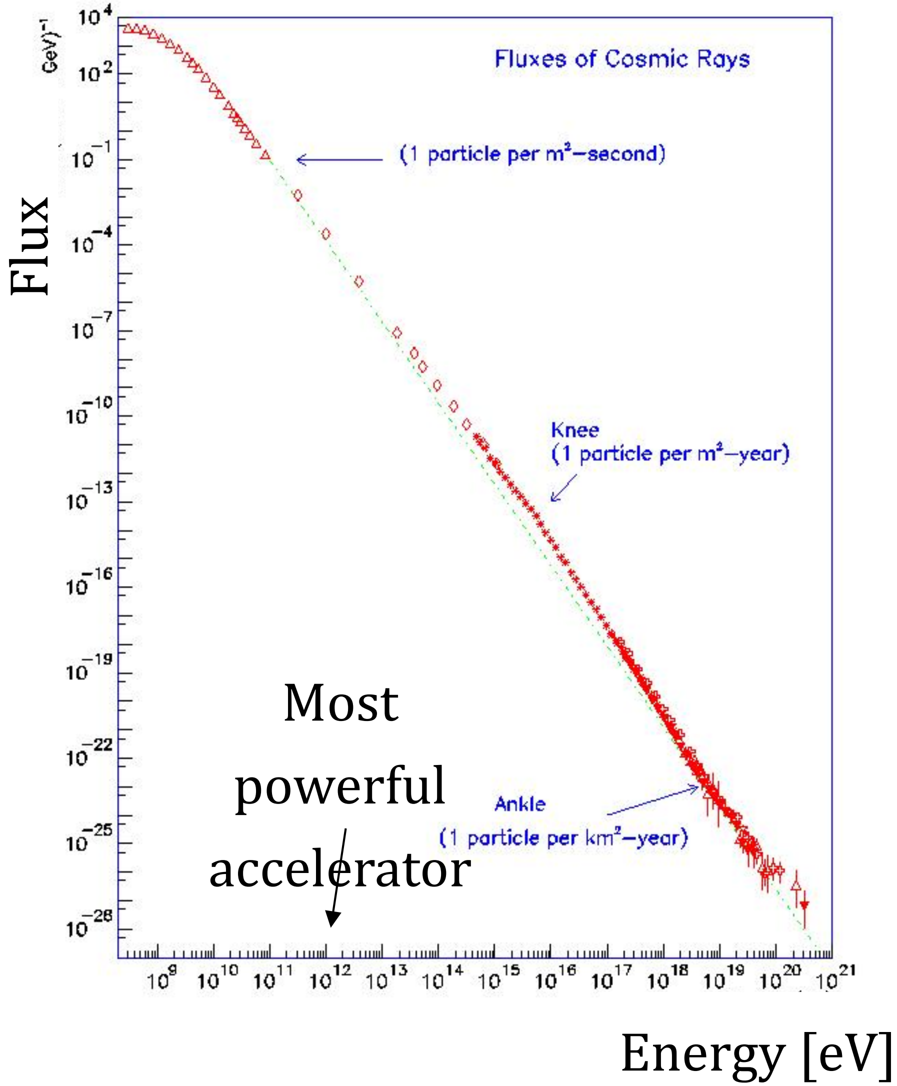


The messengers

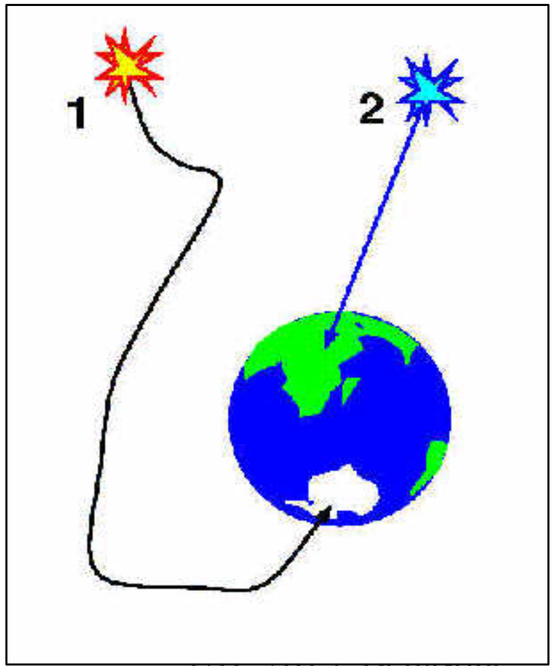
- Electromagnetic radiation:
  - X-rays
  - γ-rays
- Cosmic rays
- Neutrinos
- Gravitational waves



Cosmic rays

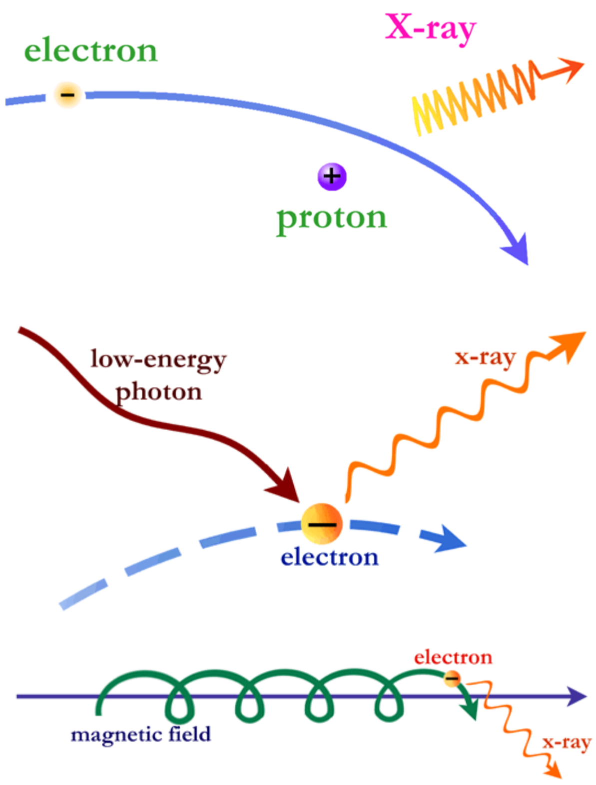


- Composition: 99% atomic nuclei
- Energies: 12 decades
- Flux: between $1/m^2/s$ and $1/km^2/yesr$



Physical processes

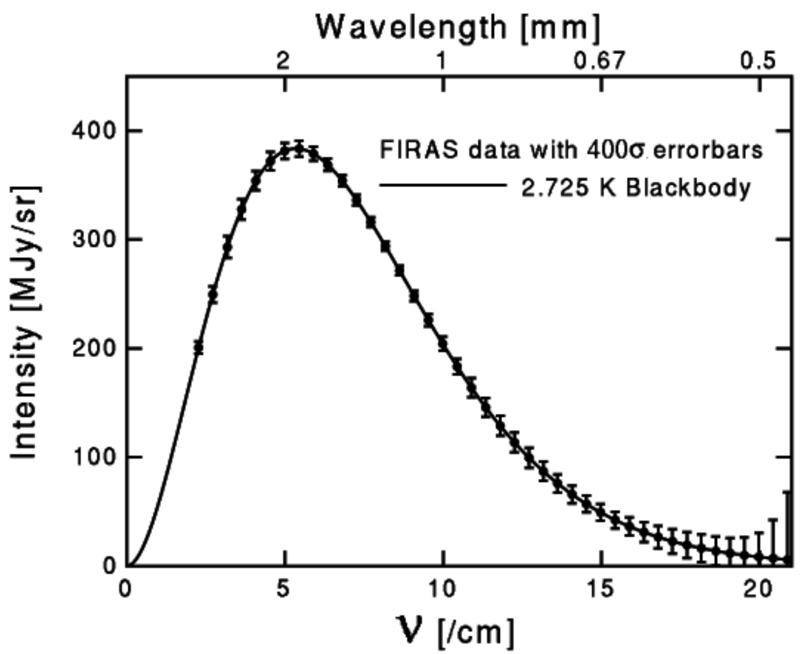
- Blackbody
- Cyclotron & synchrotron
- Bremsstrahlung
- Compton effect
- Pair creation & annihilation
- Radiation from atoms & ions
- Atomic absorption
- Radiation from nuclei



Blackbody

Example: CMB radiation

- Matter-radiation equilibrium leads to Blackbody emission
- Needs many interactions (thick matter) and long times
- Example: Solar photosphere (few cm thick) is a BB @ 5700 K

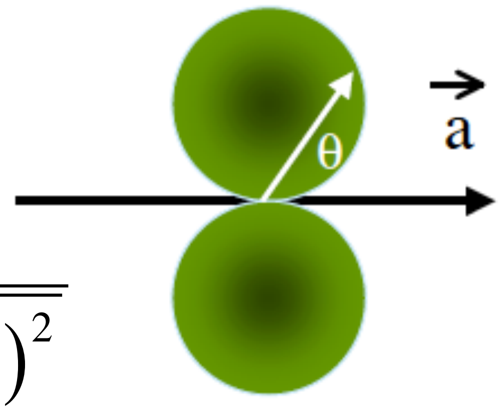


Some fundamentals

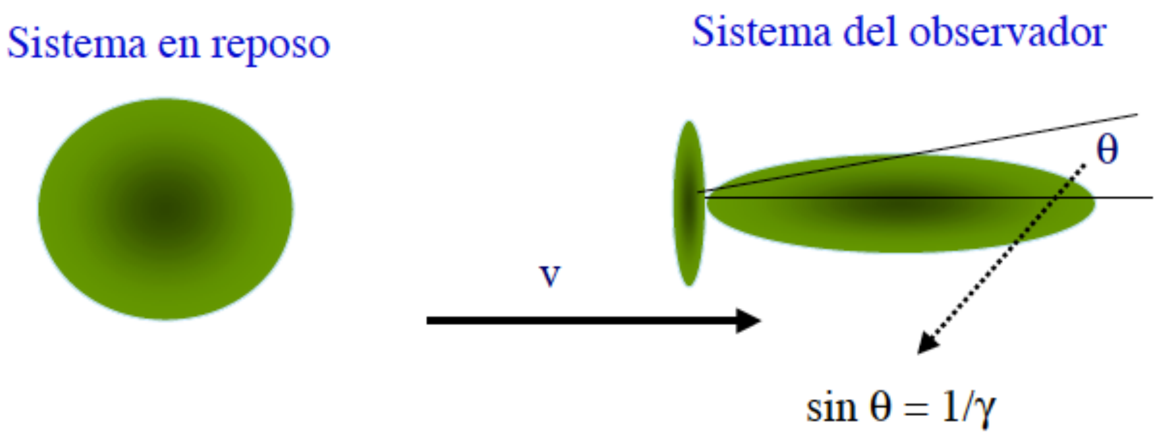
Radiation from moving charges: Larmor's formula

$$\frac{dE}{dt} = \frac{2q^2}{3c^3}\gamma^6\left[\vec{a}^{\,2} - \left(\vec{v}/c \times \vec{a}\right)^2\right]$$

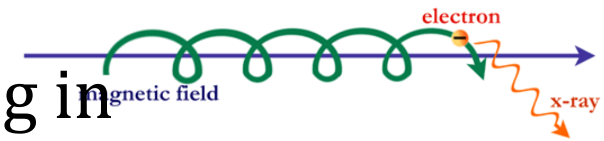
$$\gamma = \frac{1}{\sqrt{1-(v/c)^2}}$$



Relativistic beaming



Cyclotron radiation



- Charge moving in magnetic field
- Gyro frequency

$$\nu_B = \frac{eB}{4\pi\gamma mc} =$$

$$2.8/\gamma \ MHz/Gauss$$

- Radiated power

$$\frac{dE}{dt} = \frac{4}{3}\sigma_T c\left(\frac{v}{c}\right)^2 \gamma^2 U_B$$

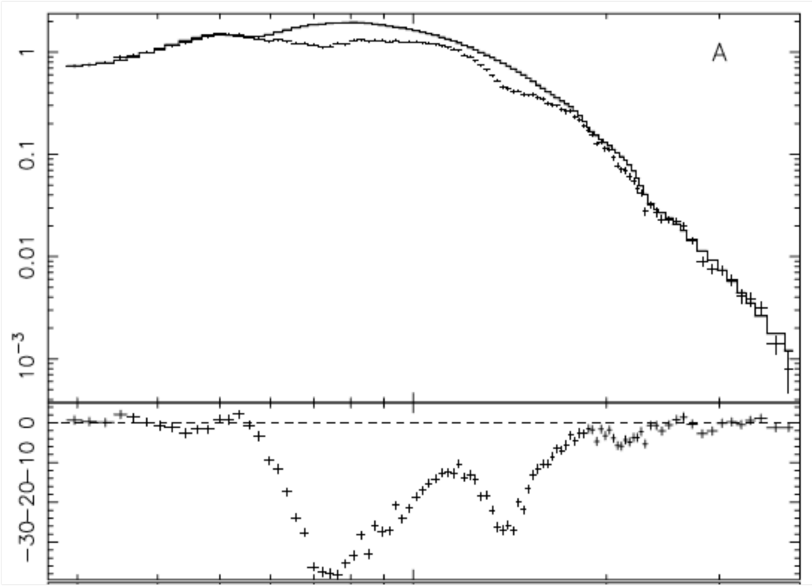
$$\sigma_T = 6.55\times10^{-25}cm^{-2}$$

$$U_B = \frac{B^2}{8\pi}$$

- Discrete spectrum, frequency υ_B.

Cyclotron absorption lines in Neutron Stars

- Isolated neutron stars emit a Black Body continuum (2.5 10^6 K for 1ES1207.4-5209)
- 4 absorption lines (0.7, 1.4, 2.1 and 2.8 keV) are present (harmonics of 0.7 keV)
- $B=8\times10^{10}$ Gauss

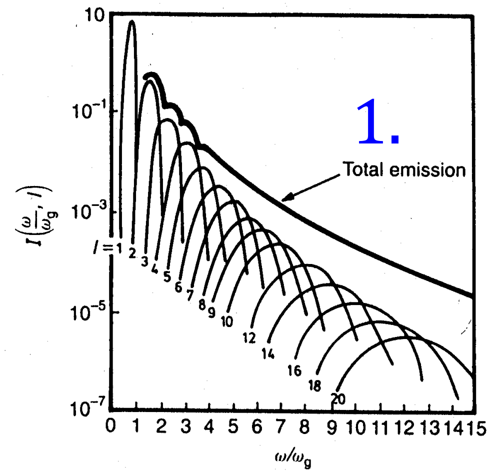


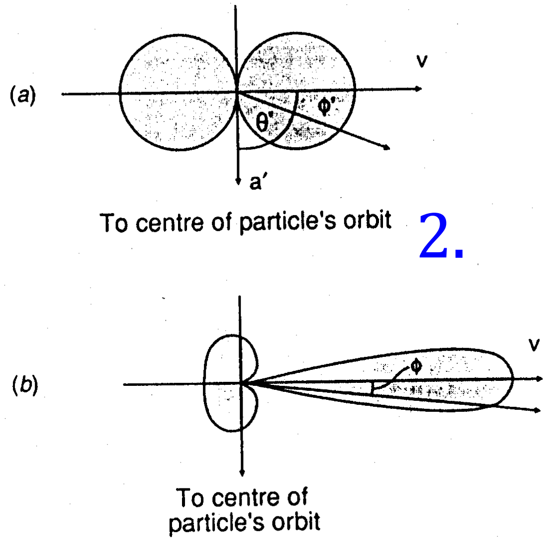
Bignami et al 2003, Nat, 423, 725

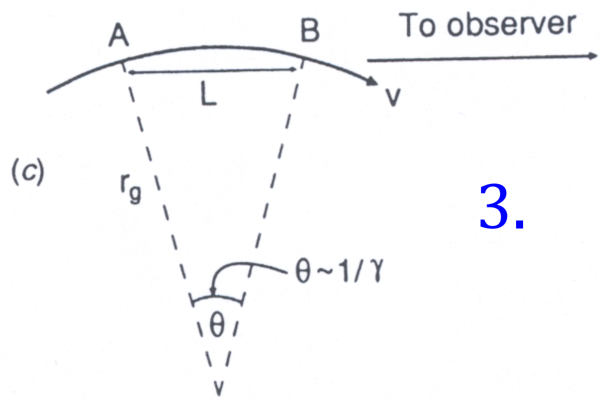
Synchrotro radiation

- Relativistic electrons in a magnetic field:
    1. Higher order harmonics υ_B
    2. Relativistic beaming
    3. Doppler effect:

  $\upsilon_{obs} \approx \gamma^2 \upsilon_{em}$







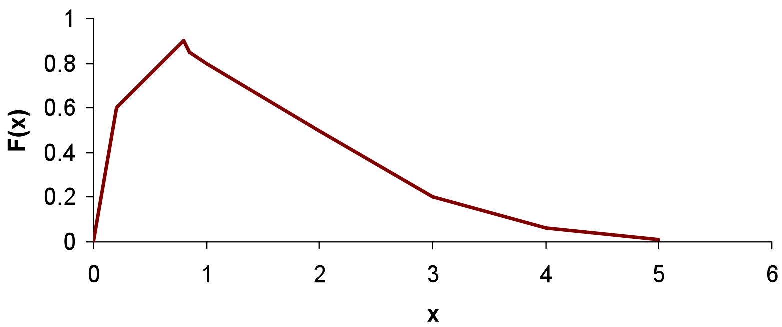
Spectrum of Synchrotron radiation

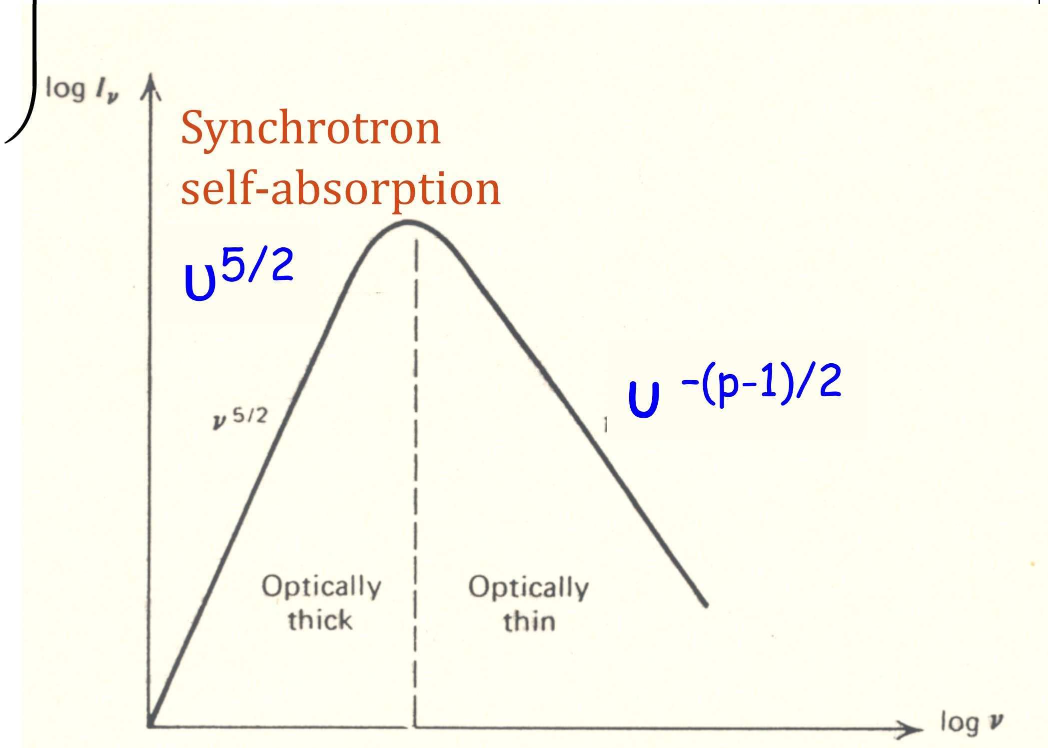
Single electron energy
γmc^2

$N(\gamma) = const\ \gamma^{-p}$

$$\frac{dE}{d\omega} = B_{\perp} \frac{3^{1/2} e^3}{mc^2} F\left(\frac{\omega}{\omega_c}\right)$$

$$\omega_c = \frac{3eB}{4\pi mc} \gamma^2 \sin\alpha$$

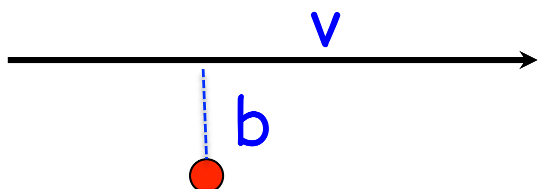


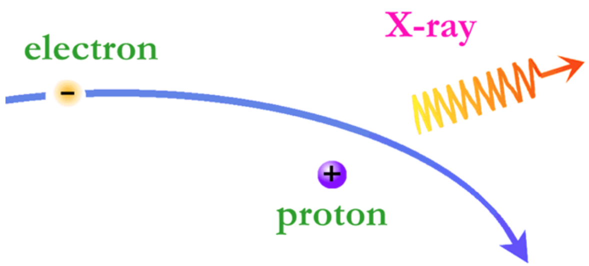


Bremsstrahlung

Basic concept

- Bending of electron trajectory when approaching an ion





Spectrum

- Break frequency

  $\upsilon_0 = v/4\pi b$
- Spectrum:

$$\frac{dE}{d\nu} \propto const \qquad \nu << \nu_0$$

$$\frac{dE}{d\nu} \propto \nu \exp\left(-\frac{\nu}{\nu_0}\right) \qquad \nu >> \nu_0$$

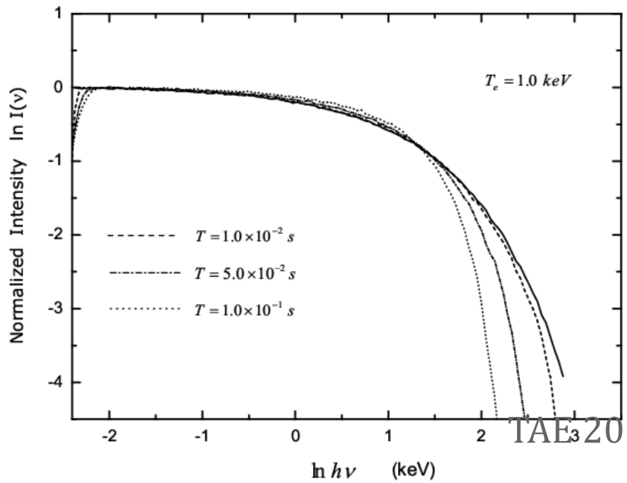
Thermal bremsstrahlung

Electrons at temperature T

$$\frac{d\mathrm{E}}{dVd\upsilon} \propto Z^2 n_i n_e T^{-1/2} g(\nu,T)\exp(-h\nu/kT)$$

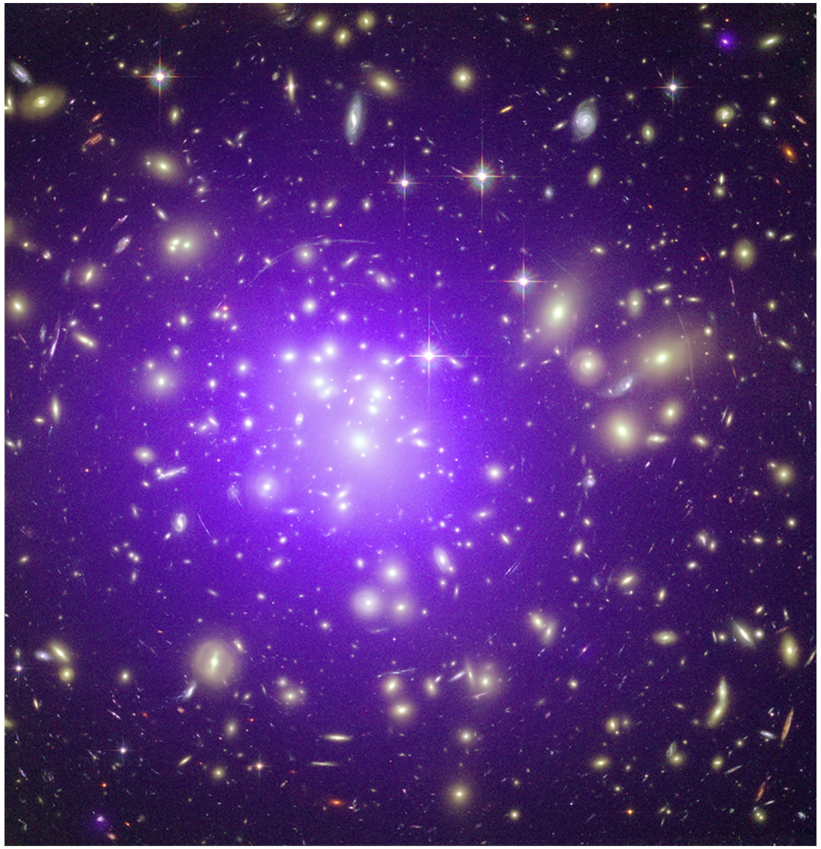
$$\frac{d\mathrm{E}}{dtdV} = 1.43\times10^{-41} Z^2 T^{1/2} n_i n_e \bar{g}(T)\; erg\; cm^{-3}\, s^{-1}$$

$$\times\left(1+const\left(\frac{kT}{mc^2}\right)\right)$$



Emission from the hot intra-cluster medium

Galaxy cluster A2029

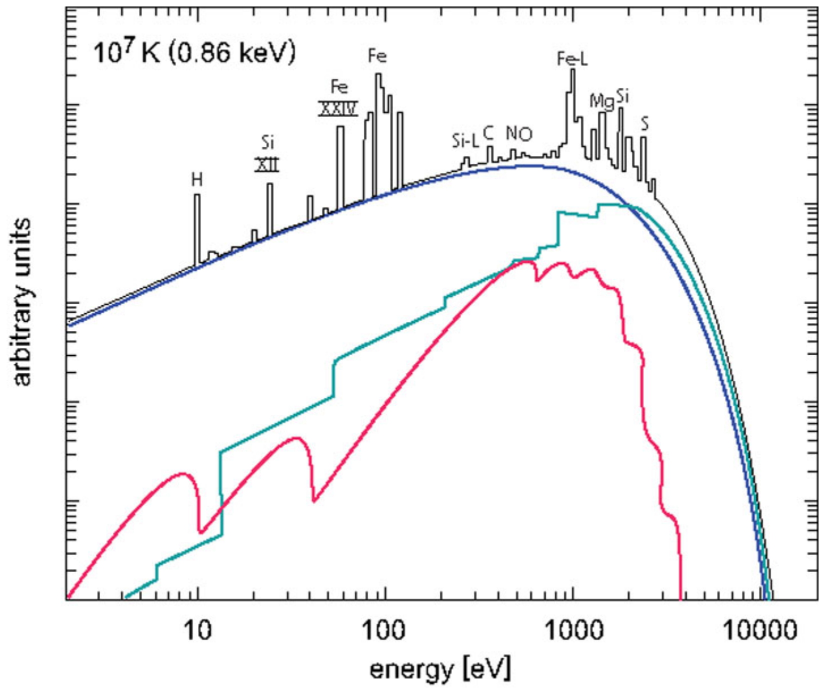


Clusters of galaxies

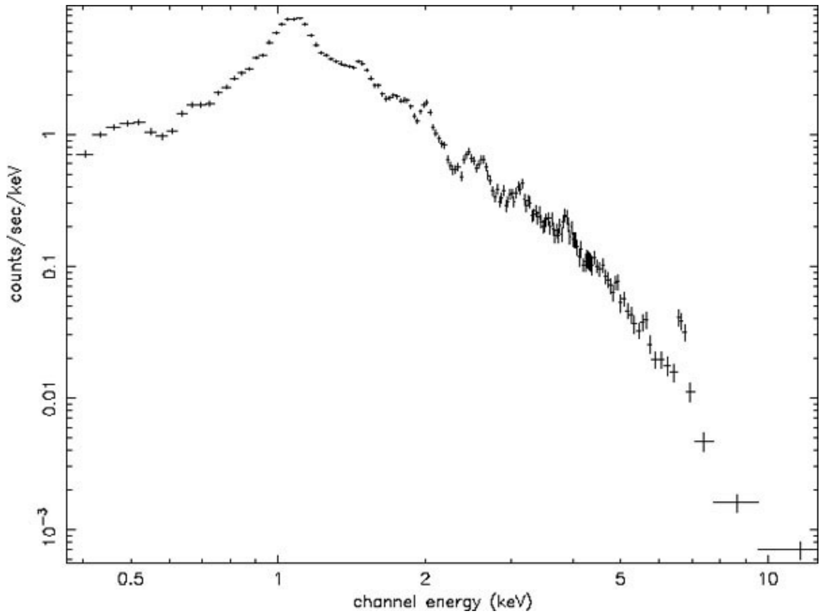
- Largest gravitationally bound structures
- Contain vast amounts of chemically enriched plasma at $T > 10^7$ K, dominating the baryonic component
- Gas is in hydrostatic equilibrium, and can be used to measure mass

Clusters: Bremsstrahlung & atomic line radiation

X-ray spectral model

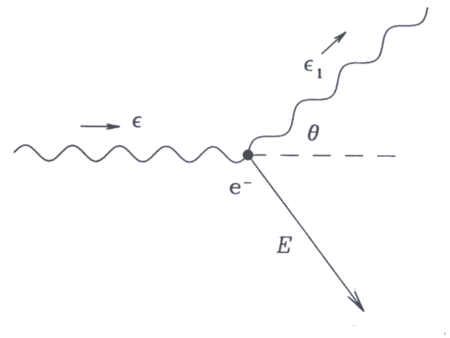


XMM-Newton X-ray spectrum of Virgo cluster



Compton effect

- Elastic scattering between electrons and photons

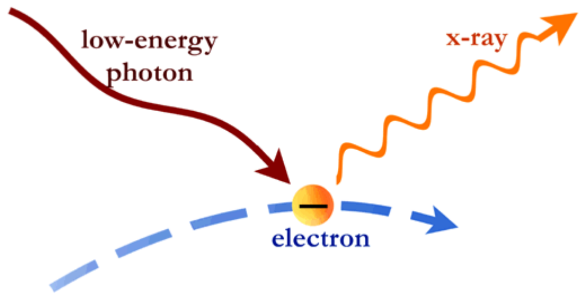


Thomson effect

$h\upsilon << mc^2$

Compton effect

- Direct $h\upsilon > E_{elec}$
- Inverse $h\upsilon < E_{elec}$



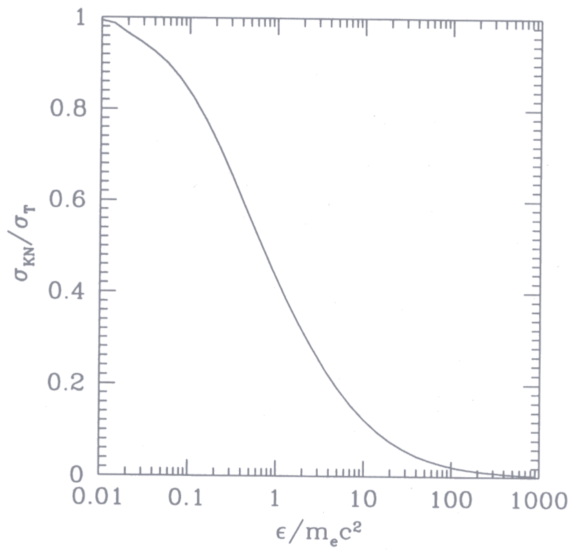
Thomson scattering

Interaction between radiation & electrons
without energy exchange

- Power dispersed by the electron

$$\frac{dE}{dt} = \sigma_T c U_\gamma$$

- Process is inefficient at relativistic energies (Klein-Nishina cross section)



Compton effect

Direct

- Electron initially at rest

$$E_{out} = \frac{E_{in}}{1 + \frac{E_{in}}{mc^2}(1 - \cos\theta)}$$

Inverse

- Relativistic electron

$$E_{out} \approx \gamma^2 E_{in}$$

- Total radiated power by Compton effect

$$\frac{d\mathrm{E}}{dt} = \frac{4}{3}\sigma_T c U_\gamma \left(\frac{v}{c}\right)^2 \gamma^2$$

Comptonisation (I)

Energy exchange per collision through Compton effect with thermal electrons

$$\frac{\Delta E}{E} = \frac{4kT - E}{mc^2}$$

Comptonisation parameter:

$$y = \frac{kT}{mc^2} N_{col}$$

Compton depth

$$\tau_T = \sigma_T \int n_e dl$$

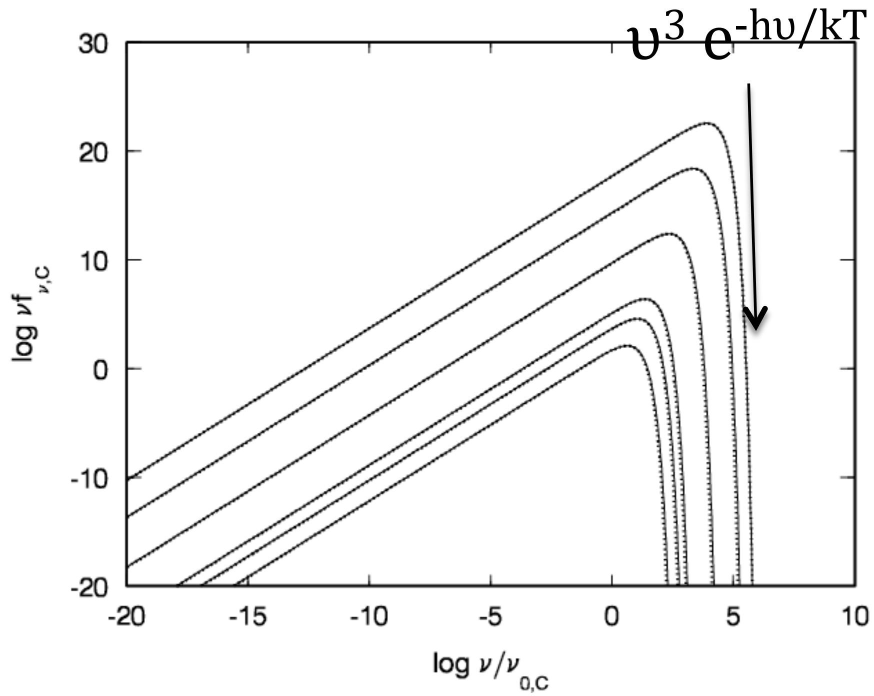
Number of Compton collisions per foton:

- $N_{col} = \tau_T$ si $\tau_T < 1$
- $N_{col} = \tau_T^2$ si $\tau_T > 1$

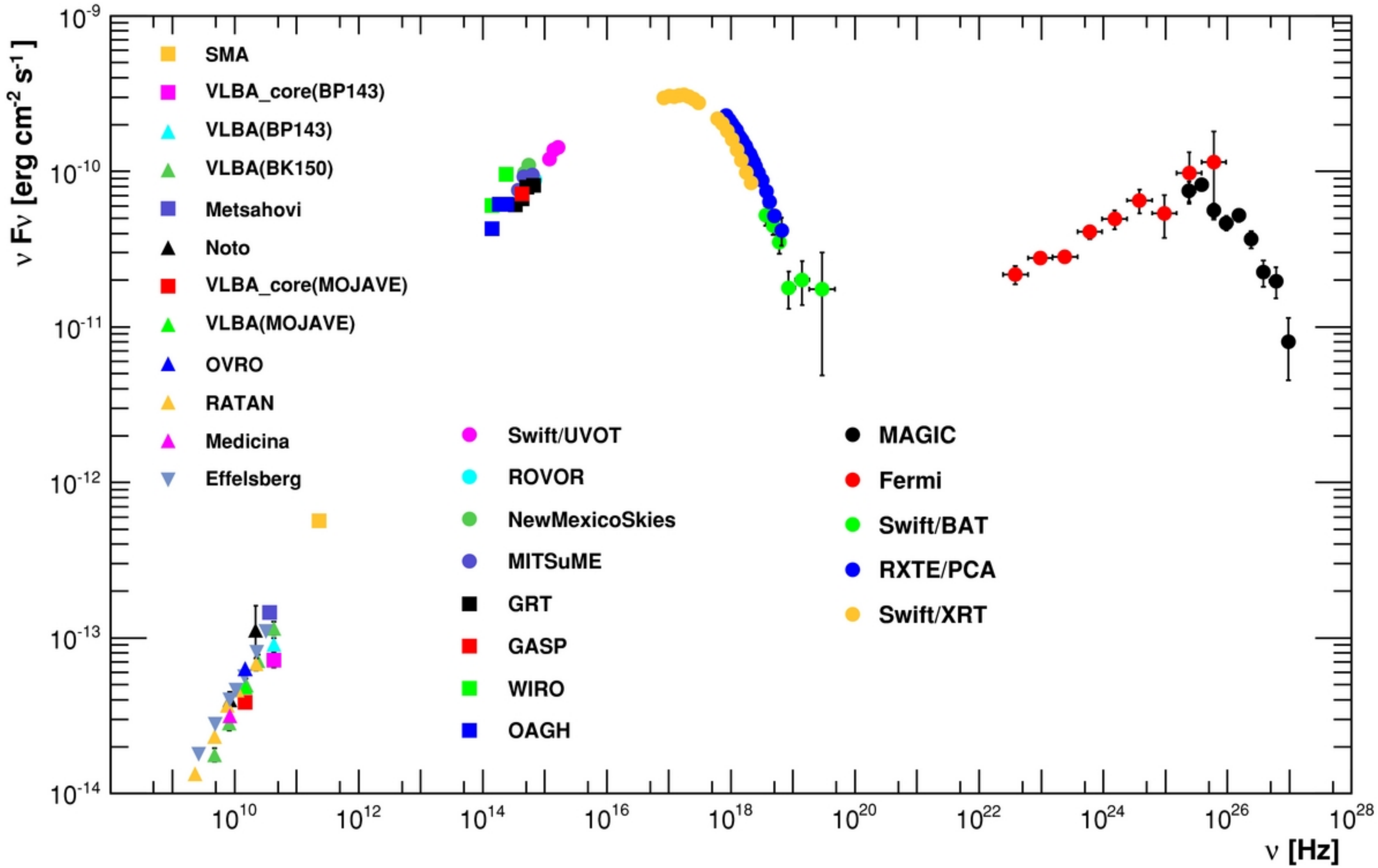
$$E_{out} = e^{4y} E_{in}$$

Comptonisation (II)

- Electromagnetic radiation going through a Compton-tick medium becomes Comptonised:
  - **Planck** spectrum if matter-radiation equilibrium is reached
  - **Wien** spectrum otherwise

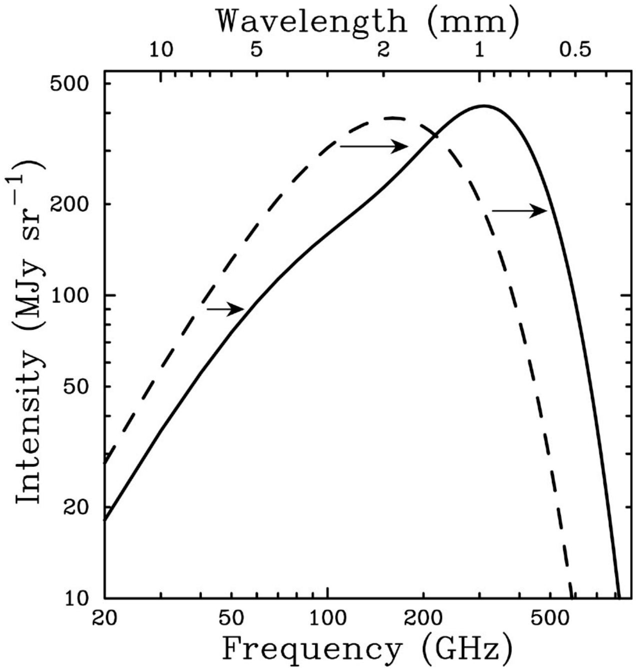


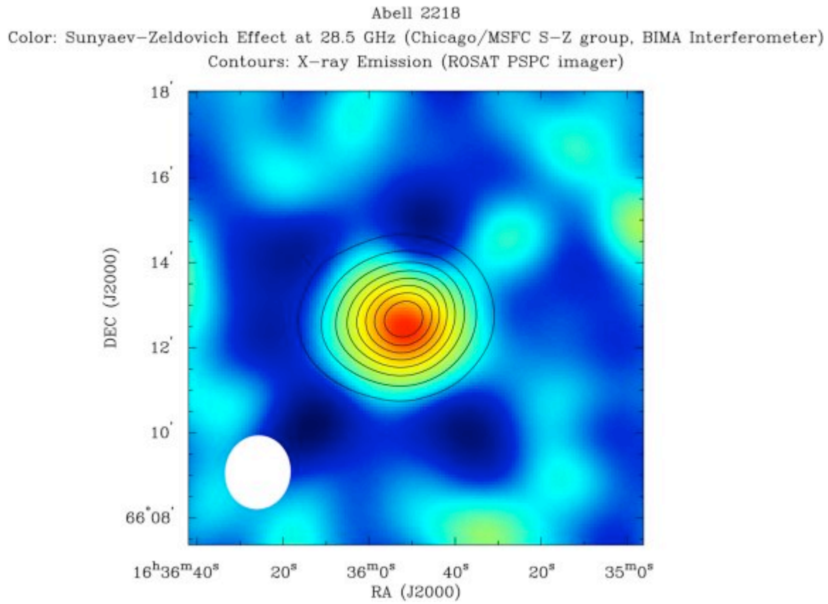
Synchrotron Self-Compton model for BL Lacs (Mrk 421)



Sunyaev-Zel'dovich effect in galaxy clusters

- Inverse Compton scattering with CMB





$$\frac{\Delta T_{CMB}}{T_{CMB}} \propto \rho_{gas} T_{gas} R$$

Compton cooling

Relativistic electrons loose energy through Compton effect

Master equation

- $N(\gamma,t)$, electron distribution
- $Q(\gamma)$, electron injection rate
- $d\gamma/dt$, cooling rate

$$\frac{\partial N}{\partial t}+\frac{\partial}{\partial \gamma}\left[\left(\frac{d\gamma}{dt}\right)N\right]=Q(\gamma)$$

Steady solutions

- $Q(\gamma)$ mono-energetic or $Q(\gamma) \approx \gamma^{-\Gamma}$, with $\Gamma<1$

$$N(\gamma) \propto \gamma^{-2}$$

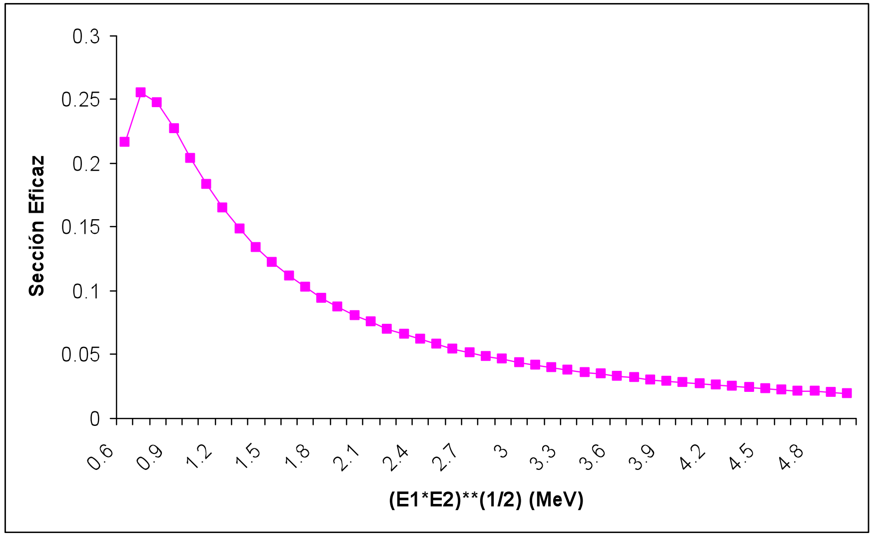
- $Q(\gamma) \approx \gamma^{-\Gamma}$, with $\Gamma>1$

$$N(\gamma) \propto \gamma^{-\Gamma-1}$$

Electron positron pairs

Energetics

$$\left(E_1 E_2\right)^{\frac{1}{2}} > mc^2$$



Compactness

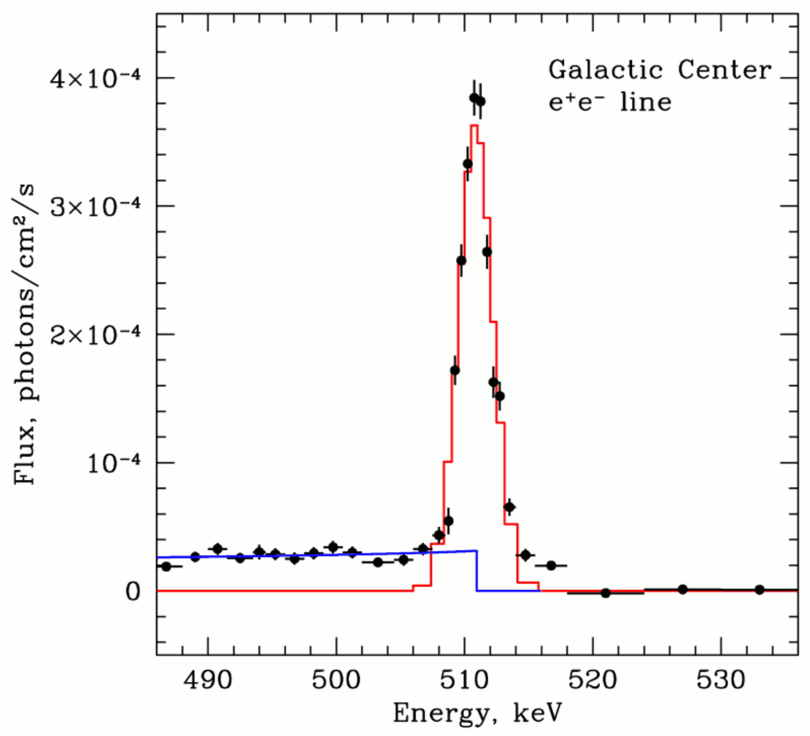
$$\tau_{\gamma\gamma} = n_\gamma \sigma_{e^+e^-} R > 1$$

Only **compact** sources can create electron-positron pairs

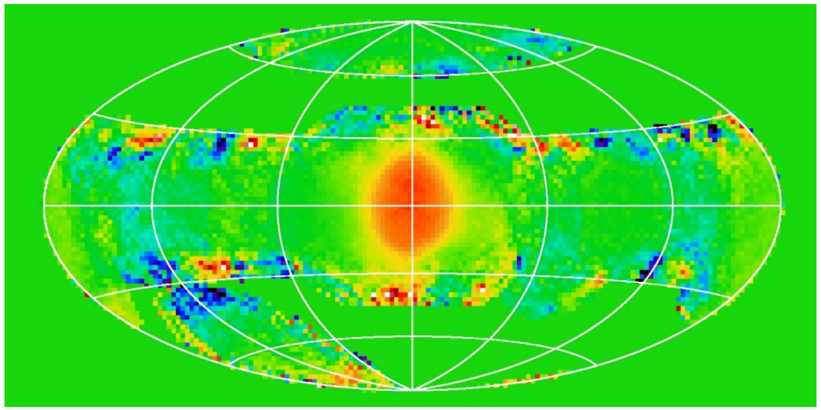
$$\ell = \frac{L\sigma_T}{Rmc^3} > 60$$

Electron-positron annihilation

INTEGRAL/SPI spectrum of the Galactic Center



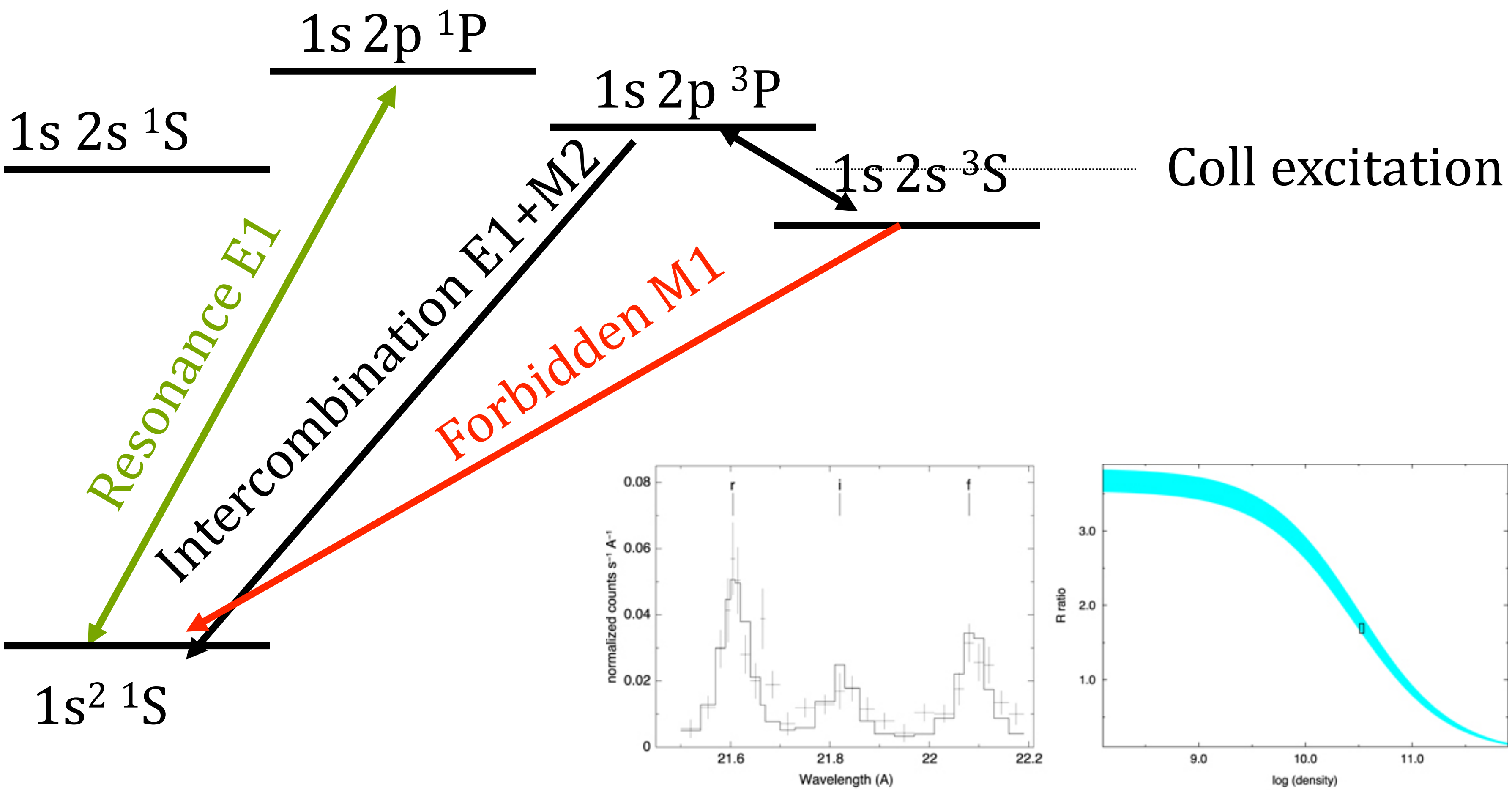
Map in e^+e^- annihilation line (INTEGRAL/SPI)



Atomic transitions in astrophysics

- Below 10^8 K some atomic species are not fully ionised, and atomic transitions appear:
  - Free-free (continuum)
  - Bound-free (photoionisation, absorption edges)
  - bound-bound (emission lines & resonance absorption lines)
- Transition probabilities E1: M1:M2 scale typically as $1:10^{-5}:10^{-8}$
- In laboratory conditions only **electric dipole transitions (or permitted)** are observed
- In astrophysics, under low density environments, **forbidden emission lines are routinely observed**.

Astrophysical plasma diagnostics using the He-like triplet



(a) OVII triplet (b) Density

Emission from atoms and ions

Type	Process	Description
Emission line	Bound-bound	A bound electron decays to a lower energy state
Emission continuum	Free-bound radiative recombination	A free electron is captured into a bound state
Emission line	Dielectronic recombination	A free electron is captured into a doubly excited state
Emission continuum	Two-photon continuum	Simultaneous two-photon emission from a meta-stable state

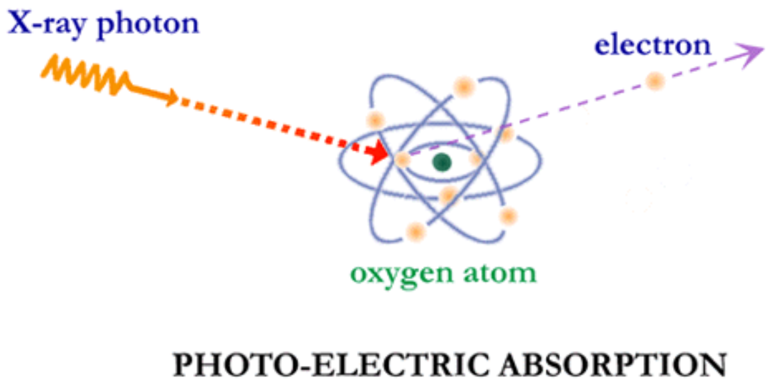
Astrophysical plasma models

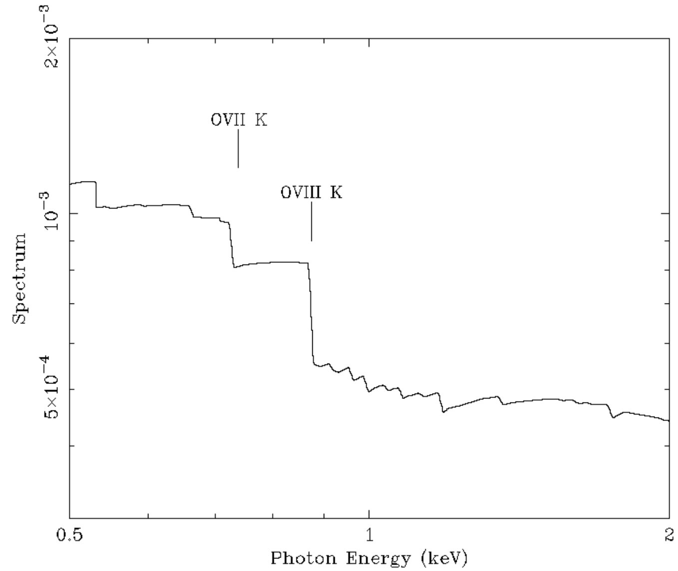
	Ionisation equilibrium
n_i	Ion density with charge state i
n_e	Free electron density
C_i	Collisional ionisation rate
α_i	Recombination rate
β_i	Photoionisation rate

Model	**τ**	**Ionisation**	**Examples**
Coronal	<<1	Collisions	Solar corona, Supernova Remnants
Nebular	<1	Photoionisation	Active galaxies
Thick	>>1	Collisions	Stellar interior

$$C_i n_i n_e + \beta_i n_i = \alpha_i n_{i+i} n_e$$

Photoelectric absorption





Cross section

$$\sigma_{abs}(\nu) \approx 7.8 \times 10^{-18} \left(\frac{\nu_{LL}}{\nu}\right)^3 \left(\frac{Z^4}{n^5}\right) \quad cm^{-2}, \quad \nu \geq \nu_{LL}$$

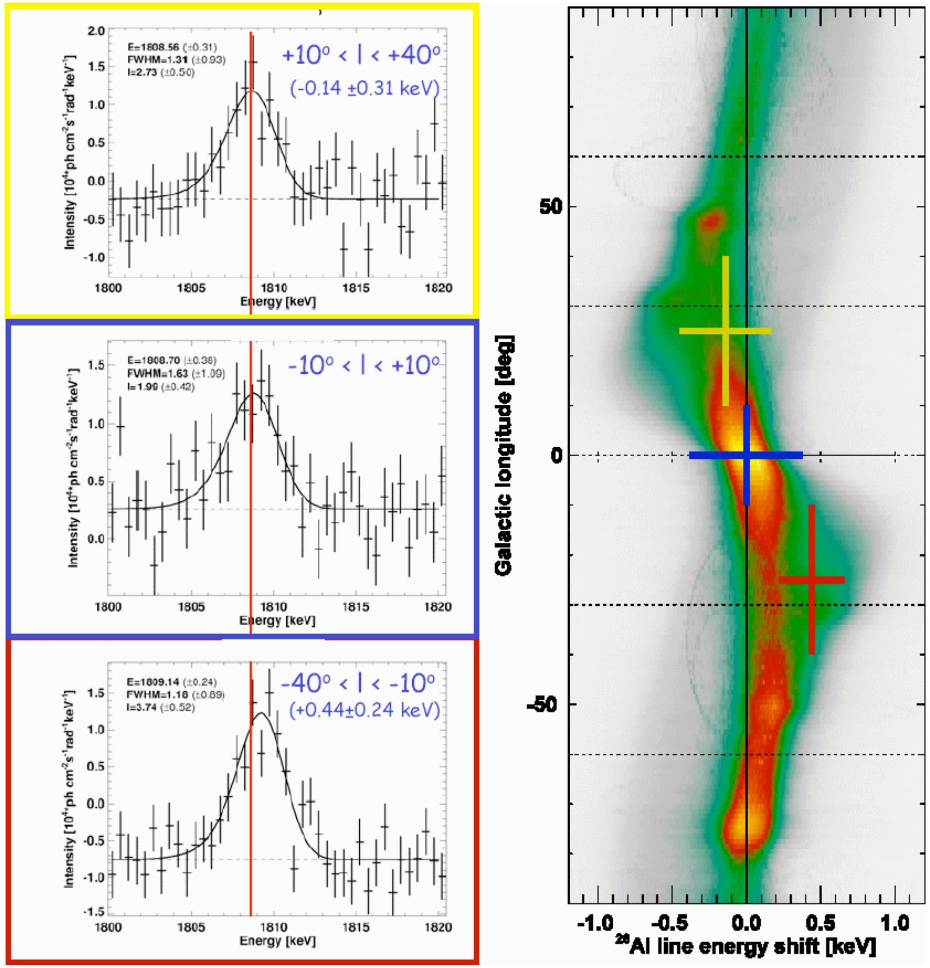
OVII K: 0.739 keV

OVIII K: 0.874 keV

Fe I K: 7.1 keV

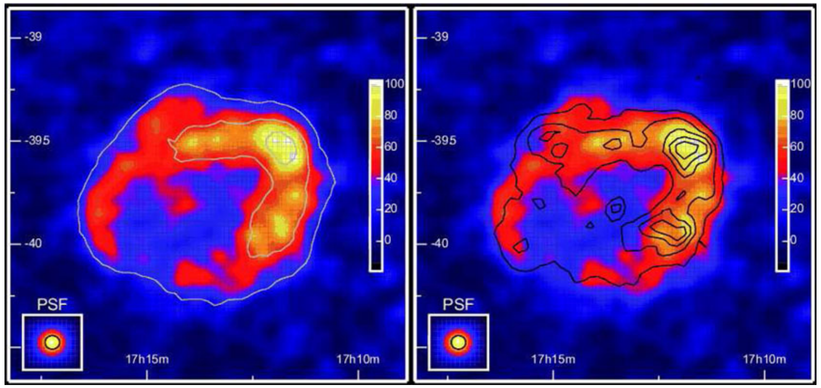
γ-ray emission processes

- Bound-bound nuclear transitions
- Electron-positron annihilation
- Pion decay
- Comptonisation by ultrarelativistic electrons

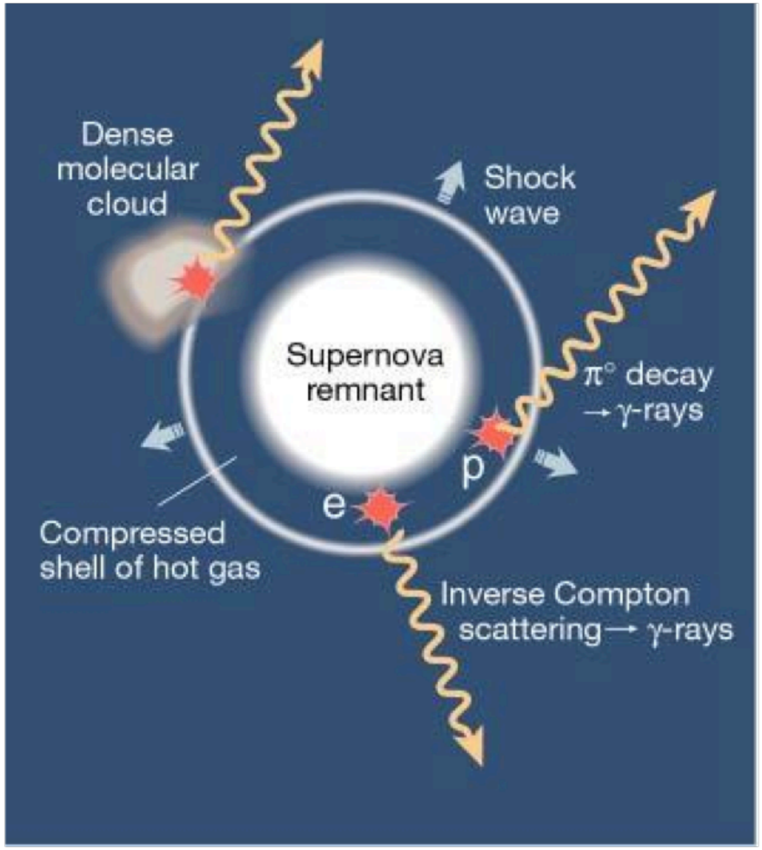


HE emission from Supernova Remnants

RX J1713-3946



Leptonic vs hadronic emission



Summary of detected sources

Messenger	# sources	Comments
X-rays (0.1-10 keV)	500.000	Hot gas, accreting sources
MeV γ-rays	1.000	Synchrotron, Compton, nuclear processes
TeV γ-rays	100	Acceleration, shocks, Supernovae
Cosmic rays	?	Active galaxies, Supernovae
Neutrinos	1+	Sun (+ Supernovae & Active nuclei)
Gravitational Waves	0	BH/NS collapse & mergers, chaotic accretion

Physical processes in high-energy astrophysics

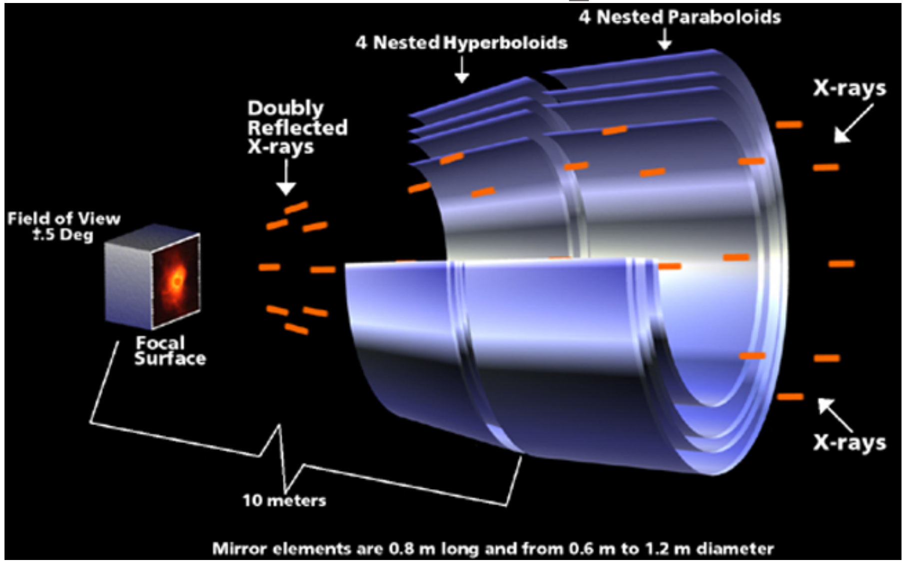
Process	Ingredients, comments
Cyclotron & Synchrotron	Electrons in magnetic fields
Bremsstrahlung	Ionised gas at > 10^6 K
(Inverse) Compton effect	(Energetic) electrons and photons
Electron-positron pairs	Photons at > 0.5 MeV and compactness
Atomic emission lines	Ions at < 10^8K. Ionisation by photons and collisions
Nuclear emission lines	Creation of unstable or metastable isotopes
Particle desintegration	Creation of unstable particles by enegetic nuclei

High-Energy Astrophysics technologies

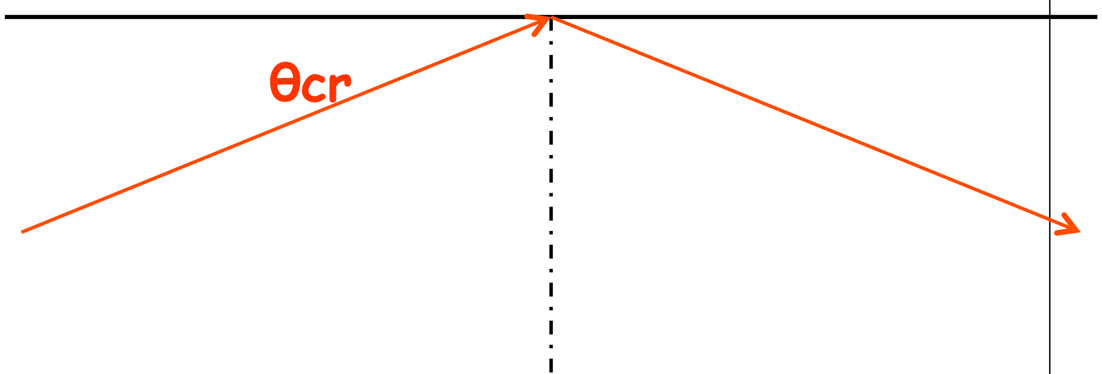
High-energy astrophysics technologies

- Grazing incidence X-ray telescopes
- X-ray detector technologies
- X-ray astronomy workhorses
- MeV-GeV γ-ray telescopes
  - Coded masks (INTEGRAL/IBIS , INTEGRAL/SPI)
  - Laue lenses
  - Compton telescopes (COMPTEL)
  - Pair telescopes (Fermi)
- Imaging Atmospheric Cerenkov Telescopes
  - Current & future Cerenkov facilities

X-ray grazing incidence telescopes

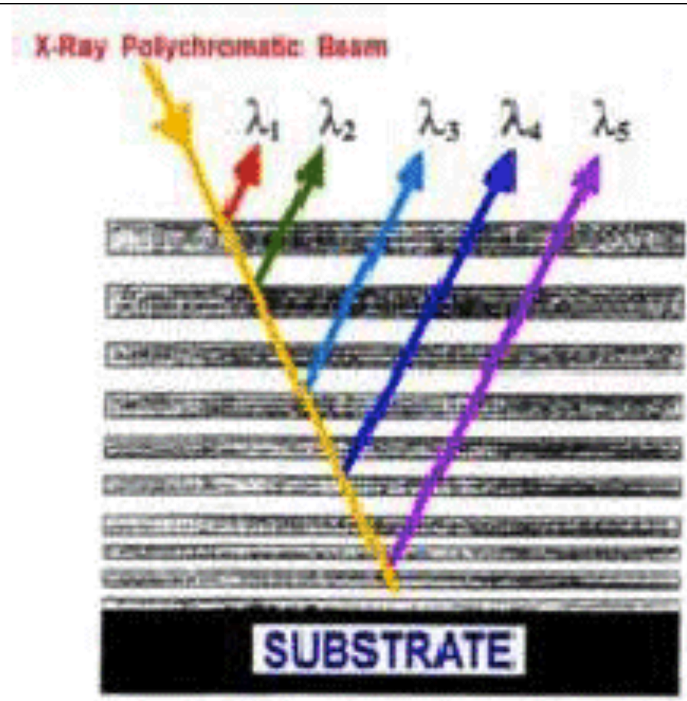


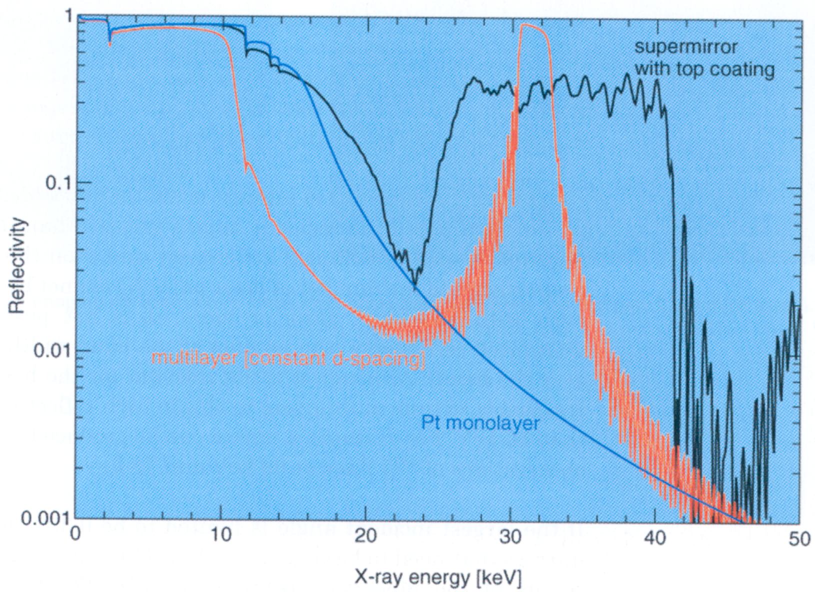
- Normal incidence of X-rays towards a "reflecting" surface leads to absorption or transmission only.
- Grazing incidence (total reflection): $\theta < \theta_{cr} \sim 1^{o}$ @ 1 keV for an Au coated surface

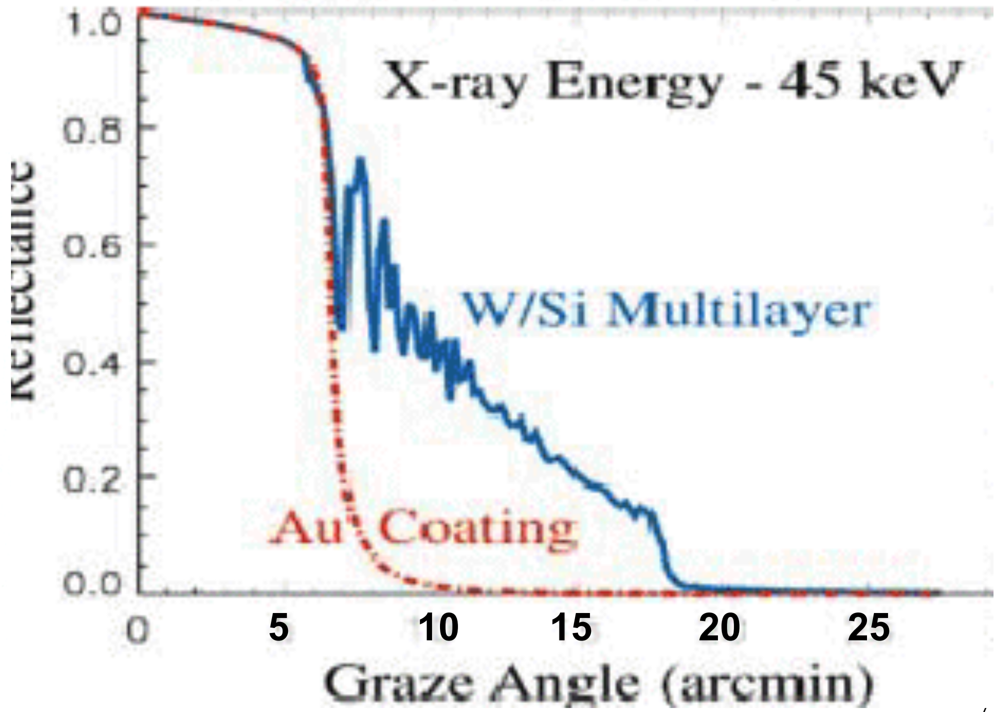


Multi-layers

- Sequence of thin metal-isolating layers
  - Improves reflectivity at high energies
  - Bragg condition: wavelength ~ layer thickness



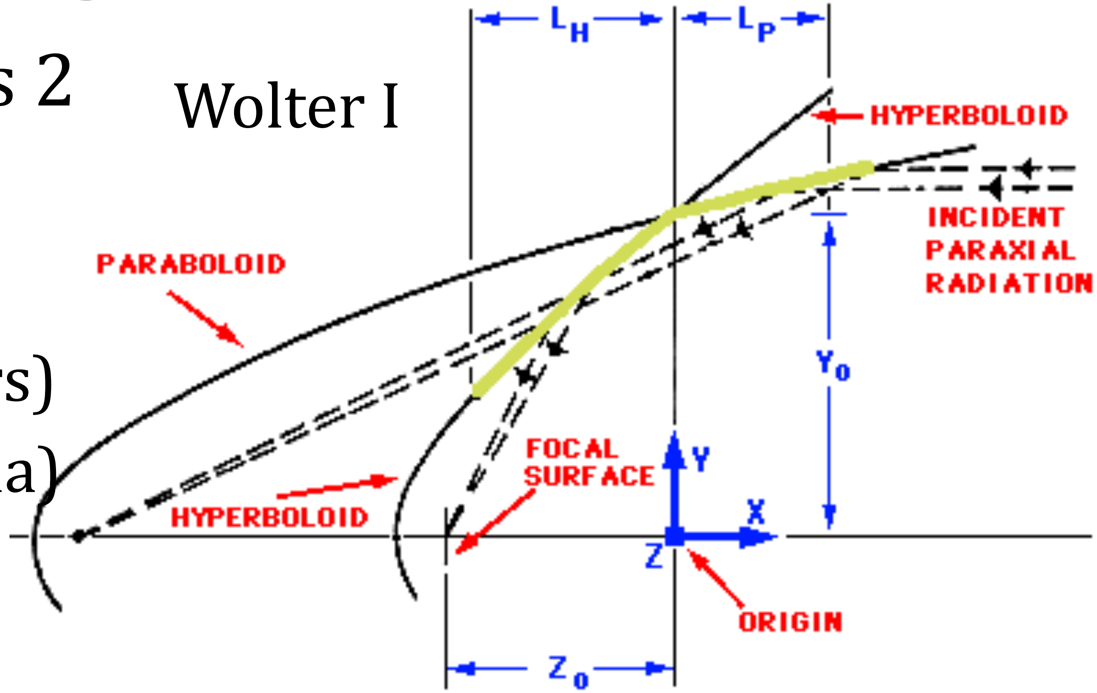




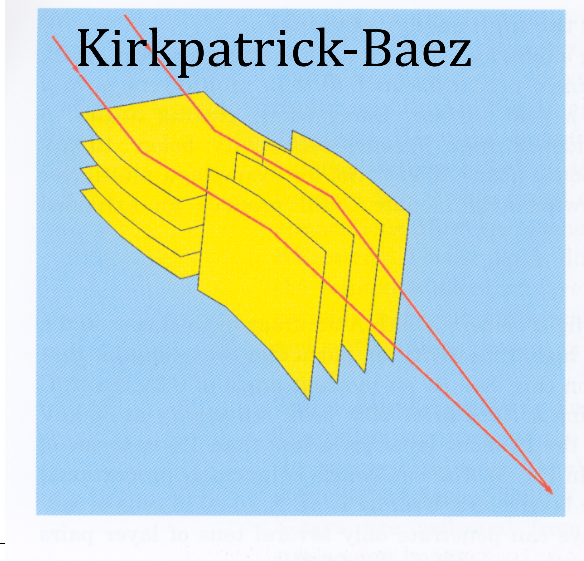
X-ray optical designs

- Forming images requires 2 reflections
- Two main designs:
  - Kirkpatrick-Baez (cylinders)
  - Wolter (parabola hyperbola)

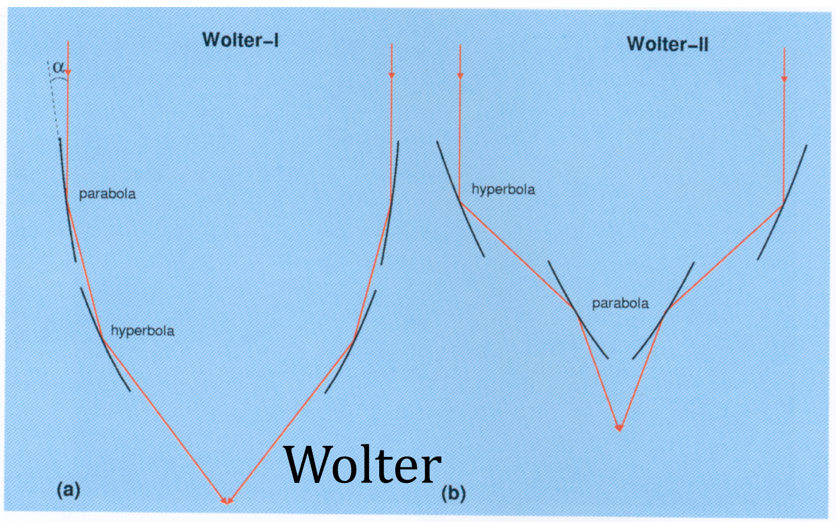
Wolter I



Kirkpatrick-Baez



nutshell



Wolter

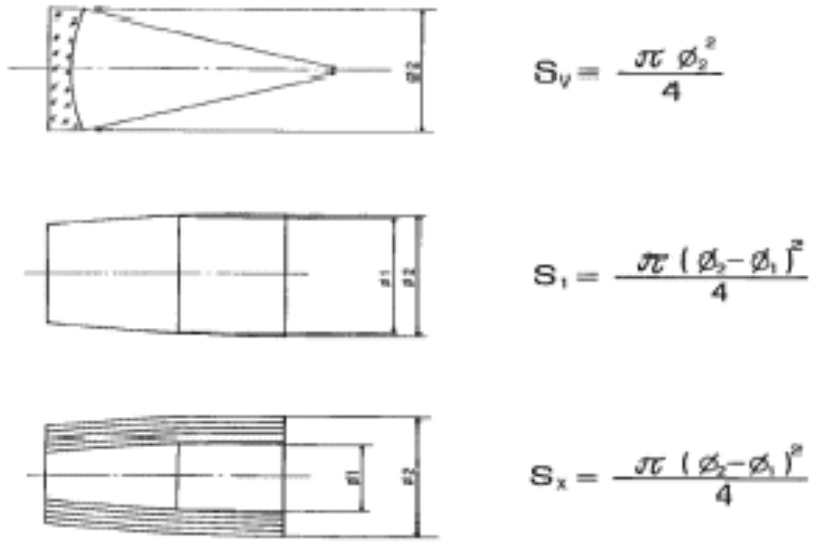
Optical nesting

- **Utility** of a mirror pair:

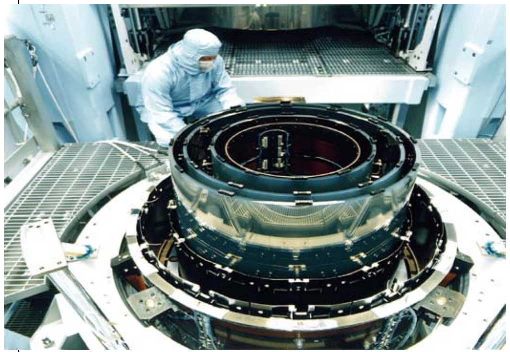
$$\frac{A_{eff}}{A_{geom}} = R^2(\theta_{cr})\sin\theta_{cr} \leq 8\%$$

Mirror nesting increases effective area

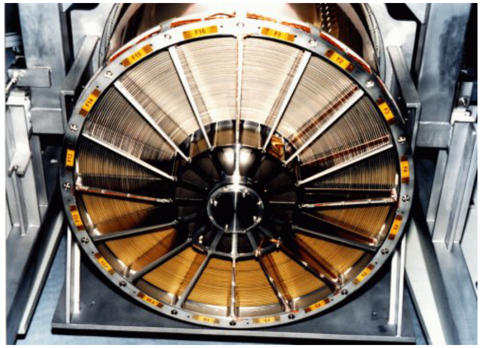
- Reflecting surfaces must be super-polished (rms<5Å)
- Field of view~ θ_{cr}, depends on photon energy



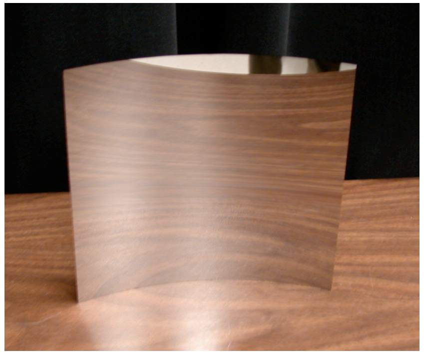
Substrates



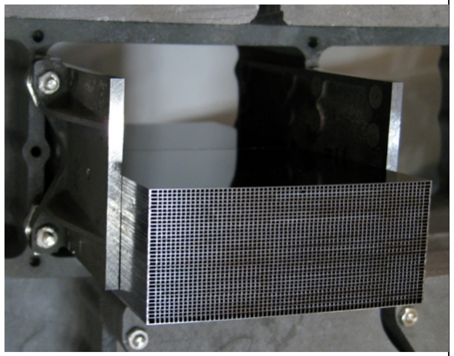
CHANDRA
0.5″ HEW
18500 kg/m^2



XMM-NEWTON
14″ HEW
2300 kg/m^2



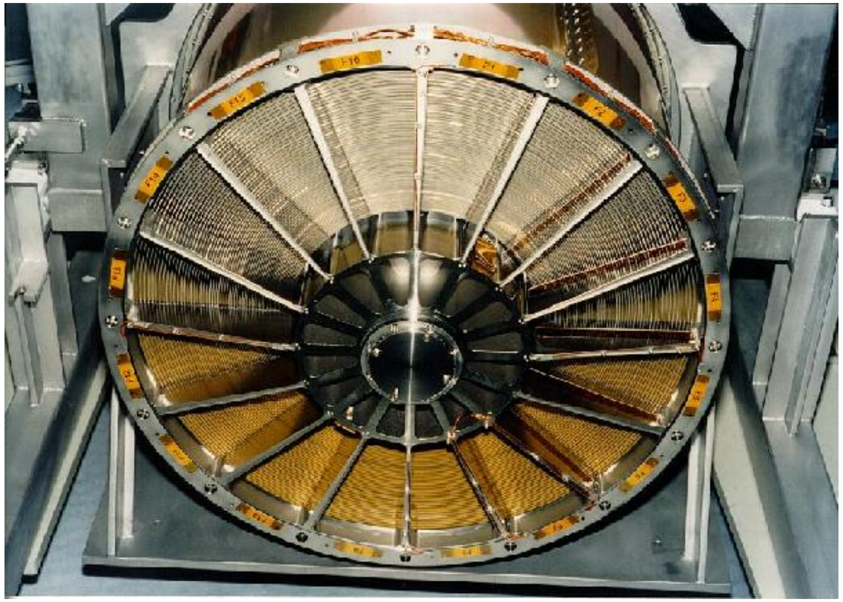
Slumped Glass
5″ HEW
~270 kg/m^2

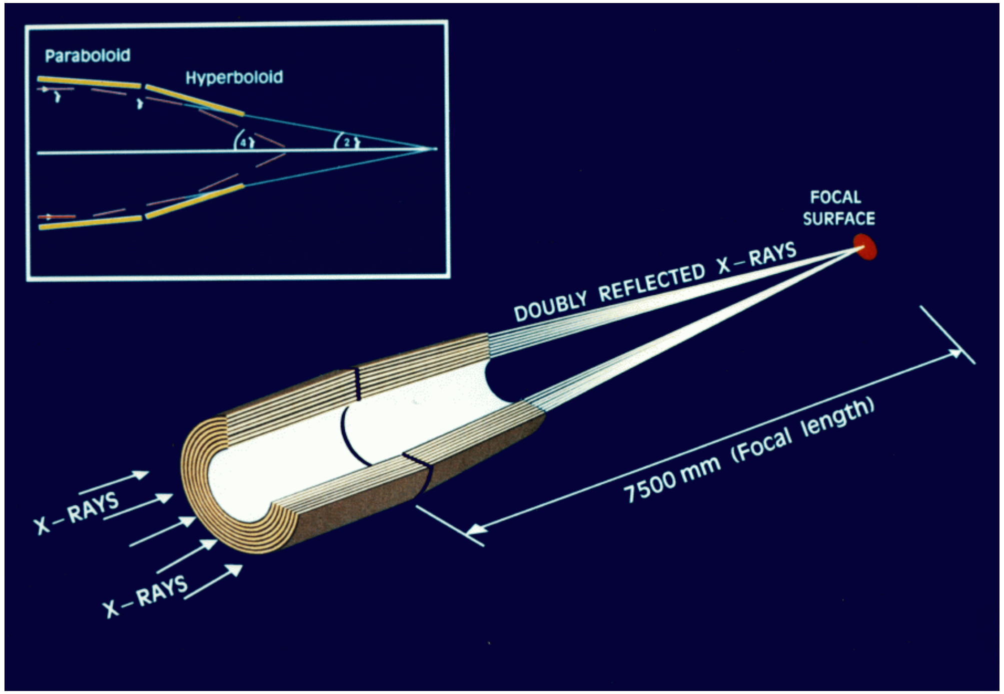


Si-HPO
5″ HEW
~200 kg/m^2

Lightweight options

Example: XMM-Newton (ESA)

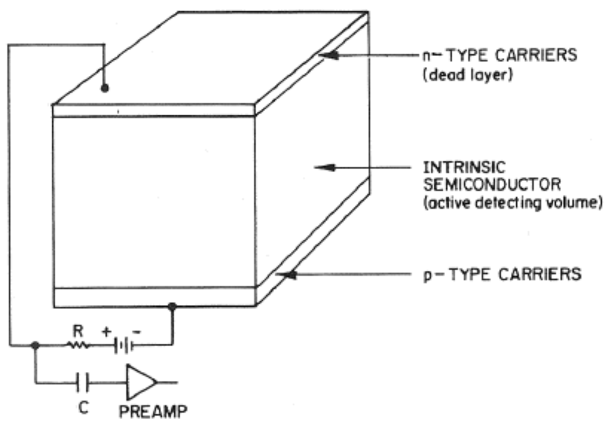




- X-ray **observatory**, operational since 1999:
- Substrate: Electroformed Ni
- Focal length: 7.5m
- 58 nested mirror pairs per telescope

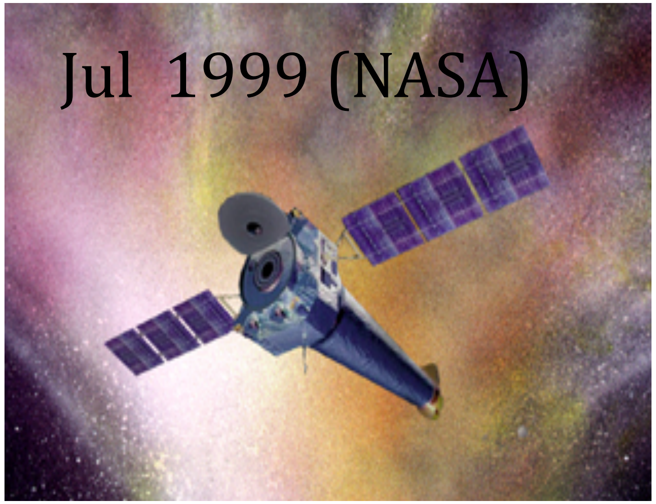
Workhorse detectors: Charge-Coupled Devices (CCDs)

- Semiconductor devices
- Each absorbed X-ray creates hundreds of electron-hole pairs
  - Subsequent electronic readout can measure the total deposited energy
- Spectral resolution $E/\Delta E \sim 30\ E(\text{keV})^{1/2}$



Next generation of Si detectors is based on Active Pixel Sensors (DEPFET), capable of reading out the device much faster.

XMM-Newton & Chandra: Current X-ray astronomy workhorses



XMM-Newton:

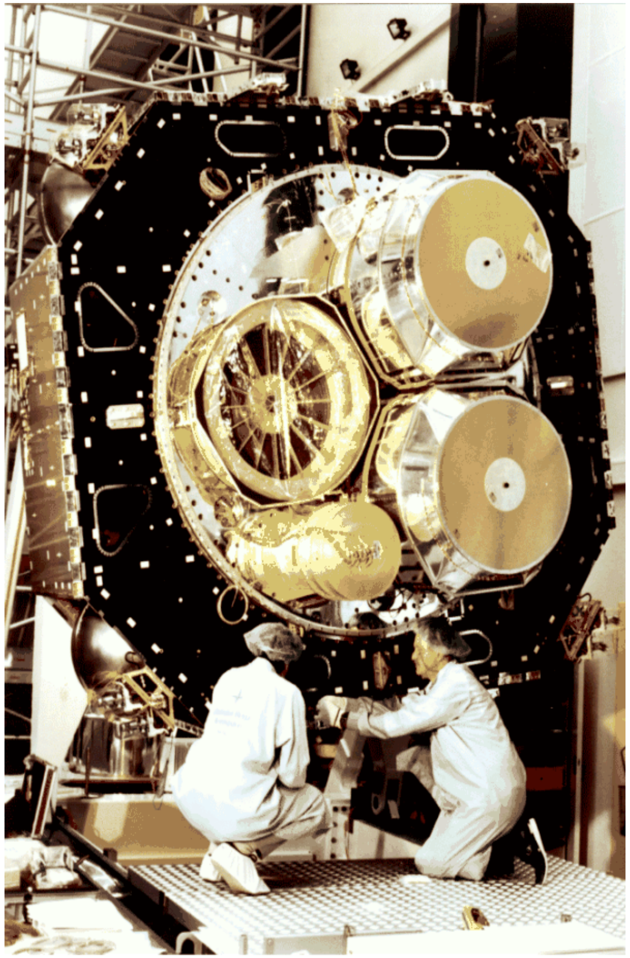
- Effective area 0.4 m^2
- Angular resolution: 15'' HEW
- Limiting sensitivity: 10^{-15} erg cm^{-2} s^{-1}

Chandra:

- Effectve area: 0.08 m^2
- Angular resolution: 0.5'' HEW
- Limiting sensitivity: <10^{-16} erg cm^{-2} s^{-1}

The scientific impact of XMM-Newton

- Launch in December 1999
- Most productive ESA mission
- 300 papers/year, similar to the VLT
- Huge user community involved: 4000 registered users
- All areas served: from solar system bodies to galaxies and cosmology
- Mission currently extended to 2018.
    - Technically extendable on 2-yearly basis until late 2020s



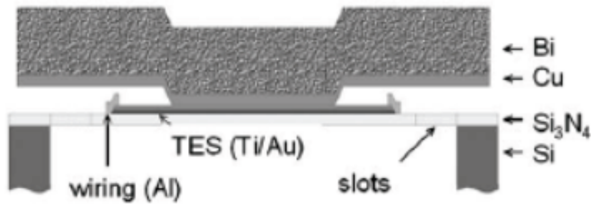
XMM-Newton mirrors during integration

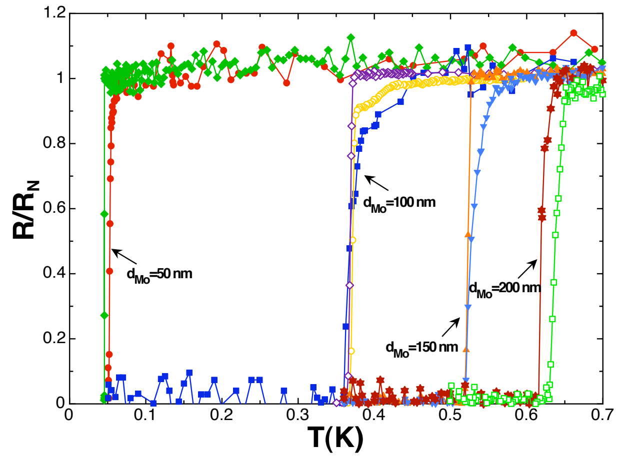
Image courtesy of Dornier Satellitensysteme GmbH

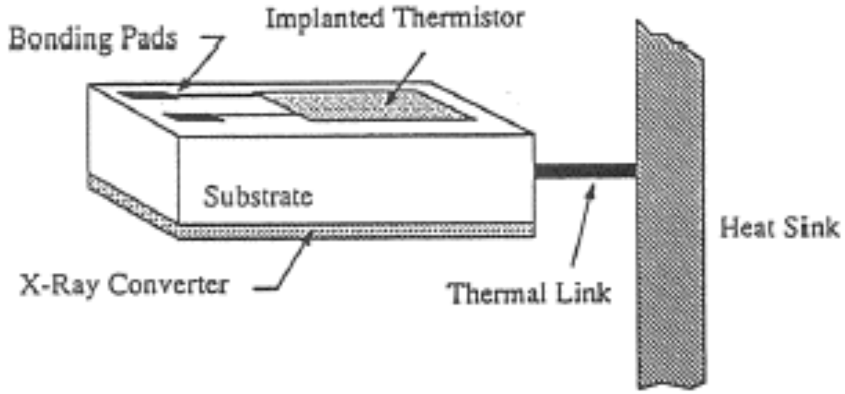
European Space Agency

Next frontier in X-ray detectors: Microcalorimeters

- X-ray photon to phonon conversion, coupled to a sensitive thermometer
- The sensor measures a sharp increase in the resistivity
- Limitations:
  - Relatively slow readout, modulated by thermal link to the heat sink
  - Operational temperature ~100 mK, requires a cooling chain, often using cryogens

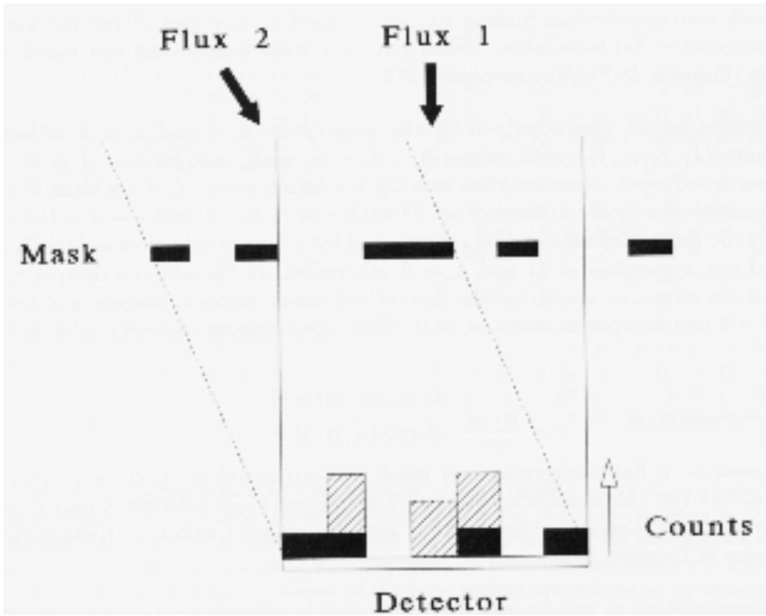






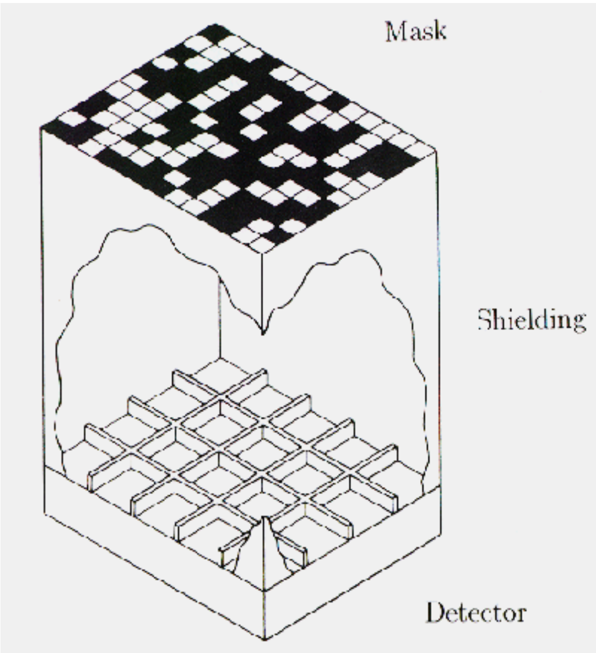
Low-energy γ-ray (~MeV) optics: Coded masks

- Produces multiplexed signal:
  - Needs a position-sensitive detector (CdTe or CdZnTe)
  - Both signal and noise spread over all detector
- Coded masks:
  - Distribution of holes and opaque zones at a distance from detector
  - Energy-dependent opacity: limited ϒ-ray range
  - Image reconstruction technique required

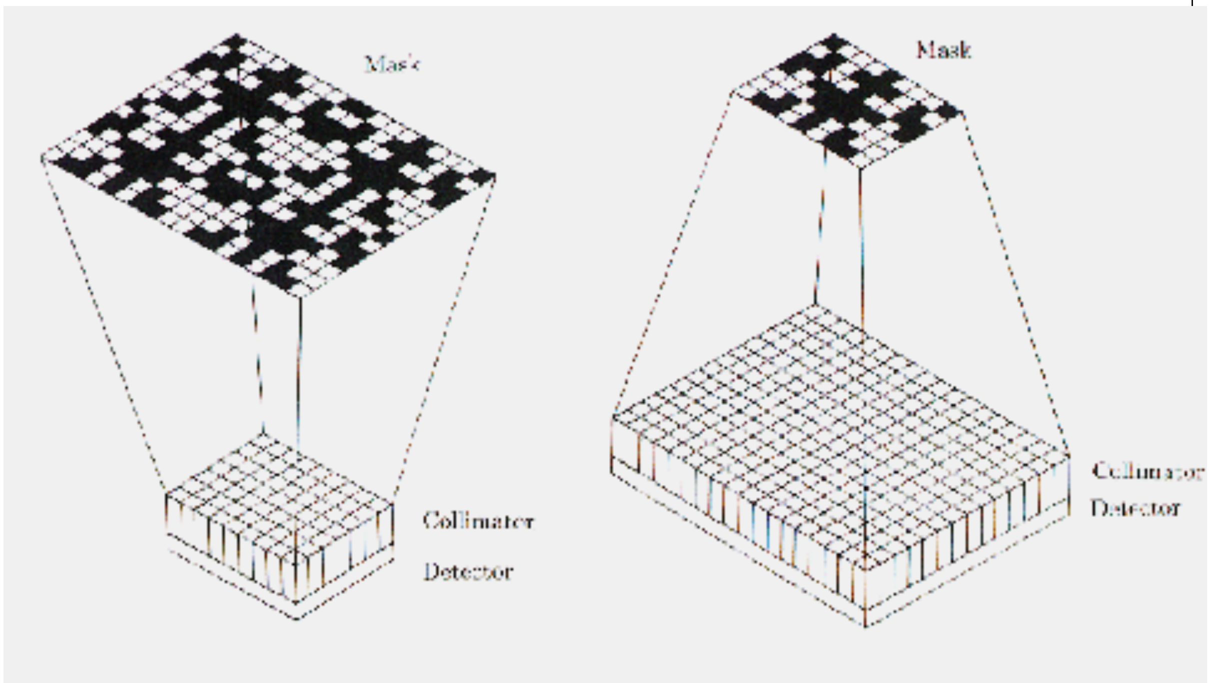


Coded mask optics

Simple



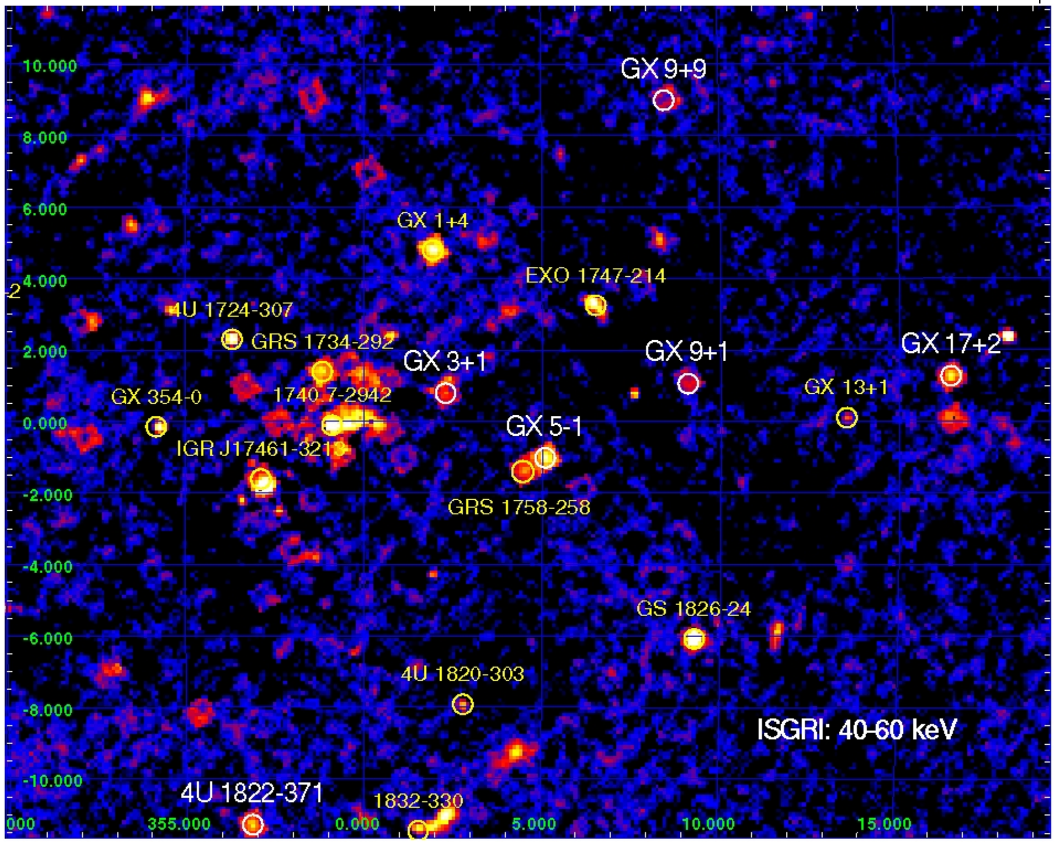
Optimised



Coded masks: image reconstruction

INTEGRAL/IBIS

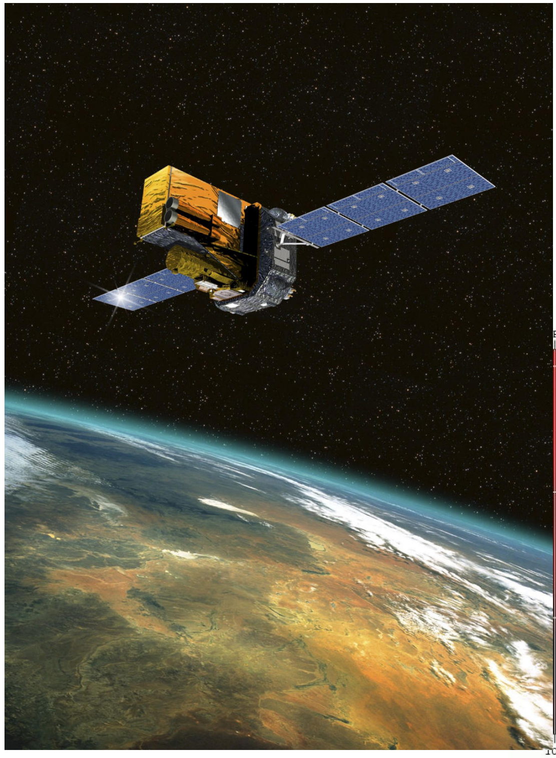
Reconstructed image

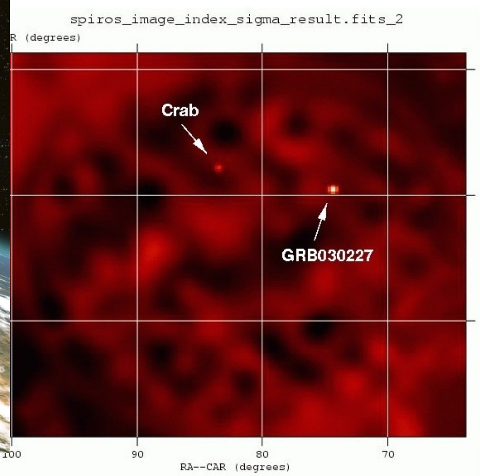


INTEGRAL (ESA)

Launch: 17 Oct 2002

Range: 20 keV – 10 MeV





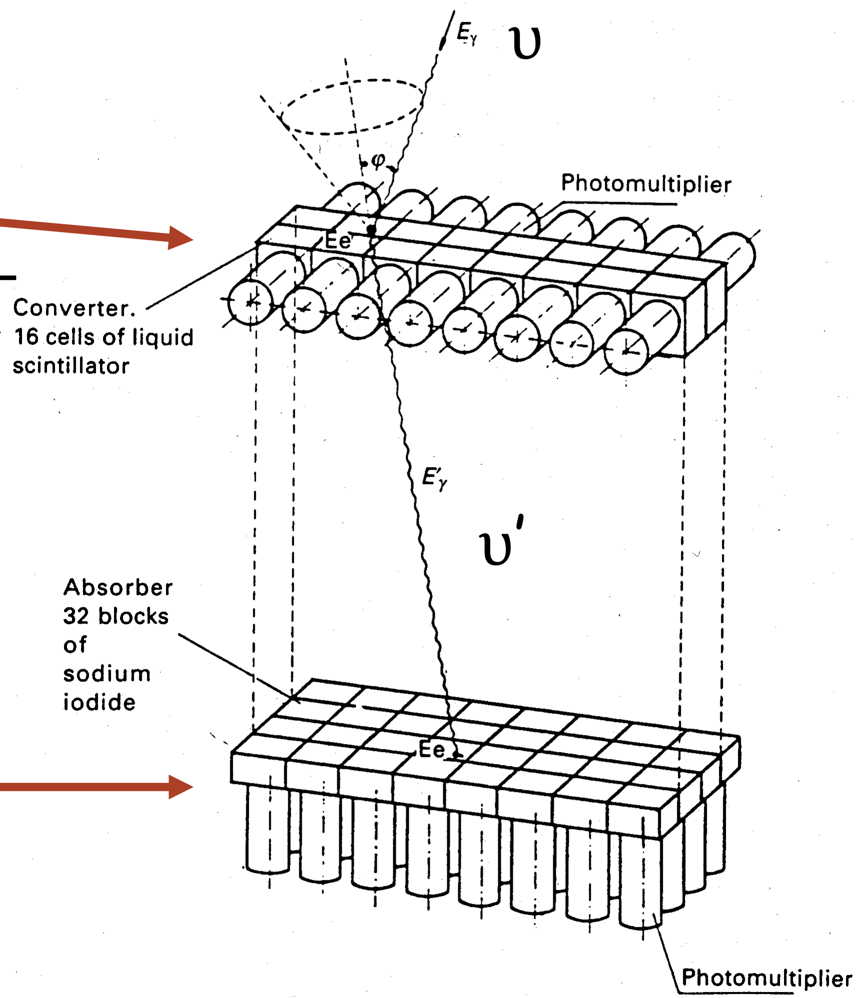
- SPI: γ -ray spectrometer
  - Coded mask
  - High spectral resolution, low spatial resolution
- IBIS: γ -ray imager
  - Coded mask
  - Low spectral resolution, higher spatial resolution and large field of view (12°)
- JEM-X: X-ray, monitor
  - Coded mask
  - Microstrip positional counters
- OMC: Optical Monitor Camera
  - Optical telescope
  - Imaging and time resolved photometry of pre-selected areas in the field of view

Compton telescopes (0.3-30 MeV)

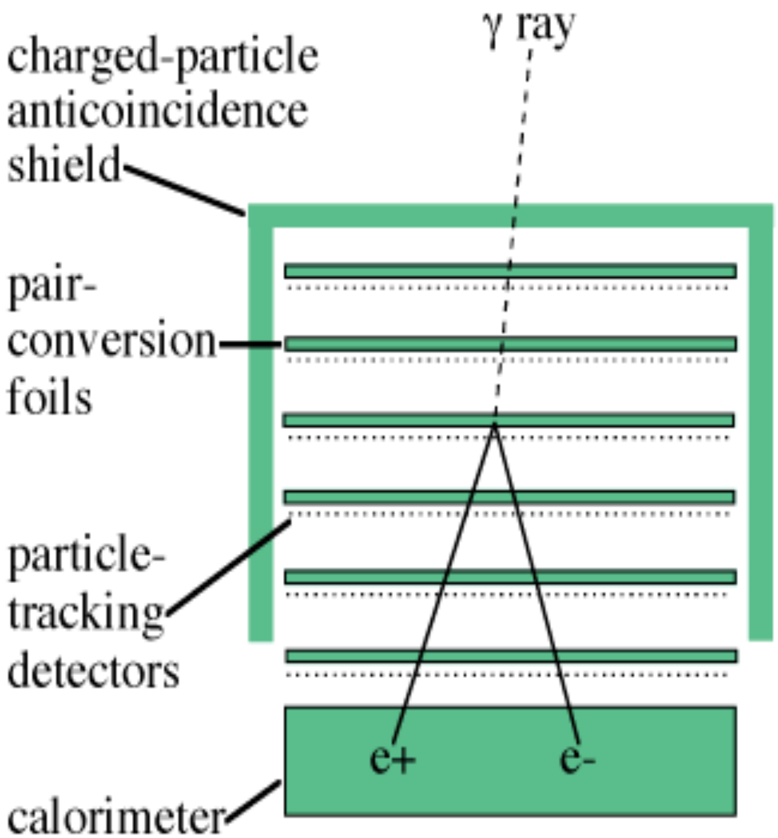
- ϒ-rays undergo Compton effect in top layer (**converter**)

$$\frac{\nu}{\nu'} = 1 + (1 + \cos\varphi)\frac{h\nu}{mc^2}$$

- Measure electron recoil energy h(ν-ν')
- Measure energy of dispersed photon in **absorber** hν'
- Work out incident photon energy hν and direction θ

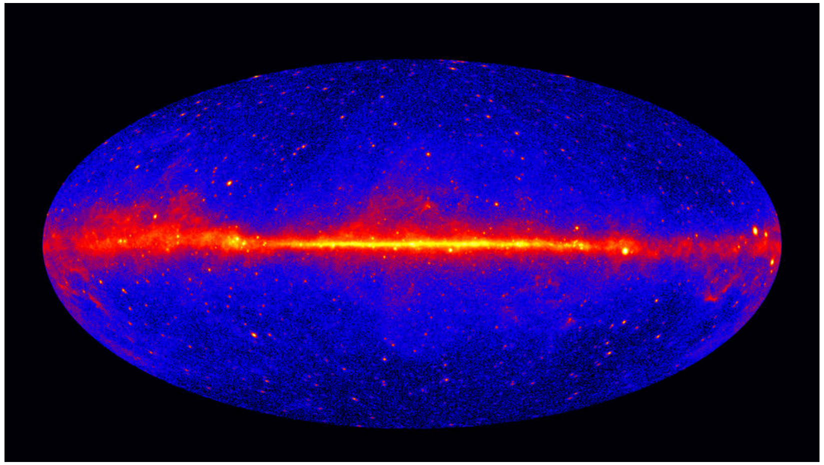


Electron-positron pair telescopes (~GeV)



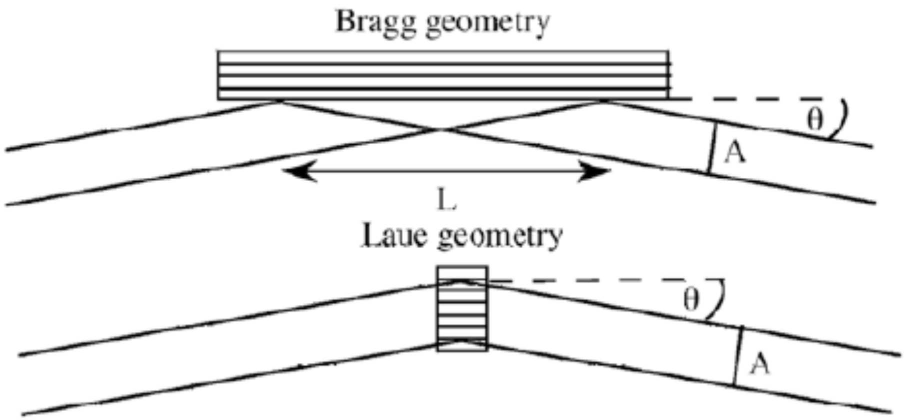
- High-energy ϒ-rays de (~MeV-GeV) create an e^+e^- pair
- The particle tracking detectors in subsequent layers trace the incoming direction of the photon
- The calorimeter measures its energy

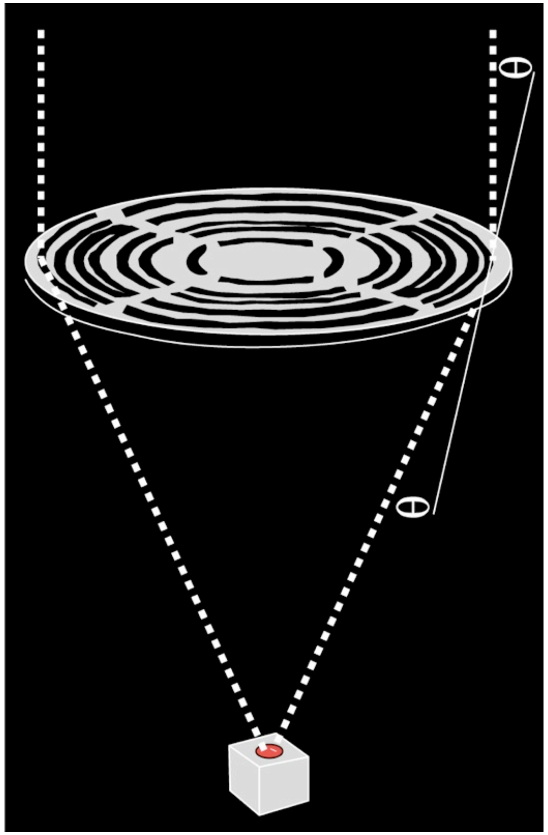
Fermi (June 2008) - NASA



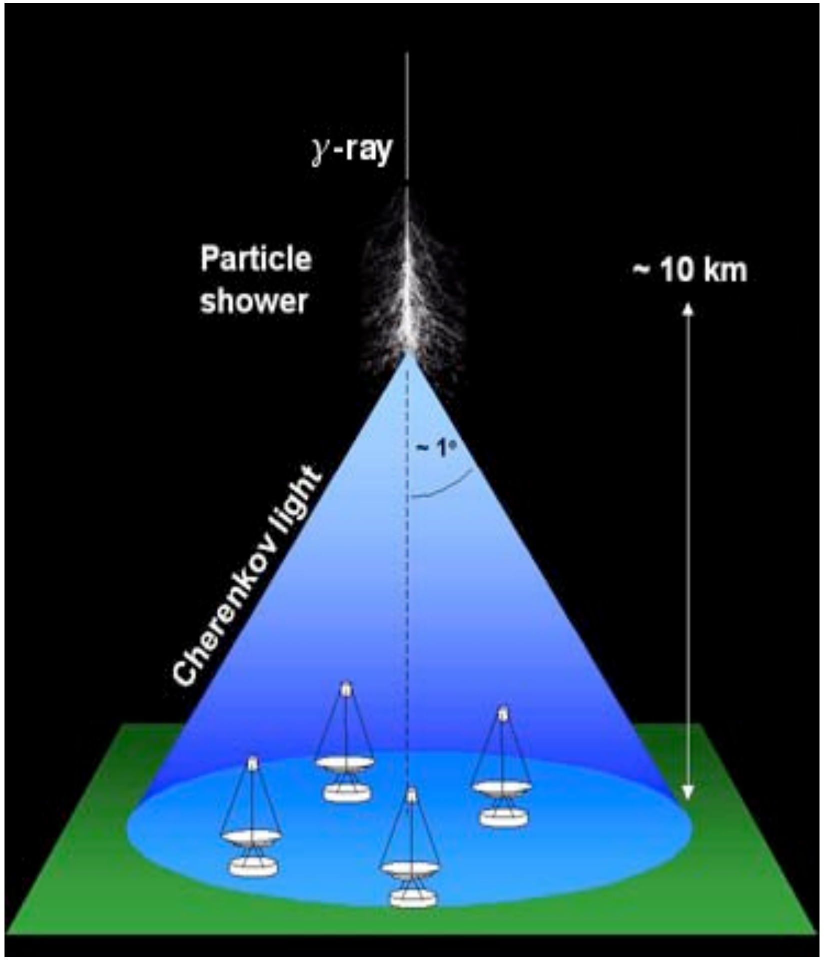
Laue lenses

- Bragg effect into a crystal, reflection on different layers
- Focal length is energy dependent and ~100m long.





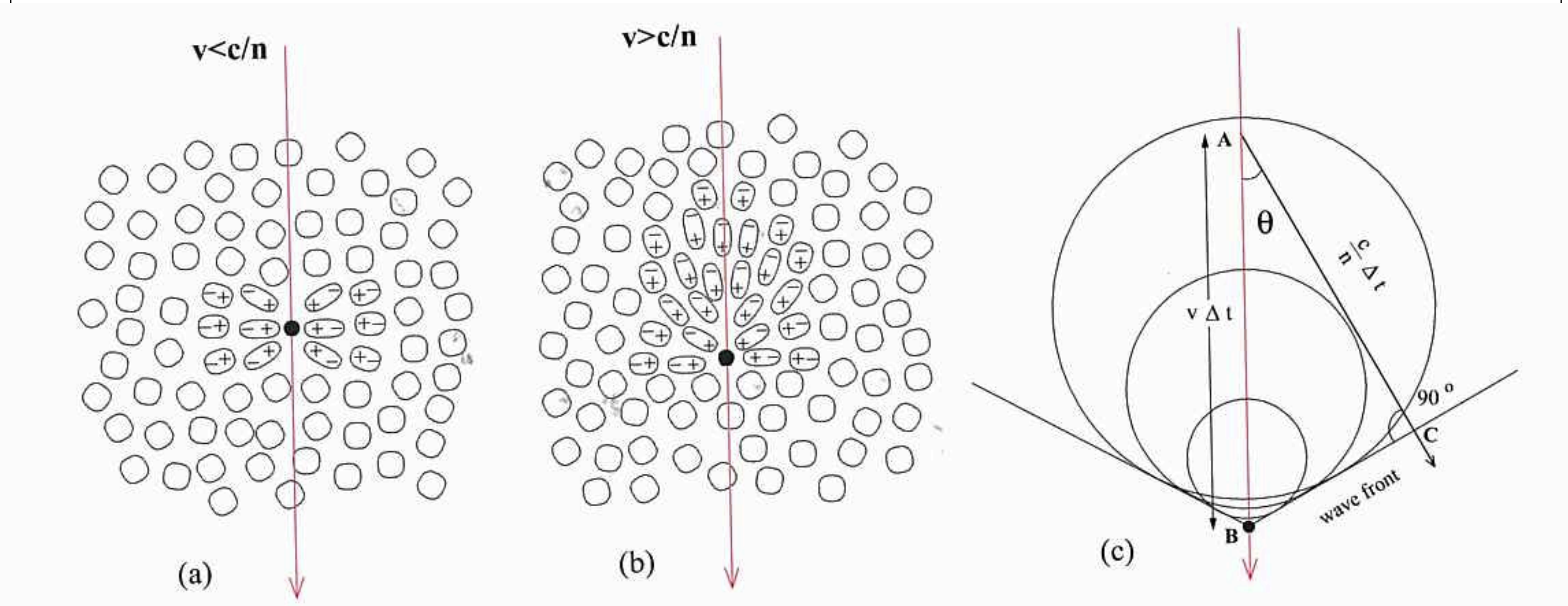
Imaging Atmospheric Cerenkov Telescopes



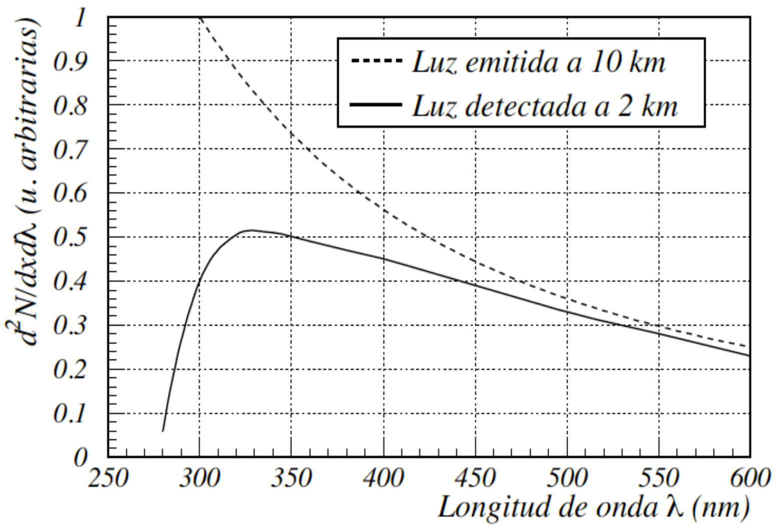
- TeV γ-rays desintegrate in the higher atmosphere.
- After several physical processes they give rise to a Cerenkov atmospheric shower
- The blue light flash is very short.

Cerenkov effect

Charged particles with velocity > c/n



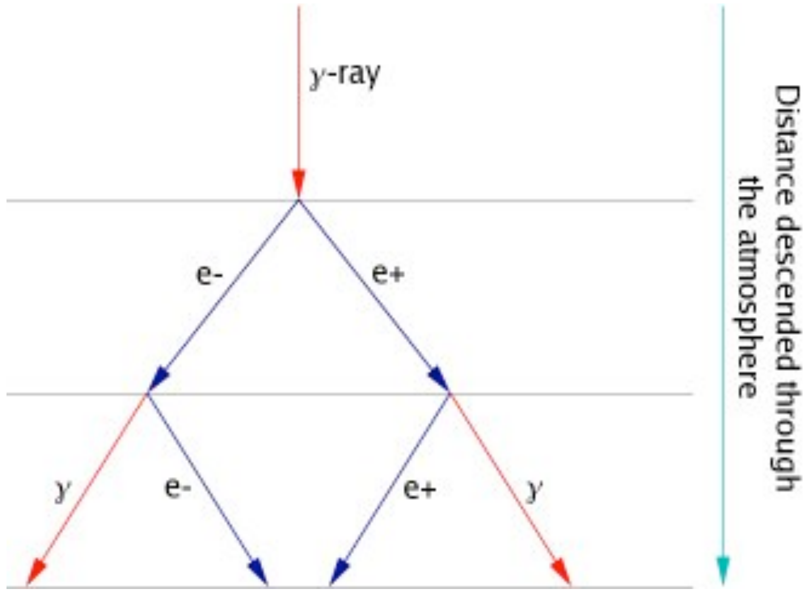
Atmospheric Cerenkov radiation



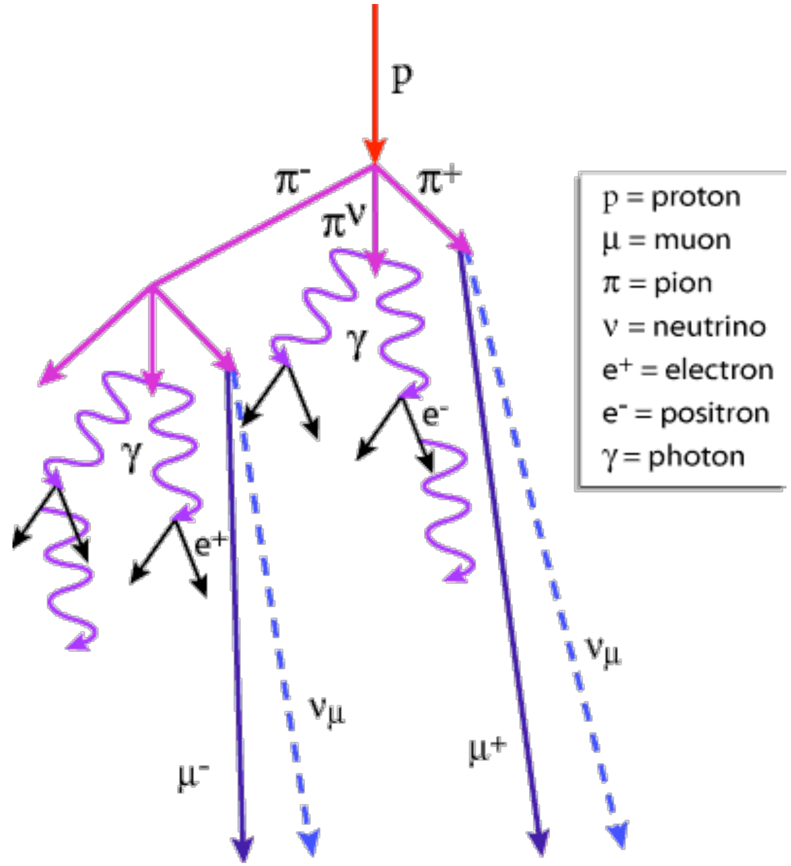
- Mostly converted in Ultraviolet radiation
- Absorption and Mie scattering of the radiation makes it detectable mostly in the blue part of the optical spectrum.

Atmospheric showers

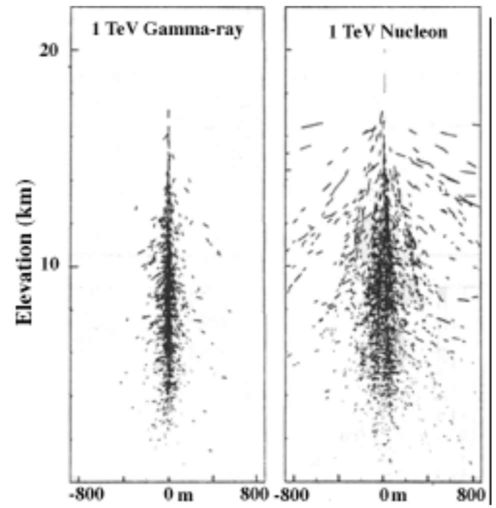
Photonic

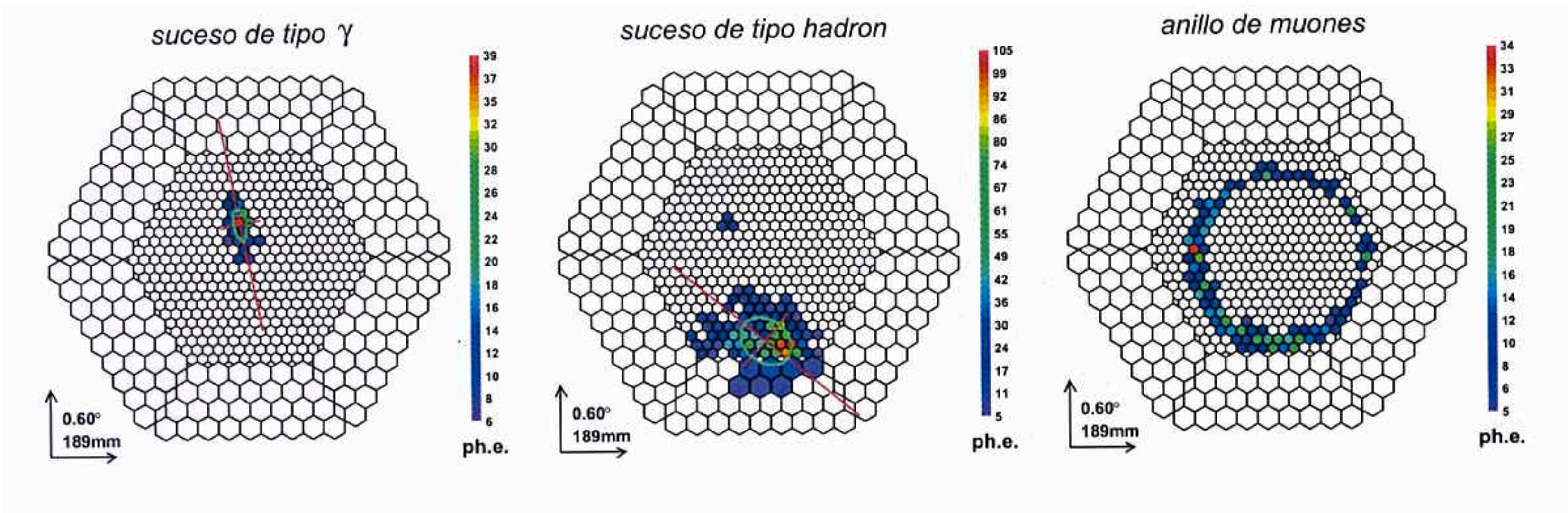


Hadronic

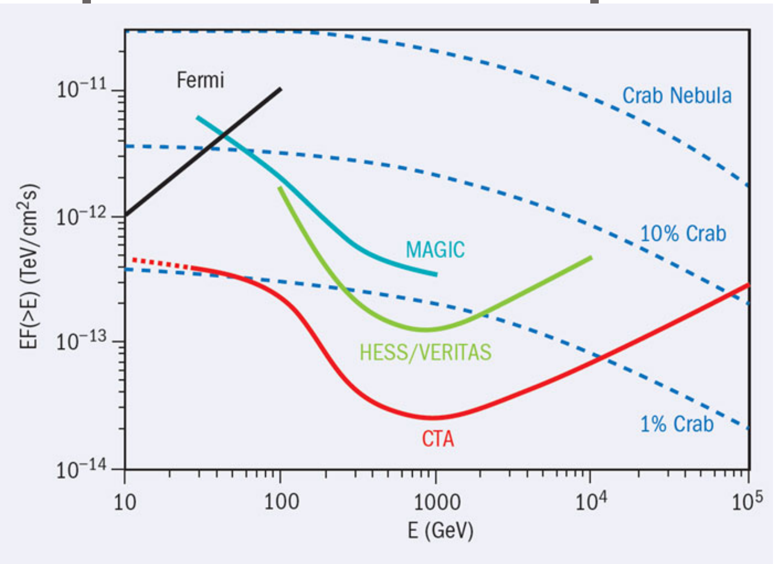


IACT signals from photonic and hadronic cascades.





Current TeV telescope landscape



CTA – Cerenkov Telescope Array

- **First** Atmospheric Cerenkov telescope **γ-ray Observatory**
- Sites: La Palma (Spain) & ESO Paranal (Chile)
- Construction 2018-2023
- Dynamic range: 0.05-50 TeV
- Science objectives:
  - Origin of cosmic rays
  - Black Holes, jets and Extragalactic Bakcground Light/SF history
  - The nature of Dark Matter & other questions in fundamental physics