PHY418 PARTICLE ASTROPHYSICS

Emission of High Energy Photons

X-ray and γ-ray astrophysics

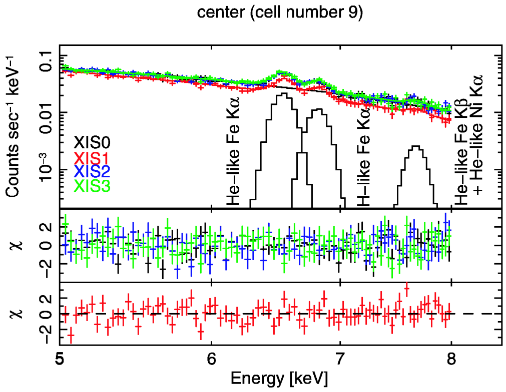
- The atmosphere is opaque to wavelengths shorter than the near UV
  - therefore most high-energy photon detection is space-based
- For detection purposes, there are essentially four energy or wavelength ranges:
  - X-rays (~0.1 – 15 keV)
    - can be detected with focusing optics
  - hard X-rays – soft γ-rays (~15 keV – 20 MeV)
    - require coded mask apertures
  - intermediate-energy γ-rays (~20 MeV – 300 GeV)
    - space-based pair-production spectrometers
  - high-energy γ-rays (30 GeV – many TeV)
    - ground-based detection of air showers, cf. cosmic rays

HIGH ENERGY PHOTON EMISSION

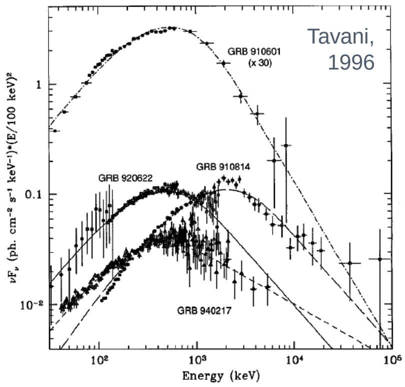
Emission Mechanisms

Emission Mechanisms

- Bremsstrahlung and synchrotron radiation extend from the radio up into the X-ray and even soft γ-ray regions

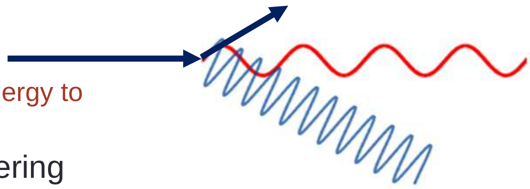


X-ray spectrum of Coma IGM showing bremsstrahlung plus iron K-lines (*Suzaku*)



Some GRB spectra fitted with a synchrotron radiation model

Inverse Compton scattering



- Compton scattering:
  - X-ray photon transfers energy to stationary electron
- Inverse Compton scattering
  - High-energy electron transfers energy to low-energy photon
    - photon can be from ambient background, e.g. CMB, or can be synchrotron radiation from same population of fast electrons (***synchrotron-self-Compton*** or ***synchro-Compton***)
- In rest frame of electron we have

$$-\frac{dE}{dt} = c\sigma_{\mathrm{T}} U_{\mathrm{rad}}$$

where $U_{\mathrm{rad}} = S/c$ (S is magnitude of Poynting vector)
  - energy density of photons of frequency ν is $n_\nu h\nu$

Inverse Compton scattering

- In lab frame (primed):
  - $h\nu' = \gamma h\nu(1 + \beta\cos\theta)$; $\Delta t = \gamma\Delta t'(1 + \beta\cos\theta)$
  - $U'_{\mathrm{rad}} = U_{\mathrm{rad}}\gamma^2(1 + \beta\cos\theta)^2$
  - average over solid angle: $U'_{\mathrm{rad}} = U_{\mathrm{rad}}\gamma^2\left(1 + \frac{1}{3}\beta^2\right) = \frac{4}{3}U_{\mathrm{rad}}\left(\gamma^2 - \frac{1}{4}\right)$
- Energy gain is difference between this and $c\sigma_T U_{\mathrm{rad}}$:

$$\frac{dE}{dt} = \frac{4}{3}c\sigma_{\mathrm{T}} U_{\mathrm{rad}}\beta^2\gamma^2$$

  - same form as synchrotron radiation, different energy density
- Maximum energy gain (head-on collision) is $4\gamma^2 h\nu_0$
- Mean energy gain is $\frac{4}{3}\gamma^2 h\nu_0$
  - similarity of these implies sharply peaked spectrum

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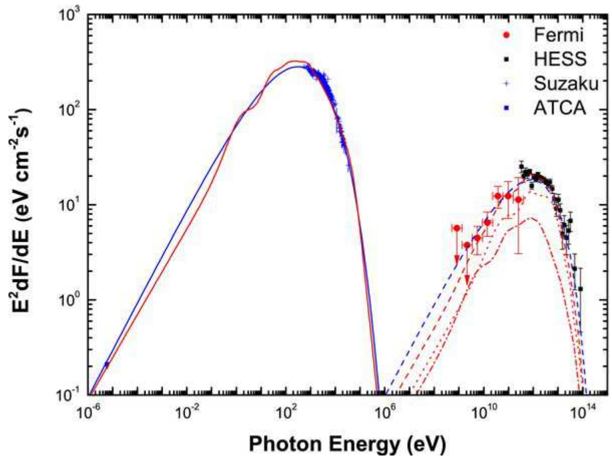
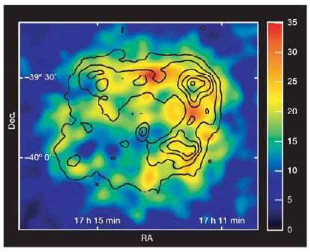
Synchrotron and inverse Compton

Spectral energy distribution of young SNR **RX J1713.7−3946**



Note the similar shapes of the synchrotron radiation spectrum (radio to X-rays) and the inverse Compton emission (γ-rays)



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Neutral pion decay

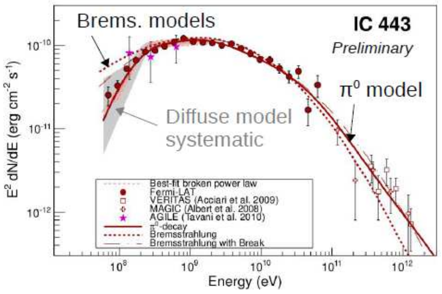
- If an object accelerates protons to high energies, we should get neutral pion production via $p + p \rightarrow p + p + \pi^0$
    - (i.e. energetic proton hits ambient gas)
  - π^0 then decays to two photons
  - in pion rest frame, photons are back to back with $E = \frac{1}{2} m_\pi c^2$
    - as pion has zero spin, photon directions are isotropic in this frame
  - boosted to lab frame, photon energy spectrum is flat between $\frac{1}{2}m_\pi c^2\gamma(1-\beta)$ and $\frac{1}{2}m_\pi c^2\gamma(1+\beta)$
    - of course in real world, pions do not all have same energy, so spectrum will be convolution of this with pion spectrum
    - pion production in pp or pγ interactions measured in lab, so this spectrum is known
- Also $p + \gamma \rightarrow p + \pi^0$ as in GZK, but this has *much* higher threshold for typical photon energies

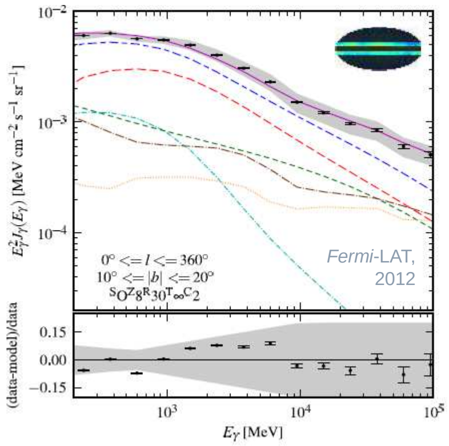
Decay energetics

- Energy threshold for π^0 production:
  - in $p + p \to p + p + \pi^0$:
    - minimum centre-of-mass energy is $2m_p+m_\pi$
    - therefore $E_{\rm tot}^2 - p_{\rm tot}^2 = 2m_p^2(\gamma+1) = \left(2m_p + m_\pi\right)^2 = 4m_p^2\left(1+\frac{m_\pi}{2m_p}\right)^2$ (in units in which $c = 1$)
    - so $\gamma = 1 + \frac{2m_\pi}{m_p} + \frac{m_\pi^2}{2m_p^2} = \frac{E_{\rm min}}{m_p}$
    - hence the minimum proton kinetic energy E_K = 280 MeV
  - threshold for production of Δ resonance is not that much higher
    - $2m_p + m_\pi$ = 2×938 + 135 = 2011 MeV/c^2; $E_K \geq$ 280 MeV
      $m_\Delta + m_p$ = 1232 + 938 = 2170 MeV/c^2; $E_K \geq$ 634 MeV
  - much low-energy pion production should go via Δ resonance

Diffuse γ-ray emission in Galaxy

- Dominated by π^0 decay at energies below ~50 GeV
  - this is caused by cosmic rays scattering in Galactic gas
- Some SNR spectra also show “pion bump”





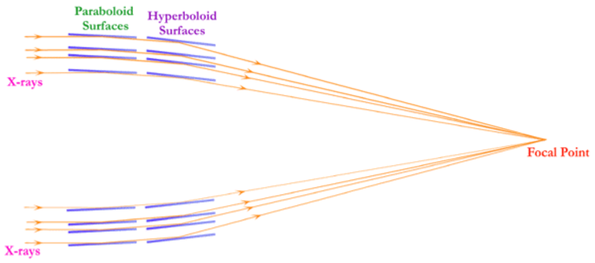
pion decay; inverse Compton; bremsstrahlung; isotropic background; sources; total diffuse Galactic; total with isotropic BG and sources

HIGH ENERGY PHOTON EMISSION

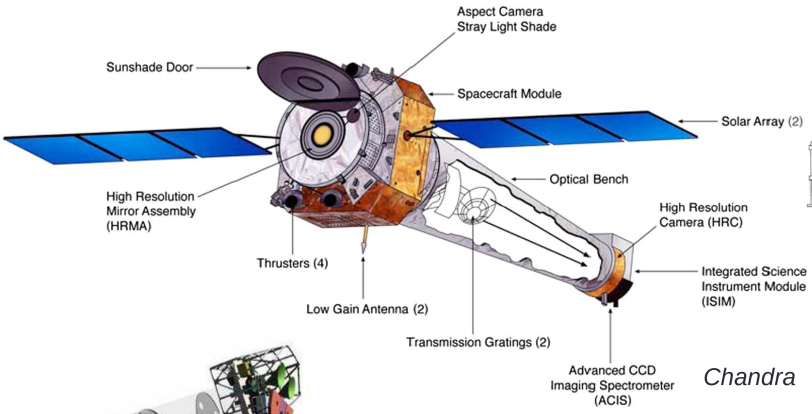
X-Rays

X-rays: detection and sources

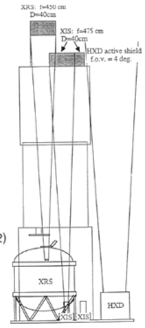
- Modern X-ray telescopes use focusing optics
  - however, X-rays do not reflect at normal incidence
  - hence use ***grazing incidence optics***
    - *any* part of a parabola focuses light to a point
    - use the high part of the curve instead of the bowl at the bottom
    - multiple nested mirrors to increase effective area
  - Detector at focus is usually silicon-based: typically CCDs (as with optical astronomy)
    - *Chandra* HRC uses microchannel plates



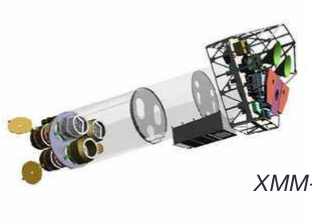
Modern X-ray telescopes



Chandra



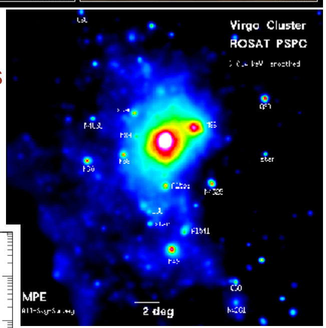
Suzaku

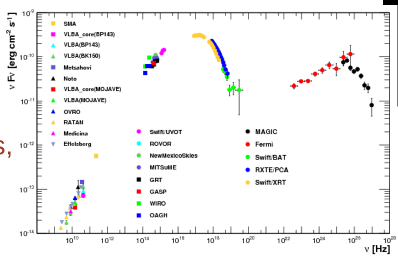


XMM-Newton

X-ray sources

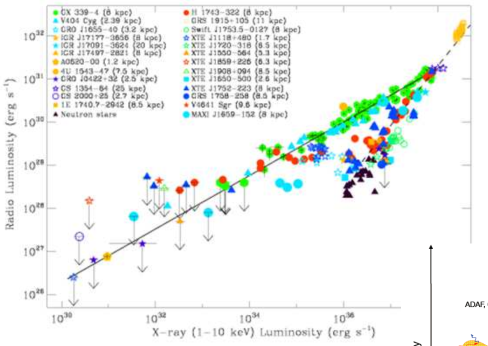
- Thermal bremsstrahlung
  - from accretion discs, e.g. in close binaries containing a compact object
  - from the intracluster medium of rich clusters of galaxies
- Non-thermal emission (usually synchrotron)
  - from populations of fast electrons
  - SNR, GRBs, AGN





Spectral energy distribution of active galaxy Mkn 421

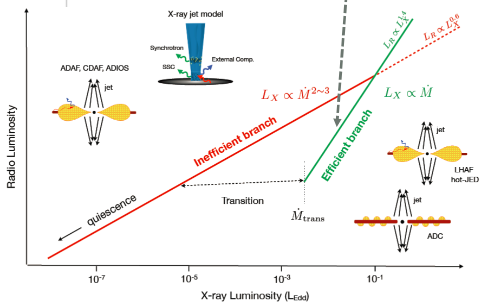
Radio and X-ray luminosity



Sample of X-ray binaries

radio-loud AGN live here

interpretation (Panessa 2013)

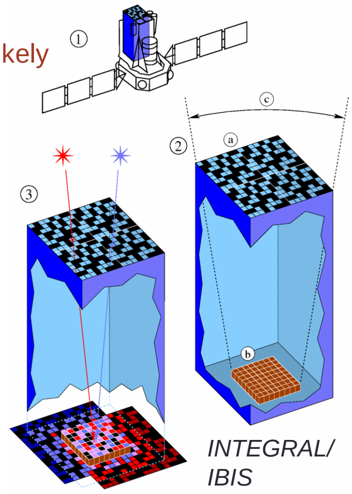


HIGH ENERGY PHOTON EMISSION

Low-energy γ-rays

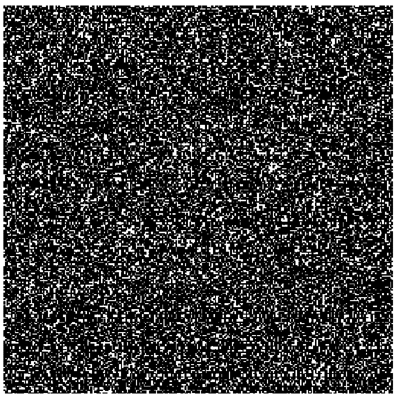
Coded mask apertures

- Above a few 10s of keV even grazing-incidence reflection doesn't work
  - and below 20 MeV or so the photon is unlikely to initiate an electromagnetic shower
- This makes direction-sensitive detection difficult
  - Some instruments use ***collimators***
    - restrict angle of incoming radiation
    - necessarily poor field of view
  - Preferred option is ***coded masks***
    - Principle: each direction results in a distinctive shadow pattern, so image can be recovered by deconvolution



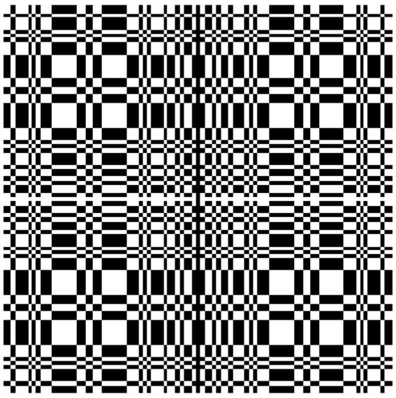
INTEGRAL/ IBIS

Coded mask apertures



Beppo-SAX WFC

INTEGRAL IBIS



Coded mask patterns vary from apparently random to highly structured, but are in fact designed according to established principles

Better angular resolution than collimators (WFC: 5' (source location <1')) coupled with wide field of view (WFC: 20° × 20°)

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Decoding coded mask images

- The image on the detector is a convolution of the sky pattern and the mask pattern, plus background

$$\mathbf{D} = \mathbf{O} \otimes \mathbf{M} + \mathbf{B}$$

  - There are various techniques for tackling this
    - explicit deconvolution is possible but dangerous, as it is a matrix inversion operation; if elements of the inverse are large the result may be dominated by background noise
    - usual technique is to cross-correlate with a reconstruction matrix

- $$\hat{\mathbf{O}} = \mathbf{D} \odot \mathbf{R} = \mathbf{O} \otimes (\mathbf{M} \odot \mathbf{R}) + \mathbf{B} \odot \mathbf{R}$$
  - the aim is to construct **R** such that $\mathbf{M} \odot \mathbf{R} \approx \mathbf{I}$ and $\mathbf{B} \odot \mathbf{R} \approx \mathbf{0}$
    - there are various standard tools to do this, e.g. using an iterative method in which contributions from strong sources are progressively removed to simplify the residual image (Iterative Removal of Sources)

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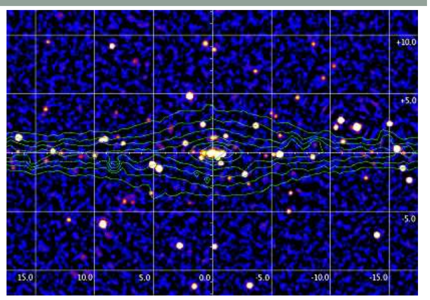
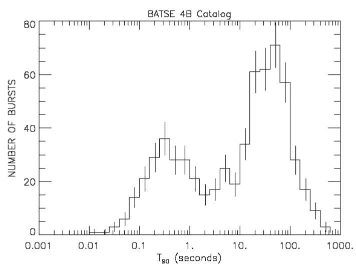
Soft γ-ray sources

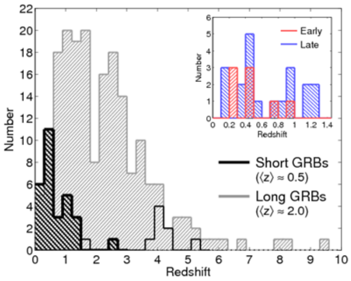


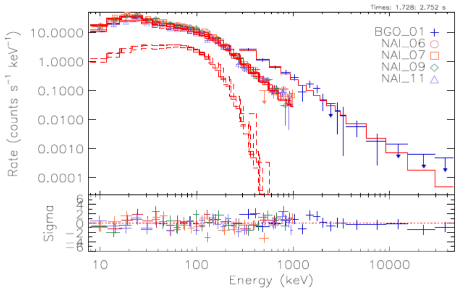
IBIS map of Galactic bulge region

- Coded mask arrays are inferior to imaging X-ray telescopes and pair-creation spectrometers
  - however, this energy range is very important for some source types
- Most important source class: gamma-ray bursts (GRBs)
  - transient bursts of γ-rays from extragalactic sources
  - two classes: long (or long-soft) and short (or short-hard); boundary around 2 s (for 90% of emission)
    - the two classes are real but the 2 s boundary may not be optimal

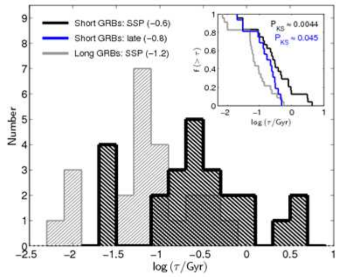


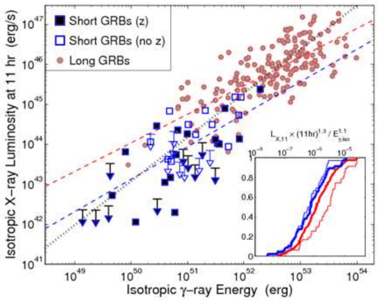
Gamma-ray bursts





Spectrum of a long GRB, fitted with blackbody + synchrotron



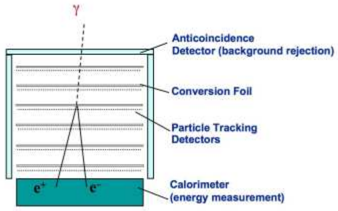


Long GRBs are brighter, more distant and located in galaxies with higher star formation rates

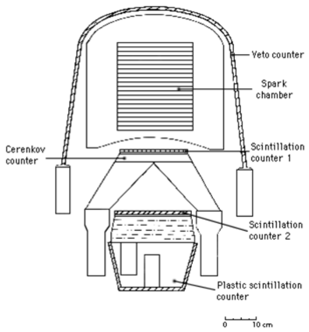
HIGH ENERGY PHOTON EMISSION

Intermediate-energy γ-rays

Pair-conversion spectrometers

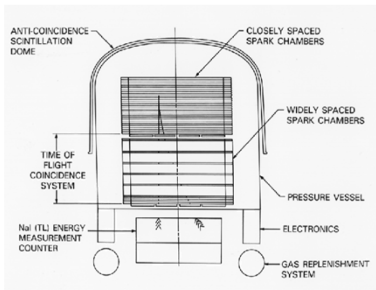


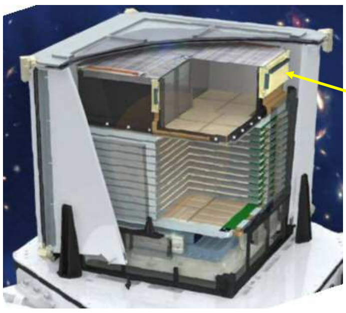
- Above a few 10s of MeV, photons will readily convert into e^+e^- pairs
  - these are charged particles and can be tracked using ionisation detectors
  - their energies can subsequently be measured using calorimetry
- All intermediate-energy detectors are conceptually identical
  - anticoincidence shield (scintillator)
    - vetoes charged particles coming in from outside
  - converter-tracker (metal foils plus spark chambers or silicon strips)
    - provide material for pair conversion (requires external field) plus position-sensitive detectors to track converted pair
  - calorimeter (inorganic crystal scintillator—NaI or CsI)
    - induce electromagnetic shower and measure energy



COS-B (1975-1982)

EGRET (1991-2000)

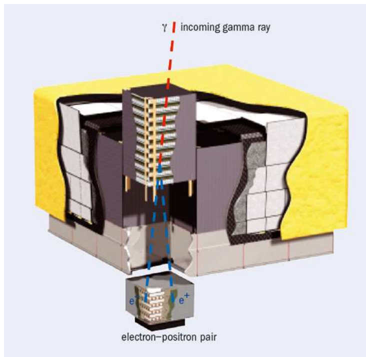




AGILE (2007-)

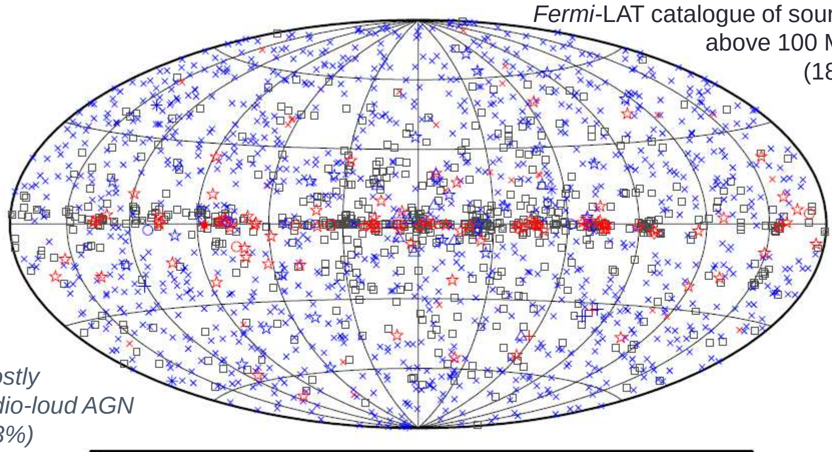
HXD

Fermi-LAT (2008-)



Sources of GeV-energy γ-rays

Fermi-LAT catalogue of sources above 100 MeV (1873)

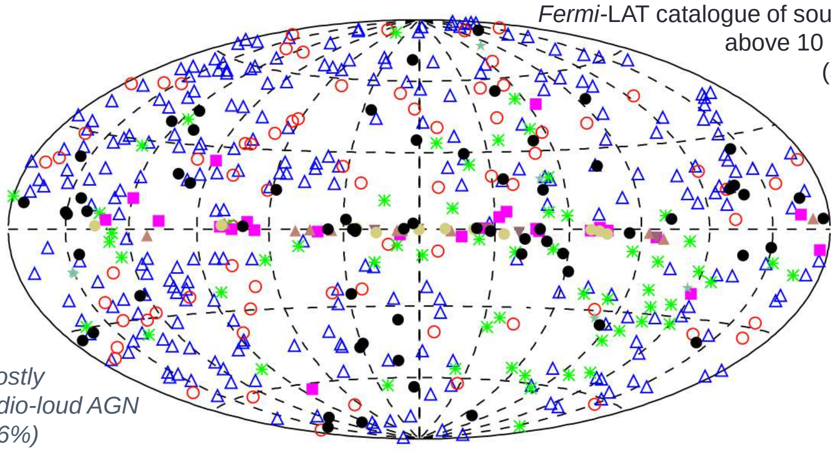


mostly radio-loud AGN (63%)

□ No association	⊡ Possible association with SNR or PWN	
× AGN	☆ Pulsar	△ Globular cluster
✳ Starburst Gal	◇ PWN	⊠ HMB
+ Galaxy	○ SNR	✷ Nova

Sources of GeV-energy γ-rays

Fermi-LAT catalogue of sources above 10 GeV (514)



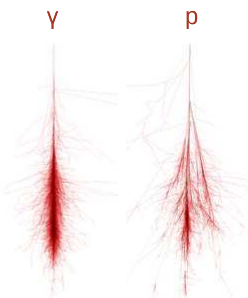
mostly radio-loud AGN (76%)

△ BL Lac	○ FSRQ	✳ AGNs of unknown type
■ PSR	▲ SNR	▼ PWN
● Other Galactic objects	★ Other (non-beamed) Extragalactic objects	● No association

HIGH ENERGY PHOTON EMISSION

High-energy γ-rays

Photon-induced air showers

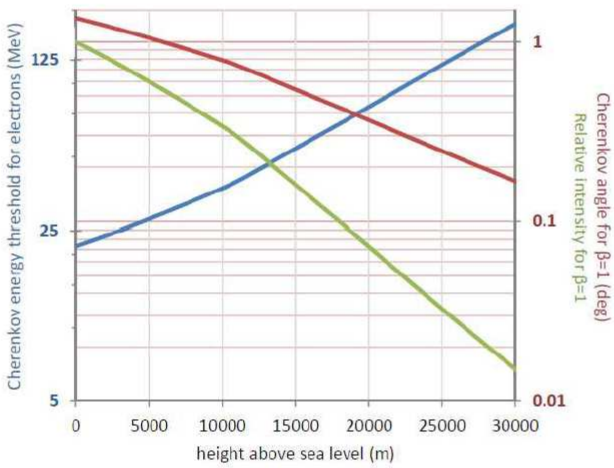


- Very-high-energy γ-rays are uncommon
  - space-based detectors are too small to get a decent rate
  - also, measurement quality degrades because larger showers leak out of back of calorimeter
- Therefore, as with charged cosmic rays, go for ground-based detectors and detect the shower produced in the atmosphere
  - very little of a photon shower reaches ground, so applicable techniques are nitrogen fluorescence and Cherenkov radiation
    - high-energy photon detectors tend to choose Cherenkov emission because of its high directionality (as photons point back to their source, direction reconstruction is important to identify optical counterparts of γ-ray sources)

Cherenkov radiation

- Cherenkov emission per unit time is
$$I(\omega) = \frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}\omega \mathrm{d}t} = \frac{\omega e^2 \beta}{4\pi\epsilon_0 c}\left(1 - \frac{1}{n^2\beta^2}\right)$$
  - $I(\omega) \propto \omega$, hence Cherenkov light is blue (but note n also depends on ω, proportionality is not exact)
  - very little dependence on particle energy once $\beta \simeq 1$
  - but ***number of particles in shower*** depends on energy of incoming particle, so *total light yield* does provide a measure of the energy of the particle initiating the shower
- TeV-energy photon produces only ~100 Cherenkov photons per square metre
  - need large collecting areas (~100 m^2 typical)
  - but light pool is ~60000 m^2, so large effective area for low fluxes

Cherenkov radiation from air showers



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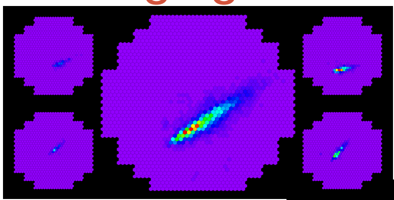
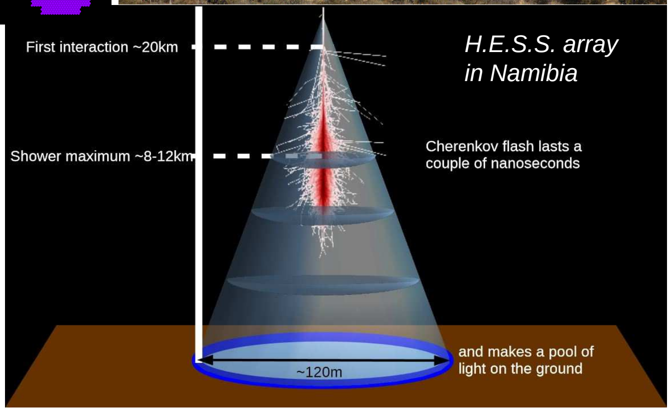
Imaging air Cherenkov telescopes



Stereo imaging with multiple telescopes improves shower reconstruction.

Photon showers are identified by shower shape.

Sources can be located to within a few arcsec (for H.E.S.S.); γ energy measurement ~15%



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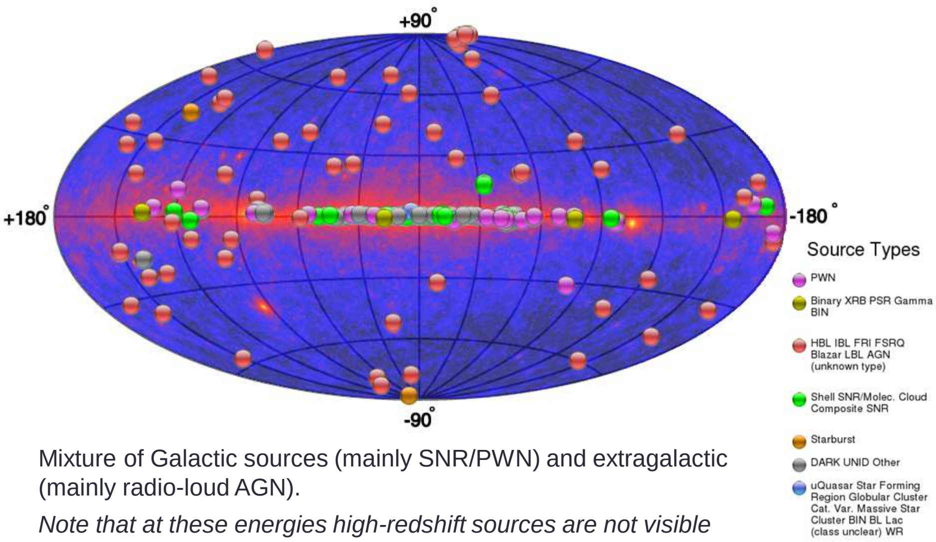
TeV photon sources



Mixture of Galactic sources (mainly SNR/PWN) and extragalactic (mainly radio-loud AGN).

Note that at these energies high-redshift sources are not visible

Summary

You should read section 2.4 of the notes.

You should know about

- *inverse Compton effect*
- *π^0 decay*
- *grazing incidence optics*
- *coded masks*
- *pair-conversion spectrometers*
- *air Cherenkov telescopes*
- *source types*

- The atmosphere is not transparent to high-energy photons
- Detection techniques depend on energy
  - grazing-incidence optics for X-rays
  - coded masks or collimators for hard X-rays/soft γ-rays
  - pair conversion spectrometers for intermediate-energy γ-rays
  - air-shower detection by Cherenkov emission for TeV photons
- Emission mechanisms include brems-strahlung and synchrotron radiation plus inverse Compton scattering and π^0 decay
  - former dominate for lower energies (X-rays), latter two for high energies
- Sources include supernova remnants and pulsars (Galactic) and radio-loud AGN
  - most important ***transient*** sources are GRBs

Next: high-energy neutrinos

- production
- Waxman-Bahcall bound
- interactions with matter
- detection

Notes section 2.5