Messenger: photon

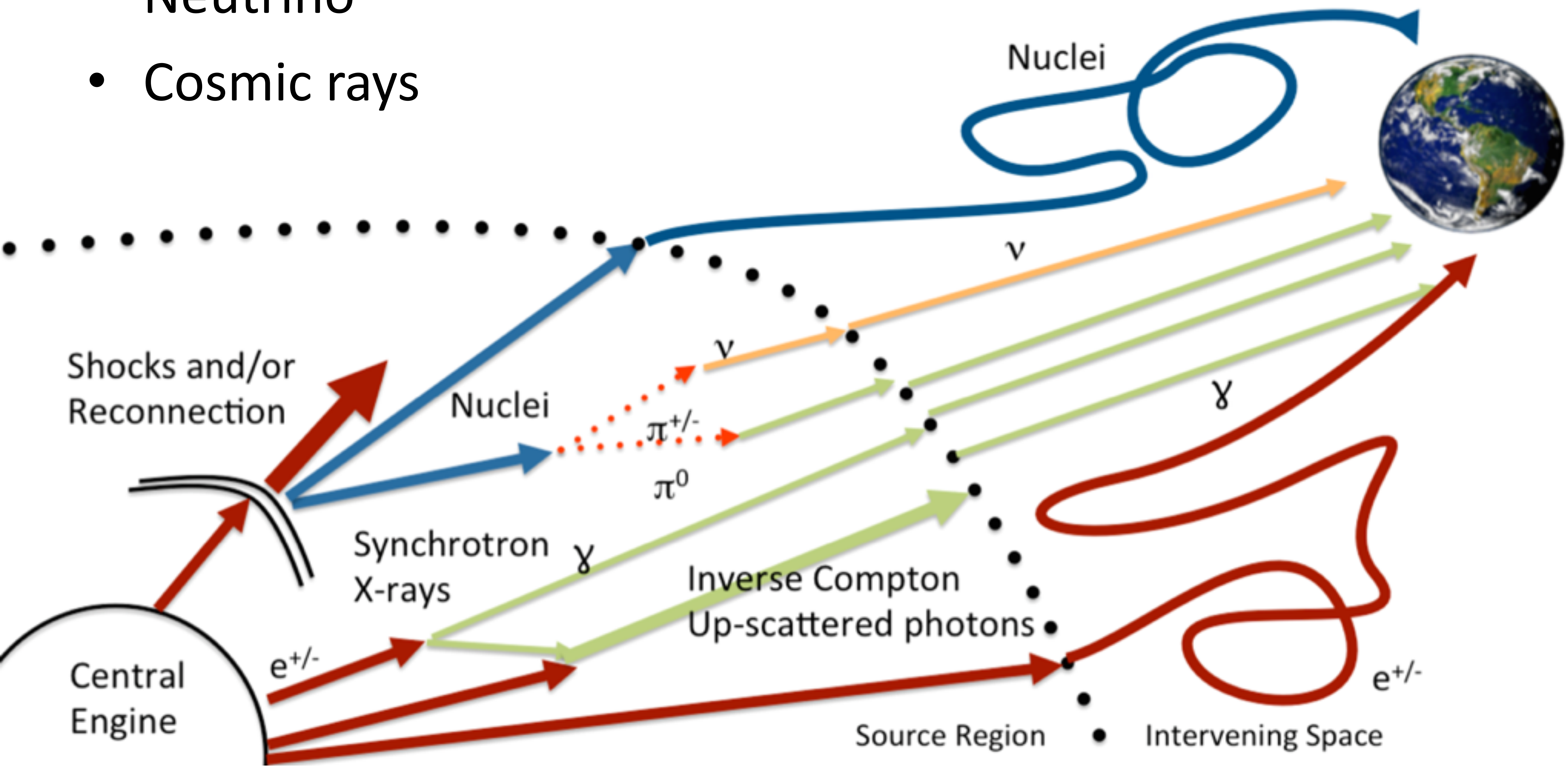
multi-wavelength astrophysics

Antonio Stamerra
INAF - Osservatorio Astrofisico di Torino
and
SNS - Scuola Normal Superiore di Pisa

7TH IDPASC SCHOOL
Asiago, Italy, 20 - 30 June 2017

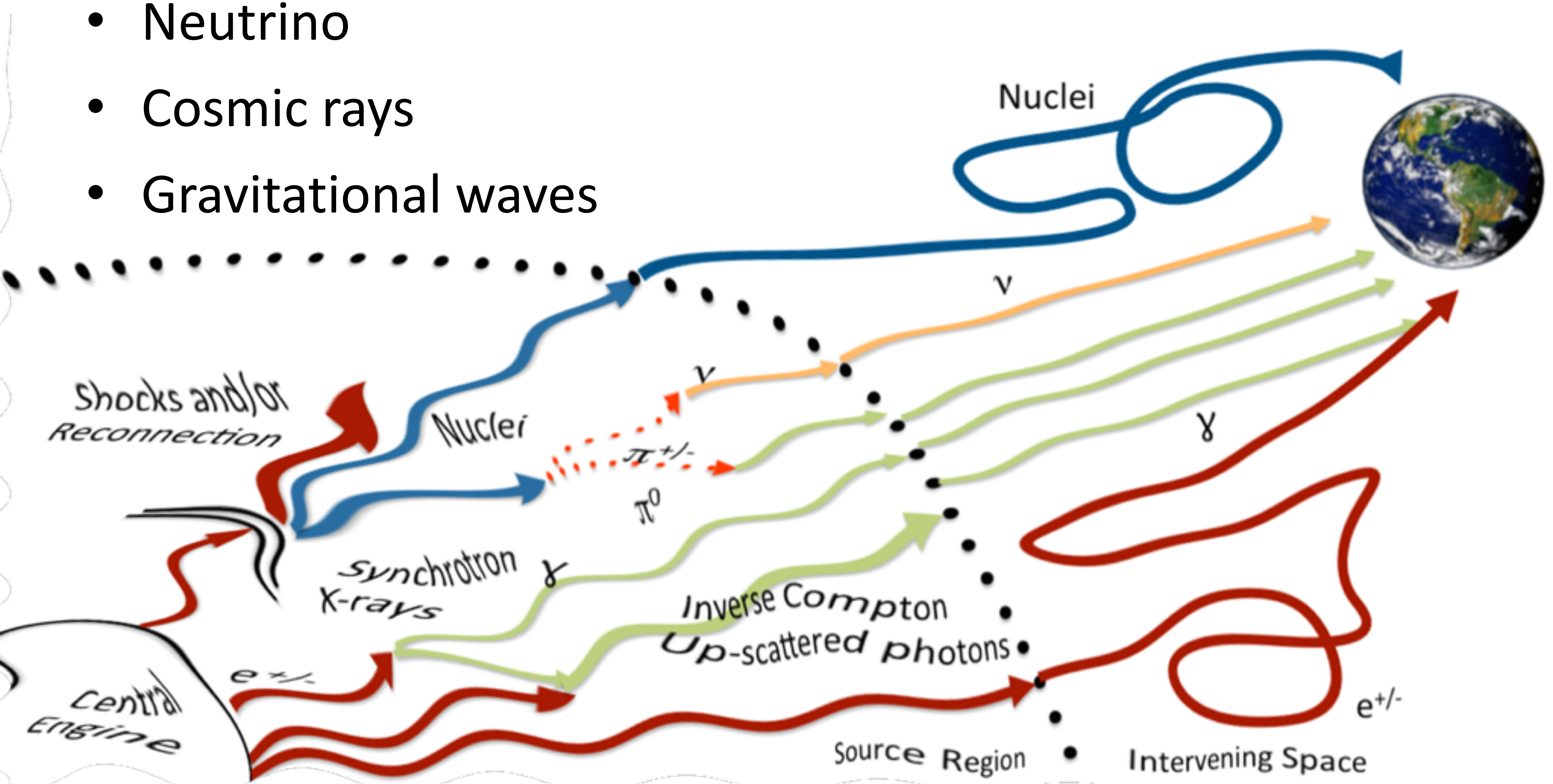
Multi-messenger observations of high-energy astrophysical sources

- Photons
- Neutrino
- Cosmic rays

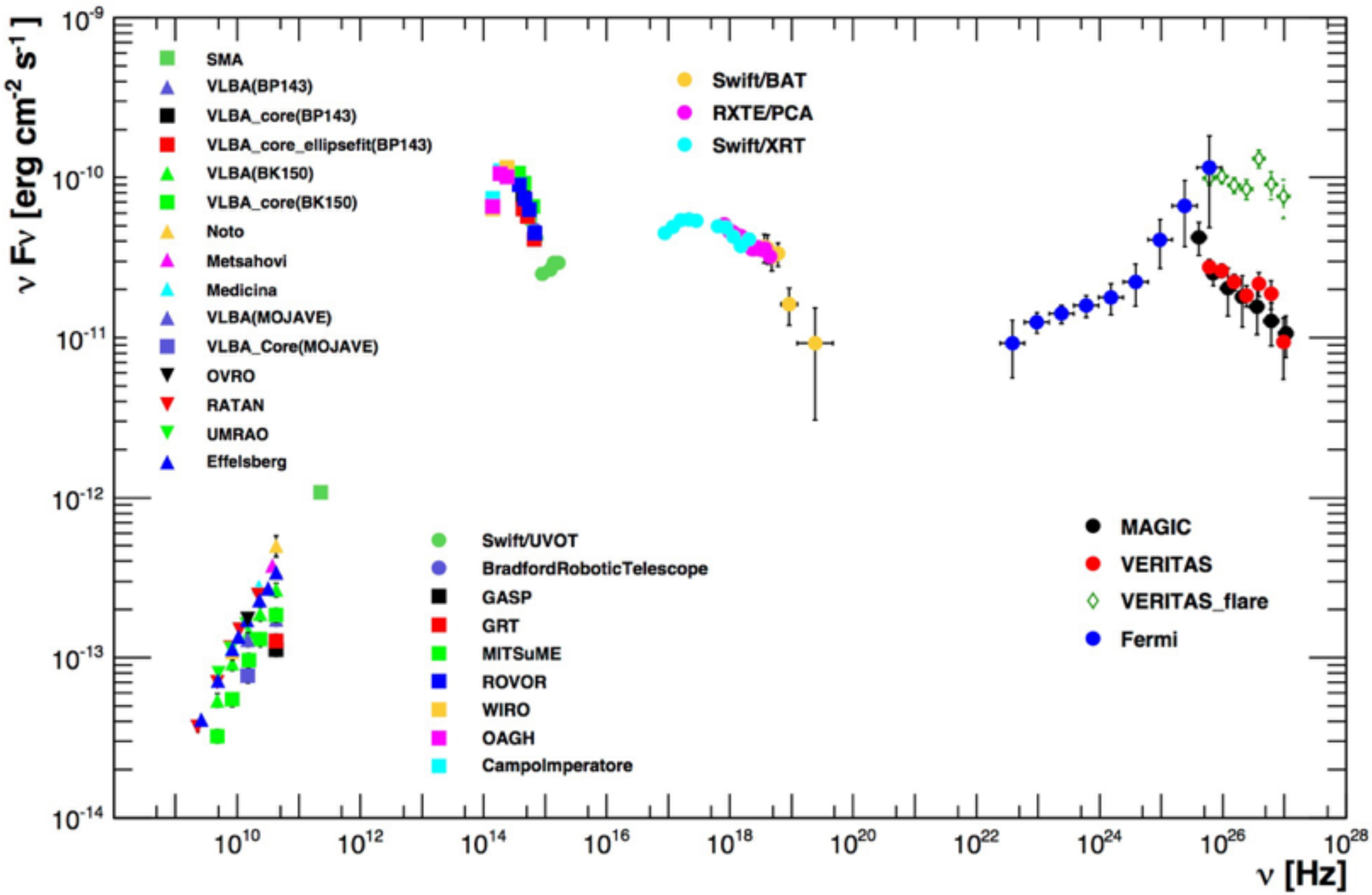


Multi-messenger observations of high-energy astrophysical sources

- Photons
- Neutrino
- Cosmic rays
- Gravitational waves



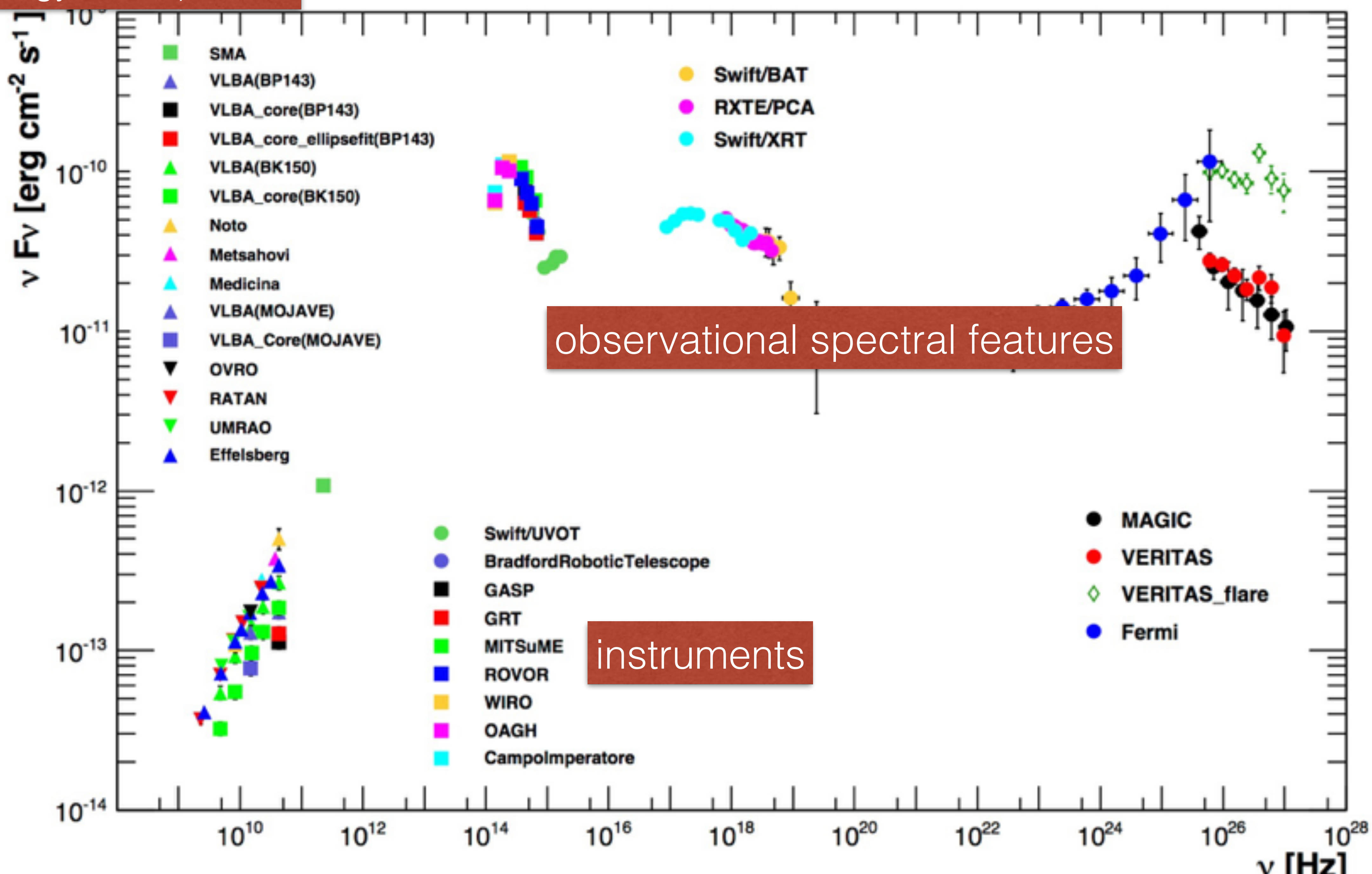
Outline



ν Fν [erg cm^{-2} s^{-1}]
ν [Hz]
SMA
VLBA(BP143)
VLBA_core(BP143)
VLBA_core_ellipsefit(BP143)
VLBA(BK150)
VLBA_core(BK150)
Noto
Metsahovi
Medicina
VLBA(MOJAVE)
VLBA_Core(MOJAVE)
OVRO
RATAN
UMRAO
Effelsberg
Swift/BAT
RXTE/PCA
Swift/XRT
Swift/UVOT
BradfordRoboticTelescope
GASP
GRT
MITSuME
ROVOR
WIRO
OAGH
CampoImperatore
MAGIC
VERITAS
VERITAS_flare
Fermi

Outline

observational quantities
(energy, flux,...)



observational spectral features

instruments

Outline

How do we study multi-wavelength emission from astrophysical processes

- Read a SED
- Thermal and non-thermal emission
- Instruments
- Build SED from (archival) data

Basic definitions

- Luminosity
- (spectral/photon) Flux density
- Spectrum
  - photon spectrum - flux
  - SED

unresolved
(point source)

Source: luminosity

- Spectral luminosity: energy emitted per unit time in the (unit) energy/frequency interval

$$L_\nu = \frac{dE}{dt\, d\nu}$$ [W Hz^{-1}] or [erg s^{-1} Hz^{-1}]

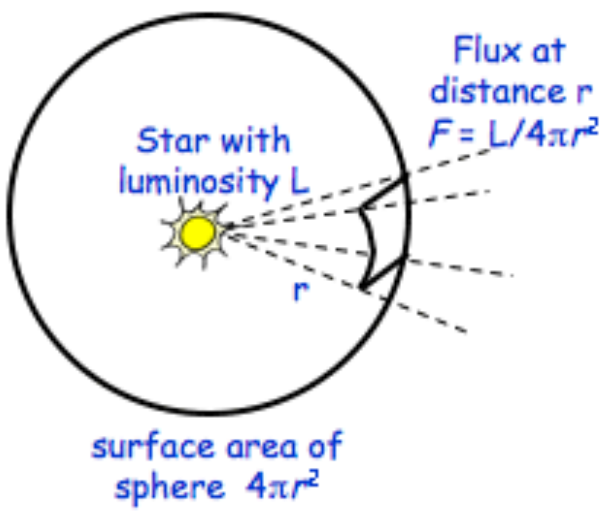
- Bolometric luminosity: energy emitted per unit time, at all frequencies

$$L_{bol} = \int_0^\infty L_\nu d\nu \qquad \mathrm{[W]}$$

unresolved
(point source)

Detector: flux

- Spectral flux density (or energy flux density)



$$F_\nu = \frac{L_\nu}{4\pi D^2} \qquad [\mathrm{W\,m^{-2}\,Hz^{-1}}]$$
$$[\mathrm{erg\ s^{-1}\,cm^{-2}\,Hz^{-1}}]$$

$$F_\nu(\nu) = \frac{dE}{\mathrm{d}t\,\mathrm{d}A\,\mathrm{d}\nu}$$

1 Jy = 10^{-26} W m^{-2} Hz^{-1}
10^{-23} erg s^{-1} cm^{-2} Hz^{-1}

- Energy flux (plotted in SED)

$$\nu F_\nu(\nu) = \nu \frac{dE}{\mathrm{d}t\,\mathrm{d}A\,\mathrm{d}\nu} = \frac{dE}{\mathrm{d}t\,\mathrm{d}A\,\mathrm{d}(\log\nu)}$$

unresolved
(point source)

Detector: flux

- Photon flux density per unit frequency interval (useful for high-energy telescopes)

$$F_p(\nu) = \frac{dN}{\mathrm{d}t\,\mathrm{d}A\,\mathrm{d}\nu} \qquad [\mathrm{ph\,s^{-1}m^{-2}\,Hz^{-1}}]$$

- Photon flux density per unit energy interval

$$F_p(E) = \frac{dN}{\mathrm{d}t\,\mathrm{d}A\,\mathrm{d}E} \qquad [\mathrm{ph\,m^{-2}\,s^{-1}\,eV^{-1}}]$$

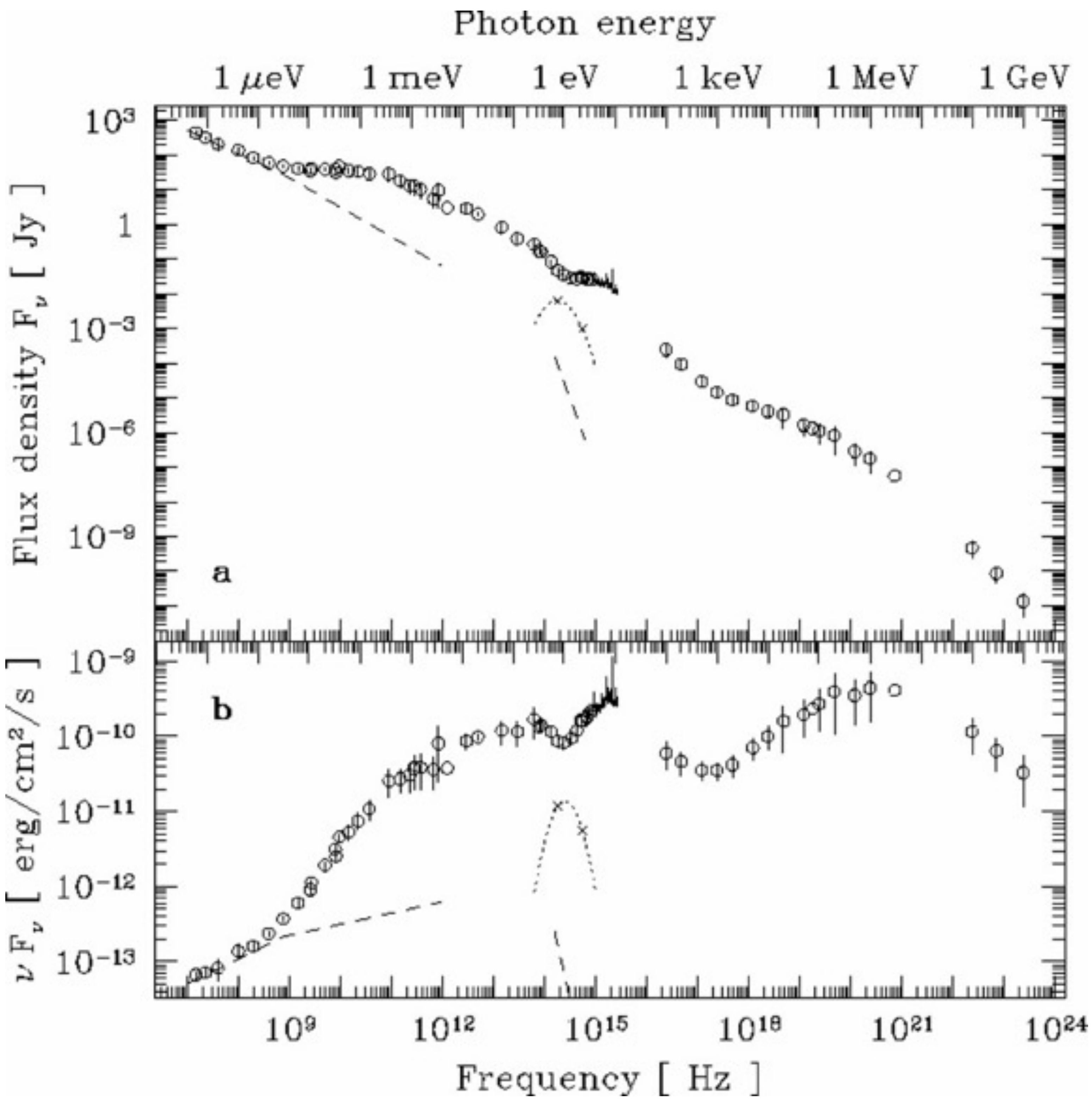
keV^{-1}

J^{-1}

Energy Flux density $\quad EF_p\mathrm{d}E = F_\nu \mathrm{d}\nu$

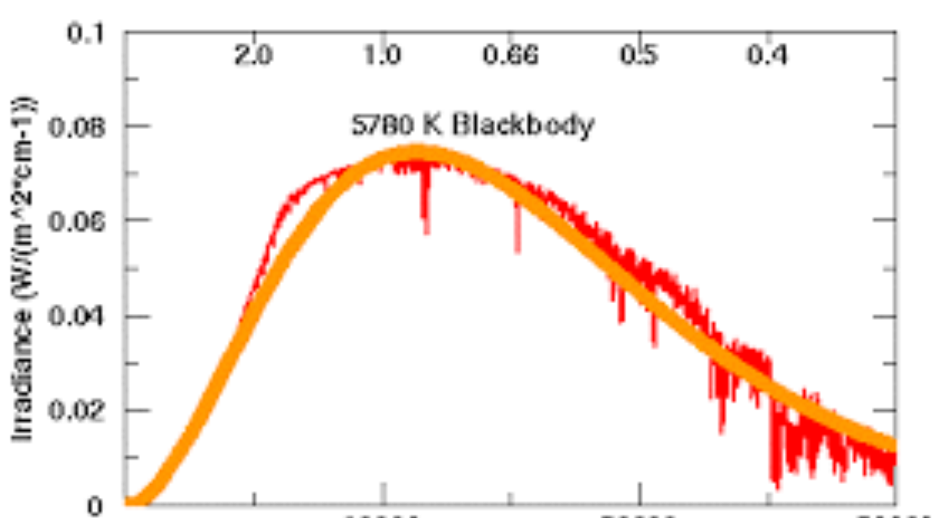
Energy Flux ➞ **SED** $\quad E^2 F_p\mathrm{d}E = \nu F_\nu \mathrm{d}\nu$

Flux density and SED



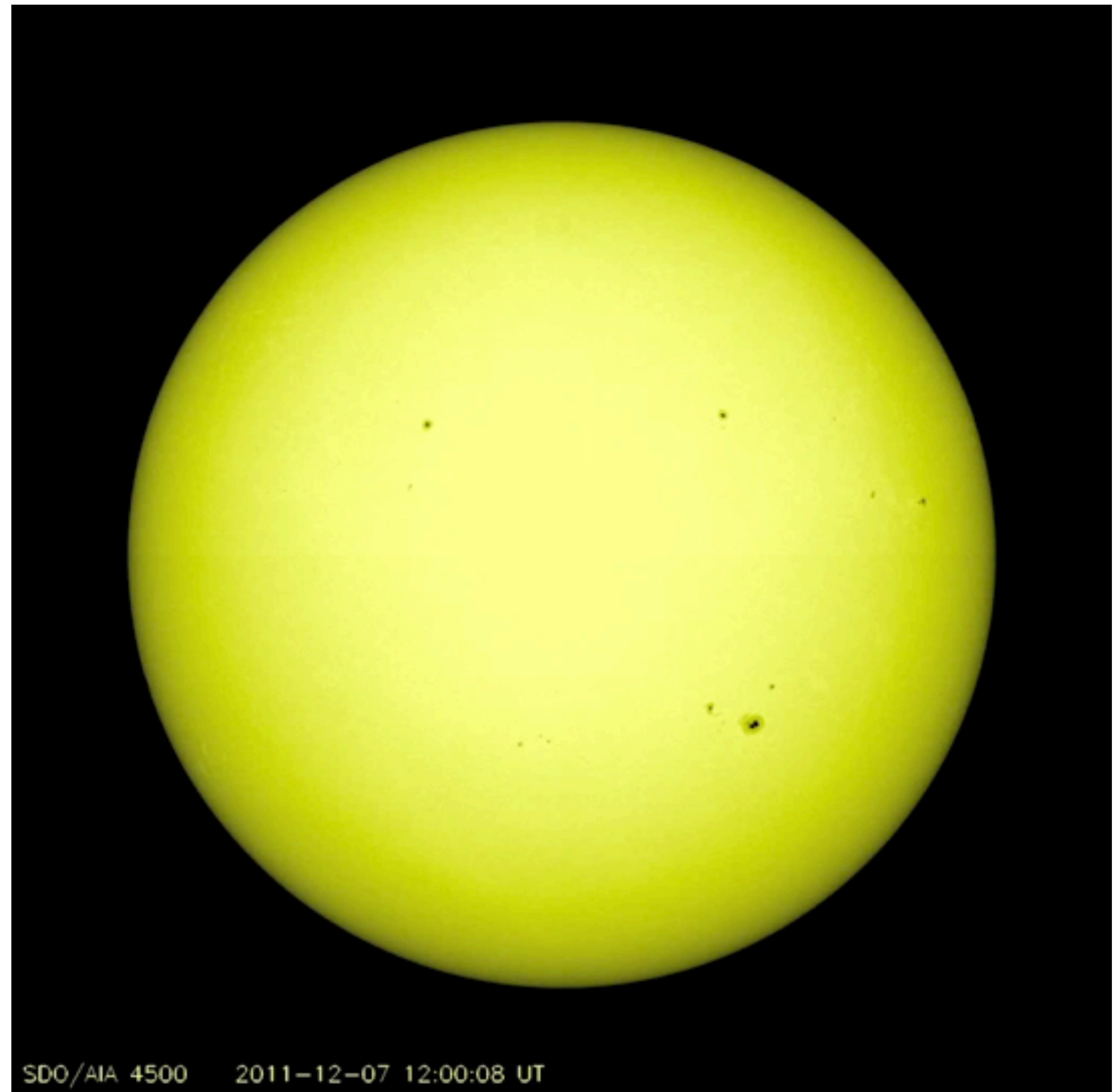
Thermal processes

- The sun
  - T_{phot} = 5770 K



frequency

L_{sun}= 3.8x10^{26} W = 3.8x10^{33} erg/s

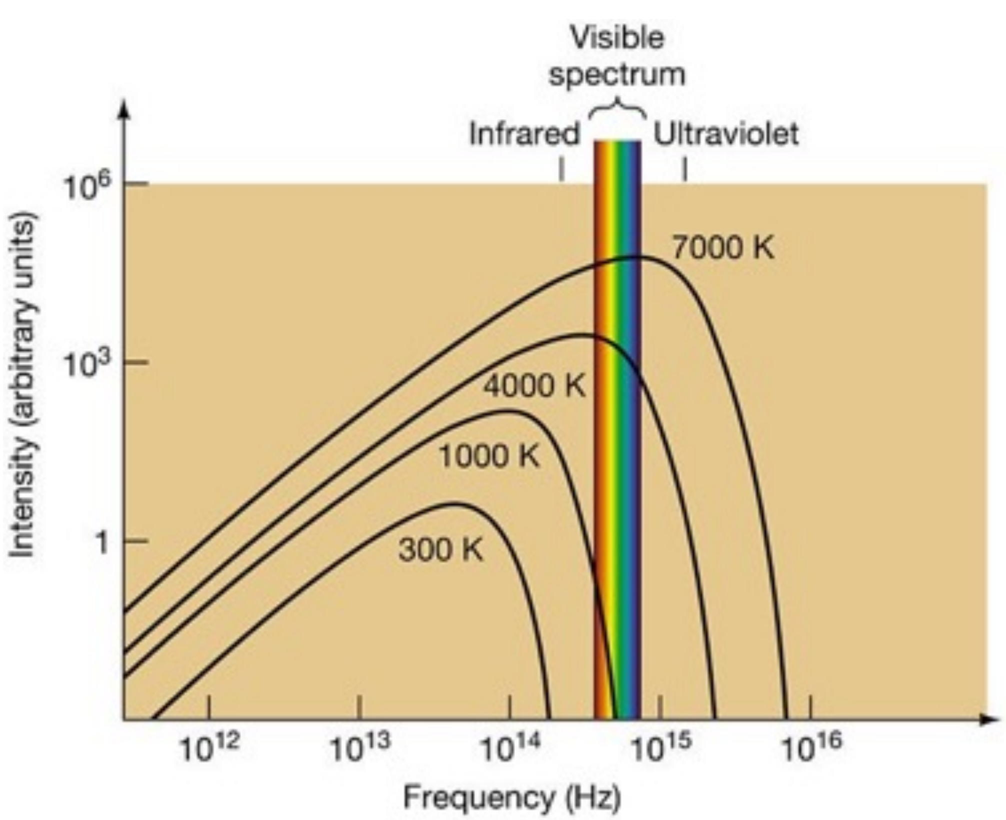


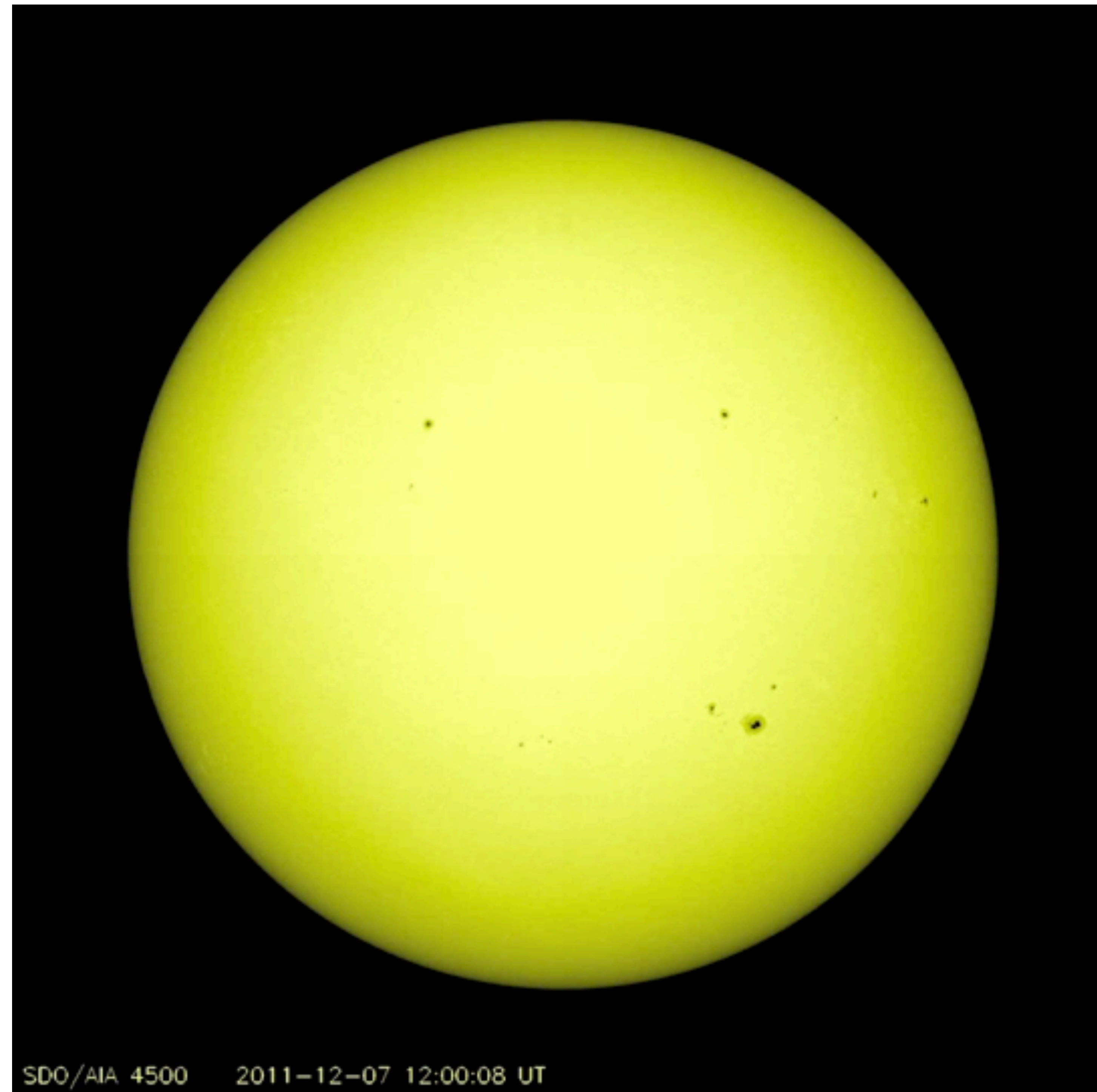
Thermal processes

- The sun

$$B_\nu = \frac{8\pi h\nu^3}{c^2}\frac{1}{e^{\frac{h\nu}{kT}}-1}$$

$$[\mathrm{J\,s^{-1}\,m^{-2}\,Hz^{-1}}]$$





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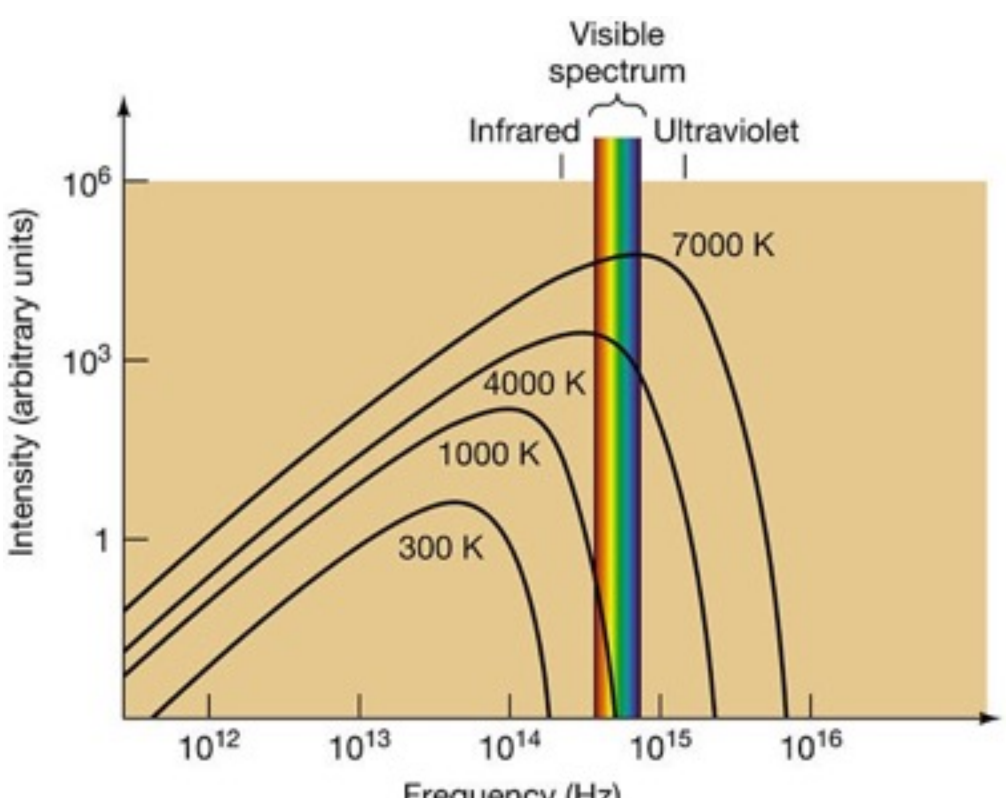
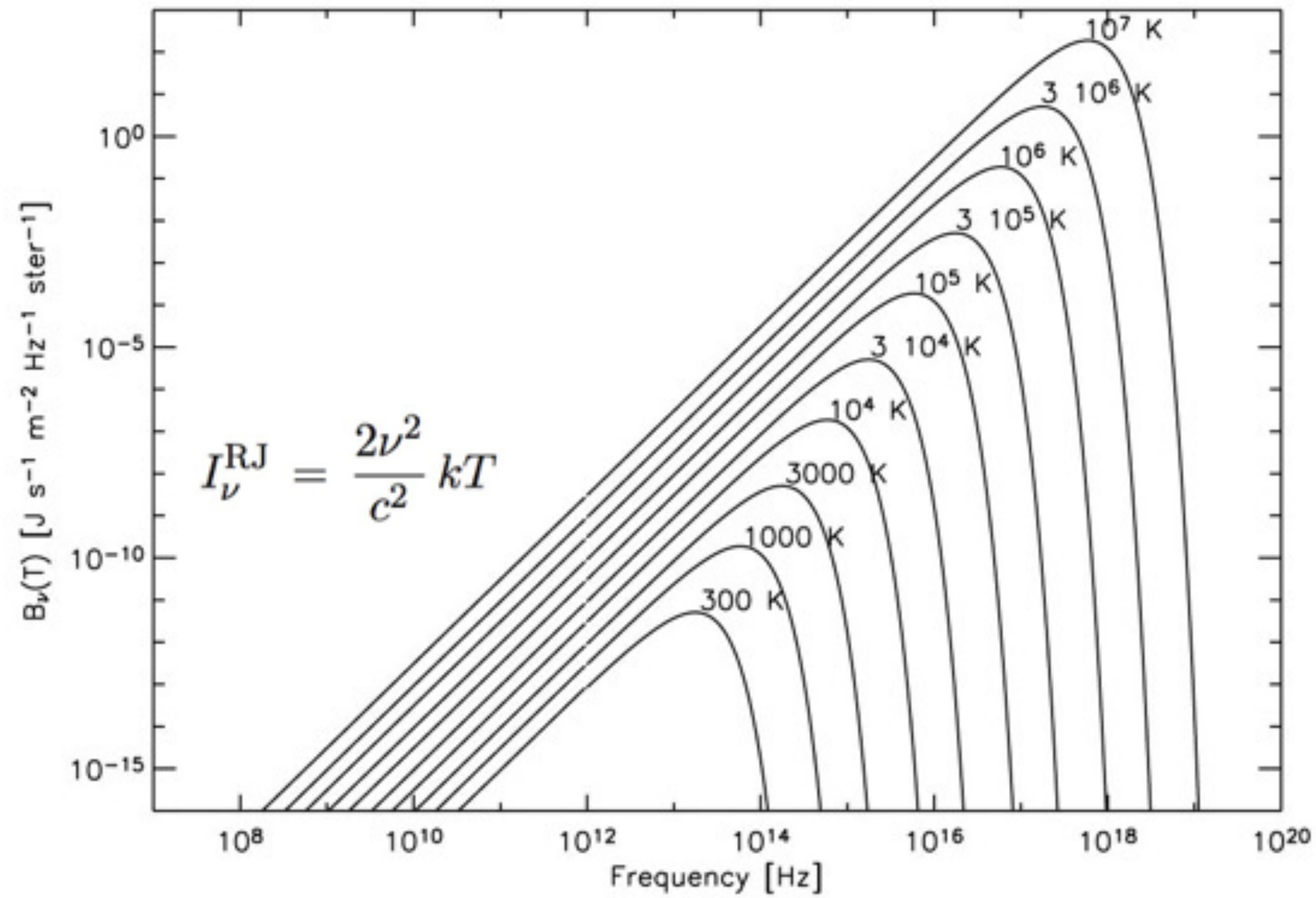
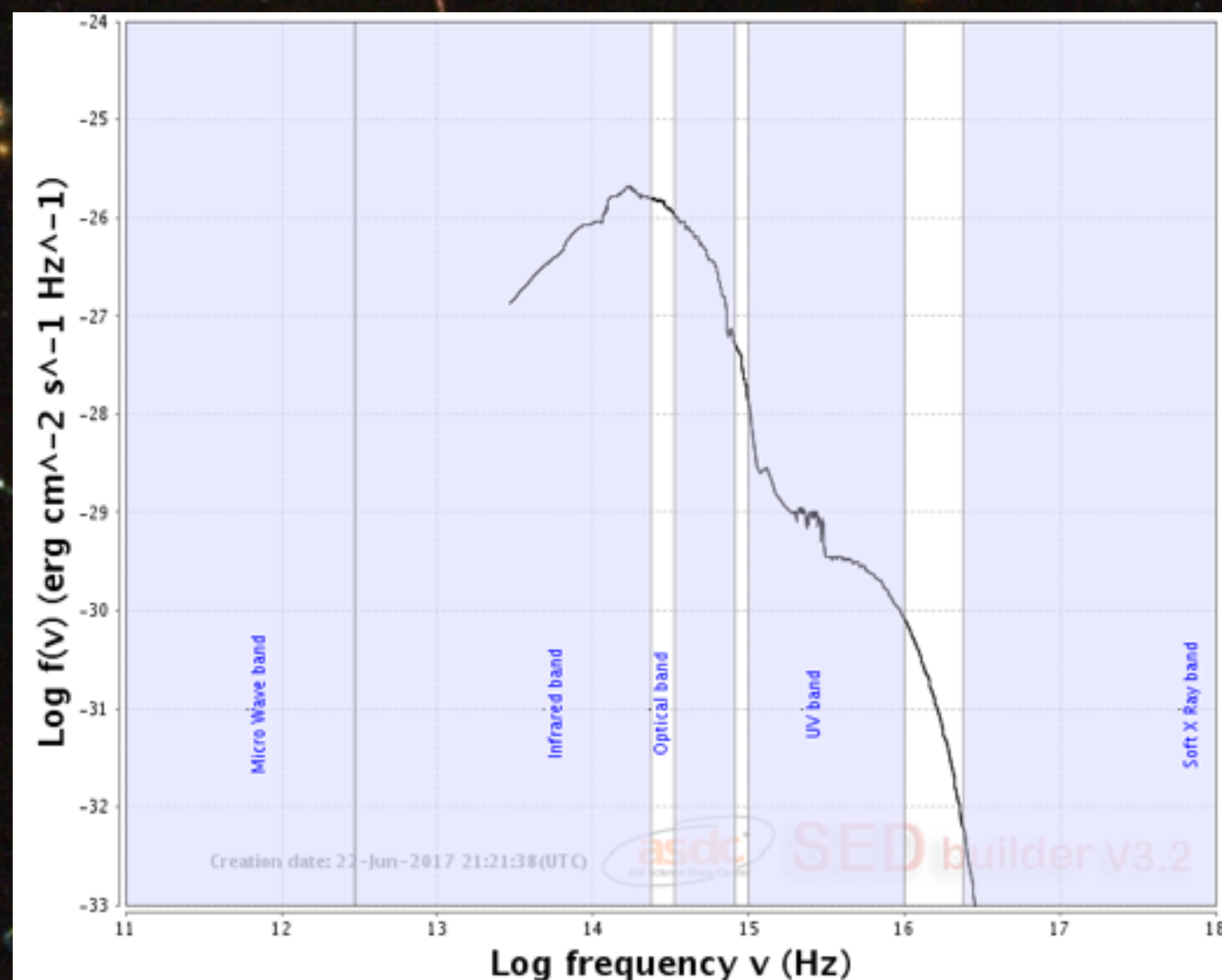




μm IR optical UV X-ray

Thermal processes

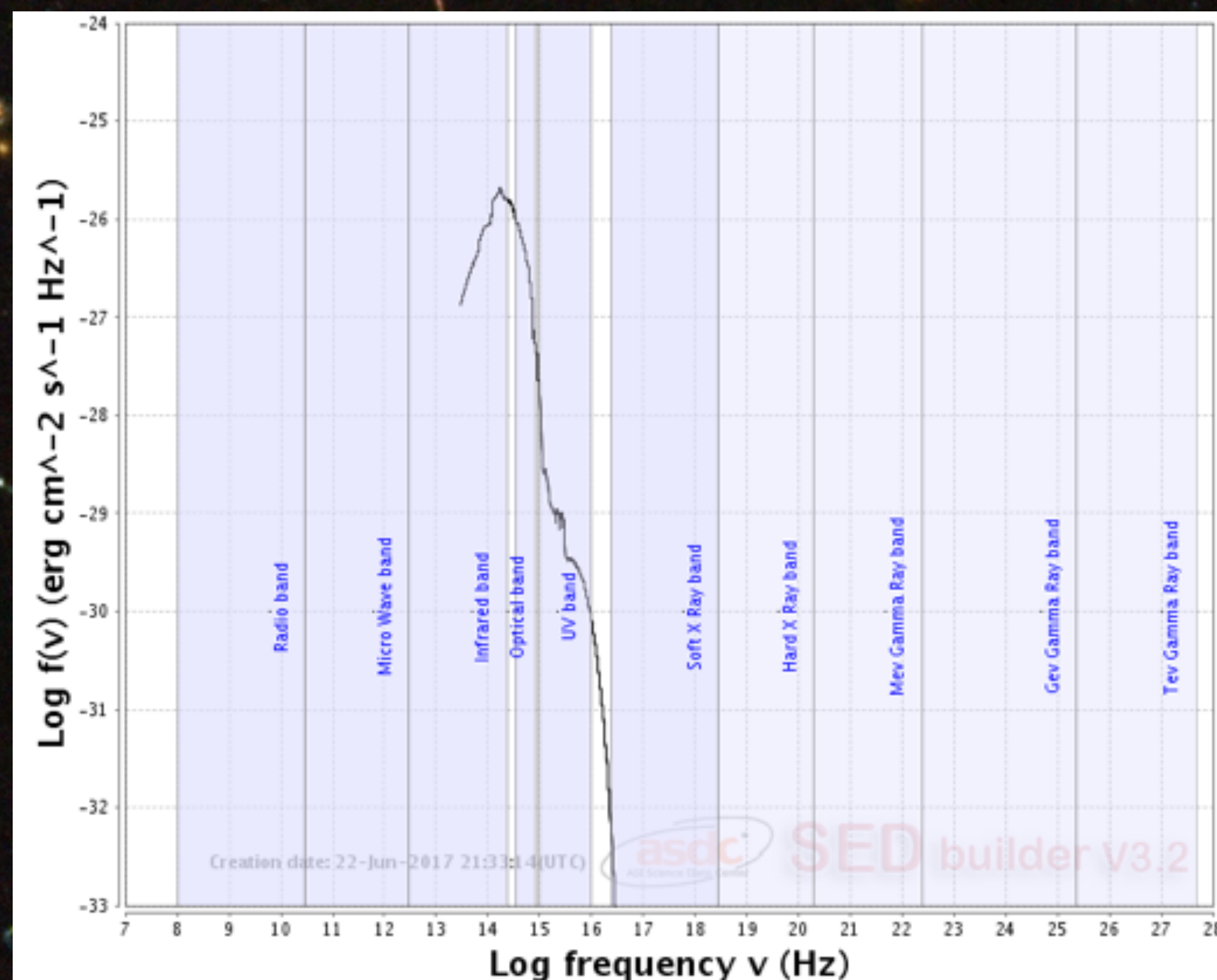
- Galaxies: at 0th order are ensembles of star black bodies...



$L_{gal} = 10^{34\text{-}37}$ W = $10^{41\text{-}44}$ erg/s

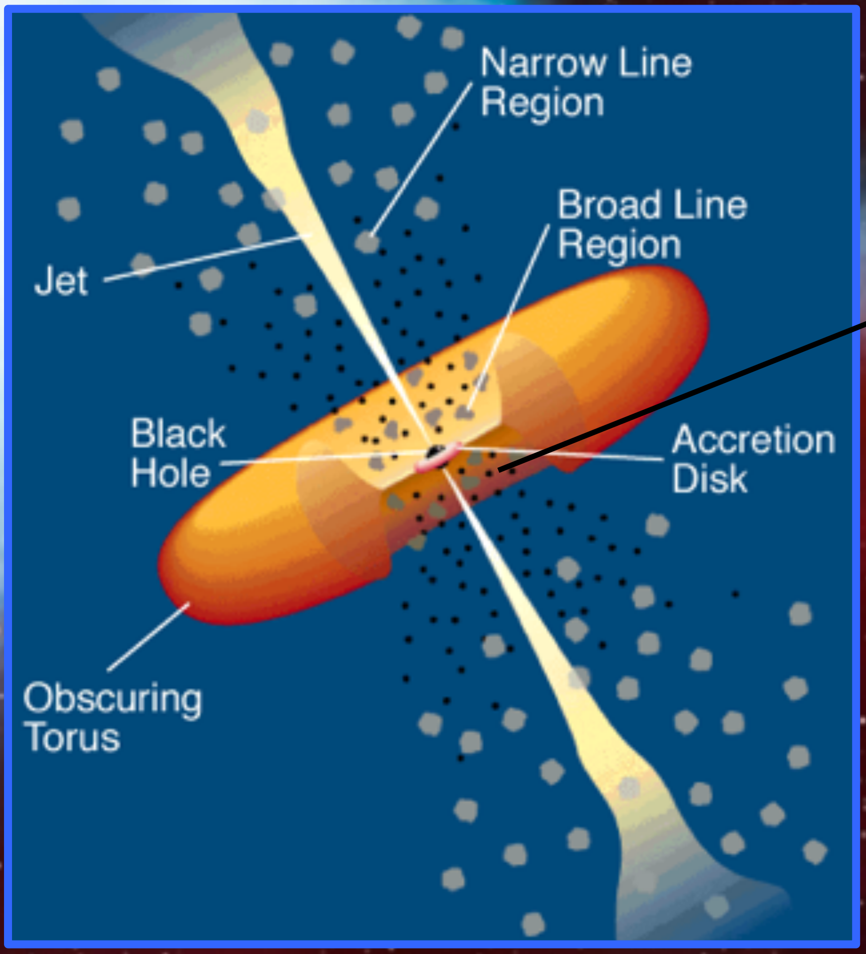
Thermal processes

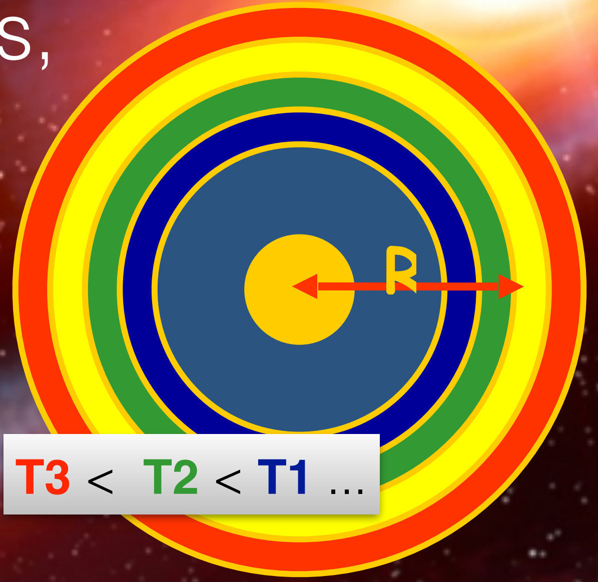
- Galaxies: at 0th order are ensembles of star black bodies...

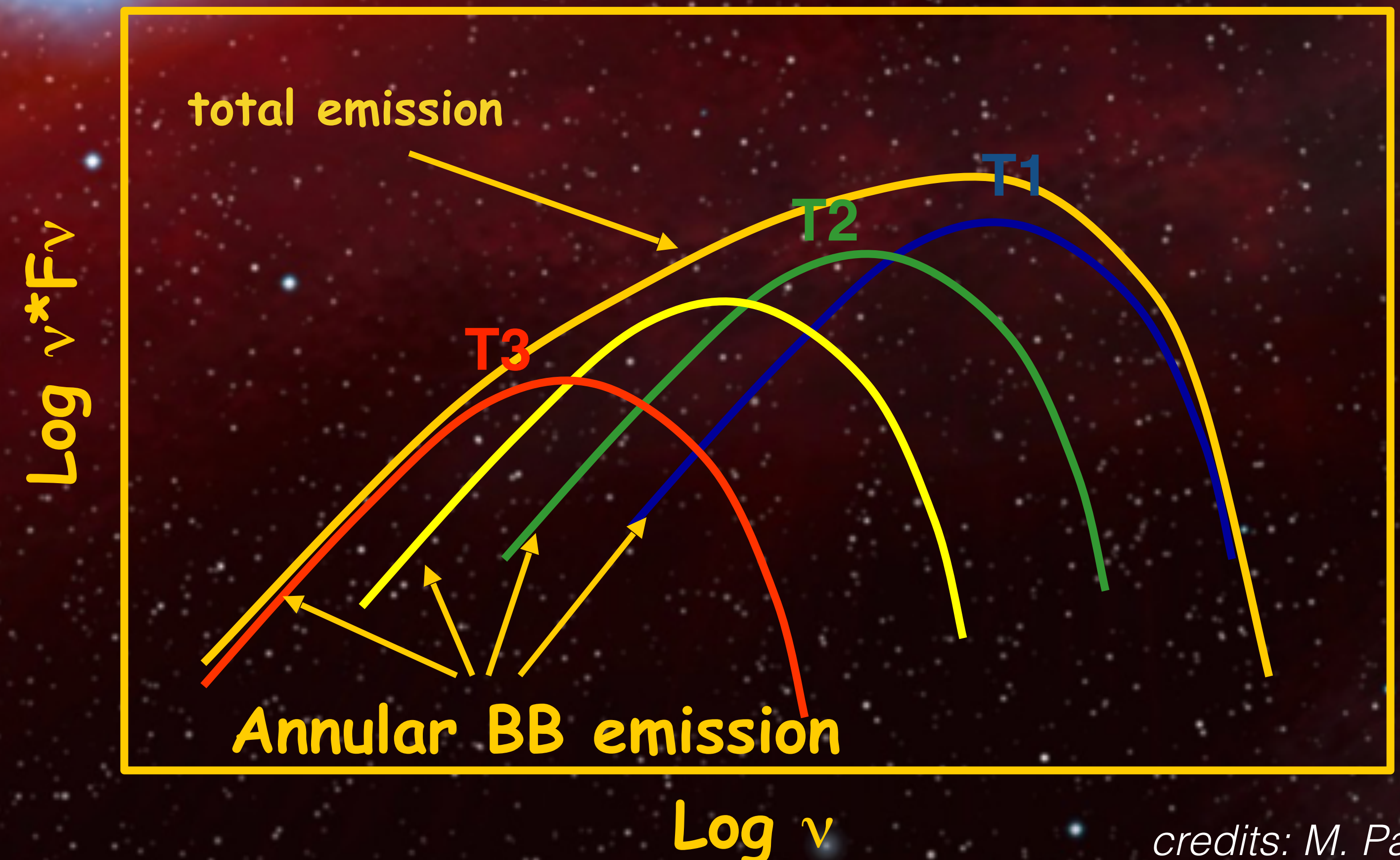


Thermal processes

Accretion disk (binary star systems, microquasars, quasars, AGN...)







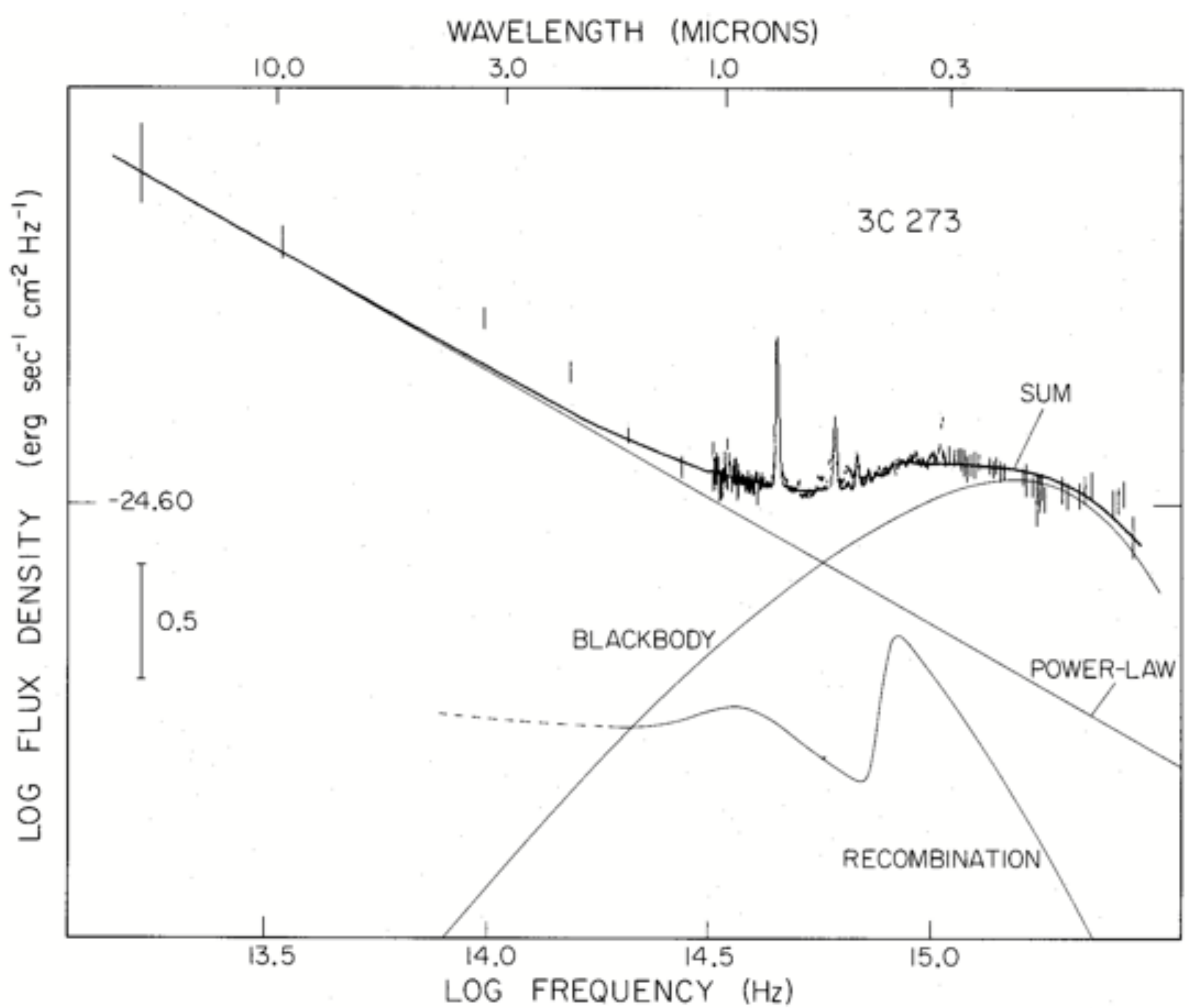
$L_{AccDisk} = 10^{34\text{-}37}$ W $= 10^{33\text{-}38}$ erg/s

$T \sim 10^7$ K

credits: M. Paolillo

Thermal processes

- Accretion disk: blue bump



Jansky 1932

DIRECTIONAL STUDIES OF ATMOSPHERICS AT HIGH FREQUENCIES*

BY

KARL G. JANSKY

(Bell Telephone Laboratories, New York City)

Summary—*A system for recording the direction of arrival and intensity of static on short waves is described. The system consists of a rotating directional antenna array, a double detection receiver and an energy operated automatic recorder. The operation of the system is such that the output of the receiver is kept constant regardless of the intensity of the static.*

Data obtained with this system show the presence of three separate groups of static: Group 1, static from local thunderstorms; Group 2, static from distant thunderstorms, and Group 3, a steady hiss type static of unknown origin.

Curves are given showing the direction of arrival and intensity of static of the first group plotted against time of day and for several different thunderstorms.

Static of the second group was found to correspond to that on long waves in the direction of arrival and is heard only when the long wave static is very strong. The static of this group comes most of the time from directions lying between southeast and southwest as does the long wave static.

Curves are given showing the direction of arrival of static of group three plotted against time of day. The direction varies gradually throughout the day going almost completely around the compass in 24 hours. The evidence indicates that the source of this static is somehow associated with the sun.

INTRODUCTION

FOR some time various investigators have made records of one type or another of the direction of arrival of static on the long wavelengths. Watson Watt has made a comprehensive study of the direction of arrival of static in England. Others working under him have used apparatus similar to his in Australia and Africa. Captain Bureau has done considerable work on the study of static in France. In this country, L. W. Austin with E. B. Judson working with him has worked on the long-wave static problem. Harper and Dean, also of this country, have made a study of the direction of arrival of long-wave static in Maine. Very little work, however, has been done on the direction of arrival of short and very short-wave static with the exception of the series of observations made by Mr. Potter as described in his paper on short-wave noise.[1]

* Decimal classification: R114. Original manuscript received by the Institute, May 26, 1932. Presented at the meeting of the American Section of the U.R.S.I. at Washington, D. C., April 29, 1932.

[1] R. K. Potter, "High-frequency atmospheric noise," PROC. I.R.E., vol. 19, p. 1731; October, (1931).

Reber 1940

NOTES

COSMIC STATIC

Several papers[1] have been published which indicate that an electromagnetic disturbance in the frequency range 10–20 megacycles arrives approximately from the direction of the Milky Way. It has been shown[2] that black-body radiation from interstellar dust particles is not the source of this energy.

The antenna system shown in Figure 1 was constructed for the investigation of this phenomenon.[3] The receiver can be set at the desired declination by rotating along the meridian on the circular tracks at each side. Readings at a fixed declination are taken over an interval of several hours, the rotation of the earth providing the change in right ascension.

The drum at the focal point is an artificial black body described elsewhere.[4] The entire receiving system has an effective cone of acceptance approximately 3° in diameter.

The output is indicated by a microammeter so connected that any intercepted energy will cause the readings to decrease. A few typical records are shown in Figure 2, in which the individual points are omitted because they lie too close together. The magnitude of the dip in the curve gives a measure of the intensity of the received energy. Over a long period, as the apparatus warms up, the zero level will gradually rise. The dotted line indicates the run which would have been obtained had no radiation been captured.

The results of preliminary measures of the variation of the static

[1] K. G. Jansky, *Proc. I.R.E.*, **20**, 1920, December, 1932; **21**, 1387, October, 1933; **23**, 1158, October, 1935; **25**, 1517, December, 1937. H. T. Friis and C. B. Feldman, *Bell Tech. J.*, **16**, 337, July, 1937.

[2] Whipple and Greenstein, *Proc. Nat. Acad. Sci.*, **23**, 177, 1937.

[3] For details of the instrumental design and the method of reduction of the data see G. Reber, *Proc. I.R.E.*, **28**, 68, 1940.

[4] G. Reber, *Communications*, **18**, 5, December, 1938.

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621

Cosmic Rays as the Source of General Galactic Radio Emission

K. O. KIEPENHEUER
Yerkes Observatory, University of Chicago, Williams Bay, Wisconsin
June 20, 1950

THE galactic radio emission is not a thermal free-free radiation of interstellar gas, as was first believed. The electronic temperature would have to be of the order of 100,000° in contradiction to all spectroscopic evidence which gives values around 10,000°. Stars could be considered as sources only under very artificial assumptions. The observed intensities, which must come from the outermost layers of stellar atmospheres, could not be blackbody radiation[1] and might be understood only in terms of coherent plasma oscillations of extended regions. The formation and maintenance of these oscillations is hardly possible in stellar atmospheres.[2]

1 It will now be shown that the general cosmic radiation* of our star system is a high frequency source of sufficient power. In interstellar space, at least inside the interstellar clouds which occupy about 5 percent of space, the mean density of kinetic energy ought to be of the same order as the magnetic-field energy; therefore, fields of around 10^{-6} gauss are to be expected. An energetic electron with energy $W \gg m_0c^2$, which is circulating in this field, is radiating electromagnetic energy into a very narrow cone whose angular aperture is m_0c^2/W in the direction of motion. Therefore, an observer at rest receives very short pulses corresponding to a frequency which is very much higher than the classical Larmor frequency, ν_0. The mean spectral intensity distribution of this radiation will then be[3]

$$P(\nu) \approx (e^2/\pi R)(\nu/\nu_0)^{\frac{1}{3}}$$

for $\nu_0 \ll \nu < \nu_c$, where R is the radius of the electron's circular orbit
2 and $\nu_c = \frac{3}{2}\nu_0(W/m_0c^2)^2$.* If n_e is the number of electrons per cm³ with energy W, the emissivity of high frequency radiation will be

$$\epsilon_\nu \Delta\nu = n_e P(\nu)\Delta\nu = (e^2H/\pi W)n_e(\nu/\nu_0)^{\frac{1}{3}}\Delta\nu \text{ ergs/cm}^3\text{/sec.}$$

This increases steadily with frequency until $\nu = \nu_c$ and then decreases rapidly. The observed distribution[1,4] within the frequency range of 10 to 3000 Mc seems rather to be $\propto \nu^{-0.3}$. We therefore expect to be already in a region with $\nu \geq \nu_c$. Also the involved interstellar magnetic field strengths might vary through space and so influence sensibly the spectral intensity distribution. If the thickness of the emitting layer is D, the intensity of the radiation becomes $I = \epsilon_\nu \Delta\nu D$. Let us suppose that there is one

Radio emission from Milky Way explained with synchrotron emission

Jansky 1932

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Radio emission from Milky Way
explained with synchrotron emission

Giacconi 1962
discovery Sco X-1 source

PHYSICAL REVIEW LETTERS

Volume 9 DECEMBER 1, 1962 Number 11

EVIDENCE FOR X RAYS FROM SOURCES OUTSIDE THE SOLAR SYSTEM*

Riccardo Giacconi, Herbert Gursky, and Frank R. Paolini
American Science and Engineering, Inc., Cambridge, Massachusetts

and

Bruno B. Rossi
Massachusetts Institute of Technology, Cambridge, Massachusetts

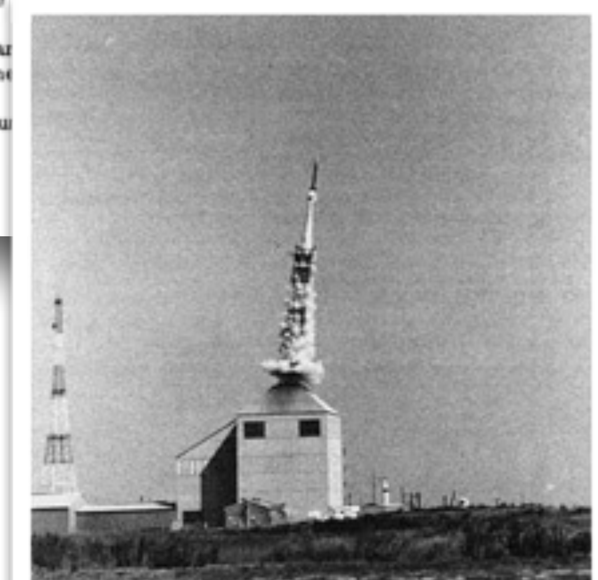
(Received October 12, 1962)

Data from an Aerobee rocket carrying a payload consisting of three large area Geiger counters have revealed a considerable flux of radiation in the night sky that has been identified as consisting of soft x rays.

The entrance aperture of each Geiger counter consisted of seven individual mica windows com-
ted into one face of the
ers had windows of
e counter had windows
itivity of these detec-
n 2 and 8 Å, falling
e to the transmission
pacity of the windows,
s coated with lamp-
t light transmission.
disposed symmetrically
s of the rocket, the
aking an angle of 55°
flight, the normal to
h the sky, at a rate
of the rocket, forming
to the longitudinal axis.
was used to limit the
rs. Also included in
aspect system similar
rian and Kreplin.[1] The
were normal to the
ket. Each Geiger cou

ter was placed in a well formed by an anticoincidence scintillation counter designed to reduce the cosmic-ray background. The experiment was intended to study fluorescence x rays produced on the lunar surface by x rays from the sun and to explore the night sky for other possible sources. On the basis of the known flux of solar x rays, we had estimated a flux from the moon of about 0.1 to 1 photon cm⁻² sec⁻¹ in the region of sensitivity of the counter.

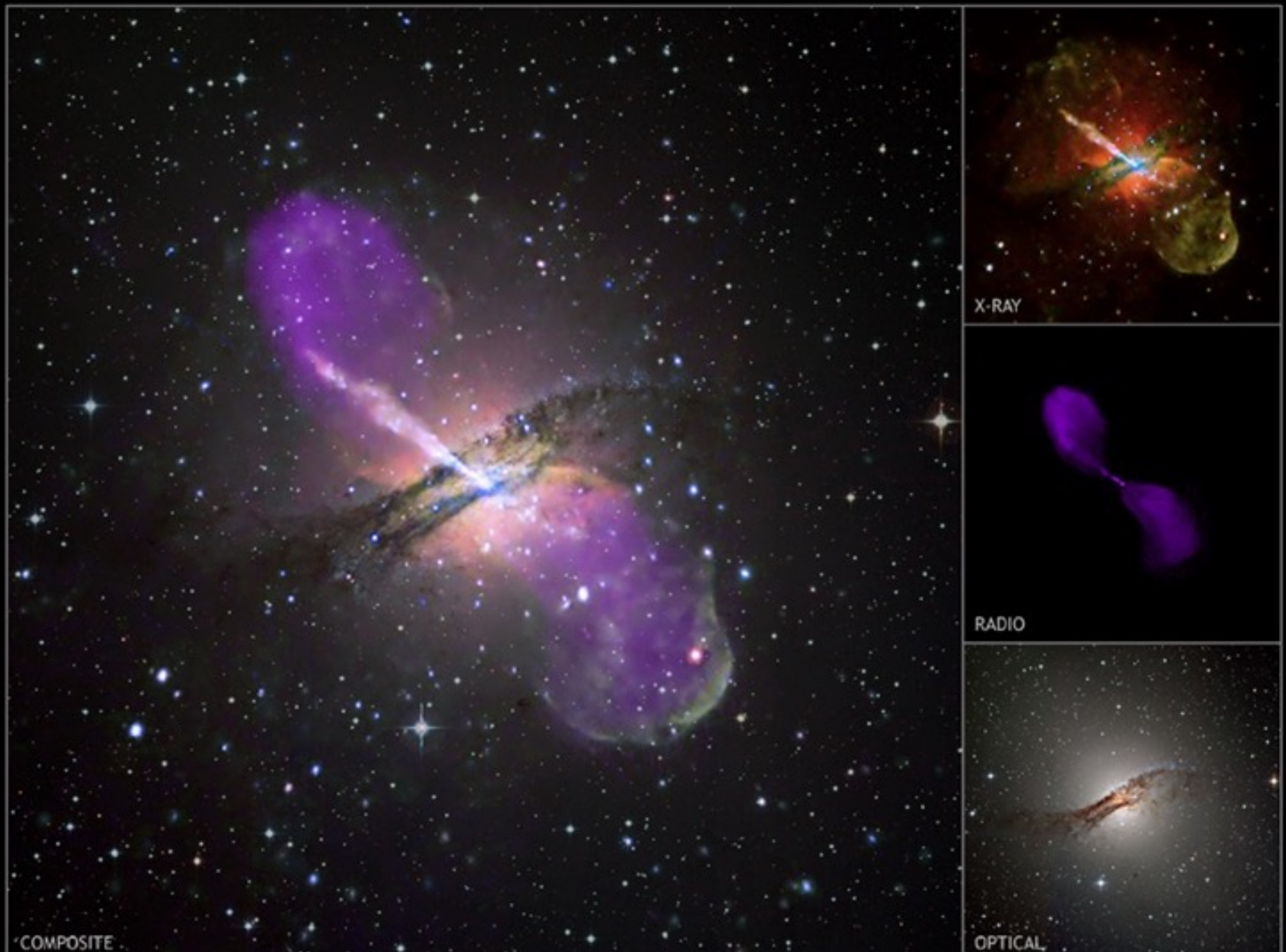
The rocket launching took place at the White Sands Missile Range, New Mexico, at 2359 MST on June 18, 1962. The moon was one day past full and was in the sky about 20° east of south and 35° above the horizon. The rocket reached a maximum altitude of 225 km and was above 80 km for a total of 350 seconds. The vehicle traveled almost due north for a distance of 120 km. Two of the Geiger counters functioned properly during the flight; the third counter apparently arced sporadically and was disregarded in the analysis. The optical aspect system functioned correctly. The rocket was spinning at 2.0 rps



Multi wavelength view of non-thermal processes

- Centaurus-A with HST (optical)

Multi wavelength view of non-thermal processes

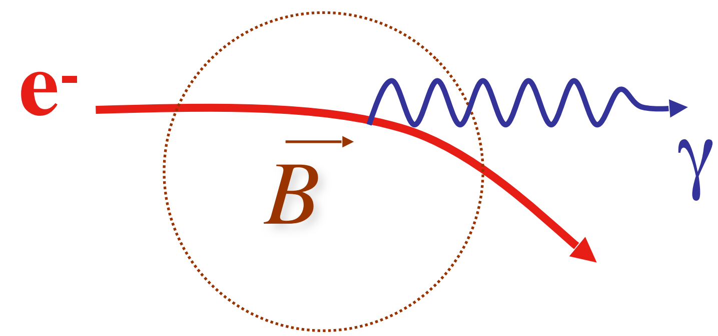


Non-thermal processes

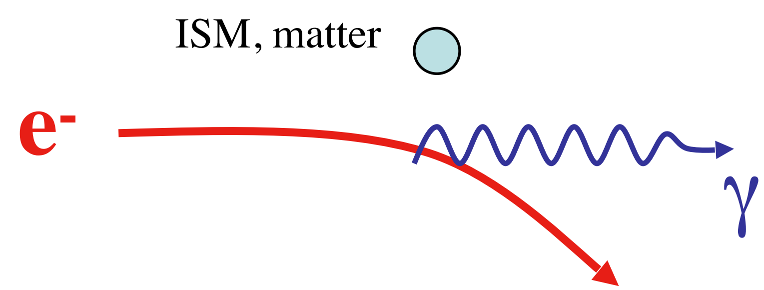
- Do not depend on the temperature of the emitter
- **Highly energetic particles (TeV, PeV --> CR...)**
  - High energetic tail of high-temperature distribution (thermal bremsstrahlung, inverse Compton)
  - Particle accelerated
    - Fermi processes
    - electric field acceleration (pulsars, BH ergosphere)
- We exclude non-thermal processes emitting at specific frequency (e.g. masers)

Non-thermal processes

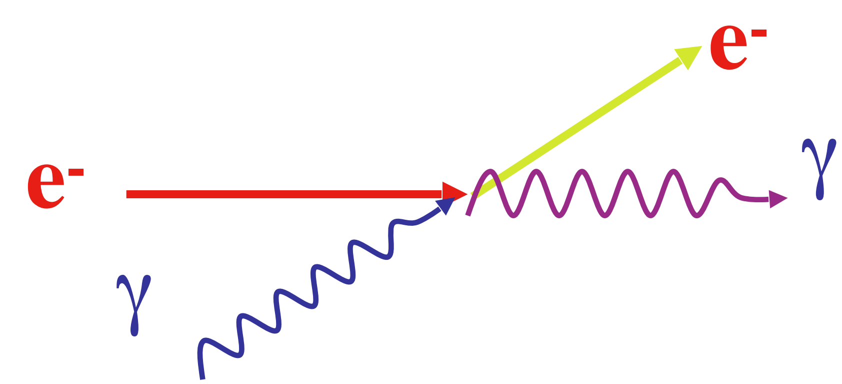
- Synchrotron radiation



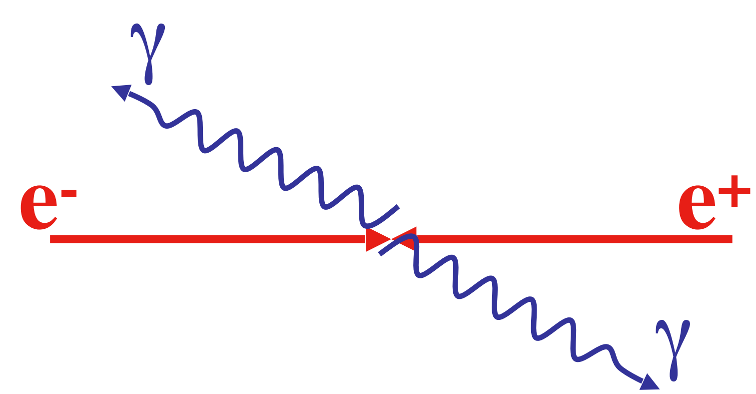
- Bremsstrahlung



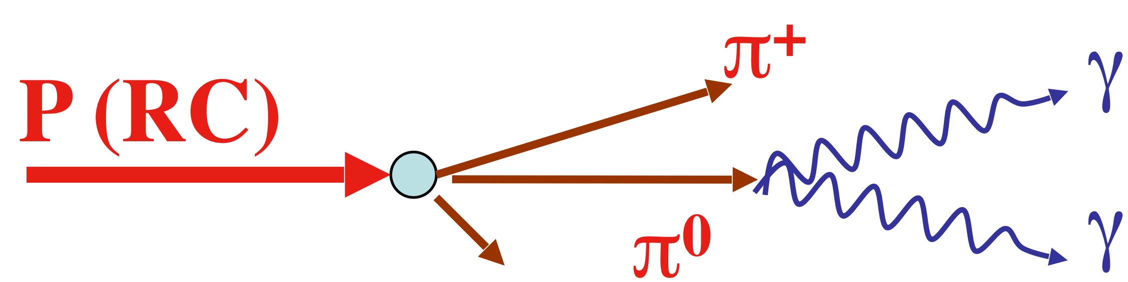
- Inverse Compton



- Annihilation

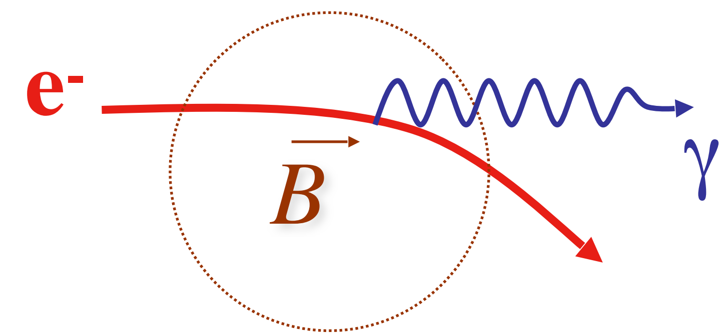


- Particle collisions - cascades

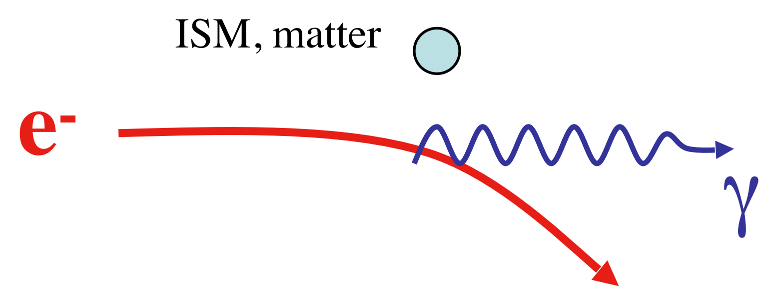


Non-thermal processes

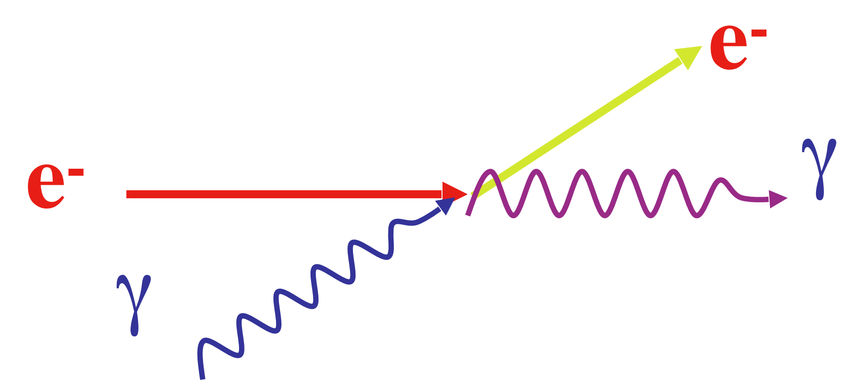
- **Synchrotron radiation**



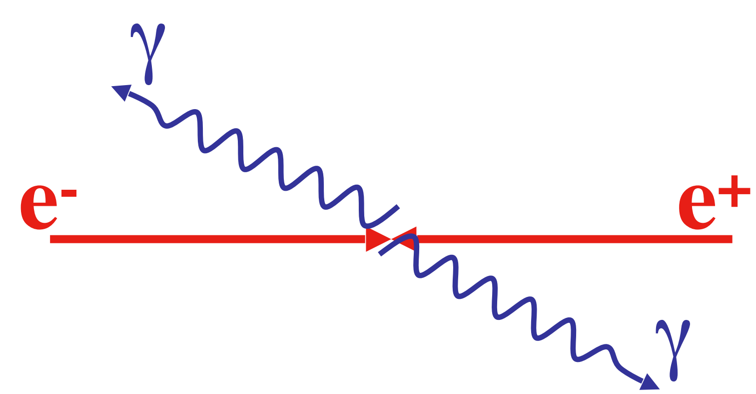
- Bremsstrahlung



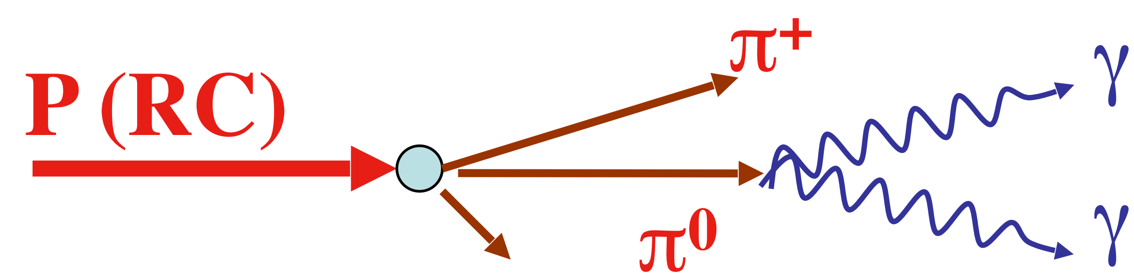
- **Inverse Compton**

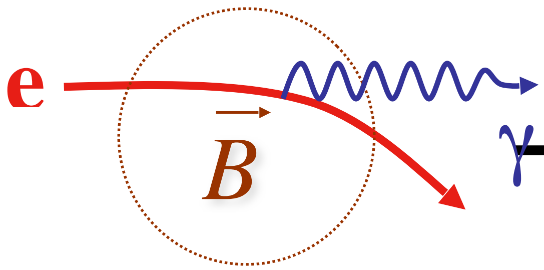


- Annihilation



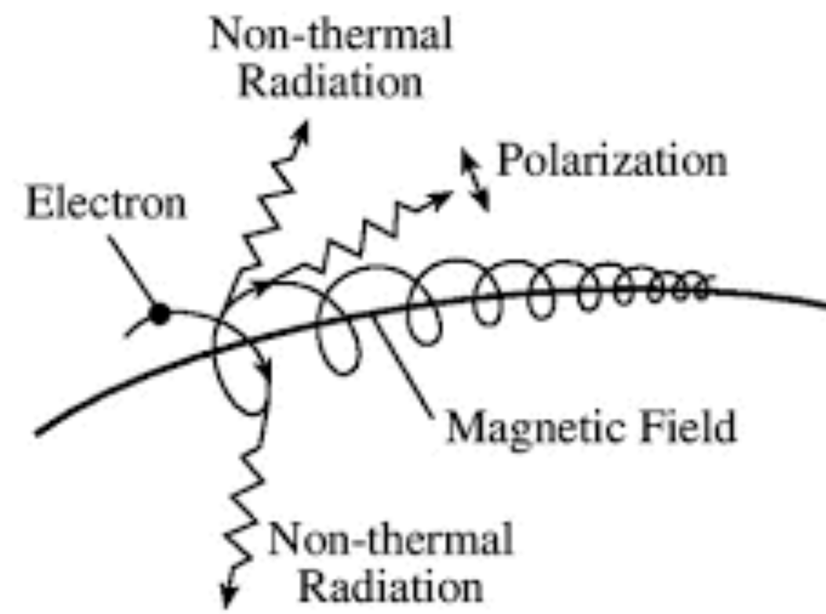
- **Particle collisions - cascades**



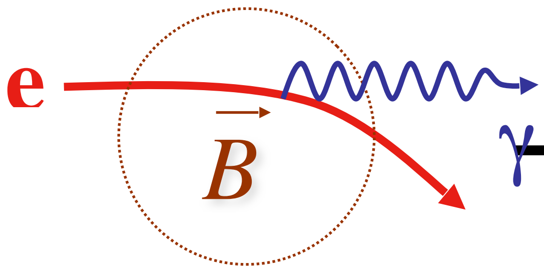


The spectral shape of synchrotron emission

Synchrotron frequency

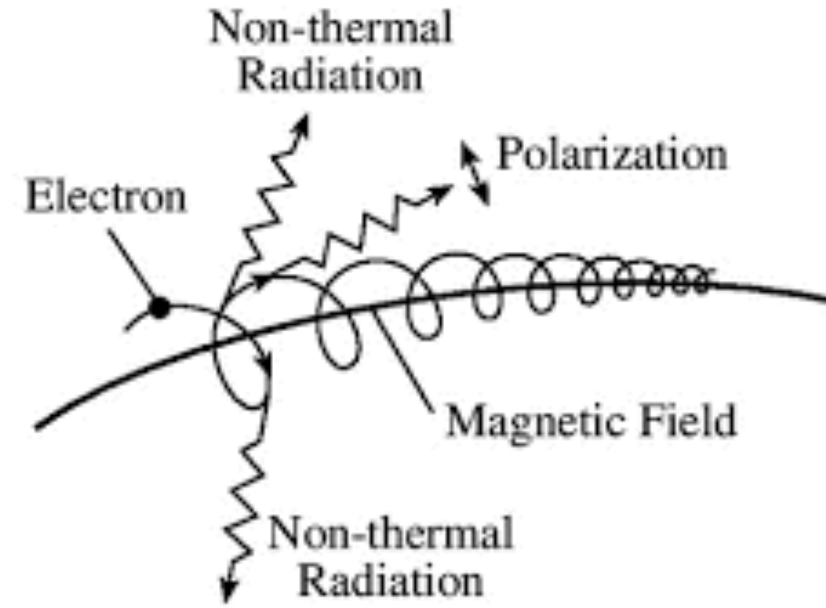


- Cyclotron frequency $$\omega_{cyc} = \frac{qB}{m}$$
  - Sinusoidal; single frequency
- Relativistic beaming: length contraction + doppler shift



The spectral shape of synchrotron emission

Synchrotron frequency



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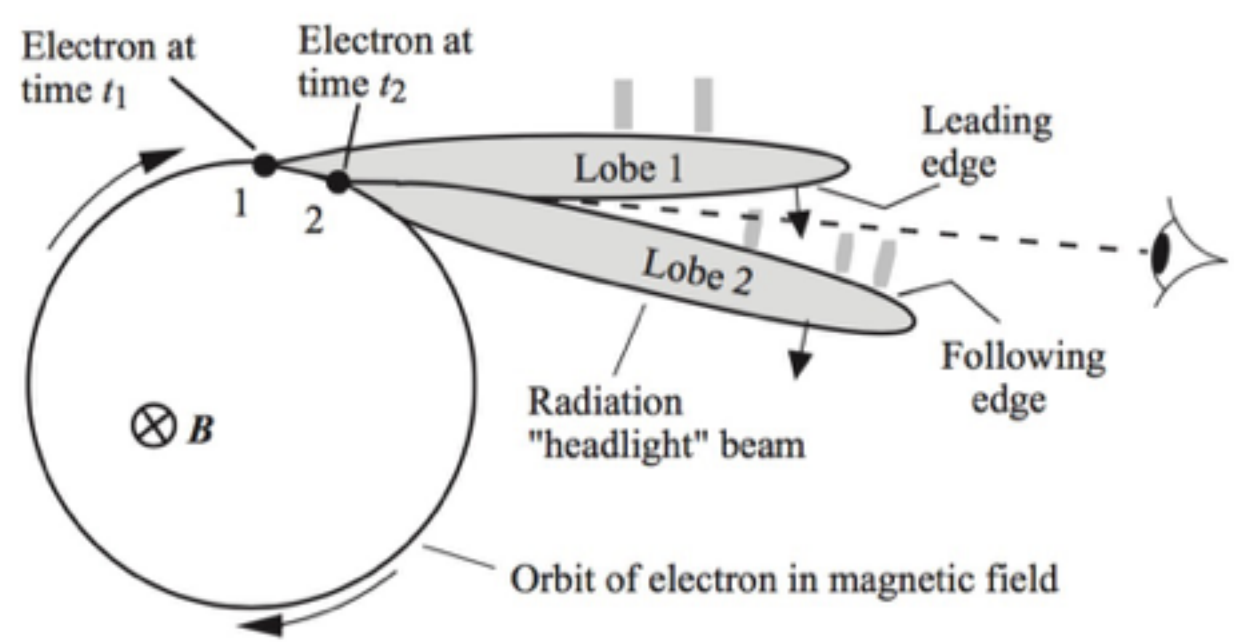
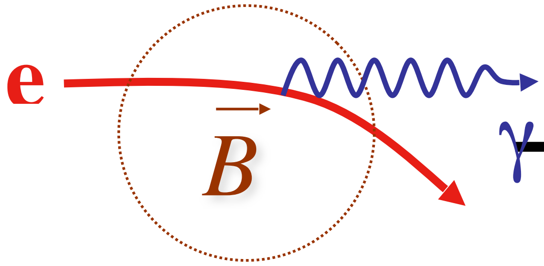
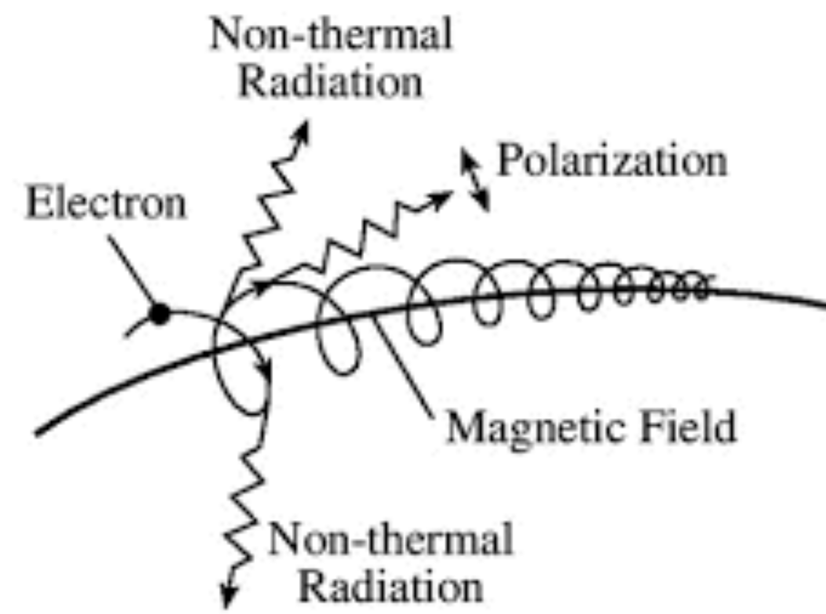


Bradt, Astrophysical processes



The spectral shape of synchrotron emission

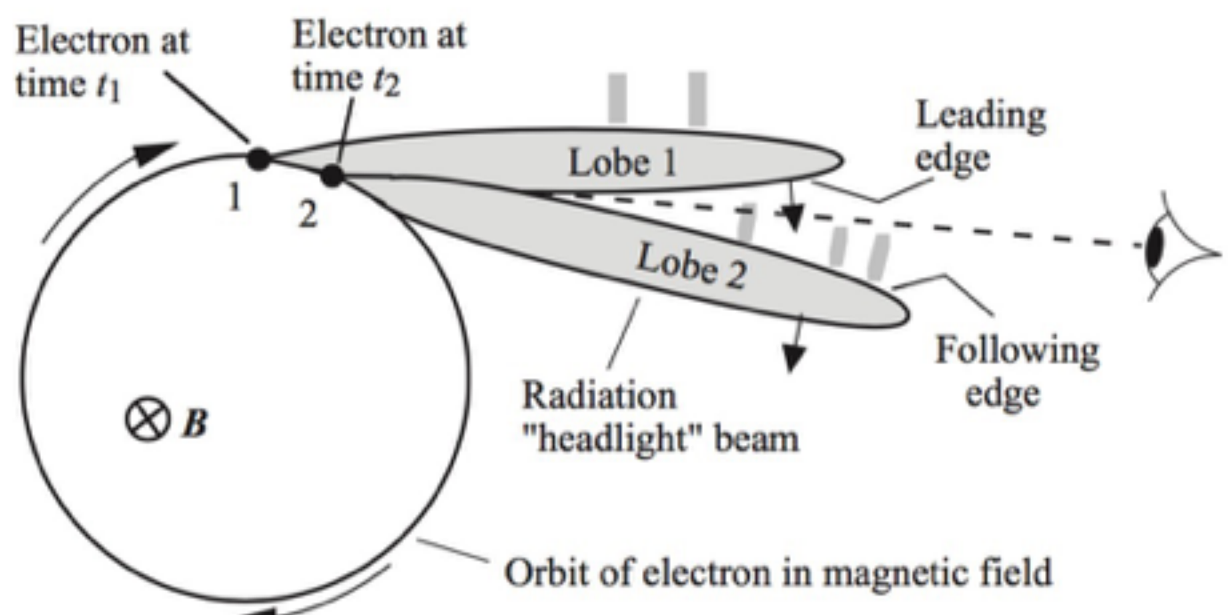
Synchrotron frequency



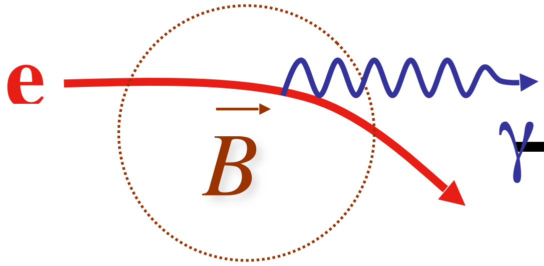
- Cyclotron frequency $$\omega_{cyc} = \frac{qB}{m}$$
  - Sinusoidal; single frequency
- Relativistic beaming: length contraction + doppler shift
- $t_{pulseSync} \sim (1-\beta)t_{emit} \sim 1/2\gamma^2$

$$\boxed{\omega_{sync} \sim \gamma^2 \omega_{cyc}}$$

$$\nu_{sync} = \frac{1}{2\pi}\gamma^2 \frac{qB}{m} \sin\phi$$ pitch angle



Bradt, Astrophysical processes



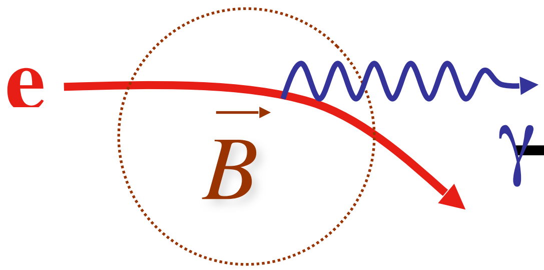
The spectral shape of synchrotron emission

Synchrotron power (*single particle*)

- Larmor formula $$P = \frac{2}{3}\frac{q^2 a^2}{c^3}$$
- acceleration $a = qE/m$ $E = -\gamma v B$ $v \sim c$

$$\boxed{P \sim \gamma^2 B^2}$$

$$P_{sync} = \frac{2q^2}{3m^2c^3} B^2 \gamma^2 \beta^2 \sin\phi$$



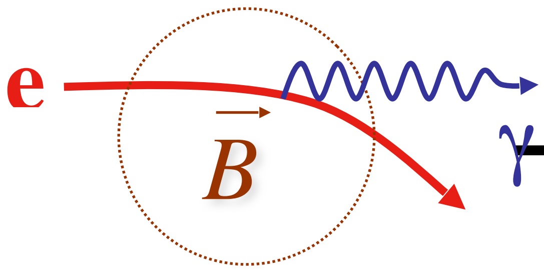
The spectral shape of synchrotron emission

Synchrotron power (*single particle*) - <u>cooling time</u>

$$P_{sync}^{isotropic} = -\frac{4}{3}\sigma_T c U_B \gamma^2 \beta^2$$

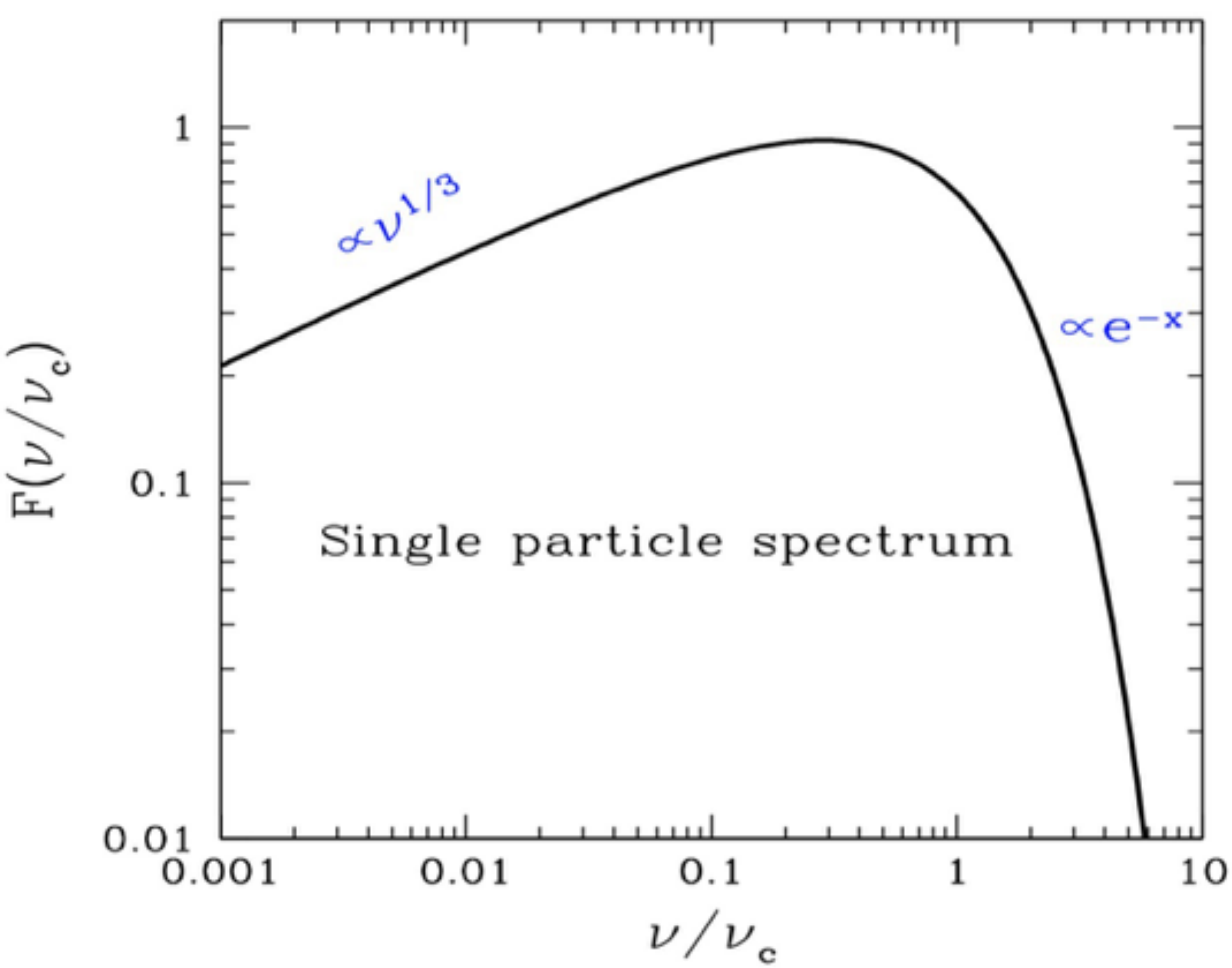
$$\frac{dE}{dt}[W] = -2.66 \times 10^{-20}\, \beta^2 \gamma^2 U_B [J/m^3]$$

$$t_{sync}^{cool} = \frac{E}{dE/dt} = \frac{2.75 \times 10^8}{B^2 \gamma}[s] = \frac{24.57}{B^2 \gamma}[yr]$$



The spectral shape of synchrotron emission

- **Synchrotron spectrum** (*single particle*)



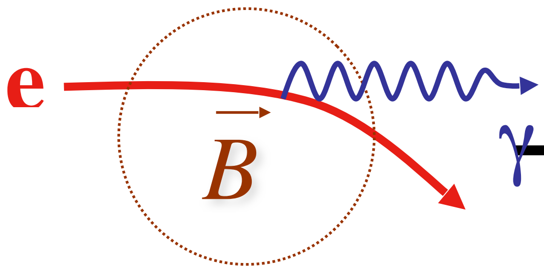
exact solution:

$$F(\nu/\nu_c) \equiv \frac{\nu}{\nu_c}\int_{\nu/\nu_c}^{\infty} K_{5/3}(y)dy$$

Approximation:

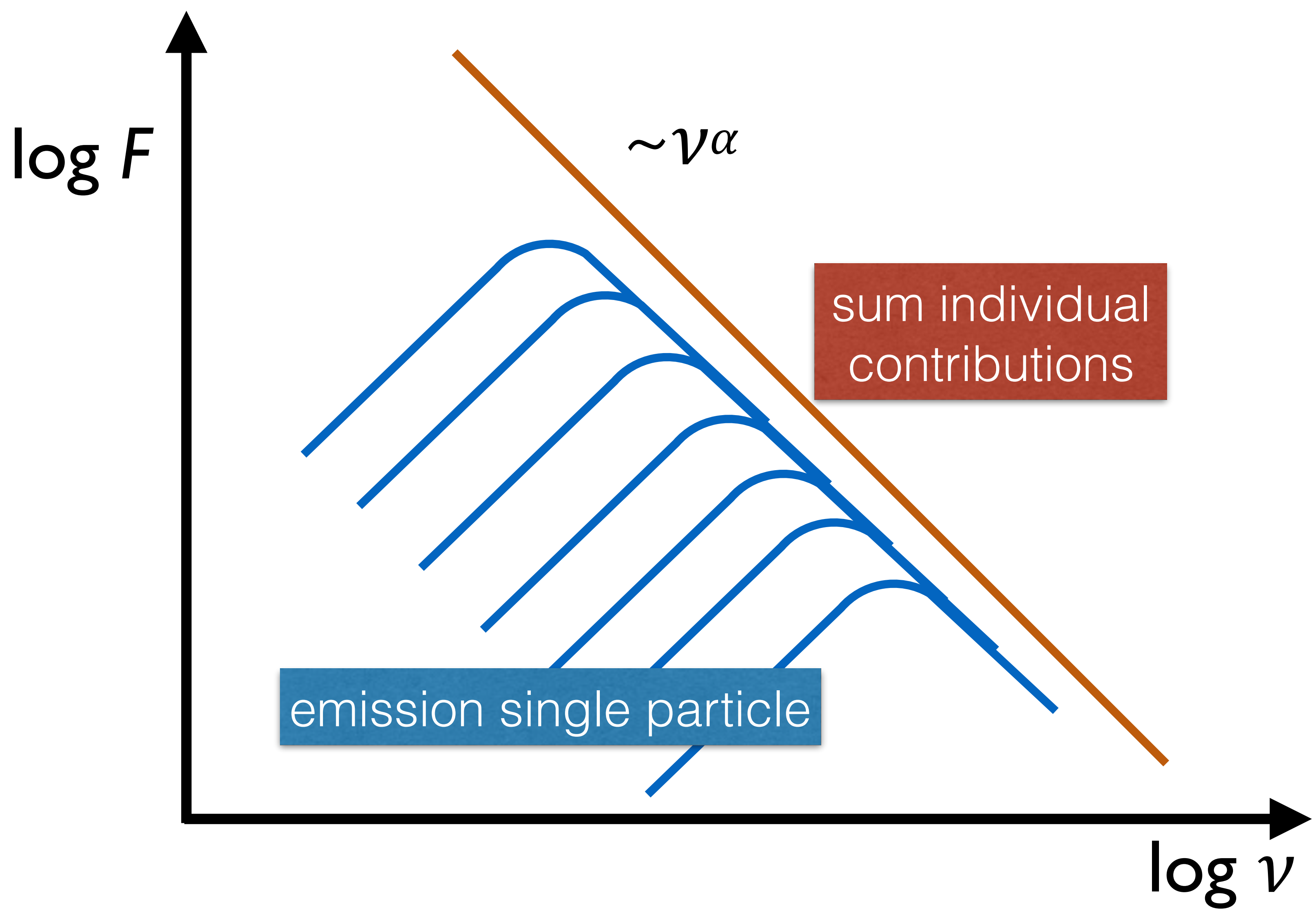
$$F(\nu/\nu_c) \sim \frac{4\pi}{\sqrt{3}\Gamma(1/3)}\left(\frac{\nu}{2\nu_c}\right)^{1/3} e^{-\nu/\nu_c}$$

http://www.brera.inaf.it/utenti/gabriele/total.pdf



The spectral shape of synchrotron emission

Ensemble of emitting particles



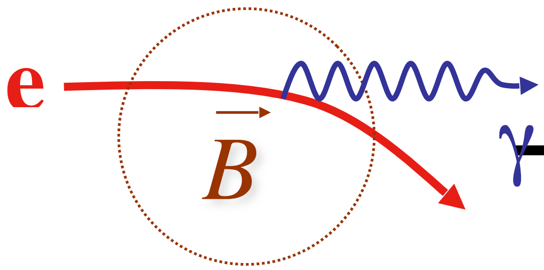
The particle-SED connection

- Particle energy distribution $$\frac{dN}{dE} \propto E^p$$
- Emitted power $$\frac{dP}{dE} \propto \frac{dN}{dE} P_{el}$$
- Power single electron $P_{el}^{sync} \sim \gamma^2 B^2 \sim E^2 B^2$
- Assume power radiated all at the ν_{sync} frequency

$$\nu_{sync} \propto \gamma^2 B \sim E^2 B$$

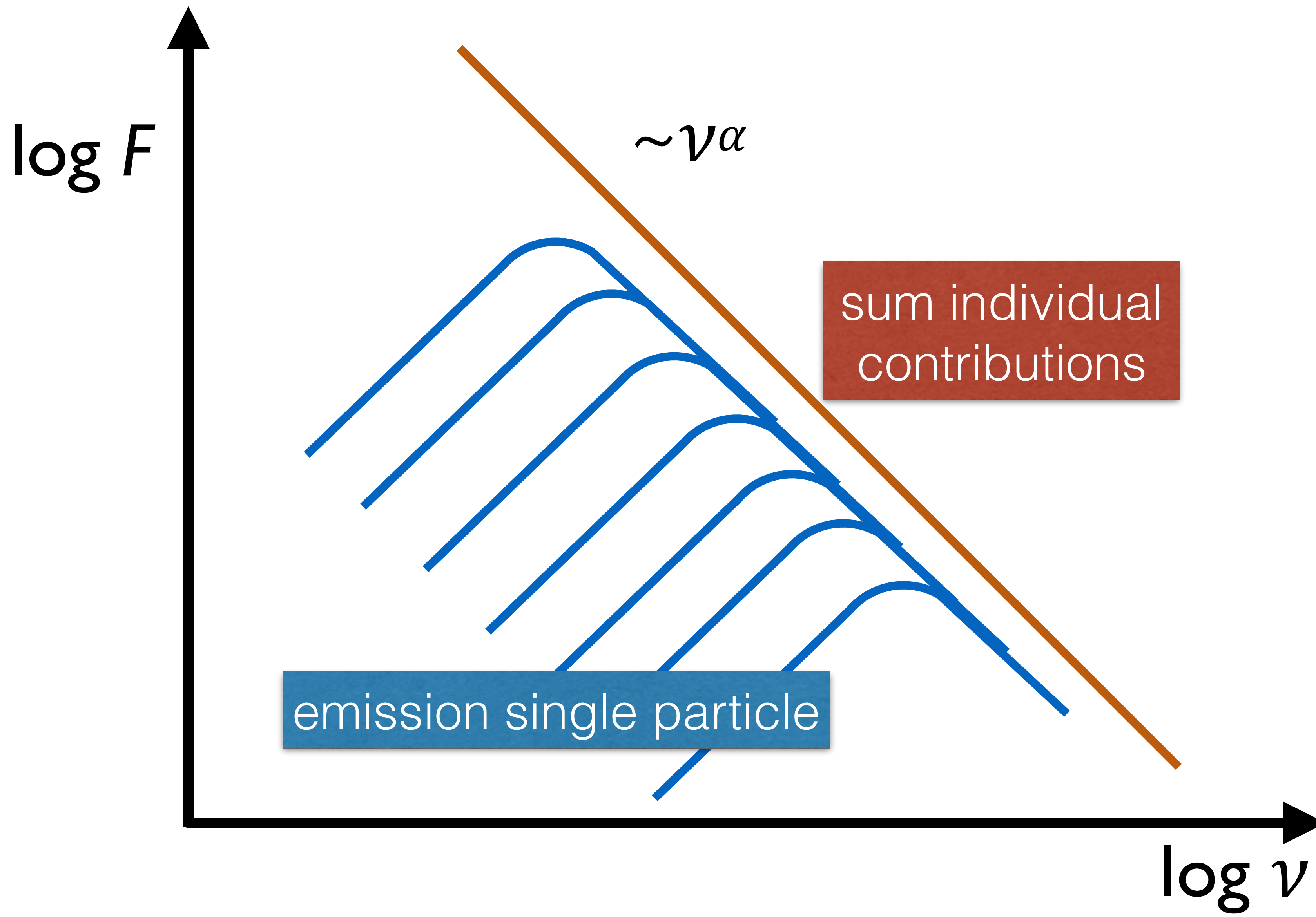
$$\frac{dP}{d\nu} \propto B \left(\frac{\nu}{B}\right)^{\frac{1+p}{2}} \sim \nu^\alpha$$

$$\boxed{\alpha = \frac{1+p}{2}}$$



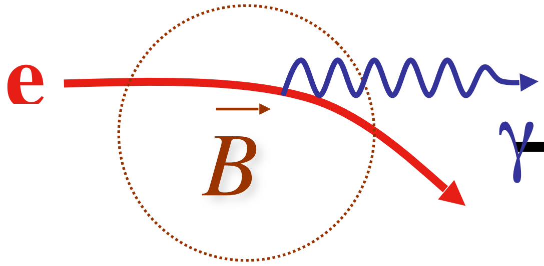
The spectral shape of synchrotron emission

Ensemble of emitting particles



$$\alpha = \frac{1+p}{2}$$

$$\frac{dN}{dE} \propto E^p$$



The spectral shape of synchrotron emission

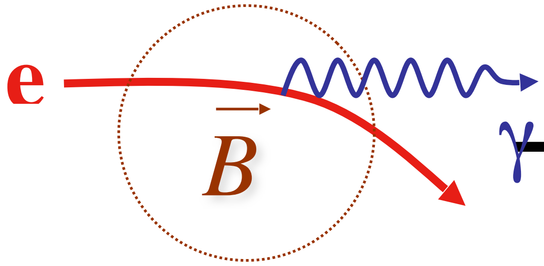
Self-absorption

- black-body sets upper limit to emissivity

$$kT_\nu \sim \gamma mc^2 \sim mc^2 (\frac{\nu}{\nu_{sync}})^{1/2}$$

- Rayleigh-Jeans limit $$I(\nu) = 2kT\frac{\nu^2}{c^2}$$

$$I(\nu) = 2kT\frac{\nu^2}{c^2} \sim 2mc^2\nu^2\frac{\nu}{\nu_{sync}} \sim \frac{\nu^{5/2}}{B^{1/2}}$$



The spectral shape of synchrotron emission

Self- absorption

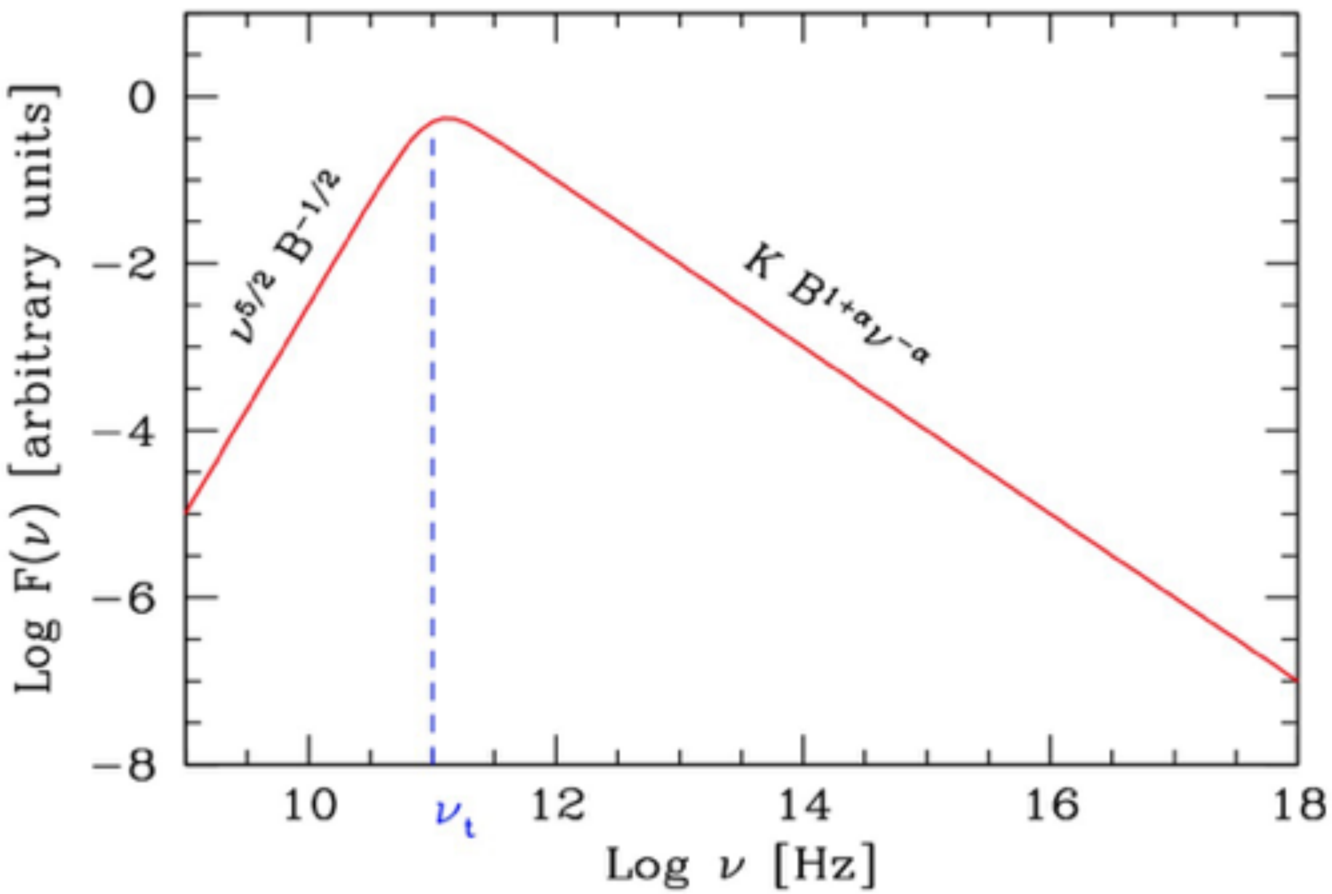
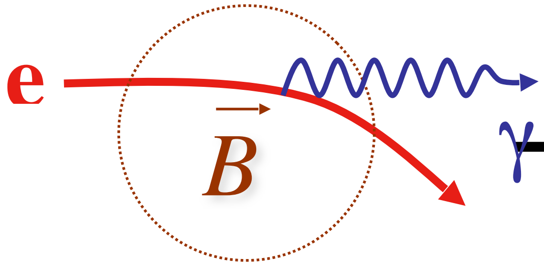


Figure 4.6: The synchrotron spectrum from a partially self absorbed source. Observations of the self absorbed part could determine B. Observations of the thin part can then determine K and the electron slope p.

http://www.brera.inaf.it/utenti/gabriele/total.pdf



The spectral shape of synchrotron emission

- Self-Absorption at different frequencies

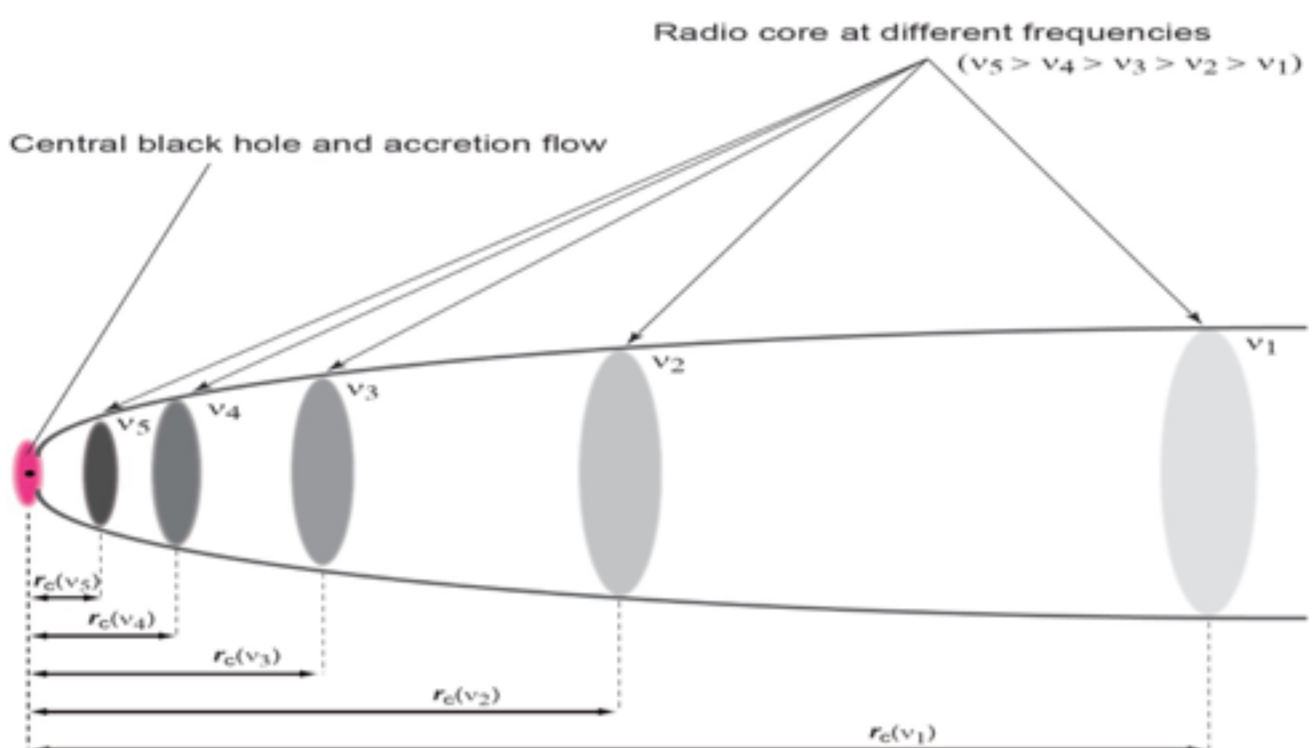
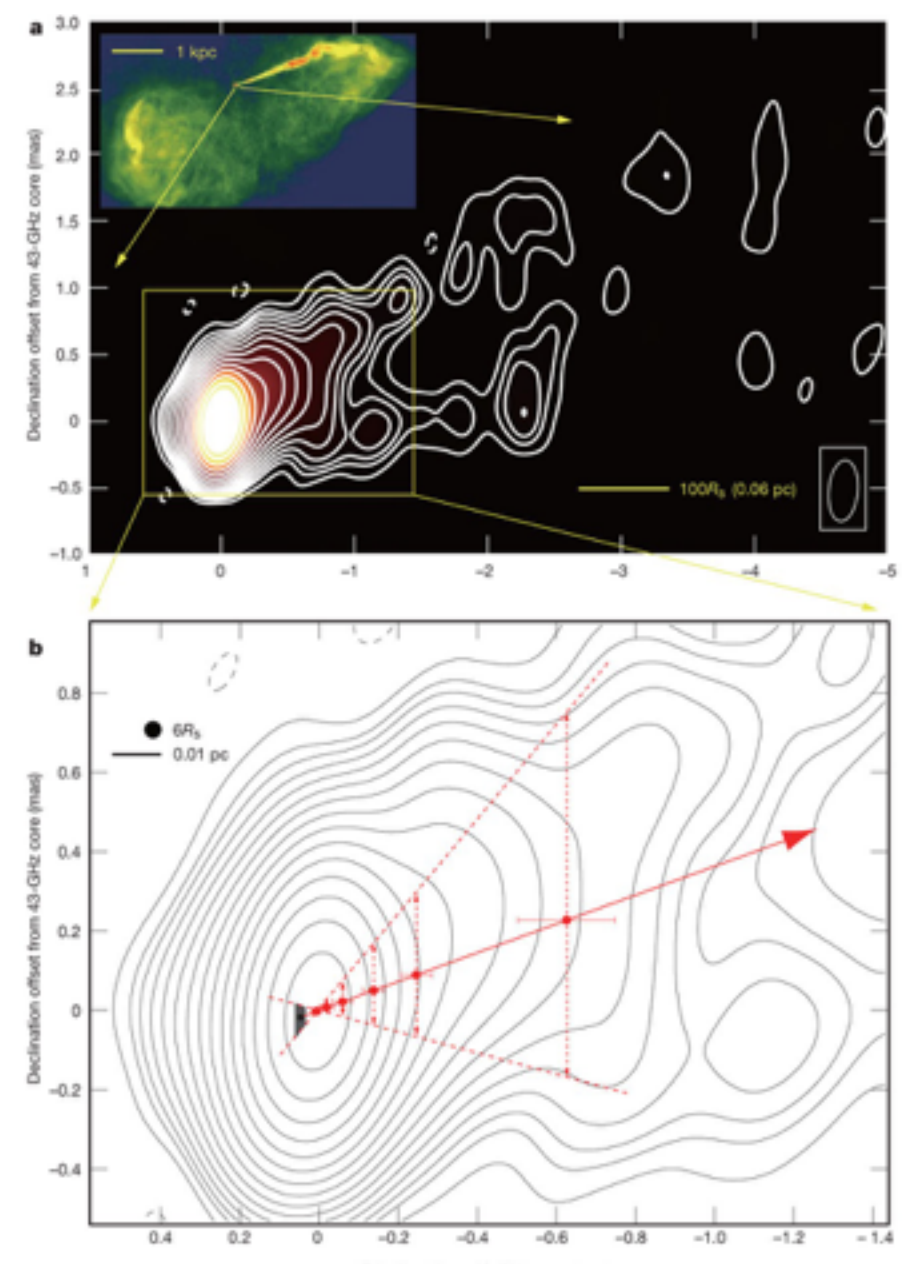
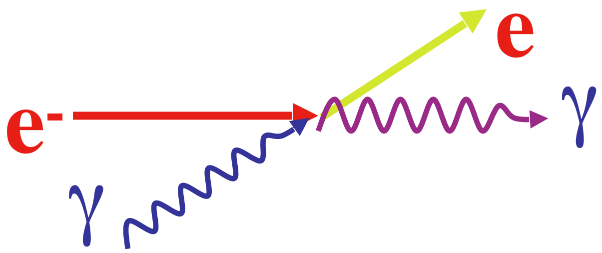


Fig.2 Diagram illustrating the core-shift of a jet . Optical depth for SSA (τ_{SSA}) is a function of the electron number density N_e, the magnetic field B and the observing frequency ν. Since τ_{SSA} decreases with increasing frequency, the separation between the central engine and a radio core at a given ν satisfies $r_c(\nu) \propto \nu^{-\alpha}$ ($\alpha > 0$) when the radial profiles of N_e and B in the jet show power law dependences.



Hada+2011

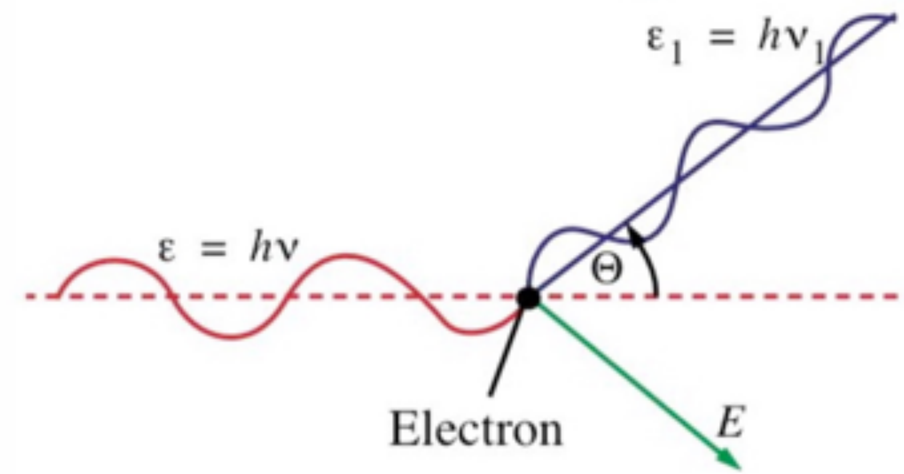


Inverse Compton

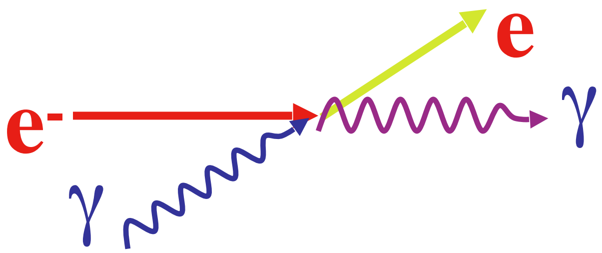
- Energy gained by electron

$$\varepsilon_1 = \frac{\varepsilon}{1 + \frac{\varepsilon}{m_e c^2}(1 - \cos\Theta)}$$

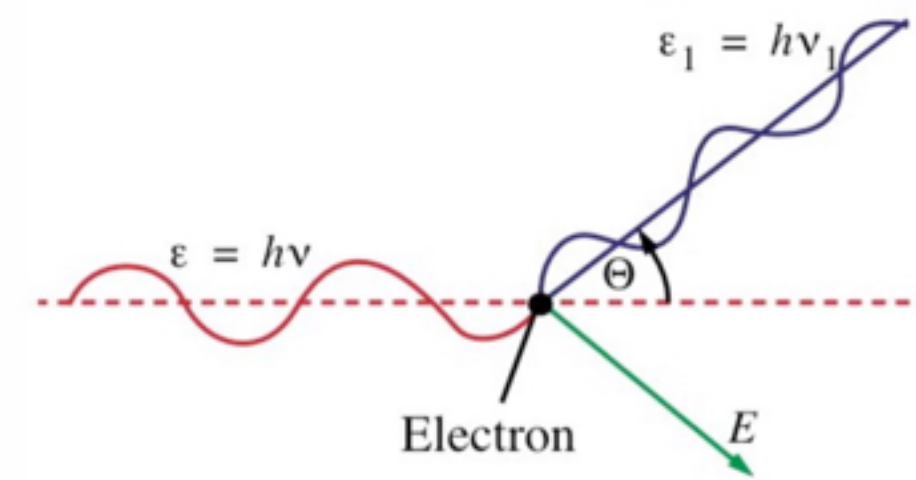
$$\epsilon_1 \sim \gamma^2 \epsilon$$



- Power emitted



Inverse Compton



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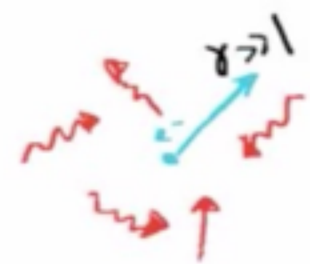
$$\epsilon_1 \sim \gamma^2 \epsilon$$

- Power emitted



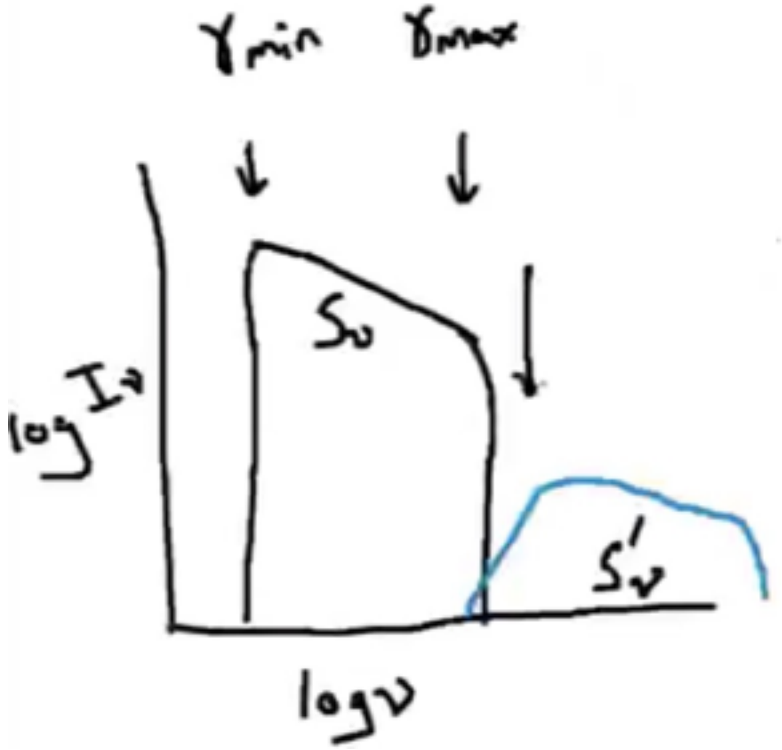
$$P \sim \sigma_T c\, n_{ph} \Delta\epsilon$$

$$P_{IC} = \frac{4}{3}\sigma_T c\, \beta^2 \gamma^2 U_{ph}$$

$$U_{ph} = \int n_{ph} \epsilon\, d\epsilon$$

$$\frac{P_{IC}}{P_{sync}} = \frac{U_{ph}}{U_B}$$

SSC



- U_{ph} --> synchrotron radiation field

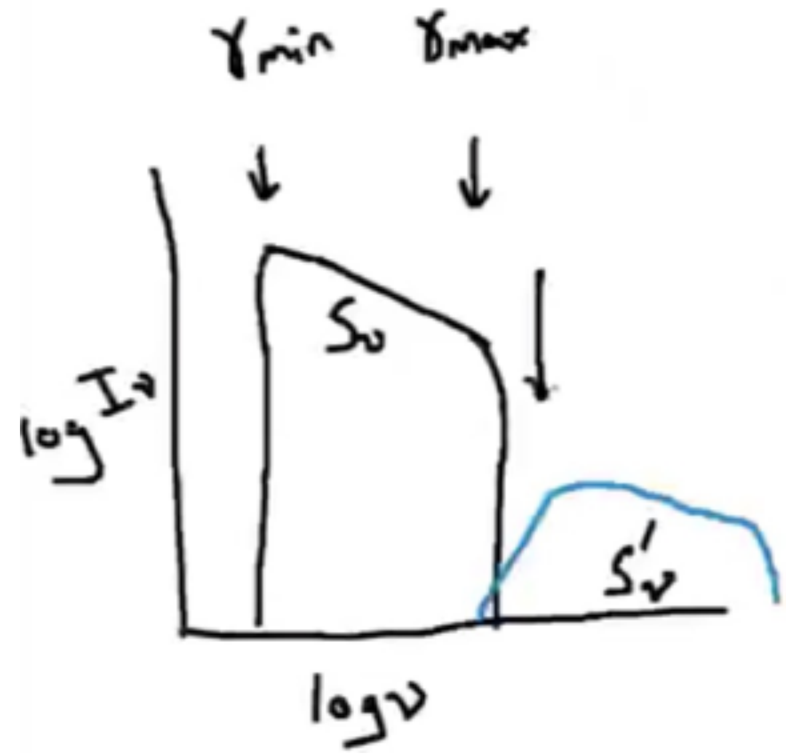
$$S'_\nu \sim \tau \int_{\nu_{min}}^{\nu_{max}} S_{\nu'} \int_{\gamma_{min}}^{\gamma_{max}} \delta(\nu' - \frac{\nu}{\gamma^2}) d\nu' N_0 \gamma^p d\gamma$$

opacity (optical thin: linear)

sync radiation

electron distribution

SSC



- U_{ph} --> synchrotron radiation field

$$S'_\nu \sim \tau \int_{\nu_{min}}^{\nu_{max}} S_{\nu'} \int_{\gamma_{min}}^{\gamma_{max}} \delta(\nu' - \frac{\nu}{\gamma^2}) d\nu' N_0 \gamma^p d\gamma$$

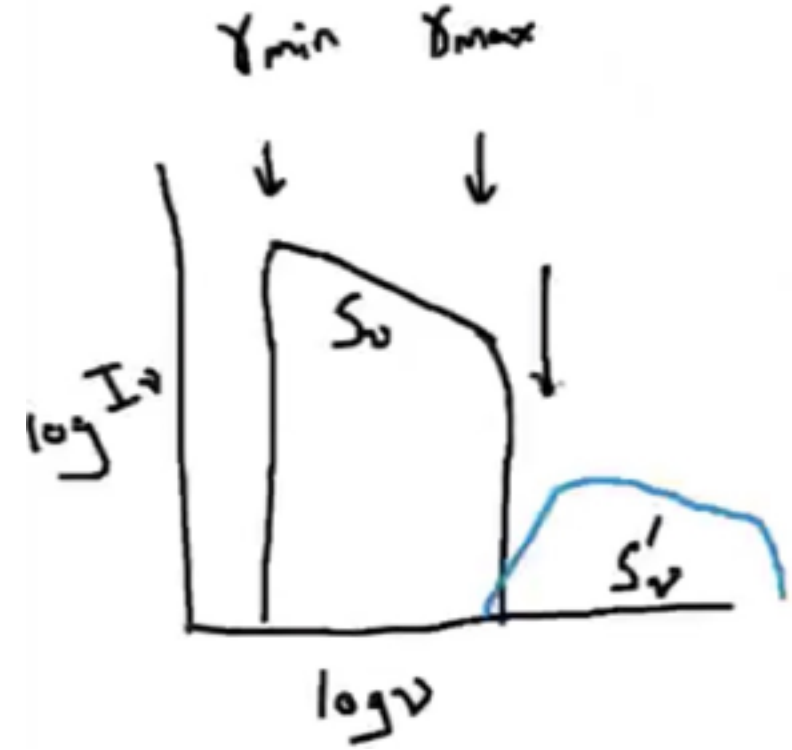
opacity (optical thin: linear)

sync radiation **electron distribution**

- $\nu_{min} = \gamma^2 \nu'_{min}$ $\nu_{max} = \gamma^2 \nu'_{max}$
- Power law $S_\nu = C_0 \nu^\alpha$

$$\alpha = \frac{1+p}{2}$$

SSC



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opacity (optical thin: linear)

sync radiation **electron distribution**

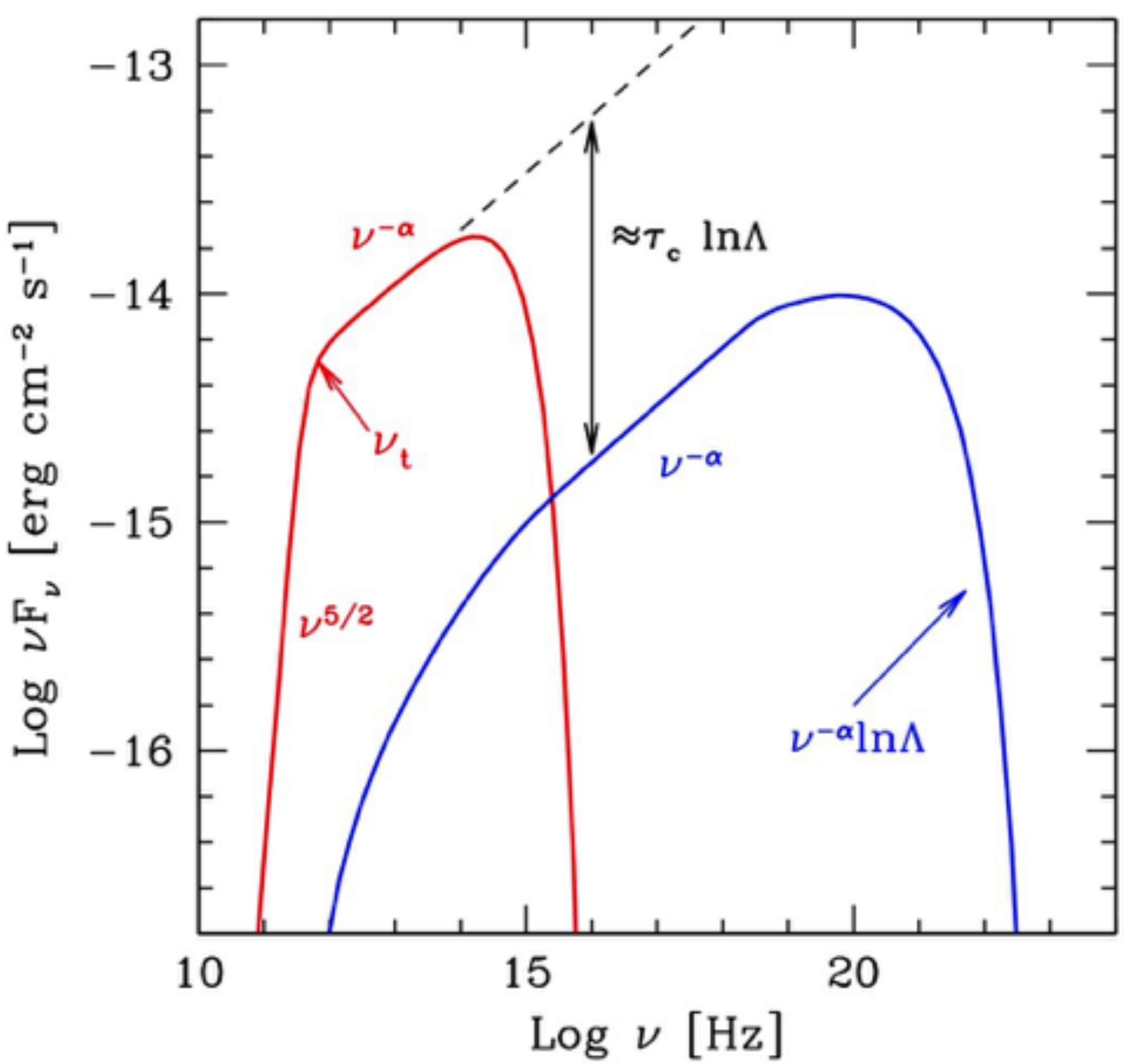
- $\nu_{min} = \gamma^2 \nu'_{min}$ $\nu_{max} = \gamma^2 \nu'_{max}$
- Power law $S_\nu = C_0 \nu^\alpha$ $\alpha = \frac{1+p}{2}$

$$S'_\nu \sim \tau (C_0 \nu^\alpha) N_0 \int_{\gamma_{min}}^{\gamma_{max}} 1/\gamma d\gamma \sim \tau S_\nu N_0 \ln\Lambda$$

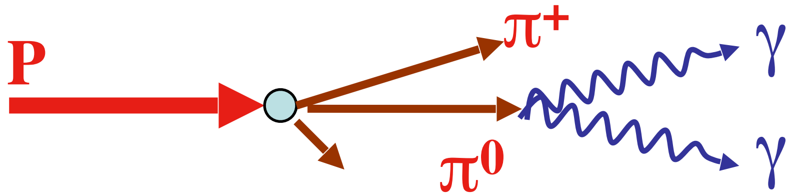
$$L_{IC} \sim L_{sync} \tau \ln\Lambda$$

SSC

- U_{ph} --> synchrotron radiation field



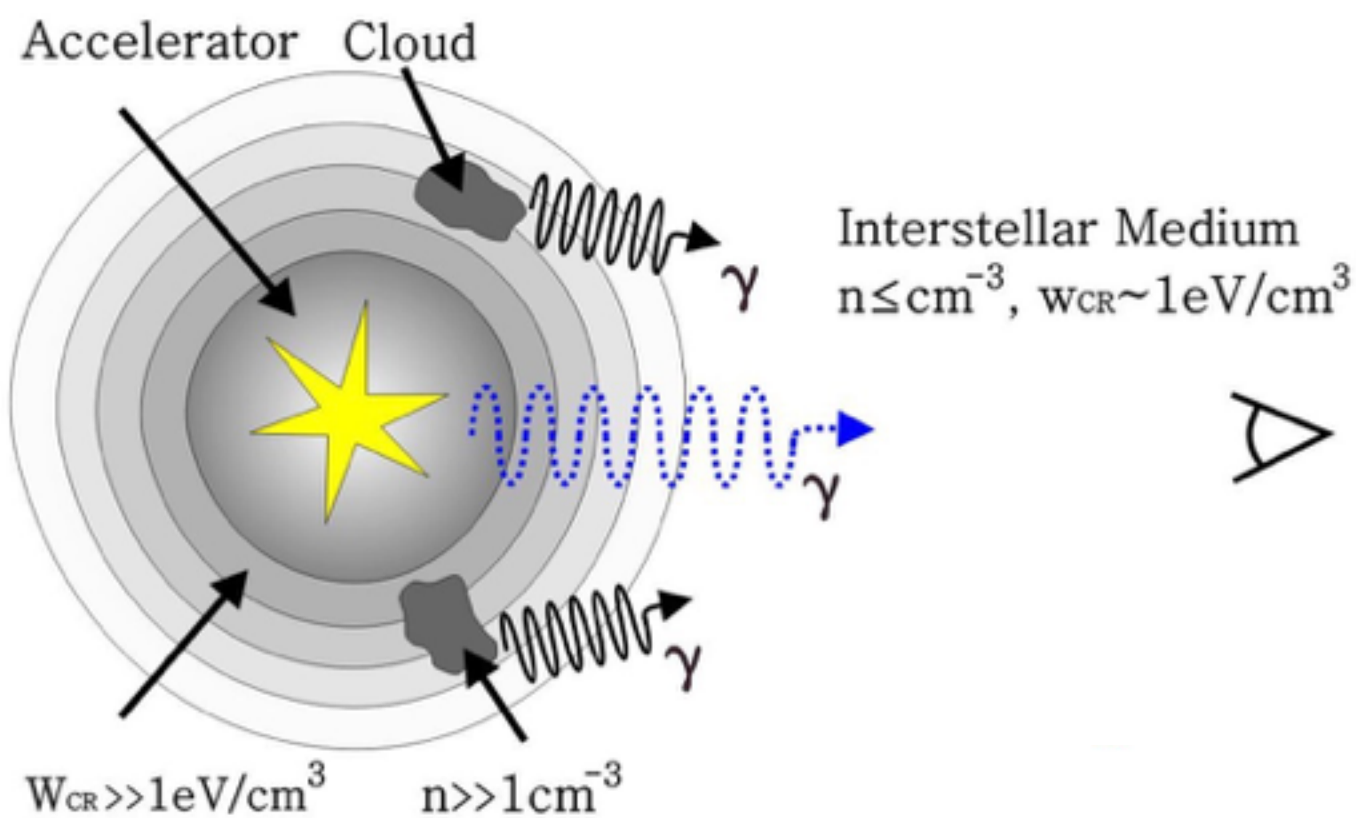
Ghisellini, radiative processes in high energy astrophysics, arXiv:1202.5949



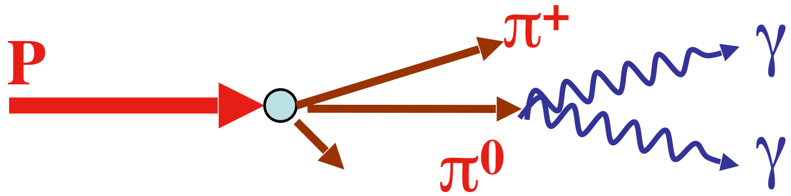
Hadronic emission

- accelerated proton (injected spectrum)
- target proton (ISM, molecular cloud...)

$$
\begin{aligned}
p+p &\rightarrow p+p+n_1(\pi^+ + \pi^-) + n_2\pi^0 \\
\pi^\pm &\rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu \, , \\
\pi^0 &\rightarrow 2\gamma \, , \\
\mu^\pm &\rightarrow e^\pm + \nu_e/\bar{\nu}_e + \bar{\nu}_\mu/\nu_\mu \, .
\end{aligned}
$$

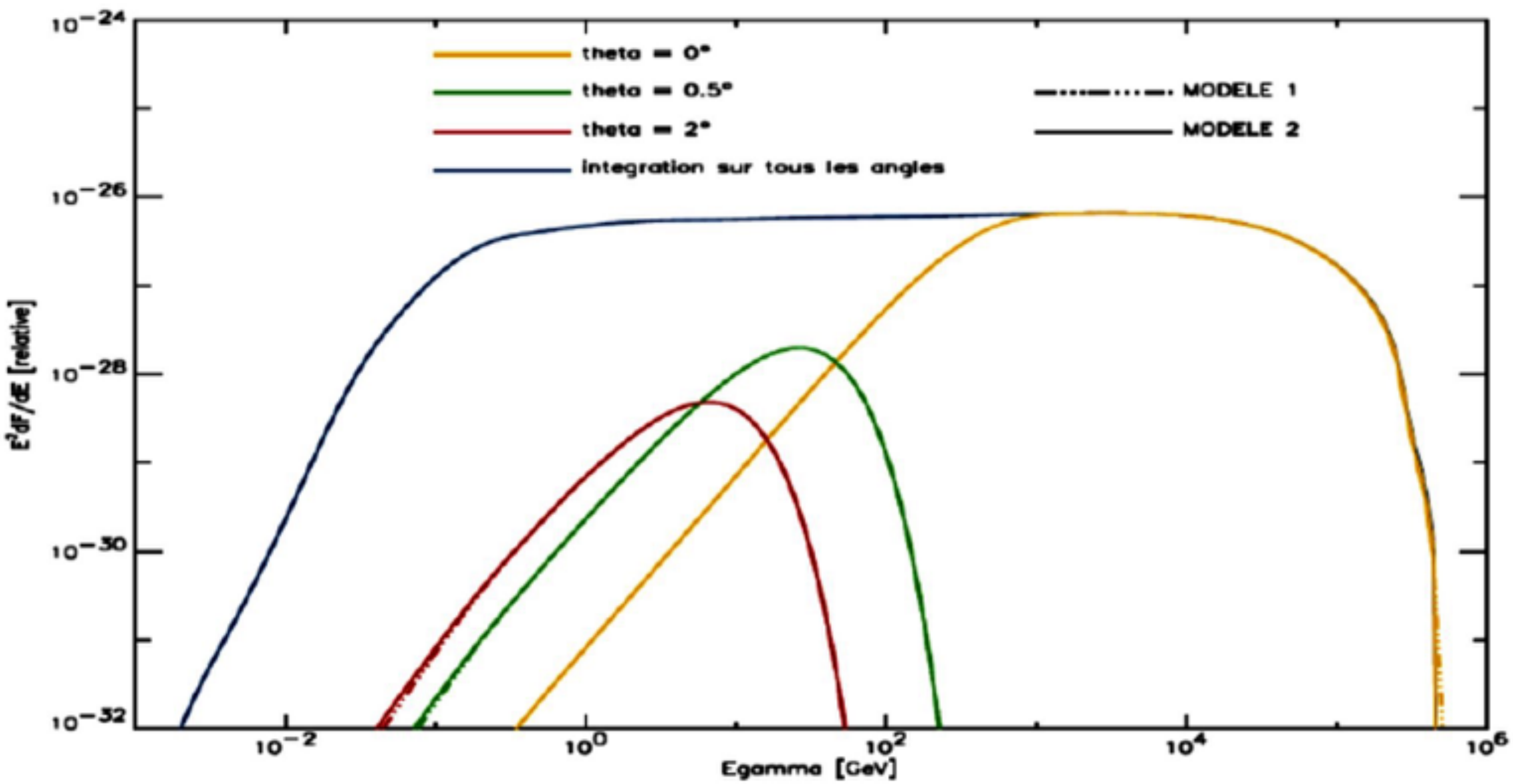


$$E'_{th} = \left(m_1^2c^4 + m_2^2c^4 + 2E_1E_2 - 2p_1p_2c^2\cos(\theta_{1,2})\right)^{1/2} \geq Mc^2$$

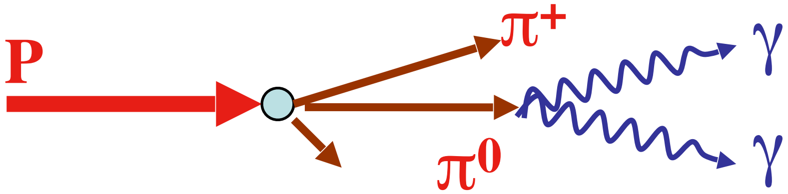


Hadronic emission

- Anisotropic

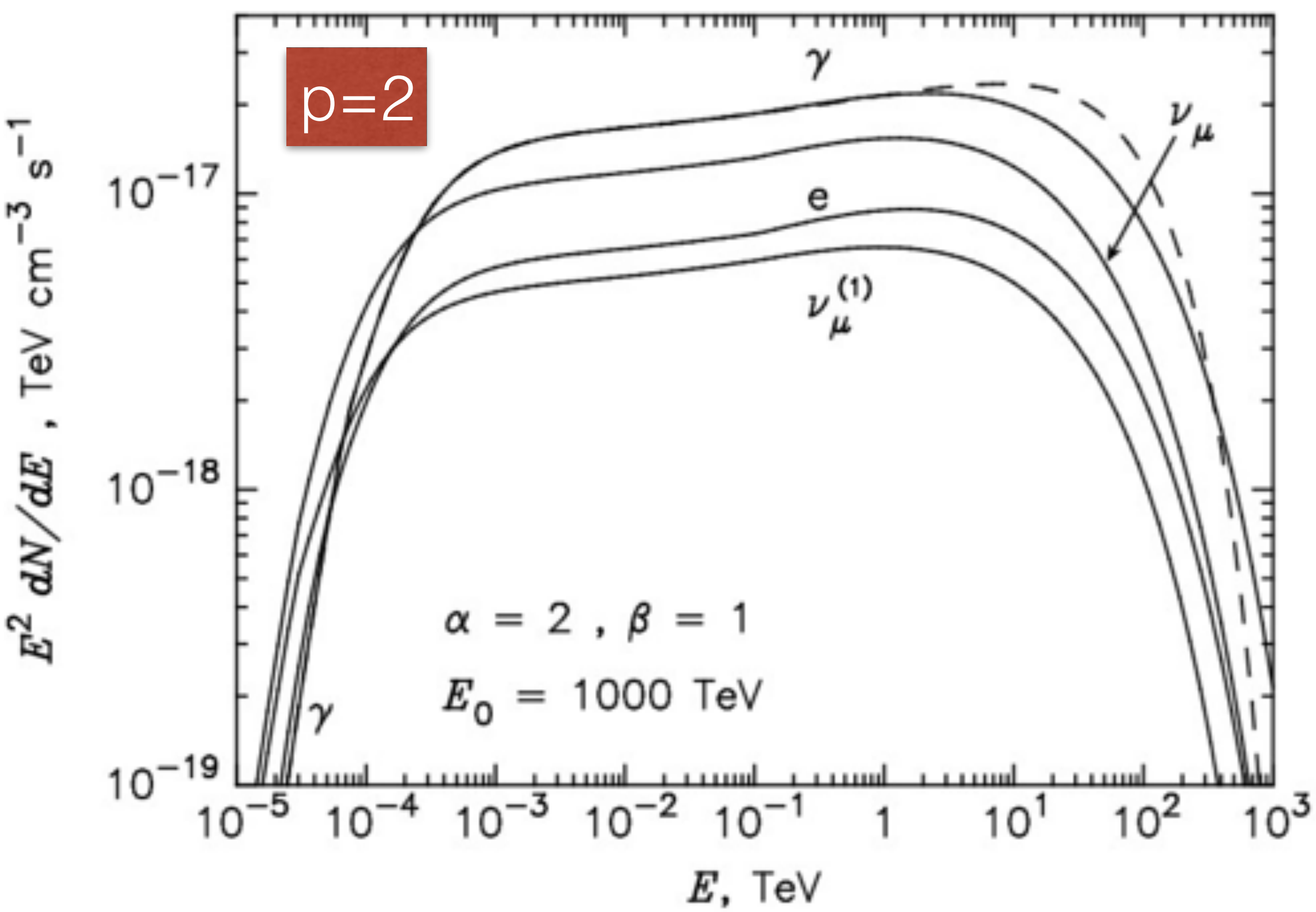


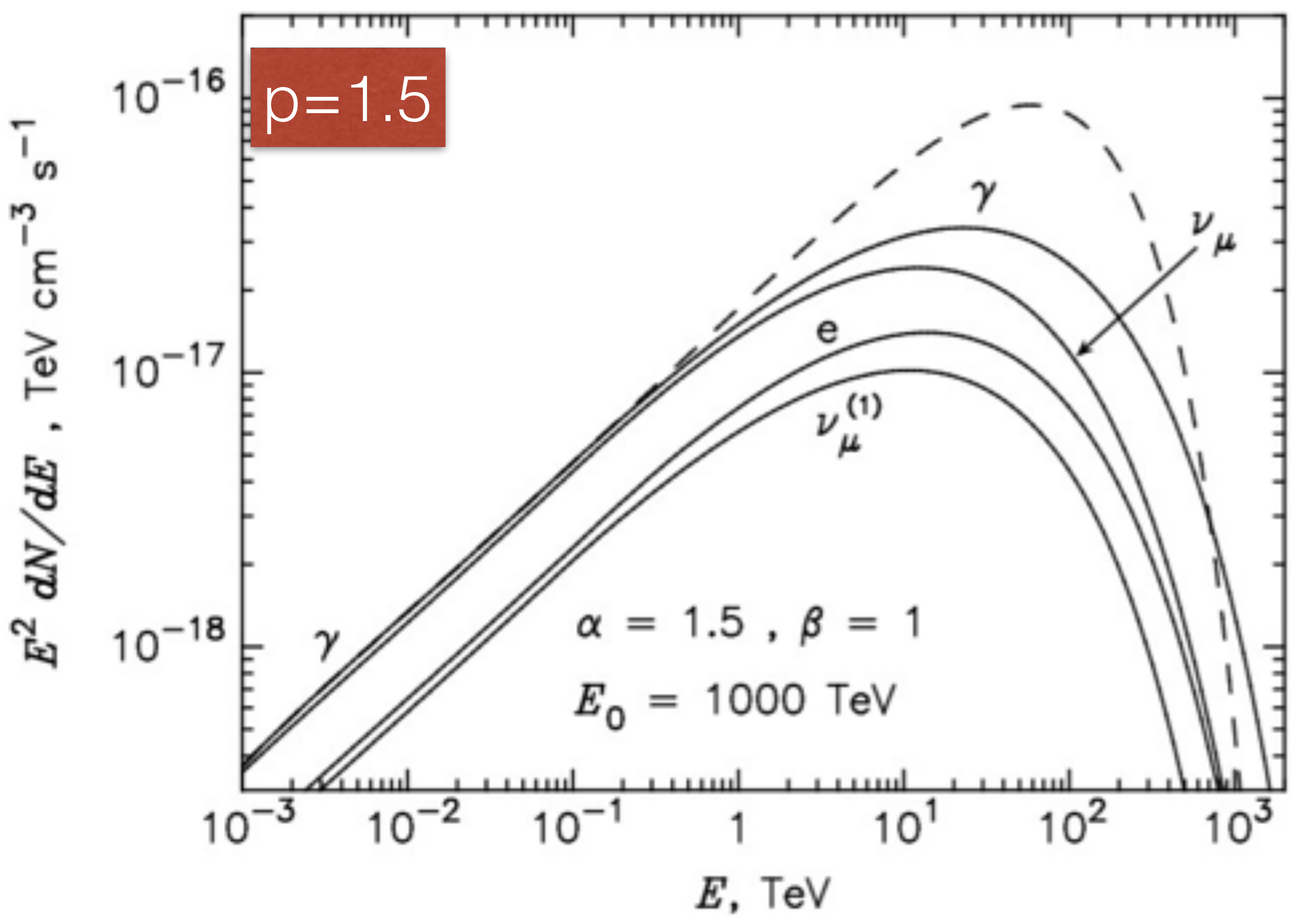
Karlsson N. & Kamae T., 2008, ApJ, 674, 278



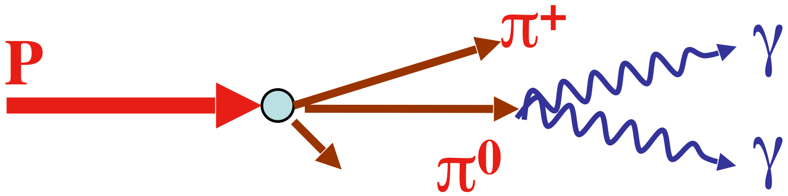
Hadronic emission

- accelerated proton (injected spectrum)
- target proton (ISM, molecular cloud...)

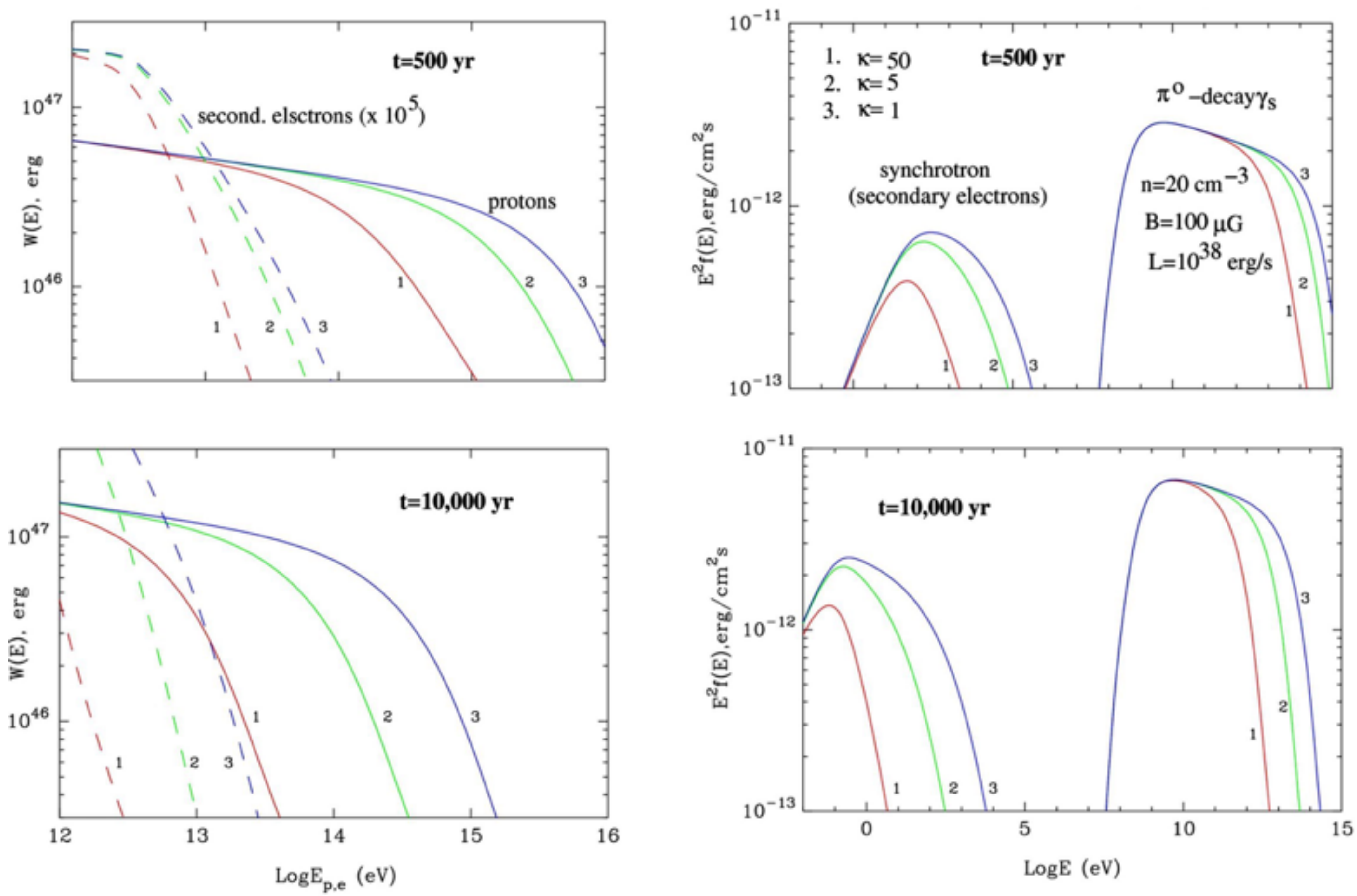




Kelner+ 2006



Hadronic emission



Observe non-thermal processes

- SED
- Observational techniques and instruments

SED

- Crab nebula

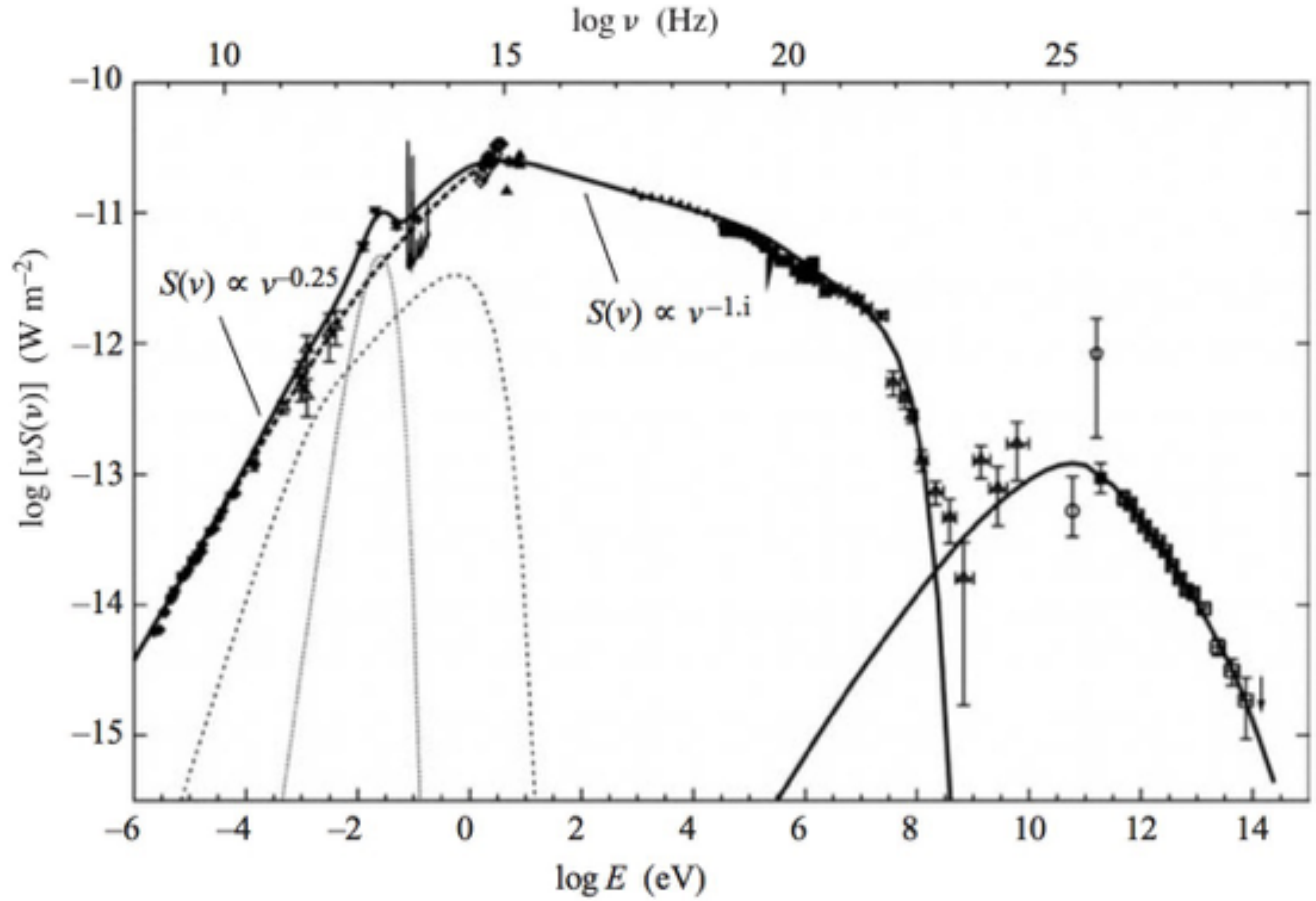


Fig. 8.2: Spectral energy distribution (SED), $\nu S(\nu)$, for photons from the Crab nebula over 19 decades of frequency reaching from the radio to TeV gamma rays with compressed horizontal scale. The straight-line segments and polarization measurements indicate that most emission up to about 100 MeV is synchrotron emission. The solid lines are a fit to the data for a synchrotron self-Compton (SSC) model (Section 9.4) for a nebular magnetic field of 16 nT with contributions from a millimeter synchrotron (radio) region and from nebular dust (narrow and broader light dashed peaks, respectively). The heavy dashed line is the SSC contribution without these two components. The peak at TeV energies is attributed to synchrotron photons that have been upscattered via inverse Compton scattering (Chapter 9). [Compiled by HEGRA team from HEGRA TeV data and the literature; F. Aharonian *et al.*, *ApJ* **614**, 897 (2004)]

Observation techniques

- Instruments to observe at different wavelength (brief overview)

Atmospheric absorption

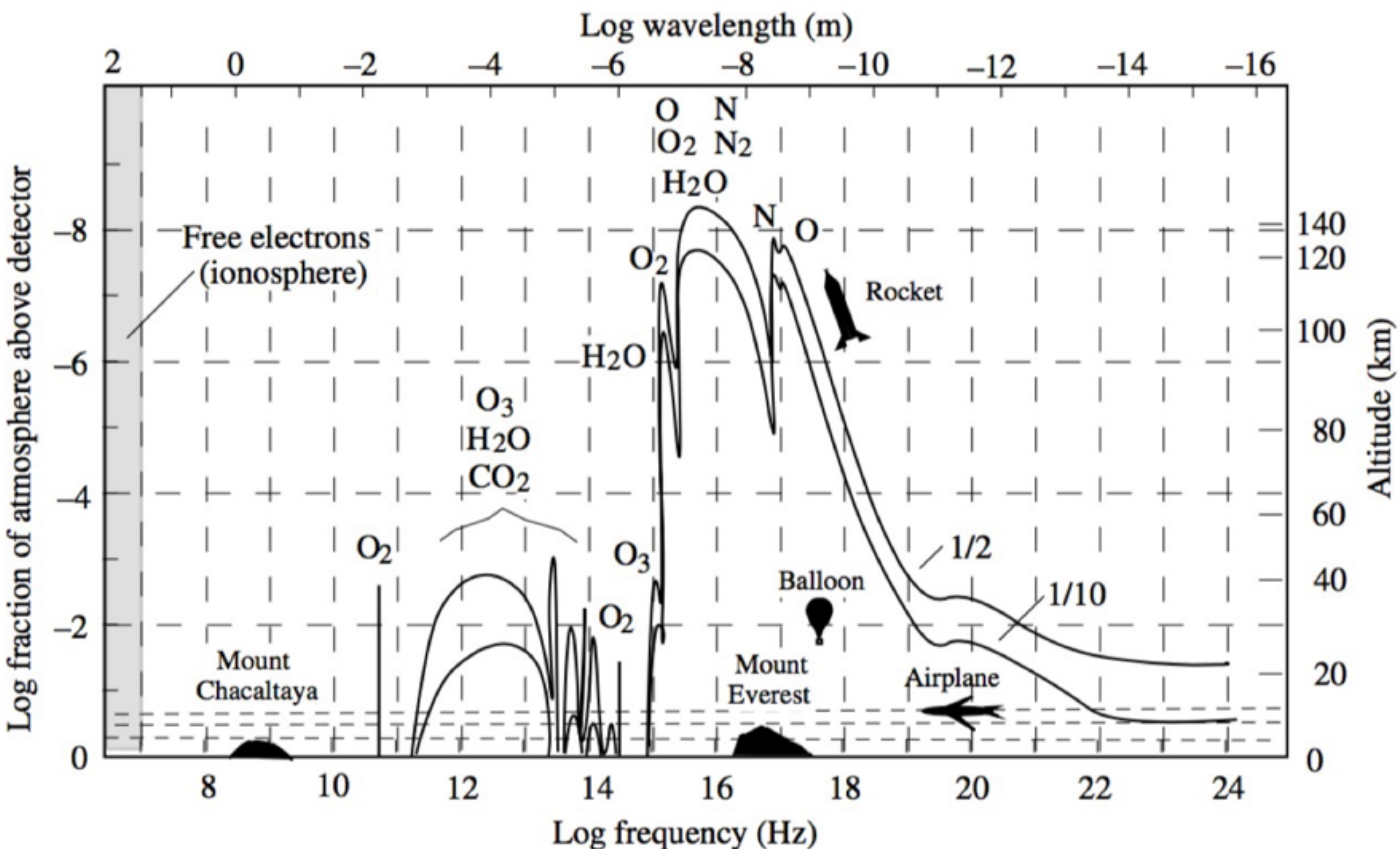


fig.2.2 Bradt "Astronomy methods"

0.1 -100 GHz

Radio

- angular resolution
- sensitivity

$$\Delta\theta = \frac{1.22\lambda}{D}\,[rad]$$

- Flux
  - SED points
  - catalogues
    (3C, NVSS, FIRST,...)

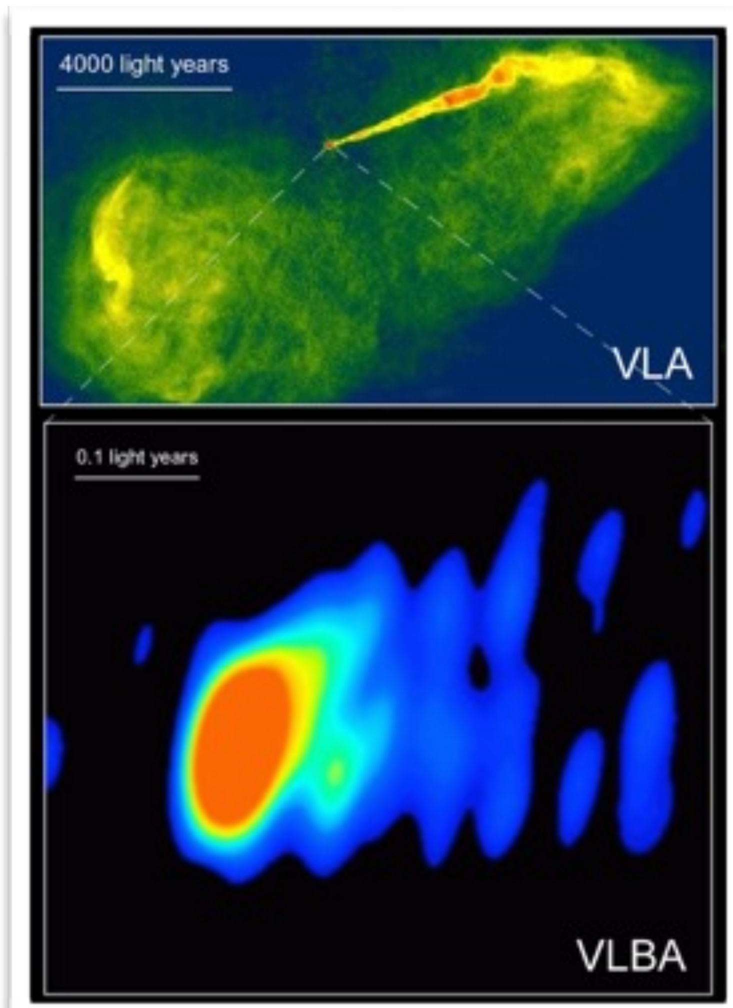
Radio

0.1 -100 GHz

- angular resolution
- sensitivity

$$\Delta\theta = \frac{1.22\lambda}{D}\,[rad]$$

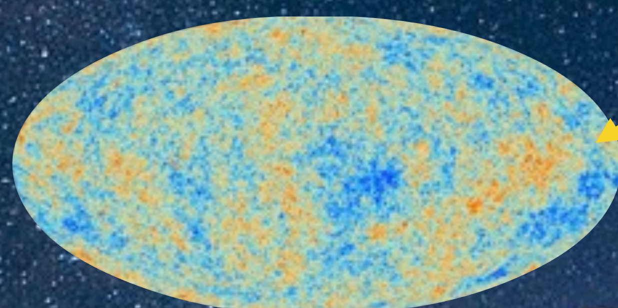
- Flux
- Interferometry
- Polarization

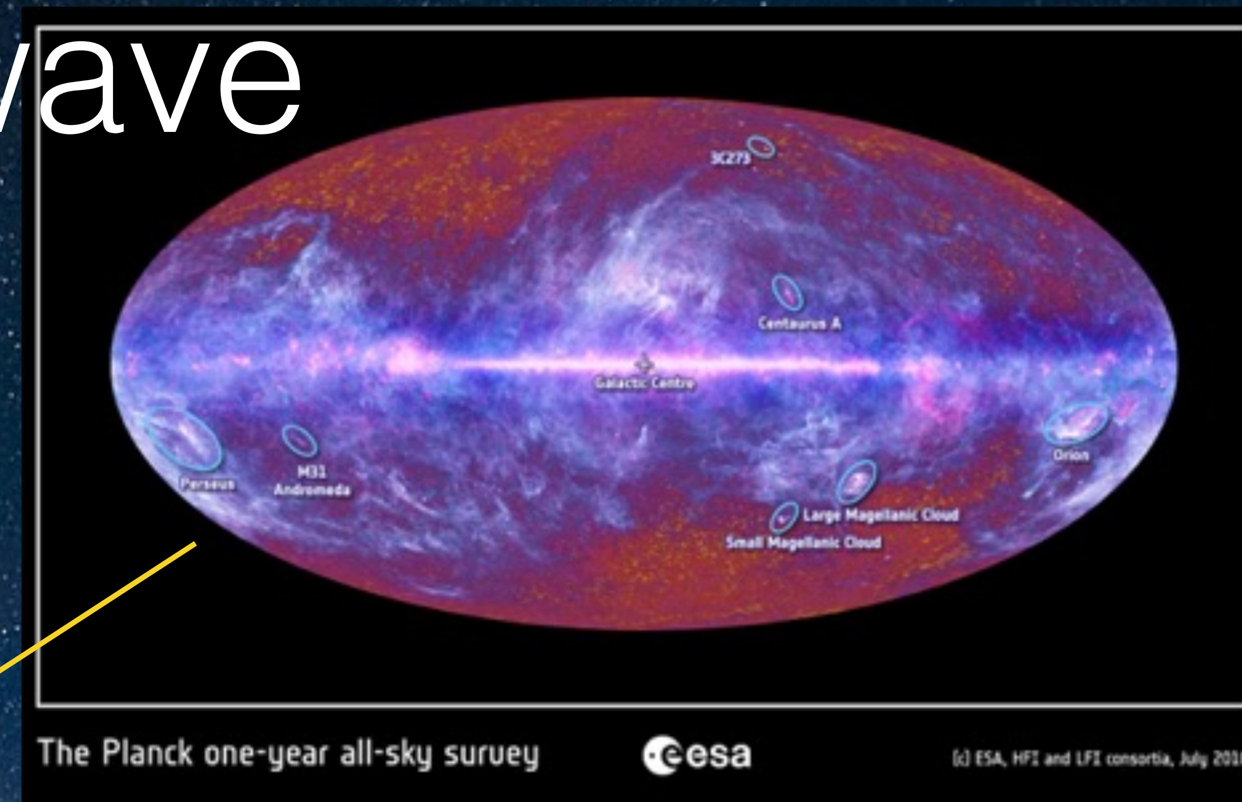


100- 900 GHz

Microwave

- **Space** (Planck, COBE, WMAP,..)
- **Ground** (ALMA, IRAM, JCWT, ...)`
- **CMB**



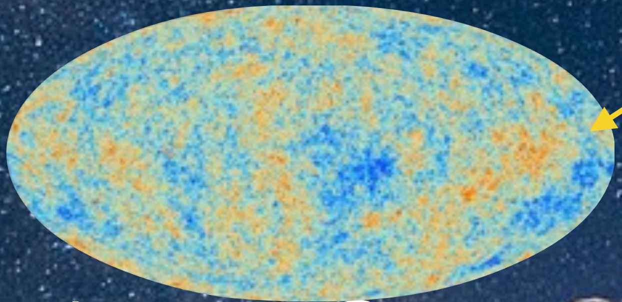


The Planck one-year all-sky survey

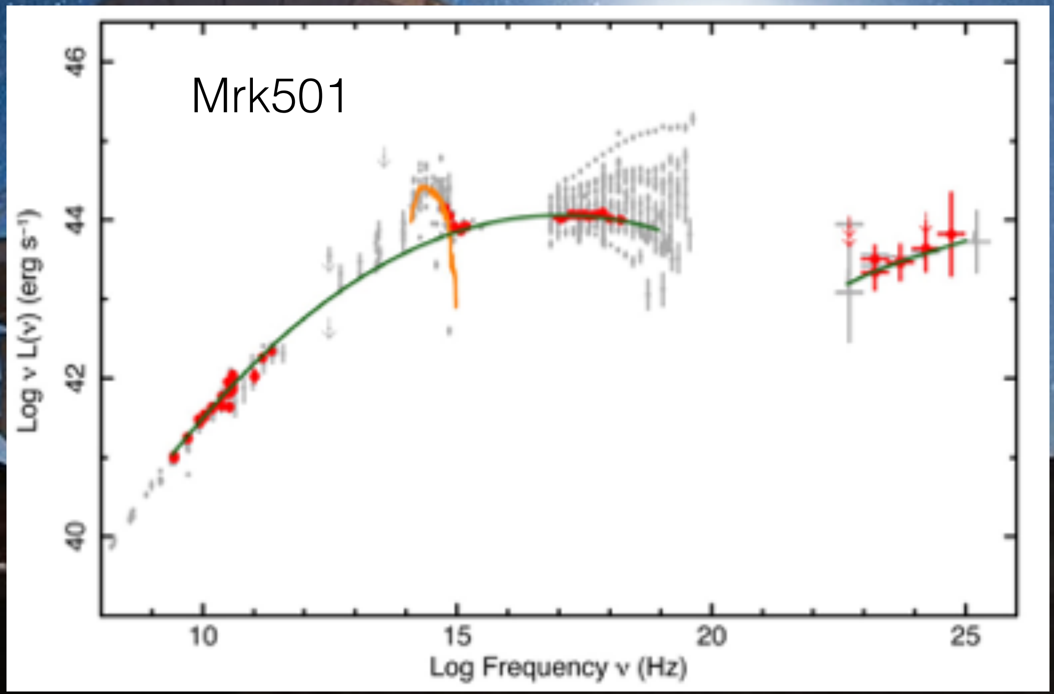
Microwave

100- 900 GHz

- **Space** (Planck, COBE, WMAP,..)
- **Ground** (ALMA, IRAM, JCWT, ...)`
- **CMB**



- Early Release Compact Source Catalog (ERCSC)



A&A 541, A160 (2012)
DOI: 10.1051/0004-6361/201117825
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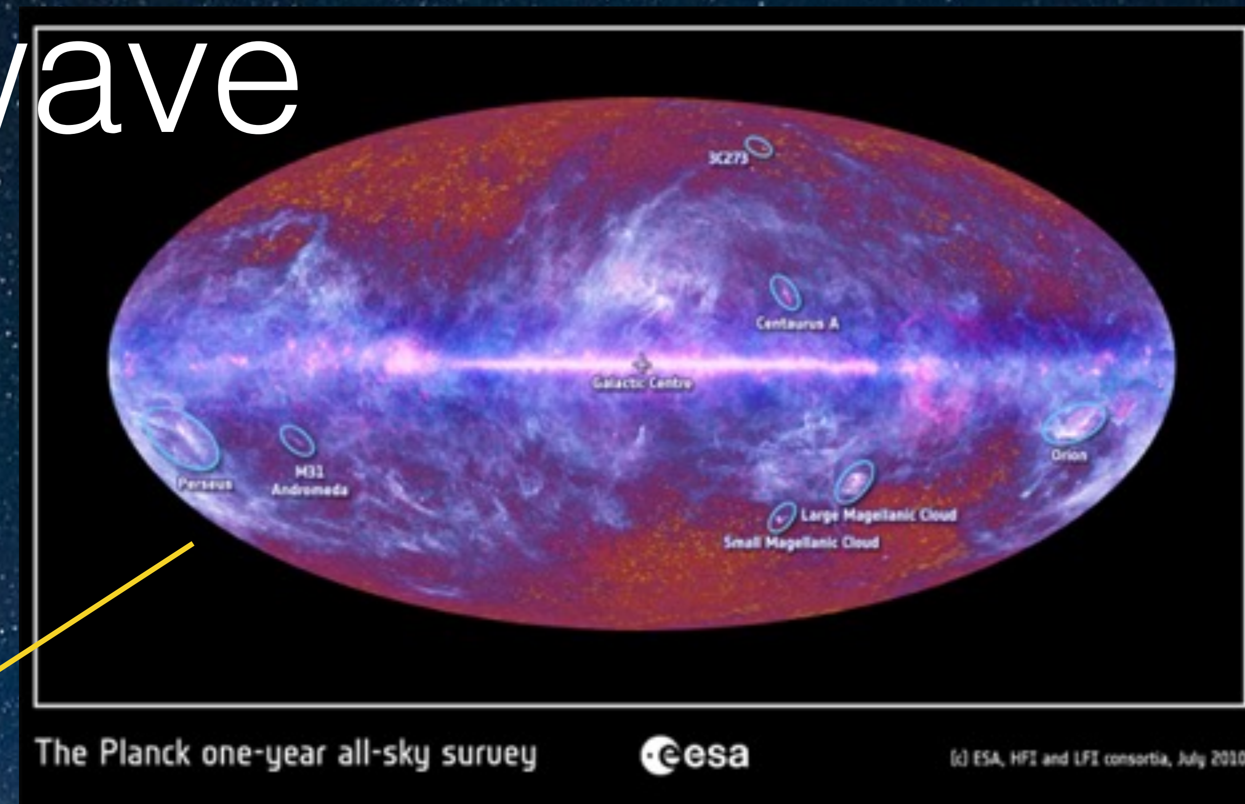
Astronomy & Astrophysics

Simultaneous *Planck*, *Swift*, and *Fermi* observations of X-ray and γ-ray selected blazars

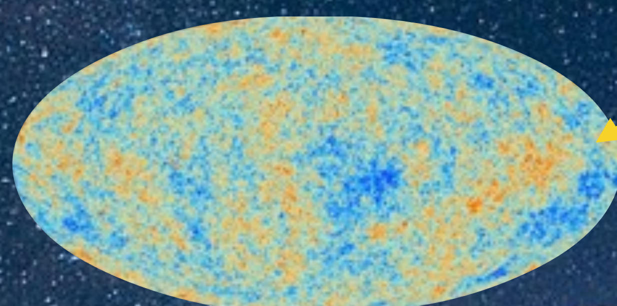
P. Giommi[2,3], G. Polenta[2,23], A. Lähteenmäki[1,19], D. J. Thompson[5], M. Capalbi[2], S. Cutini[2], D. Gasparrini[2],

100- 900 GHz

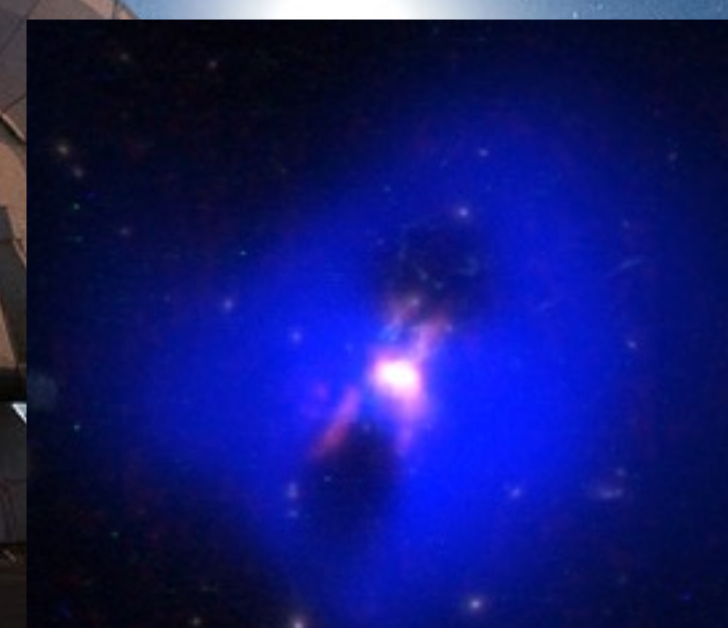
Microwave



- **Space** (Planck, COBE, WMAP,..)
- **Ground** (ALMA, IRAM, JCWT, ...)`
- **CMB**



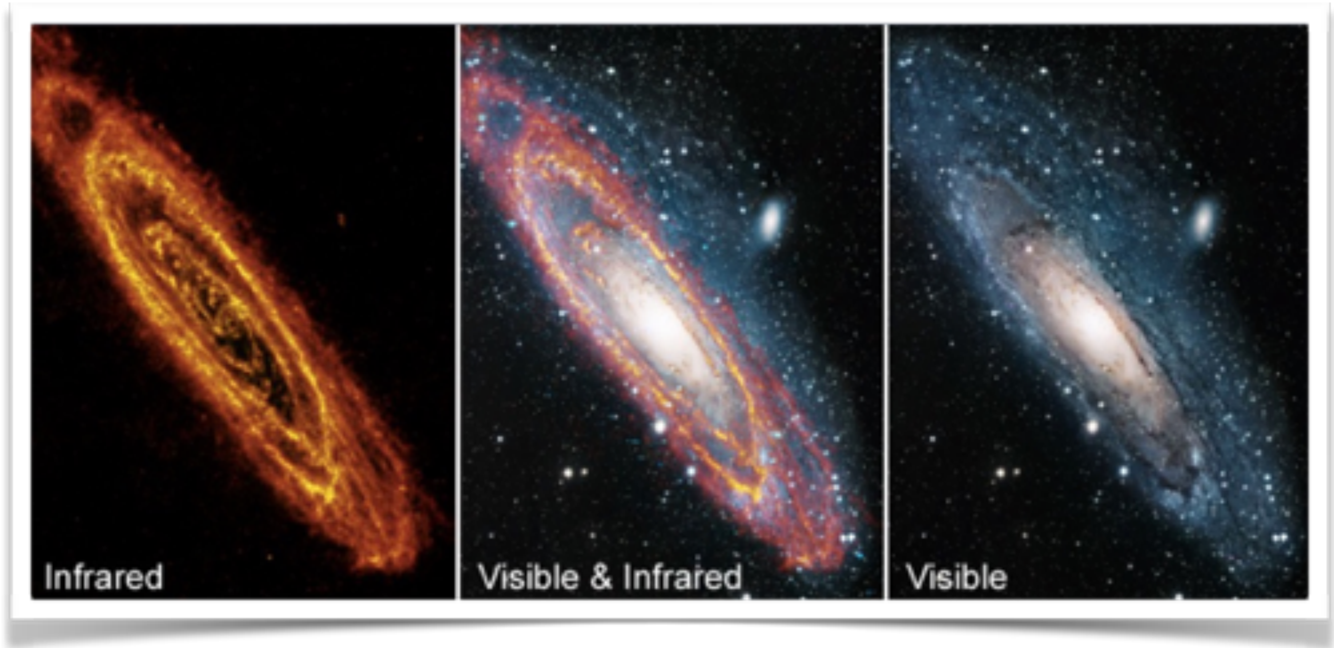
- **Morphologies (interferometry)**
- **Trace molecular gas** (Spectral analysis)
- **High-z sources**



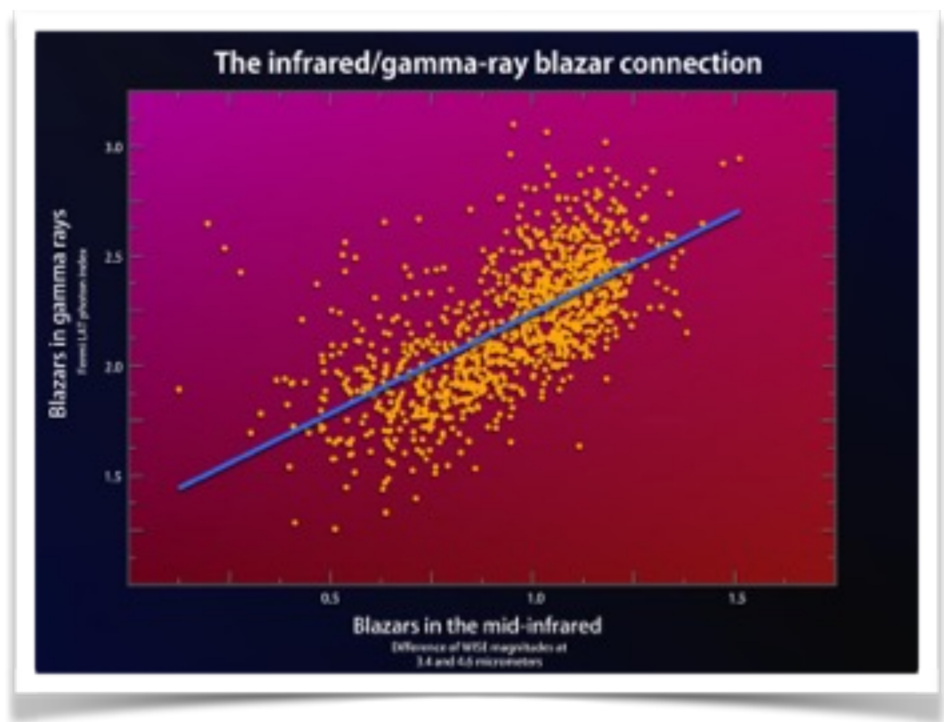
Phoenix cluster
Russell+2016

Infrared

- Thermal objects
  - dusty objects
  - cool objects
  - high-z quasars
  - molecular lines

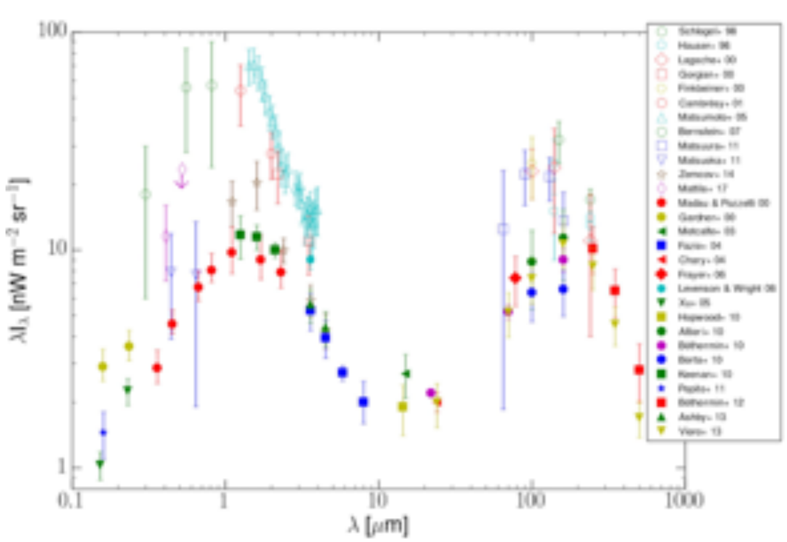


- Non-thermal component from synchrotron emission



WISE

- EBL



SOFIA

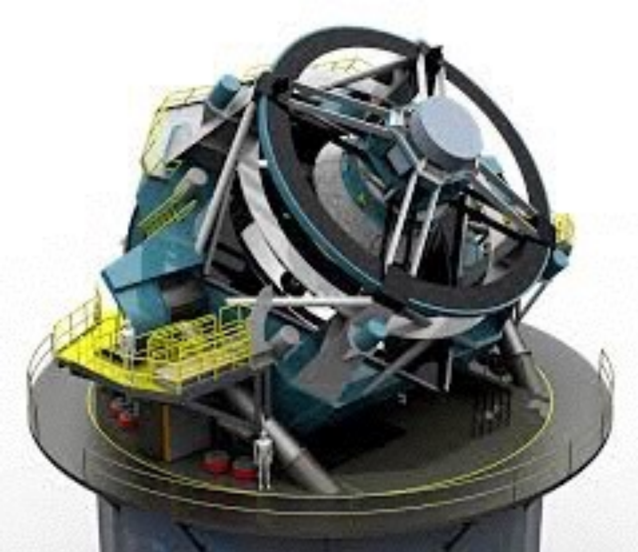
Infrared

- Main issue: thermal background
- Cryogenic systems

- Survey: WISE, 2MASS

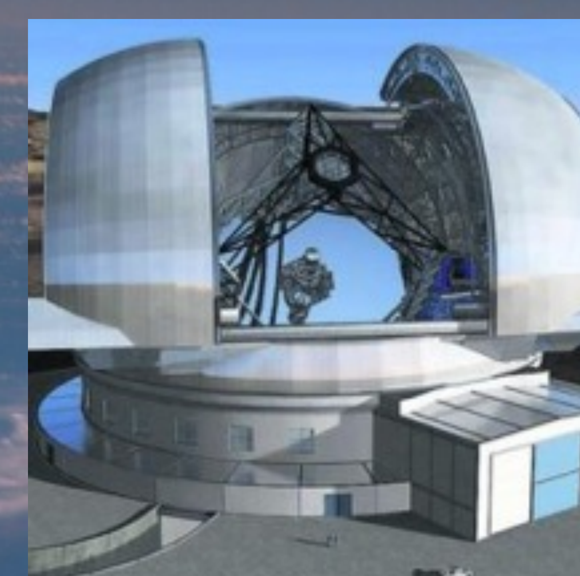
Herschel
3.5 m

JWST
2018



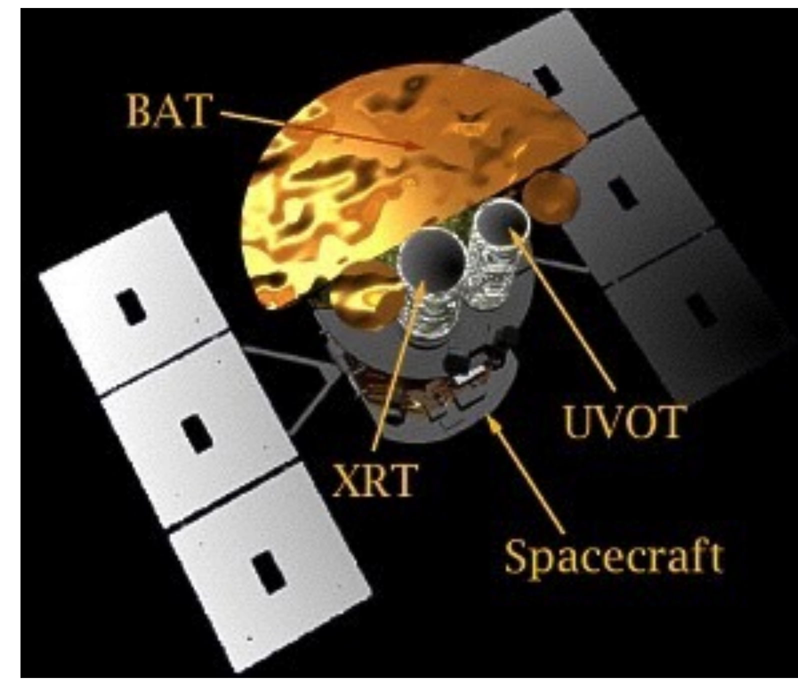
Optical

- Most popular: HST, GTC, Sloan, x-shooter (VLT)
  - NOT, TNG,
- Future: LSST, ELT, JWST,
- Surveys: SDSS, LSST, Pan-STARRS…
- Search of transients



Ultraviolet

- Traces hot (10^{4-5} K) moderately ionised gas
  - e.g. corona from accretion disks
- Also continuum non-thermal emission
- HST-FUV camera
- satellites: IUE, EUVE, FUSE, GALEX
- Small telescopes on other satellites
  - Swift/UVOT, XMM/OM



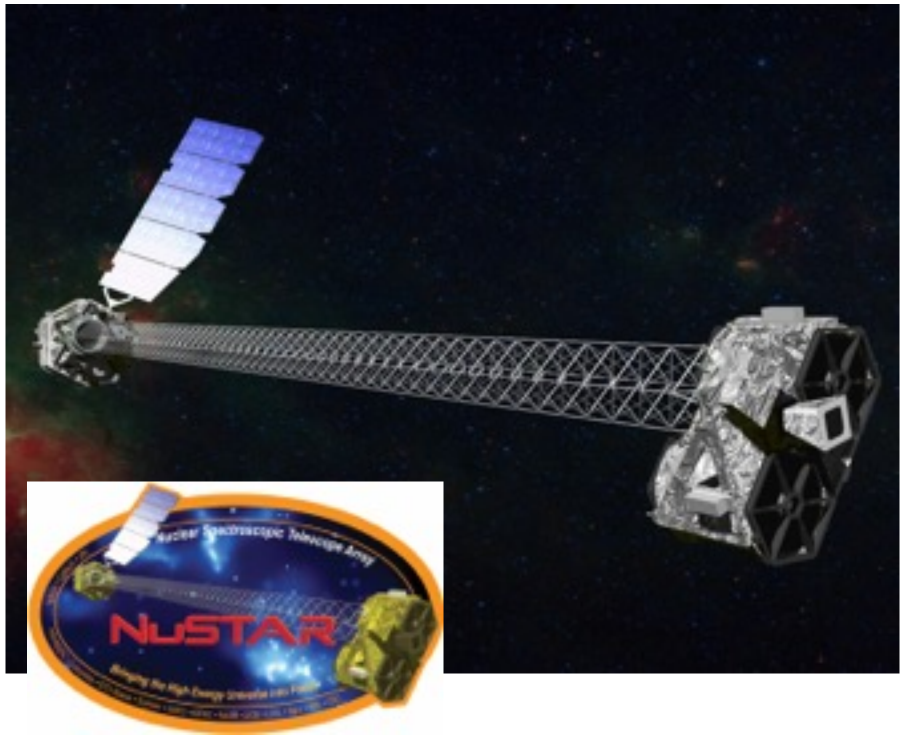
Comparison of UV/Vis/IR

	UV	Optical	IR
sources of emission	massive stars, WHIM, Ly α	many	dust, cool objects, molecules
detectors	based on microchannel plates	CCDs	HgCdTe etc. arrays, bolometers
major telescopes	GALEX, HST	many	Spitzer, Herschel, ground
surveys	GALEX	SDSS	2MASS, WISE

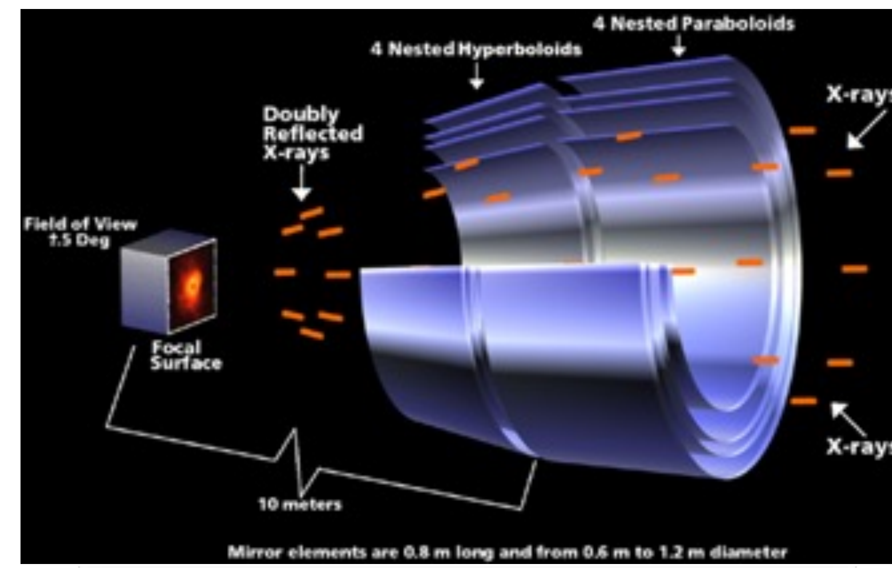
... from telescopes to particle detectors...

...from a wave to a particle.... Atom/nucleus --> 1 Å ~ 12 keV

- E < ~ keV
- Focussing telescopes, with direct imaging of the source
- E > ~ keV (X-ray, γ-ray)
  - particle detectors
    - image and parameters from the source are reconstructed from secondary particles produced by the interaction within the detector



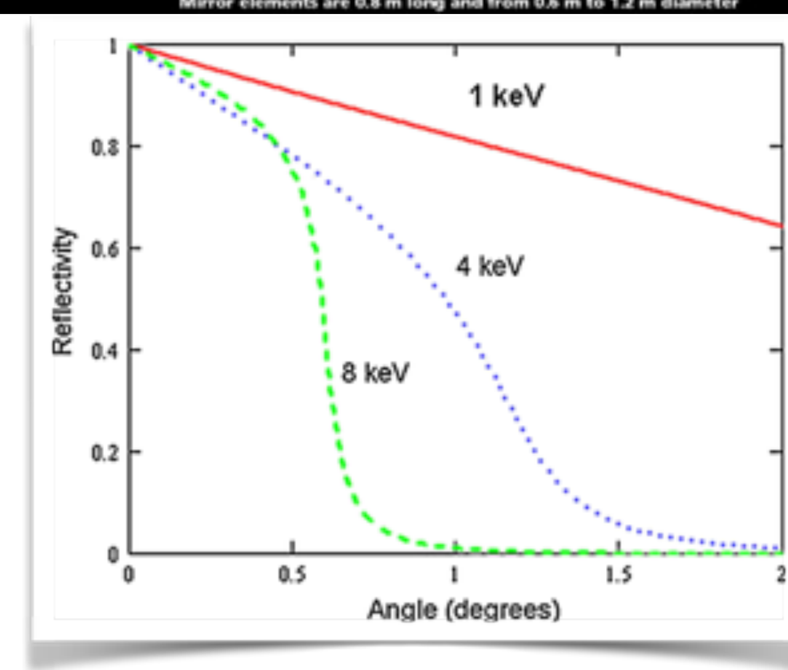
X-ray

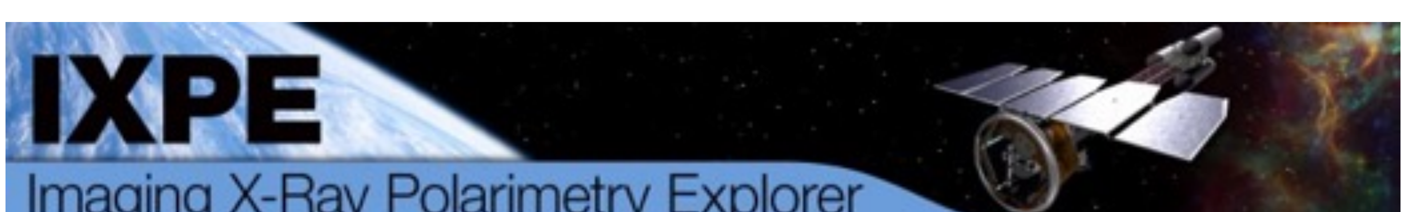


- Absorption (coded masks)
    - low sensitivity; wide FoV
- Grazing incidence
    - high resolution; high sensitivity; small FoV

new frontier!

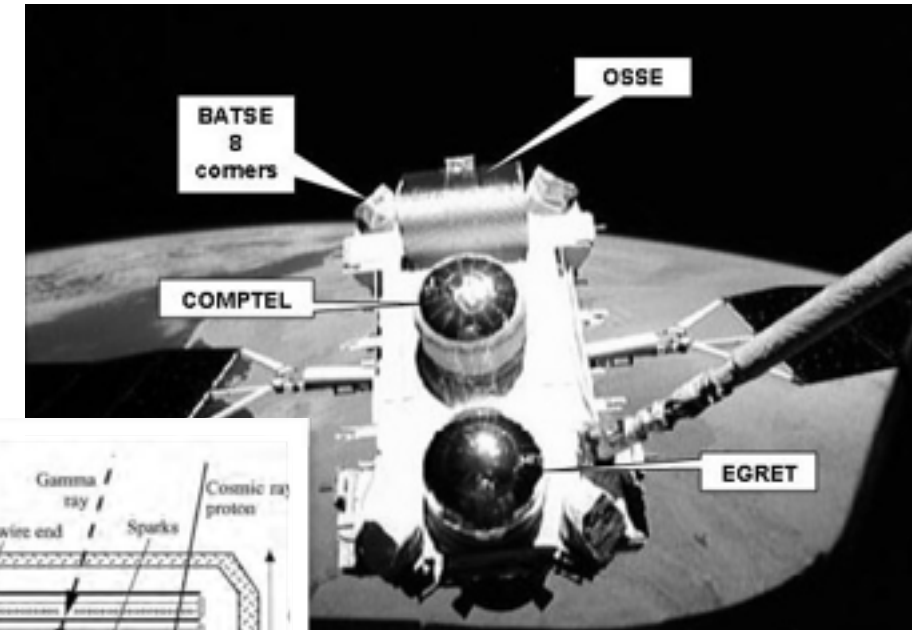
- X-ray polarimetry (IXPE, XIPE)

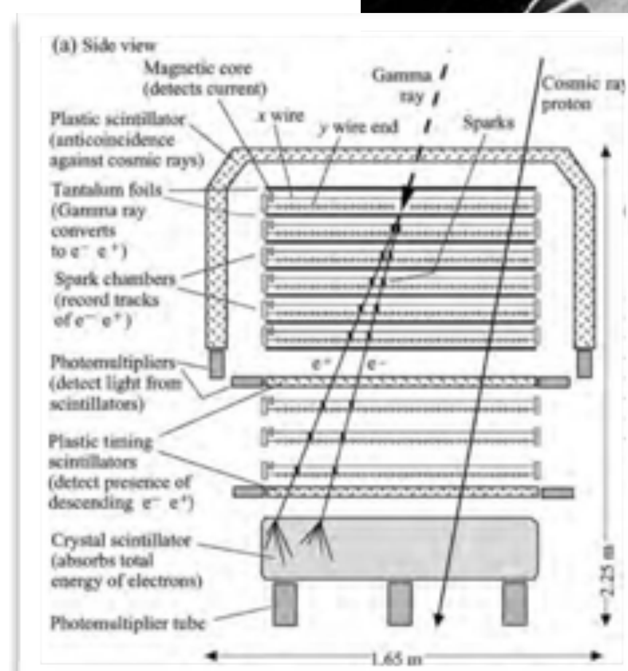


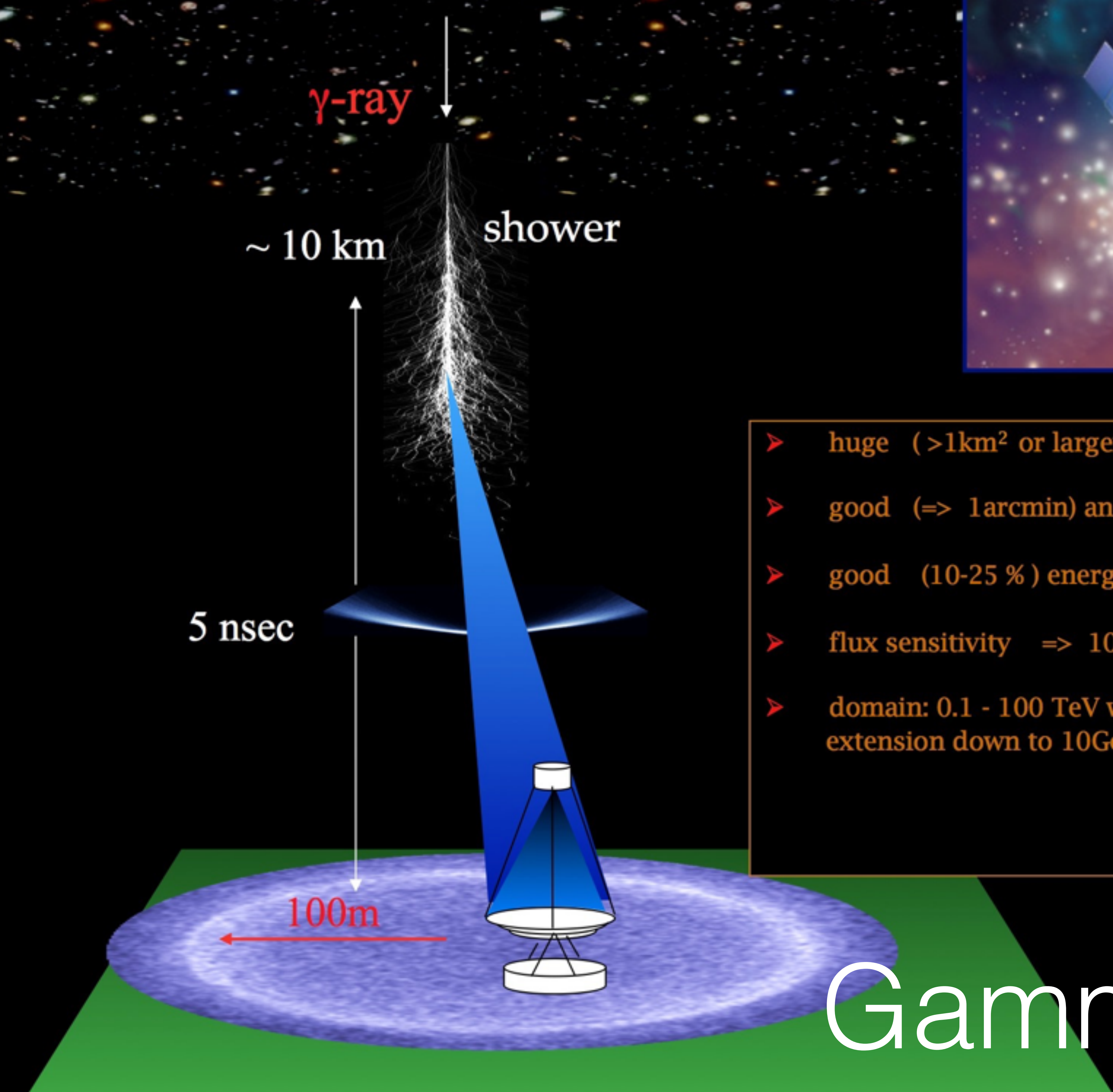


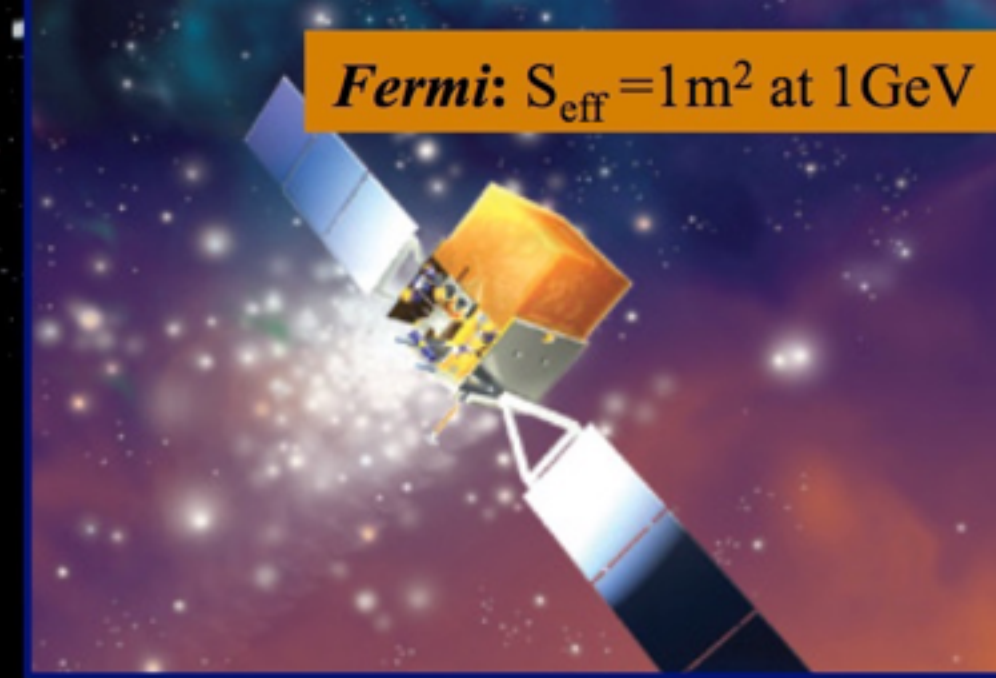
Gamma-ray

- Particle detection techniques
  - geiger (first satellites)
  - Particle tracking
    - Spark chambers (EGRET)
    - Silicon trackers (Fermi/LAT)
  - Calorimeter
    - built in detector (LAT): space based
    - Atmosphere (IACTs): ground based





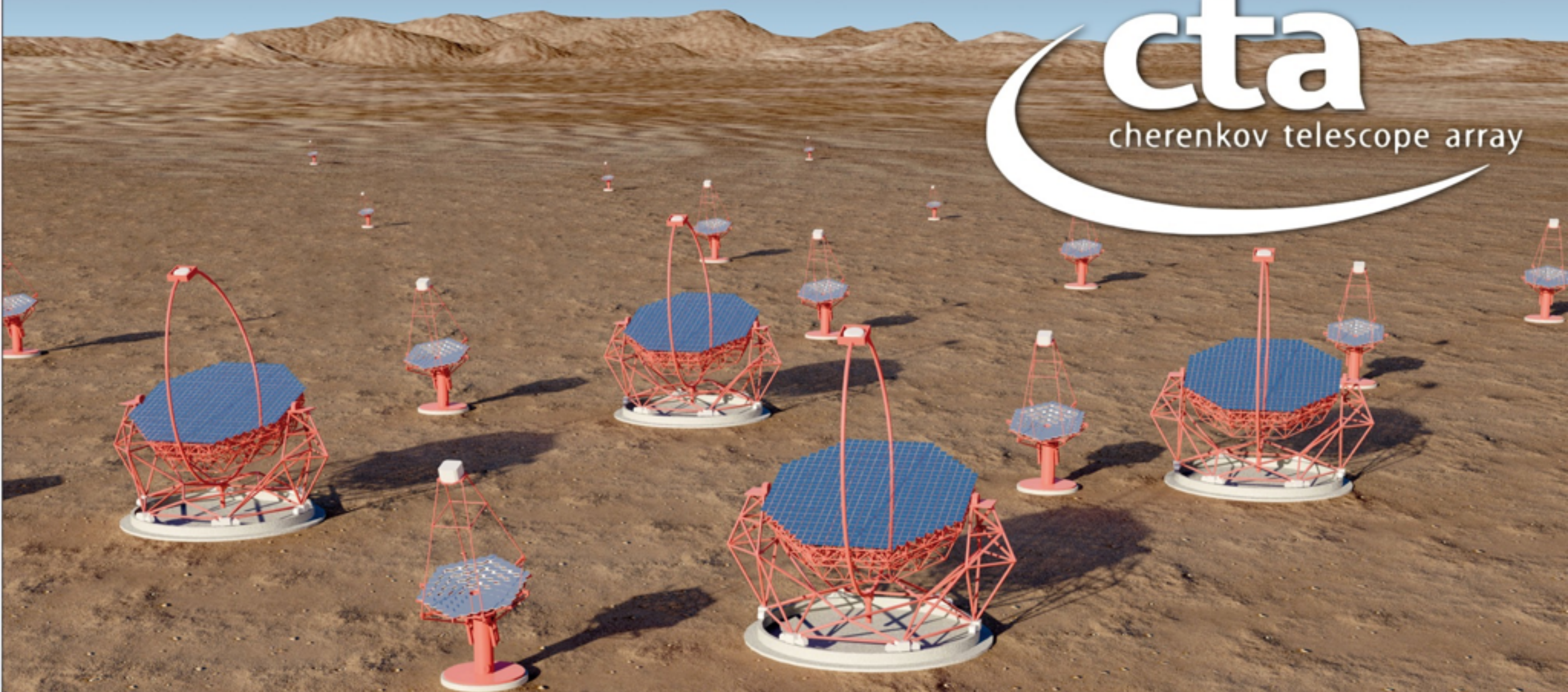




- huge (>1km² or larger) detection area
- good (=> 1arcmin) angular resolution
- good (10-25 %) energy resolution
- flux sensitivity => 10^{-14} erg/cm² s
- domain: 0.1 - 100 TeV with a potential of extension down to 10GeV and up to 1PeV

Gamma-ray

32 countries, 209 institutes, >1300 members, ~250M€ investment, construction planned for 2018-2022. Two sites, N & S, with > 100 telescopes total!

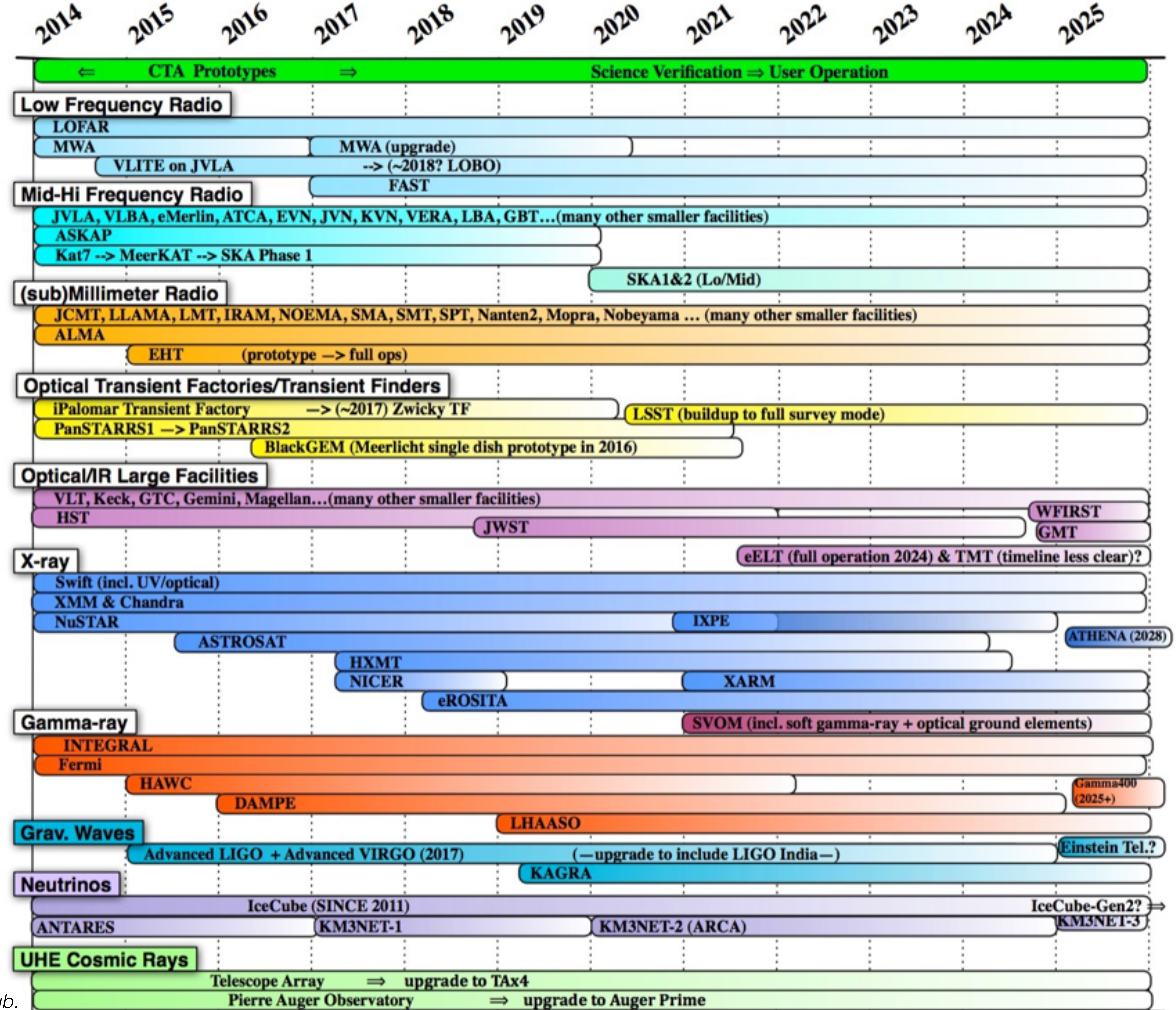


Key design goals:

- Range overlapping Fermi: 20 GeV-200+ TeV
- 10x better sensitivity at TeV energies and 10x better effective energy coverage
- Larger field of view for surveys
- Improved angular resolution
- Improved pointing accuracy
- Full sky coverage: one array per hemisphere

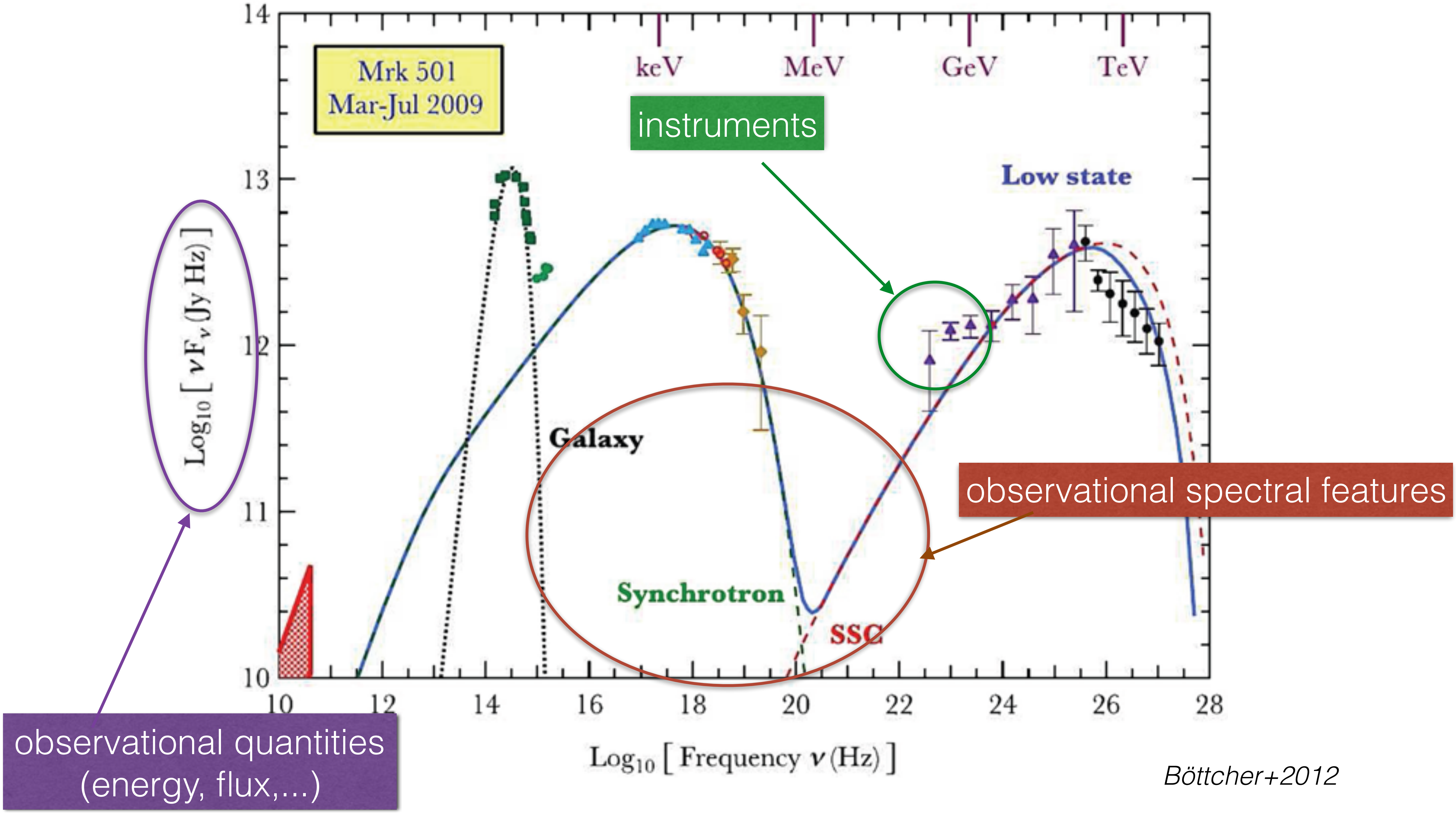
The present and the future

of multi-wavelength and multi-messenger facilities



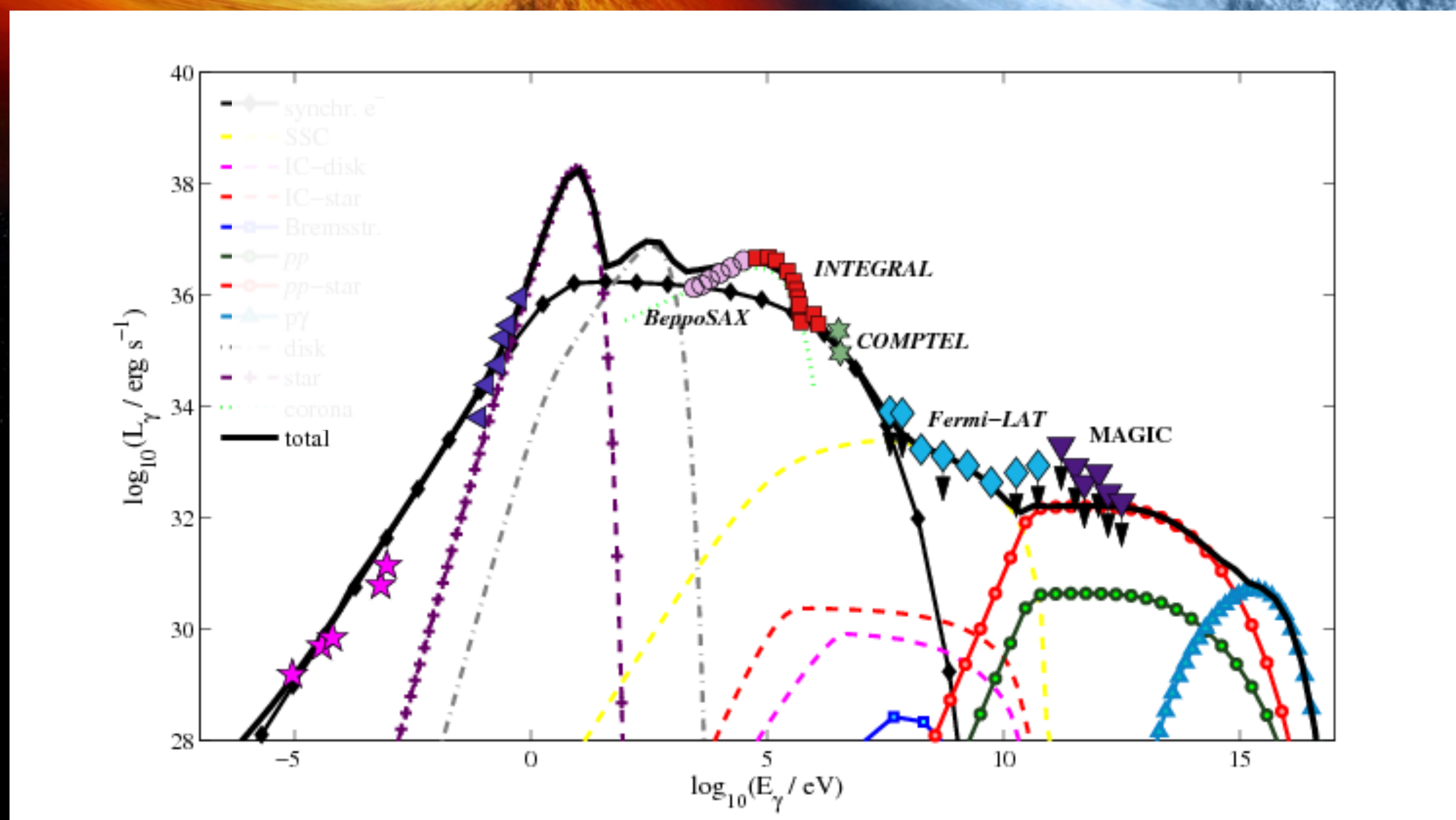
CTA Science book, in pub.

Read the SED



Böttcher+2012

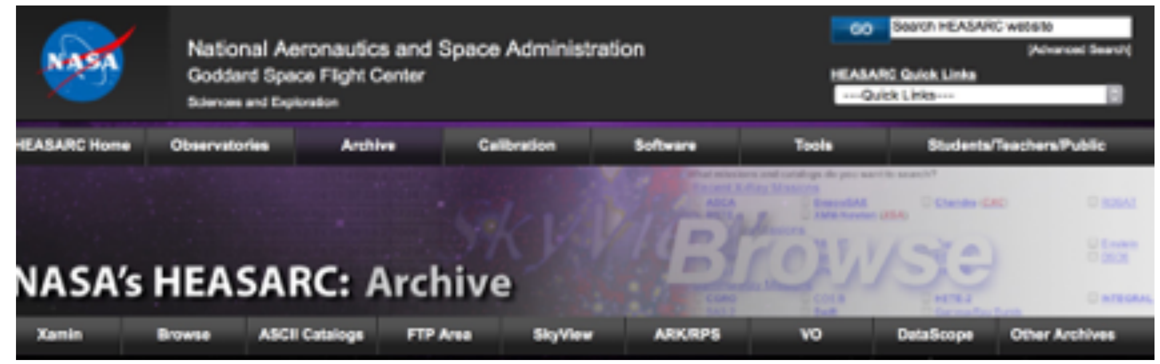
Homework



synchr. e⁻
SSC
IC−disk
IC−star
Bremsstr.
pp
pp−star
pγ
disk
star
corona
total
INTEGRAL
BeppoSAX
COMPTEL
Fermi−LAT
MAGIC
$\log_{10}(L_\gamma$ / erg s$^{-1})$
$\log_{10}(E_\gamma$ / eV)
40
38
36
34
32
30
28
−5
0
5
10
15

Cyg X-1

Build a SED with observational data



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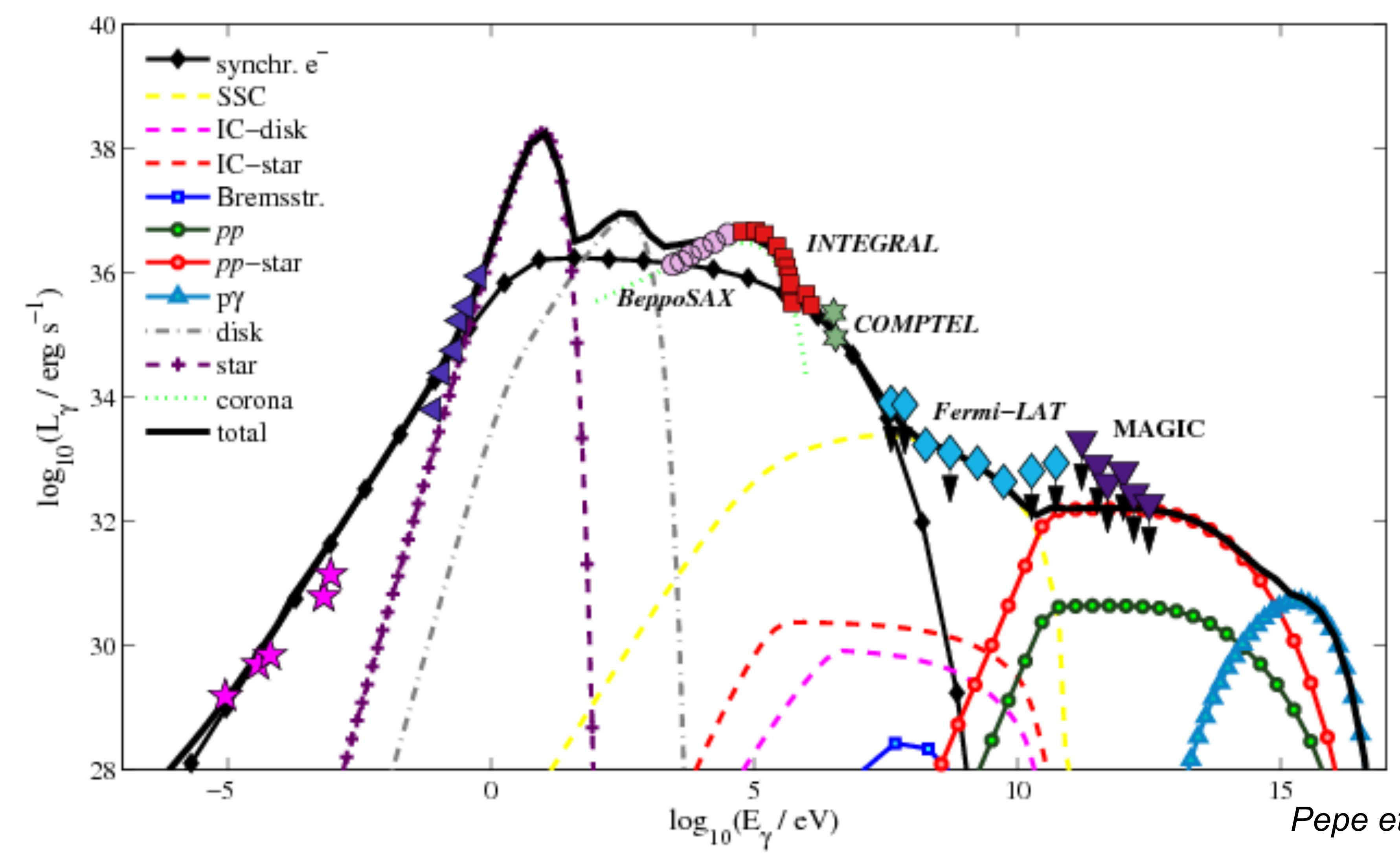


Pepe et al. 2015

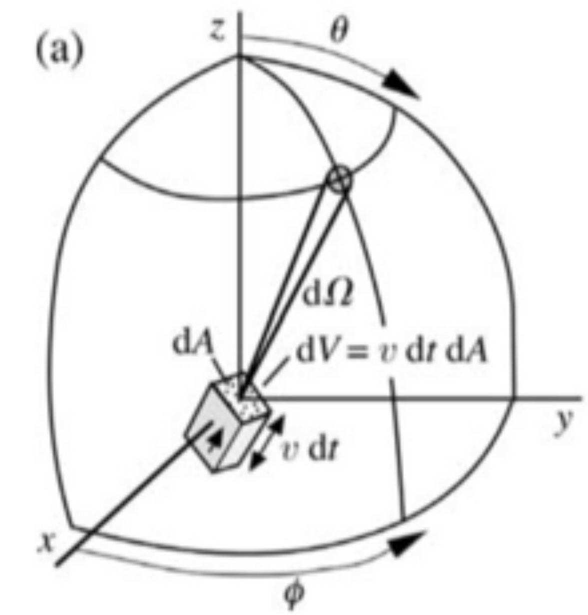
Cyg X-1

Beaming

$$\delta = \frac{1}{\Gamma(1 - \beta cos\theta)}$$

$$\begin{aligned}
I(\nu) &= h\nu \frac{dN}{dt\, d\nu\, d\Omega\, dA} \\
&= \delta h\nu' \frac{dN'}{(dt'/\delta)\, \delta d\nu'\, (d\Omega'/\delta^2)\, dA'} \\
&= \delta^3\, I'(\nu') = \delta^3 I'(\nu/\delta)
\end{aligned}$$

Radiative transfer equation

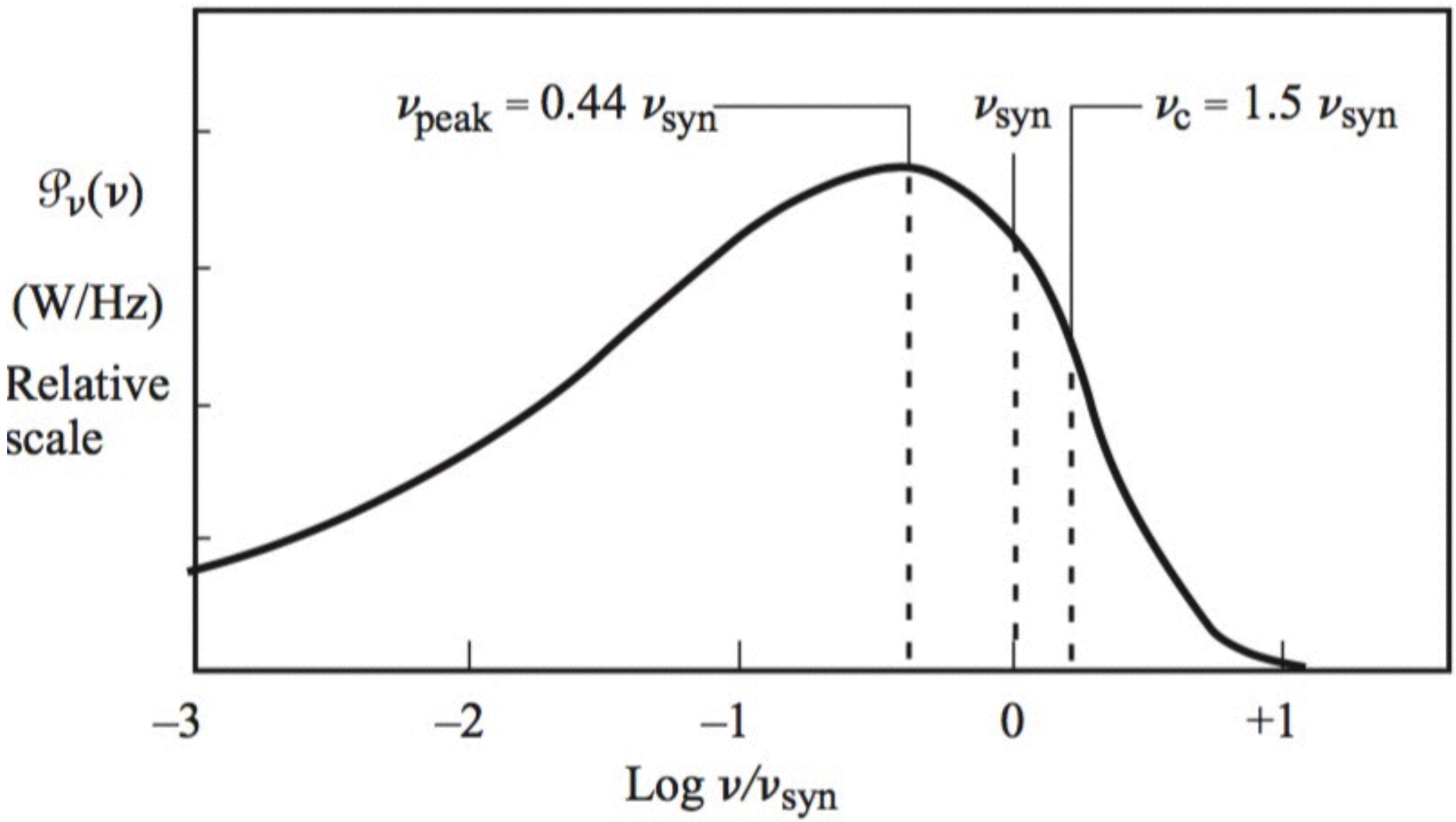


- Intensity $$I(\nu) = h\nu \frac{dN}{dt\, d\nu\, d\Omega\, dA}$$
- Absorption (abs coeff.)

$$\frac{\mathrm{d}I(\nu)}{\mathrm{d}s} = -\alpha_\nu I(\nu) \quad I(\nu) = I_0 \exp^{-\tau} \quad \tau = -\alpha_\nu s$$

- Source: volume emissivity $\boldsymbol{j}_\nu$ [W m^{-3} Hz^{-1} sr^{-1}]
- Radiative transfer equation $$\frac{dI_\nu}{ds} = -\alpha_\nu I_\nu + j_\nu$$

$$\frac{\mathrm{d}I(\nu)}{\mathrm{d}\tau} = -I(\nu) + S_\nu$$



$\nu_{peak} = 0.44\ \nu_{syn}$
ν_{syn}
$\nu_c = 1.5\ \nu_{syn}$
$\mathcal{P}_\nu(\nu)$
(W/Hz)
Relative scale
–3
–2
–1
0
+1
Log ν/ν_{syn}