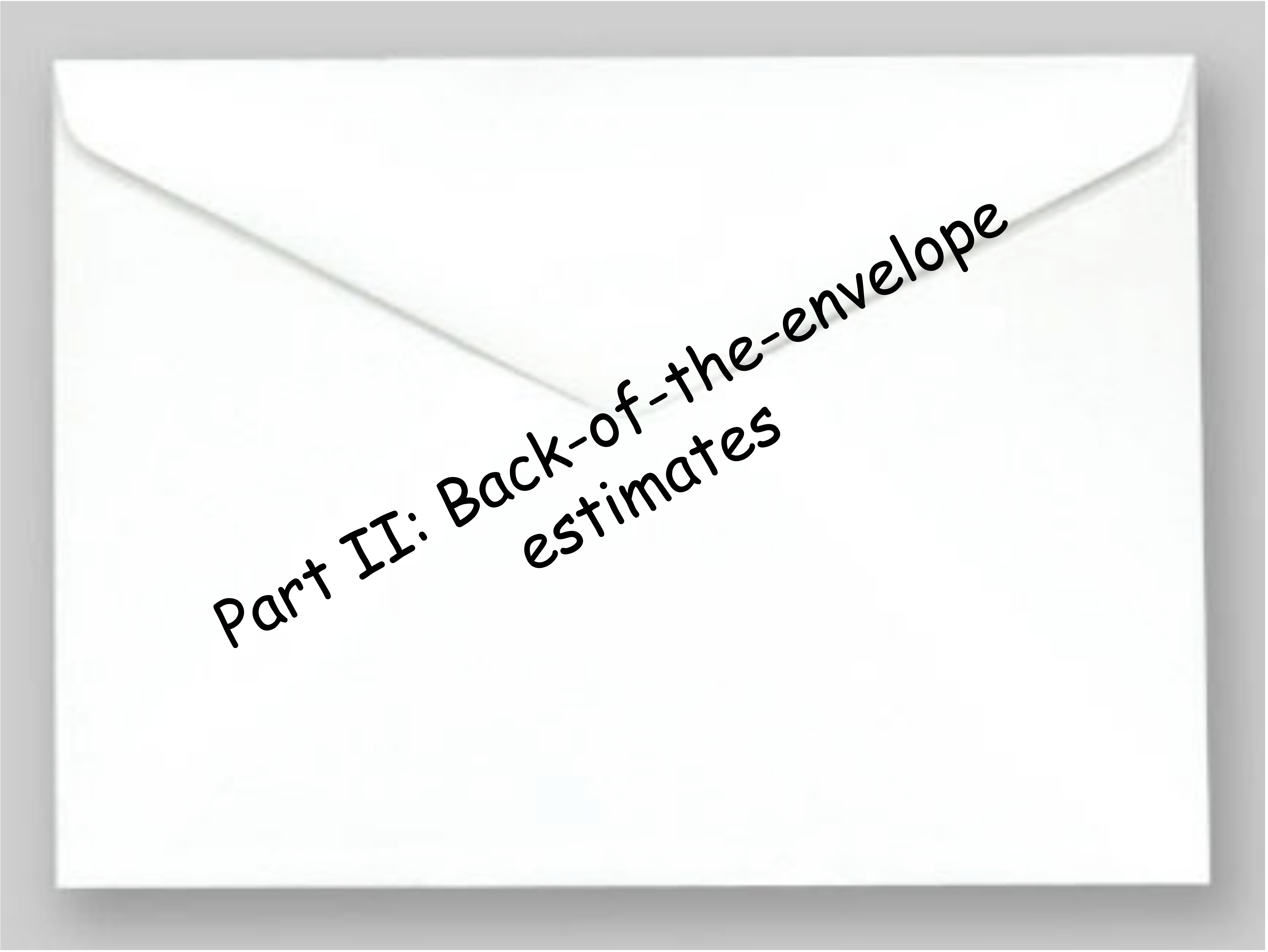
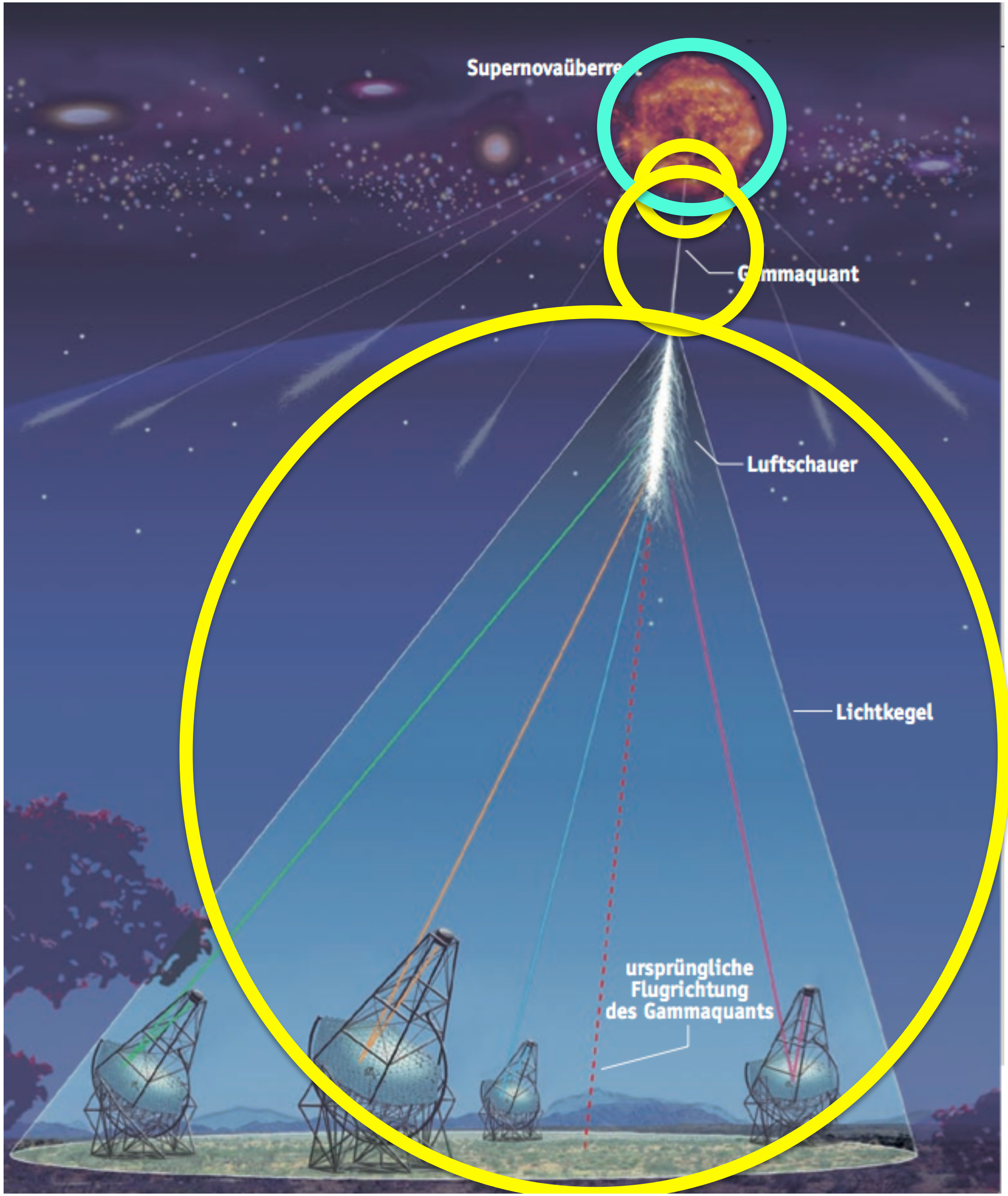

Part II: Back-of-the-envelope
estimates



Supernovaüberrest
Gammaquant
Luftschauer
Lichtkegel
ursprüngliche
Flugrichtung
des Gammaquants

Back of the envelope estimates

Warning:

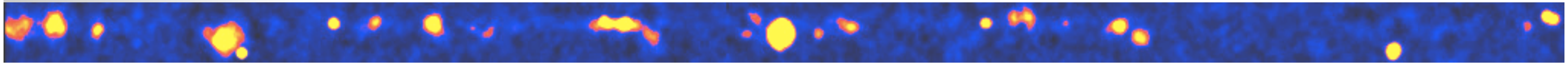
People get the right answers either

(a) because they have done / looked up the detailed calculation and know the right answers

(b) because they are really great scientists with a lot of intuition

Case (b) is relatively rare…

Topics



- Preliminaries: Units, coordinates & other useful(?) stuff
- Gamma ray production by protons
  - Basics
  - Gamma-ray visibility of supernova remnants
  - Seeing molecular clouds in gamma rays
- Radiation processes involving electrons
  - Inverse Compton scattering
  - Synchrotron radiation
  - Radiation cooling
  - Application to real objects
- Gamma ray propagation - will they reach us?
- Cosmic particle accelerators
  - Supernova remnant kinematics
  - Supernova remnant shocks
  - Particle propagation and particle acceleration
  - Some of the fine print
- The receiving end: Detecting gamma rays

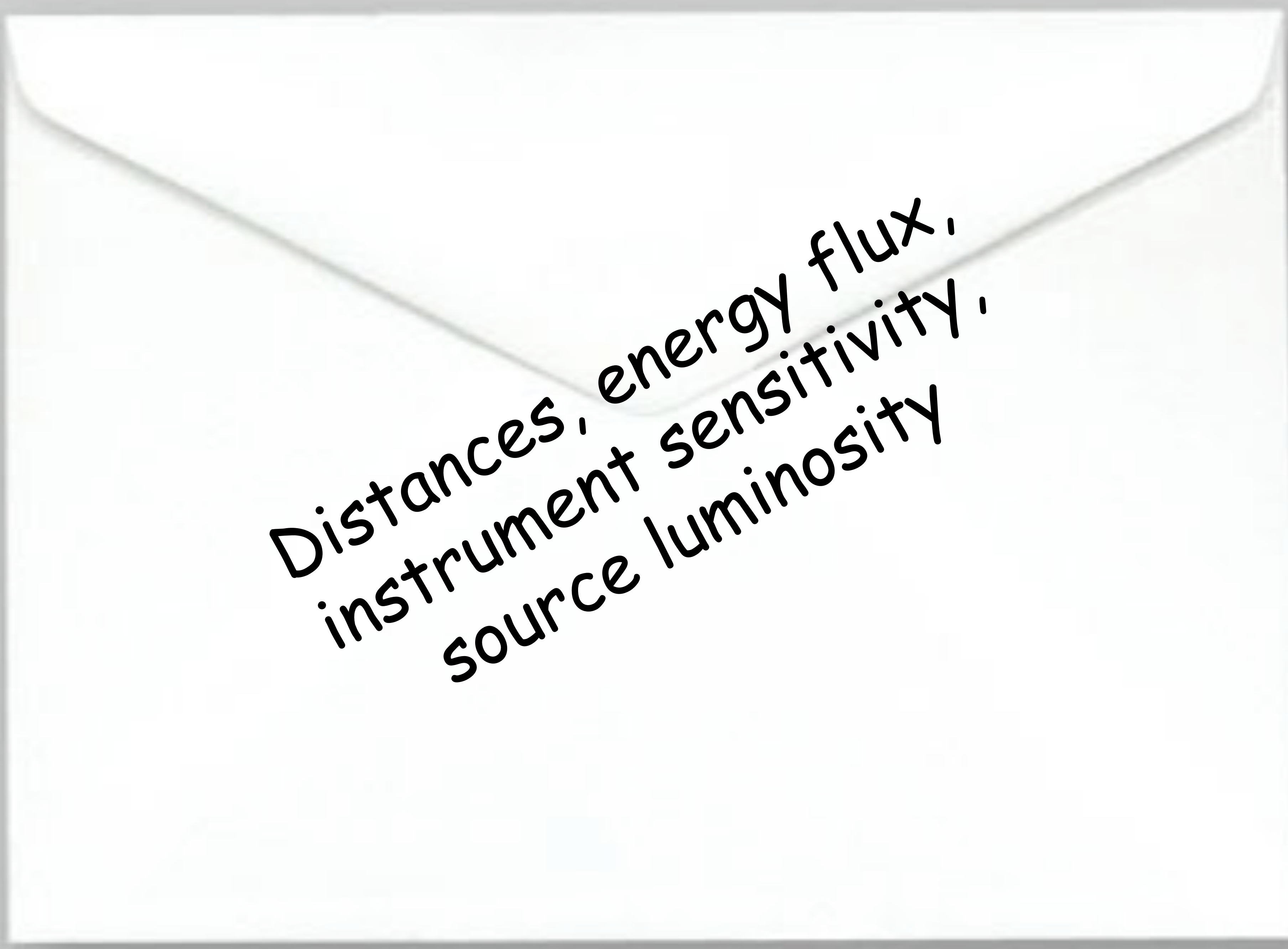
Should do all of this on the blackboard, but

(a) bit too time consuming

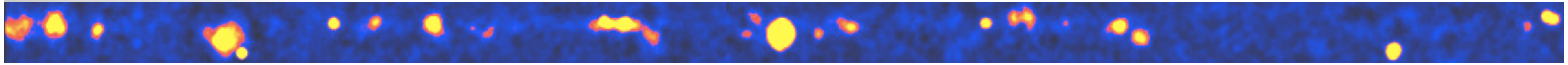
(b) transparencies may help for reference

Stop me if I’m going too fast or something is unclear

Preliminaries:
Units, coordinates
& other useful(?) stuff


Distances, energy flux,
instrument sensitivity,
source luminosity

Useful units, numbers, dimensions



Energy, distance

1 erg = 10^{-7} J; 1 TeV ≈ 1.6 erg;
Supernova $E_{kin} \approx 10^{51}$ erg

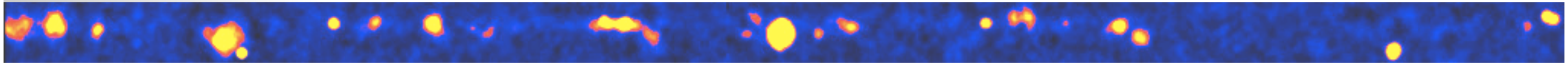
1 yr ≈ $\pi \, 10^{7}$ s

1 pc ≈ 3.26 LJ ≈ $3.1 \cdot 10^{18}$ cm ≈ 1000 km/s x 1000 yr
Distance to center of Galaxy ≈ 8.5 kpc
Surface of kpc sphere ≈ $1.2 \cdot 10^{44}$ cm^2
Distance to M31 (Andromeda) ≈ 800 kpc
Distance to Centaurus A ≈ 4 Mpc

Redshift z=0.1 ≈ 0.4 Gpc
Surface of Gpc sphere ≈ $1.2 \cdot 10^{56}$ cm^2

Gyroradius of (z=1) particles: $r_{pc} \approx E_{PeV}/B_{\mu G}$

Useful units, numbers, dimensions



Instrument sensitivity

assume

100 detected photons for image (reasonable)

background-free (somewhat optimistic)

optical telescope (few eV)

10 m aperture, 1 h, 100% eff

$3 \cdot 10^{-8}$ ph/cm^{2}s ~ 10^{-7} eV/cm^{2}s ~ $2 \cdot 10^{-19}$ erg/cm^{2}s

X-ray satellite (keV)

50 ks, eff. mirror aperture 500 cm^2 (Chandra)

$4 \cdot 10^{-6}$ ph/cm^{2}s ~ 10^{-14} erg/cm^{2}s

Fermi-LAT (few 100 MeV)

1 yr, 2 sr, eff. area 8000 cm^2

$2 \cdot 10^{-9}$ ph/cm^{2}s ~ 10^{-12} erg/cm^{2}s

Cherenkov telescope (few 100 GeV)

50 h, eff. area 50000 m^2

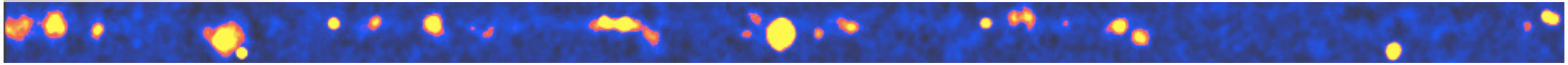
10^{-12} ph/cm^{2}s ~ $5 \cdot 10^{-13}$ erg/cm^{2}s

required source luminosity @ 1 kpc:
~10^{32} erg/s

Sun thermal lumi
~$4 \cdot 10^{33}$ erg/s

Crab pulsar spin-down
~$5 \cdot 10^{38}$ erg/s

Useful units, numbers, dimensions

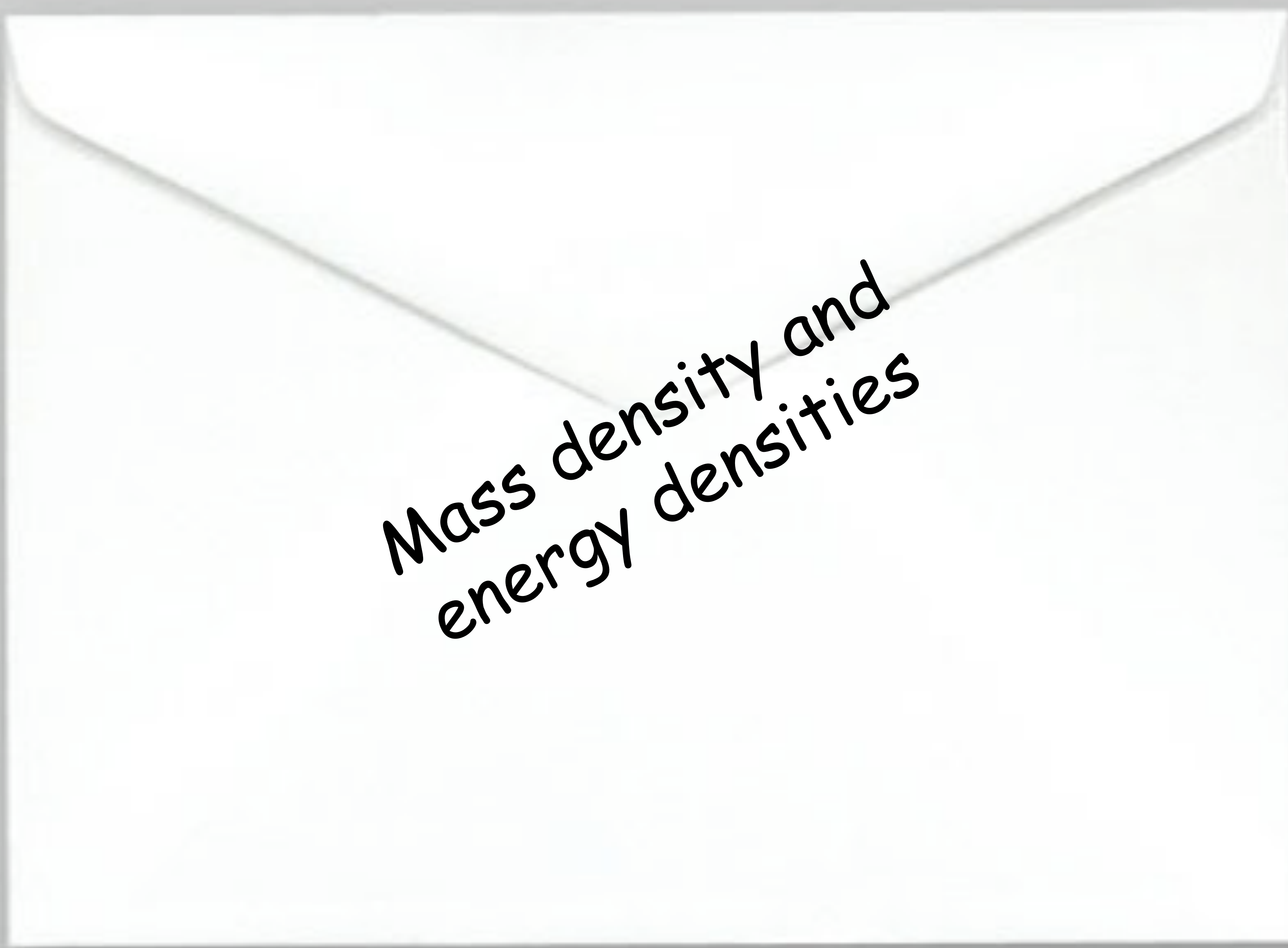


Crab-like pulsar, assume 1% of spin-down
(1% of $5\cdot 10^{38}$ ergs/s) into radiation
{note: actual Crab has 10^{-5} into VHE gamma rays)

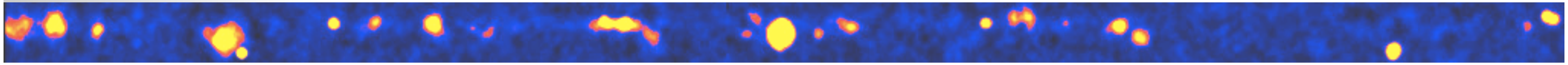
at 1 kpc	$4\cdot 10^{-8}$ ergs/cm^{2}s
at center of Galaxy	$5\cdot 10^{-10}$ ergs/cm^{2}s
at LMC (50 kpc)	$2\cdot 10^{-11}$ ergs/cm^{2}s
at Andromeda	$6\cdot 10^{-14}$ ergs/cm^{2}s

Dropping mass into BH, at 1% mc^2

1 solar mass / yr @ 1 Gpc	$5\cdot 10^{-12}$ ergs/cm^{2}s


Mass density and
energy densities

Useful units, numbers, dimensions



Mass, density

Solar mass ≈ $2 \cdot 10^{30}$ kg
Proton mass ≈ $1.7 \cdot 10^{-27}$ kg

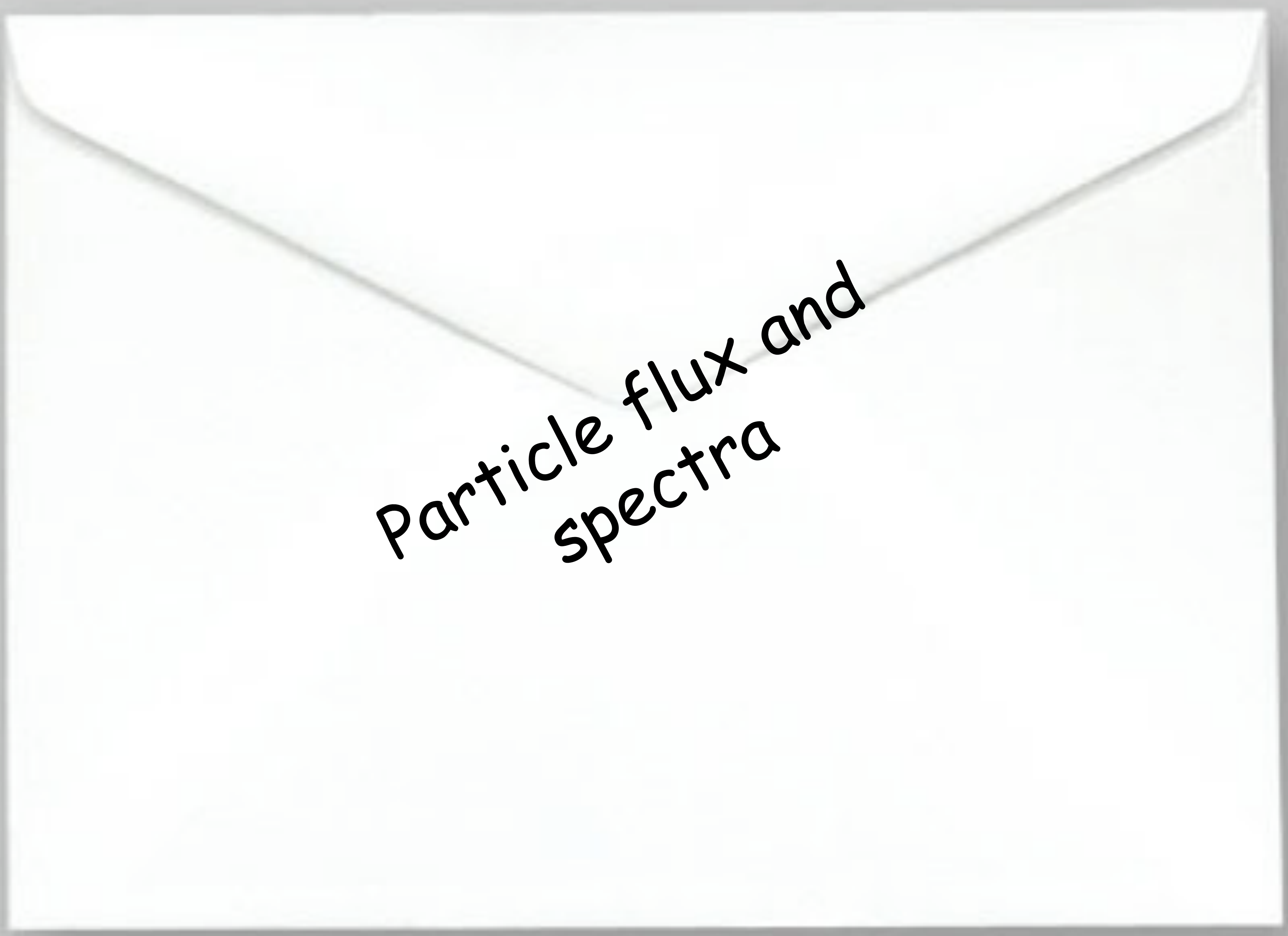
Typical interstellar density ≈ 1 H/cm^3
≈ $5 \cdot 10^{28}$ kg/pc^3
≈ 0.025 M_{sol}/pc^3
≈ 1M_{sol}/ sphere of 2 pc radius

Useful units, numbers, dimensions

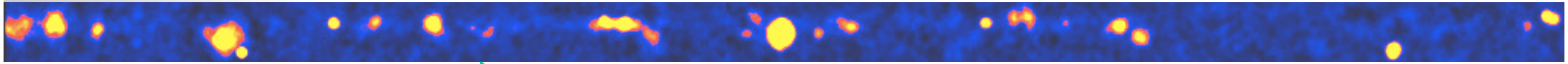
Energy density

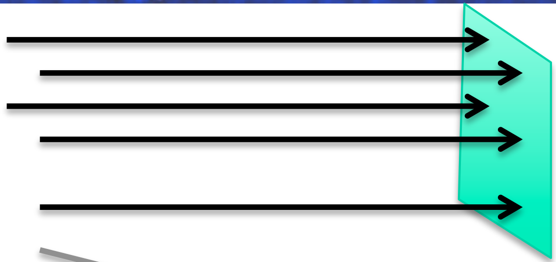
Typical interstellar magnetic field ≈ few μG ≈ few 10^{-10} T

Energy density in cosmic rays	≈ 1 eV / cm^3
Energy density in starlight	≈ 1 eV / cm^3
Energy density in CMB	≈ 0.25 eV / cm^3
Energy density in B-field	≈ 0.03 $B^2_{\mu G}$ eV / cm^3
1 eV / cm^3	≈ $5 \cdot 10^{43}$ erg/pc^3

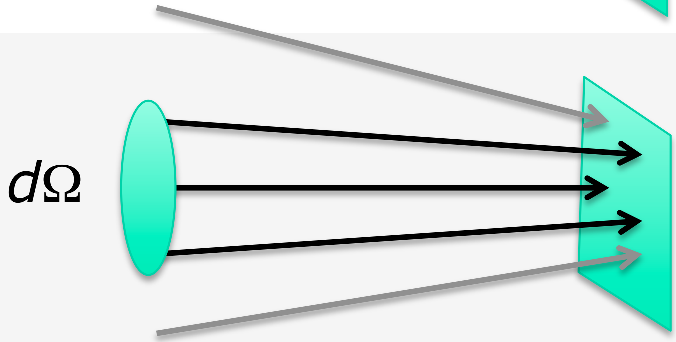

Particle flux and
spectra

Particle (or photon) density and flux



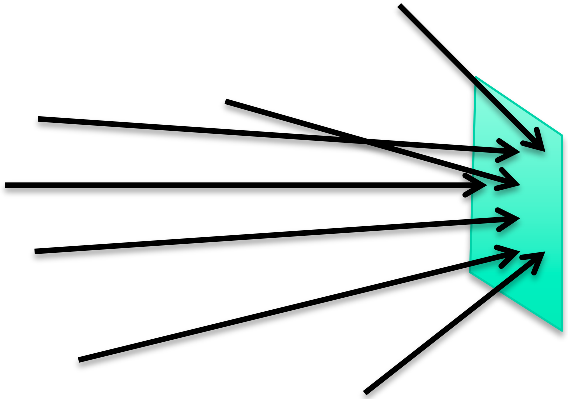


$$\Phi\left[1/cm^2 s\right] = \frac{d^2N}{dA_\perp dt} = \rho v$$



$$\Phi\left[1/cm^2 s\ sr\right] = \frac{d^3N}{dA_\perp dt d\Omega} = \frac{\rho v}{4\pi}$$

for isotropic flux

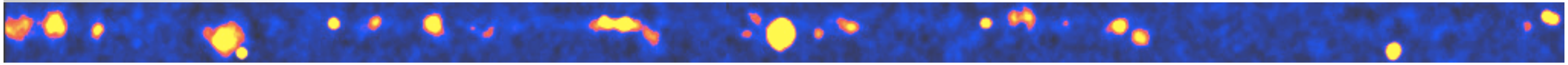


$$\Phi\left[1/cm^2 s\right] = \frac{d^2N}{dAdt}$$

$$= \int_0^1 \frac{d^3N}{dA_\perp dt\ d\cos\theta} \cos\theta\, d\cos\theta$$

$$= 2\pi\left(\frac{\rho v}{4\pi}\right)\int_0^1 \cos\theta\, d\cos\theta = \frac{\rho v}{4}$$

Spectral index



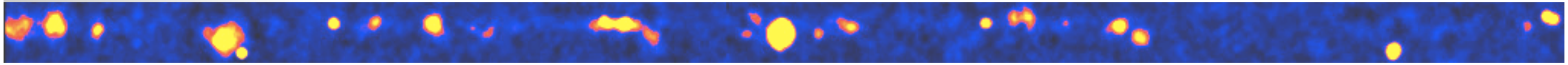
usually use photon index, defined as

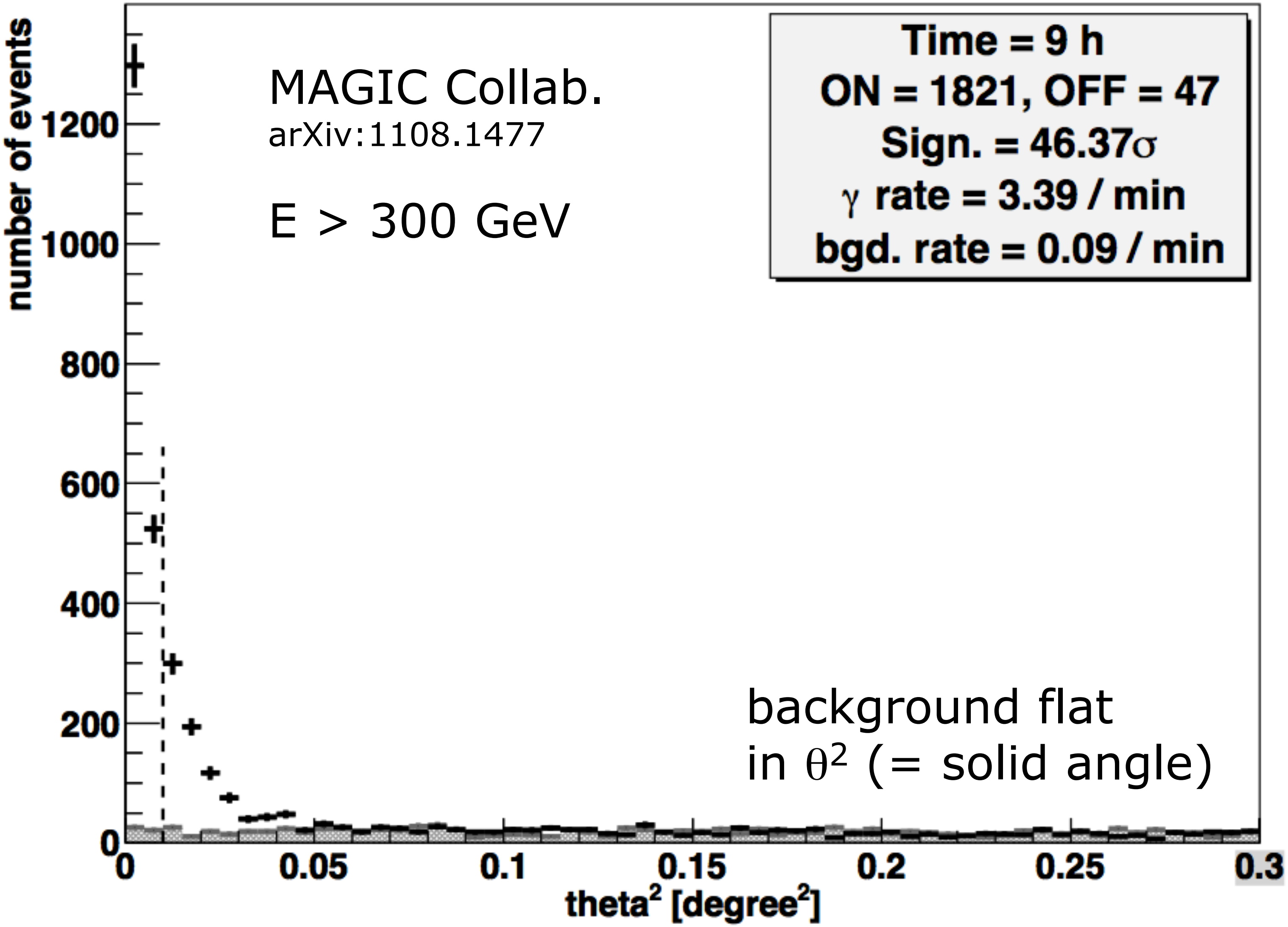
$$\Phi = \frac{d^3N}{dAdEdt} = CE^{-\Gamma} = C'(E/E_0)^{-\Gamma}$$

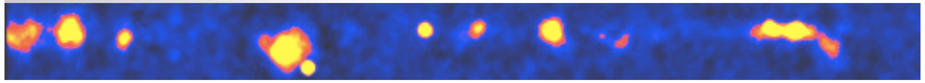
for E_o = 1 TeV

$C' \approx 3.5 \cdot 10^{-11}$ cm^{-2}s^{-1}TeV^{-1}	for Crab Nebula ($\Gamma \approx 2.5$)
$C' \approx 1 \cdot 10^{-5}$ cm^{-2}s^{-1}sr^{-1}TeV^{-1}	for cosmic ray protons ($\Gamma \approx 2.7$)
$C' \approx 1 \cdot 10^{-10}$ cm^{-2}s^{-1}TeV^{-1}	… within 0.1^{o} radius
$C' \approx 1.5 \cdot 10^{-8}$ cm^{-2}s^{-1}sr^{-1}TeV^{-1}	for cosmic ray electrons ($\Gamma \approx 3$)
$C' \approx 1.5 \cdot 10^{-13}$ cm^{-2}s^{-1}TeV^{-1}	… within 0.1^{o} radius

Crab Nebula with MAGIC CT







Spectral energy distribution (SED)

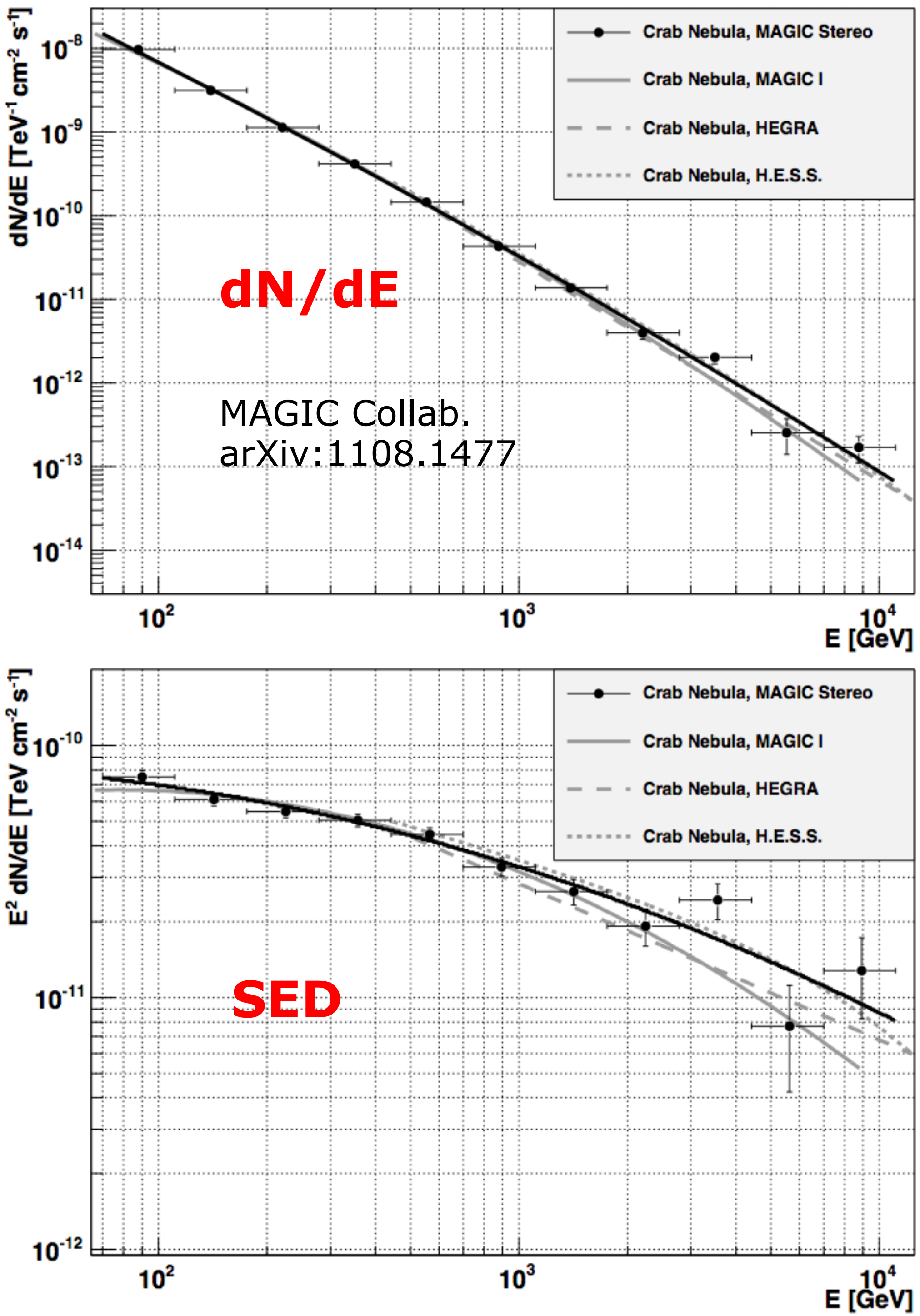
$$\text{SED:}\quad E^2 \frac{dN}{dE} = E \frac{dN}{d\log E}$$

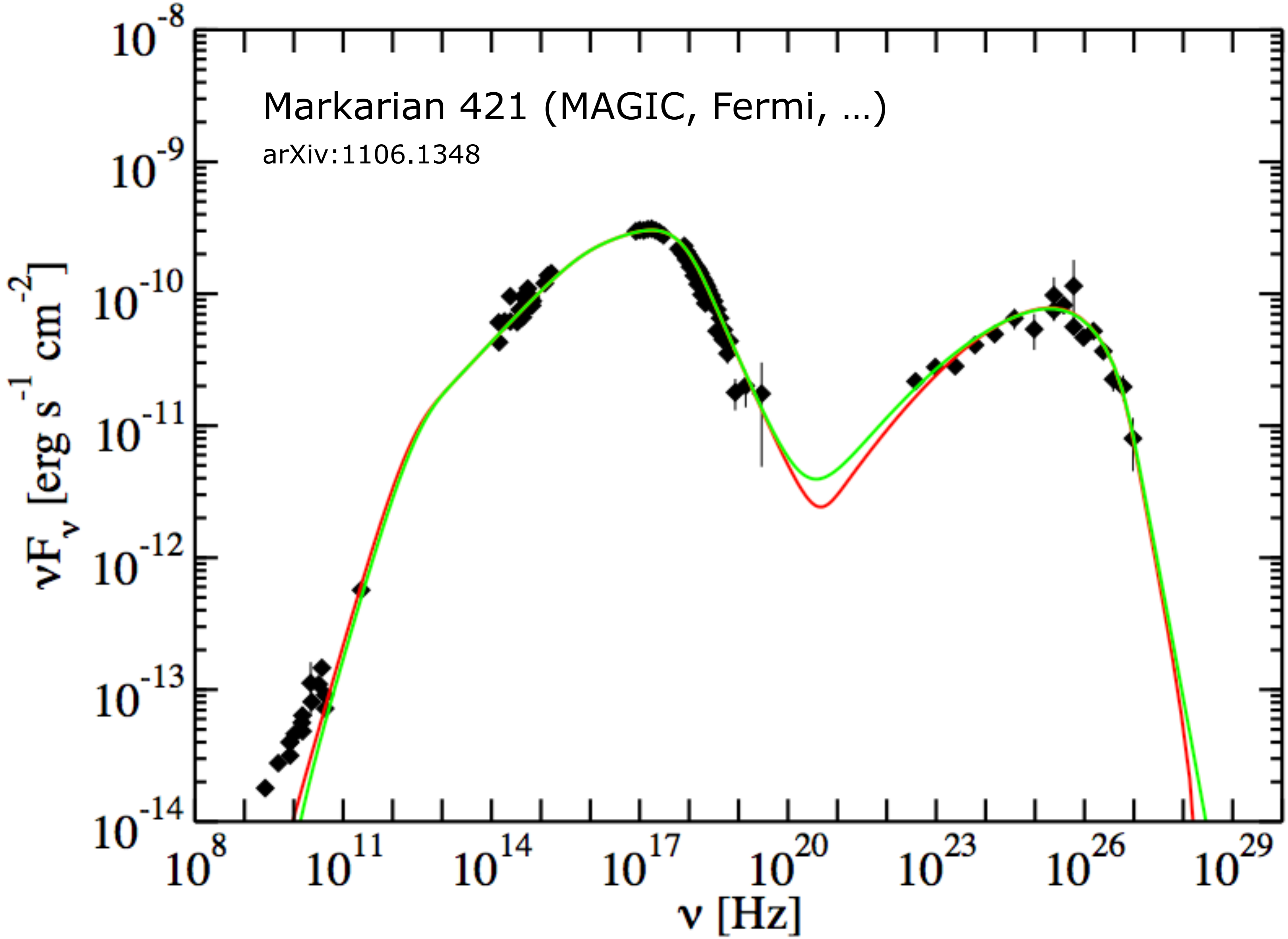
~Energy flux per decade of spectrum

Units: Energy/time*area

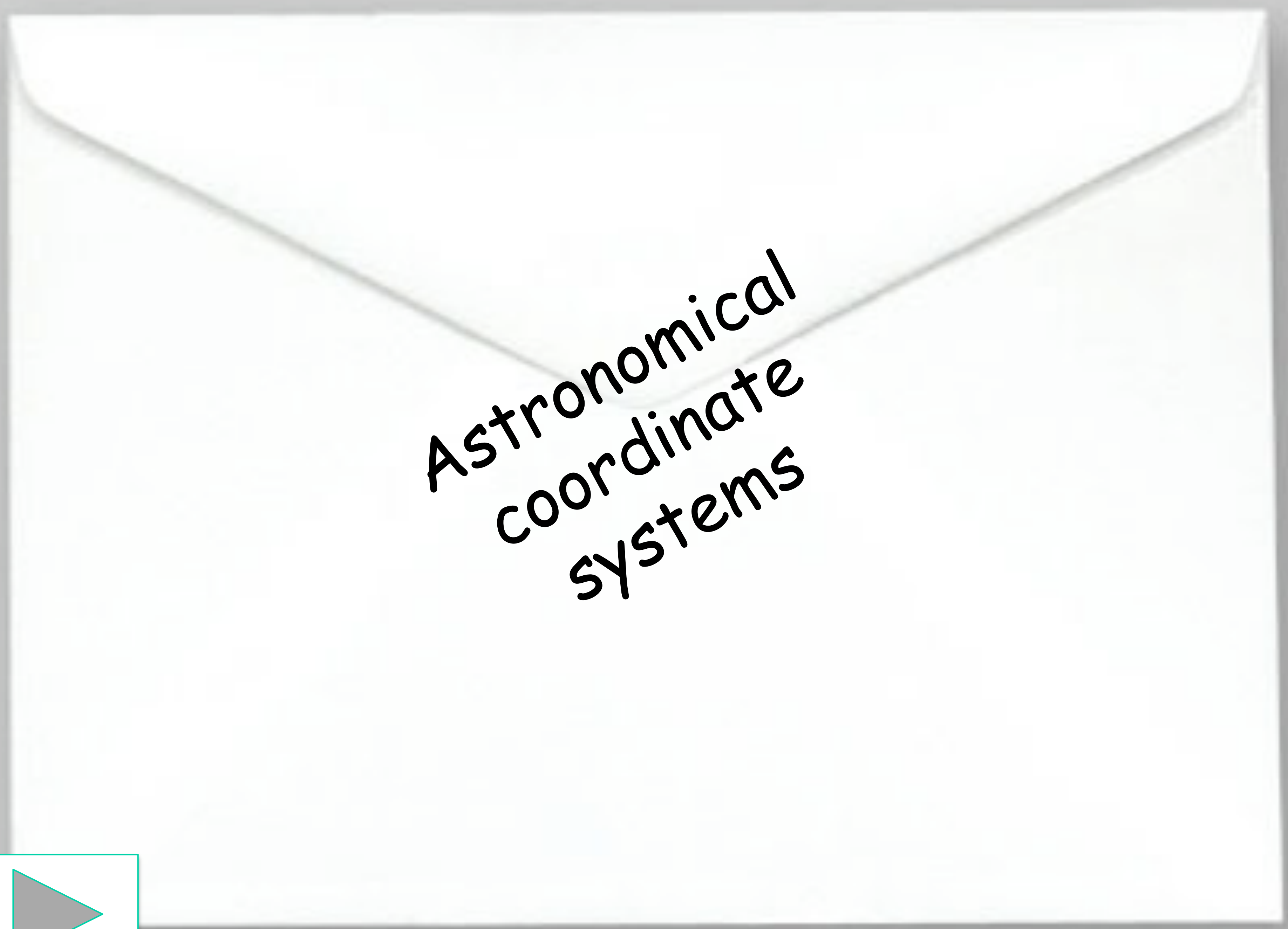
also often written as

$$\nu F_\nu(\nu) = \nu \frac{dE}{d\nu}$$

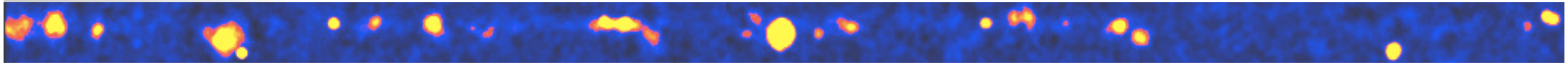




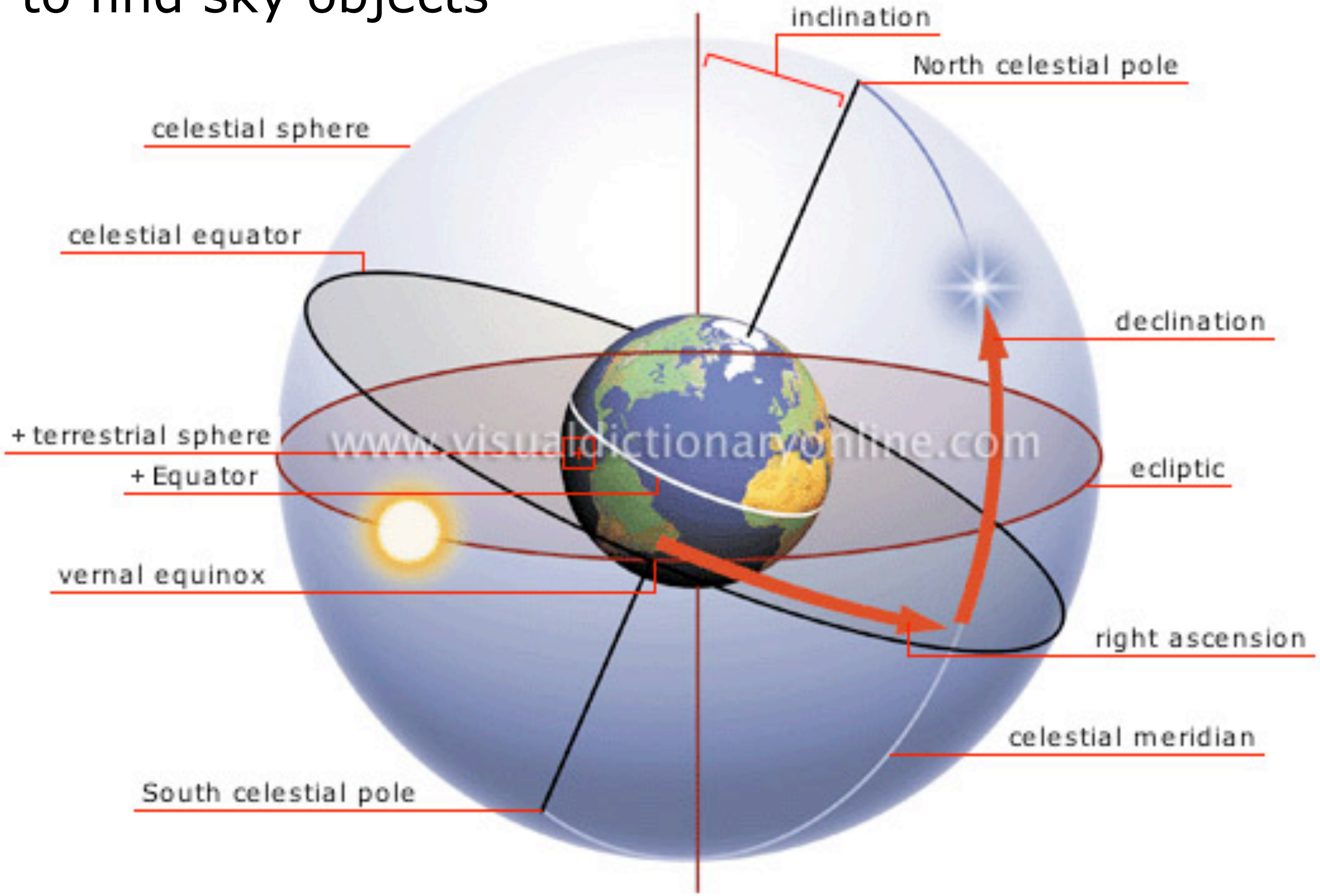
Markarian 421 (MAGIC, Fermi, ...)
arXiv:1106.1348
νF_ν [erg s^{-1} cm^{-2}]
ν [Hz]
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{8}
10^{11}
10^{14}
10^{17}
10^{20}
10^{23}
10^{26}
10^{29}


Astronomical
coordinate
systems

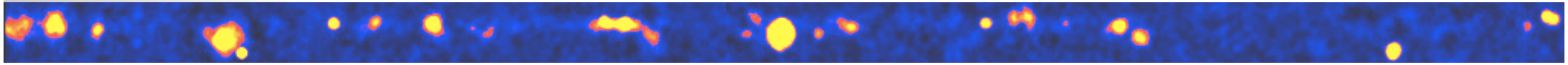
Local coordinate system: alt, az



Rotates with Earth
Not very helpful to find sky objects



Celestial coordinates: RA, Dec

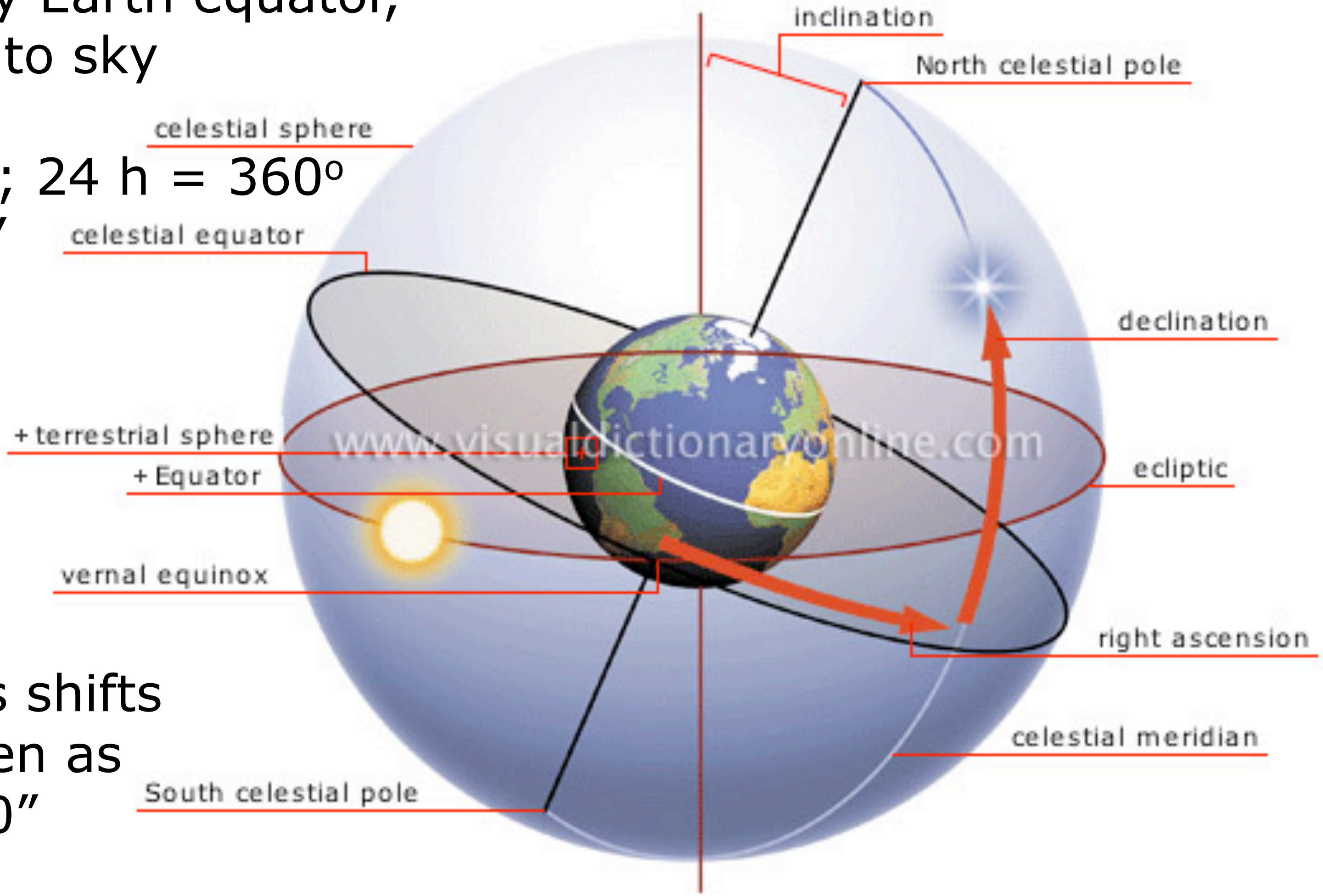


Equatorial system:
plane defined by Earth equator,
directions fixed to sky

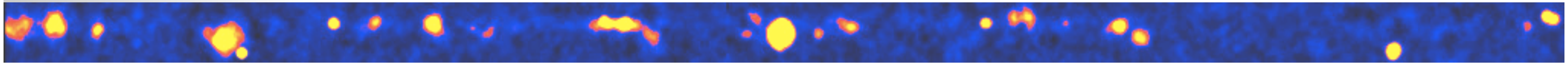
RA in $xx^h yy^m zz^s$; 24 h = 360^o
Dec in $xx^o yy' zz''$

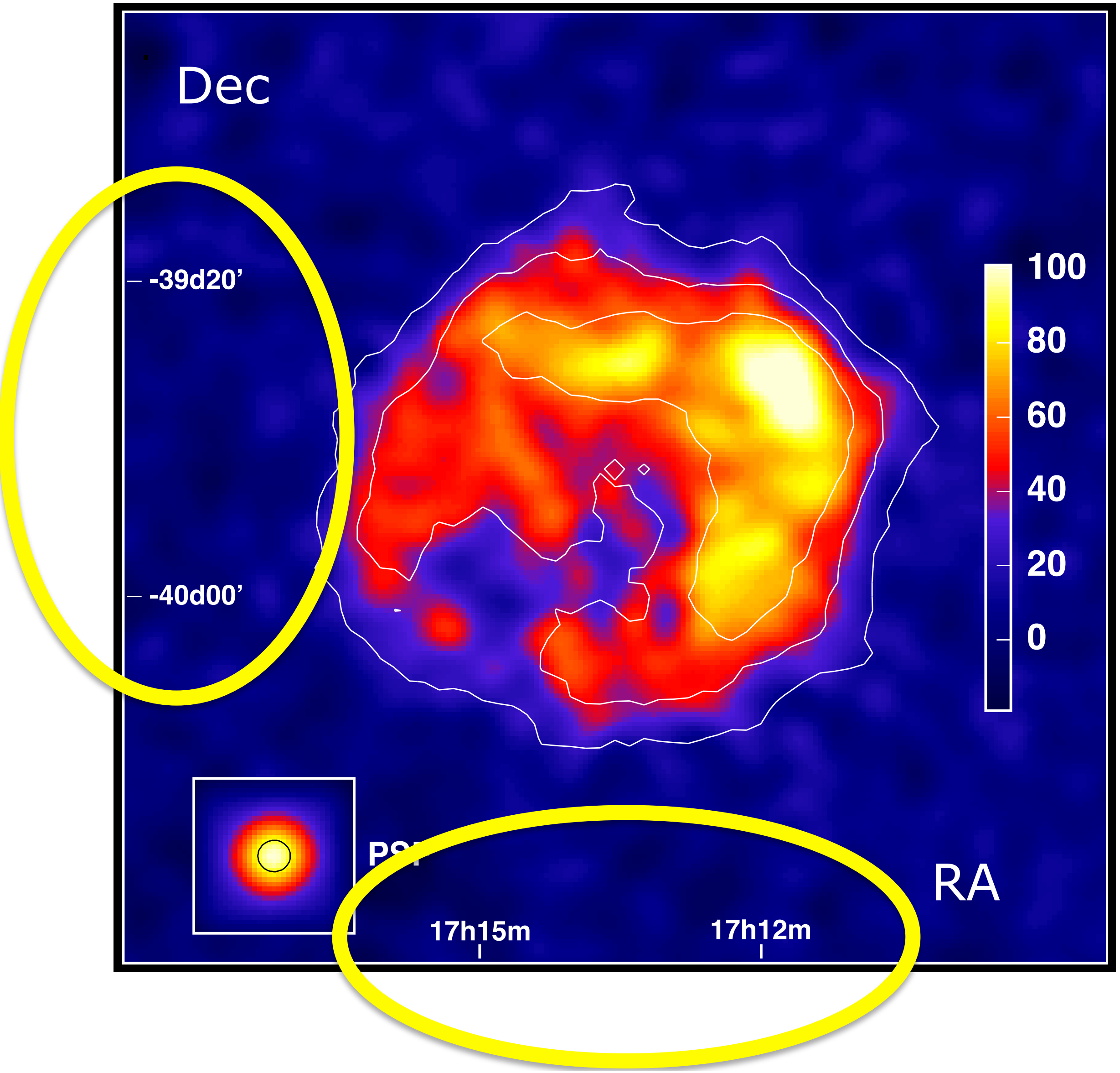
1 ′ = 0.017^o
1 ^{m} = 0…0.25^o

Since Earth axis shifts
coordinates given as
“B1950”, “J2000”

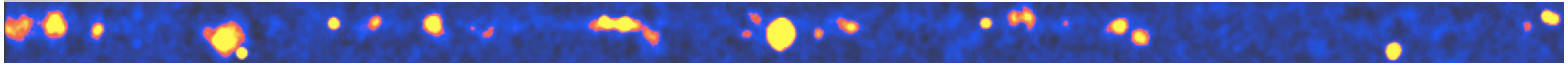


Celestial coordinates: RA, Dec

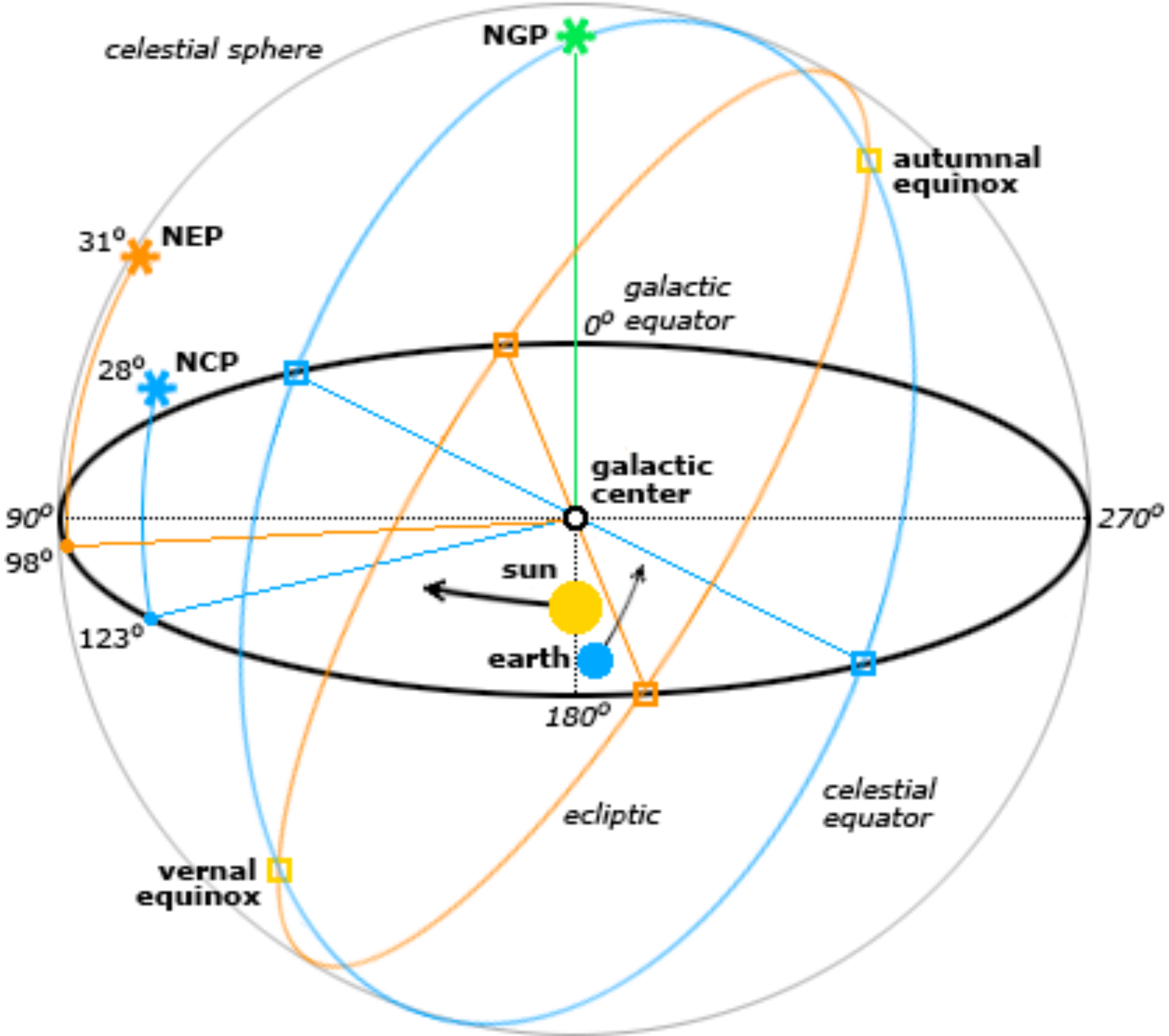




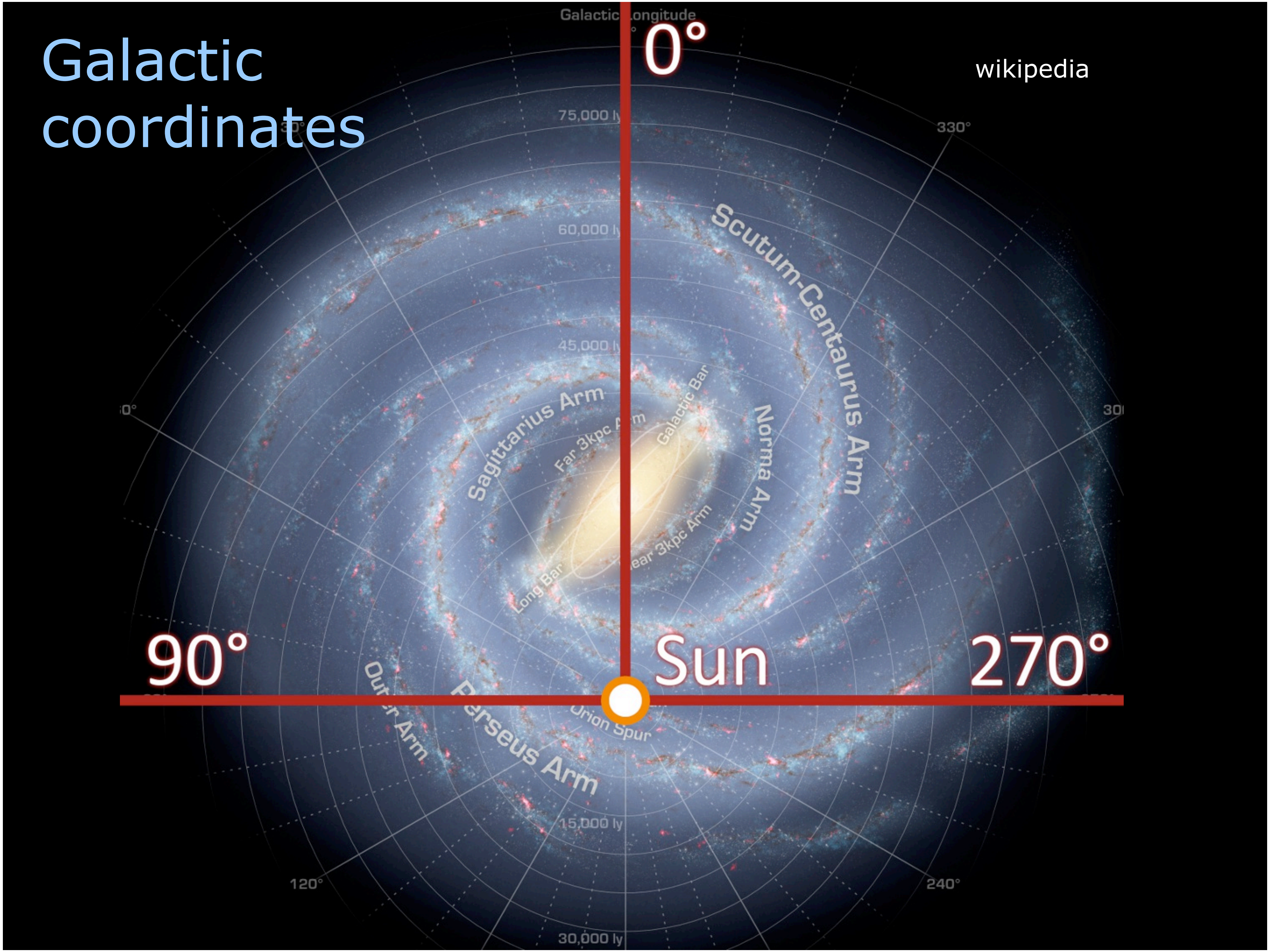
Galactic coordinates



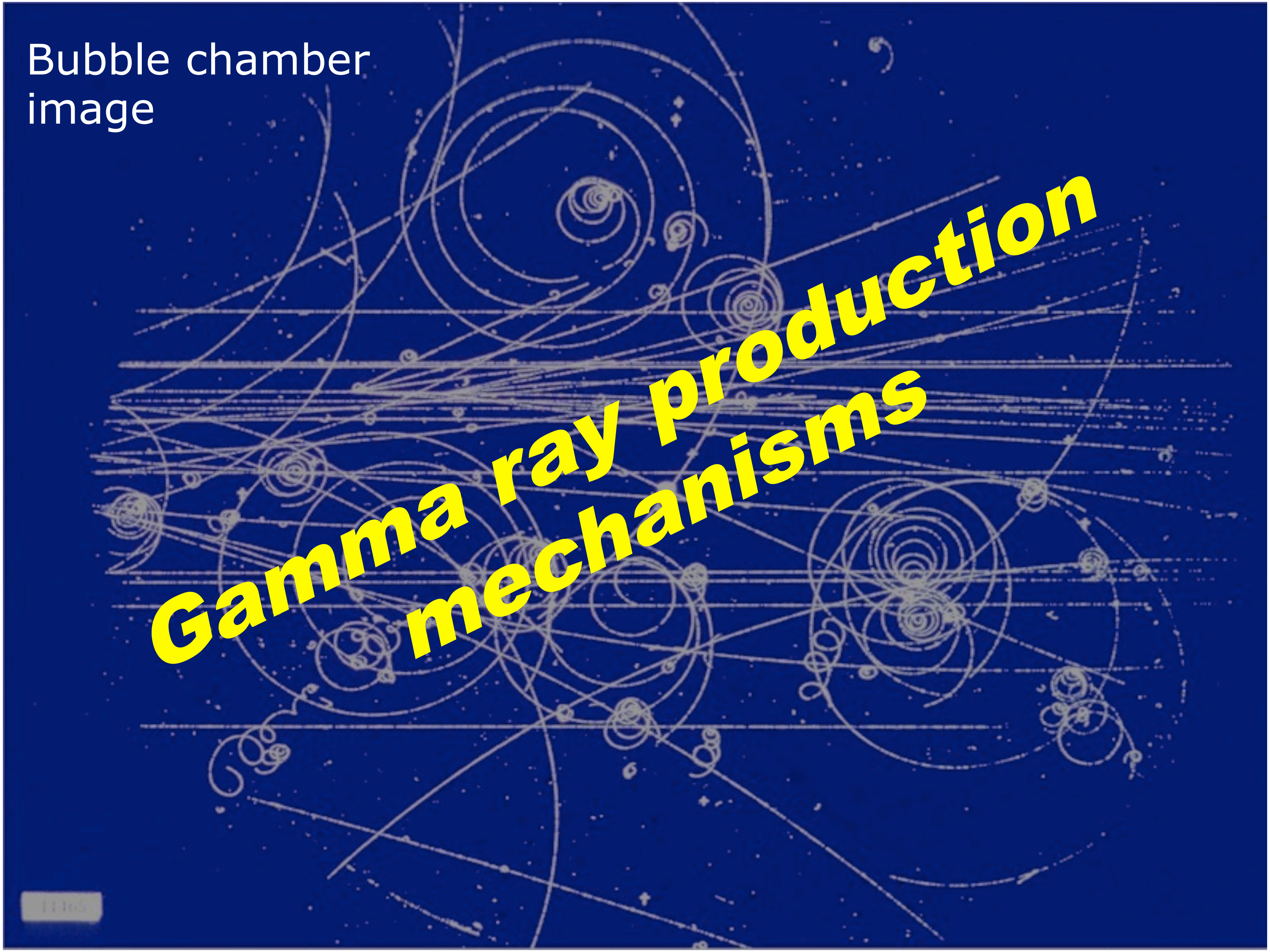
wikipedia

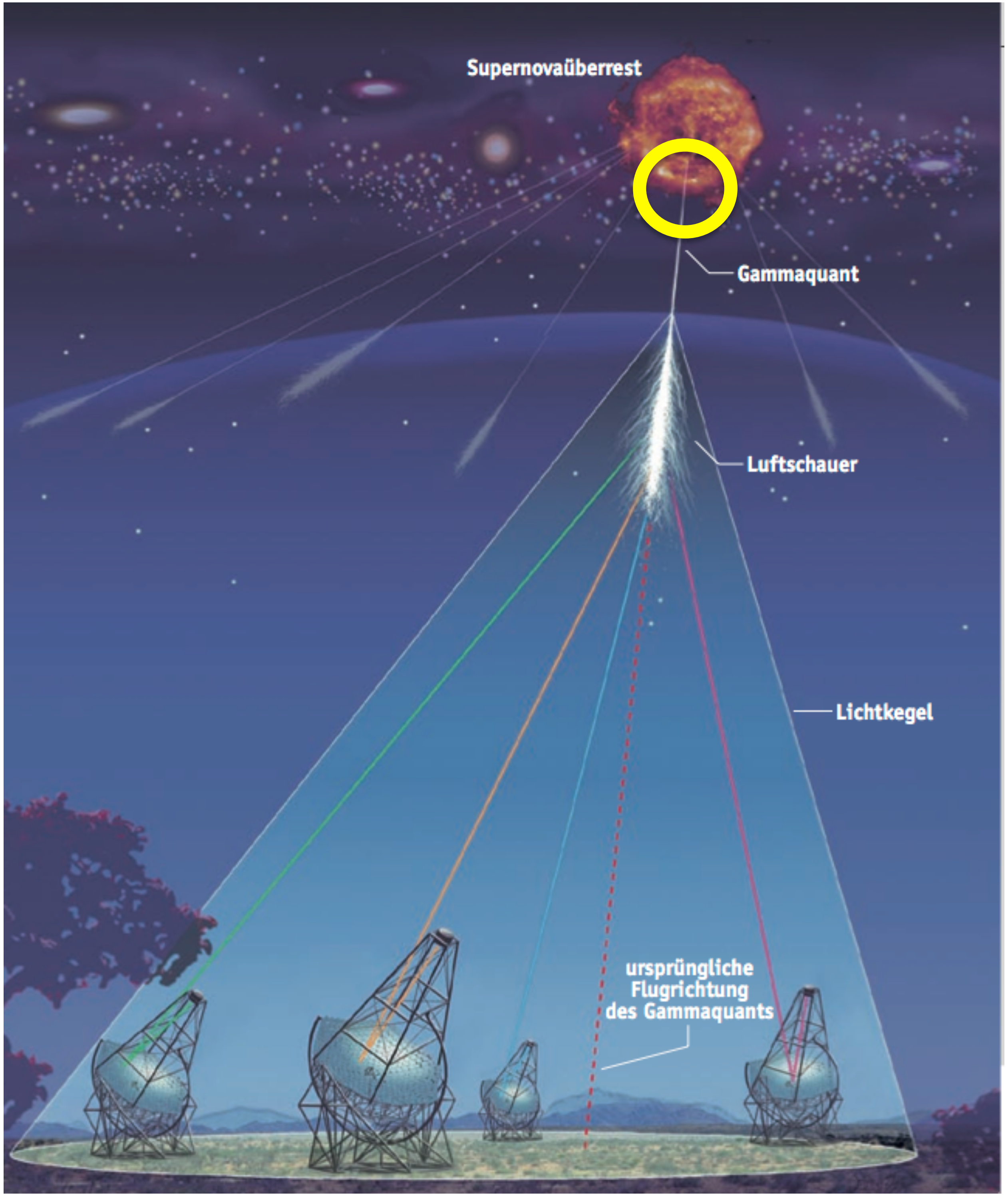


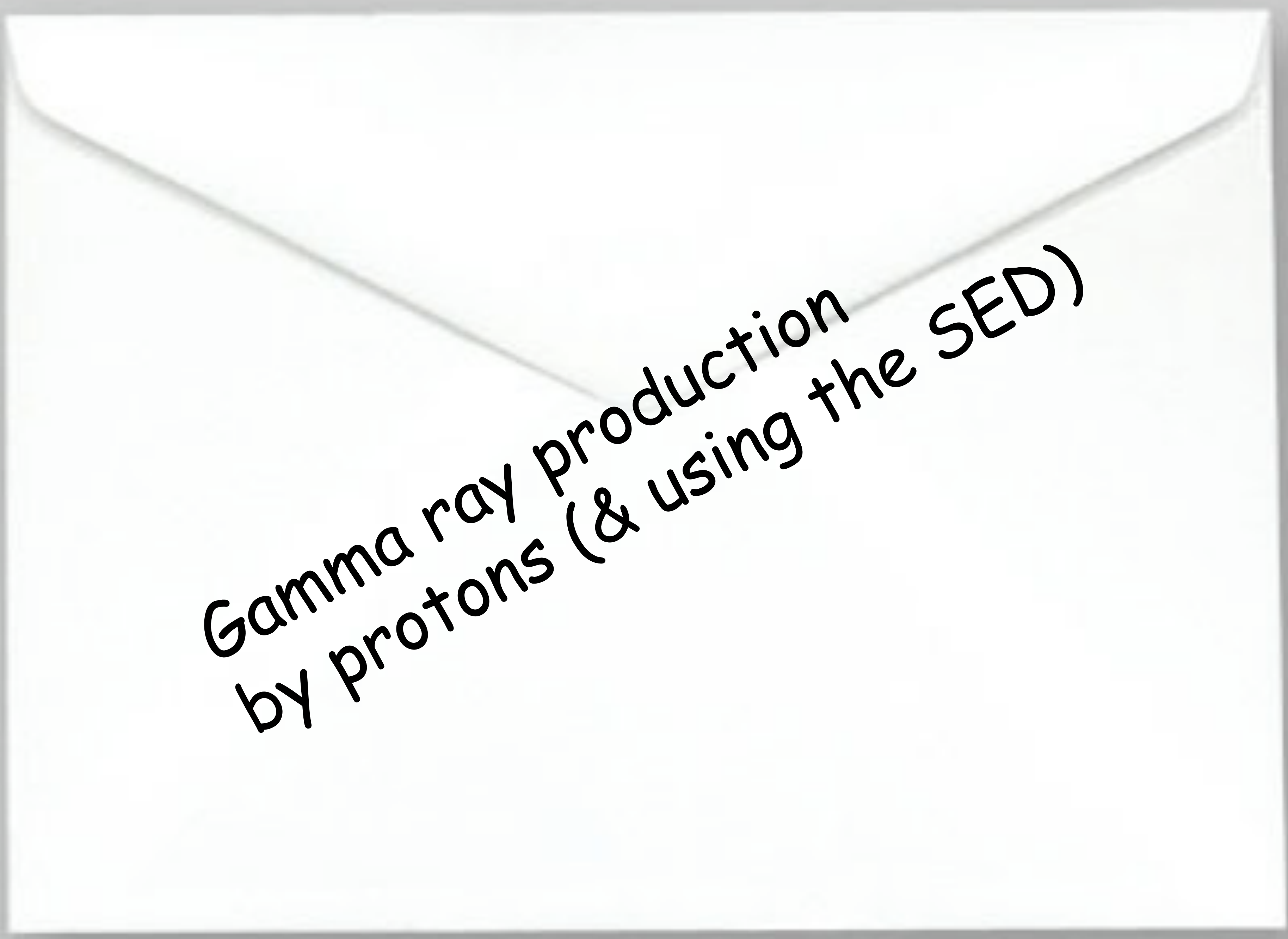
Galactic coordinates



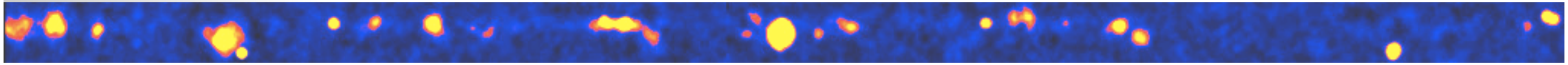
Gamma ray production mechanisms

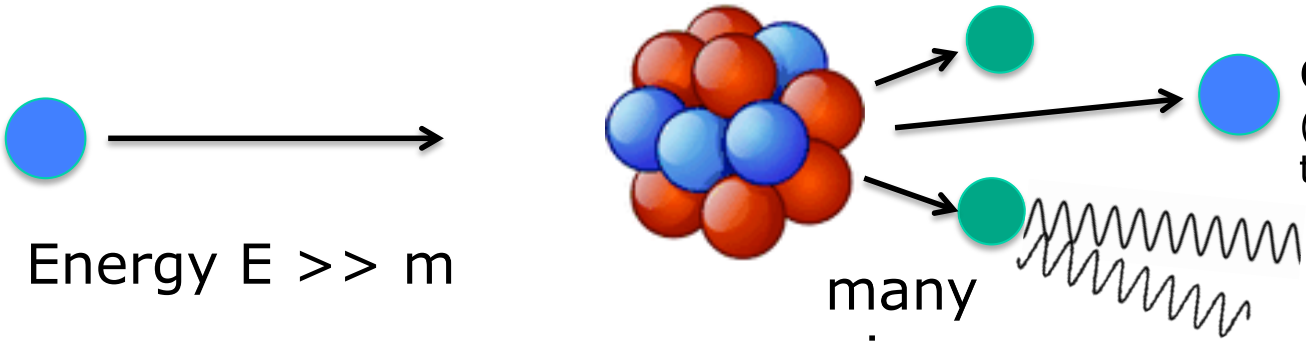

Bubble chamber image


Supernovaüberrest
Gammaquant
Luftschauer
Lichtkegel
ursprüngliche
Flugrichtung
des Gammaquants


Gamma ray production
by protons (& using the SED)

Gamma ray production by protons



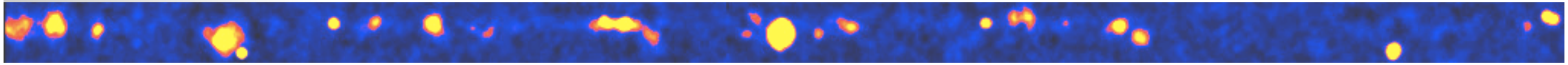


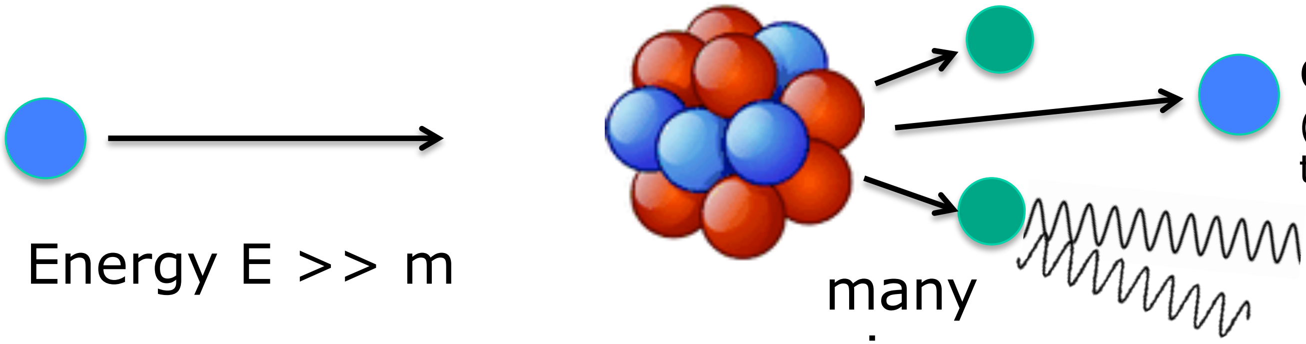
Cross section for p H (i.e. p p) collisions:

Proton size ~ 1 fm
Strong interactions have short range
➜ Cross section σ O(π 10^{-30} m^2) ≈30 mb (Reality ≈40 mb)

Interaction rate $r = \sigma\, c\, \rho \approx 4\cdot10^{-26}$ cm^2 $3\cdot10^{10}$ cm/s n/cm^3
$\approx 10^{-15}$ n/s $\approx 3\cdot10^{-8}$ n/yr
≈ energy-independent!

Gamma ray production by protons





Scaling variable $\quad x = E_\gamma / E_P \quad$ masses play no role since E >> m

Distribution in x: $$\frac{dN}{dx} \propto \frac{(1-x)^{4\ldots5}}{x}$$

Interaction dynamics / valence quark distributions

Longitudinal phase space

Normalisation: (per interaction)

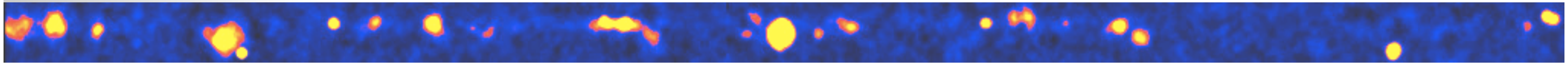
$$\int E_\gamma \frac{dN}{dE_\gamma} dE_\gamma = \eta E_P \approx \frac{1}{2}\frac{1}{3} E_P$$

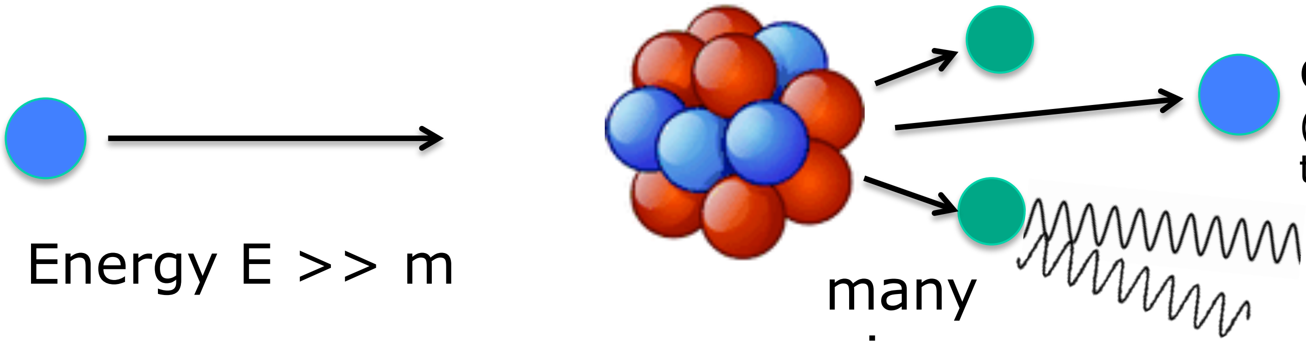
$$\int x \frac{dN}{dx} dx = \eta \approx \frac{1}{6}$$

Equal numbers of π^+, π^-, π^0

Leading particle keeps 50% energy

Gamma ray production by protons

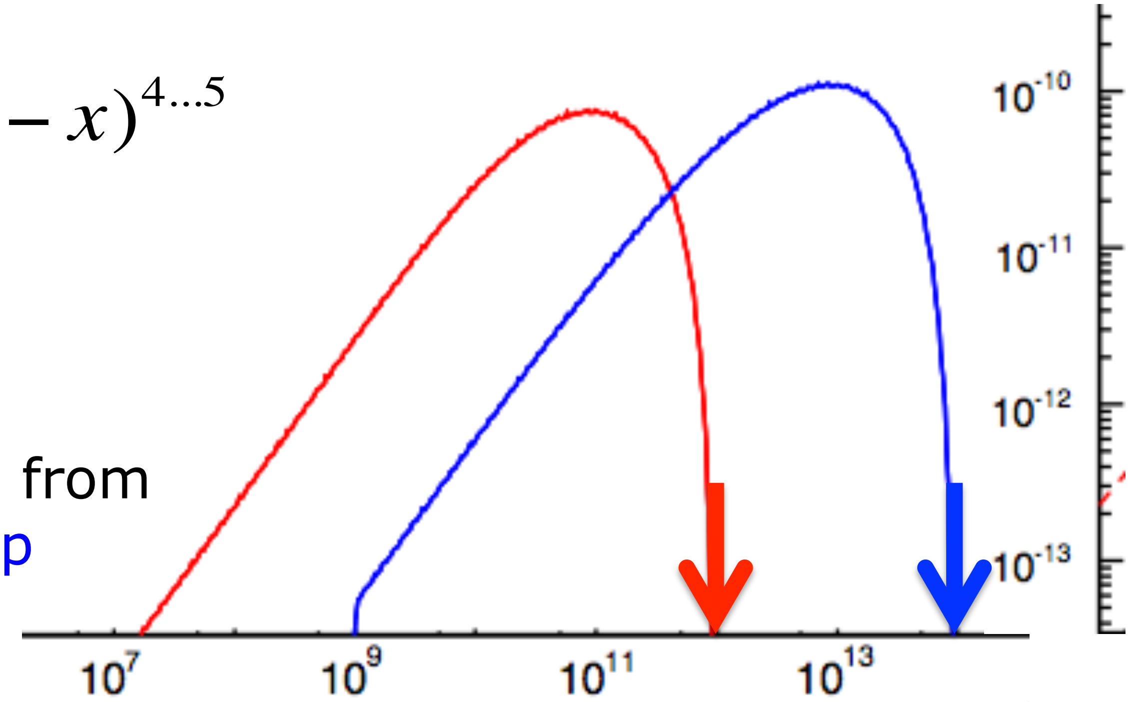




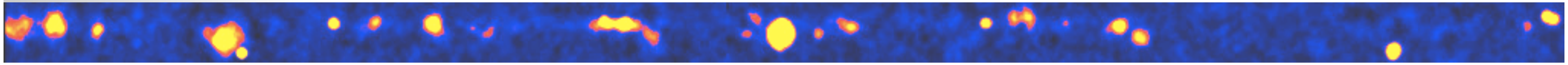
Gamma ray SED

$$E_\gamma^2 \frac{dN}{dE_\gamma} \propto x^2 \frac{dN}{dx} \propto x(1-x)^{4\ldots5}$$

peaks at x ≈ 0.2



Gamma ray production by protons

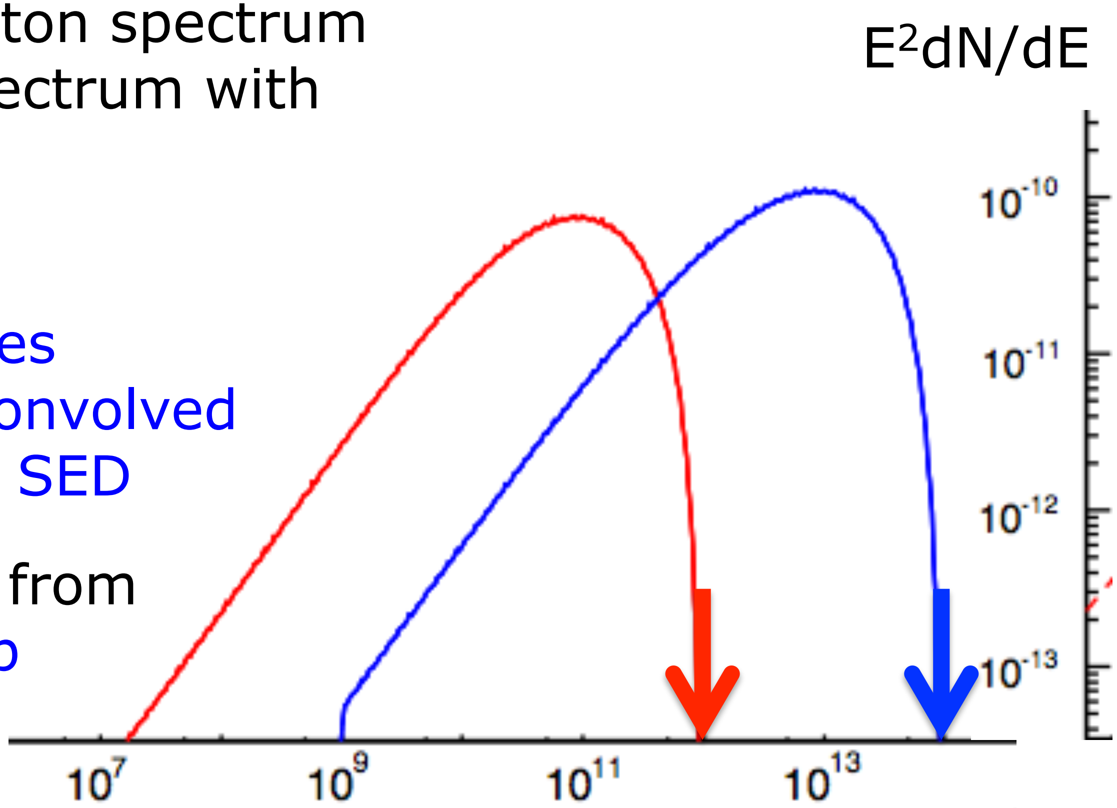


Gamma ray spectrum follows proton spectrum, roughly $\Phi_\gamma(E) \sim \Phi_p(10E)$, with features smeared over about one decade in energy, and appearing about a decade lower in energy

In particular, a power law proton spectrum gives a power law gamma spectrum with same index (±0.2)

Gamma ray SED
= Proton SED times
cross section, convolved
with p→gamma SED

Gammas from
100 TeV p
1 TeV p



Gamma ray production by protons

Valuable reference and parametrizations:

Energy spectra of gamma-rays, electrons and neutrinos produced at interactions of relativistic protons with low energy radiation

S.R. Kelner* and F.A. Aharonian†

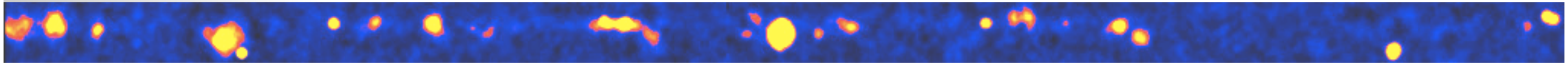
We derived simple analytical parametrizations for energy distributions of photons, electrons, and neutrinos produced in interactions of relativistic protons with an isotropic monochromatic radiation field. The results on photomeson processes are obtained using numerical simulations of proton-photon interactions based on the public available Monte-Carlo code SOPHIA. For calculations of energy spectra of electrons and positrons from the pair production (Bethe-Heitler) process we suggest a simple formalism based on the well-known differential cross-section of the process in the rest frame of the proton. The analytical presentations of energy distributions of photons and leptons provide a simple but accurate approach for calculations of broad-band energy spectra of gamma-rays and neutrinos in cosmic proton accelerators located in radiation dominated environments.

PACS numbers: 12.20.Ds, 13.20.Cz, 13.60.-r, 13.85.Qk

arXiv:0803.0688


Application:
Gamma-ray visibility
of supernova remnants

Gamma ray visibility of SNR



Typical energy: 10^{51} erg; typical density $n=1/cm^3$

Shared between pdV work, heat, magnetic field, particles …
all are somehow related … assume roughly equal shares …

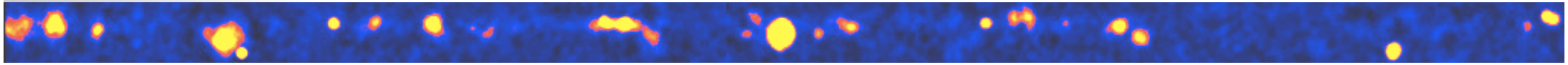
➜ O(10%) ≈ 10^{50} erg in protons

Interaction rate O(10^{-15}/s); 1/6 of energy into gammas
➜ gamma ray luminosity ≈ $2 \cdot 10^{34}$ erg/s

Spread (~uniformly) over 7 decades of SED
(~100 MeV (pion mass) to ~PeV)
➜ TeV gamma ray luminosity ≈ $2 \cdot 10^{33}$ erg/s

Gamma ray energy flux
➜ $\phi \approx 2 \cdot 10^{33}$ (erg/s) $E_{51} n/(4\pi d^2) \approx 2 \cdot 10^{-11}\, E_{51} n/d^2_{kpc}$ erg/(s cm^2)

The “official” answer



Supernova remnant visibility in gamma rays
Drury, Aharonian, Völk A&A 287 (1994) 959

F(>1TeV) $\approx 9{\cdot}10^{-11}\ \theta\ E_{51}\ n/d^2_{kpc}$ ph/cm²s

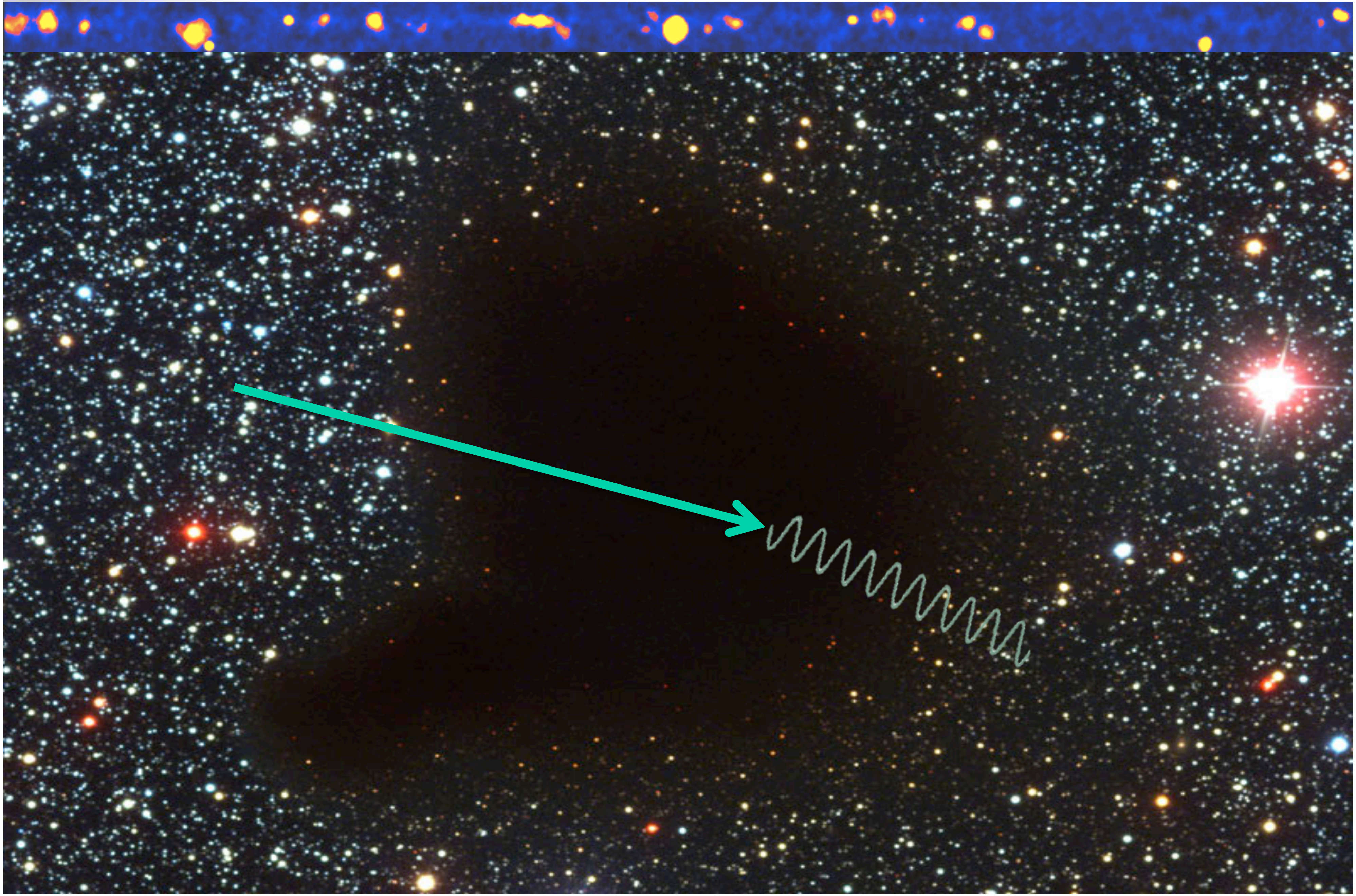
Efficiency $\theta \approx 0.1$

$\approx 3.5{\cdot}10^{-11}\ E_{51}\ n/d^2_{kpc}$ erg/cm²s, 1…10 TeV

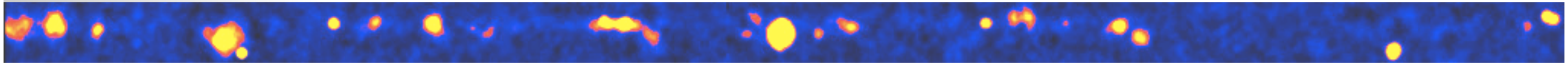
Sensitivity limit: $\approx 10^{-12}$ erg/cm²s

Application:
Seeing molecular clouds
in gamma rays

Seeing molecular clouds in gamma rays



Seeing molecular clouds in gamma rays



Cosmic ray flux (p)	$\phi \approx 10^{-1}\ E^{-2.7}_{TeV}$ /TeV m^2 s sr
Other nuclei:	x1.6
Cosmic ray density	$\rho_{CR} = 4\pi\ \phi/c$
Energy density	0.0015 eV/cm^3 10-100 TeV

Gamma ray luminosity 1-10 TeV

$$L \approx f_\gamma\, \rho_{E,CR} V_{Cloud}/\tau \approx (1/6)\ \rho_{E,CR}(M_{Cloud}/M_H n)/(10^{15}\ s/n)$$

$$\approx 5{\cdot}10^{26}\ M_{cloud,sol}\ \mathrm{erg/s}$$

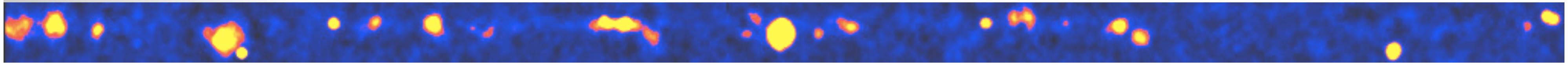
$$\phi \qquad \approx 4{\cdot}10^{-12}\ M_6/d^2_{kpc}\ \mathrm{erg/cm^2 s}$$

$$\approx 0.1\ M_6/d^2_{kpc}\ \text{Crab units}$$

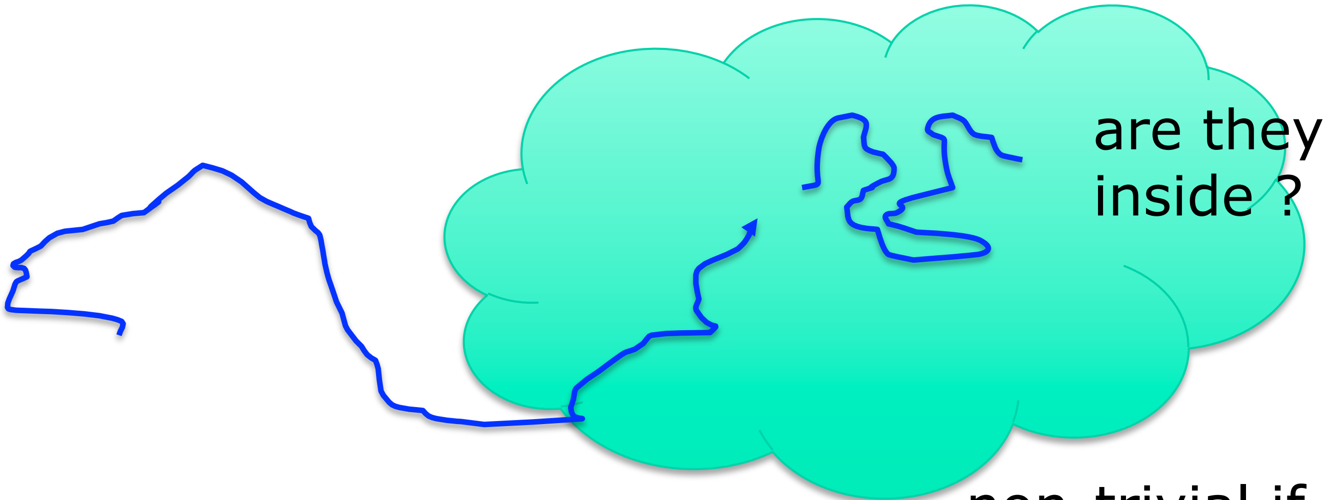
cloud mass in
10^6 solar masses

Correct answer:

Cosmic ray penetration in clouds



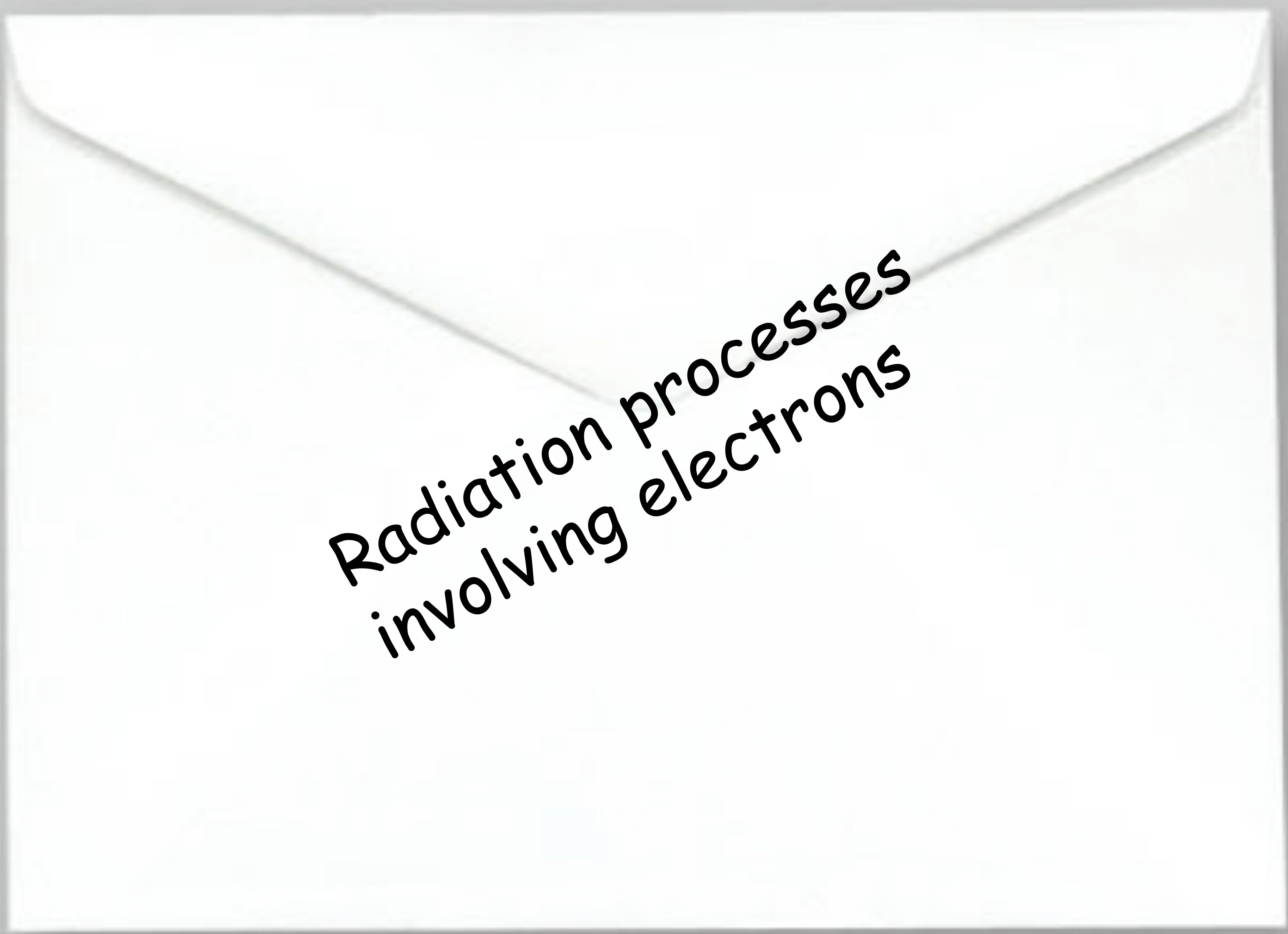
Cesarsky & Völk, A&A 70 (1978) 367
Everett & Zweibel, arXiv:1107.1243
Fatuzzo et al., arXiv:1010.0059



do they get in?

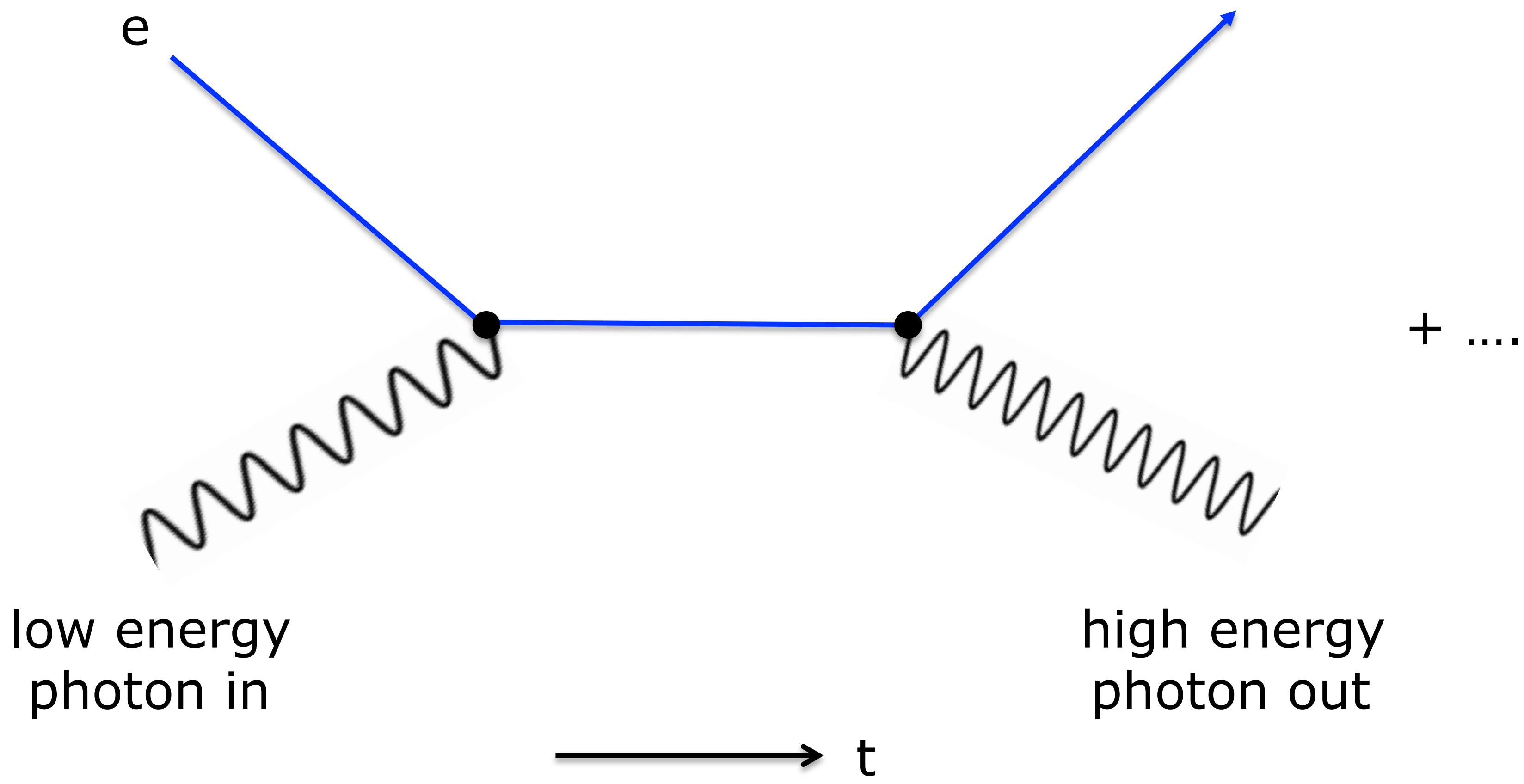
non-trivial if
curvature radius in B fields
small compared to cloud size

➜ discussion of CR propagation


Radiation processes
involving electrons

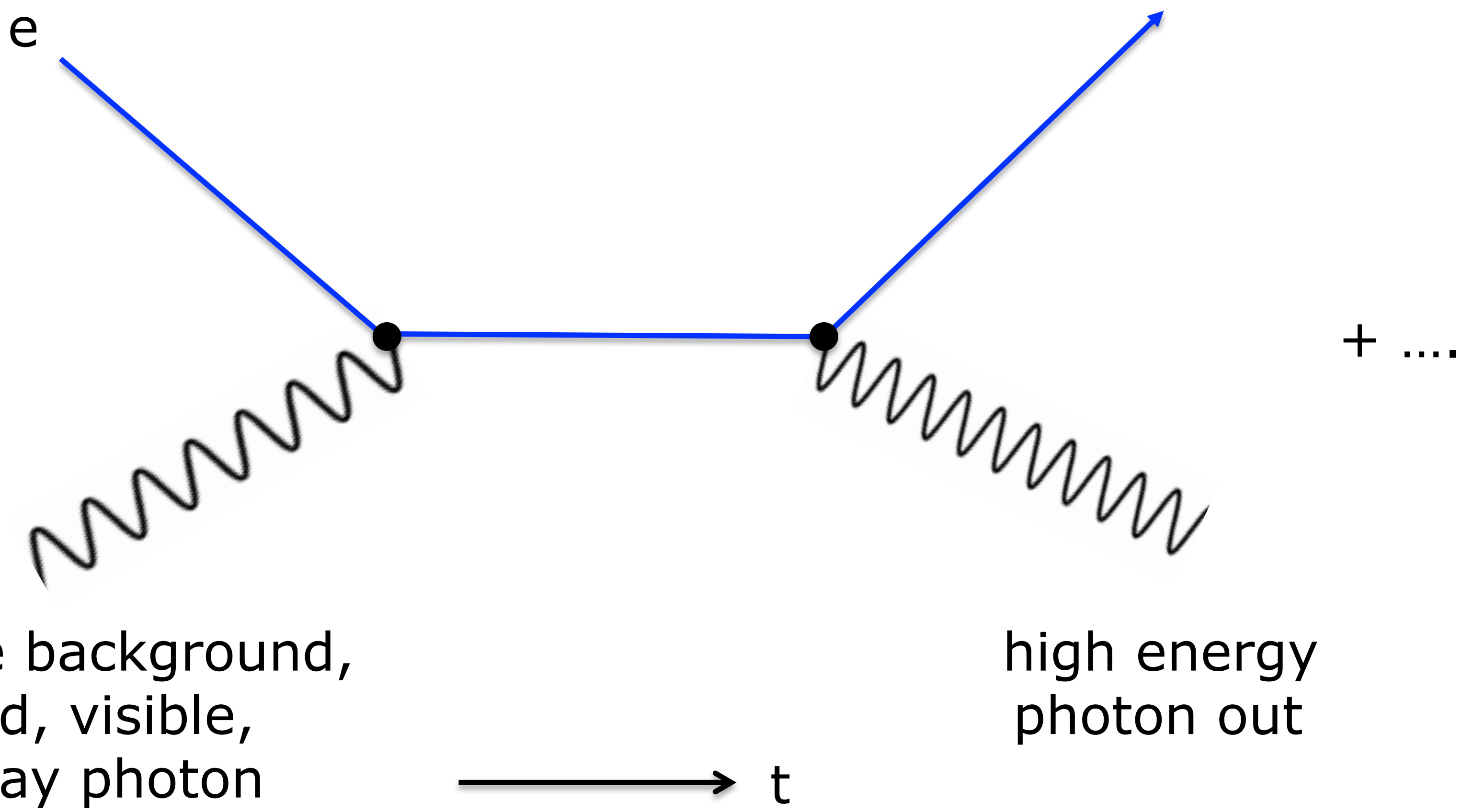
The God Diagram

… describes everything!



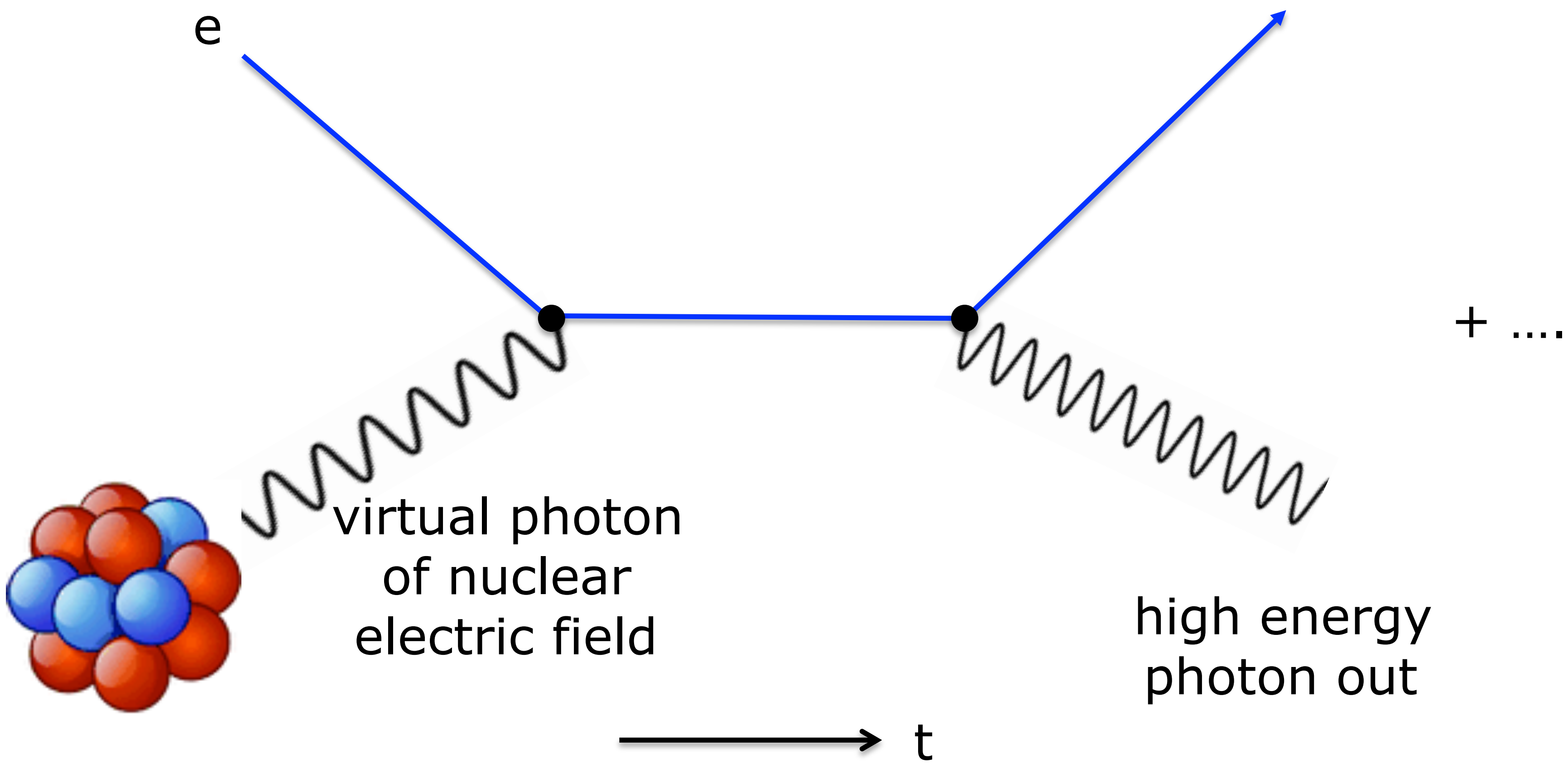
The God Diagram

Inverse Compton Scattering



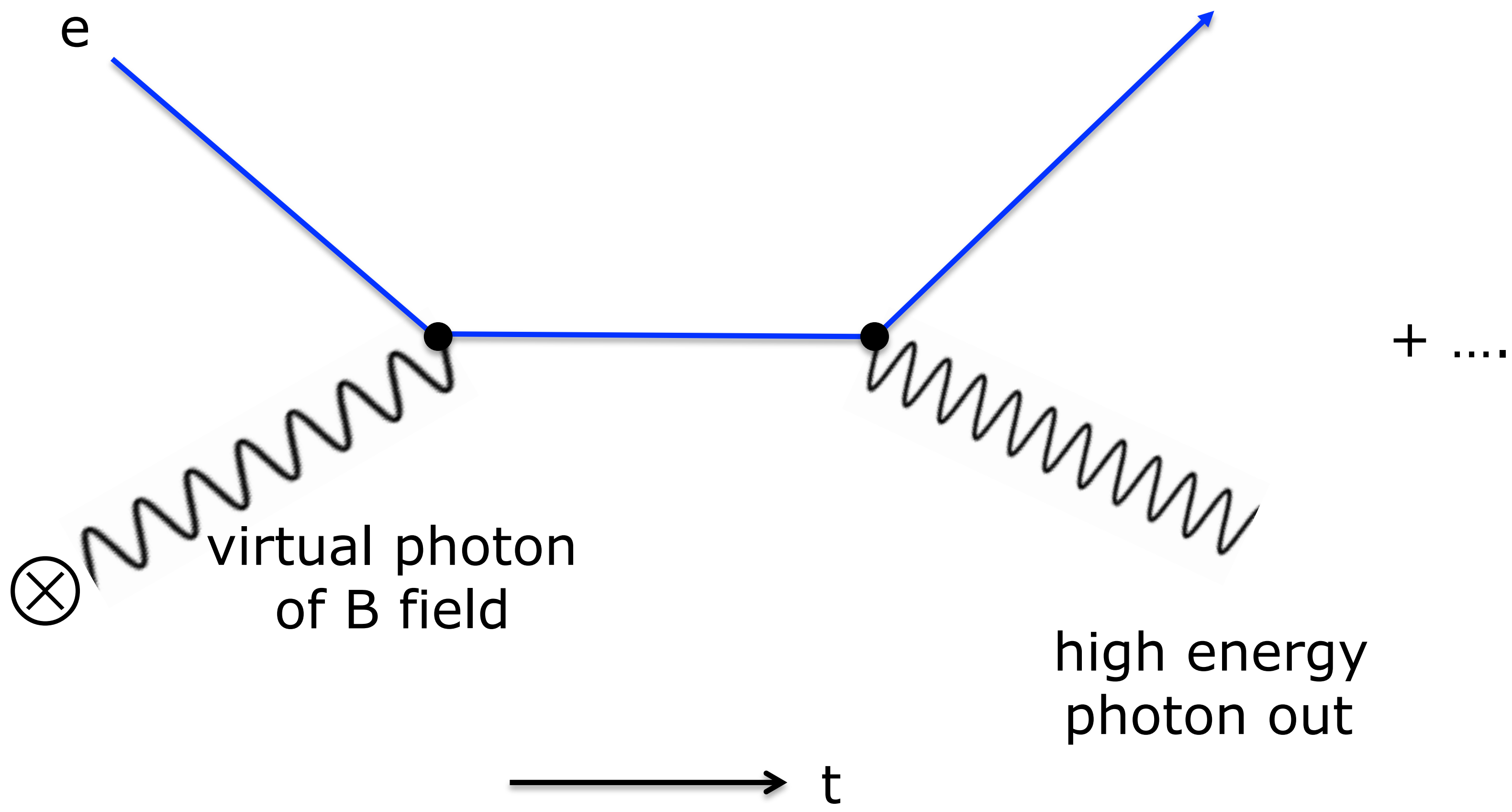
The God Diagram

Bremsstrahlung



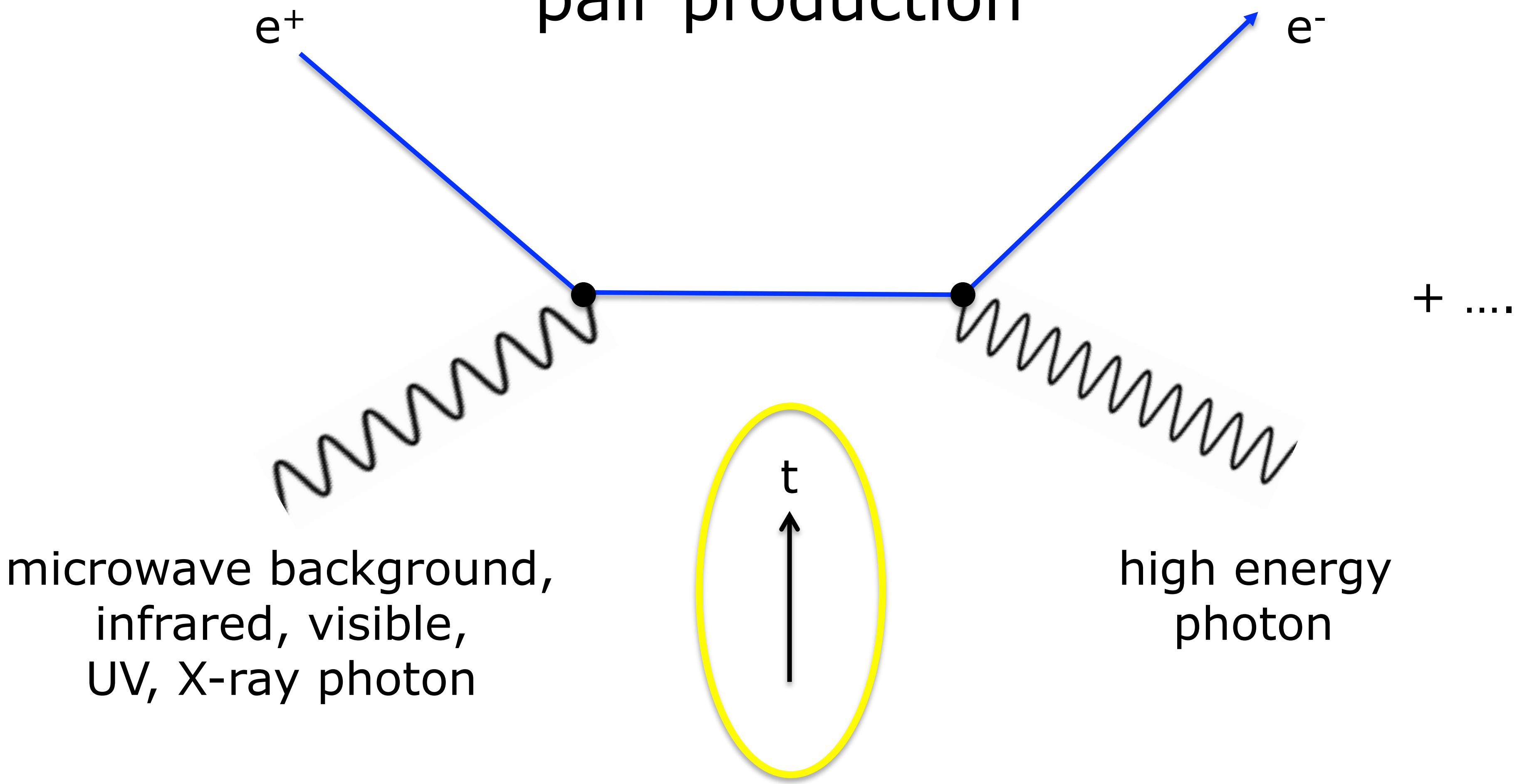
The God Diagram

Synchrotron radiation



The God Diagram

fringe benefit:
photon absorption by
pair production



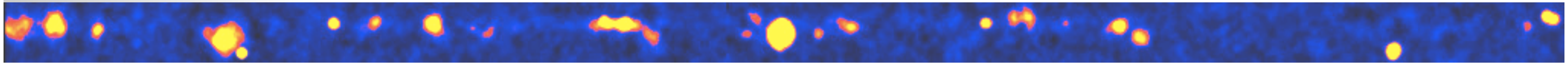
Exact treatment & detailed discussion

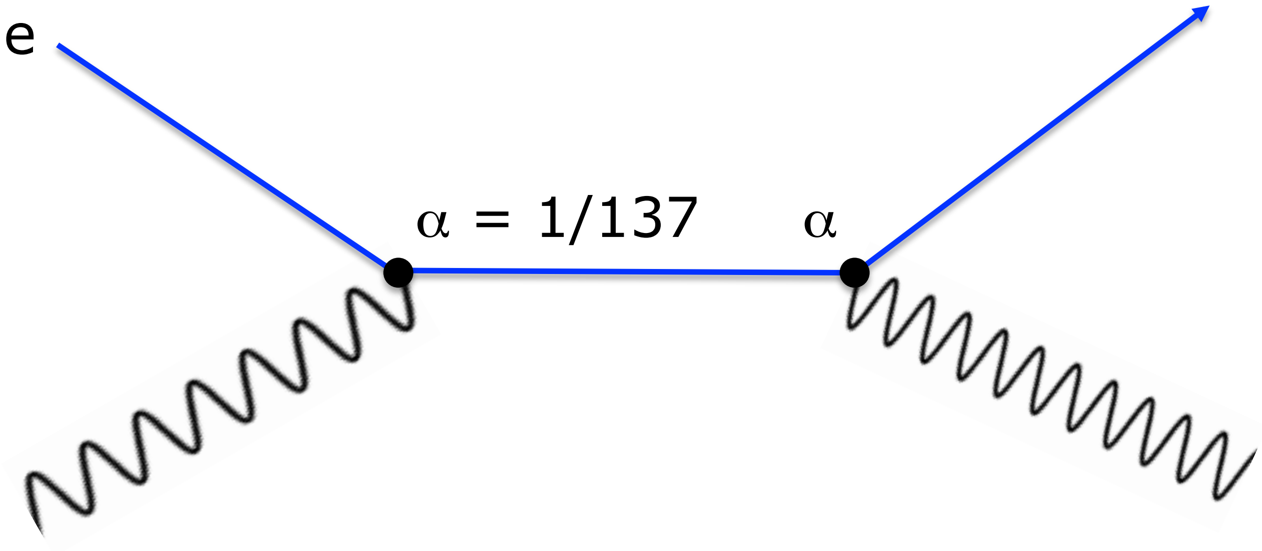
THE reference:

Bremsstrahlung, Synchrotron Radiation, and Compton Scattering of High-Energy Electrons Traversing Dilute Gases
Blumenthal & Gould
Reviews of Modern Physics, vol. 42, pp. 237-271


Inverse Compton
scattering

Cross section



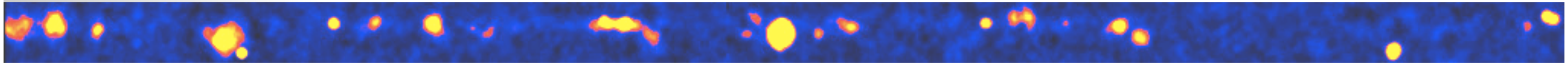


total cross section σ depends only on cms energy $\sqrt{s}$

in units where $\hbar = c = 1$, σ has dimension $1/E^2$

hence $\sigma \approx \alpha^2/s$ up to factors of order unity

Cross section



for simplicity, consider head-on collision

$$s = (E_e + E_{ph})^2 - (p_e - p_{ph})^2 \underset{E_e >> m_e}{\approx} m_e^2 + 4E_e E_{ph}$$

Thomson limit $\quad 4E_e E_{ph} << m_e^2$

$$s \approx m_e^2 \quad ; \quad \sigma \approx \text{const} \approx \frac{\alpha^2}{m_e^2}$$

Klein Nishina limit $\quad 4E_e E_{ph} >> m_e^2$

$$s \approx 4E_e E_{ph} \quad ; \quad \sigma \approx \frac{\alpha^2}{4E_e E_{ph}}$$

Cross section

$\hbar c \cong 200 \text{ MeV fm}$

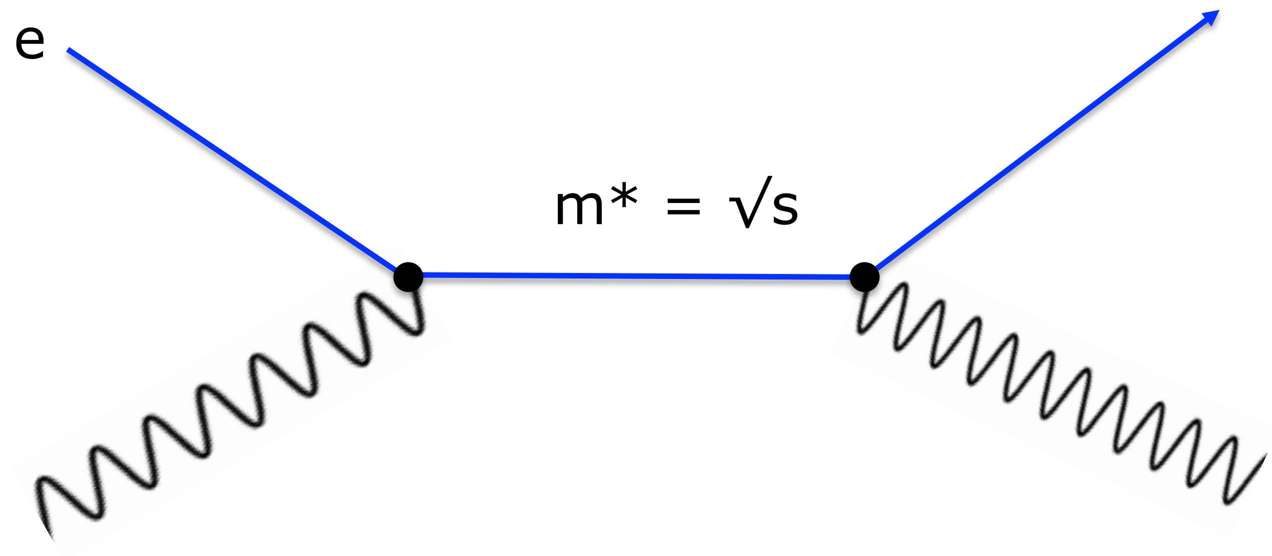
In useful units

$$\frac{\alpha^2}{m_e^2} = \left(\frac{e^2}{4\pi\varepsilon_o \hbar c}\right)^2 \frac{1}{m_e^2 c^4} (\hbar c)^2 = \frac{e^4}{16\pi\varepsilon_o^2 m_e^2 c^4}$$

Correct answer: $16 \rightarrow 6$

"Thomson cross section" $6.6 \cdot 10^{-29}\ \text{m}^2$

Kinematics

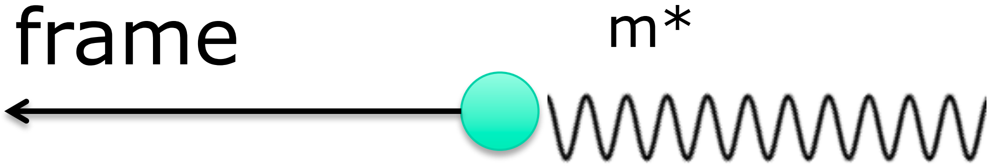


$$s = m^{*2} \underset{E_e >> m_e}{\approx} m_e^2 + 4E_e E_{ph}$$

Thomson limit $\quad 4E_e E_{ph} << m_e^2$

Kinematics

CM frame



$$E^*_\gamma = |p^*_\gamma| = |p^*_e|$$

$p^*_e << m_e$ (Thomson limit)

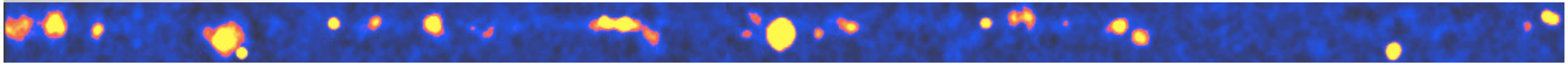
$$\Rightarrow E^*_e = \frac{p^{*2}_e}{2m_e} << |p^*_e| = |p^*_\gamma| = E^*_\gamma$$

$\Rightarrow$ all energy carried by gamma

$$E^*_\gamma \approx m^* - m_e = \sqrt{m_e^2 + 4E_e E_{ph}} - m_e \approx \frac{2E_e E_{ph}}{m_e}$$

Lab frame: boost by $\gamma = \dfrac{E_e}{m^*} \approx \dfrac{E_e}{m_e} \quad \Rightarrow \quad E_\gamma \approx \dfrac{2E_e^2 E_{ph}}{m_e^2}$

Kinematics



In useful units

$$E_\gamma[TeV] = \frac{2E_e^2[TeV]E_{ph}[eV]\times 10^{12}}{\left(511\times 10^{-9}\right)^2} \approx 8E_e^2[TeV]E_{ph}[eV]$$

Example: scattering off CMB, with $E_{ph} \approx 2\times 10^{-4}\,\mathrm{eV}$:

$$E_\gamma[TeV] \approx 0.002E_e^2[TeV]$$

10 TeV electron off CMB : $E_\gamma = 0.2$ TeV

What about energy conservation?? E_γ grows as E_e^2 !

Kinematics

$$E_\gamma \approx \frac{2E_e^2 E_{ph}}{m_e^2}$$

in the Thomson limit where $4E_e E_{ph} << m_e^2$

and hence always $E_\gamma < E_e$!

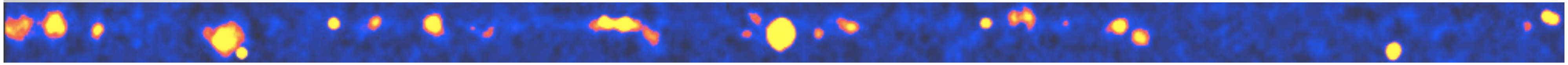
In practical units: Thomson limit

$E_e[TeV]E_{ph}[eV] < 0.1$

for scattering off visible light: $E_e < 100$ GeV

for scattering off CMB: $E_e < 500$ TeV

Spectra of IC photons

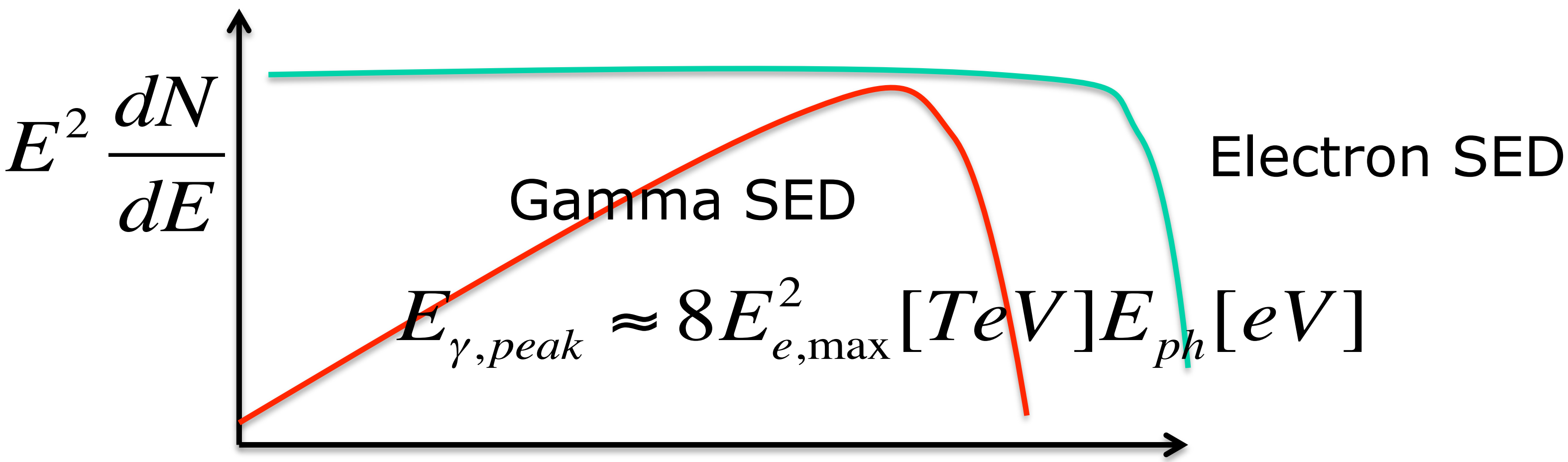


$$E_\gamma \propto E_e^2 E_{ph}$$

$$\frac{dN}{dE_\gamma} = \frac{dN}{dE_e}\frac{dE_e}{dE_\gamma} \propto E_e^{-\alpha} E_\gamma^{-1/2} \qquad (\text{since } E_e \propto E_\gamma^{1/2})$$

$$\propto \left(E_\gamma^{1/2}\right)^{-\alpha} E_\gamma^{-1/2} = E_\gamma^{-(\alpha+1)/2}$$

$\Rightarrow$ Gamma spectral index is $(\alpha+1)/2$



$$E_{\gamma,peak} \approx 8E_{e,\max}^2[TeV]E_{ph}[eV]$$

Energy loss rate

$$E_\gamma \approx \frac{2E_e^2 E_{ph}}{m_e^2} \quad \text{and} \quad \sigma \approx \frac{\alpha^2}{m_e^2}$$

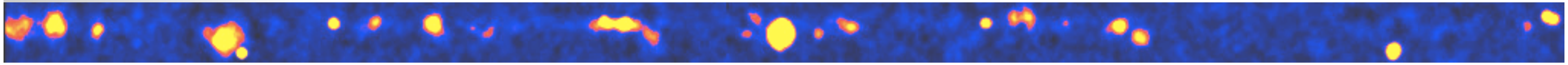
$$\frac{dE}{dt} = -E_\gamma \sigma n c \quad \text{where } n = \text{density of target photons}$$

$$n = \frac{U}{E_{ph}} \;\; ; \;\; U = \text{energy density of "target"}$$

$$\frac{dE}{dt} = -\left(\frac{2E_e^2 E_{ph}}{m_e^2}\right)\left(\frac{\alpha^2}{m_e^2}\right)\left(\frac{U}{E_{ph}}\right) c \propto E_e^2 U$$

Energy loss scales with square of electron energy
depends only on energy density of target (B, vis, CMB, ...) field

Energy loss rate



Energy density in starlight	≈ 1 eV / cm^3
Energy density in CMB	≈ 0.26 eV / cm^3
Energy density in B-field	$\approx 0.03\, B^2_{\mu G}$ eV / cm^3

Energy density in
3 μG field ≈ CMB

$$\tau = \frac{E_e}{(dE_e/dt)} \propto \frac{1}{E_e}$$

$$\tau \approx \frac{3 \cdot 10^5 \text{ yr}}{U[\text{eV/cm}^3]\; E[\text{TeV}]}$$

$$\tau_{sync} \approx \frac{10^7 \text{ yr}}{B^2[\mu\text{G}]\; E[\text{TeV}]}$$

for typical eV energy densities in target fields and multi-TeV electrons, loss time O(10^5) y

IC scattering loss history

Blumenthal & Gould, RMP 42

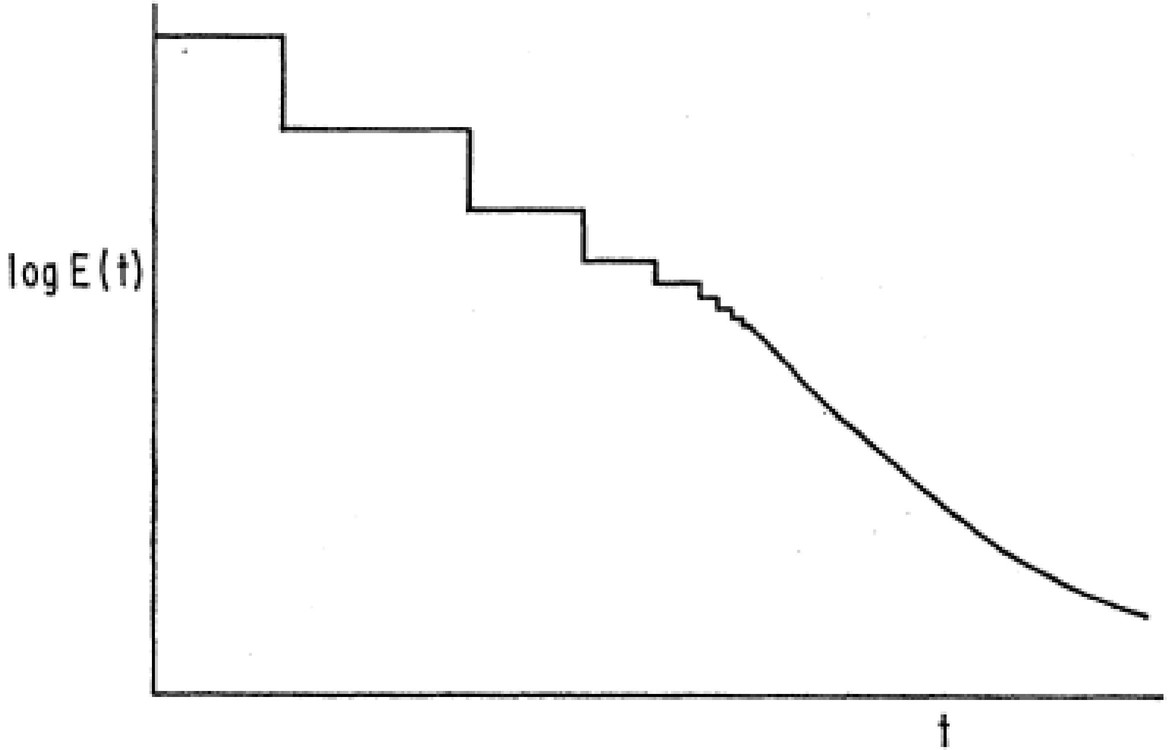
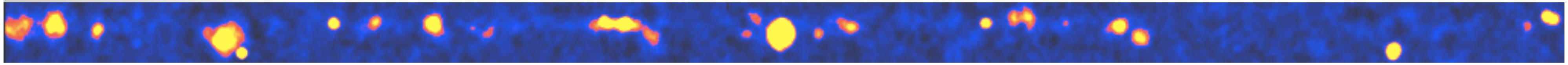
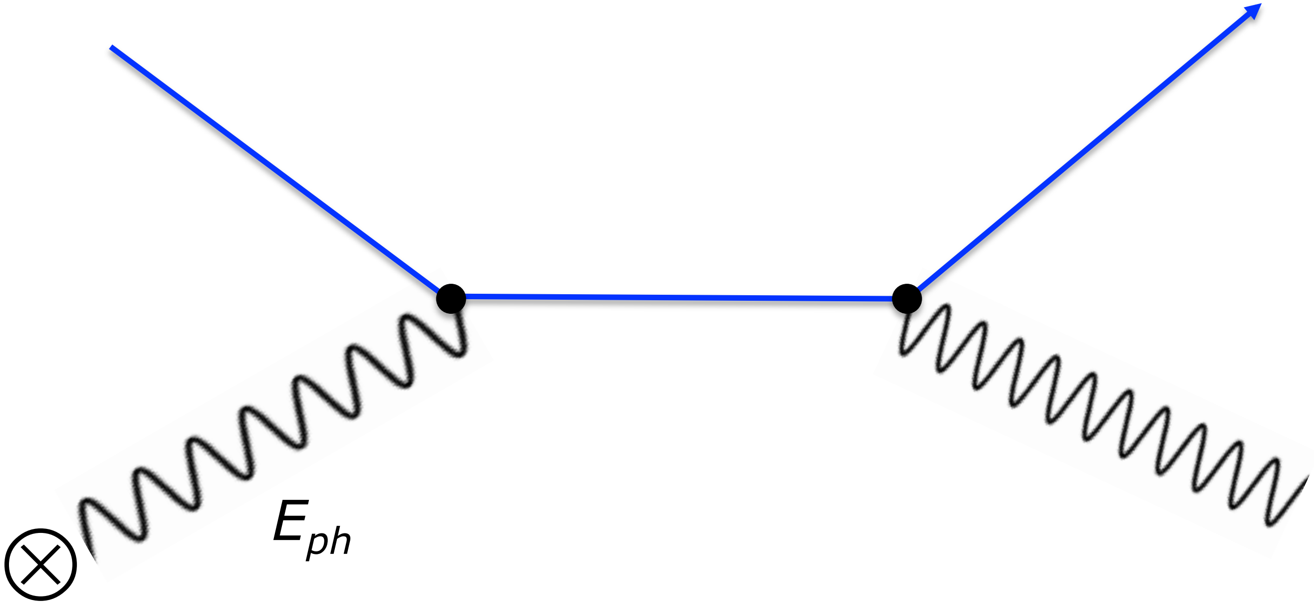


FIG. 5. Sketch of a typical time evolution of an electron's energy due to losses by Compton scattering.


Synchrotron
radiation

Synchrotron radiation





Start from $E_\gamma[\mathrm{TeV}] \approx 8 E_e^2[\mathrm{TeV}]\, E_{ph}[\mathrm{eV}]$

What is the photon energy ??

Synchrotron radiation energy

Start from $E_\gamma[\mathrm{TeV}] \approx 8 E_e^2[\mathrm{TeV}]\, E_{ph}[\mathrm{TeV}]$

What is the photon energy ??

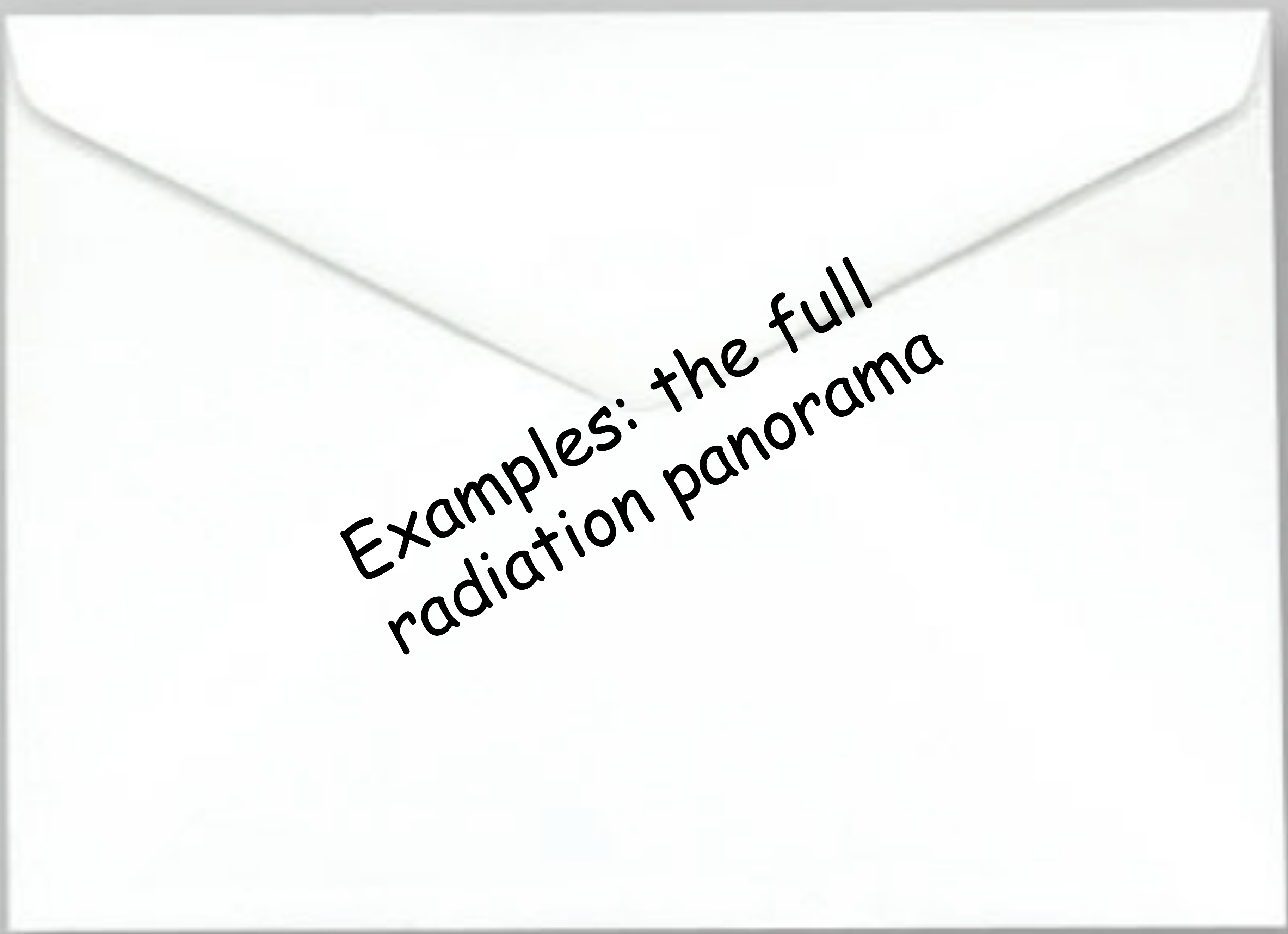
Electron in B field has one characteristic frequency

Gryo frequency $\nu = \dfrac{eB}{2\pi m_e} \approx 2.8 B[\mu\mathrm{G}]$ Hz

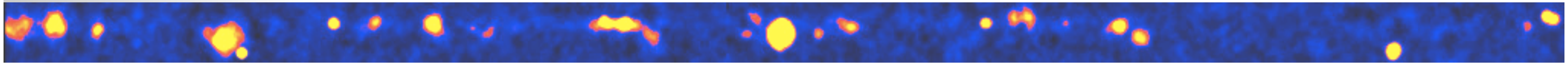
Energy $E_{ph}[\mathrm{eV}] \approx 10^{-14} B[\mu\mathrm{G}]$

Sync. radiation $E_{sy}[\mathrm{eV}] \approx 0.08 E_e^2[\mathrm{TeV}]\, B[\mu\mathrm{G}]$

Correct answer:


Examples: the full
radiation panorama

From electrons to gamma rays

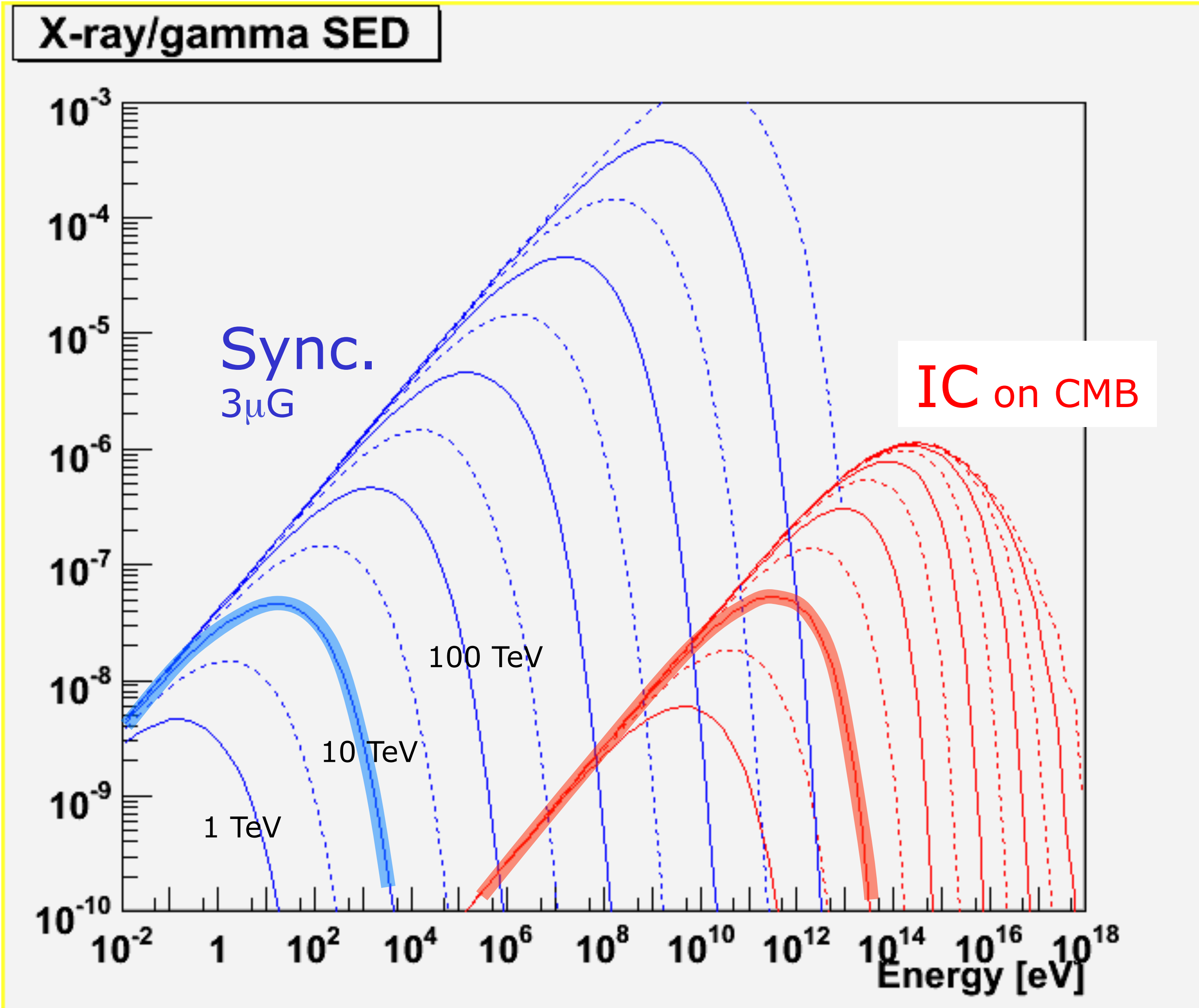


Electron spectrum with index 2 and (varied) cutoff E_{cutoff}

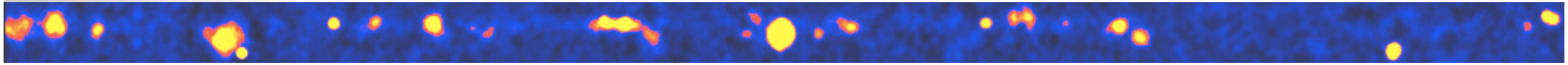
Shown:
SED E^2dN/dE

Electron spectrum is flat in this representation

Numerical integration of exact expressions incl. CMB spectrum



From electrons to gamma rays

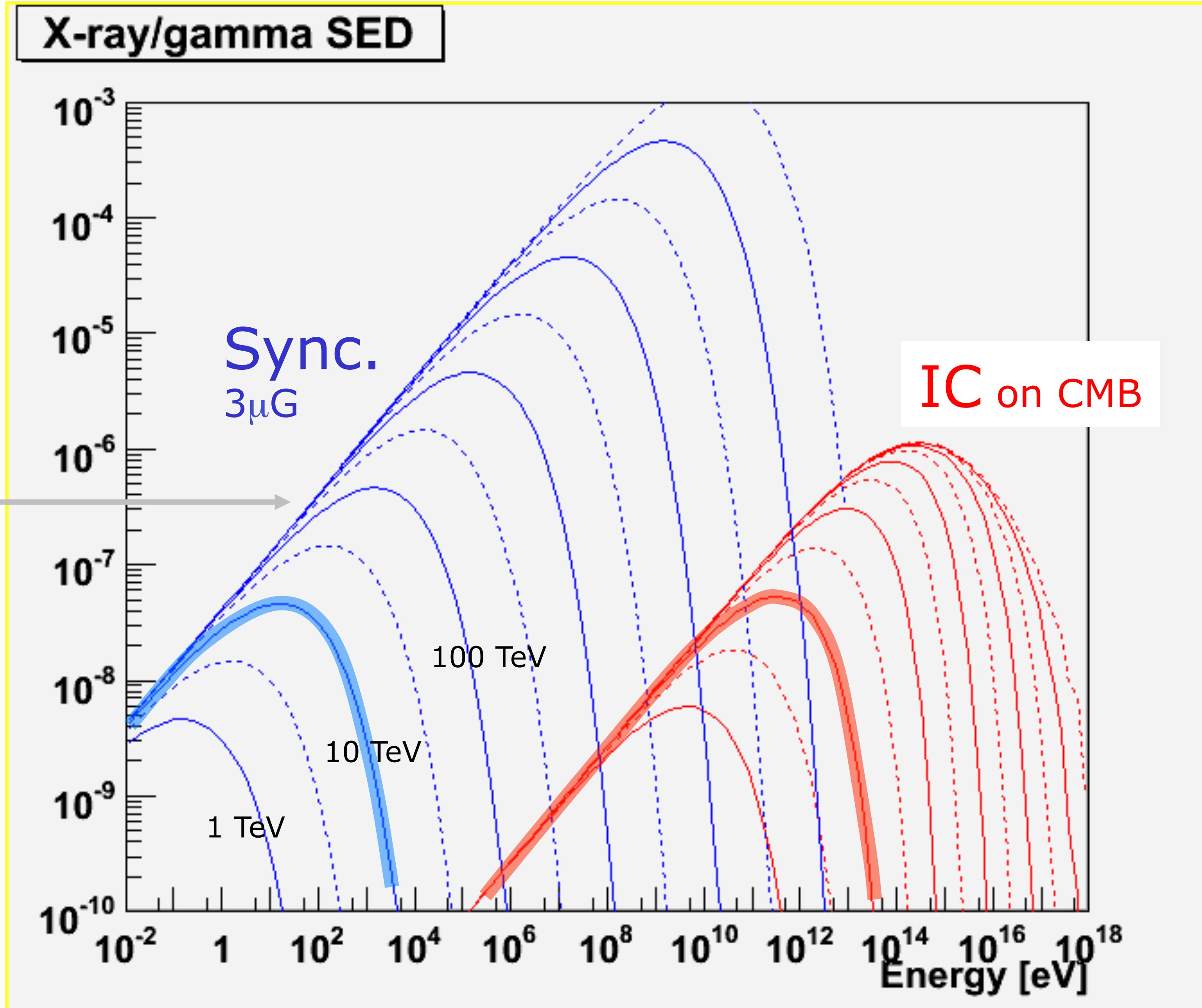


Electron spectrum with index 2 and (varied) cutoff E_{cutoff}

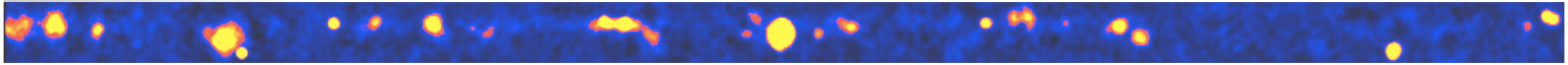
Synchr. (and IC) photon index

$\Gamma = (\Gamma_e+1)/2$

$= 1.5$ for $\Gamma_e=2$



From electrons to gamma rays



Electron spectrum with index 2 and (varied) cutoff E_{cutoff}

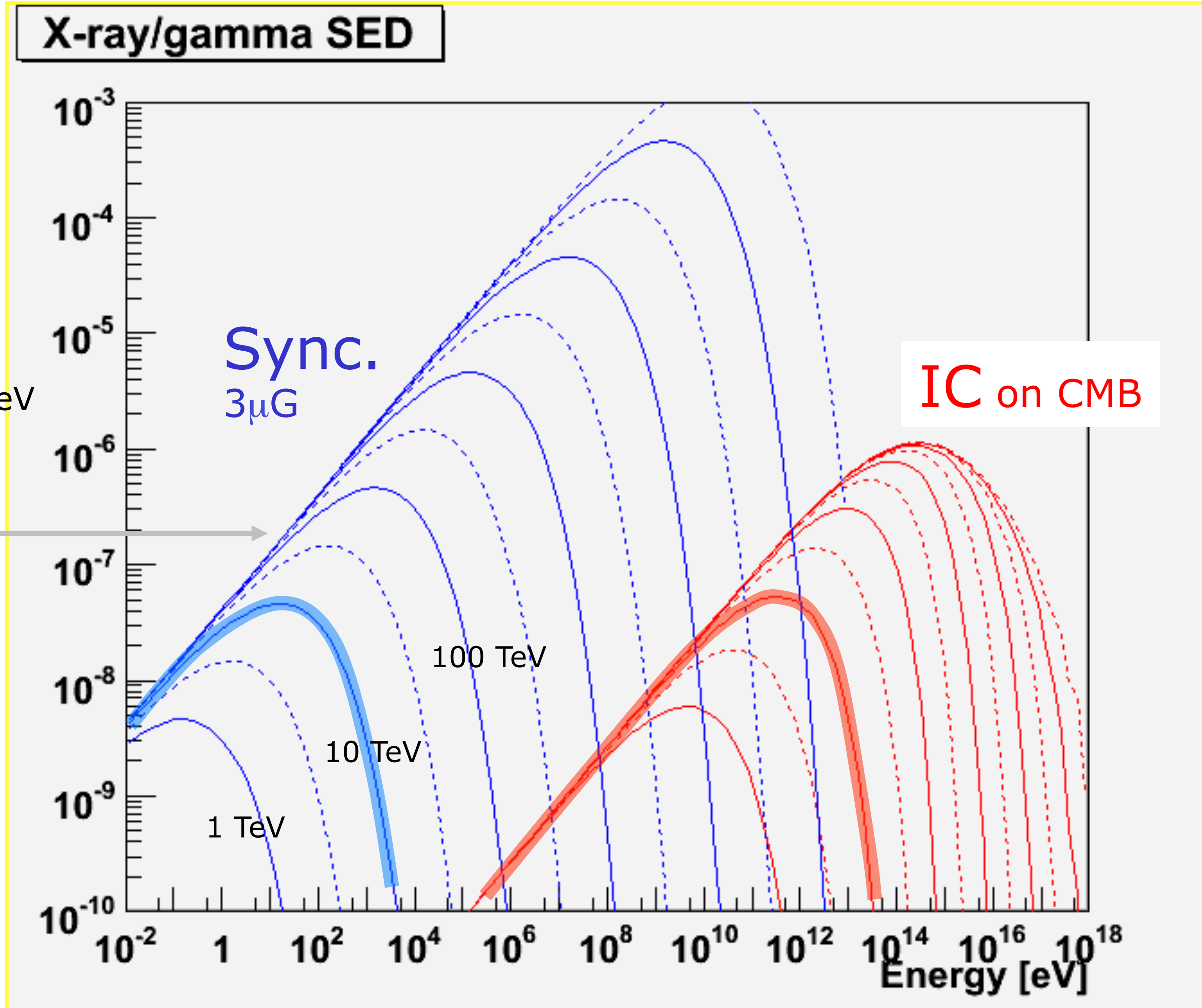
Peak sync. energy E_{eV}

$\sim 0.01\ E_{cutoff,TeV}^2\ B_{\mu g}$

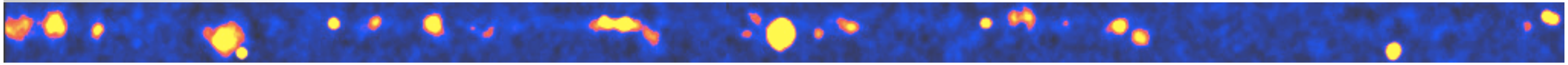
Peak sync. intensity

$\sim E_{cutoff}\ B^2$

differs somewhat
from coefficient 0.07
for monoenergetic electrons
due to convolution
with power law spectrum



From electrons to gamma rays

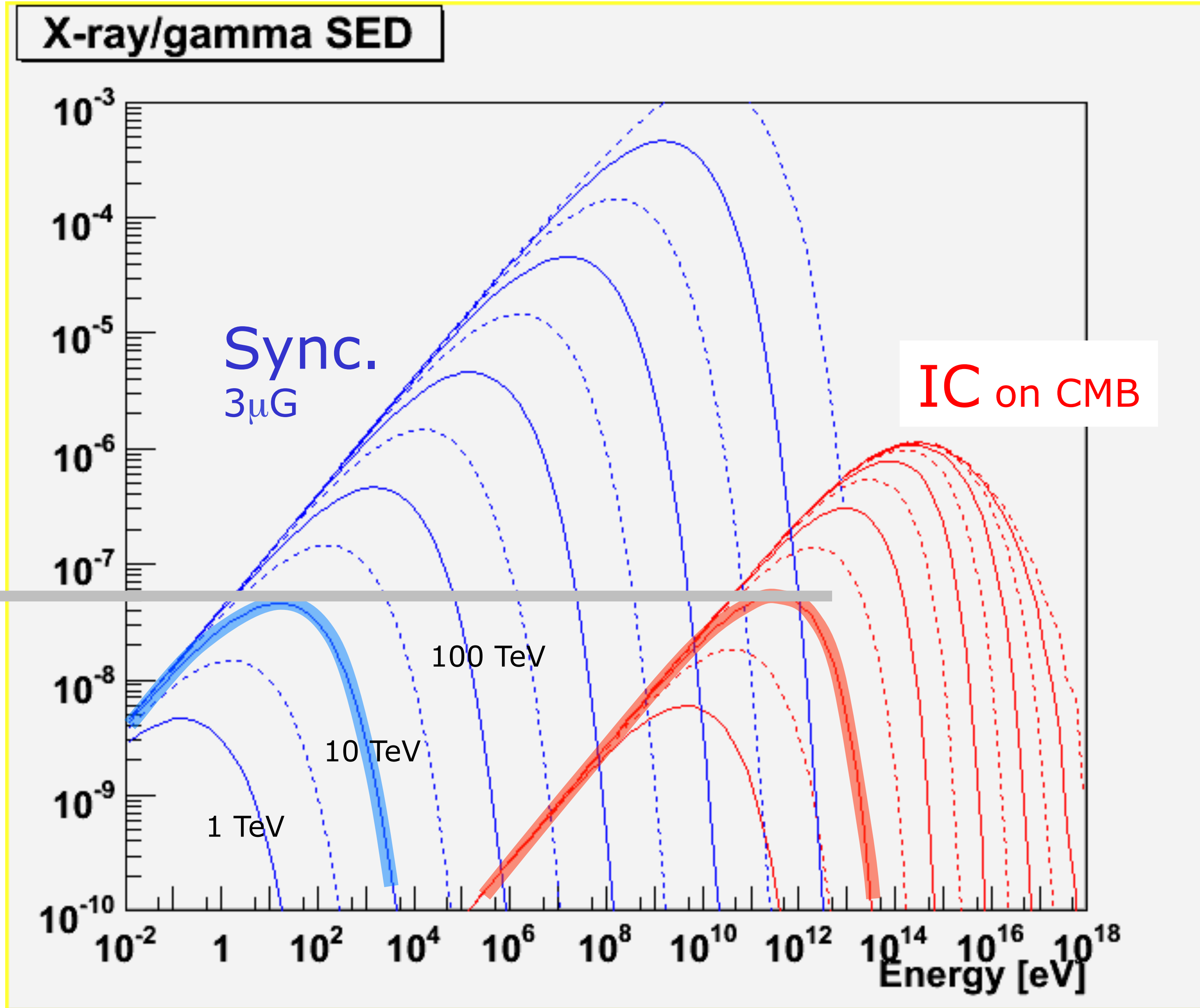


Electron spectrum with index 2 and (varied) cutoff E_{cutoff}

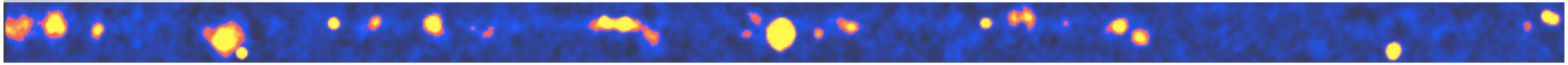
For typical conditions
$W_B \sim W_{CMB}$

hence

$I_{sync} \sim I_{IC}$



From electrons to gamma rays

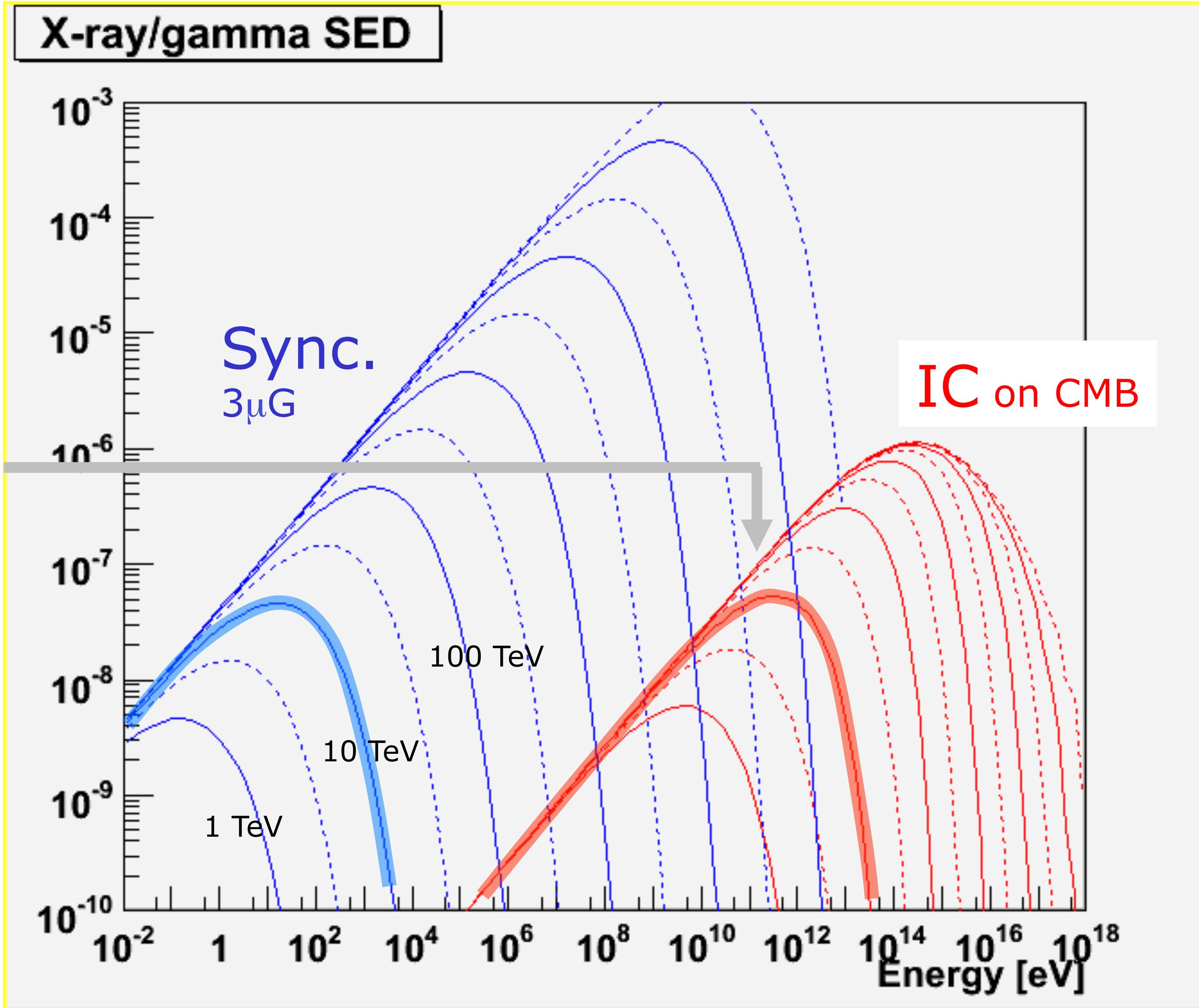


Electron spectrum with index 2 and (varied) cutoff E_{cutoff}

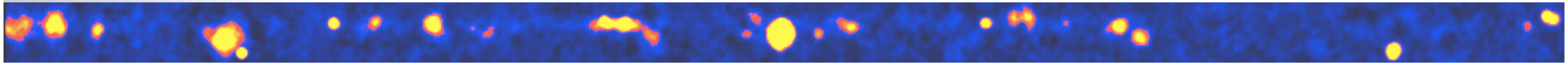
IC on CMB:

$E_{\gamma,TeV} \sim 0.003\ E_{e,TeV}^2$

had estimated 0.002 as coefficient



From electrons to gamma rays

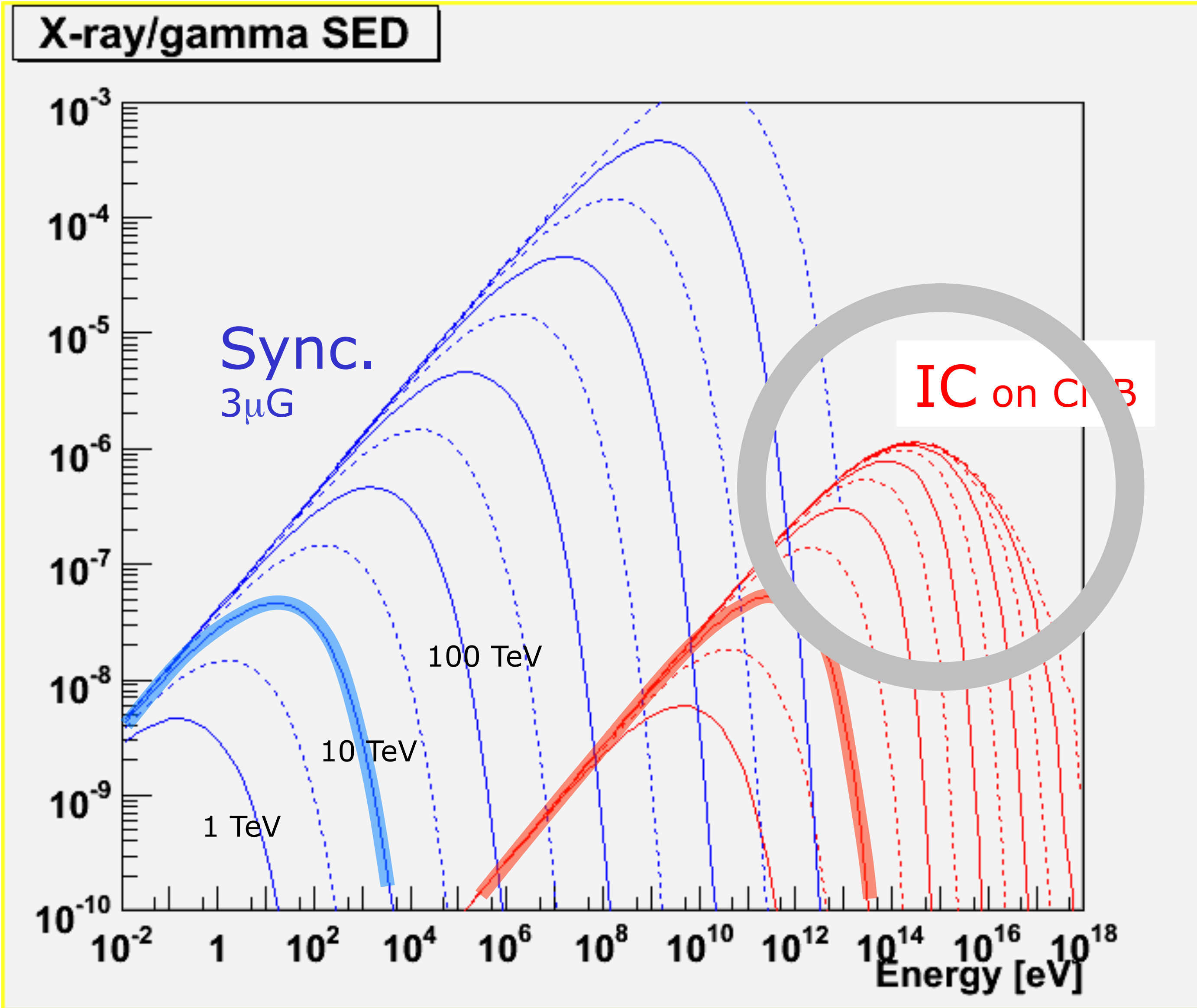


Electron spectrum with index 2 and (varied) cutoff E_{cutoff}

IC strongly reduced in Klein-Nishina regime

$4\,\varepsilon\,\gamma_e/m > 1$

F. Moderski et al.
astro-ph/0504388




Radiation cooling

Spectra & radiation cooling

Cooling modifies particle spectra

$dE/dt = \text{const}$ (Ionization losses)

➜ relative losses stronger for low-energy particles

➜ spectra become harder

$dE/dt \sim E$ (Bremsstrahlung, IC in KN regime)

➜ relative losses same for all particles

➜ (power-law) spectra keep their shape

$dE/dt \sim E^2$ (Synchrotron, IC)

➜ relative losses stronger for high-energy particles

➜ spectra become steeper

Spectra & radiation cooling

SOVIET ASTRONOMY – AJ VOL. 6, NO. 3 NOVEMBER-DECEMBER, 1962

NONSTATIONARINESS OF SPECTRA OF YOUNG SOURCES OF NONTHERMAL RADIO EMISSION

N. S. Kardashev

P. K. Shternberg State Astronomical Institute

Translated from Astronomicheskii Zhurnal, Vol. 39, No. 3, pp. 393-409, May-June, 1962

Original article submitted August 11, 1961

see also
Longair
High Energy Astrophysics

The effect of various modes of energy losses by relativistic electrons on the spectrum of sources of nonthermal cosmic radio-frequency emission is considered, as well as the effect of the systematic and stochastic acceleration of relativistic electrons. Energy spectra are found for various combinations of energy buildup and loss processes, and the time variation of the spectra is studied. The expected synchrotron radiation spectra are obtained, and the variation of these spectra during the evolution of radio sources is investigated.

Spectra & radiation cooling

Longair
High Energy Astrophysics

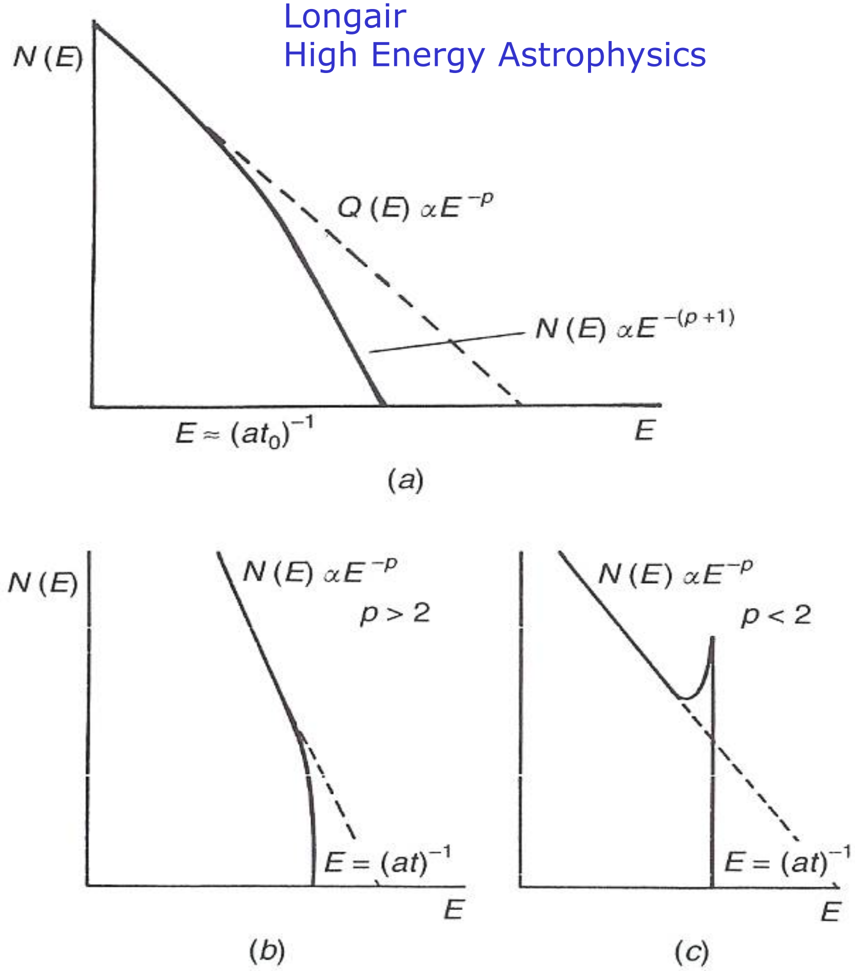


Figure 19.2. (a) A solution of the diffusion-loss equation for steady-state injection of electrons with a power-law energy spectrum $Q(E) \propto E^{-p}$ in the presence of energy losses of the form $\mathrm{d}E/\mathrm{d}t = -aE^2$. ($b$) The time evolution of a power-law energy distribution injected at $t = 0$ with no subsequent injection of electrons. In this case $p > 2$. (c) As in case (b), but with $p < 2$.

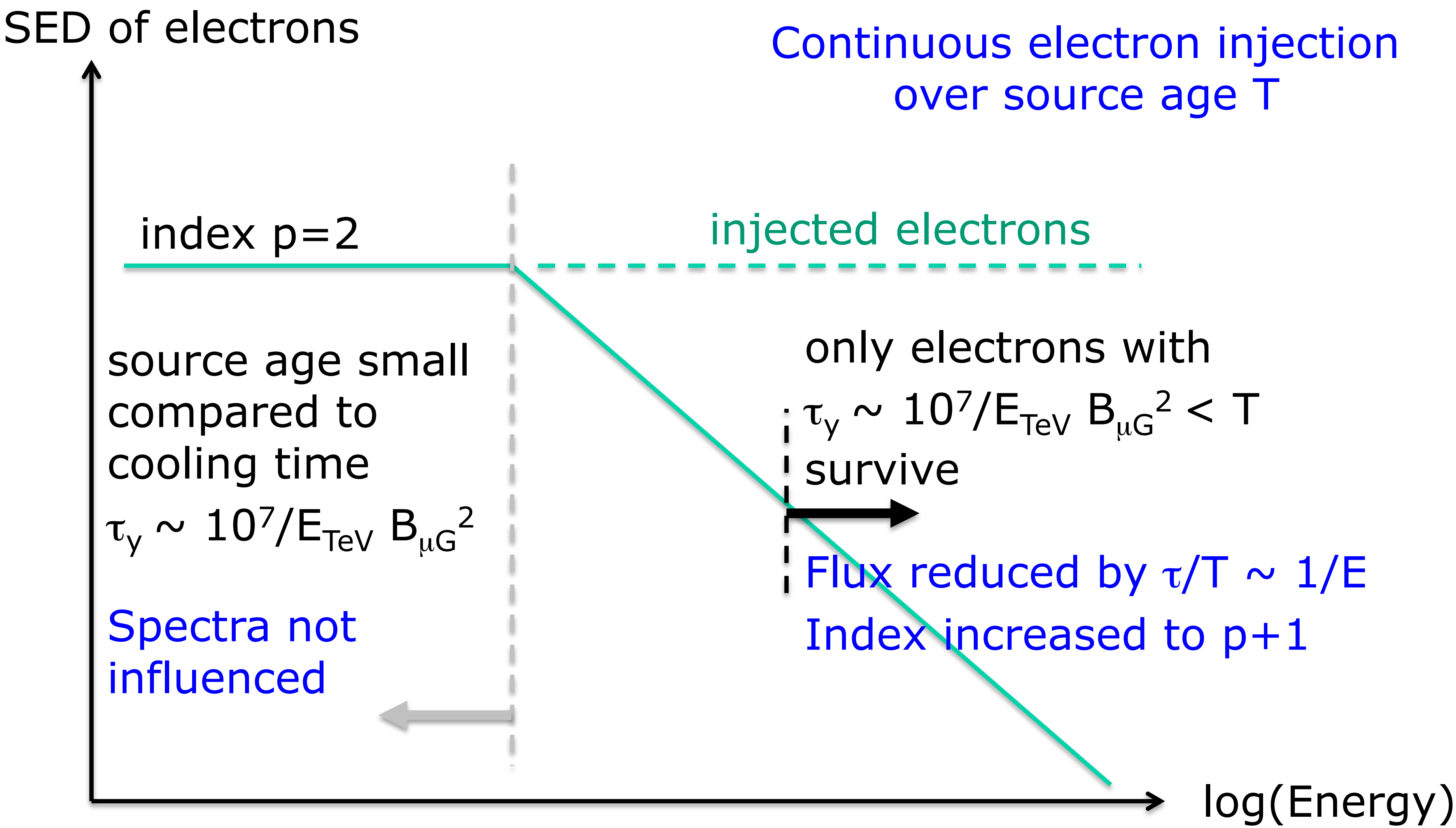
continuous injection
with index Γ:
"cooling break" $\Gamma \rightarrow \Gamma+1$
where

$\tau_y \sim 10^7/E_{TeV}\, B_{\mu G}^2 < \tau_{source}$

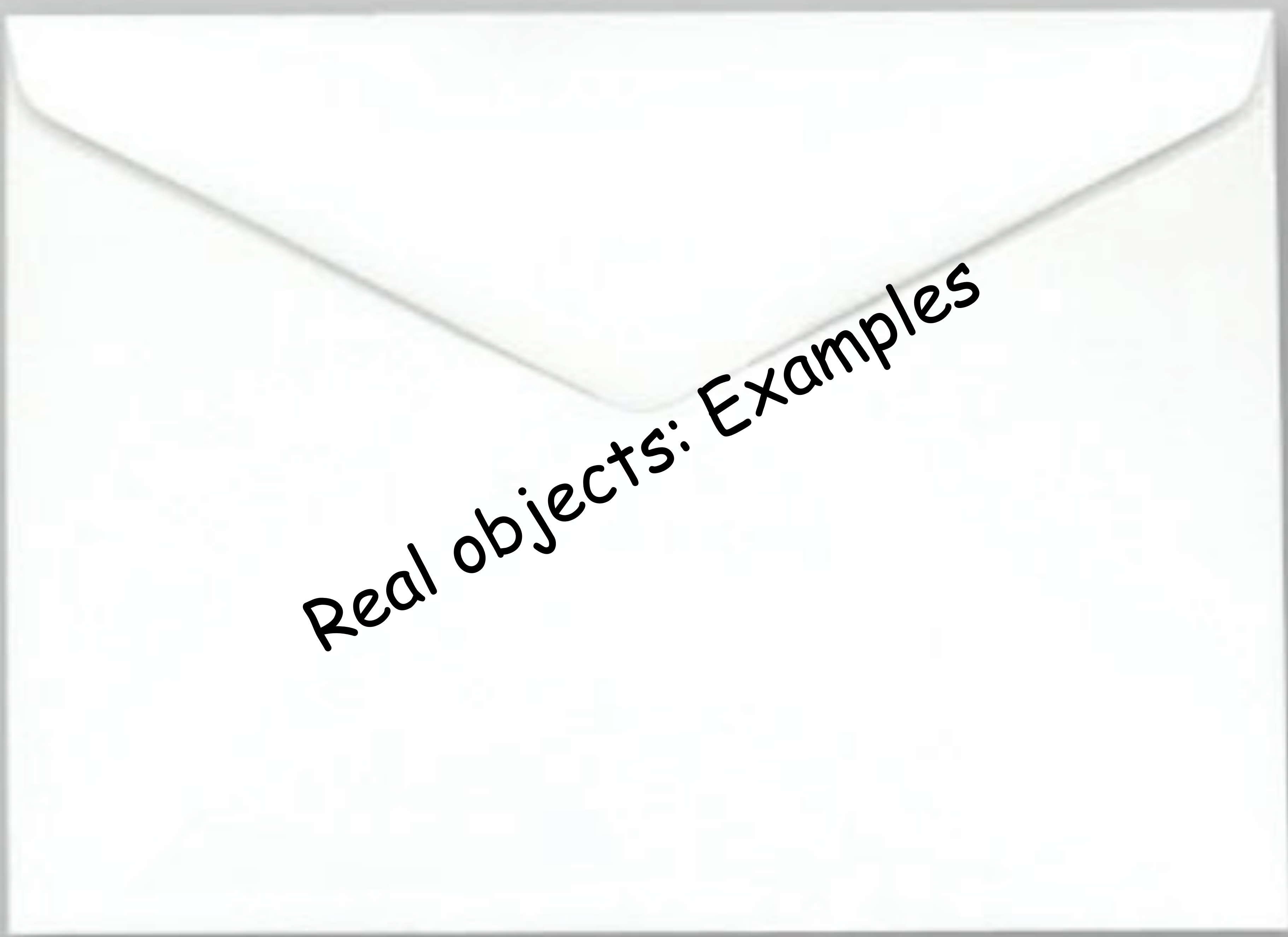
burst injection:
cutoff or pileup
where

$\tau_y \sim 10^7/E_{TeV}\, B_{\mu G}^2 = \tau_{source}$

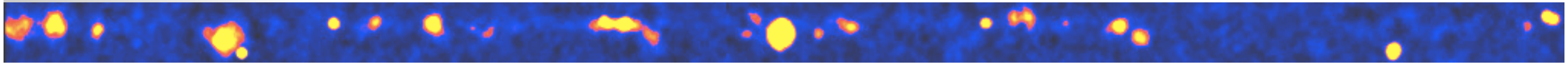
Spectra & (synch.) radiation cooling

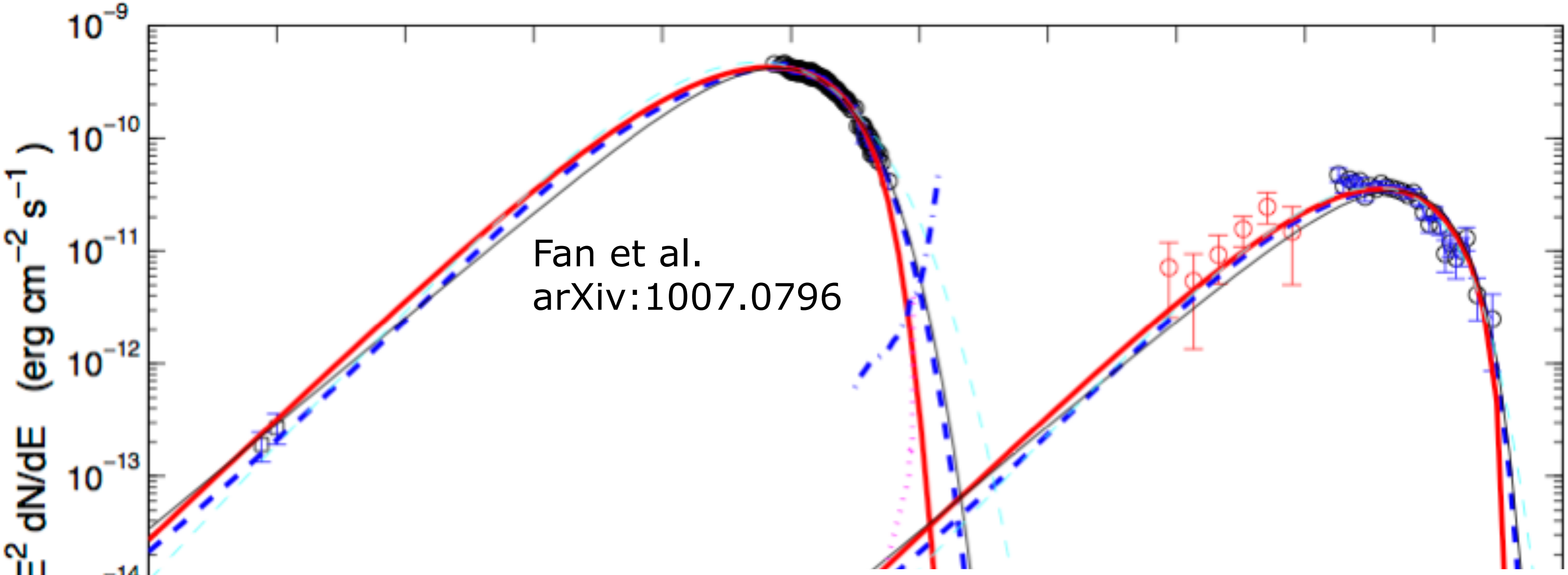


Real objects: Examples



RXJ 1713.7-3946





Modeling objects: options

(a) Fit the current distribution of radiating particles

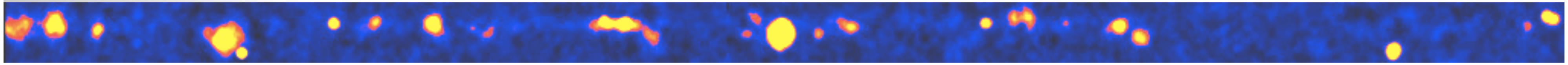
using a power law or a broken power law

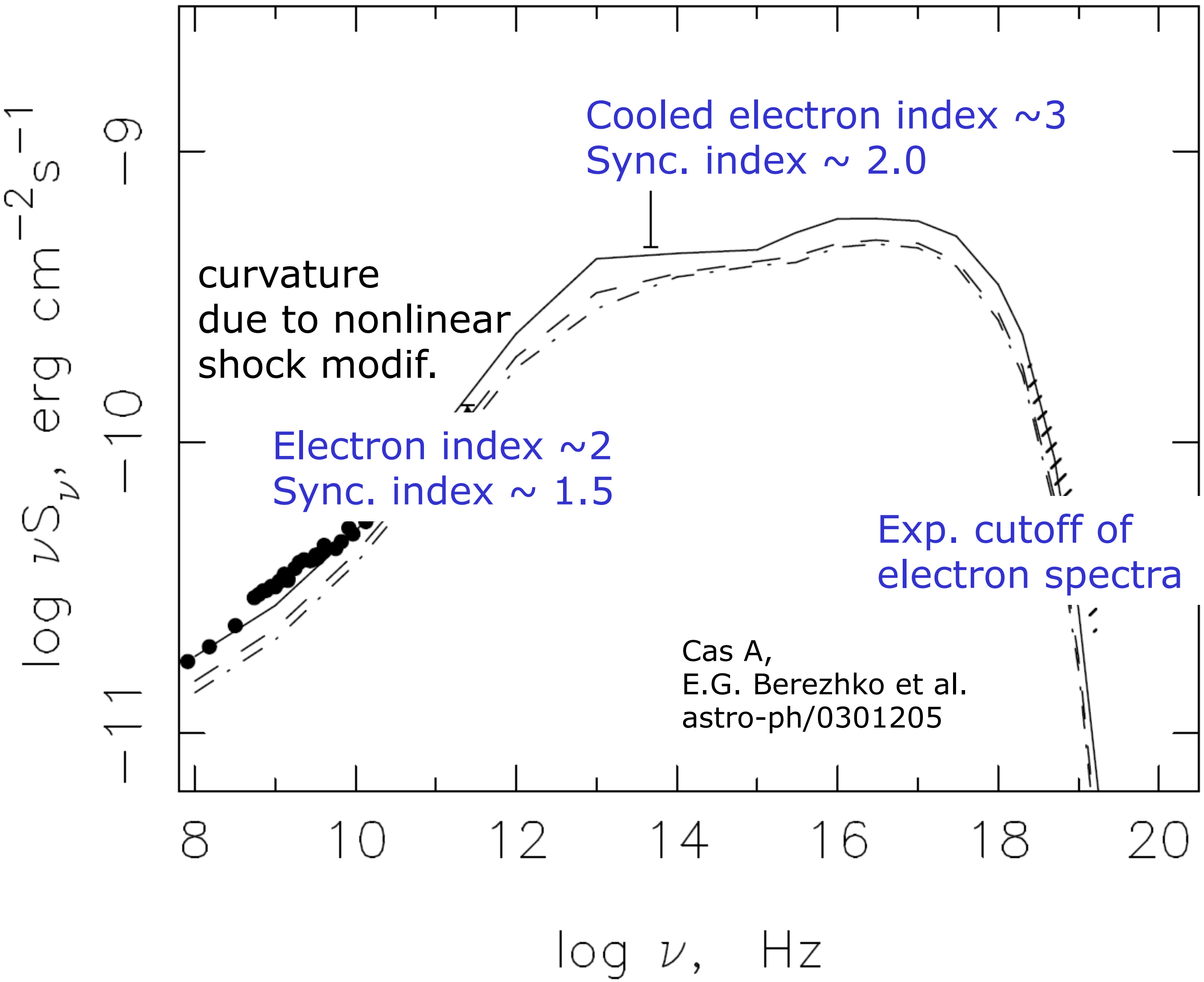
(b) Fit the injection distribution of radiating particles

includes radiative cooling and history of injection (but often neglects adiabatic losses)

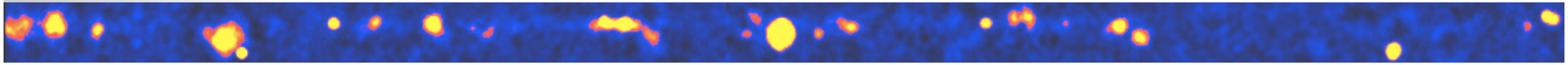
(a) Model the whole system

Cooling in synchrotron spectra from SNR

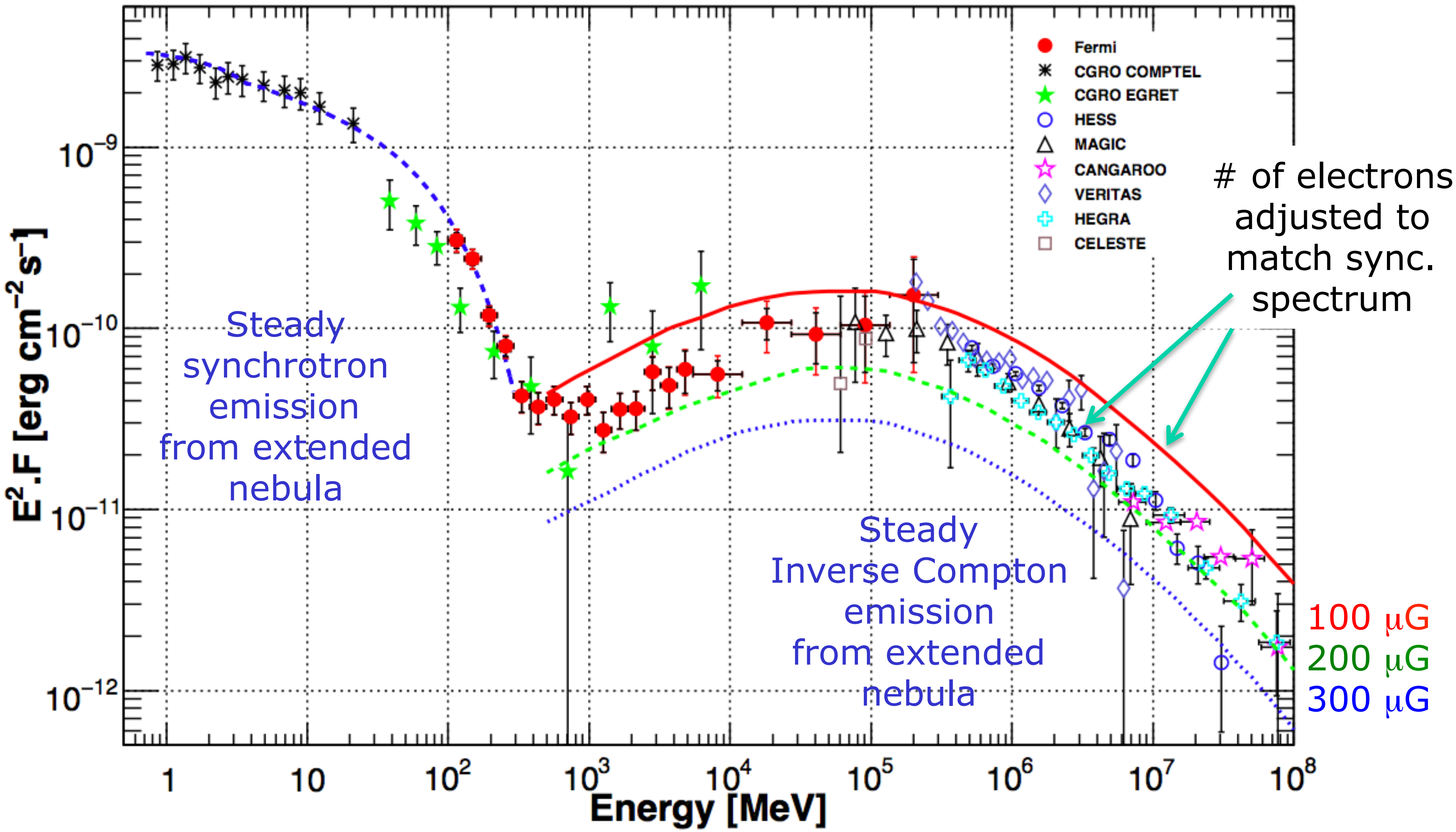




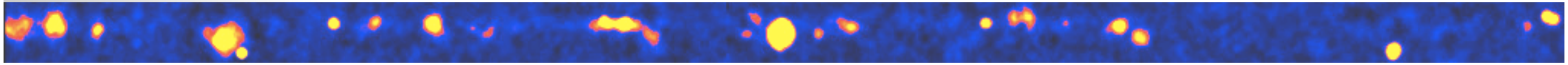
Crab Nebula: measuring the B field



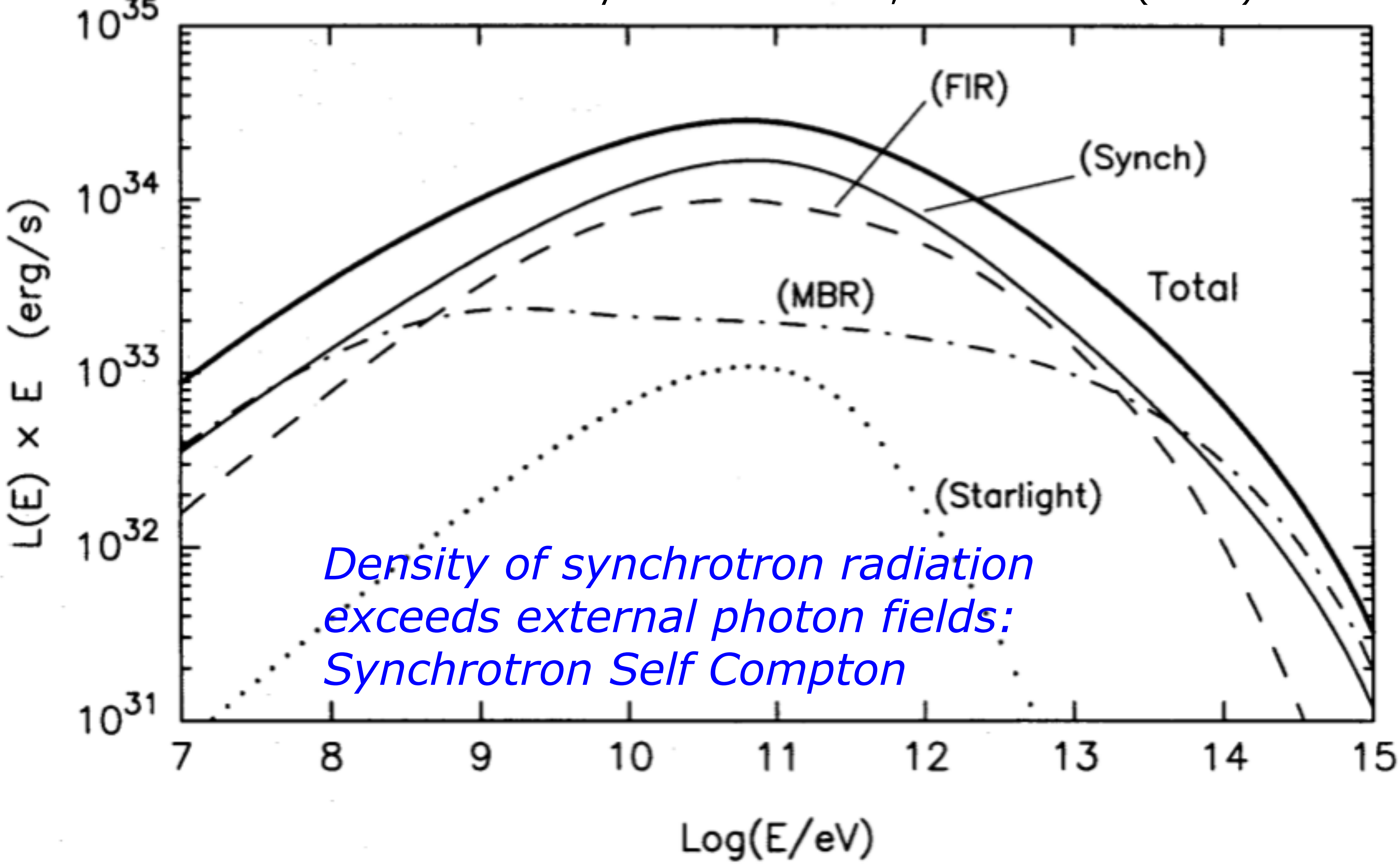
Fermi-LAT Collab. 0911.2412



Crab Nebula: Target fields for IC

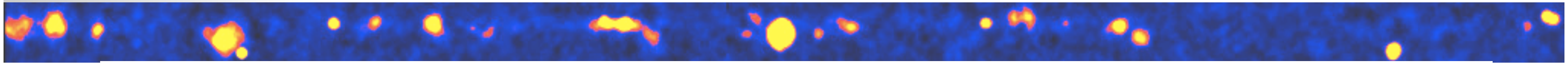


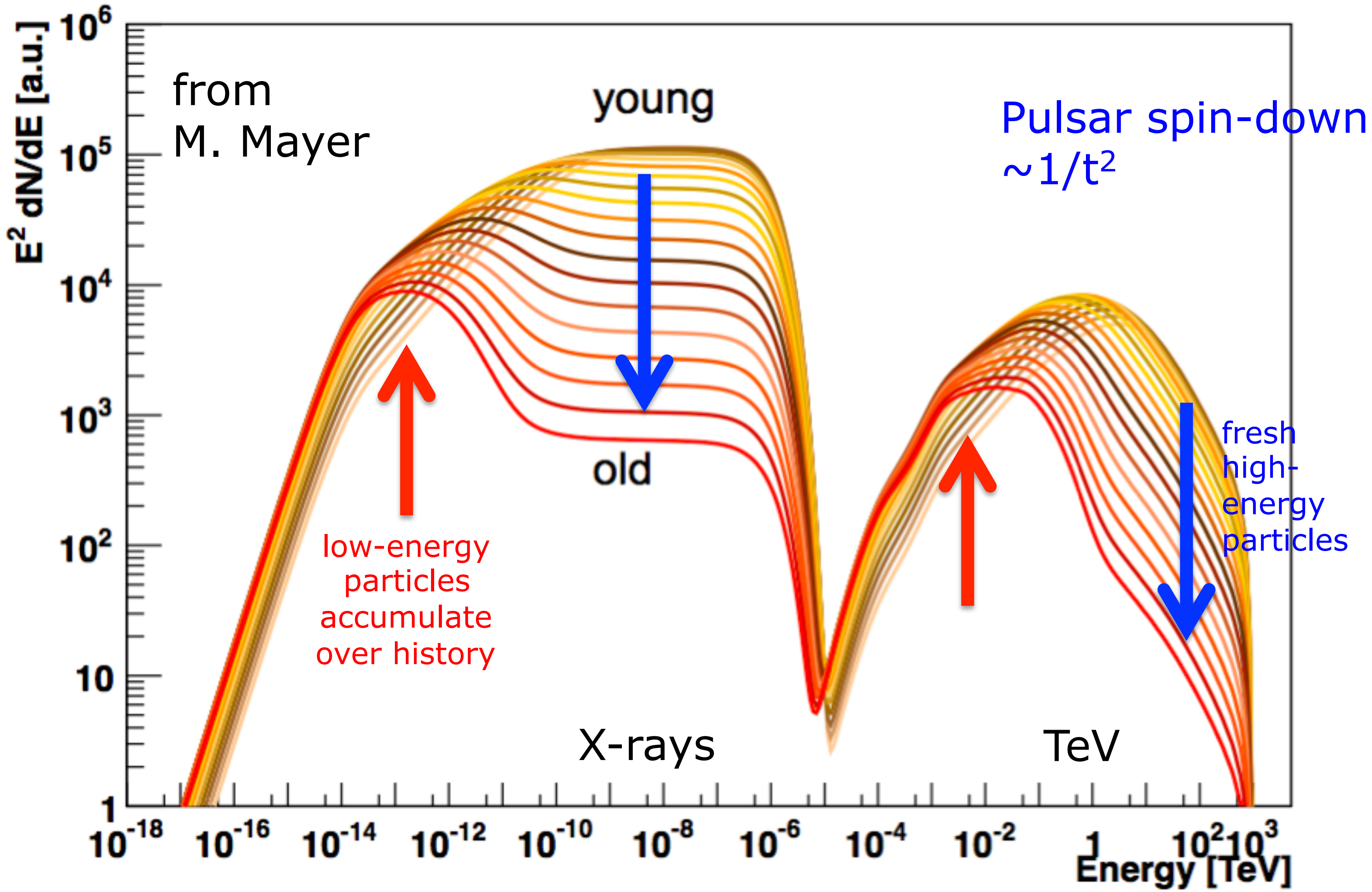
Atoyan & Aharonian, MNRAS 278 (1996) 525



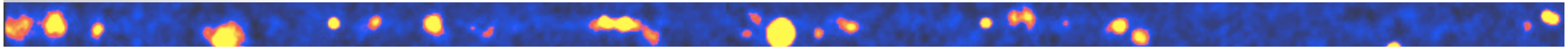
Density of synchrotron radiation exceeds external photon fields: Synchrotron Self Compton

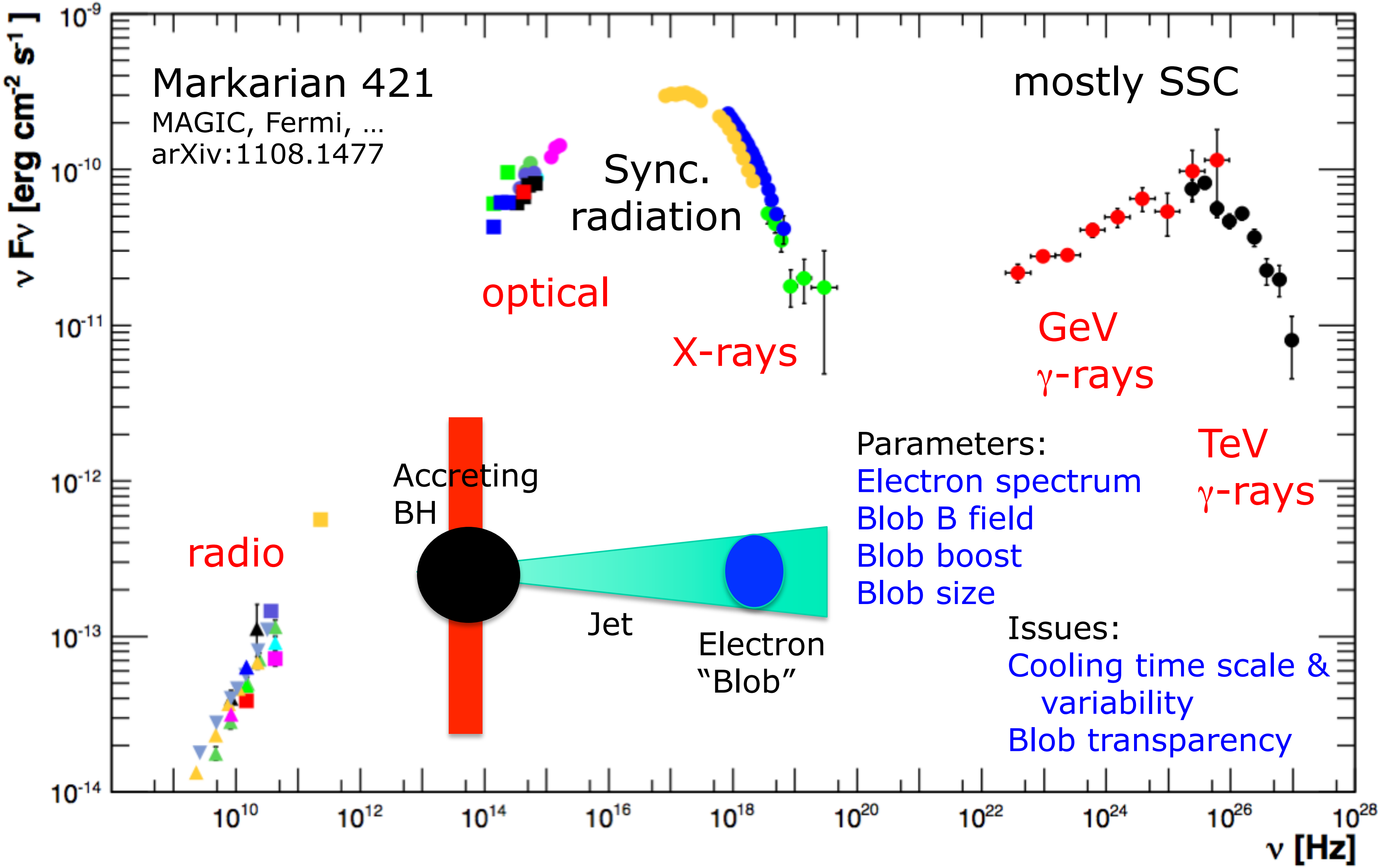
Evolution of pulsar wind nebula



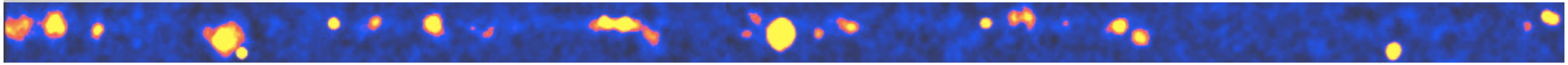


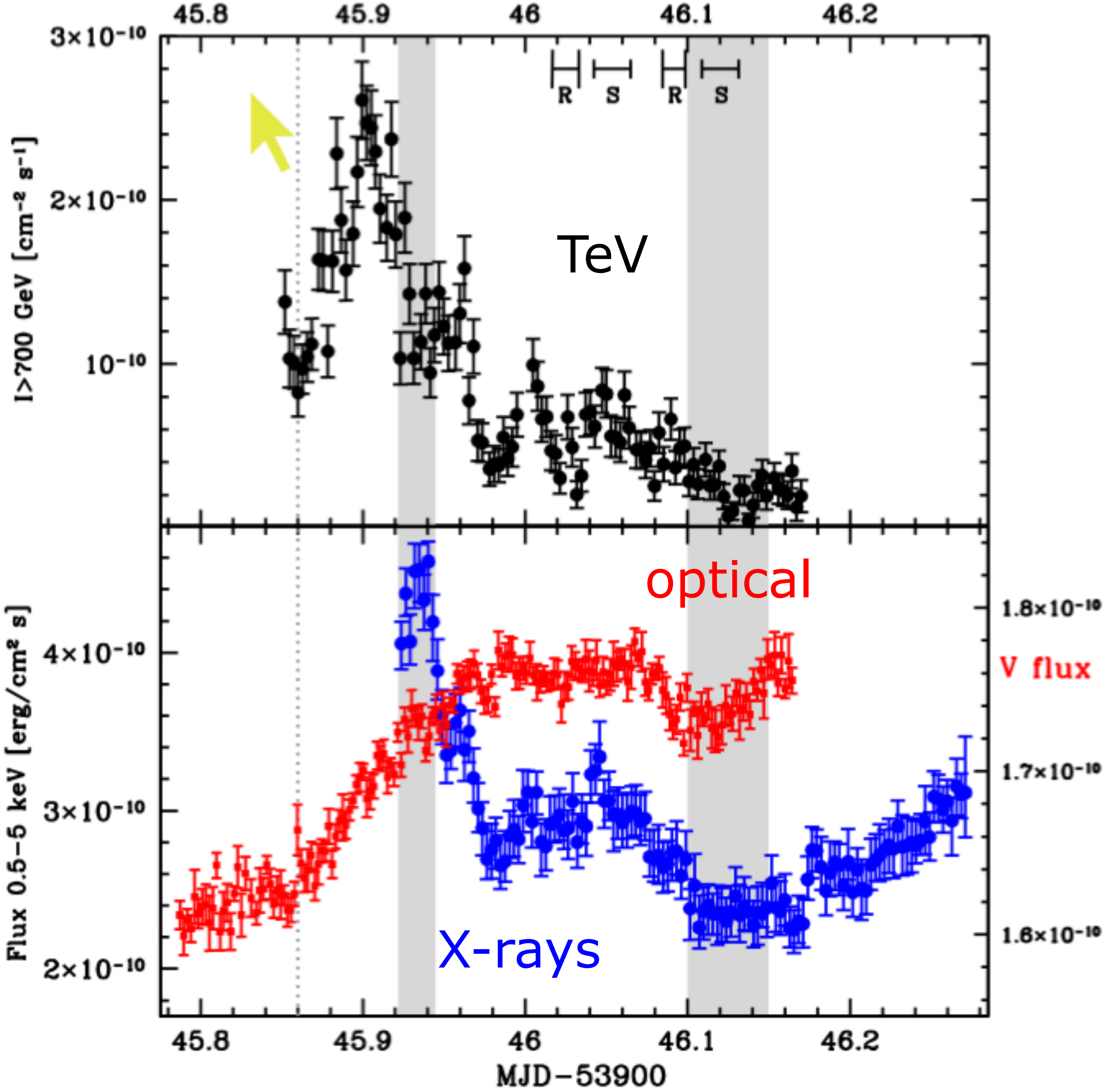
Active Galactic Nuclei

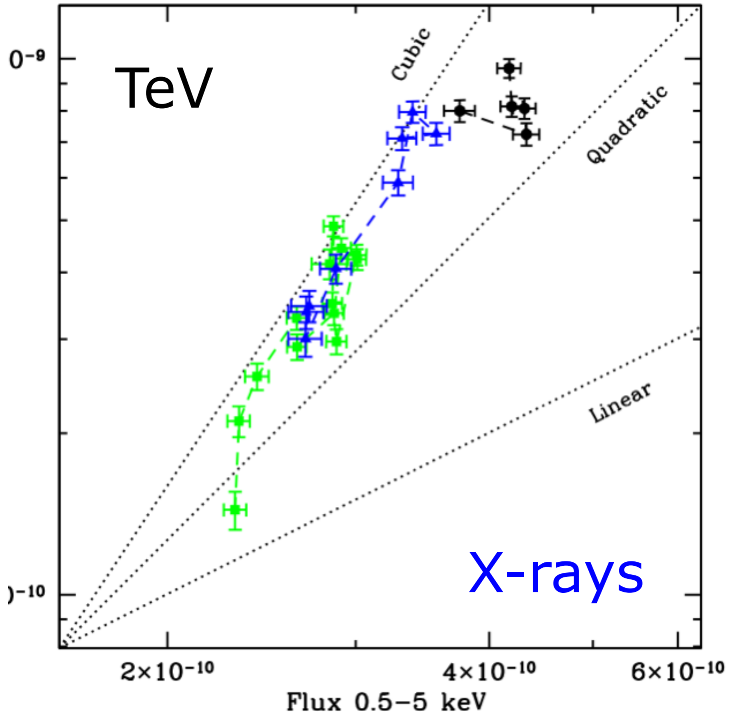




AGN variability (PKS 2155-304)

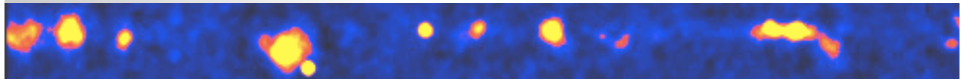


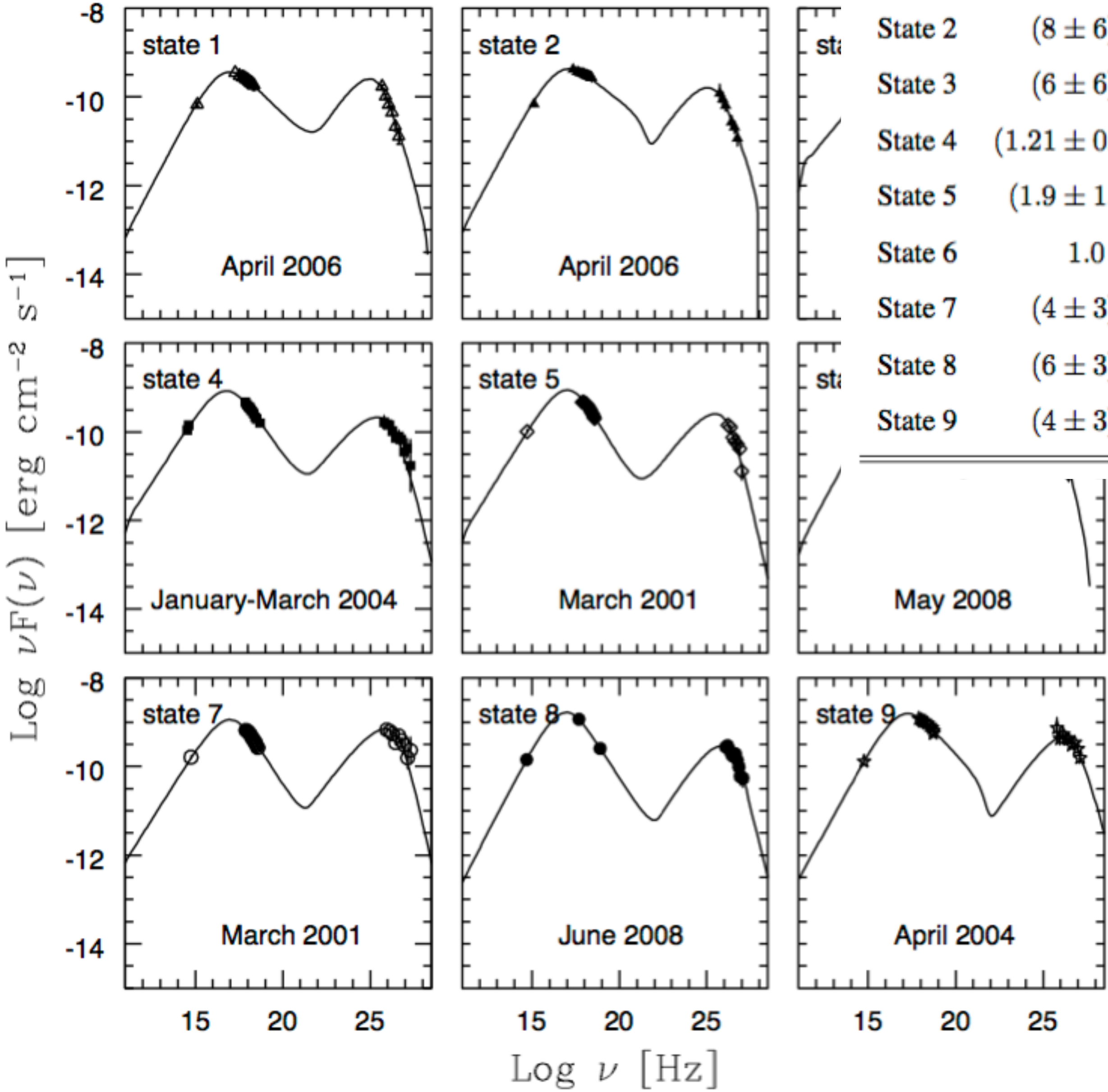




TeV flux varies stronger than X-rays

Fitting AGN SEDs

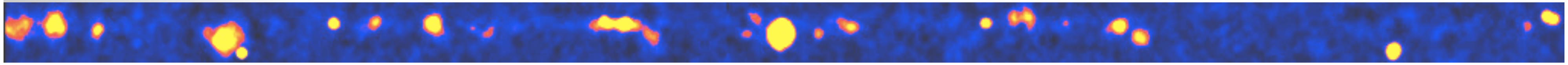




Source	B [gauss]	R [cm]	δ
State 1	$(9 \pm 3) \times 10^{-1}$	$(9 \pm 4) \times 10^{14}$	$(2 \pm 0.5) \times 10^{1}$
State 2	$(8 \pm 6) \times 10^{-1}$	$(8 \pm 4) \times 10^{14}$	$(2.7 \pm 1.1) \times 10^{1}$
State 3	$(6 \pm 6) \times 10^{-2}$	$(2.0 \pm 1.5) \times 10^{15}$	$(1.0 \pm 0.5) \times 10^{2}$
State 4	$(1.21 \pm 0.16) \times 10^{-1}$	$(1.1 \pm 1.3) \times 10^{15}$	$(8 \pm 6) \times 10^{1}$
State 5	$(1.9 \pm 1.3) \times 10^{-1}$	$(10 \pm 4) \times 10^{14}$	$(7 \pm 5) \times 10^{1}$
State 6	1.0 ± 0.7	$(6 \pm 3) \times 10^{14}$	$(2.8 \pm 1.1) \times 10^{1}$
State 7	$(4 \pm 3) \times 10^{-2}$	$(2 \pm 5) \times 10^{15}$	$(8 \pm 7) \times 10^{1}$
State 8	$(6 \pm 3) \times 10^{-2}$	$(2 \pm 1.8) \times 10^{15}$	$(1.1 \pm 0.4) \times 10^{2}$
State 9	$(4 \pm 3) \times 10^{-2}$	$(2 \pm 4) \times 10^{15}$	$(1.2 \pm 1.0) \times 10^{2}$

Mankuzhiyil et al.
arXiv:1103.0909

Topics



Preliminaries: Units, coordinates & other useful(?) stuff

Gamma ray production by protons

- Basics
- Gamma-ray visibility of supernova remnants
- Seeing molecular clouds in gamma rays

Radiation processes involving electrons

- Inverse Compton scattering
- Synchrotron radiation
- Radiation cooling
- Application to real objects

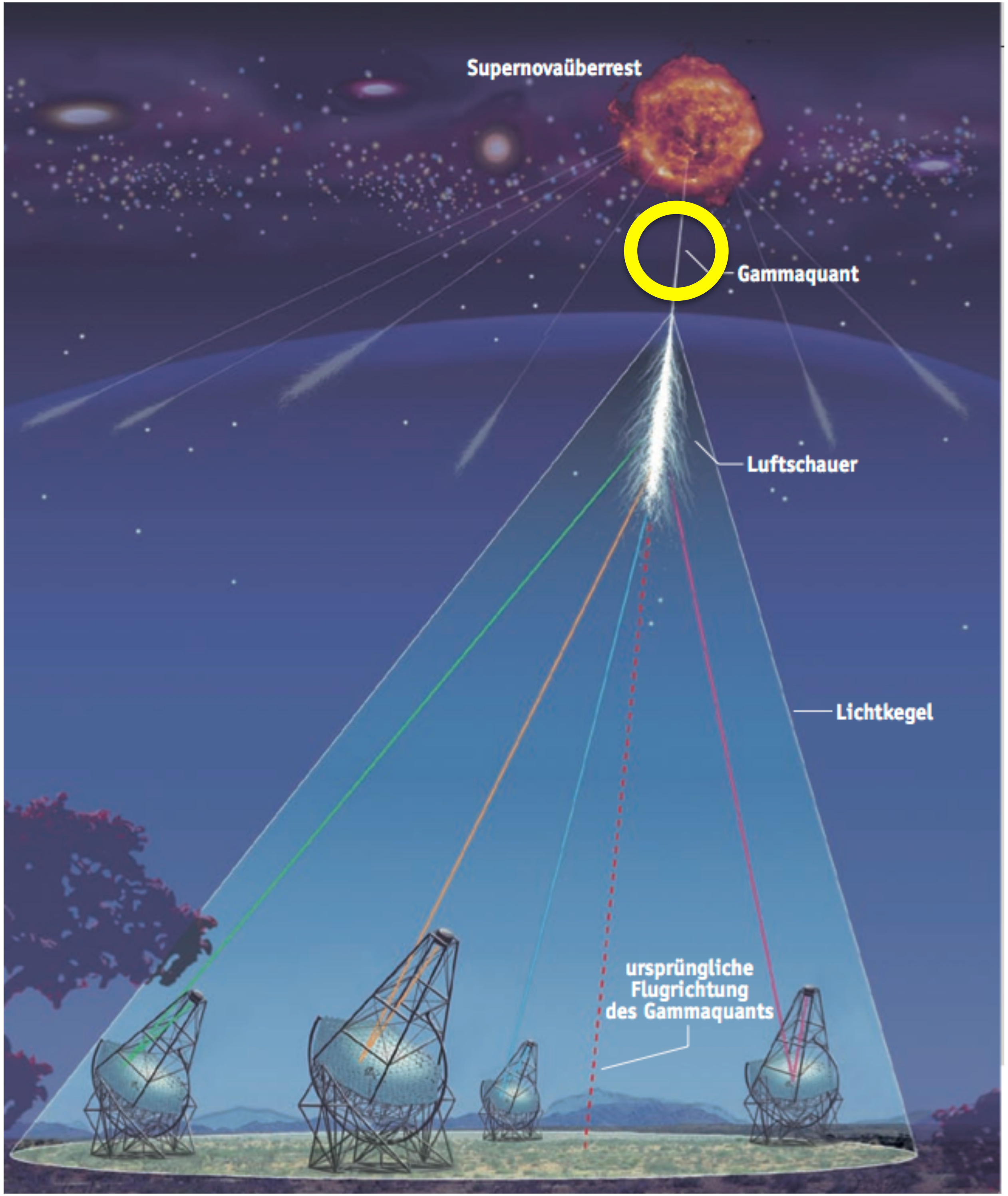
Gamma ray propagation - will they reach us?

Cosmic particle accelerators

- Supernova remnant kinematics
- Supernova remnant shocks
- Particle propagation and particle acceleration
- Nonlinear effects, escape, …

The receiving end: Detecting gamma rays


Gamma ray propagation
- will they reach us?


Supernovaüberrest
Gammaquant
Luftschauer
Lichtkegel
ursprüngliche
Flugrichtung
des Gammaquants

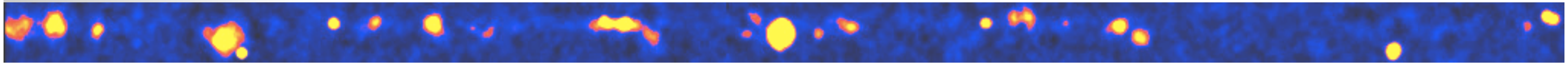
Gamma-ray absorption in matter

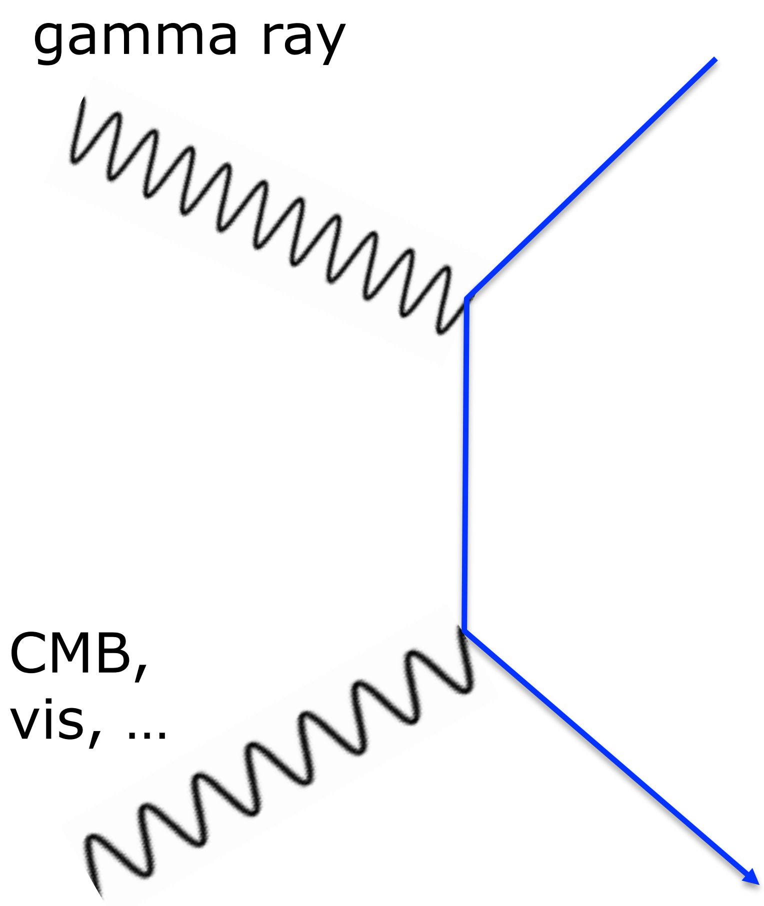
Radiation length (characteristic scale for pair conversion) is 37 g/cm^2

1 H/cm^3 over 10 kpc is 0.05 g/cm^2

Don't worry for Galactic gamma rays …

Gamma-ray absorption by radiation





Threshold: $s \approx 4E_\gamma E_{ph} > (2m_e)^2$

$E_\gamma[\text{TeV}] > 1/E_{ph}[\text{eV}]$

➜ Always in “KN” regime

Cross section drops with incr. s

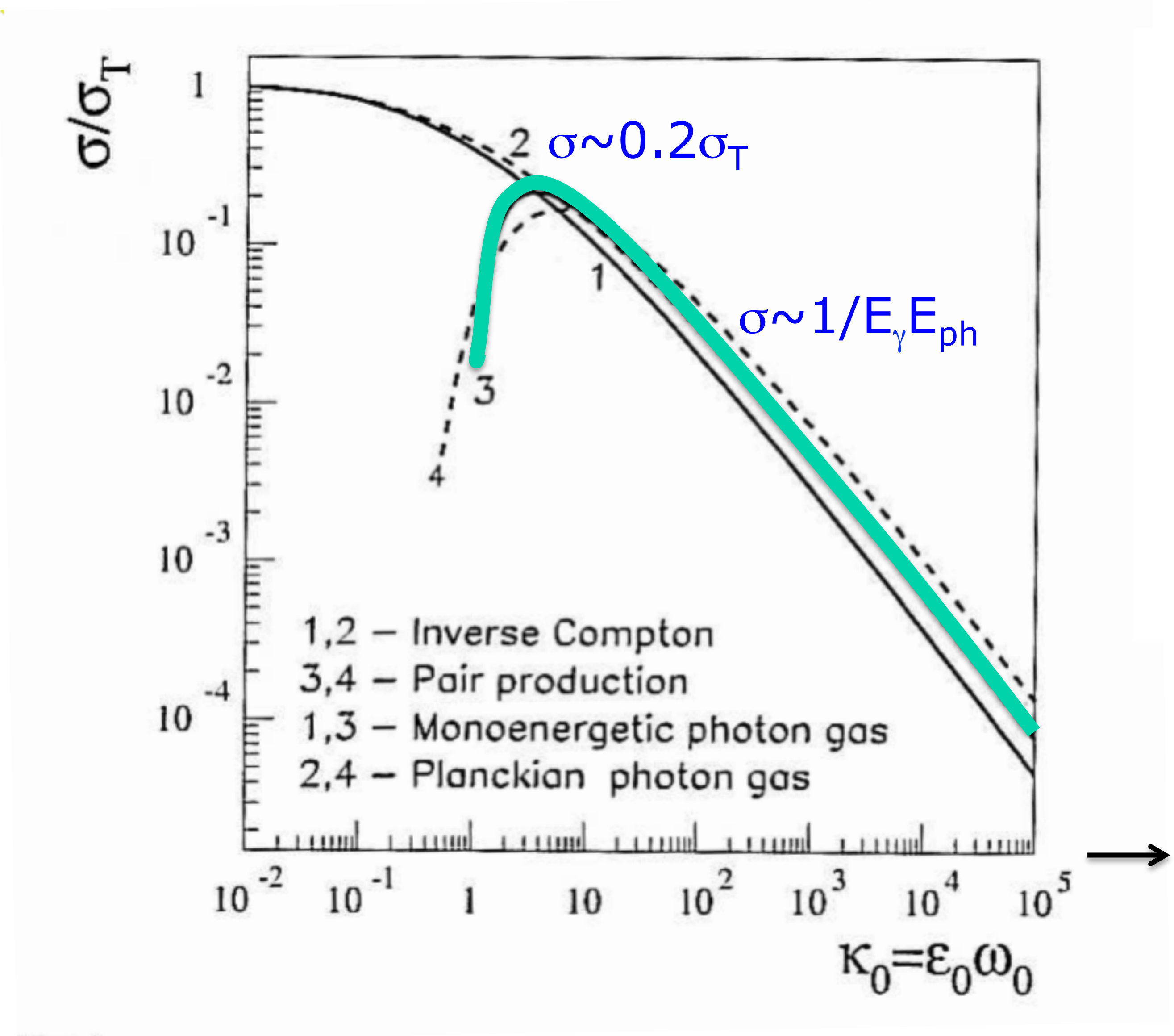
➜ Near-threshold regime dominates

TeV gamma rays in the Galaxy:
target density ~1 eV/cm^3
or ~1 photon/cm^3
assume Thomson cross section
($6 \cdot 10^{-25}$ cm^2) as upper limit

➜ Mpc range (10^{24} cm)

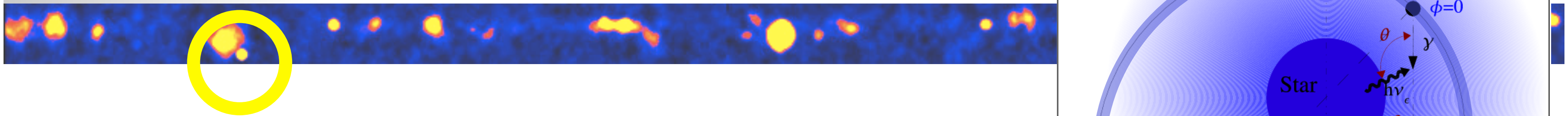
'bit more precise

Aharonian, VHE Cosmic Gamma Radiation,
World Scientific, p. 117

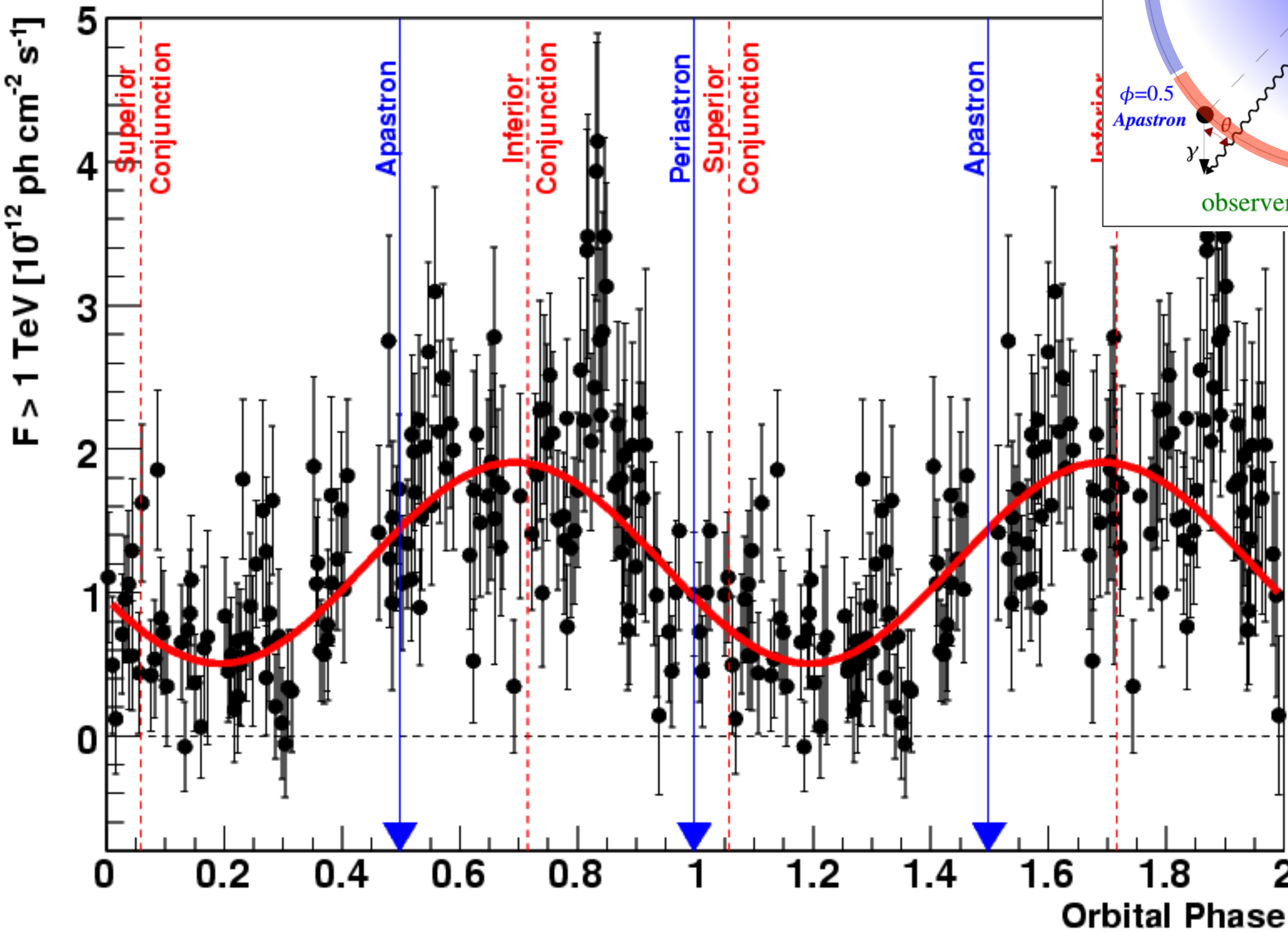


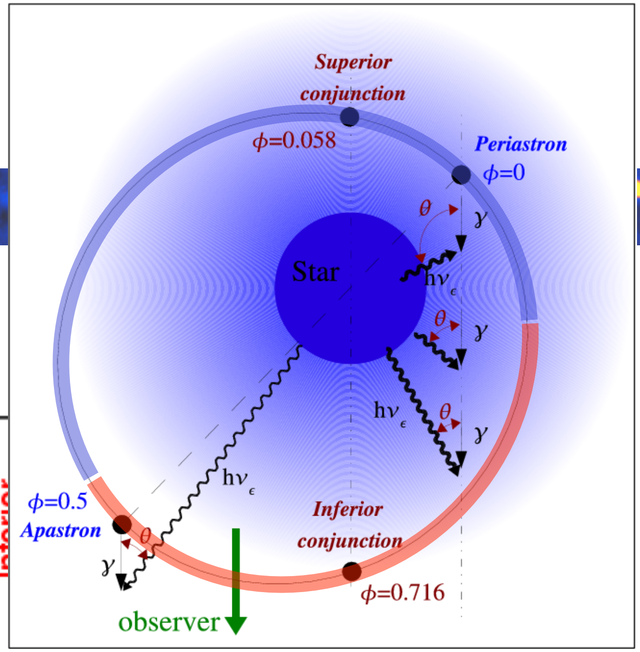
→ photon energy scaled to threshold energy

Source opacity: LS 5039



γ-Period: 3.908±0.002 days

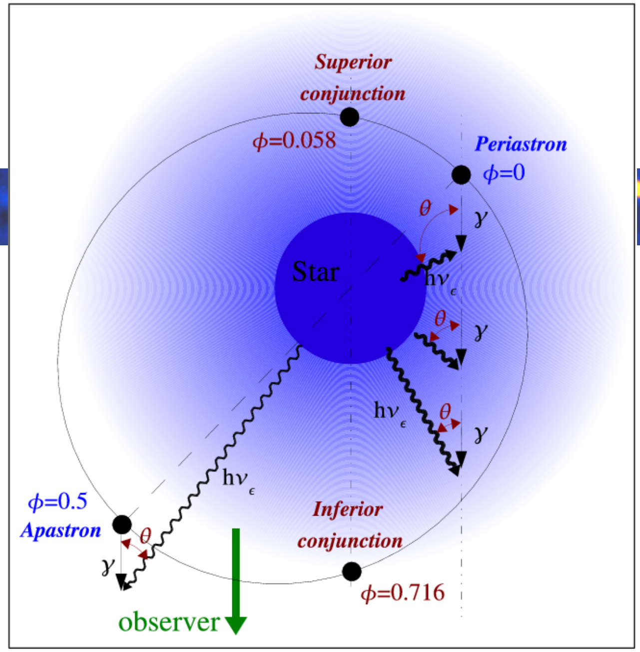




Binary LS 5039
VHE gamma-ray light curve folded using optical period

Data repeated for 2 cycles

H.E.S.S., astro-ph/0607192



20 solar mass star,
Radius ~7·10^{11} cm,
Luminosity ~10^{39} ergs/s
Orbit radius ~2·10^{12} cm
Energy density ρ of starlight?

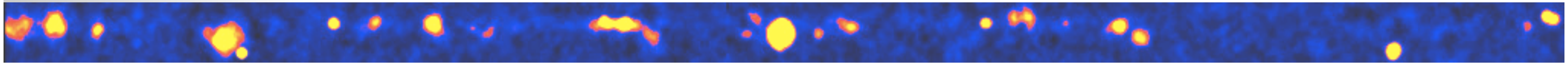
$$L = 4\pi r^2 \rho c \quad \rightarrow \quad \rho \approx \frac{2\cdot 10^3}{r_{12}^2}\ \mathrm{erg/cm^3} \approx \frac{10^{15}}{r_{12}^2}\ \mathrm{ph/cm^3}$$

$$\int \rho\, ds \approx 10^{27}\mathrm{ph/cm^2}$$

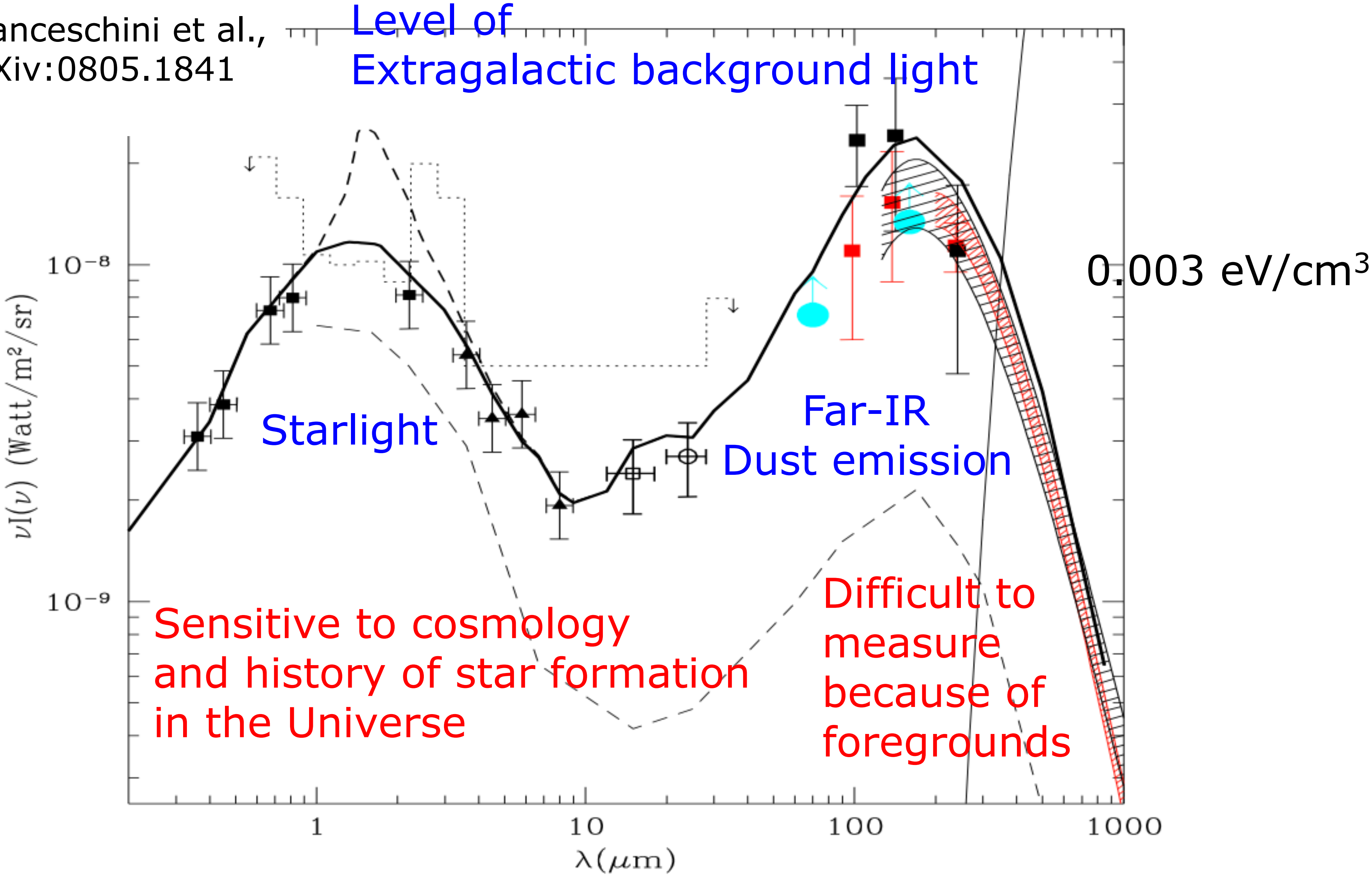
$$\sigma_T \approx 6\cdot 10^{-25}\mathrm{cm^2}; \qquad \sigma_T \int \rho\, ds >> 1$$

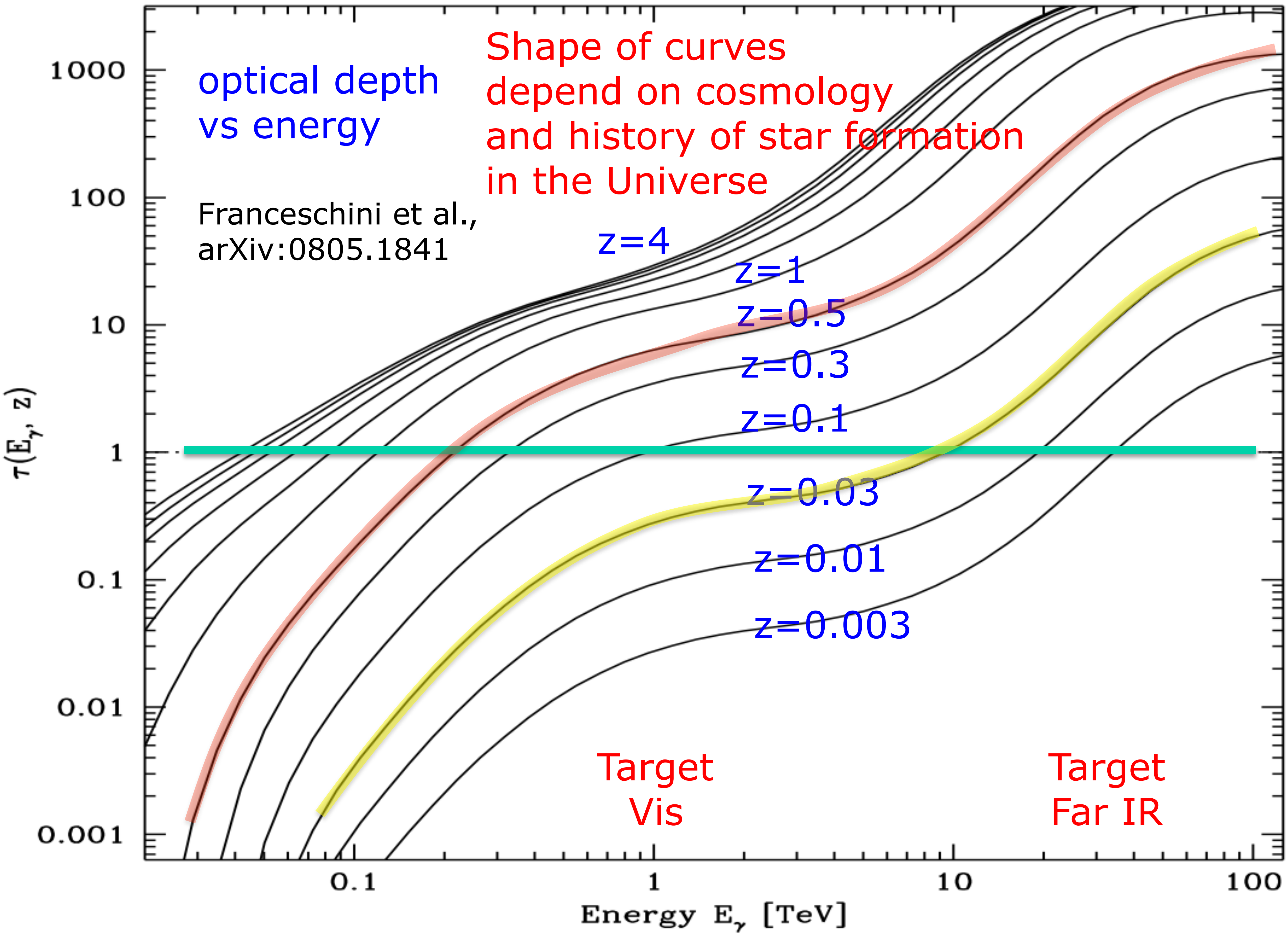
All TeV gamma rays from back side or orbit pair-produce

Extragalactic propagation



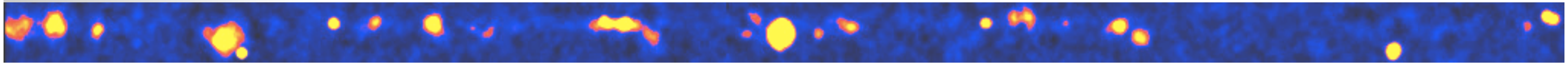
Franceschini et al., arXiv:0805.1841





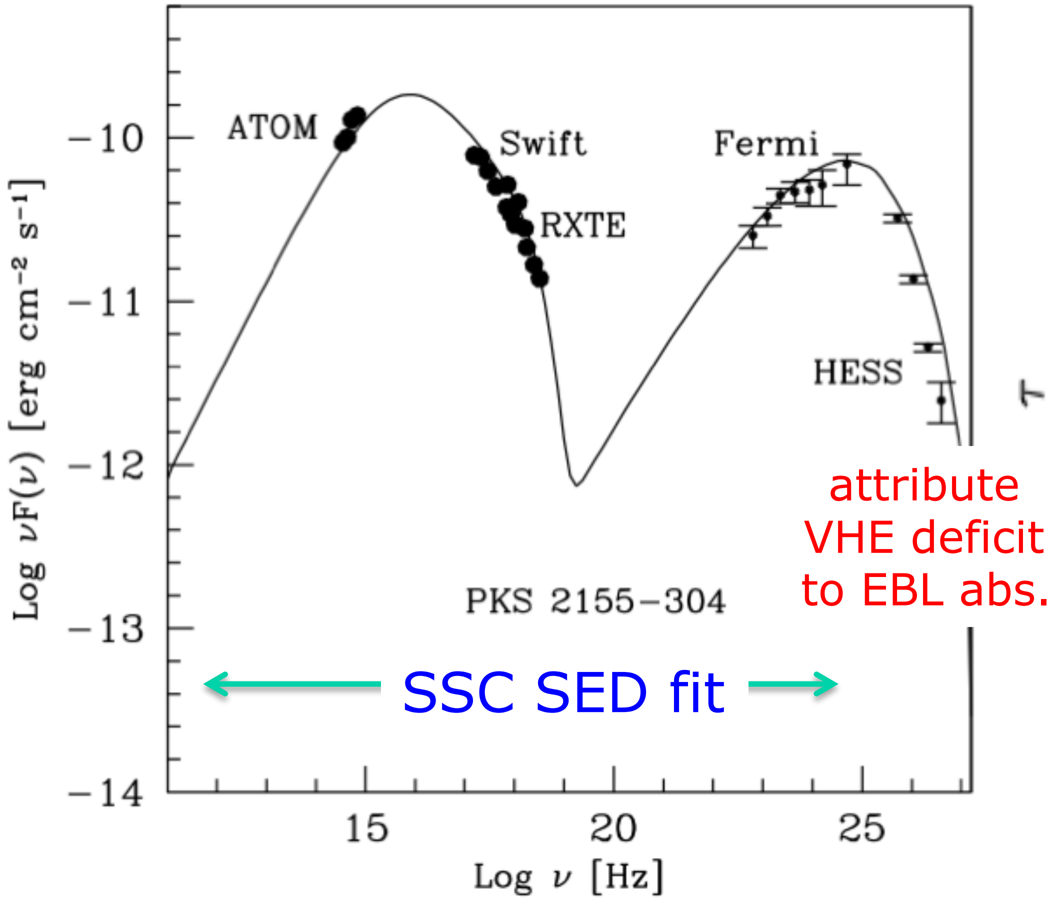
optical depth
vs energy
Shape of curves
depend on cosmology
and history of star formation
in the Universe
Franceschini et al.,
arXiv:0805.1841
z=4
z=1
z=0.5
z=0.3
z=0.1
z=0.03
z=0.01
z=0.003
Target
Vis
Target
Far IR
1000
100
10
1
0.1
0.01
0.001
0.1
1
10
100
τ(Eγ, z)
Energy Eγ [TeV]

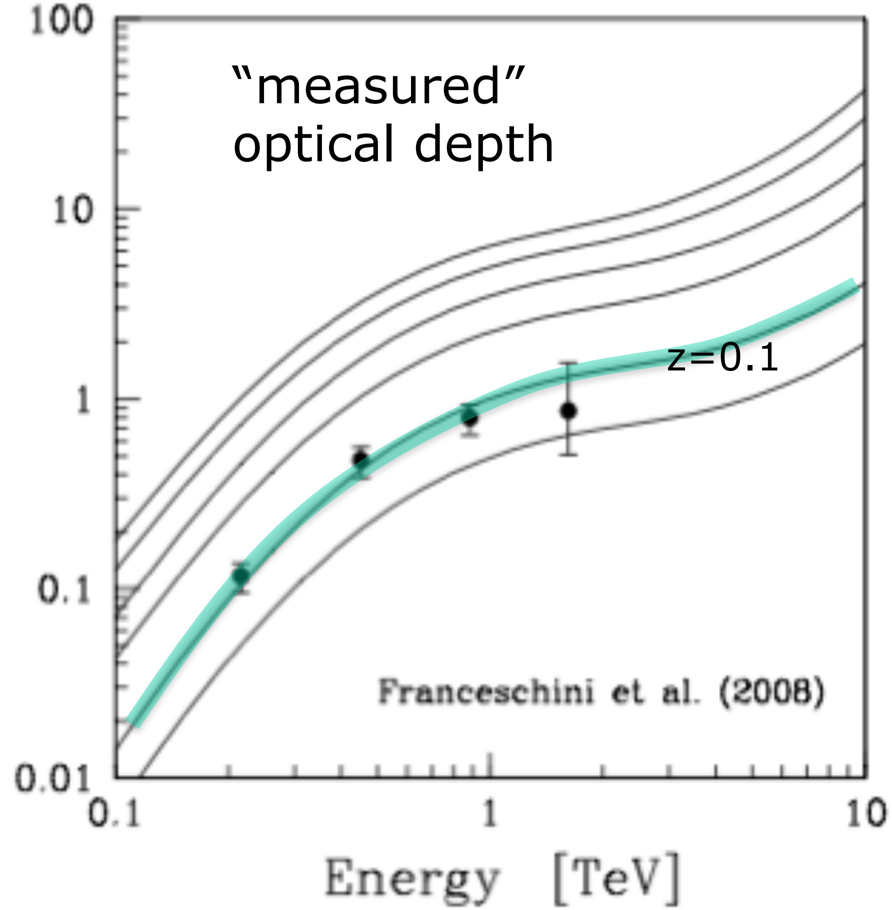
Measurement of EBL density



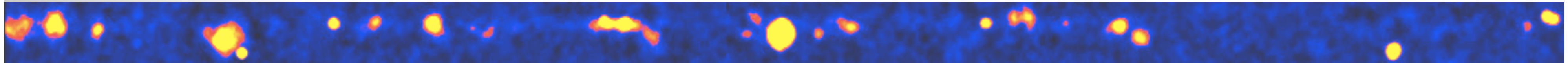
from gamma-ray attenuation

e.g. arXiv:1004.2032
and references there





less model-dependent limits:



Mazin & Raue astro-ph/0701694