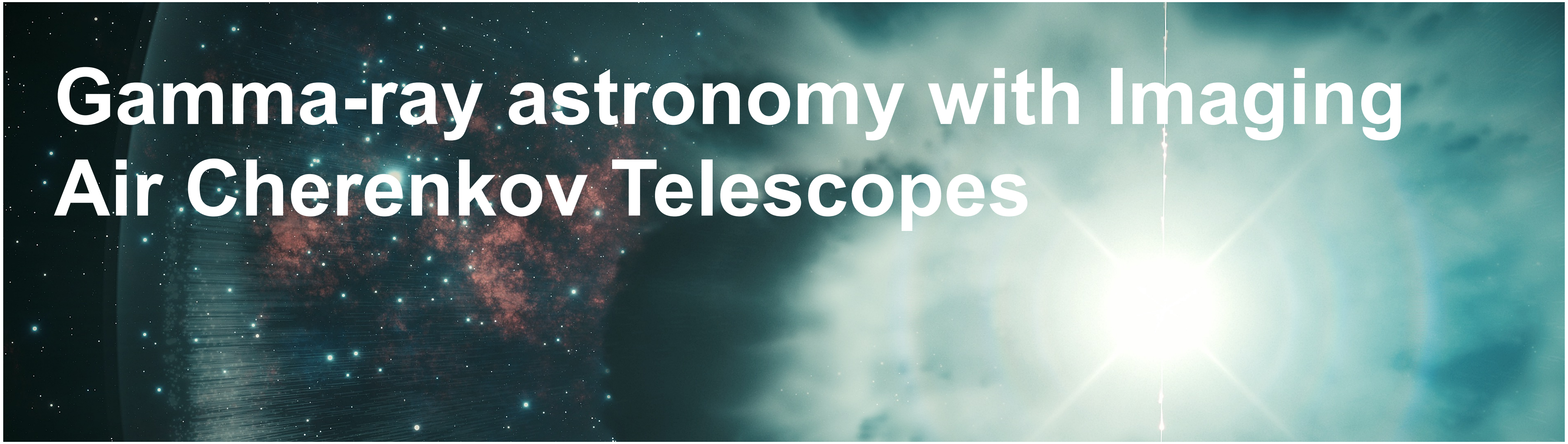


Gamma-ray astronomy with Imaging Air Cherenkov Telescopes

Christian Stegmann
International School of Cosmic Ray Astrophysics
Erice, July, 2022

1912: The discovery of comic rays

The 5th balloon flight – 7.8.1912

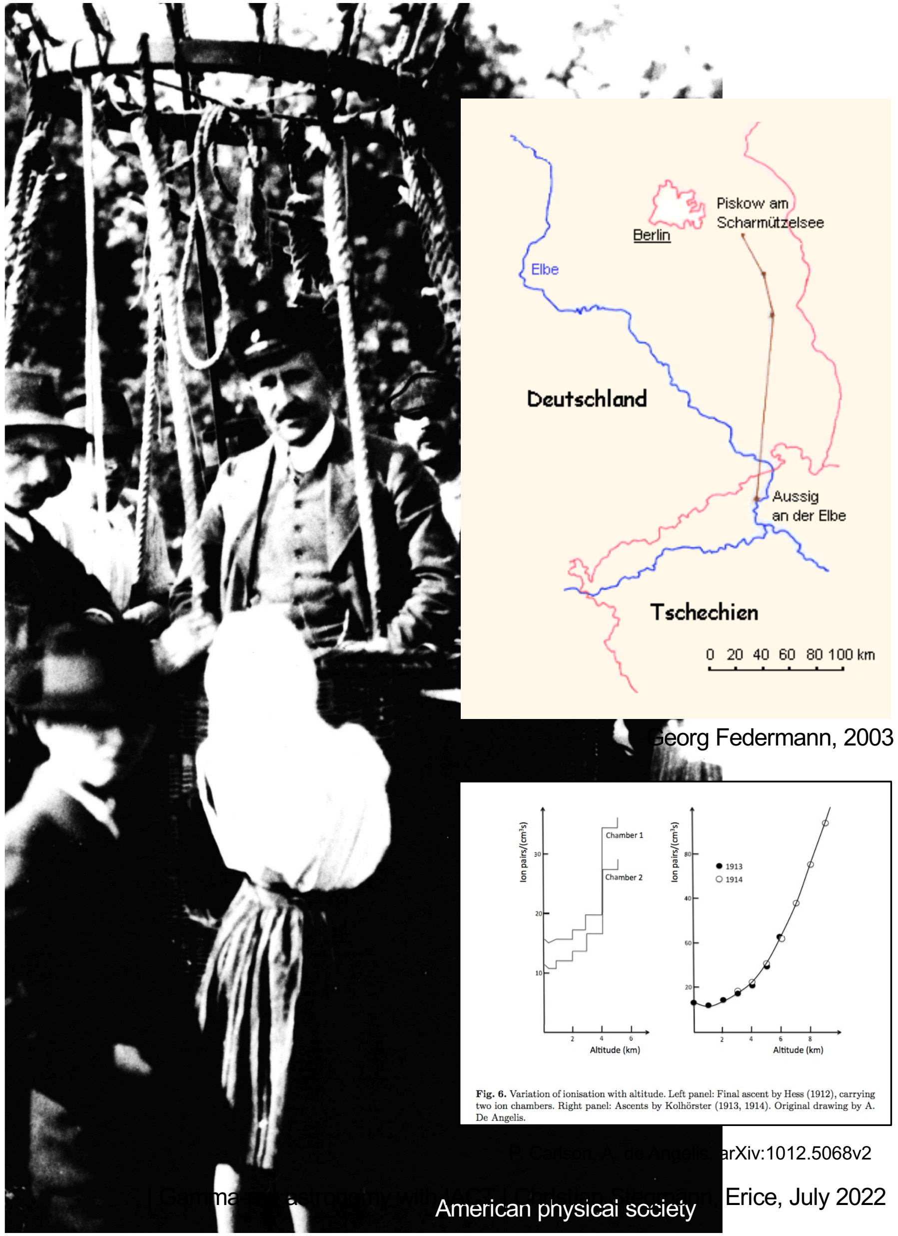


Fig. 6. Variation of ionisation with altitude. Left panel: Final ascent by Hess (1912), carrying two ion chambers. Right panel: Ascents by Kolhörster (1913, 1914). Original drawing by A. De Angelis.

P. Carlson, A. de Angelis, arXiv:1012.5068v2

Über Beobachtungen der durchdringenden Strahlung bei sieben Freiballonfahrten
Von V. F. Hess
(Physik. Zeitschr. **14**, 1084, 1912)

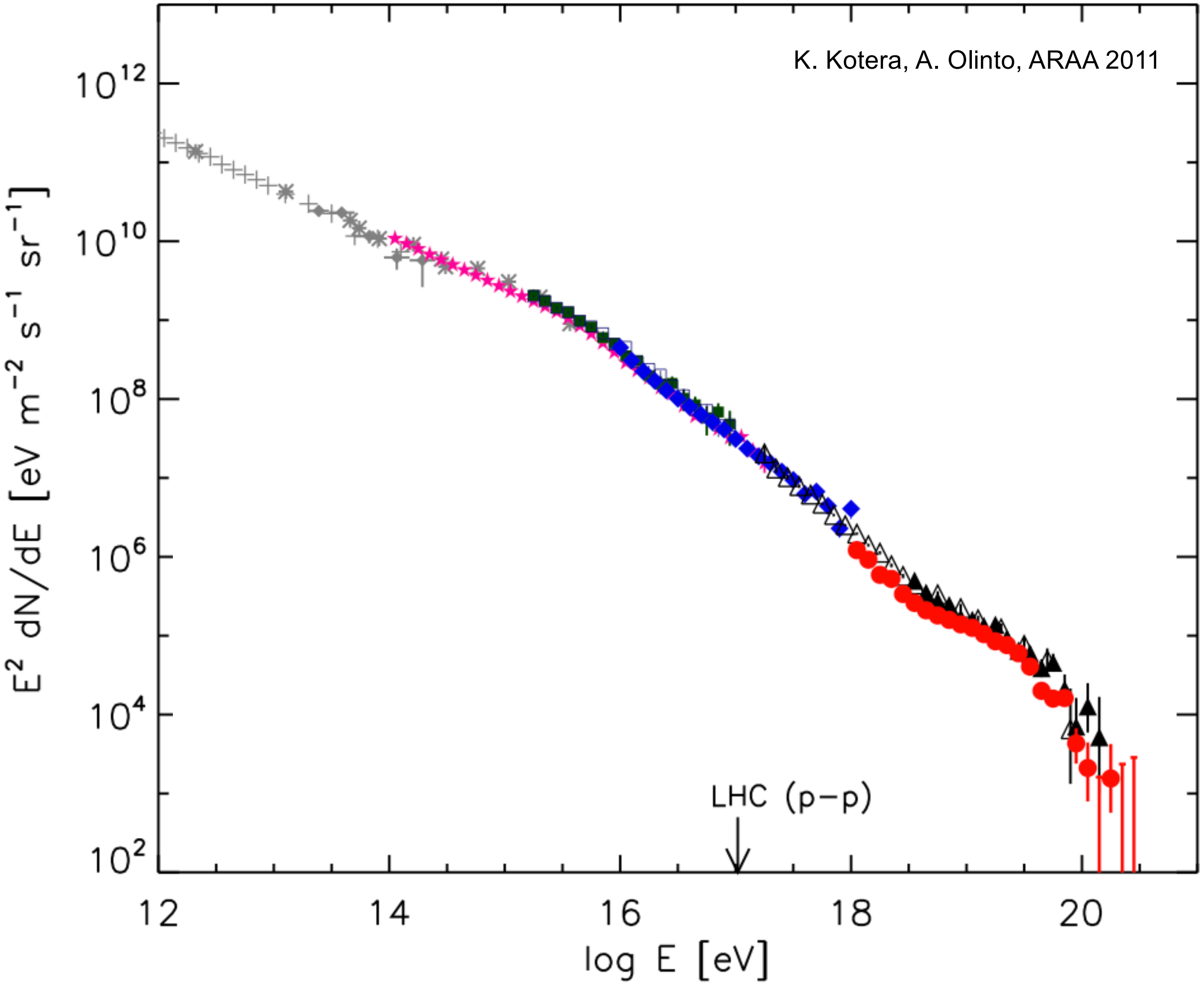
[...]

Die Ergebnisse der vorliegenden Beobachtungen scheinen am ehesten durch die Annahme erklärt werden zu können, daß eine Strahlung von sehr hoher Durchdringungskraft von oben her in unsere Atmosphäre eindringt und auch noch in den untersten Schichten einen Teil der in geschlossenen Gefäßen beobachteten Ionisation hervorruft.

[...]

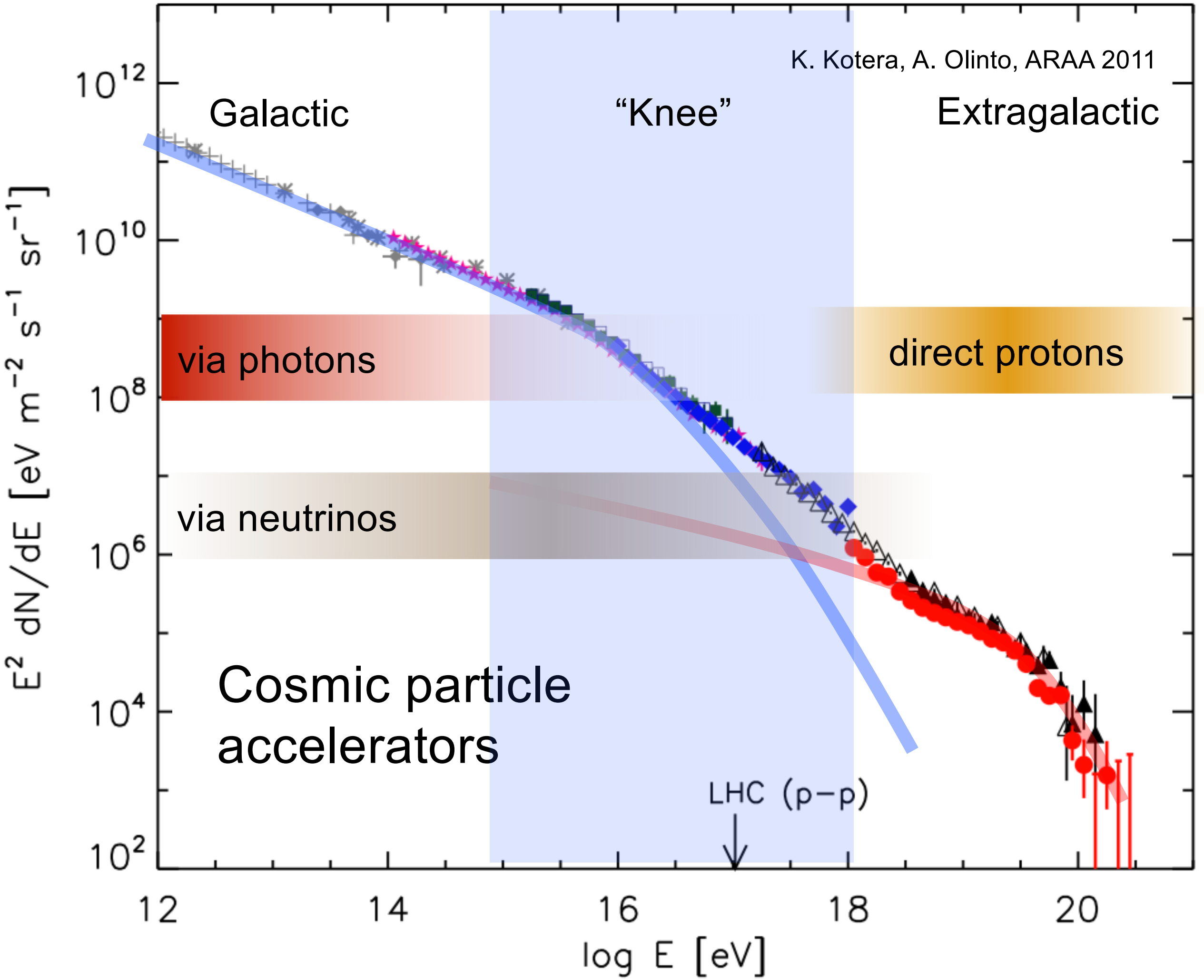
The results of the available observations seem to be best explained by the assumption that a radiation of very high penetrating power penetrates our atmosphere from above and causes a part of the ionization observed in closed vessels even in the lowest layers.

The Spectrum of Cosmic Rays

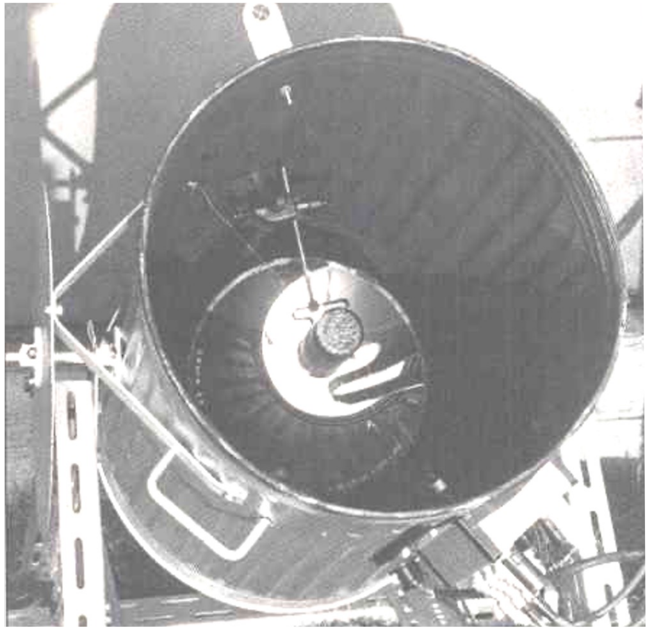
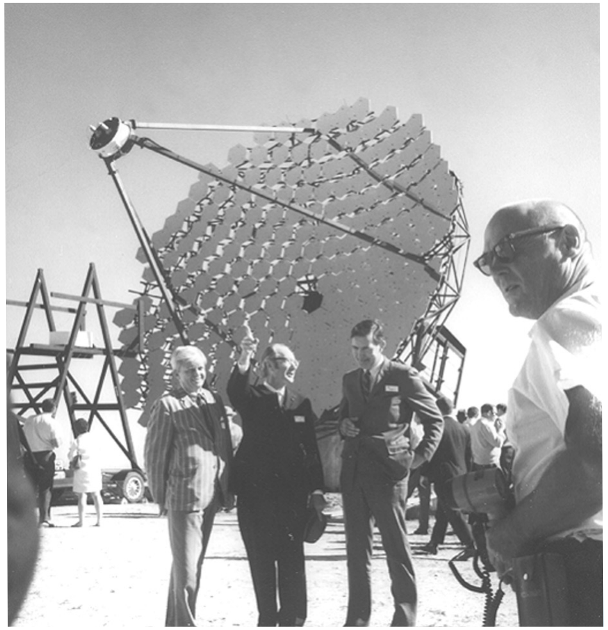
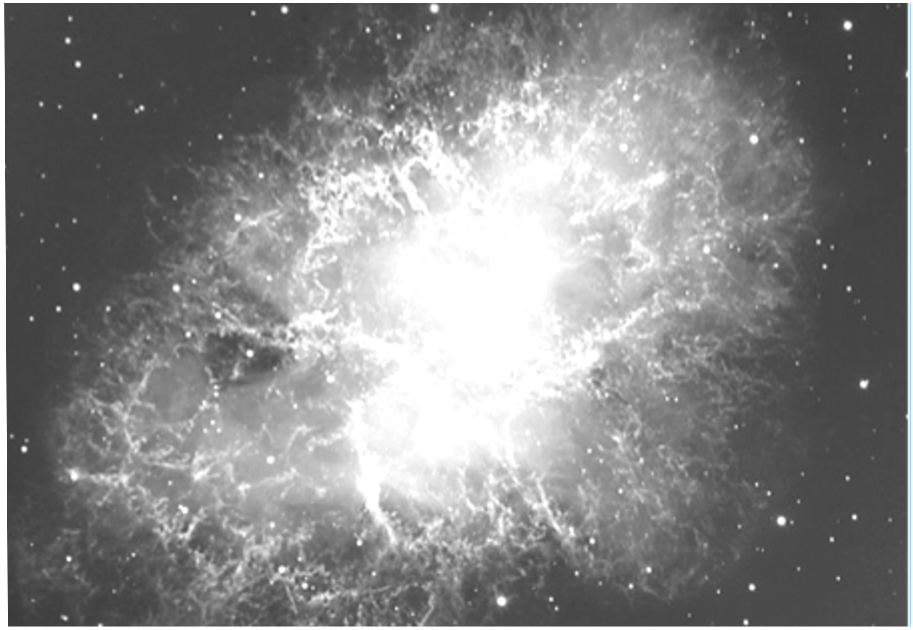


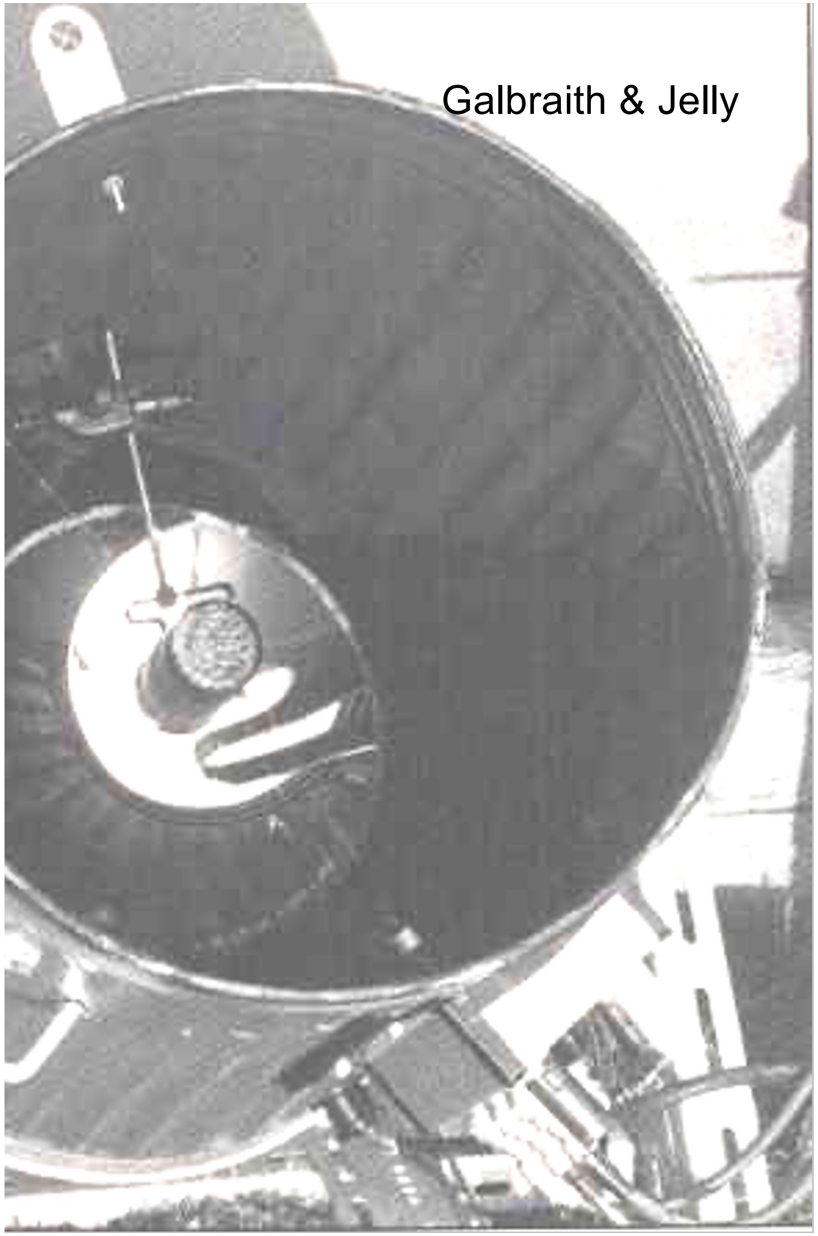
The Spectrum of Cosmic Rays

- Protons
  - directly produced in the sources
- **Photons (Gamma-rays)**
  - from protons:
    pion-decay: $\pi^0 \rightarrow \gamma\gamma$
  - from electrons:
    Inverse Compton Scattering: $e^\pm \gamma \rightarrow e^\pm \gamma$
- Neutrinos
  - from protons:
    pion-decay: $\pi^\pm \rightarrow \mu^\pm \nu_\mu$



1953 – 2004
The beginnings

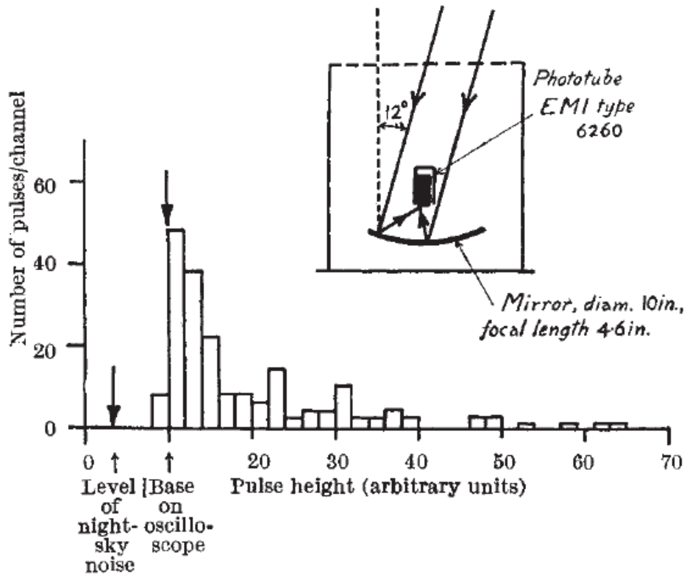


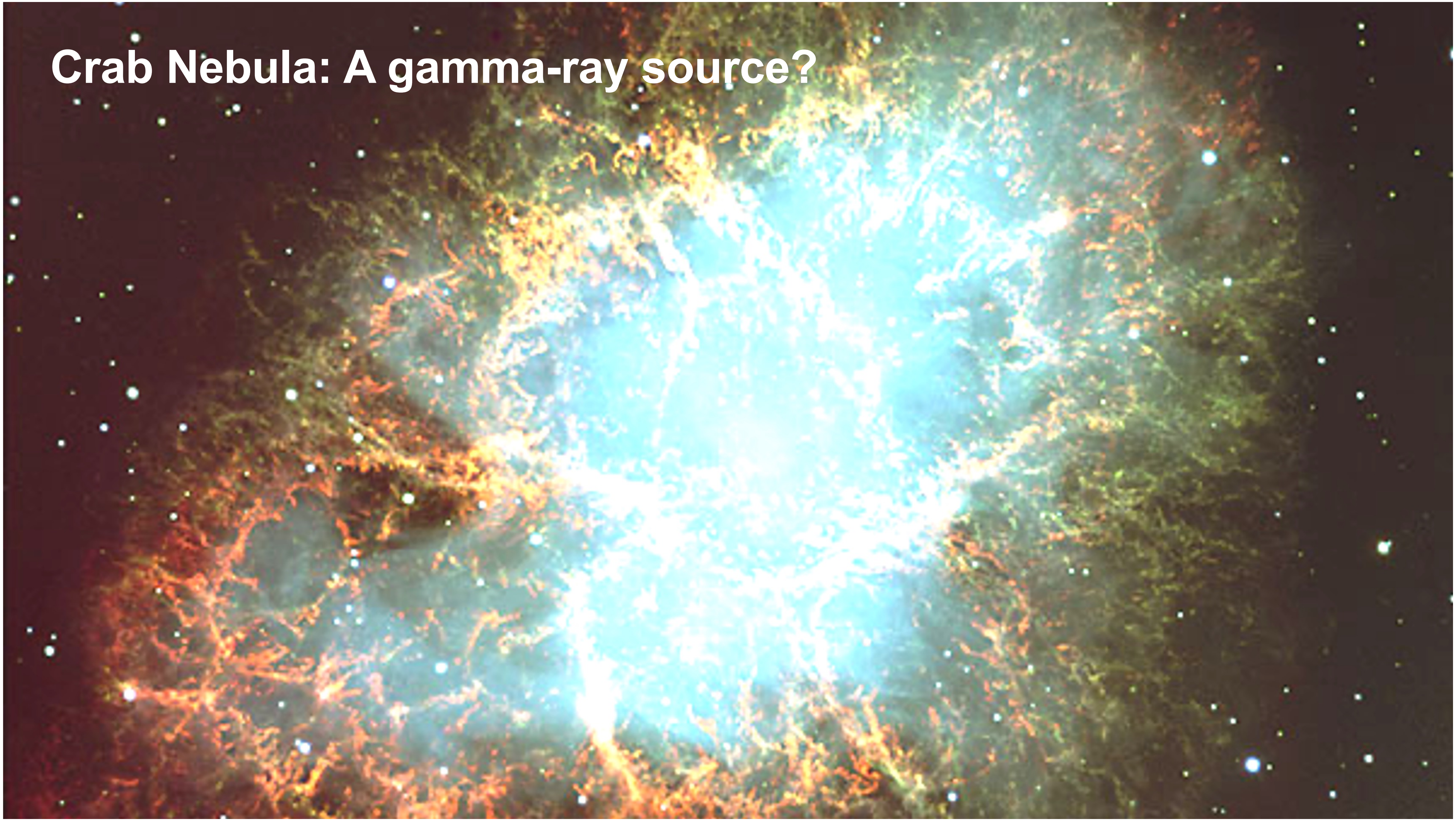
1953: The Beginning

February 21, 1953 NATURE

Light Pulses from the Night Sky associated with Cosmic Rays

In 1948, Blackett[1] suggested that a contribution approximately 10^{-4} of the mean light of the night-sky might be expected from Čerenkov radiation[2] produced in the atmosphere by the cosmic radiation. The purpose of this communication is to report the results of some preliminary experiments we have made using a photomultiplier, which revealed the




Crab Nebula: A gamma-ray source?


A big thank you to all those
who provided me with material
for the preparation, especially
Werner Hofmann

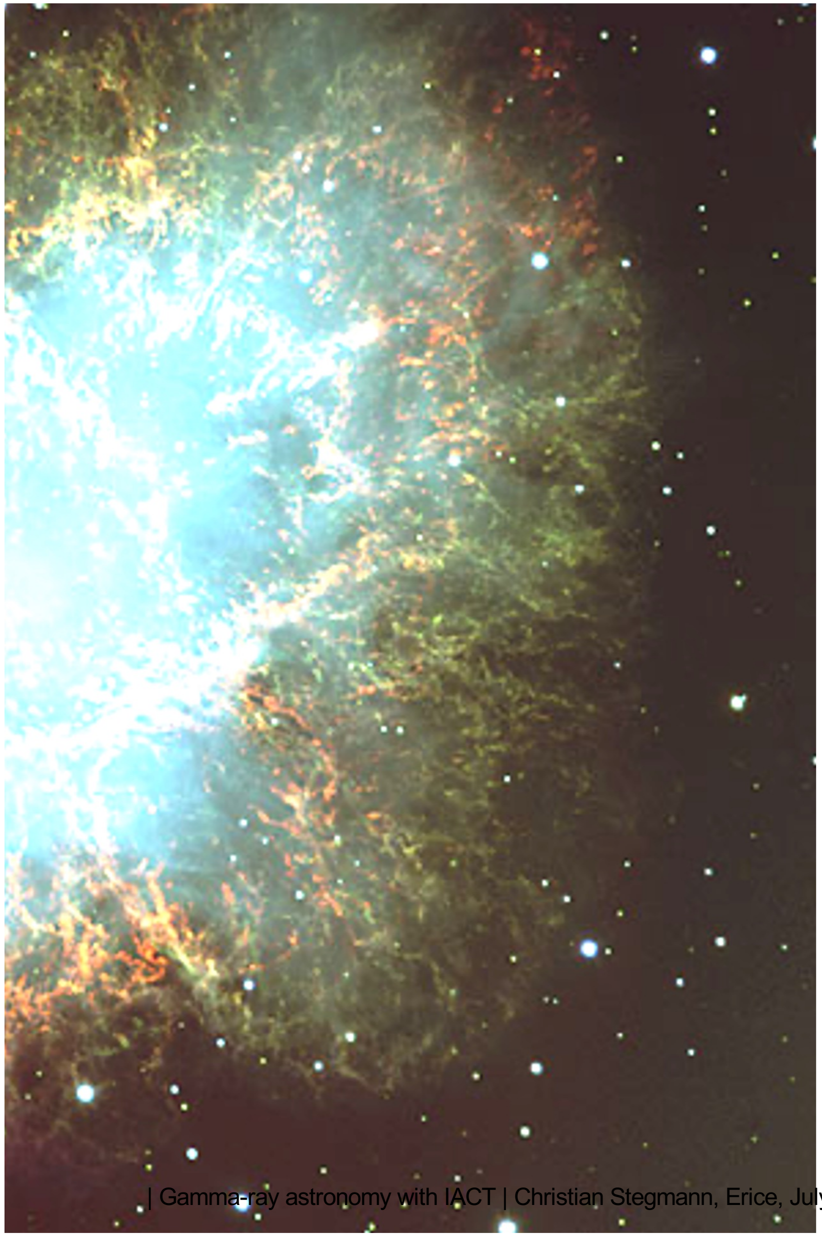
Useful units, numbers, dimensions

Energy and 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: $r_{pc} \approx E_{PeV}/B_{\mu G}$



Visibility of the Crab Nebula in Gamma-rays

Crab pulsar

- Distance ~6500 Ly
- spin-down power $\dot{E} \sim 5\times10^{38}$erg/s = 8×10^{38}TeV/s

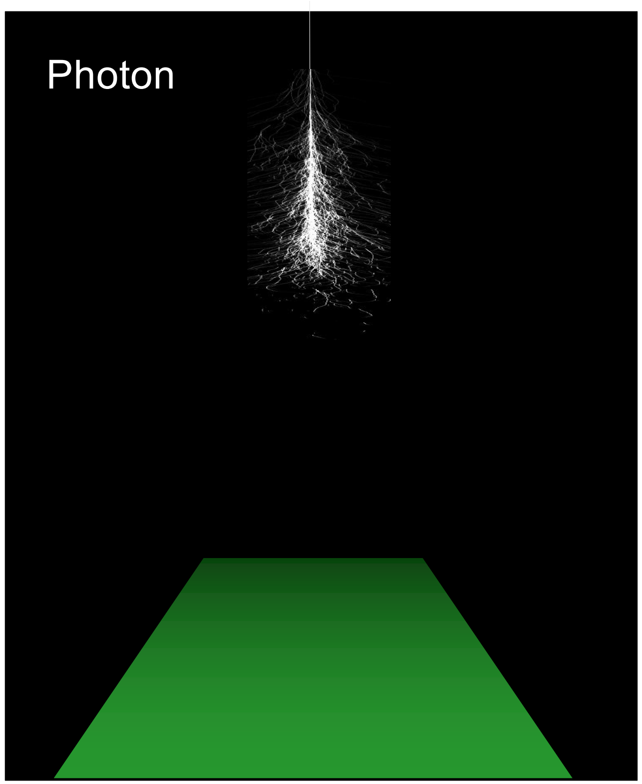
Assume

- Conversion efficiency $\eta = \frac{\mathcal{L}_\gamma}{\dot{E}} = 0.01\%$ in gamma-rays at VHE energies
- Isotropic emission
- 100 detected photons for detection (reasonable)
- background-free (somewhat optimistic)

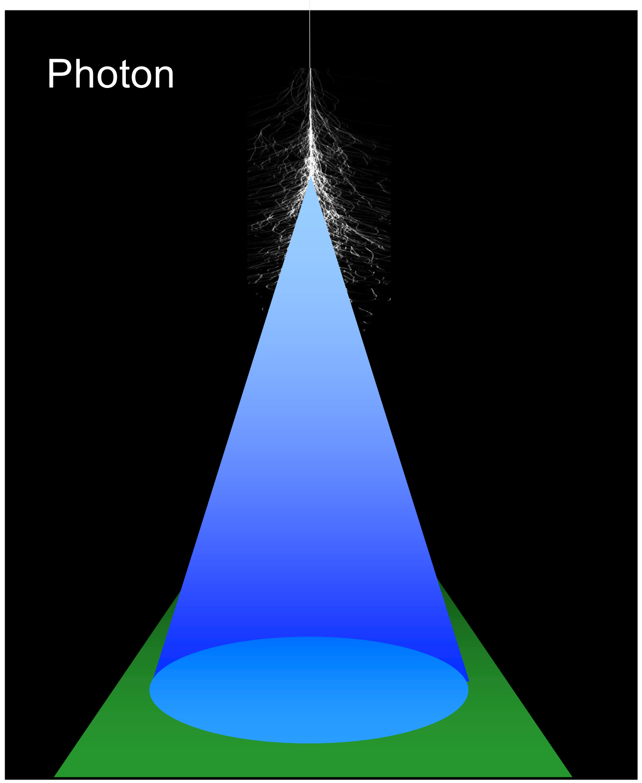
$$\Rightarrow N = \frac{A_{eff}}{A} \times \left(\frac{\dot{E}}{1\ TeV}\right) \times T_{obs}$$

We need a detector with $O(10^5)m^2$ detection area!

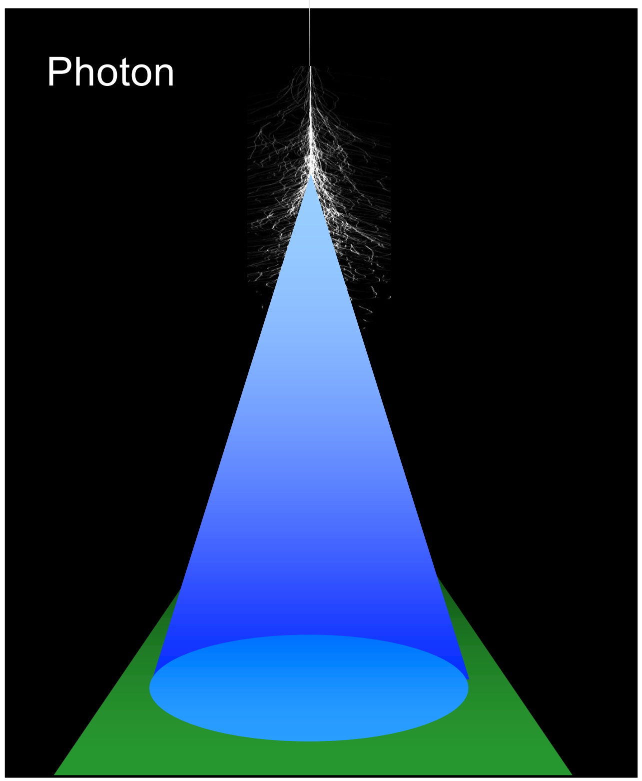
How to measure gamma-rays?



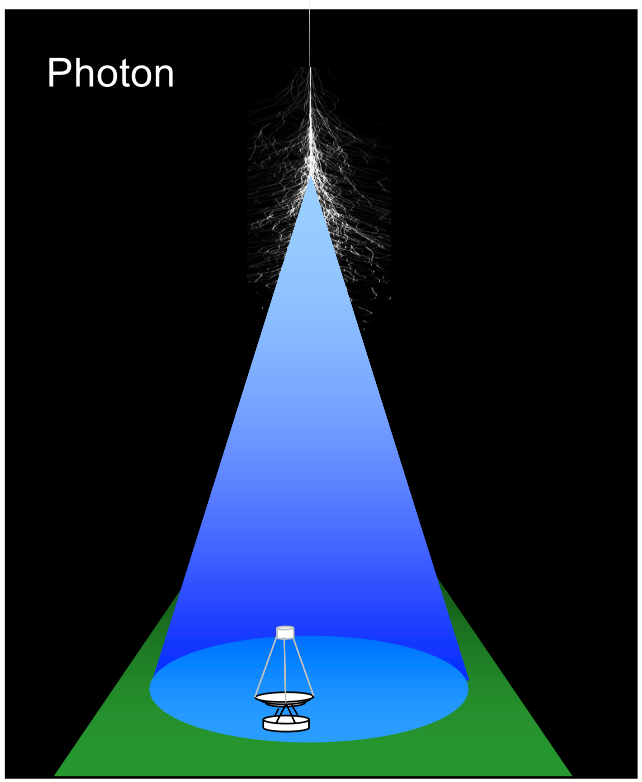
How to measure gamma-rays?

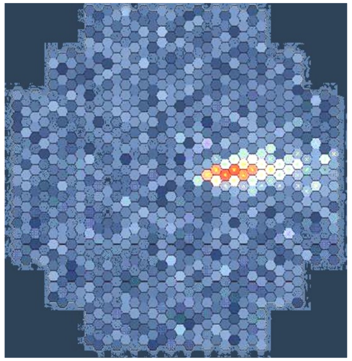


Showers look like meteors



How to measure gamma-rays?





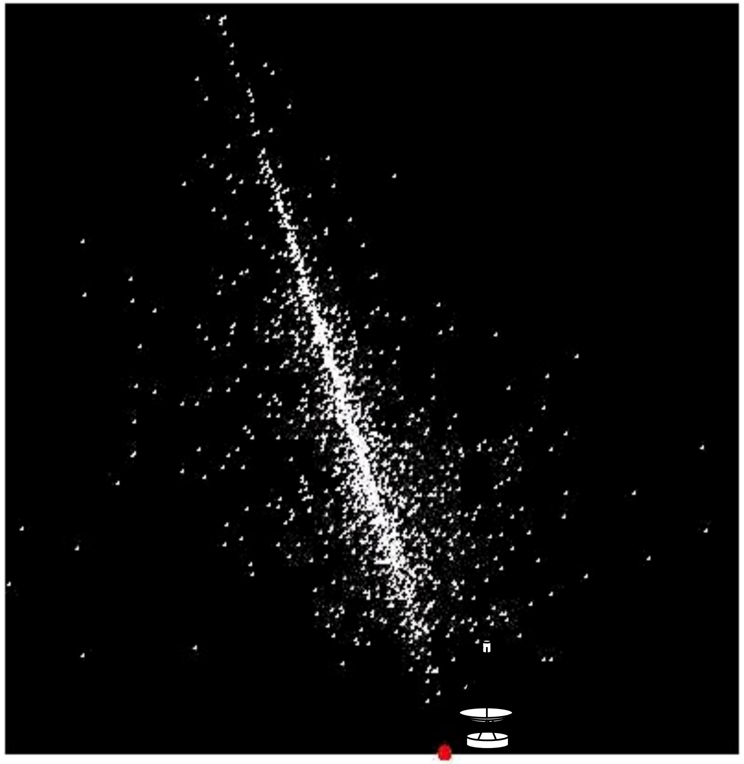
Camera image

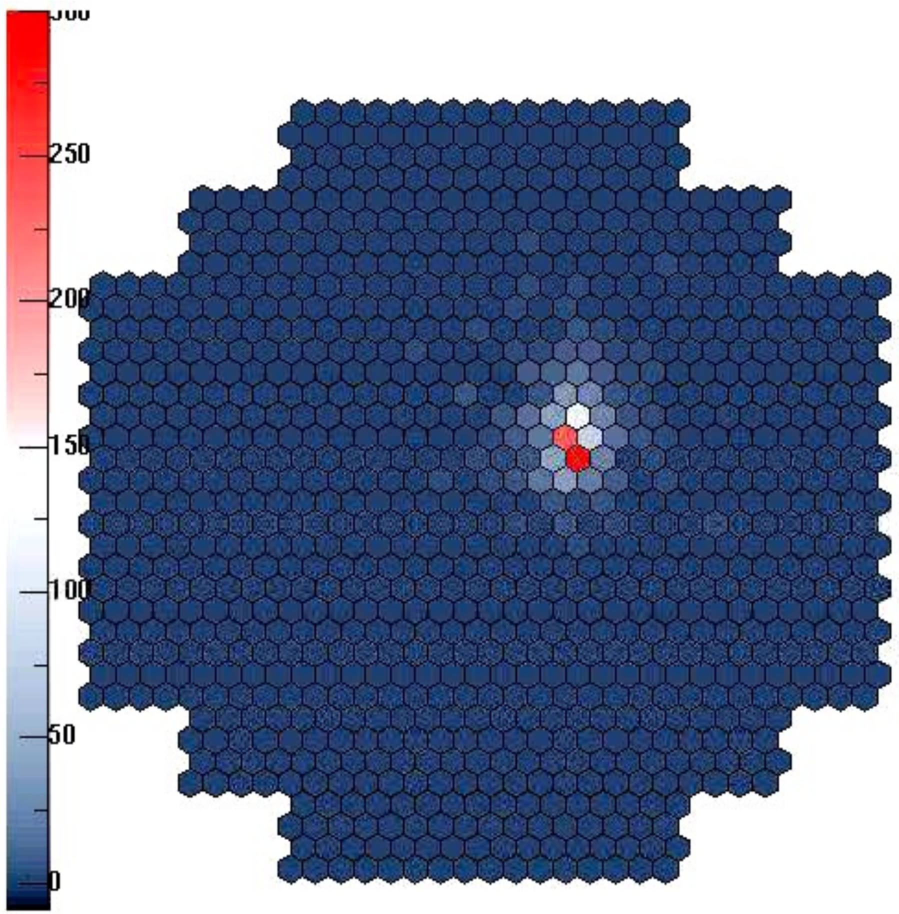
Intensity → Energy

Orientation → Direction

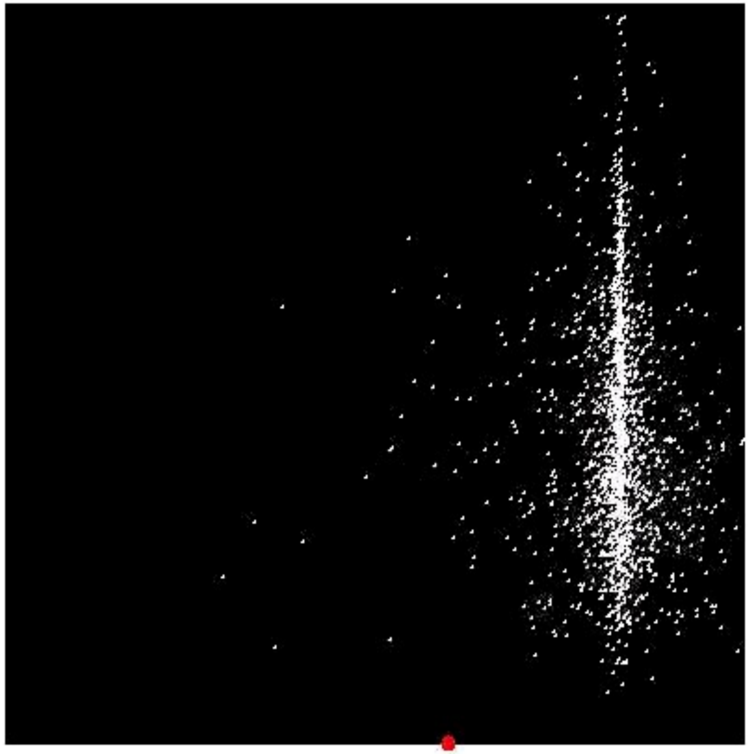
Shape → Primary

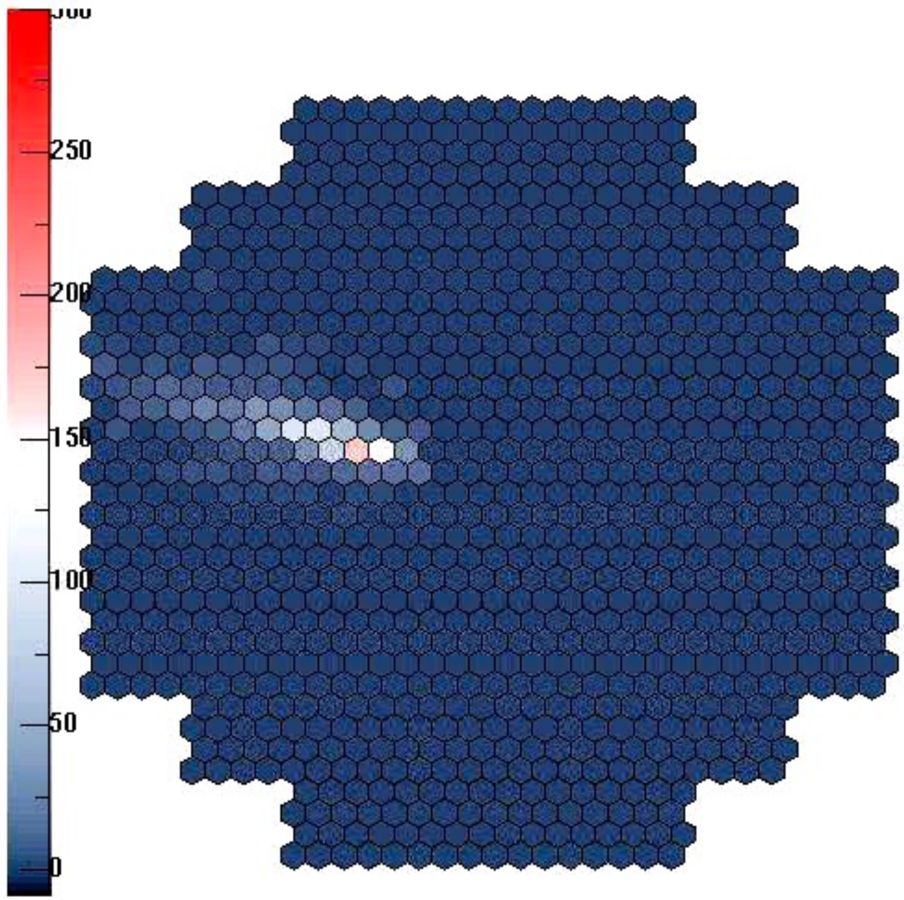
Showers in the camera



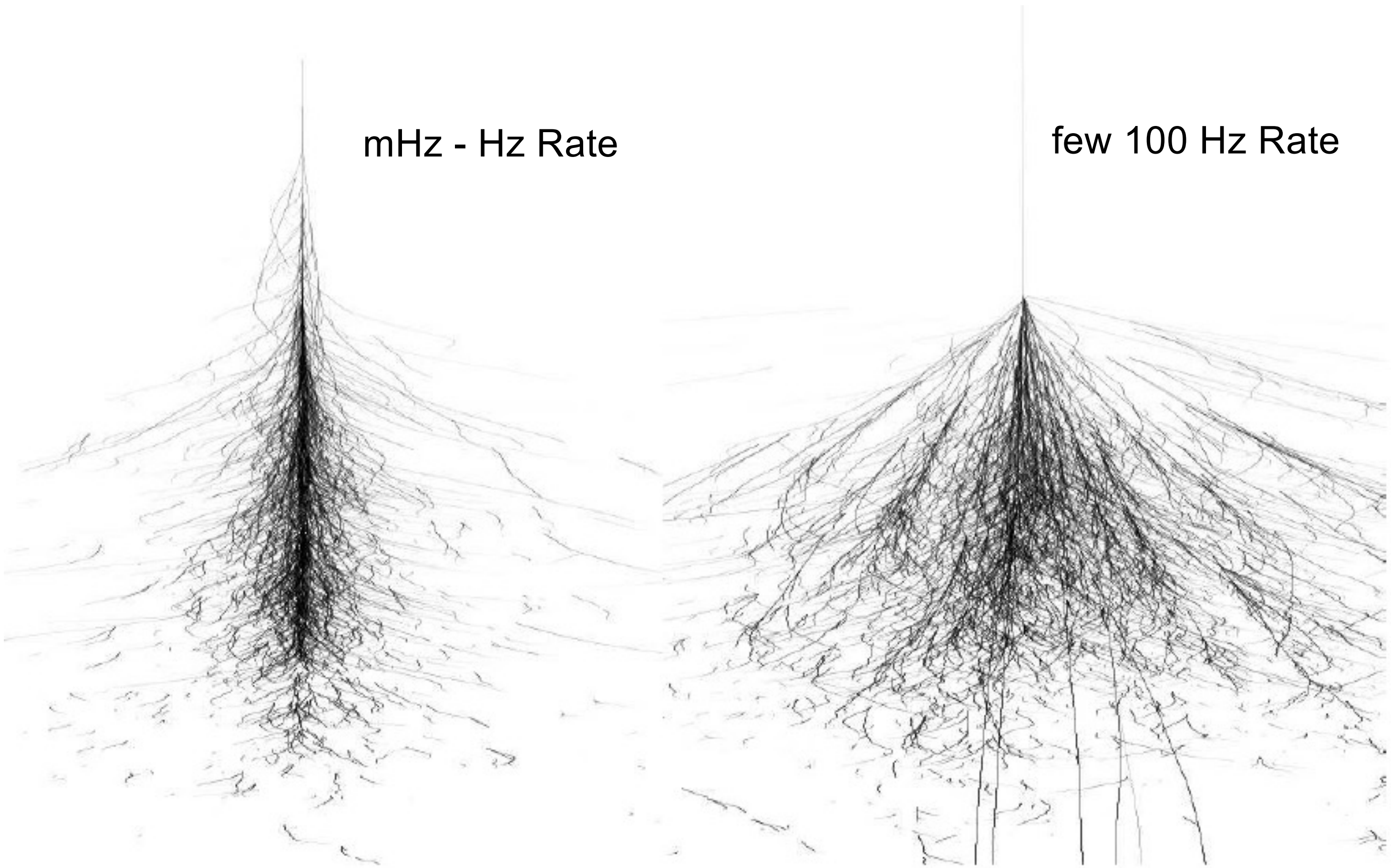


Shower in the camera



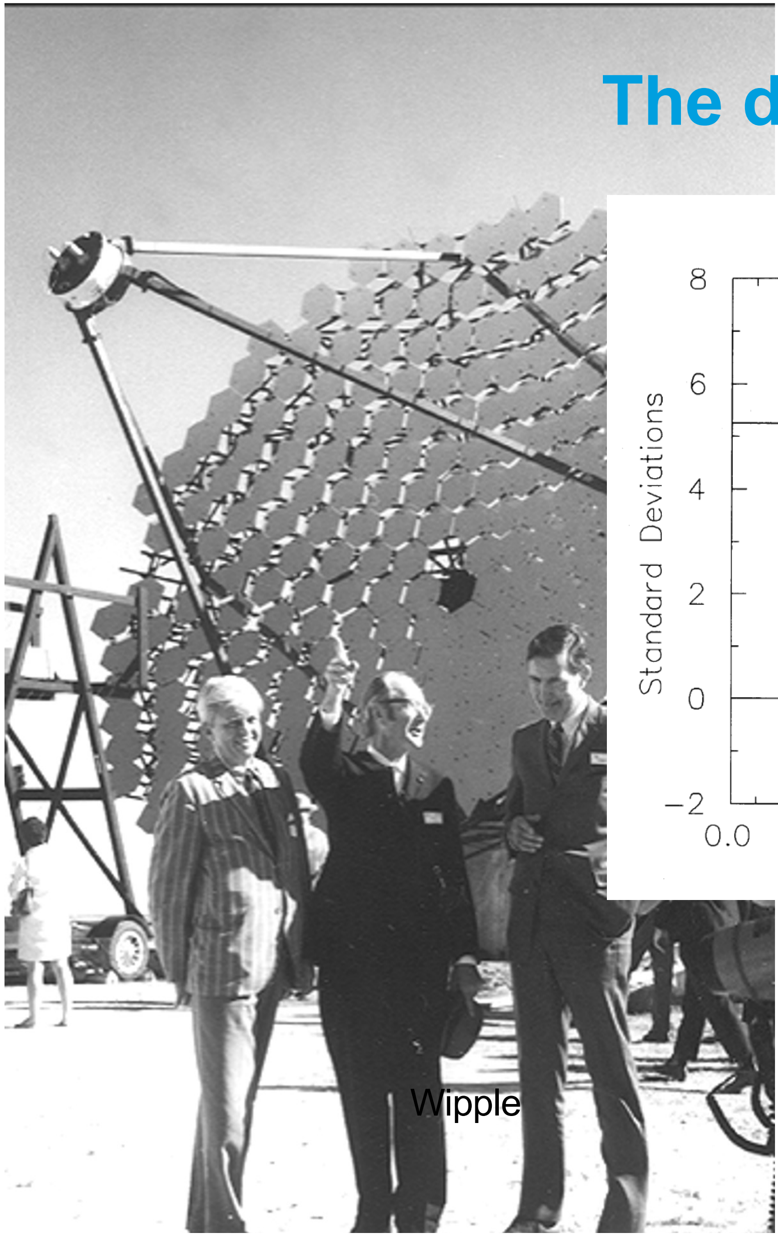


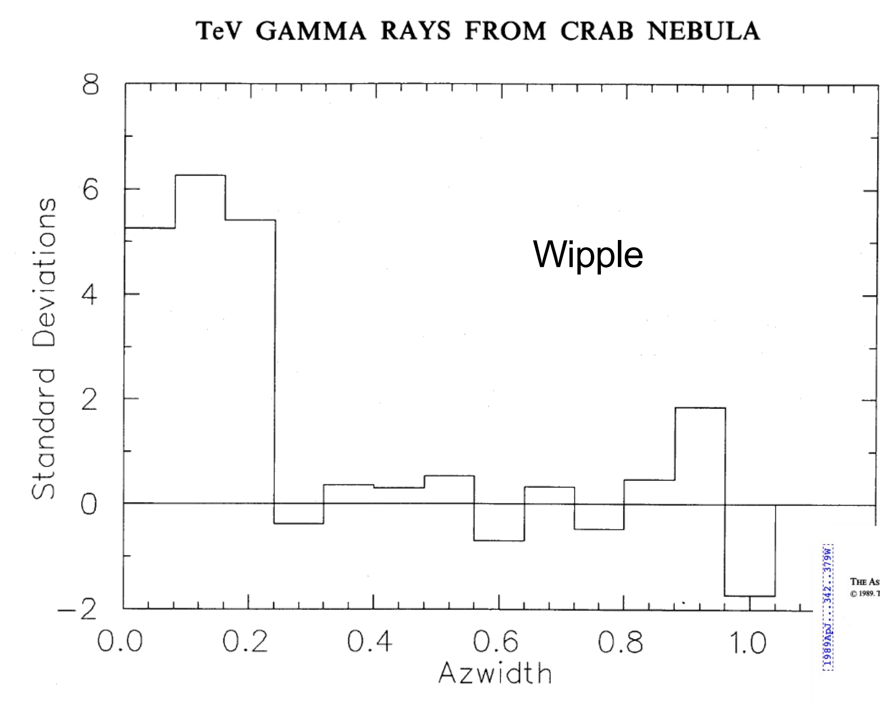
Cosmic ray veto using shower shape

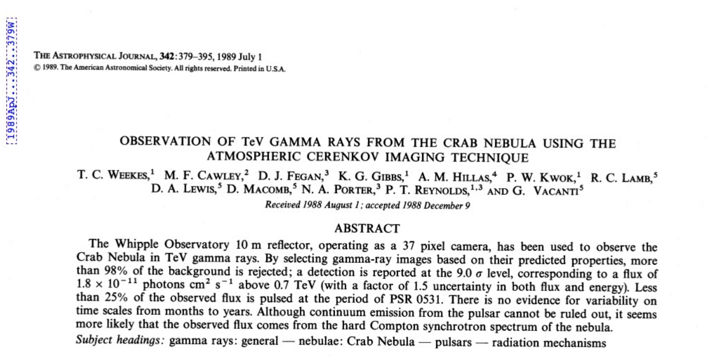


Gamma shower Hadronic shower

The discovery of the Crab Nebula in 1989







1989ApJ...342..379W

THE ASTROPHYSICAL JOURNAL, **342**:379–395, 1989 July 1

OBSERVATION OF TeV GAMMA RAYS FROM THE CRAB NEBULA USING THE ATMOSPHERIC CERENKOV IMAGING TECHNIQUE

T. C. WEEKES,[1] M. F. CAWLEY,[2] D. J. FEGAN,[3] K. G. GIBBS,[1] A. M. HILLAS,[4] P. W. KWOK,[1] R. C. LAMB,[5] D. A. LEWIS,[5] D. MACOMB,[5] N. A. PORTER,[3] P. T. REYNOLDS,[1,3] AND G. VACANTI[5]

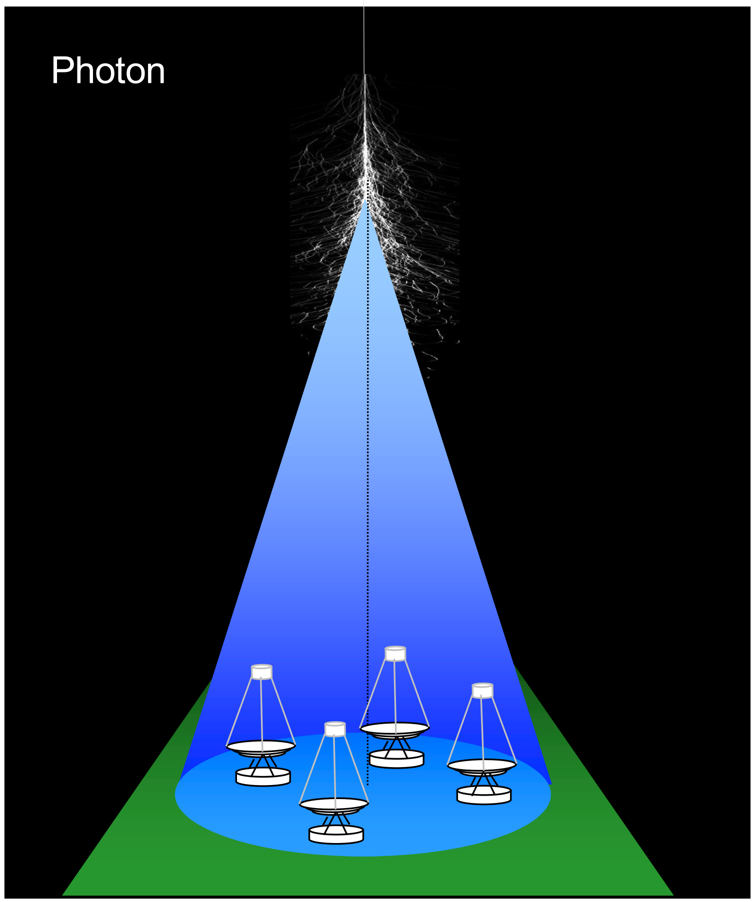
Received 1988 August 1; accepted 1988 December 9

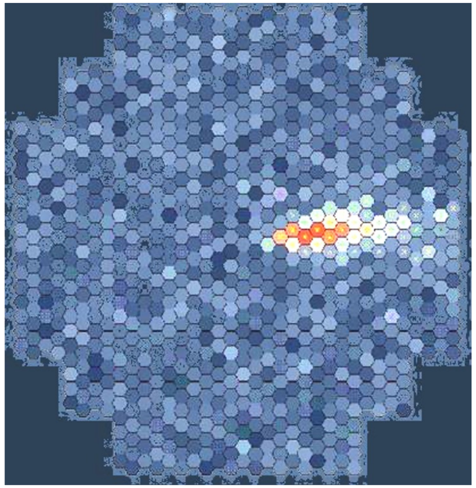
ABSTRACT

The Whipple Observatory 10 m reflector, operating as a 37 pixel camera, has been used to observe the Crab Nebula in TeV gamma rays. By selecting gamma-ray images based on their predicted properties, more than 98% of the background is rejected; a detection is reported at the 9.0 σ level, corresponding to a flux of 1.8×10^{-11} photons cm^2 s^{-1} above 0.7 TeV (with a factor of 1.5 uncertainty in both flux and energy). Less than 25% of the observed flux is pulsed at the period of PSR 0531. There is no evidence for variability on time scales from months to years. Although continuum emission from the pulsar cannot be ruled out, it seems more likely that the observed flux comes from the hard Compton synchrotron spectrum of the nebula.

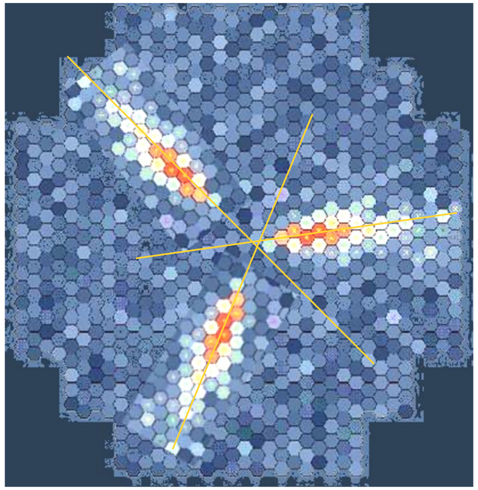
Subject headings: gamma rays: general — nebulae: Crab Nebula — pulsars — radiation mechanisms

How to measure gamma-rays from the ground?





Single telescope event

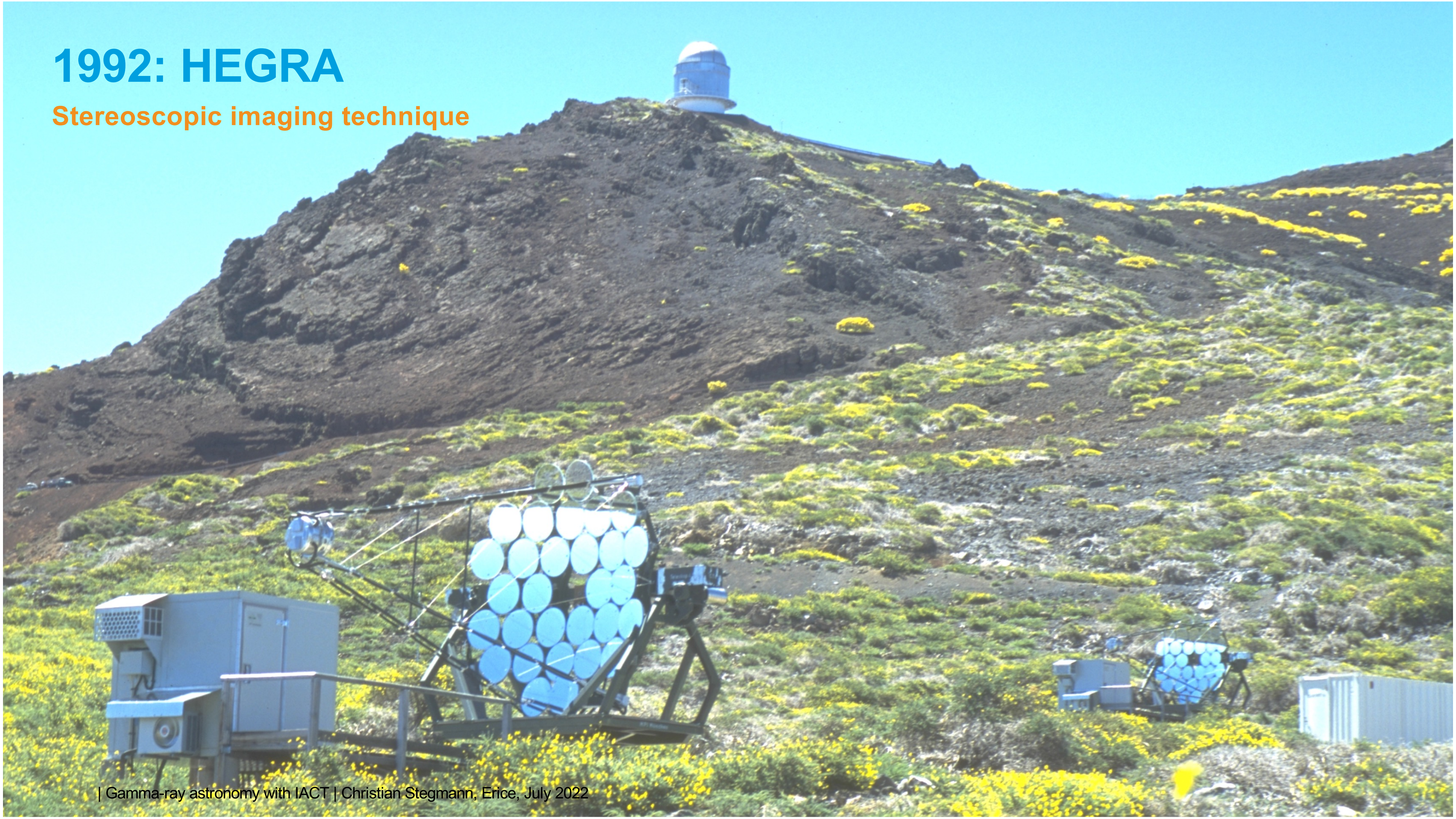


3 telescope image in common camera plane

Intensity	→ Energy
Orientation	→ Direction
Shape	→ Primary particle

1992: HEGRA

Stereoscopic imaging technique



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 luminosity
~$4 \cdot 10^{33}$ erg/s
Crab pulsar spin-down
~$5 \cdot 10^{38}$ erg/s

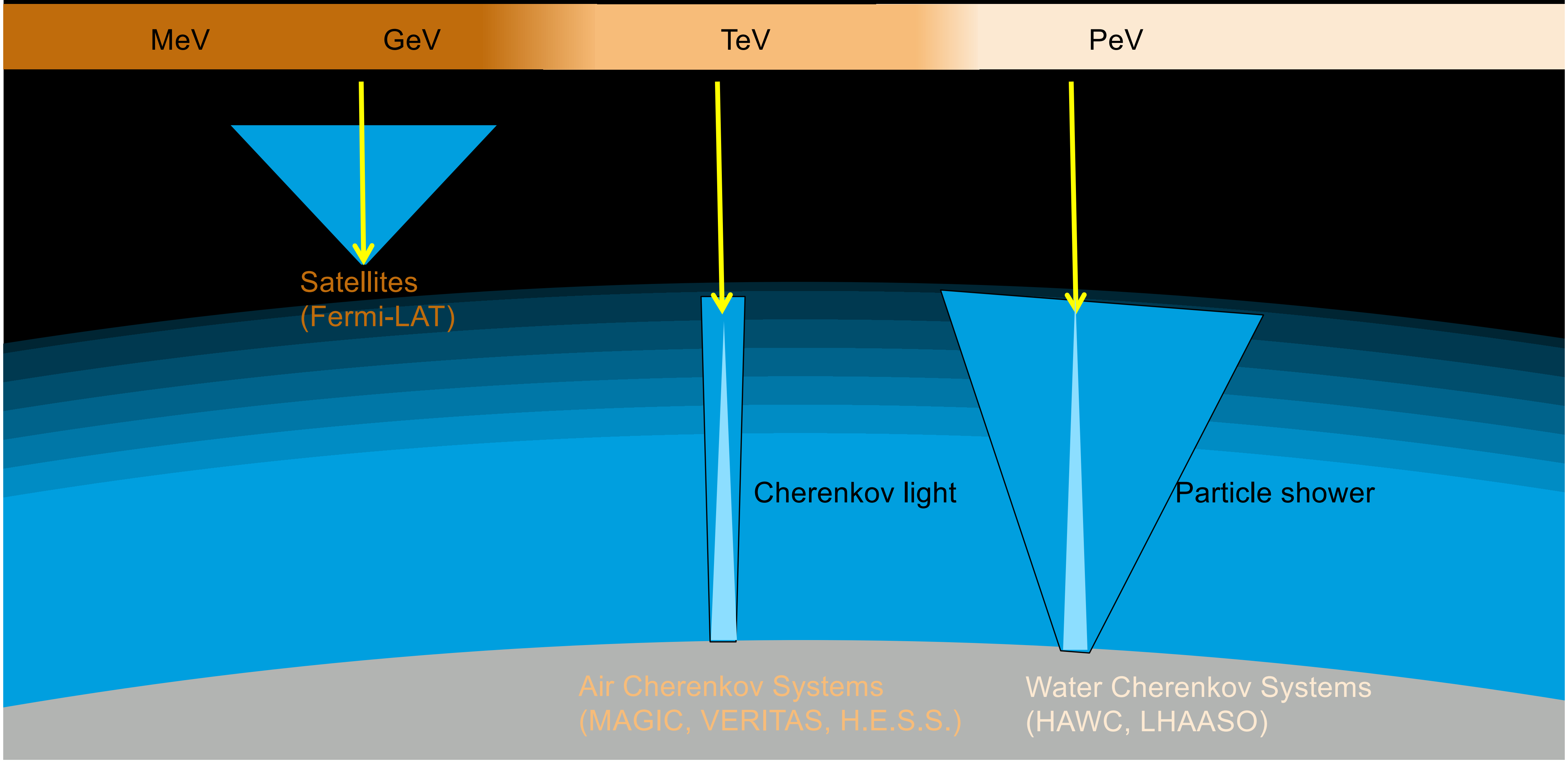
Useful units, numbers, dimensions

- 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

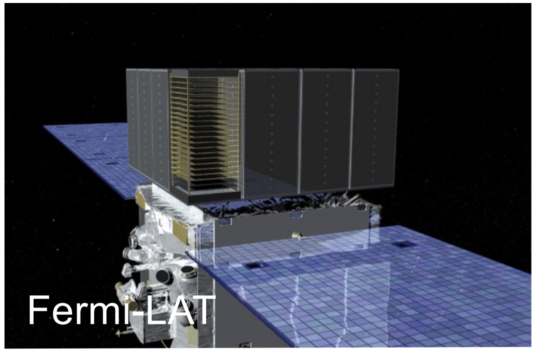
2004 – 2022
From source hunting to real astronomy

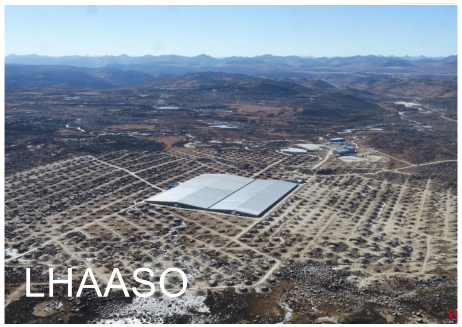
Experimental techniques



Experimental techniques

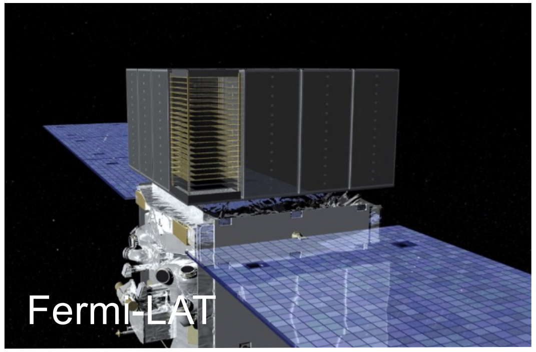
MeV GeV TeV PeV



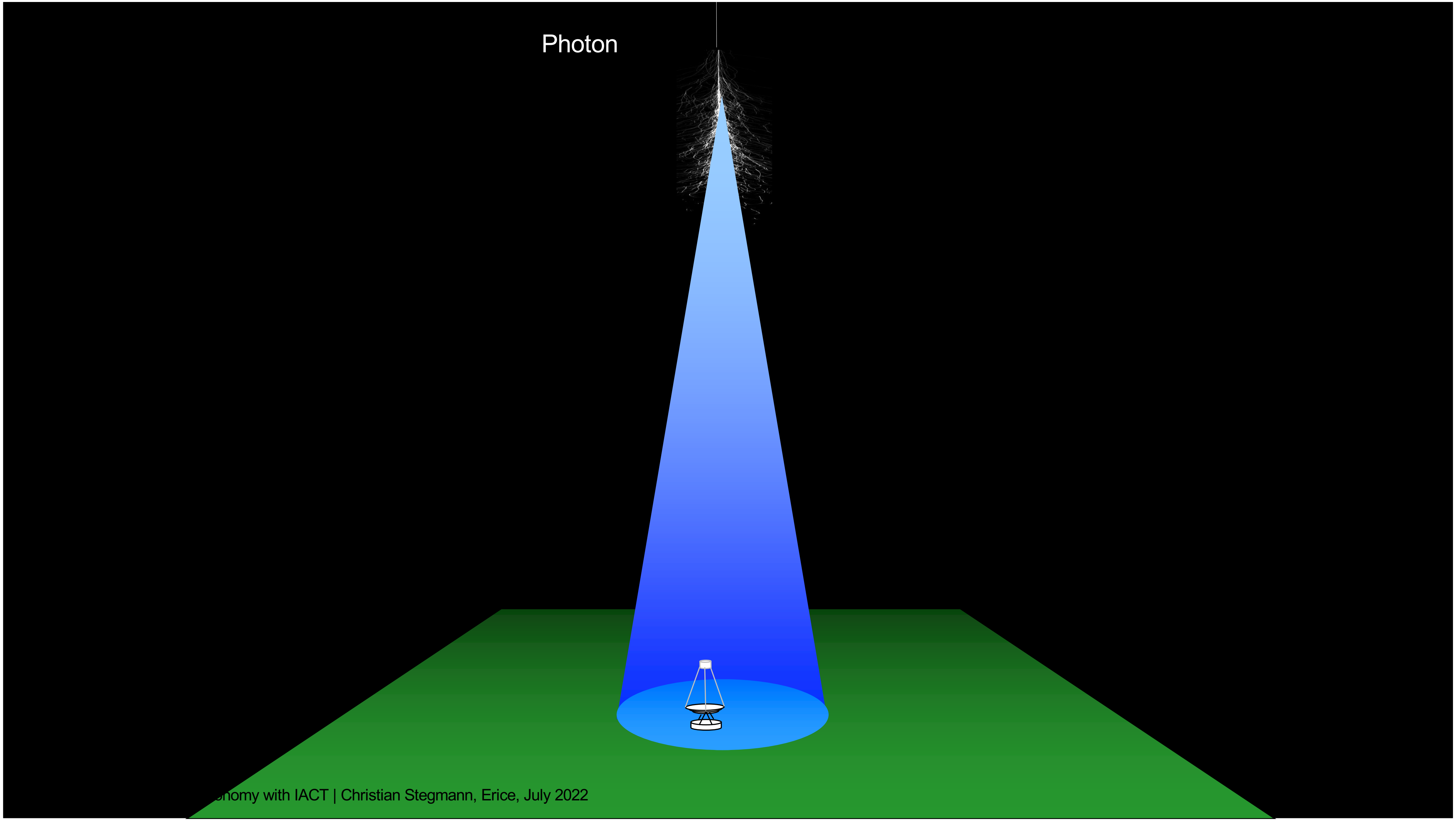


Experimental techniques

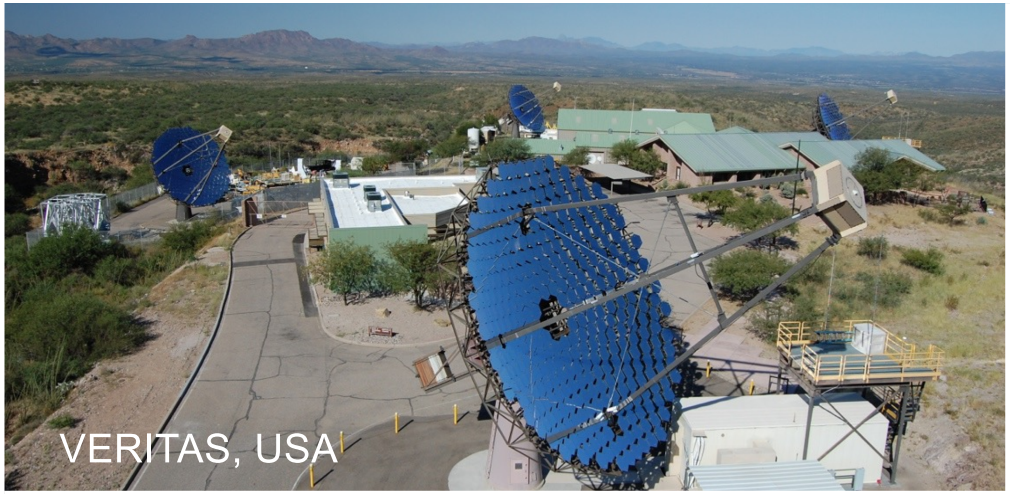
MeV GeV TeV PeV

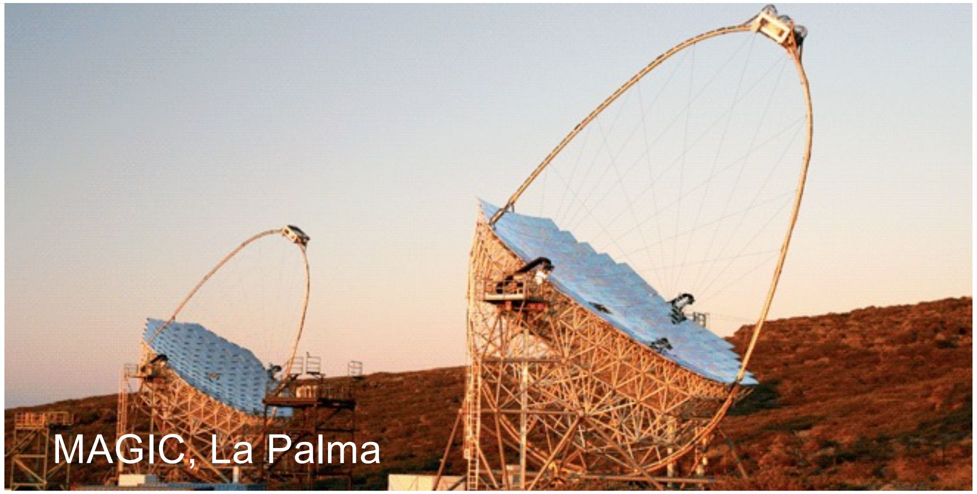


	Fermi LAT	IACTs	HAWC
Effective area	1 m^2	**10^5 m^2**	**10^5 m^2**
Field of view	**20% of the sky**	$3^o – 5^o$	**15% of the sky**
Energy res.	10%	**10%**	100% – 20%
Angular res.	$6^o – 0.3^o$	**0.1^o**	$1^o – 0.2^o$
Duty cycle	**Full year**	1400 h/year	**Full year**

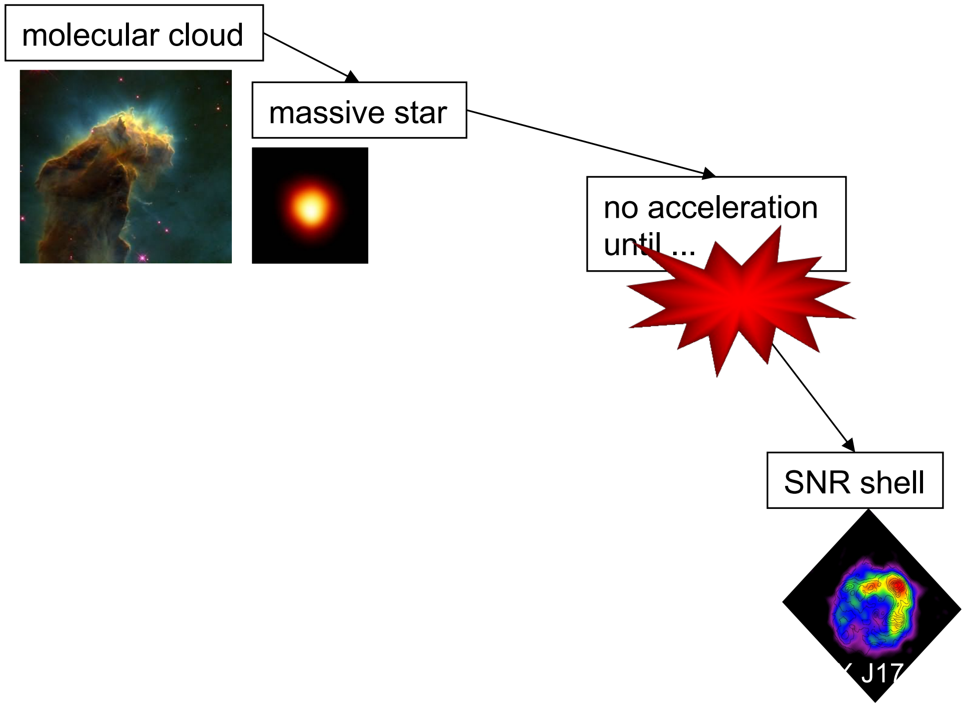

Photon

Gamma-ray astronomy – 3rd generation experiments





The sources of cosmic rays

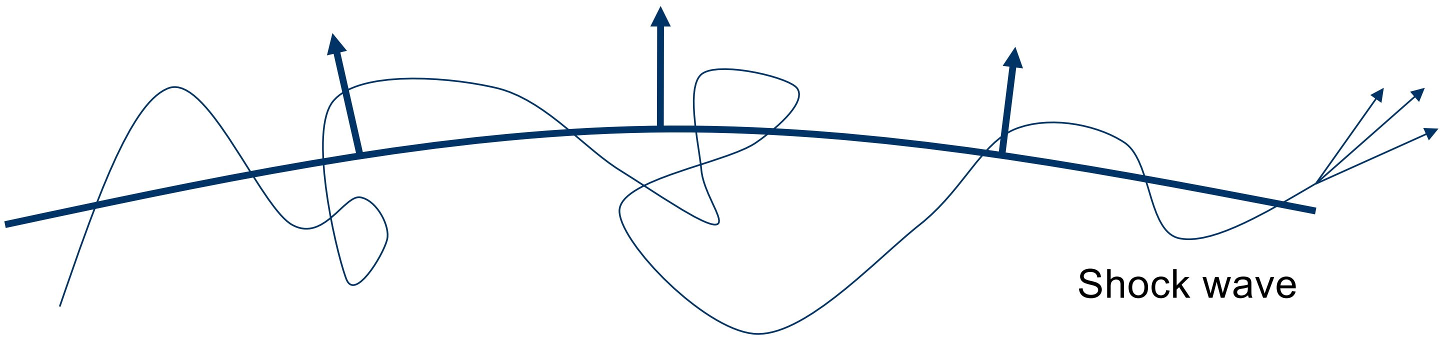


Jim Hinton

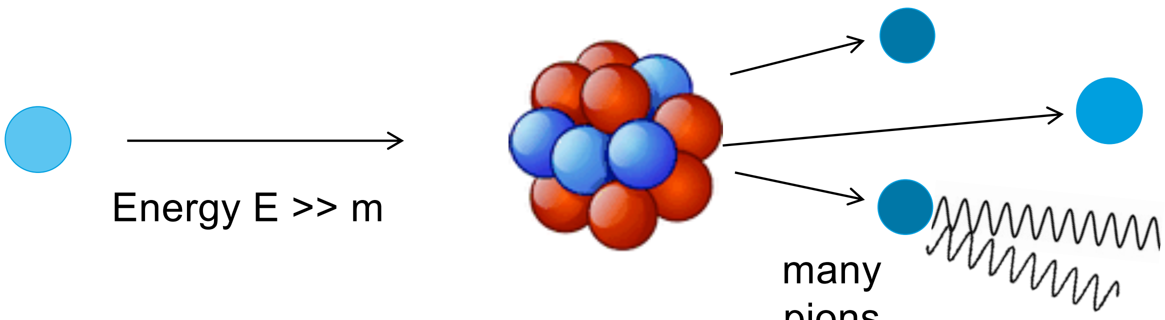
Supernova remnants – the souces of cosmic rays?

Why supernova remnants?

- Large energy release $E_{SNR} \approx 10 \cdot E_{CR}$
- Acceleration in shock waves



Gamma-ray production by protons



- **Cross section** for p H (i.e. p p) collisions:
  - Proton size ~ 1 fm
  - Strong interactions have short range

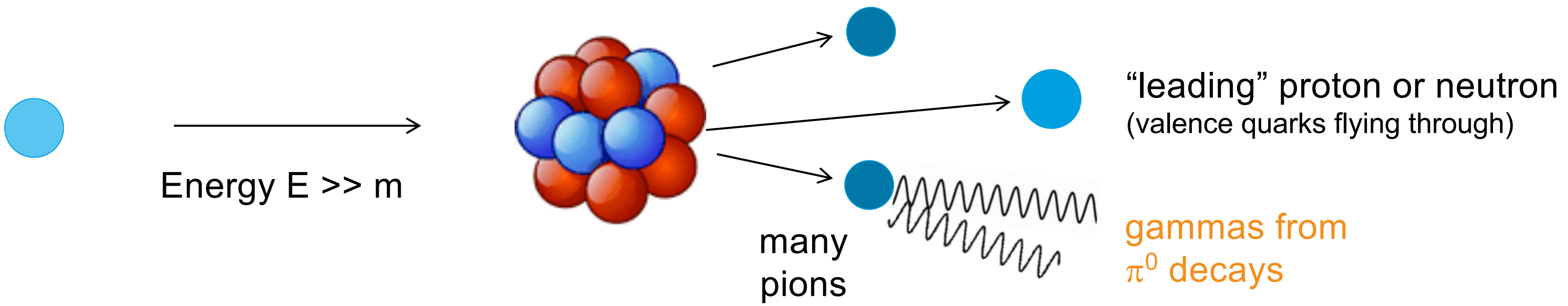
➜ Cross section $\sigma \approx \pi\ 10^{-30}\ m^2 \approx 30$ mb (Reality ≈ 40 mb)

- **Interaction rate** $\boldsymbol{r = \sigma\, c\, \rho} \approx 4 \cdot 10^{-26} cm^2 \cdot 3 \cdot 10^{10} \frac{cm}{s}\ n\, cm^{-3}$

$\approx 10^{-15}$ n/s $\approx 3 \cdot 10^{-8}$ n/yr

≈ energy-independent!

Gamma-ray production by protons

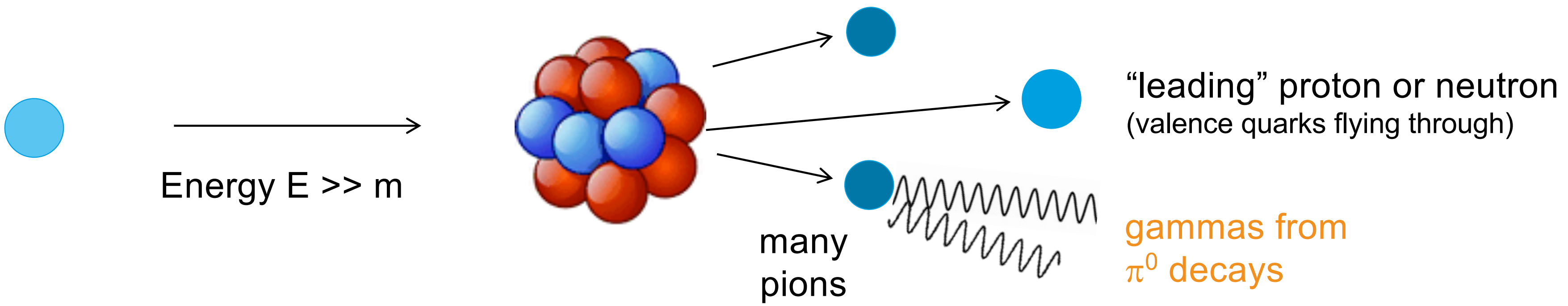


- **Scaling variable** $x = \frac{E_\gamma}{E_p}$ (masses play no role since E >> m)
- **Distribution in x** $\frac{dN}{dx} = \frac{(1-x)^{4\ldots5}}{x}$ ← Interaction dynamics / valence quark distributions; ← Longitudinal phase space
- **Normalisation (per interaction)** $\int E_\gamma \frac{dN}{dE_\gamma} dE_\gamma = \eta\, E_\gamma \approx \frac{1}{2}\frac{1}{3} E_p$

Equal numbers of π^+, π^-, π^0

Leading particle keeps 50% energy

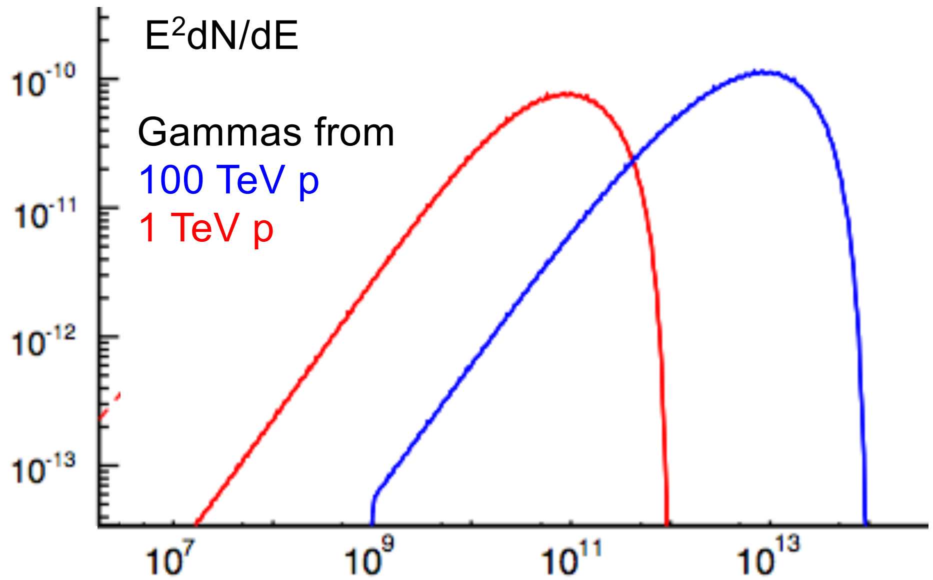
Gamma-ray production by protons



- **Gamma-ray Spectral Energy Distribution (SED)**

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

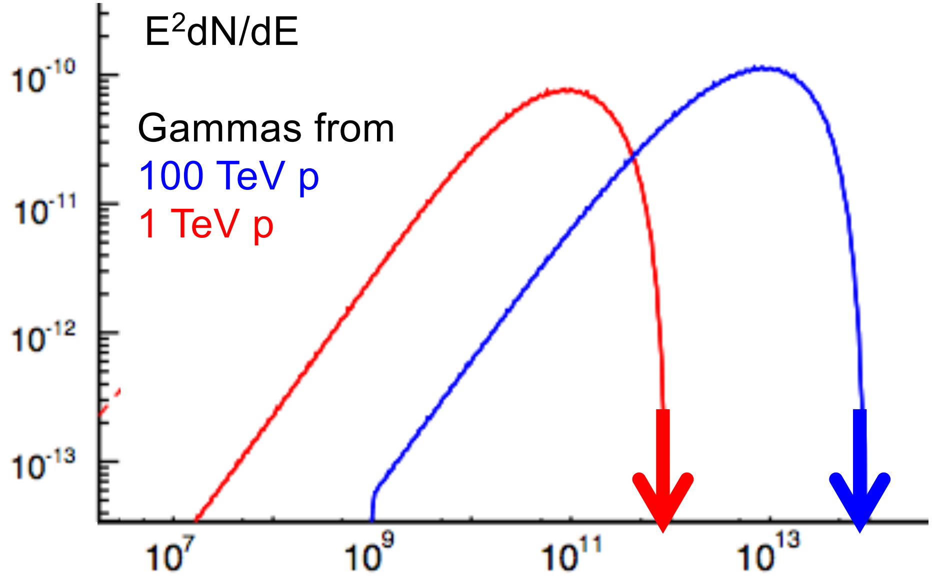
peaks at x ≈ 0.2



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**



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


O. Krause (Steward Obs.) et al., SSC, JPL, Caltech, NASA

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

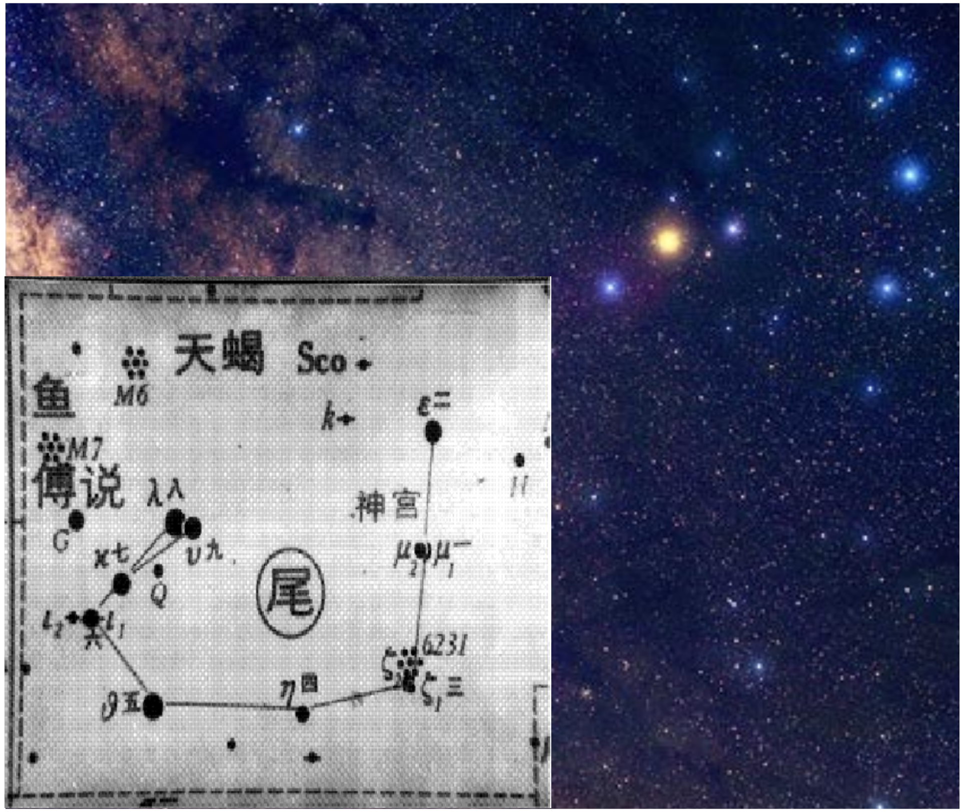
Drury, Aharonian, Völk A&A 287 (1994) 959

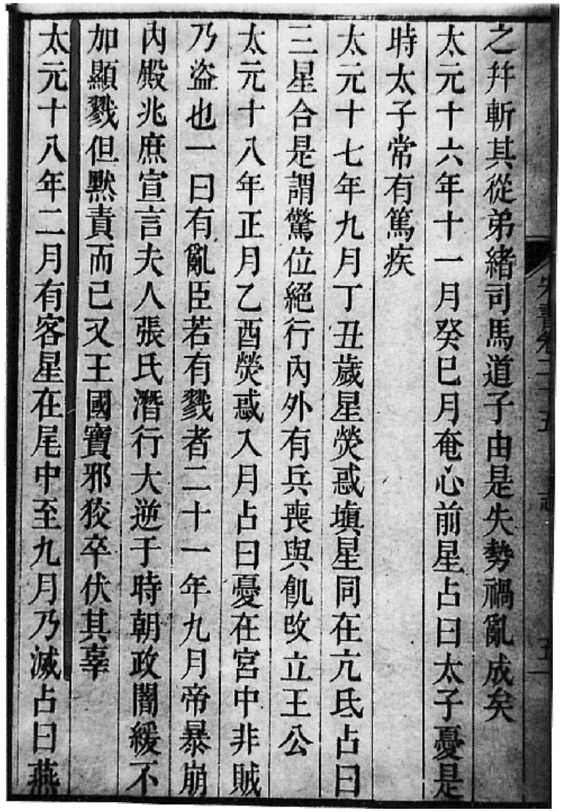
$F(>1\text{TeV}) \approx 9 \cdot 10^{-11}\, \theta\, E_{51}\, n/d^2_{kpc}$ ph/cm^{2}s

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

Sensitivity limit: $\approx 10^{-12}$ erg/cm^{2}s

Supernova Remnant RX J1713-3946



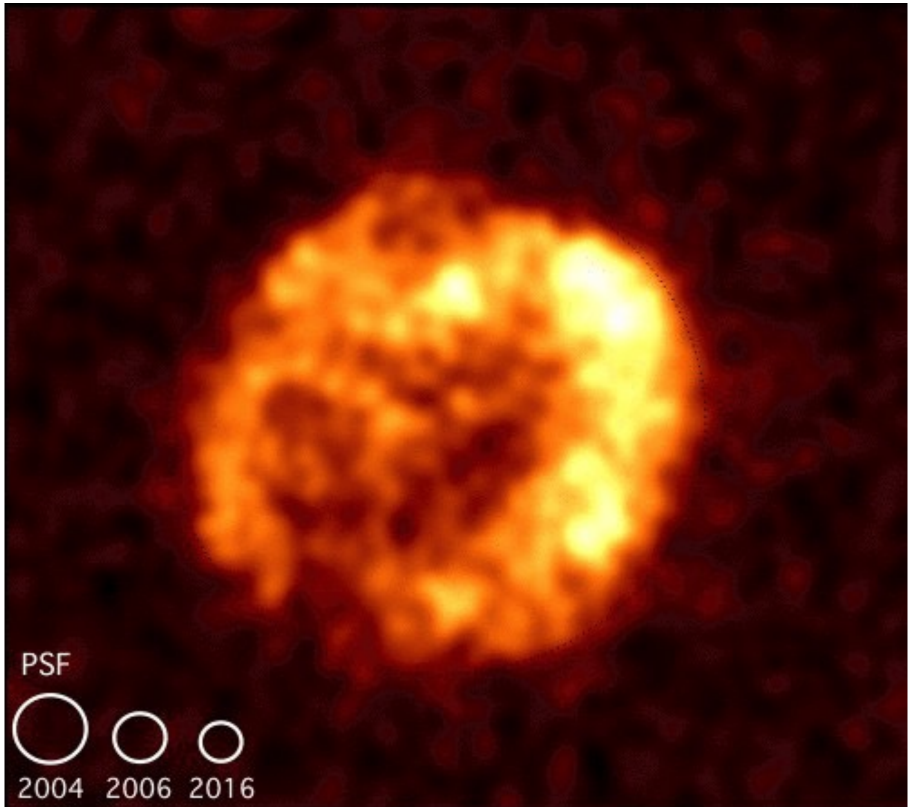


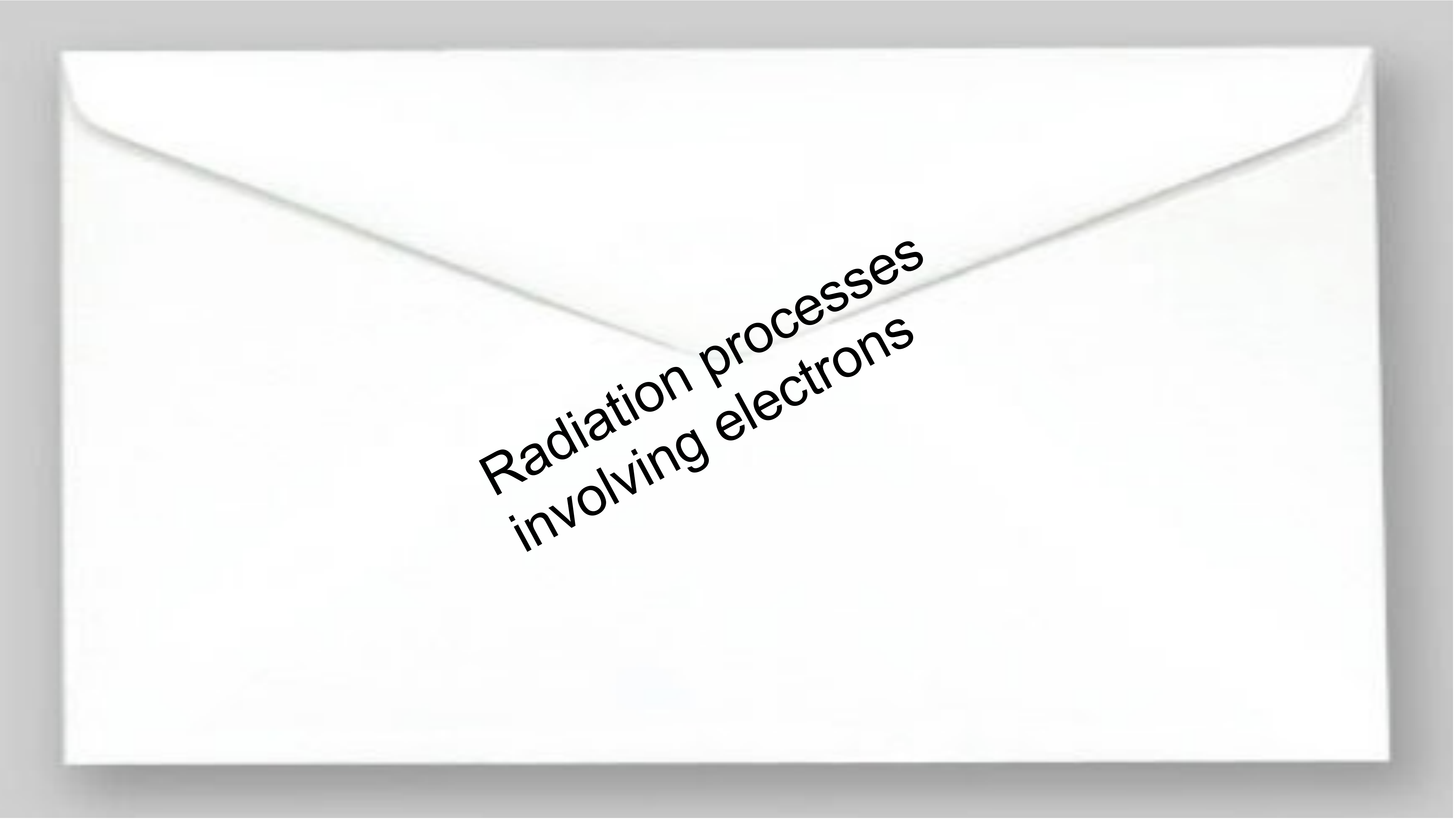
之并斬其從弟緒司馬道子由是失勢禍亂成矣
太元十六年十一月癸巳月奄心前星占曰太子憂是
時太子常有篤疾
太元十七年九月丁丑歲星熒惑塡星同在亢氐占曰
三星合是謂驚位絕行內外有兵喪與飢改立王公
太元十八年正月乙酉熒惑入月占曰憂在宮中非賊
乃盜也一曰有亂臣若有戮者二十一年九月帝暴崩
內殿兆庶宣言夫人張氏潛行大逆于時朝政闇緩不
加顯戮但默責而已又王國寶邪狡卒伏其辜
太元十八年二月有客星在尾中至九月乃滅占曰燕

"A guest star appeared in the constellation Wei during the second moon of the eighteenth year of the Tai-Yuan reign (Feb. - March 393) and disappeared during the ninth moon (Oct. - Nov. 393)."

RX J1713-3946

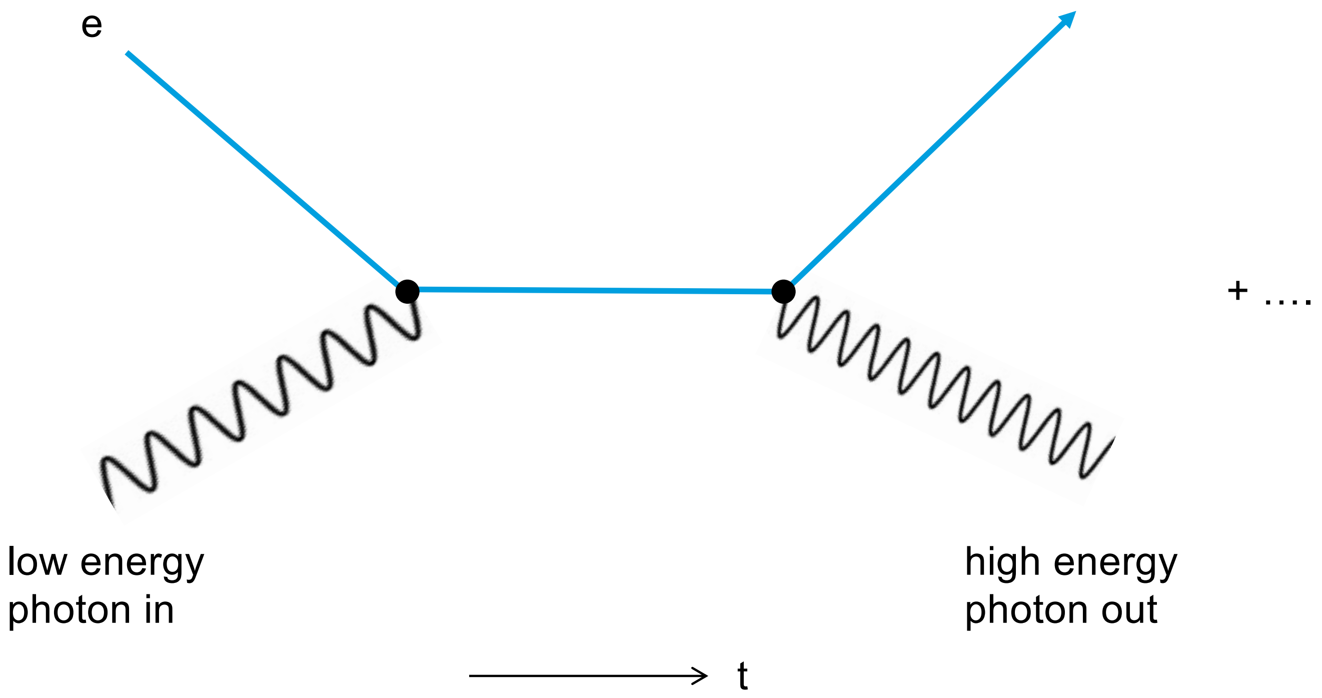
The best studied SNR in VHE gamma-rays




Radiation processes
involving electrons

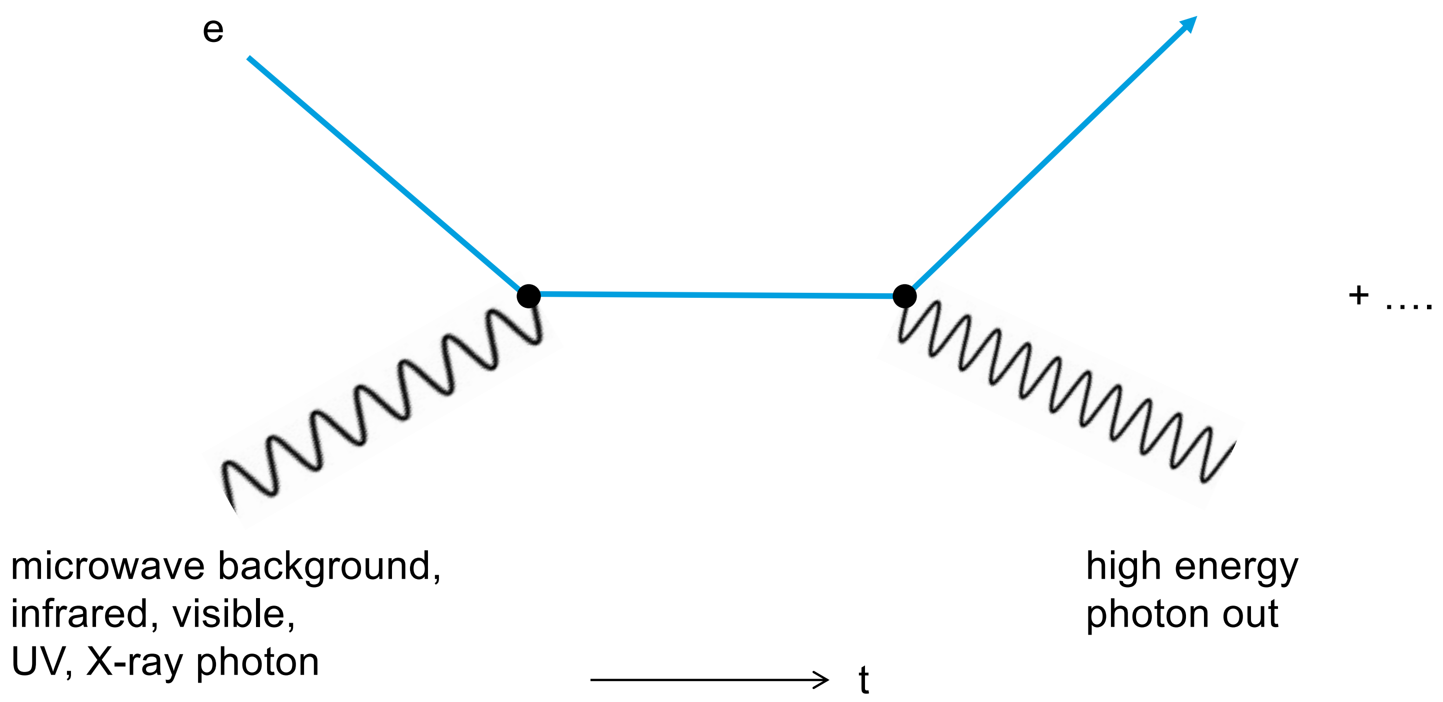
This diagram describes …

… everything



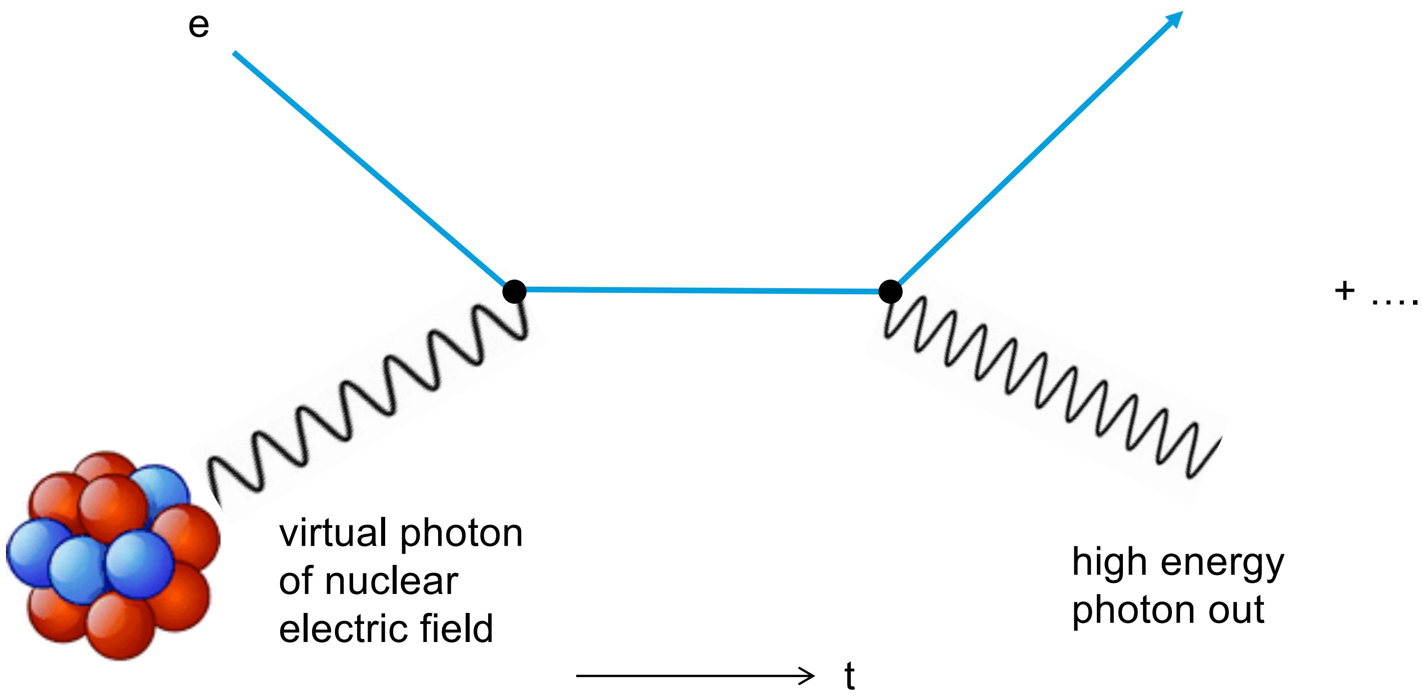
This diagram describes …

… Compton Scattering



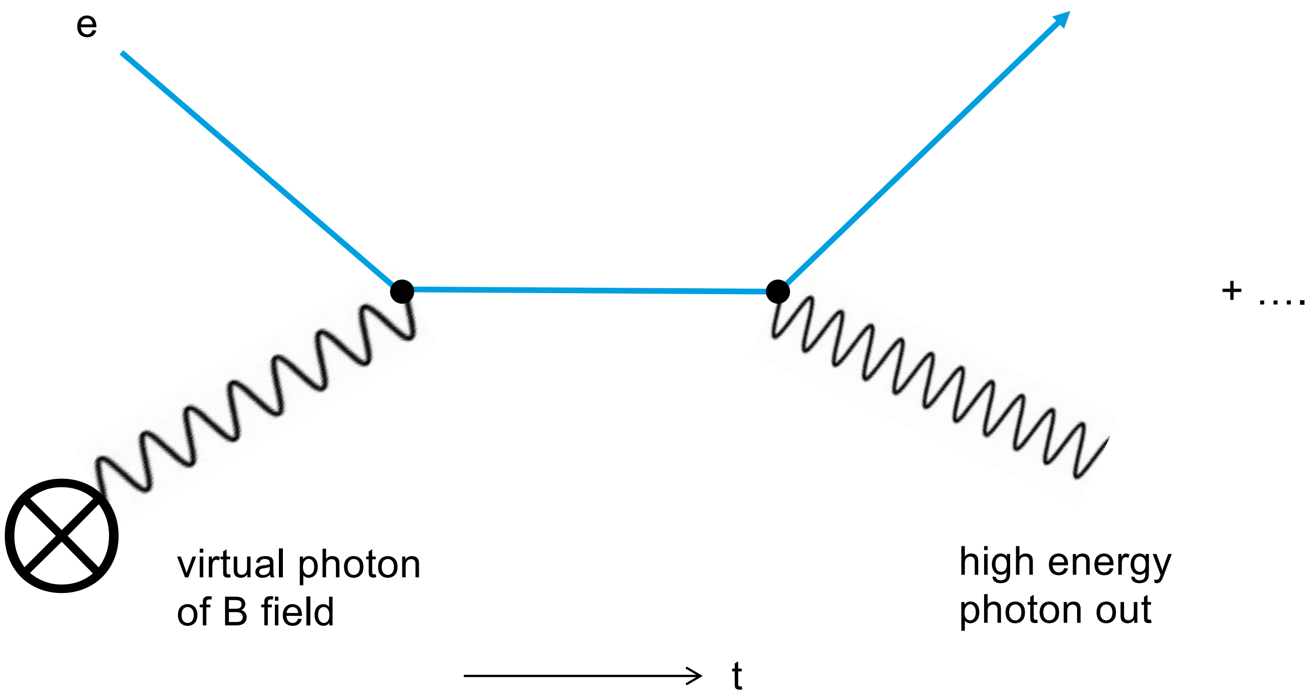
This diagram describes …

… Bremsstrahlung



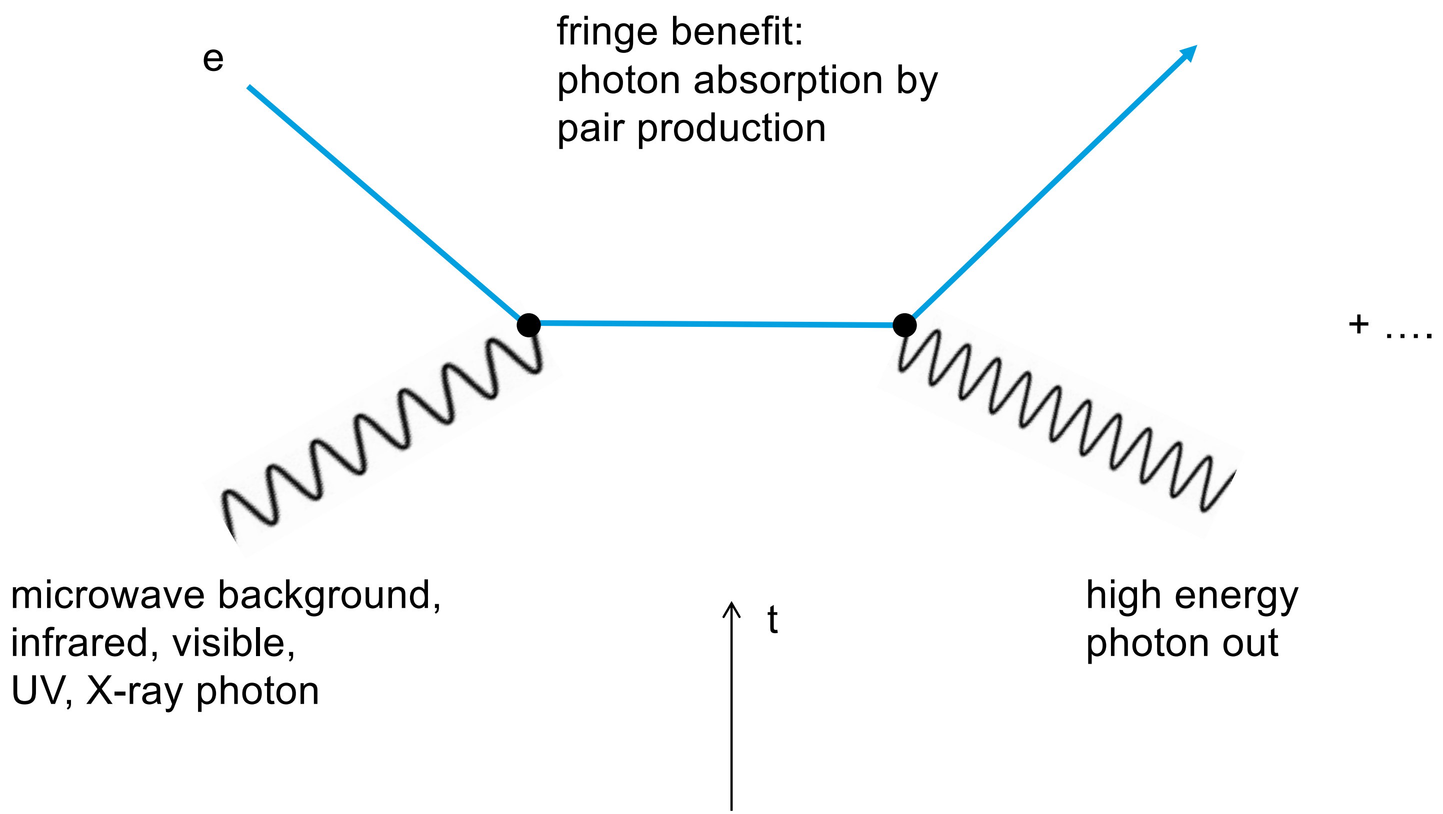
This diagram describes …

… Synchrotron Radiation



This diagram describes …

… Pair production

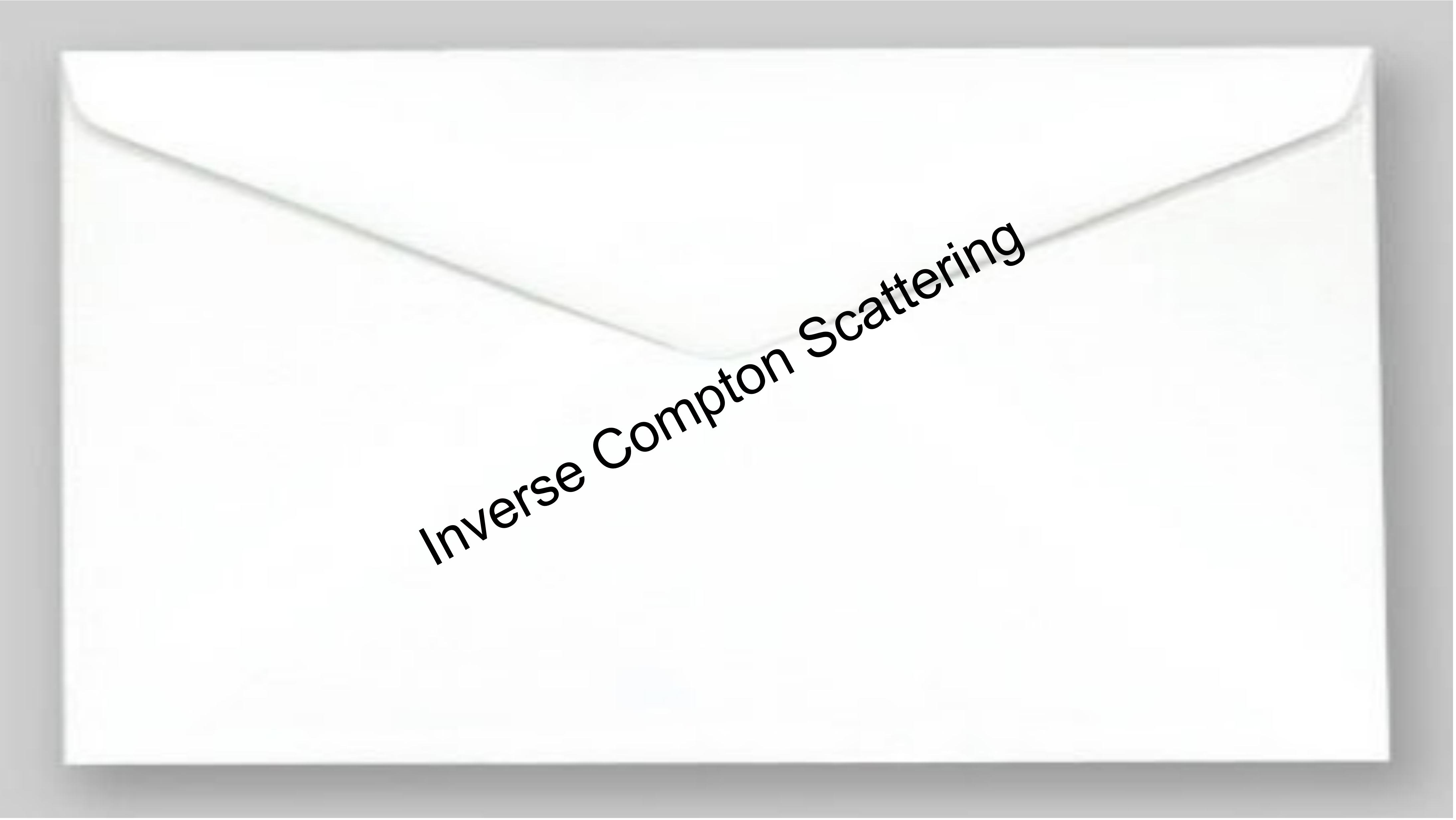


Exact treatment & detailed discussion

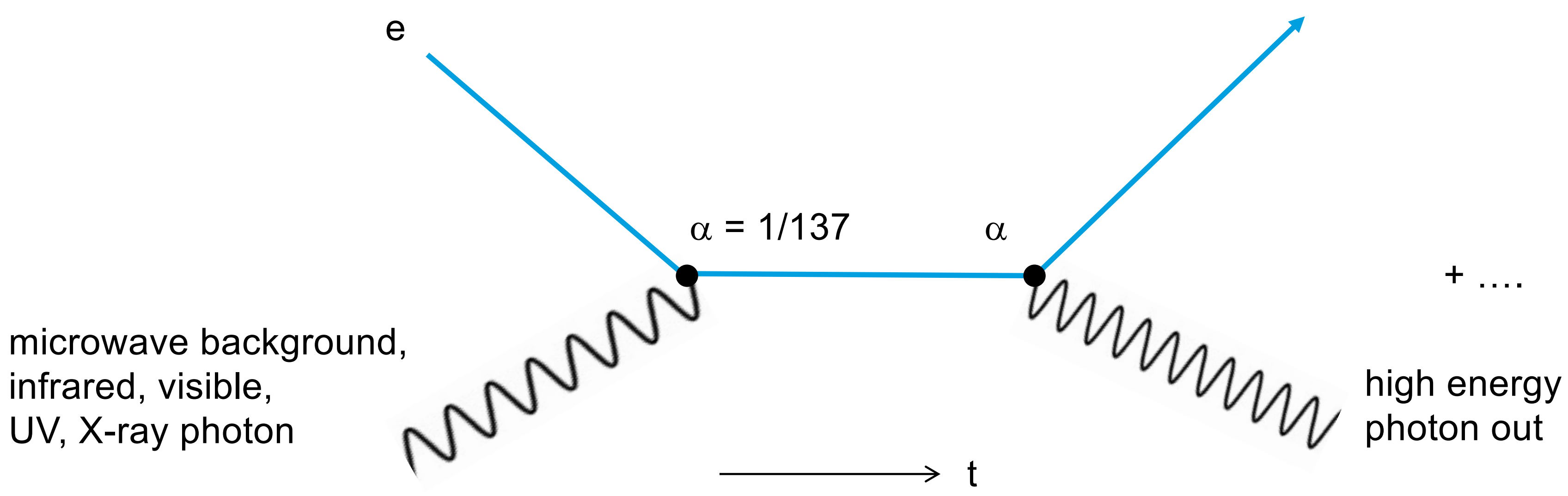
THE reference:

- 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 up to factors of order unity $\boldsymbol{\sigma \approx \alpha^2/s}$

Cross section

- for simplicity, consider head-on collision 

$$s = \left(E_e + E_{ph}\right)^2 - \left(\overrightarrow{p_e} + \overrightarrow{p_{ph}}\right)^2 \approx m_e^2 + 4\,E_e E_{ph} \qquad E_e \gg m_e$$

- **Thomson limit** $4\,E_e E_{ph} \ll m_e^2$

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

- **Klein-Nishina limit** $4\,E_e E_{ph} \gg m_e^2$

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

Cross section

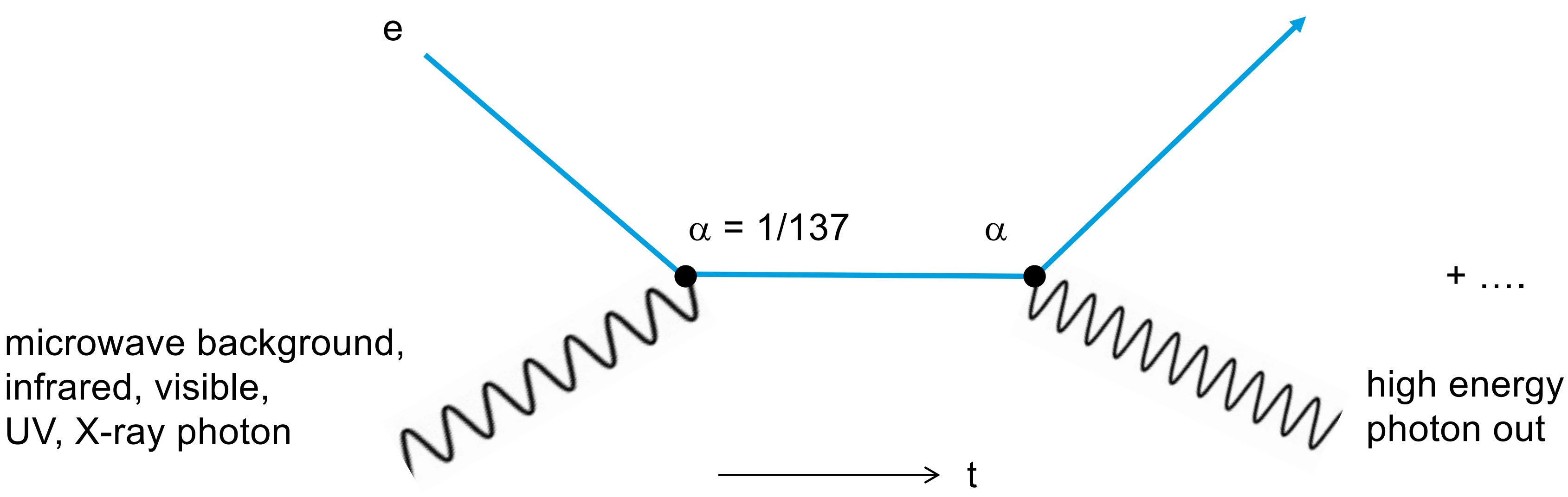
- In useful units

$$\frac{\alpha^2}{m_e^2} = \left(\frac{e^2}{4\,\pi\,\varepsilon_0 \hbar c}\right)^2 \frac{1}{m_e^2 c^4} (\hbar c)^2 = \frac{e^4}{16\pi\,\varepsilon_0^2 m_e^2 c^4} \qquad \hbar c \;\approx 200\,MeV\,fm$$

- Correct answer is 16 → 6

- “Thomson cross section” $6.6\,\cdot 10^{-29}\,m^2$

Kinematics

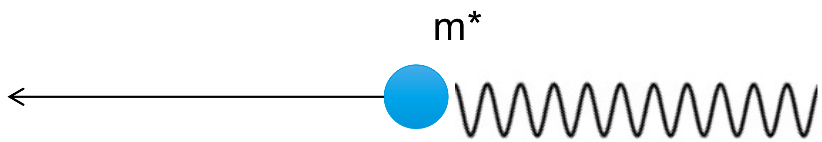


$$s = m^{*2} \approx m_e^2 + 4\,E_e E_{ph} \qquad E_e \gg m_e$$

- Thomson limit $\quad 4\,E_e E_{ph} \ll m_e^2$

Kinematics

CM frame



$$E_\gamma^* = |p_\gamma^*| = |p_e^*|$$

Thomson limit $p_e^* \ll m_e$

$$\Rightarrow E_e^* = \frac{p_e^{*2}}{2m_e} \ll |p_e^*| = |p_\gamma^*| = E_\gamma^*$$

→ all energy carried by gamma

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

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

Kinematics

- in useful units

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

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

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

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

Kinematics

- Gamma energy:

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

in the Thomson limit where $4\, E_e E_{ph} \ll m_e^2$ and hence always $E_\gamma < E_e$

- In practical units: Thomson limit

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

  - For scattering of visible light: $E_e < 100\ GeV$
  - For scattering of CMB: $E_e < 500\ TeV$

Kinematics

- Gamma energy:

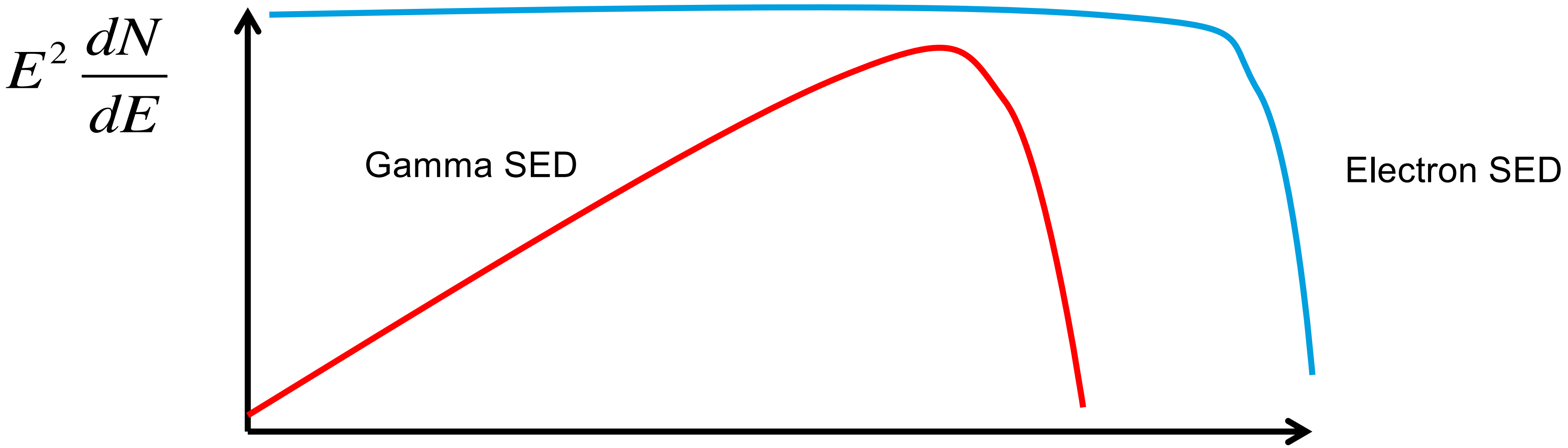
$$E_\gamma \approx E_e^2 E_{ph}$$

- Spectrum:

$$\frac{dN}{dE_\gamma} = \frac{dN}{dE_e}\frac{dE_e}{dE_\gamma} \sim E_e^{-\alpha} E_\gamma^{-\frac{1}{2}}$$

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

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



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

Energy loss rate

- Photon energy and cross section

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

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

$$n = \frac{U}{E_{ph}}$$; $U =$ energy density of the “target”

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

- 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 ≈ 0.03 B$^2_{\mu G}$ eV / cm^3

Energy density in 3 μG field ≈ CMB

- $\tau = \frac{E_e}{(dE/dt)} \sim \frac{1}{E_e}$
- $\tau = \frac{3 \cdot 10^5 \; yr}{U[eV/cm^3] \; E[TeV]}$
- $\tau_{sync} = \frac{10^7 \; yr}{B^2[\mu G] \; E[TeV]}$

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

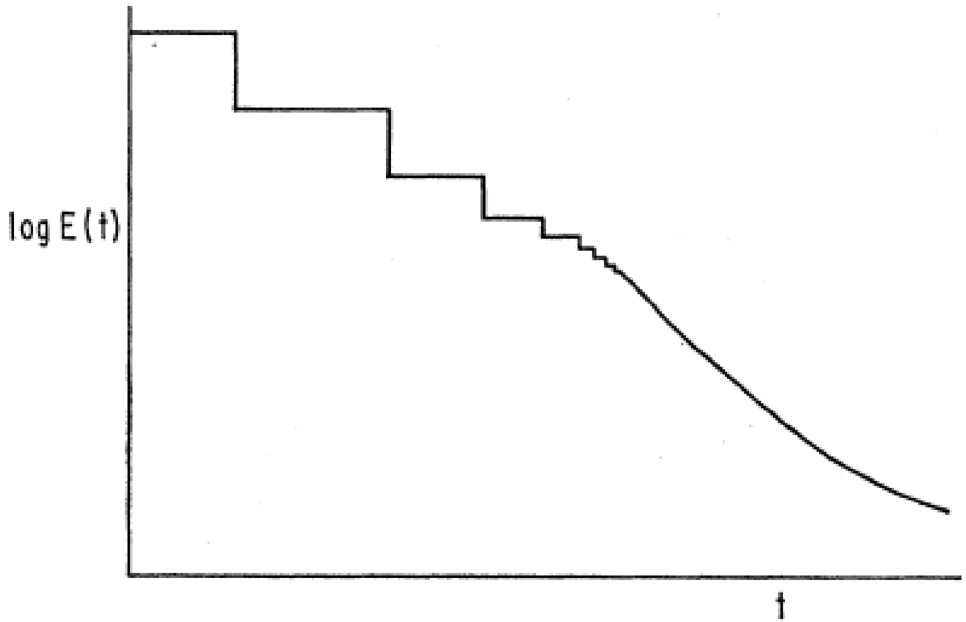
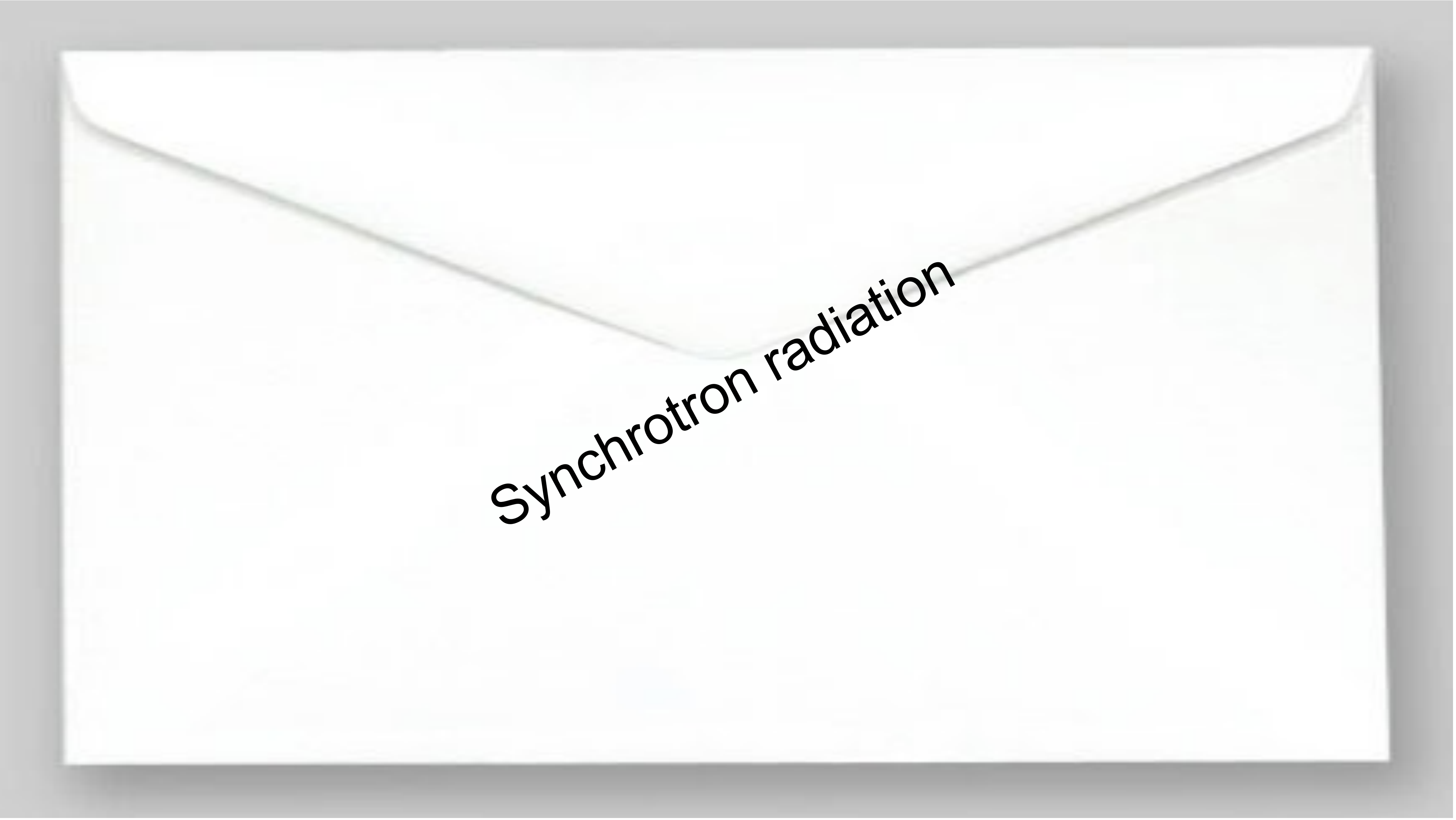
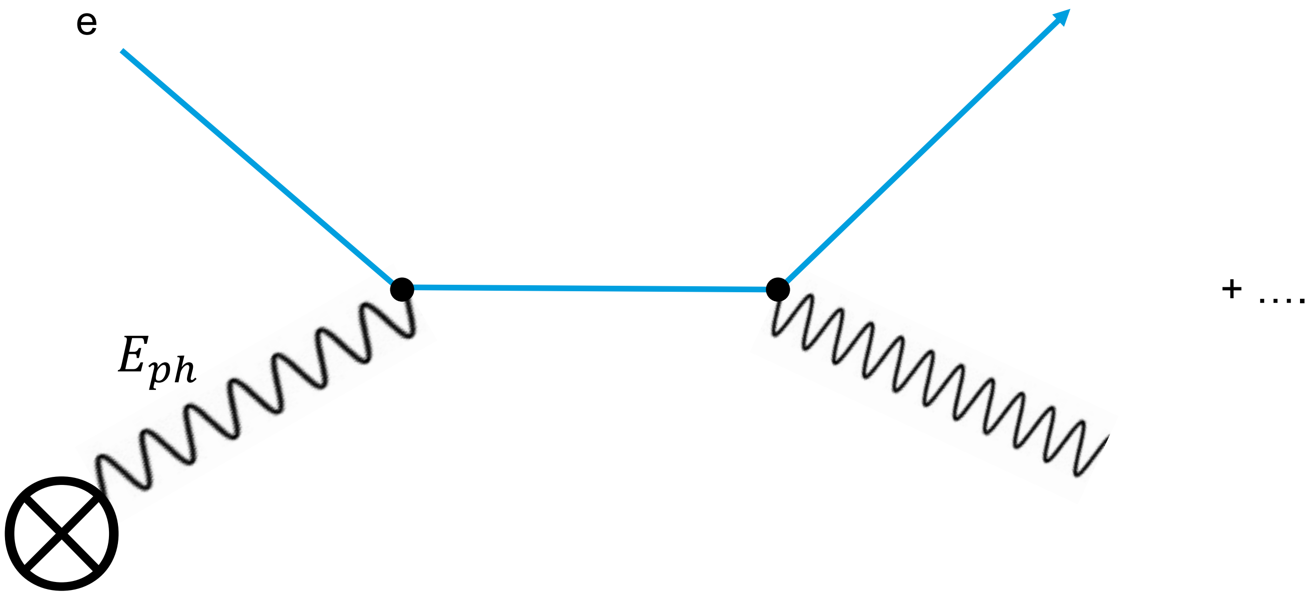


FIG. 5. Sketch of a typical time evolution of an electron's energy due to losses by Compton scattering.


Synchrotron radiation

This diagram describes …

… Synchrotron Radiation

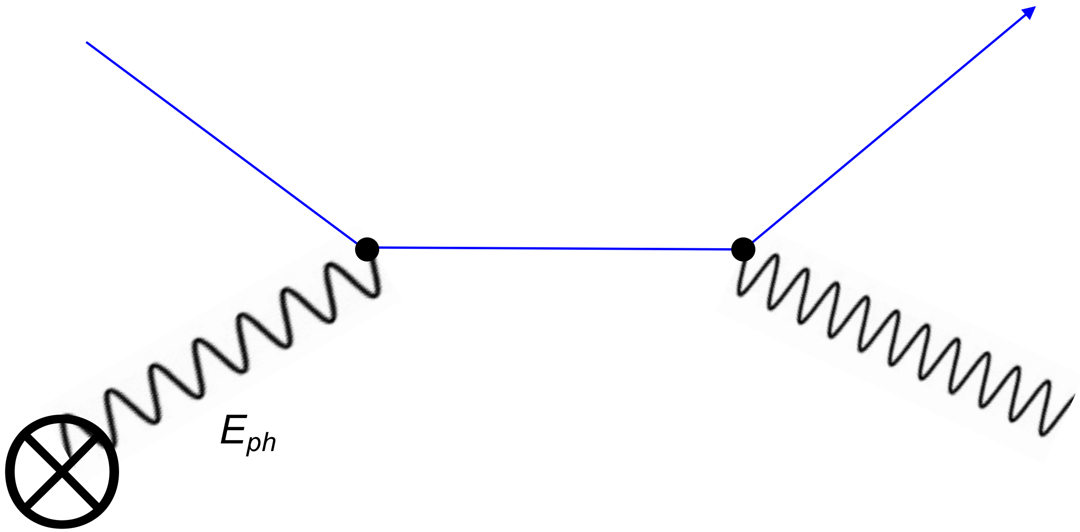


- Start from

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

- What is the photon energy?

Synchrotron radiation



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

What is the photon energy ??

Synchrotron radiation energy

- Start from

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

- What is the photon energy?
- Electron in B field has on characteristic frequency

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

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

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

- Correct answer for peak of synchrotron spectrum,after averaging over pitch angles etc.: 0.08 → 0.07