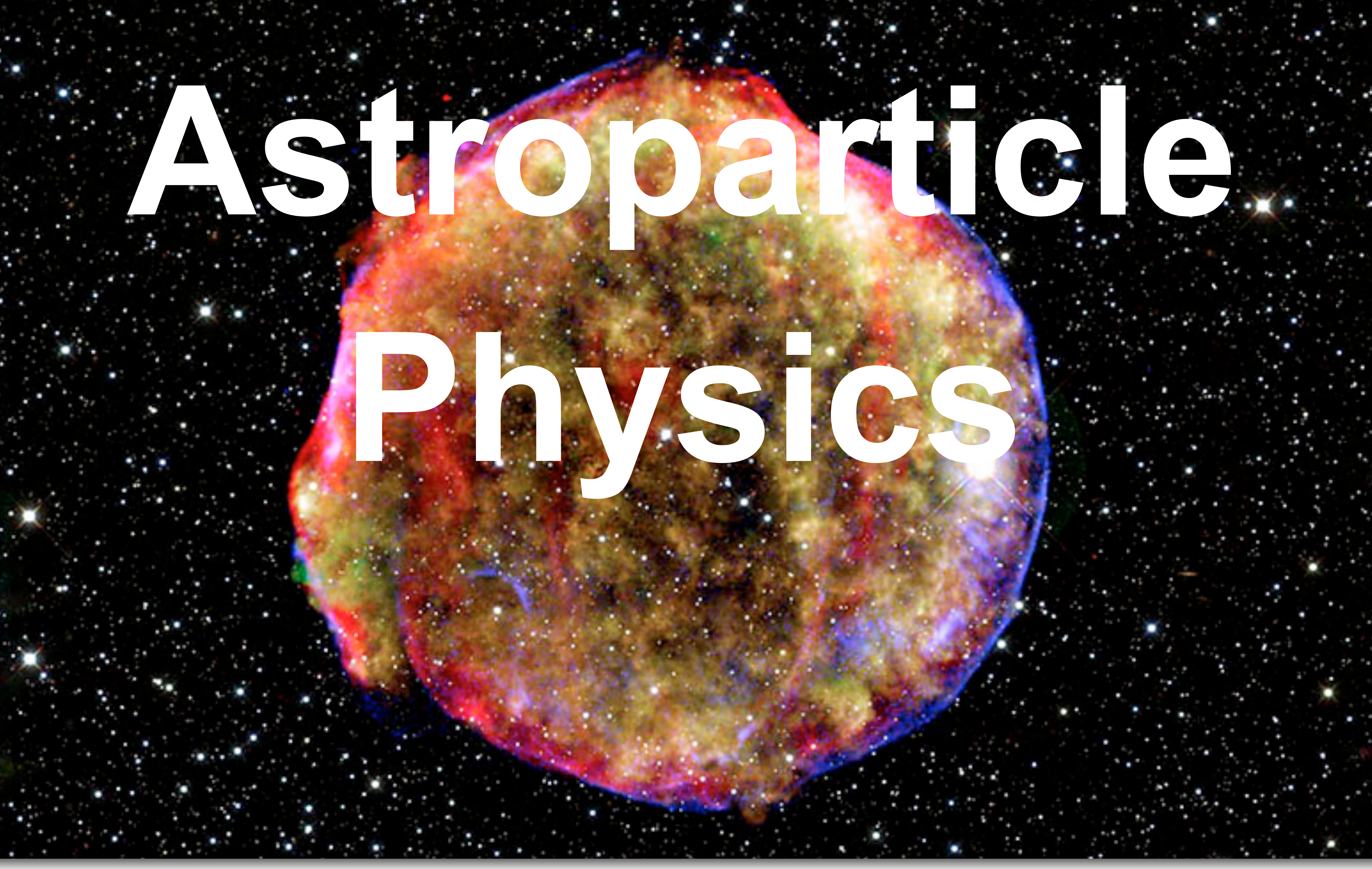
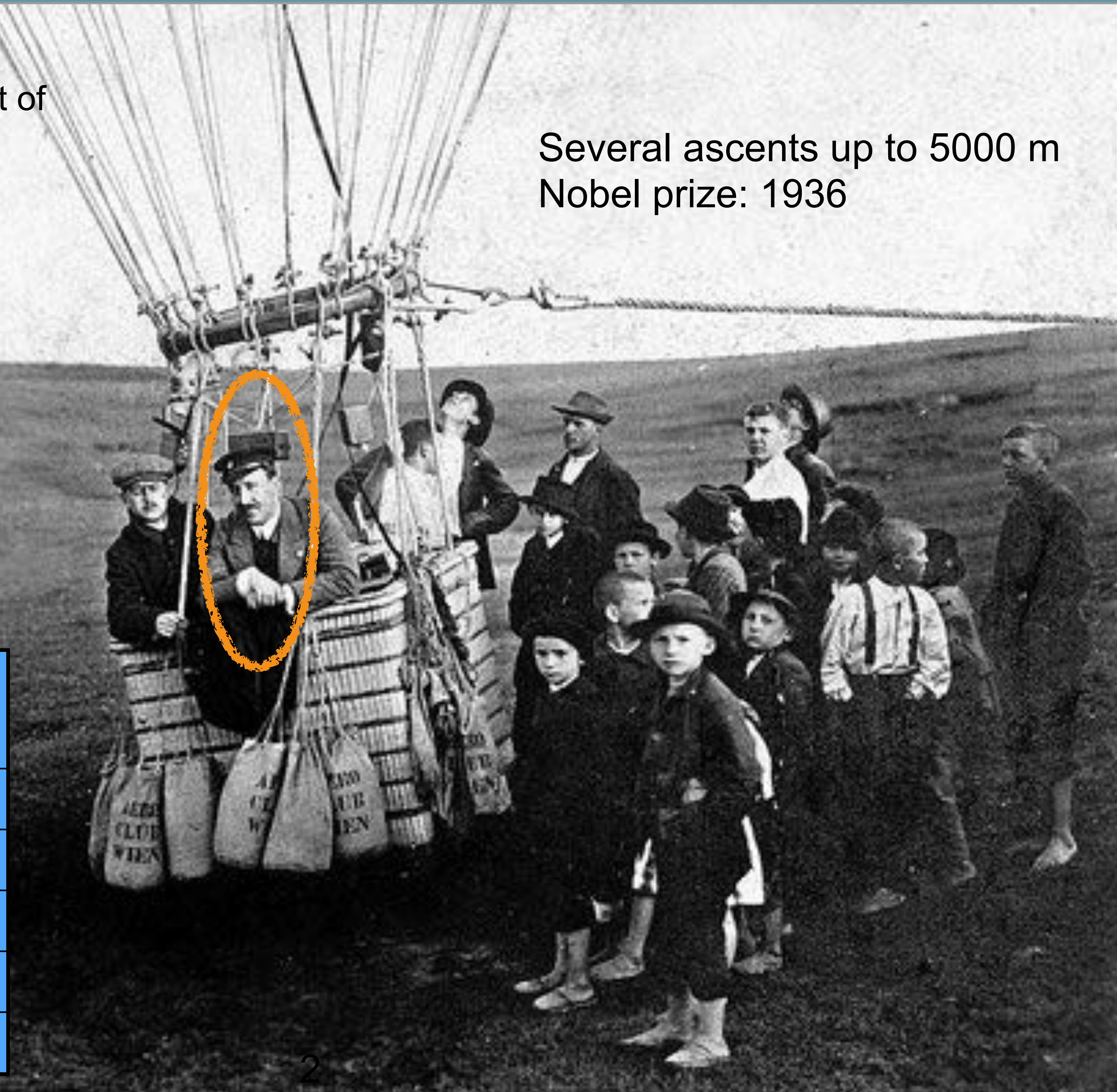
Astroparticle Physics

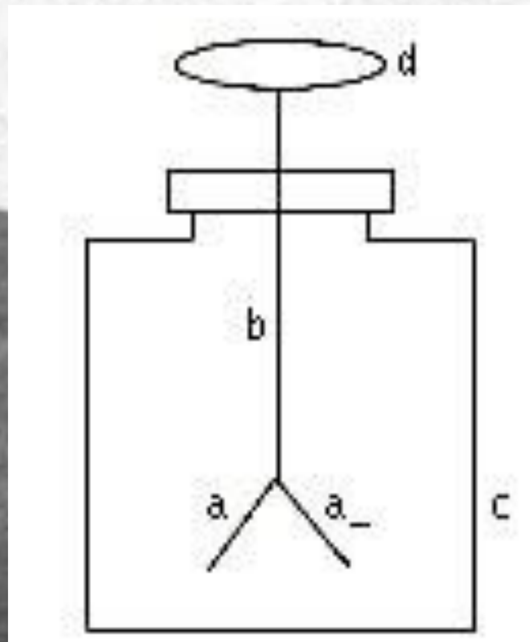


Gernot Maier

106 Years of Cosmic Rays: Victor Hess



Electroscope: measurement of discharge due to ionising particles

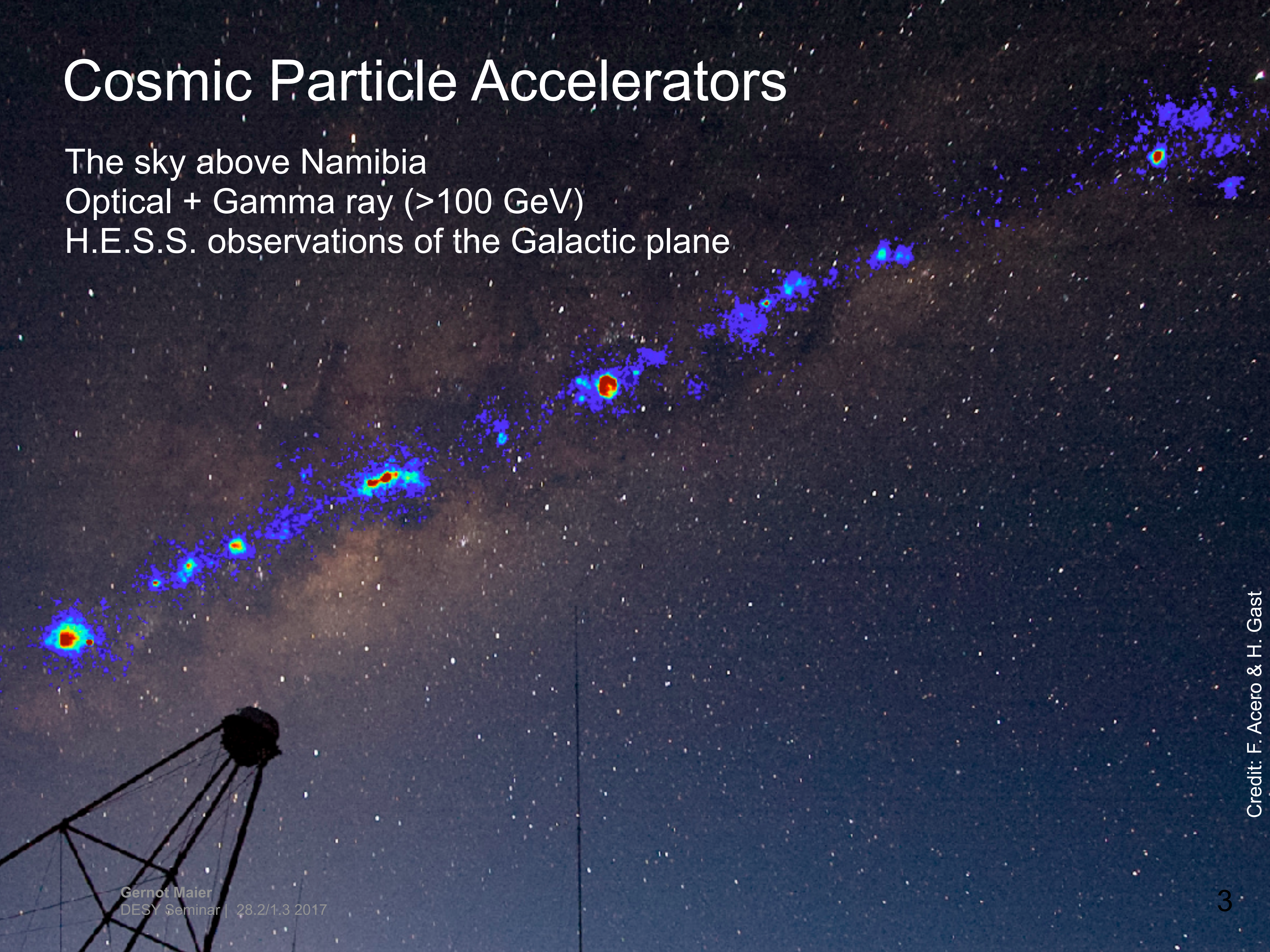


Several ascents up to 5000 m
Nobel prize: 1936

Altitude (km)	Change in Ionization (10^6 m^{-3})
0	0
1	1.2
3	8.8
4	28.7
5	61.3

Cosmic Particle Accelerators

The sky above Namibia
Optical + Gamma ray (>100 GeV)
H.E.S.S. observations of the Galactic plane



Credit: F. Acero & H. Gast

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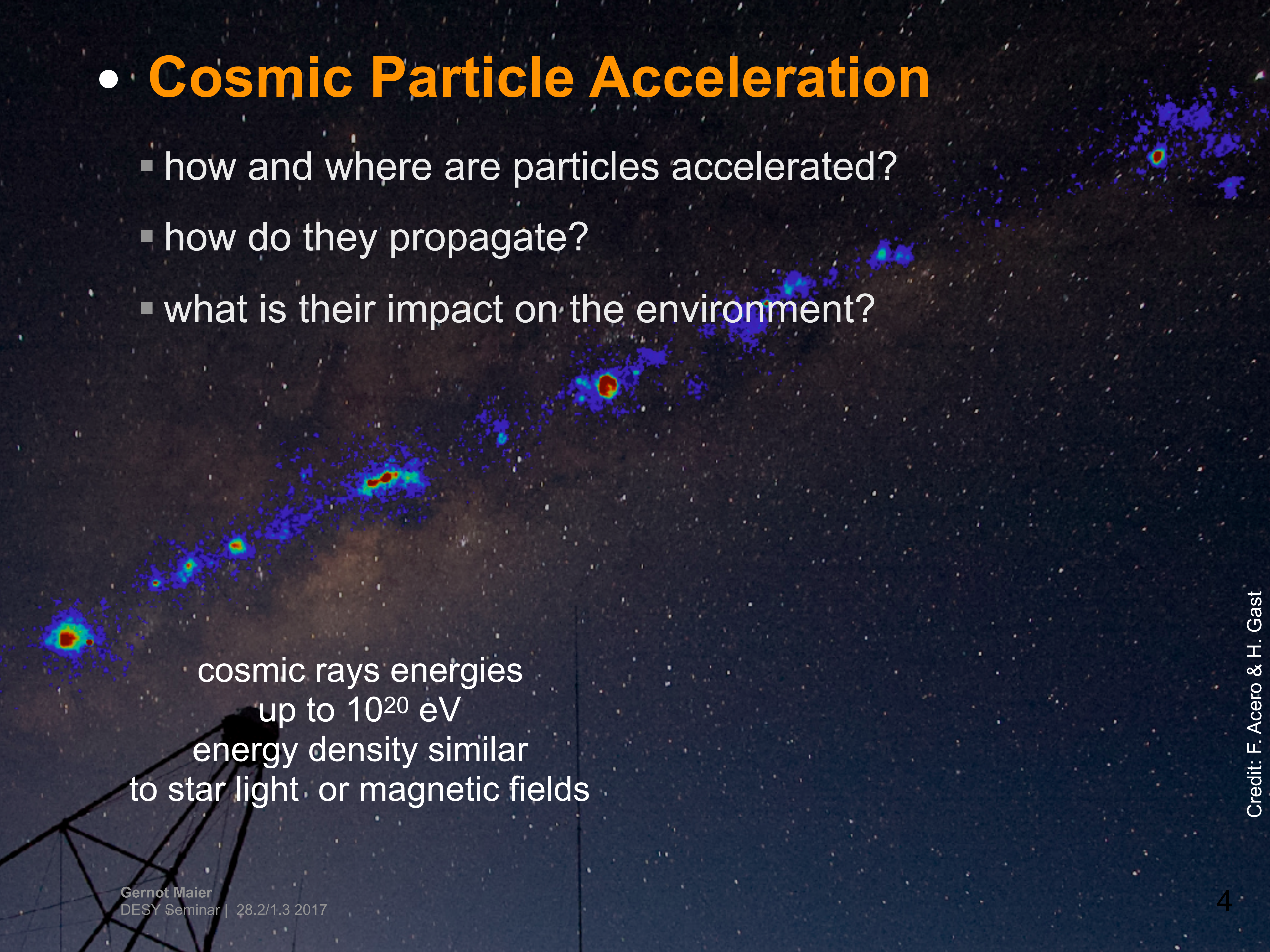
• Cosmic Particle Acceleration

- how and where are particles accelerated?
- how do they propagate?
- what is their impact on the environment?



cosmic rays energies
up to 10^{20} eV
energy density similar
to star light or magnetic fields

Credit: F. Acero & H. Gast

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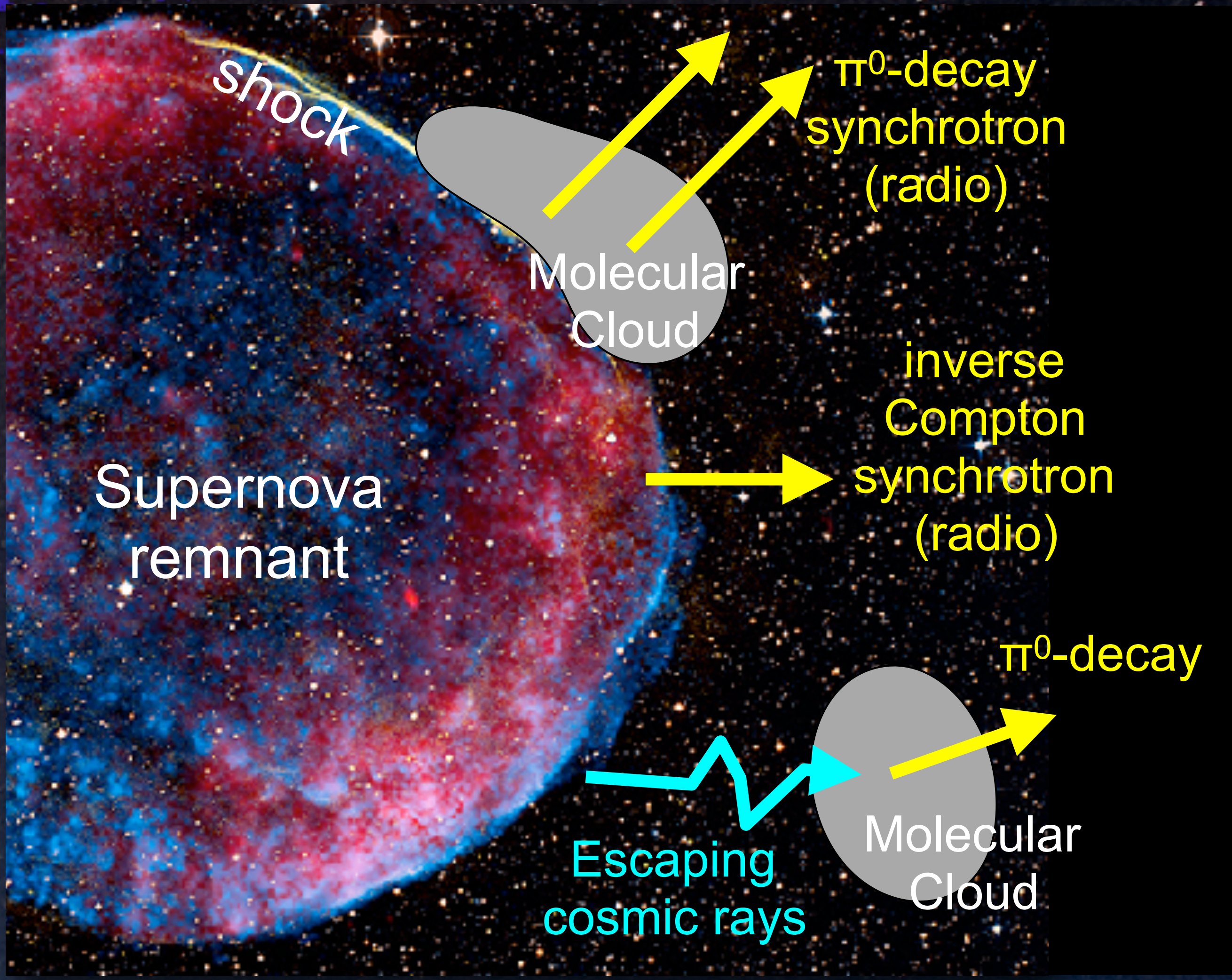
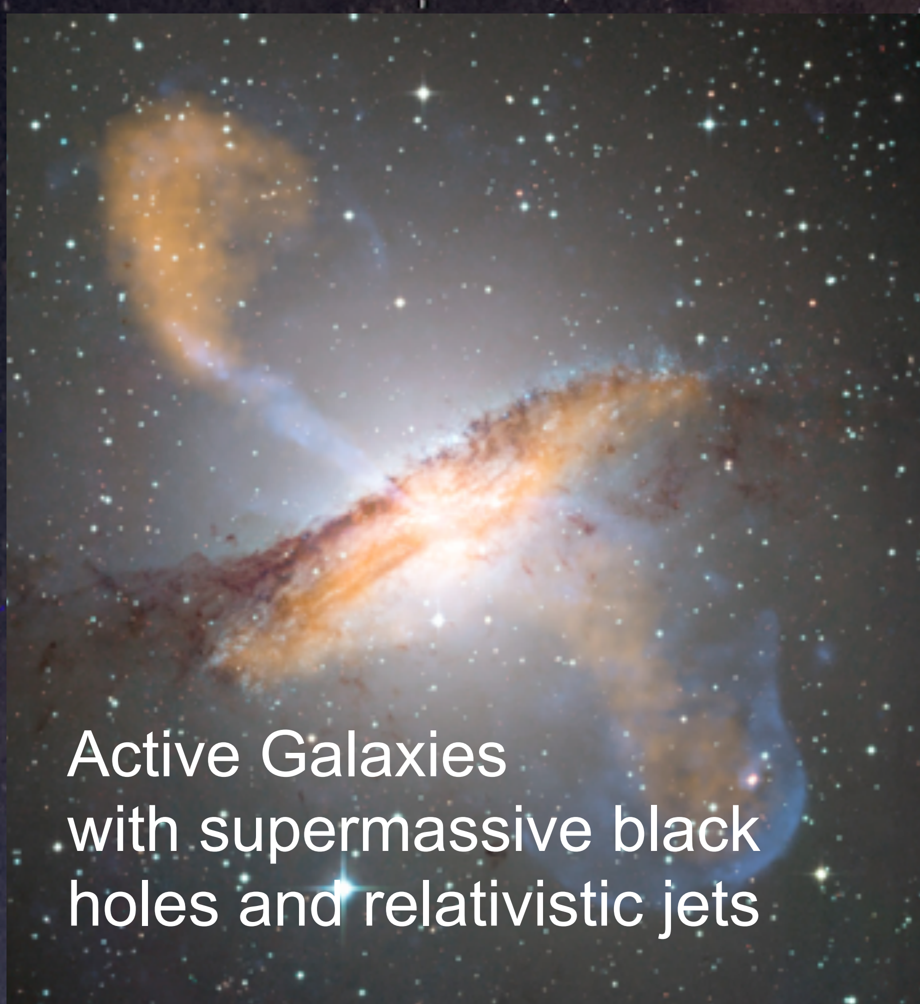



Accreting source - binary systems
Pulsars
Active Galaxies
with supermassive black
holes and relativistic jets
Credit: F. Acero & H. Gast

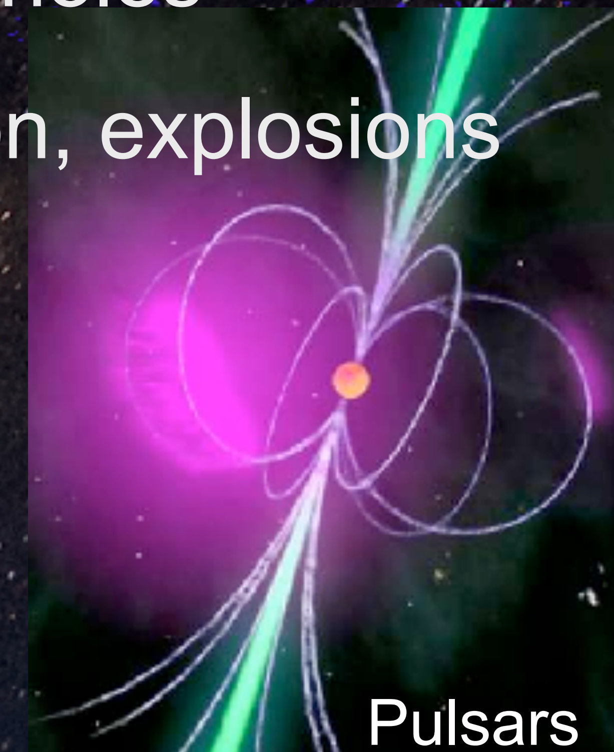
• Probing Extreme Environments

- processes close to neutron stars and black holes
- processes in relativistic jets, winds, accretion, explosions
- cosmic voids



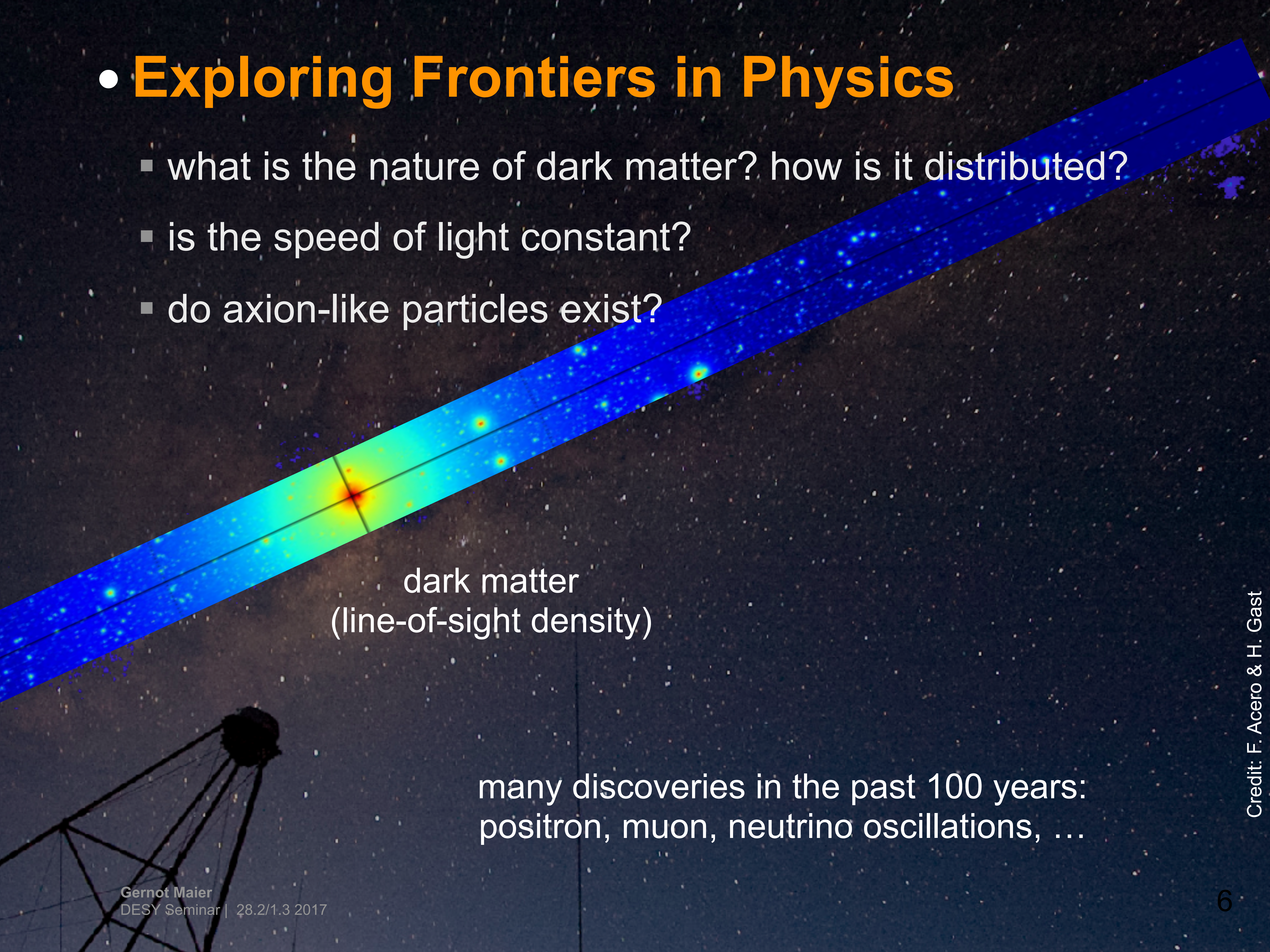
Active Galaxies with supermassive black holes and relativistic jets

Accreting source - binary systems

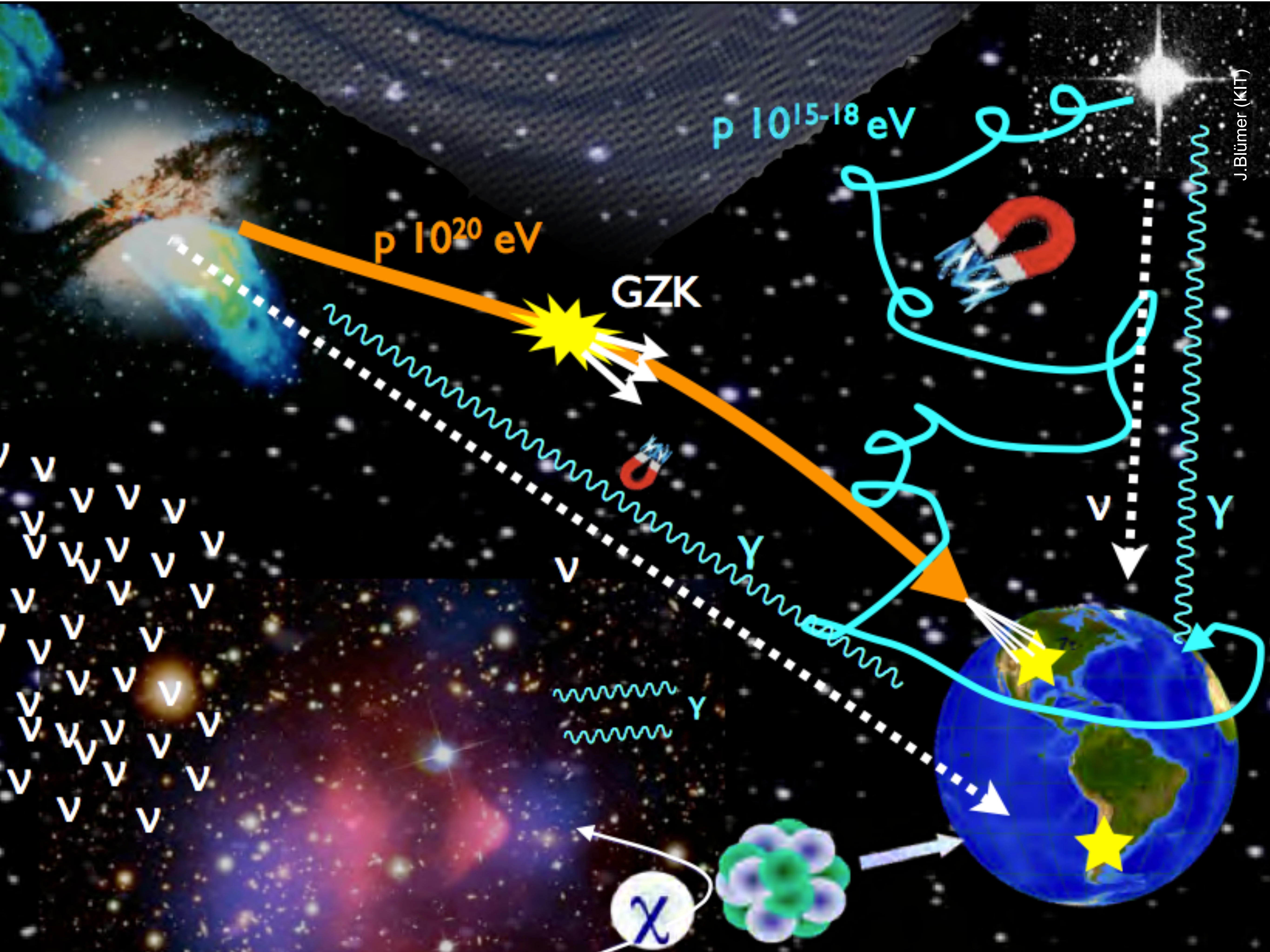


Pulsars

Credit: F. Acero & H. Gast

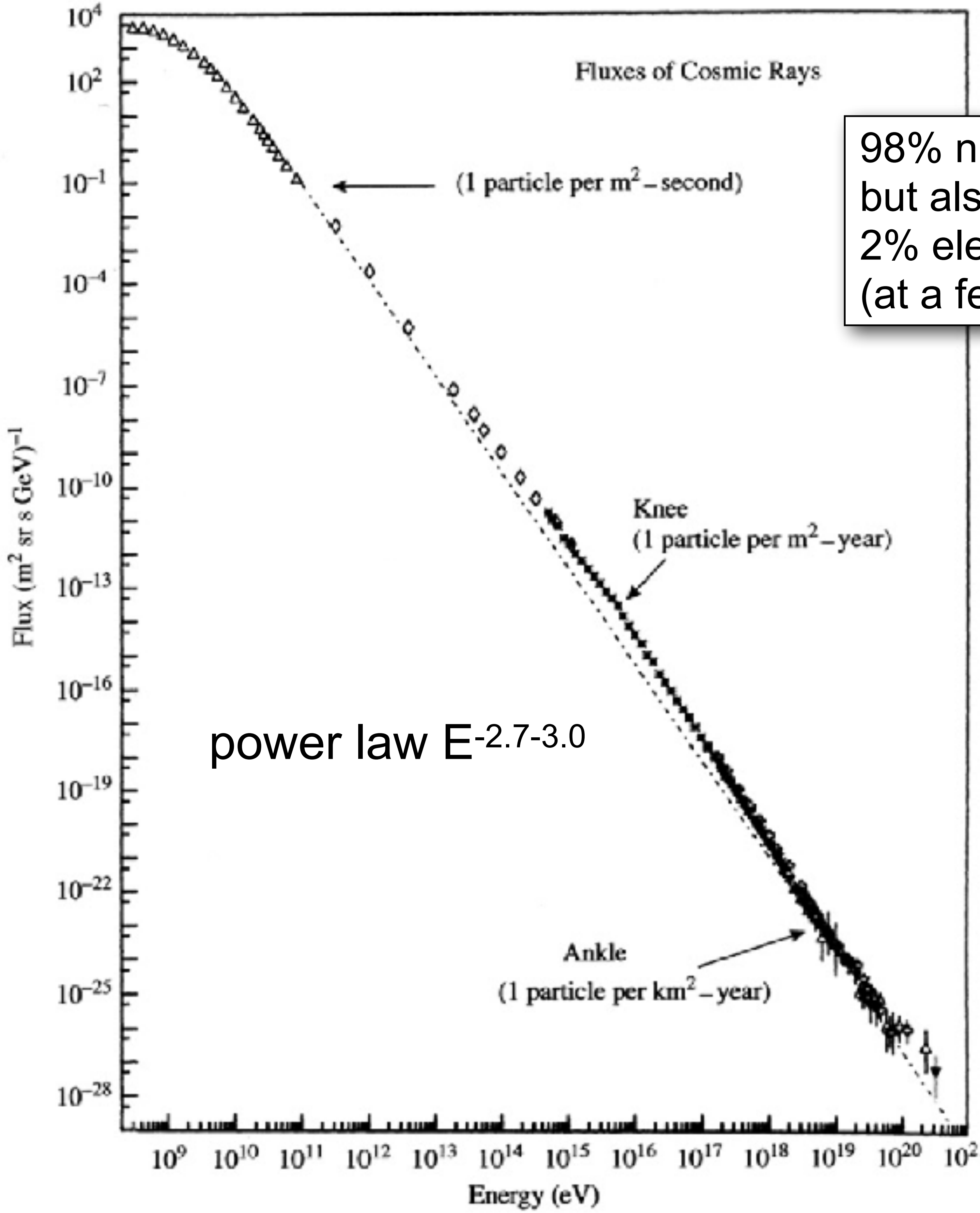


• Exploring Frontiers in Physics
what is the nature of dark matter? how is it distributed?
is the speed of light constant?
do axion-like particles exist?
dark matter
(line-of-sight density)
many discoveries in the past 100 years:
positron, muon, neutrino oscillations, …
Credit: F. Acero & H. Gast
Gernot Maier
DESY Seminar | 28.2/1.3 2017
6



p 10^{15-18} eV
J.Blümer (KIT)
p 10^{20} eV
GZK
ν
γ

The Cosmic Ray Energy Spectrum

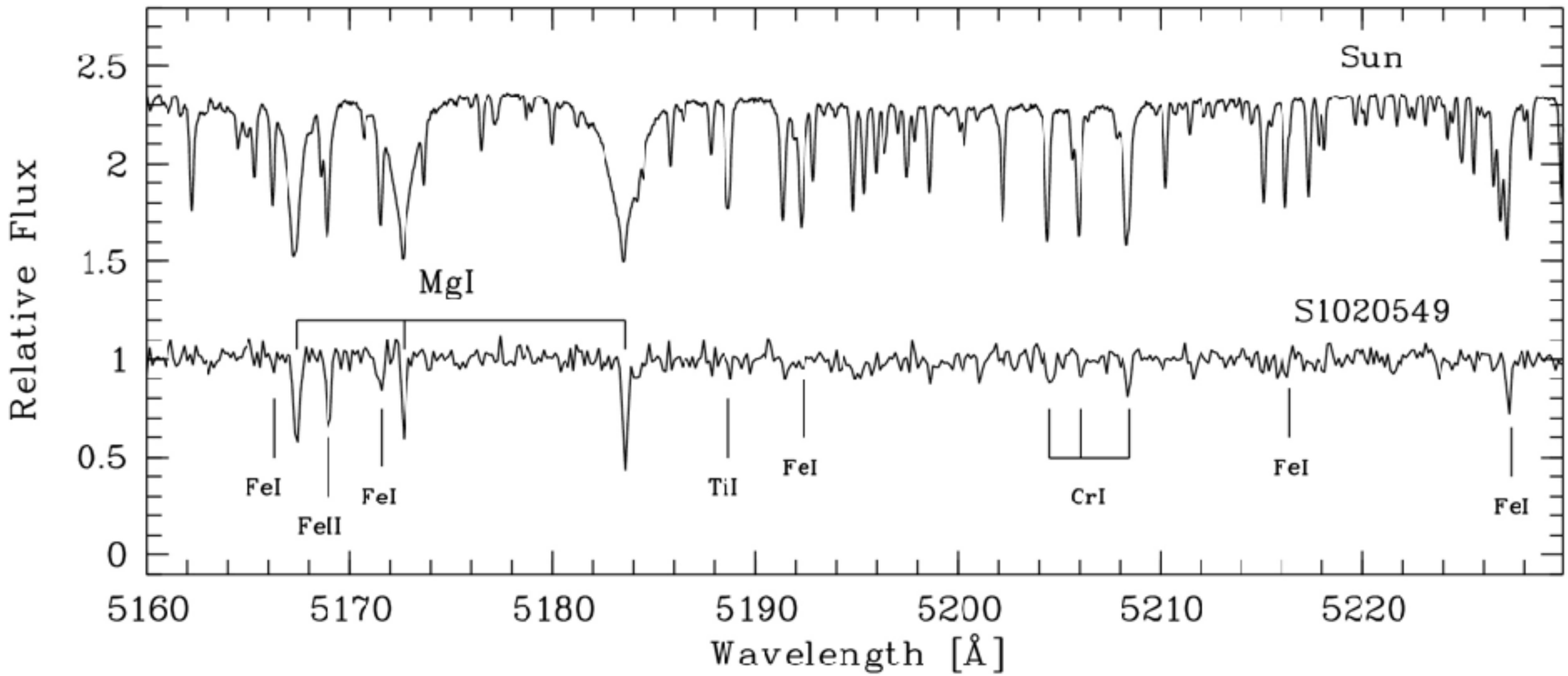


power law $E^{-2.7-3.0}$

98% nuclei, mostly p, He,
but also heavier nuclei
2% electrons
(at a few GeV)

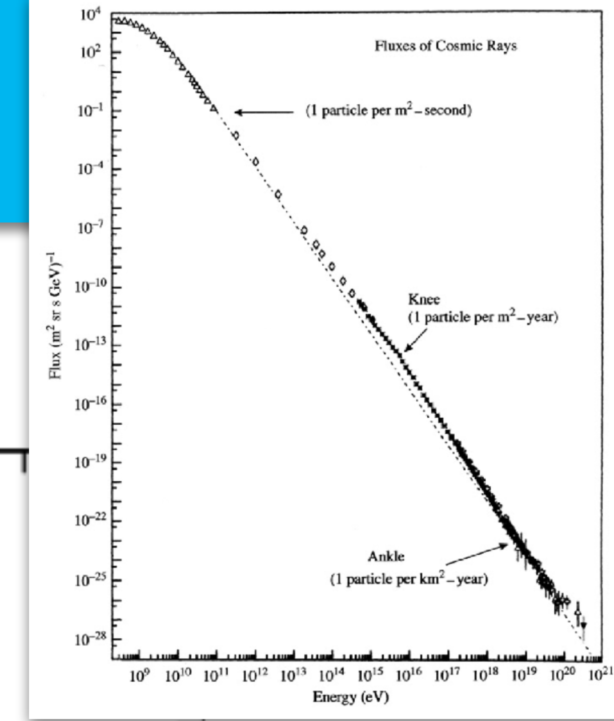
Bhattacharjee & Sigl 2000

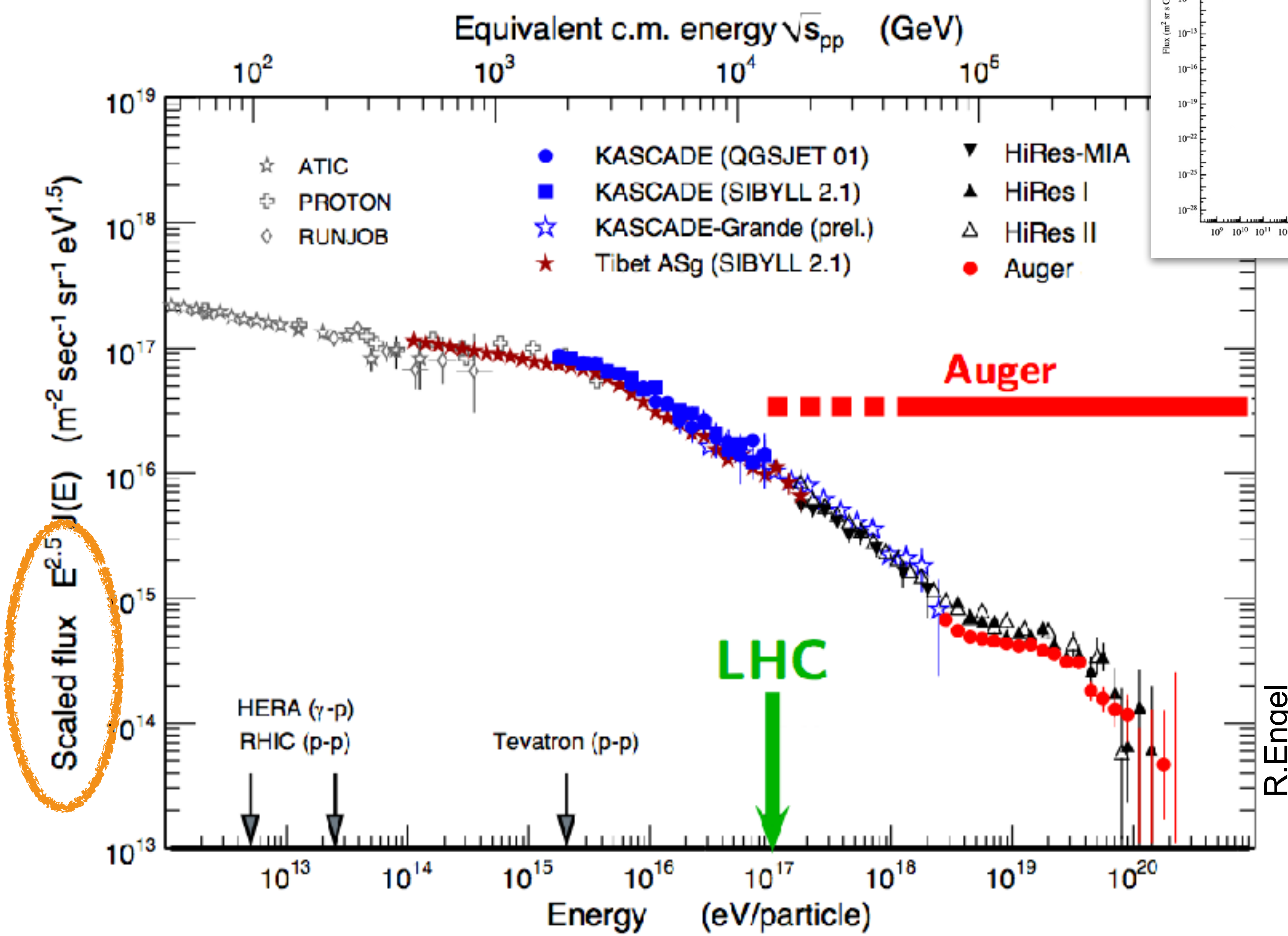
Typical spectra at optical wavelengths of celestial objects



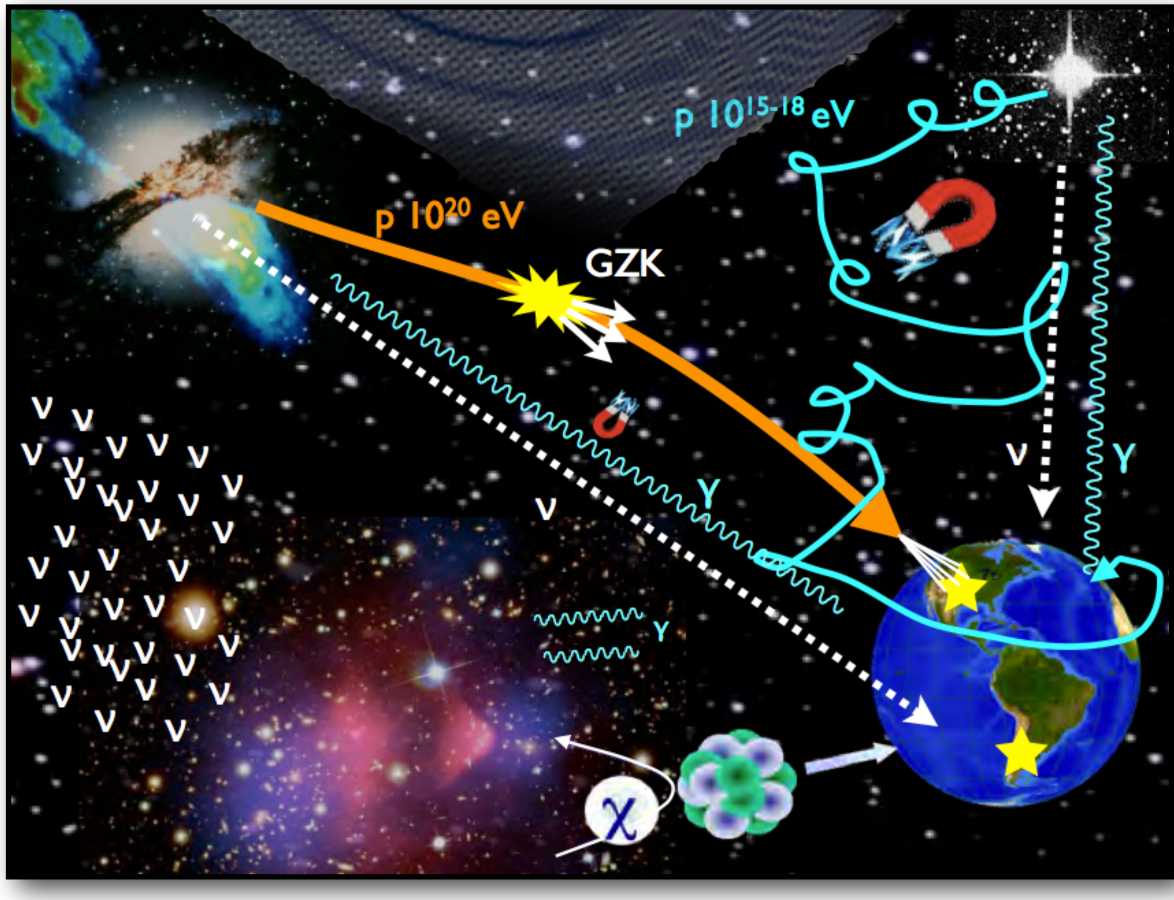
cosmic ray energy spectrum looks very different…

The Cosmic Ray Energy Spectrum





High-energy particles and their interactions (1)



- interaction with magnetic fields
  - deflection
  - energy loss through synchrotron radiation
- interaction with matter fields / other particles
  - $p_{CR} + p \rightarrow p + \pi^{0/+/-} + \ldots.$
  - Bremsstrahlung
  - inverse Compton scattering
  - pair production / annihilation
- interaction with photon fields
  - $p_{CR} + \gamma_{CMB} \rightarrow p + \pi^0$ / $p_{CR} + \gamma_{CMB} \rightarrow n + \pi^{+/-}$
  - $p_{CR} + \gamma \rightarrow p + e^+e^-$
  - $\gamma + A(N) \rightarrow (A-1) + N$
- secondary particles produce synchrotron radiation and cascades

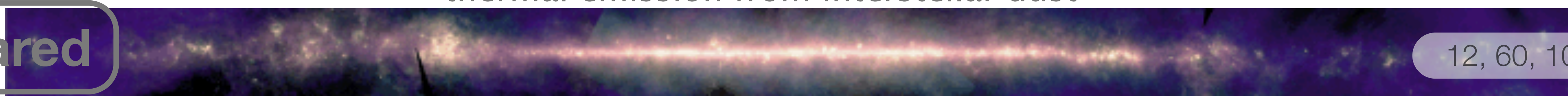
High-energy particles and their interactions (2)

star light

High-energy particles and their interactions (2)

thermal emission from interstellar dust

Infrared



12, 60, 100 μm

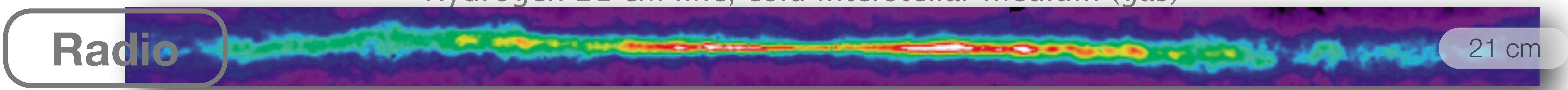
star light

Optical

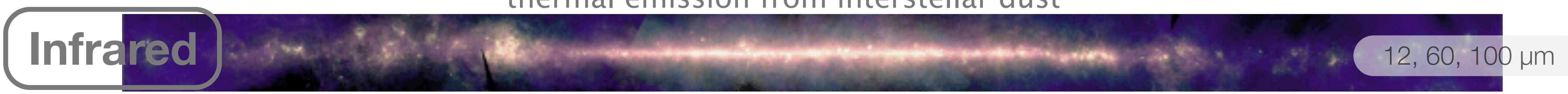
0.4-0.6 μm

High-energy particles and their interactions (2)

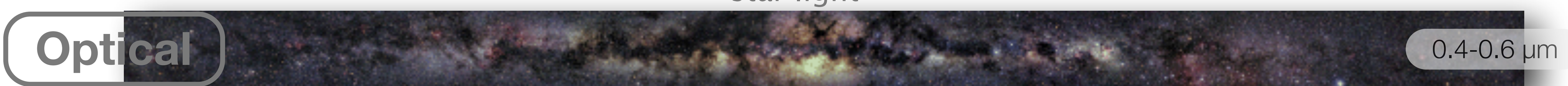
Hydrogen 21 cm line, cold interstellar medium (gas)



thermal emission from interstellar dust



star light



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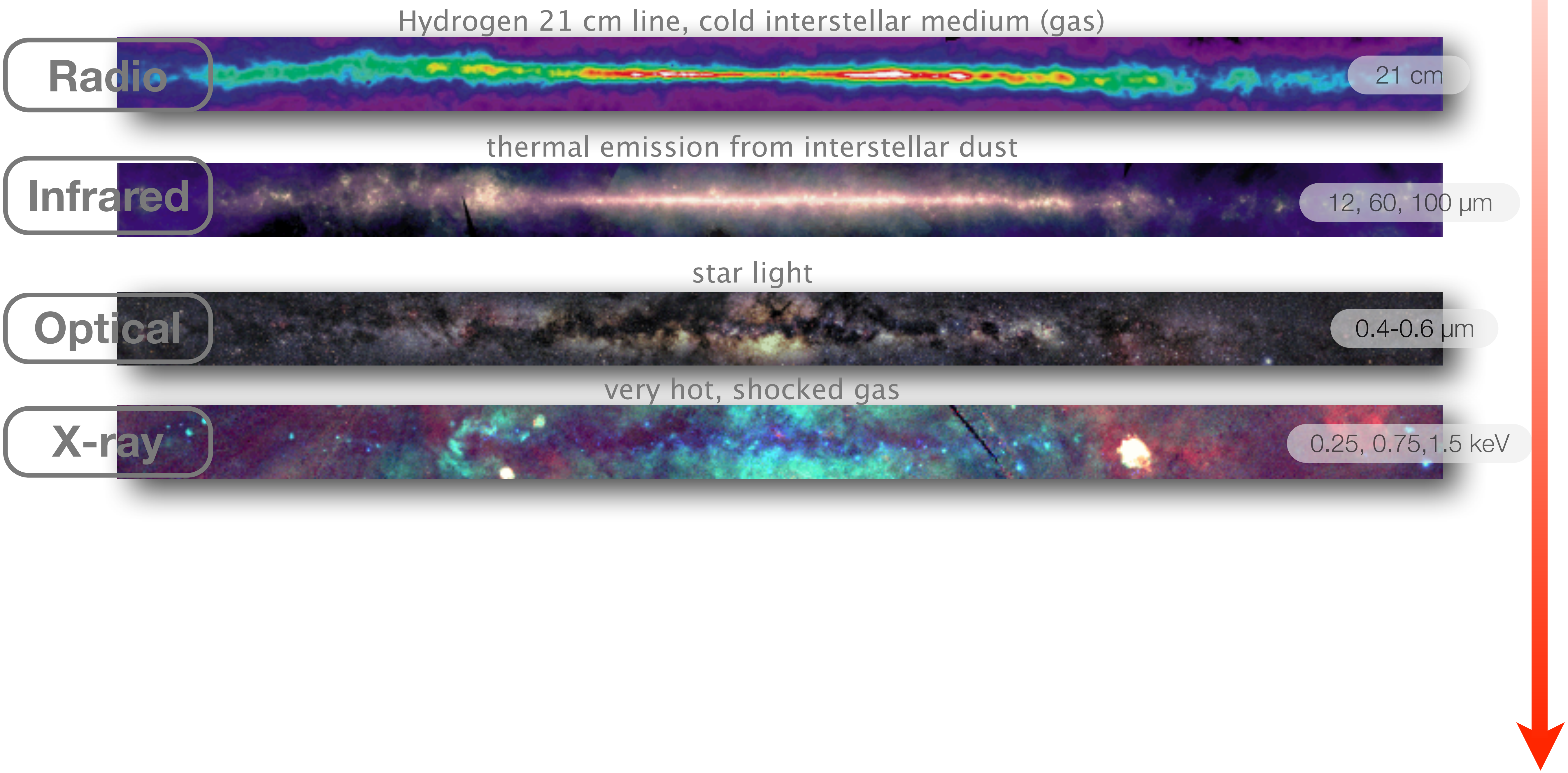

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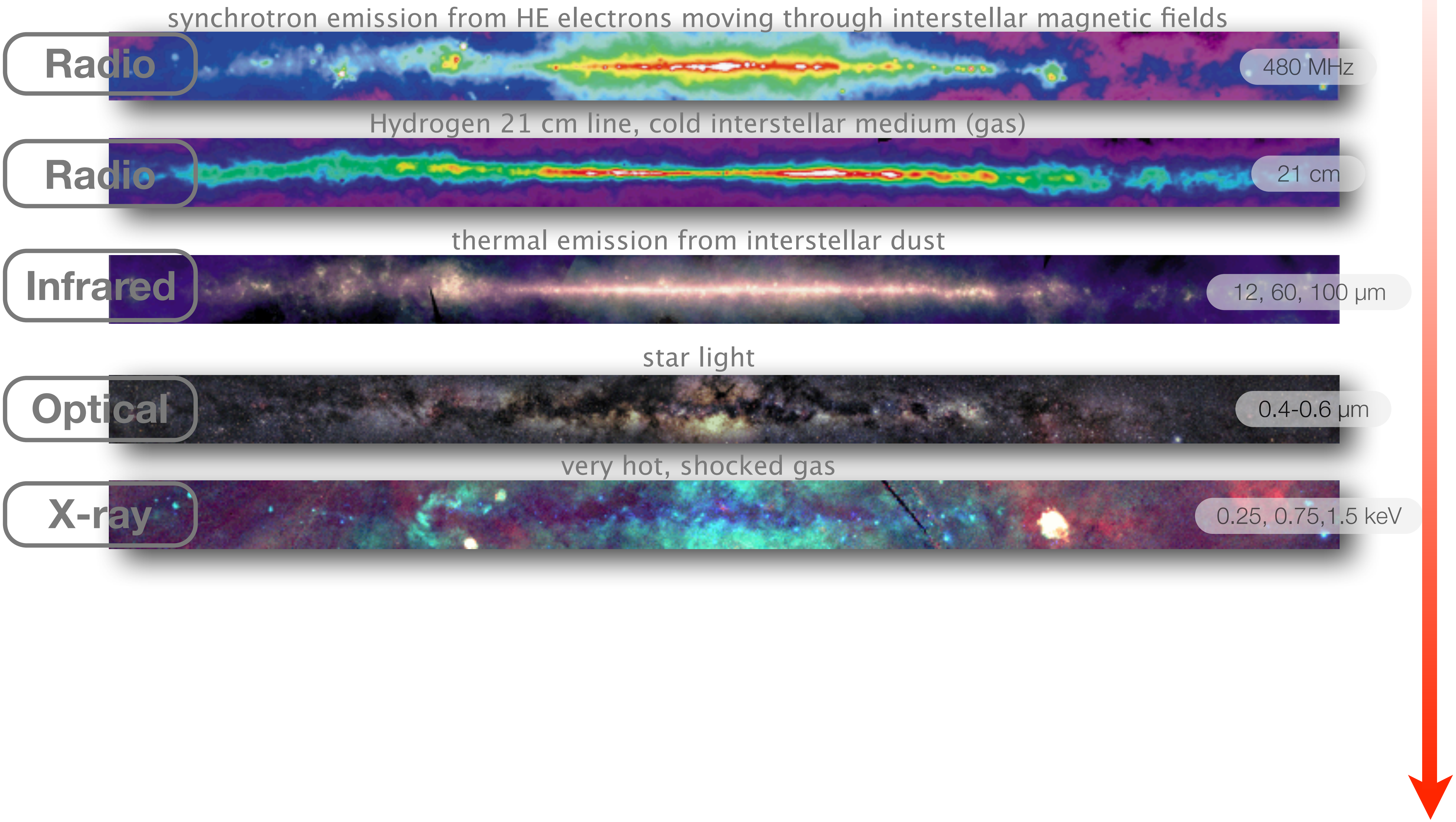

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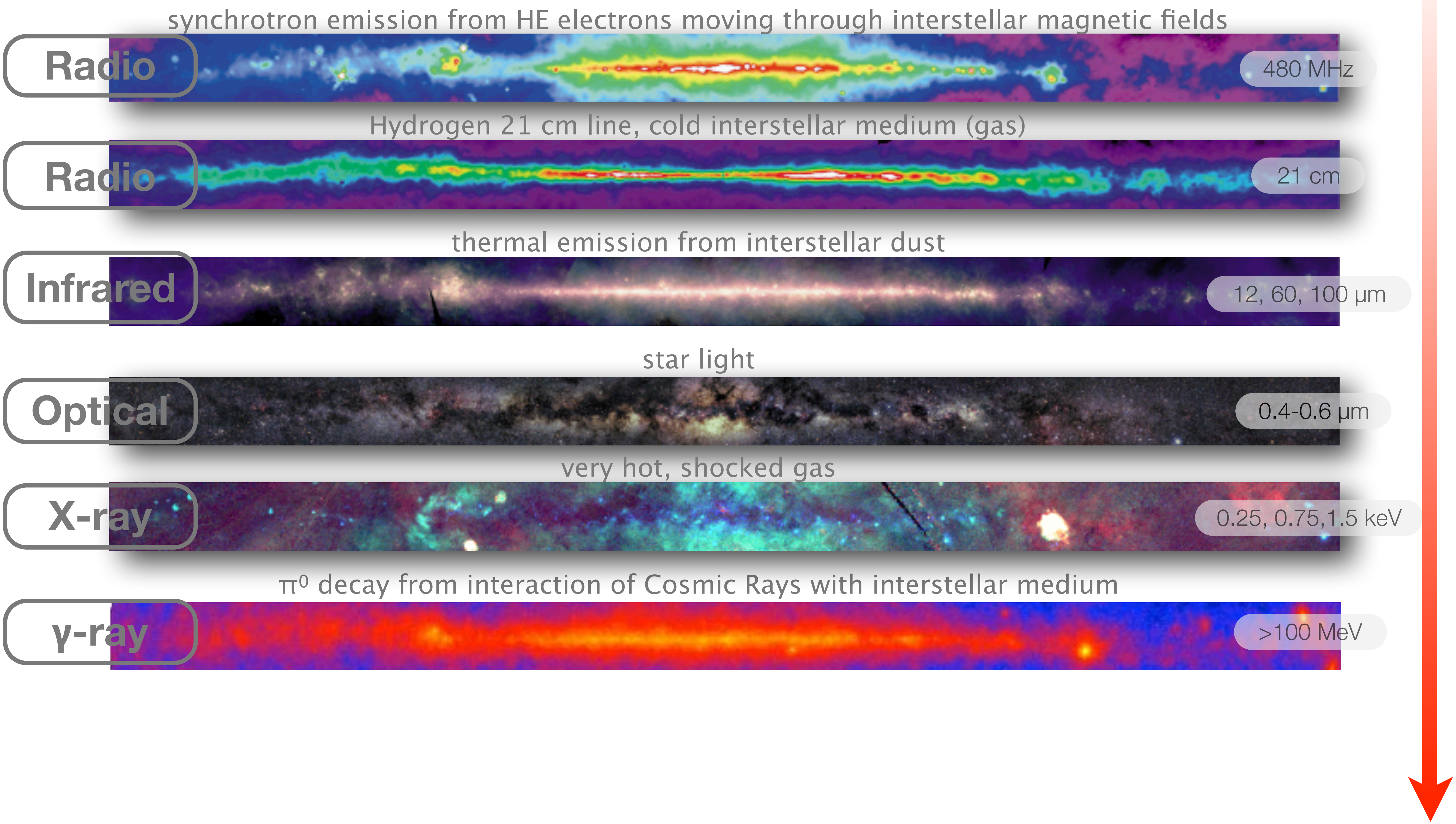

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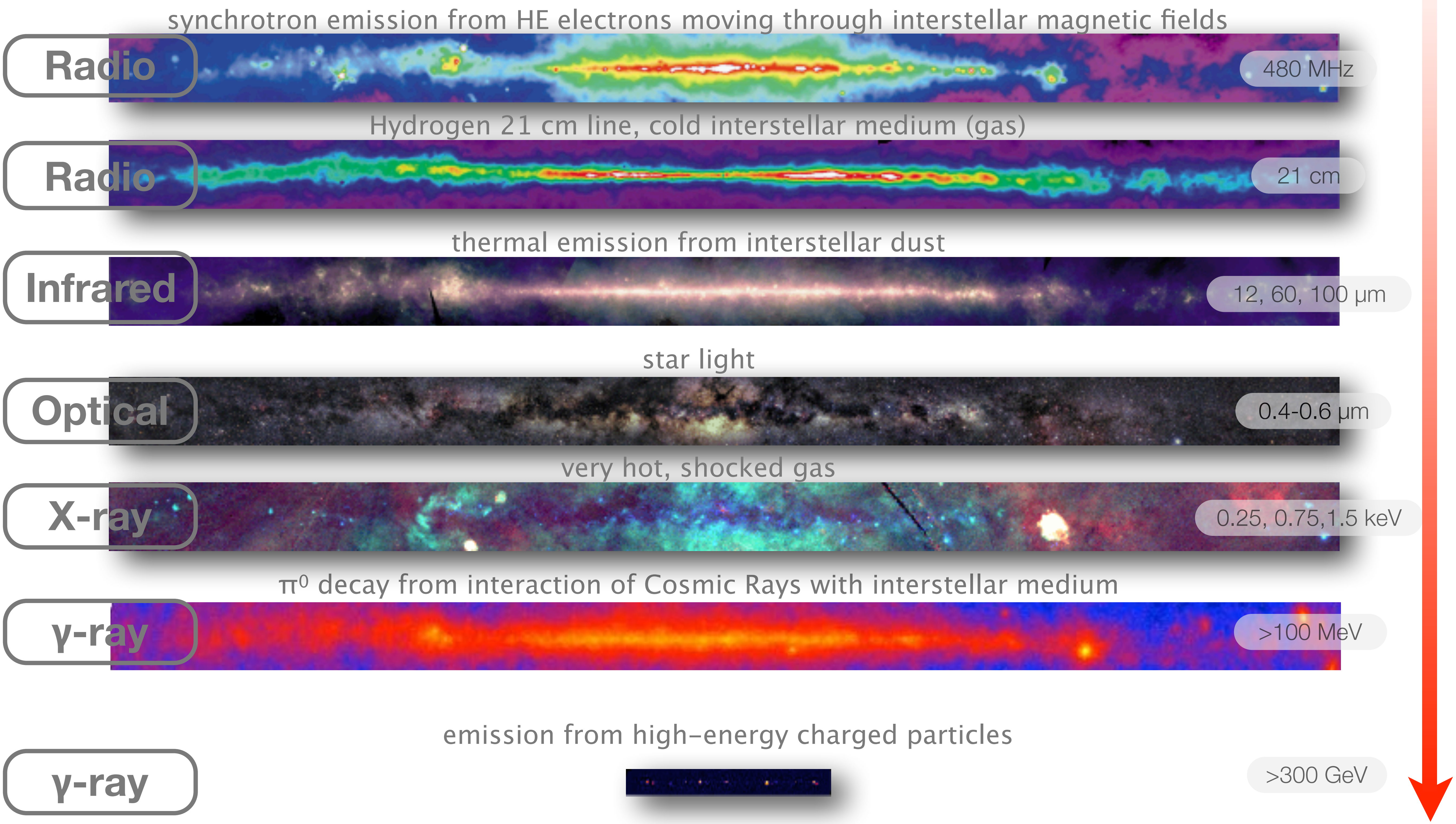
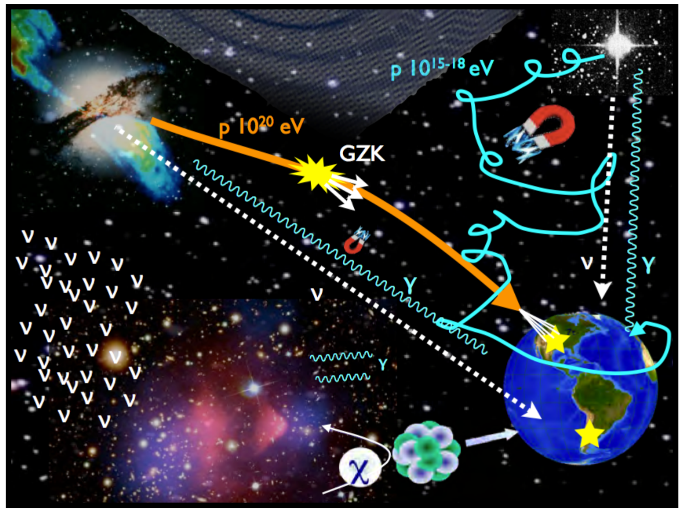


High-energy particles and their interactions (3)

$N_i(E,x,t)dE$ is density of particles of type *i* at position *x* with energy between *E* and *dE*

$$\frac{\partial N}{\partial t} = \nabla \cdot (D_i \nabla N_i) - \frac{\partial}{\partial E}(dE/dt N_i(E)) - \nabla \cdot \vec{u} N_i(E)$$

$$+ \quad Q_i(E,t) - p_i N_i + \frac{v\rho}{m} \sum_{k \geq i} \frac{d\sigma_{i,k}(E,E')}{dE} N_k(E') dE'$$



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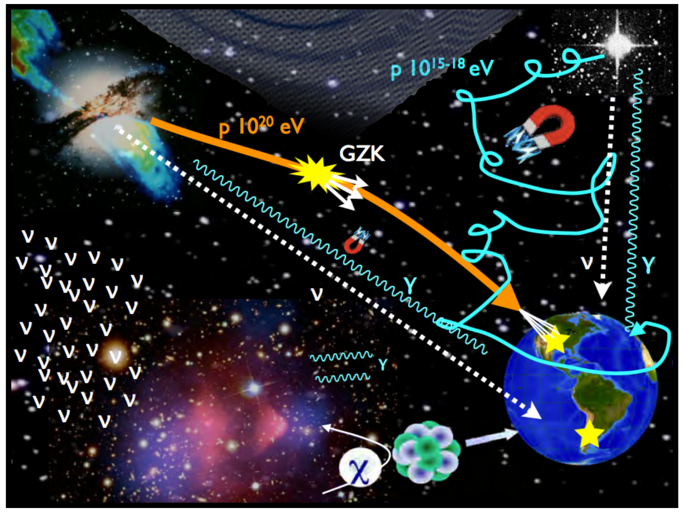
source term



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$N_i(E,x,t)dE$ is density of particles of type *i* at position *x* with energy between *E* and *dE*

diffusion with diffusion coefficient D_i

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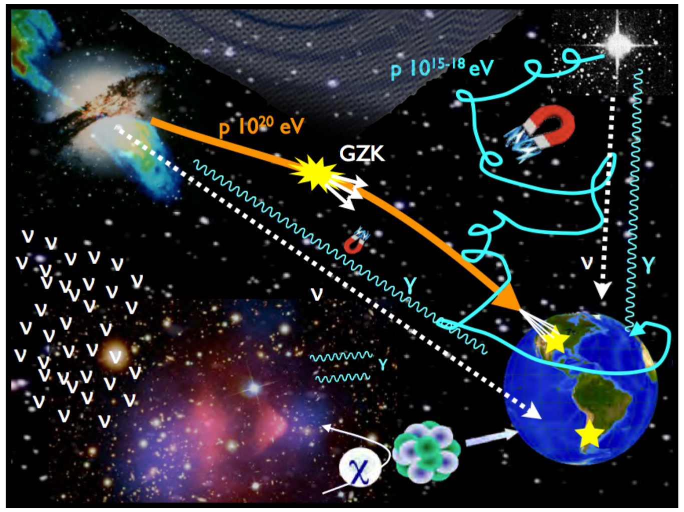

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$N_i(E,x,t)dE$ is density of particles of type *i* at position *x* with energy between *E* and *dE*

(synchrotron radiation, ionization loss, reacceleration, ...)

diffusion with diffusion coefficient D_i

energy losses and gains

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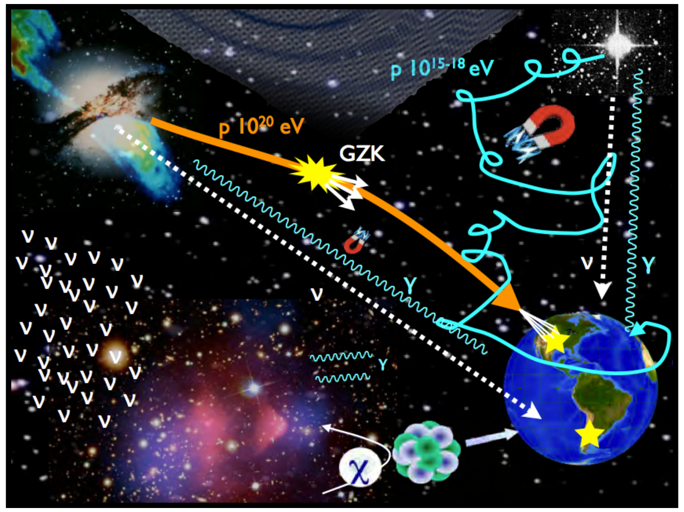

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energy losses and gains

convection with velocity $\bar{u}$

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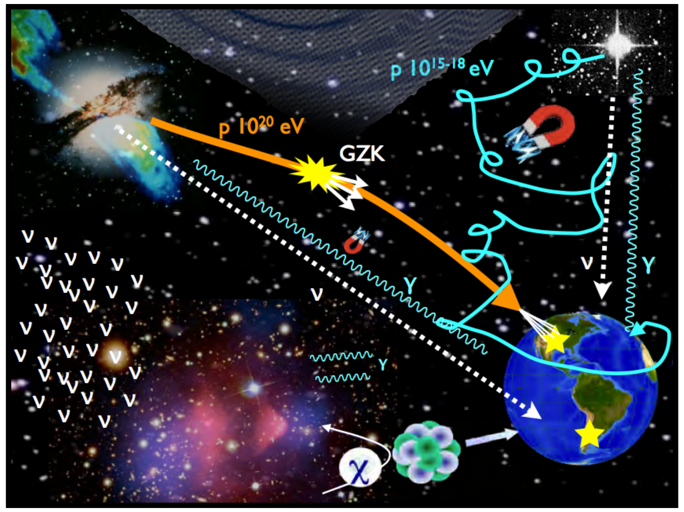

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diffusion with diffusion coefficient D_i — energy losses and gains — convection with velocity $\bar{u}$

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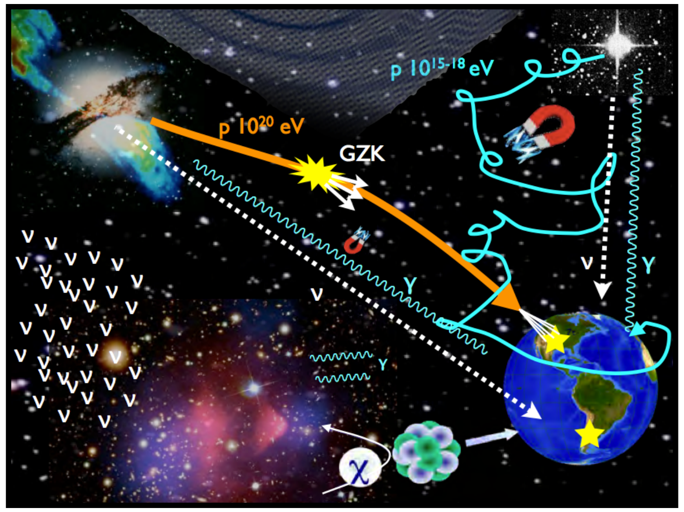
source term — loss term

$$\text{loss term } p_i = \frac{v\rho}{\lambda_i} + \frac{1}{\gamma \tau_i}$$



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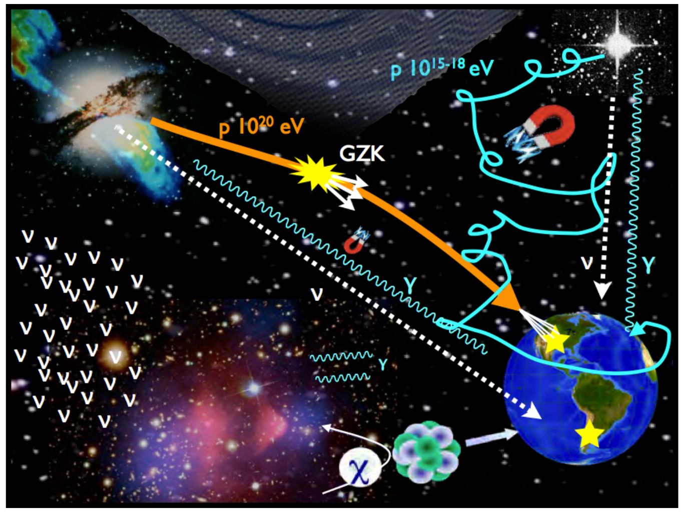
source term — loss term — cascade term: feed-down from higher energies and nuclear fragmentation processes

$$\text{loss term } p_i = \frac{v\rho}{\lambda_i} + \frac{1}{\gamma\tau_i}$$



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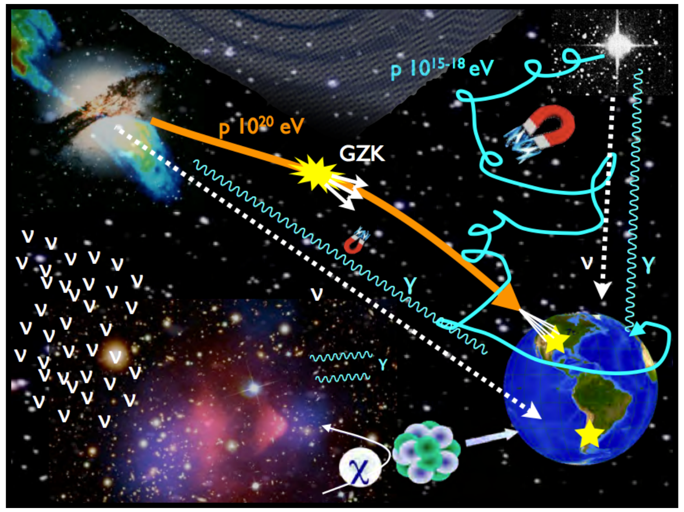
- diffusion with diffusion coefficient D_i
- energy losses and gains (synchrotron radiation, ionization loss, reacceleration, ...)
- convection with velocity ū
- source term
- loss term
- cascade term: feed-down from higher energies and nuclear fragmentation processes

$$\text{loss term } p_i = \frac{v\rho}{\lambda_i} + \frac{1}{\gamma\tau_i}$$

Secondary particles:
charged particles, neutrinos, photons



What are the sources of cosmic rays?

Is it a single source?

A single source class?

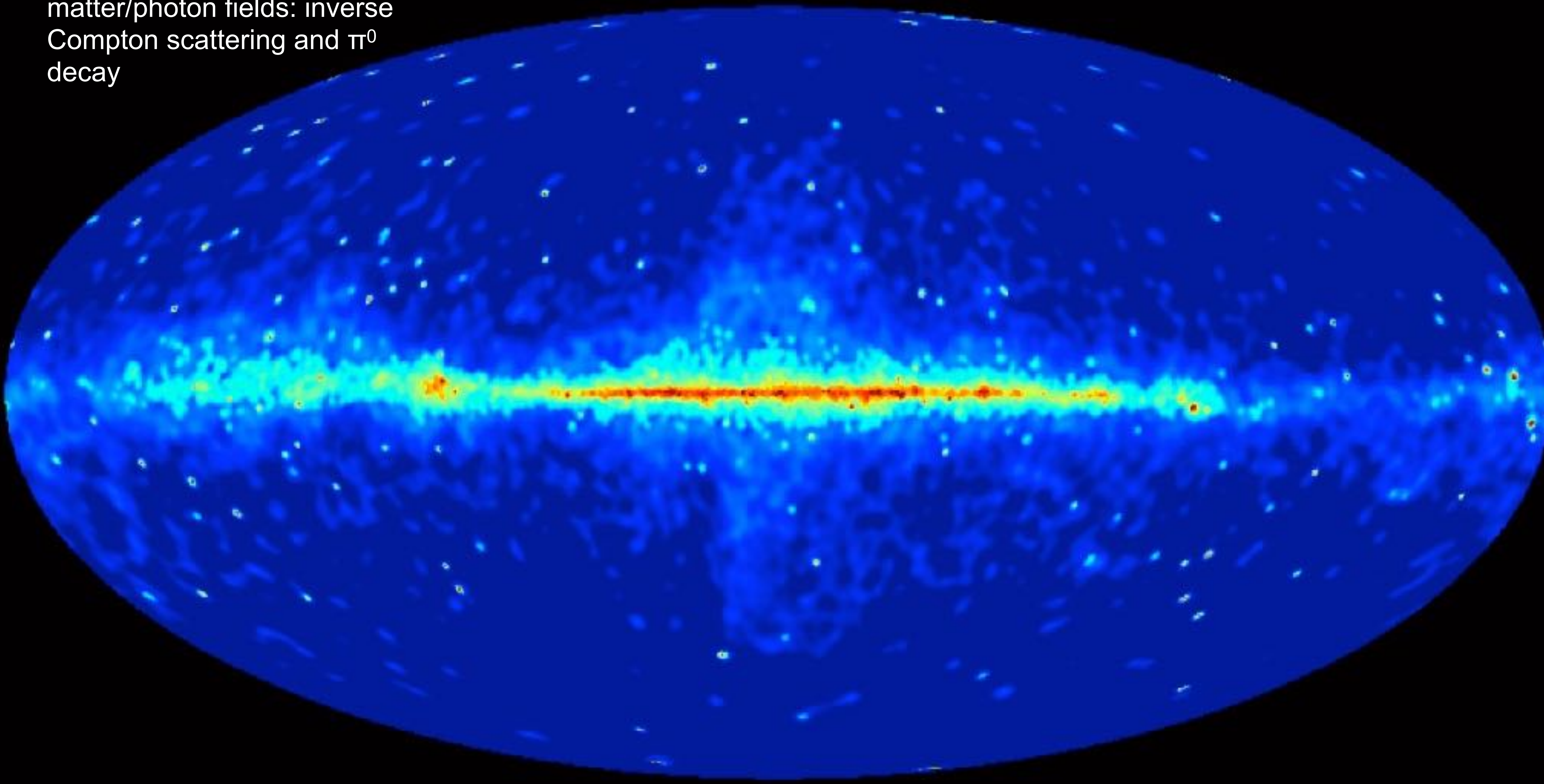
Where are they?

Galactic / extragalactic?

The high-energy gamma-ray sky

gamma rays are produced by interactions of cosmic rays with matter/photon fields: inverse Compton scattering and π^0 decay

Fermi LAT 3-years sky map > 10 GeV



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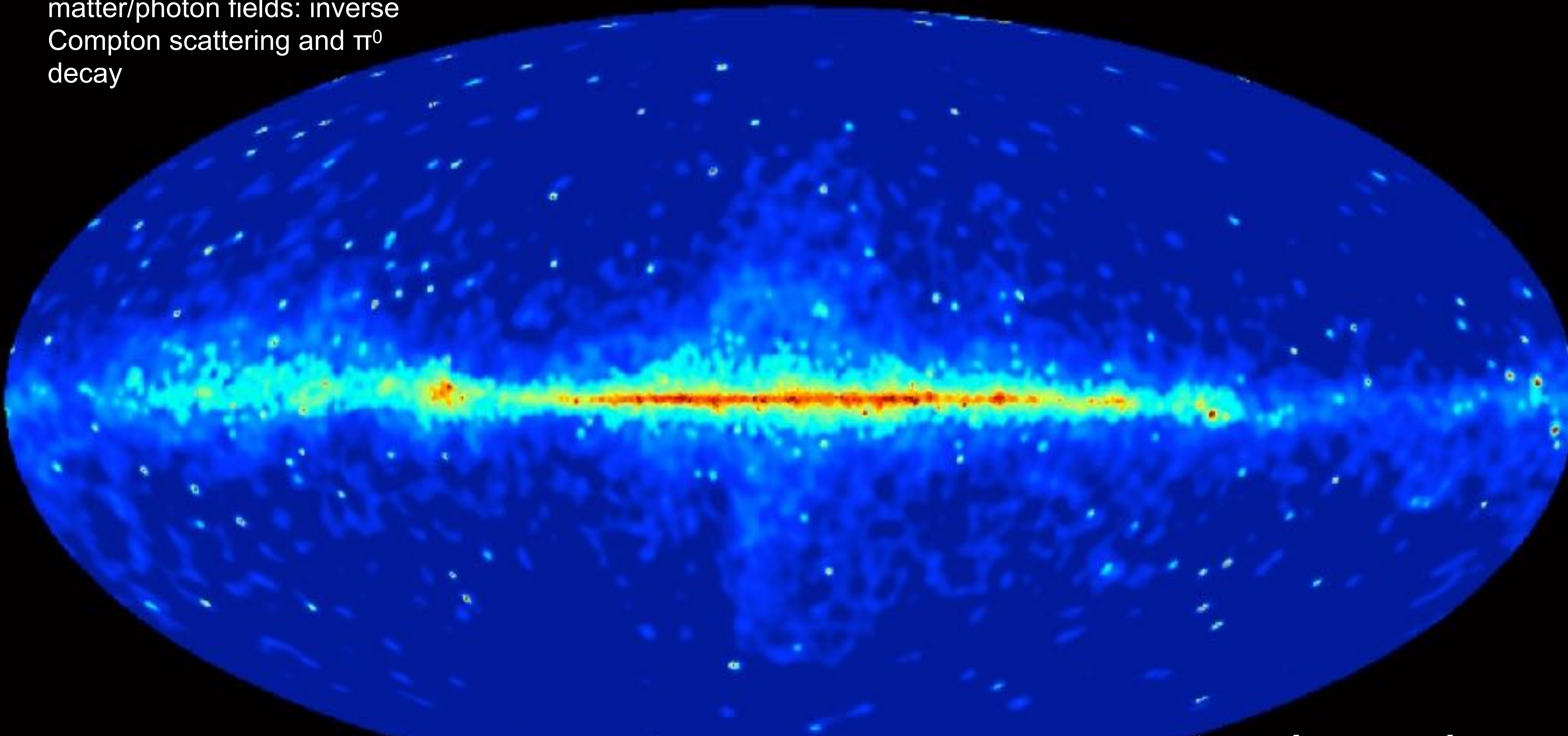

>2500 sources @ MeV-GeV
>500 sources >10 GeV
>150 sources >100 GeV

supernova remnants, pulsars, pulsar wind nebulae, binary systems, massive star clusters, starburst galaxies, active galactic nuclei (mostly blazars), gamma-ray bursts, nova, diffuse, dark matter, ...

1987A - a type II Supernova of 20 $M_\odot$

located in the Large Magellanic Cloud (163,000 ly)

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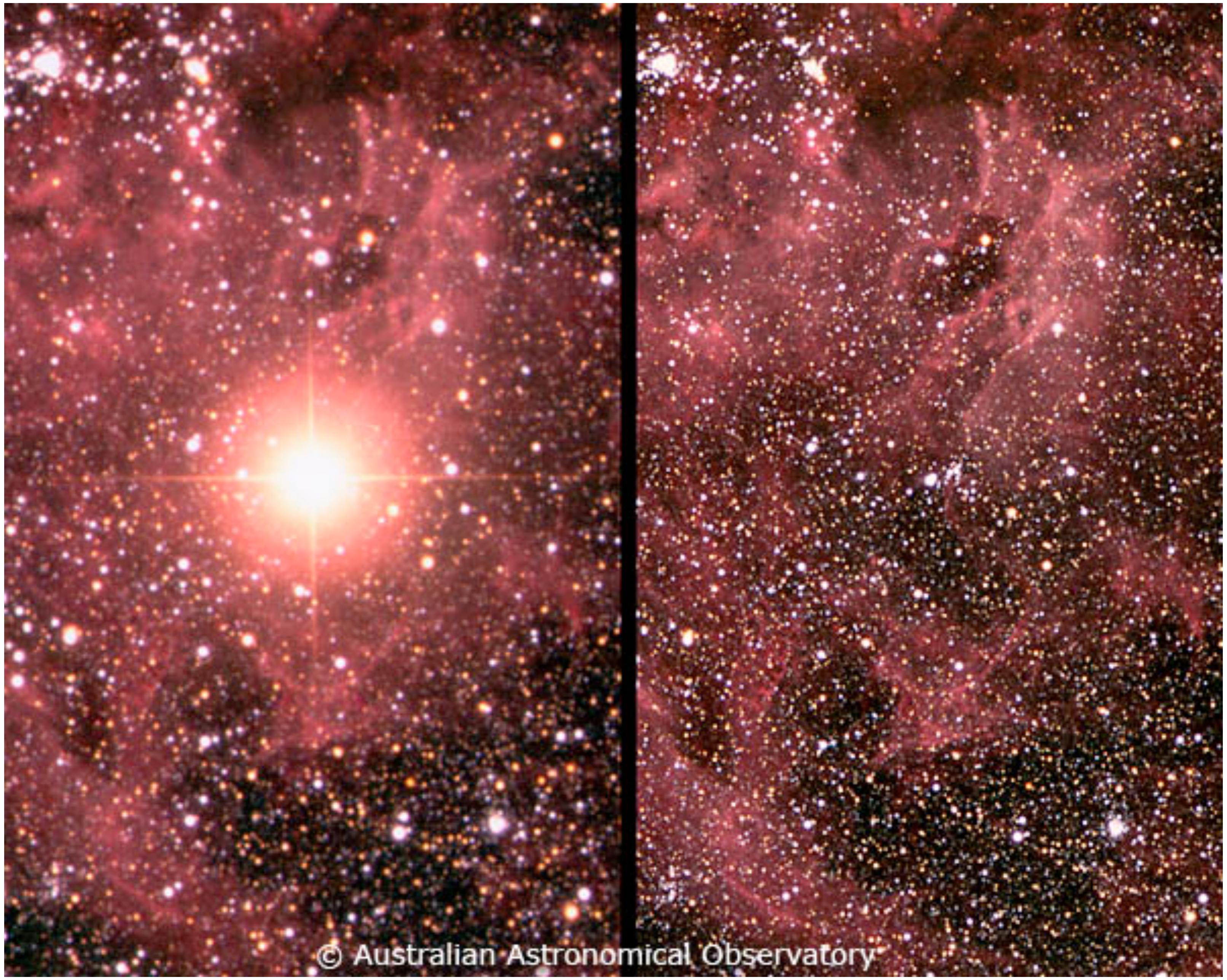
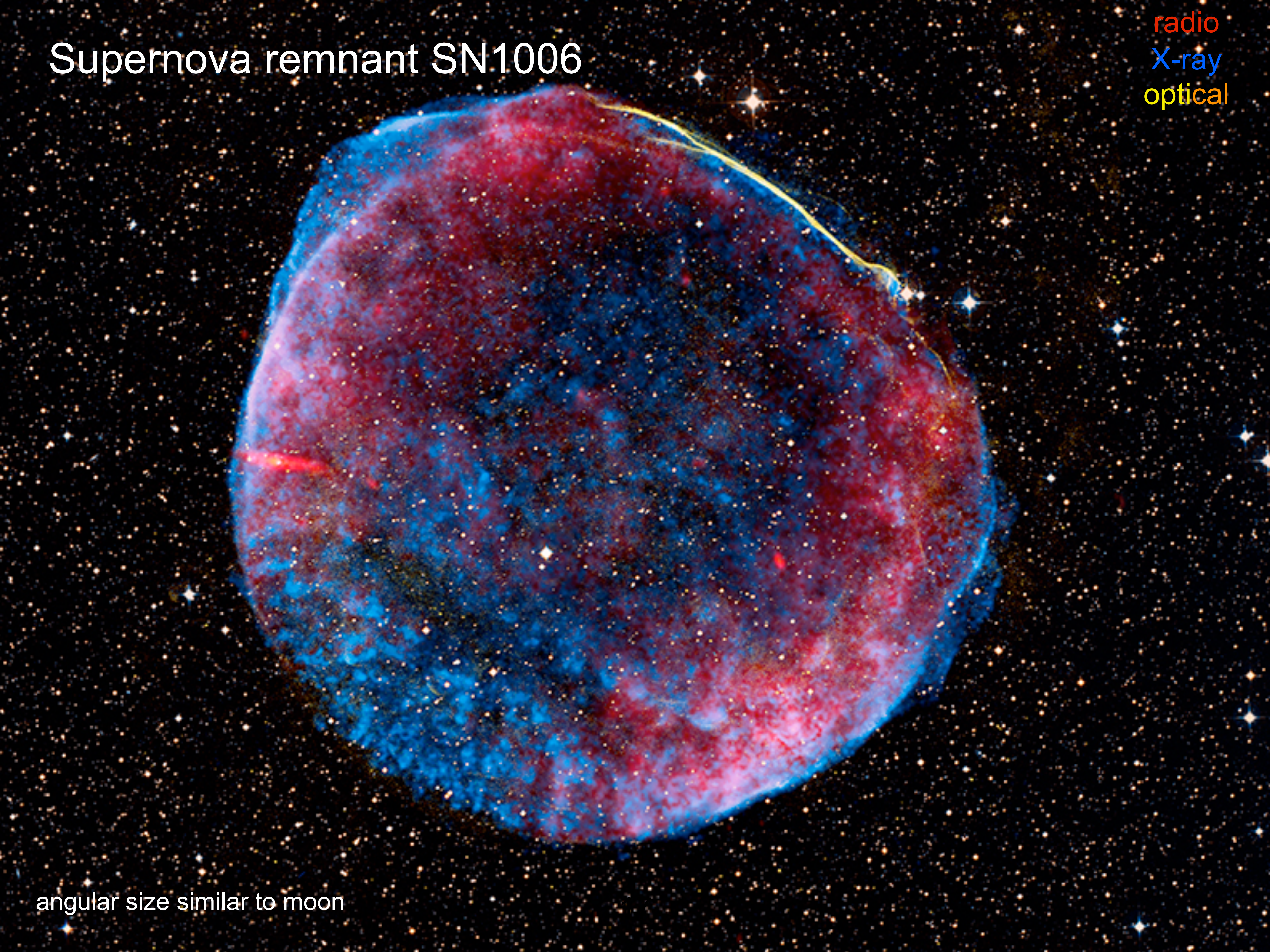
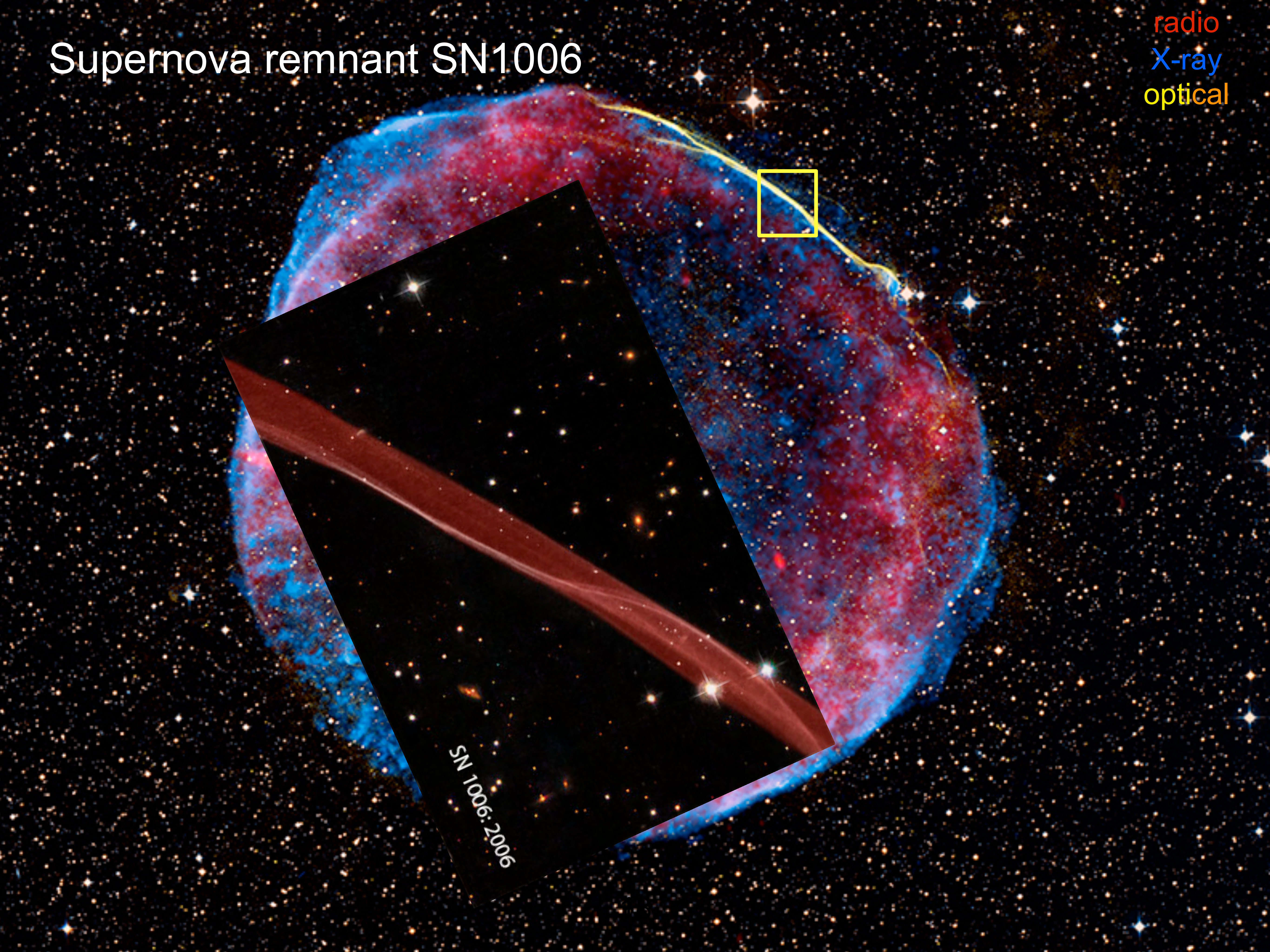


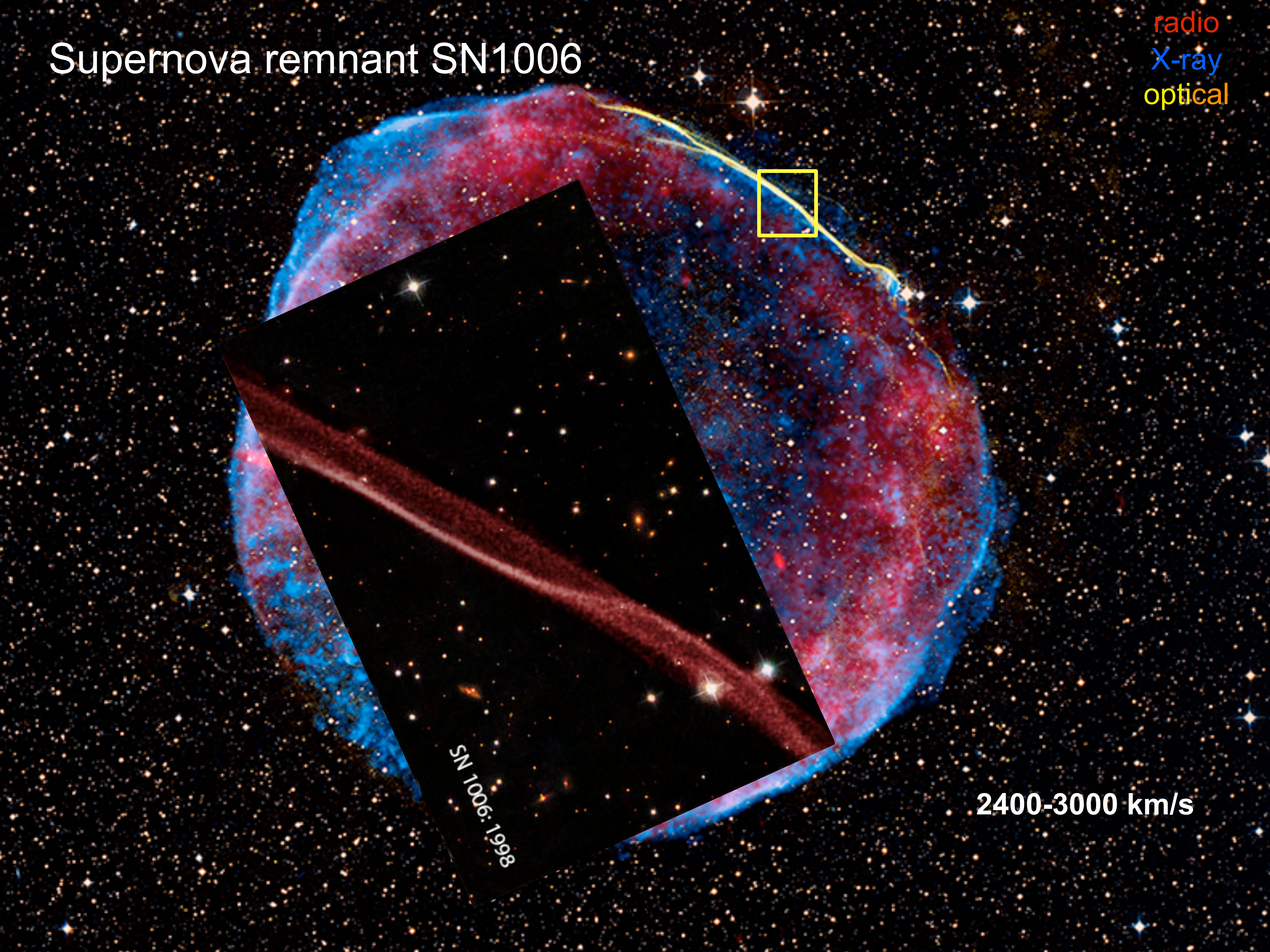
2 weeks after onset of explosion

Supernova remnant SN1006



angular size similar to moon


Supernova remnant SN1006
radio
X-ray
optical
SN 1006: 2006


Supernova remnant SN1006
radio
X-ray
optical
SN 1006: 1998
2400-3000 km/s

Energy budget for Galactic Cosmic Rays

1 erg = 10^{-7} J

assume Milky Way is filled uniformly with Cosmic Rays (CR)

CR are contained for a time t_{GD} and then diffuse out of this volume (typically $t_{GD} \approx 10^7$y)

Volume of the galactic disk: $V_{GD} = \pi(15\text{kpc})^2(500\text{pc}) \approx 10^{67}\ \text{cm}^3$

CR energy density: $\rho_E \approx 0.5\ \text{eV/cm}^3$ (similar to starlight)

$$L_{CR} = \frac{V_{GD} \cdot \rho_E}{t_G D} \simeq 3 \times 10^{40} \text{erg/s}$$

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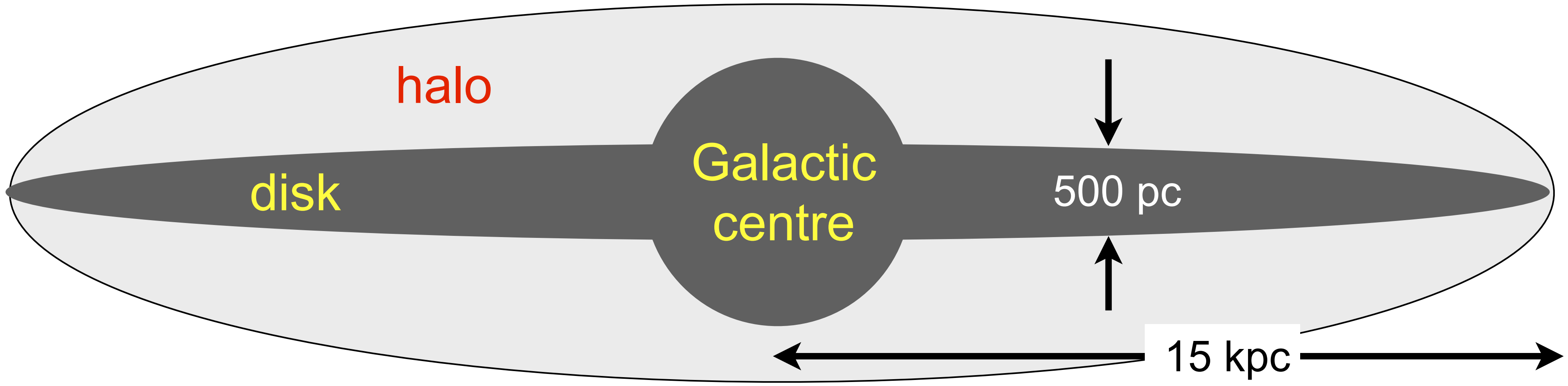

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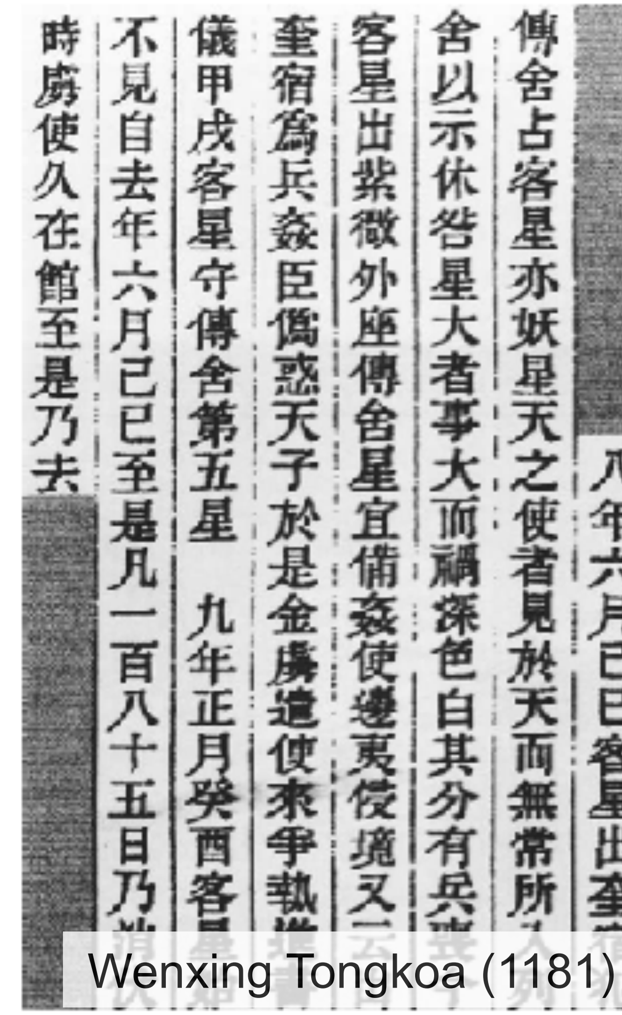
typical 2-3 Supernovae per 100 y in our Galaxy

Ejecta of 10 solar masses with velocity u ≈ 5×10^6 m/s

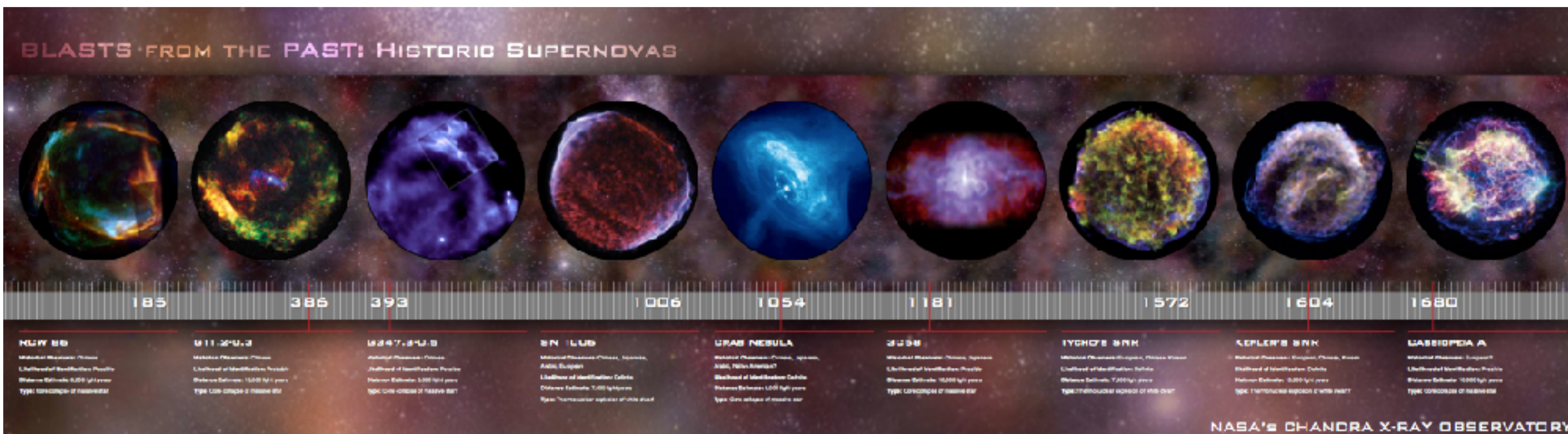
$$L_{SN} \simeq 3 \times 10^{42} \text{erg/s}$$

Historical Supernovae

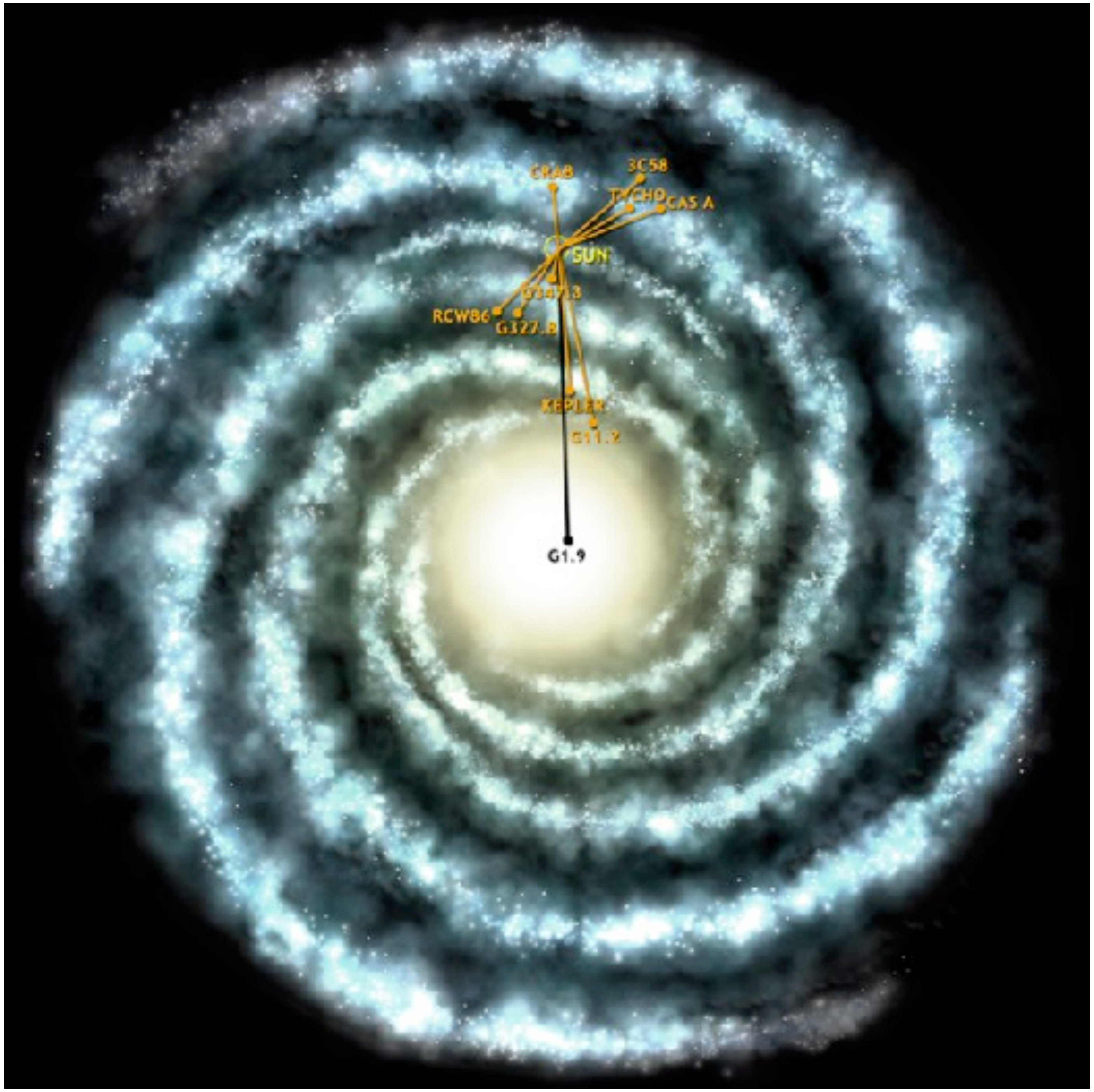
date	length of visibility	remnant	Historical Records: Chinese	Japanese	Korean	Arabic	European
AD1604	12 months	G4.5+6.8	few	–	many	–	many
AD1572	18 months	G120.1+2.1	few	–	two	–	many
AD1181	6 months	3C58	few	few	–	–	–
AD1054	21 months	Crab Nebula	many	few	–	one	–
AD1006	3 years	SNR327.6+14.6	many	many	–	few	two
AD393	8 months	–	one	–	–	–	–
AD386?	3 months	–	one	–	–	–	–
AD369?	5 months	–	one	–	–	–	–
AD185	8 or 20 months	–	one	–	–	–	–


八年六月已巳客星出奎
傳舍占客星亦妖星天之使者見於天而無常所
舍以示休咎星大者事大而禍深色白其分有兵
客星出紫微外座傳舍星宜備姦使邊夷侵境又
奎宿爲兵姦臣僞惑天子於是金虜遣使來爭執
儀甲戌客星守傳舍第五星　九年正月癸酉客
不見自去年六月己巳至是凡一百八十五日乃
時虜使久在館至是乃去

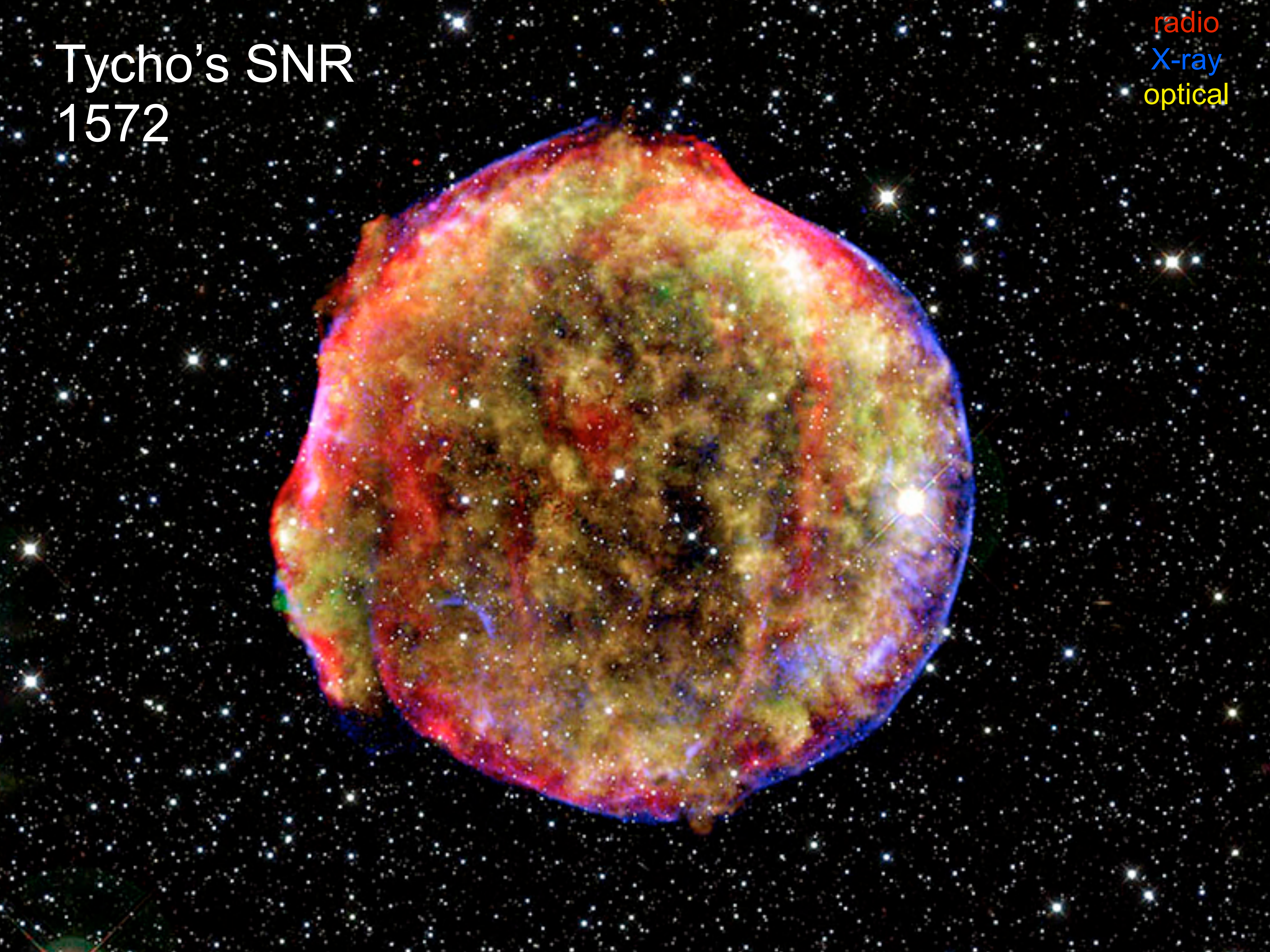
Wenxing Tongkoa (1181)

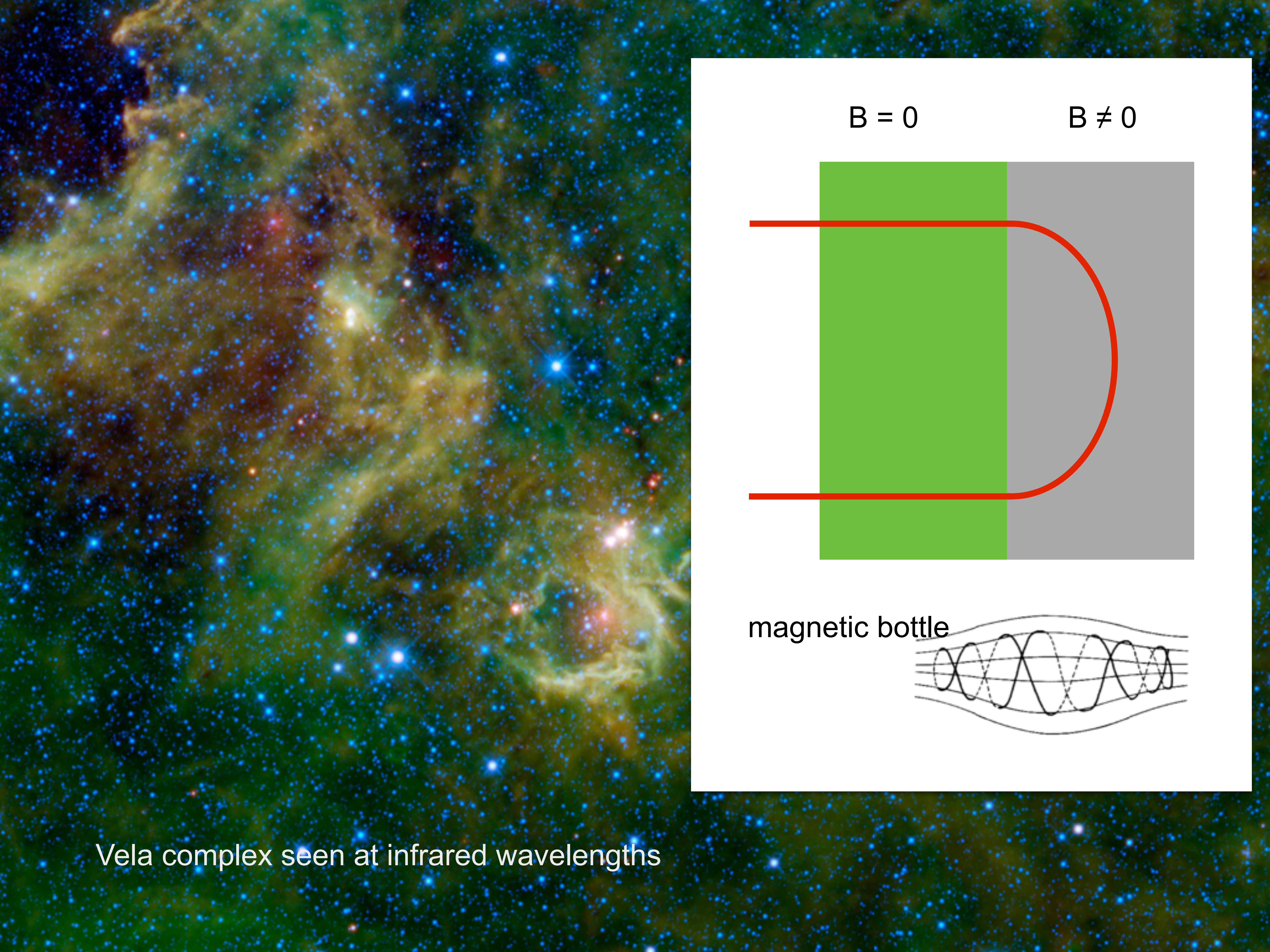


Historical Supernovae



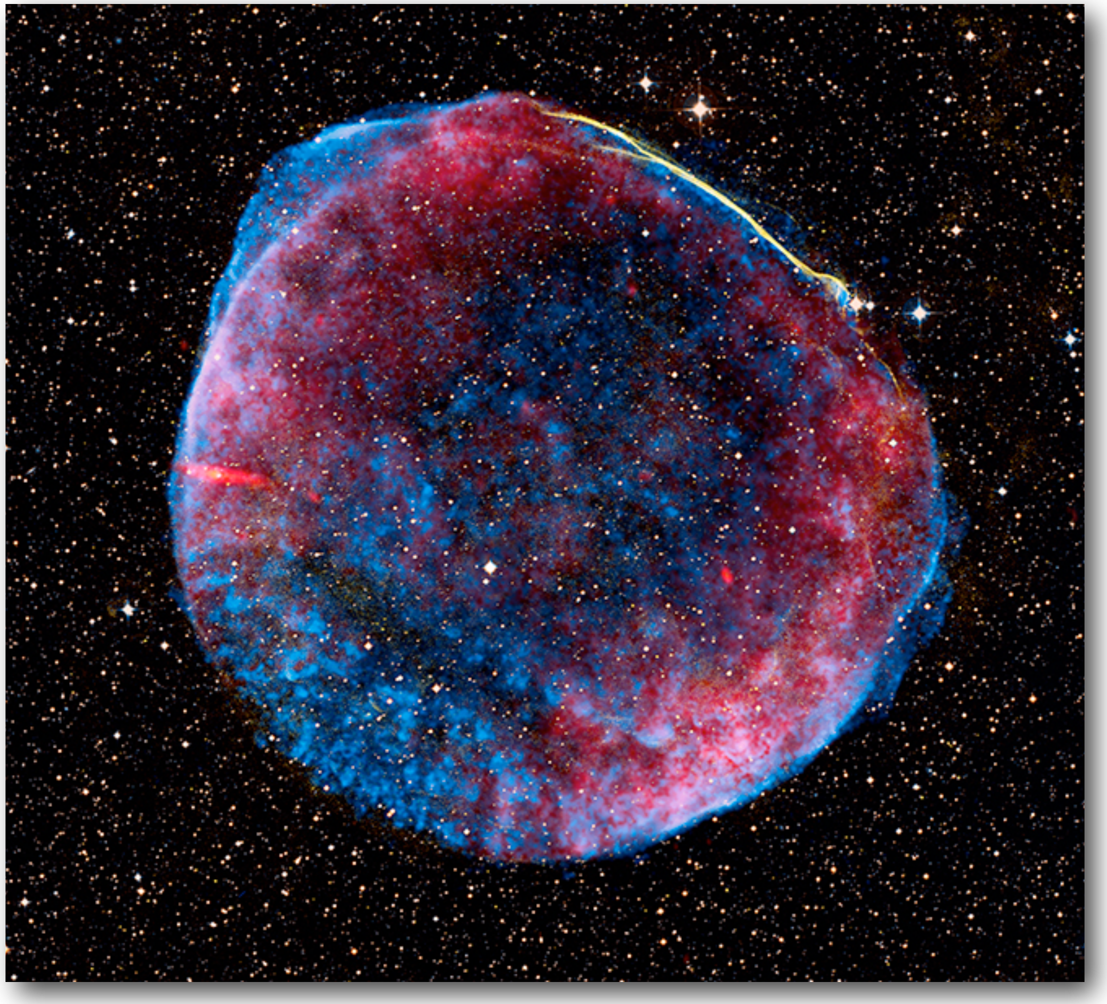
Observational effect: ~10^8 supernovae in the history of the Milky Way


Tycho's SNR
1572
radio
X-ray
optical



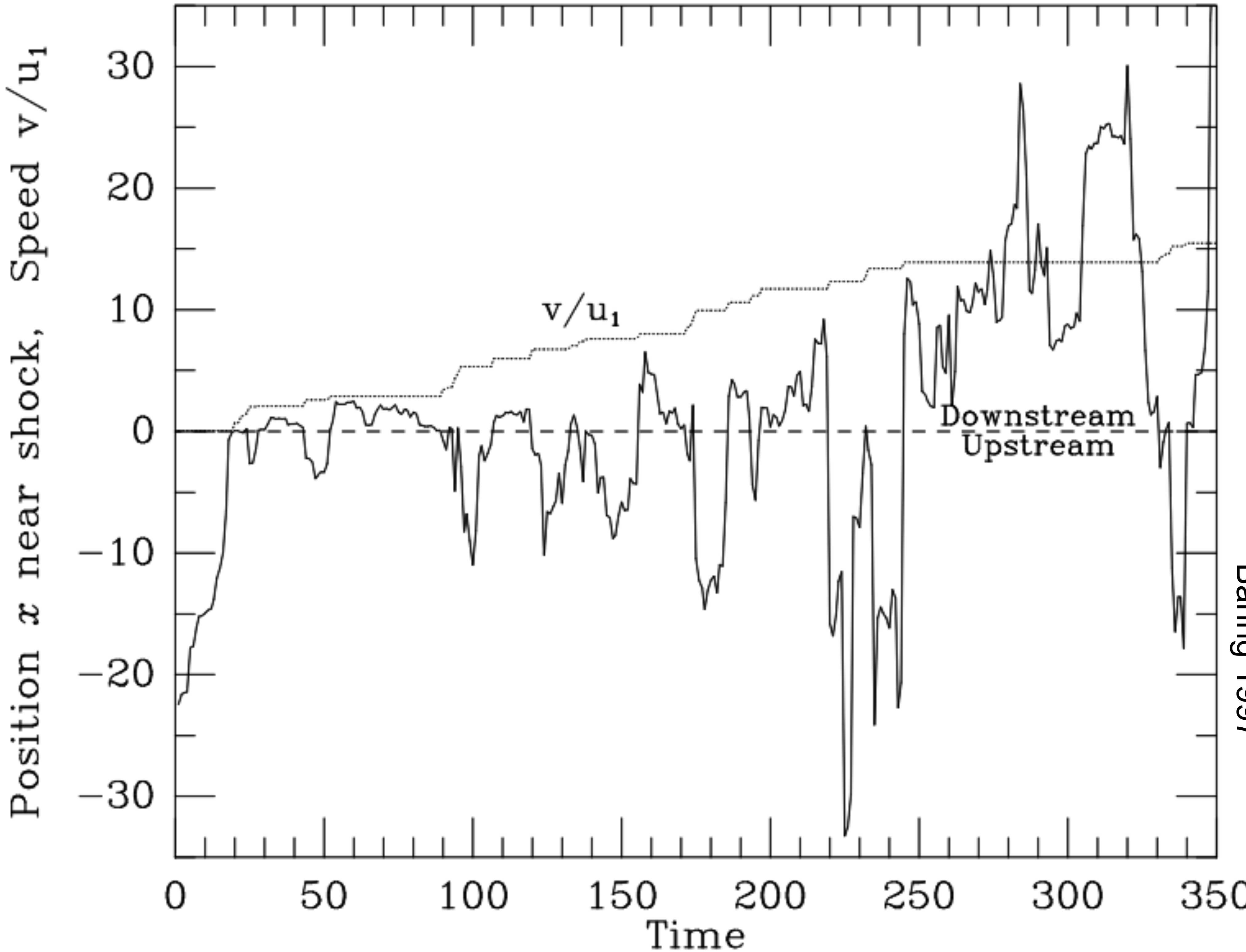
Vela complex seen at infrared wavelengths

Diffusive shock acceleration



shock:
shock speed > sound speed

Monte Carlo of first-order Fermi acceleration



Baring 1997

Energy spectrum from Fermi acceleration

Energy spectrum from Fermi acceleration

energy gain per shock passing:

$$1 + \xi = 1 + 4/3\beta$$

after *j* crossings a particle with initial energy E_0 will have

$$E = E_0(1 + \xi)^j$$

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particle escape probability from shock region P_{esc}. Number of particles > E:

$$N(\geq E) \propto \sum_{m=j}^{\infty}(1-P_{esc})^m = \frac{(1-P_{esc})^j}{P_{esc}}$$

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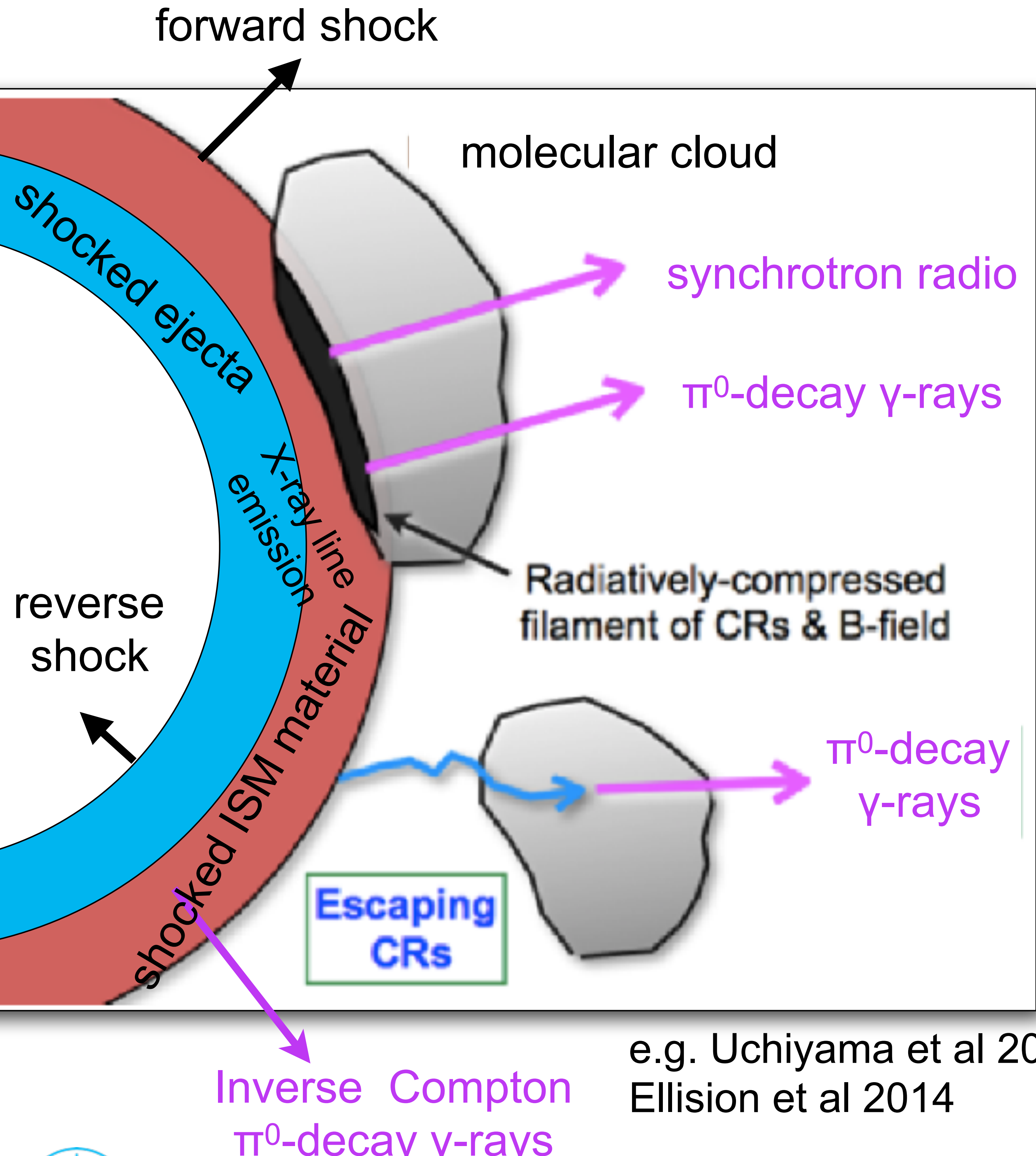
energy spectrum from Fermi acceleration:

$$N(E>0) \propto (E/E_0)^{-\gamma}$$

power law

$$\gamma = \log\left(\frac{1}{1-P_{esc}}\right) / \log(1+\xi) \approx \frac{P_{esc}}{\xi}$$

Particle acceleration in Supernova Remnants



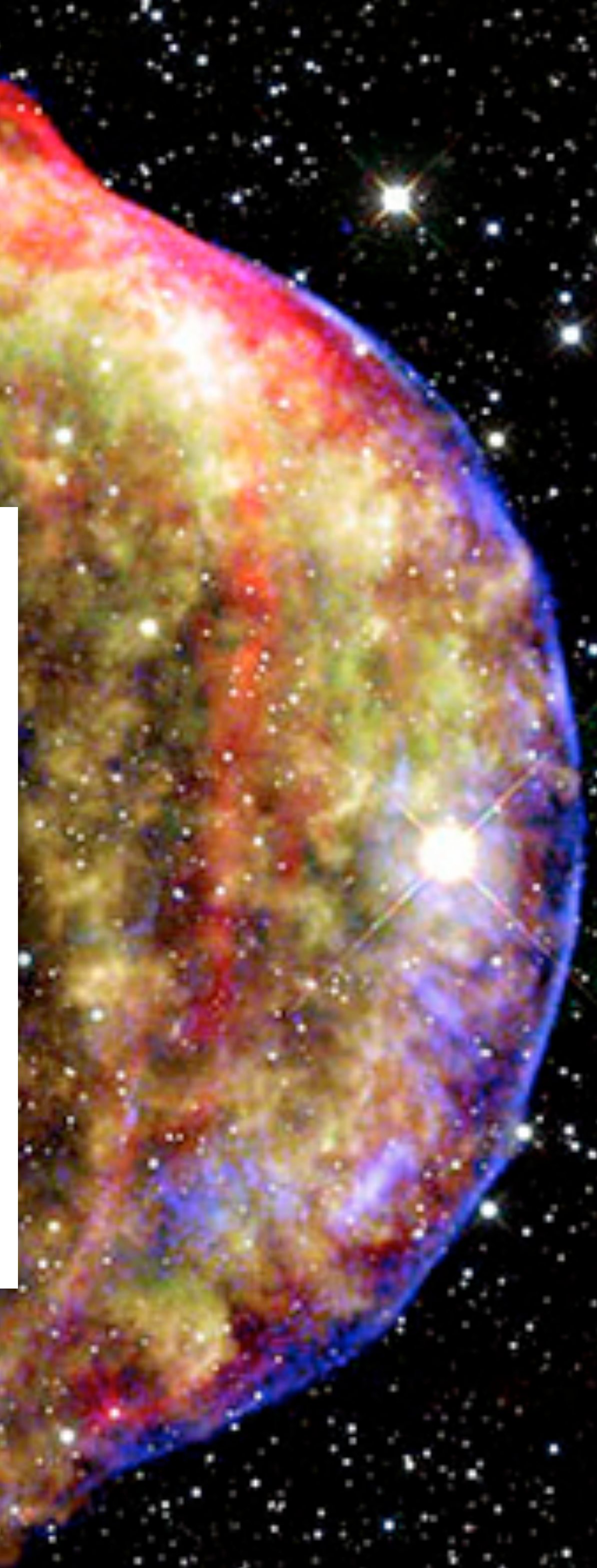
e.g. Uchiyama et al 2011
Ellision et al 2014

complex models needed to explain broadband emission:

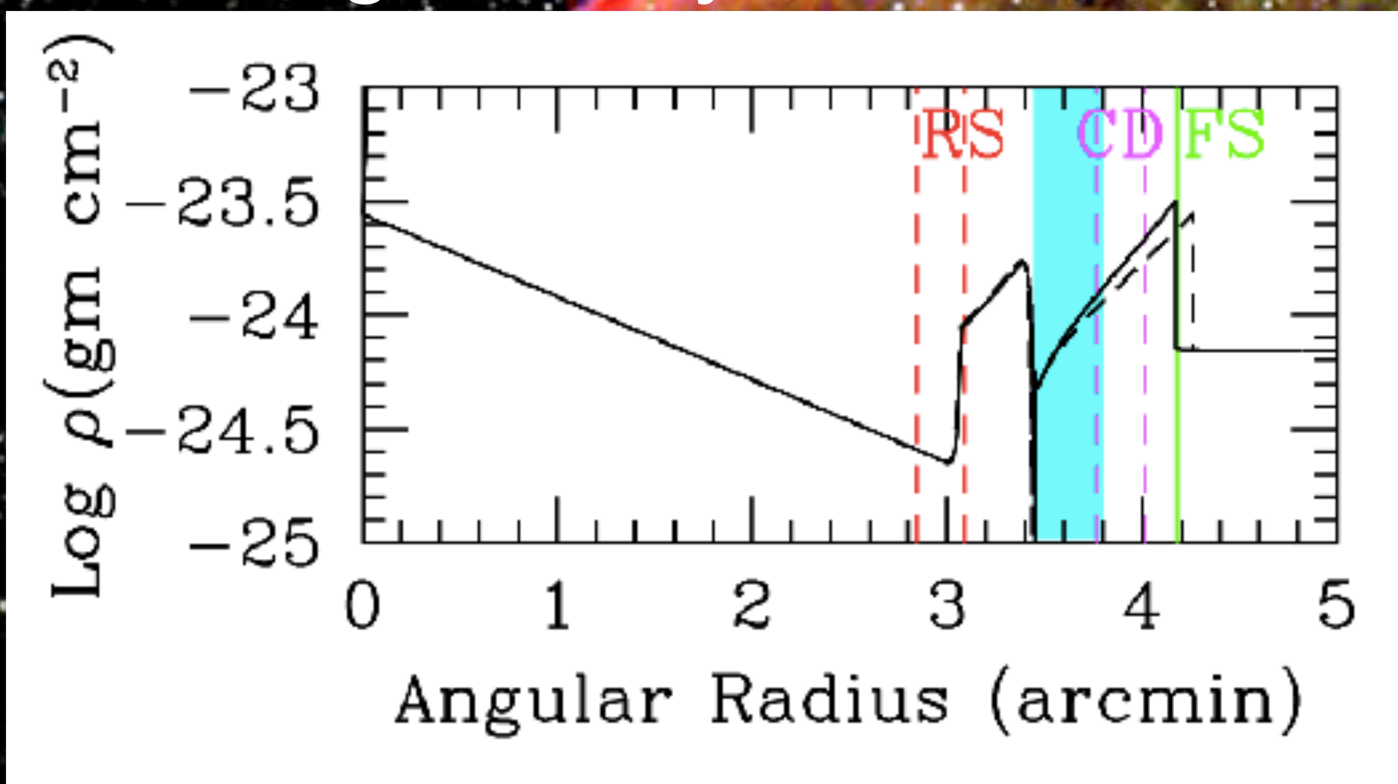
- hydrodynamic of evolving SNR ↕ feedback
- non-linear diffusive shock acceleration
- Non-equilibrium ionization: X-ray line emission at forward and reverse shocks
- ejecta composition
- magnetic field amplification
- electron and ion distributions from thermal to relativistic energies
- photon emission
- cosmic-ray propagation

Coupling of thermal and non-thermal emission

Tycho’s SNR
1572

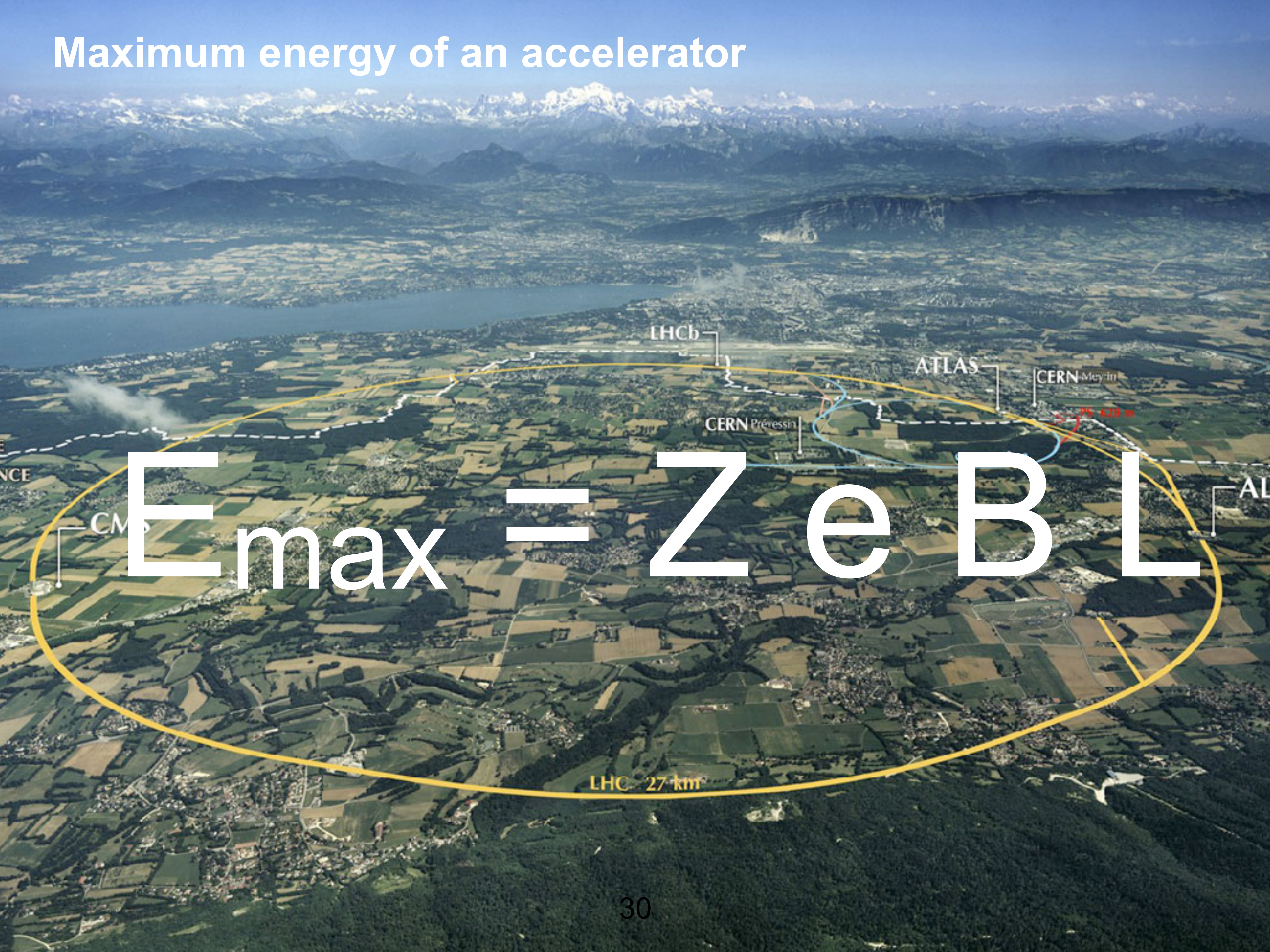


Shock geometry



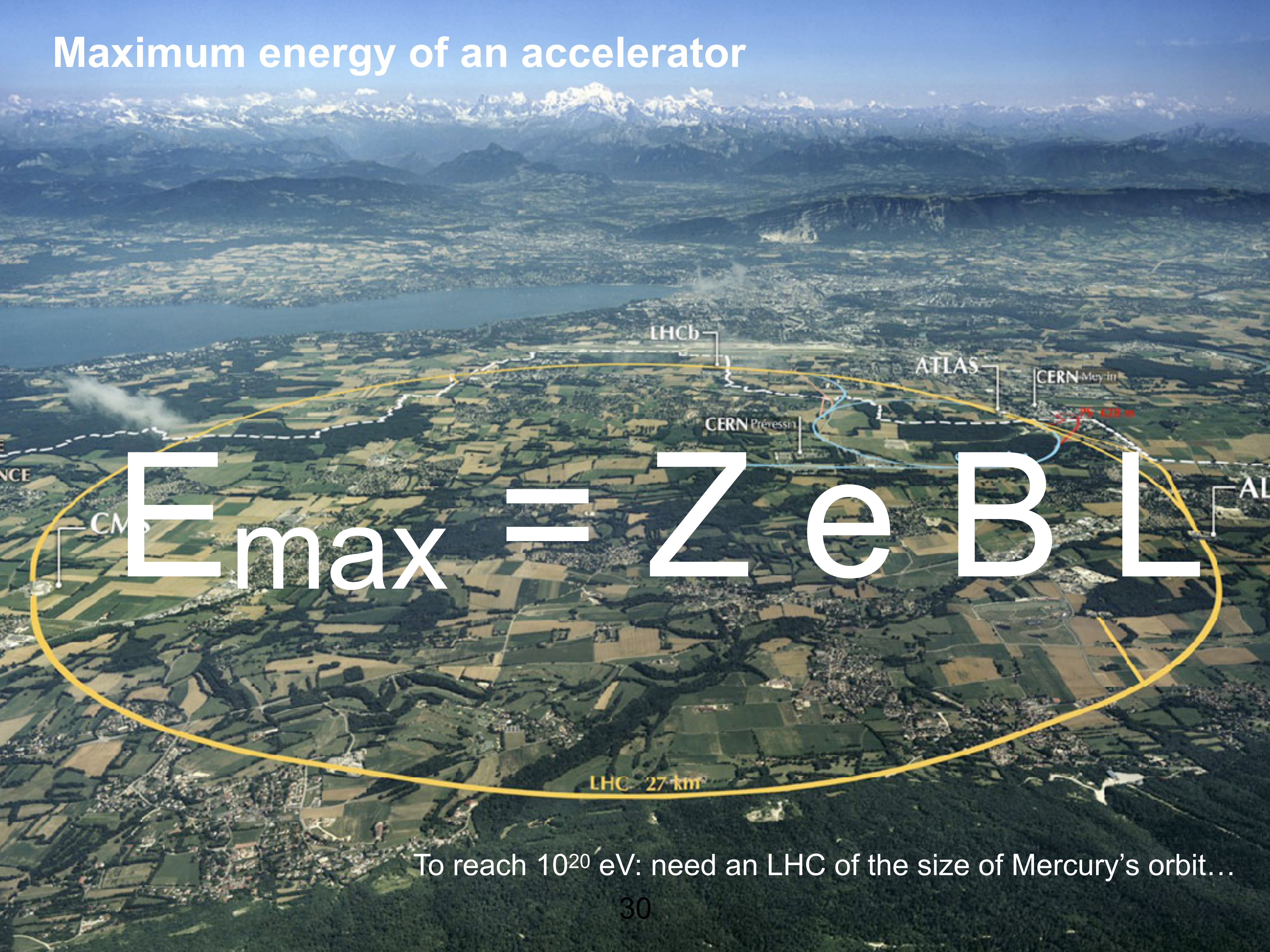
Maximum energy of an accelerator

Maximum energy of an accelerator



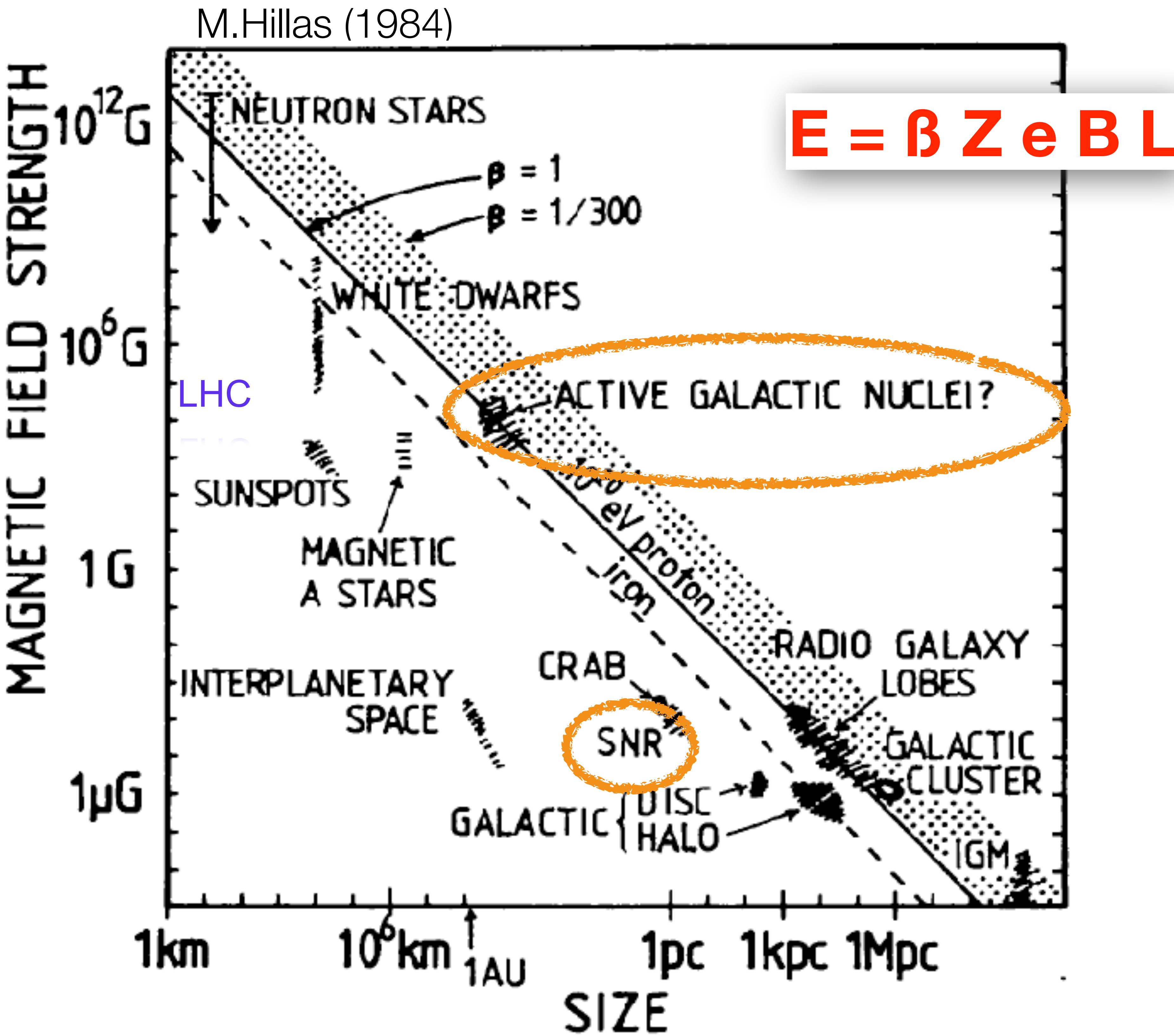
$$E_{max} = Z\, e\, B\, L$$

Maximum energy of an accelerator



$$E_{max} = Z\,e\,B\,L$$

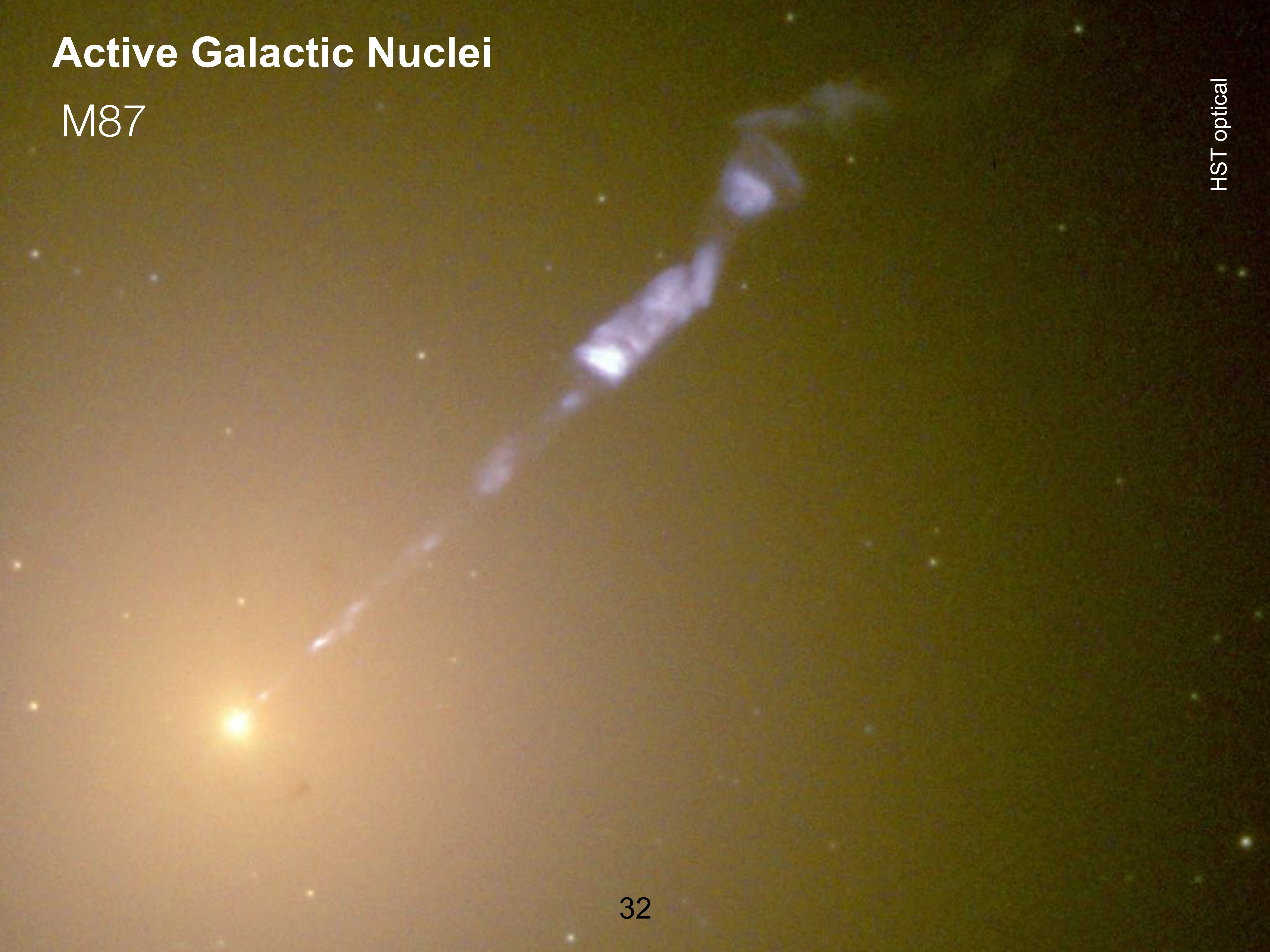
To reach 10^{20} eV: need an LHC of the size of Mercury's orbit…



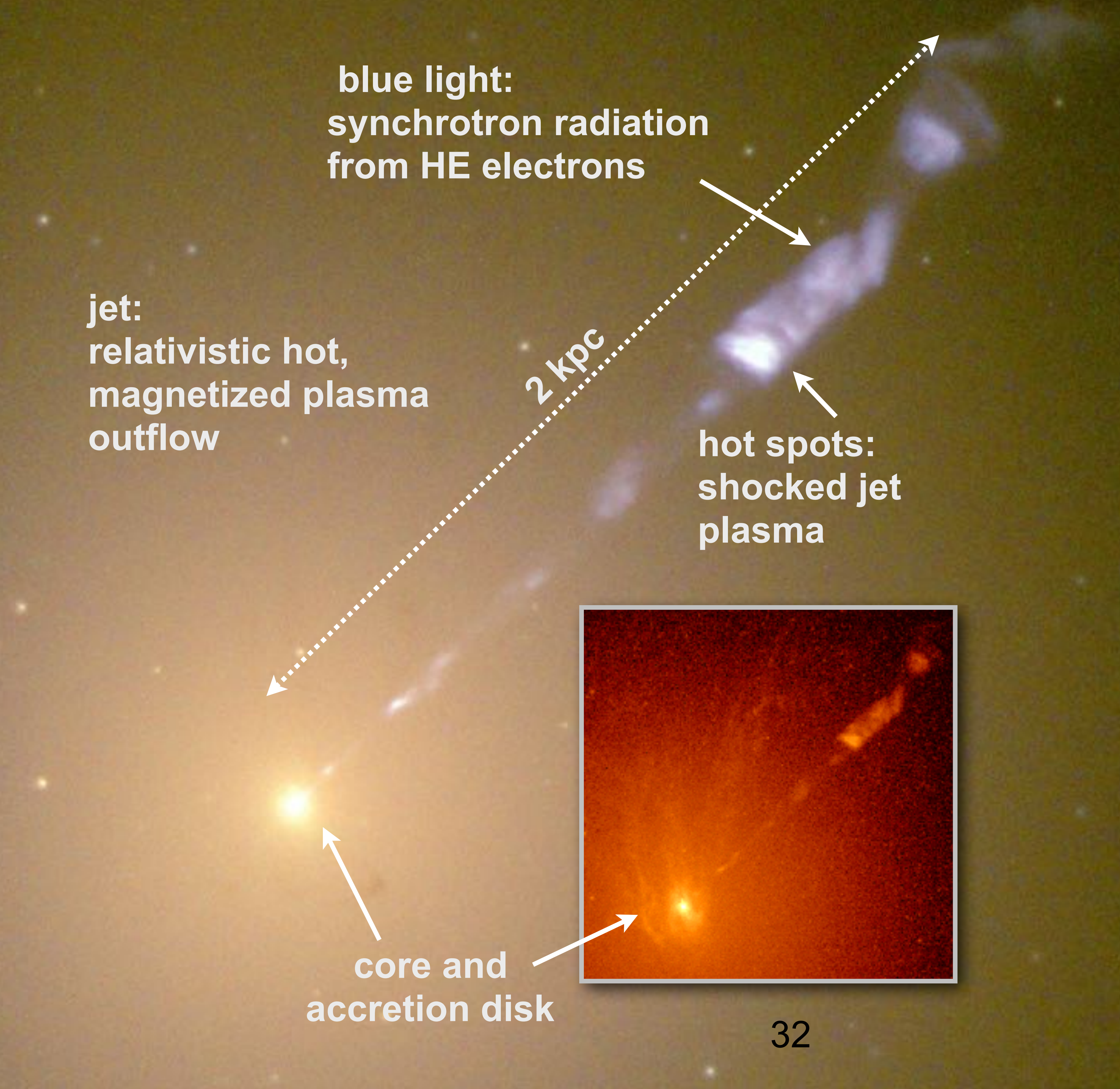
M.Hillas (1984)
E = ß Z e B L
MAGNETIC FIELD STRENGTH
10^12 G
10^6 G
1G
1μG
NEUTRON STARS
β = 1
β = 1/300
WHITE DWARFS
LHC
ACTIVE GALACTIC NUCLEI?
SUNSPOTS
MAGNETIC A STARS
eV proton
iron
RADIO GALAXY LOBES
CRAB
INTERPLANETARY SPACE
SNR
GALACTIC CLUSTER
GALACTIC
DISC
HALO
IGM
1km
10^6 km
1AU
1pc
1kpc
1Mpc
SIZE

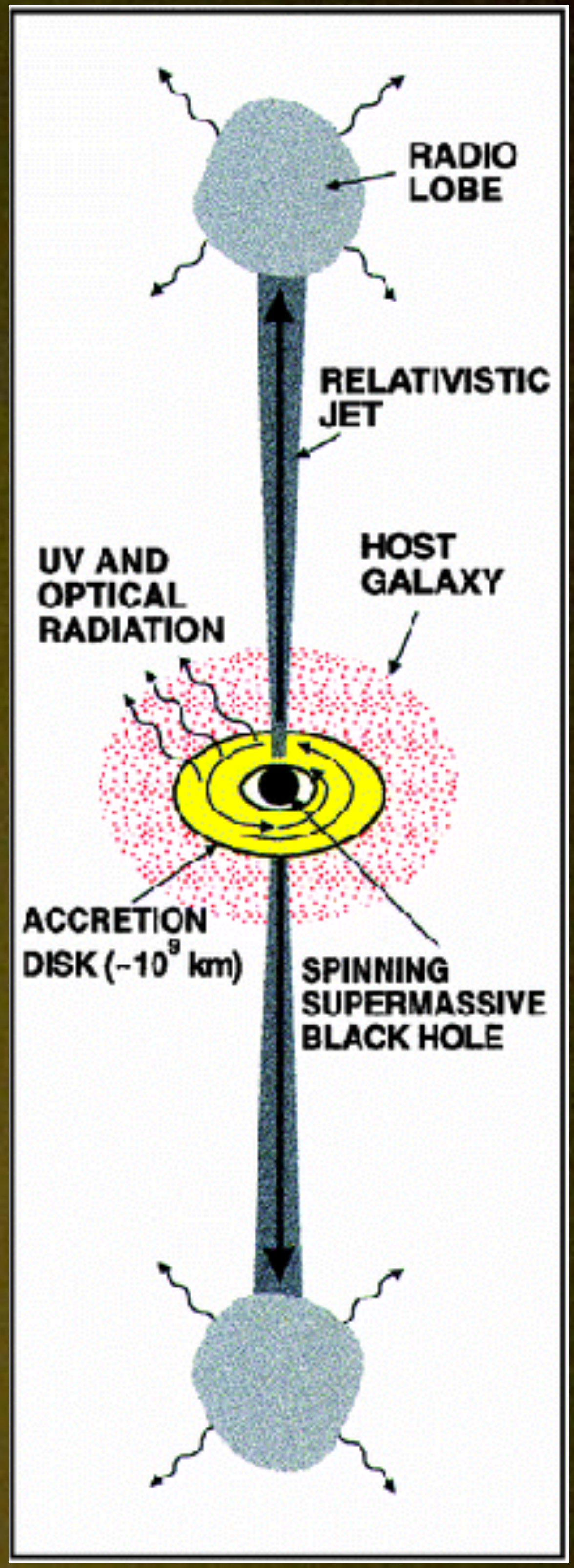
Active Galactic Nuclei

M87

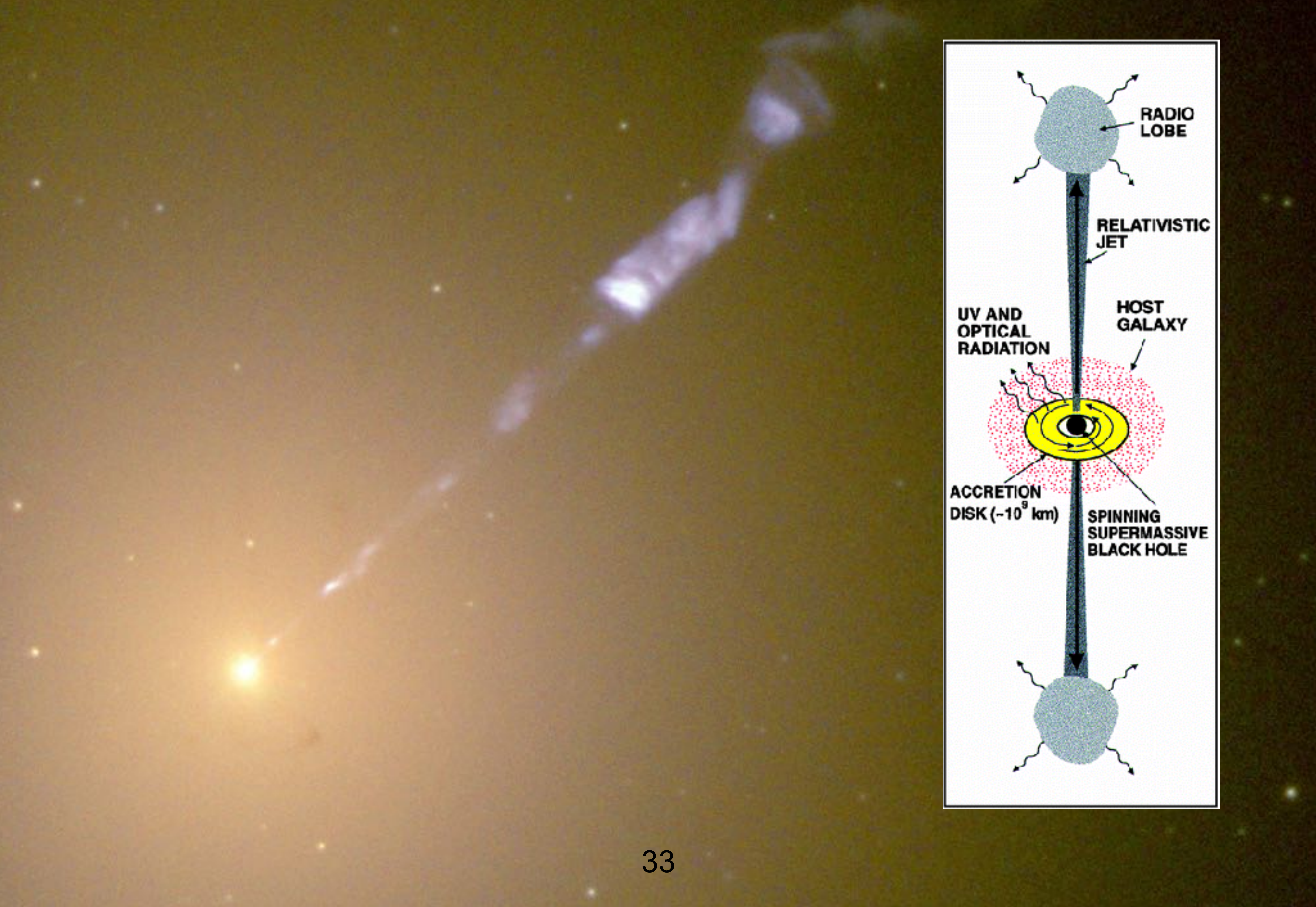


Active Galactic Nuclei





Active Galactic Nuclei: The power of accretion



Active Galactic Nuclei: The power of accretion

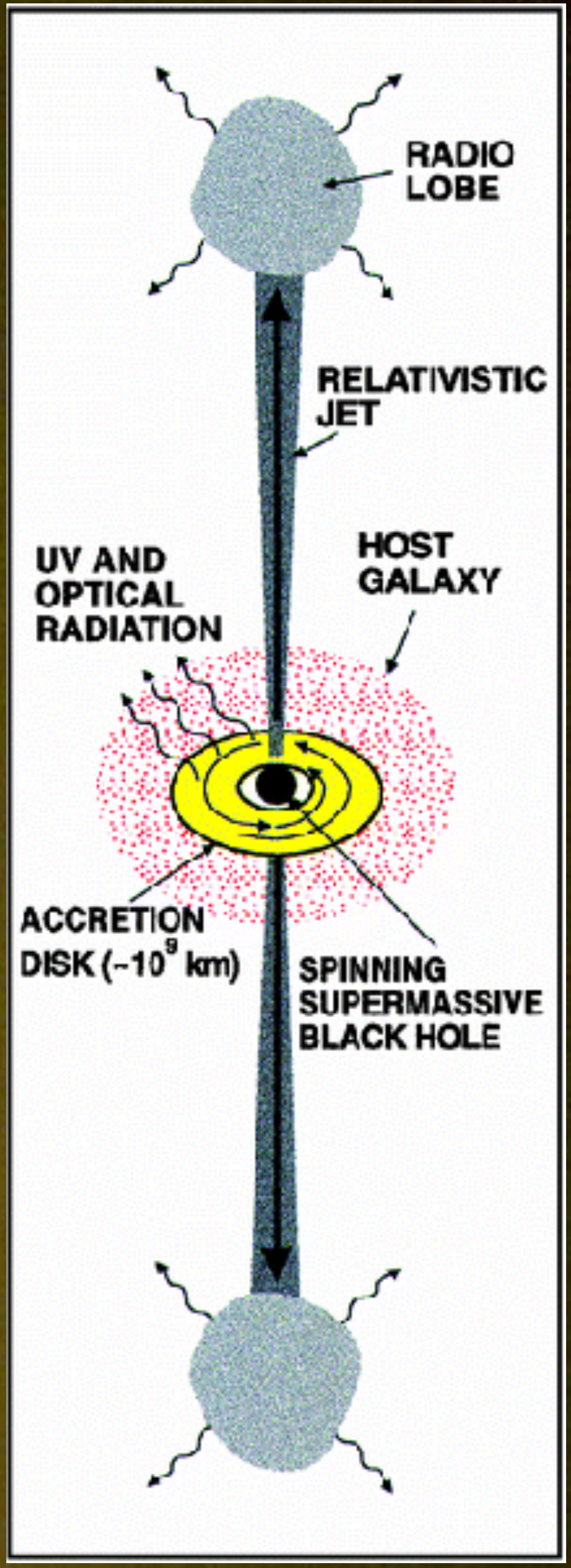
1 erg = 10^{-7} J

Gravitational energy released :

$$\Delta E_{acc} = GMm/R_*$$

Nuclear fusion of hydrogen to helium:

$$\Delta E_{nuc} = 0.007mc^2$$



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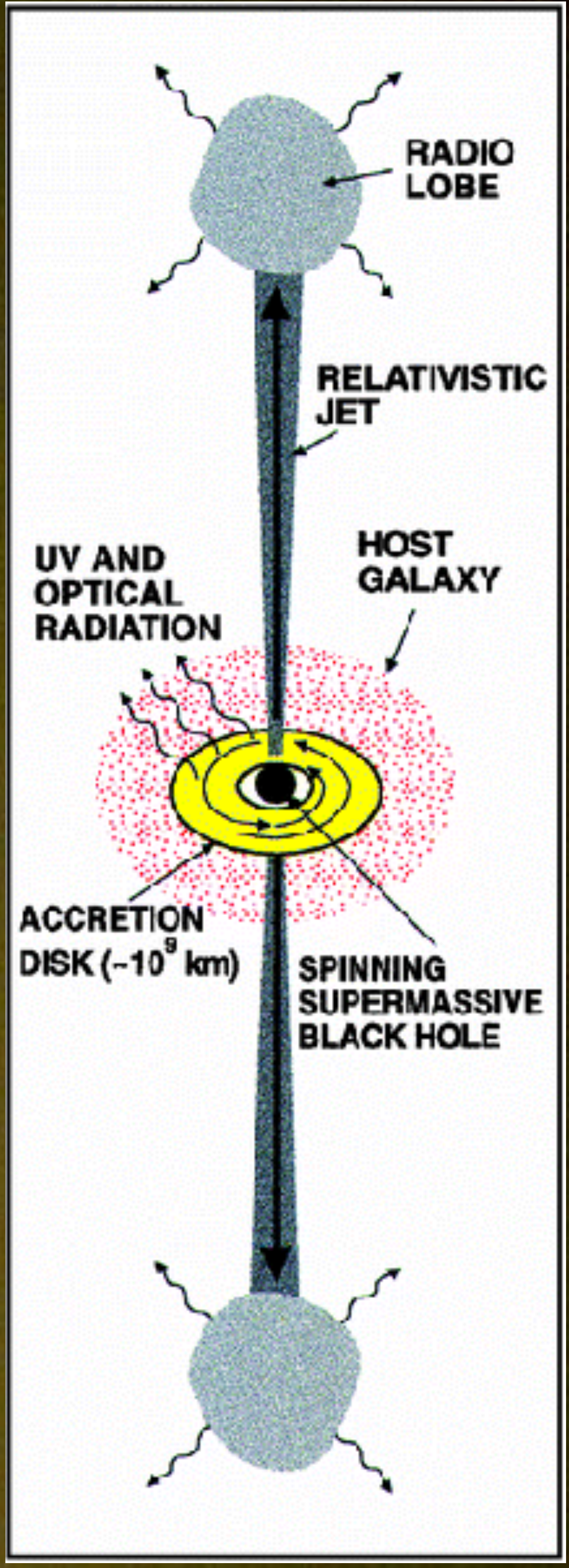

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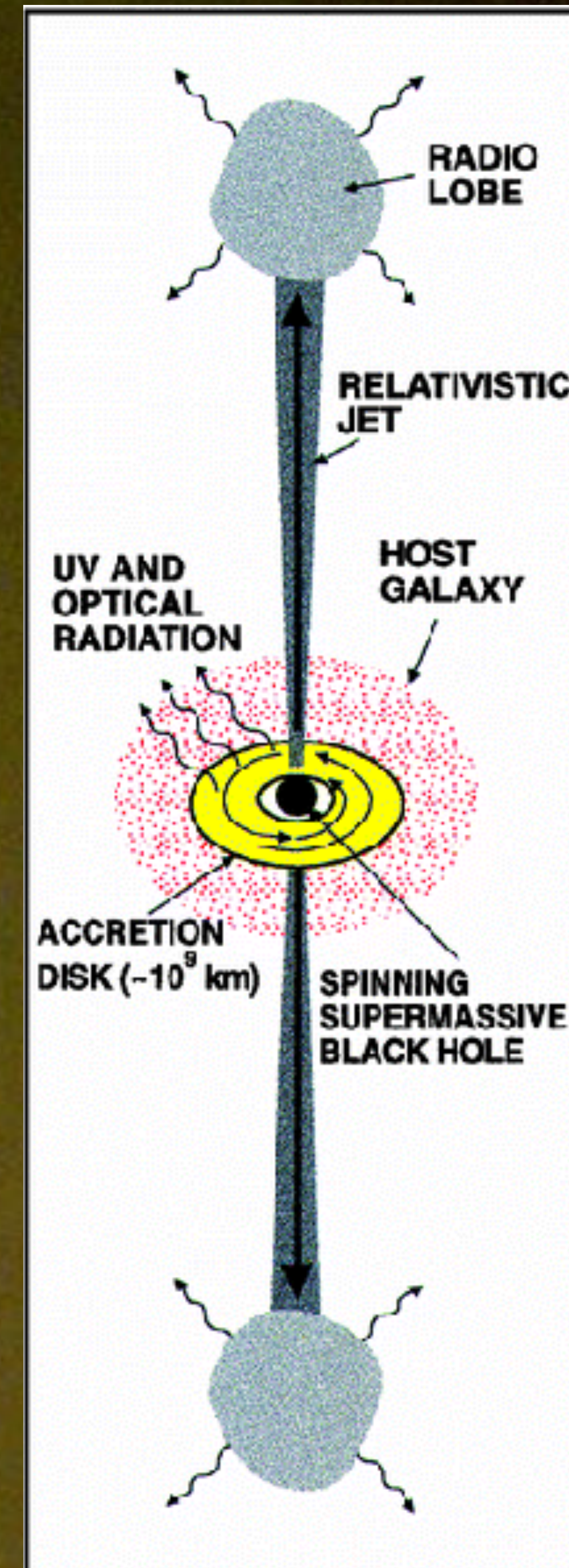

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$$\Delta E_{acc}/m \sim 10^{20} erg/g$$

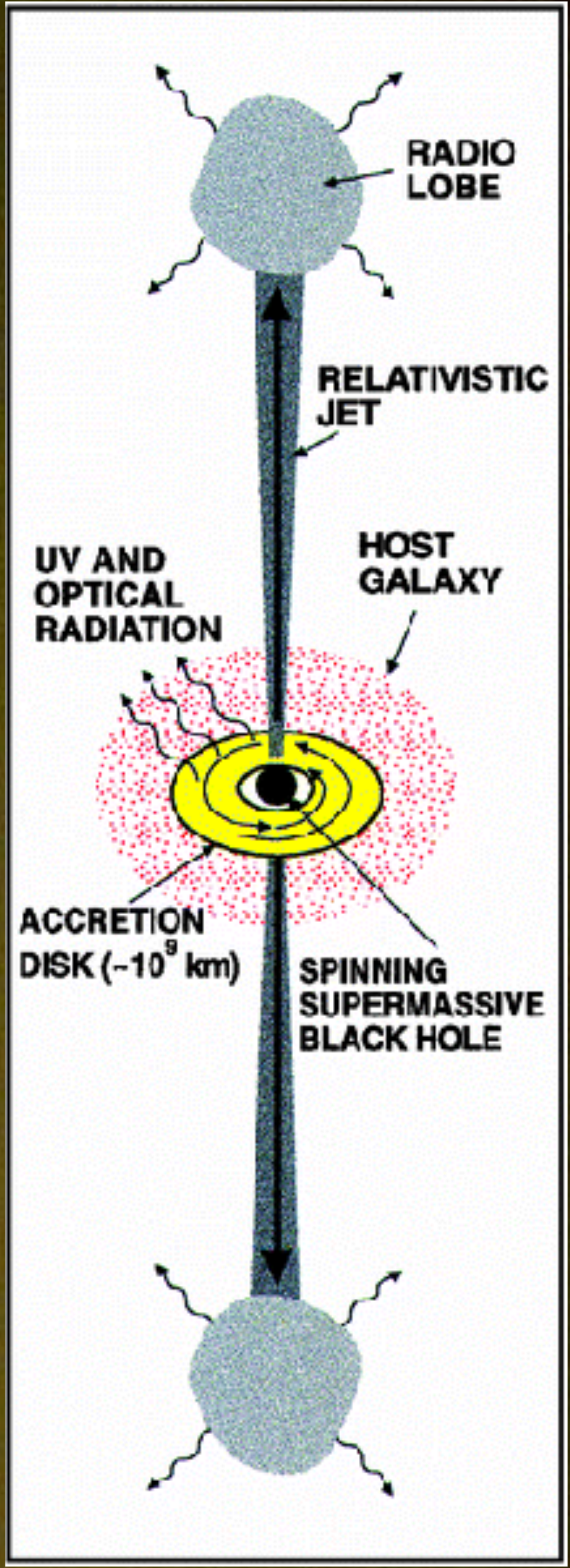
Black hole with R~6x10^9 km and M~3x10^9 $M_\odot$

$$\Delta E_{acc}/m \sim 5 \times 10^{23} erg/g$$

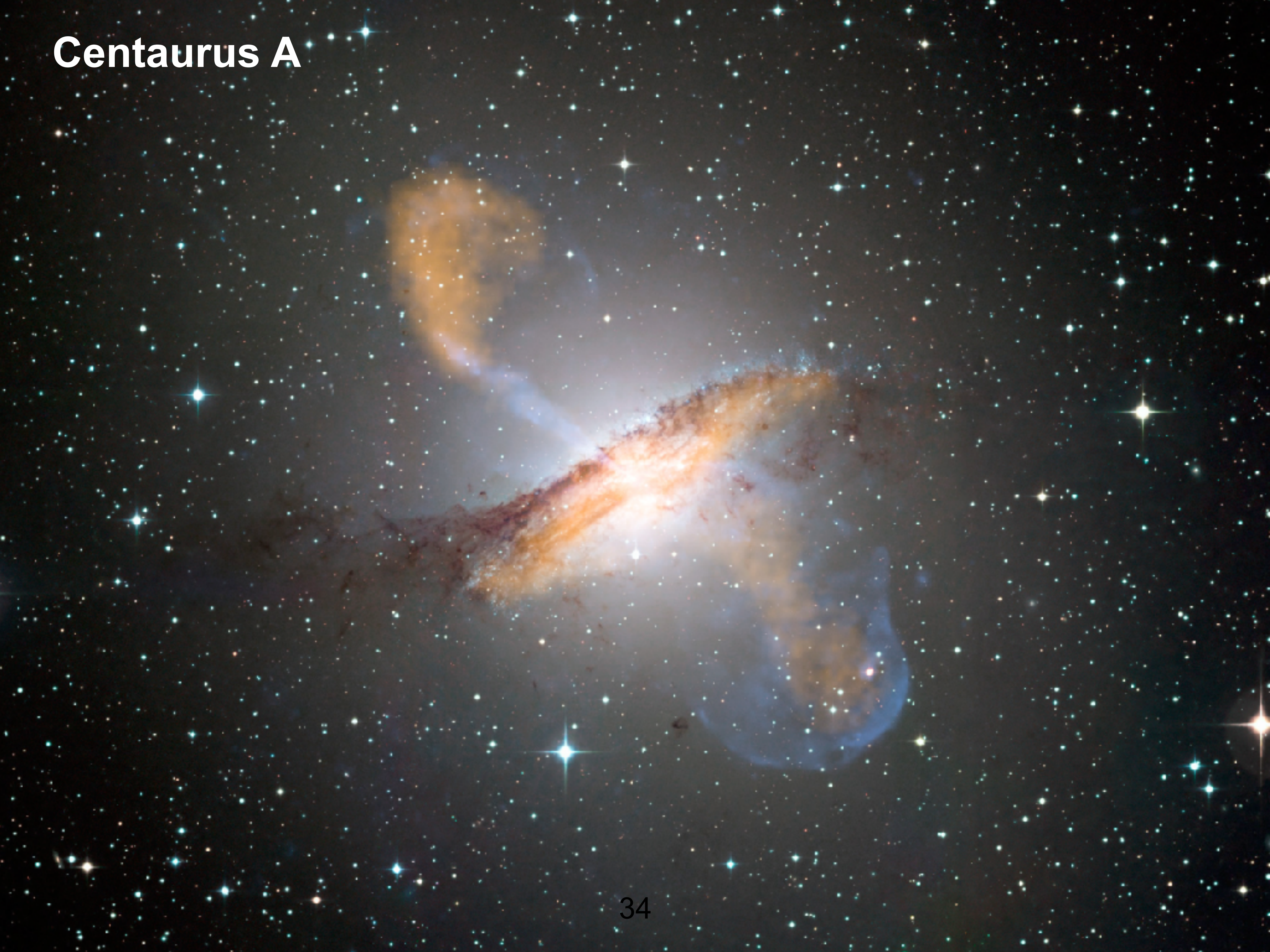
Nuclear fusion of hydrogen to helium:

$$\Delta E_{nuc} = 0.007mc^2$$

$$\Delta E_{nuc}/m \sim 6 \times 10^{18} erg/g$$



Centaurus A



Rotating black holes - Kerr black holes

event horizon for Kerr black hole

$$R_K = \frac{GM}{c^2}\left(1 + (1 - j^2)^{1/2}\right)$$

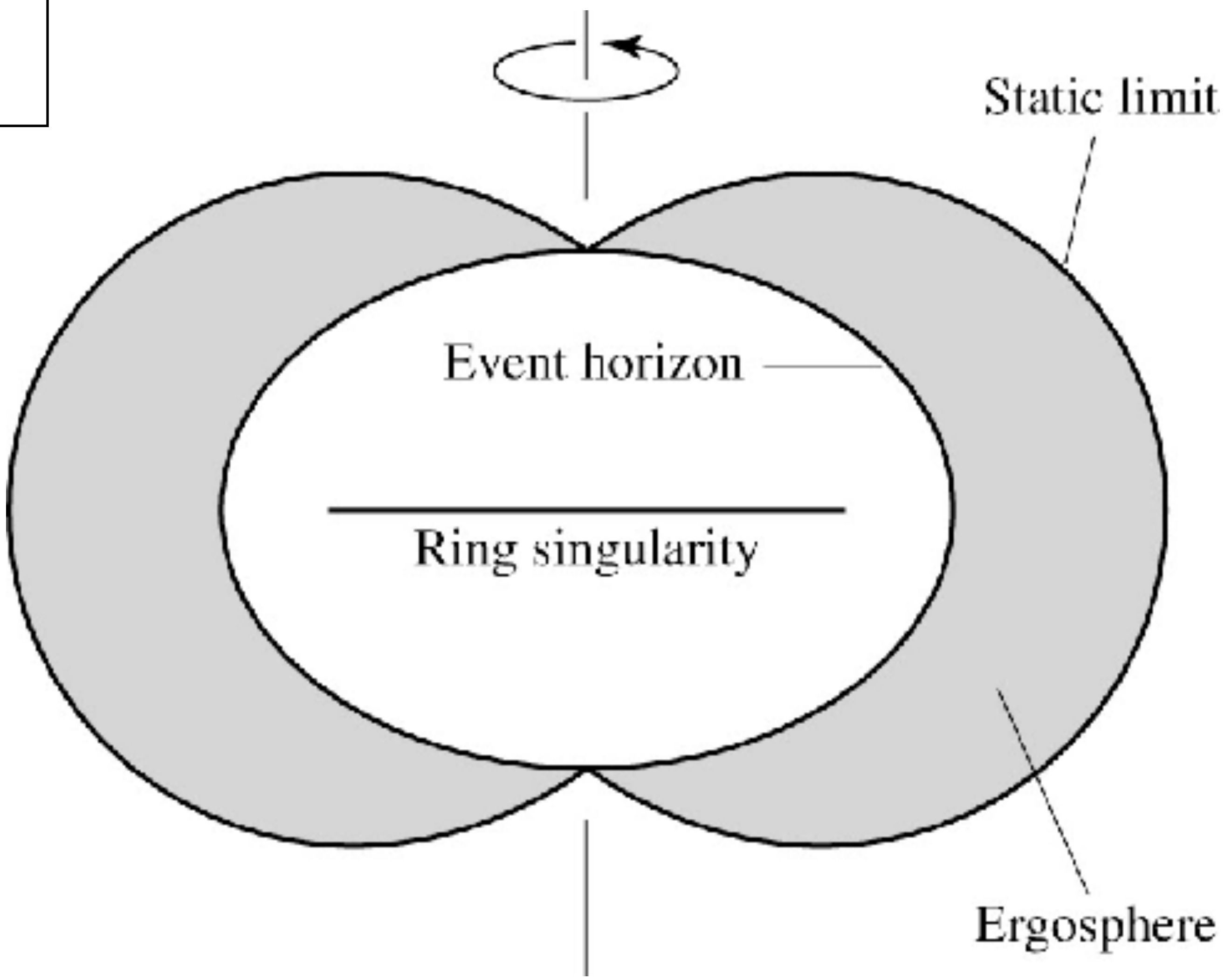
($j=J/J_{max}$);
j=0: Schwarzschild BH
j=1: $R_K = R_S / 2$

maximally rotating BH: j= ±1
(M at R_K orbiting with c)

$$J_{max} = McR = \frac{GM^2}{c}$$

ergosphere:

anything inside the ergosphere will be dragged by the BH and rotate with it ('frame dragging')

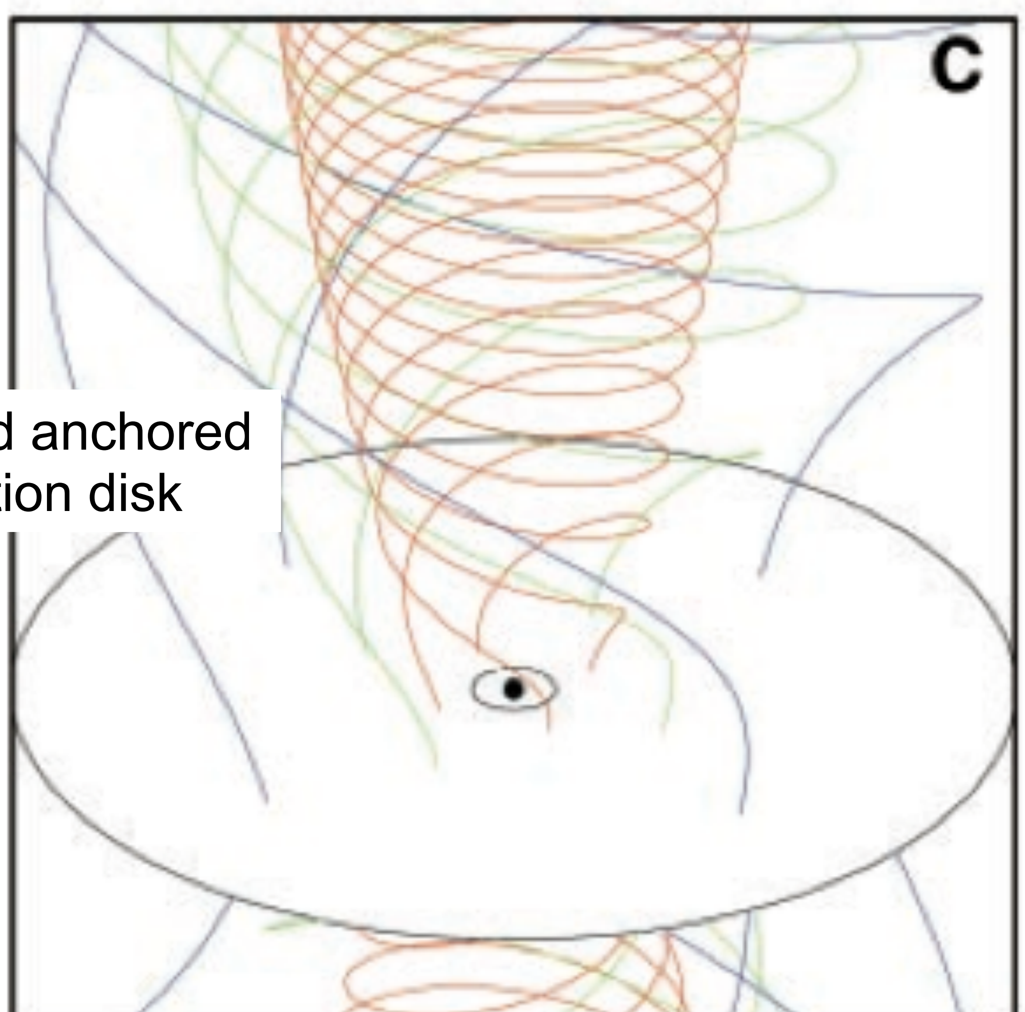


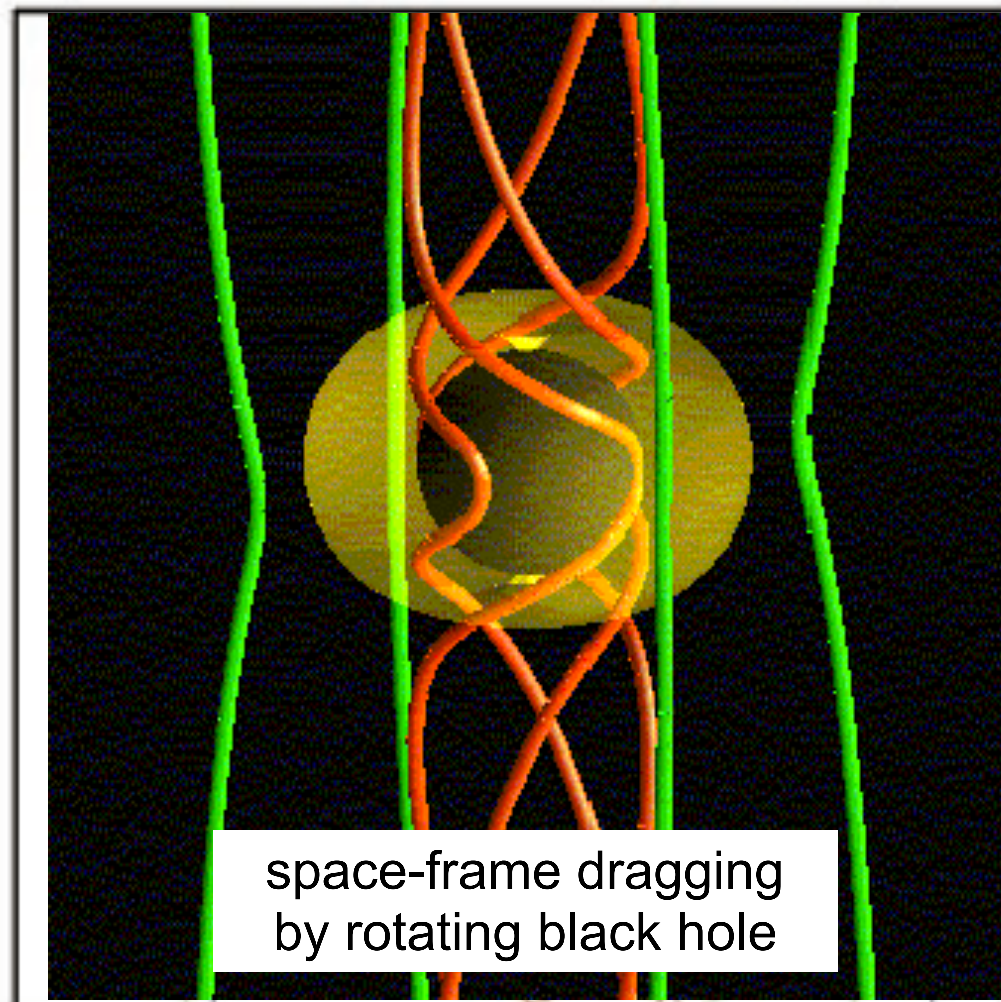
Two scenarios of magnetic field line twisting

magnetic field tied to in-falling plasma

magnetic field anchored in a accretion disk

Meier (2001)





space-frame dragging by rotating black hole

Koide et al (2002)

energy is extracted from accretion disk

extraction of energy from rotating black hole

Doppler boosting in jets

$$D = \frac{\sqrt{1-\beta^2}}{1-\beta\cos\Theta}$$

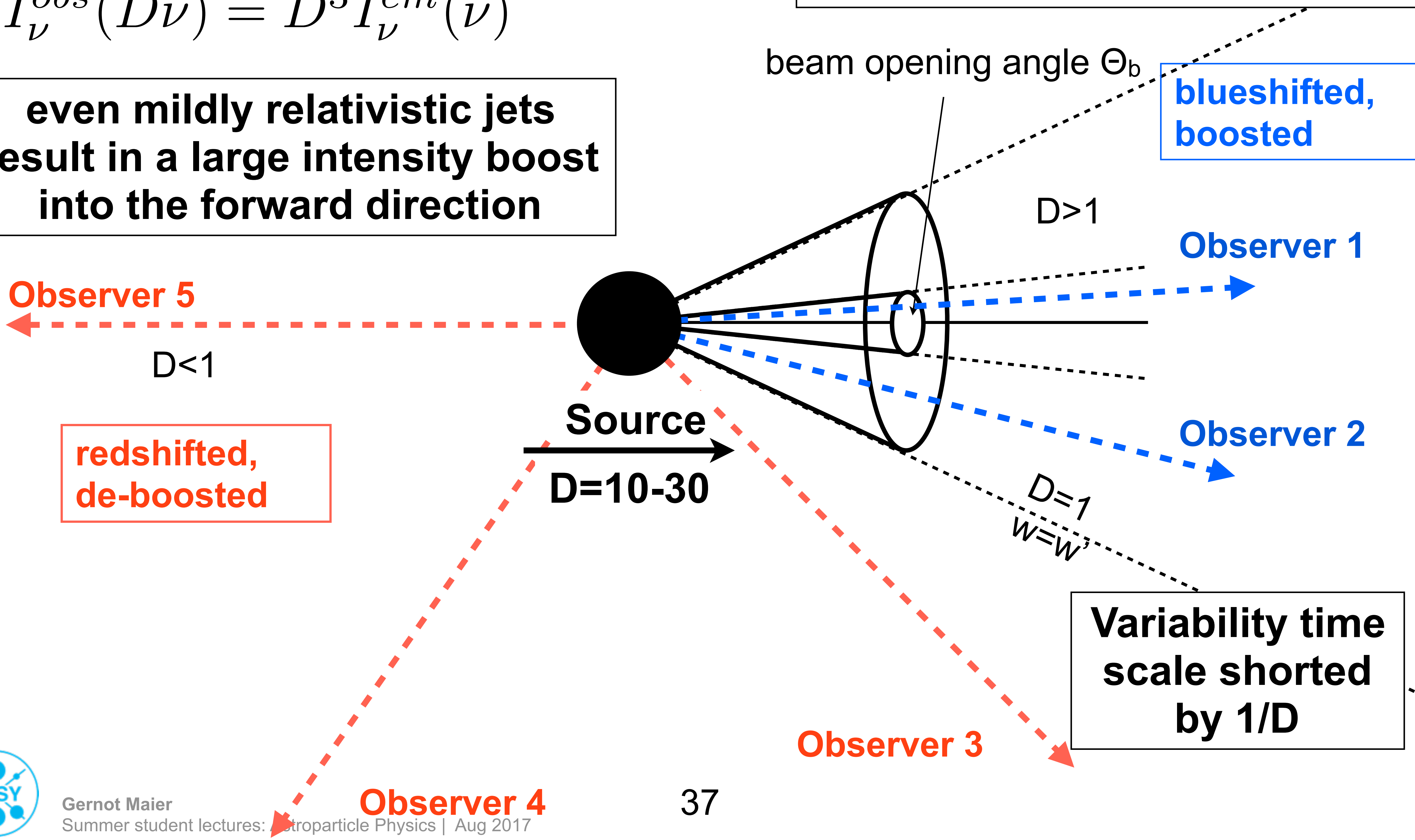
$$I_\nu^{obs}(D\nu) = D^3 I_\nu^{em}(\nu)$$

Doppler boosting of a power-law source:

$$I_\nu^{em}(\nu) \propto \nu^{-\alpha}$$

$$I_\nu^{obs} = D^{3+\alpha} I_\nu^{em}(\nu)$$

even mildly relativistic jets result in a large intensity boost into the forward direction



Variability time scale shorted by 1/D

www.desy.de/news/news_search/index_eng.html?openDirectAnchor=1431&two_columns=1

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2018/07/12

Back

Breakthrough in the search for cosmic particle accelerators

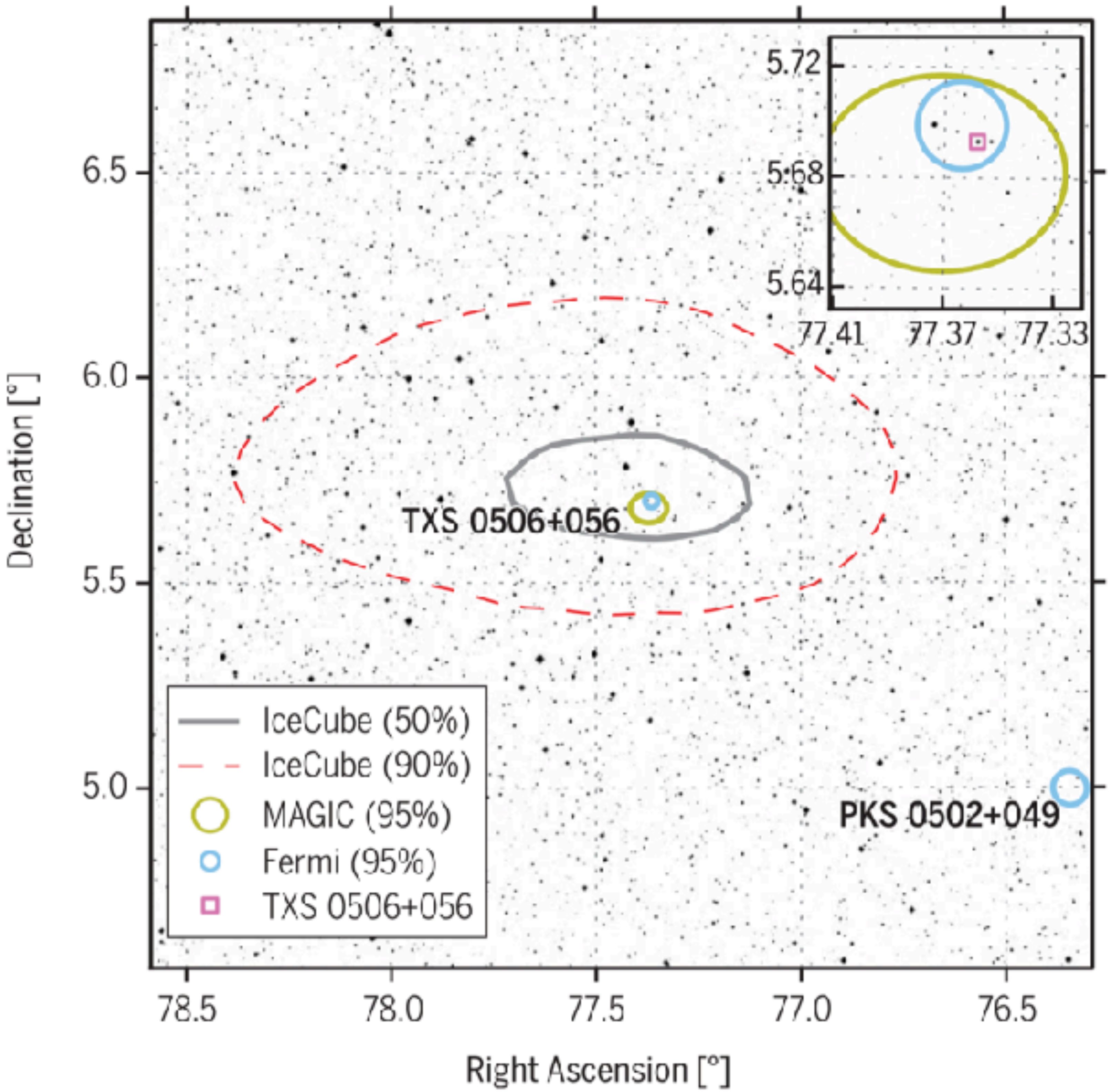
Scientists trace a single neutrino back to a galaxy billions of light years away

Using an internationally organised astronomical dragnet, scientist have for the first time located a source of high-energy cosmic neutrinos, ghostly elementary particles that travel billions of light years through the universe, flying unaffected through stars, planets and entire galaxies. The joint observation campaign was triggered by a single neutrino that had been recorded by the IceCube neutrino telescope at the South Pole, on 22 September 2017. Telescopes on earth and in space were able to determine that the exotic particle had originated in a galaxy nearly four billion light years away, in the constellation of Orion, where a gigantic black hole serves as a natural particle accelerator. Scientists from the 18 different observatories involved are presenting their findings in the journal Science. Furthermore, a second analysis, also published in Science, shows that other neutrinos previously recorded by IceCube came from the same source.

Download [2.8 MB, 3508 x 2480]

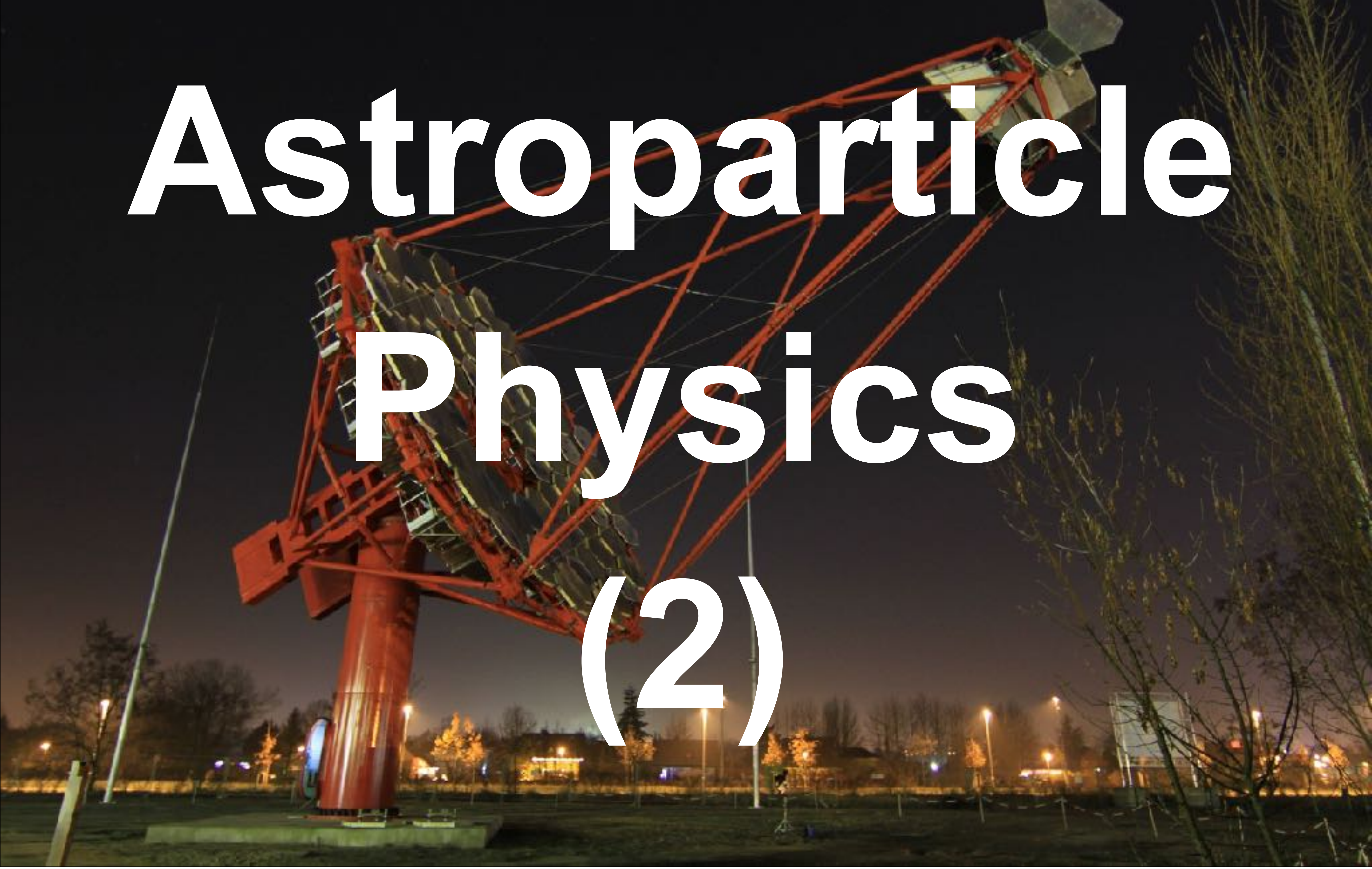
Artist's impression of the active galactic nucleus. The supermassive black hole at the centre of the accretion disk sends a narrow high-energy jet of matter into space, perpendicular to the disc. Credit: DESY, Science Communication Lab

The observation campaign, in which research scientists from Germany played a key role, is a decisive step towards solving a riddle that has



23 TeV Neutrino at the location of a gamma-ray emitting blazar…

Astroparticle Physics (2)



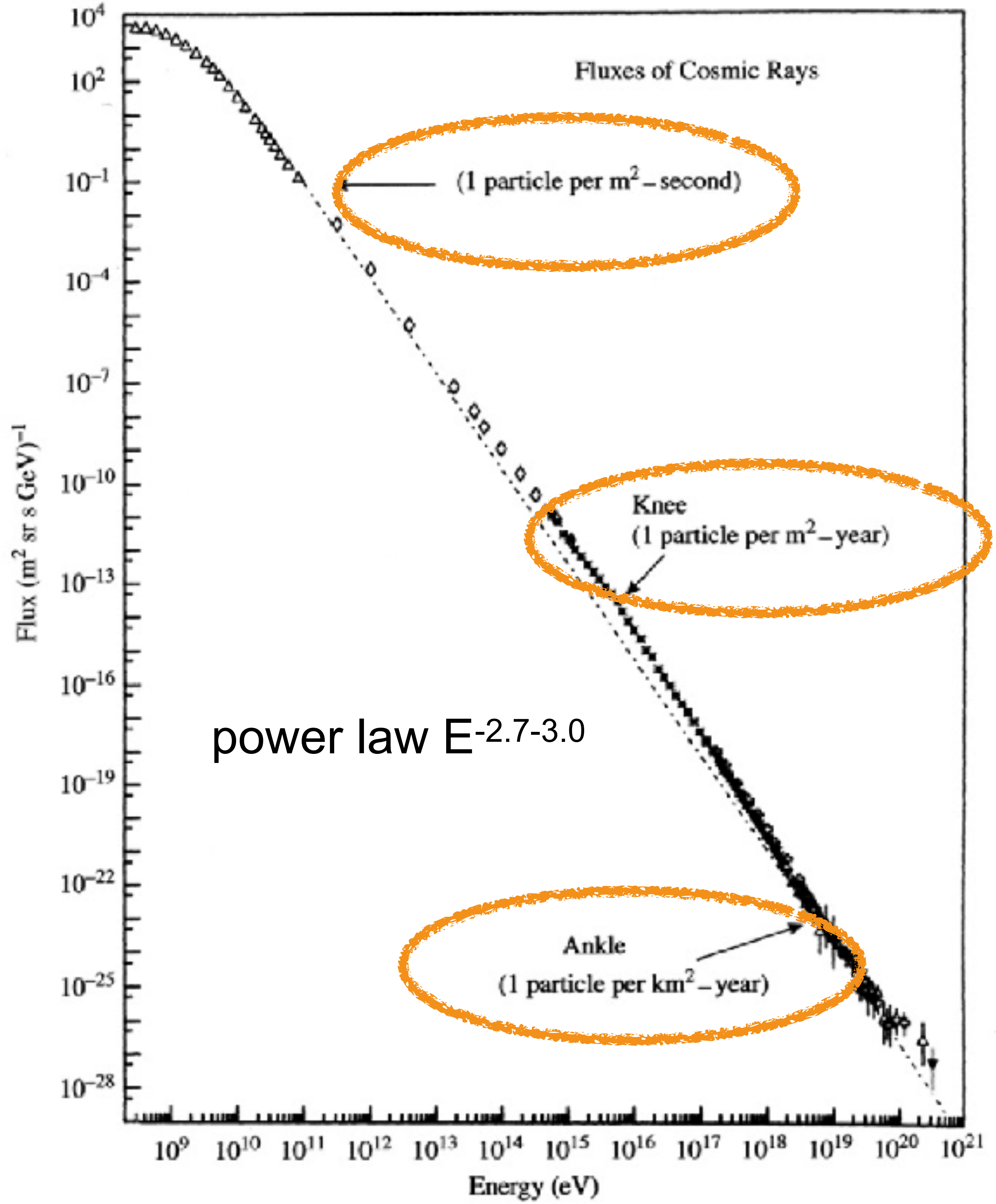
Gernot Maier

DESY

HELMHOLTZ ASSOCIATION
Alliance for Astroparticle Physics

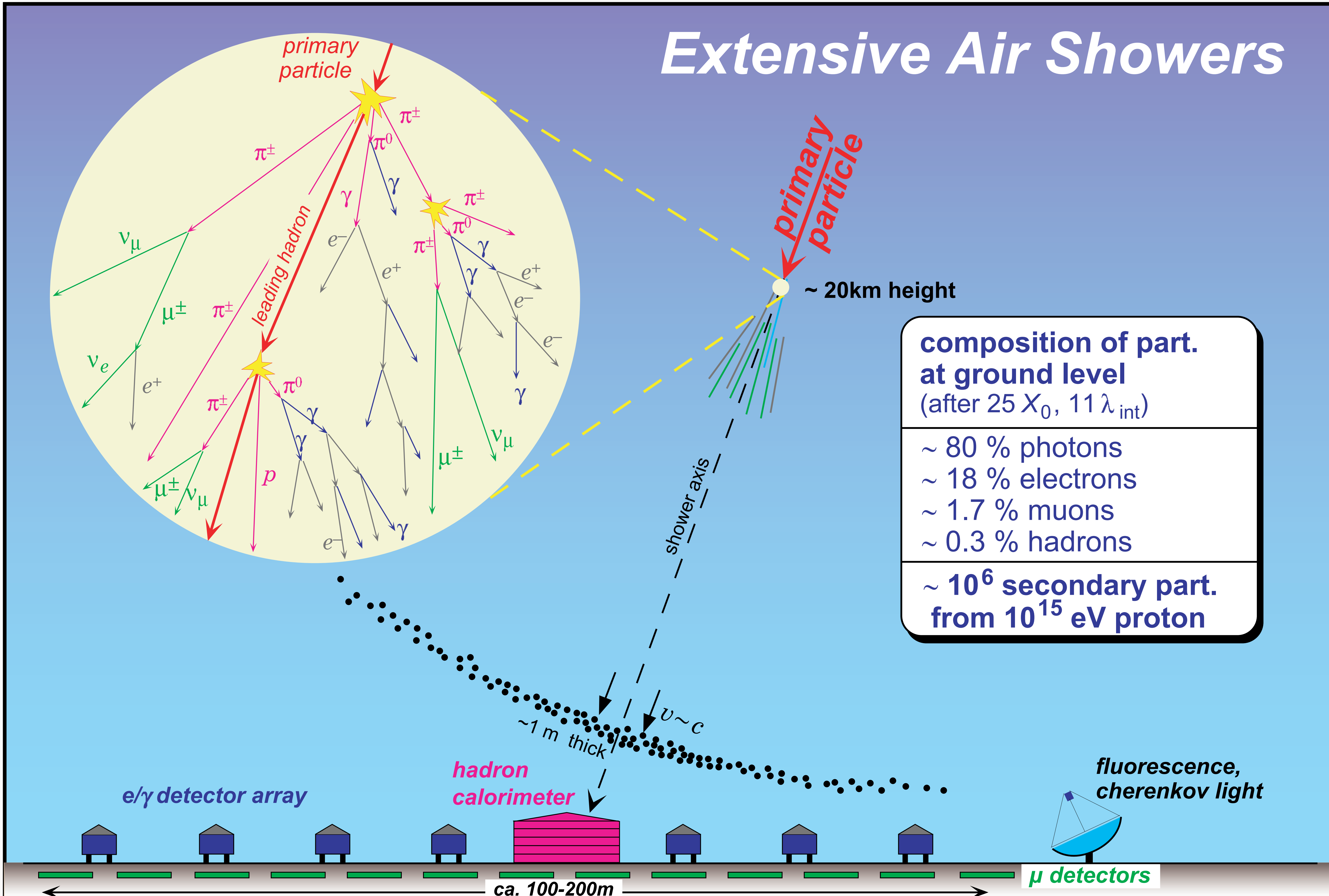
HUMBOLDT-UNIVERSITÄT ZU BERLIN

The Cosmic Ray Energy Spectrum



Bhattacharjee & Sigl 2000

Extensive Air Showers



composition of part. at ground level
(after 25 X_0, 11 λ_{int})

~ 80 % photons
~ 18 % electrons
~ 1.7 % muons
~ 0.3 % hadrons

~ 10^6 secondary part. from 10^{15} eV proton

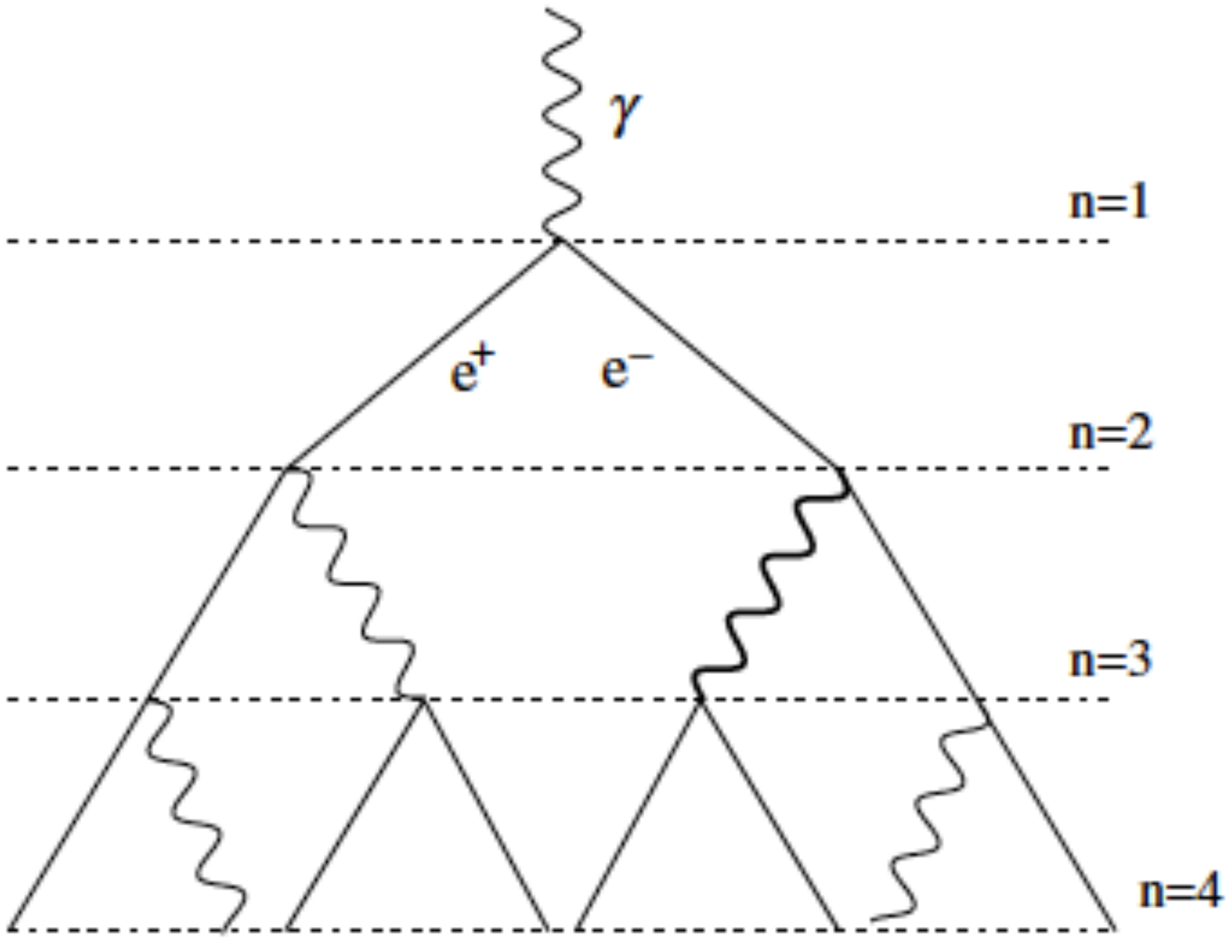
Extensive Air Shower: toy model for particle cascades

$$N(X) = 2^{X/\lambda}$$

$$E(X) = \frac{E_0}{N(X)}$$

$$N_{max} = N(X_{max}) = \frac{E_0}{E_C} \propto E_0$$

$$X_{max} = \lambda \frac{\log(E_0/E_C)}{\log 2} \propto \log(E_0)$$



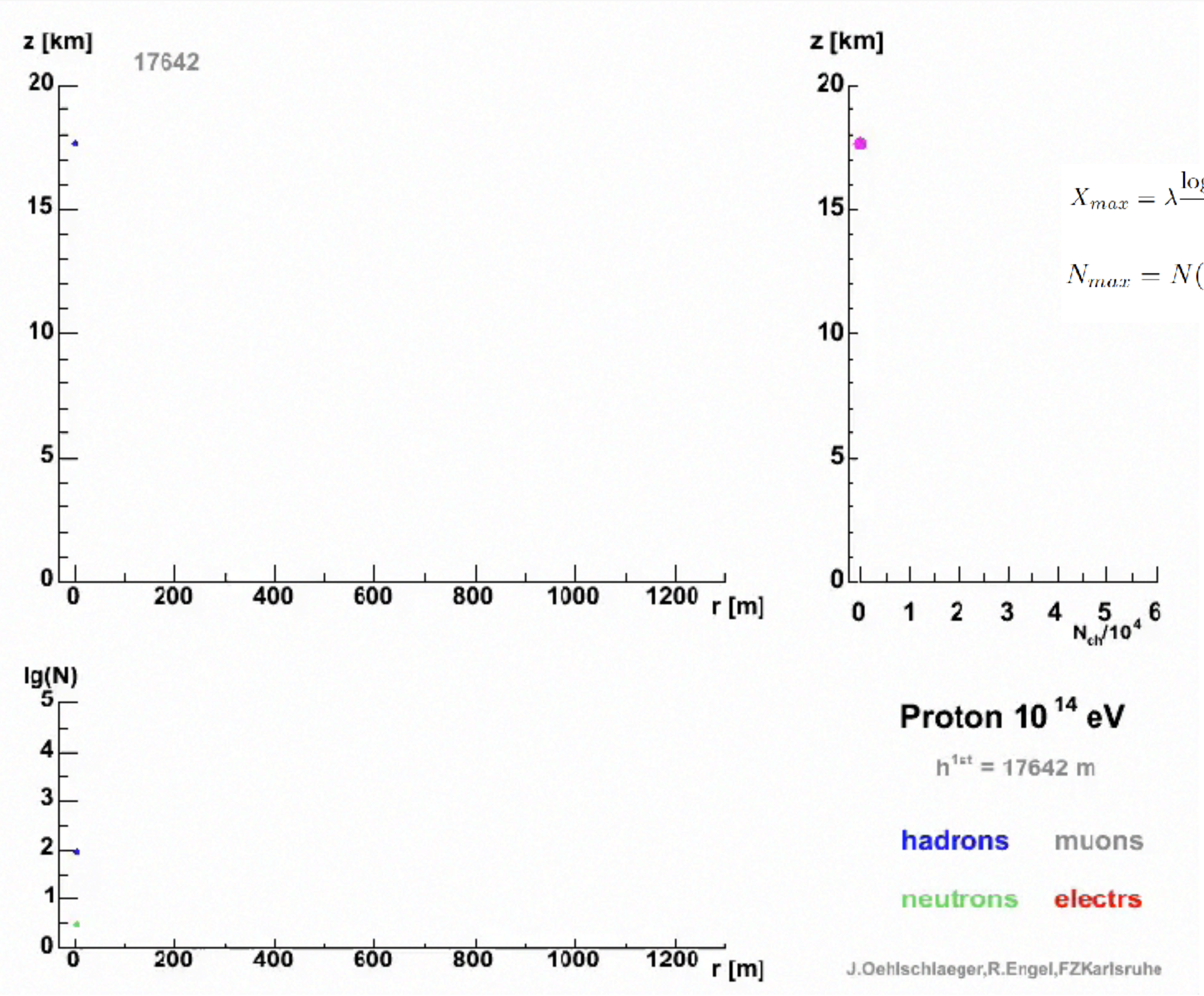
Heitler Model

here: primary particle is a photon
(similar: hadronic showers)

> Measure

- particles reaching ground
- Superluminal particles create Cherenkov light
- High-energy electrons excite nitrogen which then fluorescence

Extensive Air Shower



$$X_{max} = \lambda \frac{\log(E_0/E_C)}{\log 2} \propto \log(E_0)$$

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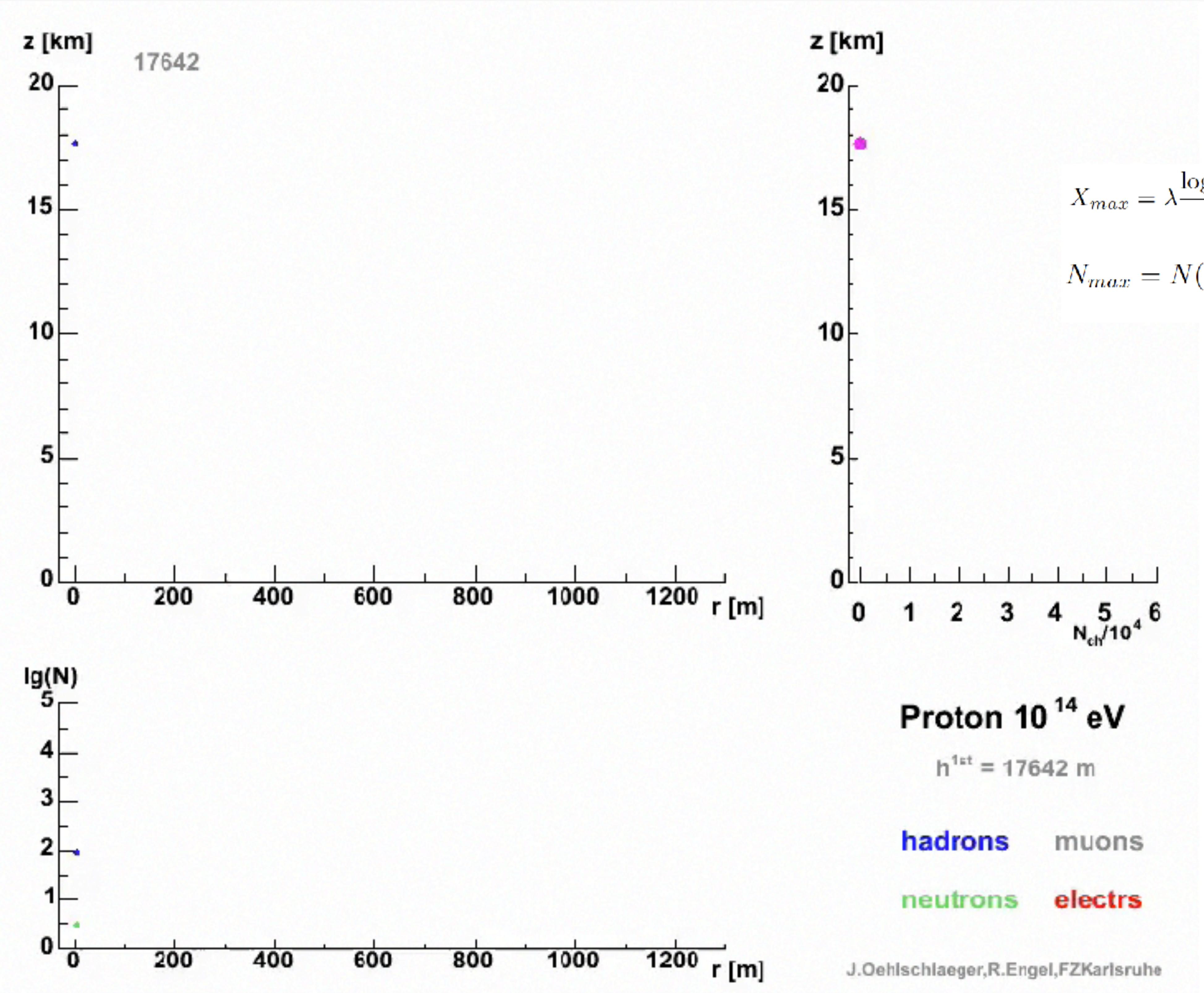

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KASCADE
Karlsruhe Shower Core and Array Detector

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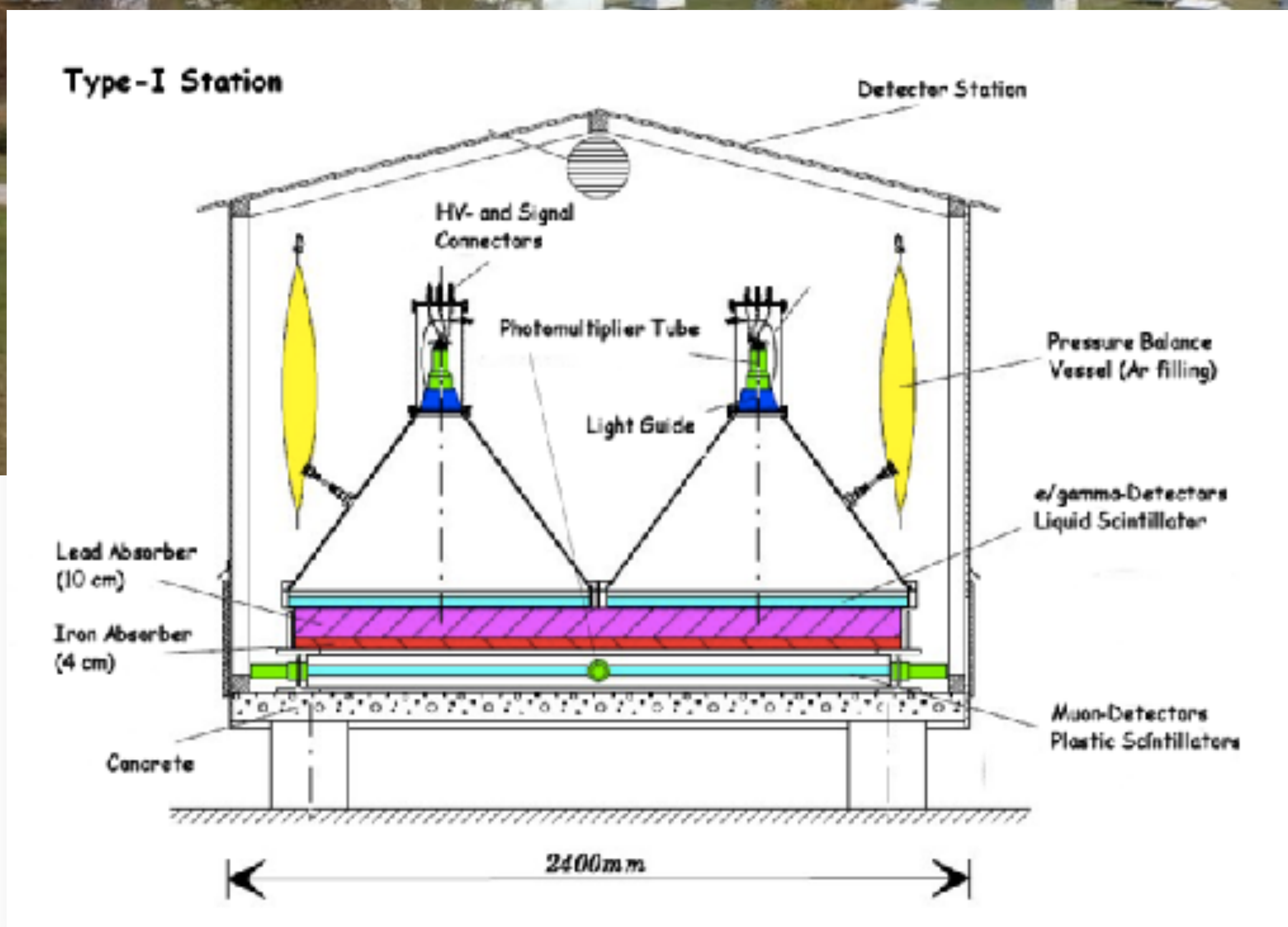
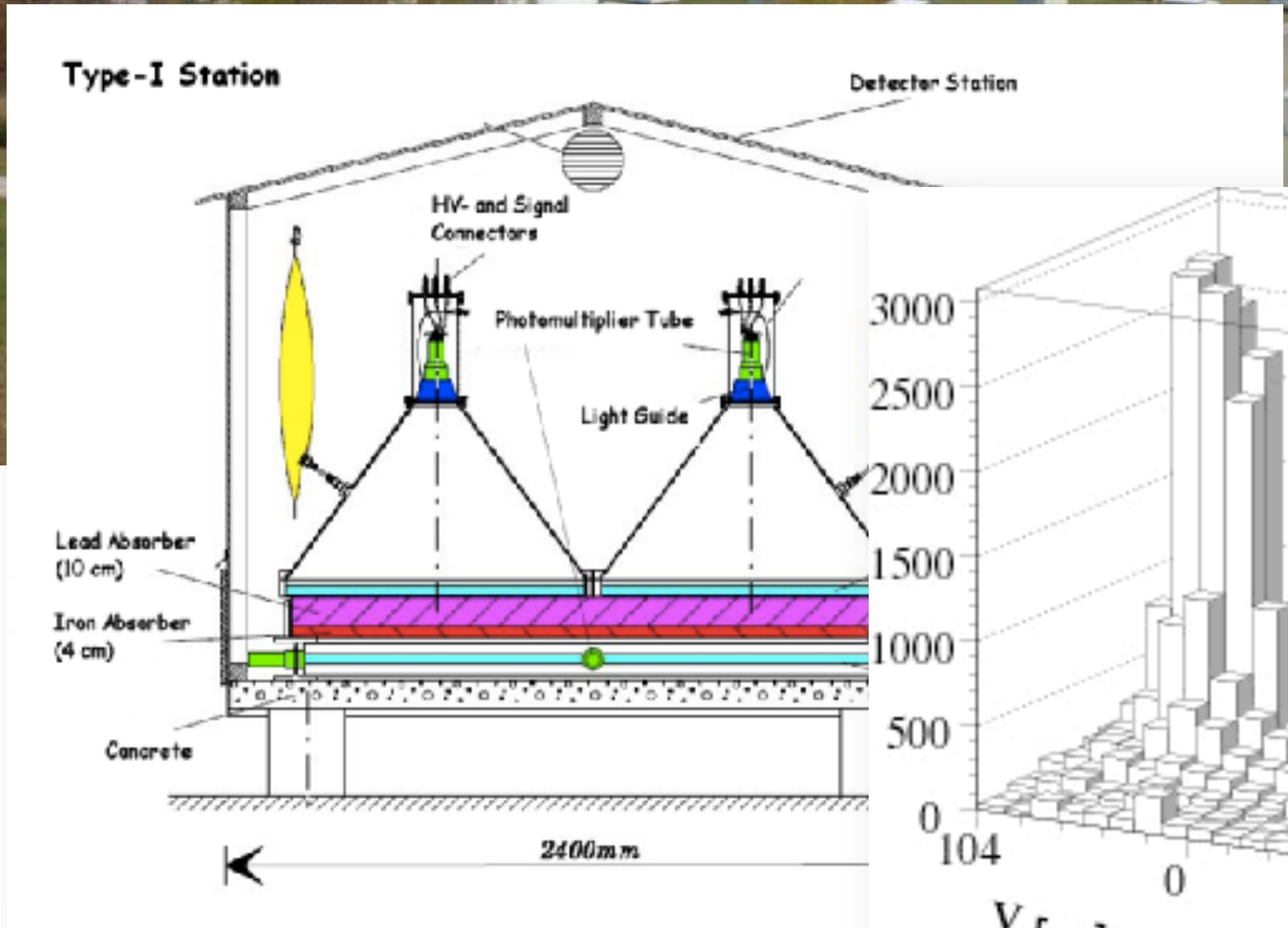
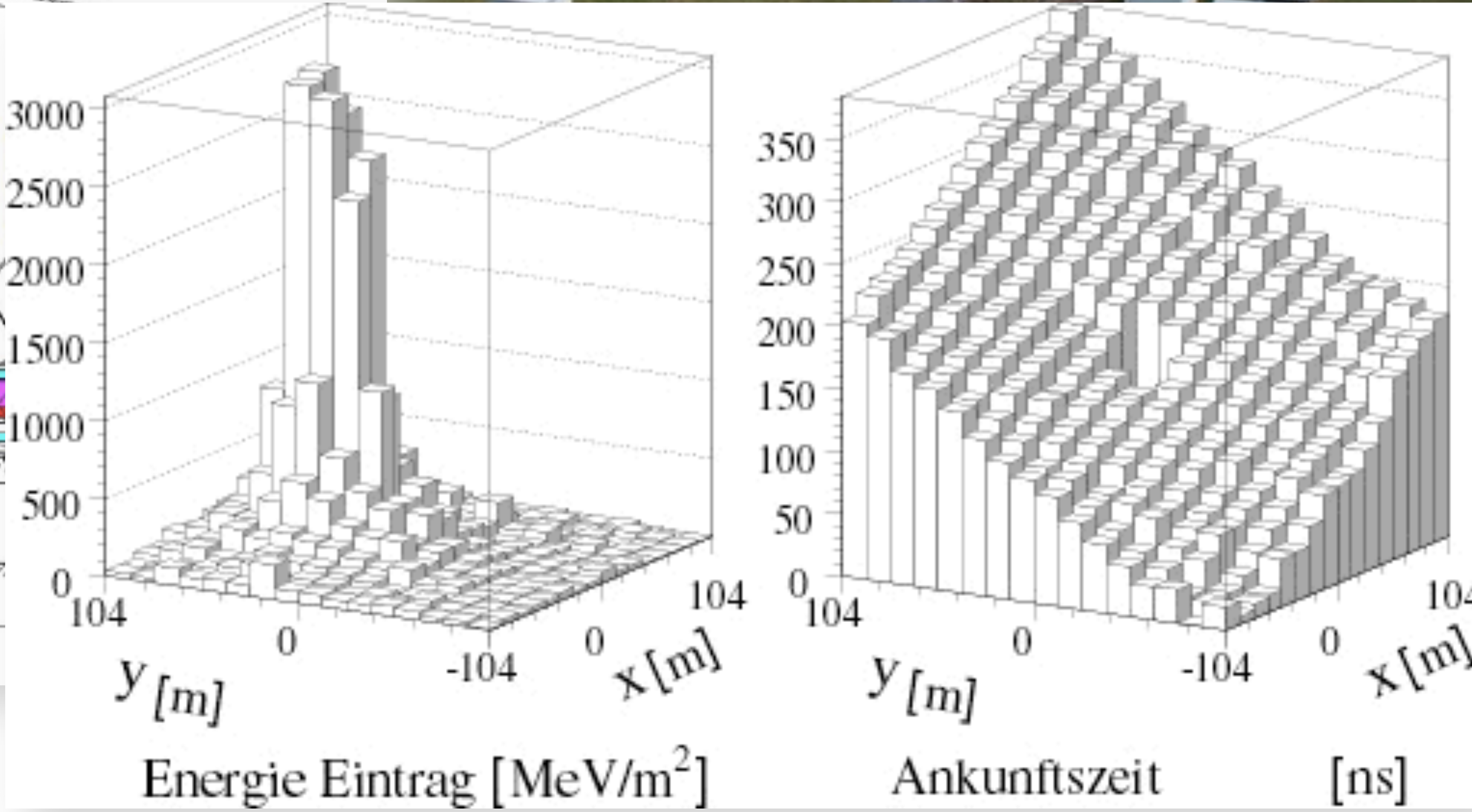


KASCADE
Karlsruhe Shower Core and Array Detector

Area 40,000 m^2





The Pierre Auger Observatory

Area 3,000 km^2

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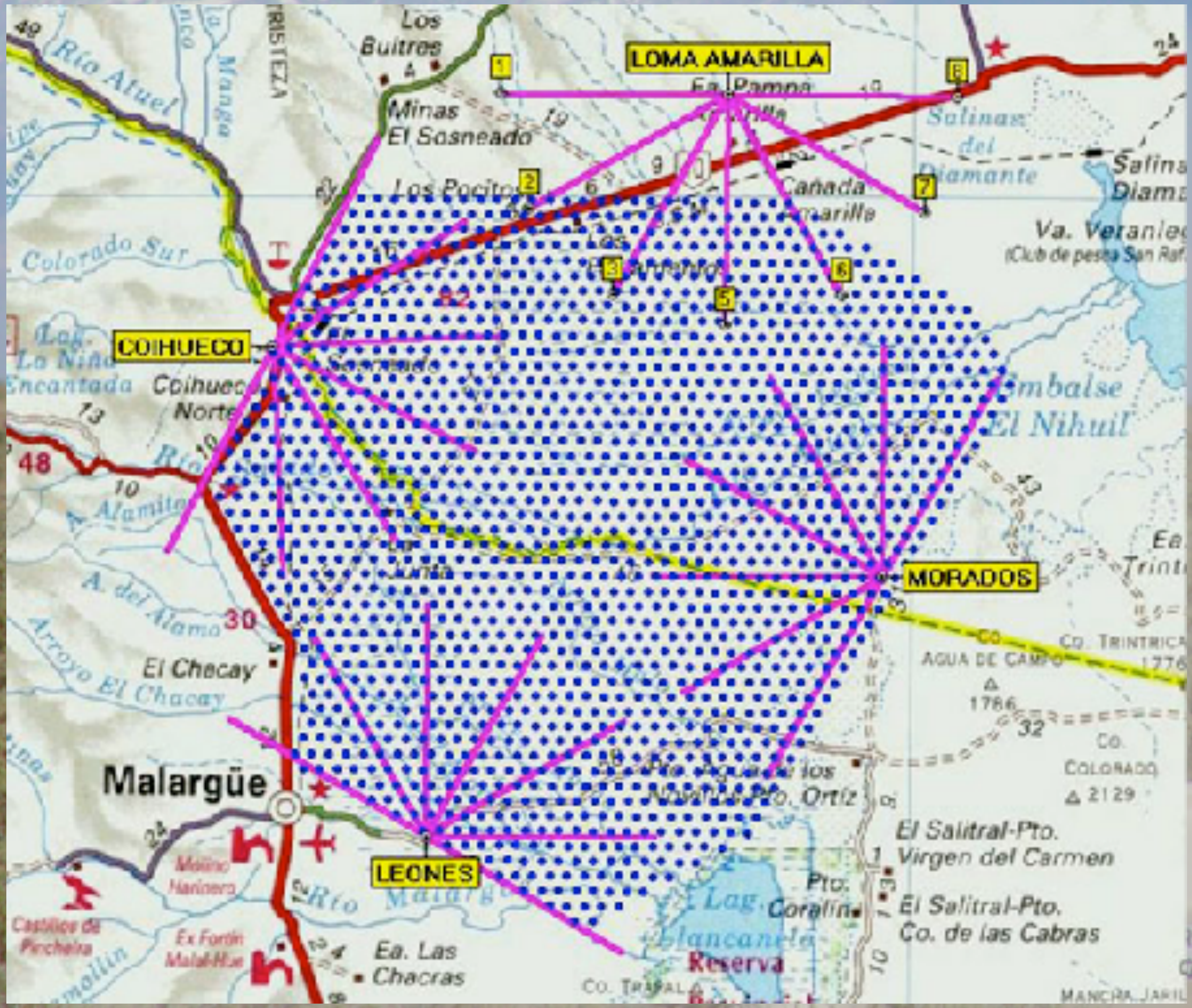
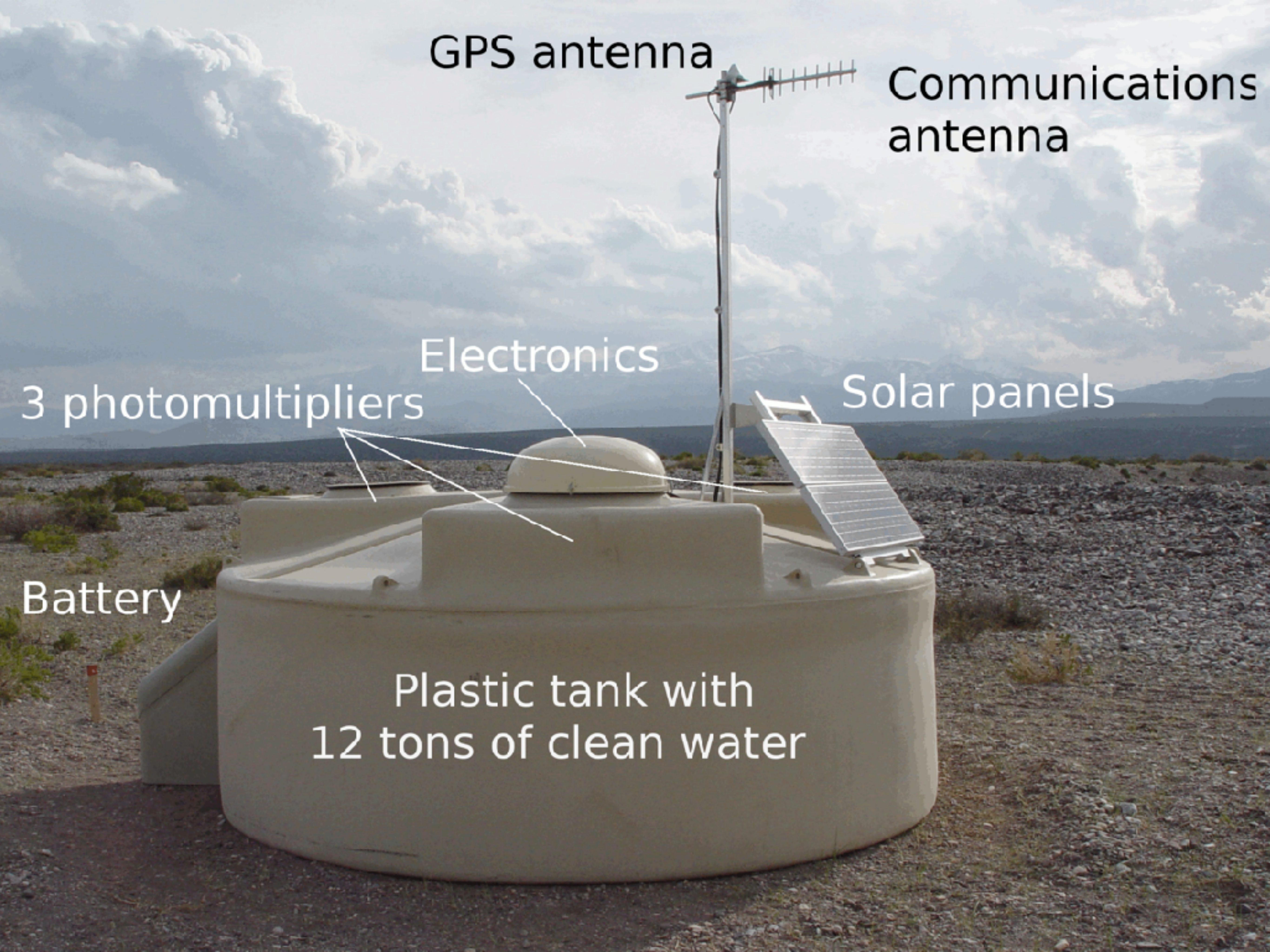
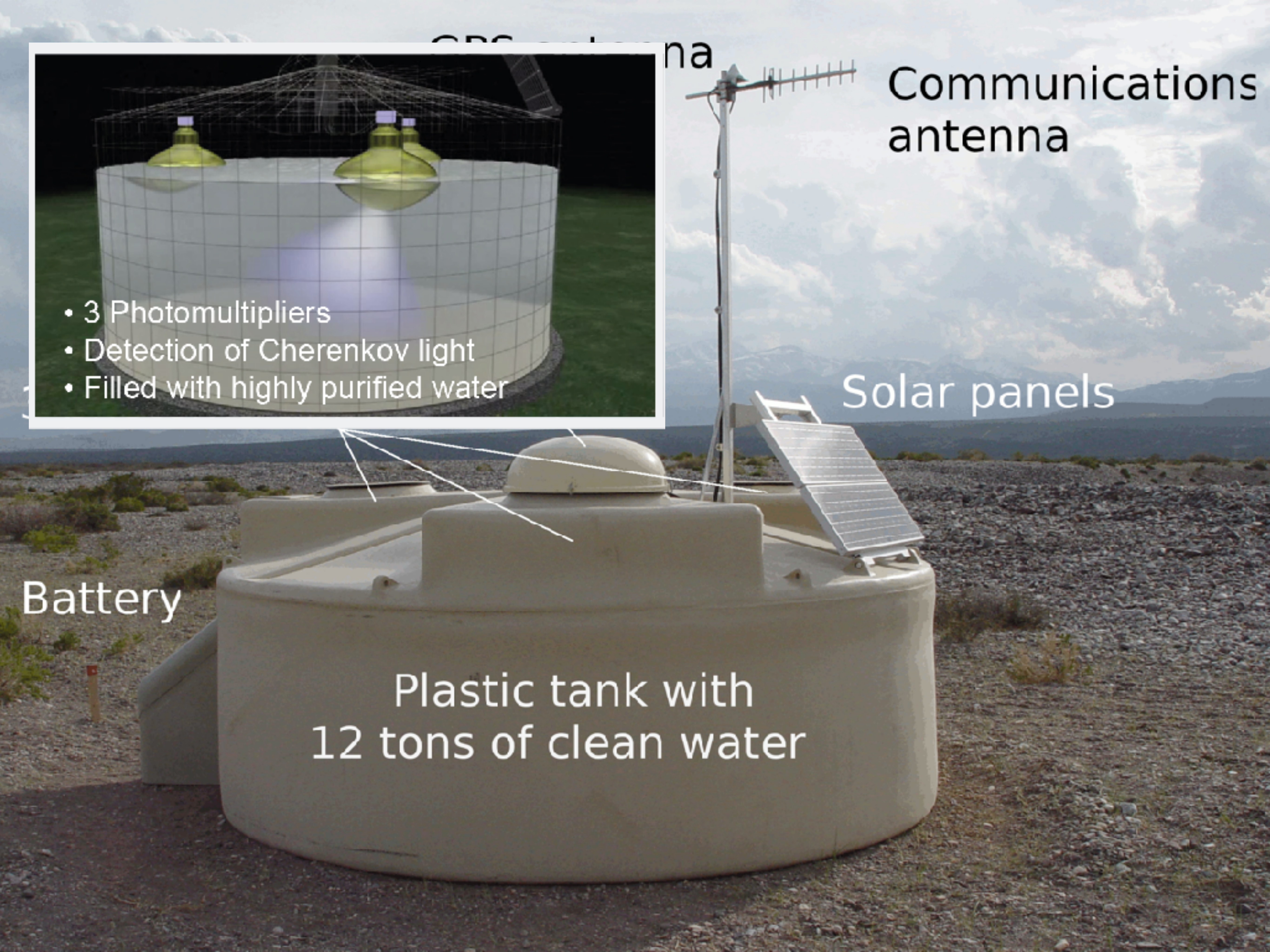
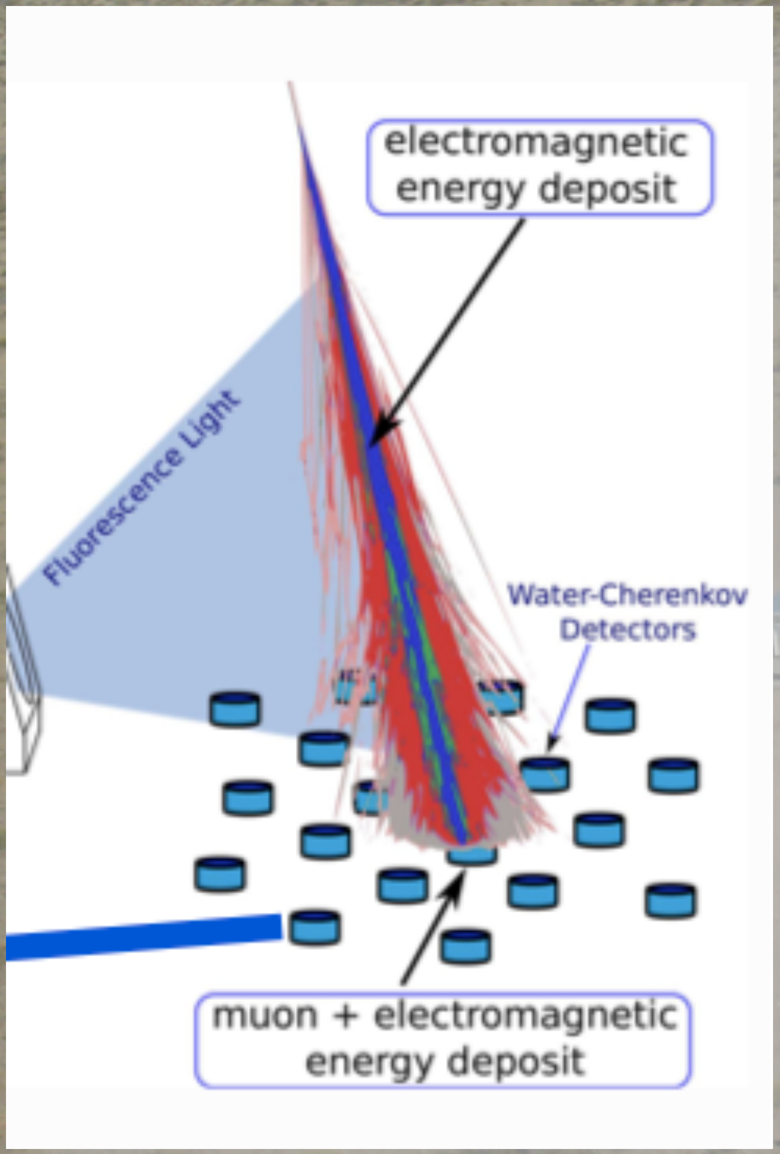
Area 3,000 km^2

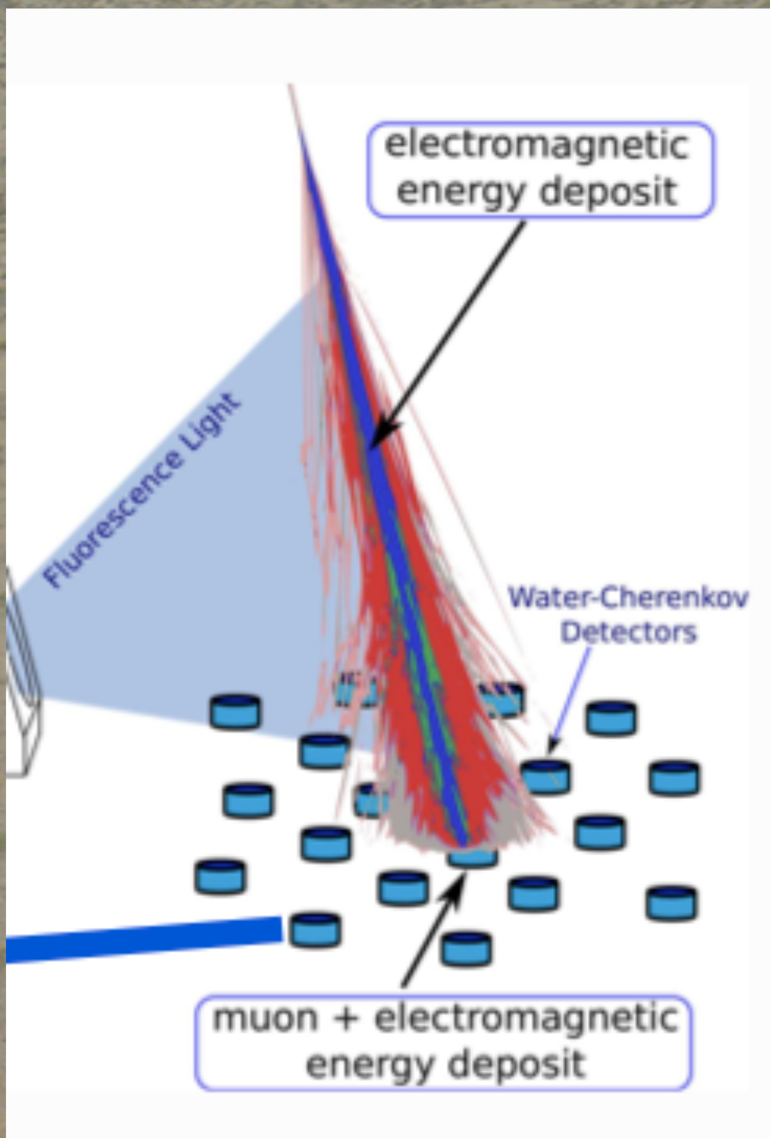



GPS antenna
Communications antenna
Electronics
3 photomultipliers
Solar panels
Battery
Plastic tank with
12 tons of clean water


• 3 Photomultipliers
• Detection of Cherenkov light
• Filled with highly purified water
Communications antenna
Solar panels
Battery
Plastic tank with 12 tons of clean water



electrons excite N_2
Decay to ground state by
isotropically emitting UV
photons ~380nm



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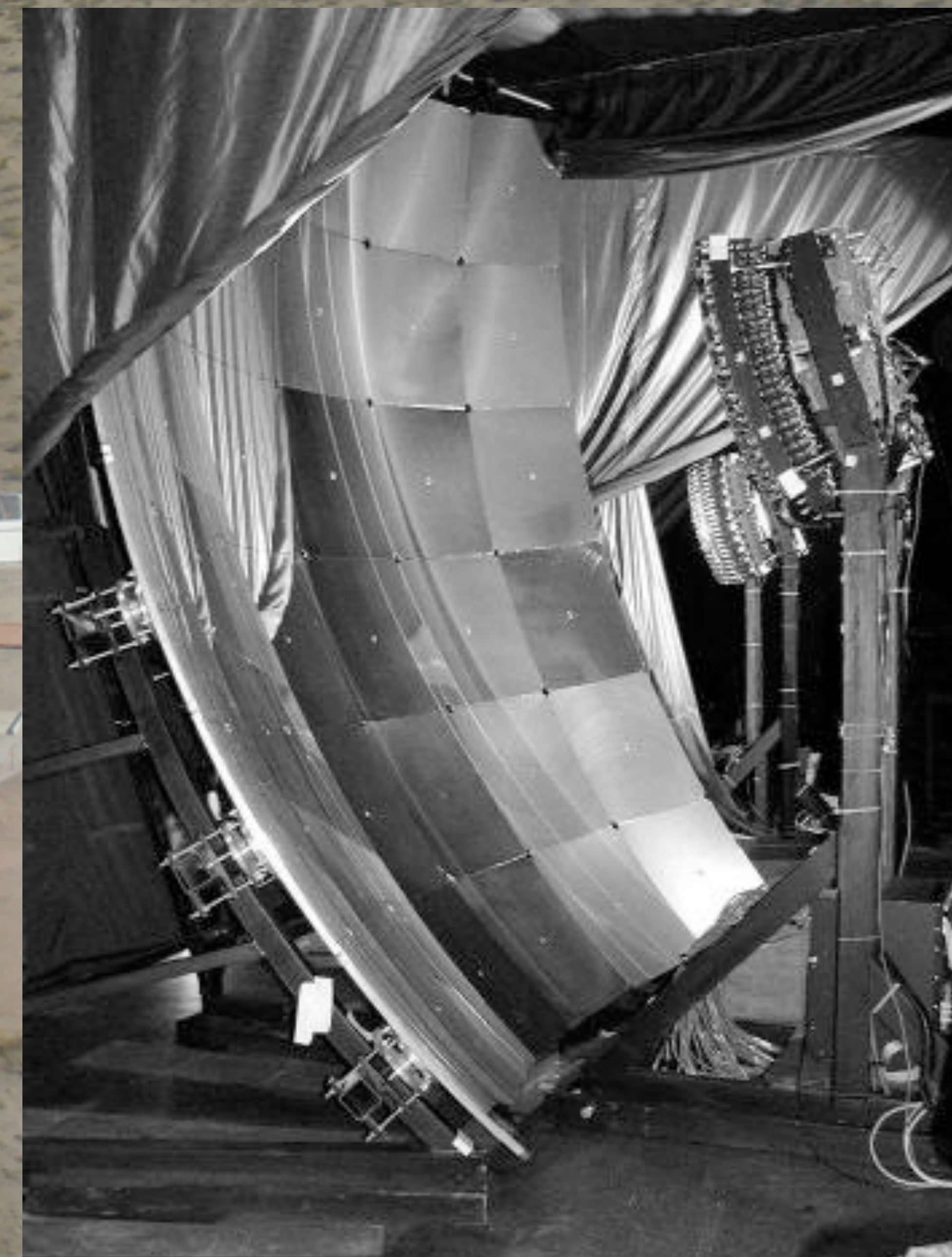
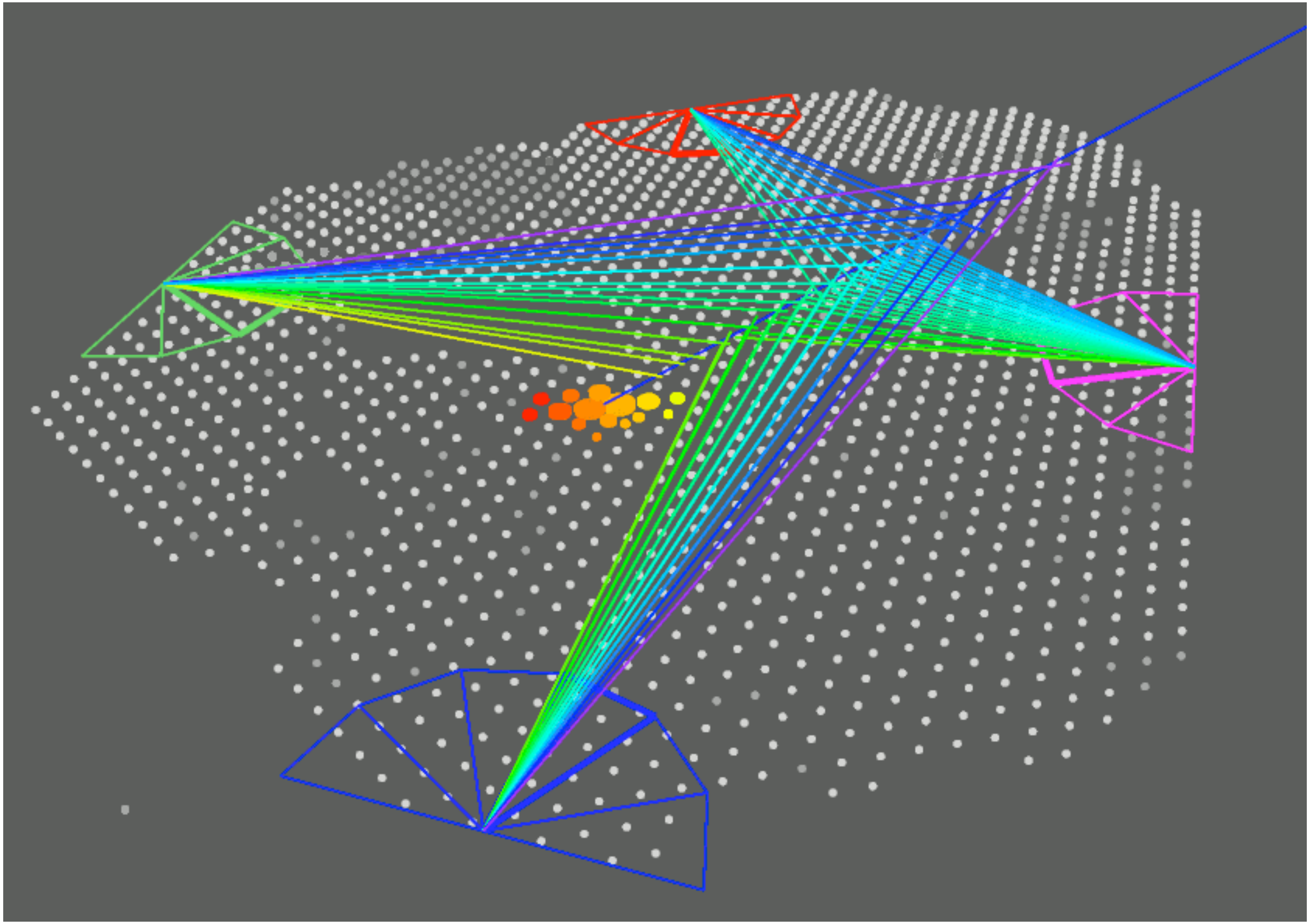


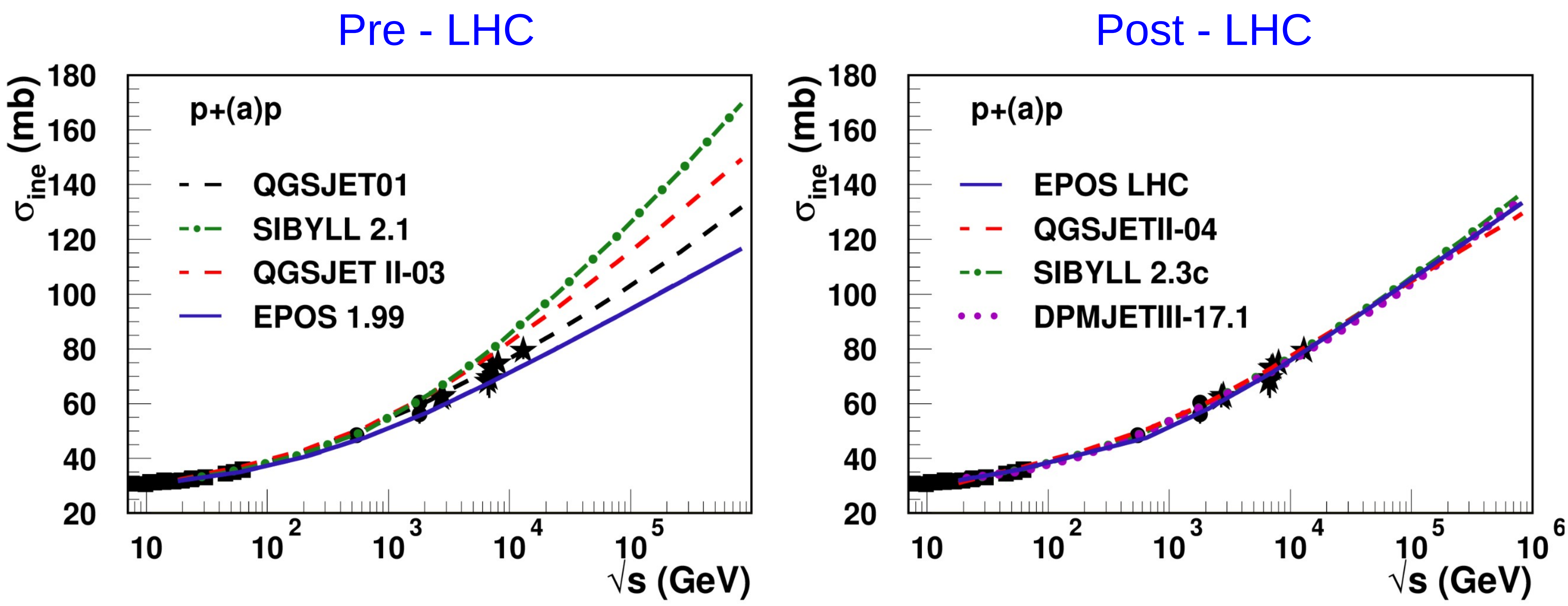
The Pierre Auger Observatory



http://www-hep2.fzu.cz/~smida/Auger-figures/Auger-quattro.gif

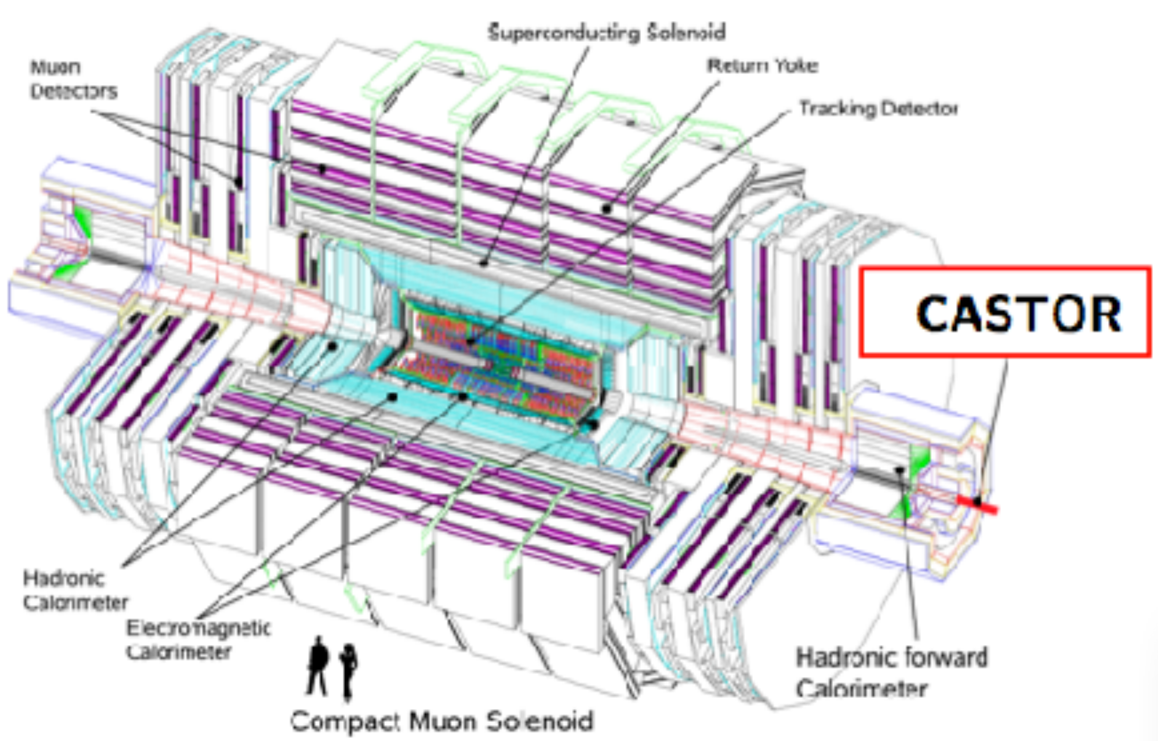
Extensive air shower: hadronic interactions

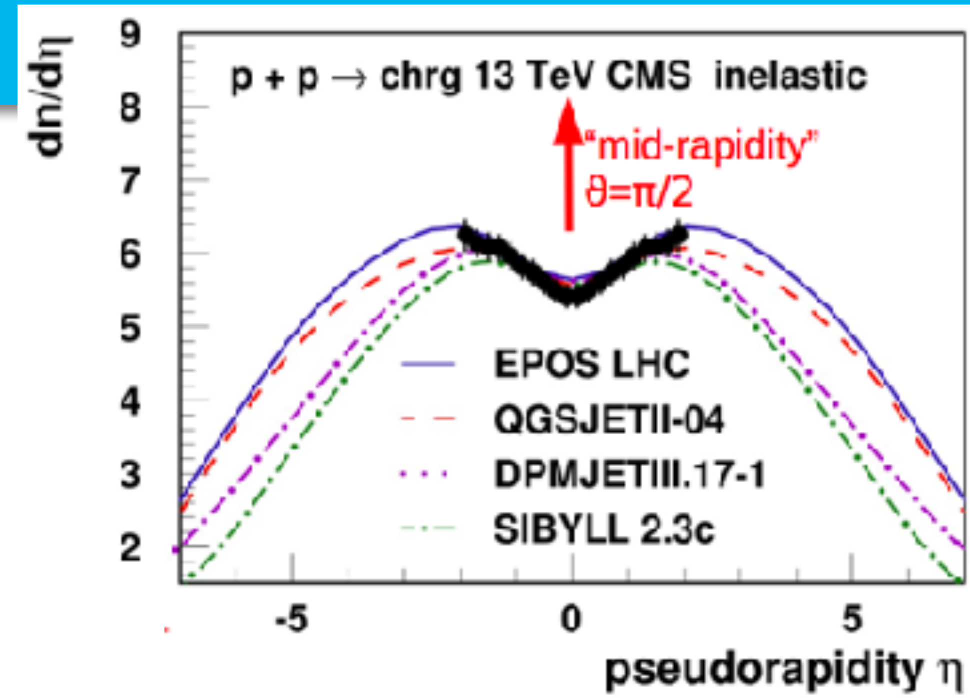
understanding of extensive air showers relies on extrapolations of several orders of magnitude using models of the hadronic interaction

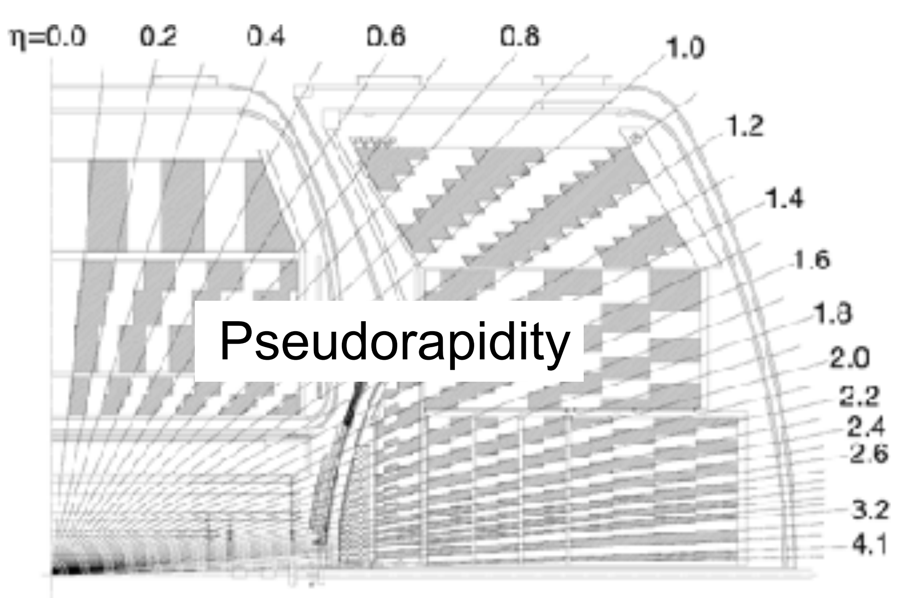


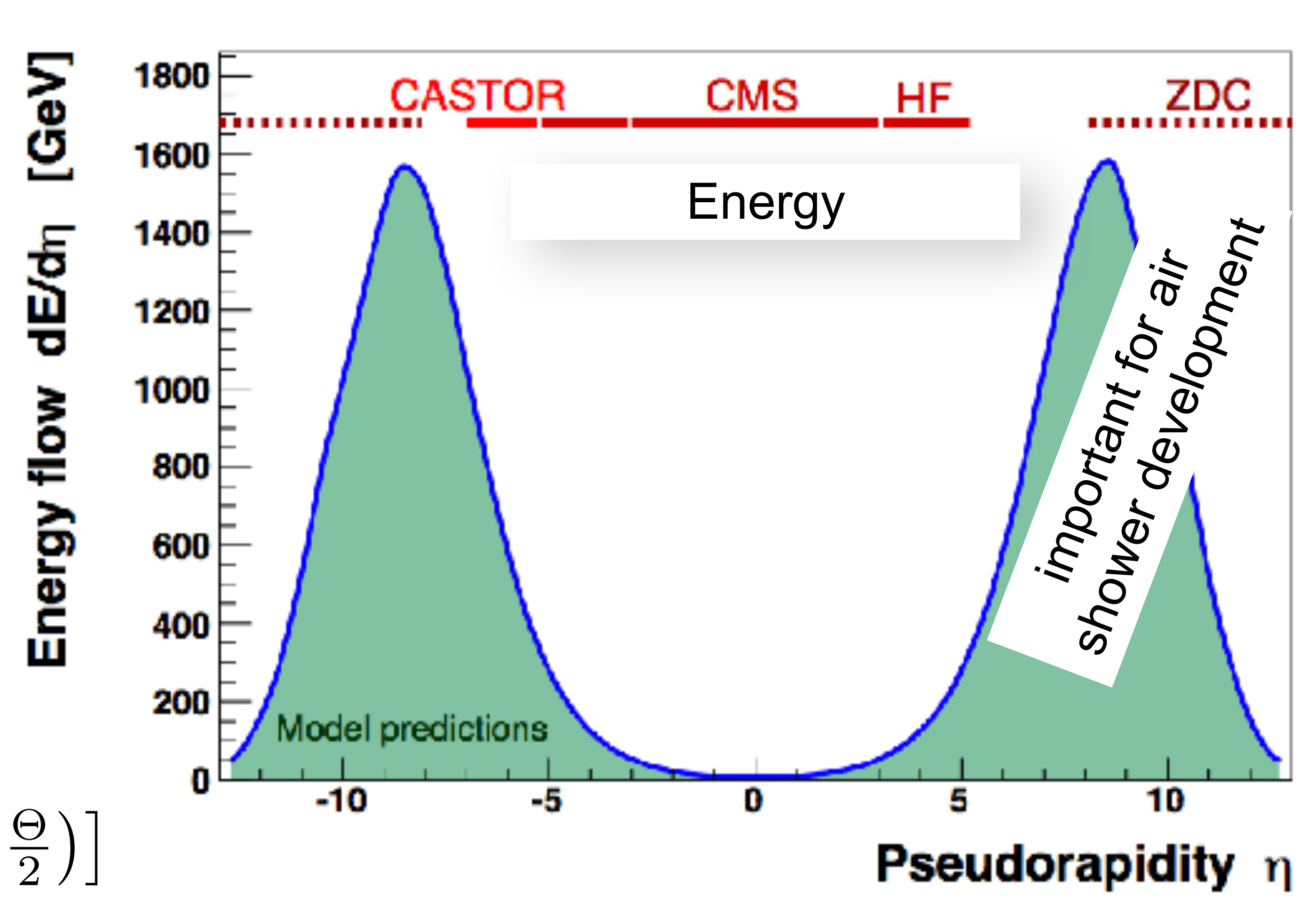
Pierog 2017

Forward direction







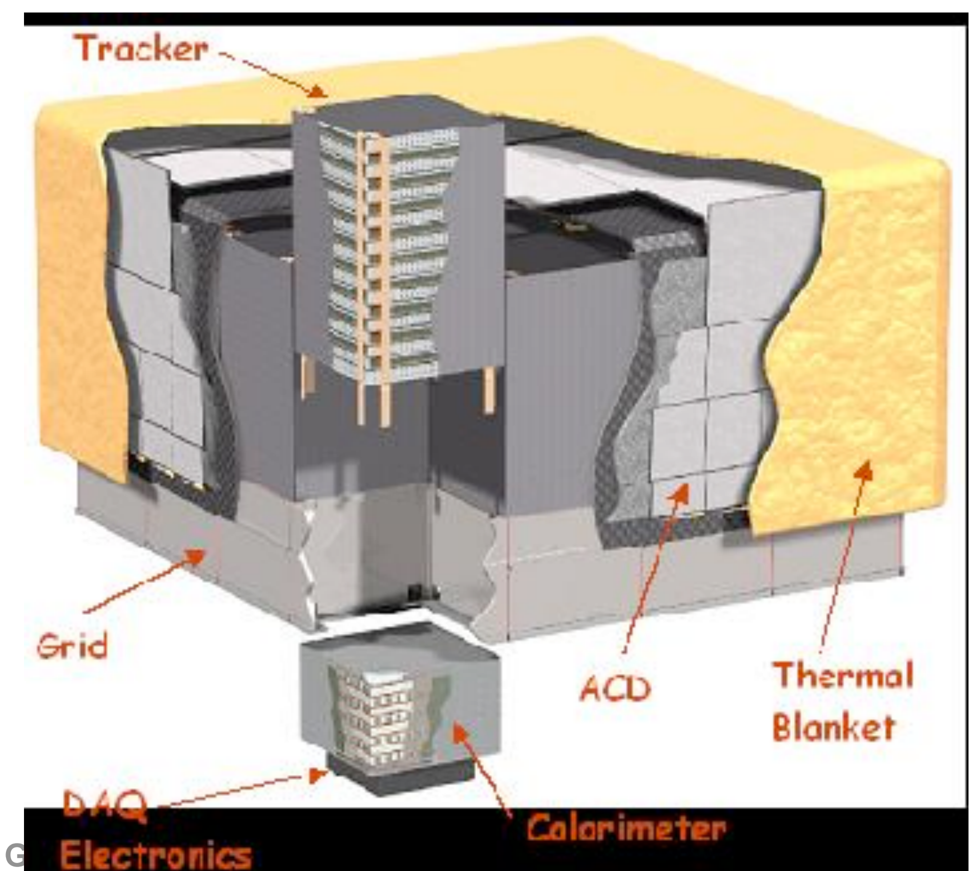


pseudorapidity: $\eta = -\ln\left[\tan\left(\frac{\Theta}{2}\right)\right]$

Observing gamma rays from space

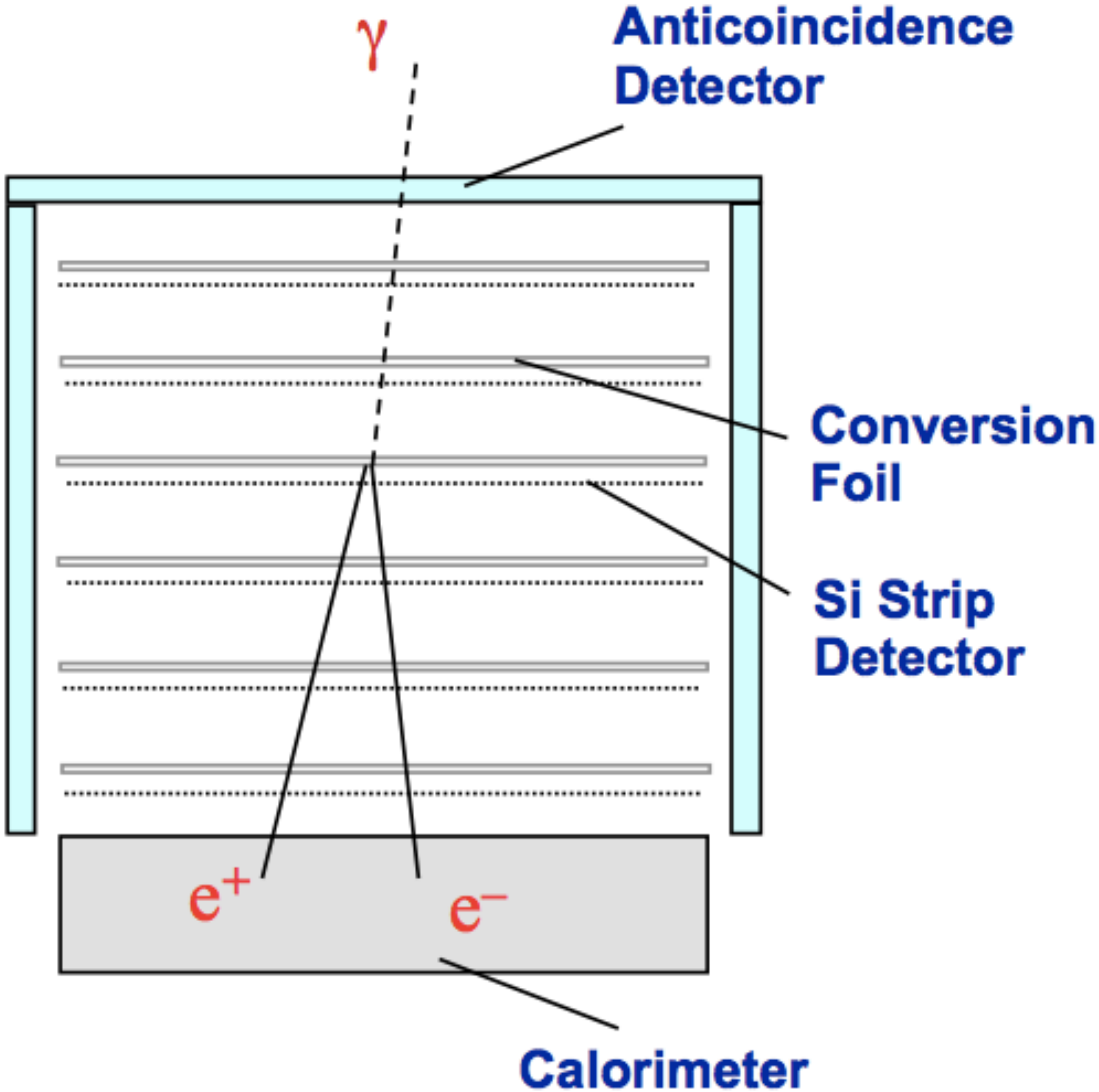
Fermi LAT:

- launched in June 2008
- pair-conversion telescope
- mostly in survey mode: Fermi observes each point in the sky every three hours



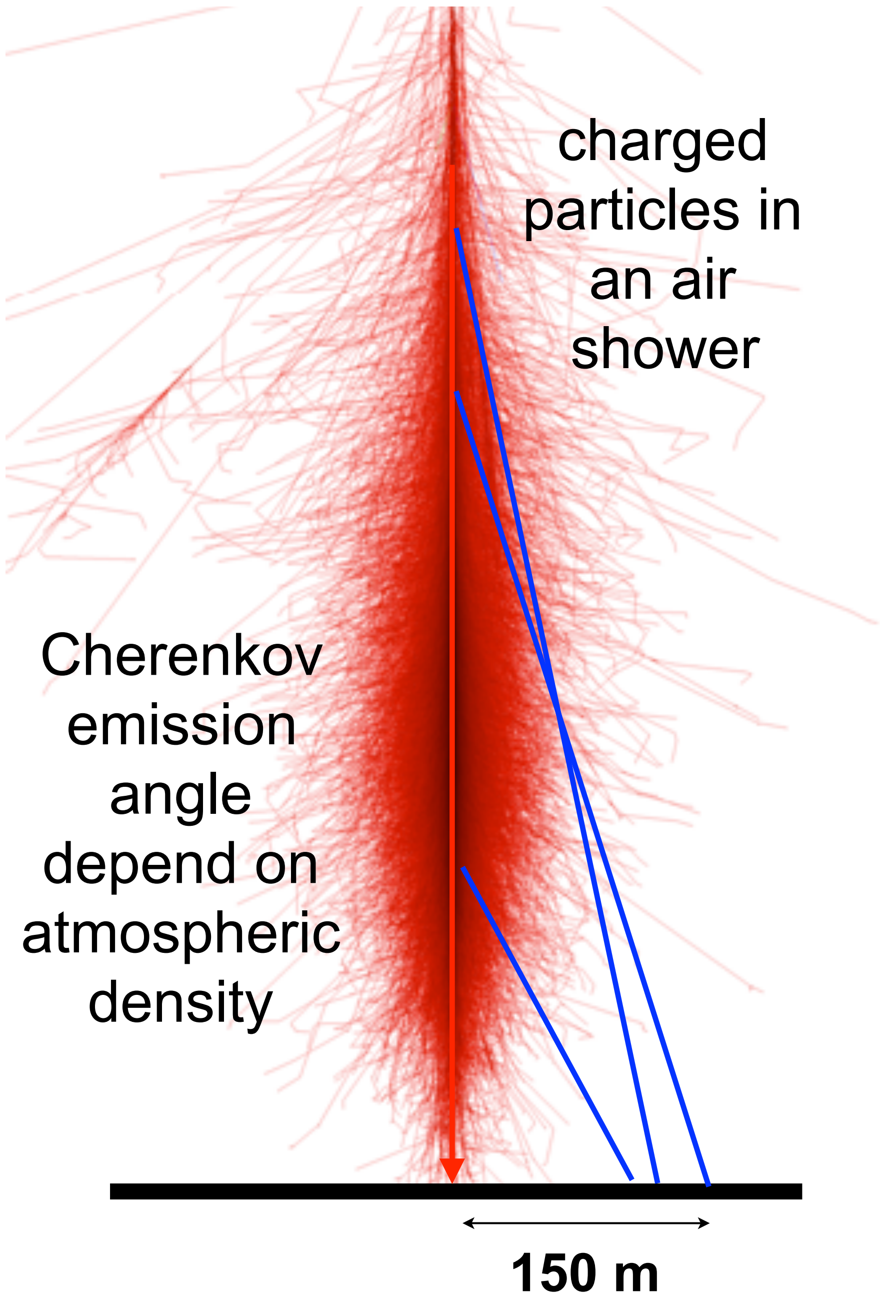
- Energy range 20 MeV to 300 GeV
- LAT Effective area: ~0.7 m^2
- AGILE Effective area: ~0.07 m^2

The Fermi Large Area Telescope



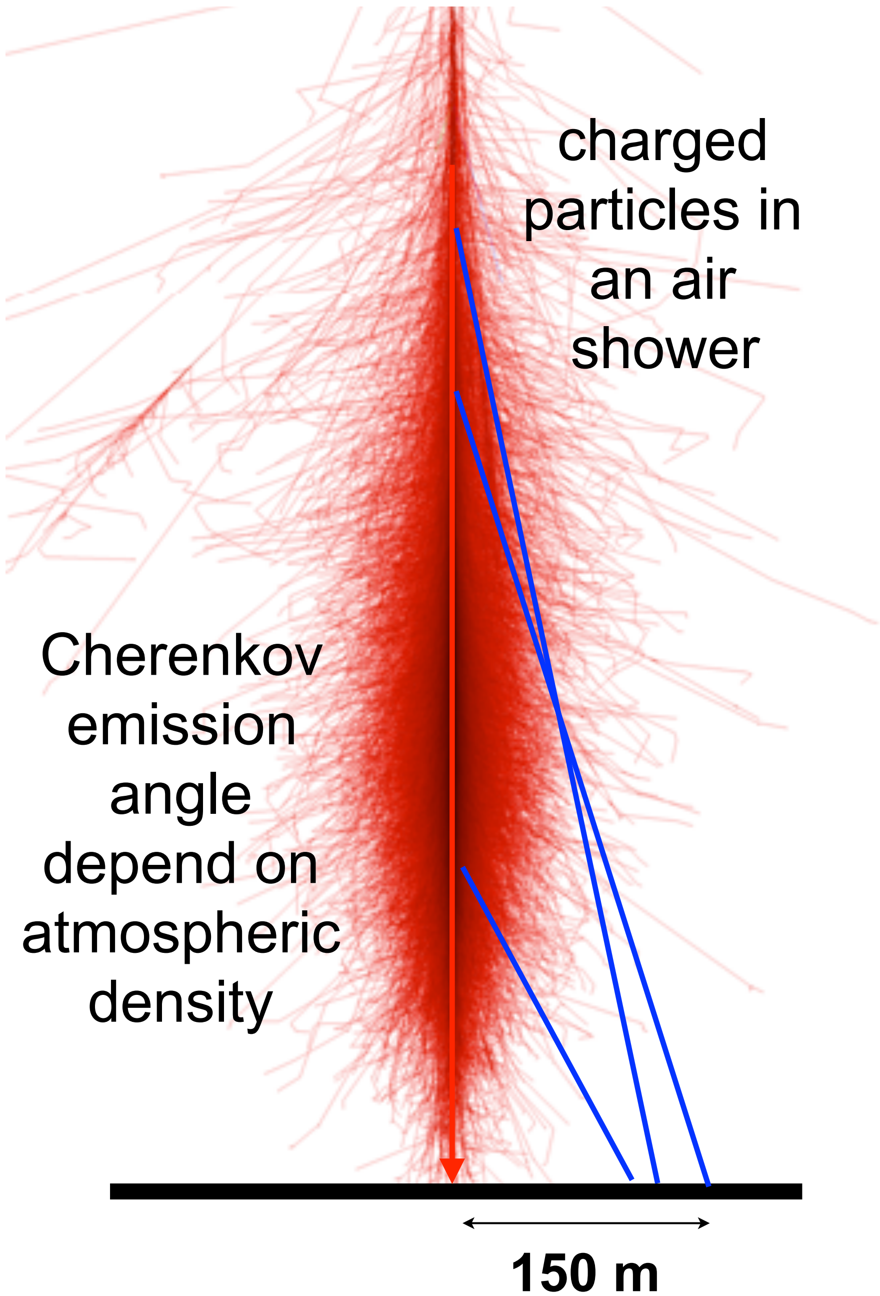
- Pair conversion detector (tungesten foils followed by tracker for e^+/e^-)
- Si strip detector to measure particle trajectories
- CsI calorimeter measures energy from the amount of scintillation produced by the e/m shower
- anti-coincidence shield to veto charged particles

Extensive Air Showers and Cherenkov Emission



Pavel Alekseyevich Cherenkov (Nobel price1958)

Extensive Air Showers and Cherenkov Emission



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emitted when velocity *v* of charged particle exceeds local speed of light: **nv/c = nß > 1**

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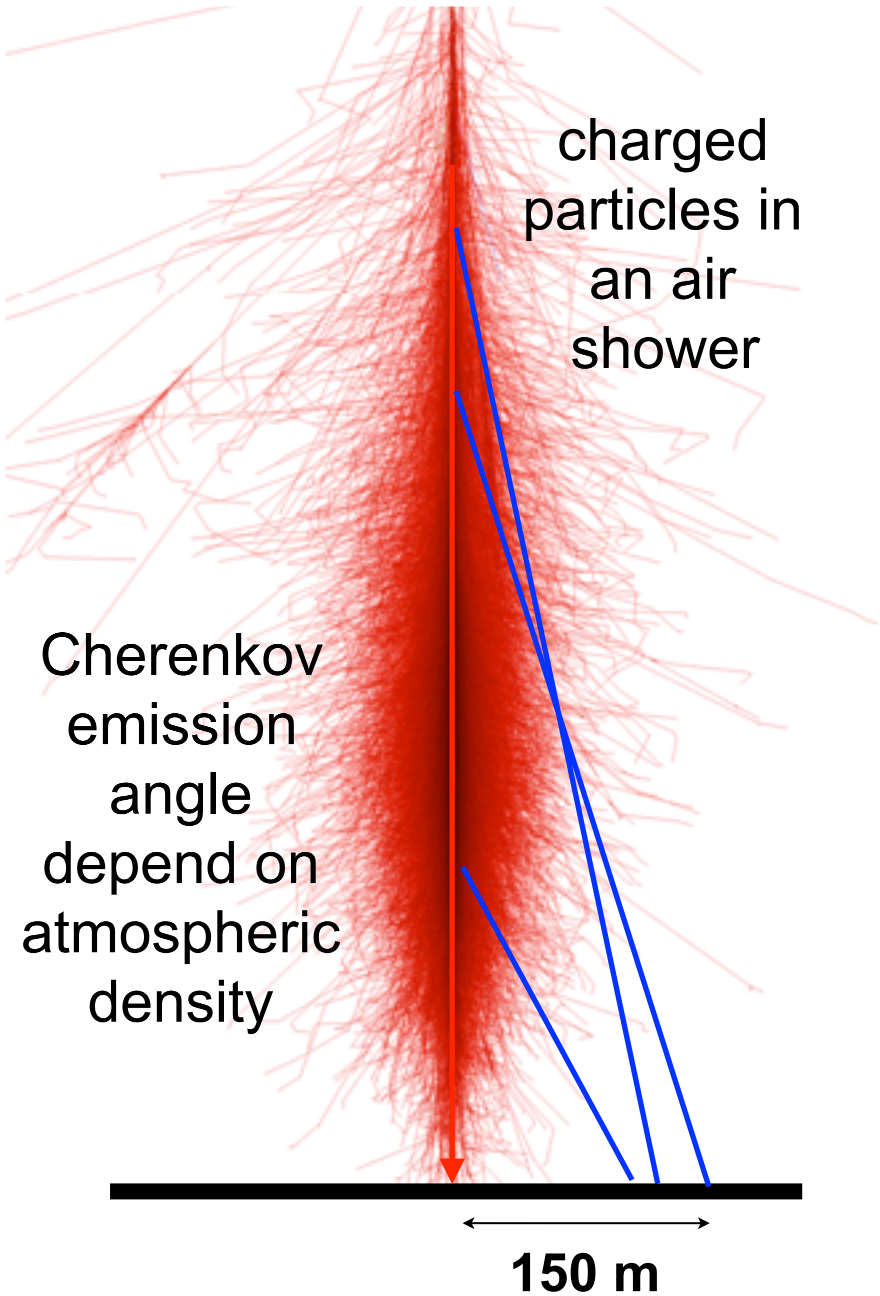

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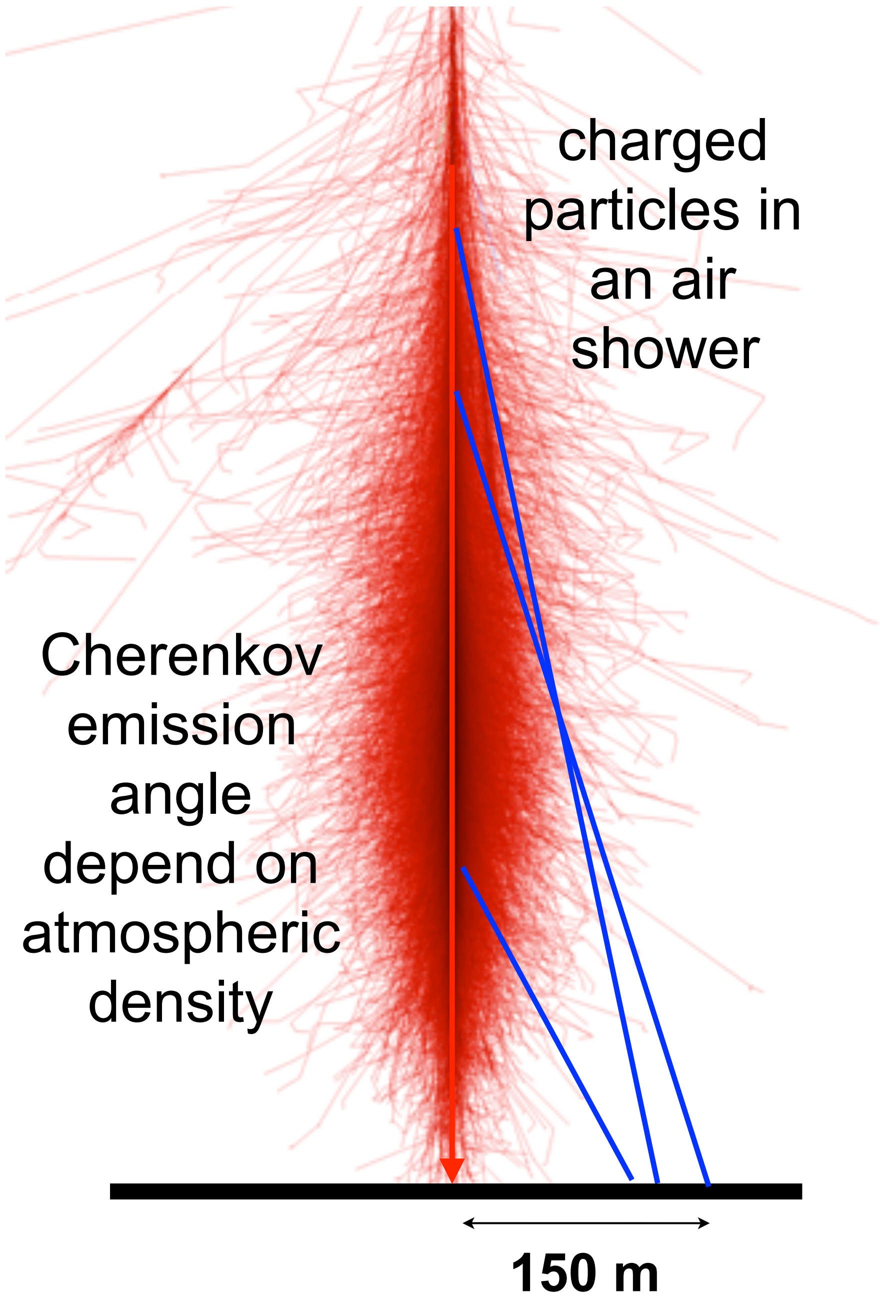
refractive index in air scales with density

$$n = 1 + 0.000283\ \rho(h)/\rho(0)$$

Extensive Air Showers and Cherenkov Emission



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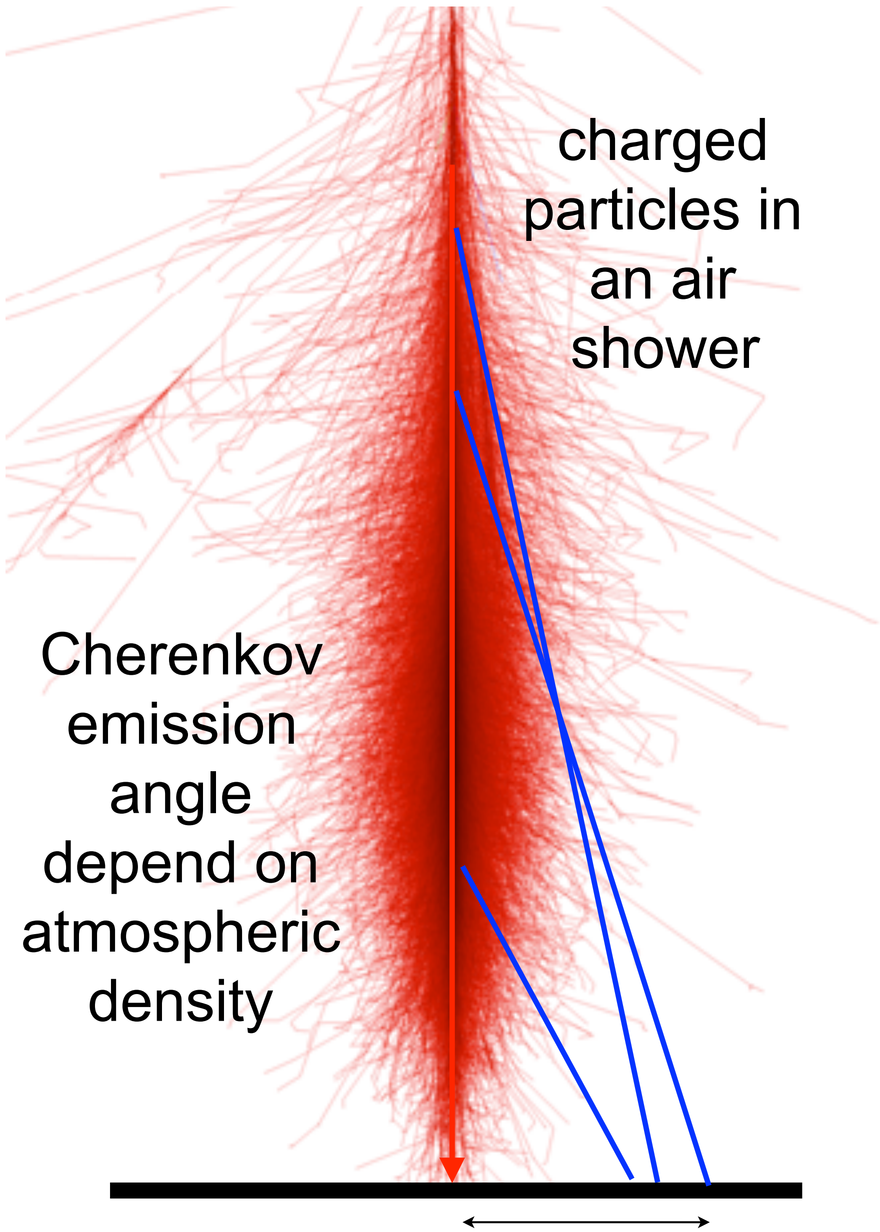
Extensive Air Showers and Cherenkov Emission



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emitted when velocity *v* of charged particle exceeds local speed of light: **nv/c = nß > 1**

refractive index in air scales with density

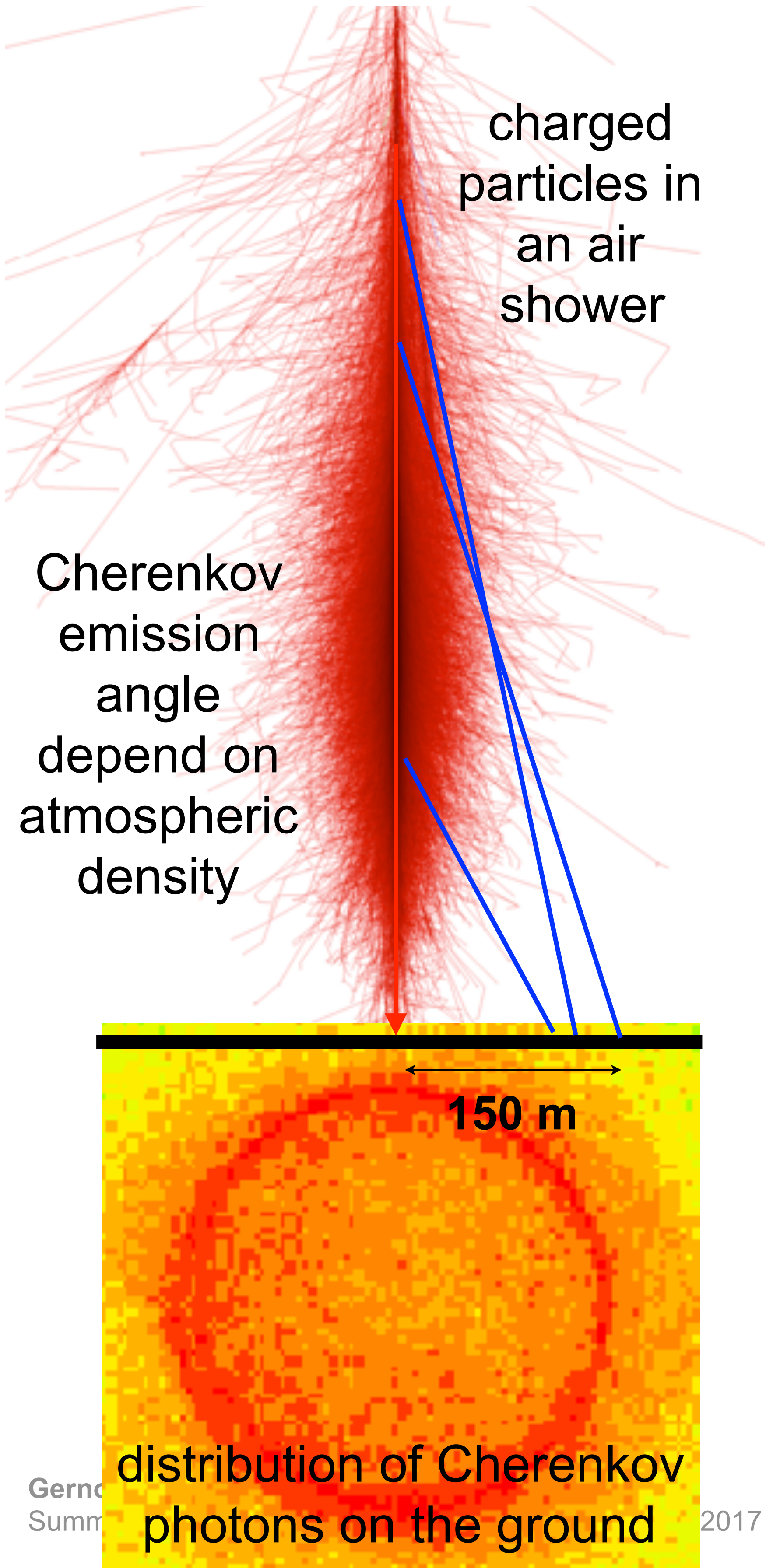
$$n = 1 + 0.000283\ \rho(h)/\rho(0)$$

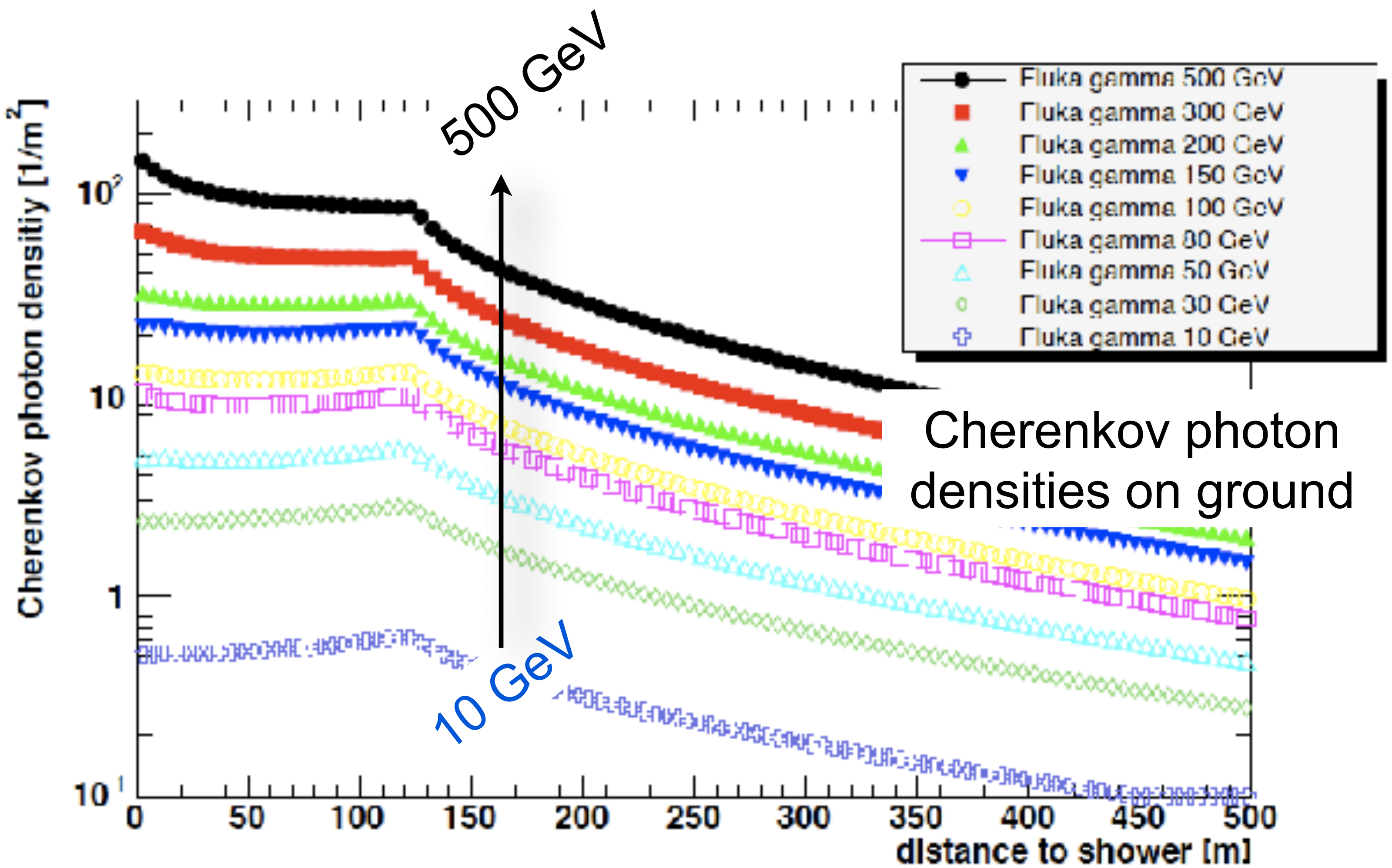
light is emitted along a cone with half opening angle θ: **cos θ = 1 / (ßn)**

number of Cherenkov photons per path length x:

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Extensive Air Showers and Cherenkov Emission

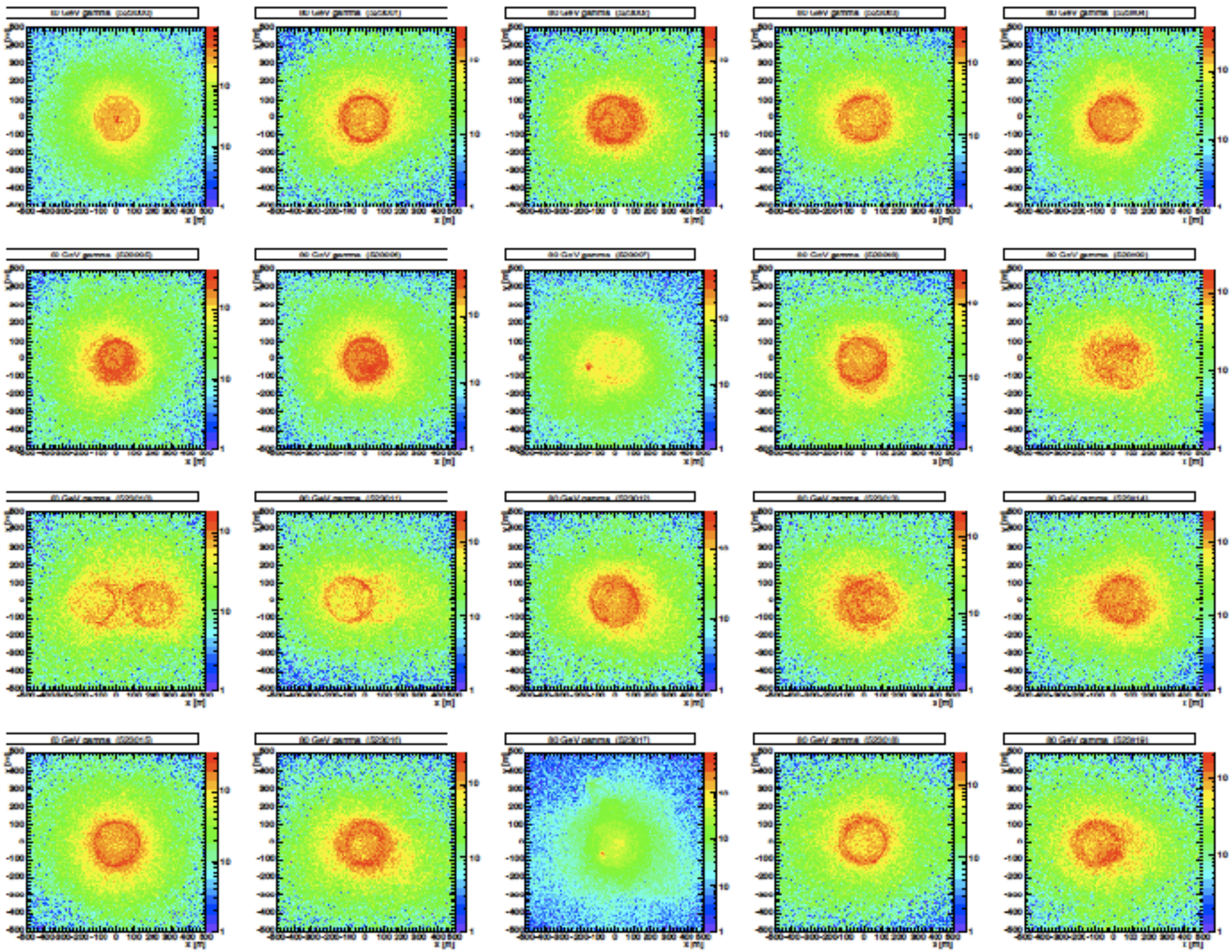




Cherenkov light from air showers: weak (~10 ph/m²), short (~ns), blue (300-550nm) flash of light

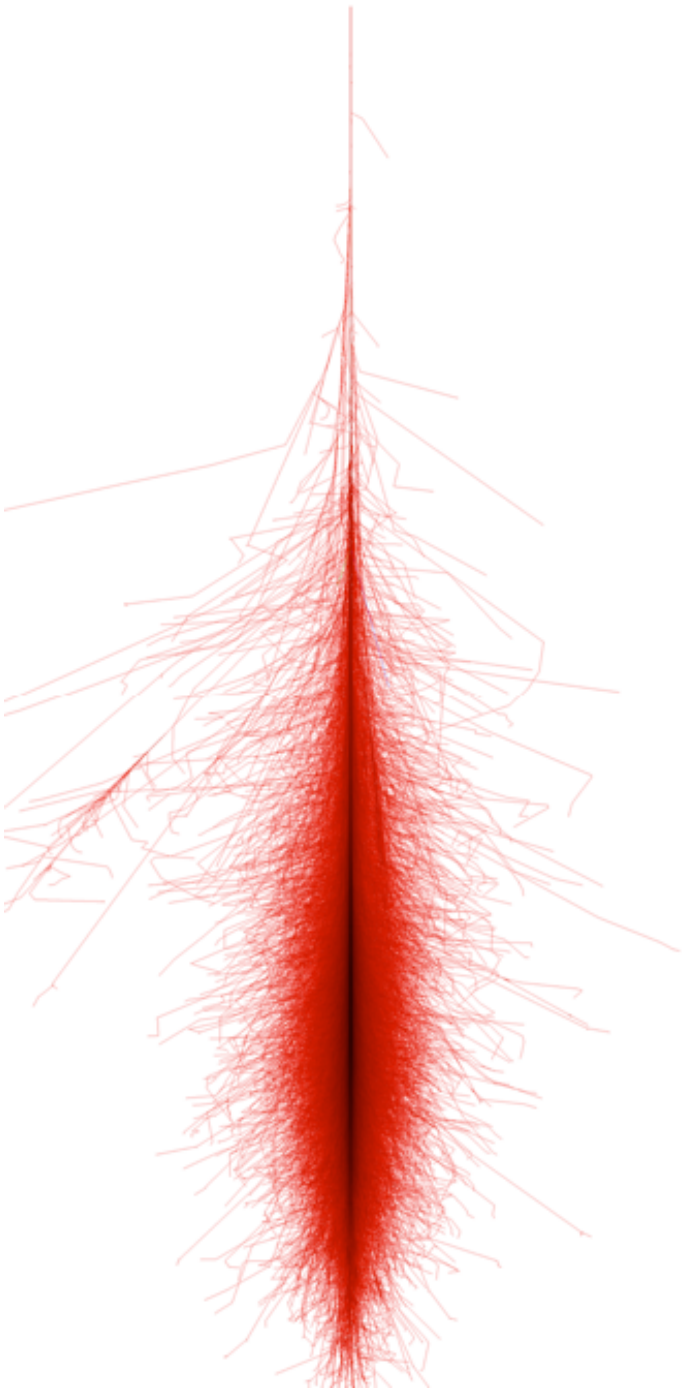
Shower fluctuations

randomly selected showers with 80 GeV primary photon energy

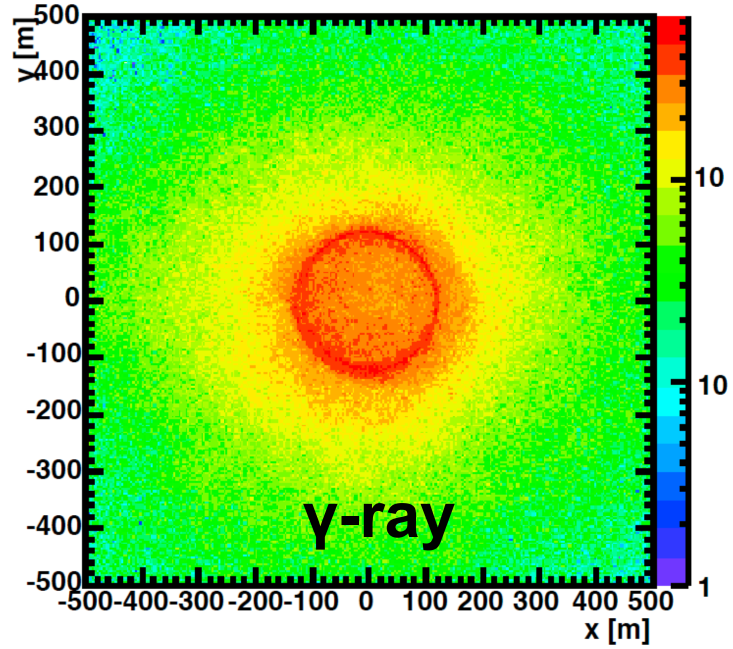


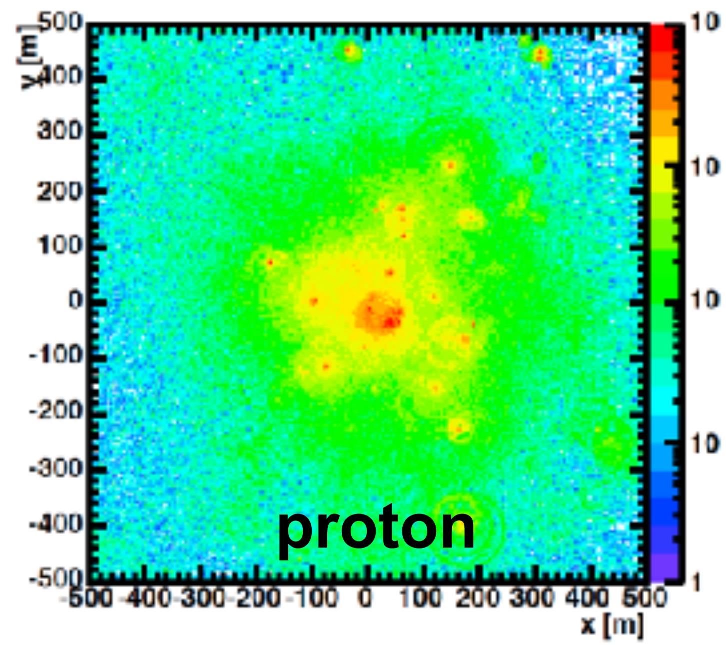
Proton vs Gamma-ray showers

γ-ray

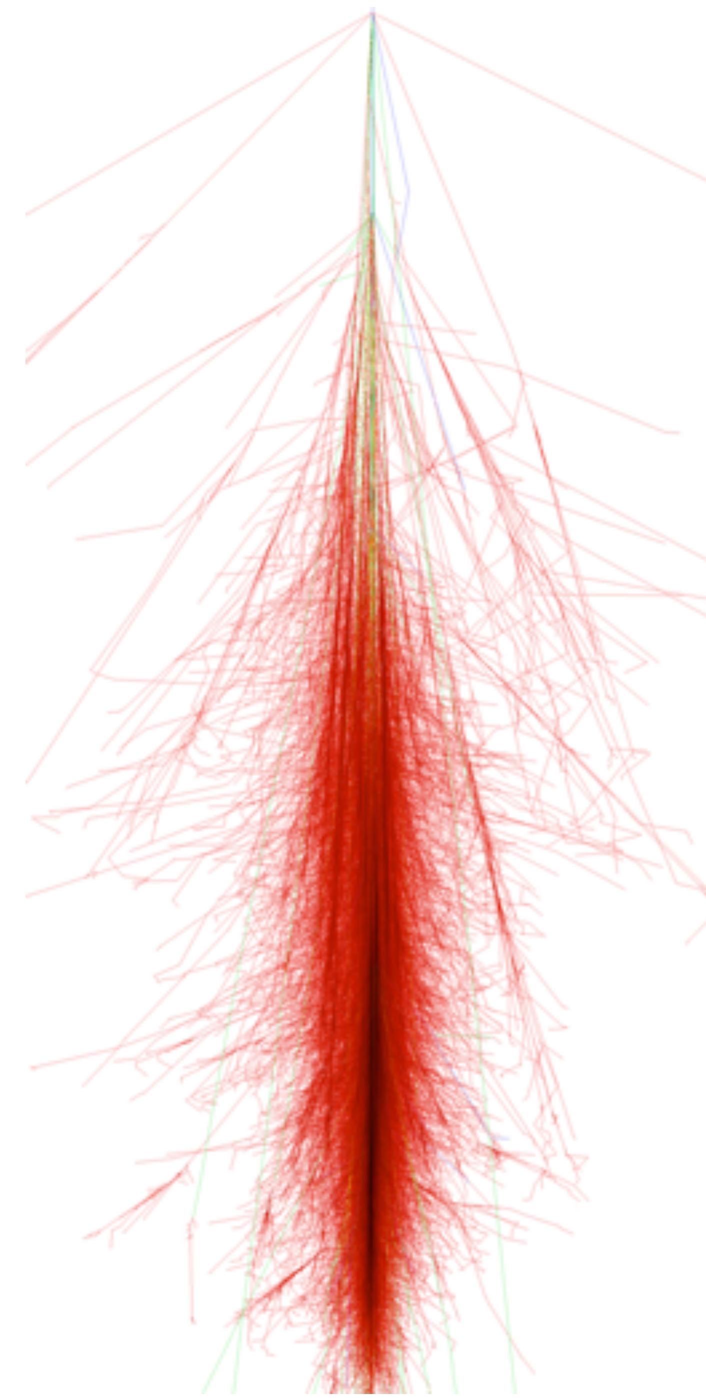


Cherenkov photons on ground

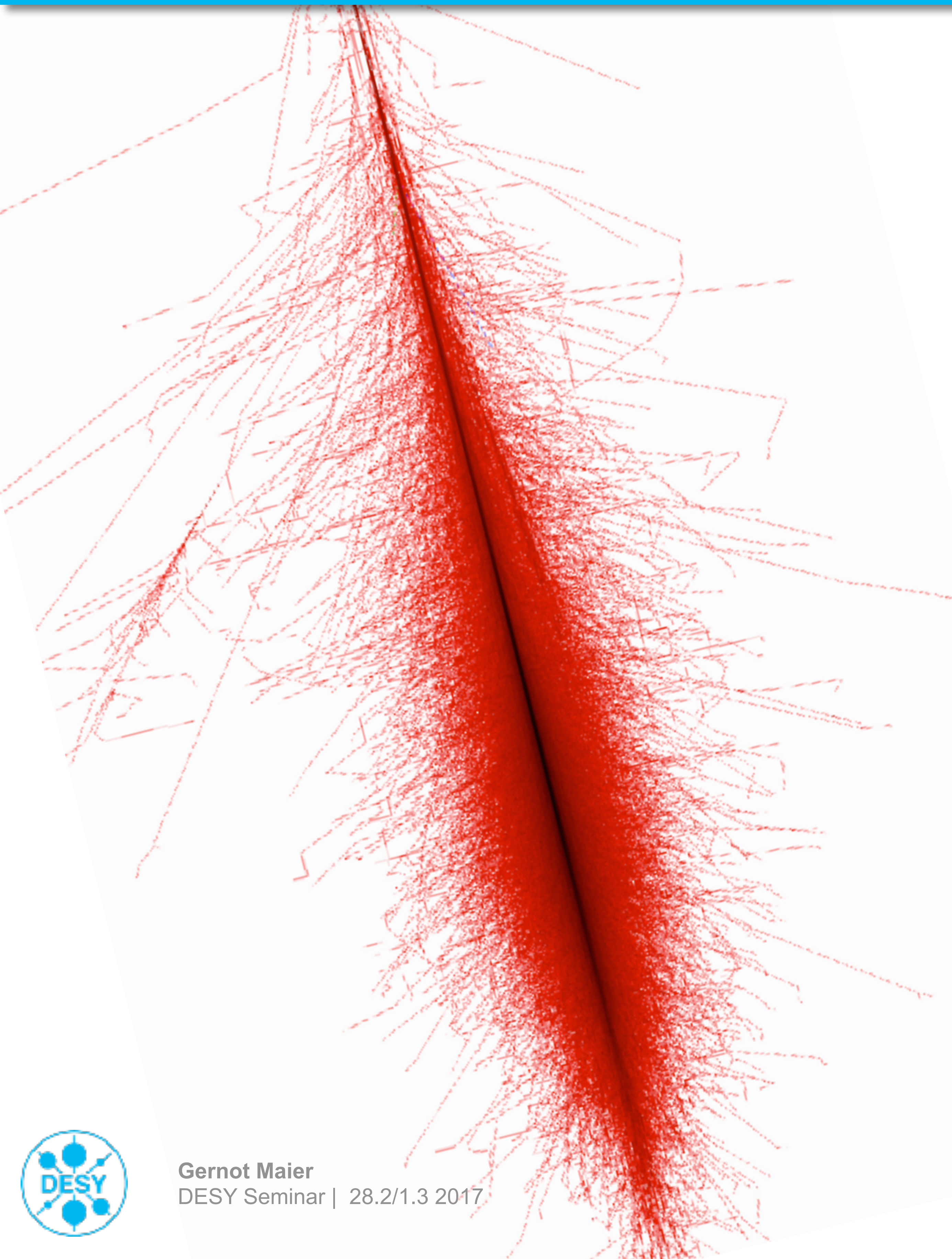


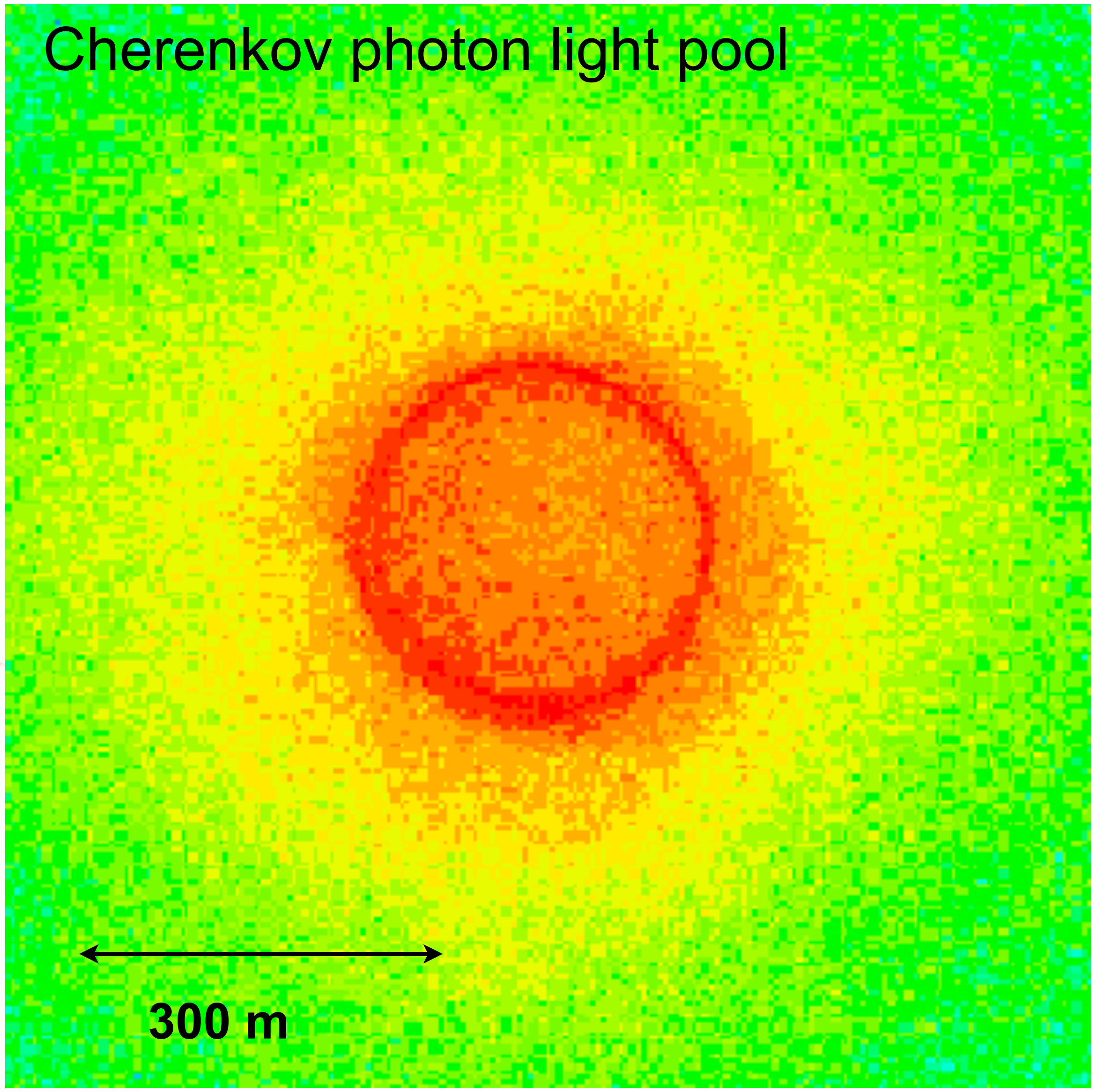


proton



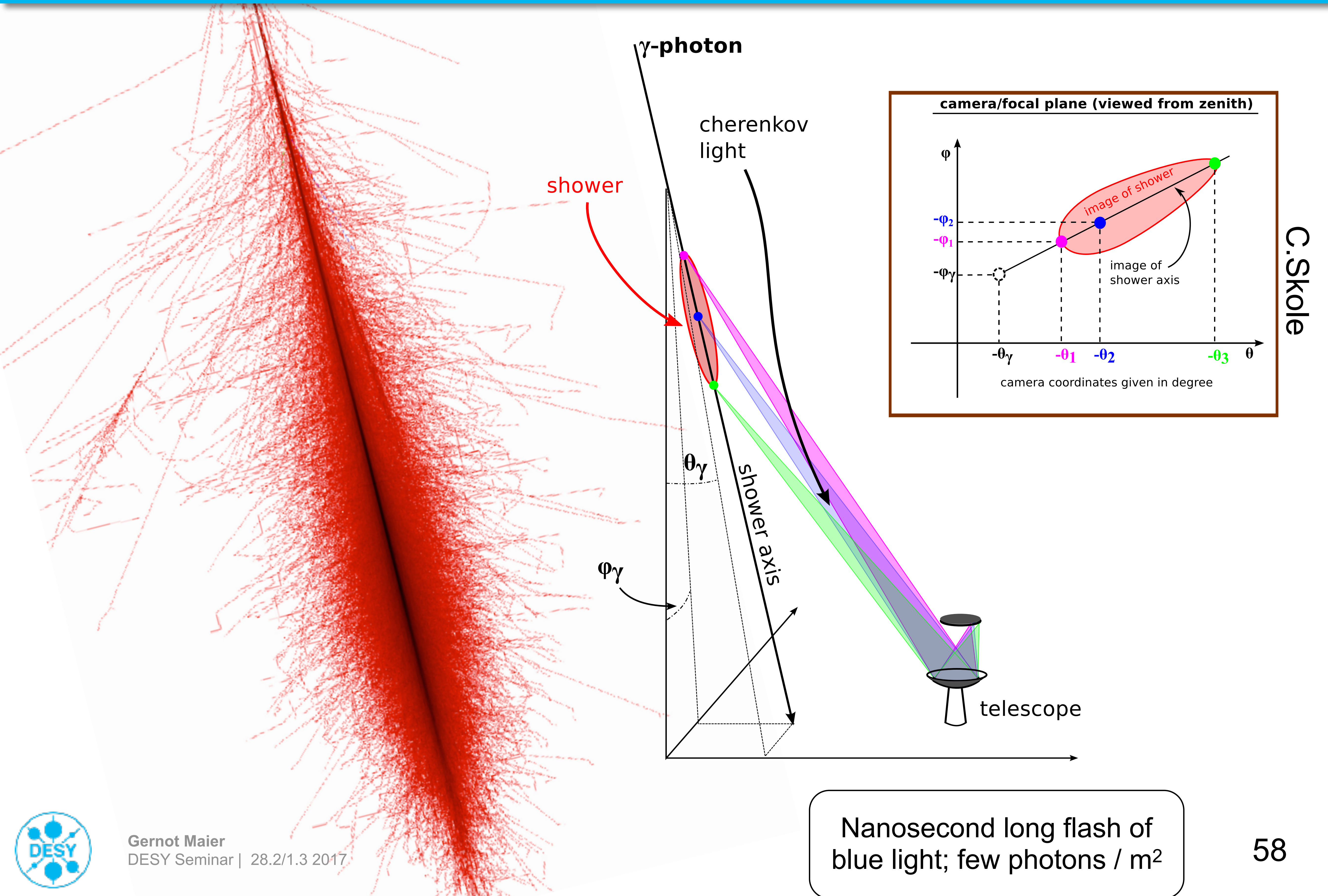
Measuring gamma-rays (20 GeV to 300 TeV)





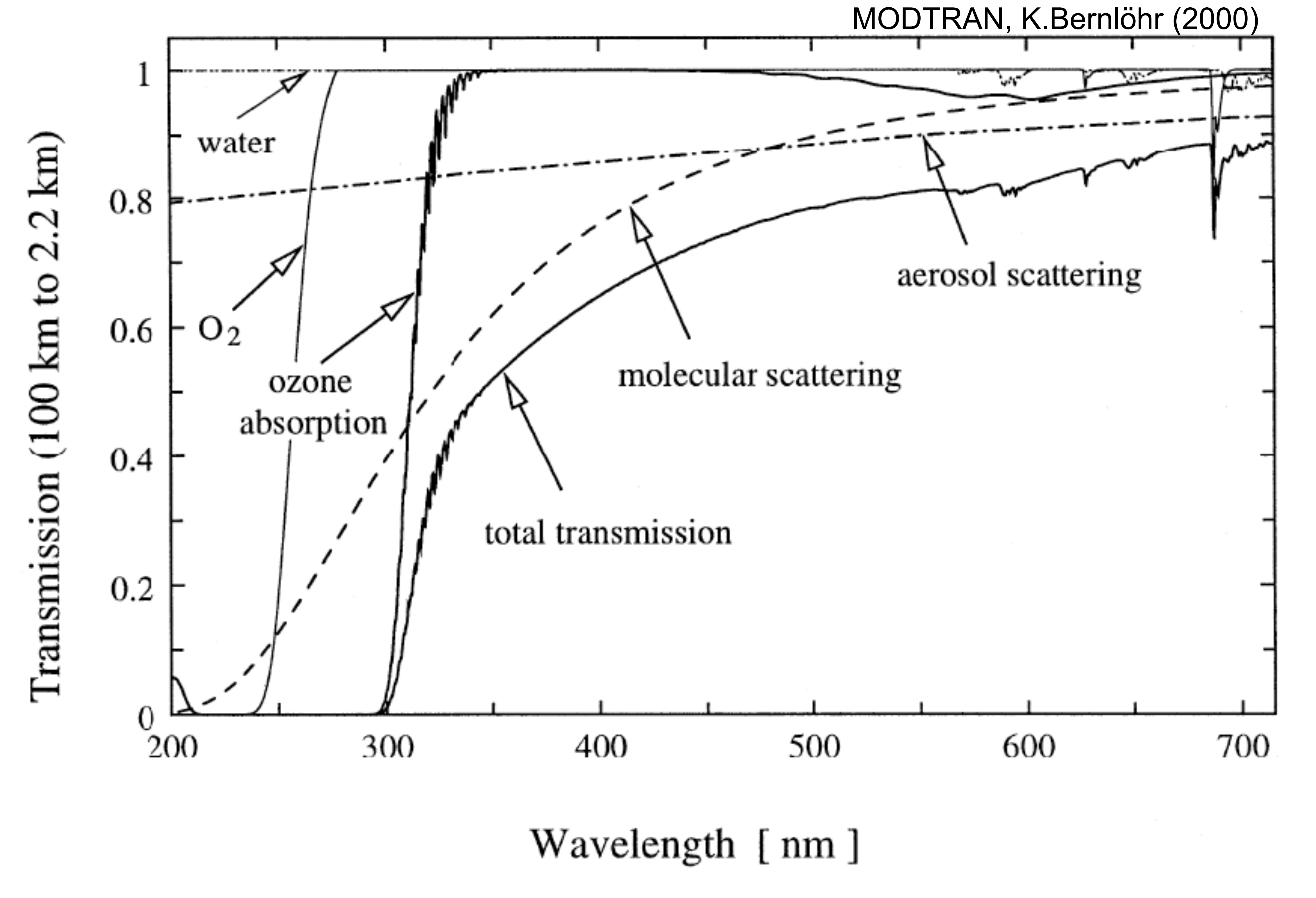
Nanosecond long flash of blue light; few photons / m²

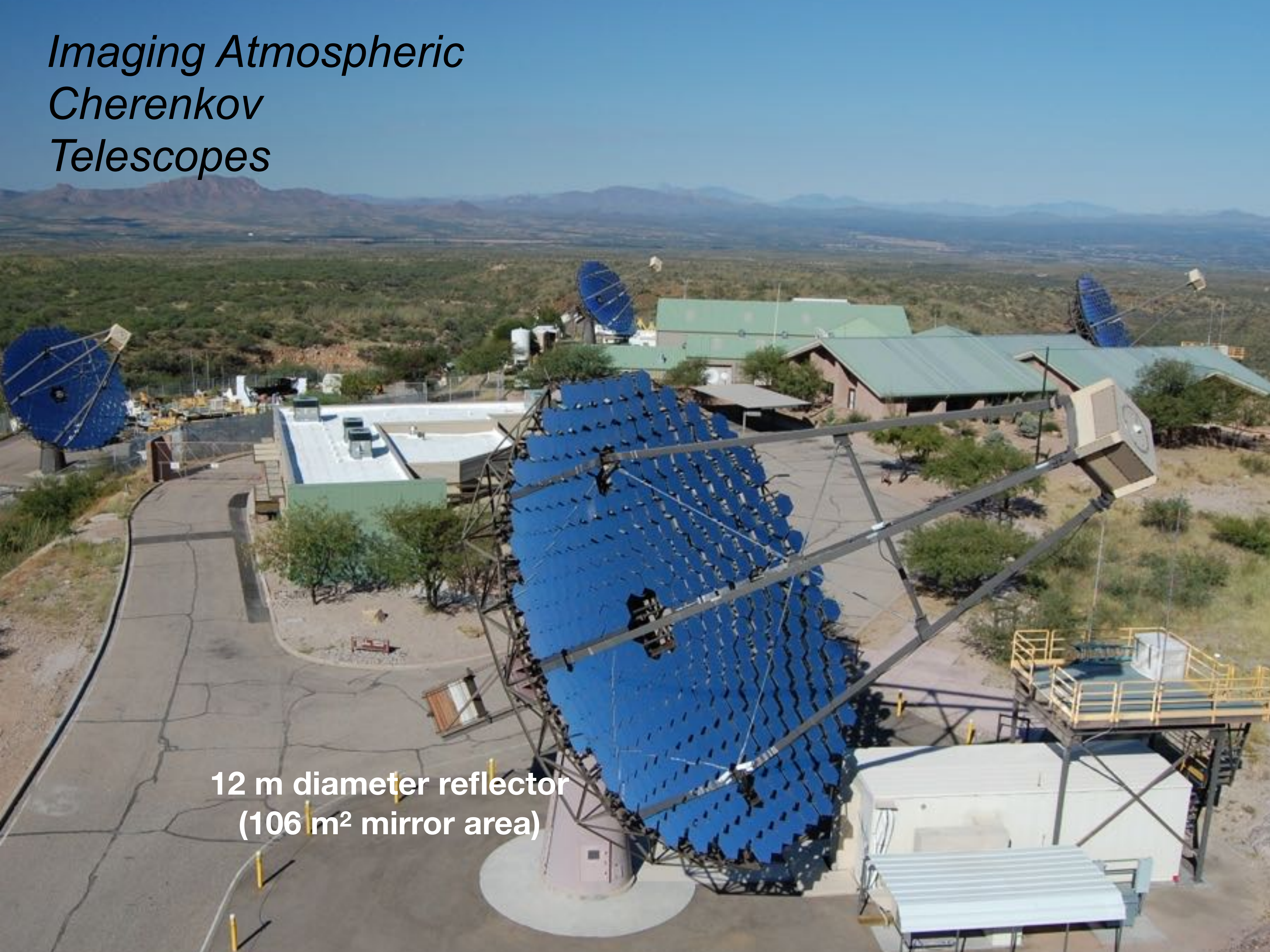
Measuring gamma-rays (20 GeV to 300 TeV)

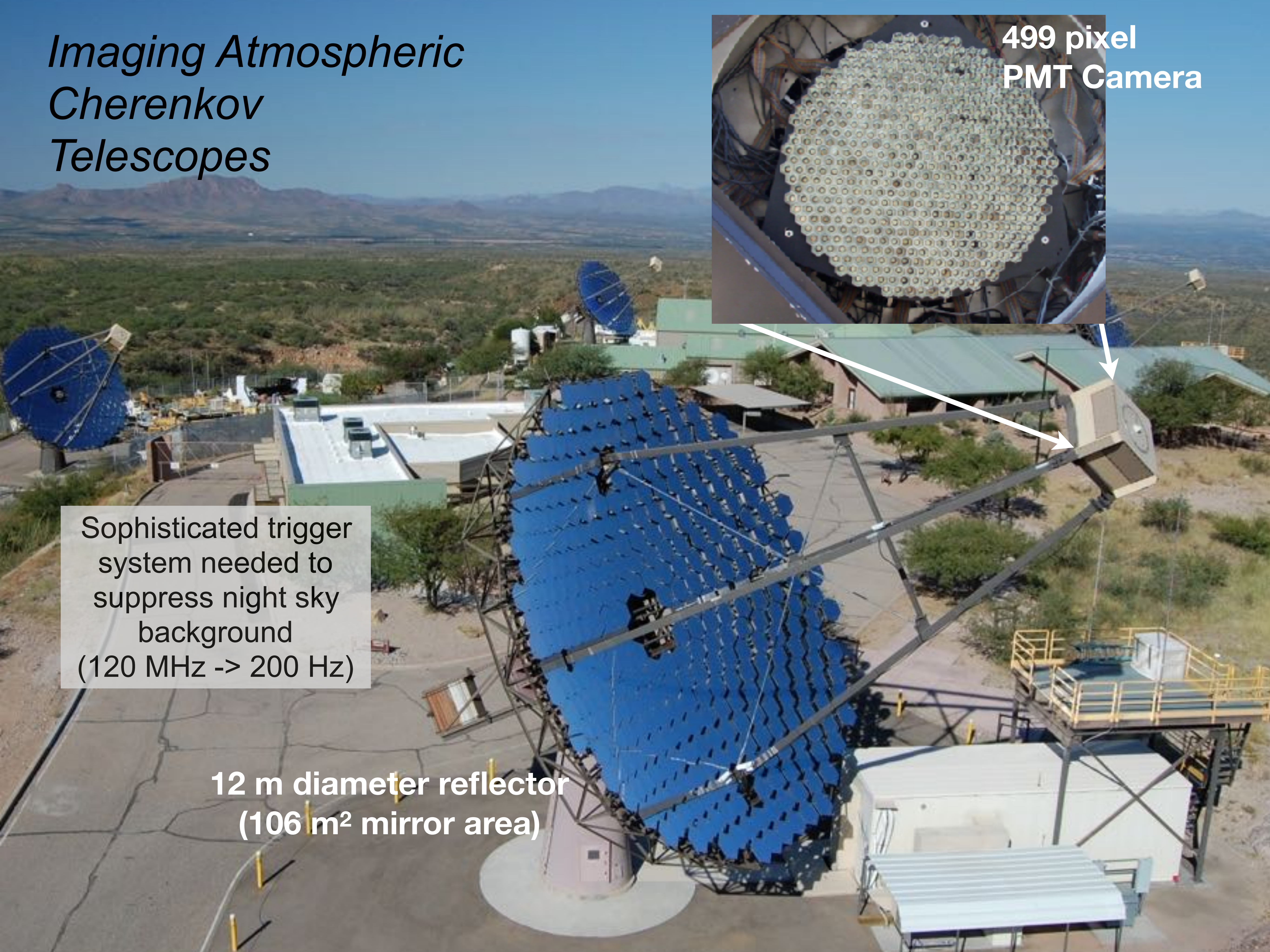


Nanosecond long flash of blue light; few photons / m^2

Atmospheric extinction

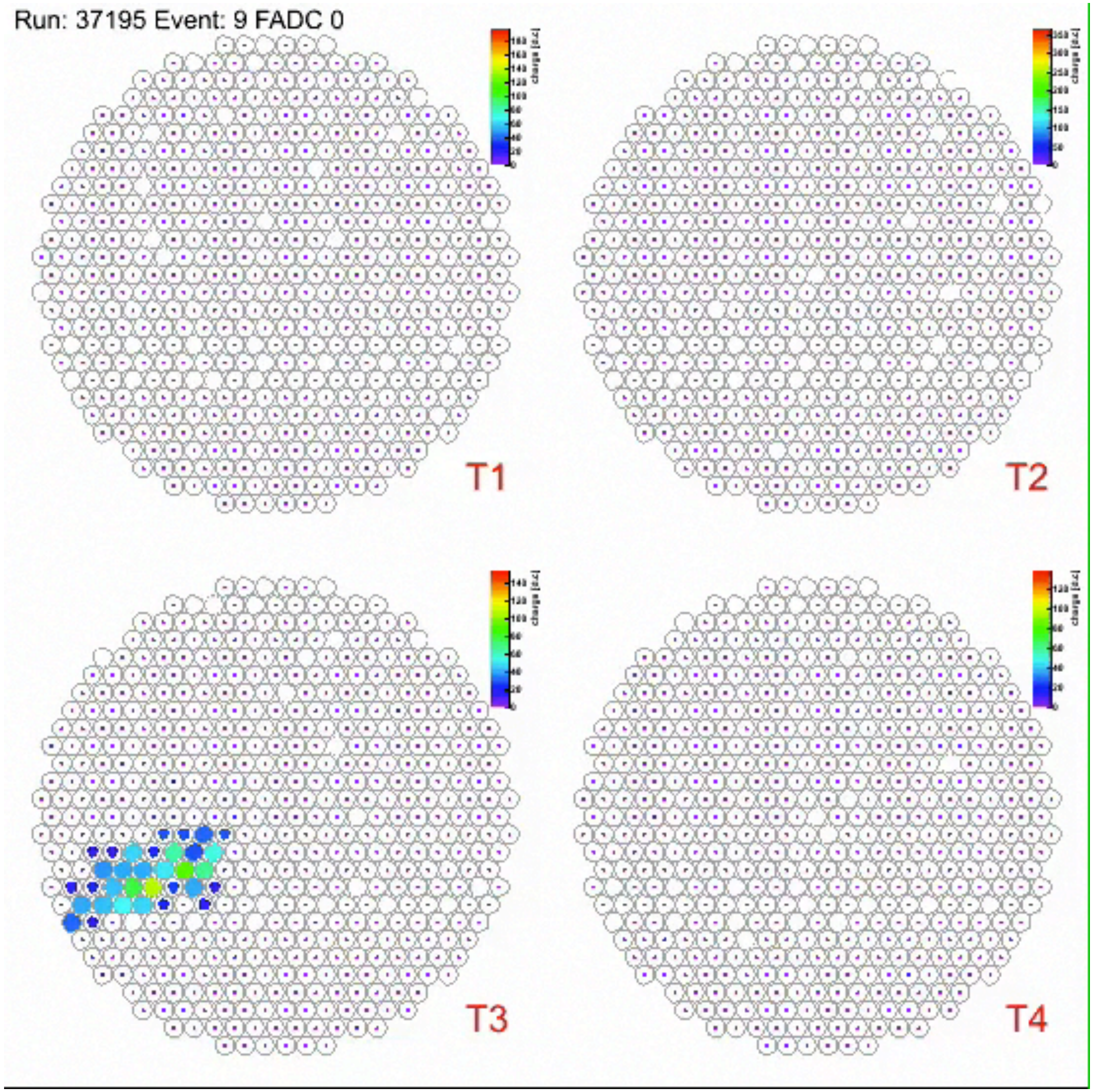



Imaging Atmospheric
Cherenkov
Telescopes
12 m diameter reflector
(106 m² mirror area)


Imaging Atmospheric Cherenkov Telescopes
499 pixel PMT Camera
Sophisticated trigger system needed to suppress night sky background (120 MHz -> 200 Hz)
12 m diameter reflector (106 m² mirror area)

Observations

event display VERITAS

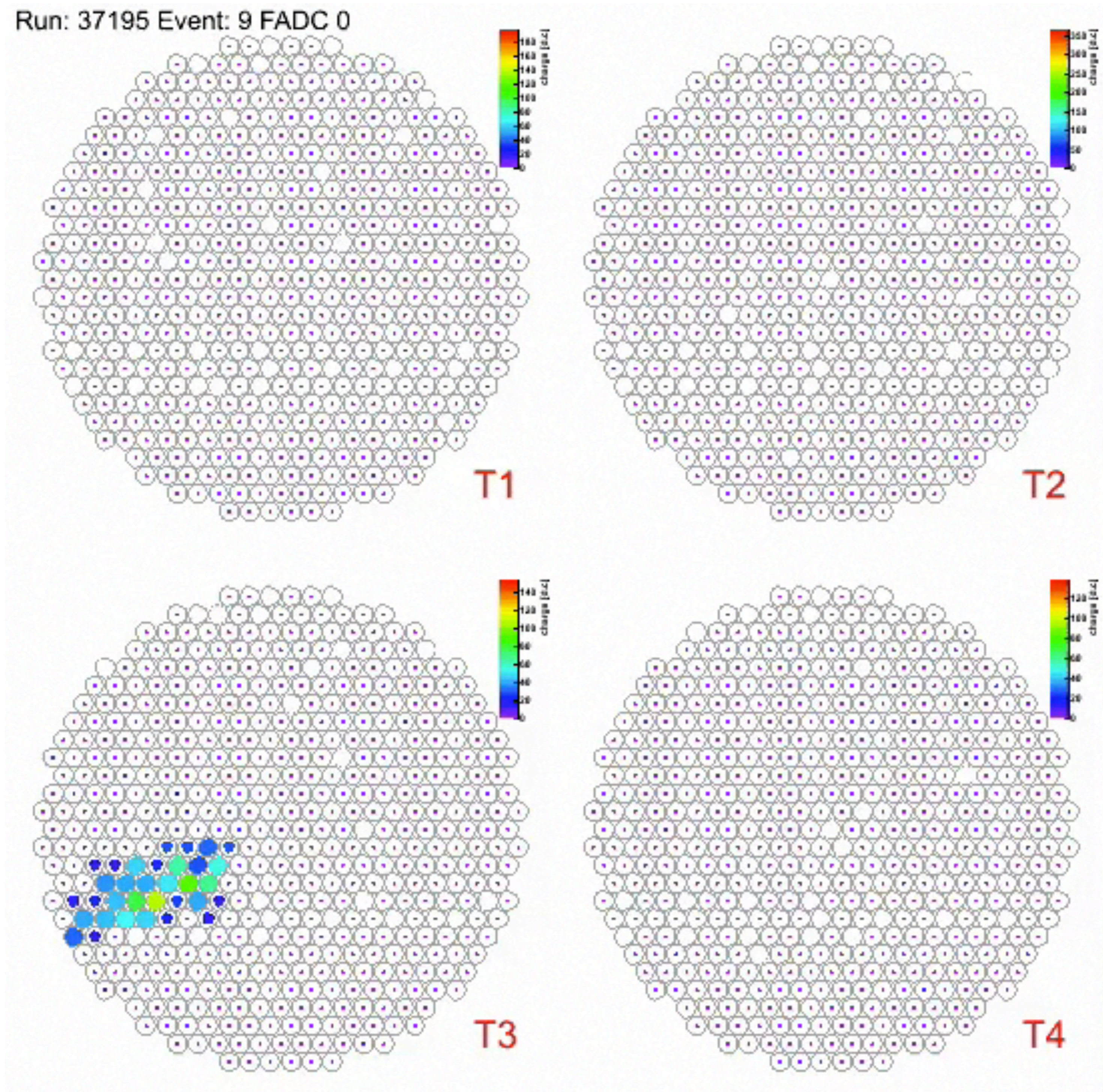


about every 1000th event is a γ-ray

(each frame 2 ns long)

Observations

event display VERITAS



about every 1000th event is a γ-ray

(each frame 2 ns long)

MAGIC

- La Palma; Spain
- two 17m telescopes with 50 GeV threshold

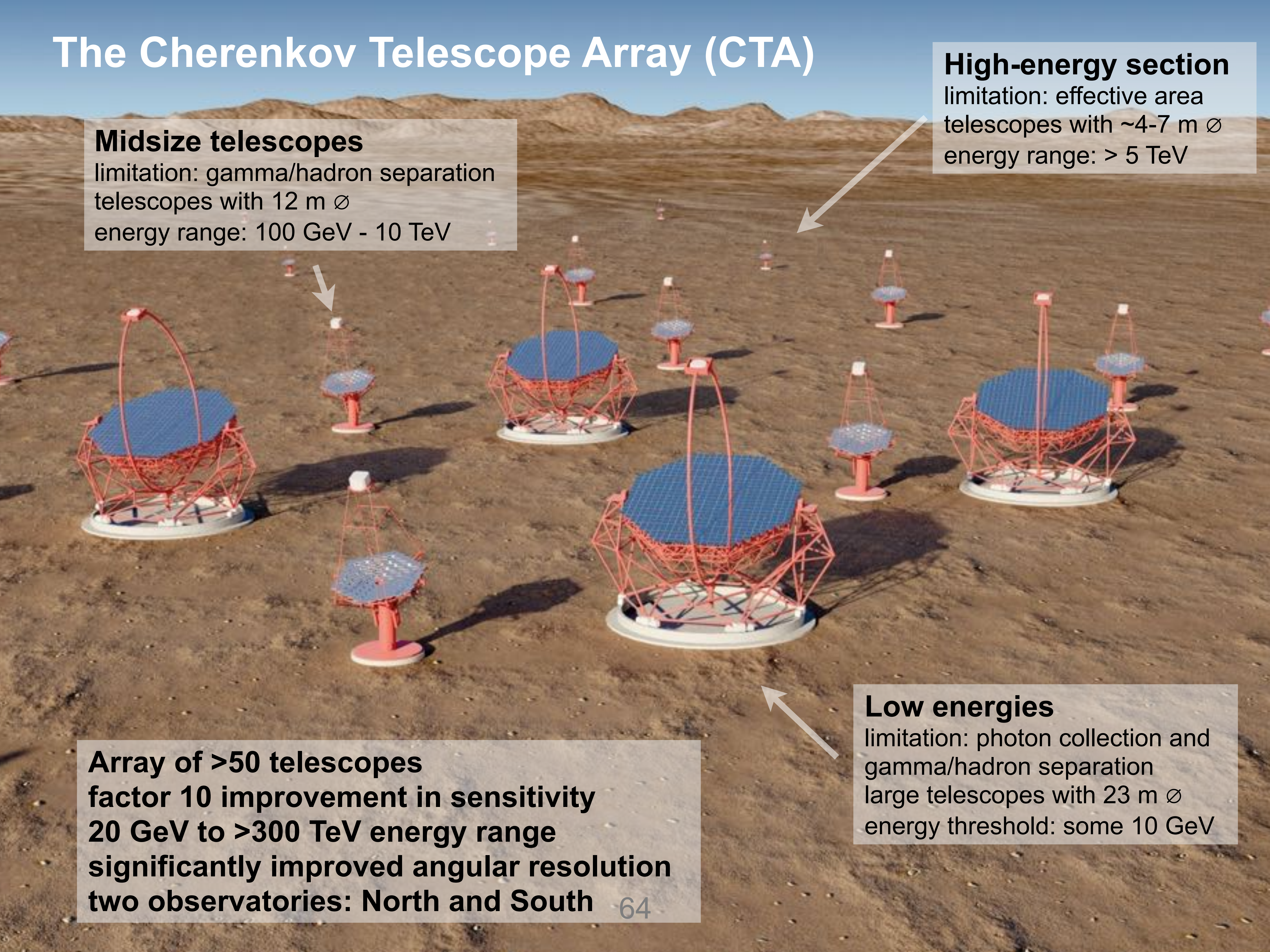
Gernot Maier

HESS

- Namibia
- array of four 12 m telescopes
- addition of a 28 m telescope
  - $614 m^2$ mirror area, 36m focal length

H.E.S.S. collaboration

The Cherenkov Telescope Array (CTA)



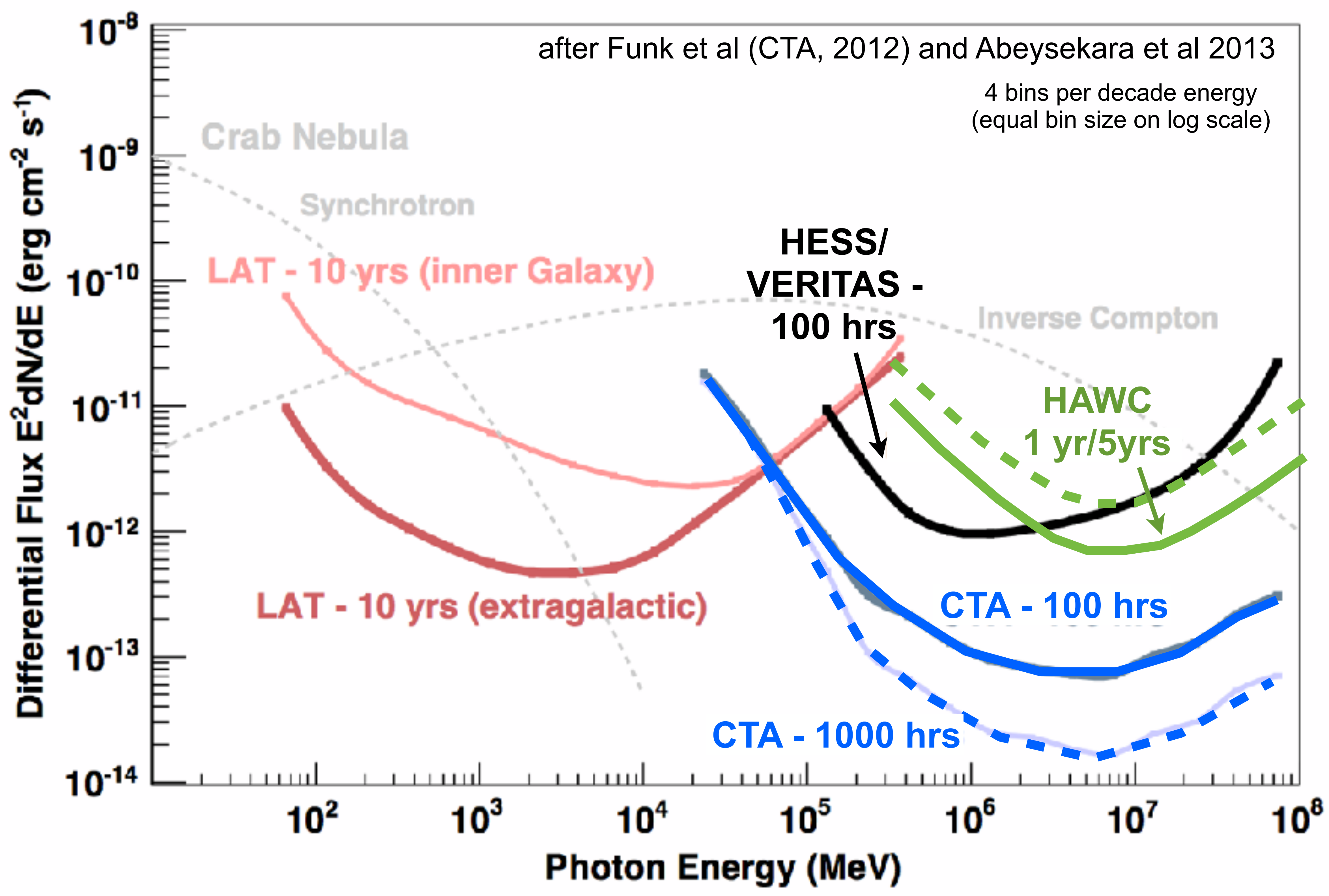
Midsize telescopes
limitation: gamma/hadron separation
telescopes with 12 m ⌀
energy range: 100 GeV - 10 TeV

High-energy section
limitation: effective area
telescopes with ~4-7 m ⌀
energy range: > 5 TeV

Low energies
limitation: photon collection and gamma/hadron separation
large telescopes with 23 m ⌀
energy threshold: some 10 GeV

Array of >50 telescopes
factor 10 improvement in sensitivity
20 GeV to >300 TeV energy range
significantly improved angular resolution
two observatories: North and South

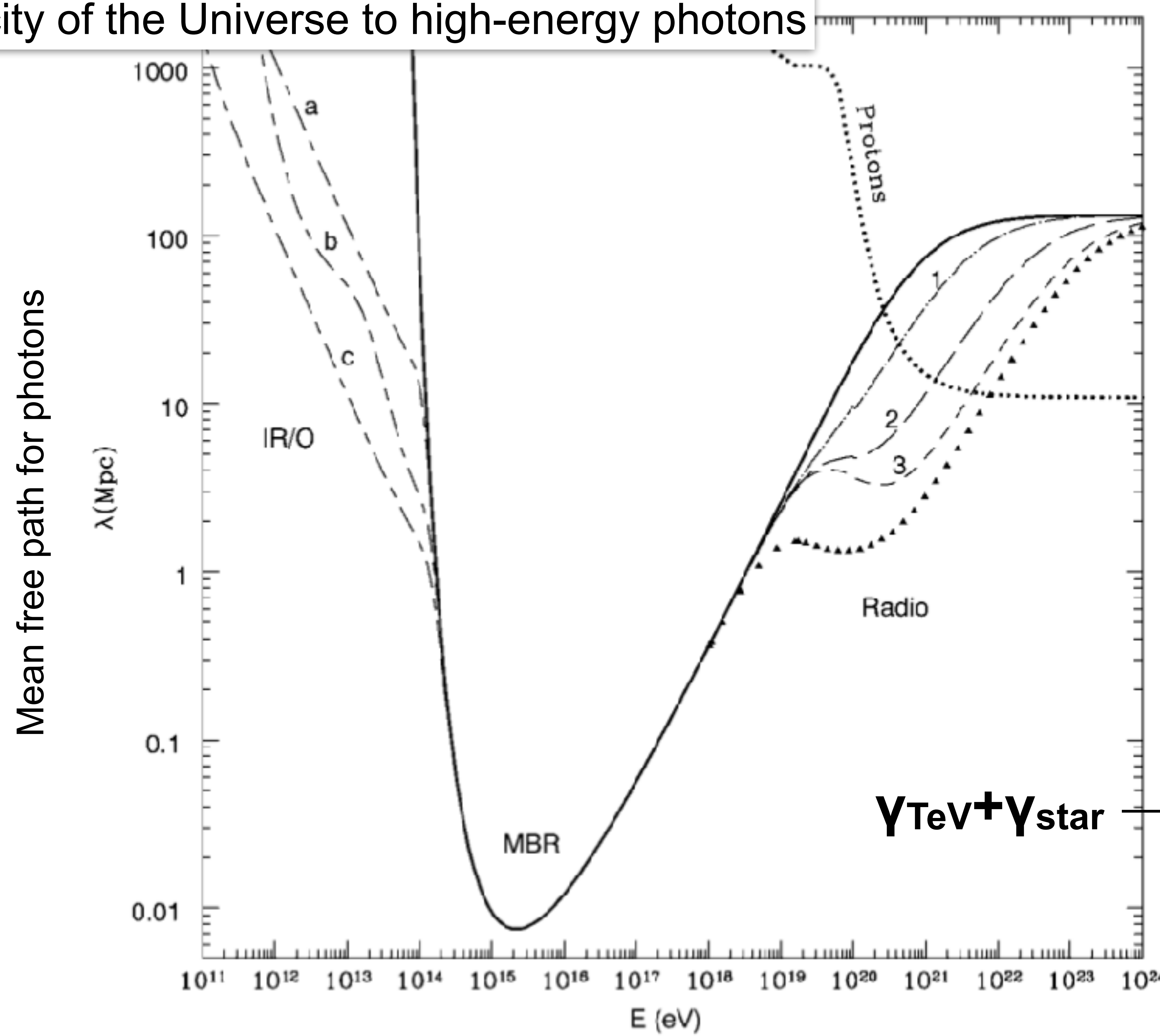
Differential Flux Sensitivity



HAWC: 24/7 duty cycle; IACTS: 1200 hrs/year

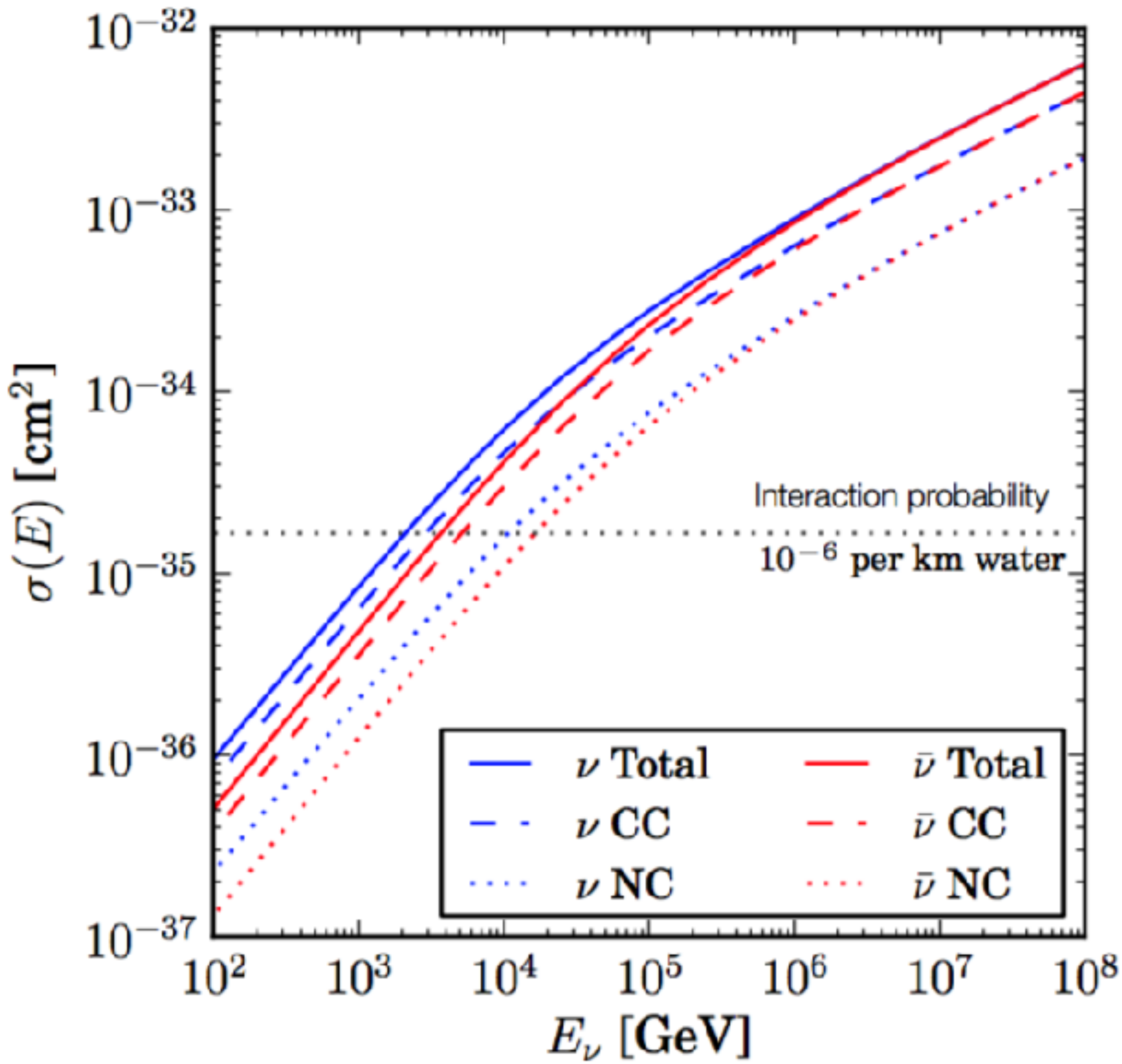
Neutrino detection

Opacity of the Universe to high-energy photons



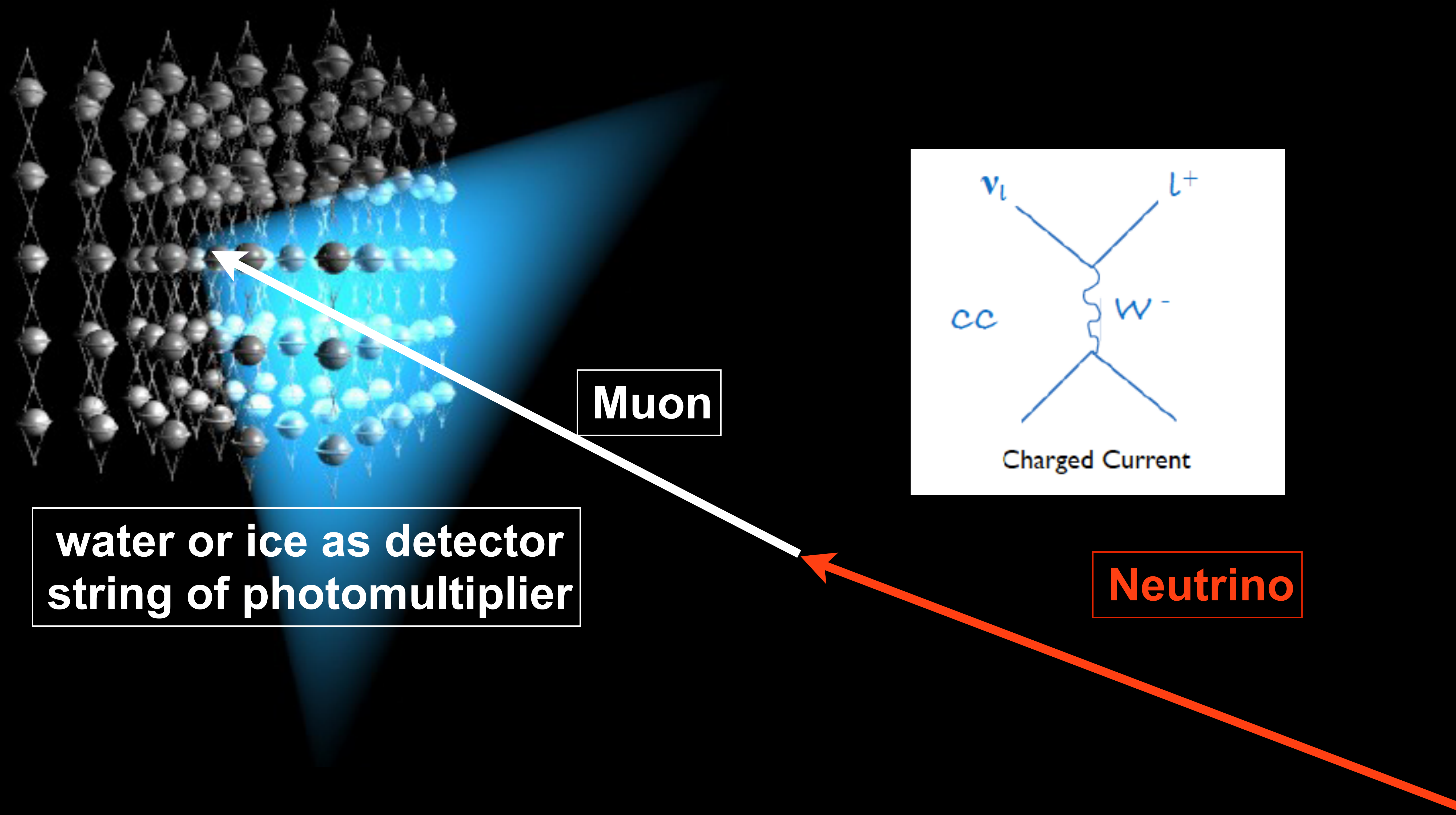
$\gamma_{TeV} + \gamma_{star} \rightarrow e^+e^-$

Neutrino detection

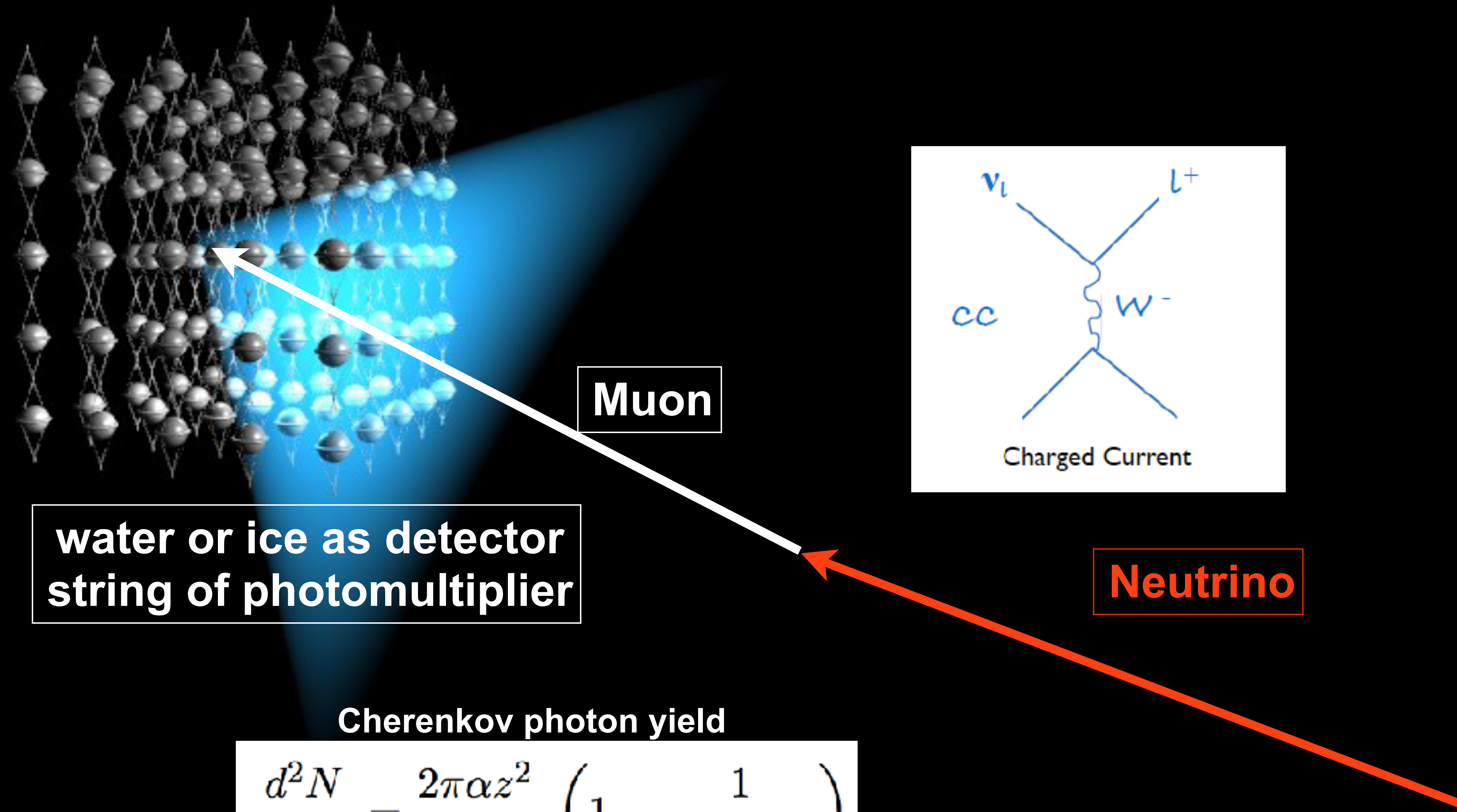


astrophysical flux:
O(10^5) per km^2 per year
above 100 TeV

High-energy neutrino detection



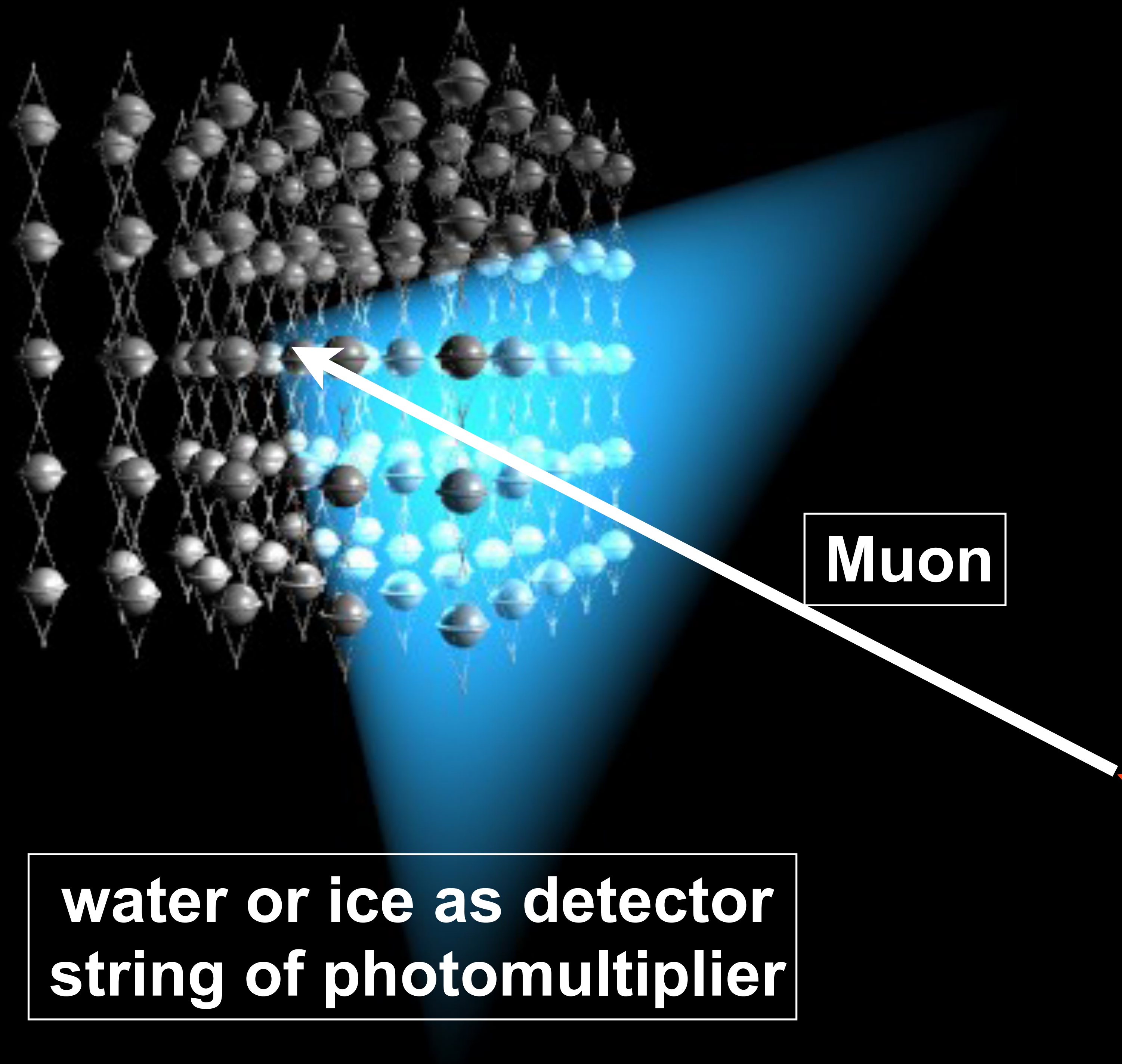
High-energy neutrino detection

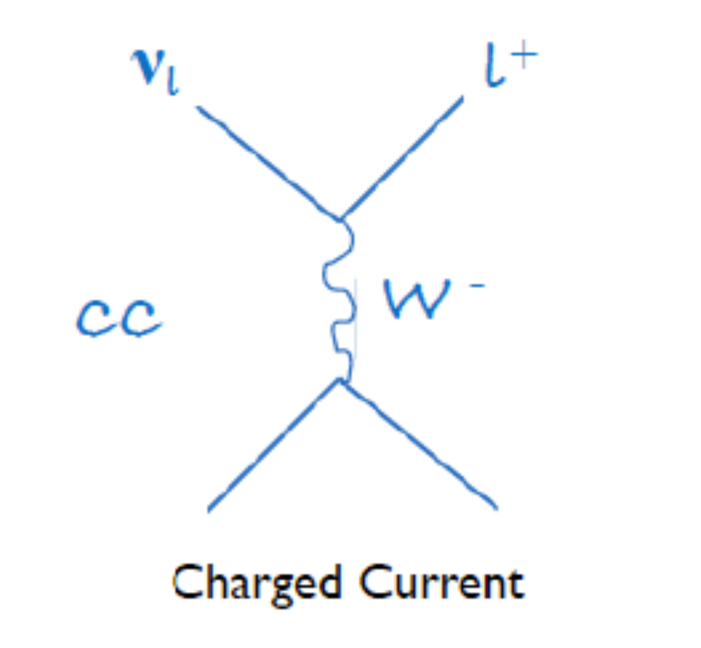


Cherenkov photon yield

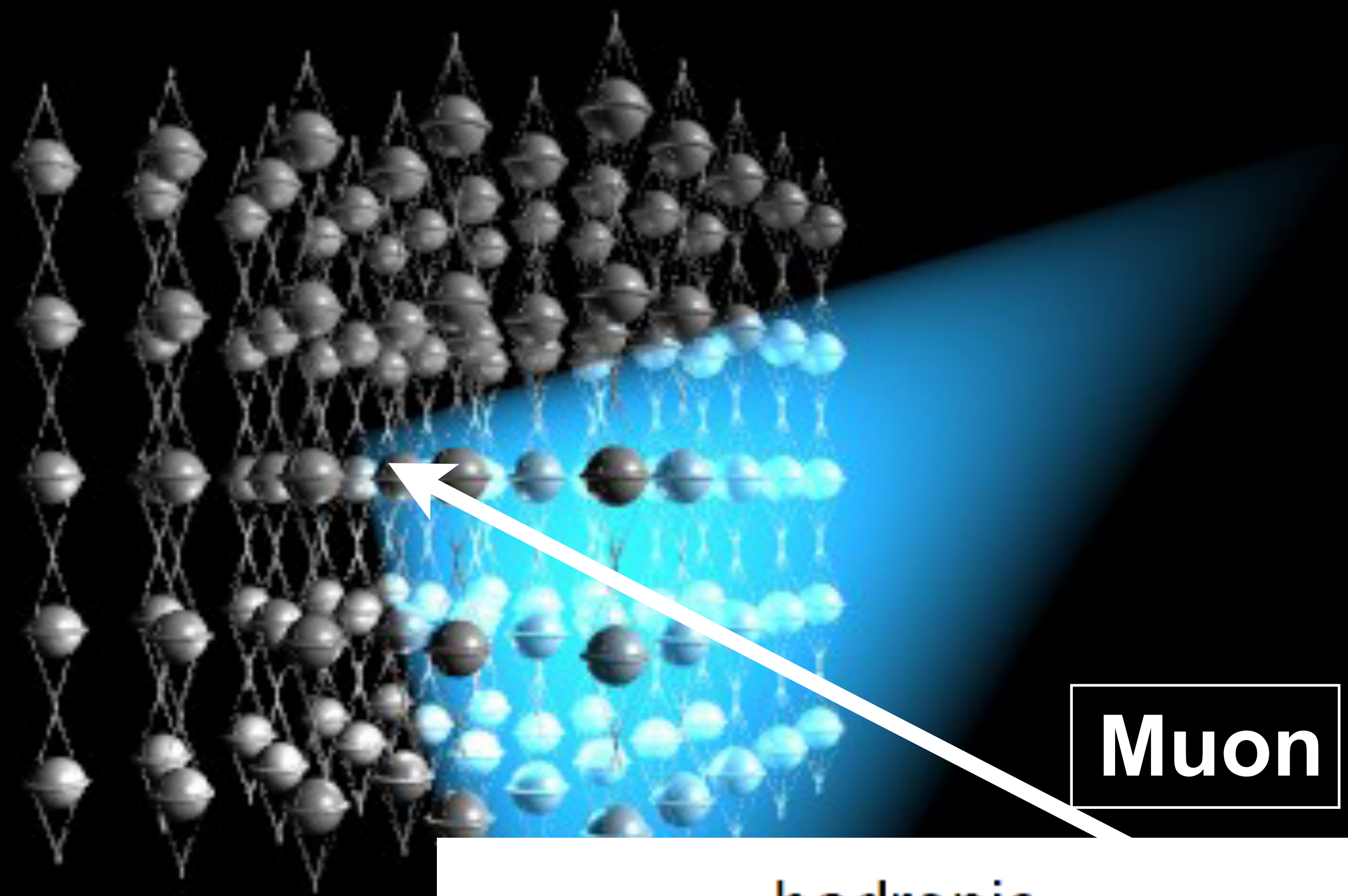
$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

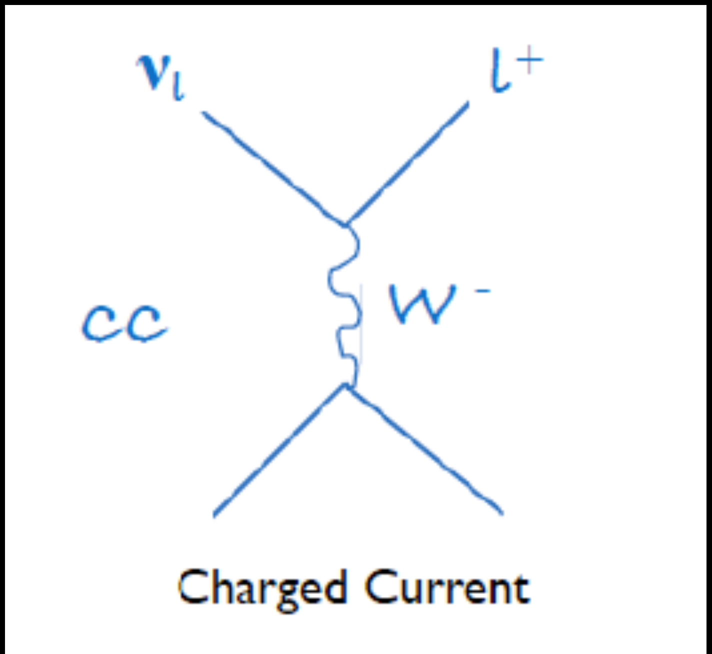
High-energy neutrino detection



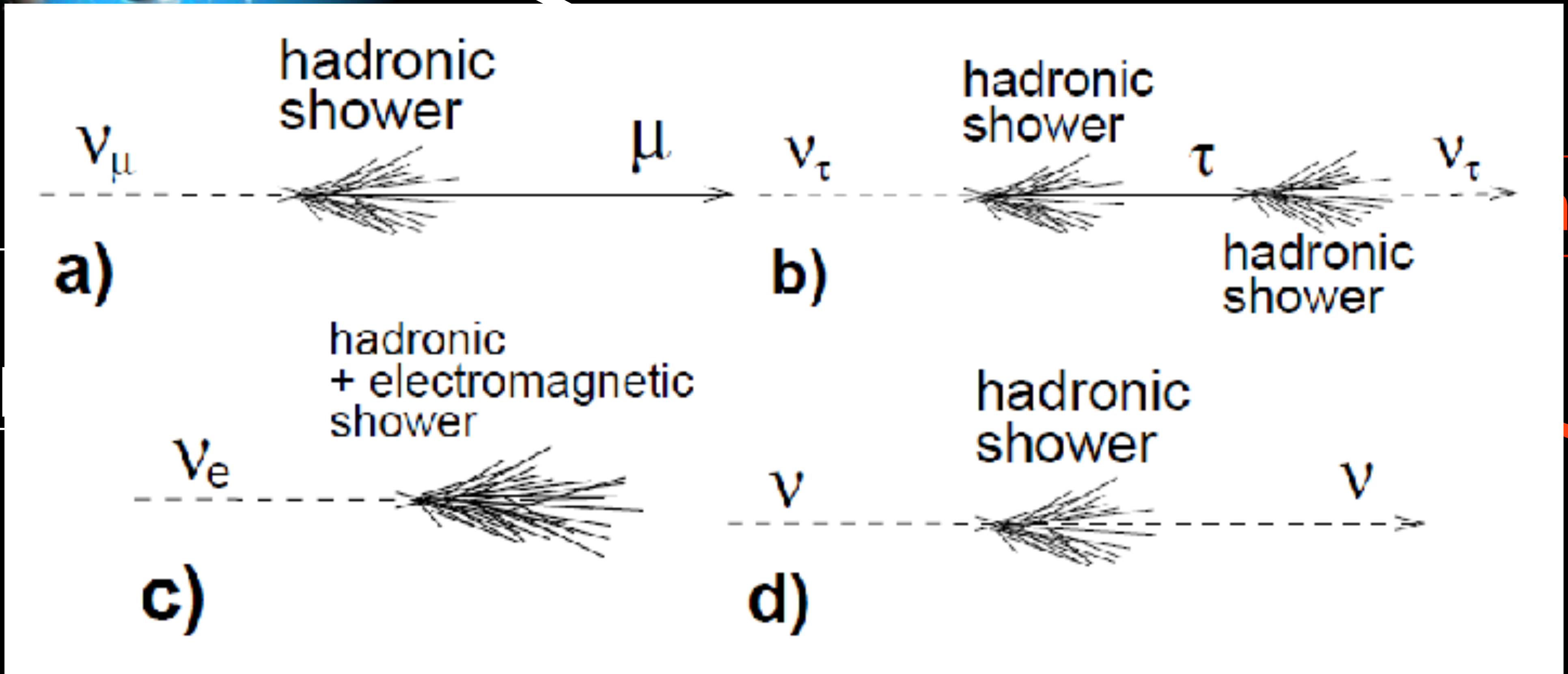


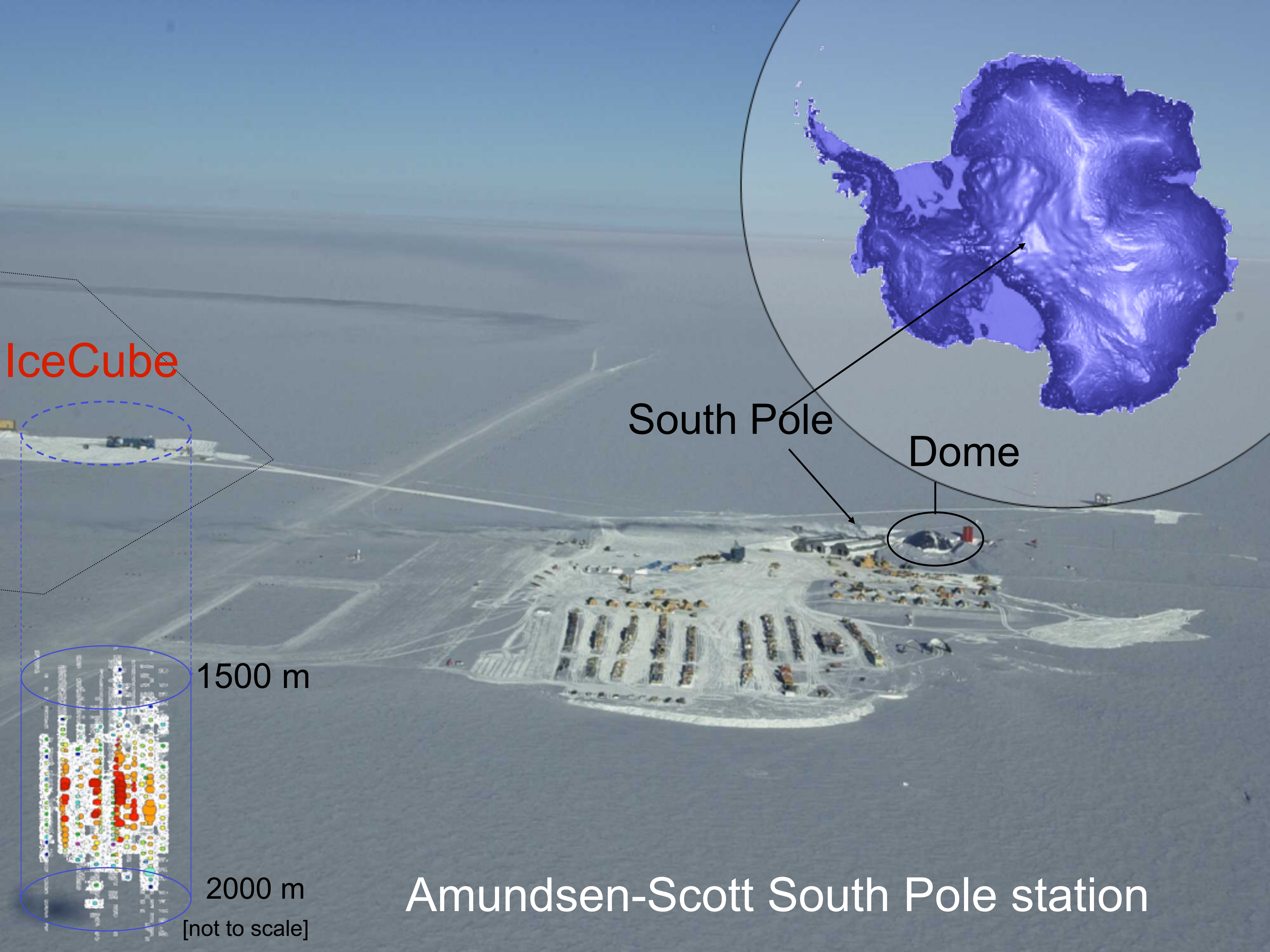
High-energy neutrino detection



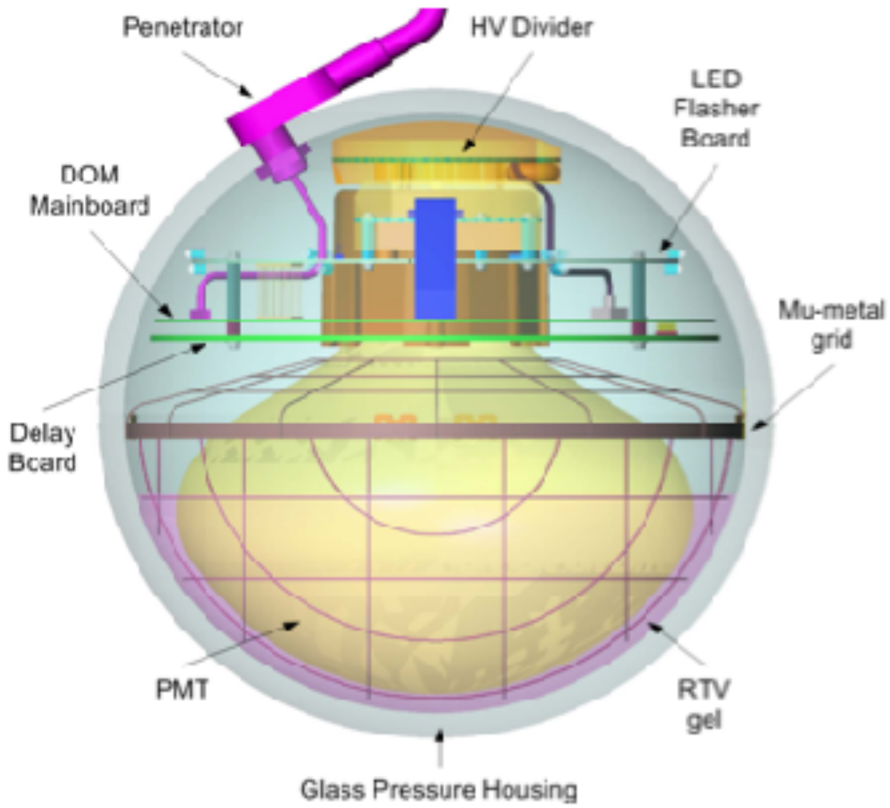


water or
string of

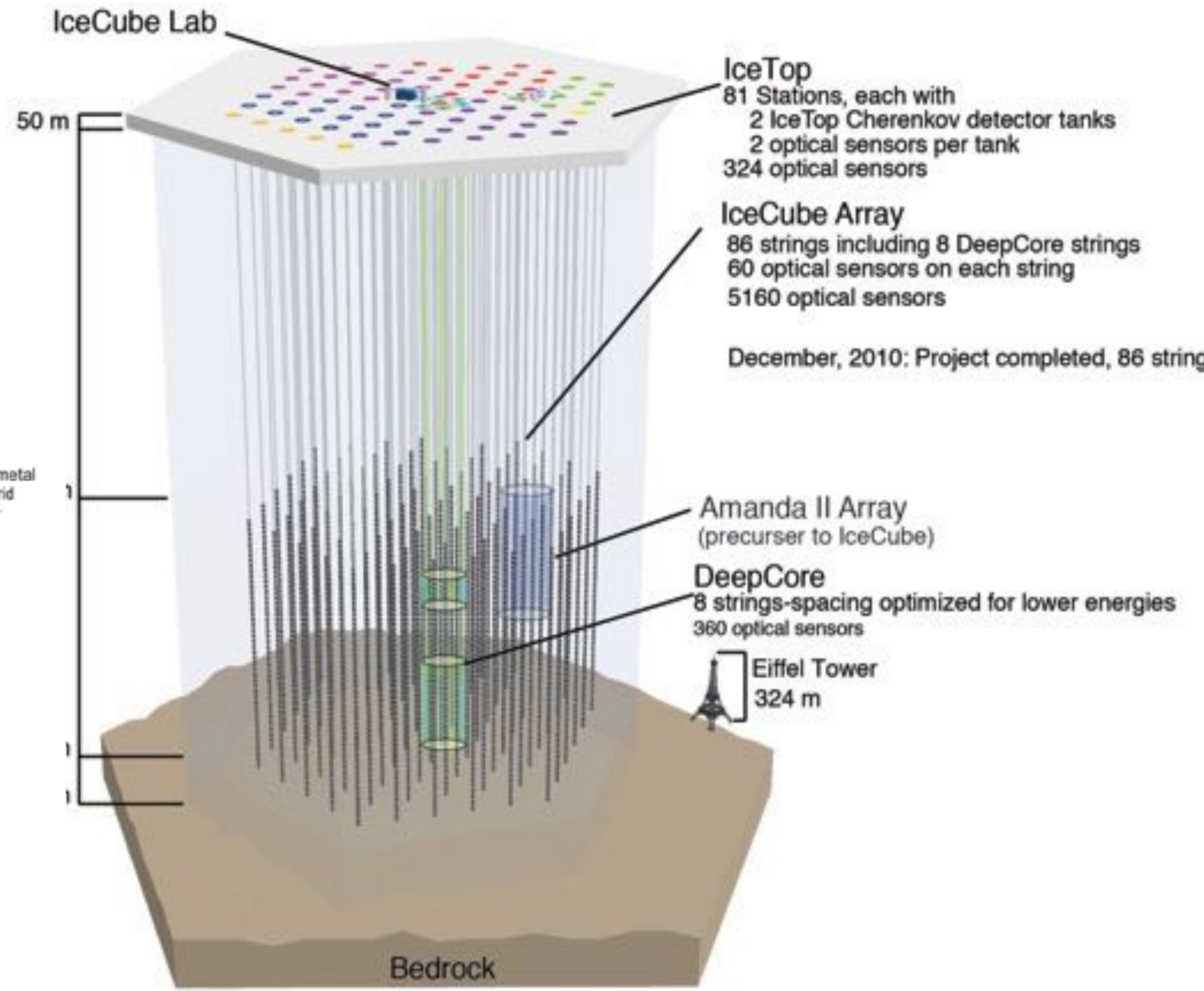



IceCube
South Pole
Dome
1500 m
2000 m
[not to scale]
Amundsen-Scott South Pole station

IceCube



light collection by DOMs




F.Halzen
5 megawatt power plant

Drilling and deployment

F.Halzen

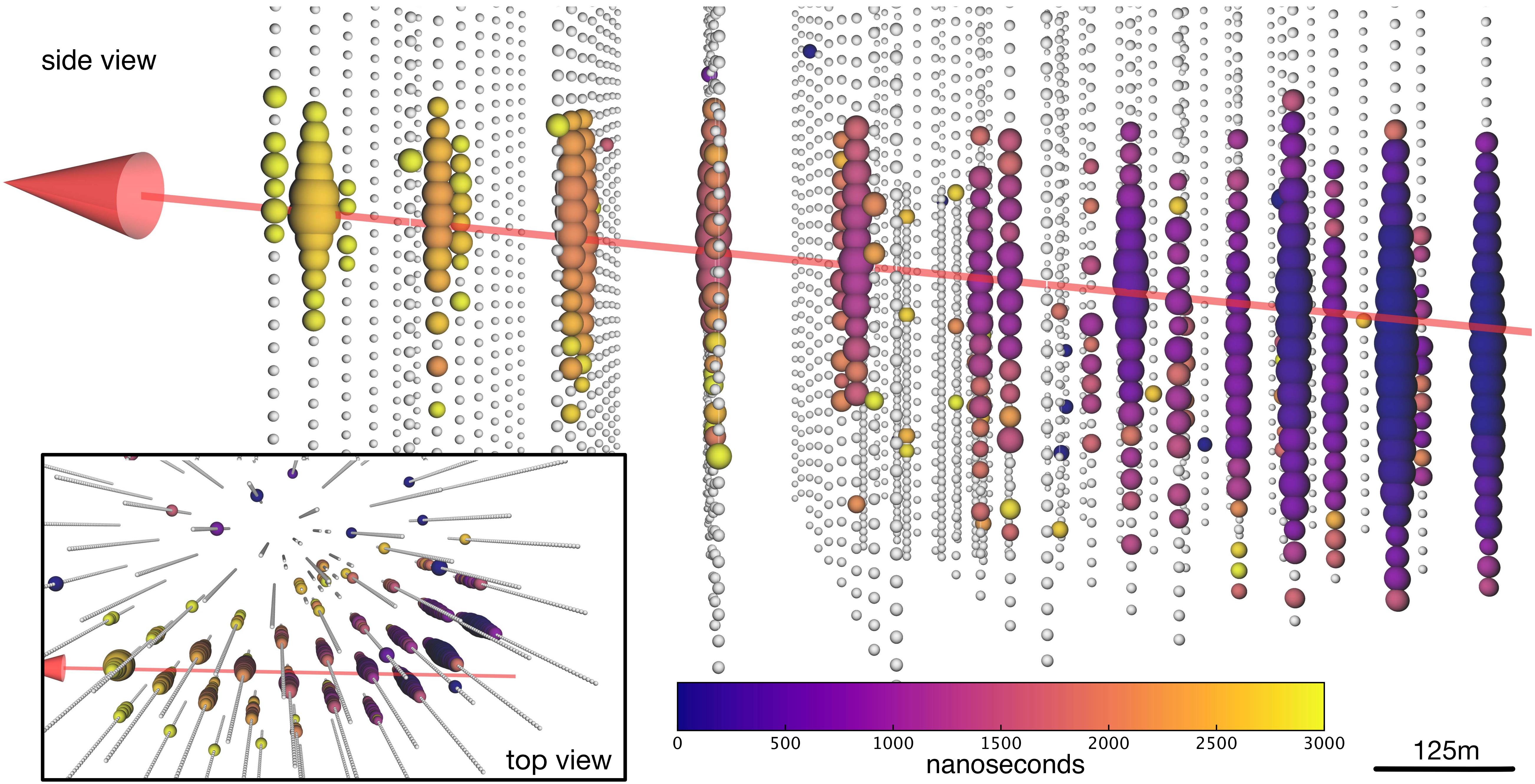
Drilling and deployment

F.Halzen

ergy, allowing
easily identi-
-neutrino as-

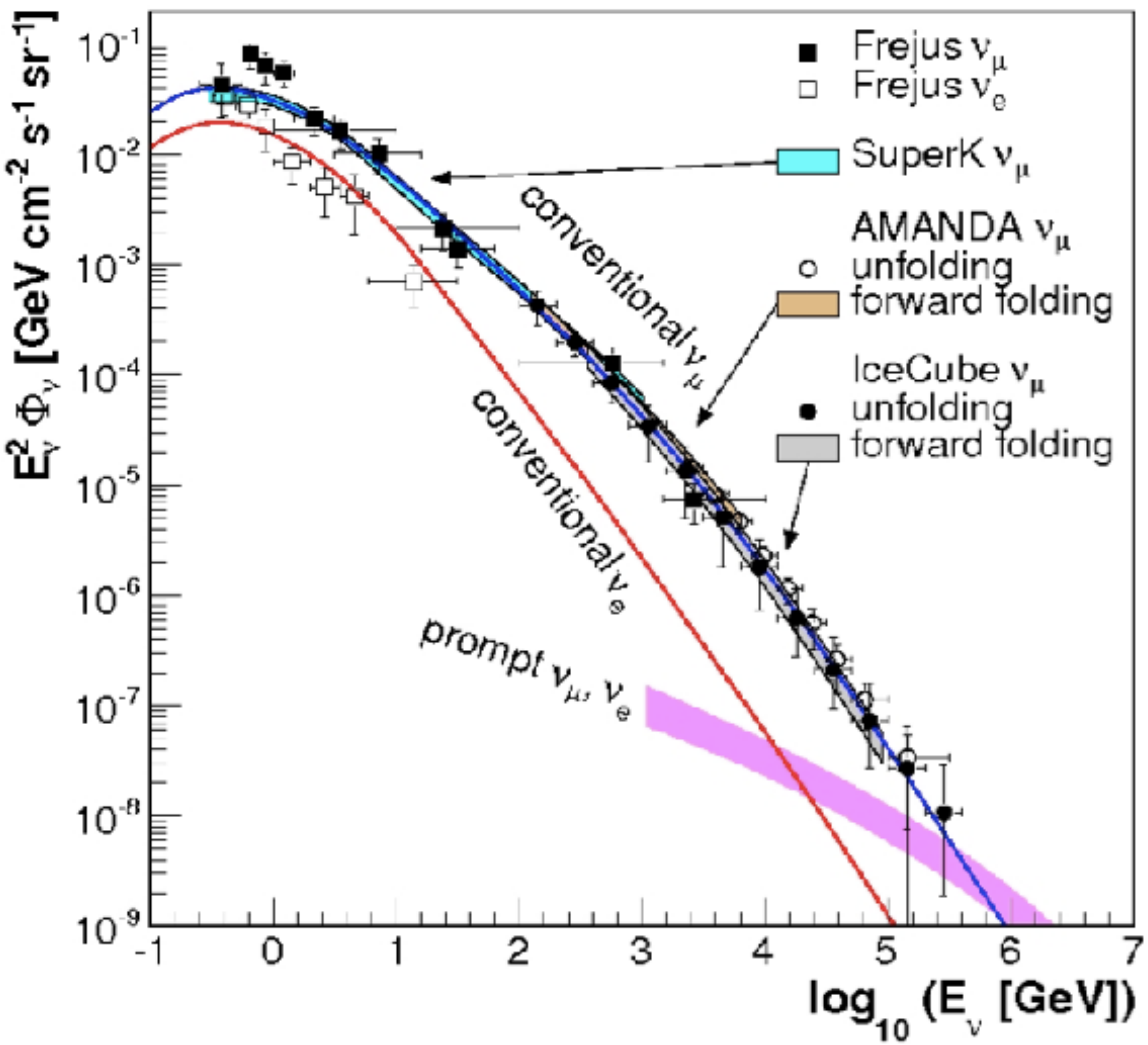
IceCube can robustly identify astrophysical neu-
trinos at PeV energies, for individual neutrinos
at several hundred TeV, an atmospheric origin

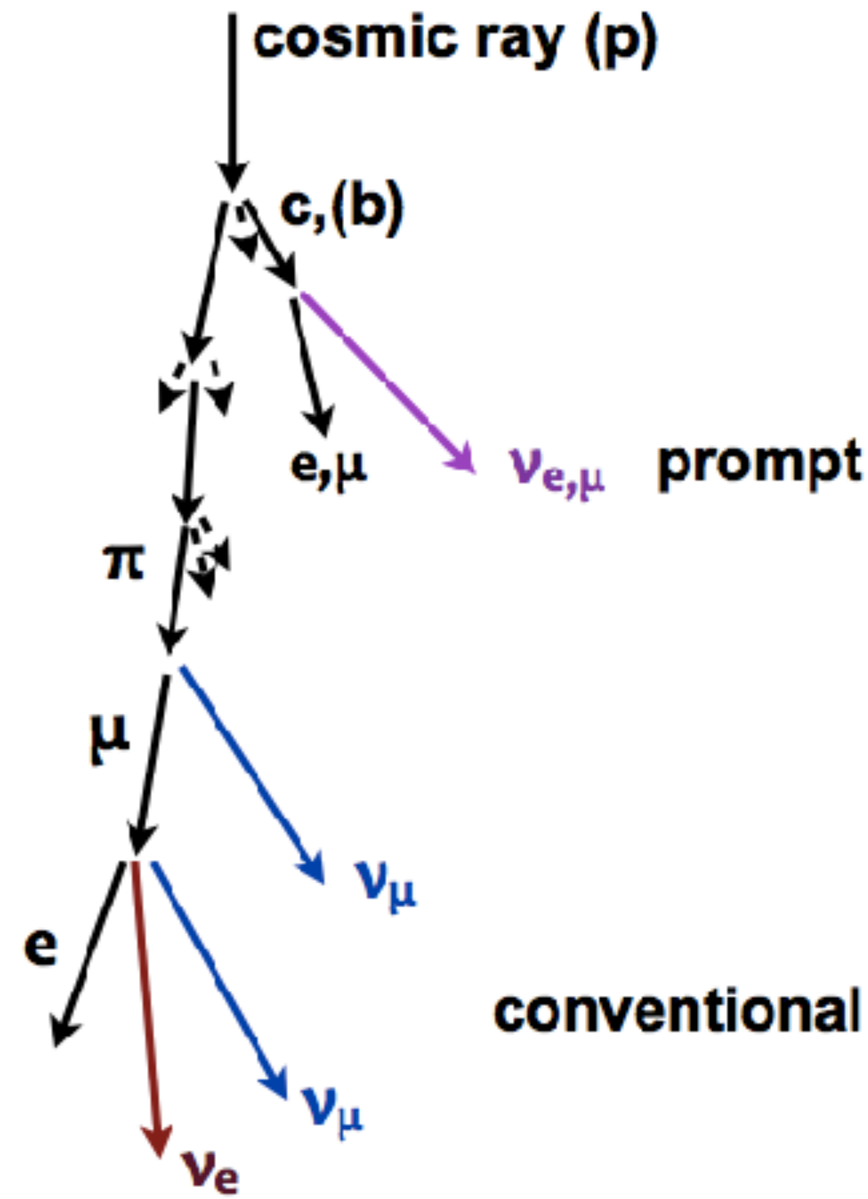
of neutrinos was found from the direction of TXS
0506+056 near the time of the alert, there are
indications at the 3σ level of high-energy neutrino



ectrons. Inset is an overhead perspective view of the event. The best-fitting track direction is shown as an arrow,
$^{+0.50}_{-0.30}$ degrees below the horizon.

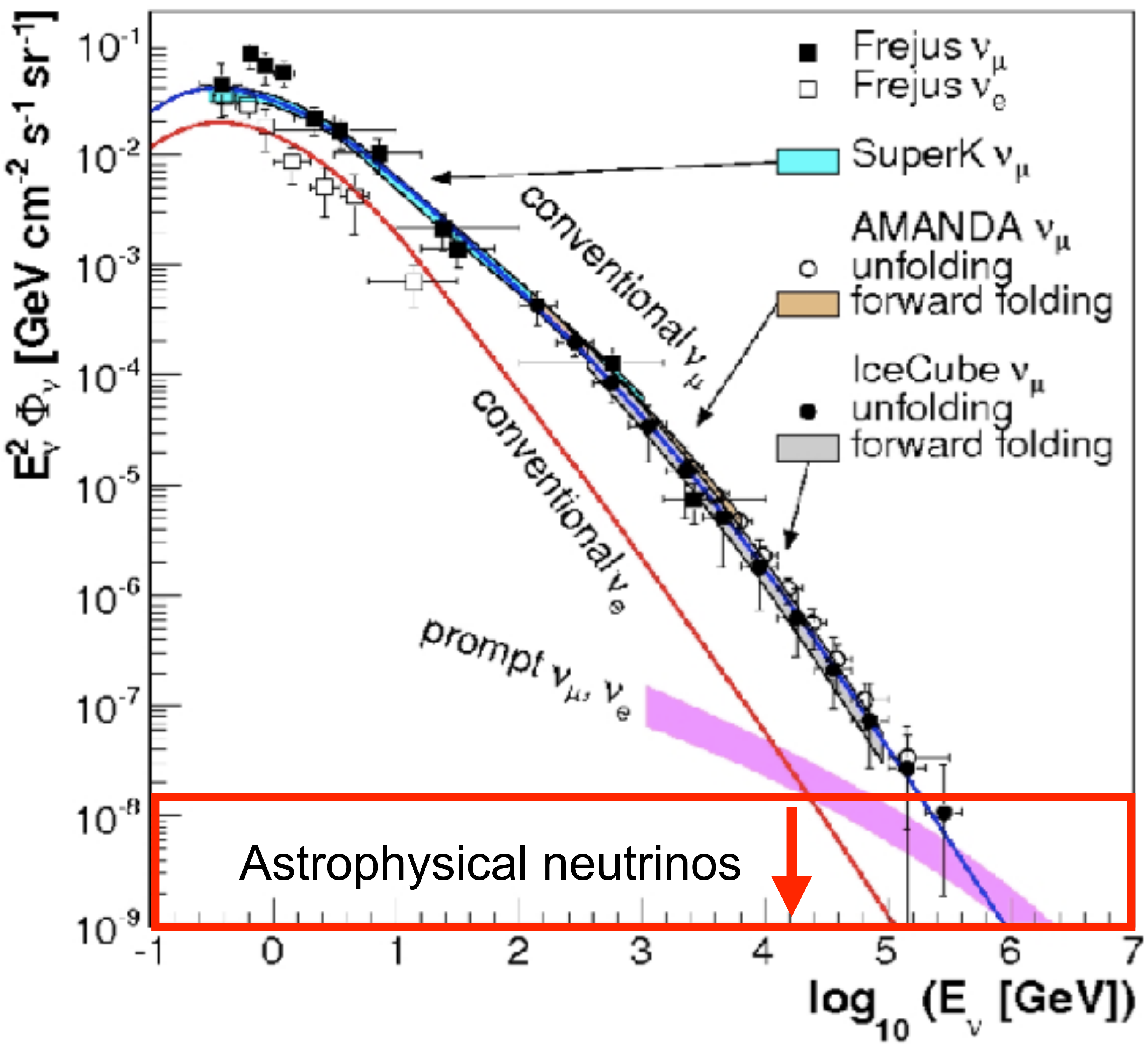
Background for neutrino measurements

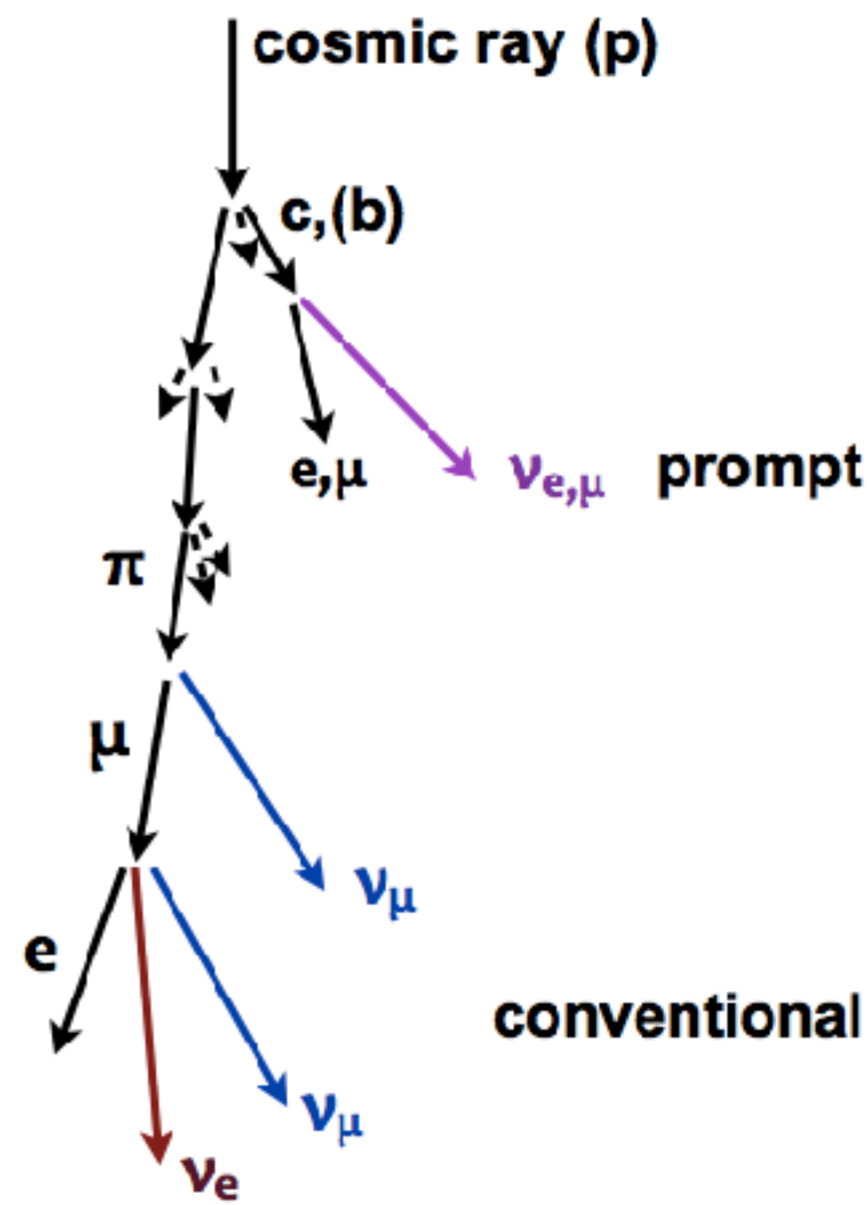




+ direct muons

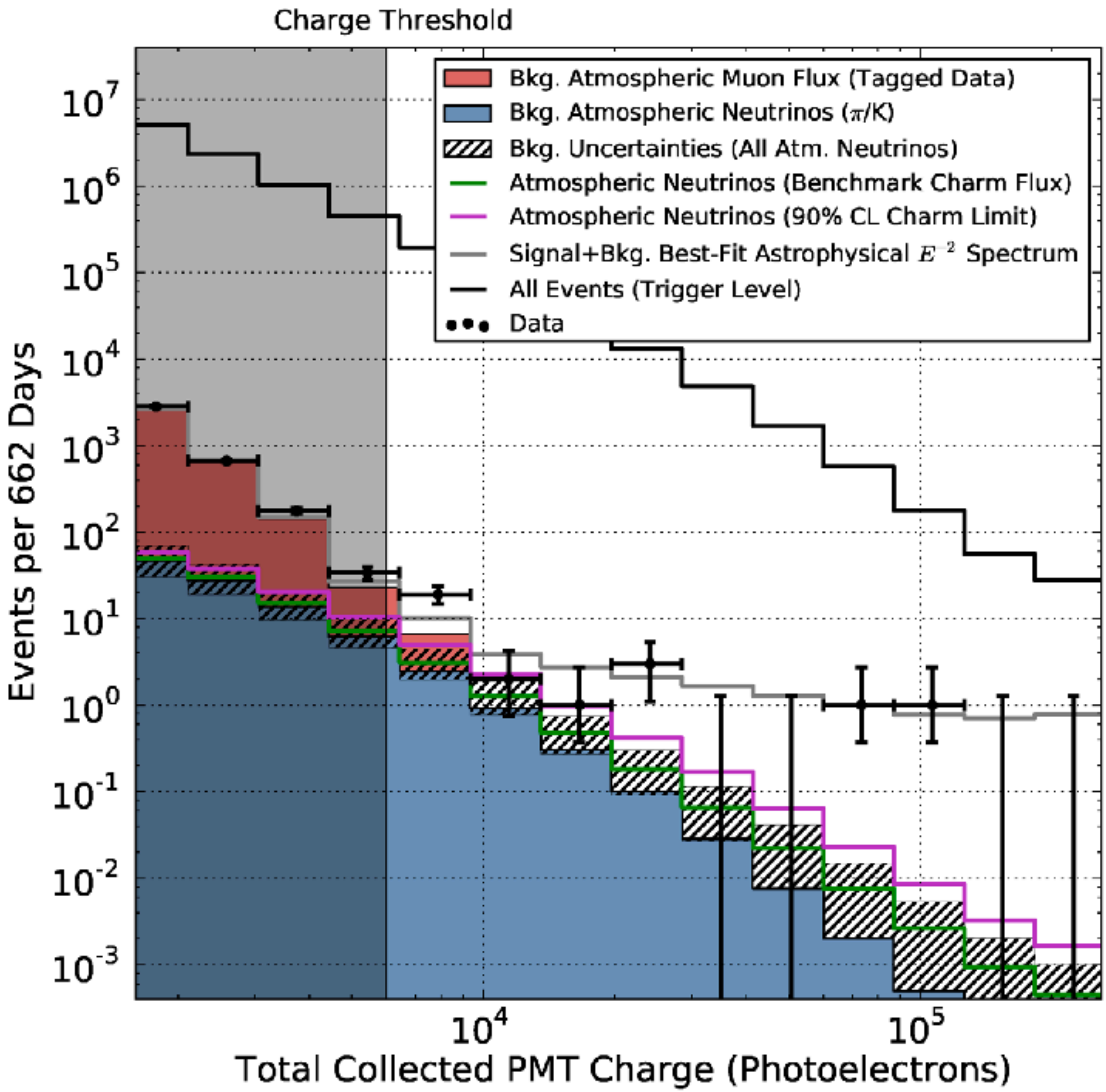
Background for neutrino measurements





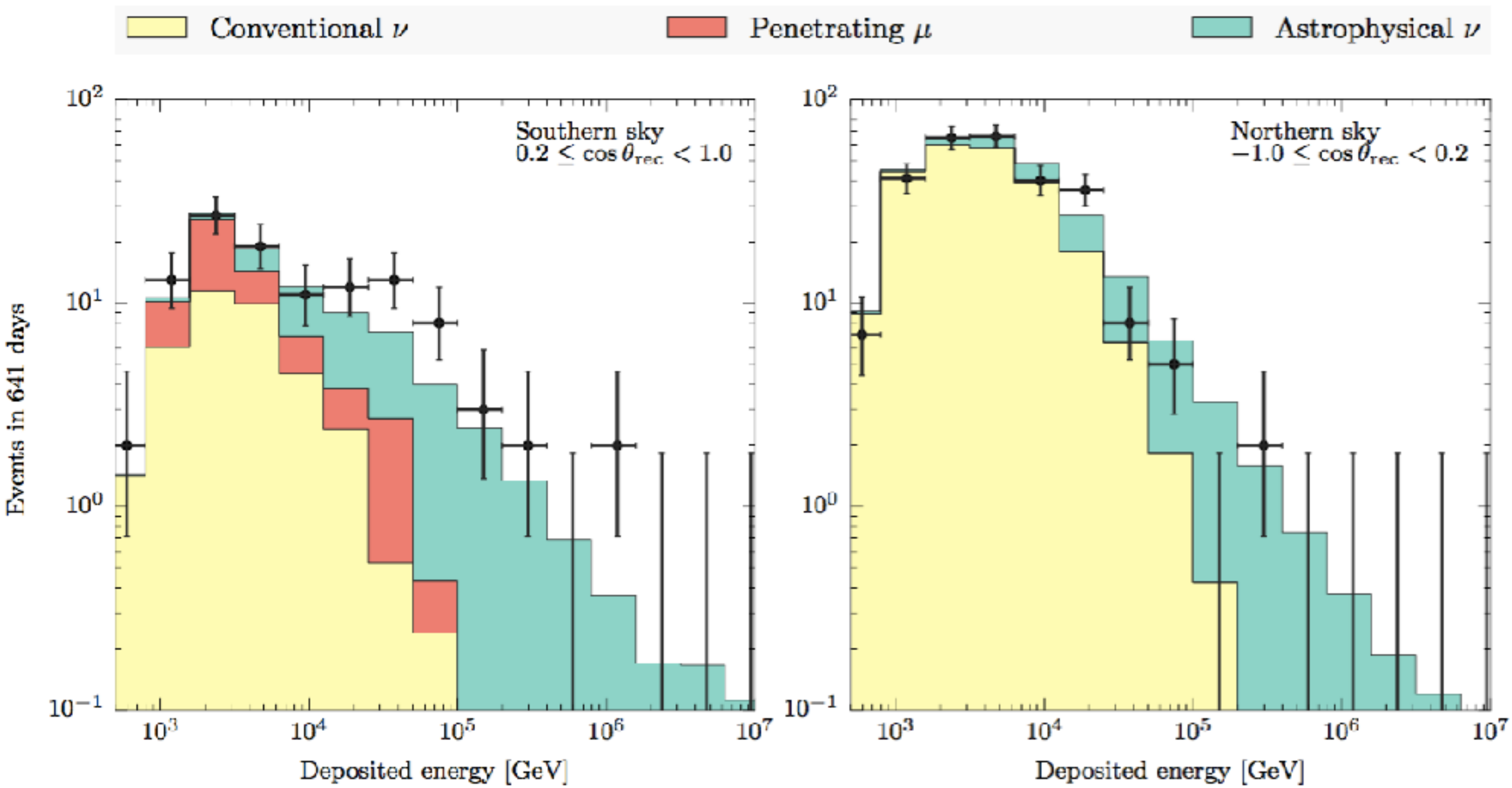
+ direct muons

Gernot Maier



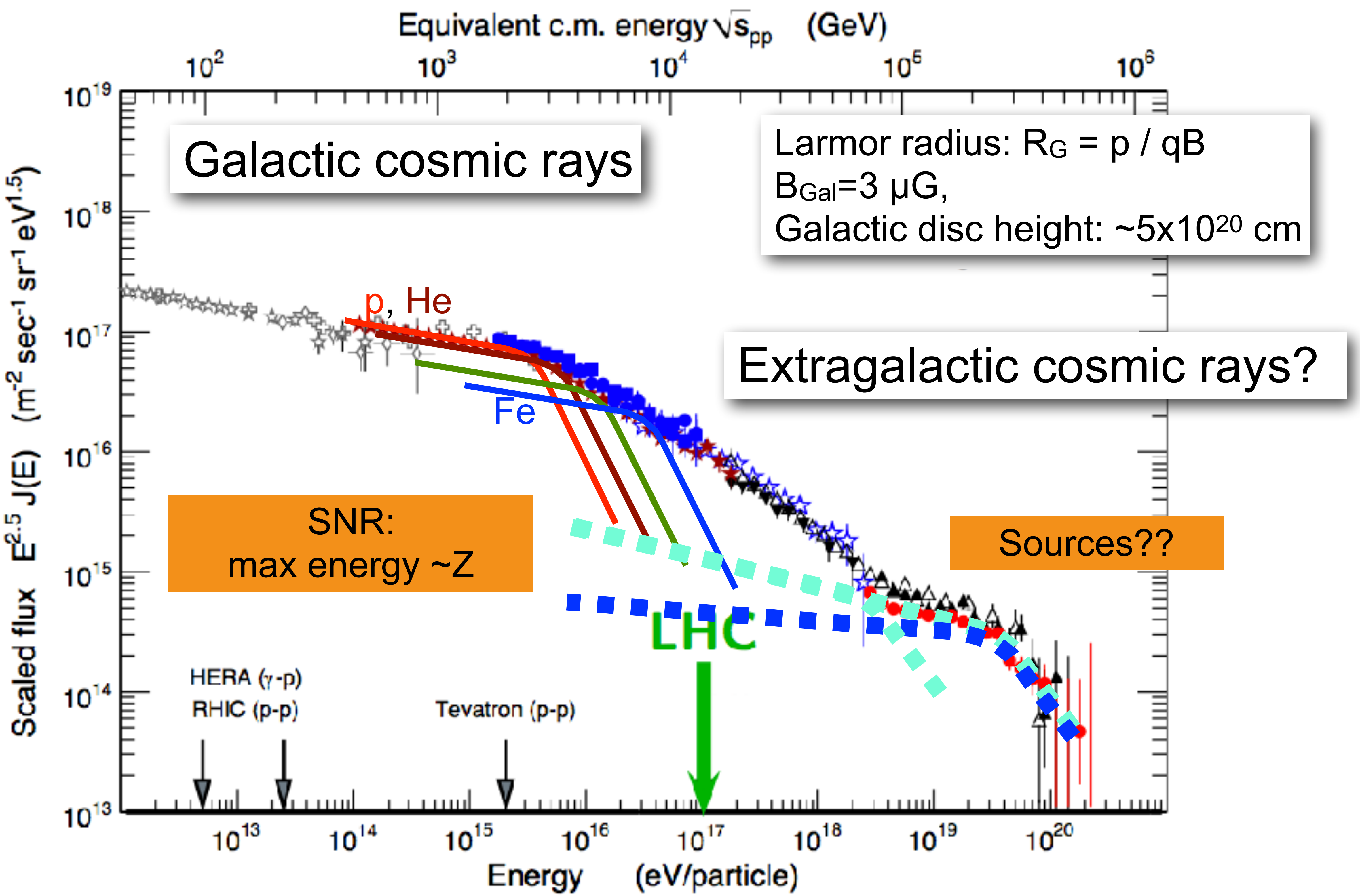
Charge Threshold
Bkg. Atmospheric Muon Flux (Tagged Data)
Bkg. Atmospheric Neutrinos (π/K)
Bkg. Uncertainties (All Atm. Neutrinos)
Atmospheric Neutrinos (Benchmark Charm Flux)
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
All Events (Trigger Level)
Data
Events per 662 Days
10^{7}
10^{6}
10^{5}
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{4}
10^{5}
Total Collected PMT Charge (Photoelectrons)

Astrophysical VHE neutrinos

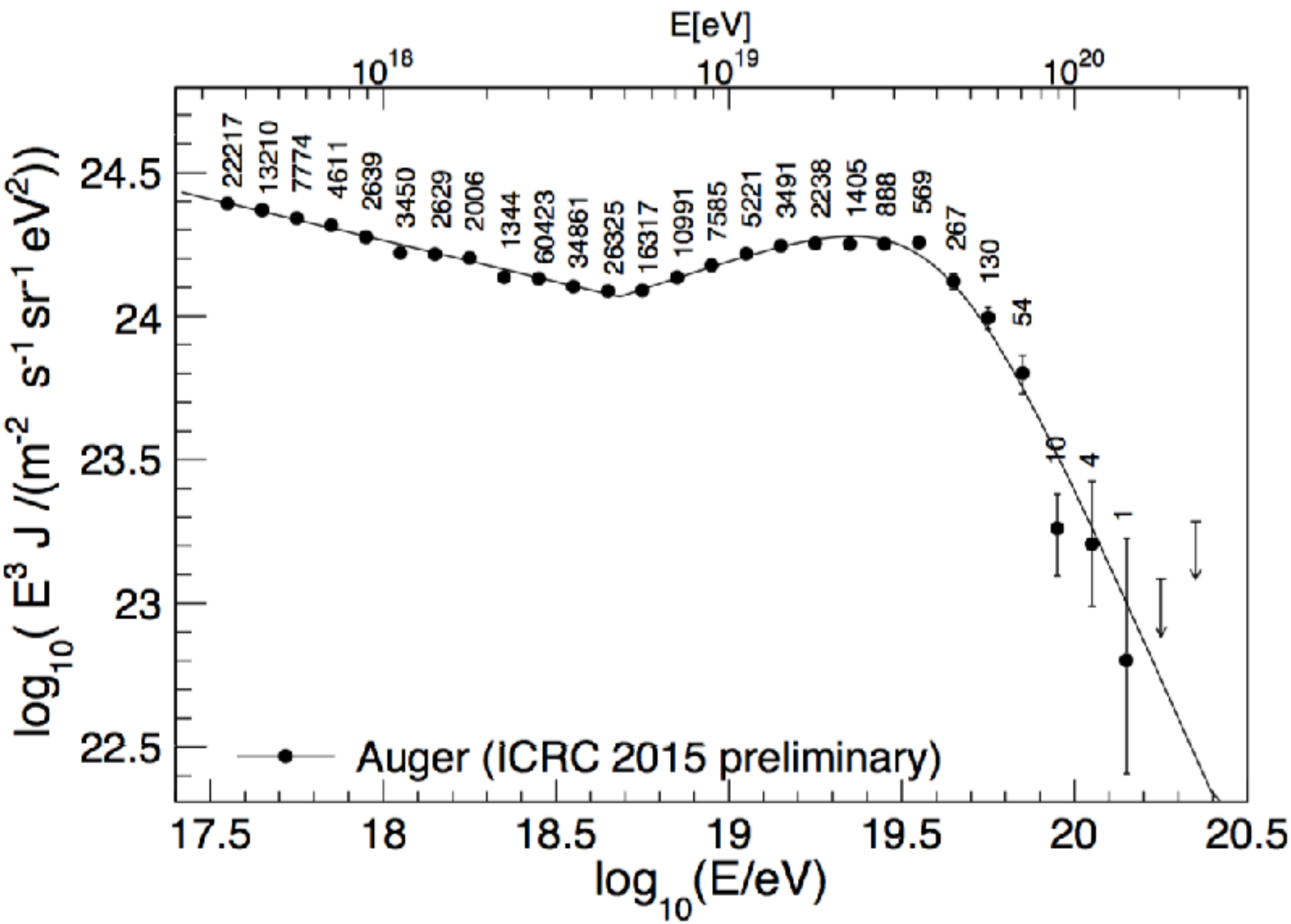


astro-ph/1410.1749

The Cosmic Ray Energy Spectrum



The Cosmic Ray Energy Spectrum



Greisen-Zatsepin-Kuzmin (GZK) cutoff

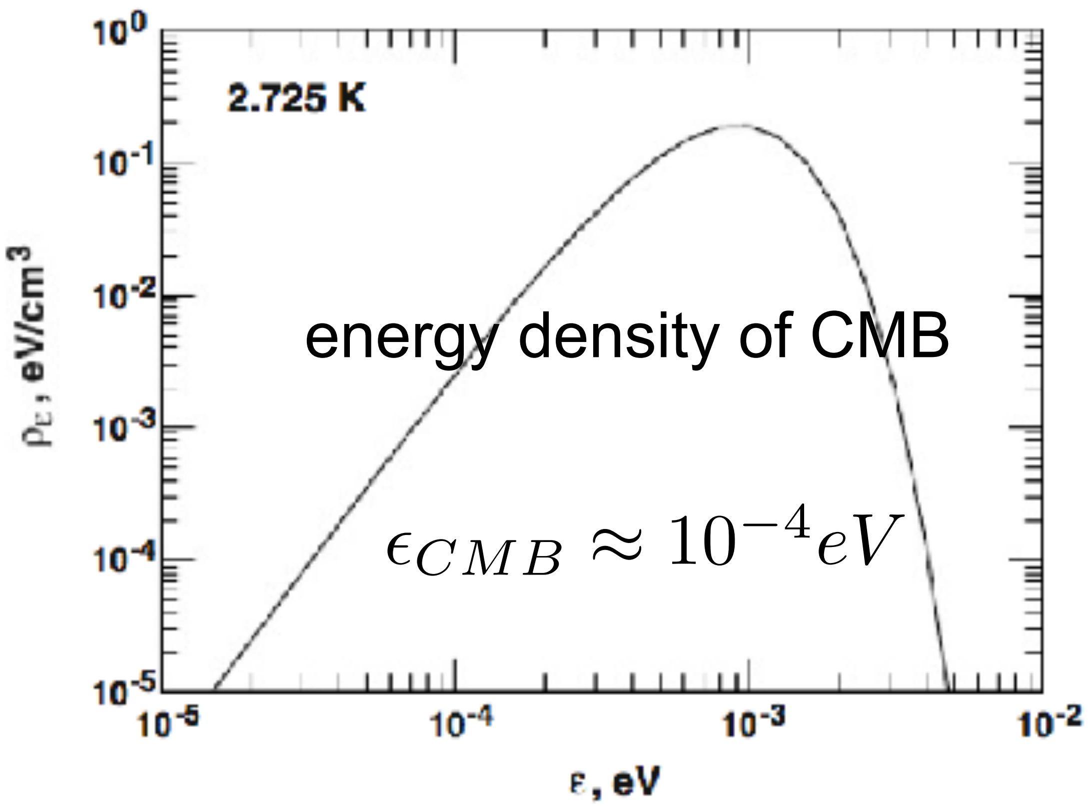
photo-pion production

$$p + \gamma_{\mathrm{CMB}} \rightarrow \Delta^{+} \rightarrow p + \pi$$

threshold:

$$E_p E_\gamma > (m_\Delta^2 - m_p^2)$$

$$\rightarrow E_{GZK} = 6 \cdot 10^{19}\ \mathrm{eV}$$



e⁺e⁻ pair production (Bethe-Heitler):

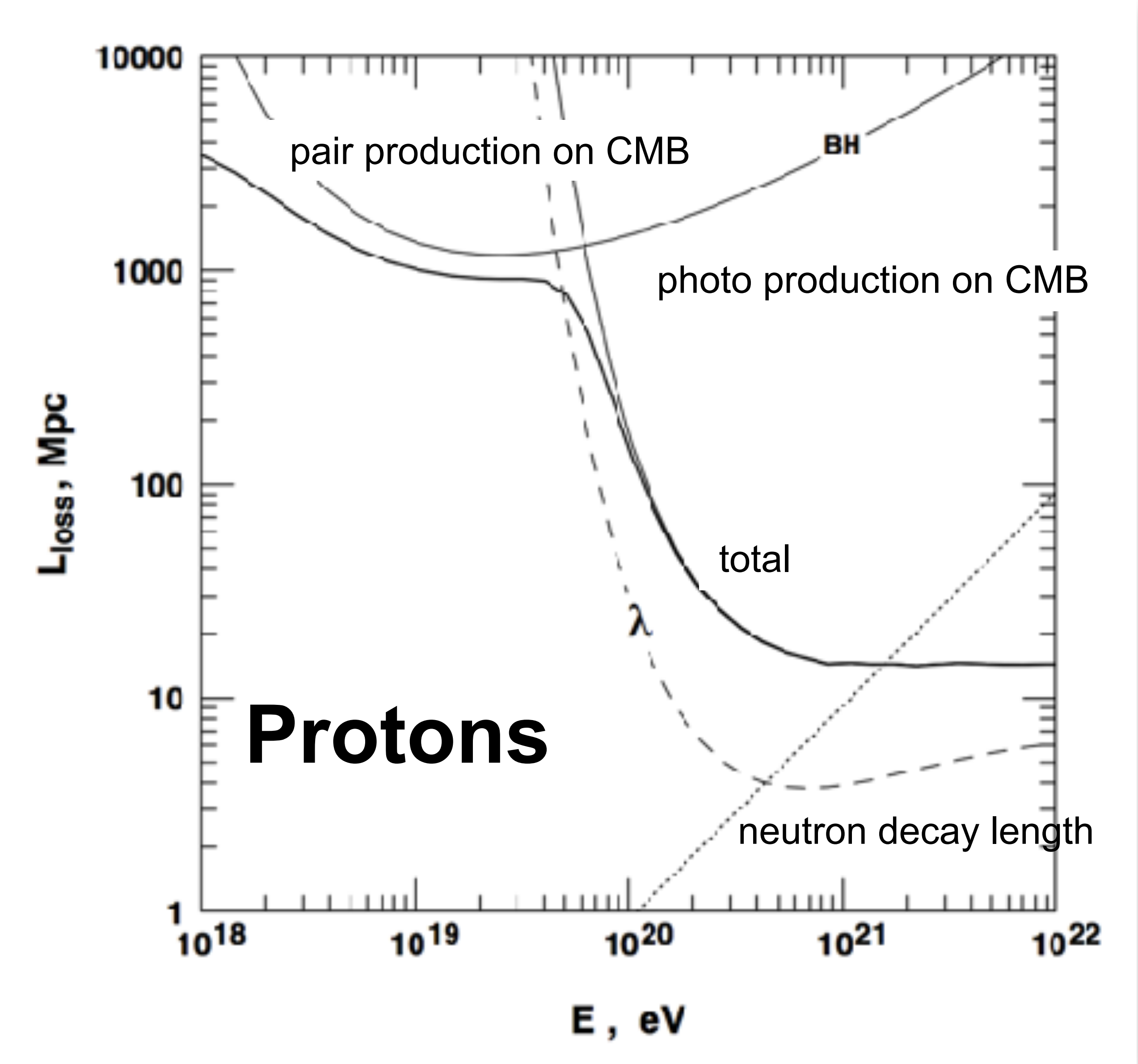
$p + \gamma \rightarrow p + e^+e^-$

$$E_{p,e^+e^-} \approx 0.8\ \mathrm{EeV}\ (\epsilon_{CMB}/\epsilon)$$

Propagation effects: protons & heavy nuclei

Loss length:

$$N(L) = N(L=0) \cdot \exp^{-L/L_{Loss}}$$

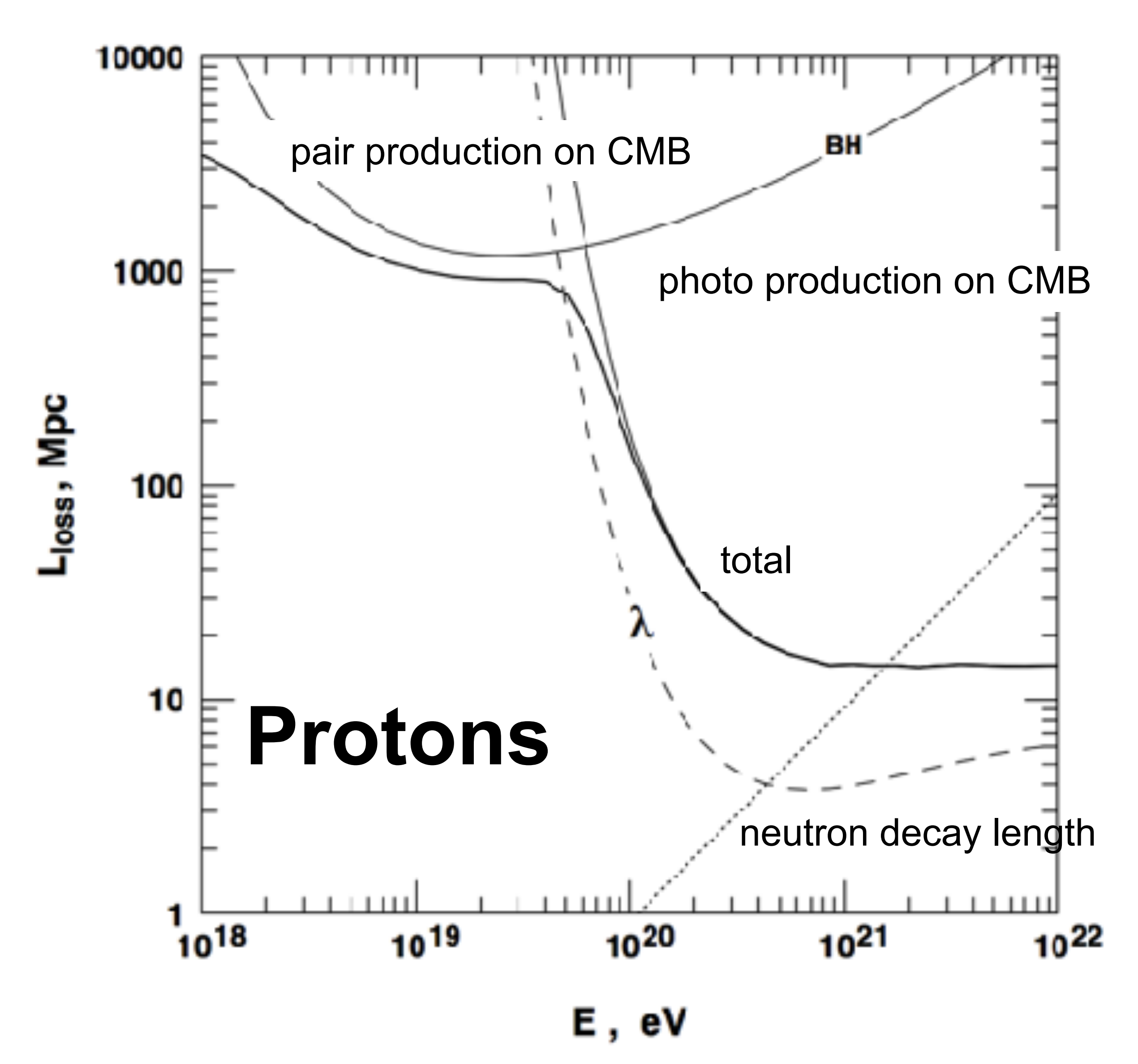


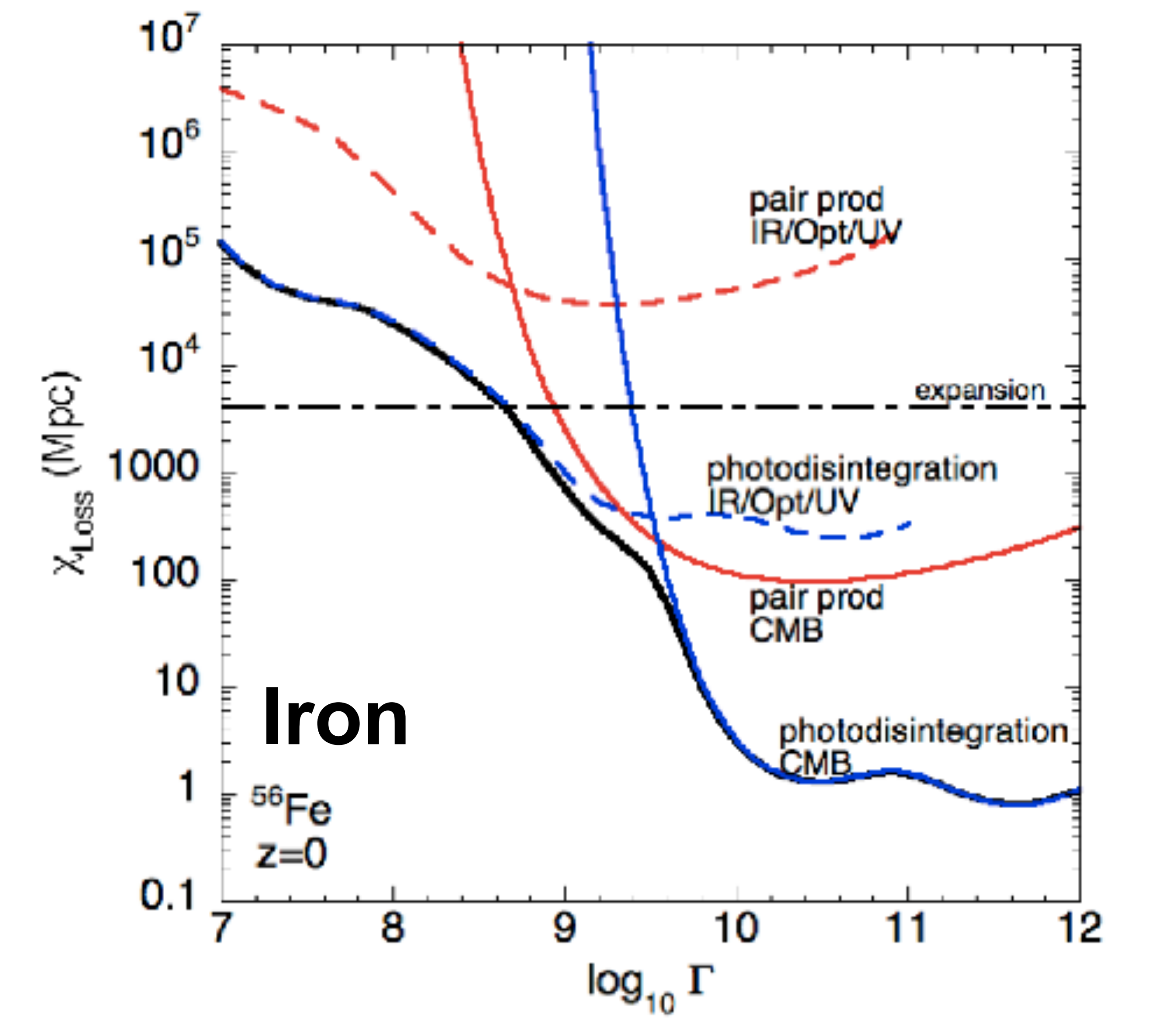
Propagation effects: protons & heavy nuclei

Loss length:

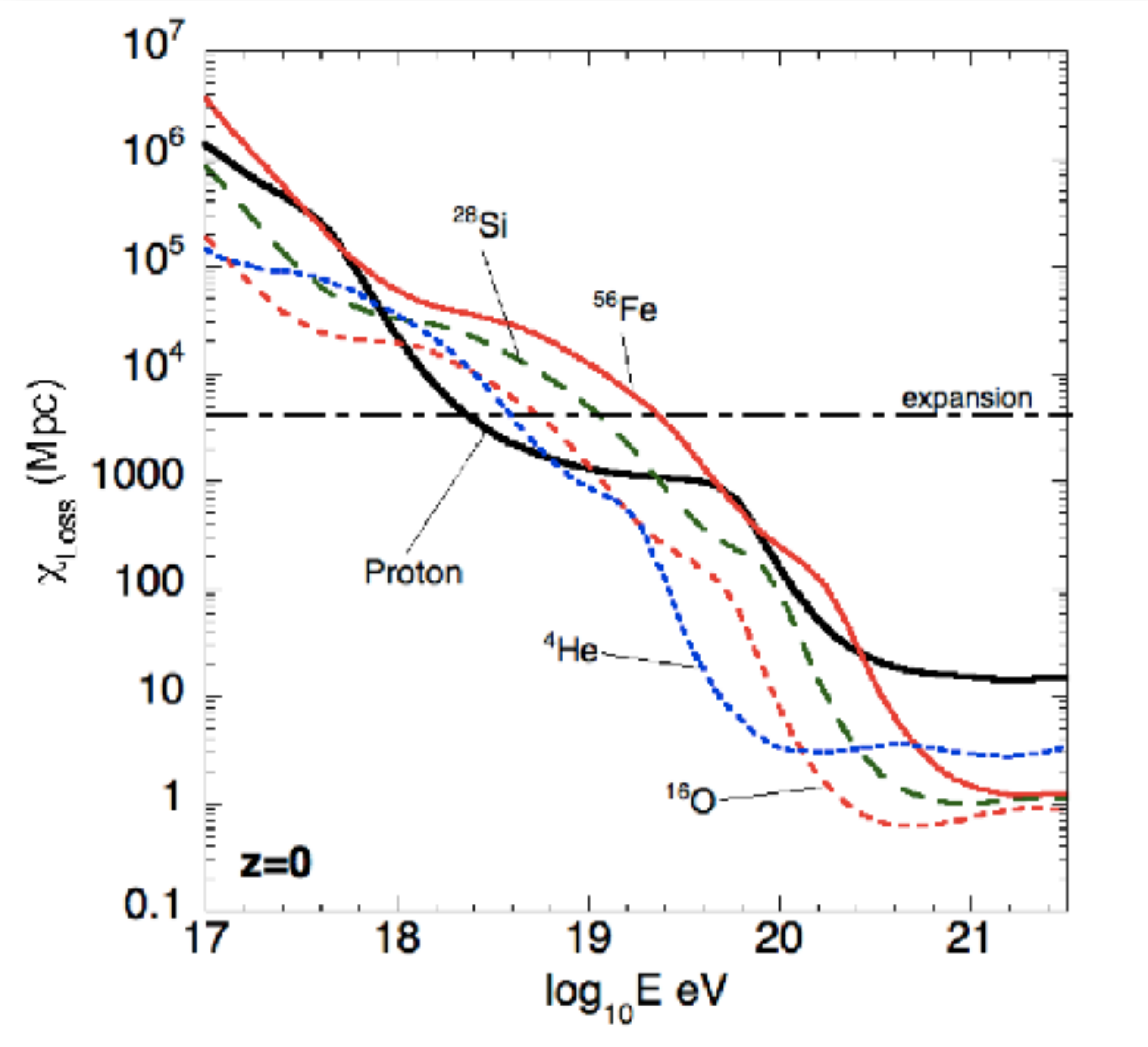
$$N(L) = N(L=0) \cdot \exp^{-L/L_{Loss}}$$

heavy nuclei: **photo dissociation** (spallation): γ + A(N) → (A-1) + N

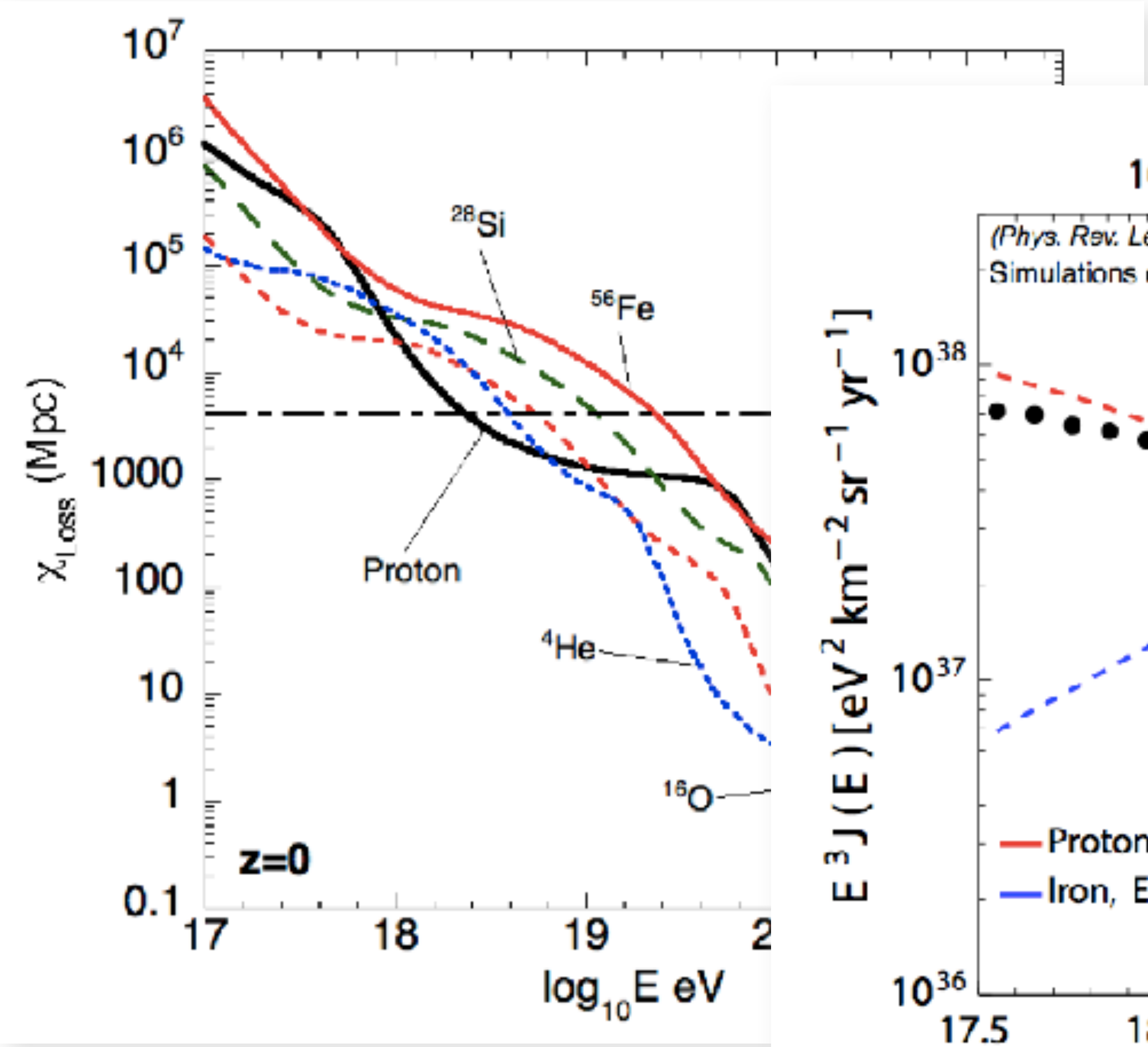


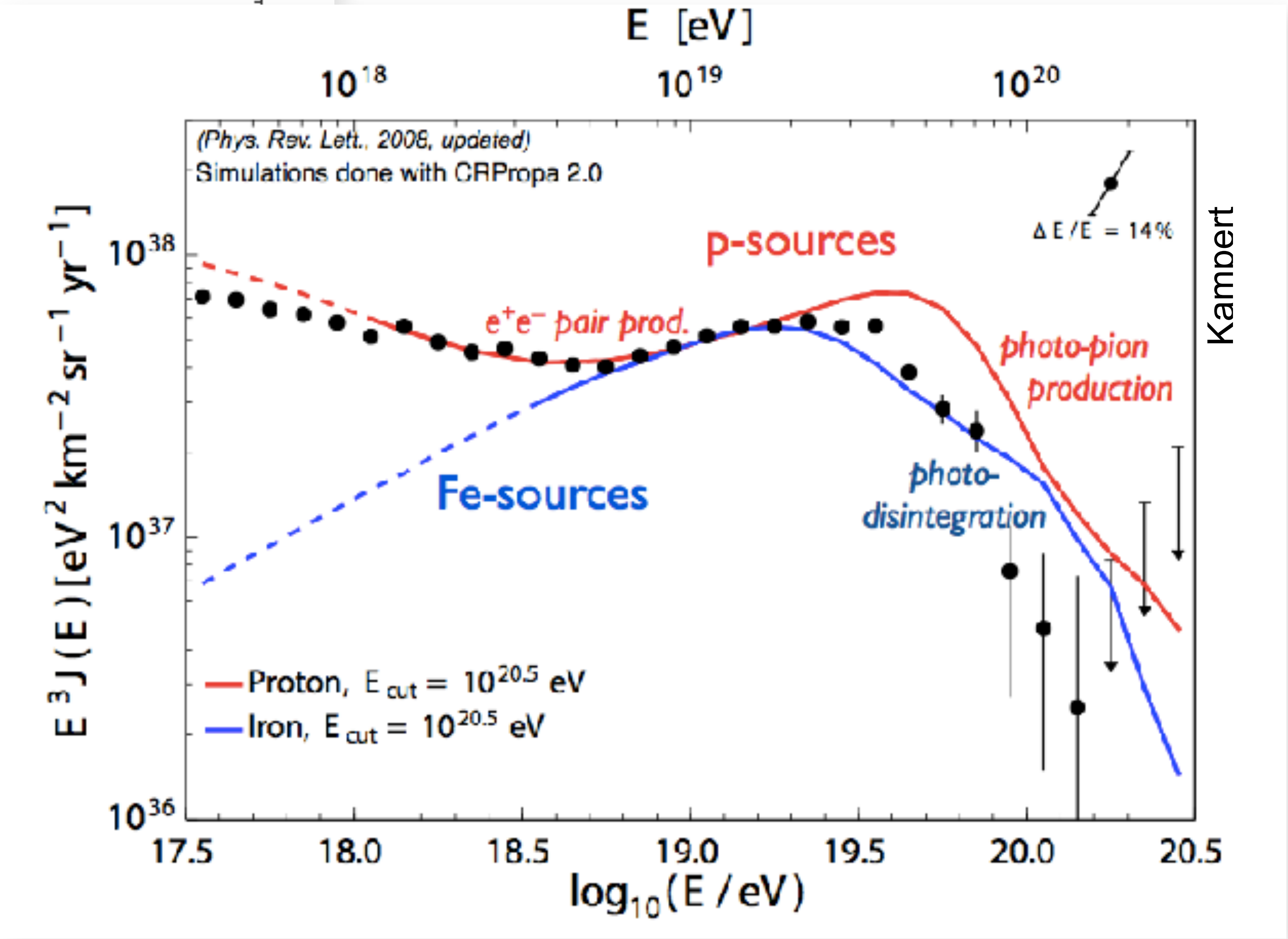


Propagation effects: protons & heavy nuclei



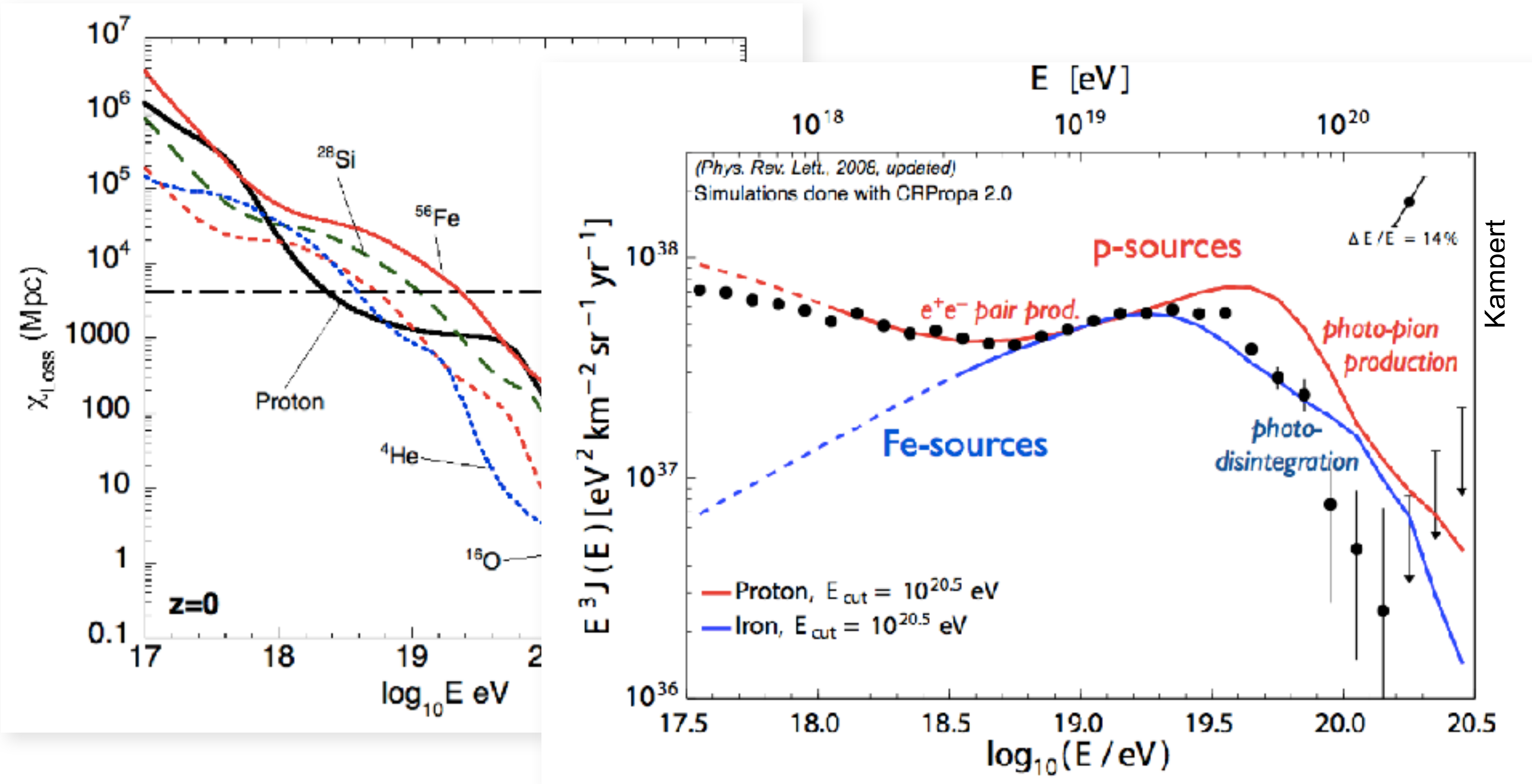
Propagation effects: protons & heavy nuclei





Kampert

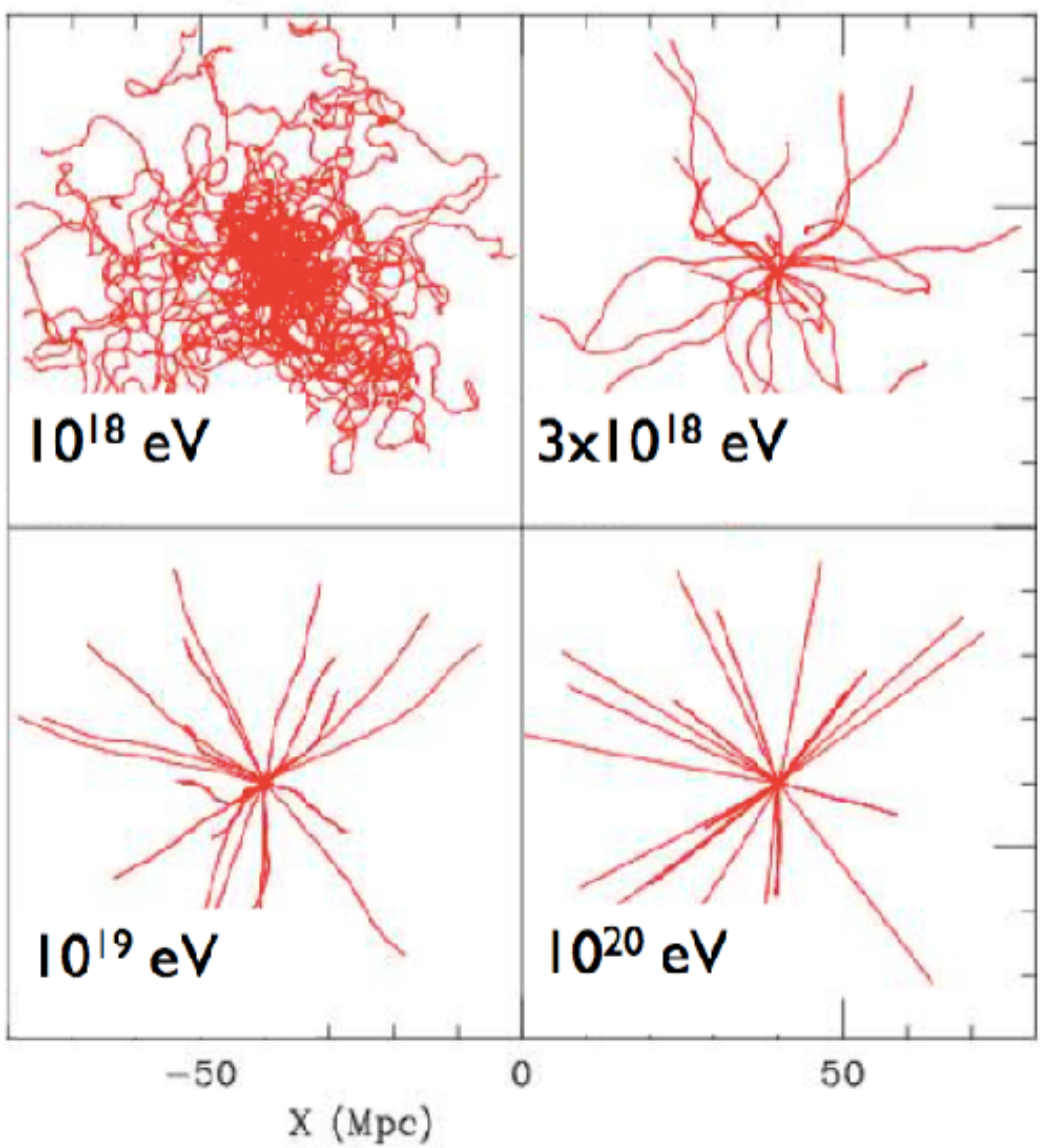
Propagation effects: protons & heavy nuclei



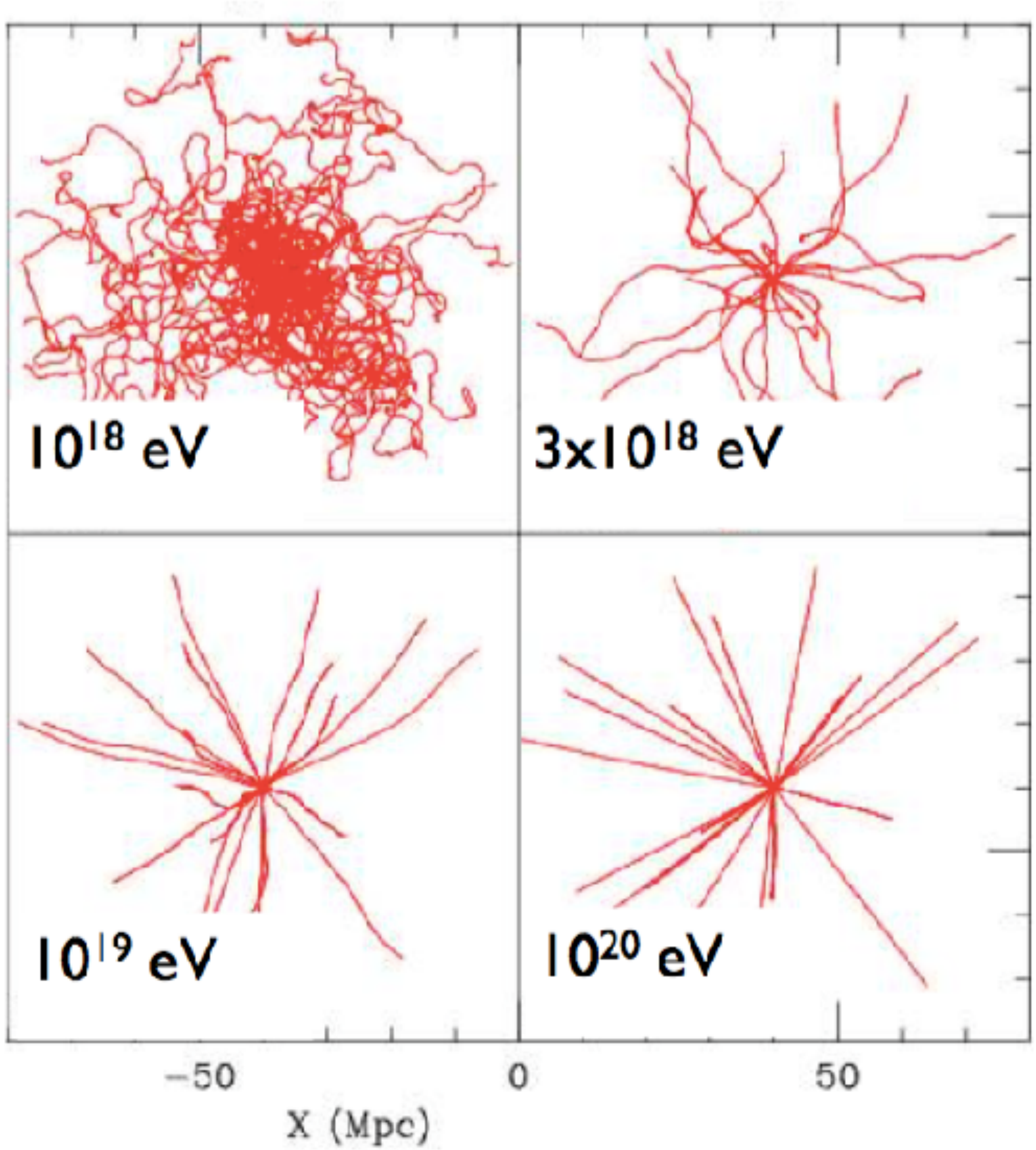
Sources producing mostly **protons**:
- suppression: GZK cut off
- ankle: pair production

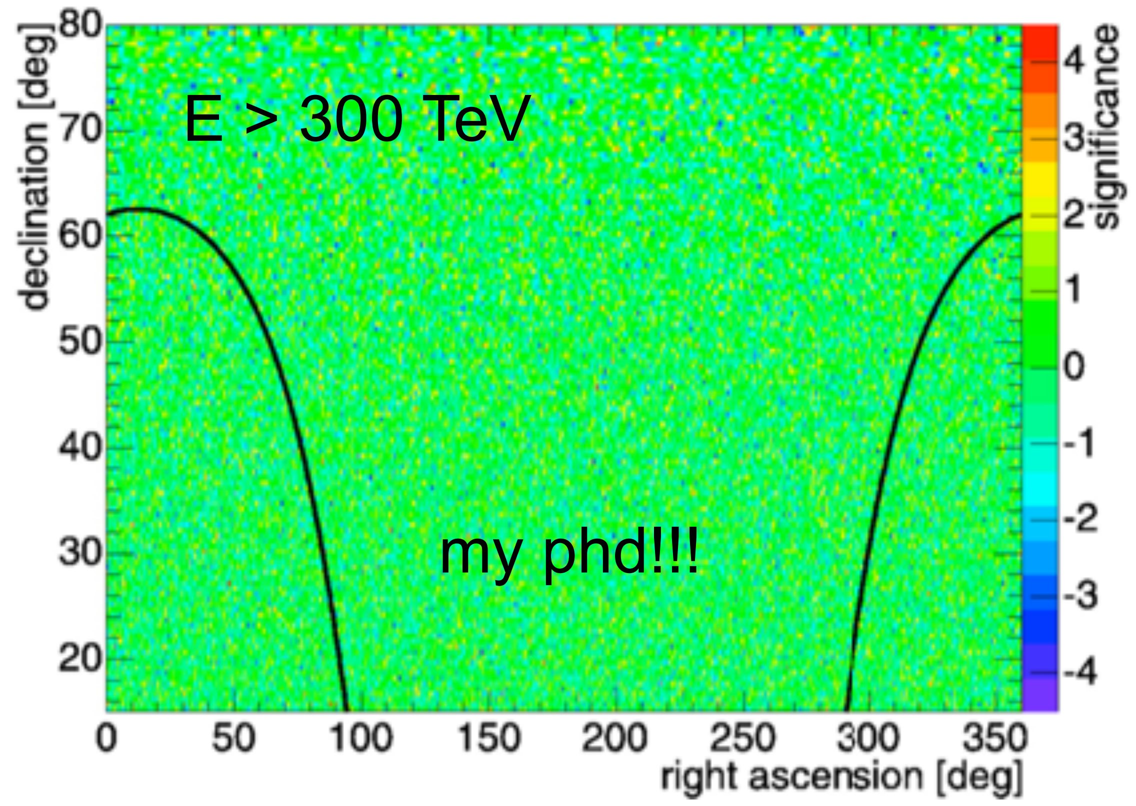
Sources producing mostly **iron**:
- suppression: photo dissociation
- ankle: transition to Galactic sources

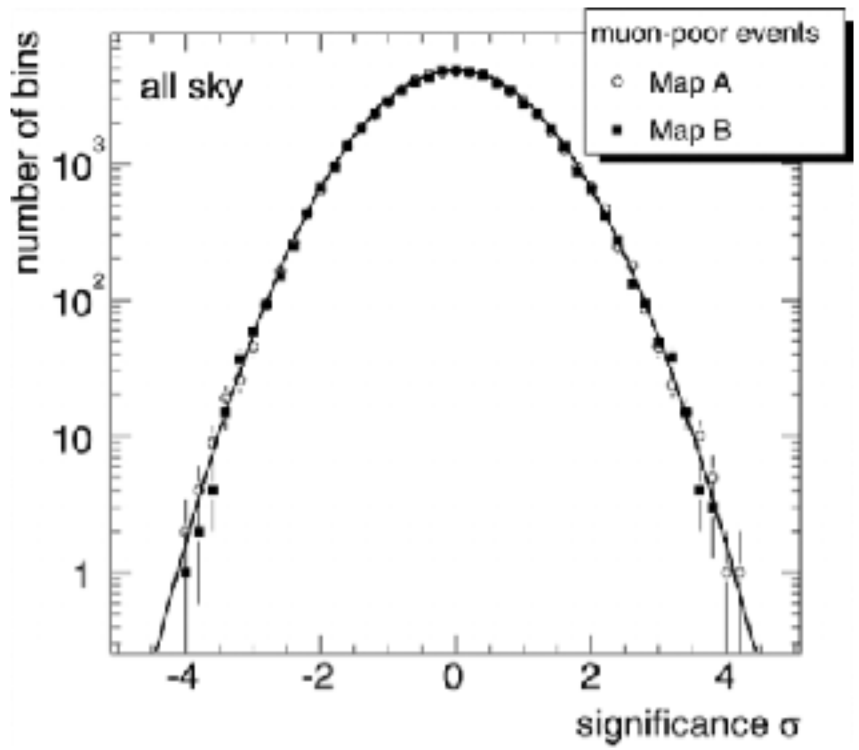
Arrival directions



Arrival directions

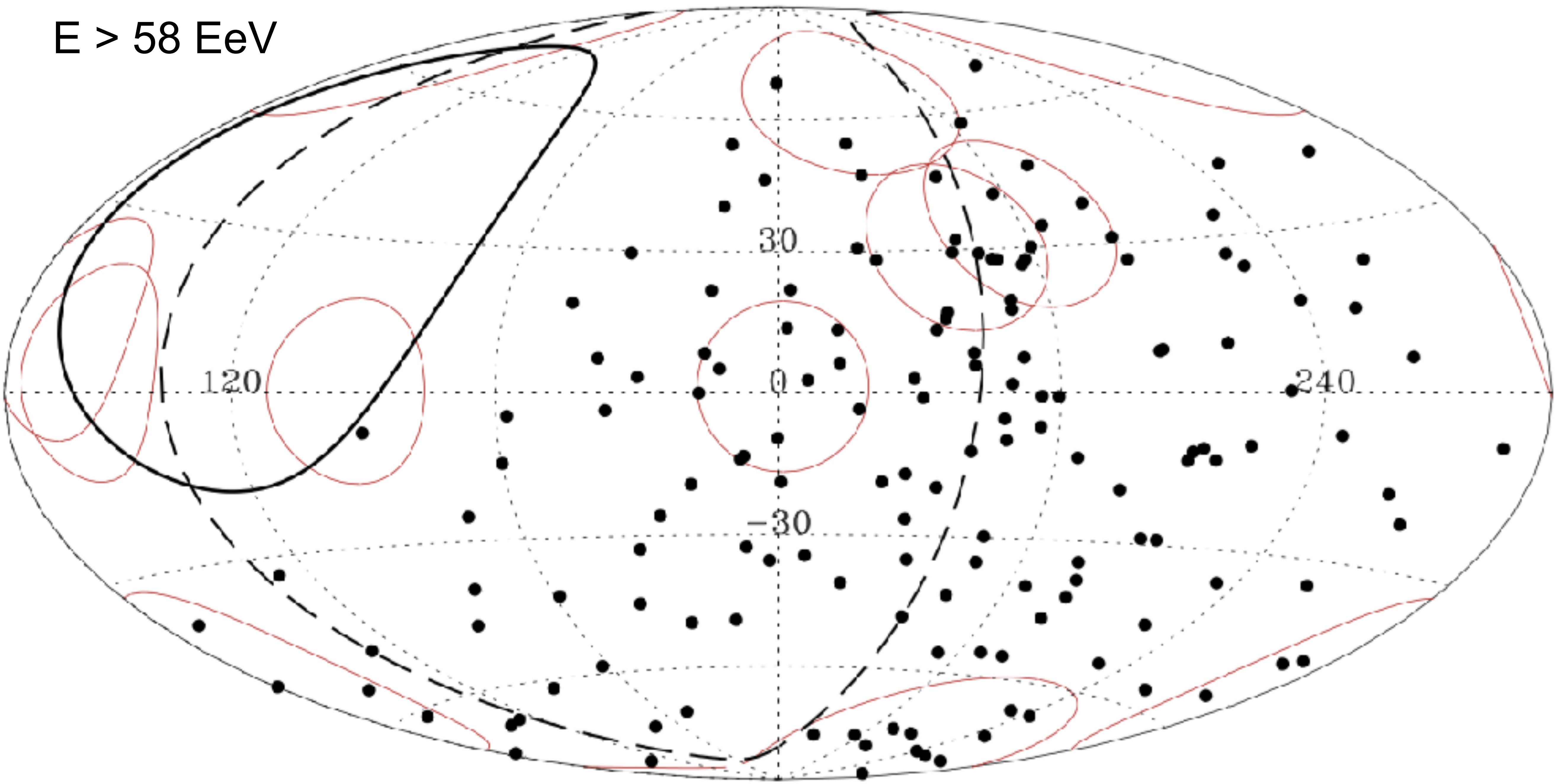






Arrival directions

E > 58 EeV



Red circles: AGNs brighter than 10^{44} erg/s and closer than 130 Mpc

Auger Collaboration

Testing Lorentz Invariance Violation

- assume Lorentz Invariance is violated

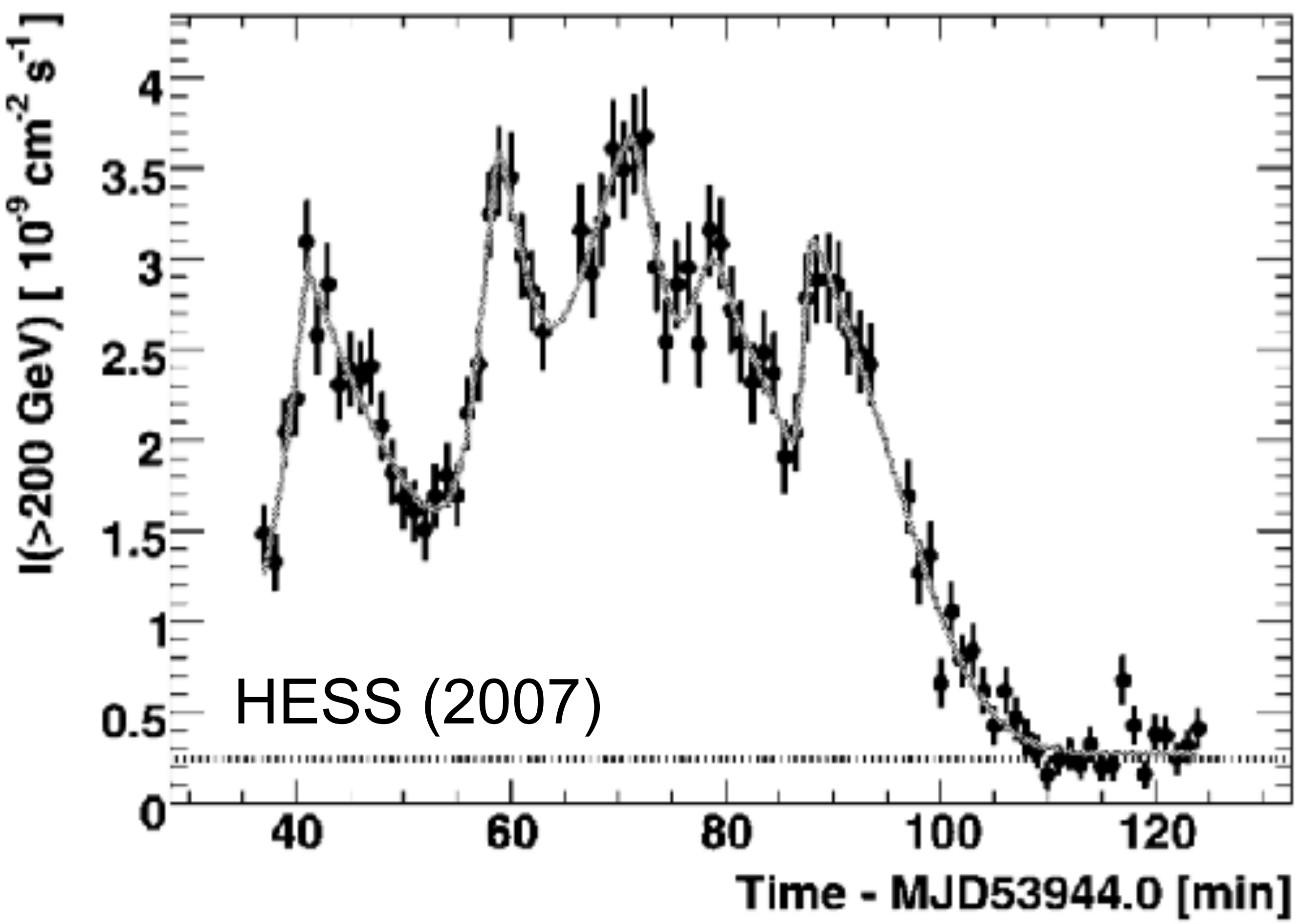
$$c^2 p^2 = E_\gamma^2 [1 \pm \xi_1 E_\gamma / E_{QG} \pm \xi_2 (E_\gamma^2 / E_{QG}{}^2) \pm \ldots]$$

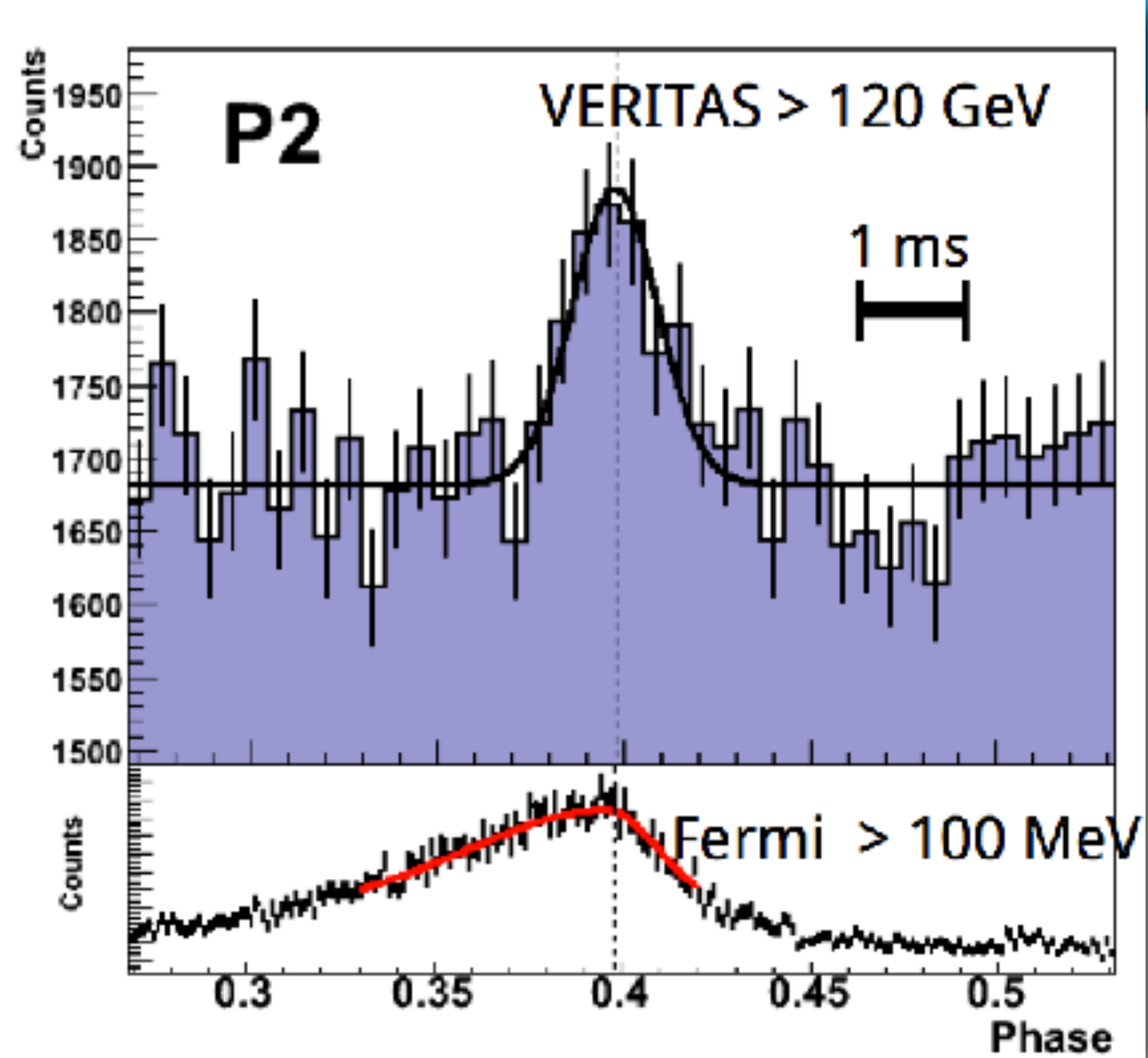
- accumulative effect (assume source at distance L)

$$\delta t \simeq \left(\frac{\Delta E}{\xi_\alpha E_{Pl}} \right)^\alpha \frac{L}{c}$$

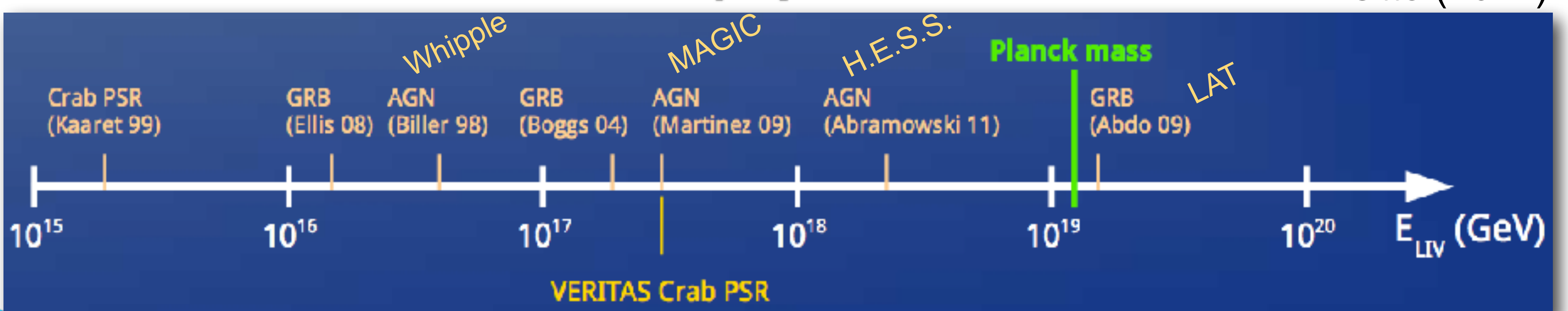
- some theories of quantum gravity predict δt ~ 10s/TeV/Gpc

Testing Lorentz Invariance



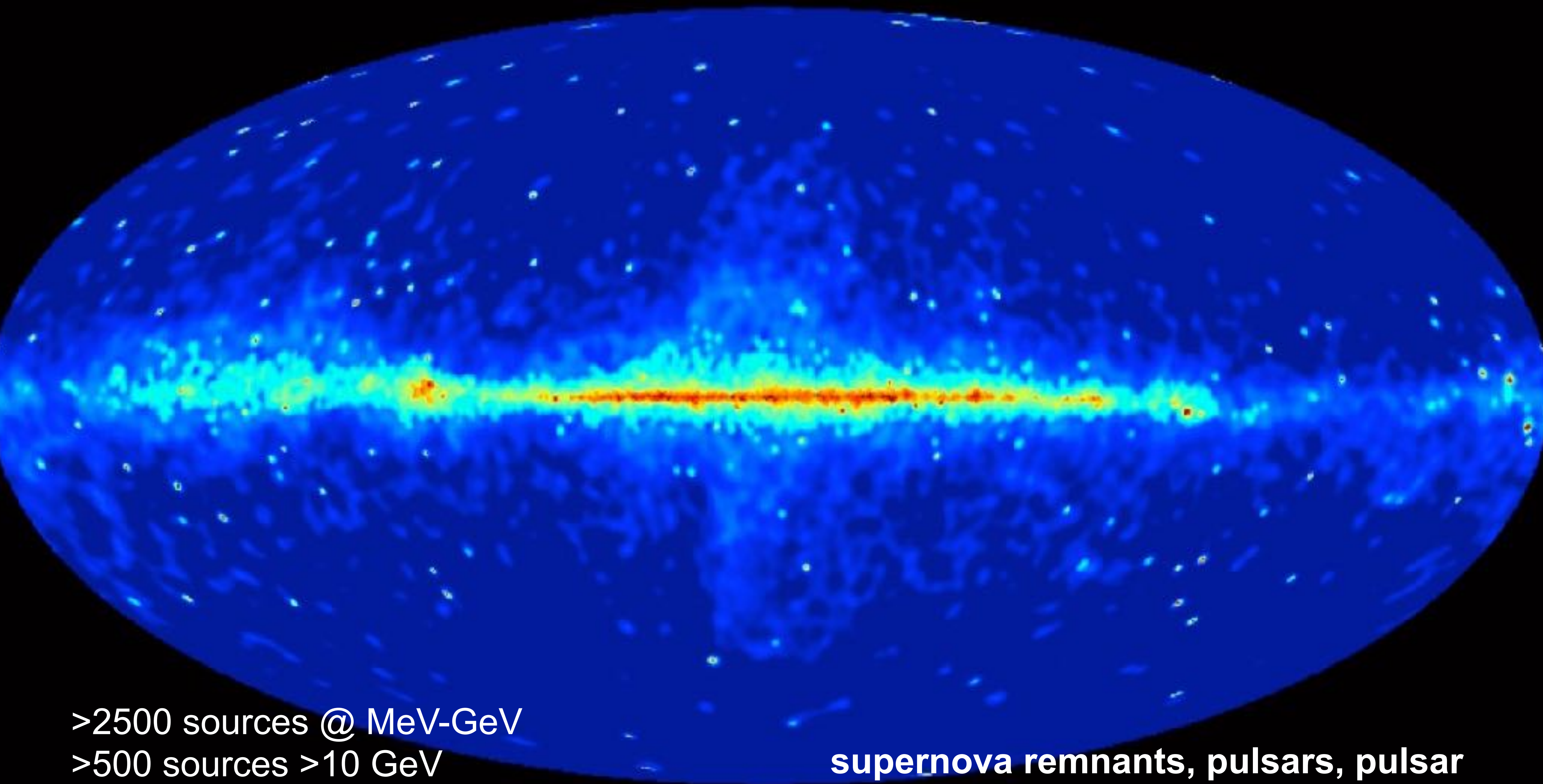


Otte (2011)



The high-energy gamma-ray sky

Fermi LAT 3-years
sky map > 10 GeV

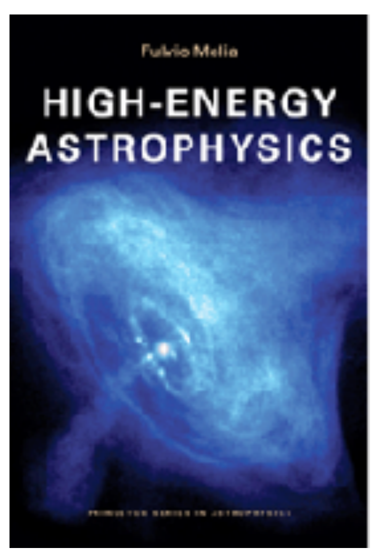


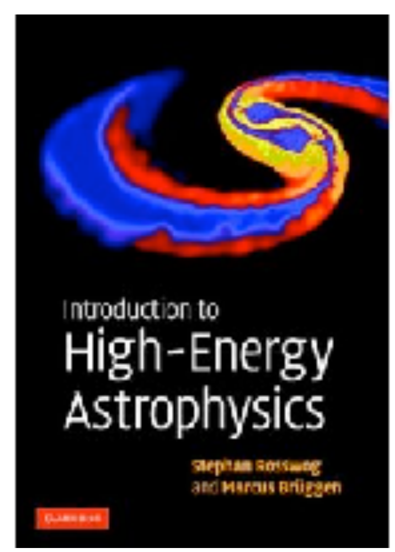
>2500 sources @ MeV-GeV
>500 sources >10 GeV
>150 sources >100 GeV

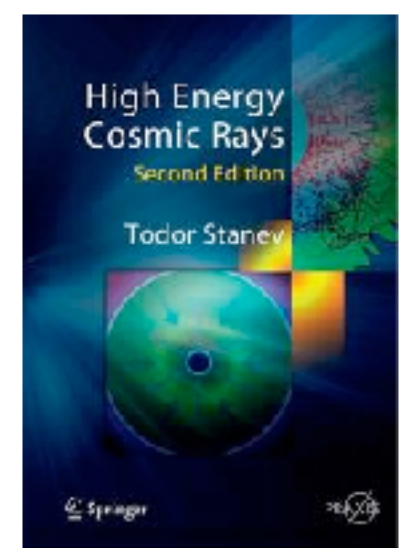
supernova remnants, pulsars, pulsar wind nebulae, binary systems, massive star clusters, starburst galaxies, active galactic nuclei (mostly blazars), gamma-ray bursts, nova, diffuse, dark matter, ...

Literature

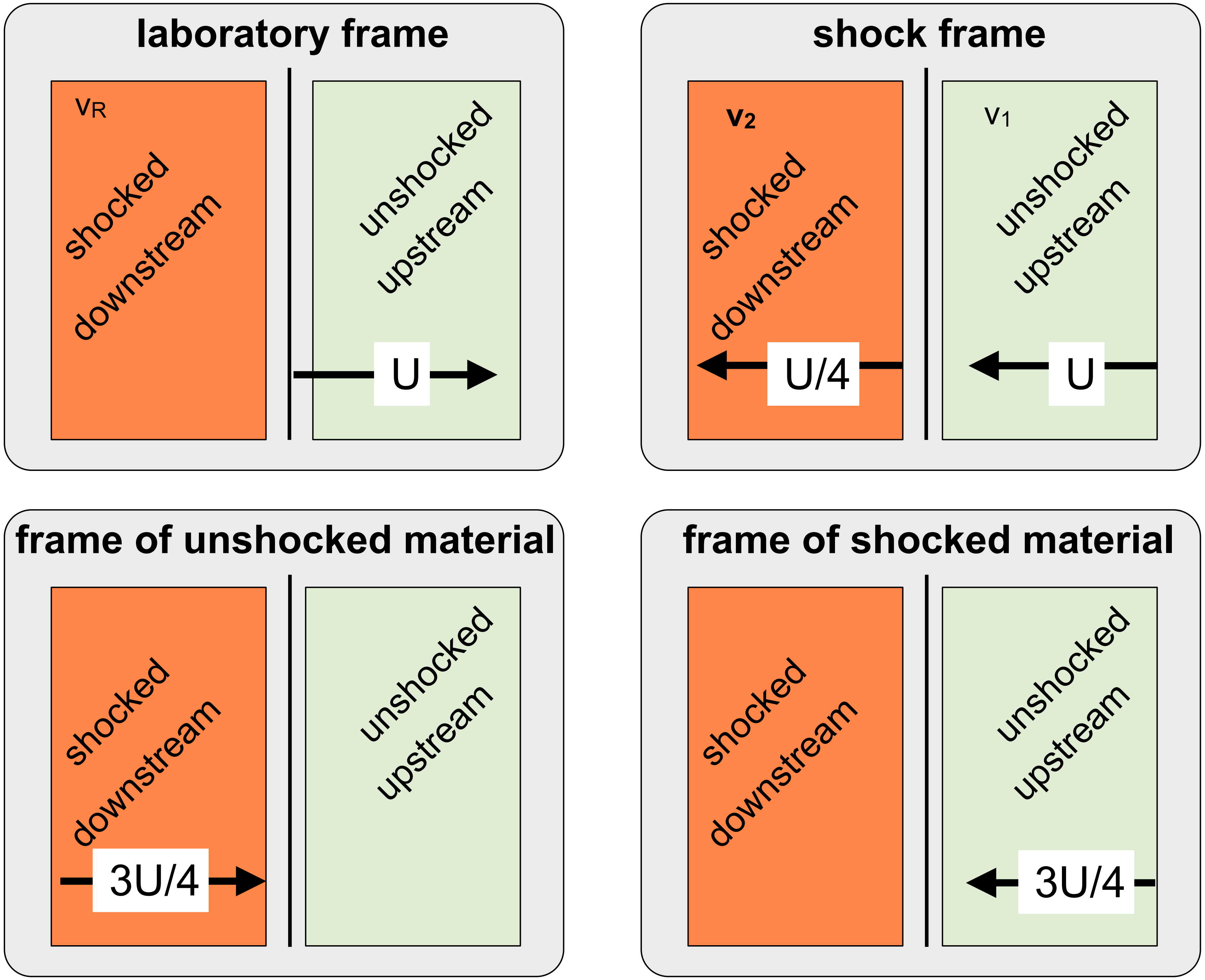
- *countless of good books: go to your (or DESY) library....*
- **Longair, M.**, High-Energy Astrophysics. *Cambridge University Press*
- **Melia, F.**, High-Energy Astrophysics. *Princeton University Press*
- **Rosswog, S. and Bruggen, M.**, Introduction to high-energy astrophysics. *Cambridge University Press*
- **Stanev, T.,** High Energy Cosmic Rays, *Springer*
- **Many reviews on astro-ph**







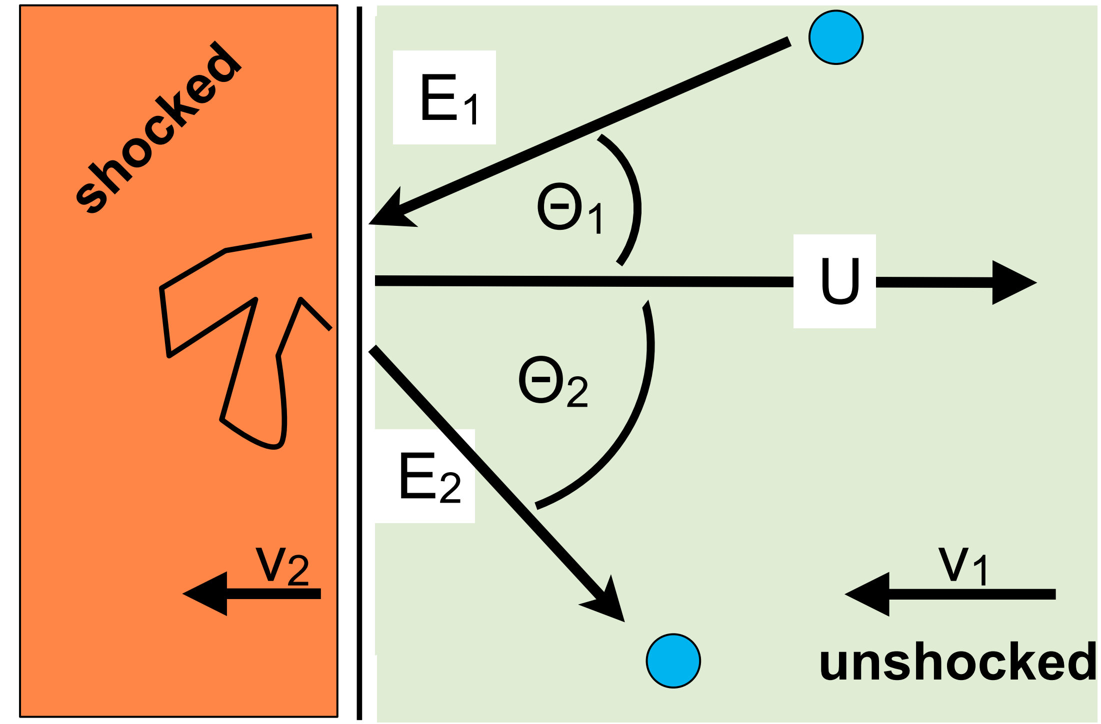
Shocks - frames of references



compression ratio

$$R \simeq \frac{U/v_R}{U/v_R - 1}$$

First-order Fermi acceleration



same situation as in second-order Fermi acceleration

quasi-isotropization of the particles direction

on average: head-on collision when crossing the shock

$$E_2 = \gamma^2 E_1 (1 + \beta \cos\Theta_2')(1 - \beta\cos\Theta_1)$$

$$< E_2 > = \gamma^2 E_1 (1 + \beta < \cos\Theta_2' >)(1 - \beta < \cos\Theta_1 >)$$

probability that pitch angle is in the angular range Θ to Θ+dΘ: proportional to sinΘdΘ

$$\langle \cos\Theta_1 \rangle = \frac{\int_{-1}^{0} \cos\Theta_1 \, d\cos\Theta_1}{\int_{-1}^{0} d\cos\Theta_1} = -\frac{2}{3}$$

$$\langle \cos\Theta_2' \rangle = \frac{\int_{0}^{+1} \cos\Theta_2' \, d\cos\Theta_2'}{\int_{0}^{+1} d\cos\Theta_2'} = \frac{2}{3}$$

$$\beta = \frac{v_1 - v_2}{c}$$

$$\gamma = \frac{1}{\sqrt{1-\beta^2}}$$

First/second-order Fermi acceleration

second-order stochastic Fermi acceleration (clouds)

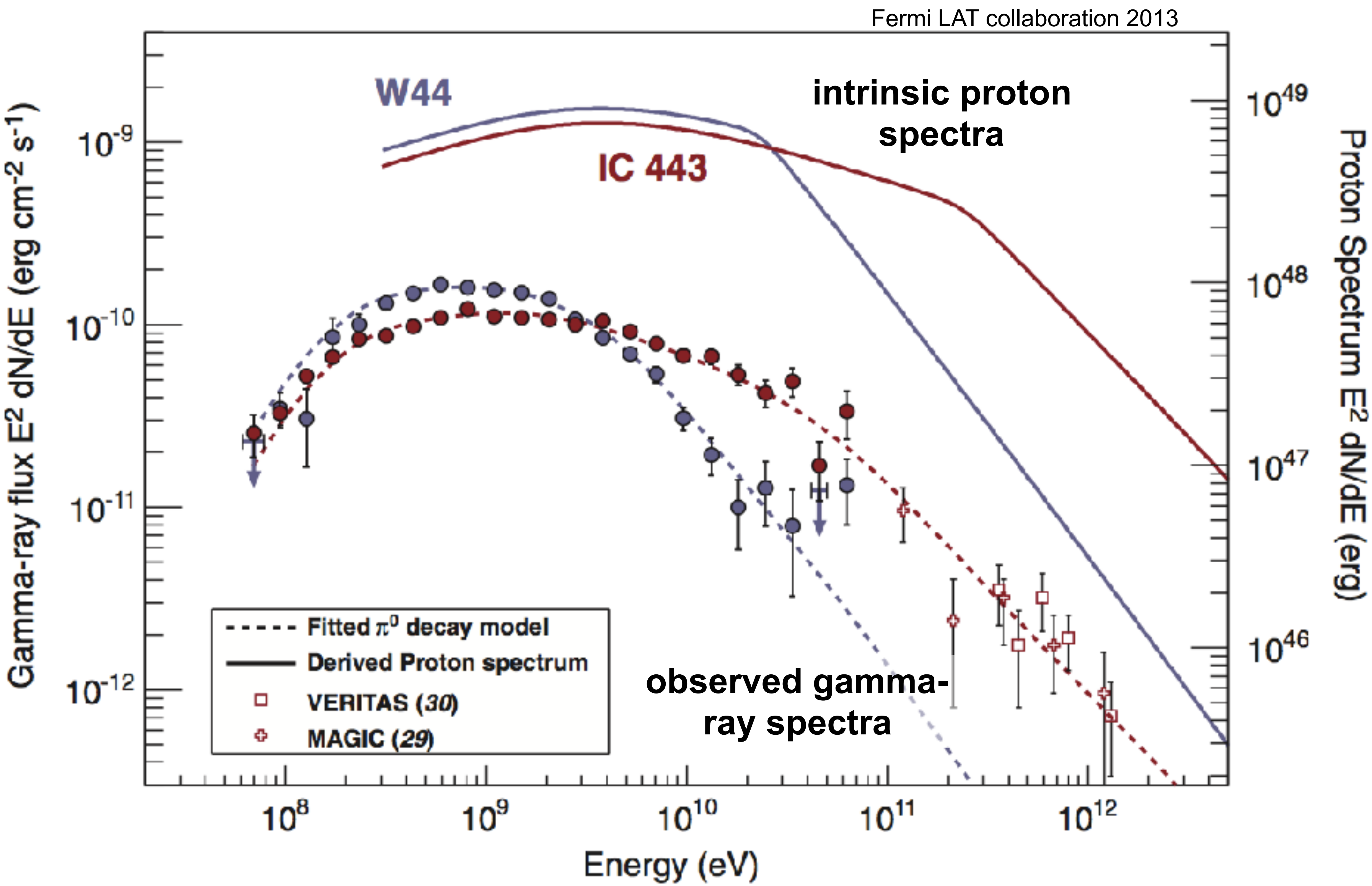
$$\frac{\Delta E}{E} = \frac{4}{3}\frac{\beta^2}{1-\beta^2} \approx \xi = \frac{4}{3}\beta^2$$

first-order stochastic Fermi acceleration (shocks)

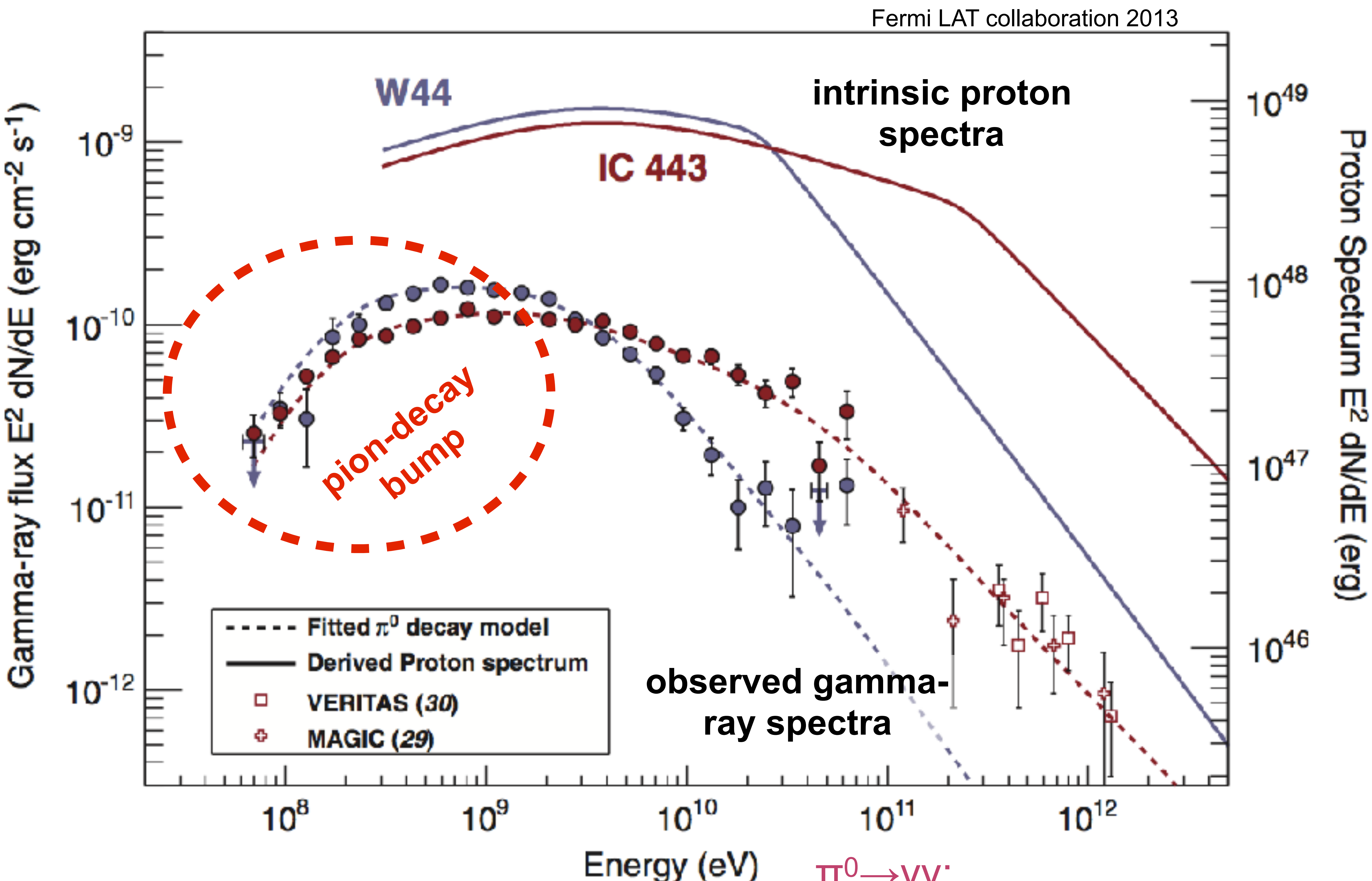
(diffussive shock acceleration)

$$\left\langle \frac{\Delta E}{E} \right\rangle = \frac{\langle E_2 \rangle - E_1}{E_1} \approx \xi = \frac{4}{3}\beta_s = \frac{4}{3}\frac{u_1 - u_2}{c}$$

Gamma-ray emission from Supernova Remnants



Gamma-ray emission from Supernova Remnants



$\pi^0 \rightarrow \gamma\gamma$:

E_γ=67.5 MeV (rest frame of π^0)