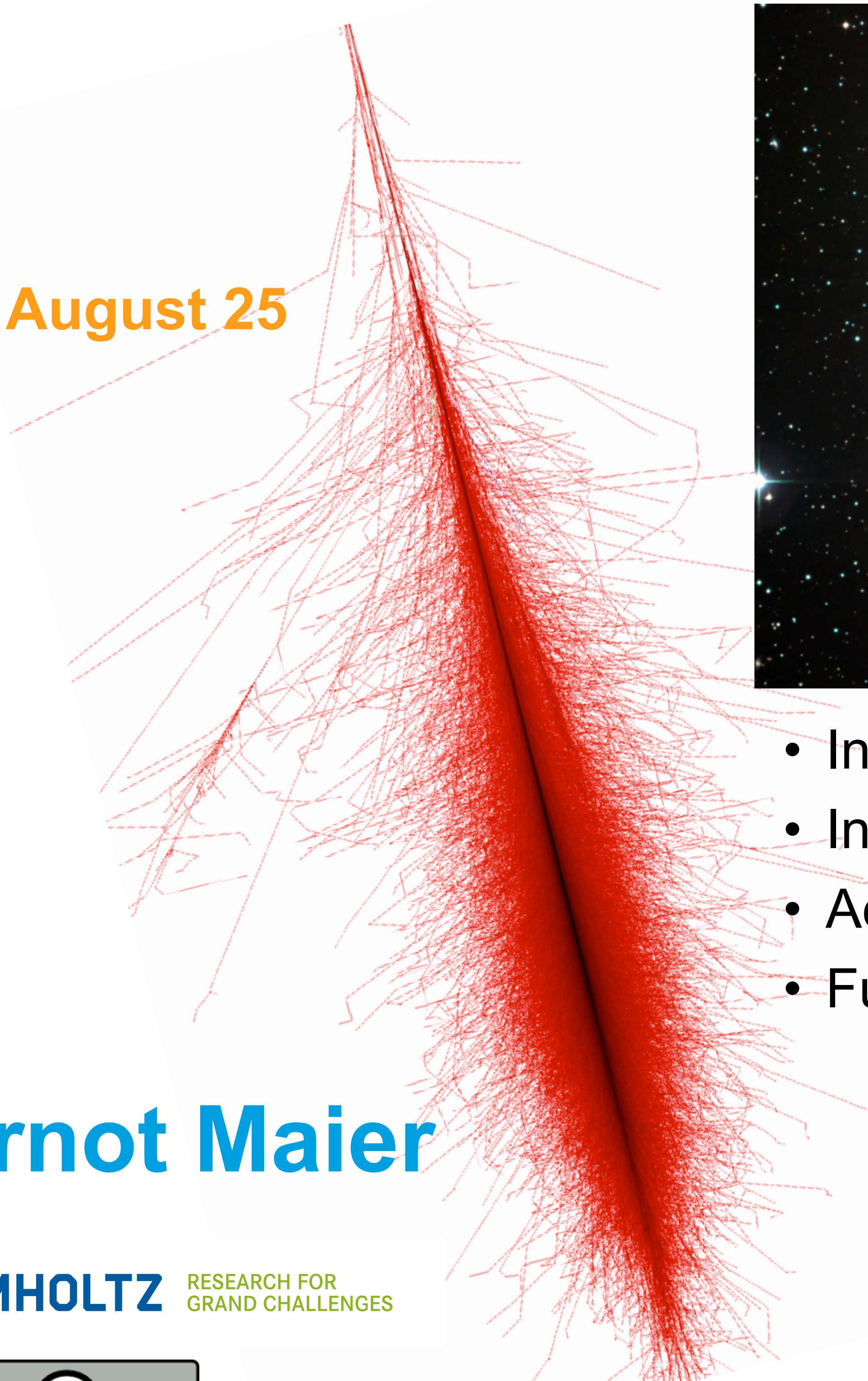
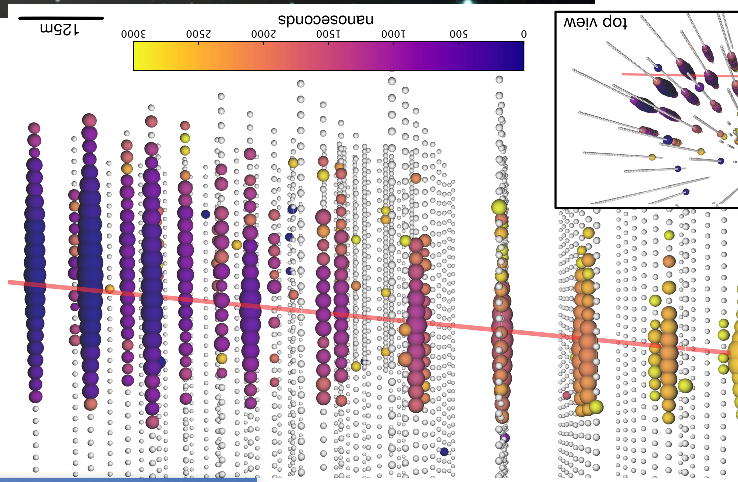
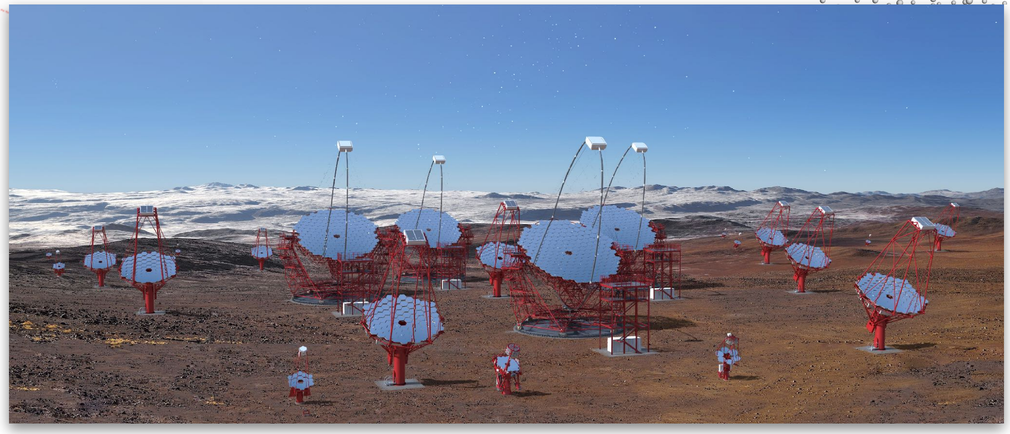
Astroparticle Physics



2022, August 25

- Introduction
- Instrumental Techniques
- Acceleration and Sources
- Fundamental Physics





Gernot Maier

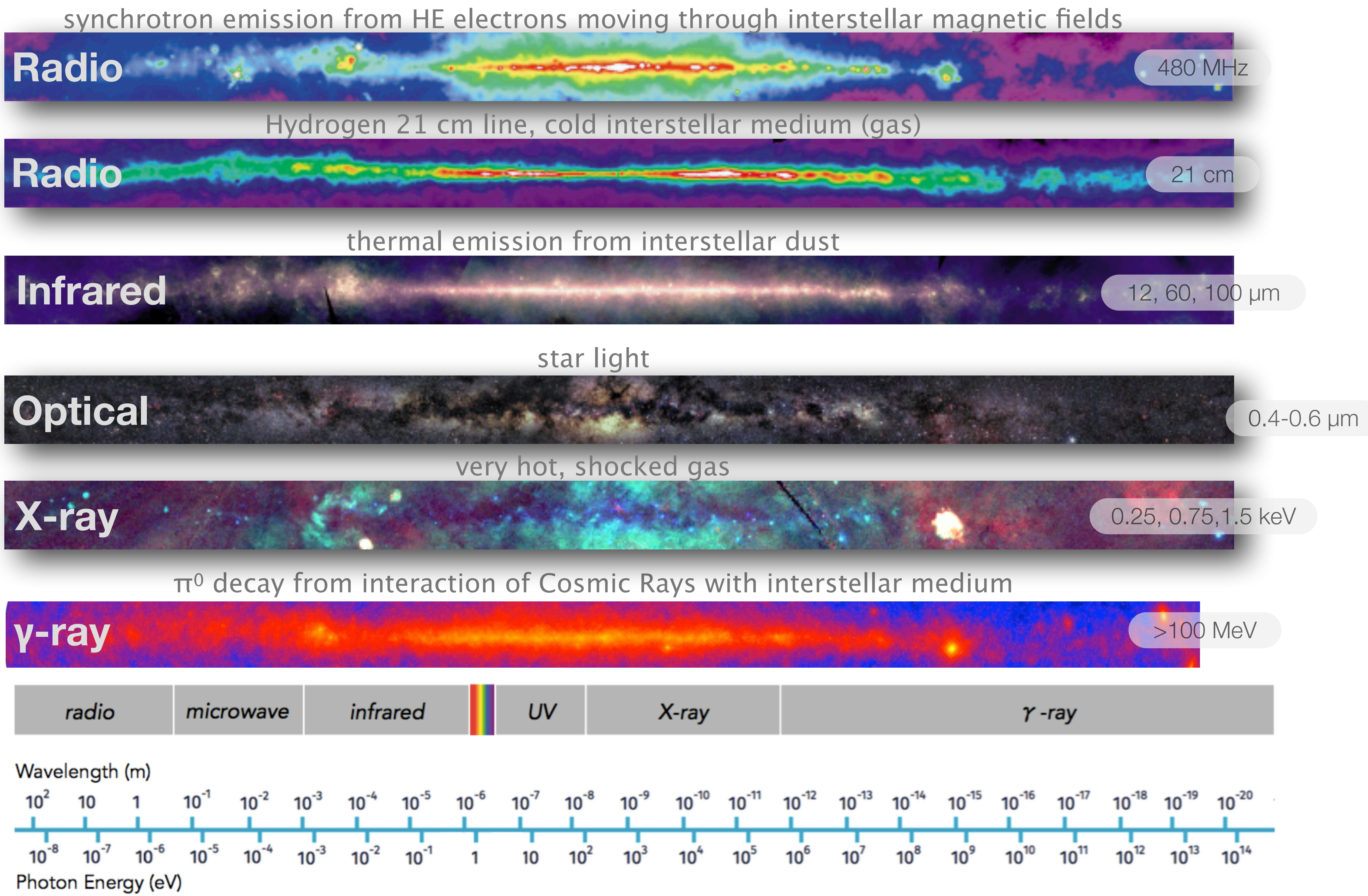
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Credit: John Quinn/CfA

Multi-wavelength astronomy

+ high-energetic particles, neutrinos, gravitational waves

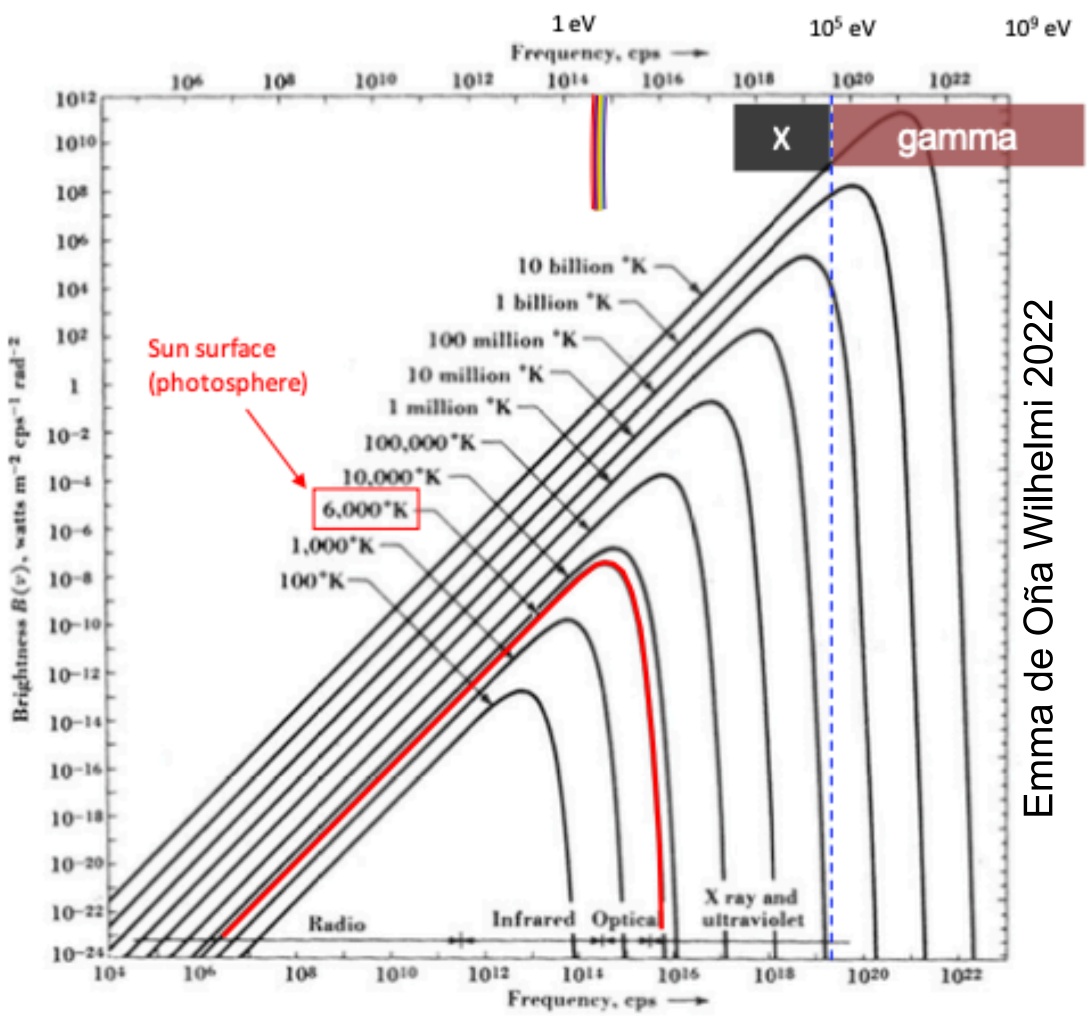


High-energy / non-thermal astronomy

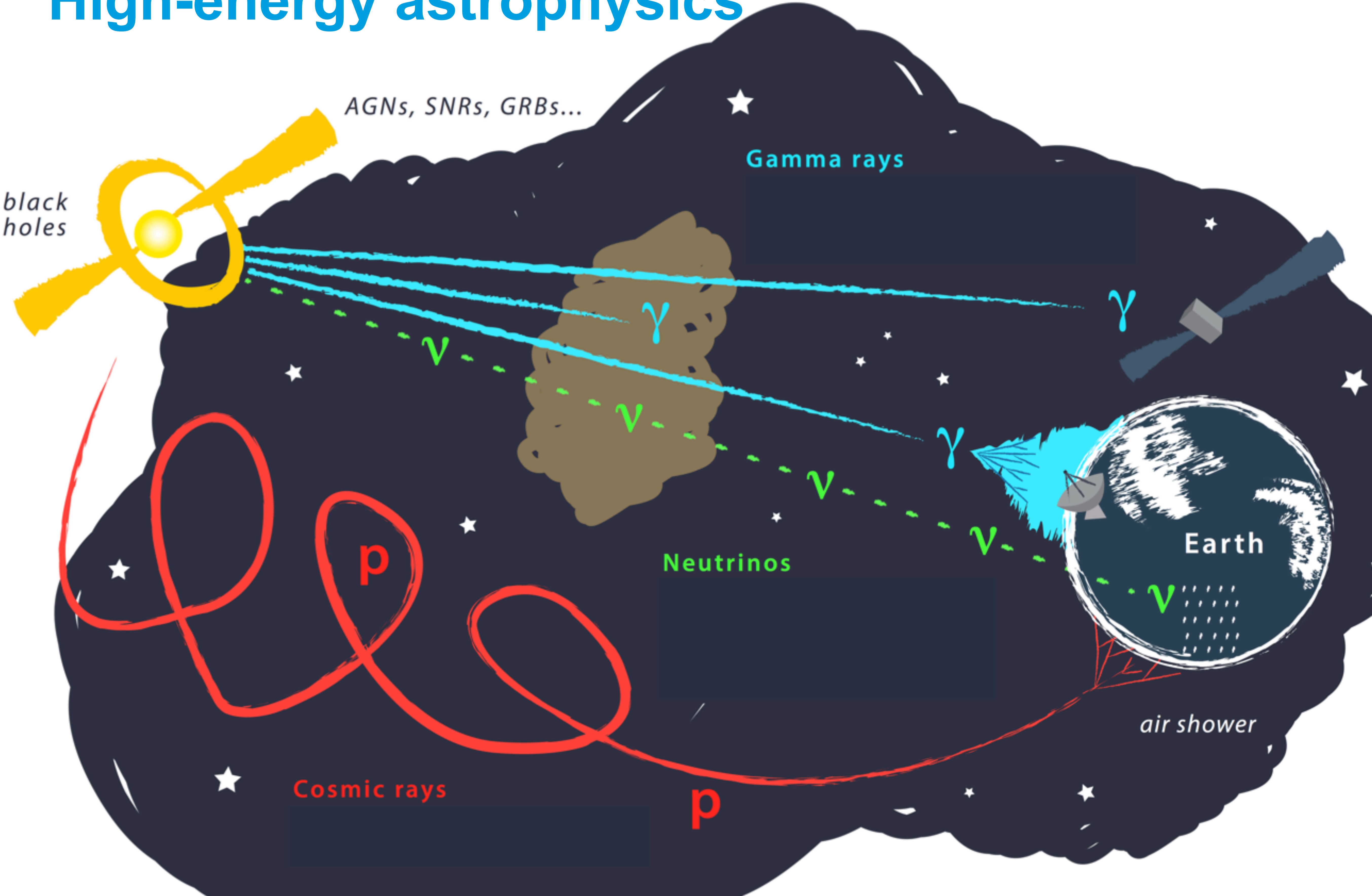
- Photons / particles with energies much higher than their rest mass
    - electron: ~5 x 10^5 eV ~ 0.6 x 10^{10} K
    - protons: ~10^9 eV ~ 10^{13} K

$$< E > \approx \frac{3}{2} k_B T$$

- hard-to-achieve temperatures non-thermal processes dominate above MeV energies

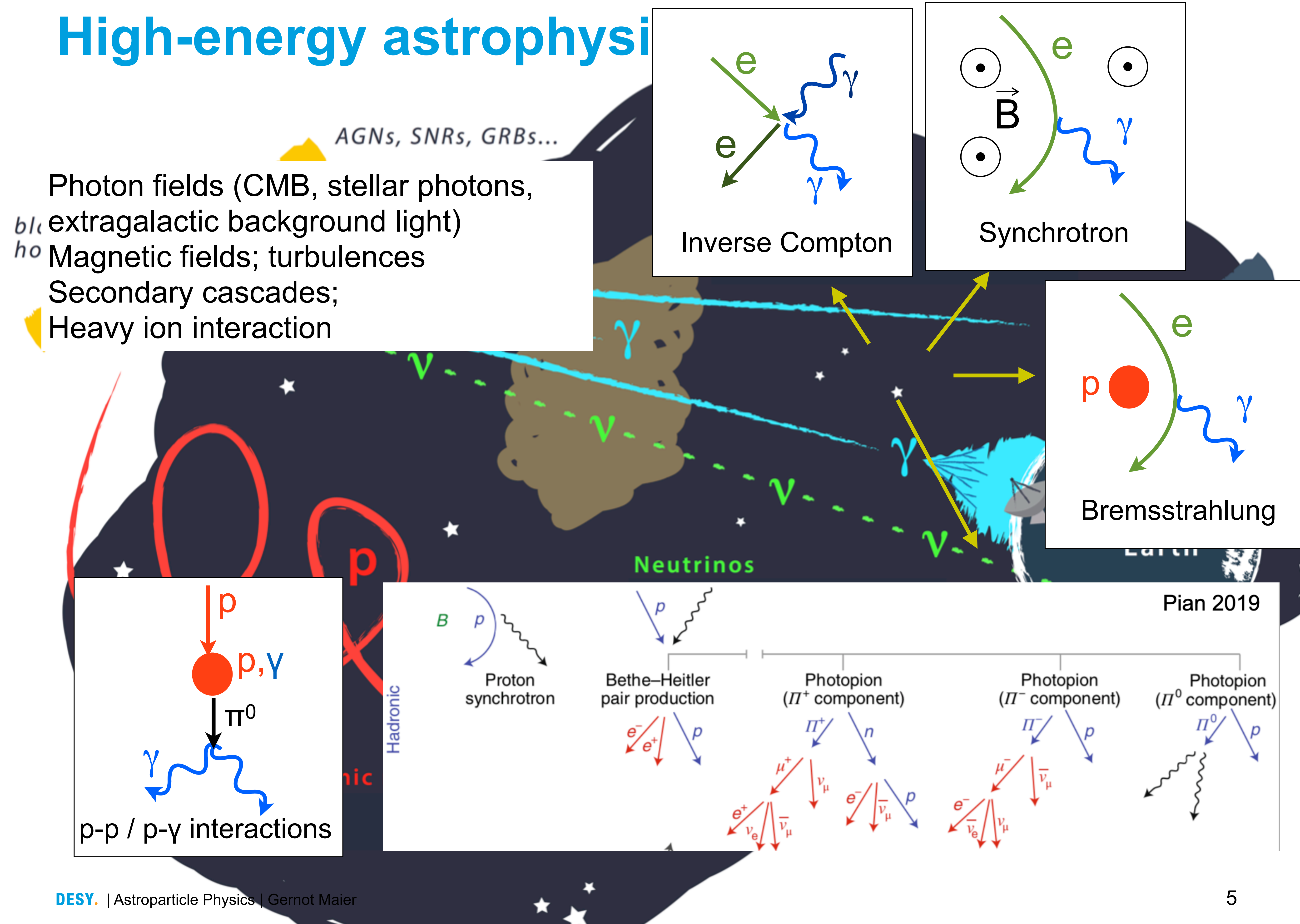


High-energy astrophysics



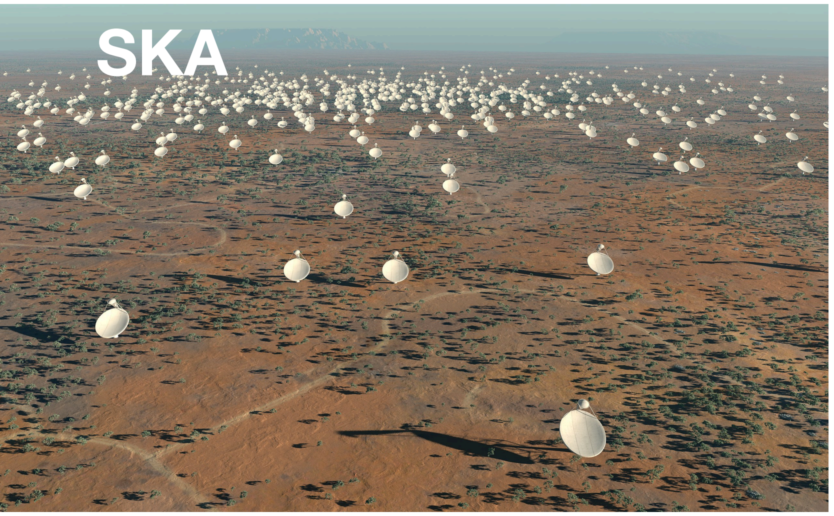
High-energy astrophysi

Photon fields (CMB, stellar photons, extragalactic background light)
Magnetic fields; turbulences
Secondary cascades;
Heavy ion interaction

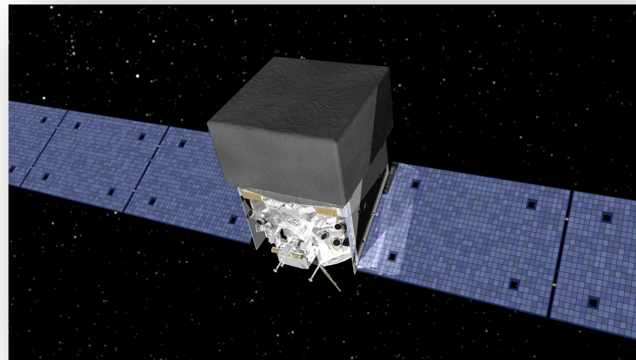


Observatories

SKA



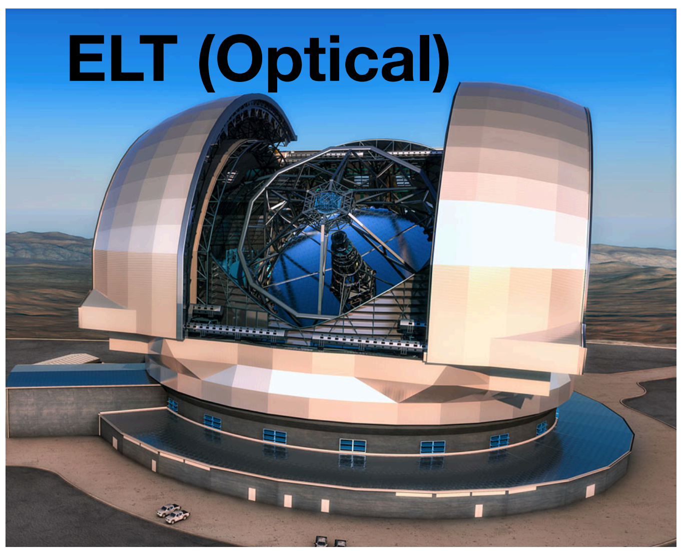
Fermi (Gamma-rays)



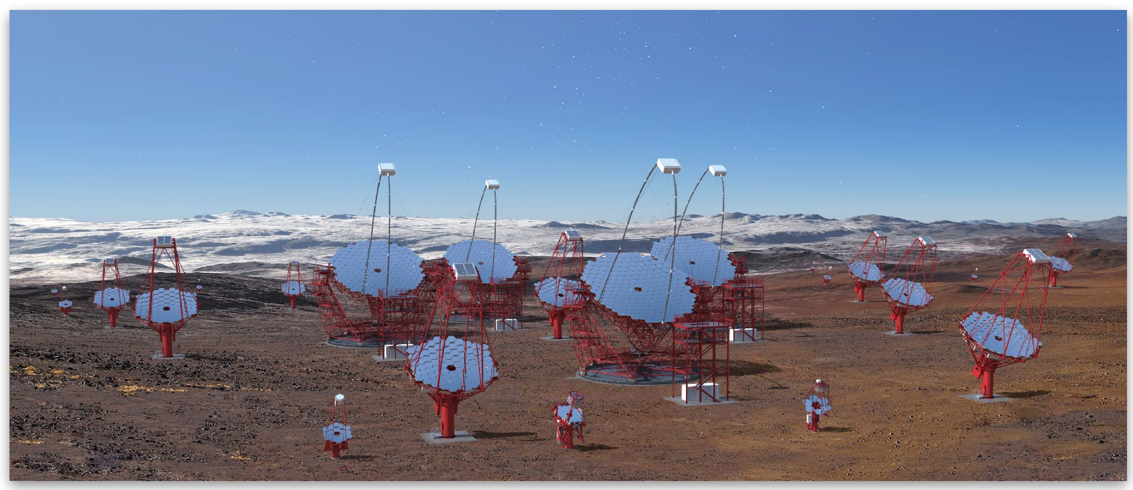
Suzaku (X-rays)

J Webb (optical, IR)

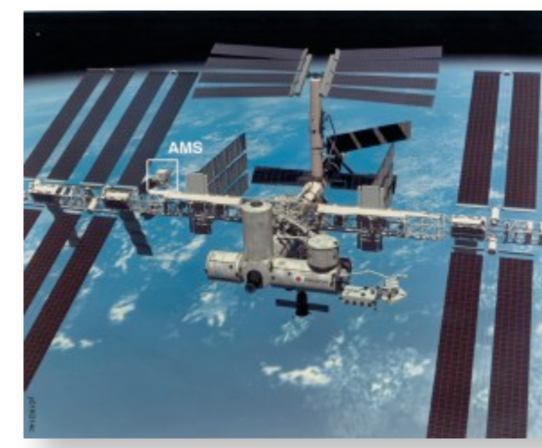
ELT (Optical)



CTA (Gamma-rays)



AMS (Cosmic Rays)



Auger (Cosmic Rays)

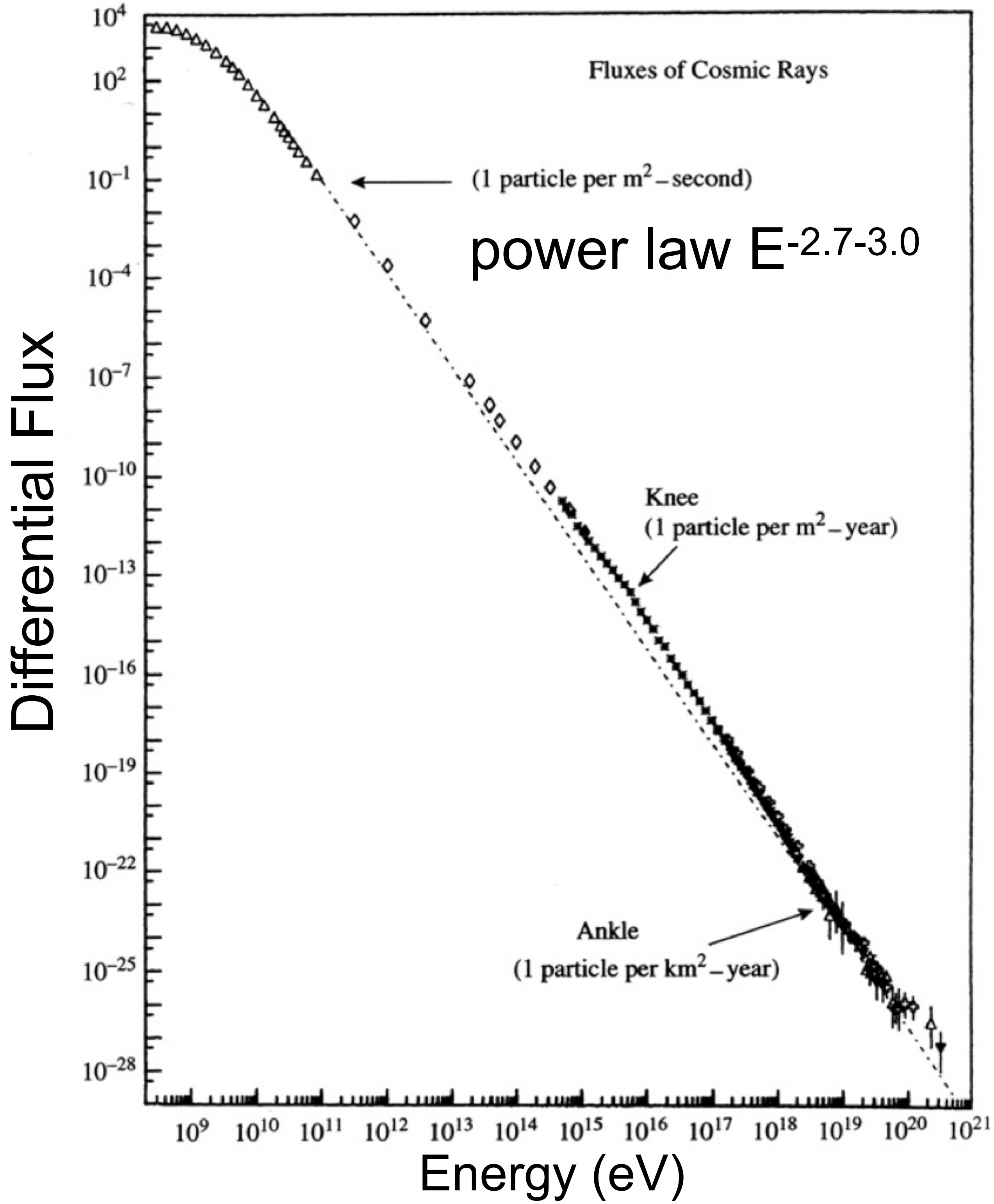
LIGO (Gravitational waves)

IceCube (Neutrinos)

Cosmic Rays

“Cosmic rays are high-energy protons and atomic nuclei which move through space at nearly the speed of light. They originate from the sun, from outside of the solar system, and from distant galaxies.” (Wikipedia)

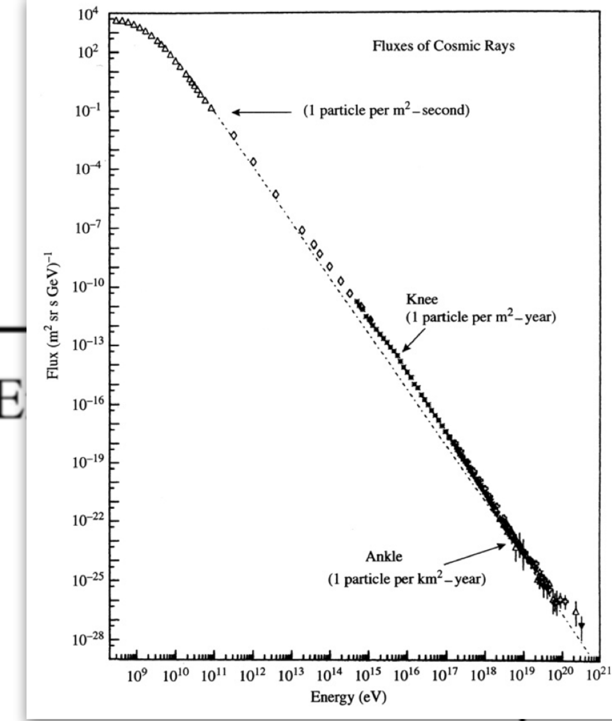
Cosmic Ray Energy Spectrum

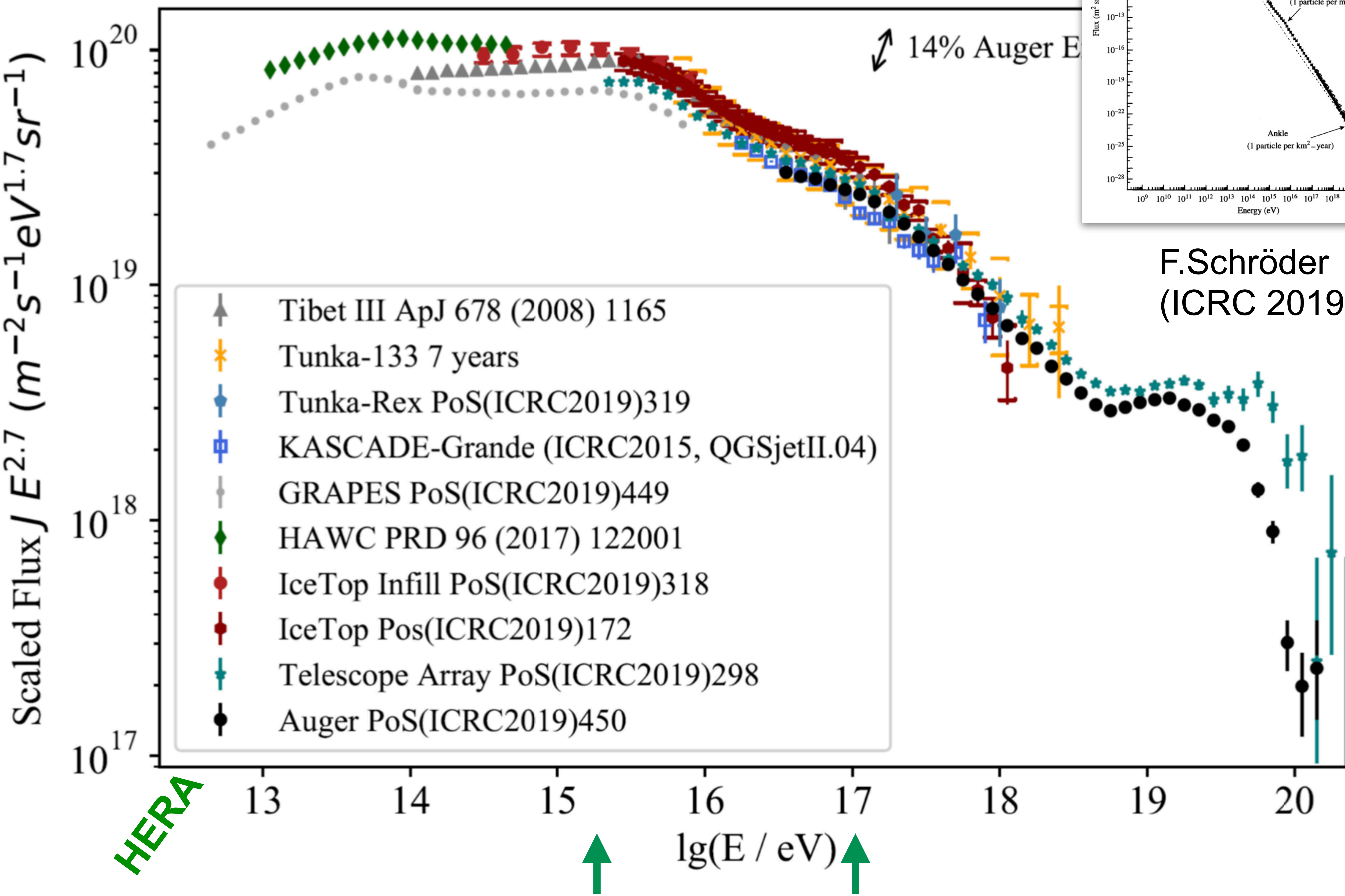


98% nuclei, mostly p, He,
but also heavier nuclei
2% electrons
(at a few GeV;
strongly energy dependent)

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

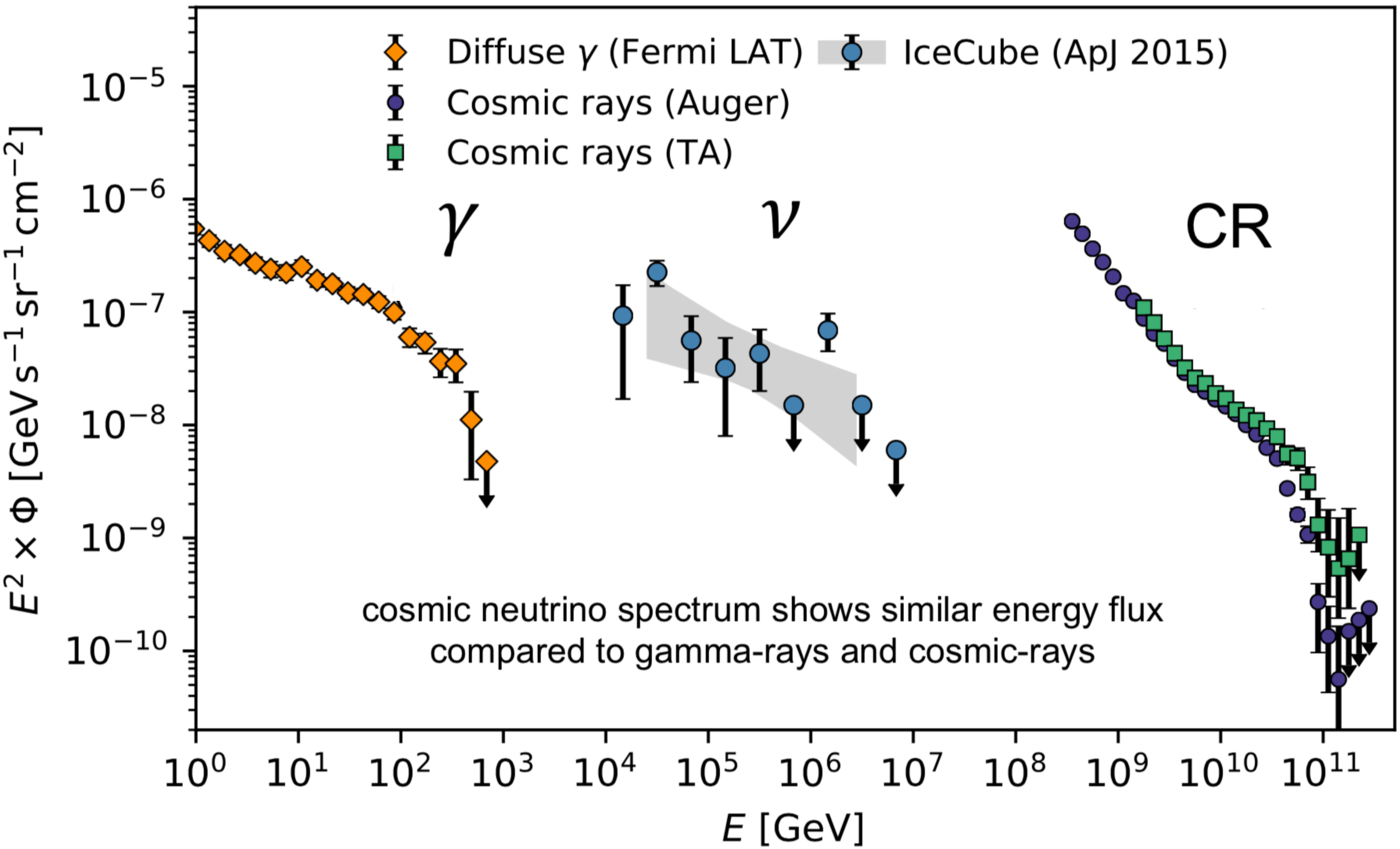
The Cosmic Ray Energy Spectrum





F.Schröder
(ICRC 2019)

Cosmic Rays, Neutrinos, Gamma rays

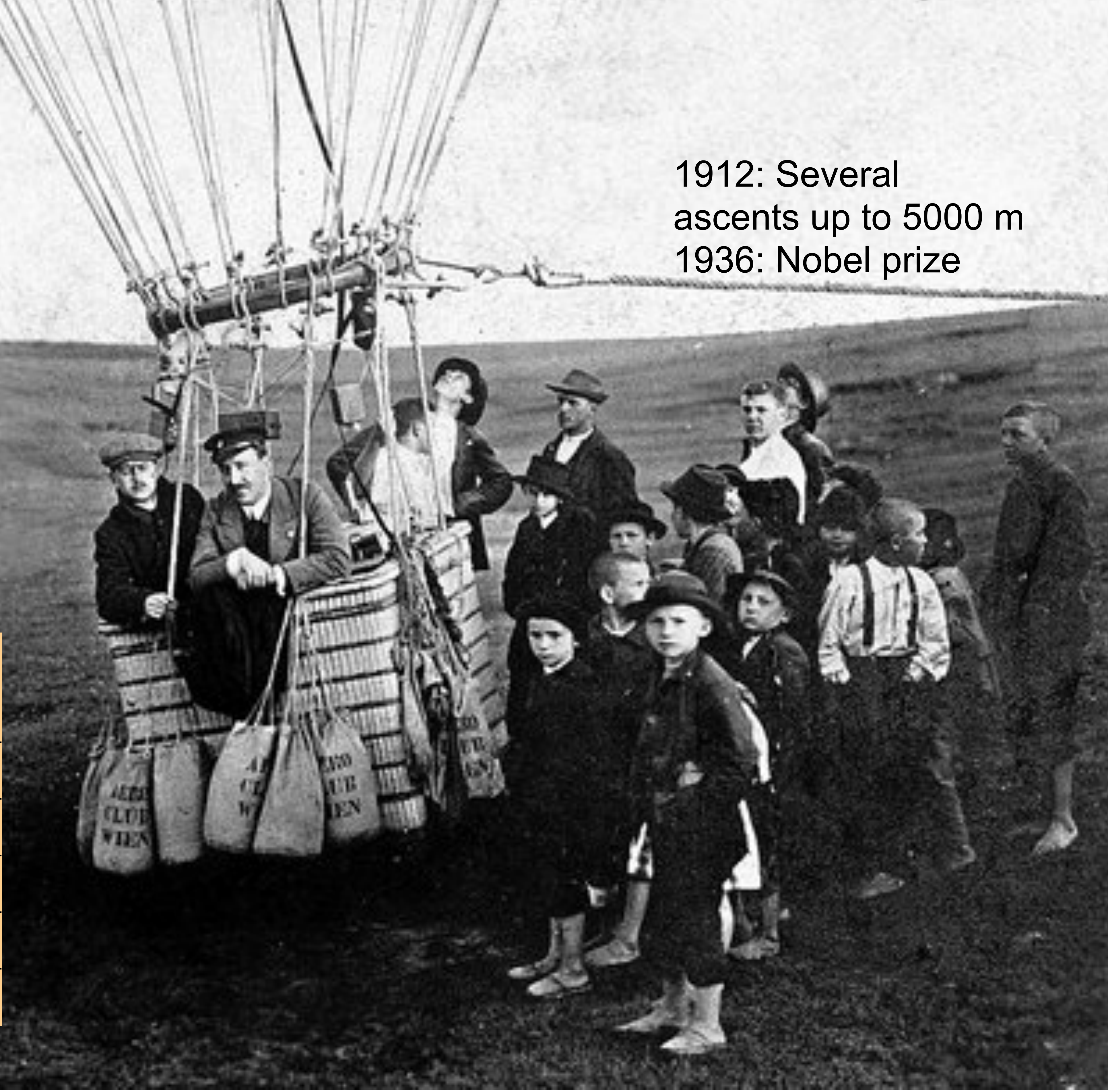


e.g. Ackermann et al, ApJ 799 (2015)

Viktor Hess

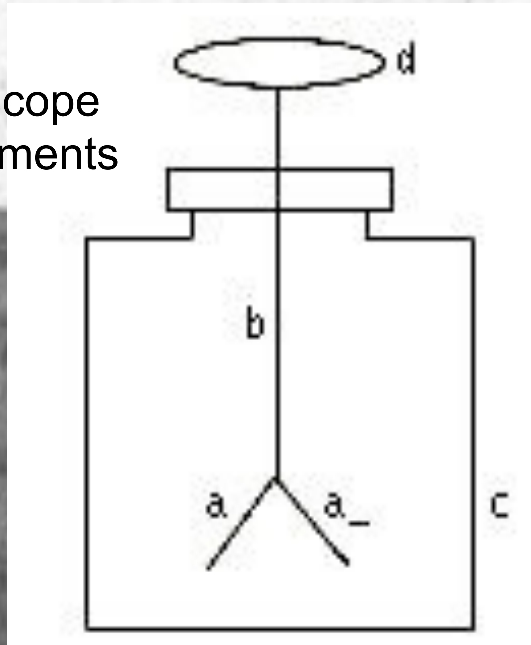
1912: Several ascents up to 5000 m
1936: Nobel prize

Viktor Hess



1912: Several ascents up to 5000 m
1936: Nobel prize

Electroscope measurements



Altitude (km)	Change in Ionization (10^6 m^{-3})
0	0
1	1,2
3	8,8
4	28,7
5	61,3

High energy astrophysics in one equation

$N_i(E,x,t)dE$ 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

convection with velocity $\bar{u}$

$$\frac{\partial N}{\partial t} = \nabla\cdot(D_i\nabla N_i) - \frac{\partial}{\partial E}(dE/dt\,N_i(E)) - \nabla\cdot\vec{u}N_i(E)$$
$$+\,Q_i(E,t) - p_iN_i + \frac{v\rho}{m}\sum_{k\geq i}\frac{d\sigma_{i,k}(E,E')}{dE}N_k(E')dE'$$

source term

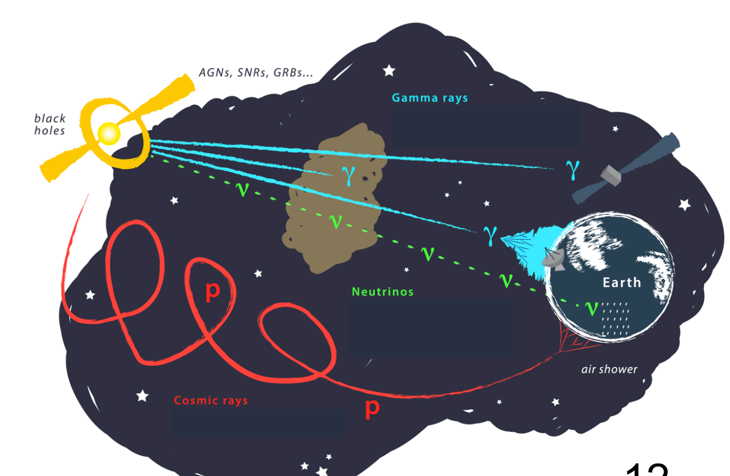
loss term

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

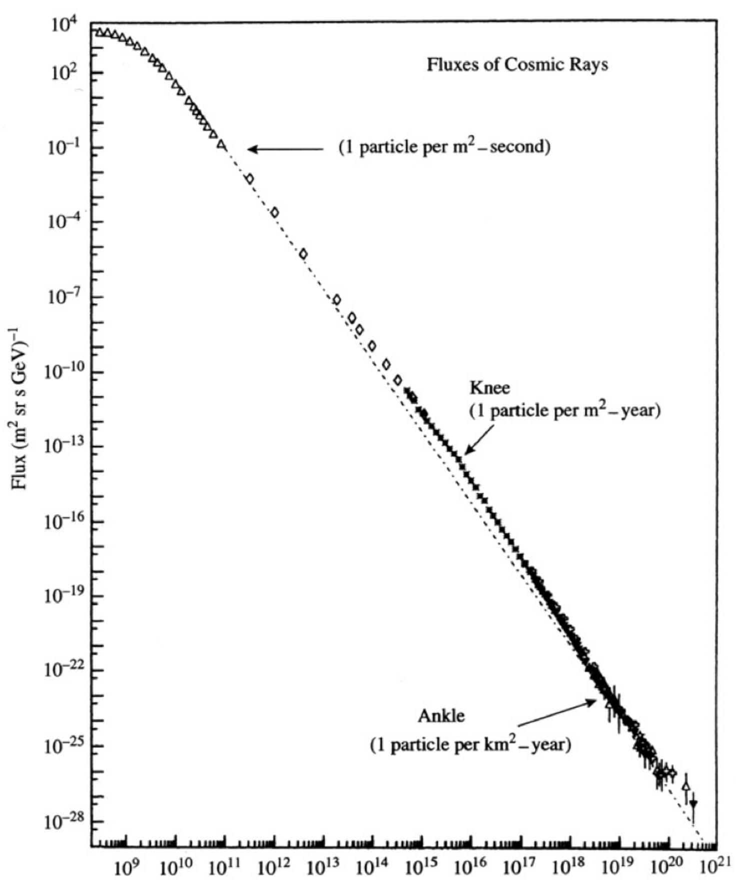
turbulences & magnetic fields

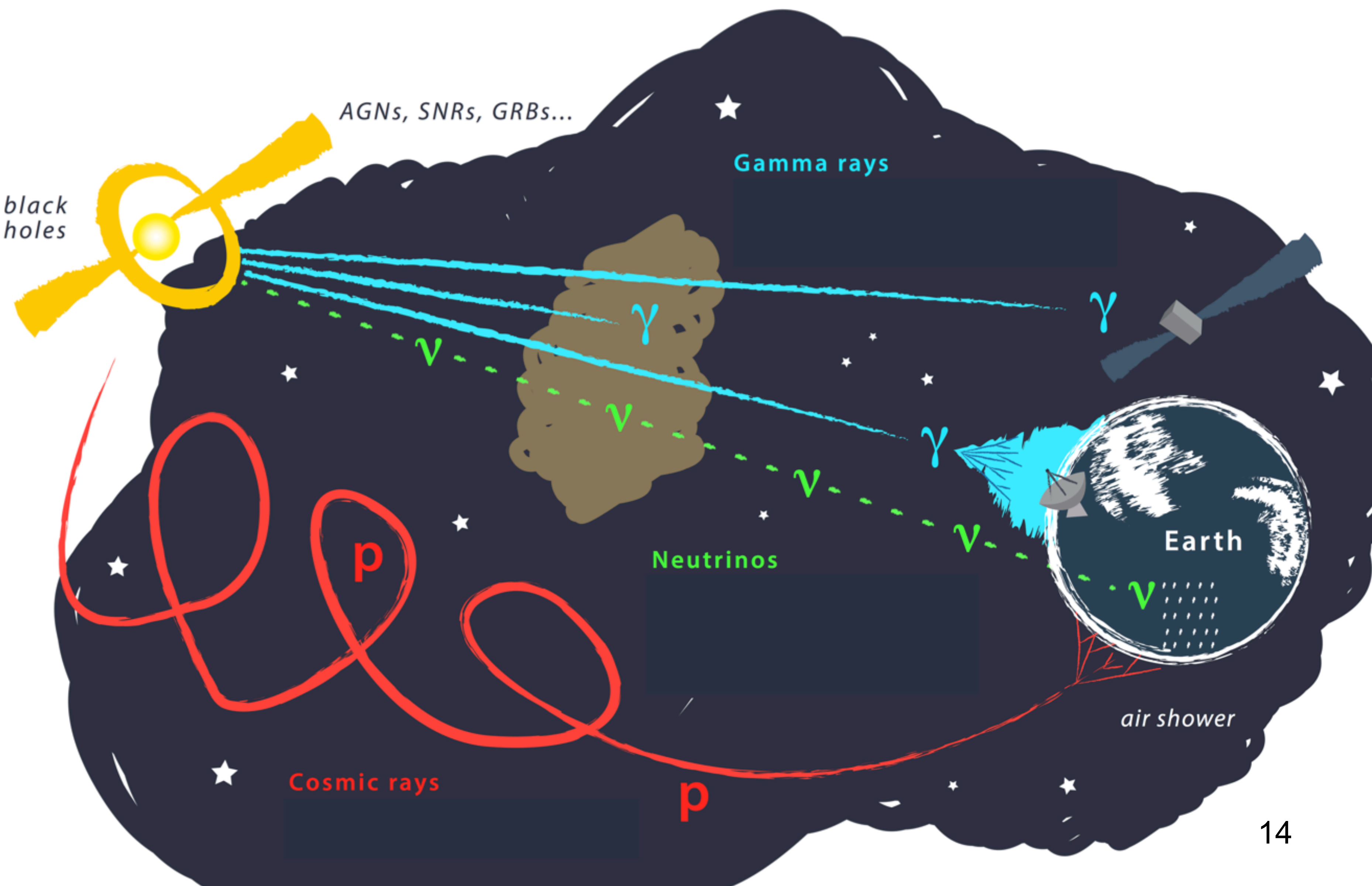


Some of the main questions in Astroparticle Physics

1. Cosmic Particle Acceleration

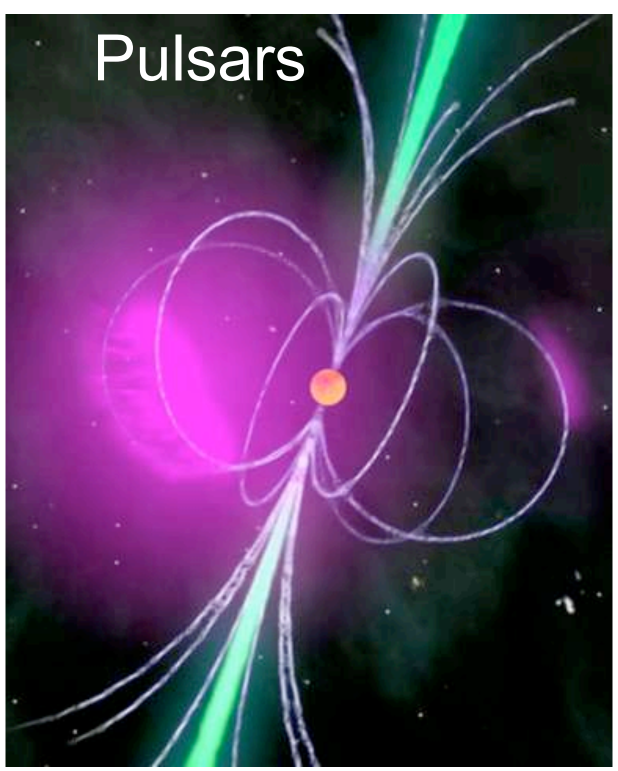
- How and where are particles accelerated?
- How do they propagate?
- What is their impact on the environment?

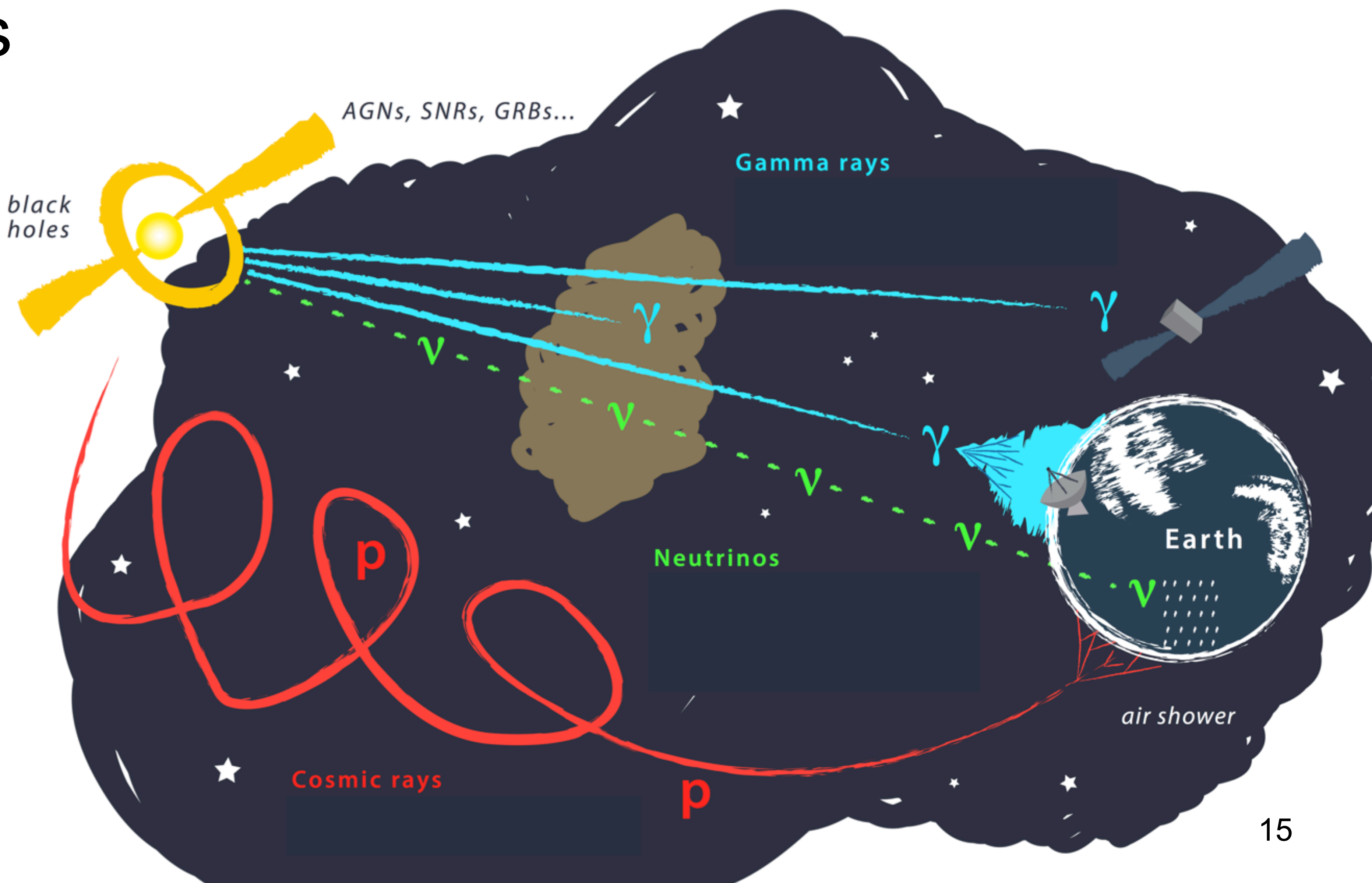




2. Probing Extreme Environments

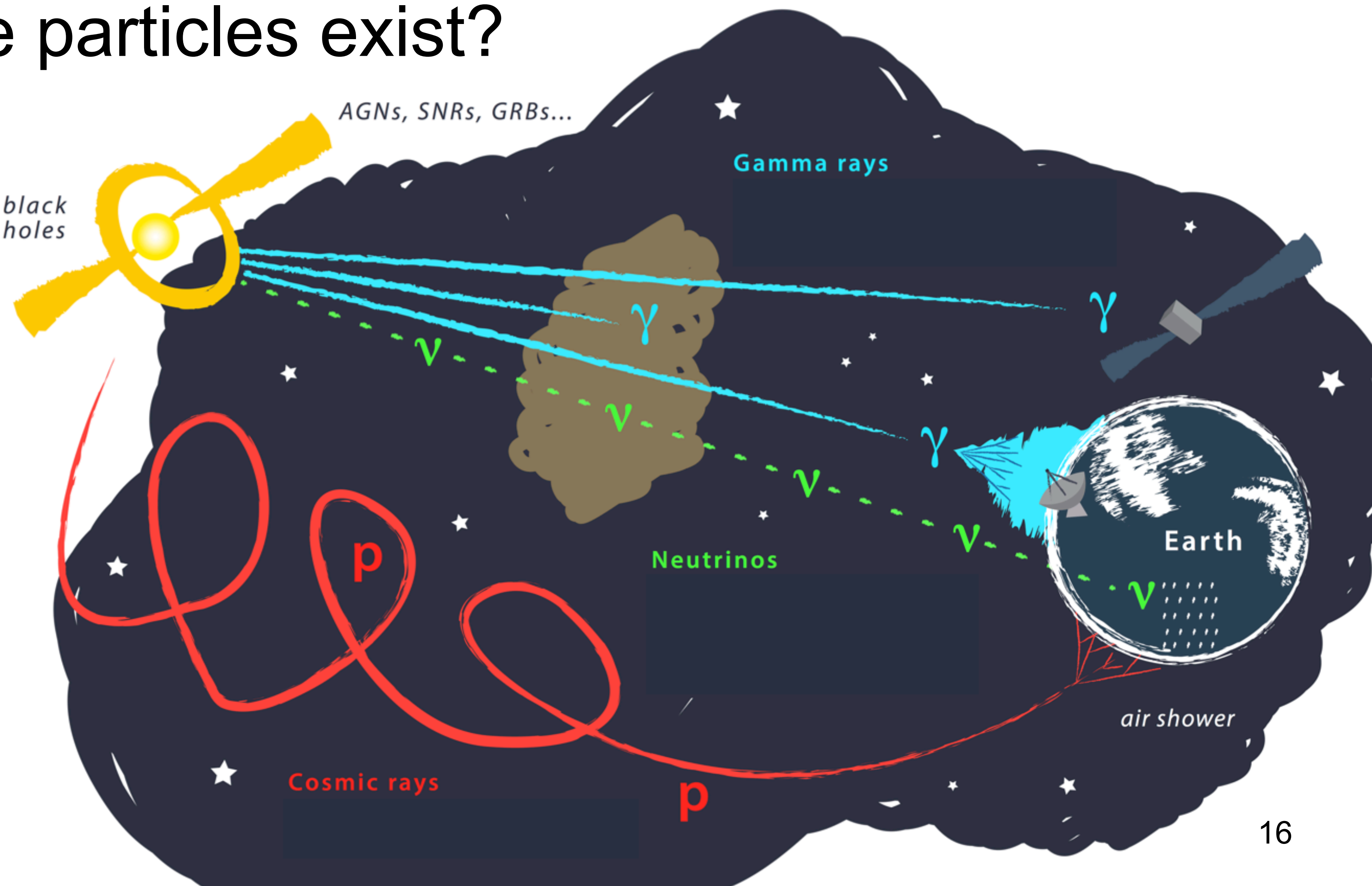
- Processes close to neutron stars and black holes
- Processes in relativistic jets, winds, accretion, explosions, pulsars
- Cosmic voids



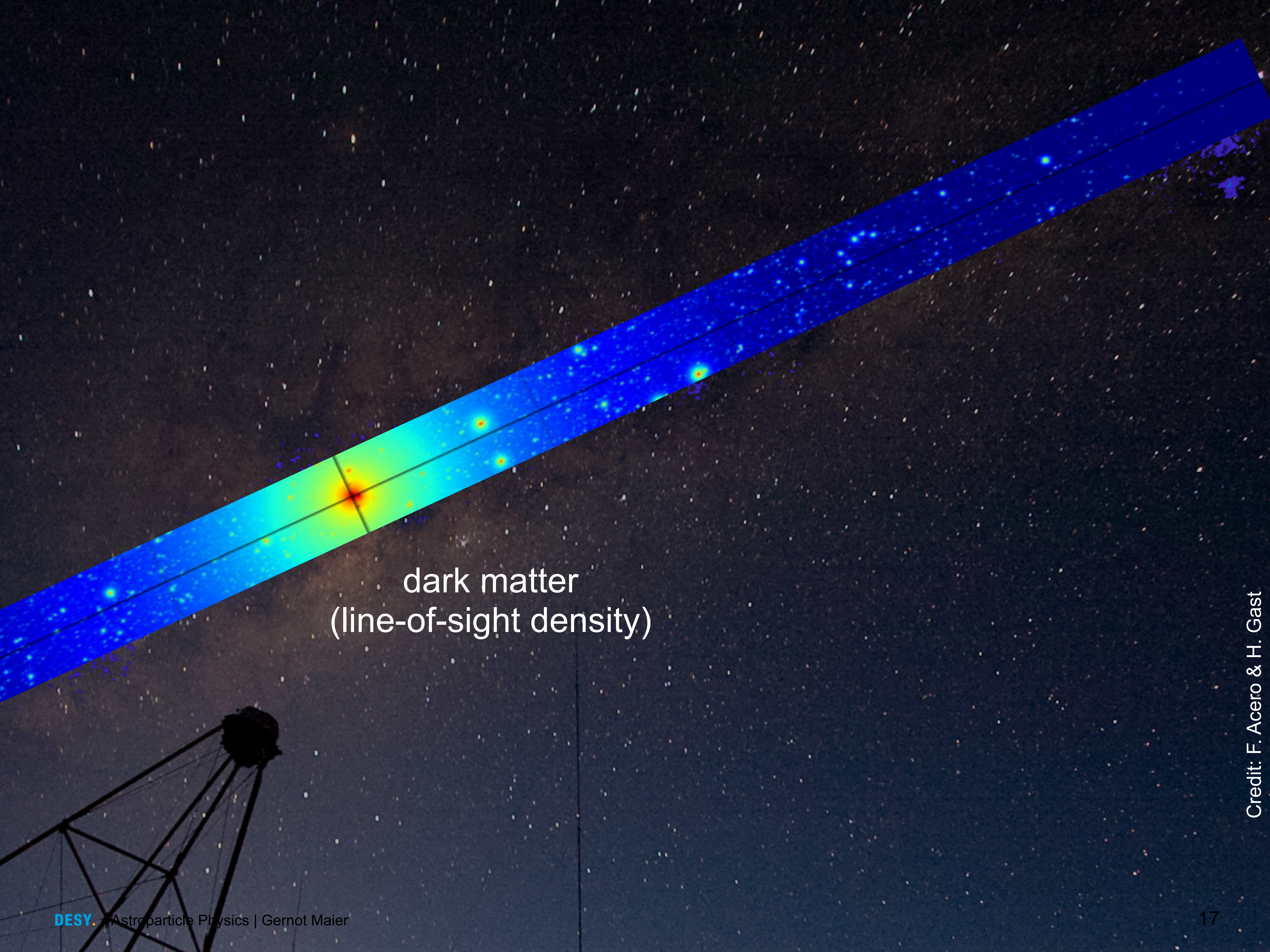


3. Exploring Frontiers of Physics

- What is the nature of dark matter?
  Does it exist at all? How is it distributed?
- Is the speed of light constant?
- Do axion-like particles exist?




Credit: F. Acero & H. Gast

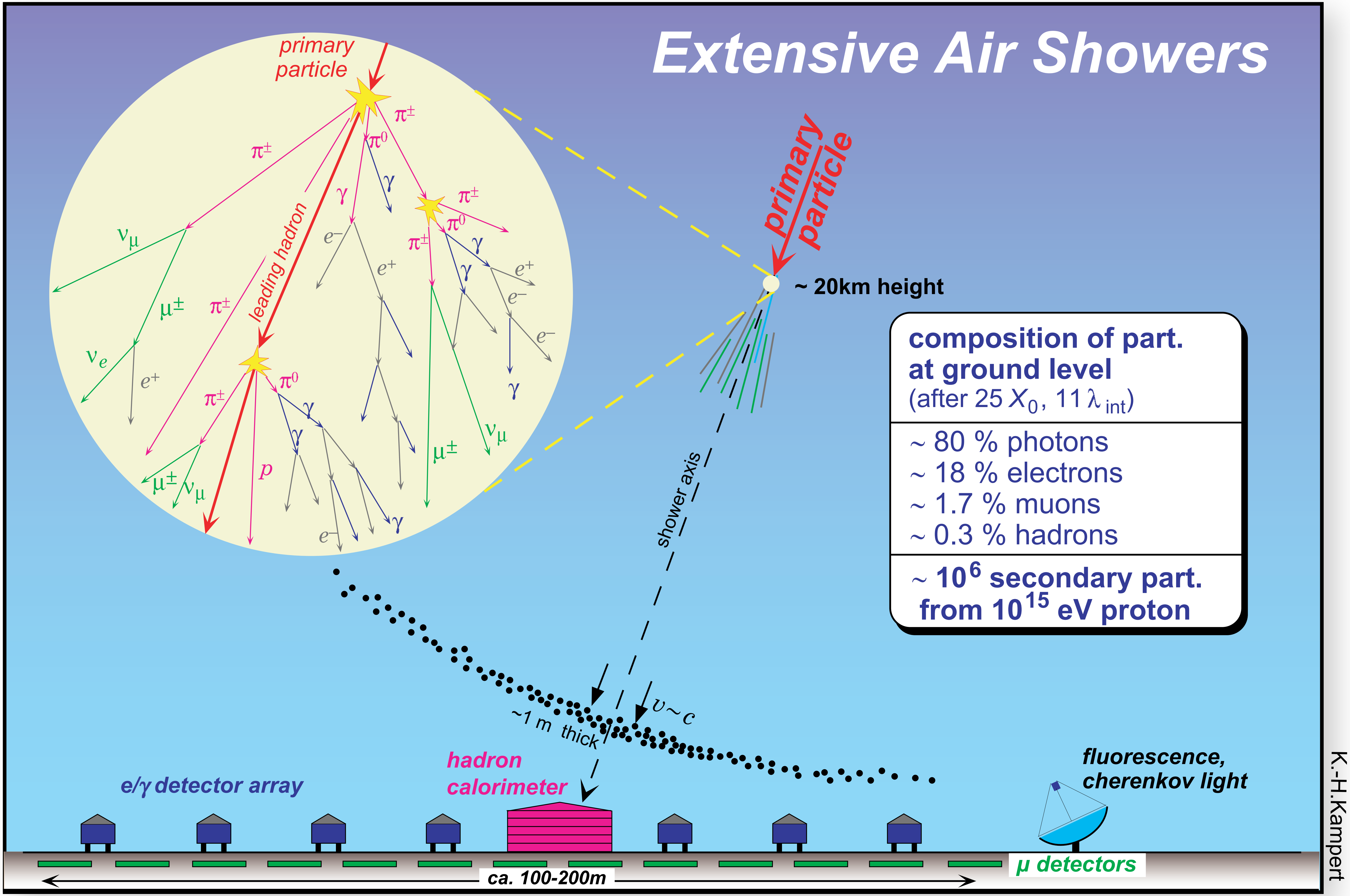

dark matter
(line-of-sight density)
Credit: F. Acero & H. Gast

Instruments

How to detect cosmic rays,

gamma rays, neutrinos, …

Extensive Air Showers



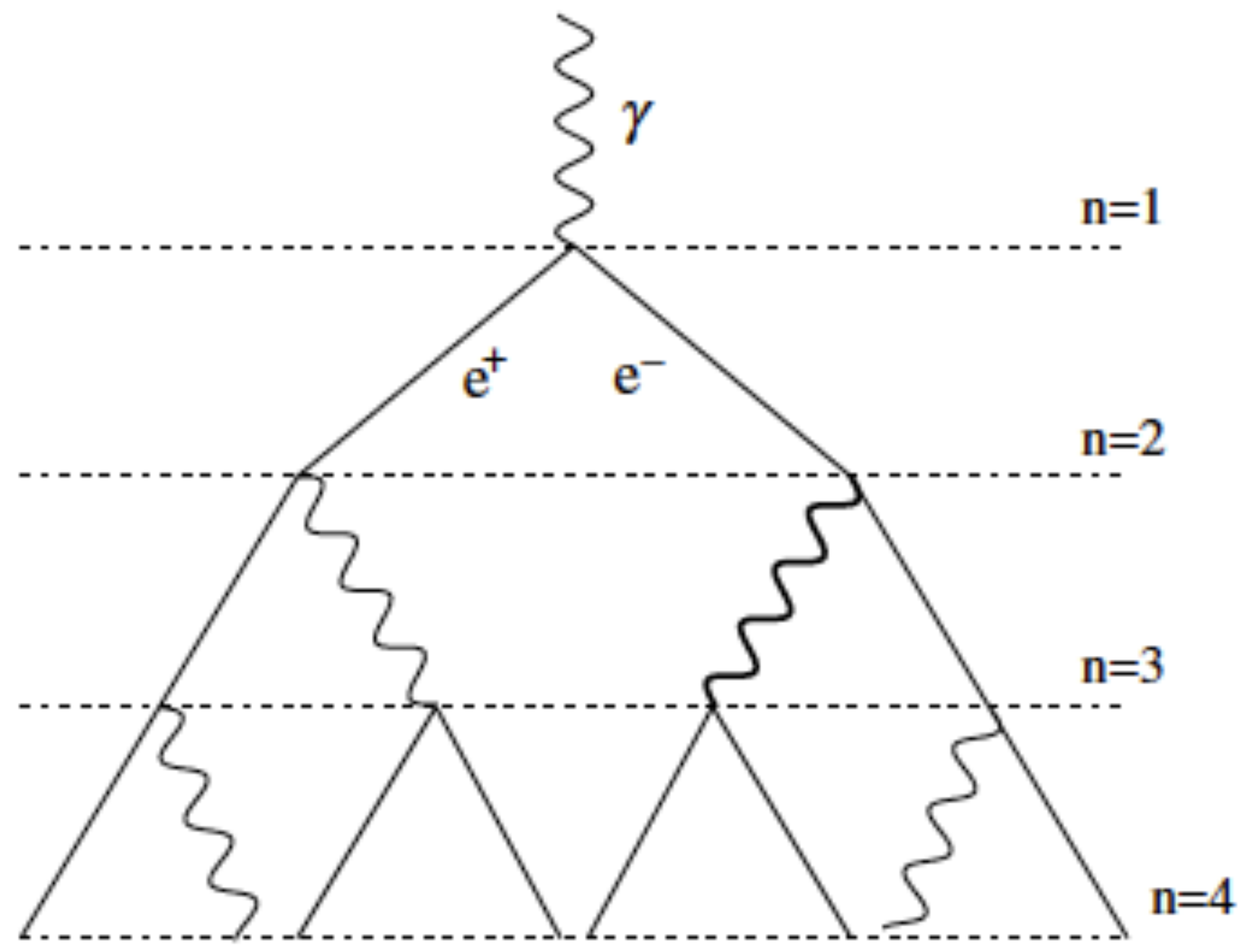
Extensive Air Shower: toy model for particle cascades

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

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

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

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

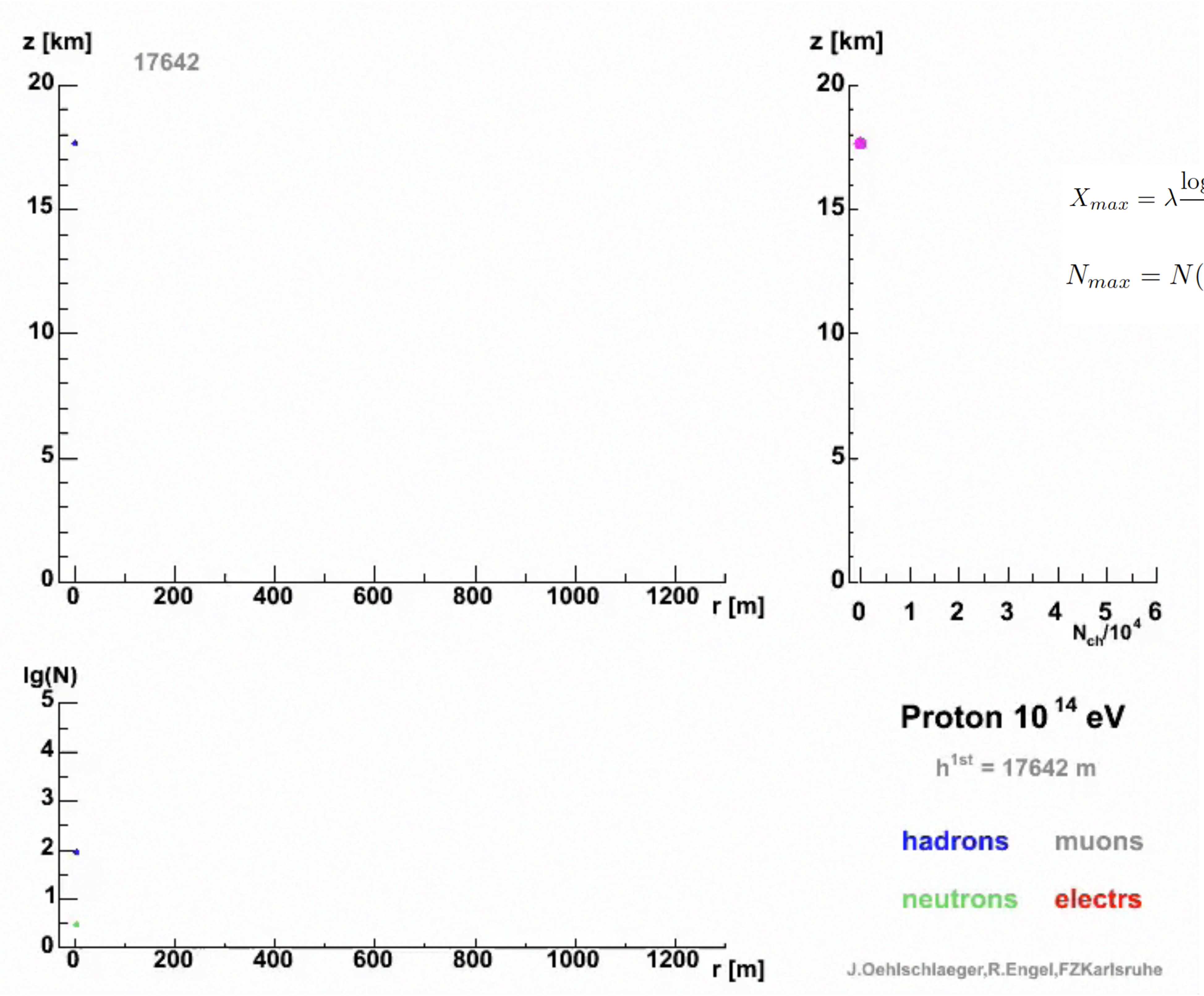


Heitler Model

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

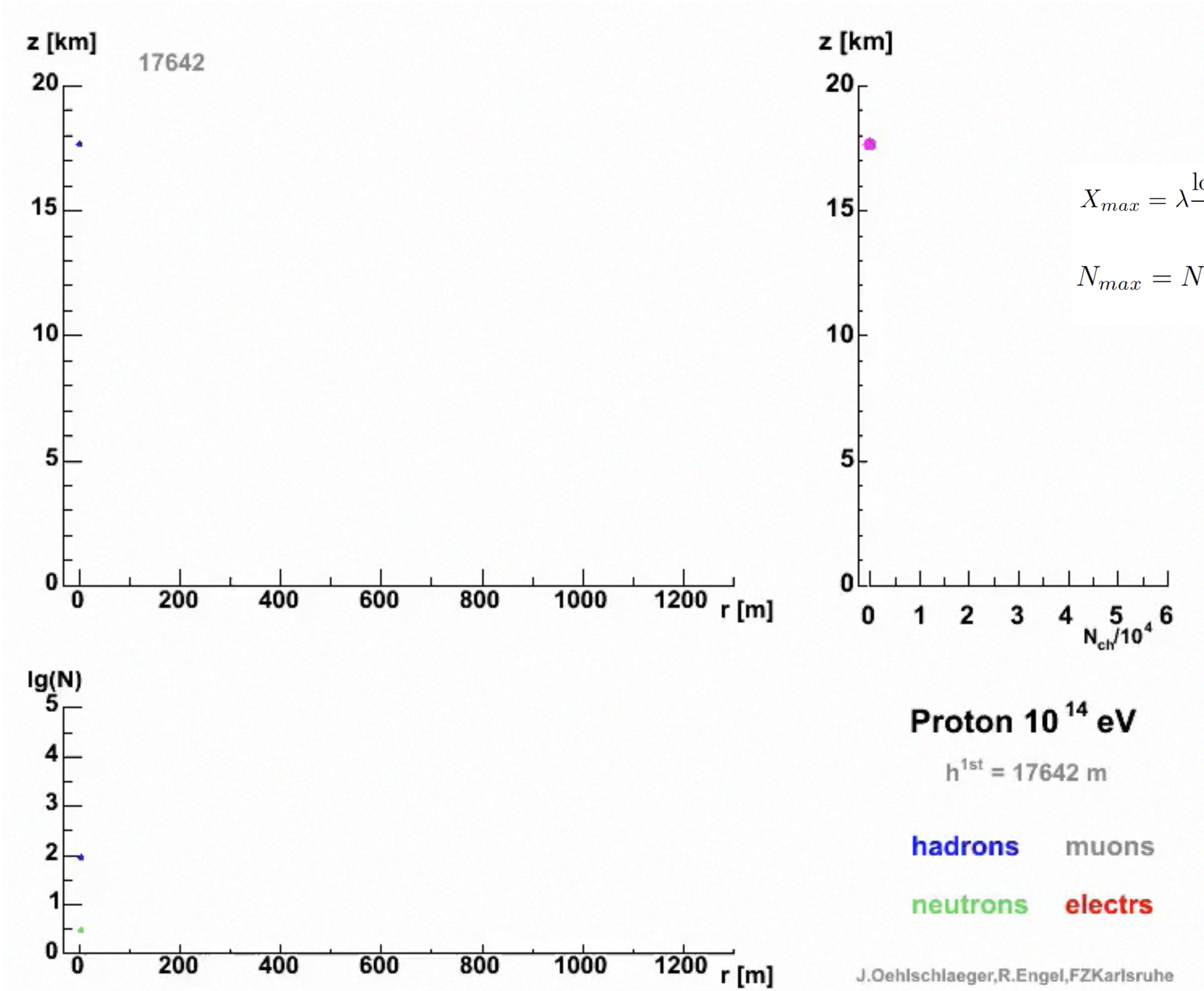
Extensive Air Shower



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

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

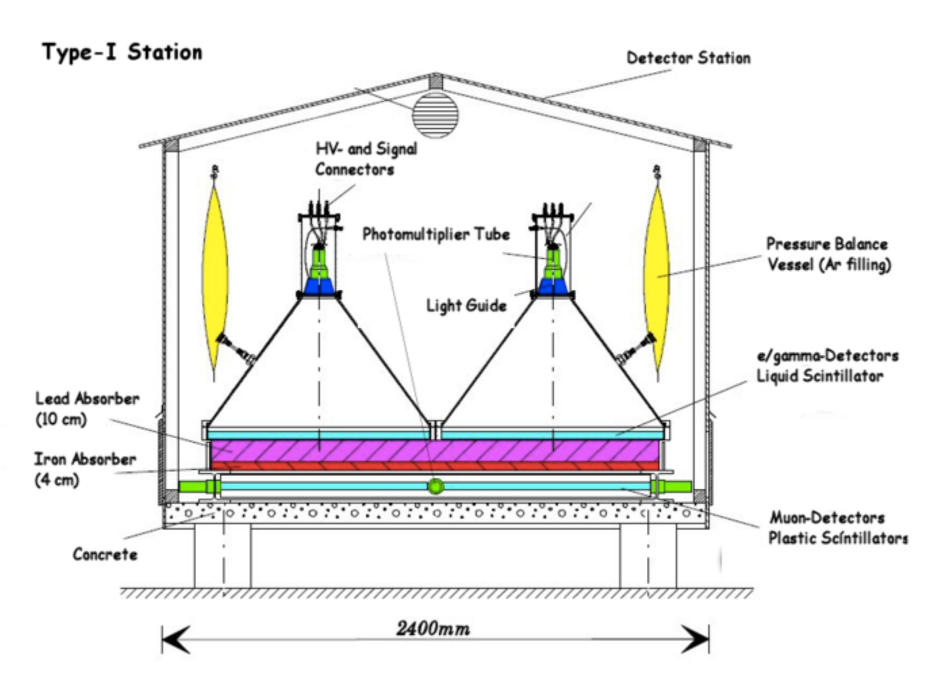
Extensive Air Shower

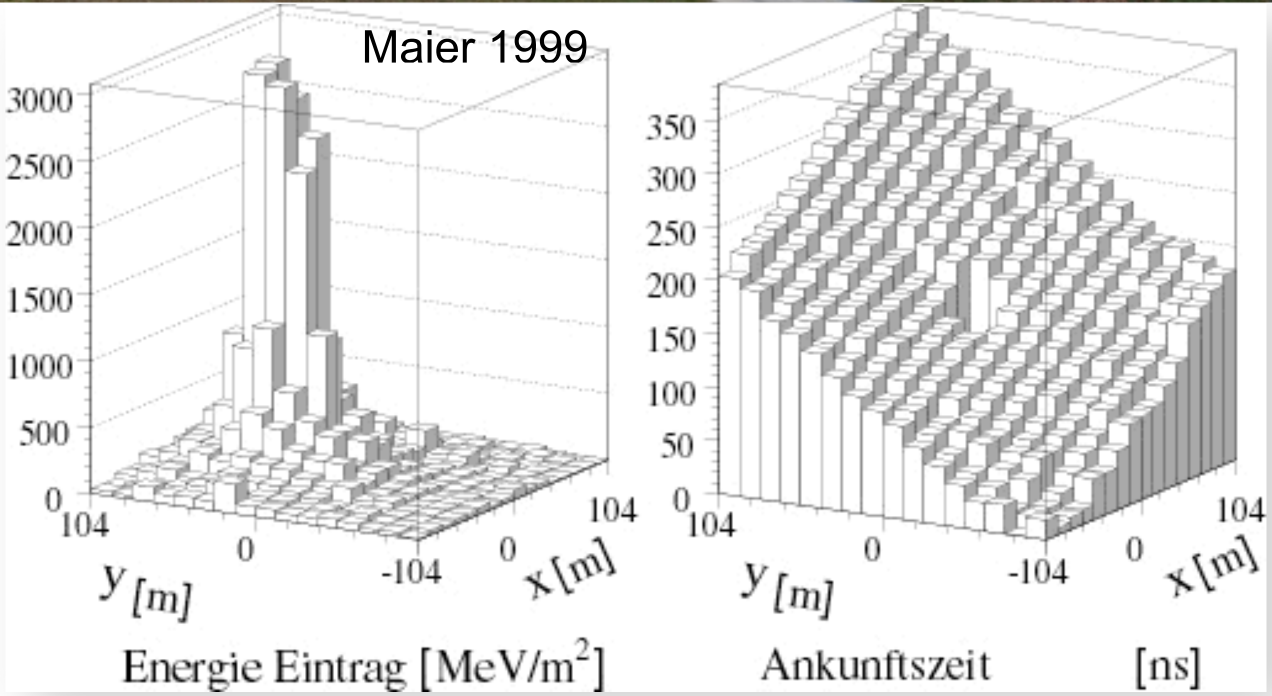


$$X_{max} = \lambda \frac{\log\left(E_0/E_C\right)}{\log 2} \propto \log(E_0)$$

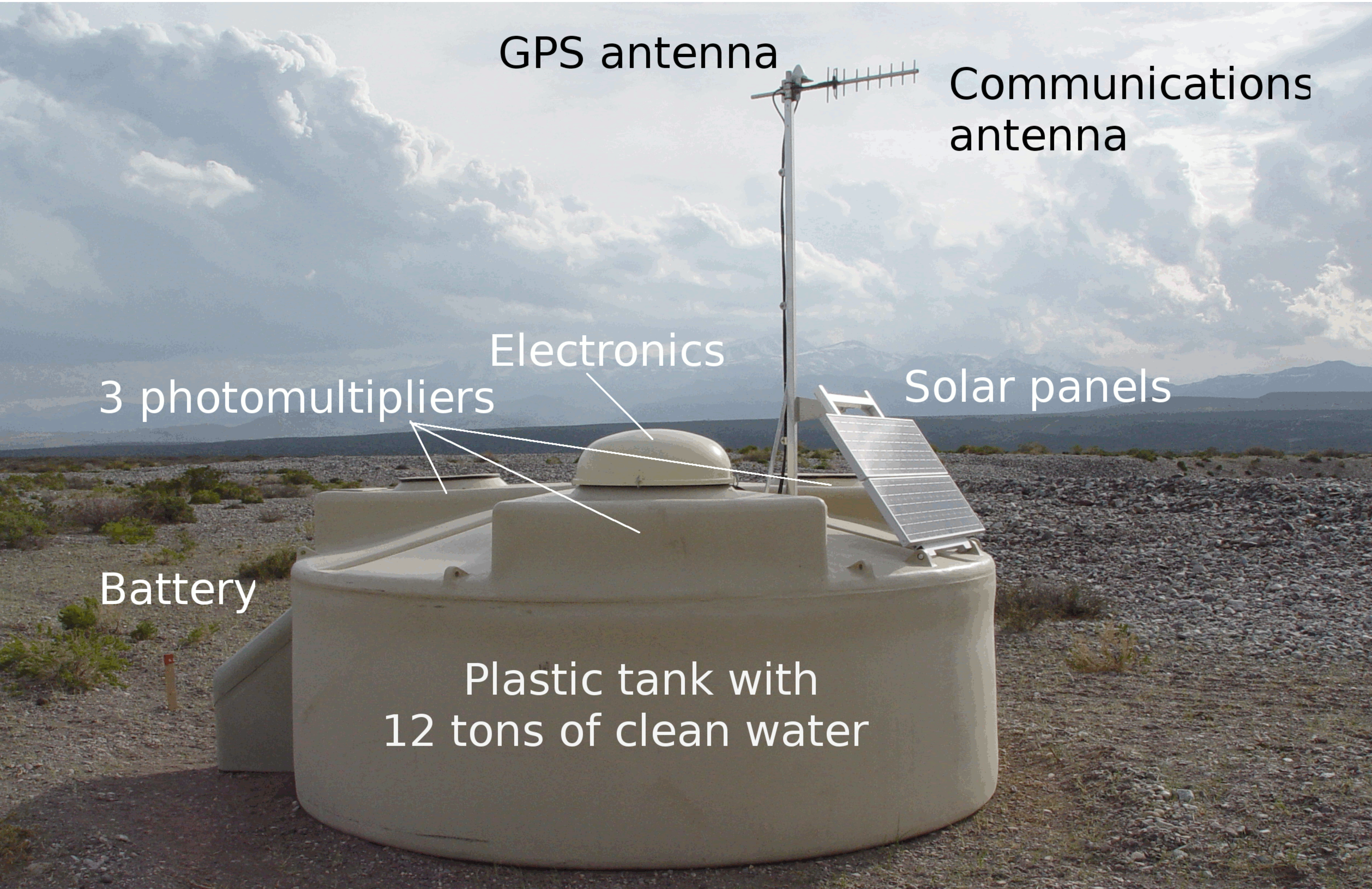
$$N_{max} = N(X_{max}) = \frac{E_0}{E_C} \propto E_0$$

KASCADE
Karlsruhe Shower Core and Array Detector

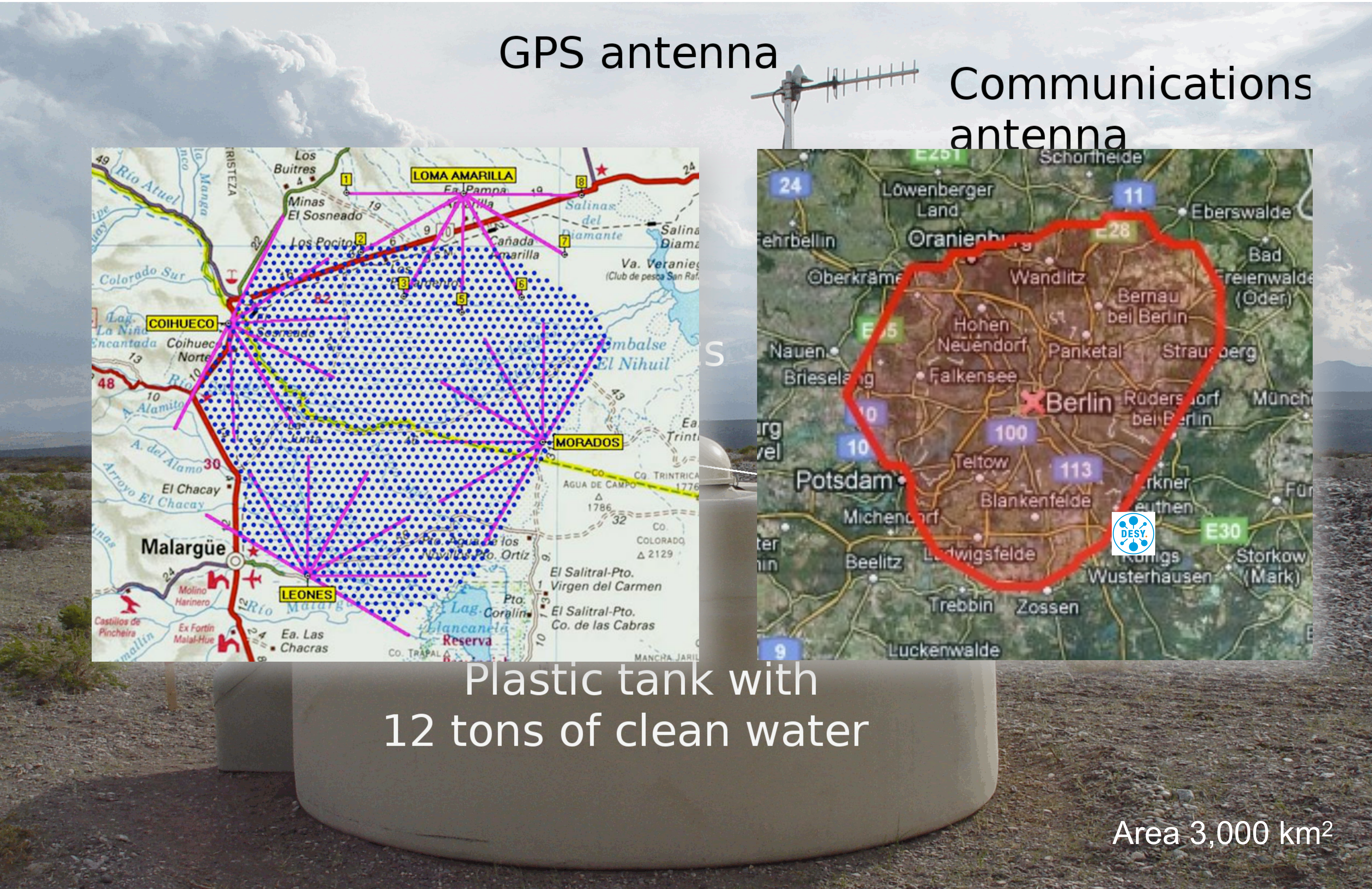


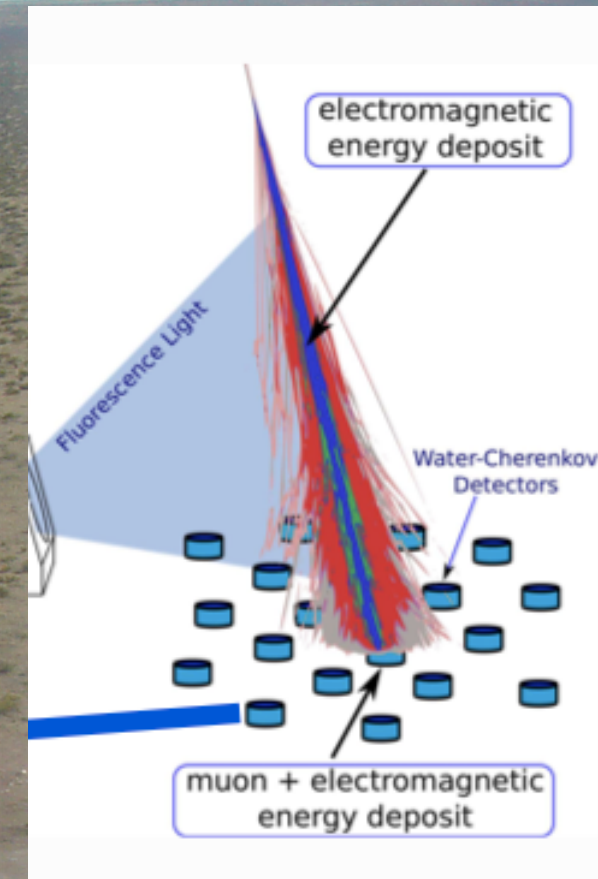


The Pierre Auger Observatory

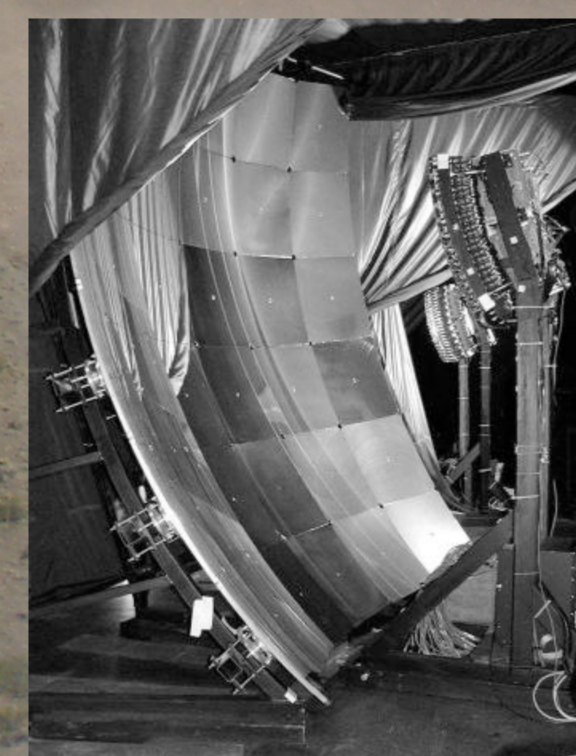


The Pierre Auger Observatory





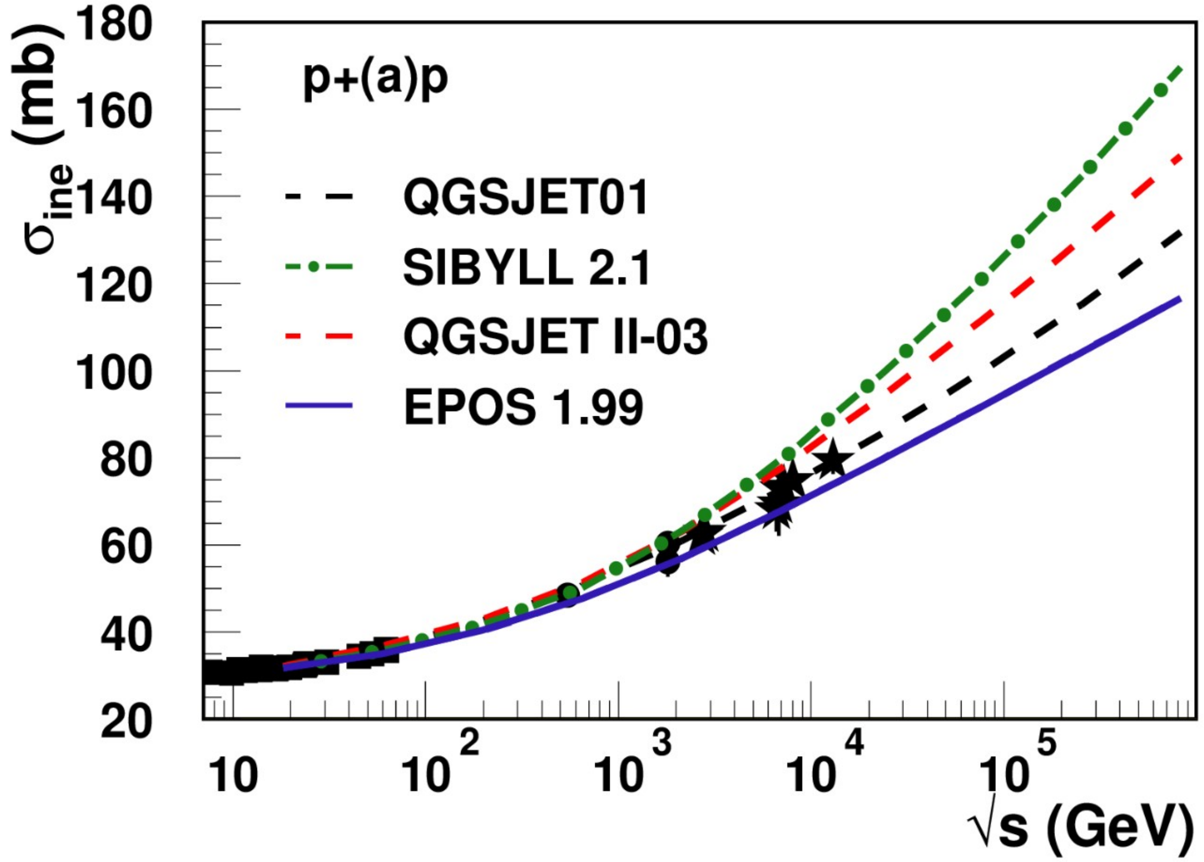
electrons excite N_2
decay to ground state by
isotropically emitting UV photons



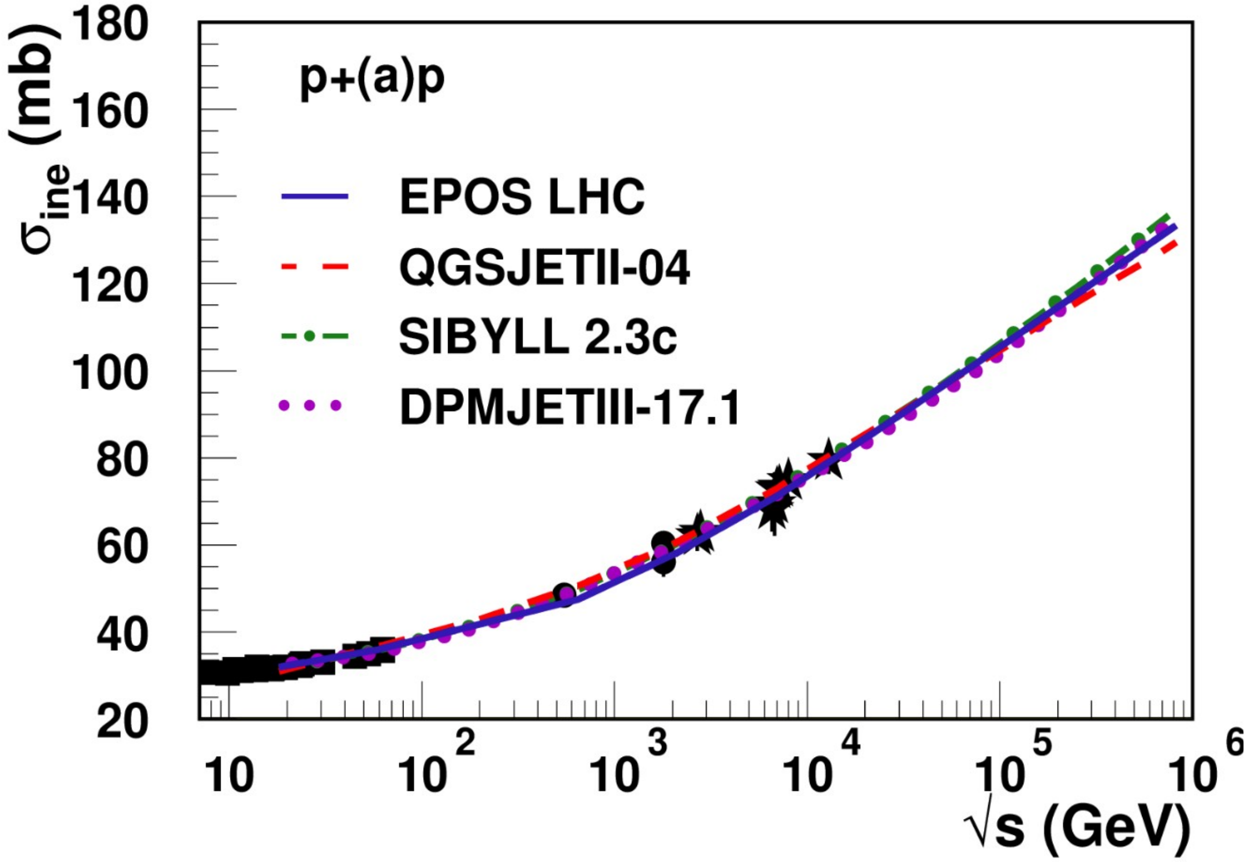
Extensive air shower: hadronic interactions

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

Pre - LHC

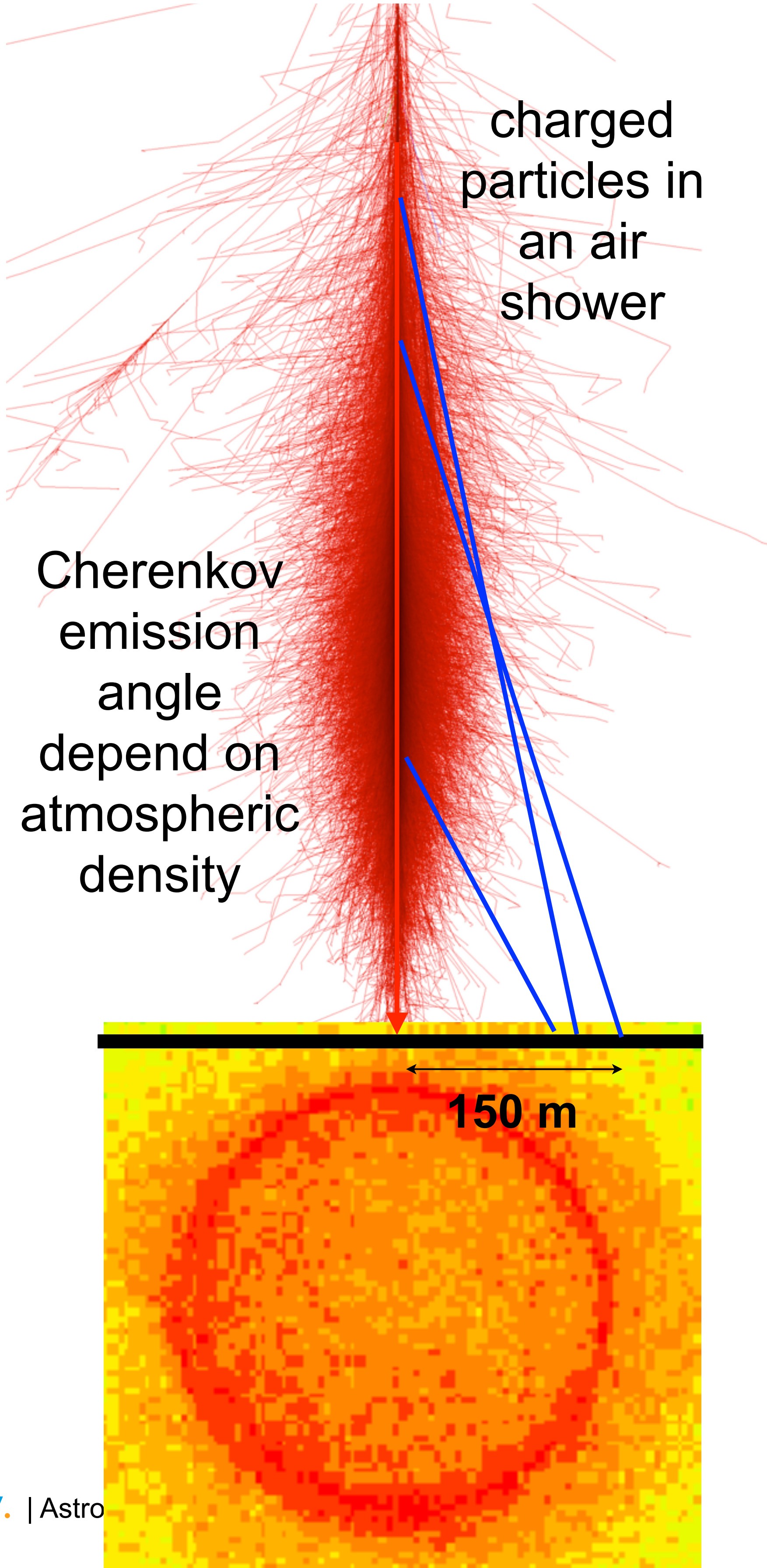


Post - LHC

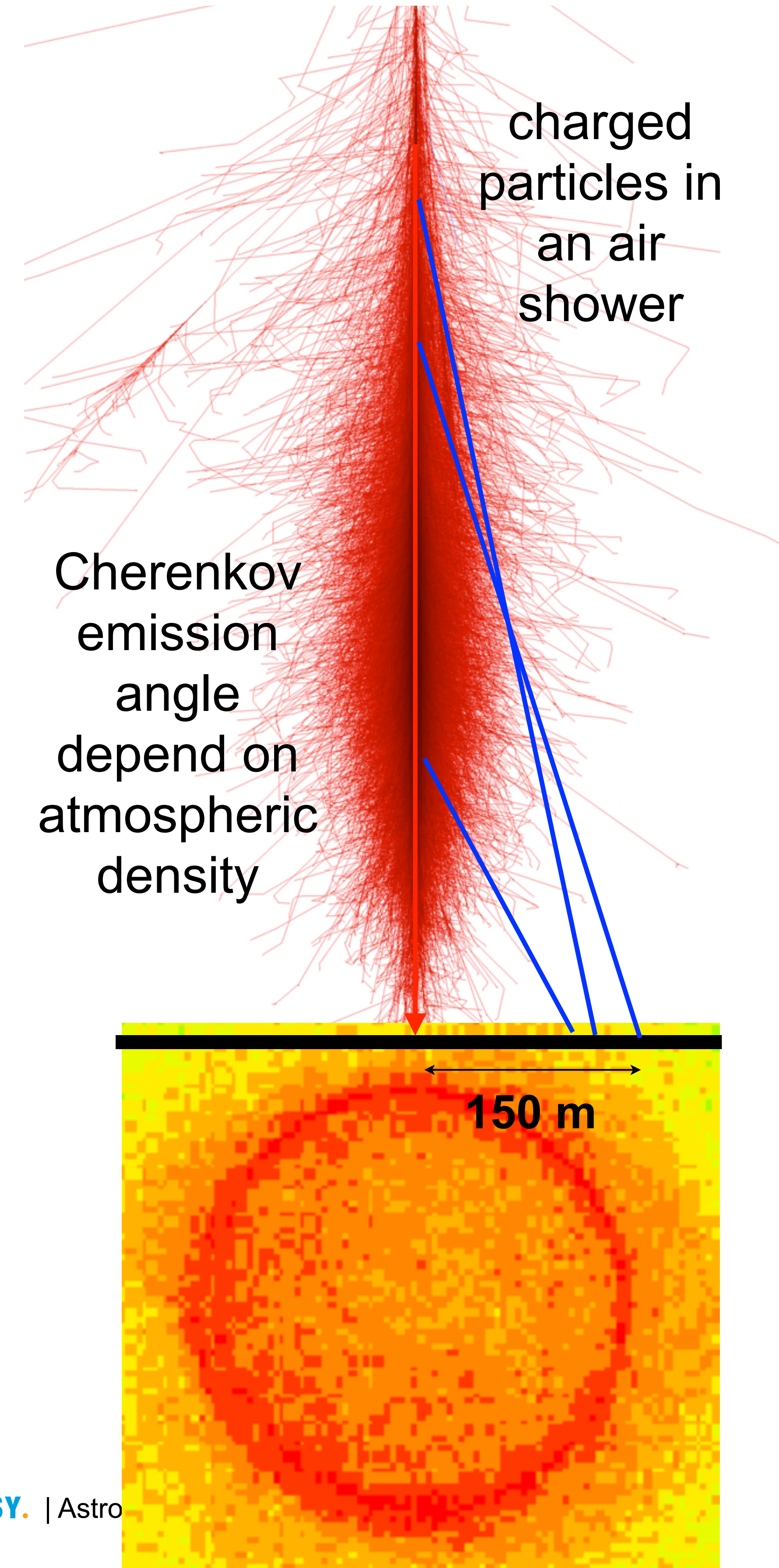


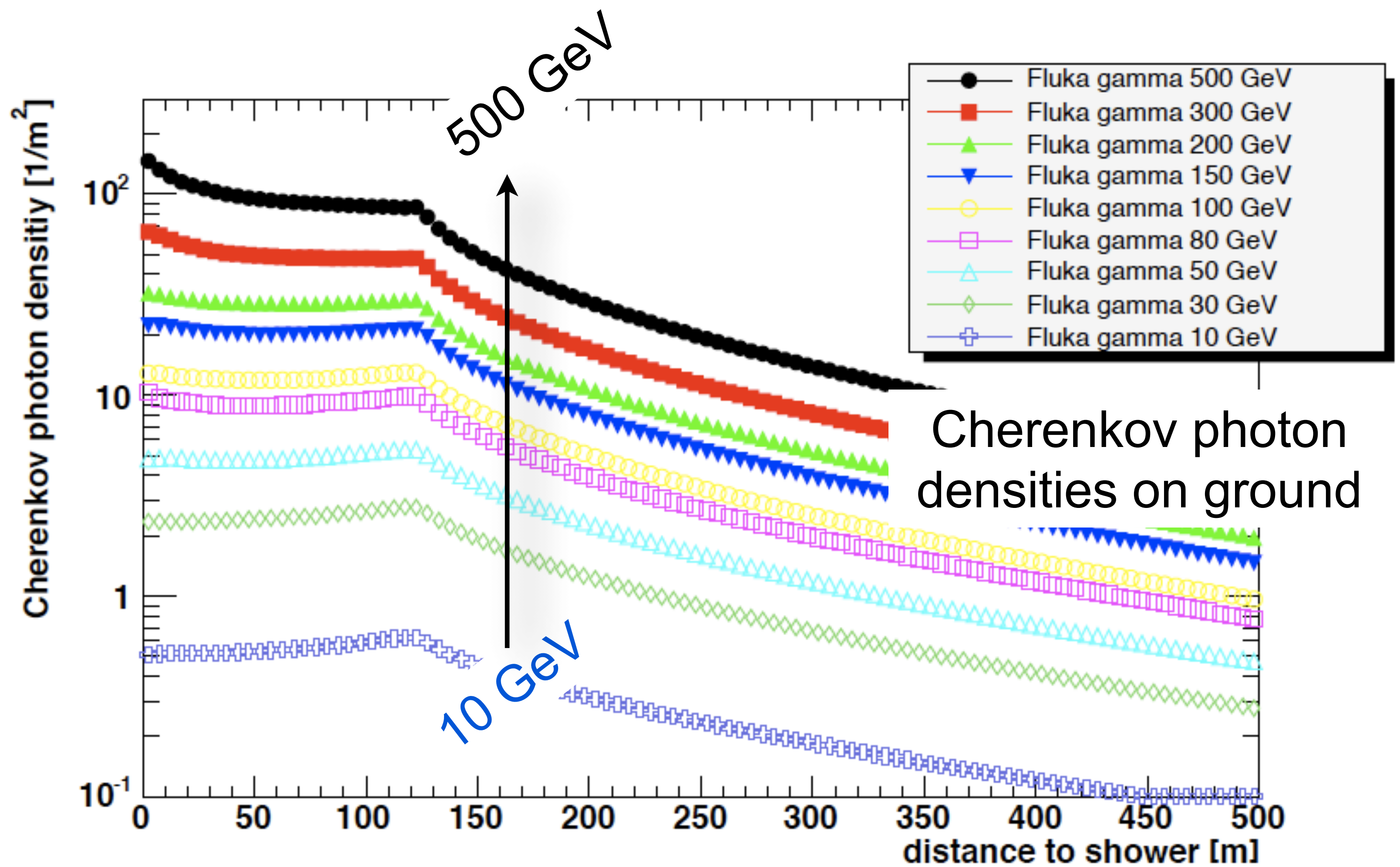
Pierog 2017

Extensive Air Showers and Cherenkov Emission



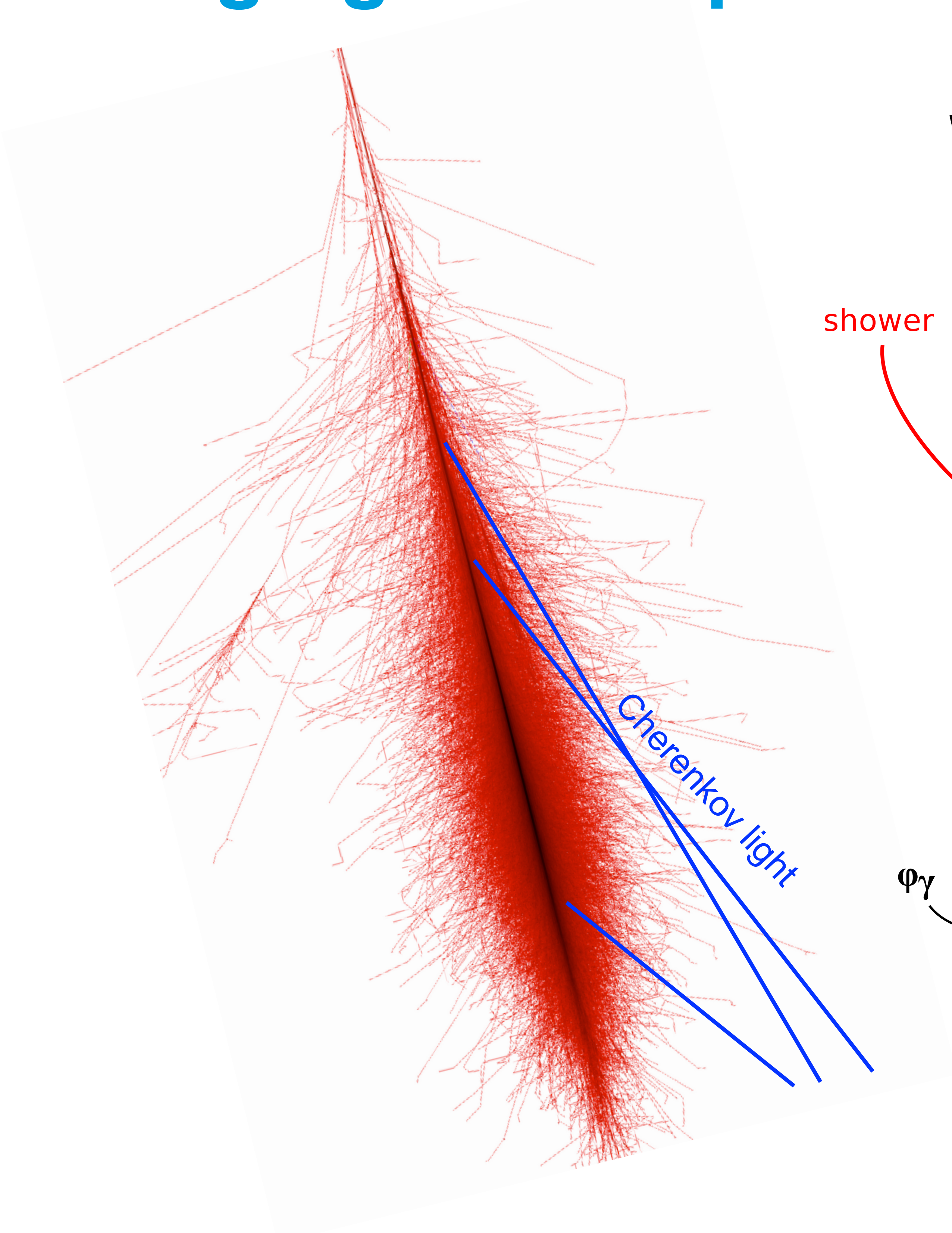
Extensive Air Showers and Cherenkov Emission

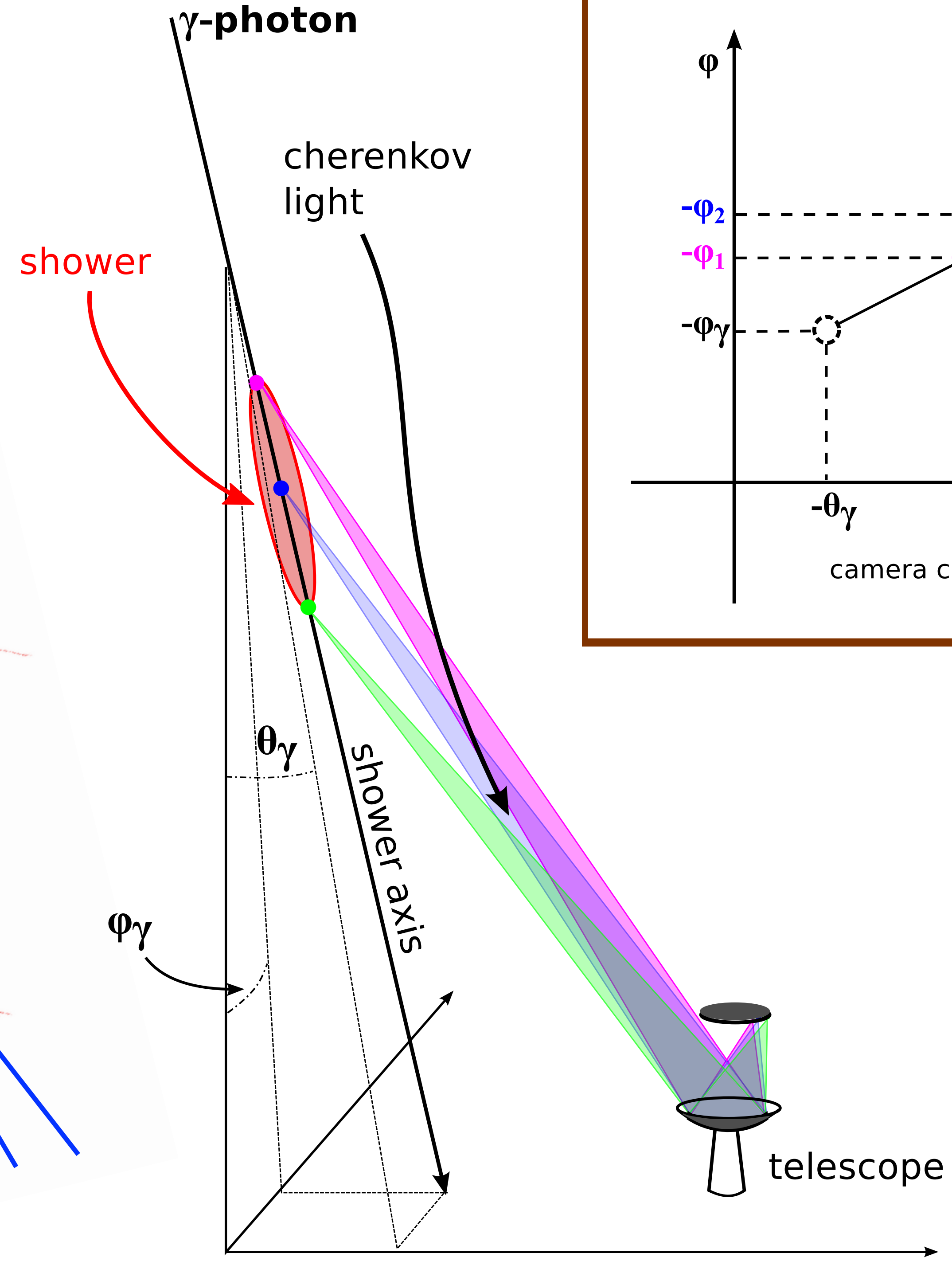


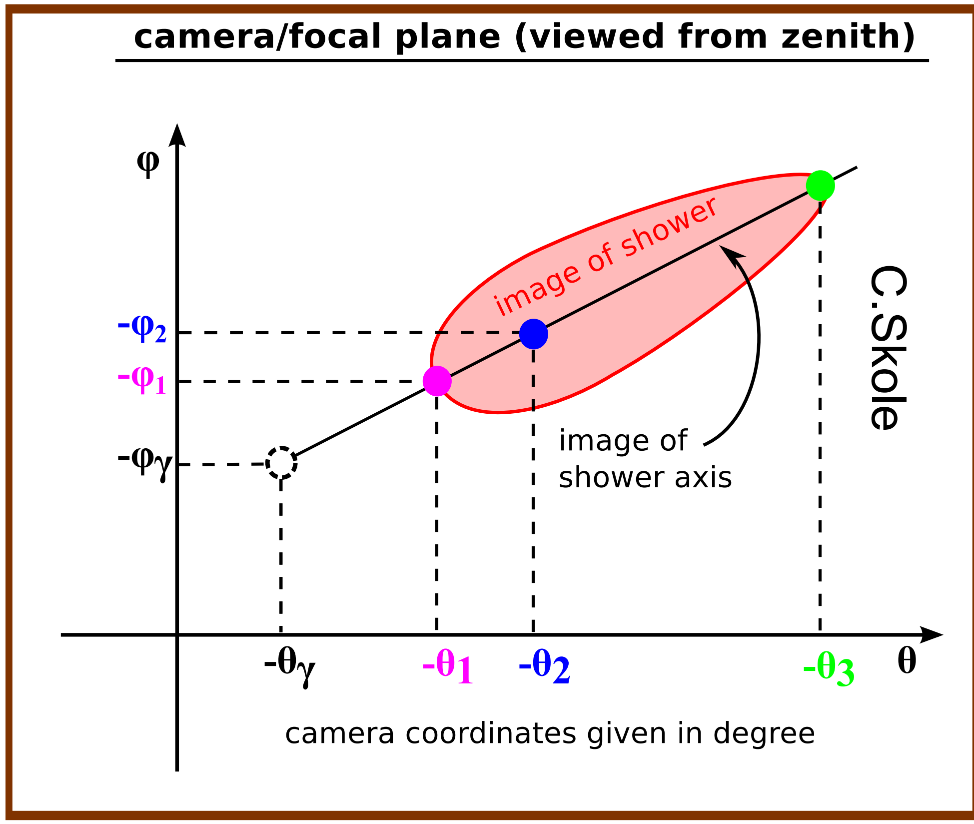


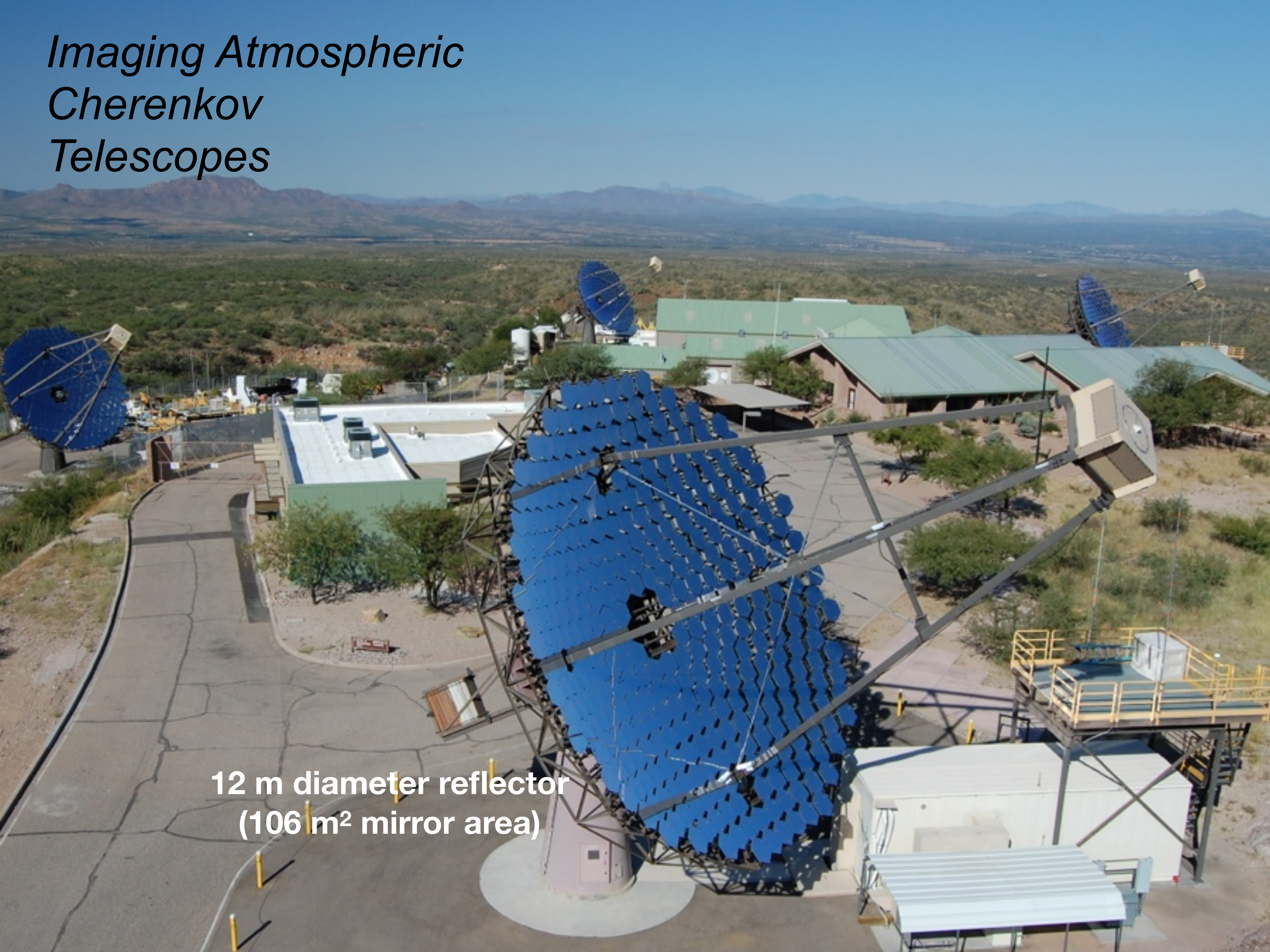
Cherenkov light from air showers: weak (~10 ph/m²), short (~ns), blue (300-550nm) flash of light

Imaging Technique - Air Showers

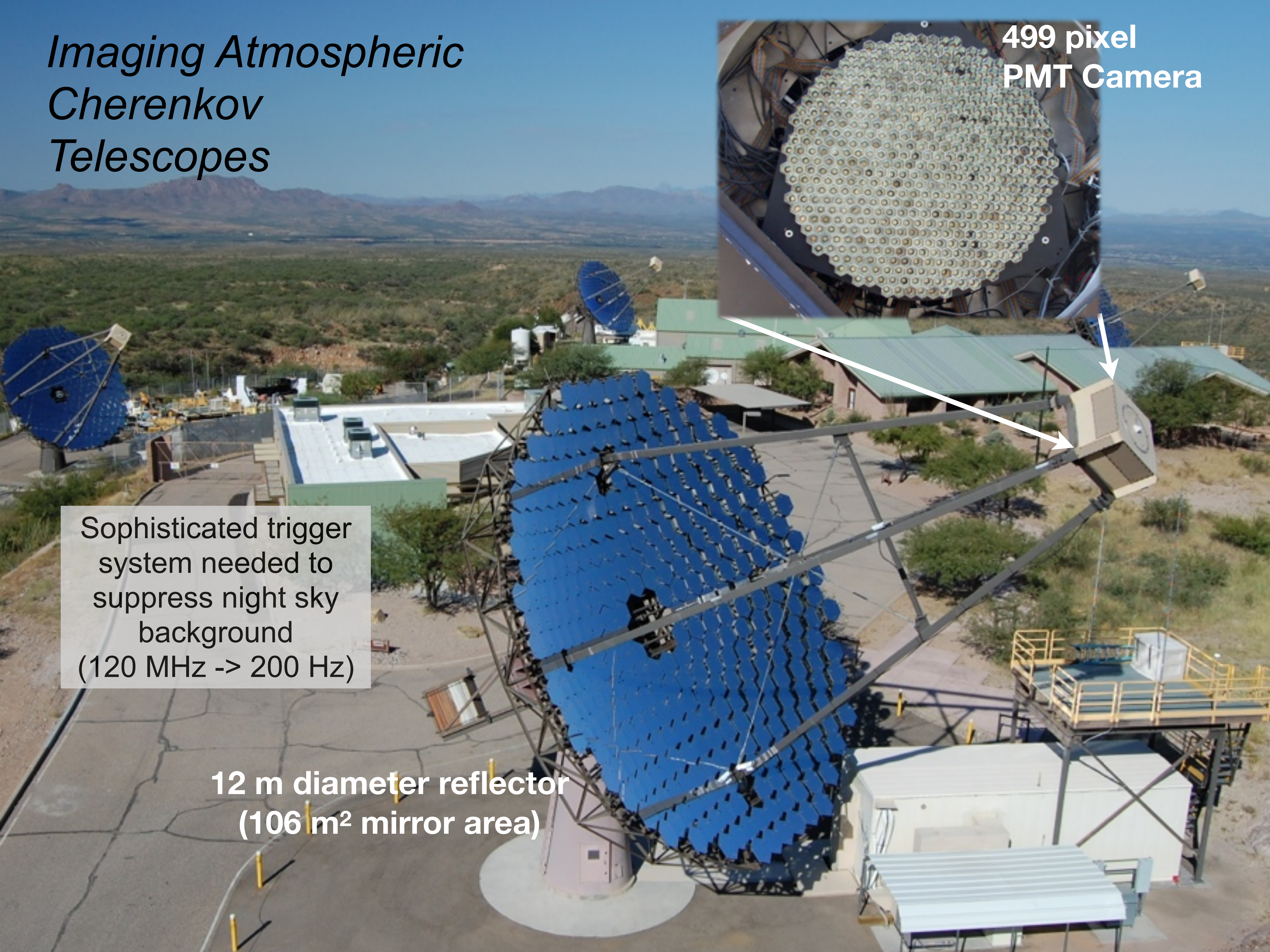




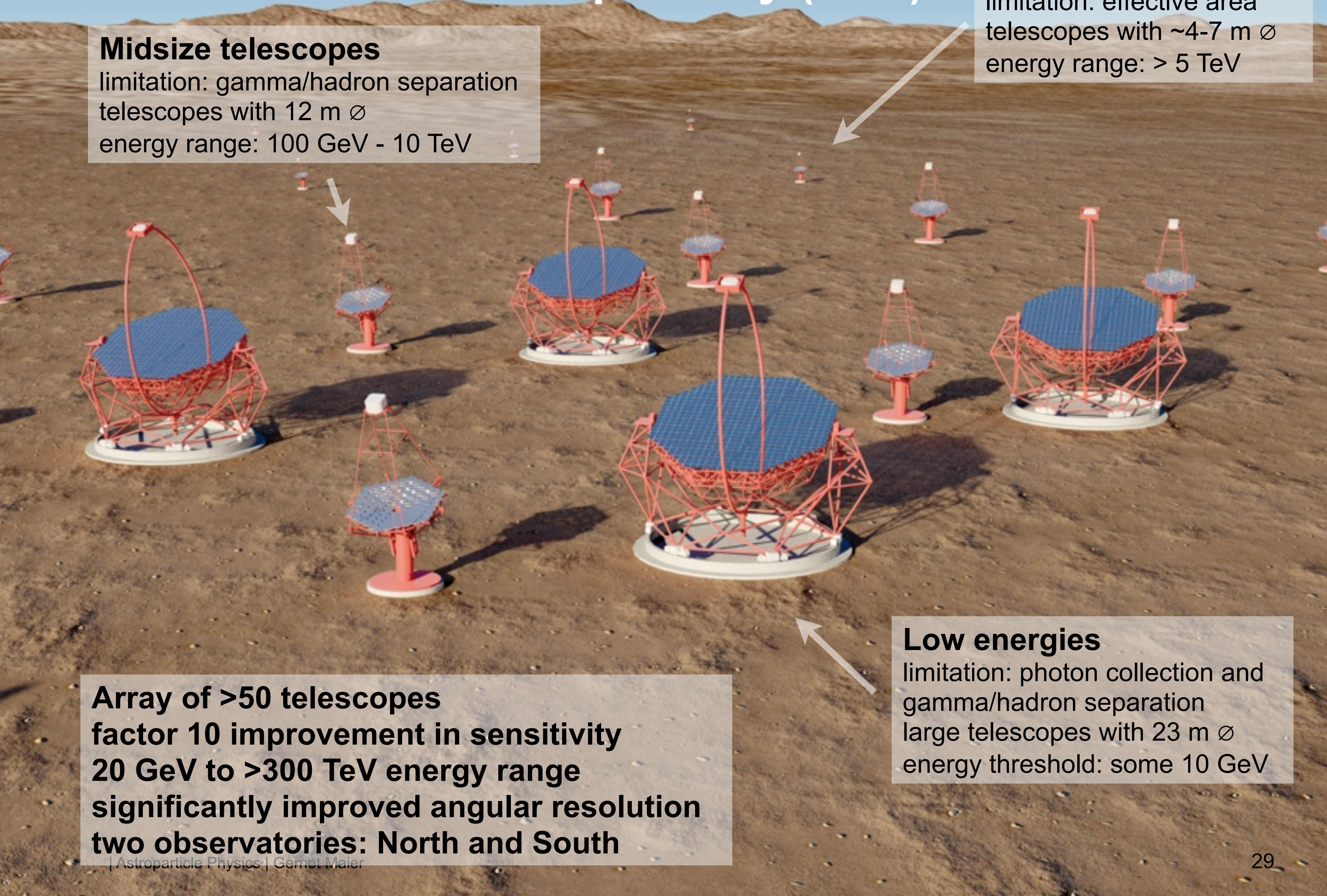



Imaging Atmospheric
Cherenkov
Telescopes
12 m diameter reflector
(106 m² mirror area)

Imaging Atmospheric Cherenkov Telescopes



The Cherenkov Telescope Array (CTA)



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

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

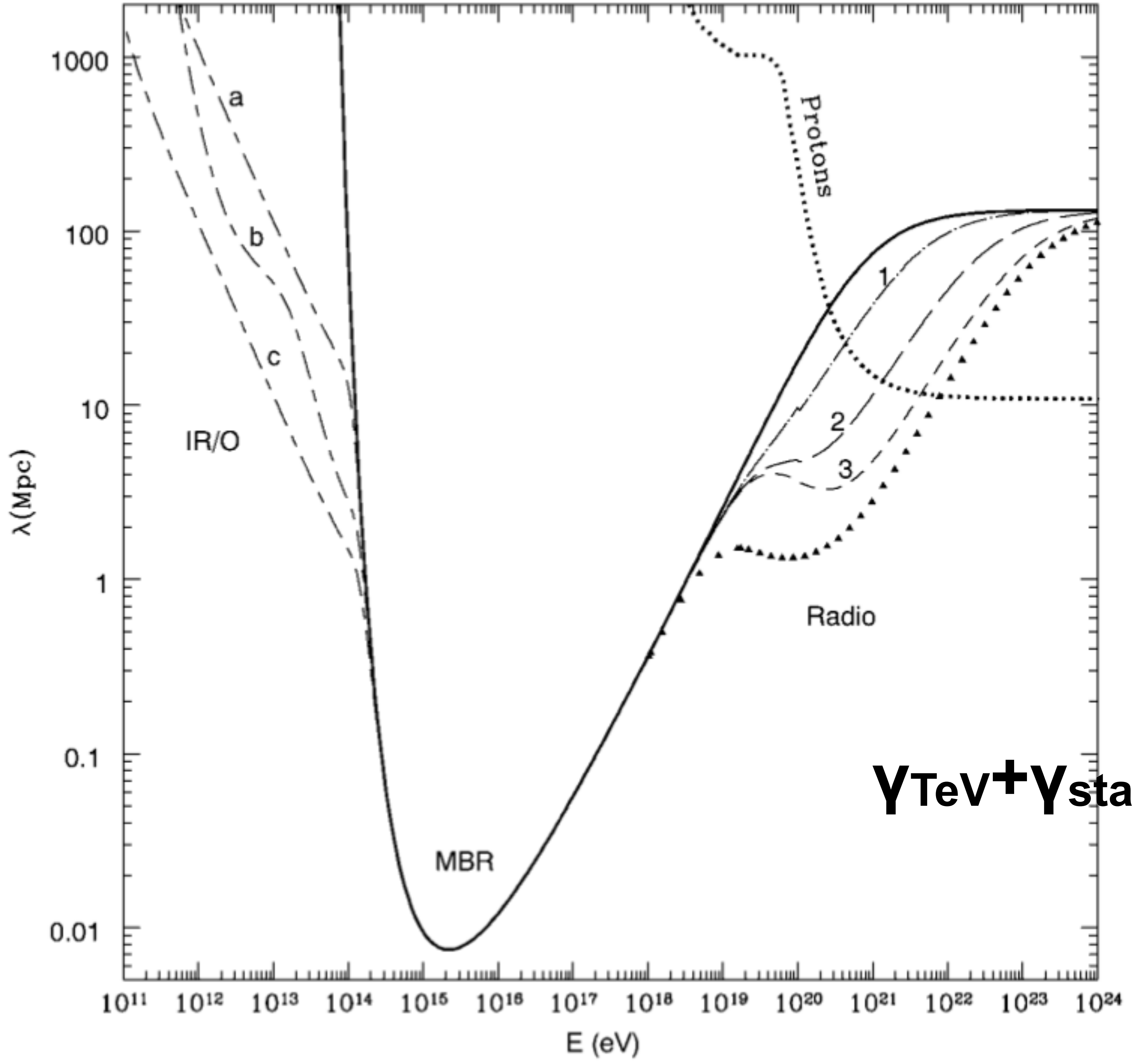
Low energies
limitation: photon collection and
gamma/hadron separation
large telescopes with 23 m ∅
energy threshold: some 10 GeV

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

The Cherenkov Telescope Array - Large Size Telescope

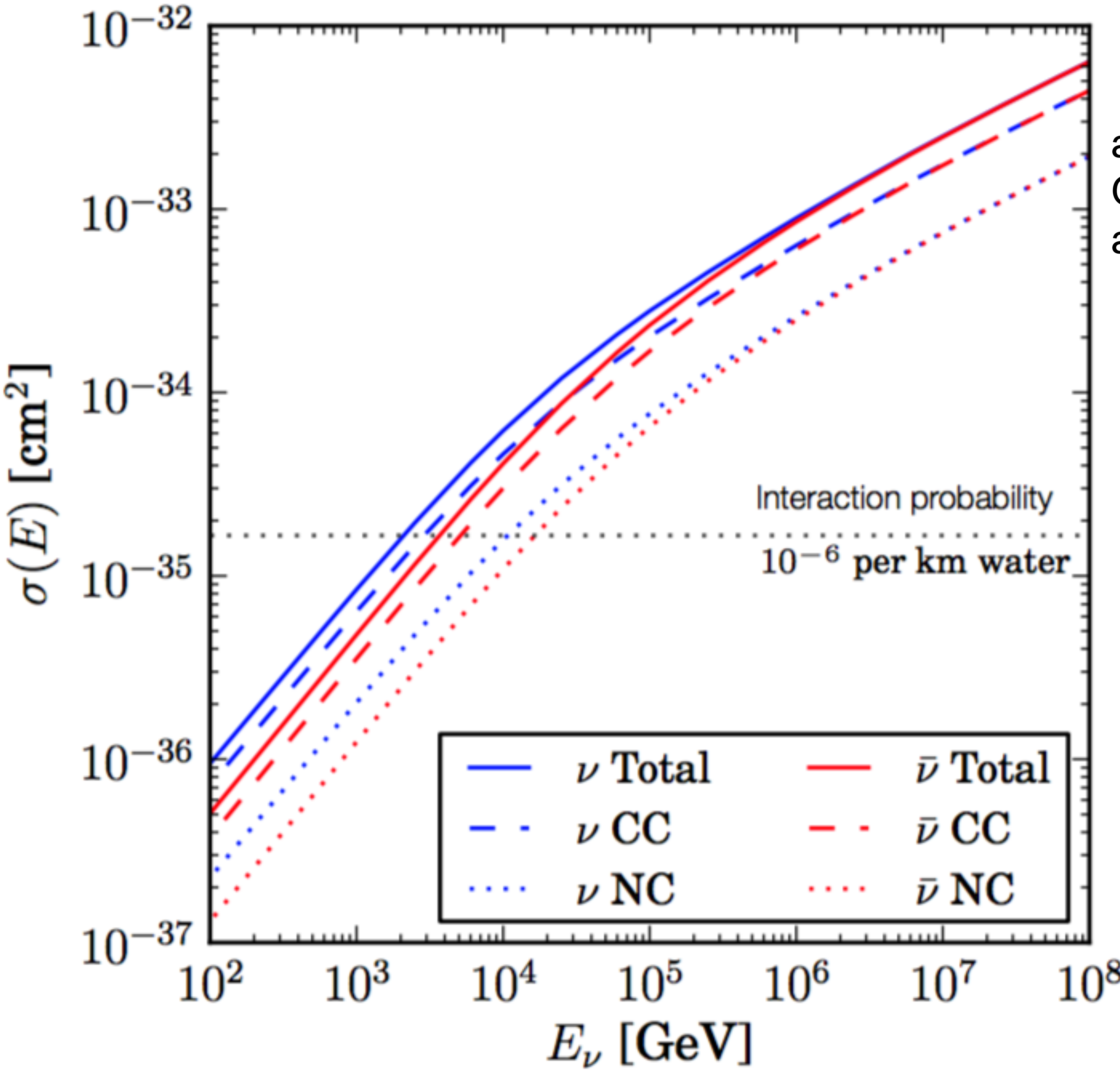
Opacity of the Universe to high-energy photons

Mean free path for photons



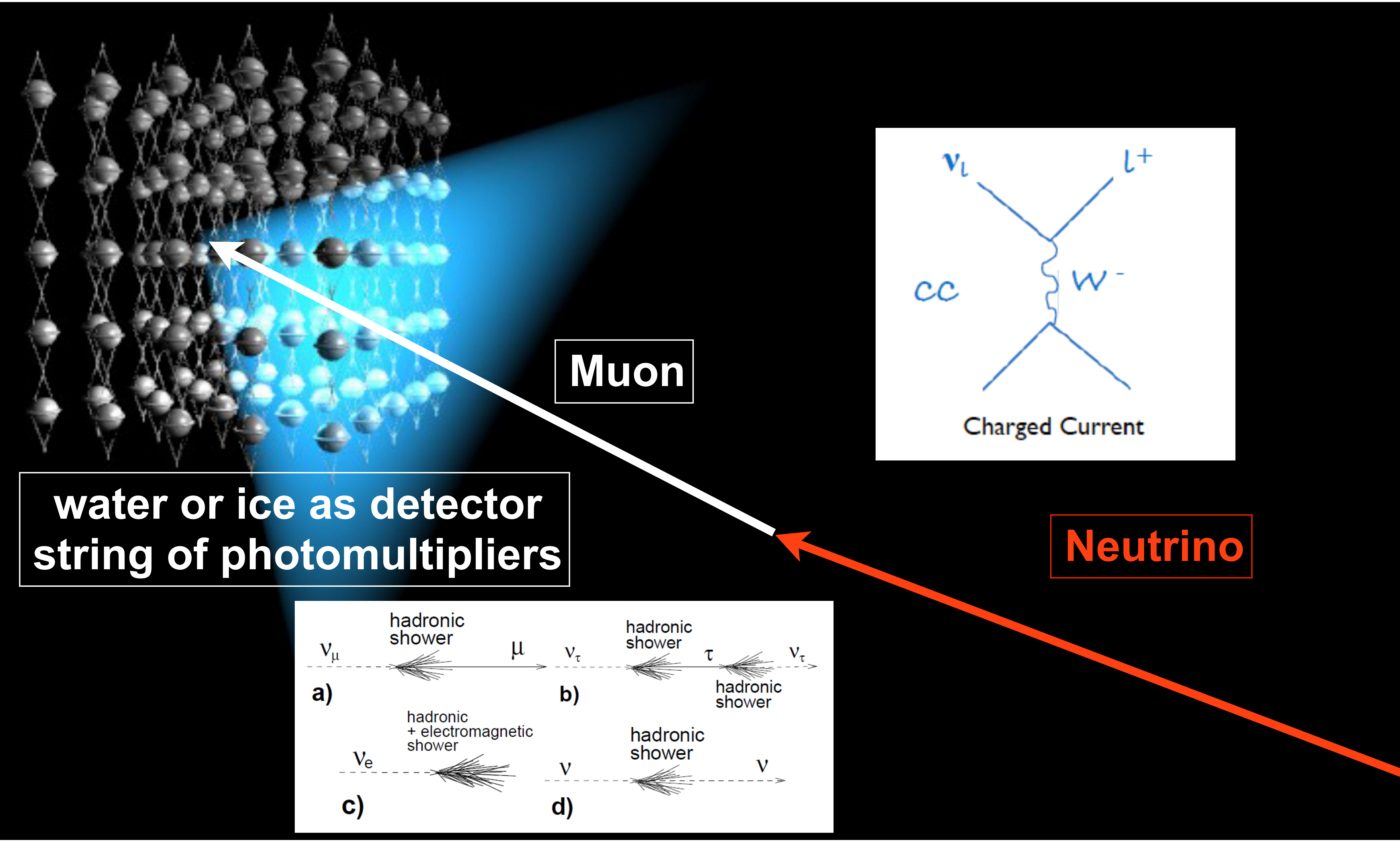
$\gamma_{TeV} + \gamma_{star} \rightarrow e^+e^-$

Neutrino detection



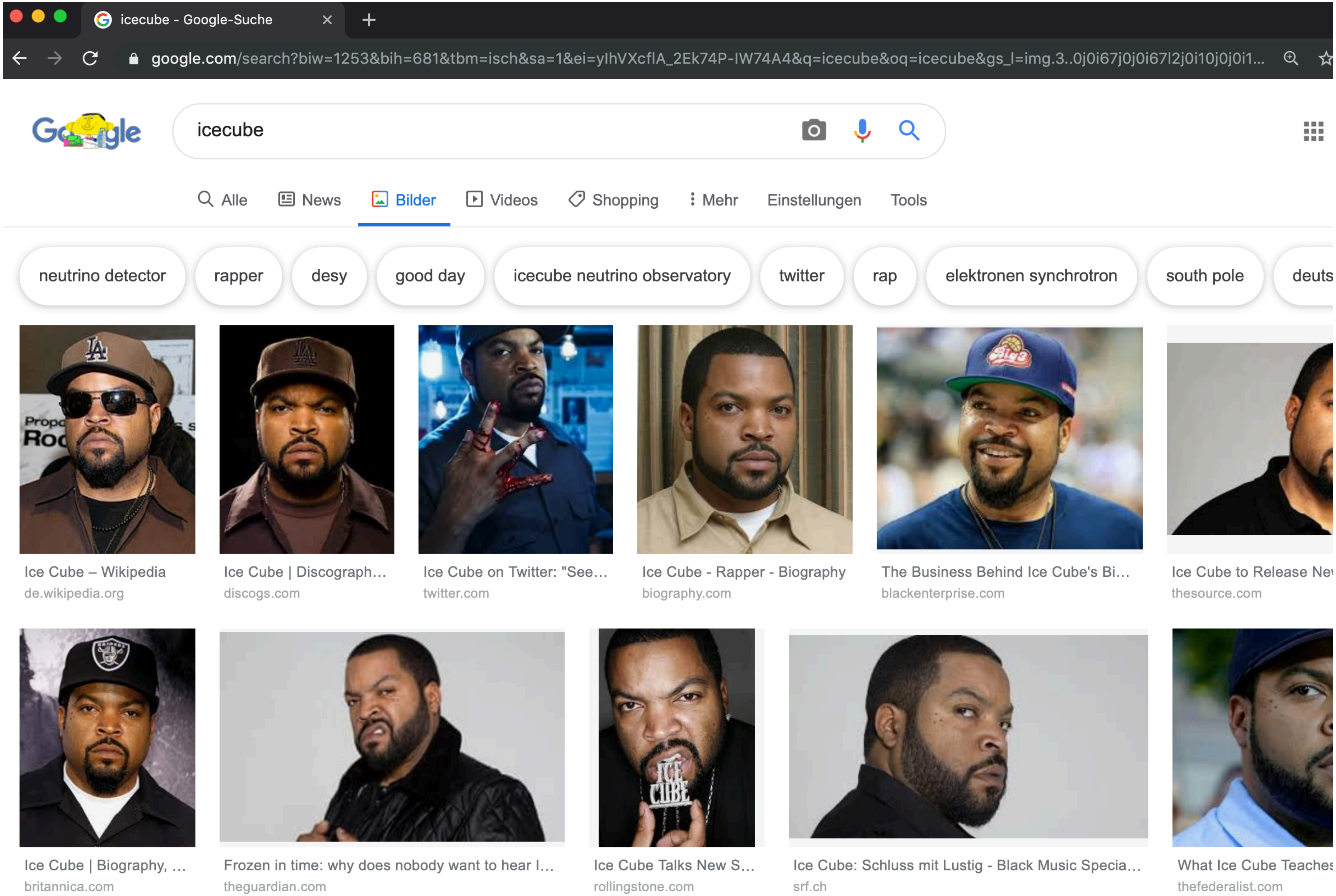
astrophysical flux:
O(10^5) per km^2 per year
above 100 TeV

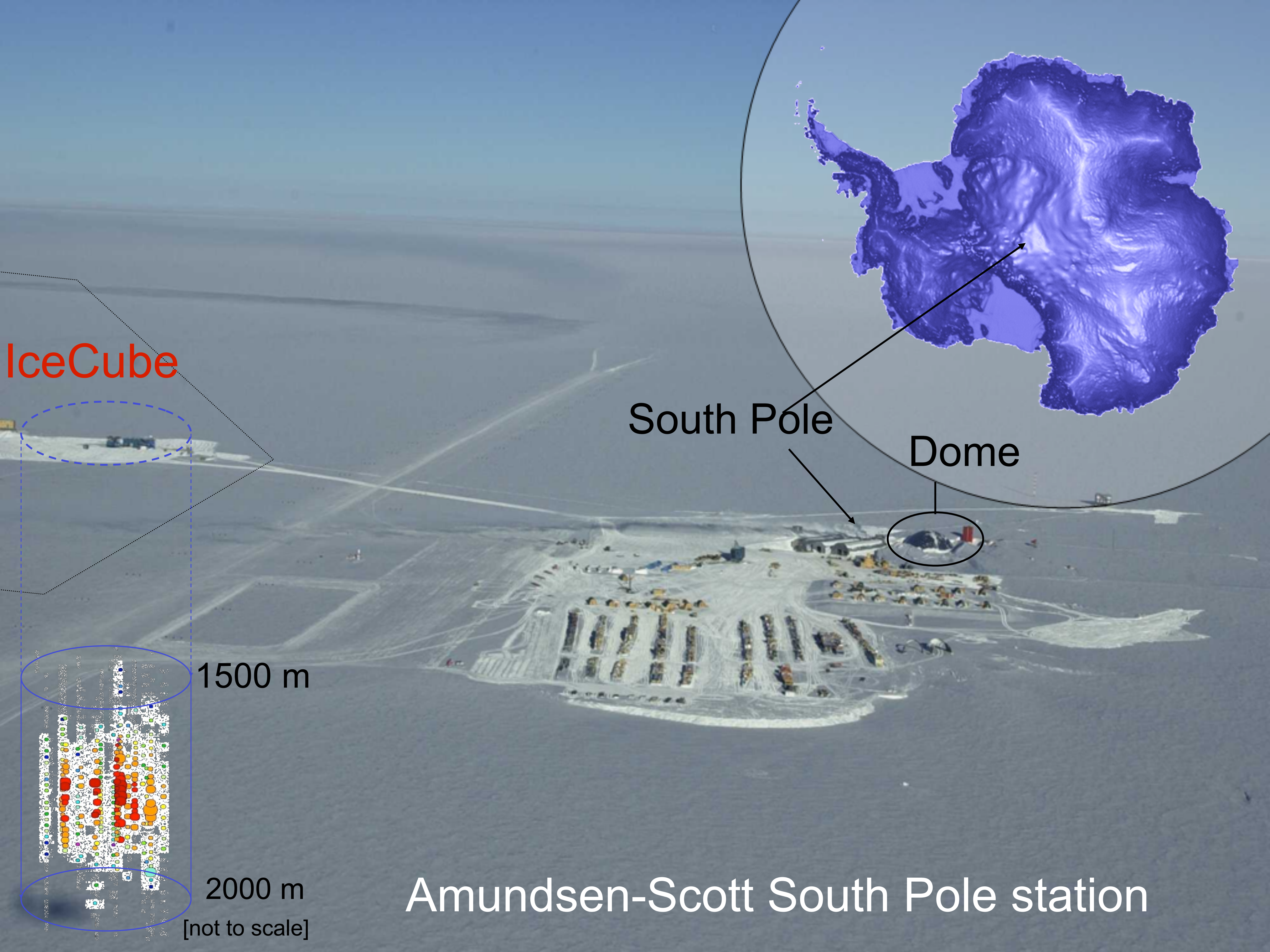
High-energy neutrino detection



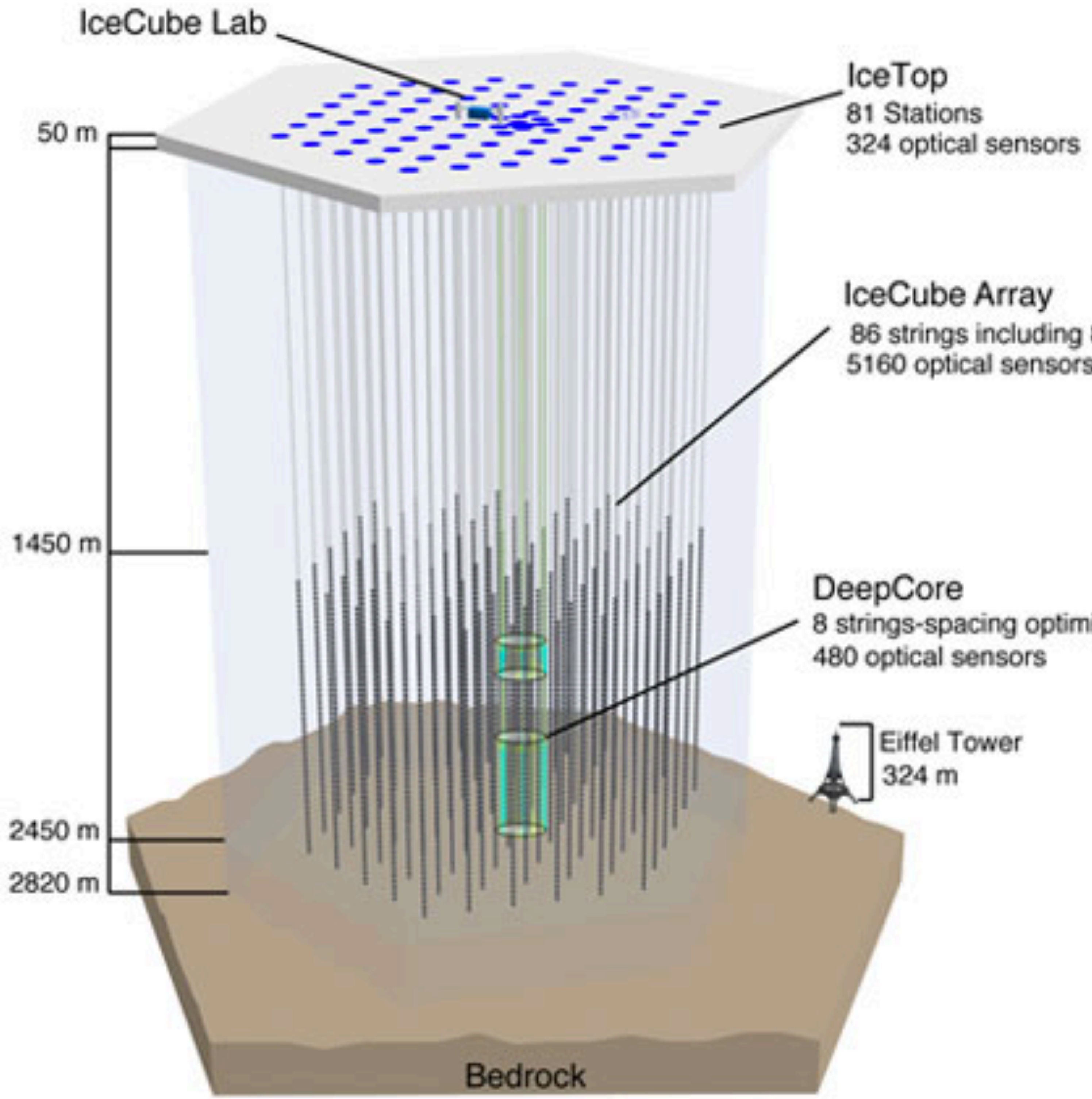
IceCube

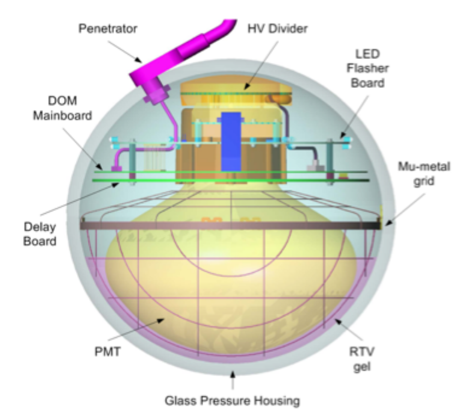
IceCube


icecube - Google-Suche
google.com/search?biw=1253&bih=681&tbm=isch&sa=1&ei=ylhVXcflA_2Ek74P-IW74A4&q=icecube&oq=icecube&gs_l=img.3..0j0i67j0j0i67l2j0i10j0j0i1...
icecube
Alle
News
Bilder
Videos
Shopping
Mehr
Einstellungen
Tools
neutrino detector
rapper
desy
good day
icecube neutrino observatory
twitter
rap
elektronen synchrotron
south pole
deuts
Ice Cube – Wikipedia
de.wikipedia.org
Ice Cube | Discograph…
discogs.com
Ice Cube on Twitter: "See…
twitter.com
Ice Cube - Rapper - Biography
biography.com
The Business Behind Ice Cube's Bi…
blackenterprise.com
Ice Cube to Release Ne
thesource.com
Ice Cube | Biography, …
britannica.com
Frozen in time: why does nobody want to hear I…
theguardian.com
Ice Cube Talks New S…
rollingstone.com
Ice Cube: Schluss mit Lustig - Black Music Specia…
srf.ch
What Ice Cube Teache
thefederalist.com


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

IceCube



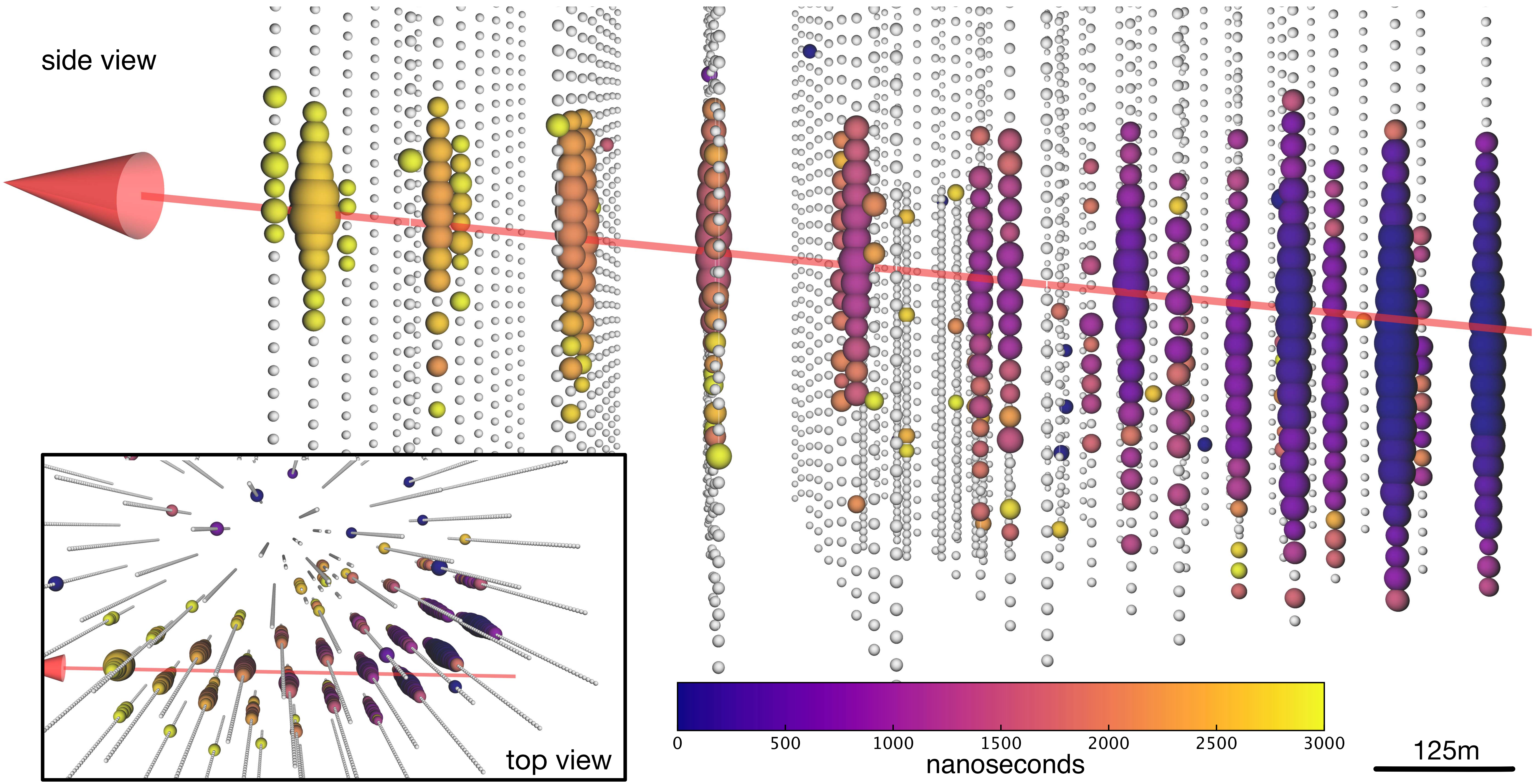


light collection by DOMs

ergy, allowing
easily identi-
-neutrino as-

IceCube can robustly identify astrophysical neutrinos 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.

Sources of Cosmic Rays

What are they?

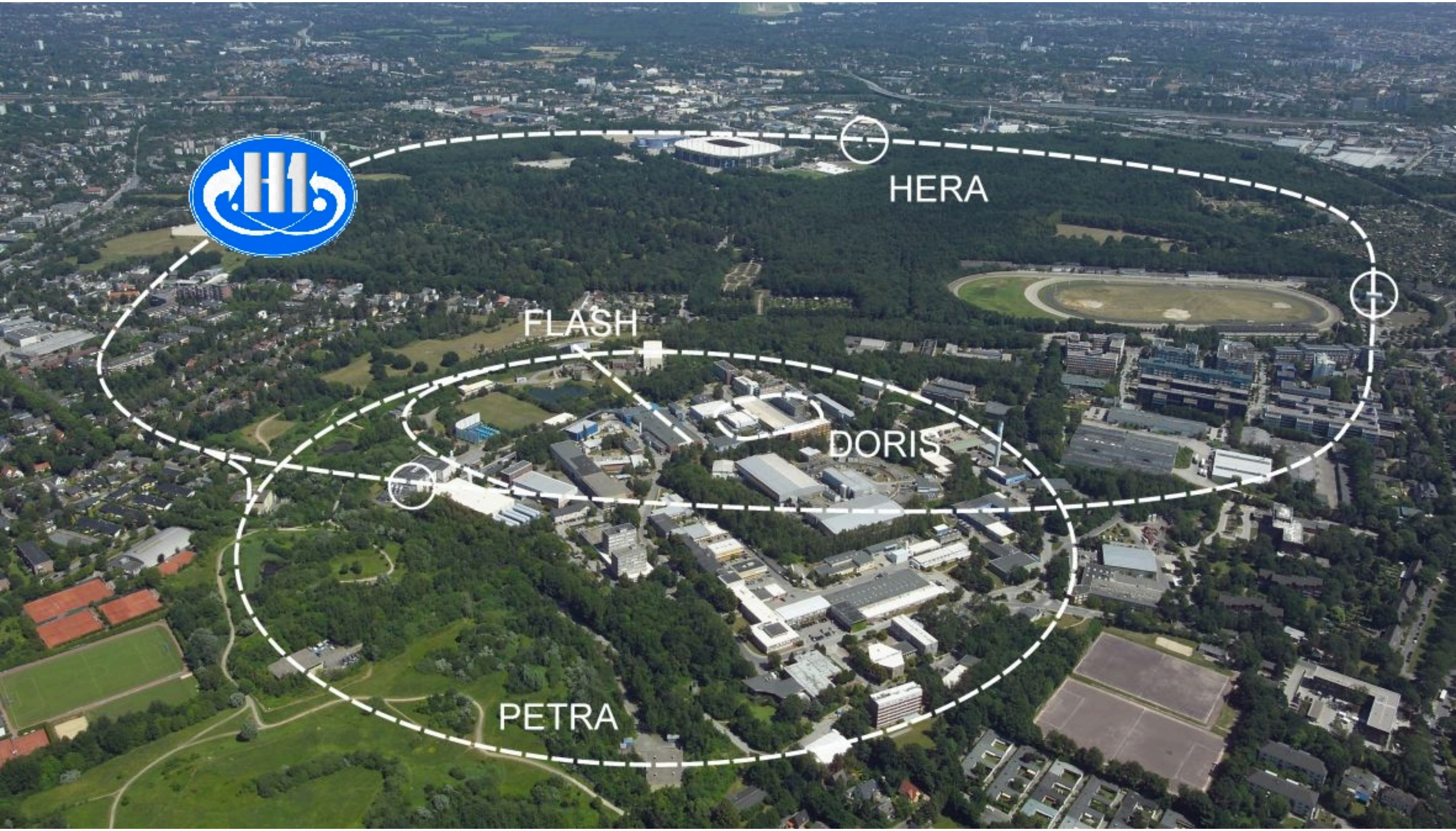
Is it a single source? A single source class?

Where are they? Galactic / extragalactic?

How?

acceleration mechanism, feedback on environment, …

Maximum energy of an accelerator



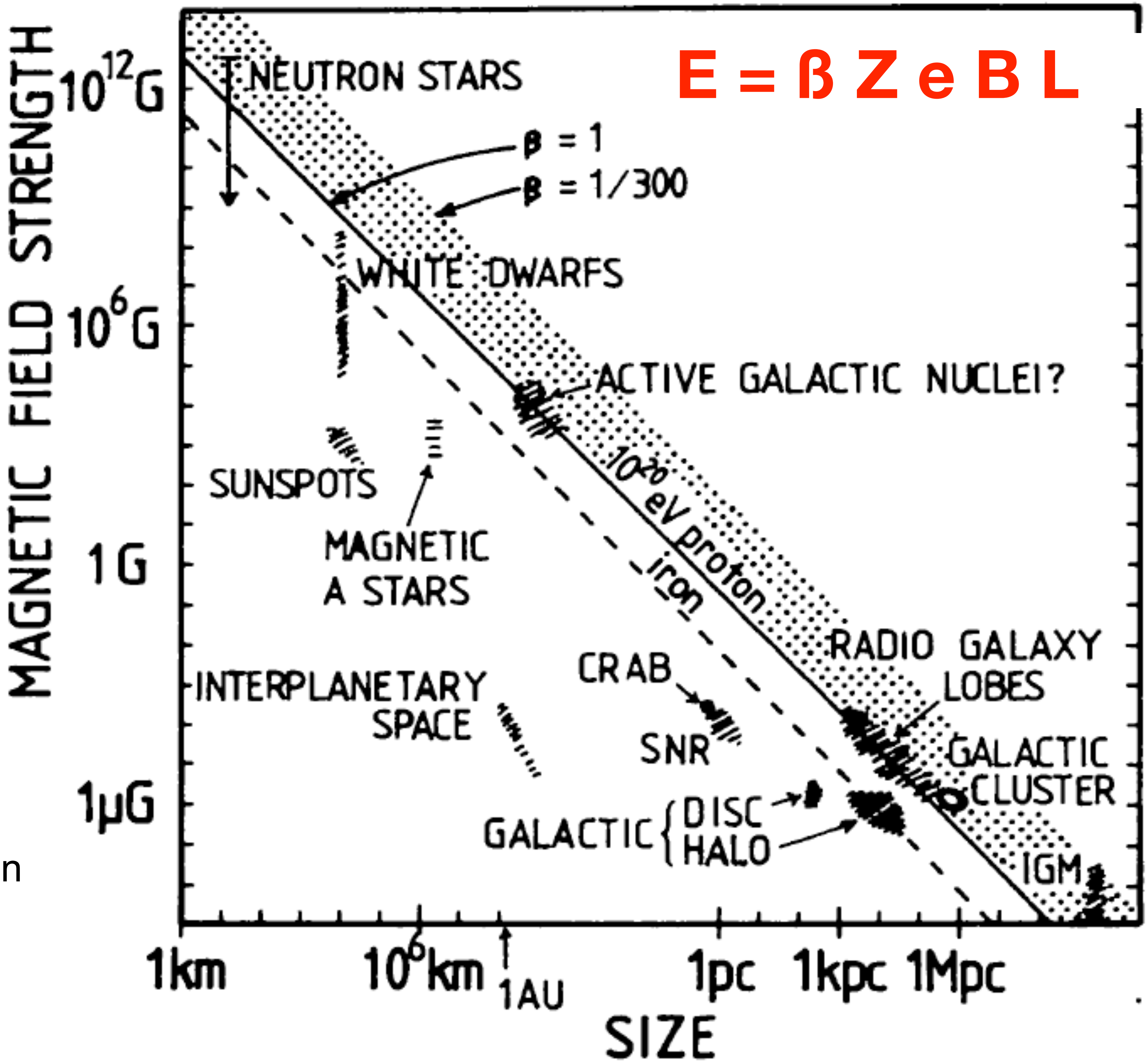
Maximum energy of an accelerator

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

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

Hillas Diagram

M.Hillas (1984)



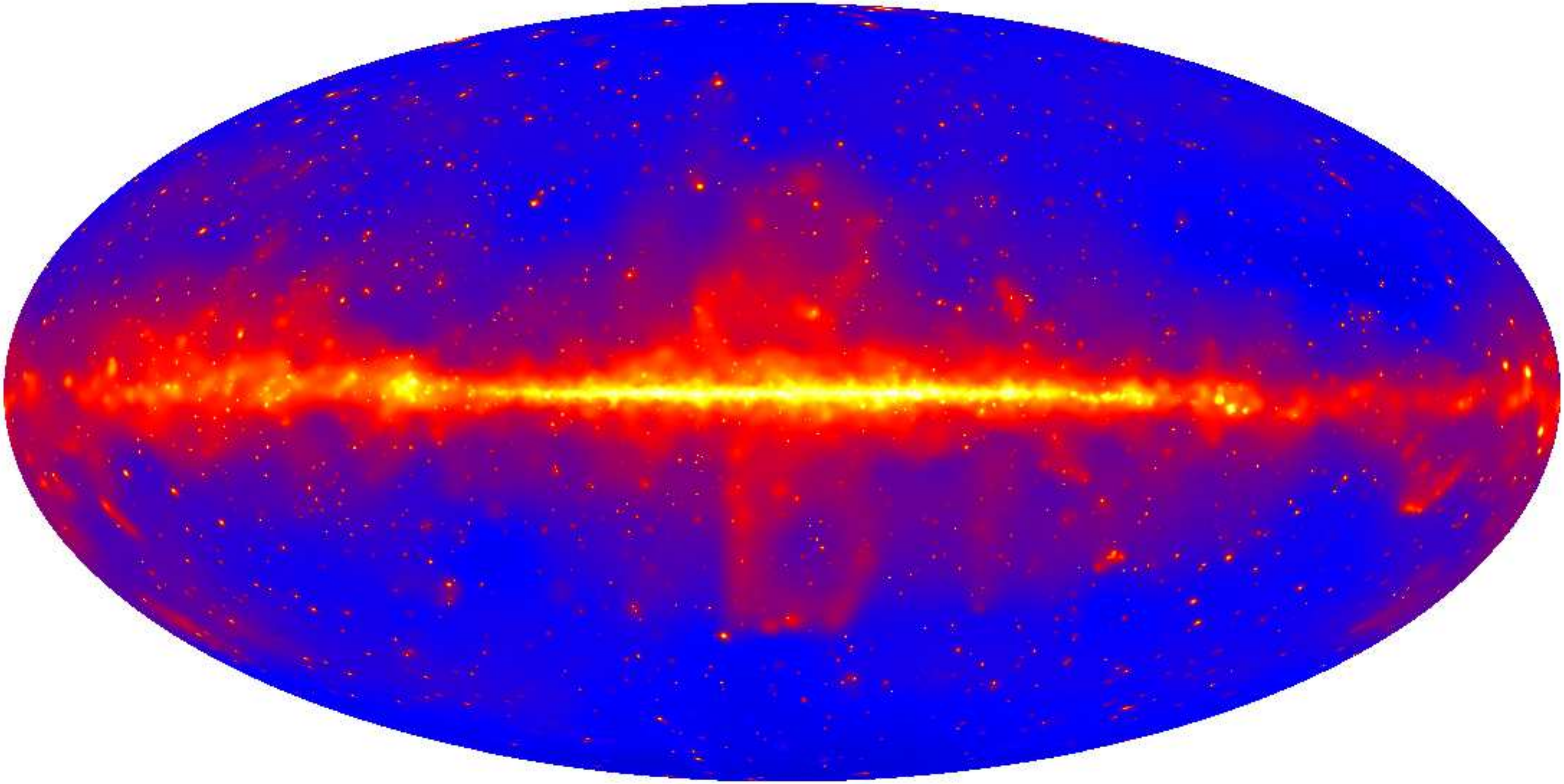
Energy limited by:

- B-field
- time for acceleration
- energy losses

Cosmic Particle Accelerators

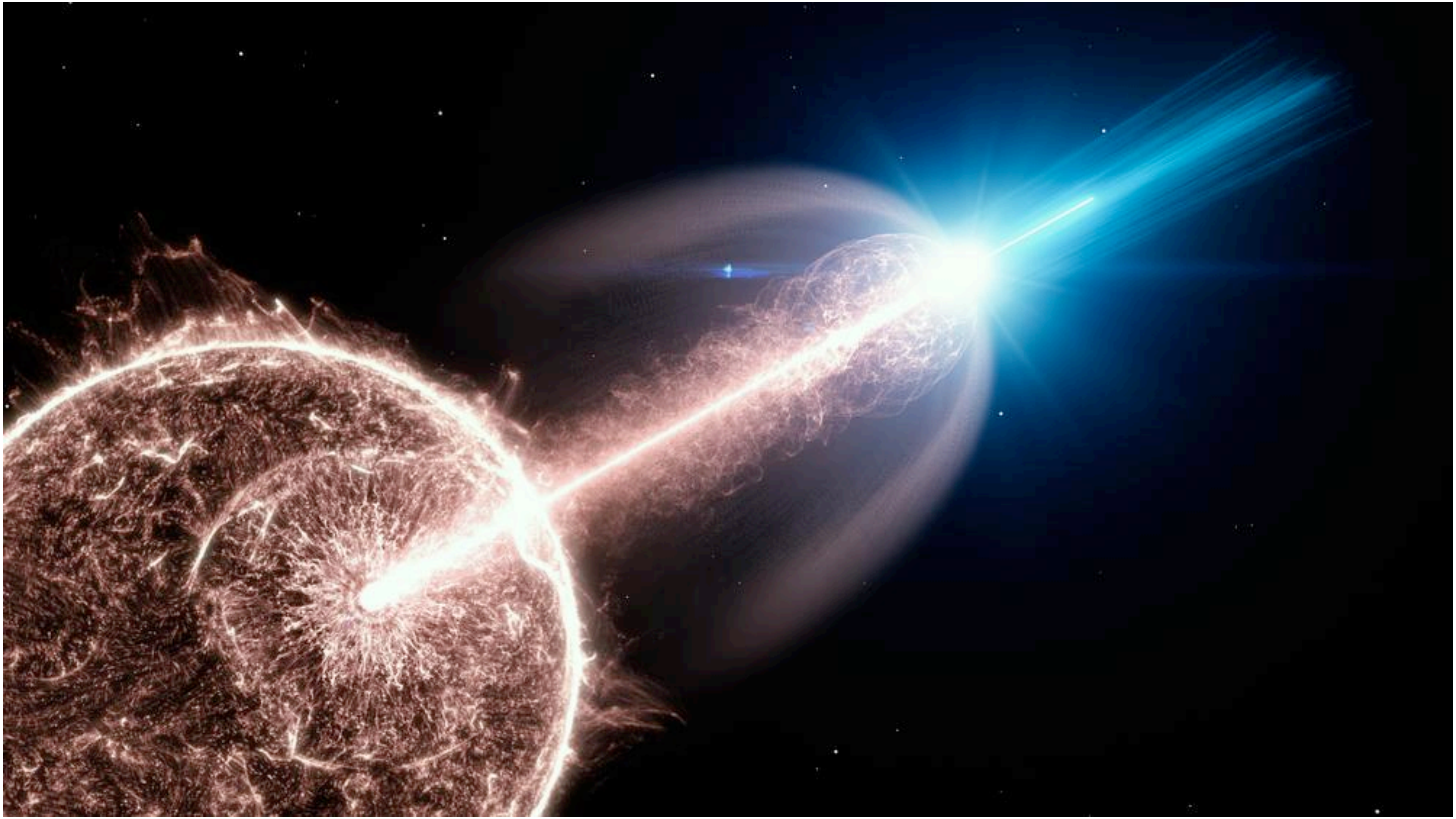
>1500 sources > 10 GeV
>150 sources > 100 GeV
diffuse emission

Fermi LAT 7-years sky map (10 GeV - 2 TeV)



Supernova Remnants, Binaries, Star forming regions, pulsar wind nebula, active galactic nuclei, gamma-ray bursts, nova, diffuse emission, dark matter, ….

Gamma-ray bursts

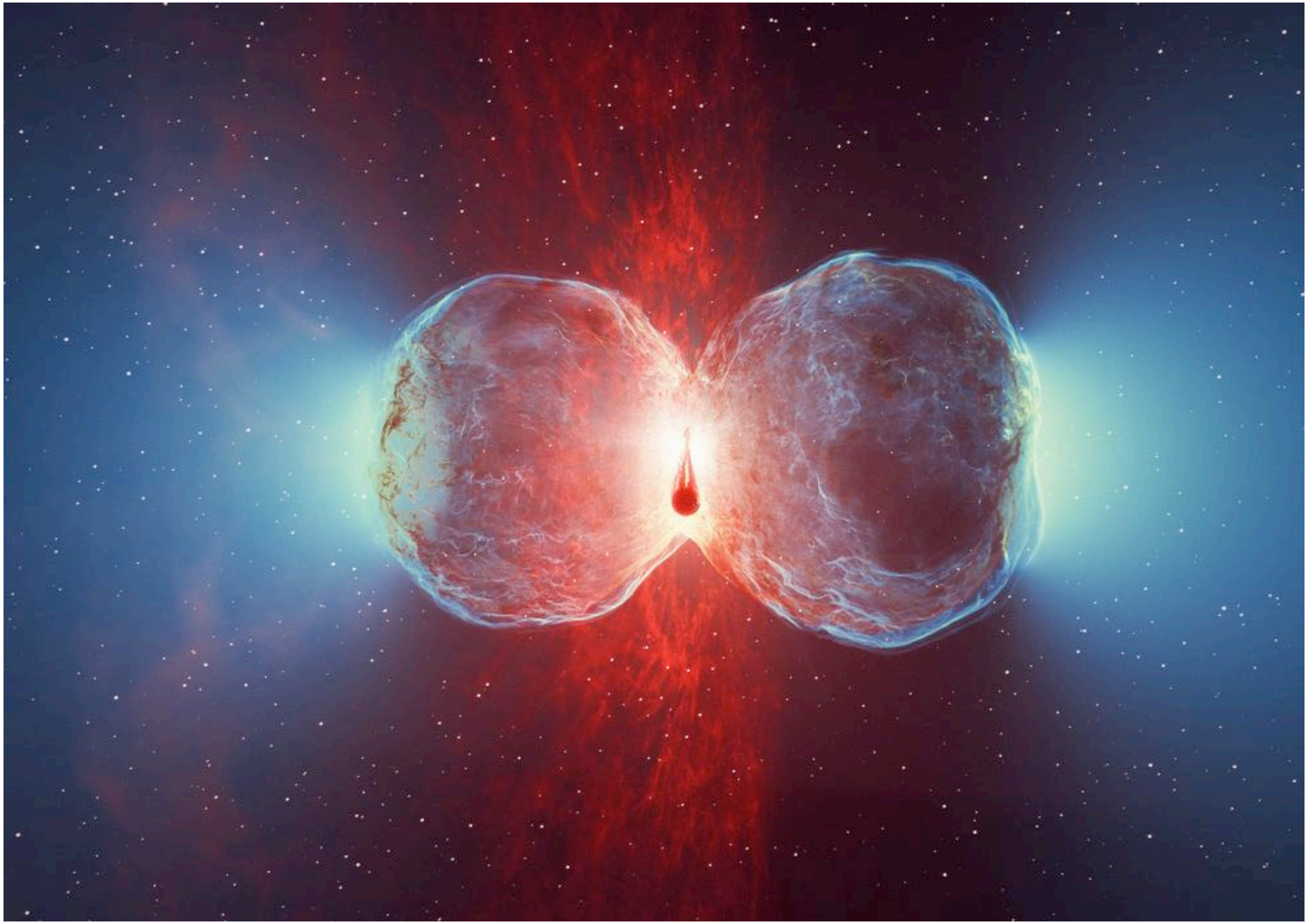


DESY, Science Communication Lab

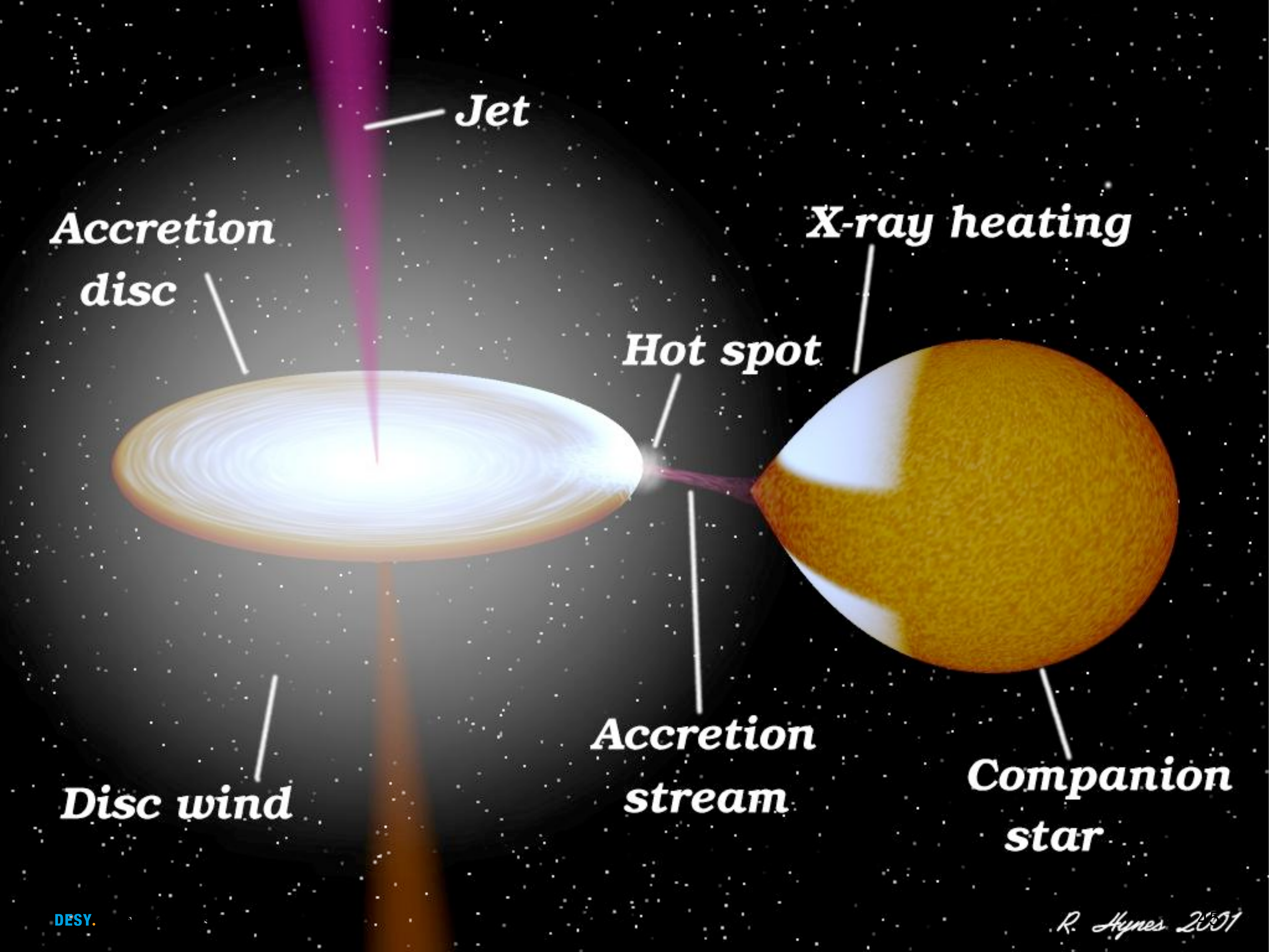
Tidal Disruption Events

DESY, Science Communication Lab

Nova



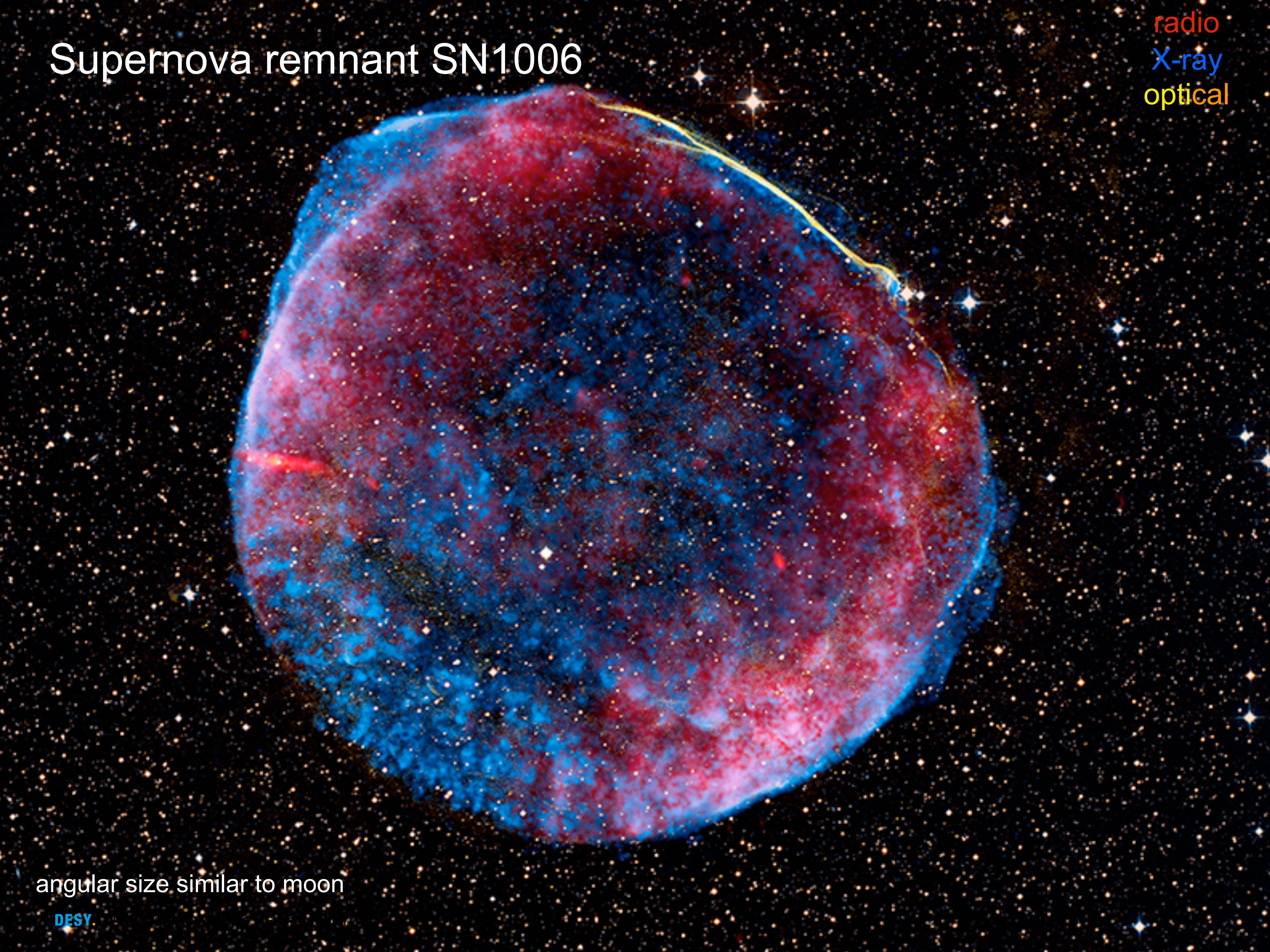
DESY, Science Communication Lab


Jet
Accretion disc
X-ray heating
Hot spot
Accretion stream
Companion star
Disc wind
R. Hynes 2001

DESY.

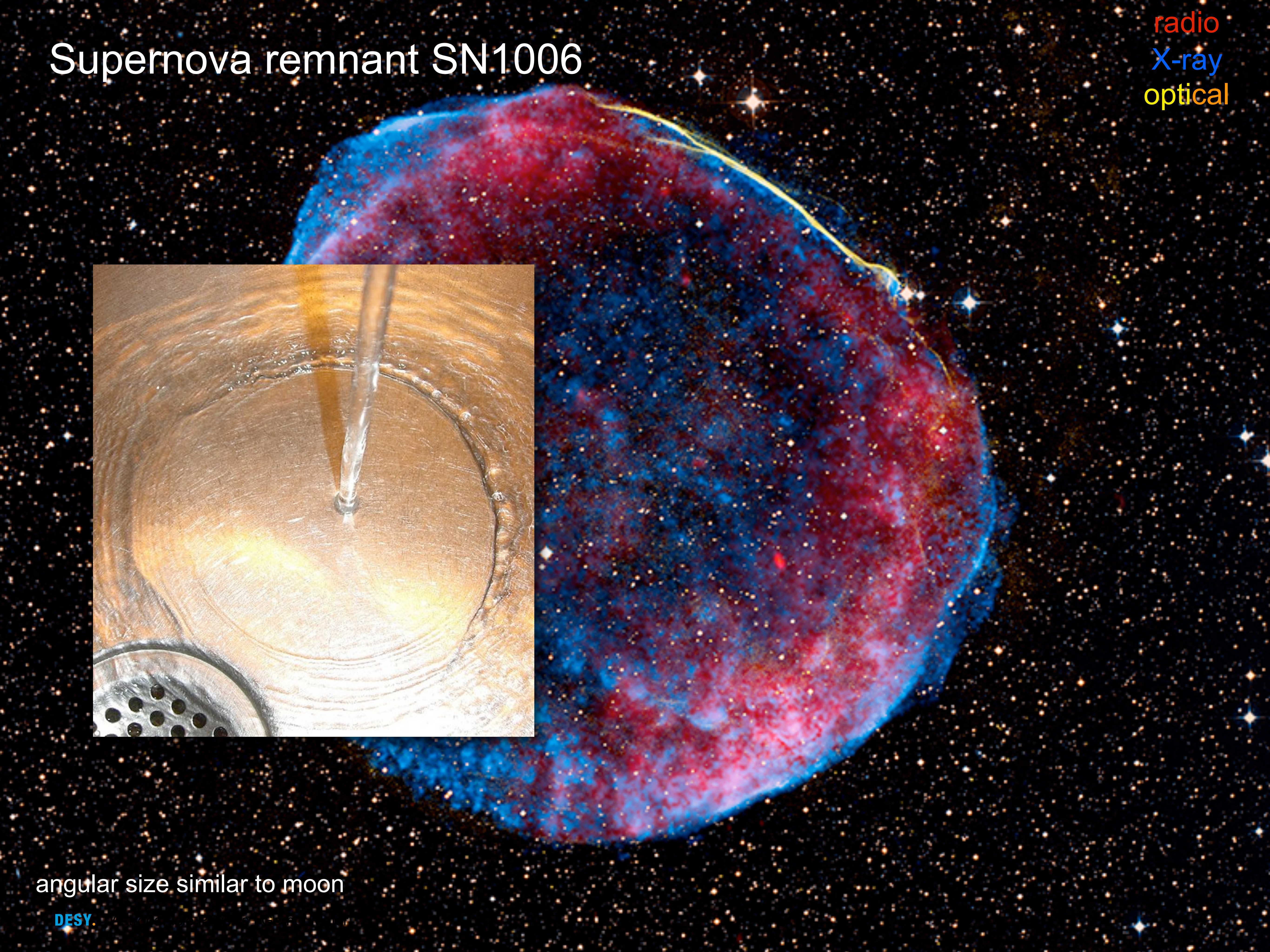
Supernova remnants

Supernova remnant SN1006

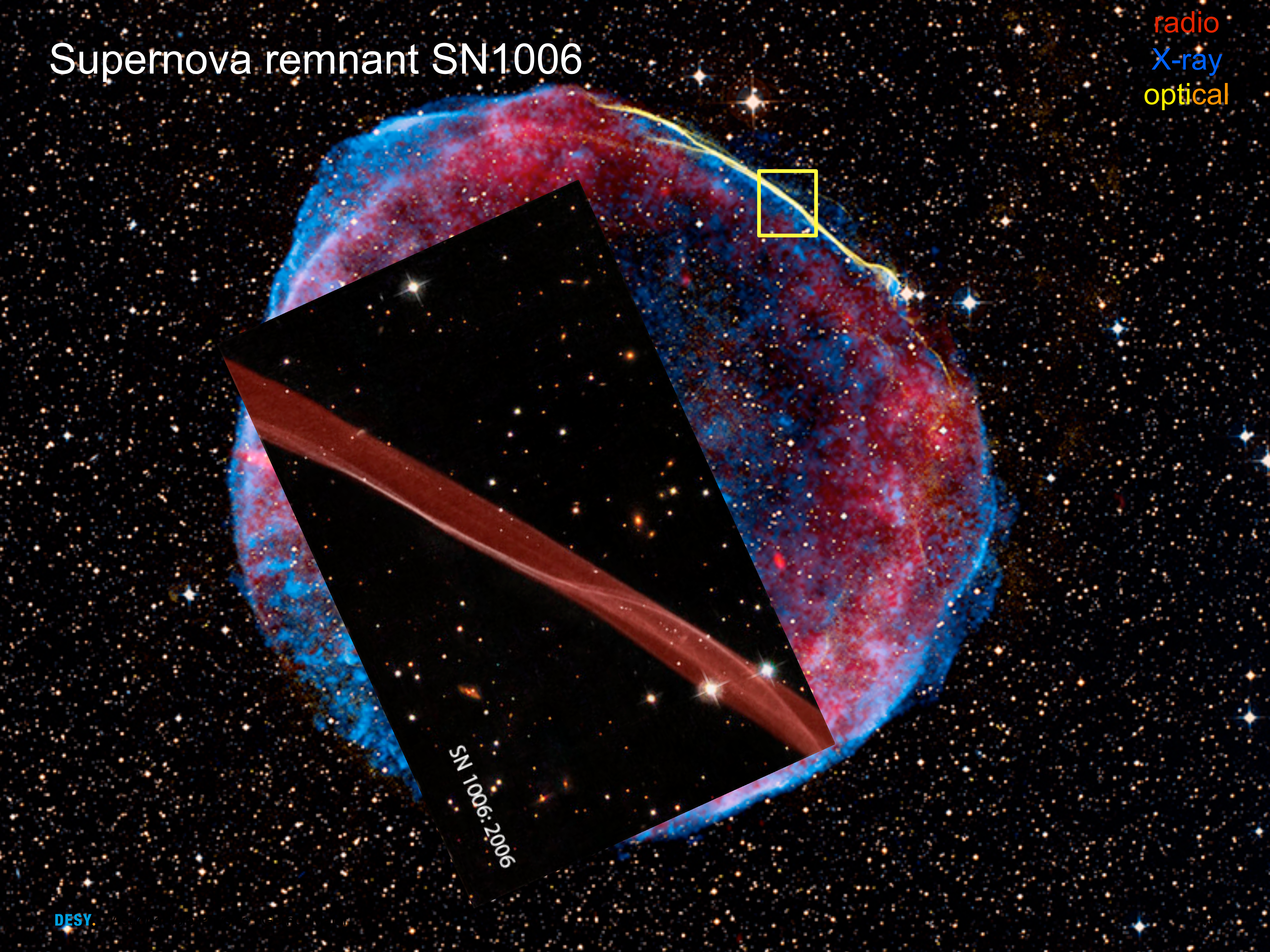


angular size similar to moon

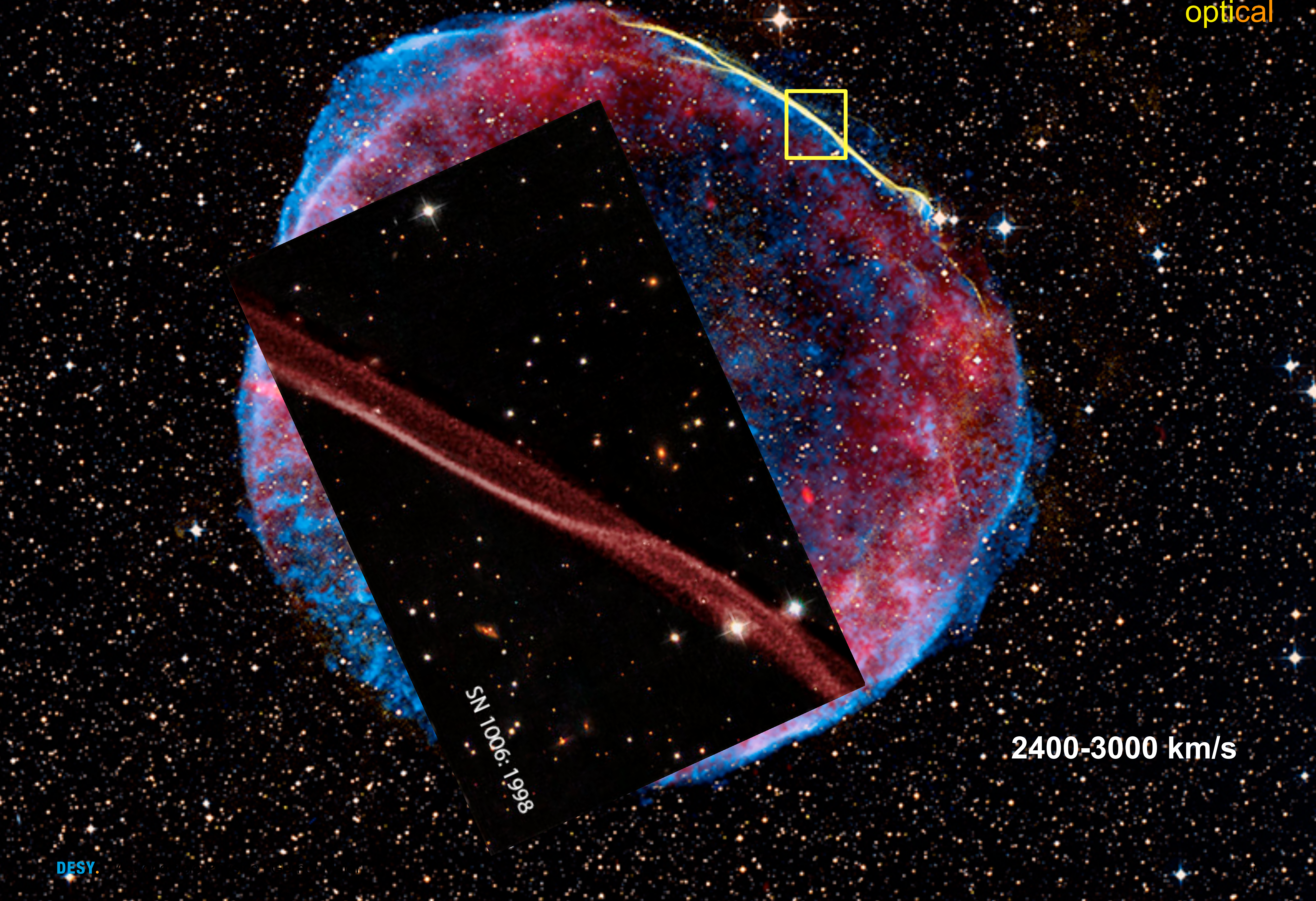
Supernova remnant SN1006



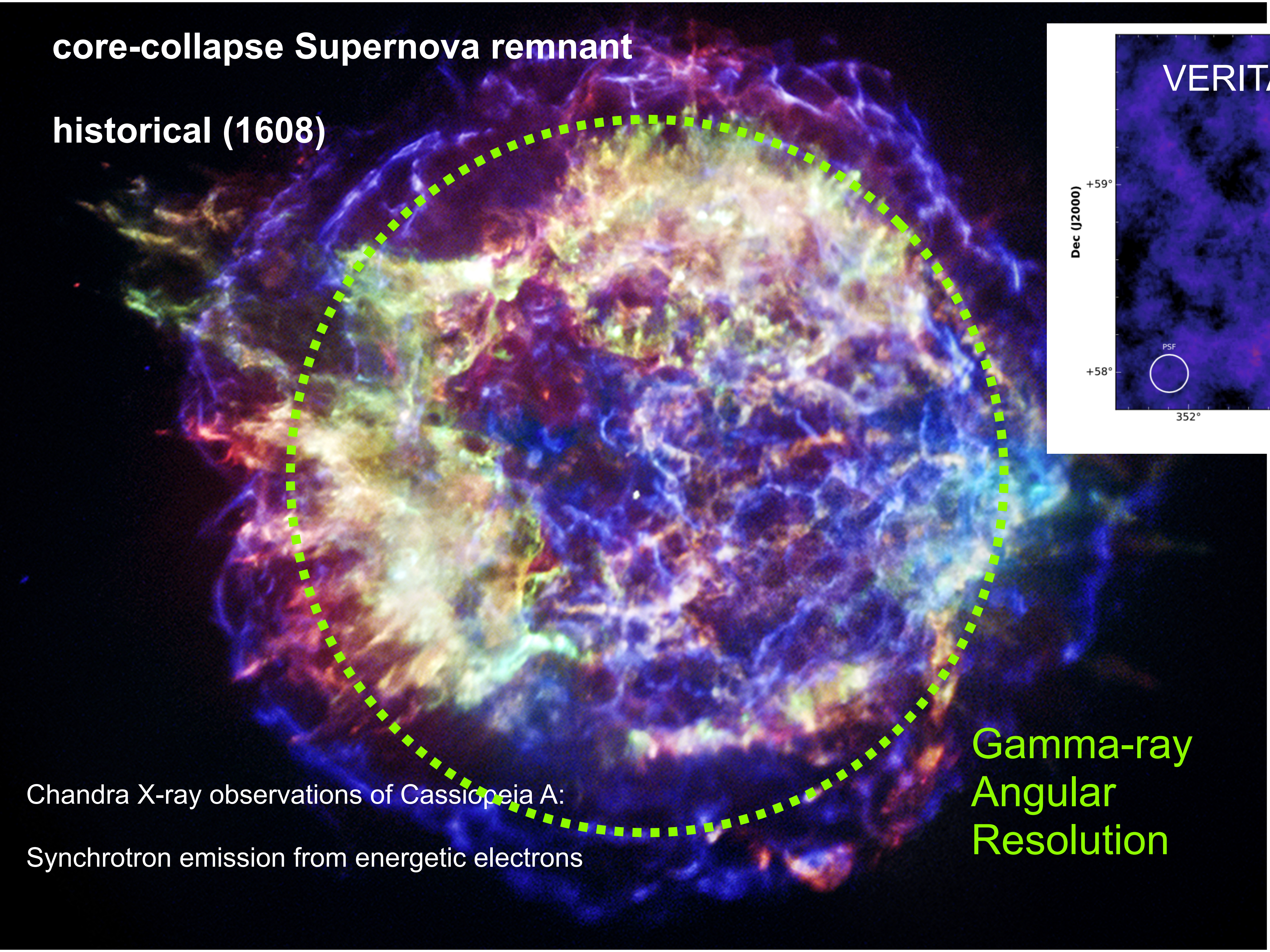
angular size similar to moon

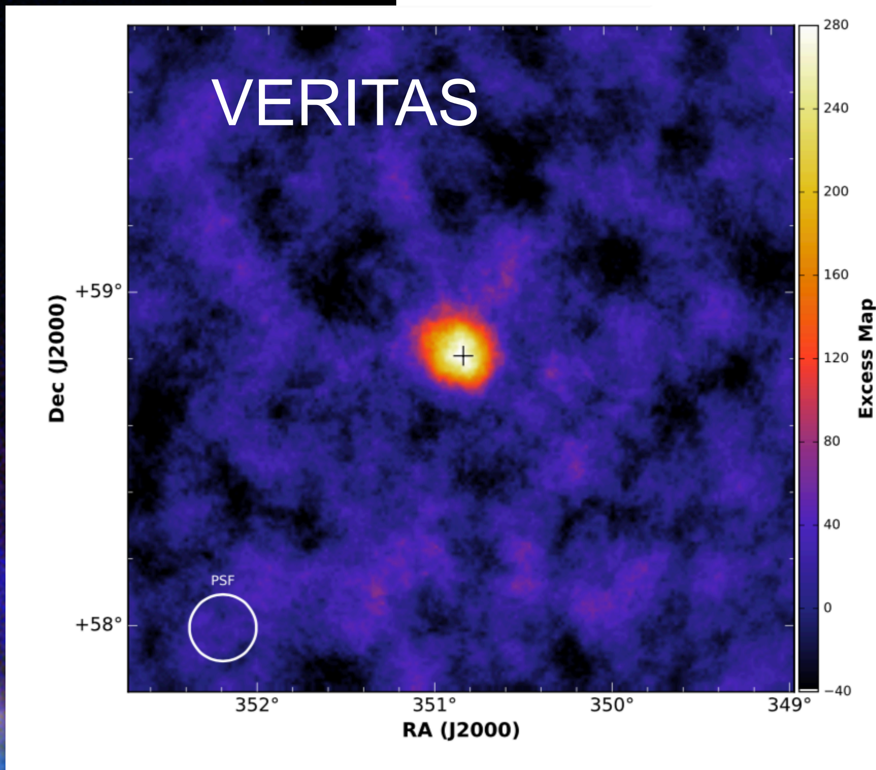

Supernova remnant SN1006
radio
X-ray
optical
SN 1006: 2006
DESY.

Supernova remnant SN1006



Cassiopeia A Supernova Remnant

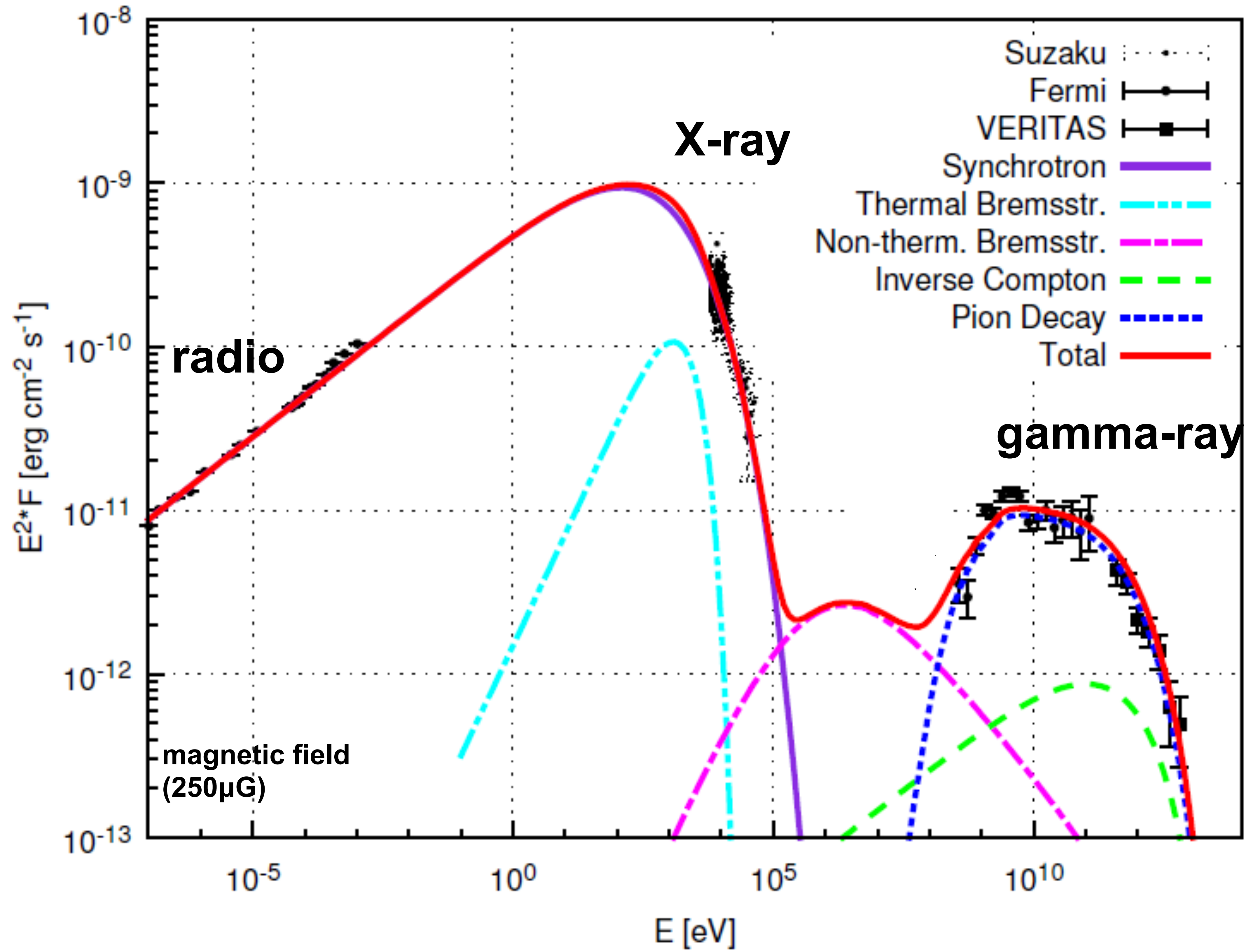




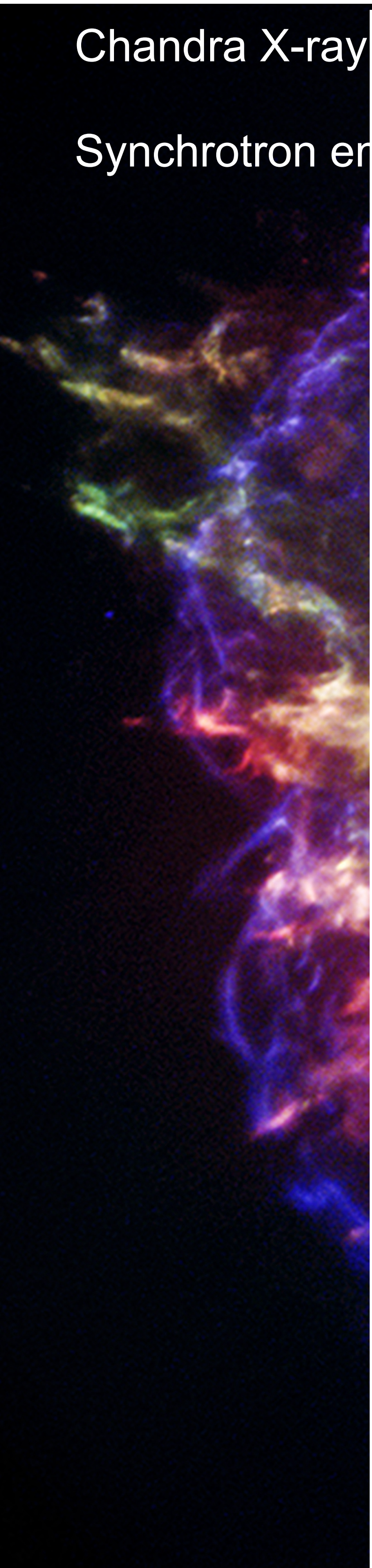
Cassiopeia A - Spectral Energy Distribution

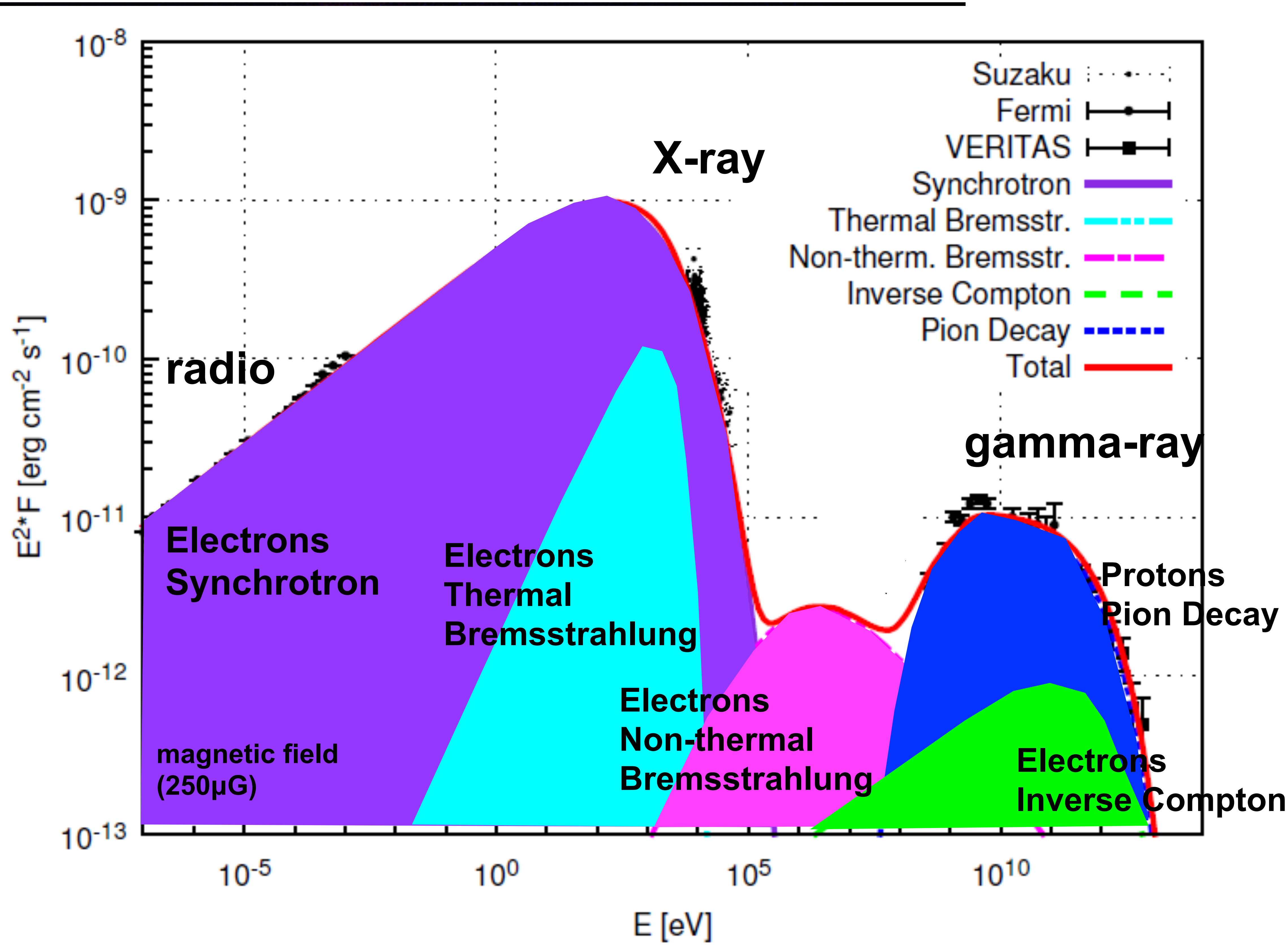
Chandra X-ray

Synchrotron er



Cassiopeia A - Spectral Energy Distribution





Supernovae Explosions & Energy Budget

assume Milky Way is filled uniformly with Cosmic Rays (CR), diffuse out diffuse out of this volume in typically $t_{GD} \approx 10^7$y

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

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

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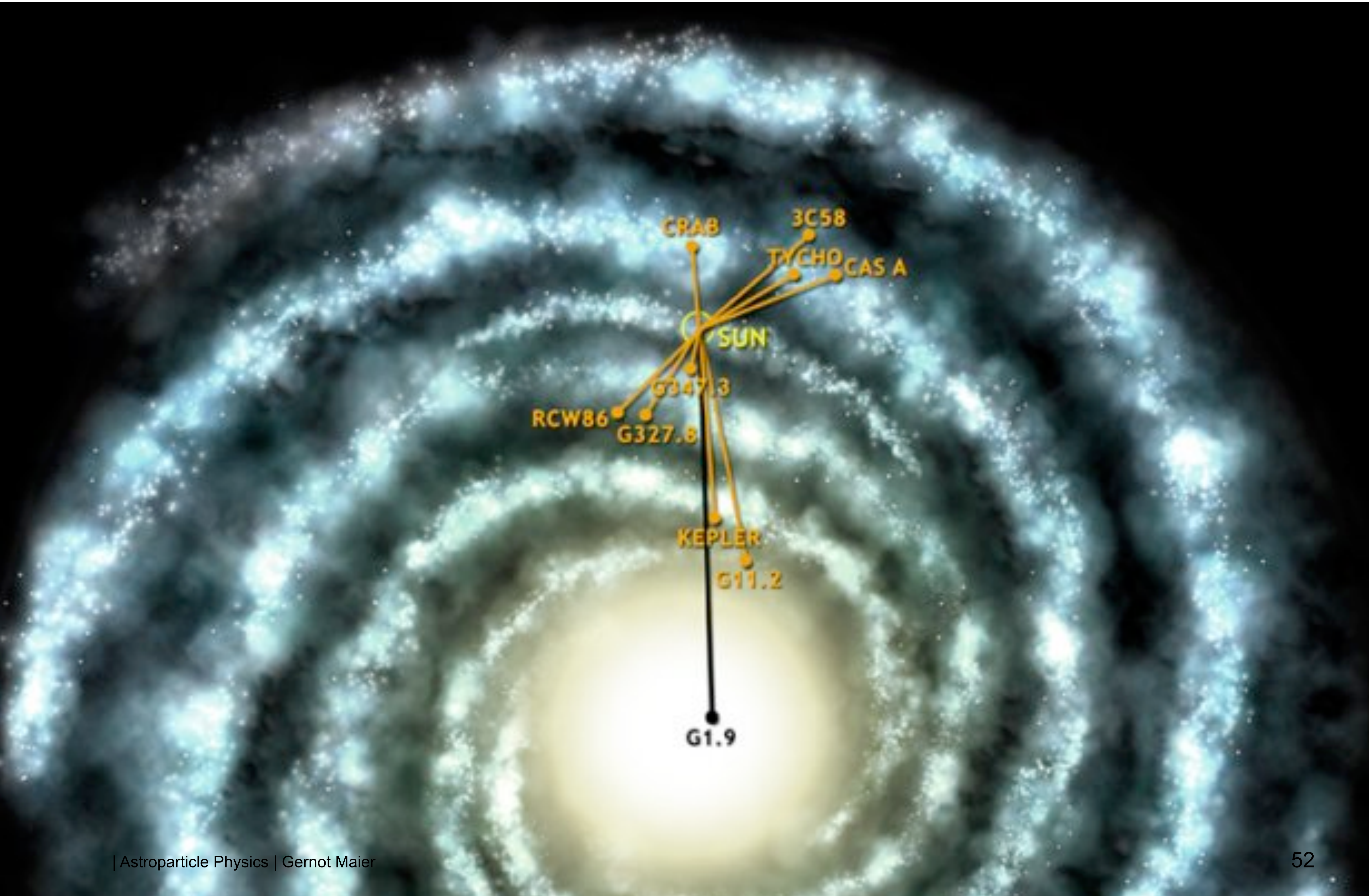
typical 2-3 Supernovae per 100 y in our Galaxy are enough to sustain this luminosity assuming a 10% conversion rate from mechanical to cosmic-ray energy

	length of		Historical Records				
date	visibility	remnant	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	–	–	–	–


八年六月己巳客星出奎
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
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)

Observational Bias…



Active Galactic Nuclei

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M87
HST optical

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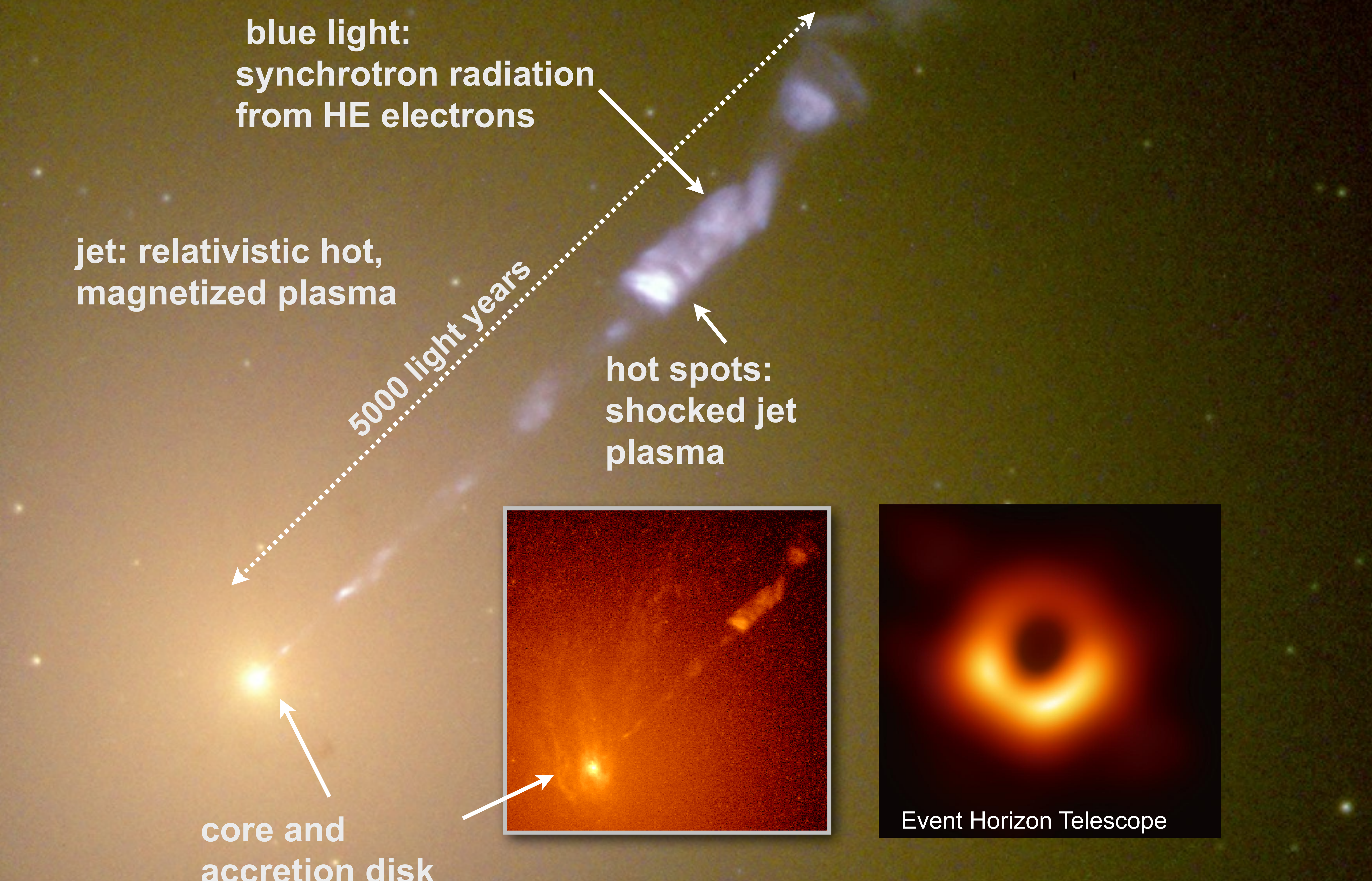
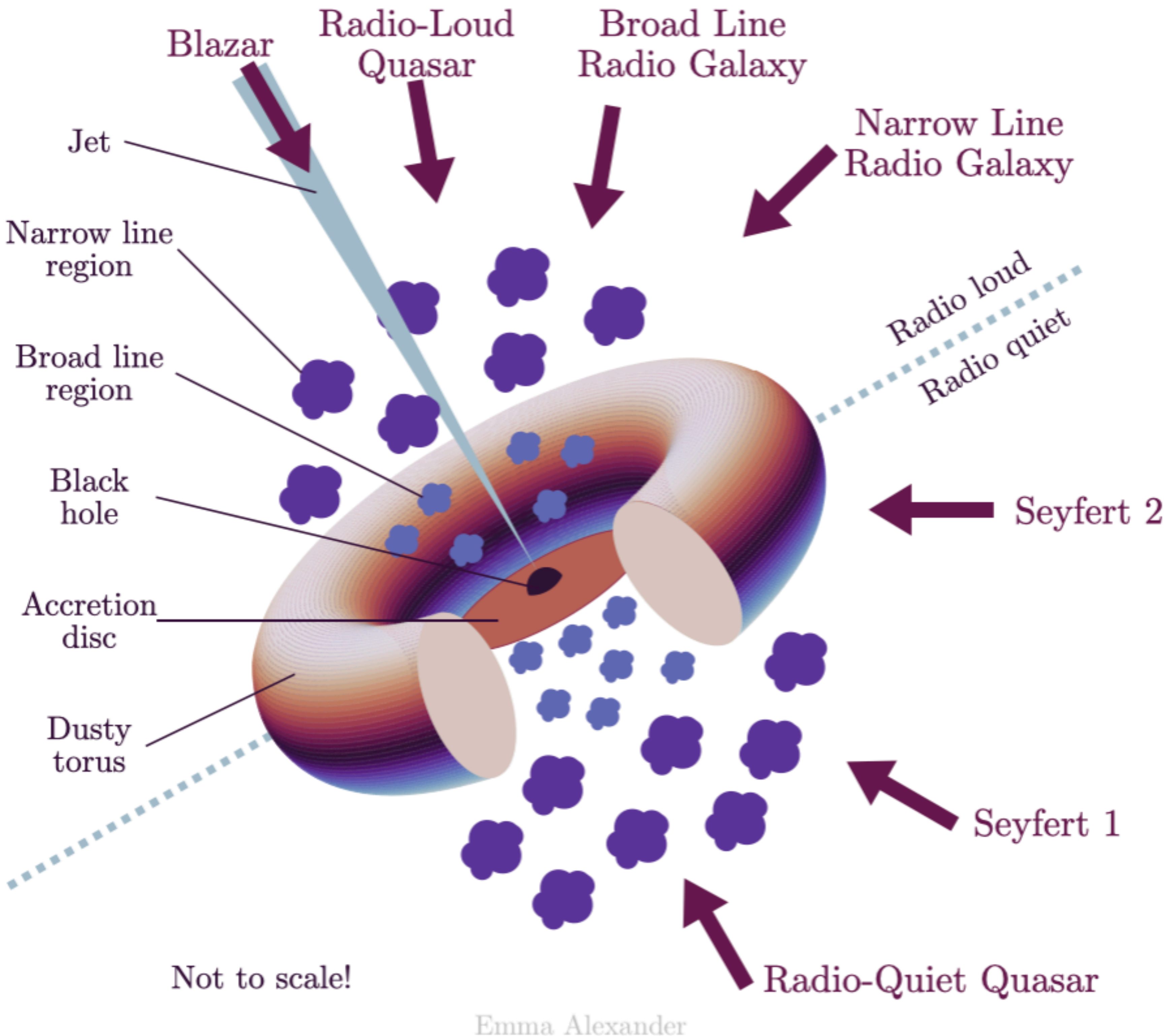



Blazar
Radio-Loud Quasar
Broad Line Radio Galaxy
Narrow Line Radio Galaxy
Jet
Narrow line region
Broad line region
Black hole
Accretion disc
Dusty torus
Radio loud
Radio quiet
Seyfert 2
Seyfert 1
Radio-Quiet Quasar
Not to scale!
Emma Alexander

Doppler boosting in jets

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

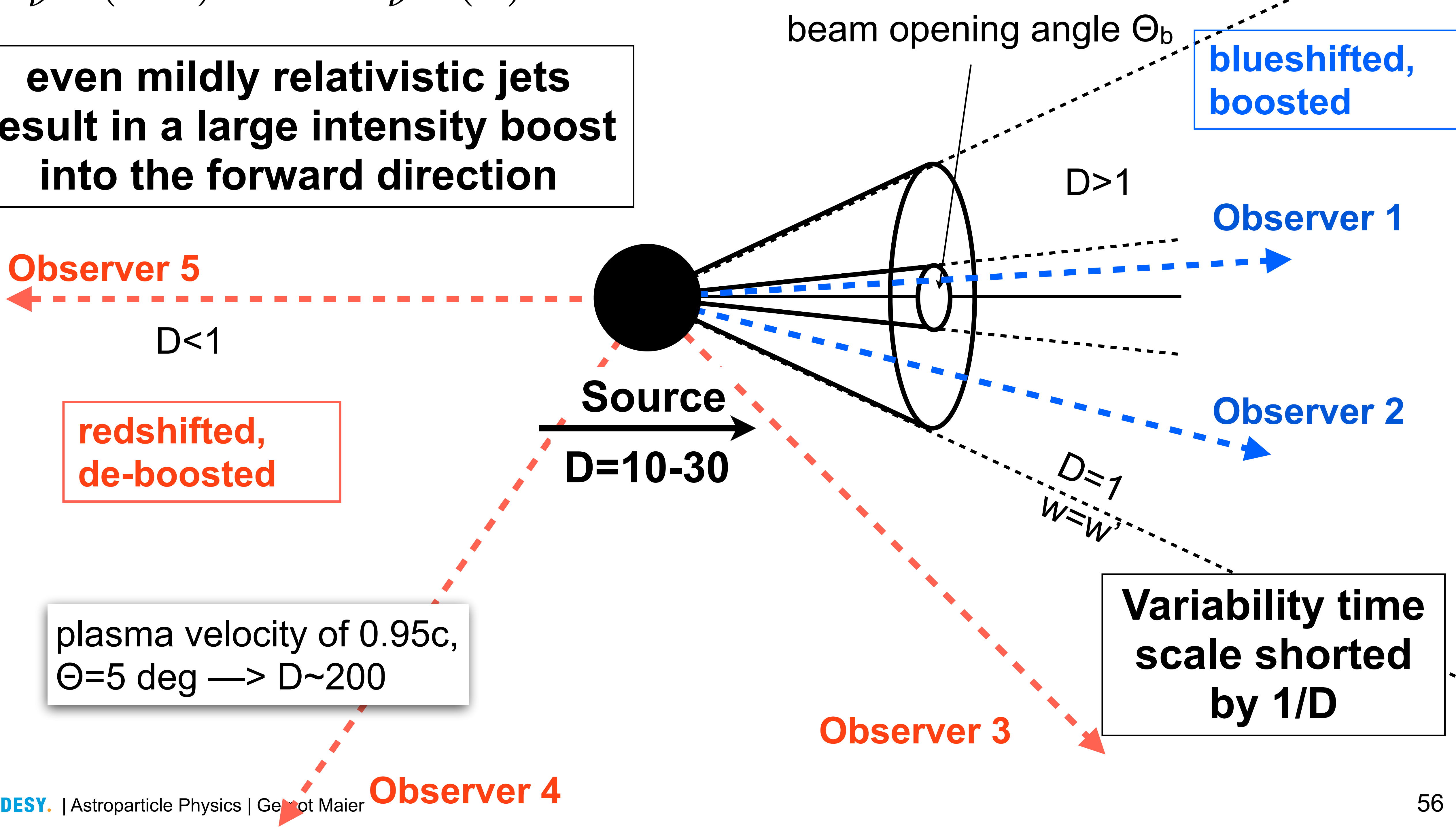
$$I_\nu^{obs}(D\nu) = D^3 I_\nu^{em}(\nu)$$

Doppler boosting of a power-law source:

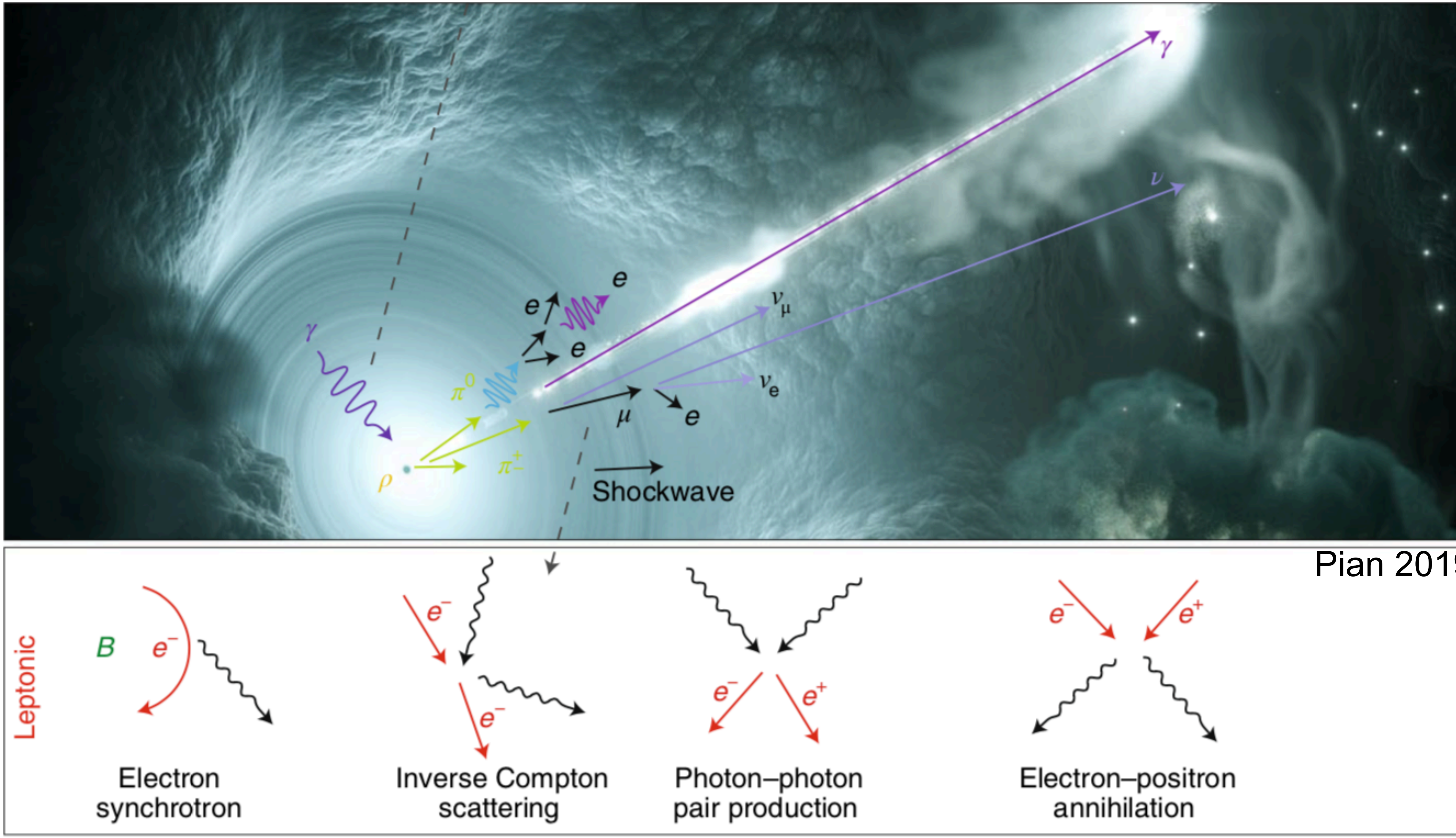
$$I_\nu^{em}(\nu) \propto \nu^{-\alpha}$$

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

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

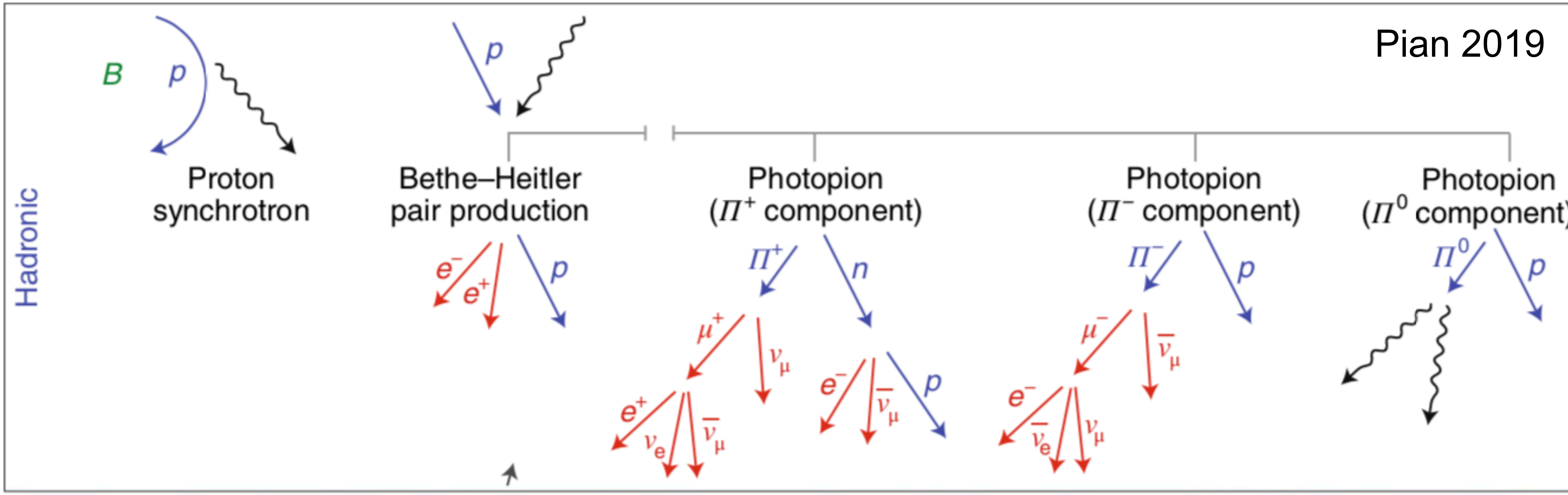


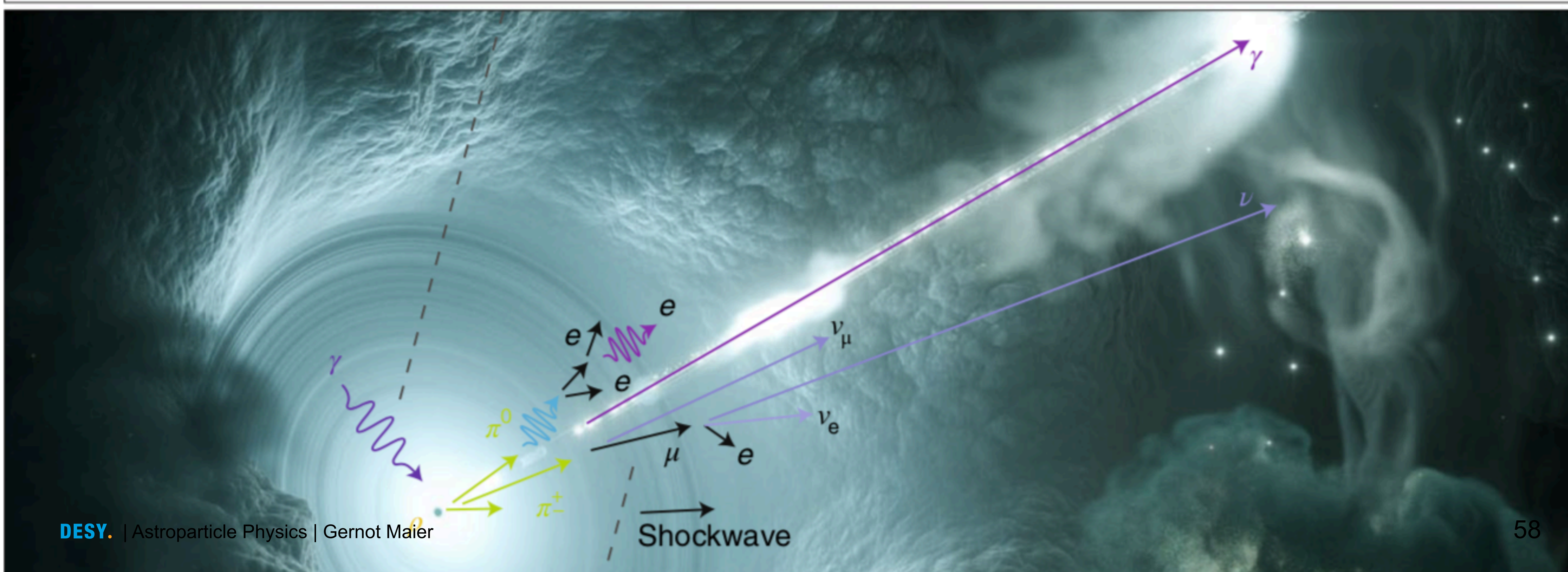
Active Galactic Nuclei - leptonic emission



Pian 2019

Active Galactic Nuclei - Hadronic emission





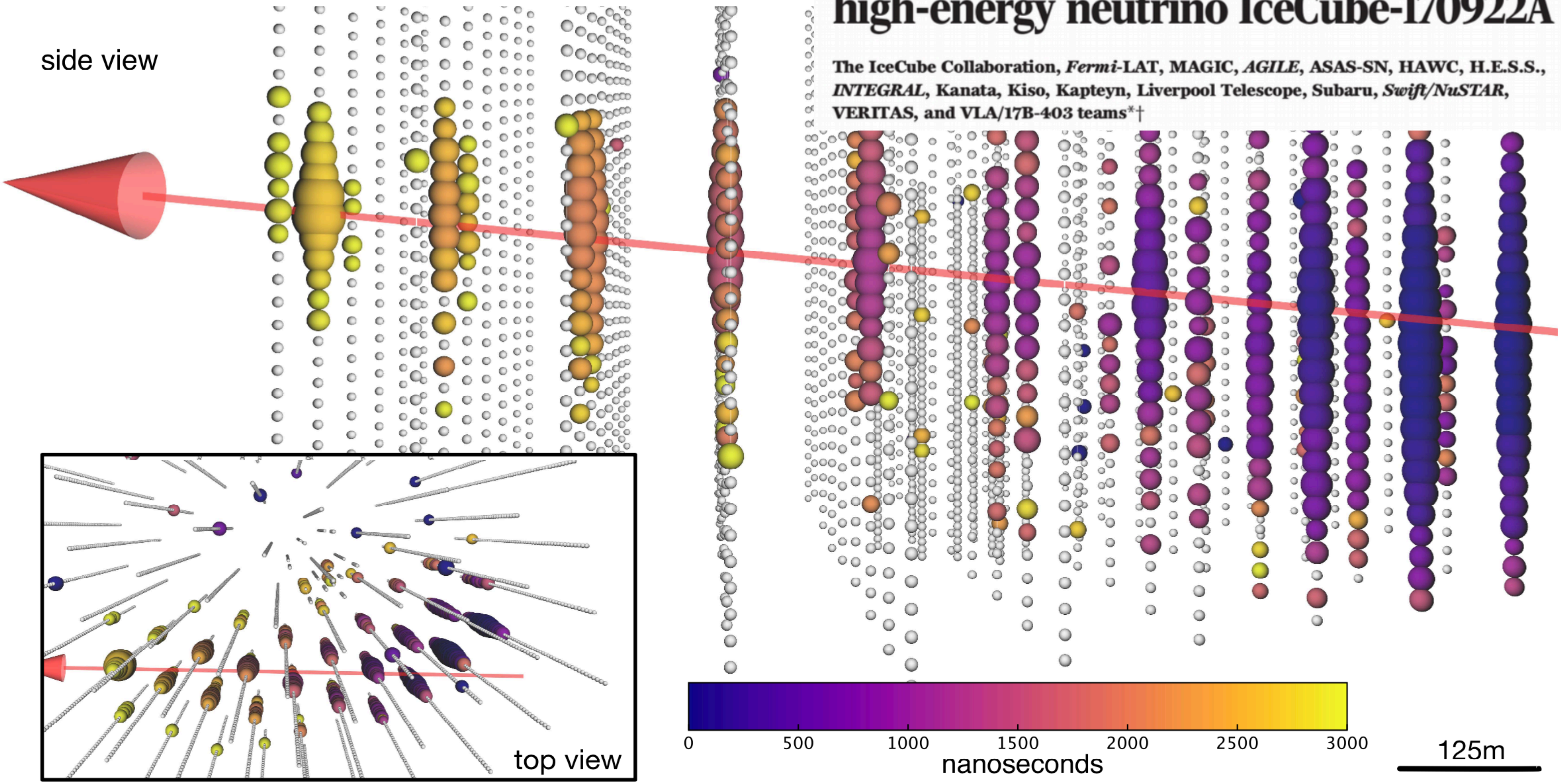
IceCube-170922A
TXS 0506+056


RESEARCH ARTICLE SUMMARY

NEUTRINO ASTROPHYSICS

Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A

The IceCube Collaboration, *Fermi*-LAT, MAGIC, *AGILE*, ASAS-SN, HAWC, H.E.S.S., *INTEGRAL*, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, *Swift/NuSTAR*, VERITAS, and VLA/17B-403 teams*†



most probable neutrino energy of 290 TeV
signalness to be 56.5%

New Physics

Random example!

Lorenz Invariance Violations

- **Standard Model** and **General Relativity**:
  best theories describing the four fundamental forces
  - no conflict between them - but fundamentally different
- —> **Quantum Theory of Gravity**?
  - zoo of theories of Quantum Gravity
  - predict in general new physics at the Planck Energy Scale

$$E_{\mathrm{Pl}} \simeq 1.2 \times 10^{19}\ \mathrm{GeV}$$

—> Lorentz Invariance Violation (LIV)

LIV: arrival time measurements

- new dispersion relation

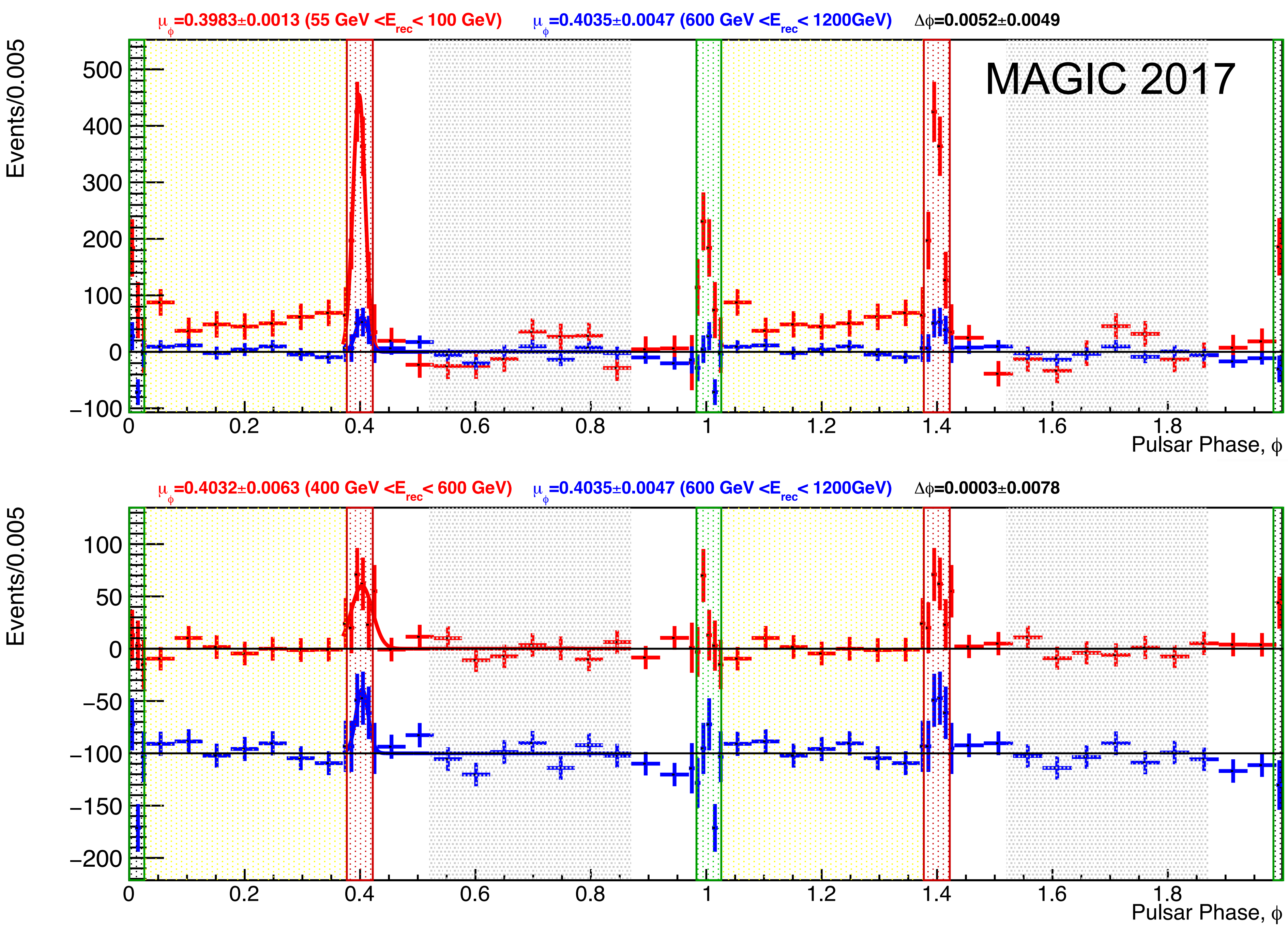
$$c^2 p^2 = E_\gamma^2 [1 \pm \xi_1 E_\gamma / E_{QG} \pm \xi_2 (E_\gamma^2 / E_{QG}{}^2) \pm \ldots]$$

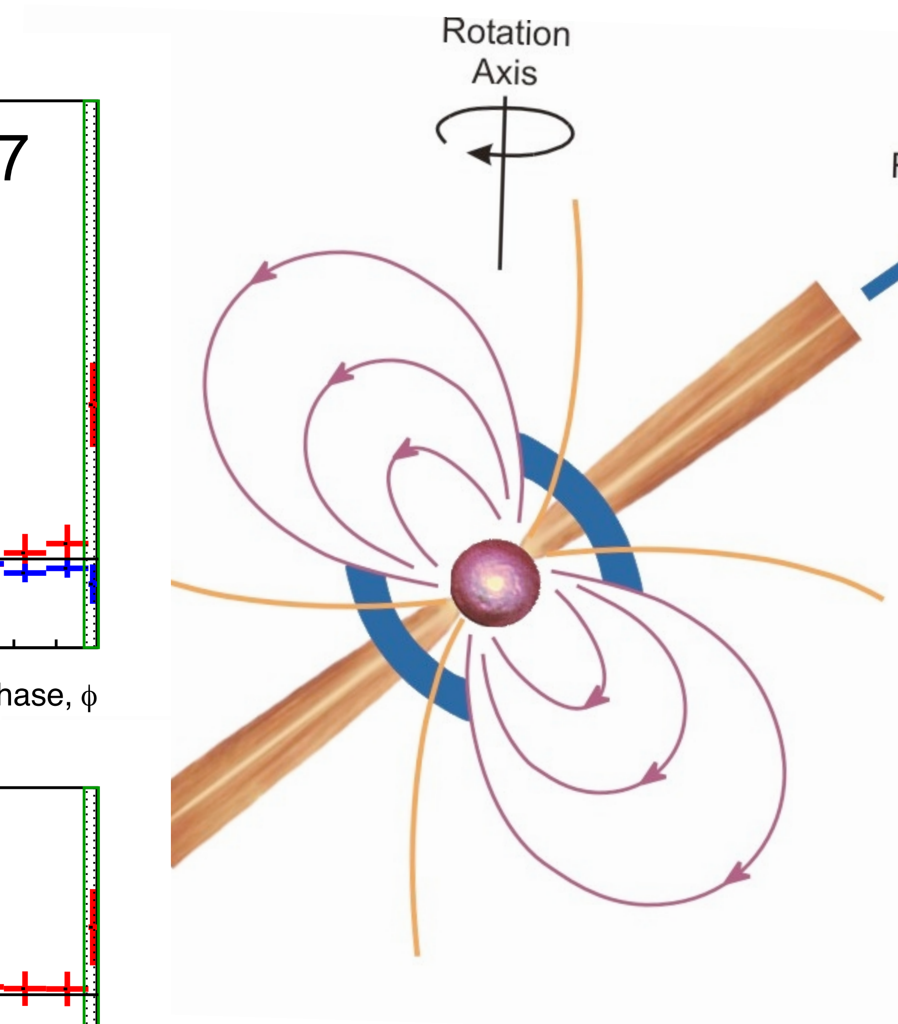
depending on sign: subluminal or superluminal case

- time delays in arrival times of photons

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

LIV: arrival time measurements - pulsars

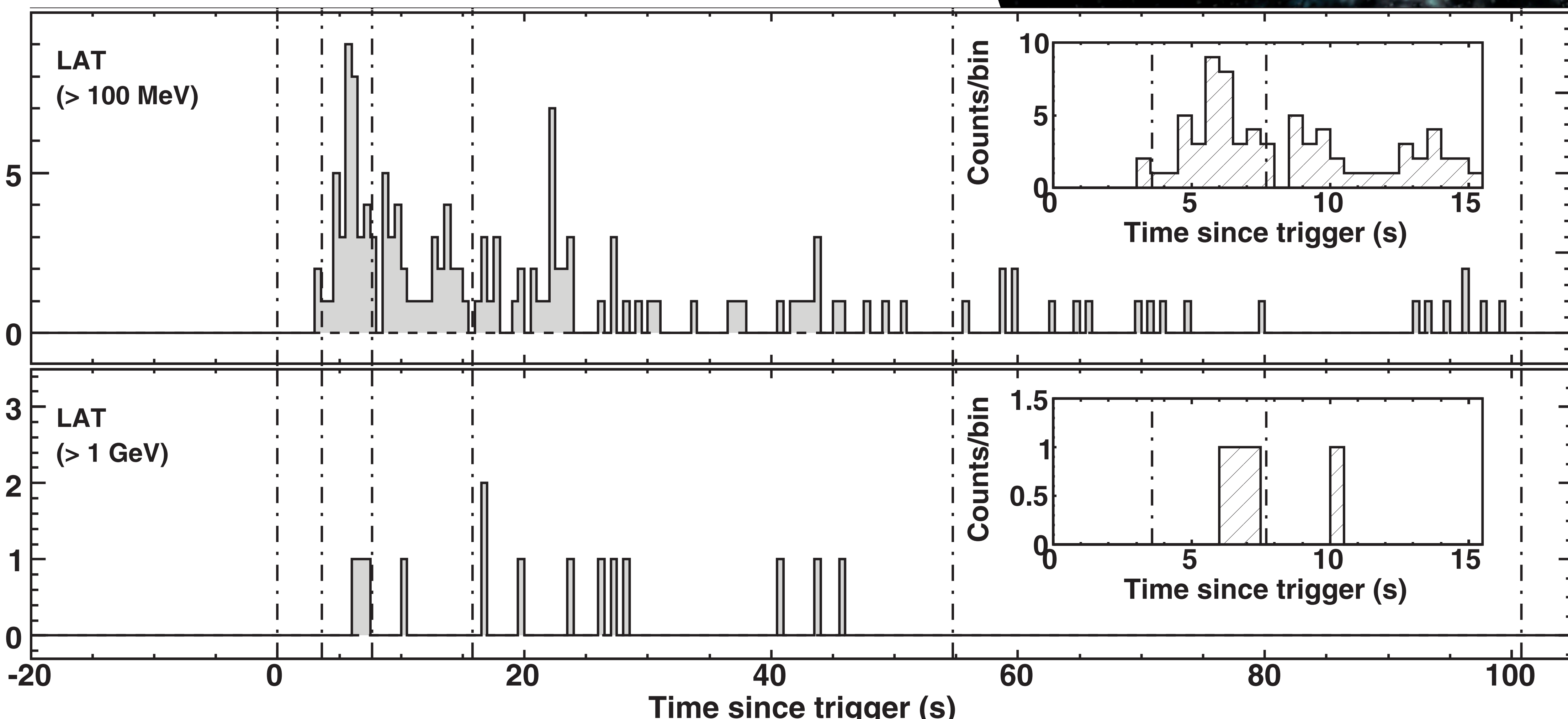




Upper limits:
~ 10^{17} - 10^{18} eV

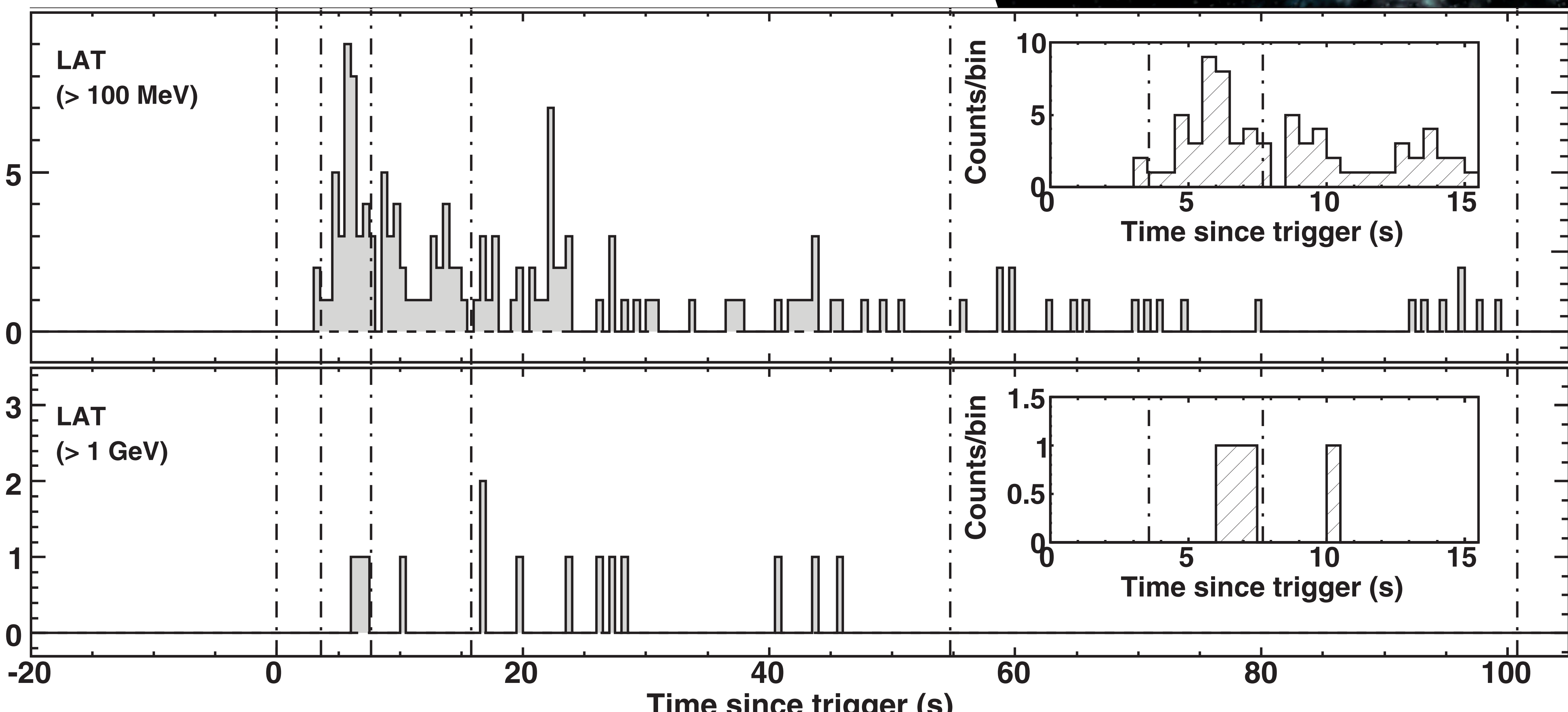
Relatively nearby - but repeating gamma-ray source

LIV: arrival time measurements - GRBs

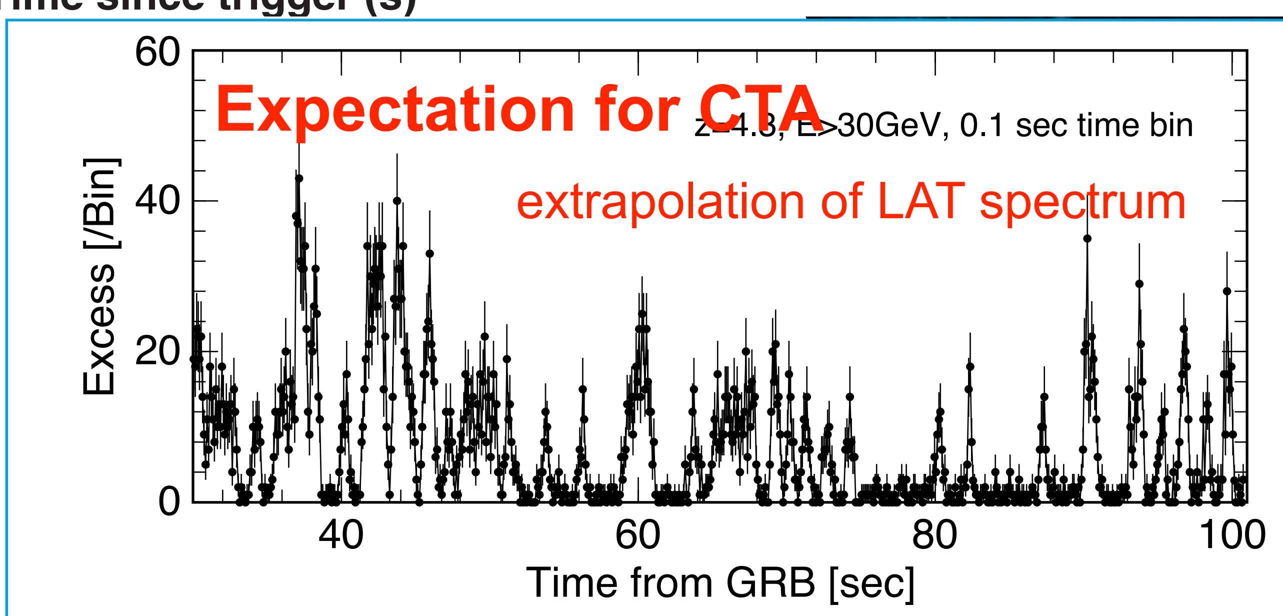


GRB 080916C
at z=4.3

LIV: arrival time measurements - GRBs



20 - 50 s for slew



GRB 080916C
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LIV measurements: pair production threshold

- opacity of Universe to TeV gamma rays due to pair production on extragalactic background light

- LIV: change in pair production threshold

$$\epsilon_{min} = \frac{m^2 c^4}{E_\gamma} - S \frac{E_\gamma^2}{4E_{LIV}}$$

- LIV: change in Compton scattering cross section (at source)

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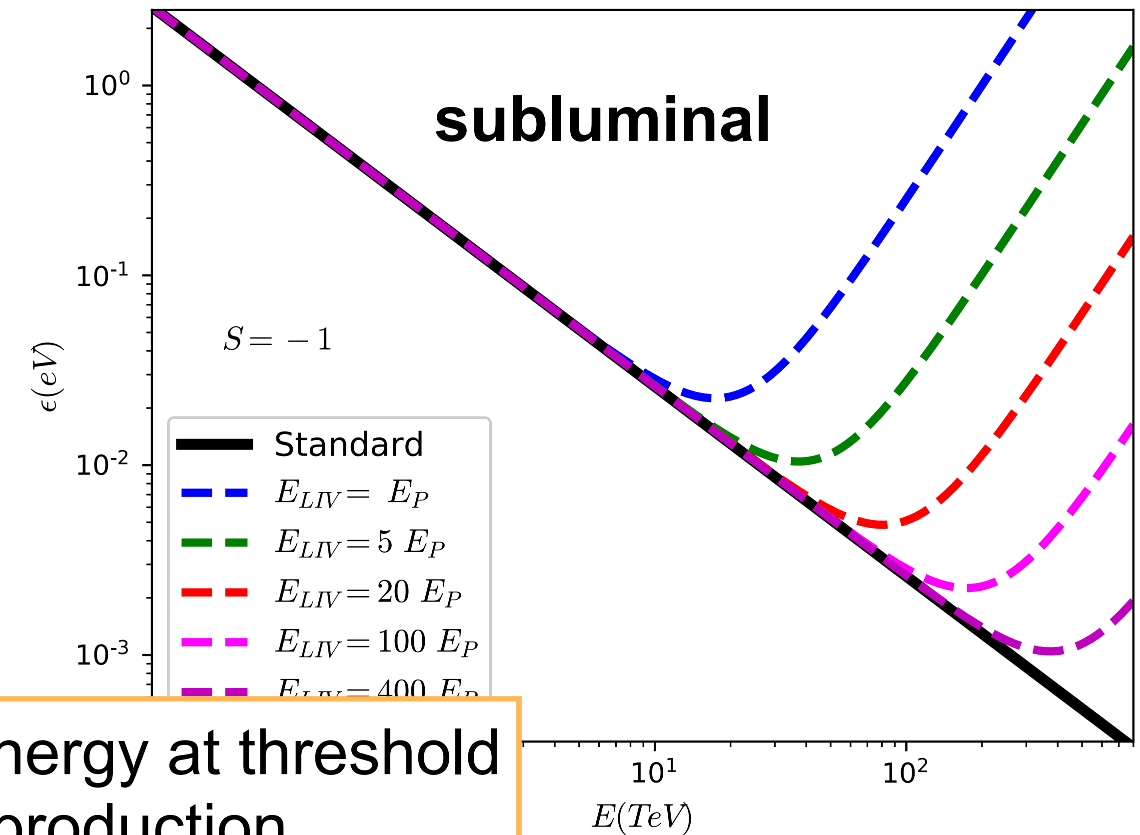
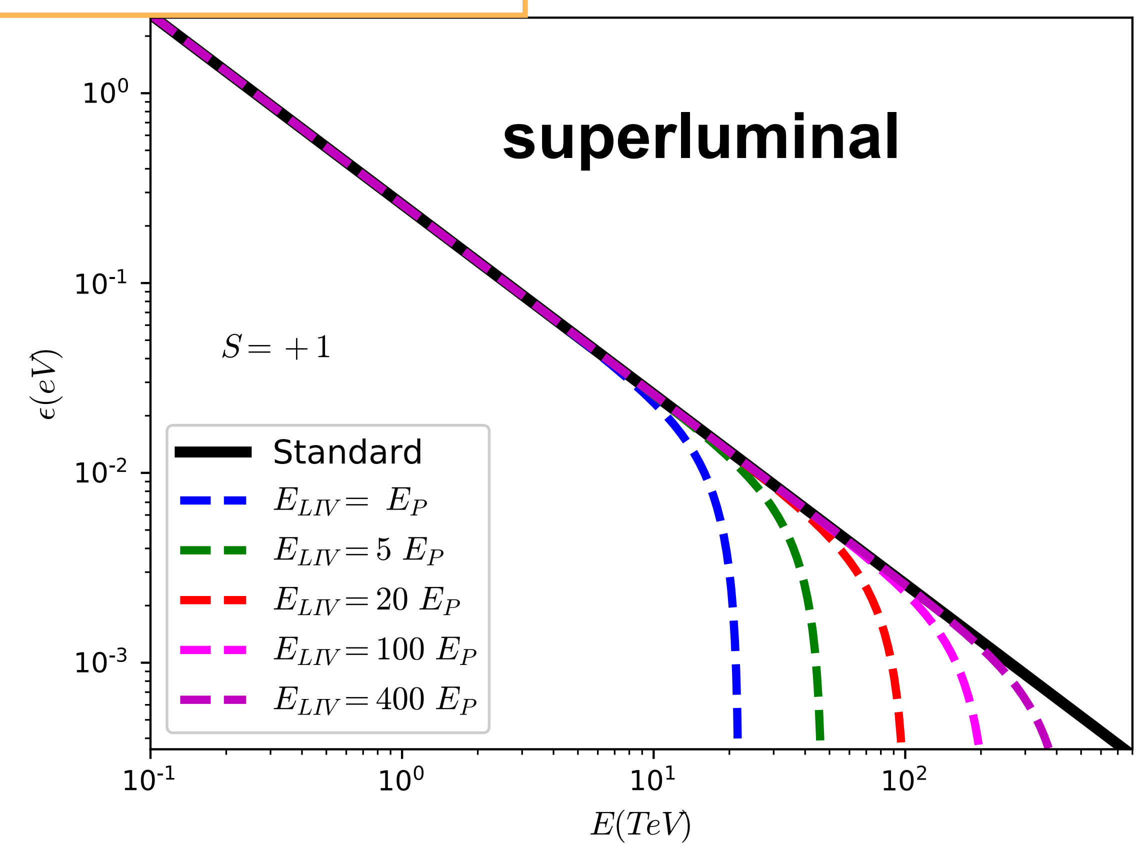


photon target energy at threshold for pair production



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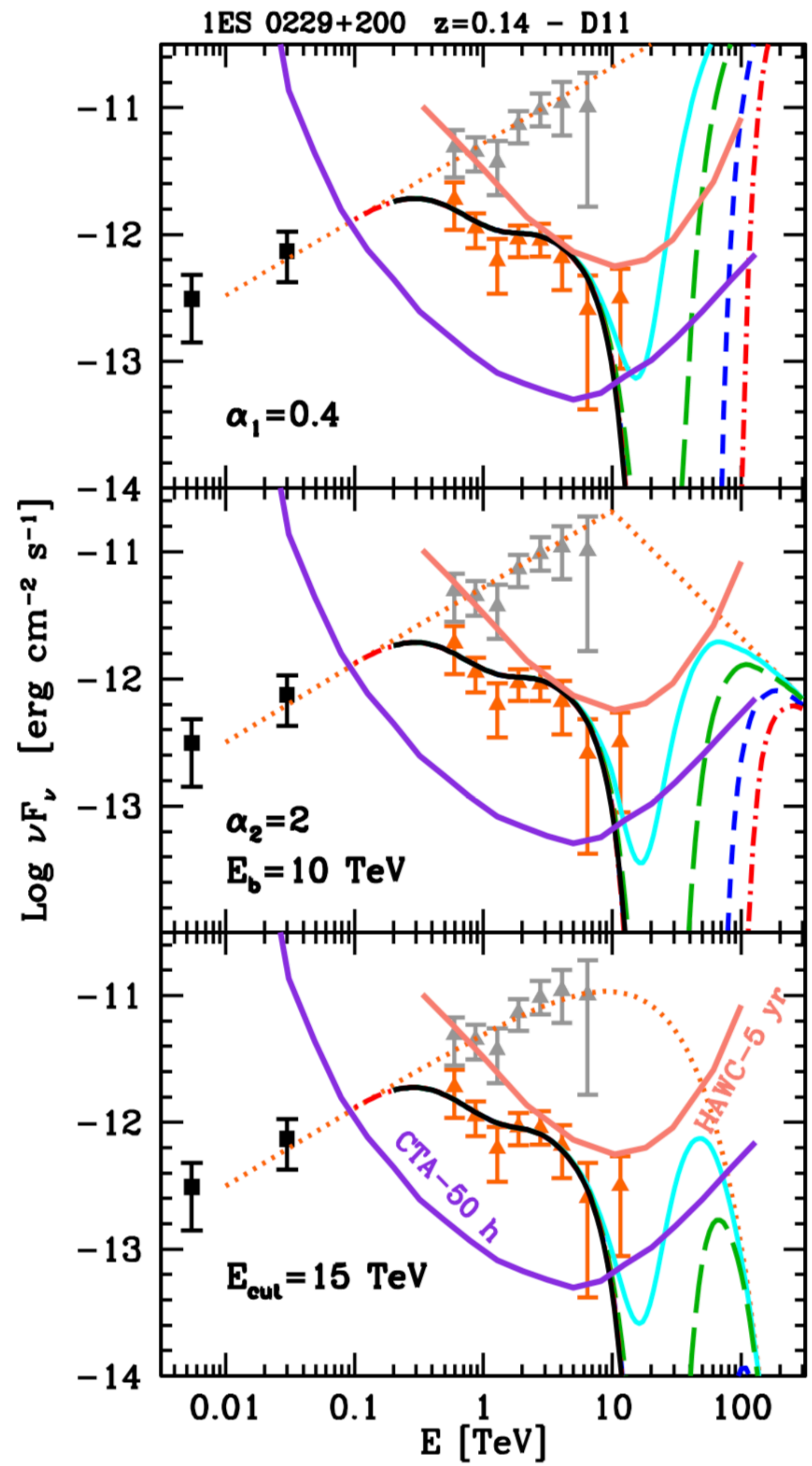

Summary - astroparticle physics

- **cosmic rays - cosmic environment - fundamental physics**
- **exciting new results from neutrino and gravitational wave observatories**
- **large number of new instruments coming online in the next years:**
  - Cherenkov Telescope Array
  - IceCube 2
  - Auger upgrades
  - Gravitational wave observatories

Credit: F. Acero & H. Gast