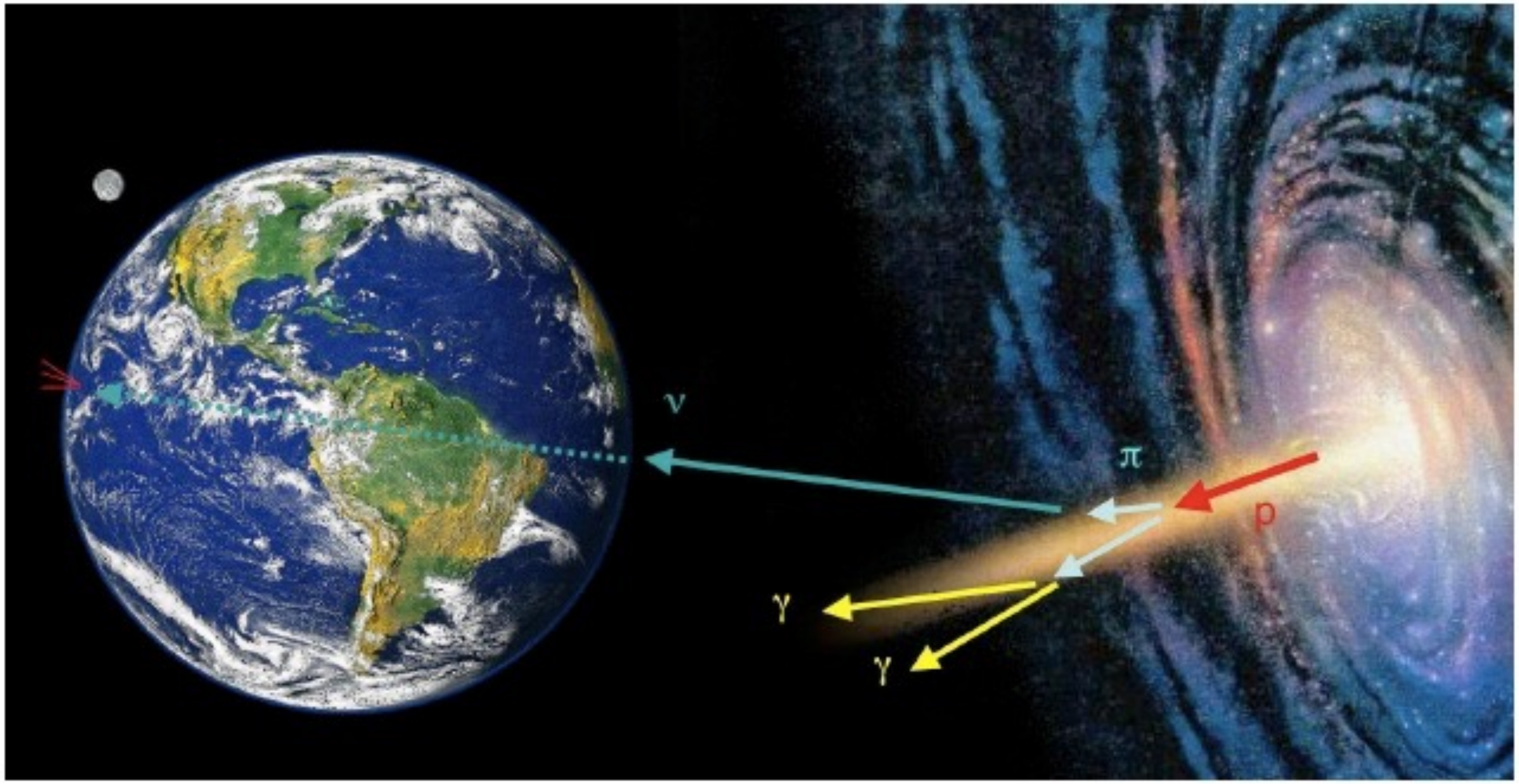
Teilchenphysik mit kosmischen und mit erdgebundenen Beschleunigern



01. Introduction

09.04.2018

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

Dr. Frank Simon

Goal of the Lecture

- Current and future accelerators
- Particle detection in high energy and astroparticle physics
- The Standard Model of particle physics
- Precision measurements in particle physics
- Cosmic acceleration mechanisms
- The physics of charged and neutral cosmic particles
- Dark Matter and Dark Energy
- Gravitational Waves
- Neutrino physics

- We are open to other topics as well - just let me know!

Organisatorial Matters

- Time: Mondays, 14:00 to 16:00
- Place: PH 127 , TUM Physik-Departement I

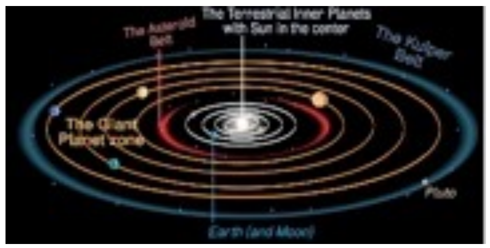
- Background
  - if possible: KTA (Introduction to nuclear, particle and astro physics)
  - in addition: Quantum field theory, theoretical particle physics
  - does not hurt: Teilchenphysik mit höchstenergetischen Beschleunigern (Higgs & Co)

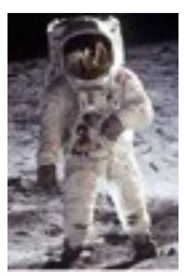
- Exercise classes: none
- Exams: Yes, if asked for
- Material: The slides will be posted after the lectures on the MPP web site: https://indico.mpp.mpg.de/category/127/

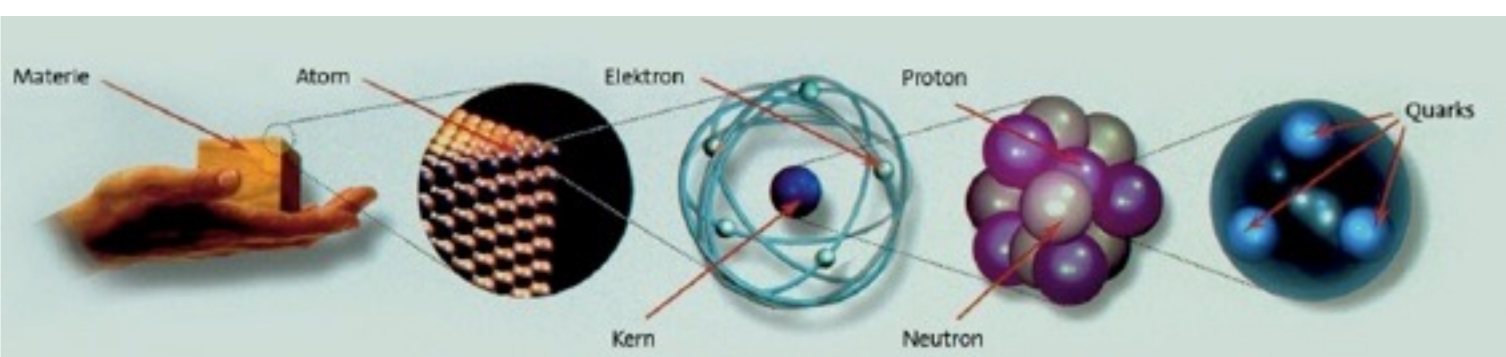
Lecture Overview

09.04.	Einführung / Introduction	
16.04.	Ground-based Accelerators	
23.04.	Cosmic Accelerators	by Bela Majorovits
30.04.	Detectors in Astroparticle Physics	
07.05.	The Standard Model	
14.05.	QCD and Jets at e^+e^- Colliders	by Siggi Bethke
21.05.	Holiday - No Lecture	
28.05.	Precision Experiments with low-energy accelerators	
04.06.	Dark Matter & Dark Energy	by Bela Majorovits
11.06.	Cosmic Rays I	
18.06.	Cosmic Rays II	
25.06.	Gravitational Waves, Neutrino Introduction	
02.07.	Neutrinos I	
09.07.	Neutrinos II	

From the very big to the very small







	Size	Mass
Universe	10^{26} m	10^{52} kg
Galaxy	10^{21} m	10^{41} kg
Solar system	10^{13} m	10^{30} kg
Earth	10^{7} m	10^{24} kg
Man	10^{0} m	10^{2} kg
Atom	10^{-10} m	10^{-26} kg
Nucleus	10^{-14} m	10^{-26} kg
Nucleon	10^{-15} m	10^{-27} kg
Quarks, Leptons	$<10^{-18}$ m	10^{-30} kg

"Astroteilchenphysik in Deutschland", http://www.astroteilchenphysik.de/, und darin angegebene Referenzen

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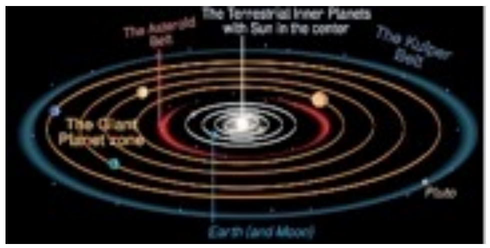

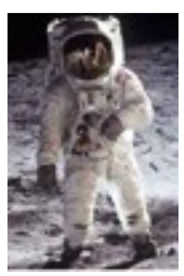

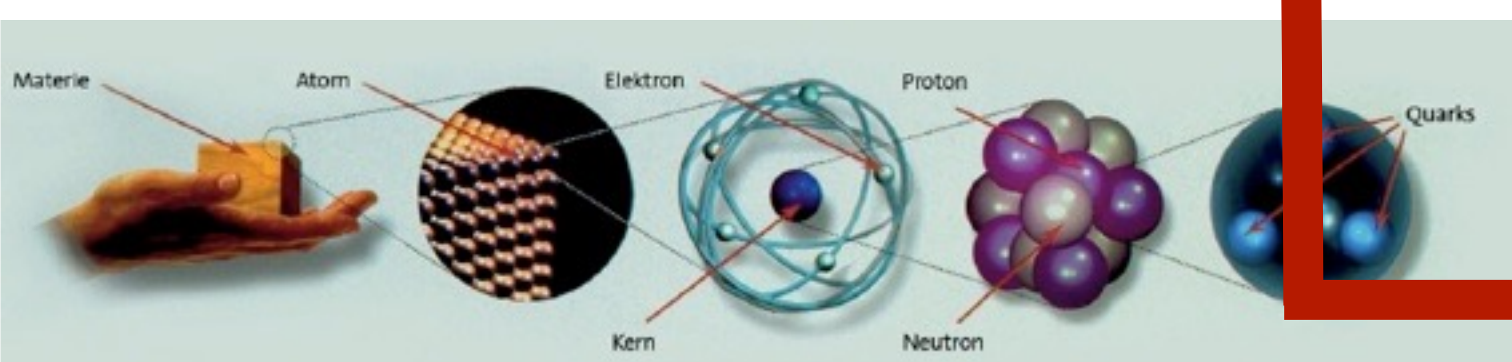

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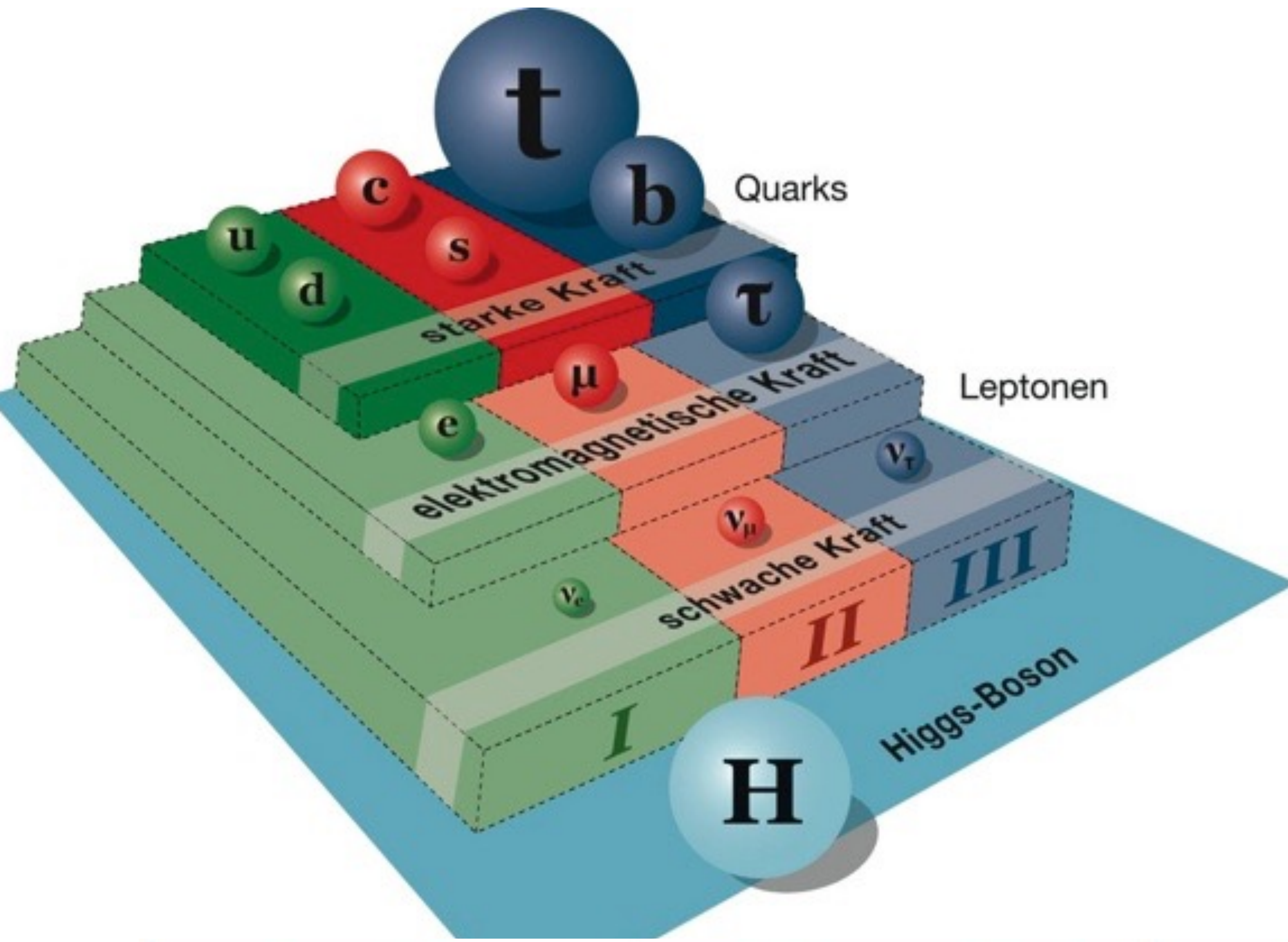
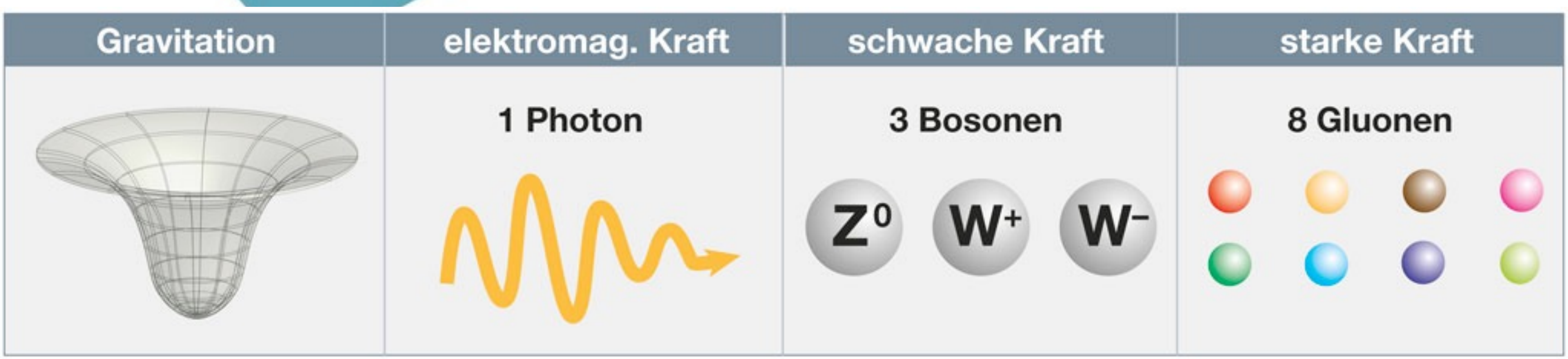
The Standard Model of Particle Physics



Interaction	Range	relative strength
Strong	subatomic	1
Electromagnetic	infinite	1/137
Weak	subatomic	10^{-14}
Gravitation	infinte	10^{-40}



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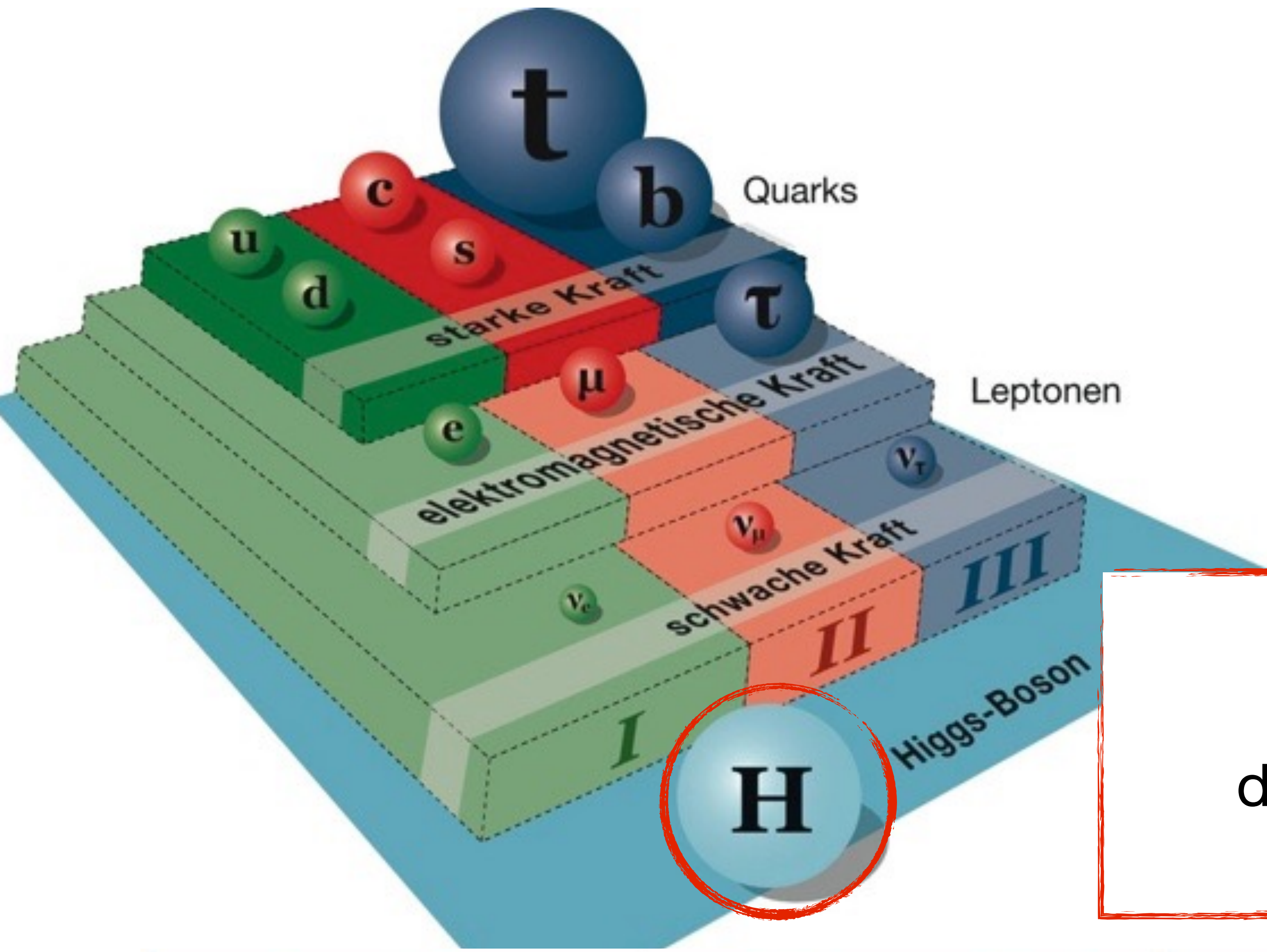

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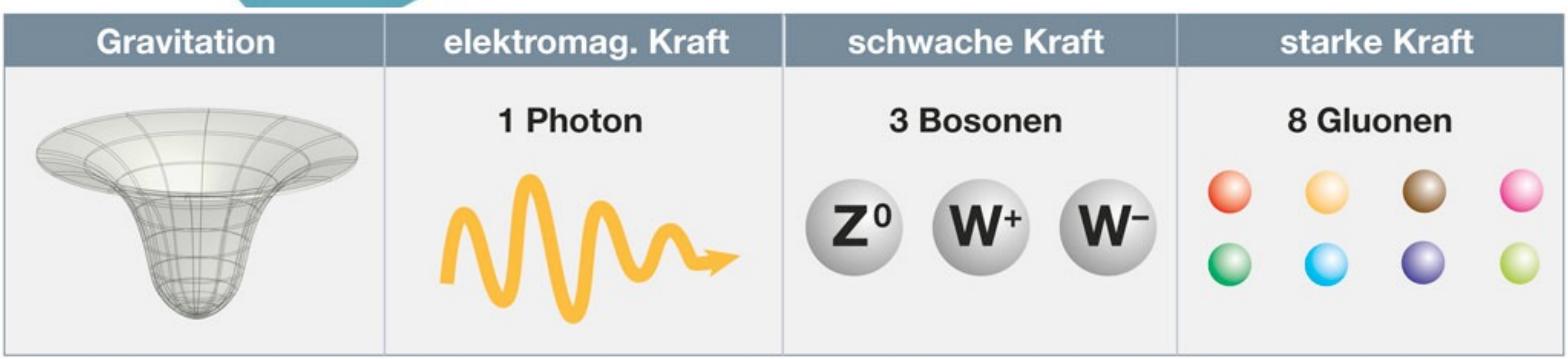
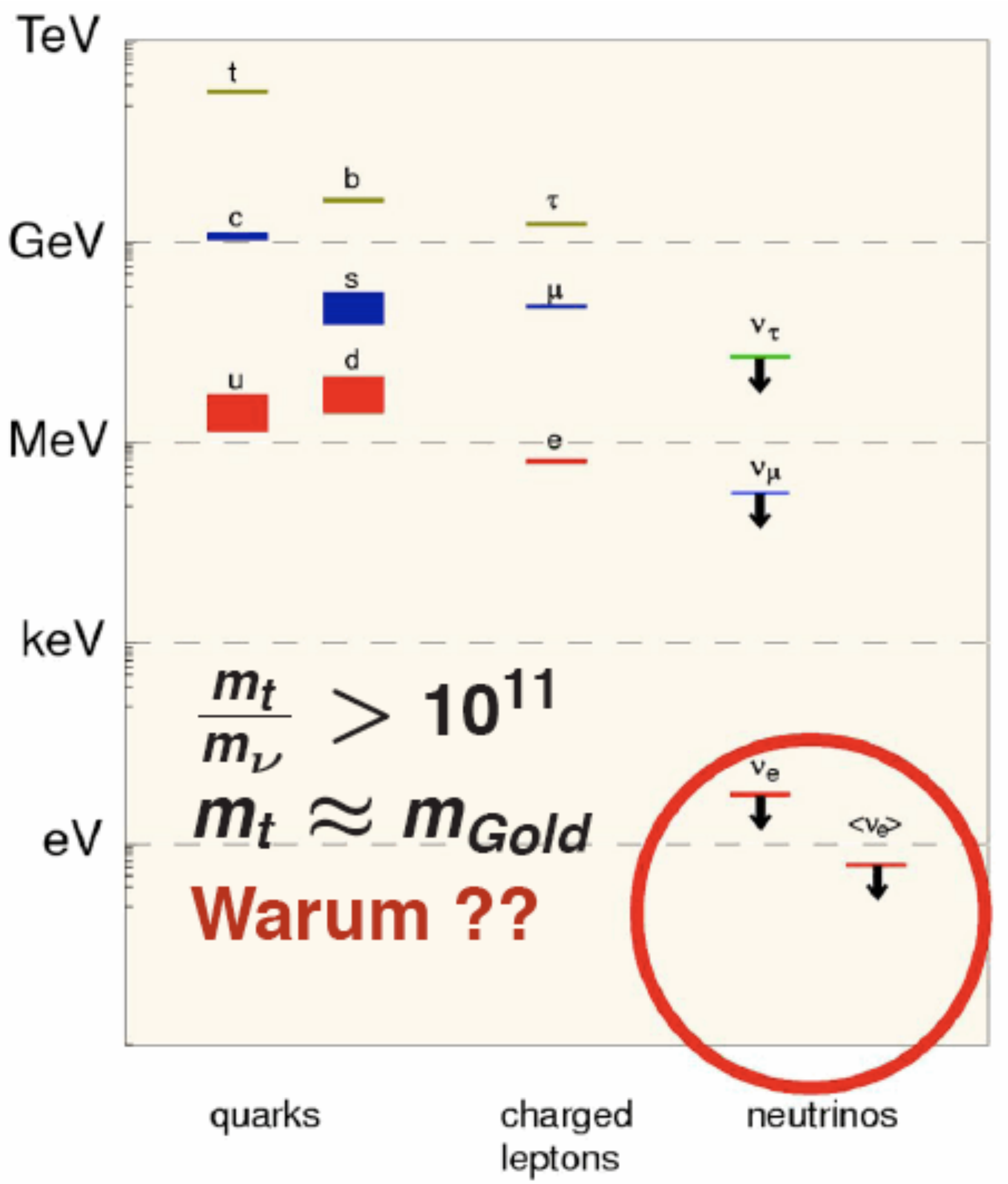
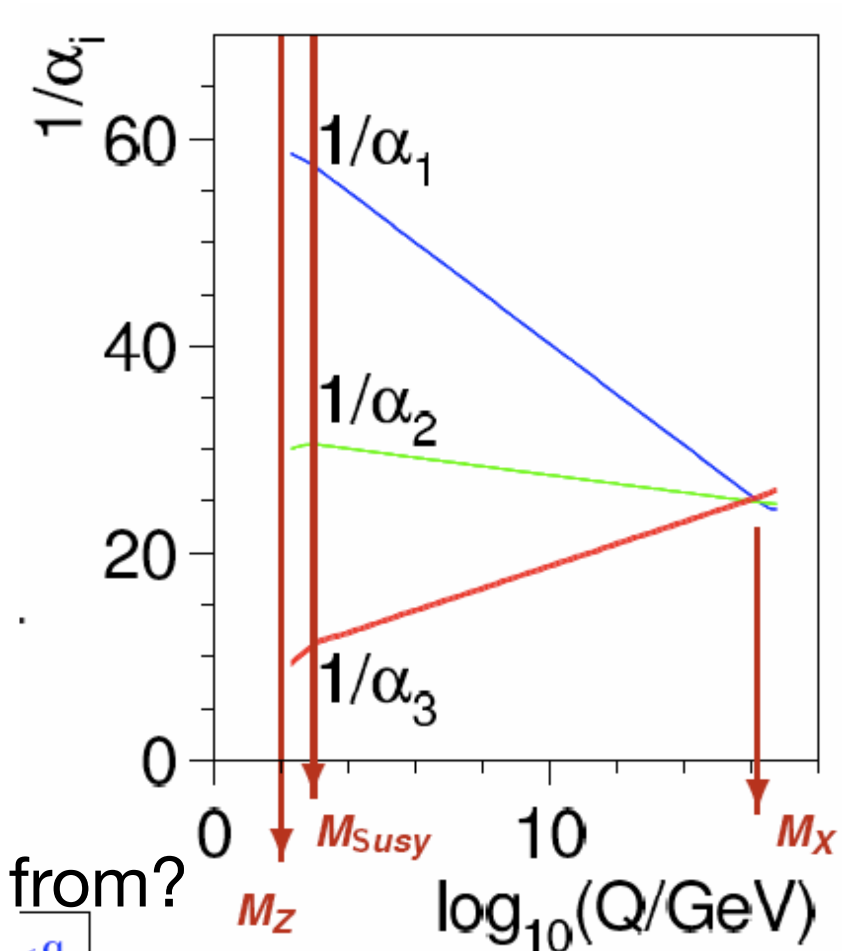
The last missing piece
discovered at LHC: July 4th, 2012



The Standard Model: Open Questions



- Where does the mass hierarchy of particles come from?
- Why are there exactly 3 families of fermions?
  - known from the measurement of the Z Boson width: Only three light neutrinos!
- Is there a unification of forces (not possible in the SM)?
  - Super-Symmetry?
  - ...



Questions connected to cosmology / astrophysics

- What is Dark Matter? Dark Energy
- Where does the matter / antimatter asymmetry come from?

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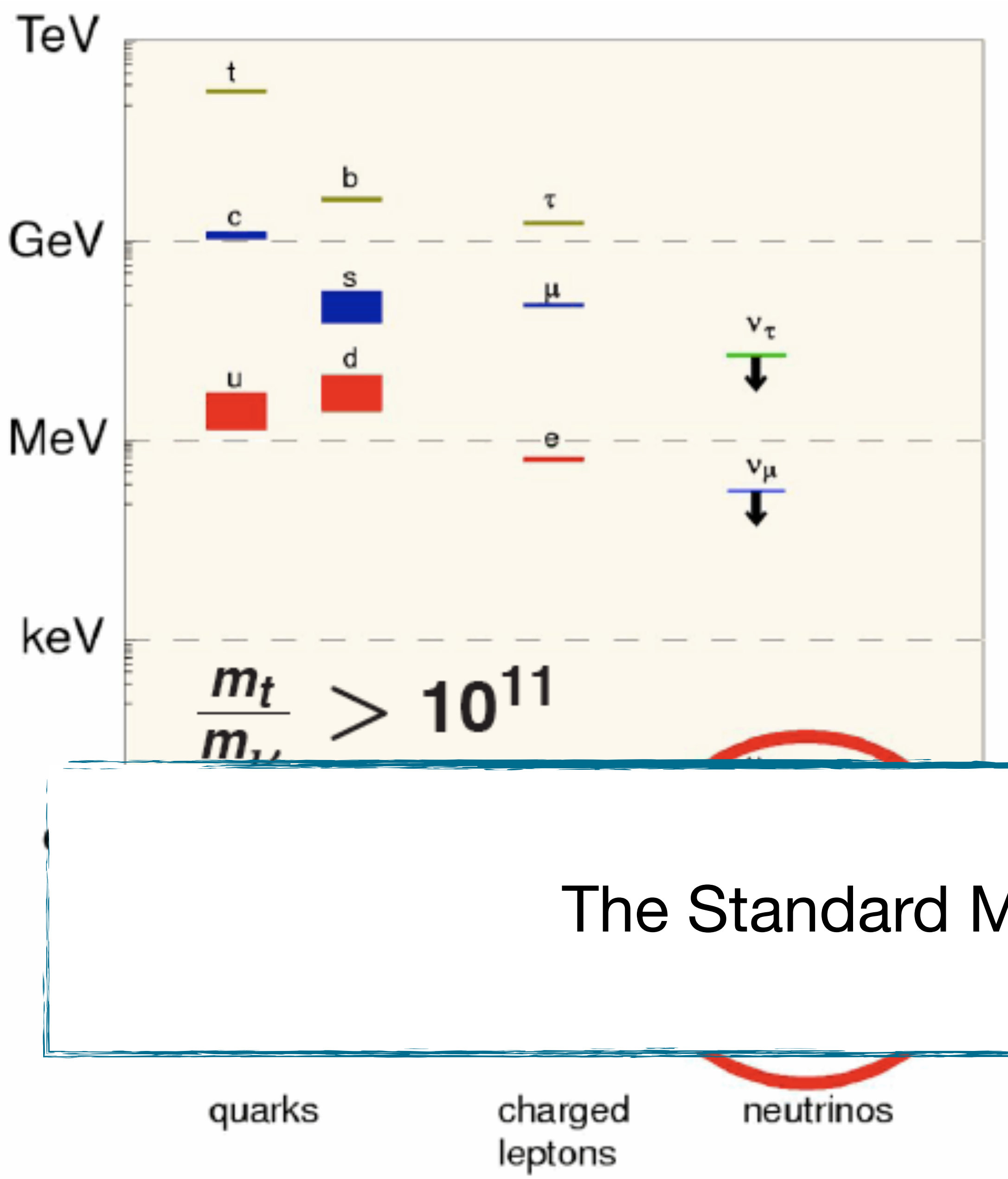

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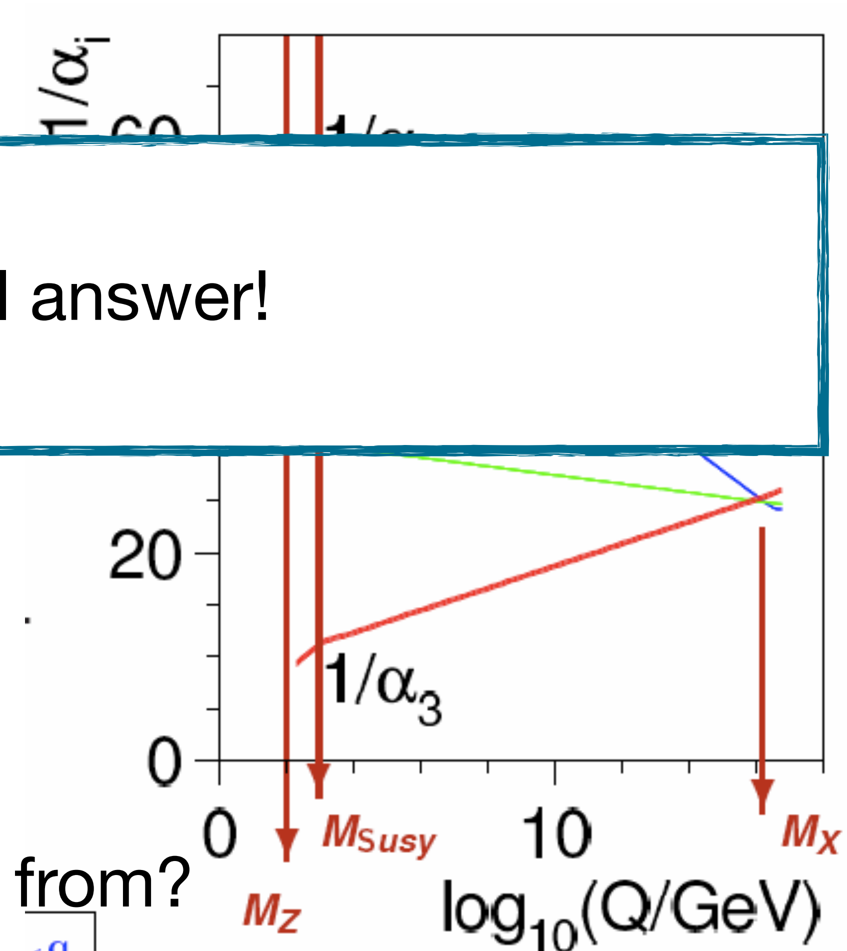

The Standard Model cannot be the final answer!

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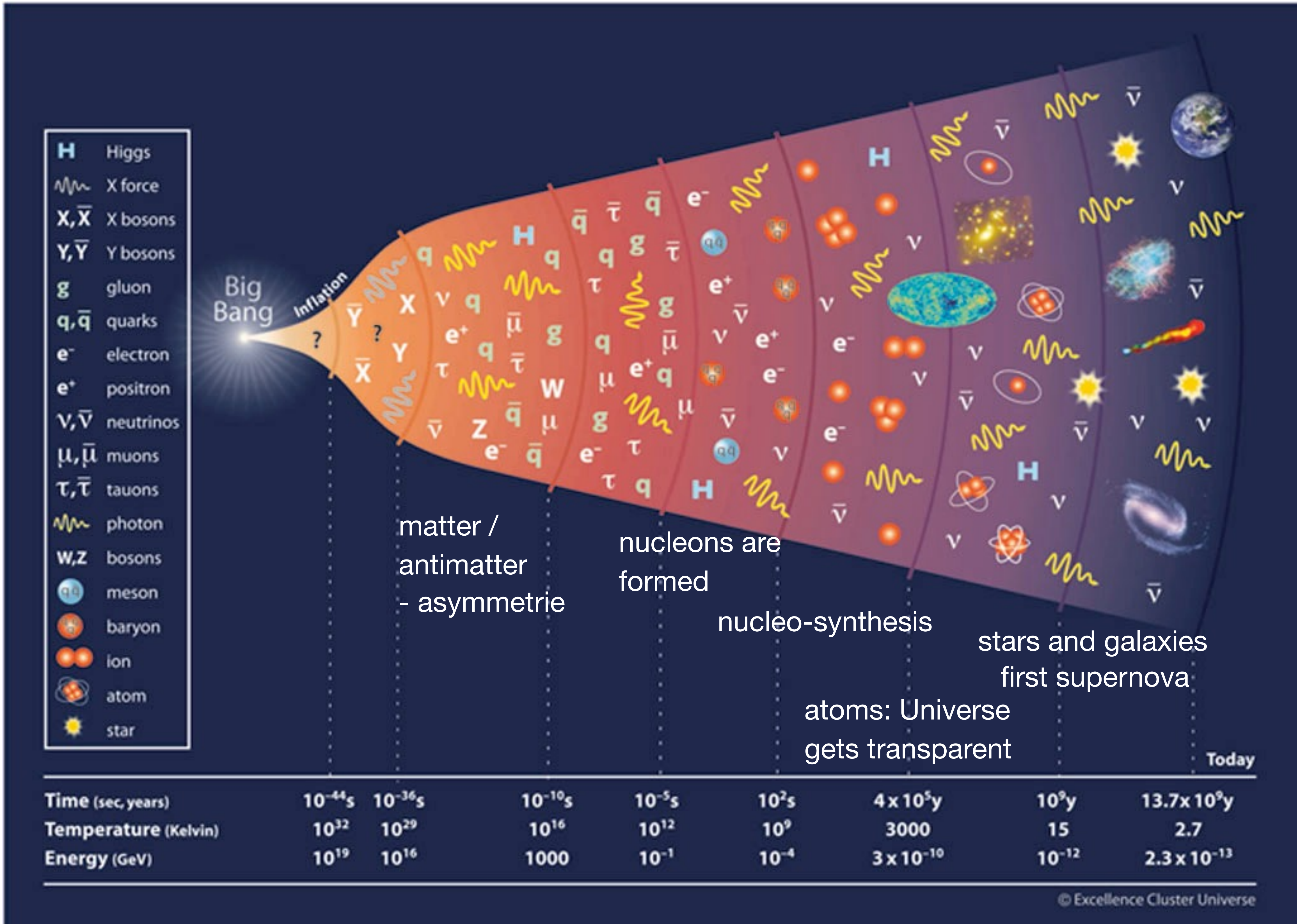
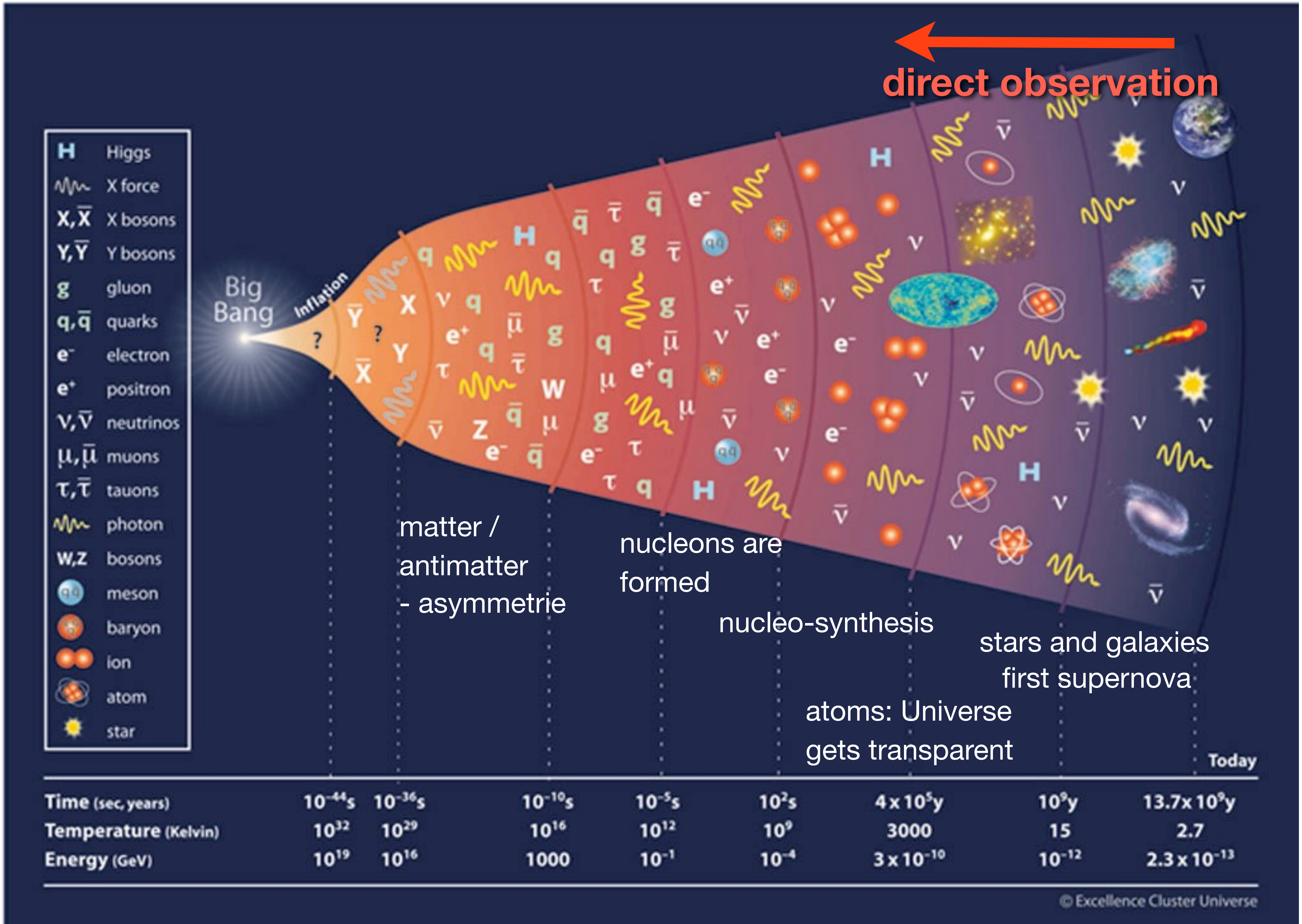
The Evolution of the Universe



The Evolution of the Universe



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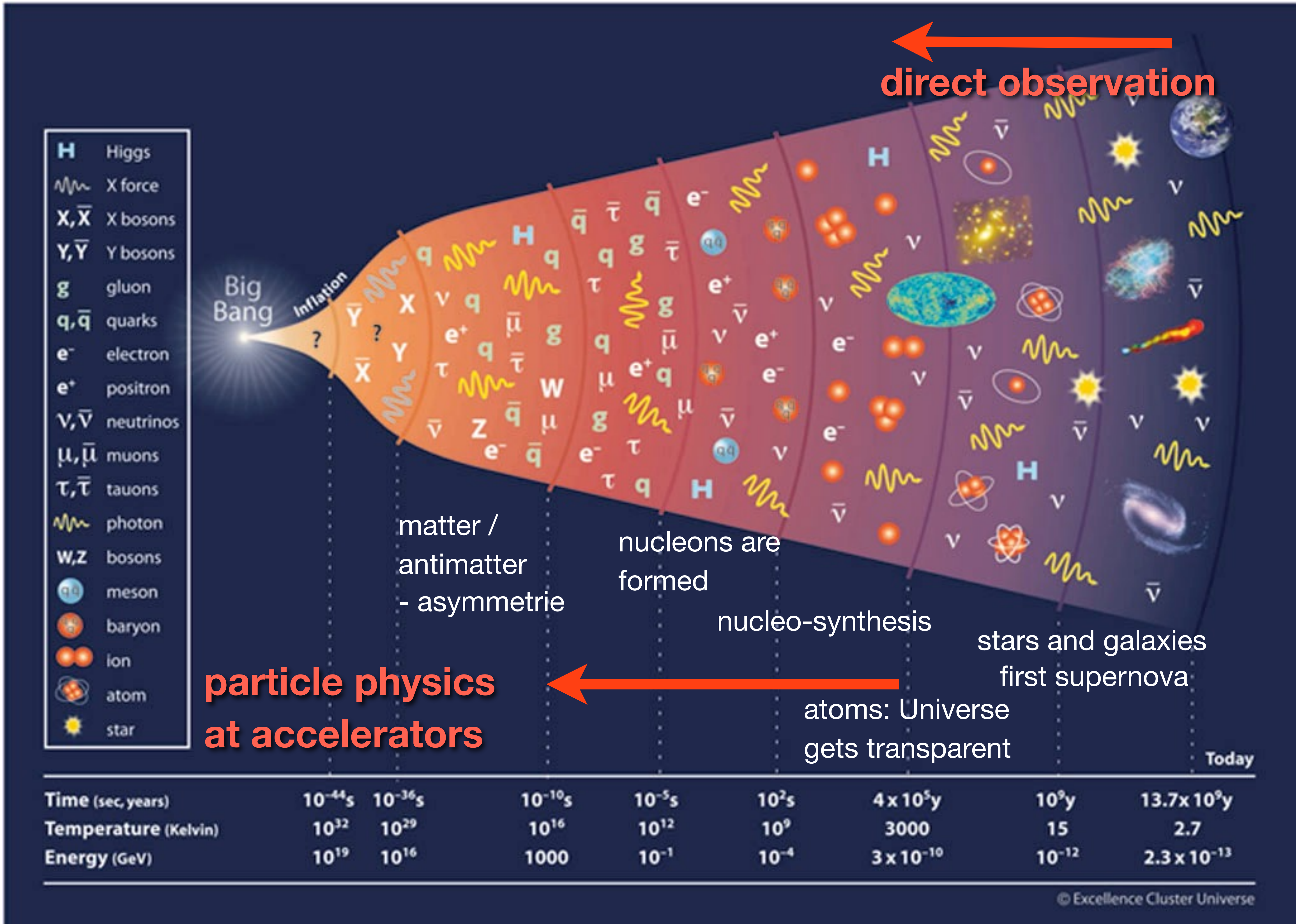
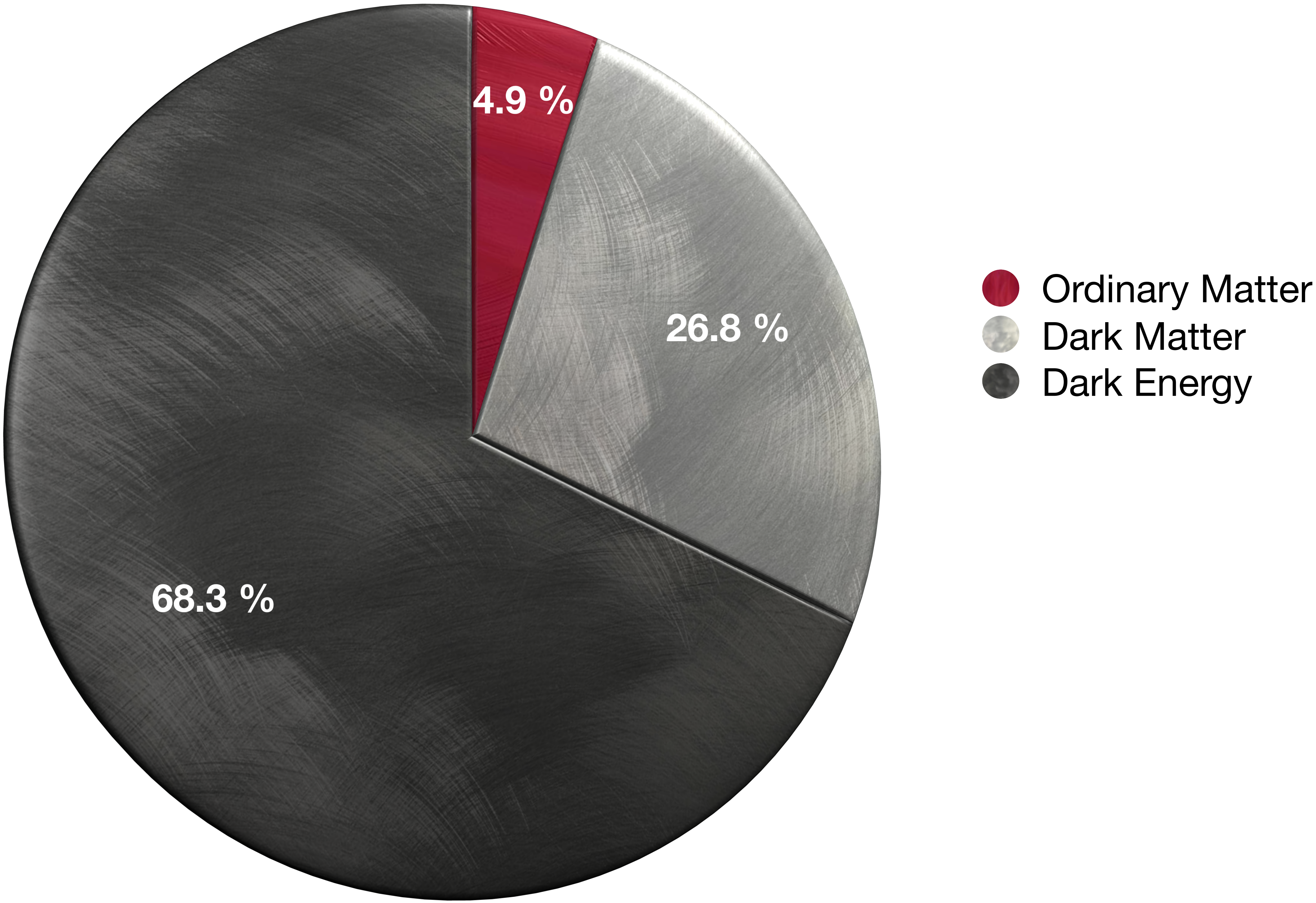
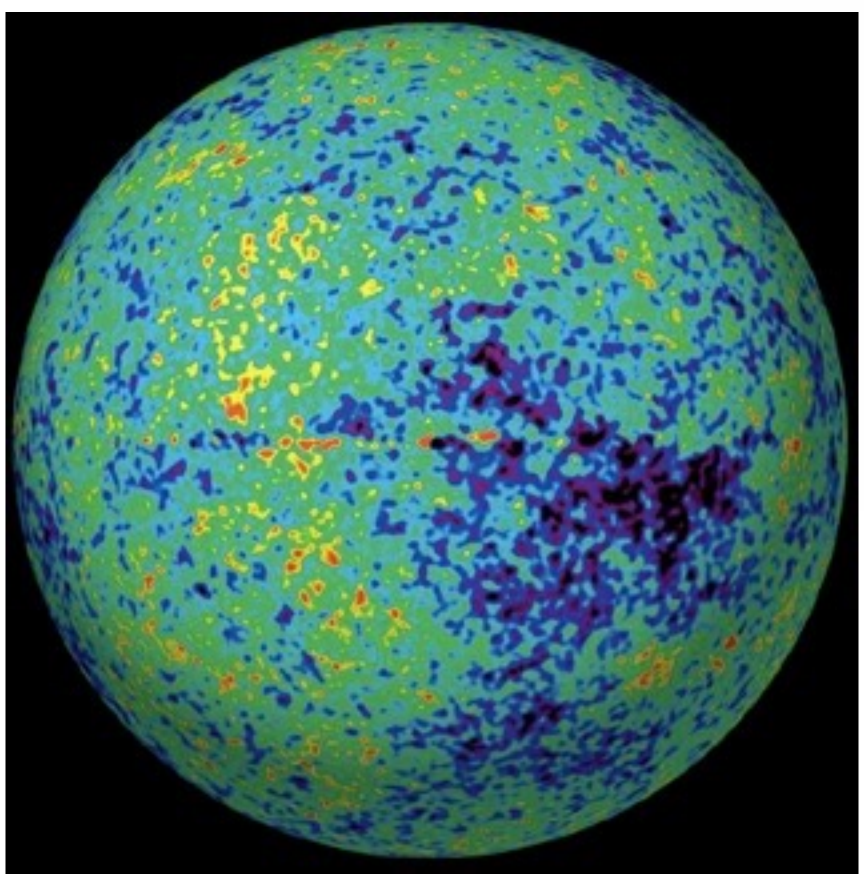


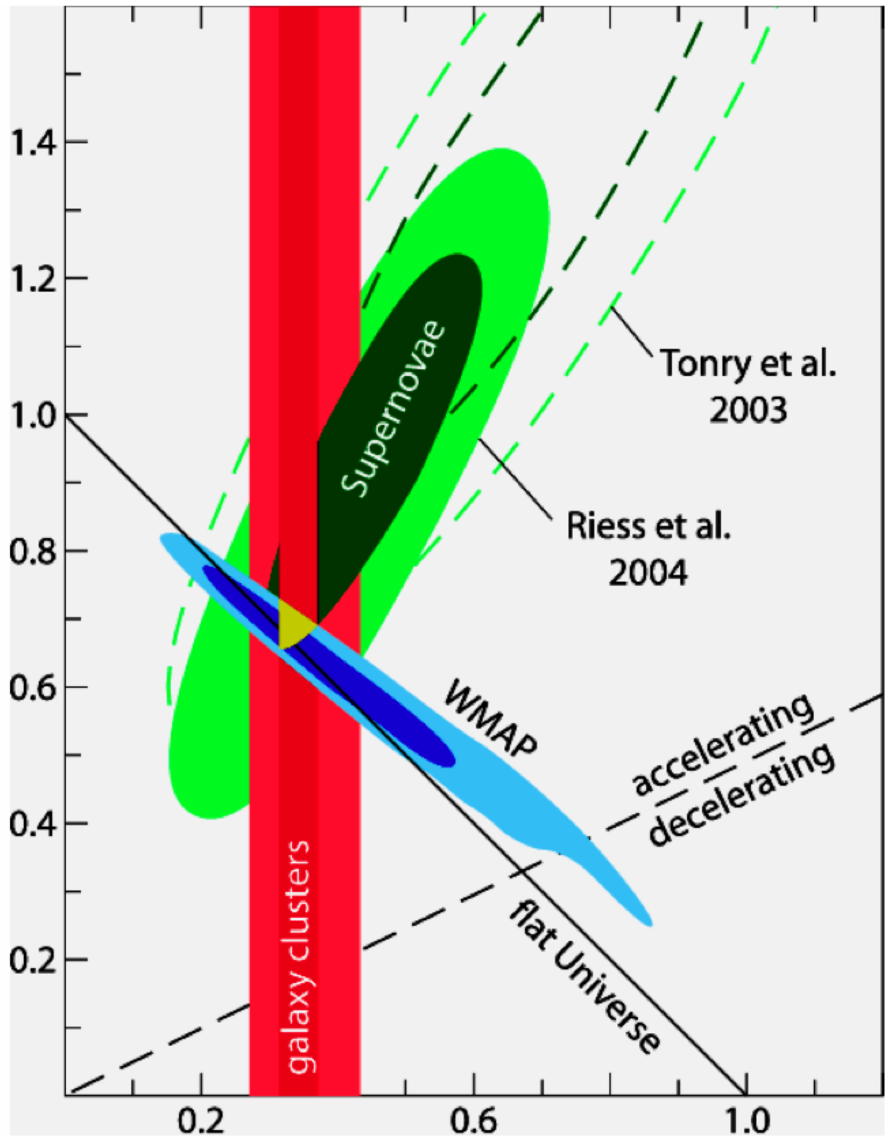
The Composition of the Universe



How do we know the composition?

- The movement of galaxy clusters shows the matter densitiy

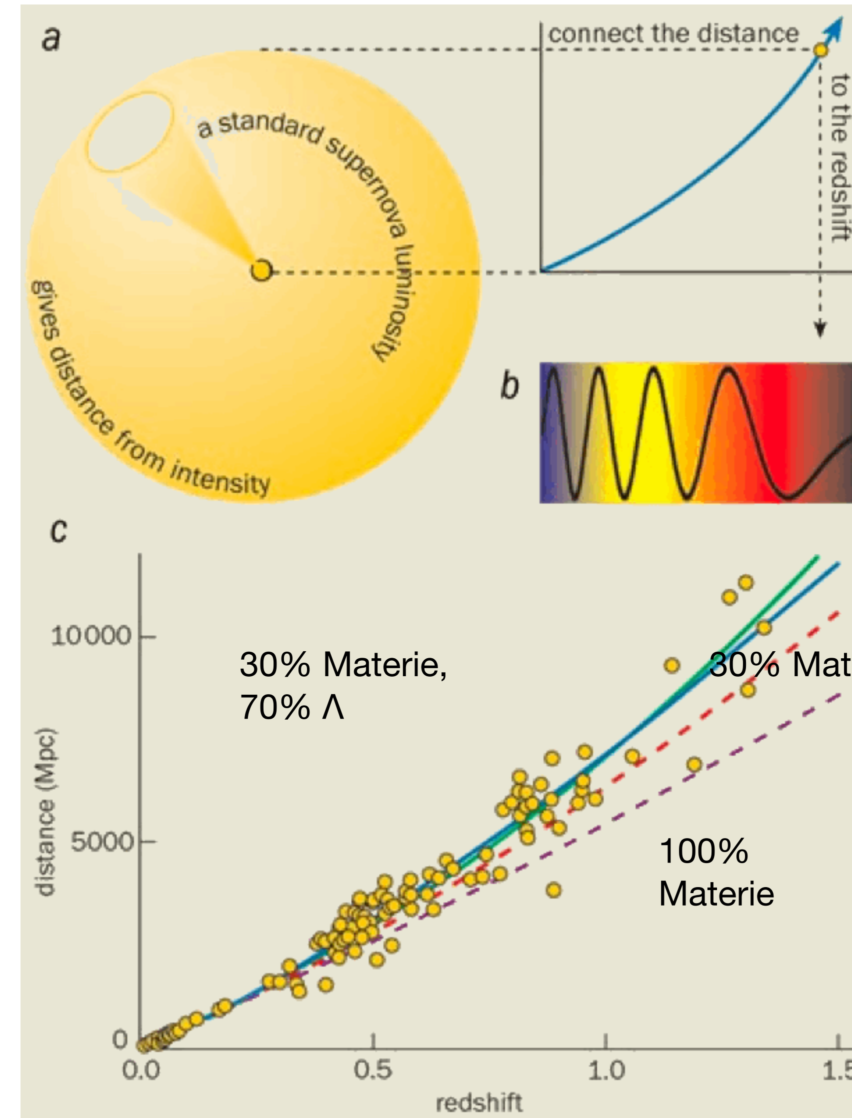




Ω_Λ

Ω_M

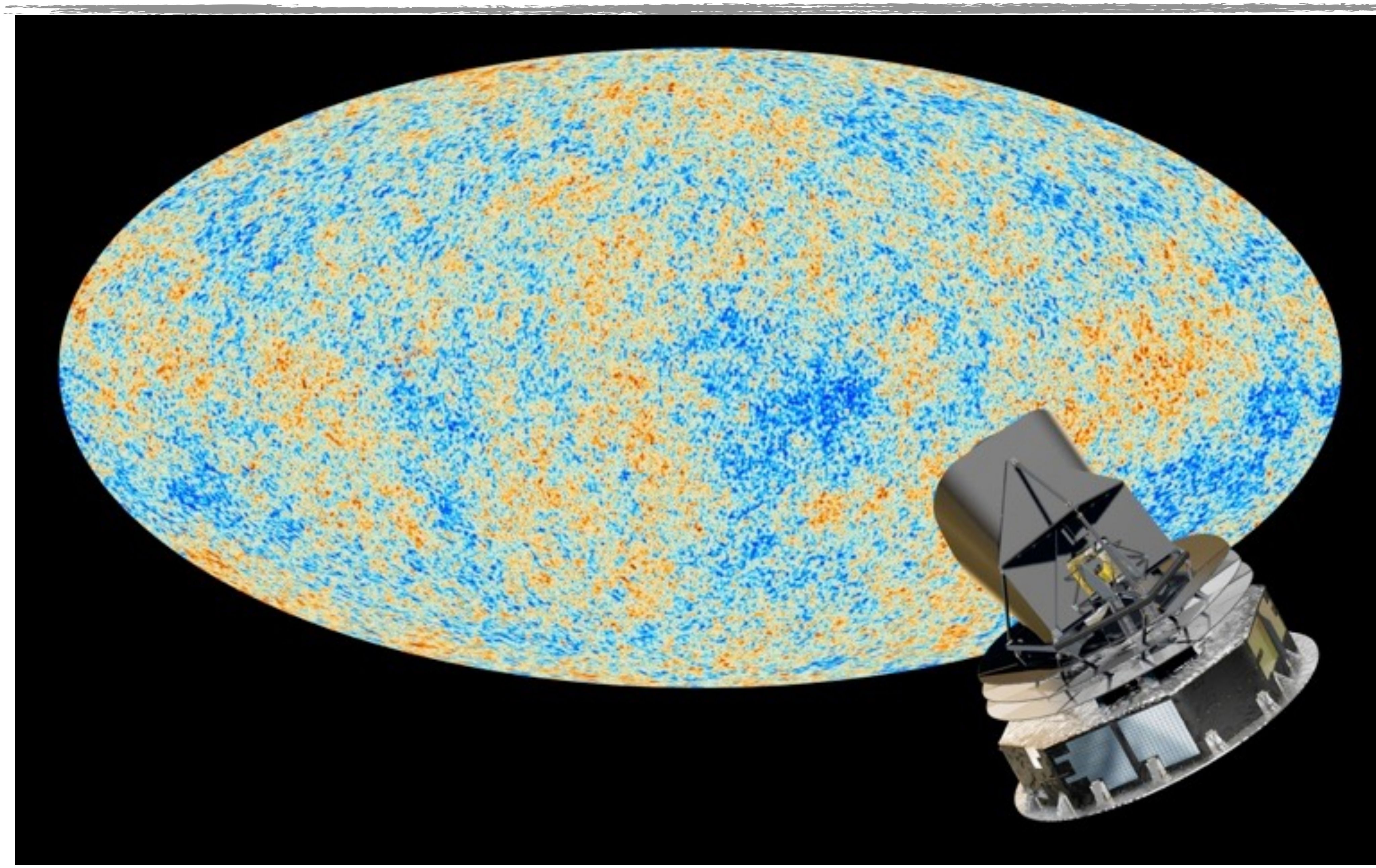
- CMB - fluctuations show that the universe is “flat”: $\Omega_\Lambda + \Omega_M = 1$



- Supernova data show that the expansion is accelerating

http://physicsworld.com/cws/article/print/19419

New Instruments - Better Results



- Planck satellite (ESA) - First results in 2013, most precise picture of the Universe at 400 000 years

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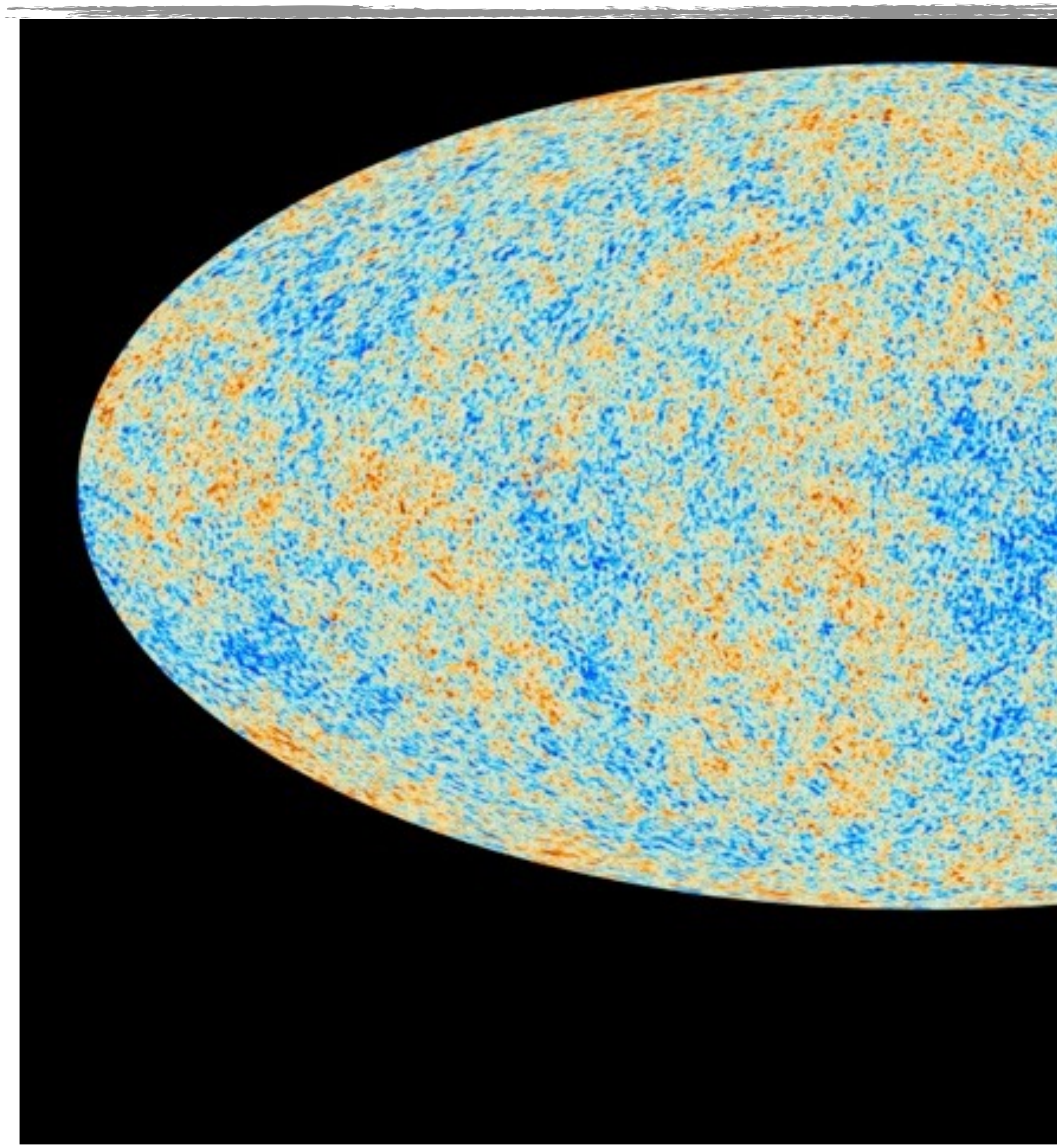

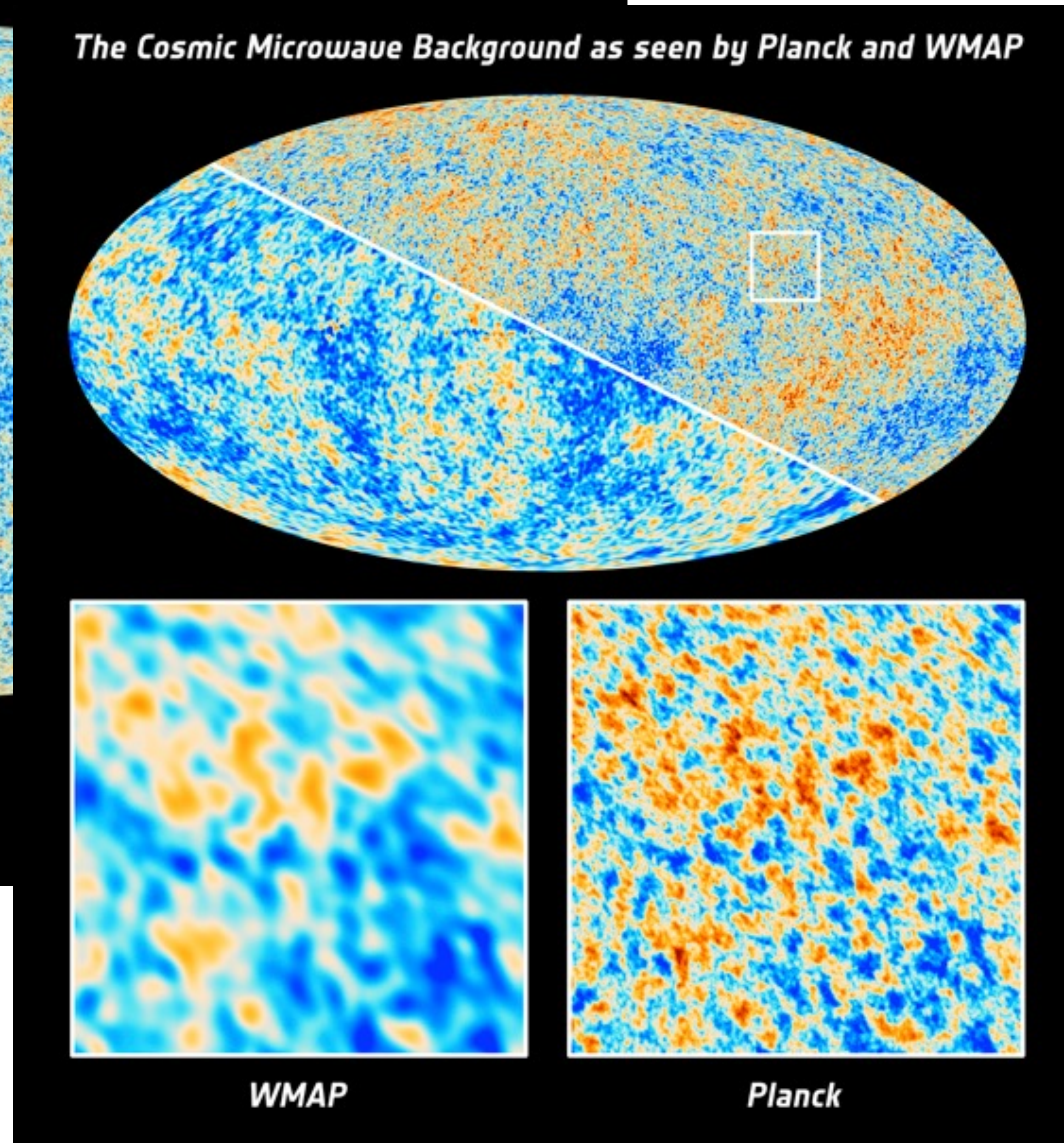

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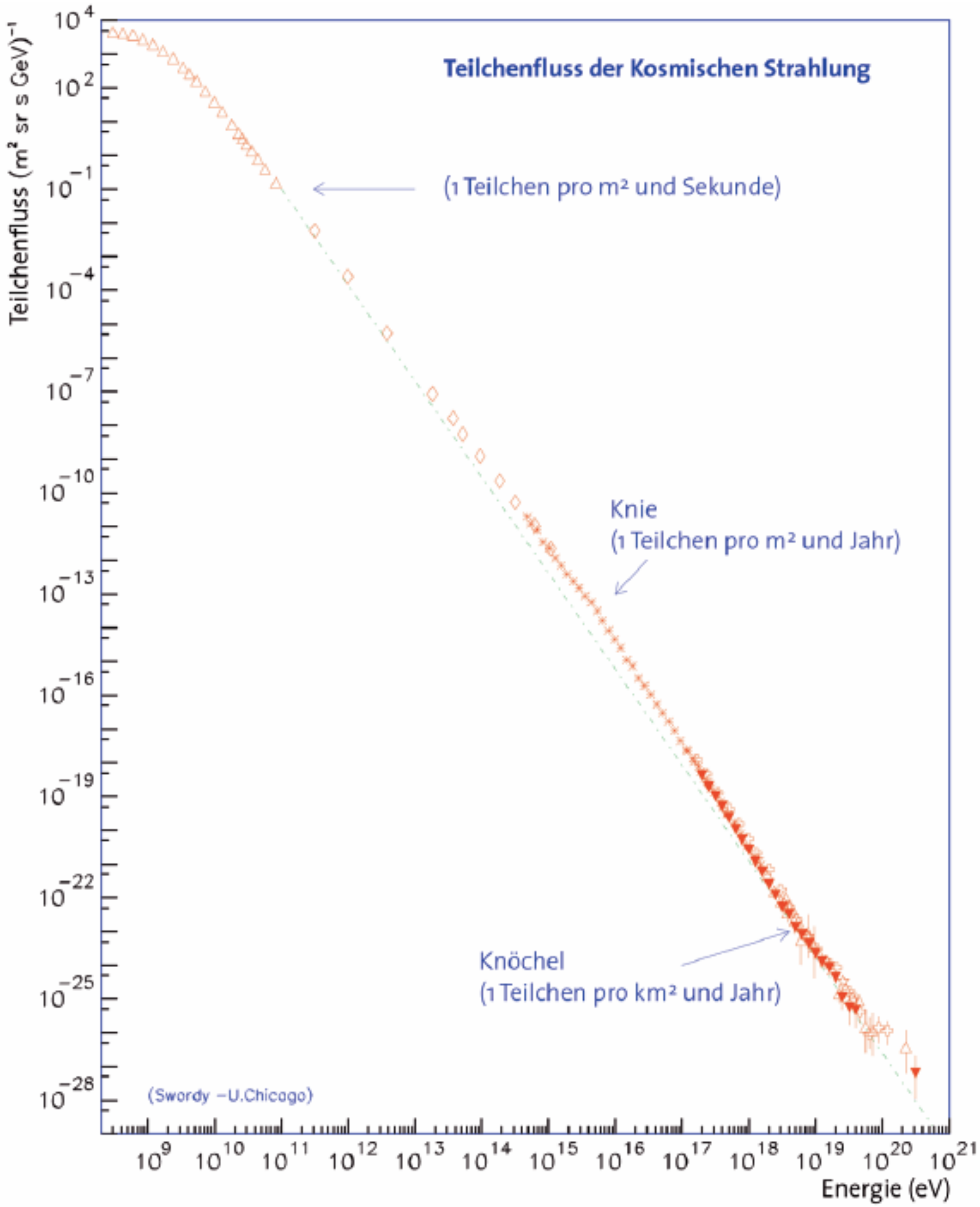
Cosmic Rays: Energy Spectrum



- Particle flux described by power law:
  - ~ $E^{-2.7}$ up to E ~ 10^{15} eV
  - ~ E^{-3} from 10^{15} to 10^{18} ev
  - ~ $E^{-2.7}$ above E ~ 10^{18} eV

- Transition from galactic to extragalactic sources?
- Cut-off effect at highest energies?

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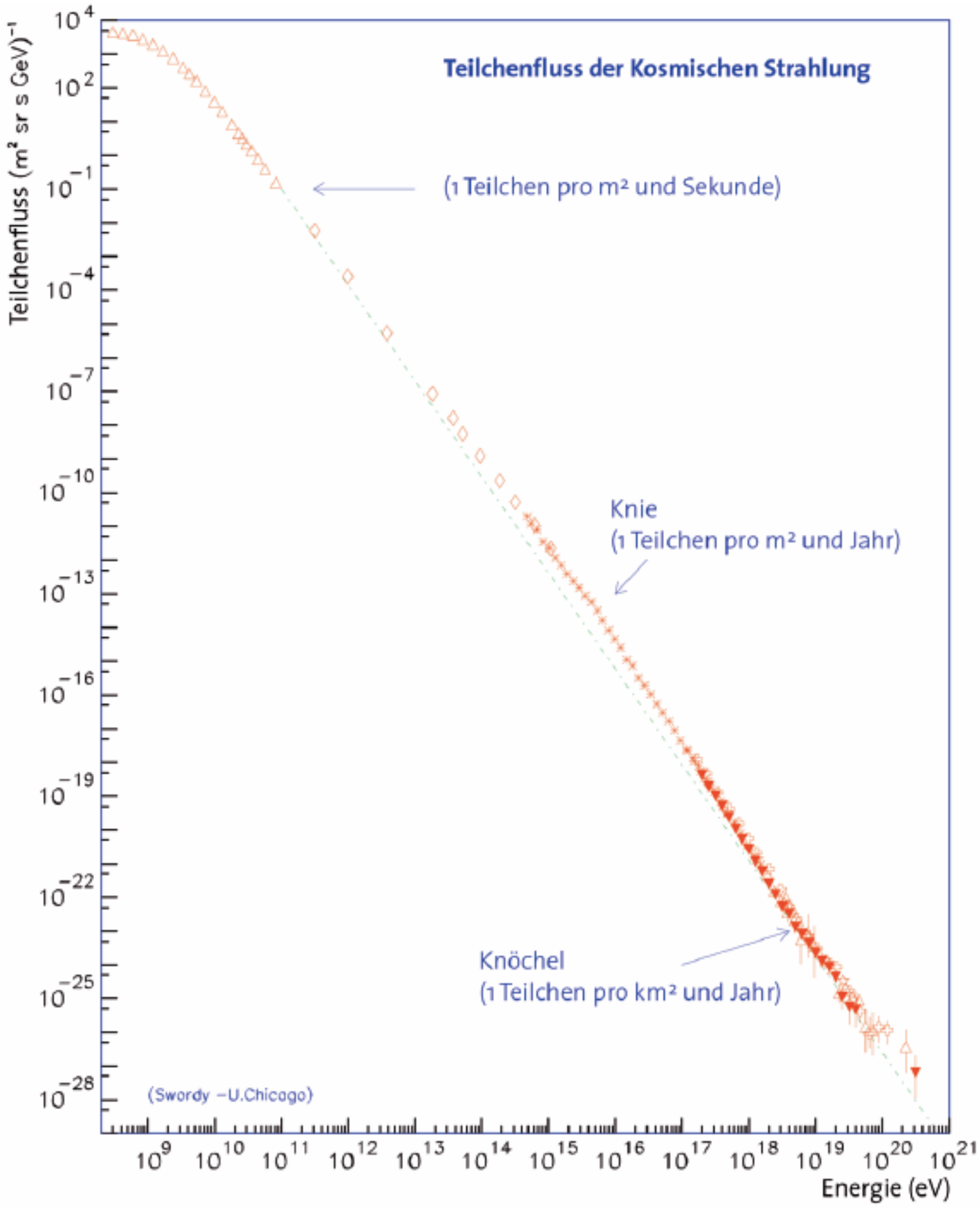

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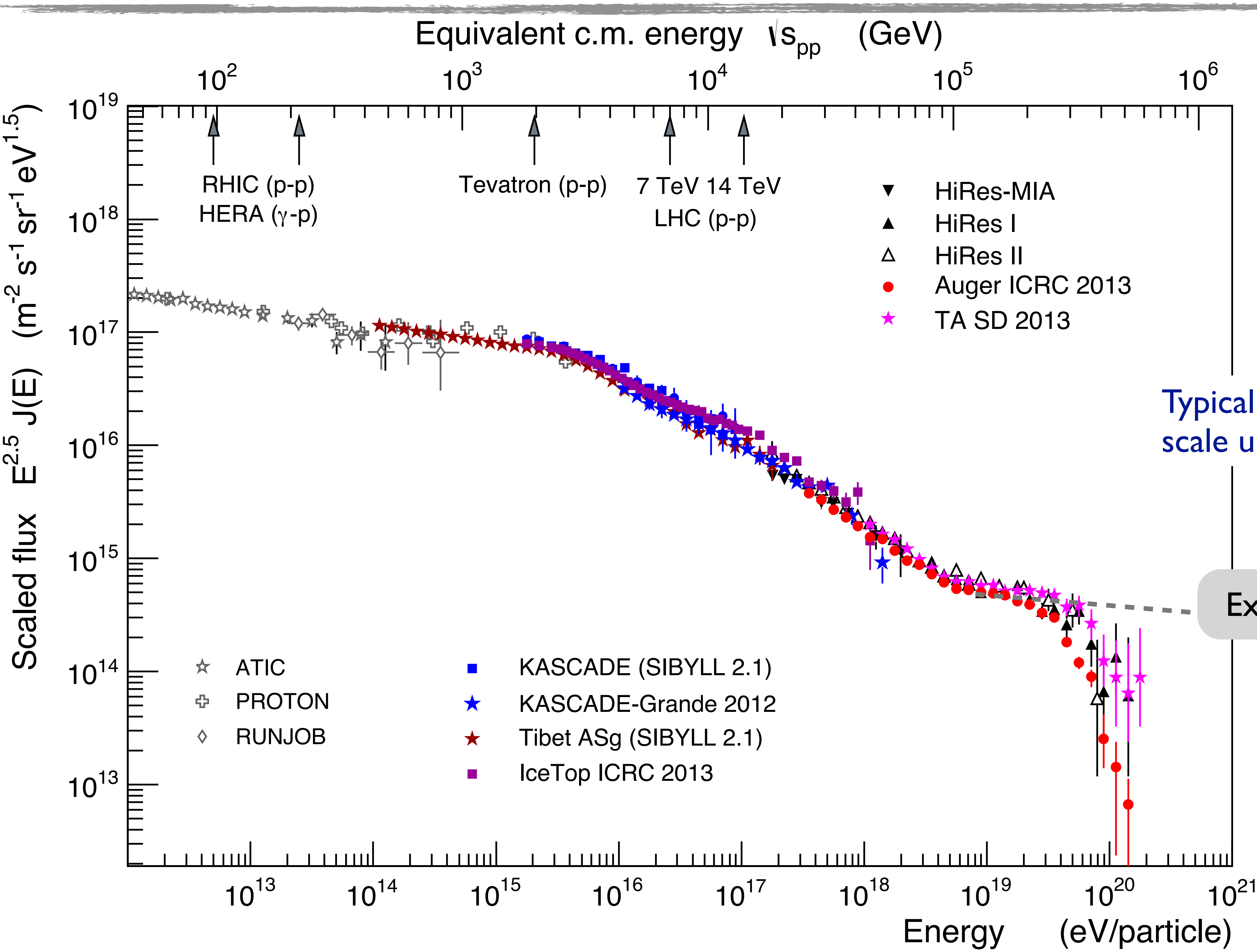
How are the particles accelerated? Which astrophysical objects are responsible?

Cosmic Rays at Highest Energies



Auger Coll. (ICRC 2013)

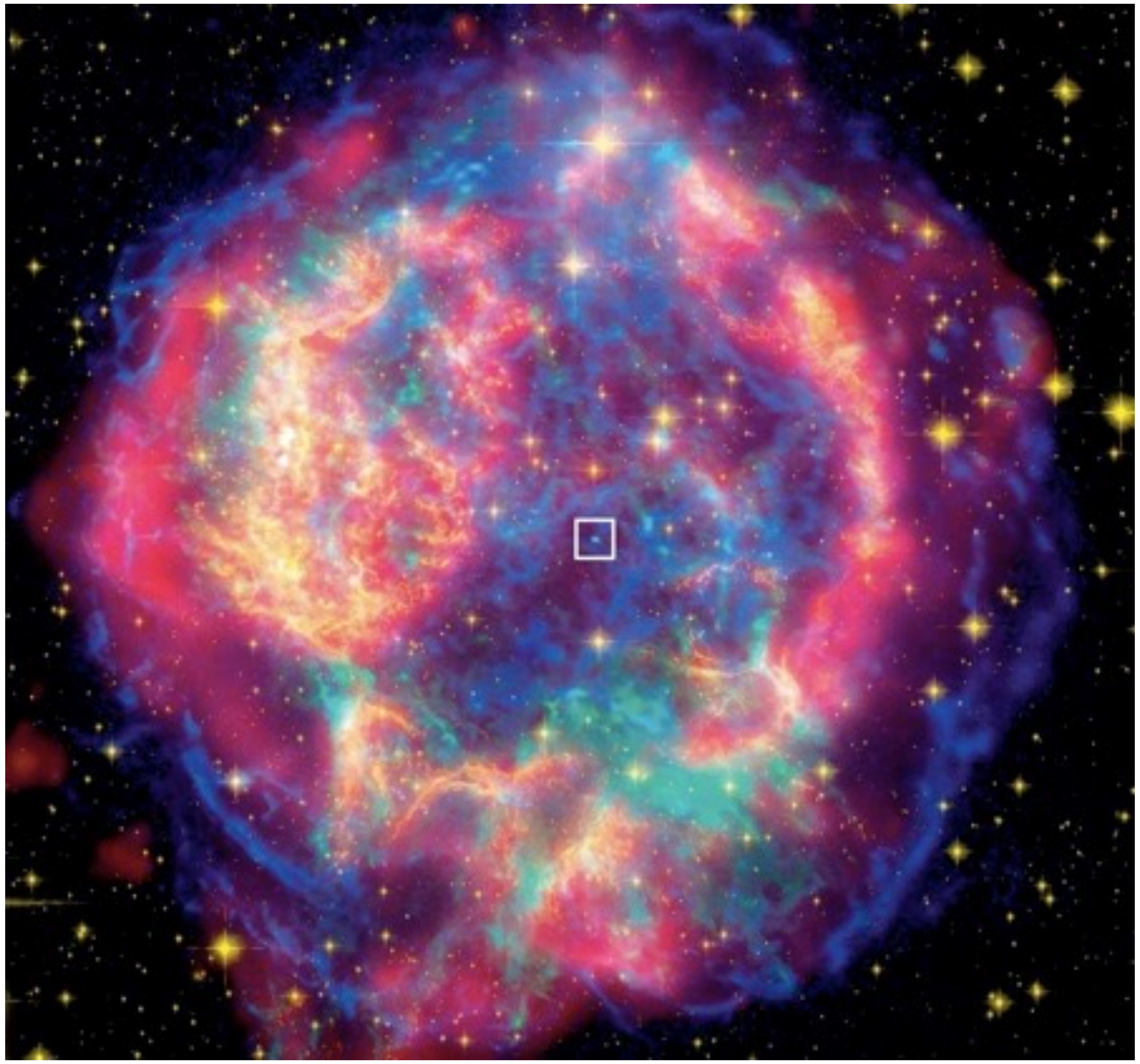
Typically 15-20% energy scale uncertainty

Extrapolated flux

Where do these particles come from?

- Strong indications for a cut - off at ~ 10^{20} eV - Interactions with CMB

Cosmic Accelerators



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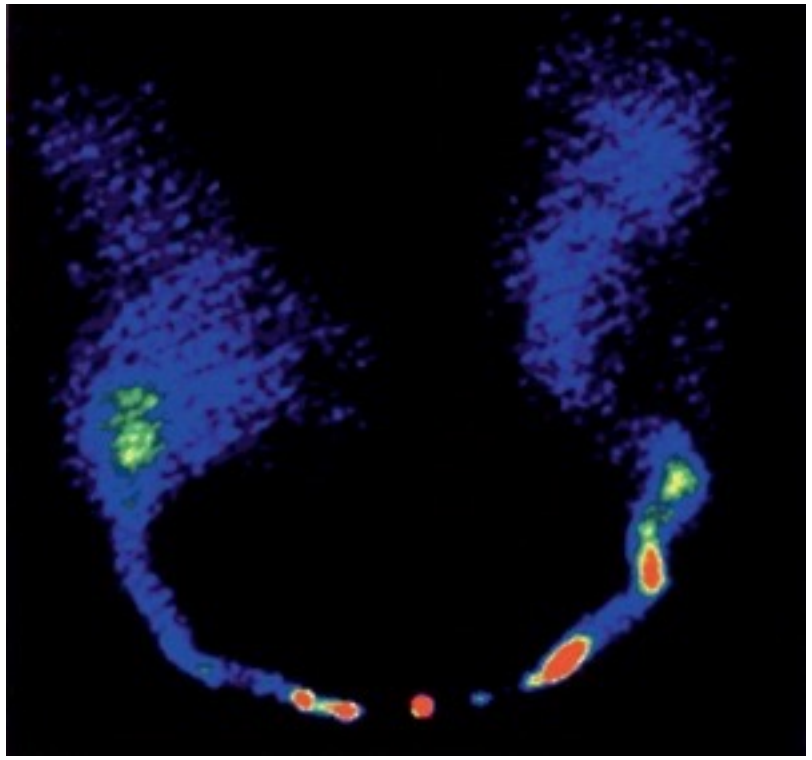
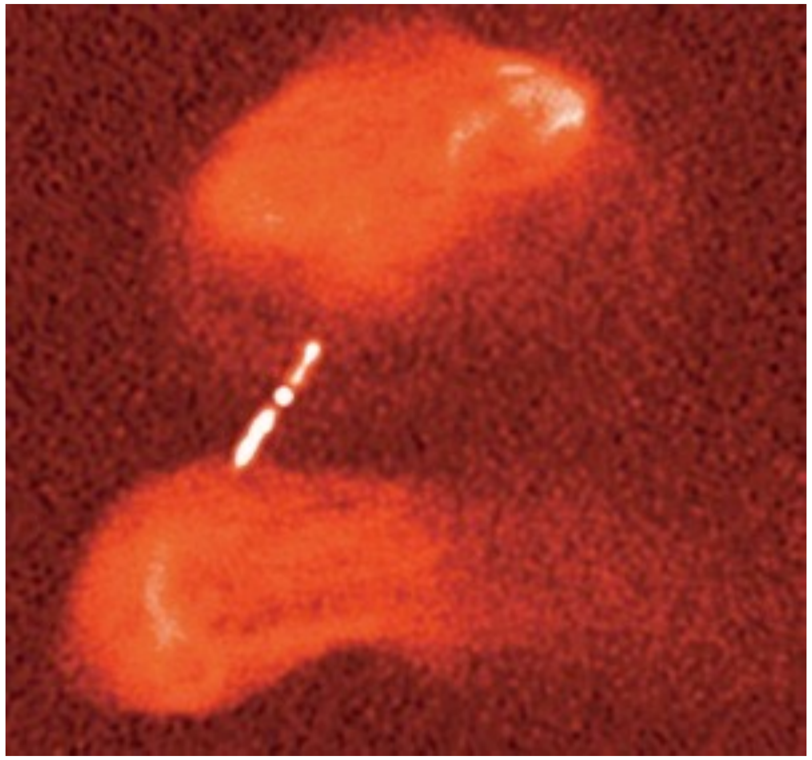
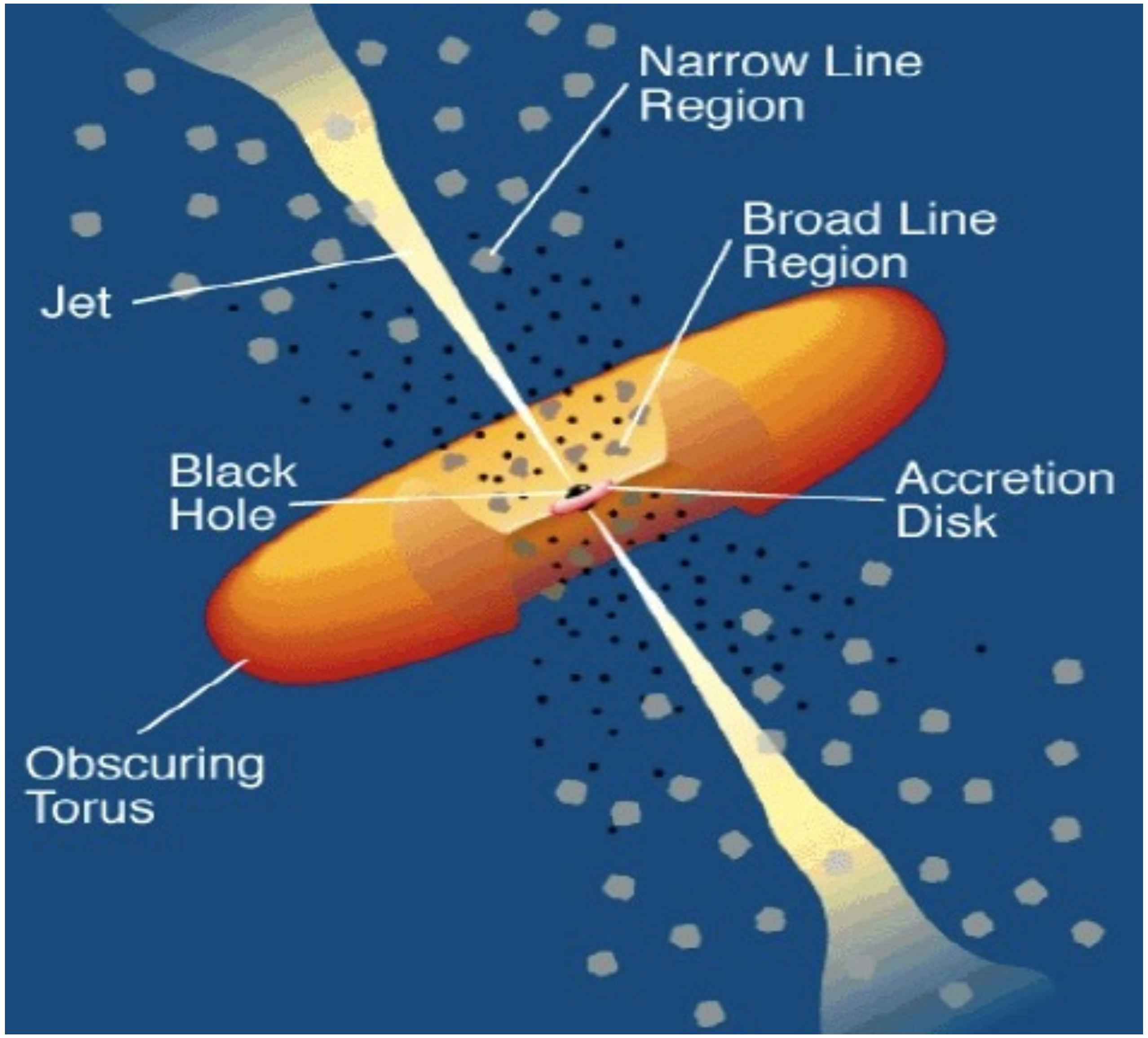
- Supernova explosion: Acceleration in shock waves
- Pulsars: Acceleration in very strong magnetic fields

  - Galactic sources for highly energetic particles

Cosmic Accelerators







- Nuclei of active galaxies (AGN)
  - There are first indications that the highest-energy particles come from AGNs

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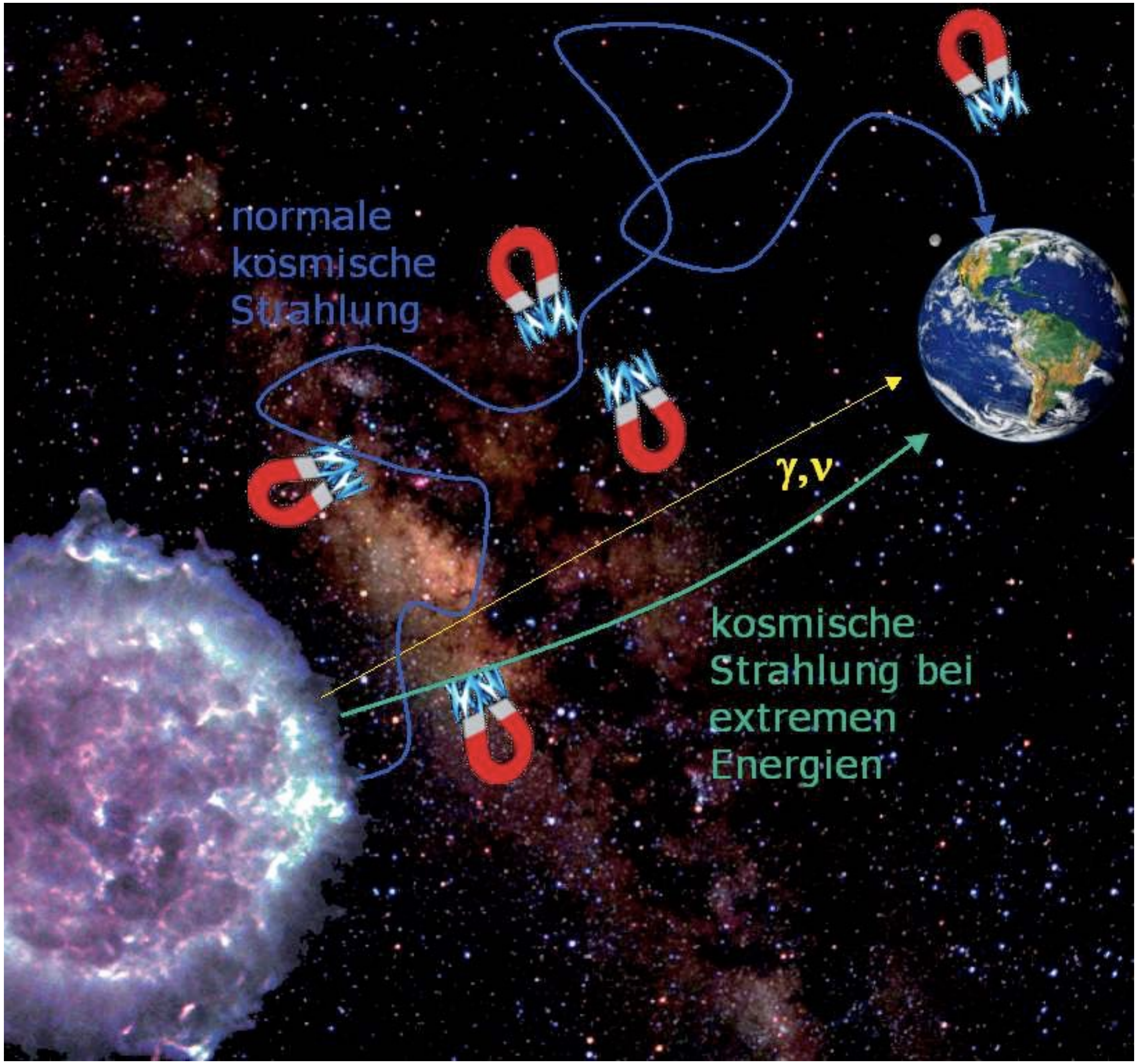
The Path to Earth



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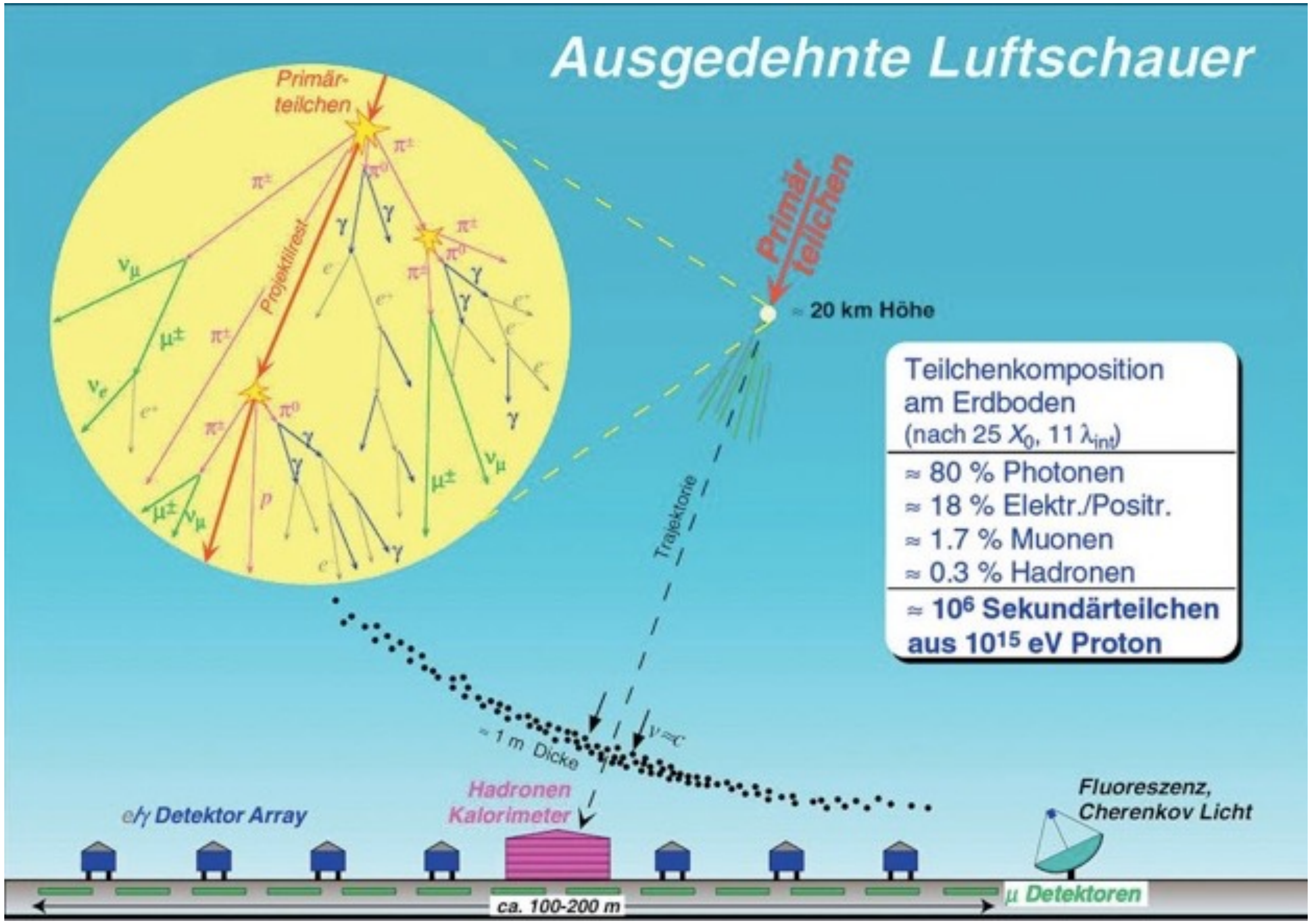
- strong deflection of charged particles in cosmic magnetic fields
- neutral particles and highest energies can provide information on their sources
  - Highly energetic photonen and charged particles have limited range!

Cosmic Rays on Earth: Air Showers



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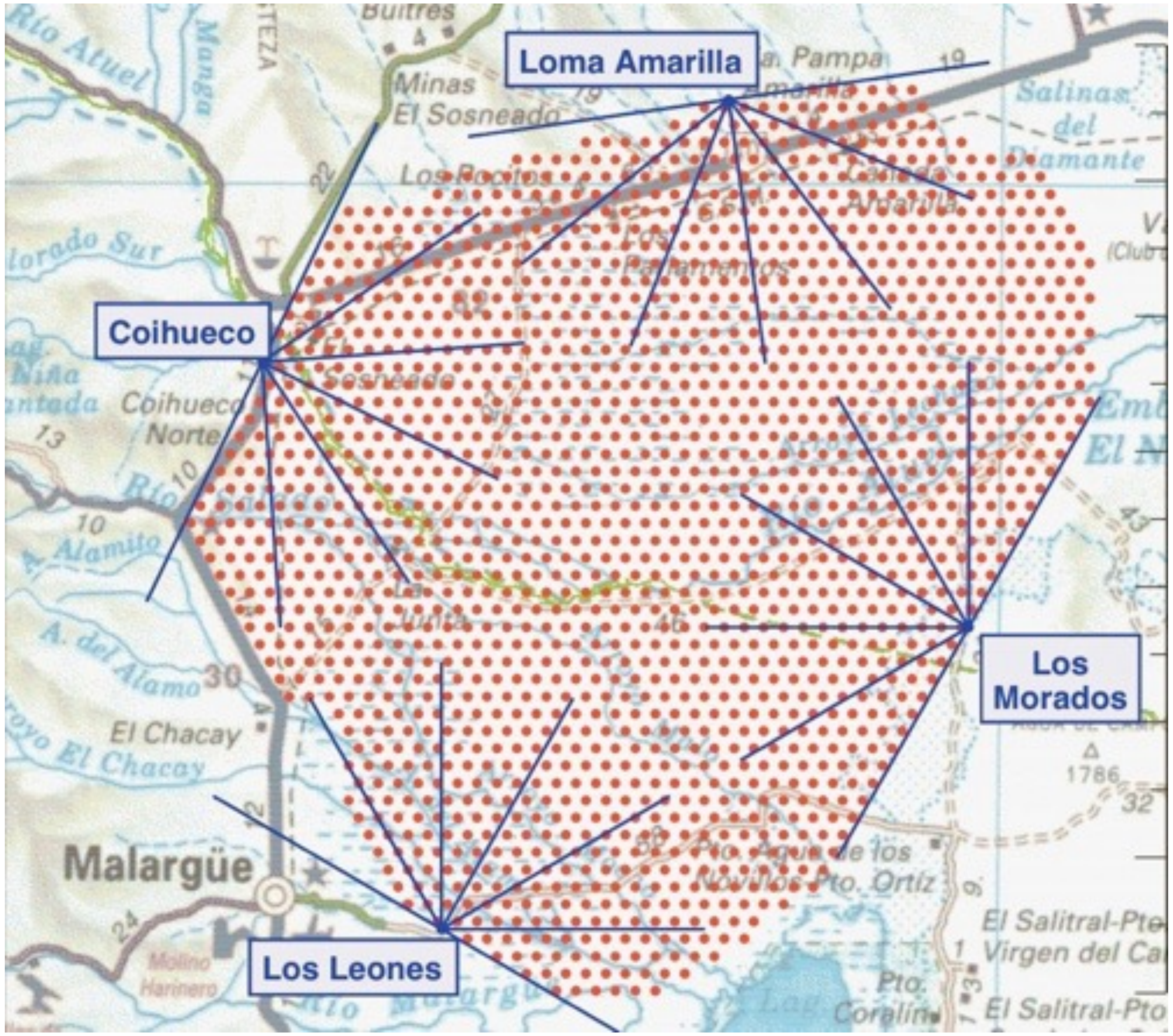
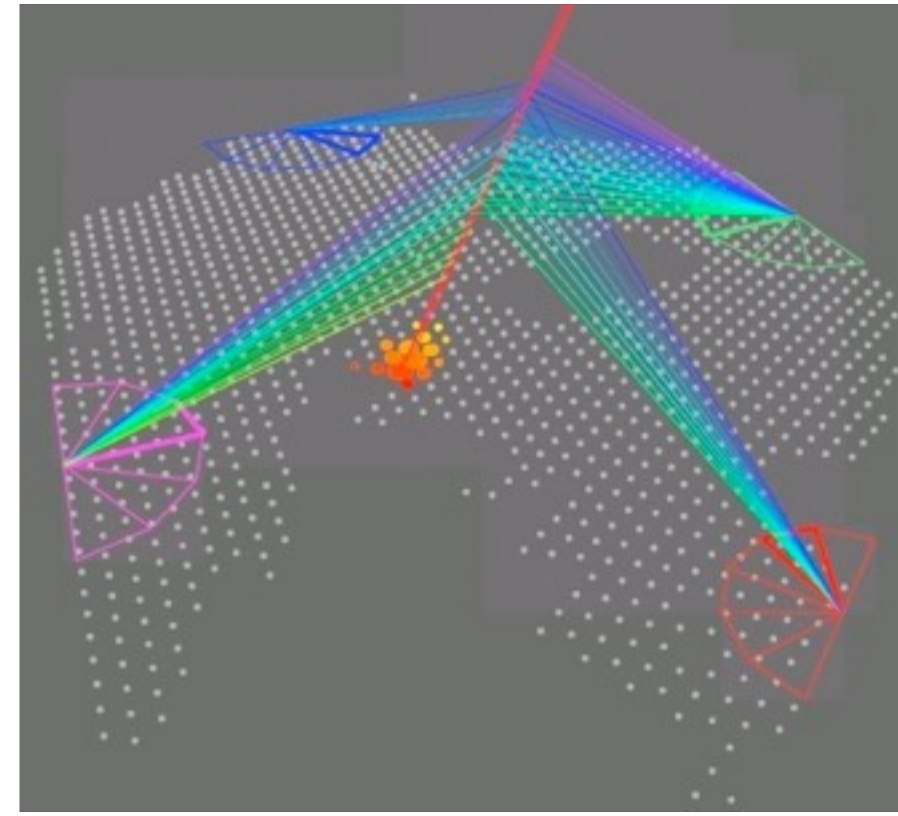
(KASCADE - Experiment, Karlsruhe)

- Highly energetic particles create "extended air showers"
  - numerous nuclear interactions in the atmosphere
  - Energy measurement by using the atmosphere as a calorimeter: Detection of charged particles, photons, fluorescence and Cherenkov light

Detector for Highest Energies: AUGER Experiment





- 2 detector-types:
  - 1600 shower detectors (water-Cherenkov)
  - 24 fluorescence telescopes
  - Total area: 3000 km^2 (~10 x Munich)

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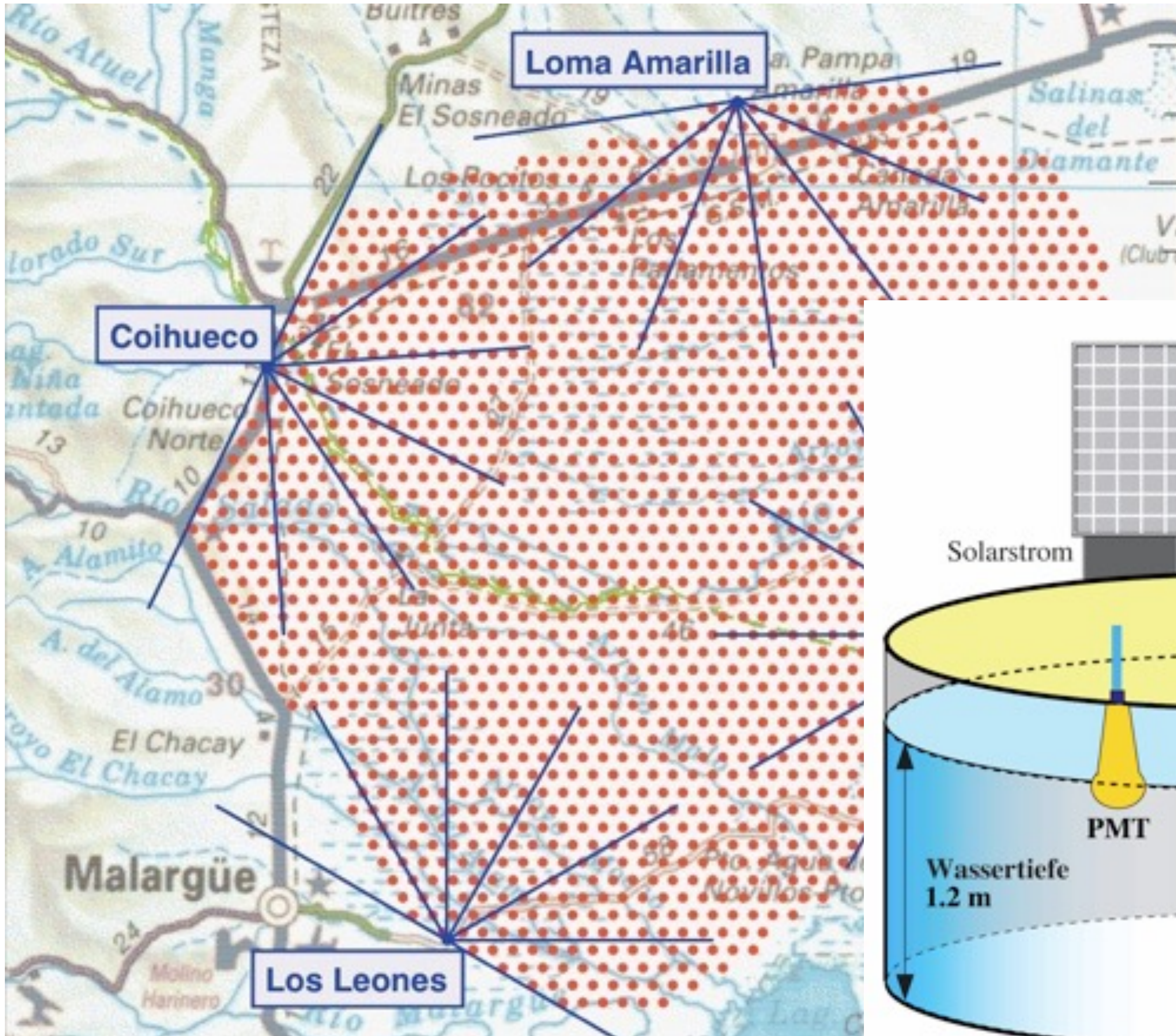

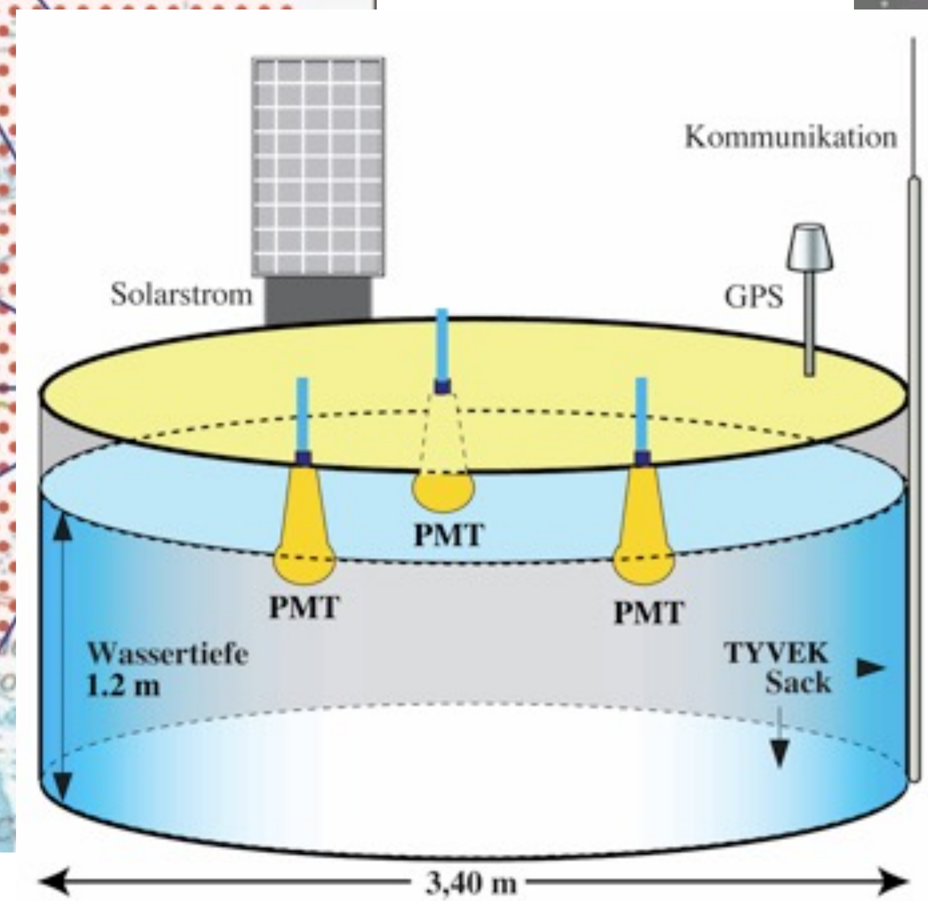

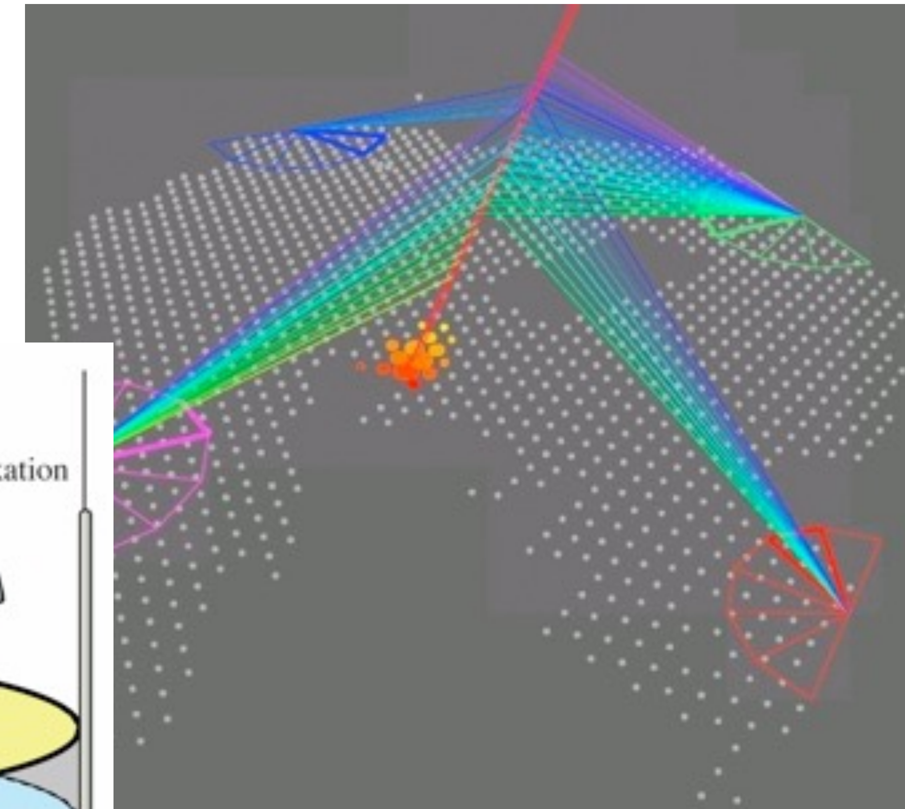

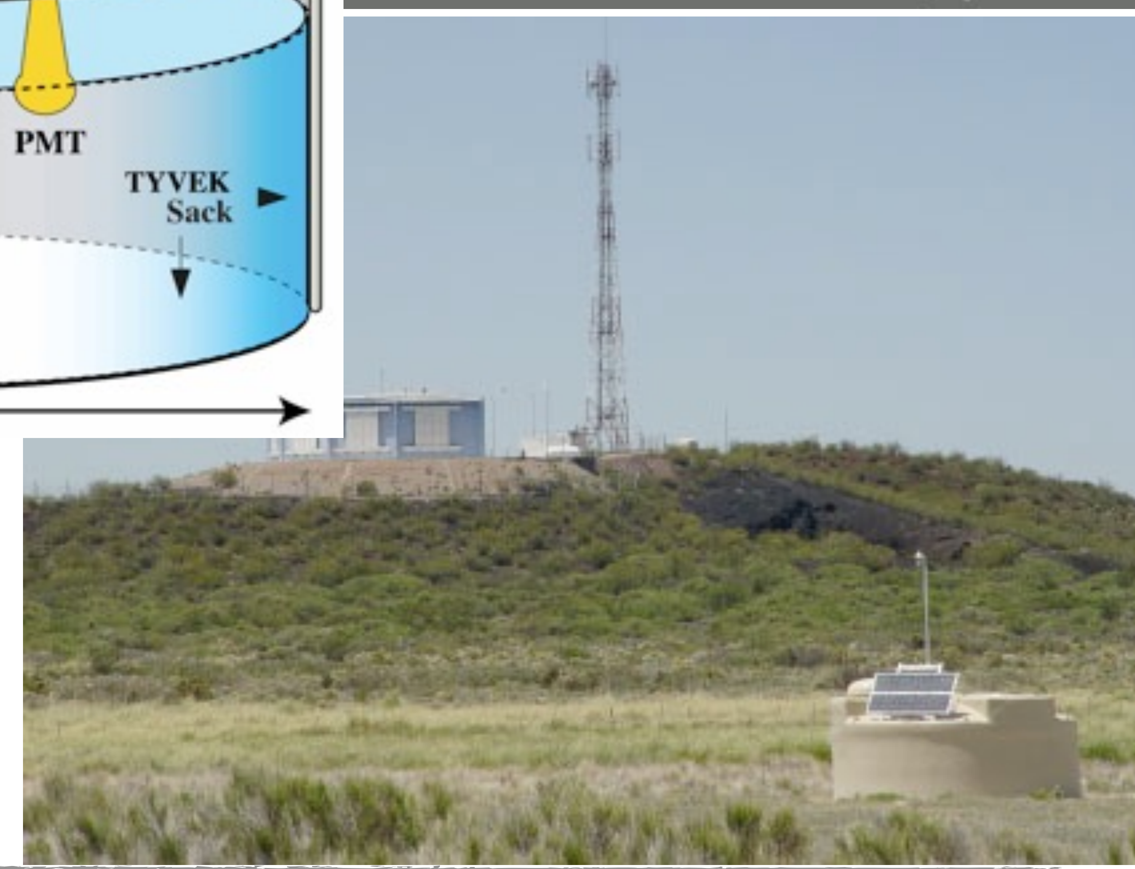

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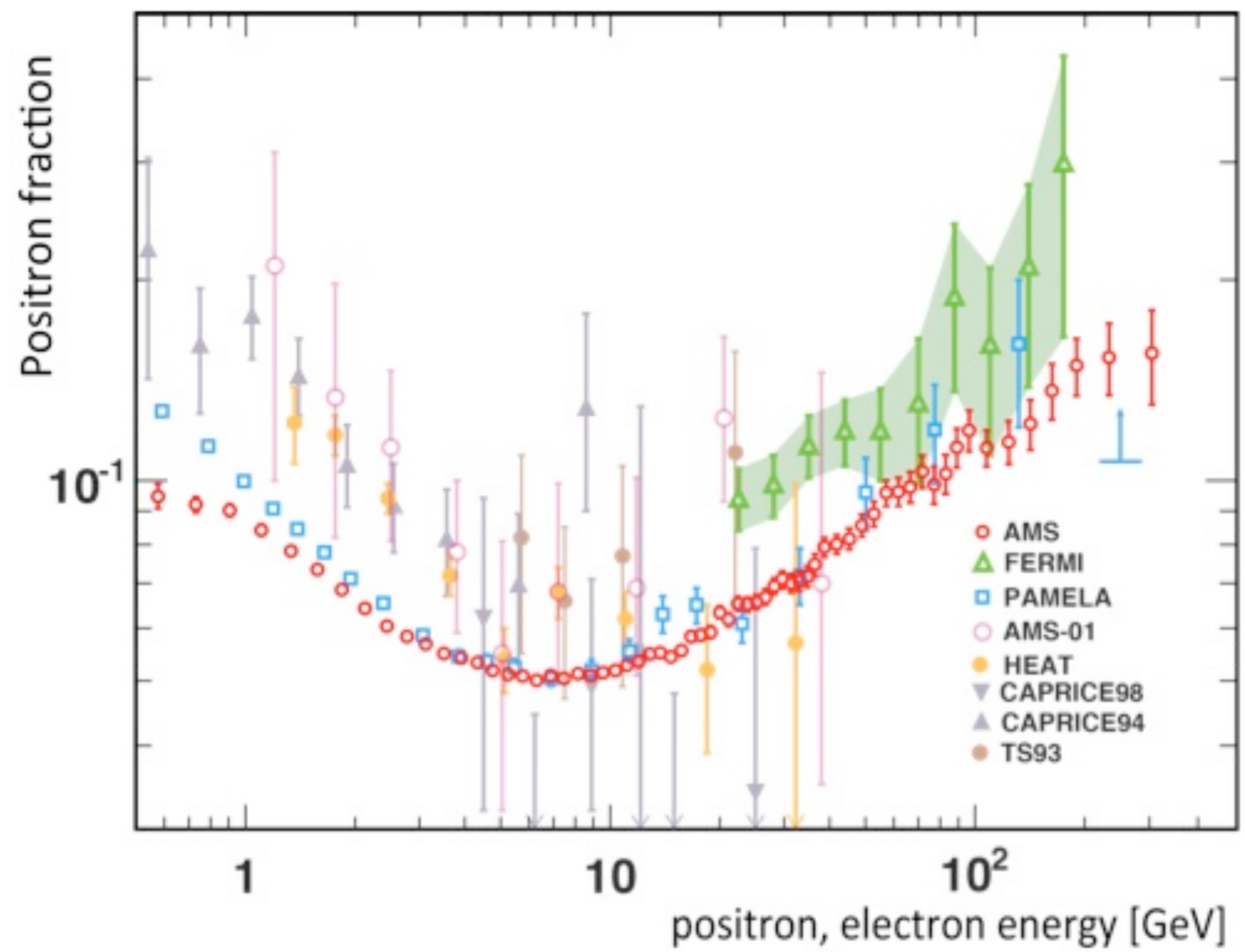
Spectacular Experiments in Space - AMS

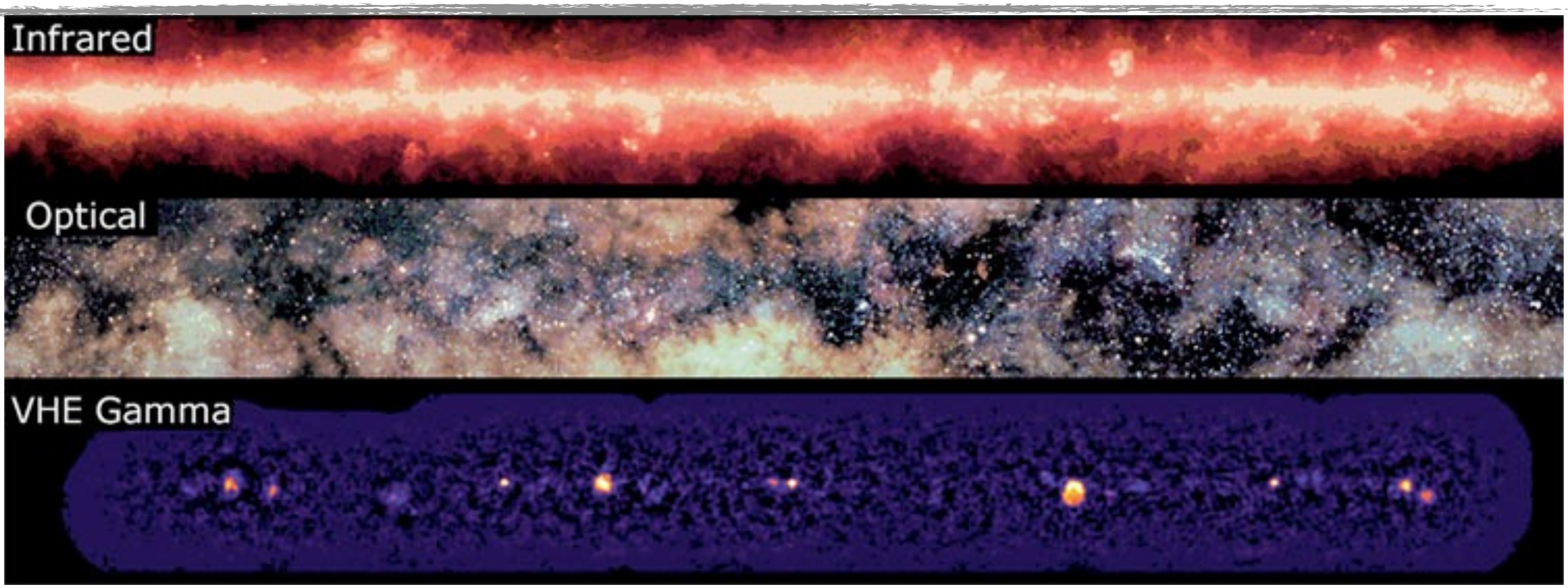
- A complete particle detector on the International Space Station



- Interesting first results: Too many positrons - confirms earlier measurements with higher precision!
  - Astrophysical phenomenon?
  - New Physics - Dark Matter?

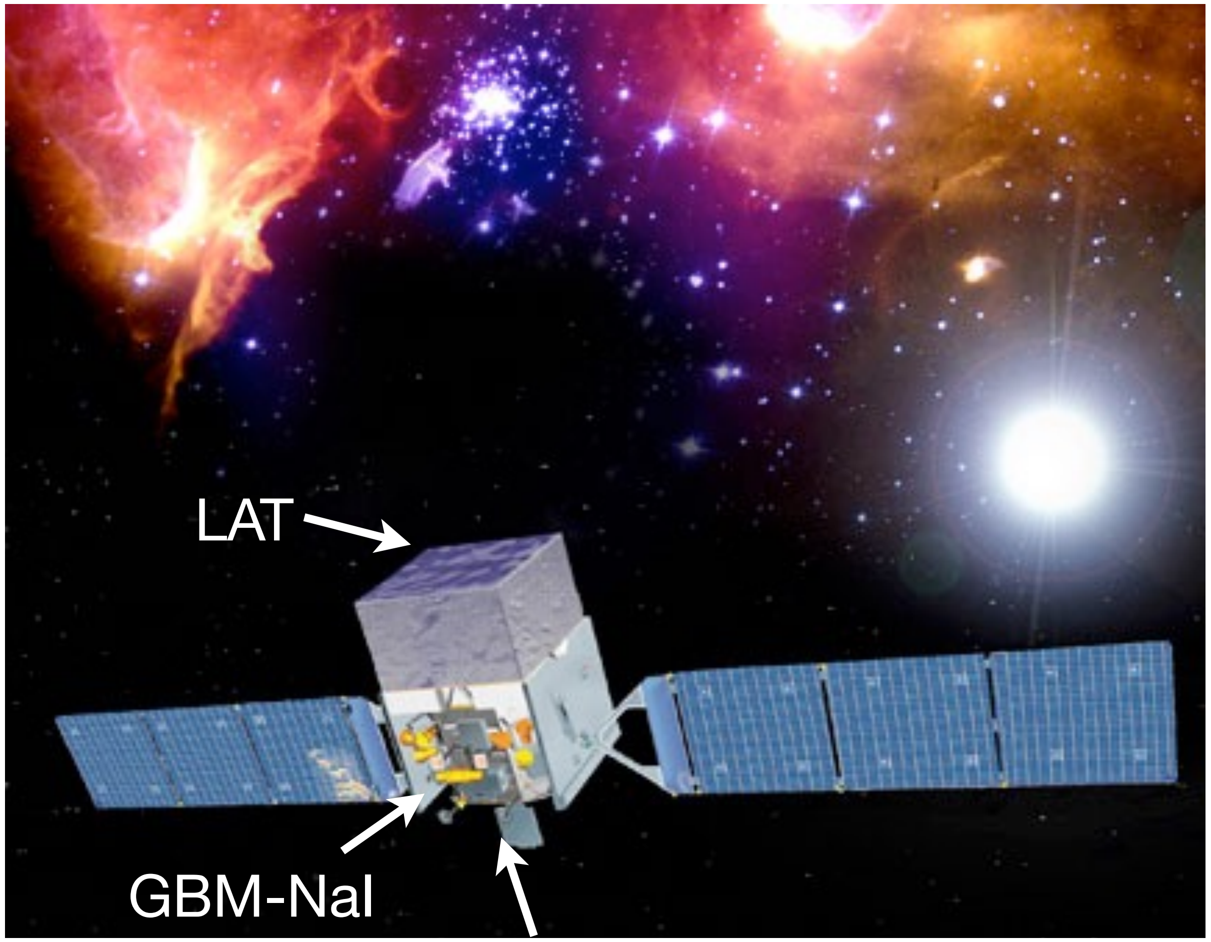
Neutral Cosmic Rays

Photons originating from the Milky Way

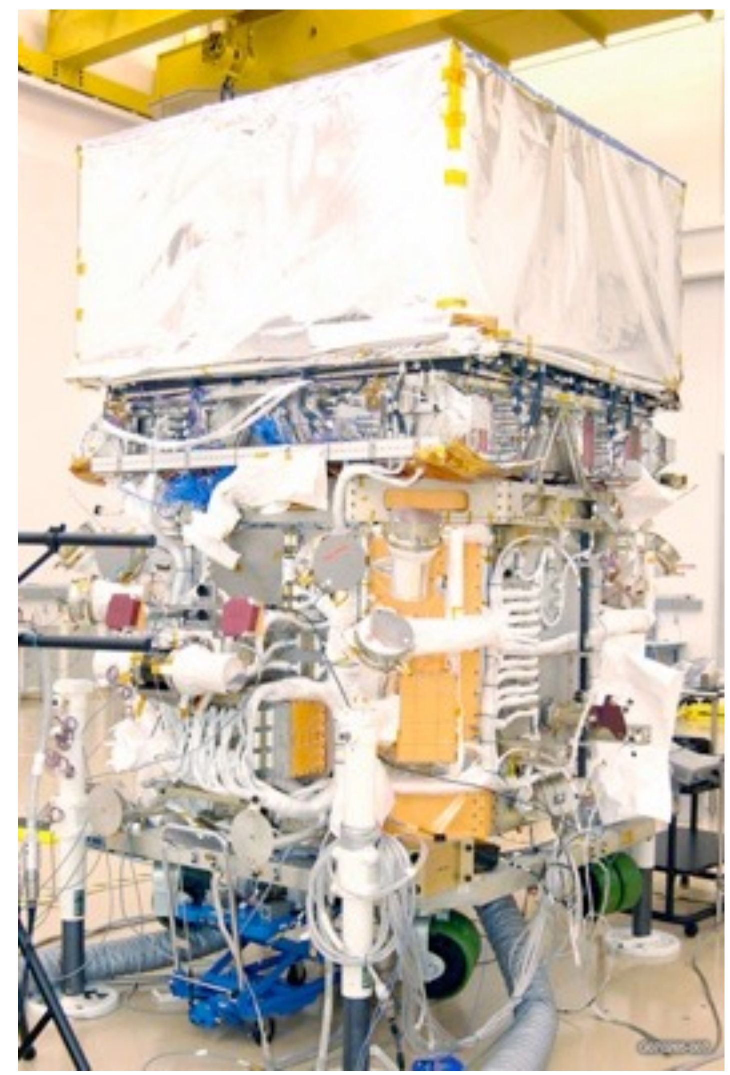


- Photons:
  - Decay of neutral pions
  - Black holes, AGNs, supernova explosions
  - Gamma-Ray-Bursts (GRB)
  - Pulsars
- Neutrinos
  - Solar neutrinos
  - Supernova explosions
  - pion decay
  - atmospheric neutrinos from air showers

Gamma und X-Ray—Astronomy: Satellites



- FERMI - data taking since August 2008
  - Energy range: 10 keV to 300 GeV
  - Data catalog (γ - spectra, sources) available



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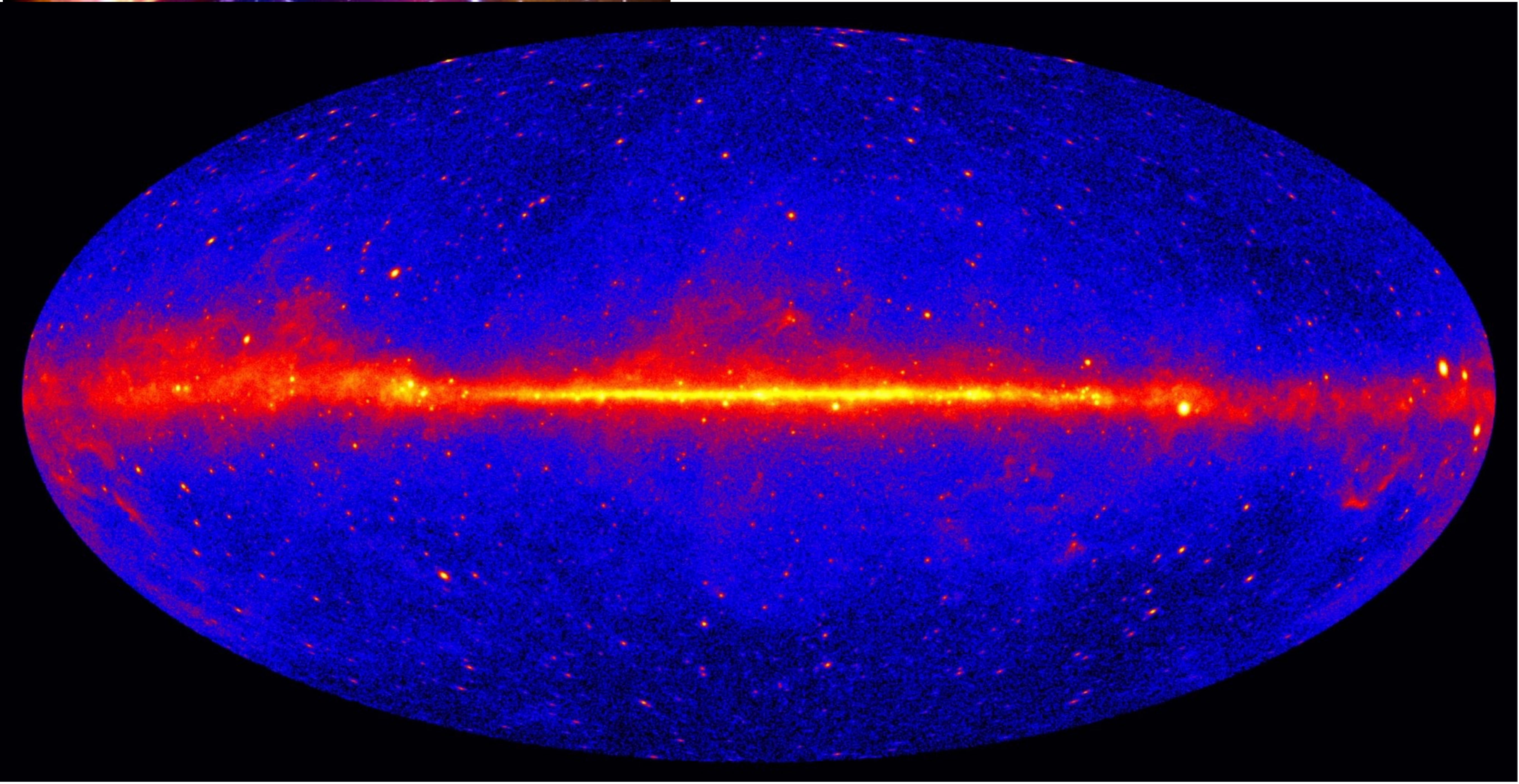
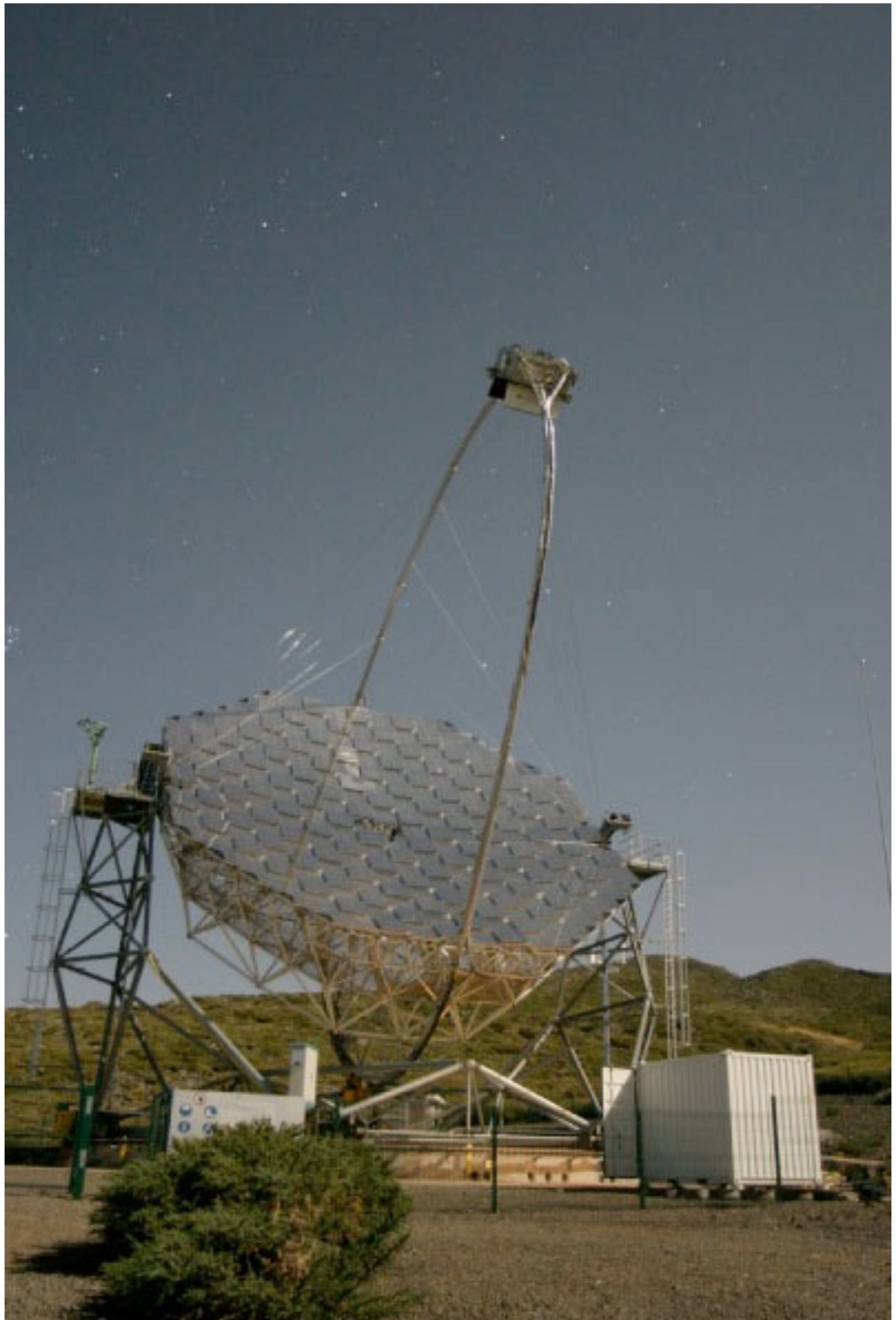
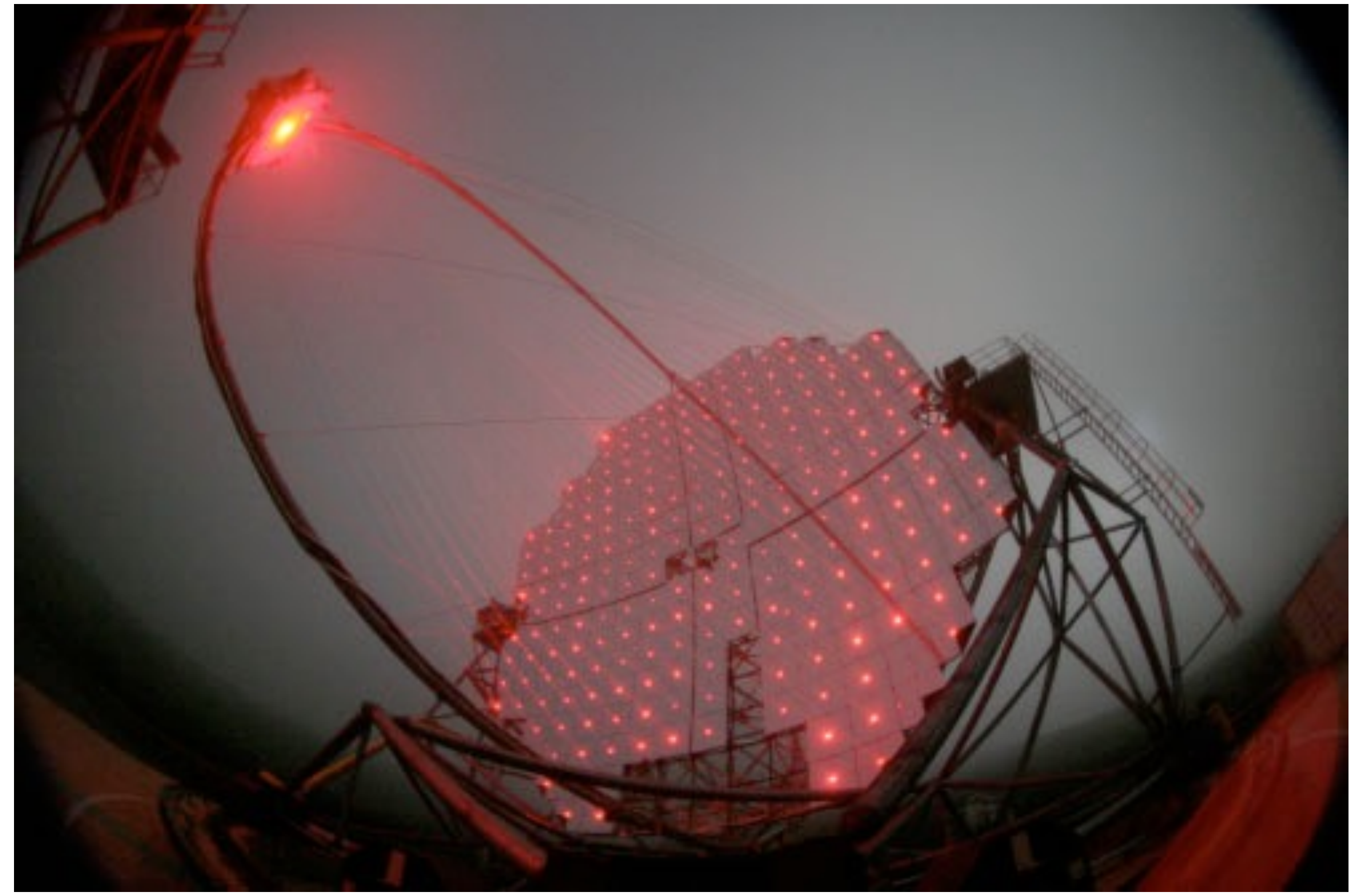


Detector for Cosmic Gamma Rays: MAGIC





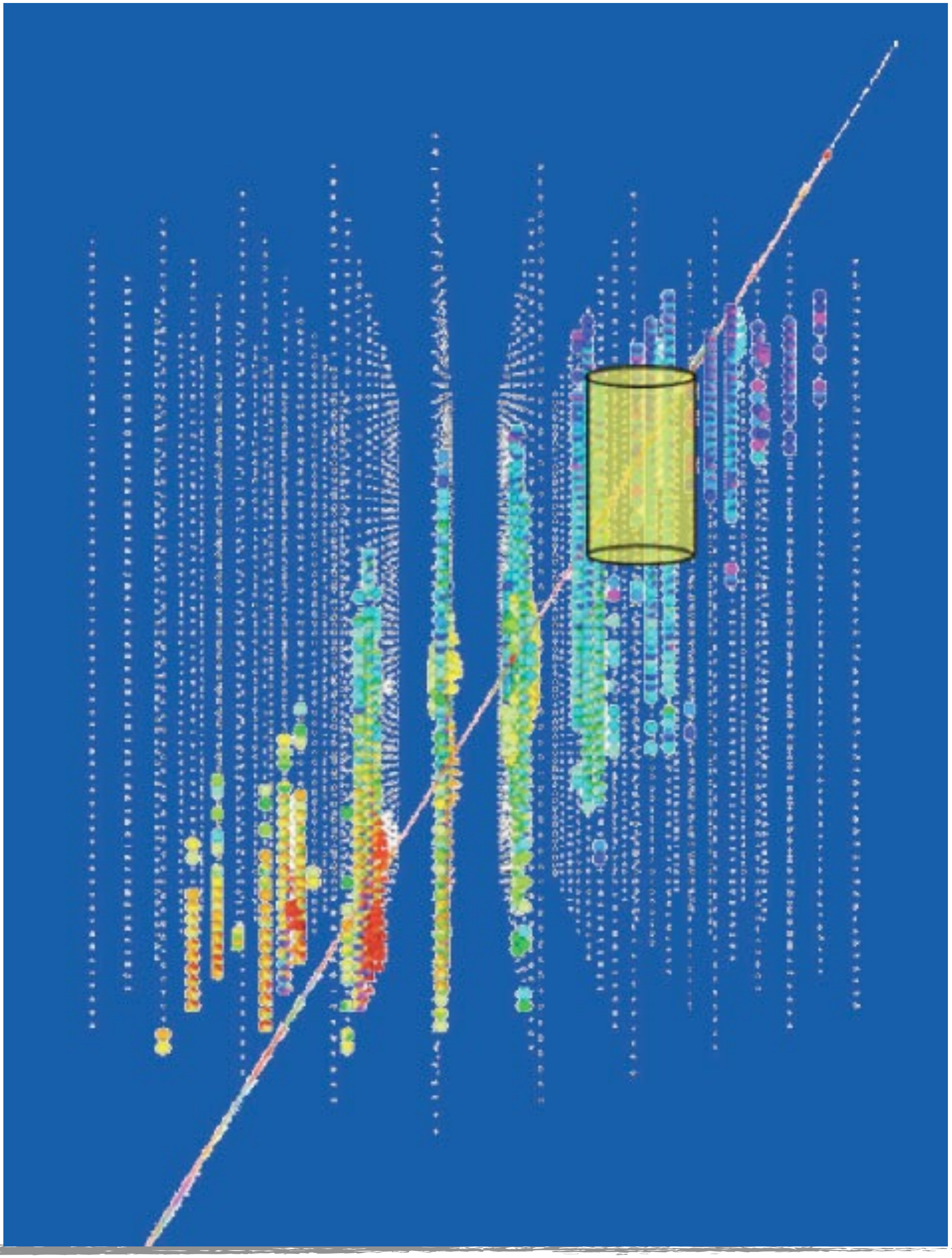
- Detection of highly energetic photons via air showers in the atmosphere
- Two telescopes with high-resolution cameras, each with 234 m^2 mirror surface
- Ultralight construction to allow fast repositioning

Highly energetic Neutrions

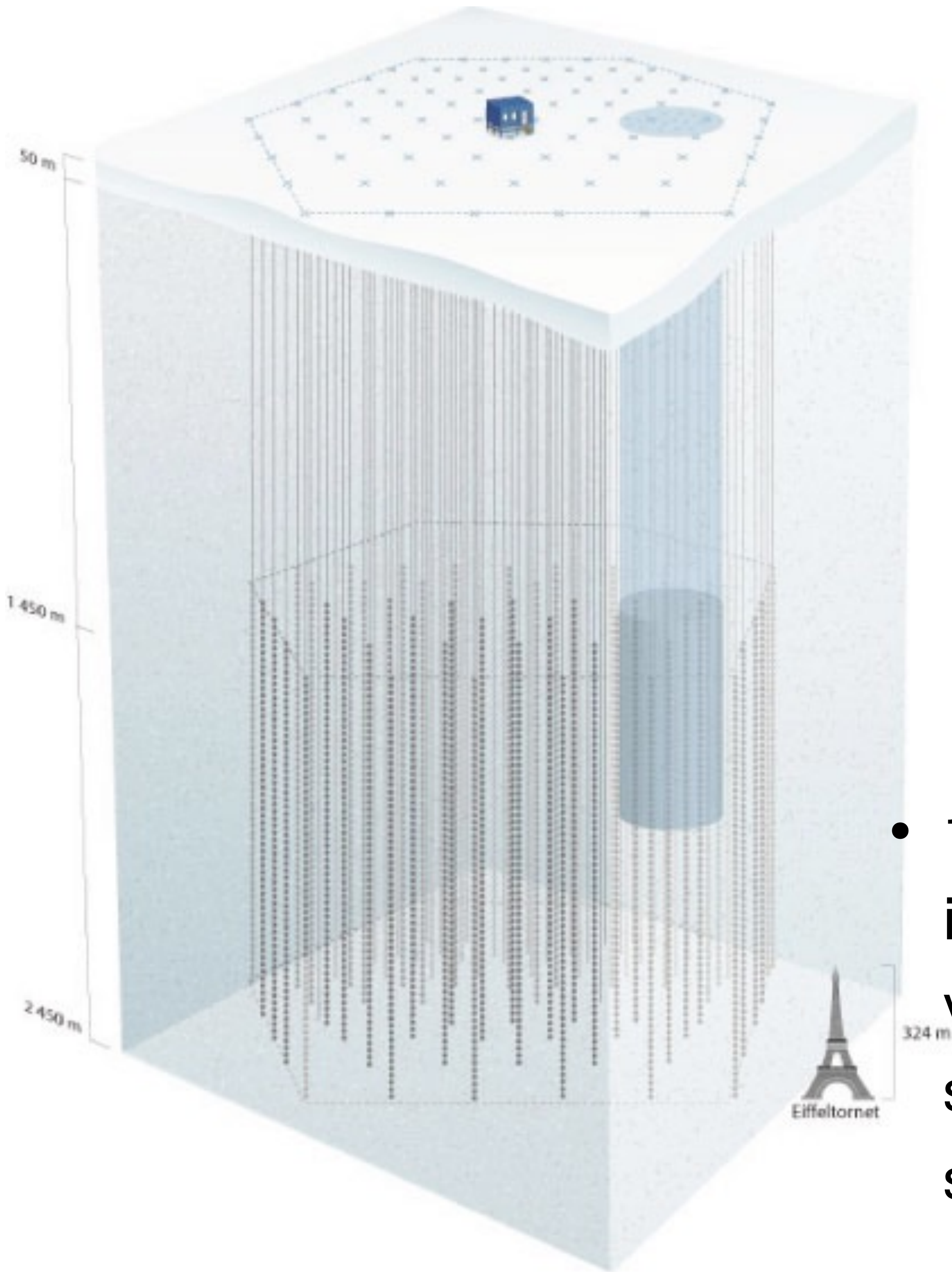
- Detection in deep underground detectors via Cherenkov light of muons or electrons produced in charged current reactions
  Example: Muon in IceCube

- Atmospheric neutrinos:
  - Are produced in air showers via pion and muon decay
  - Observation of neutrino oscillations

- Cosmic neutrinos
  - Supernovae
  - Other cosmic sources?

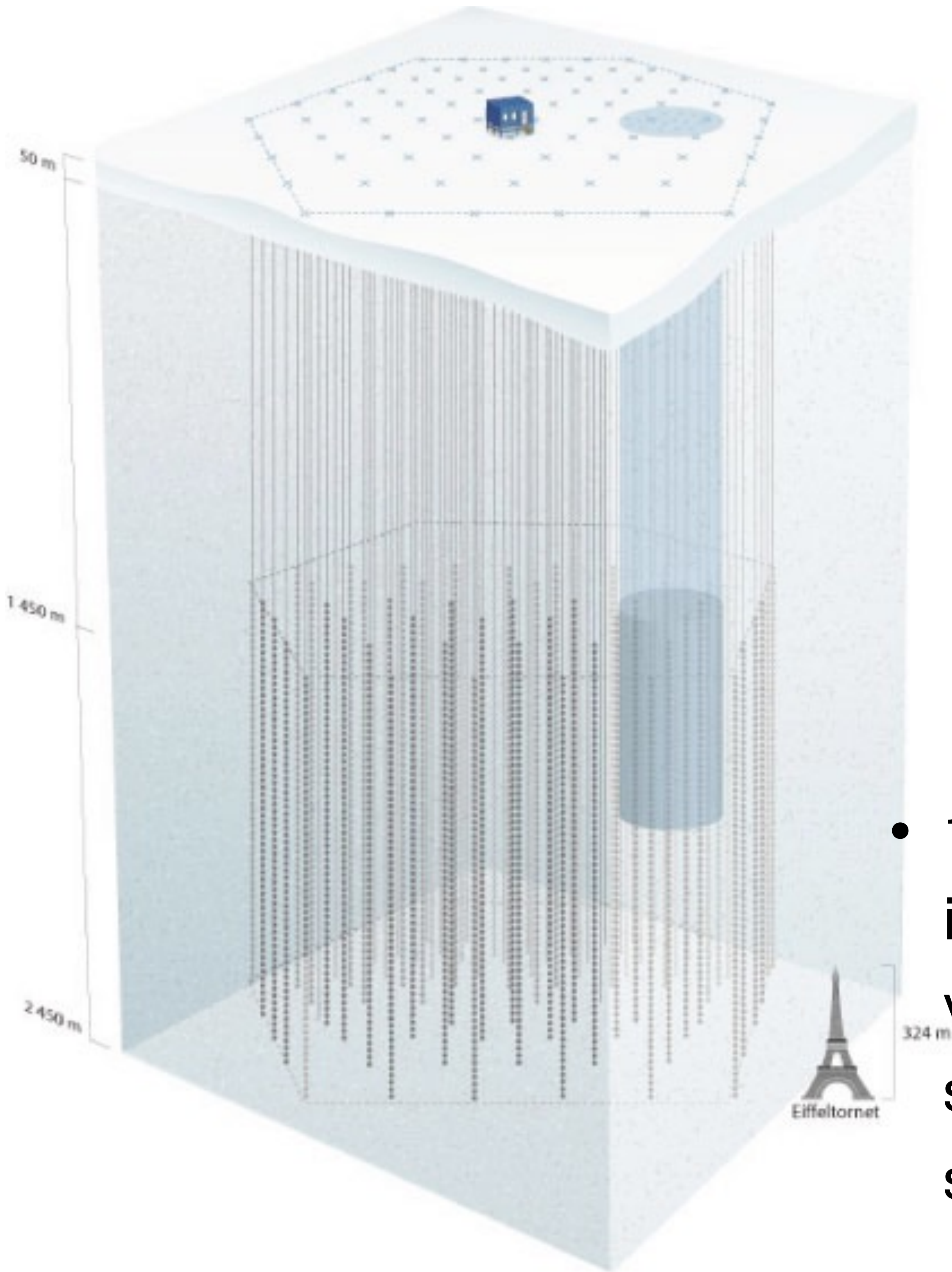


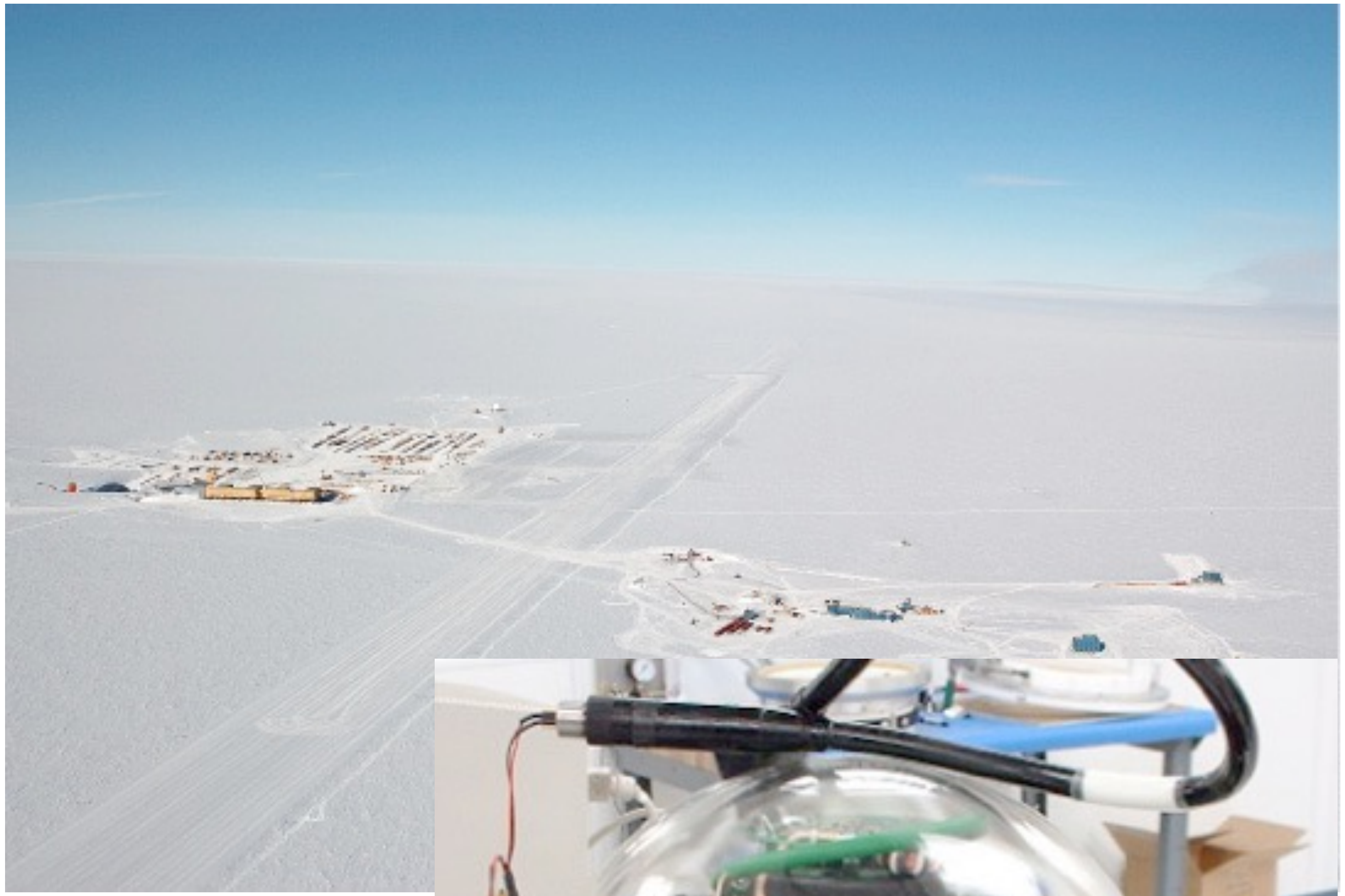
Neutrino Astrophysics: IceCube

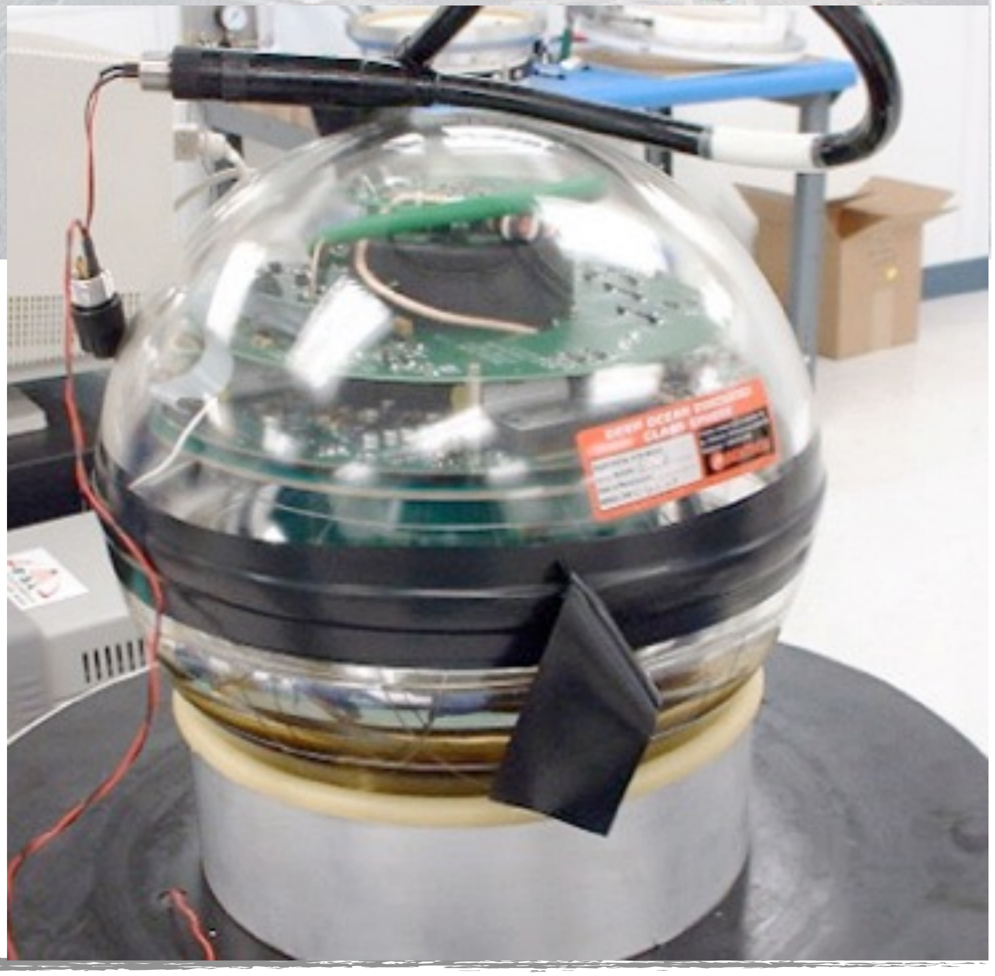


- 1 km^3 instrumented volume in the ice sheet at the south pole

Neutrino Astrophysics: IceCube







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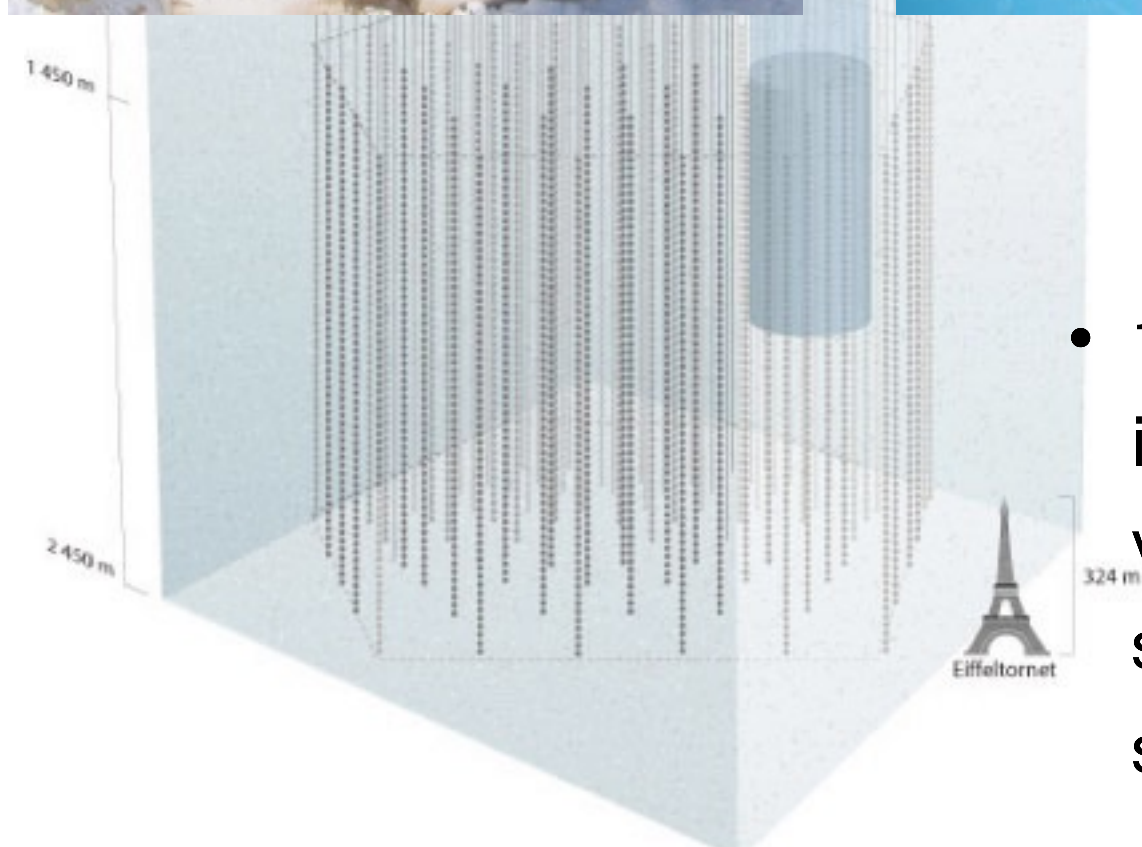
Neutrino Astrophysics: IceCube



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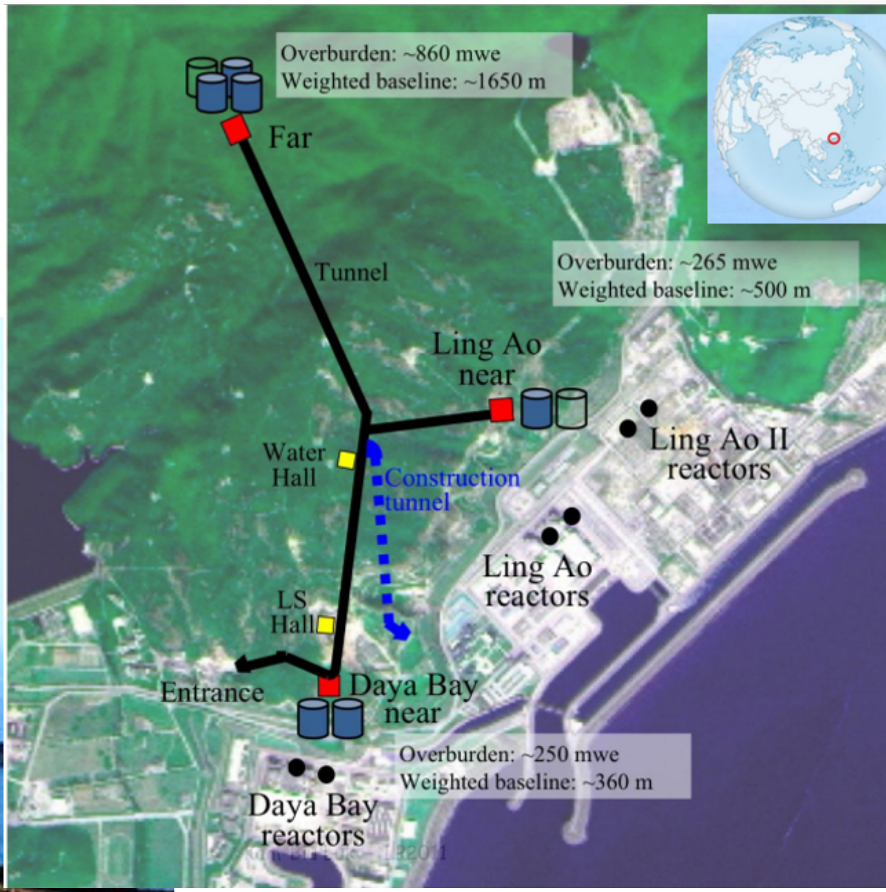
Neutrinos - also on Earth

- Moving into the era of precision physics with neutrinos: Reactors and accelerators as neutrino sources



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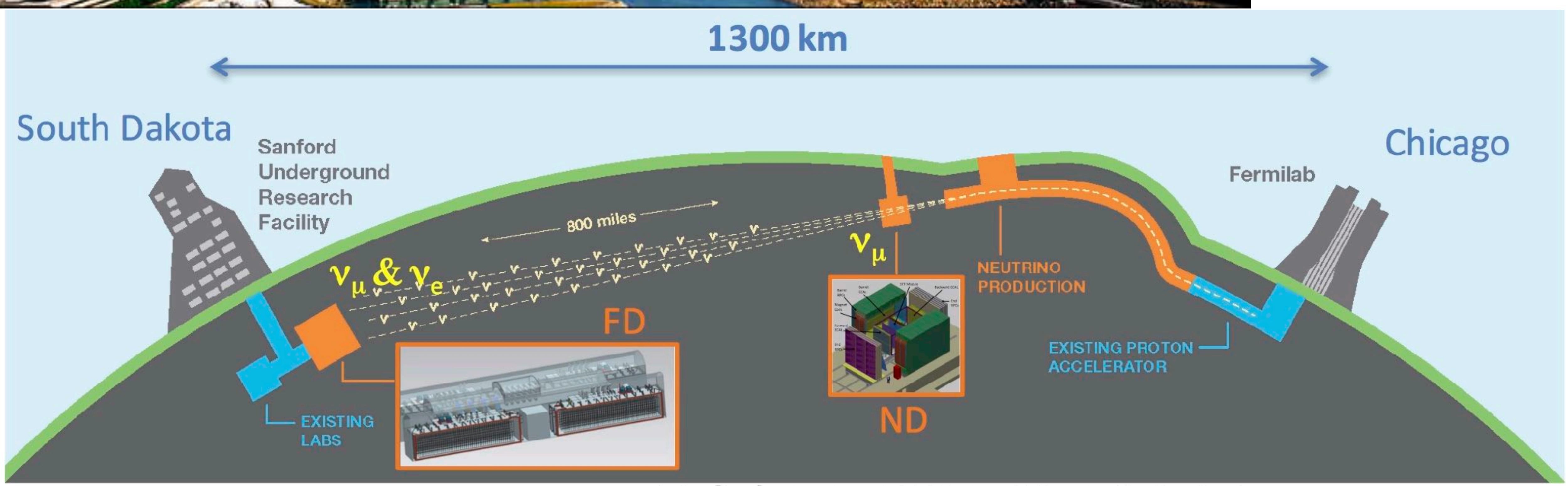
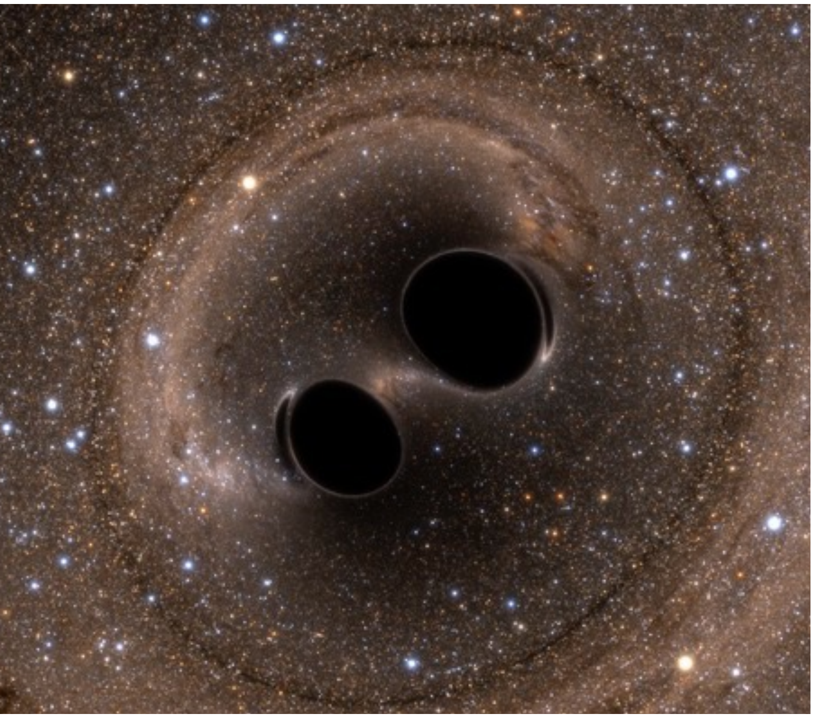


Gravitational Waves

- Spectacular discovery announced early this year: Gravitational waves seen 100 years after their prediction



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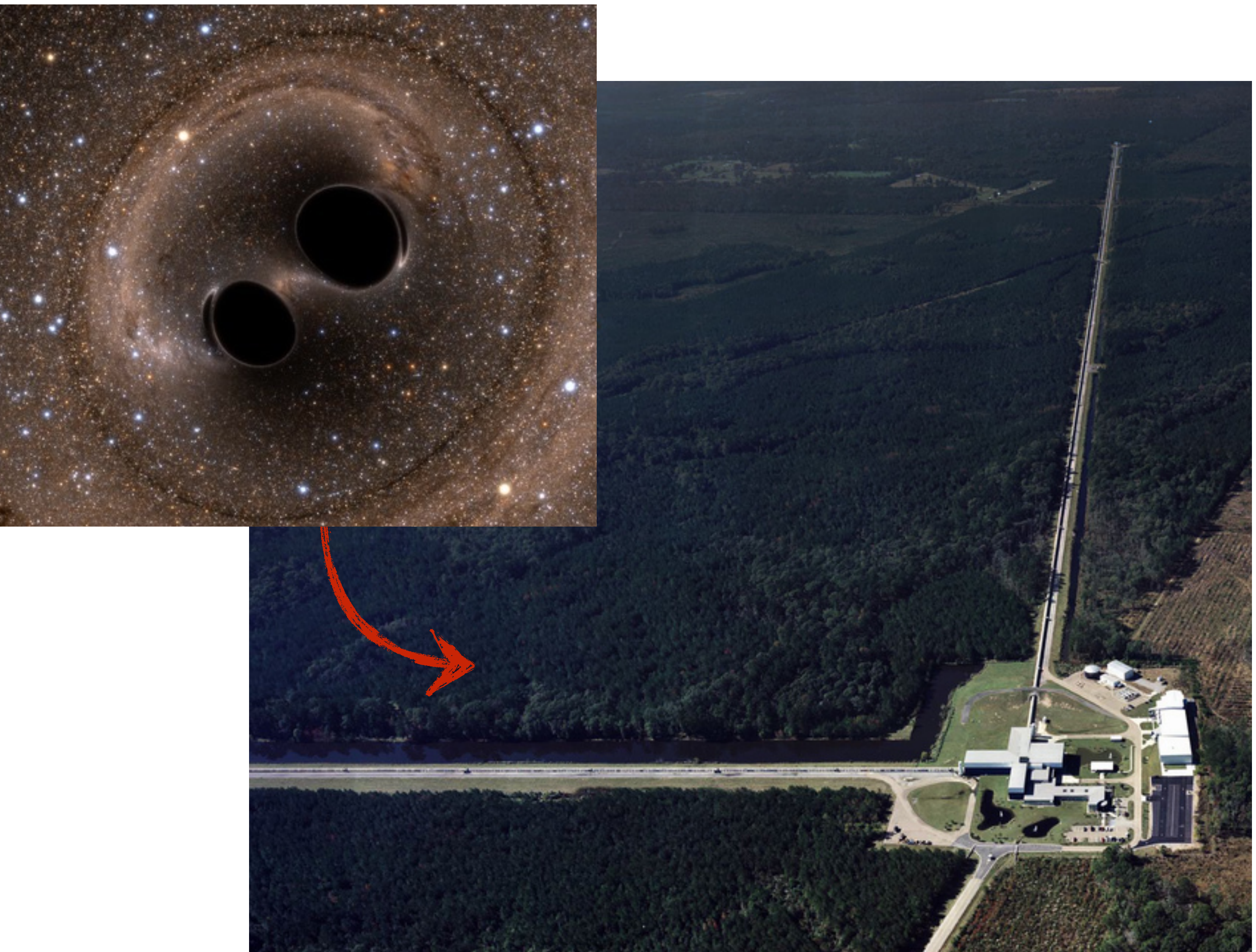

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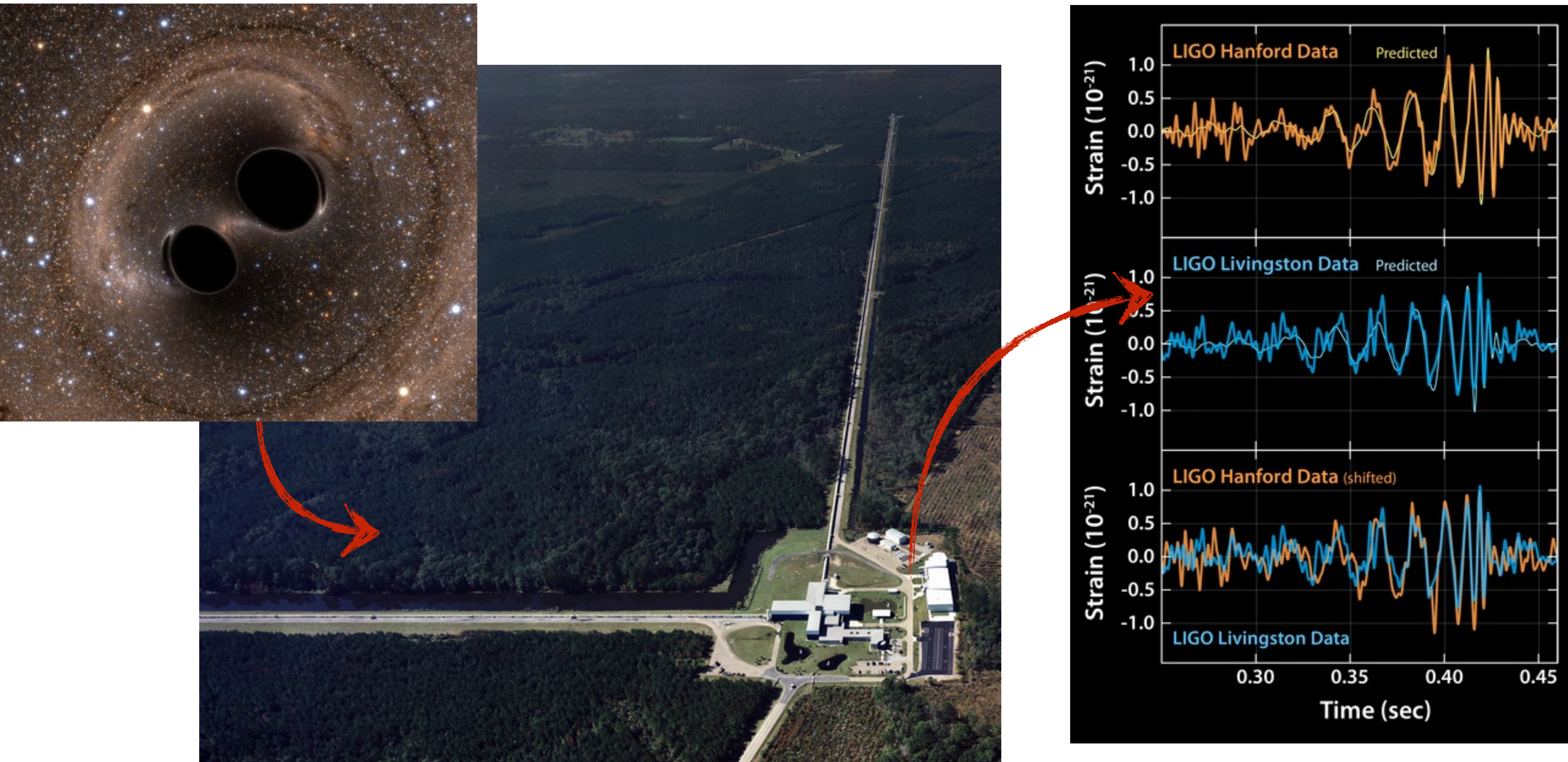
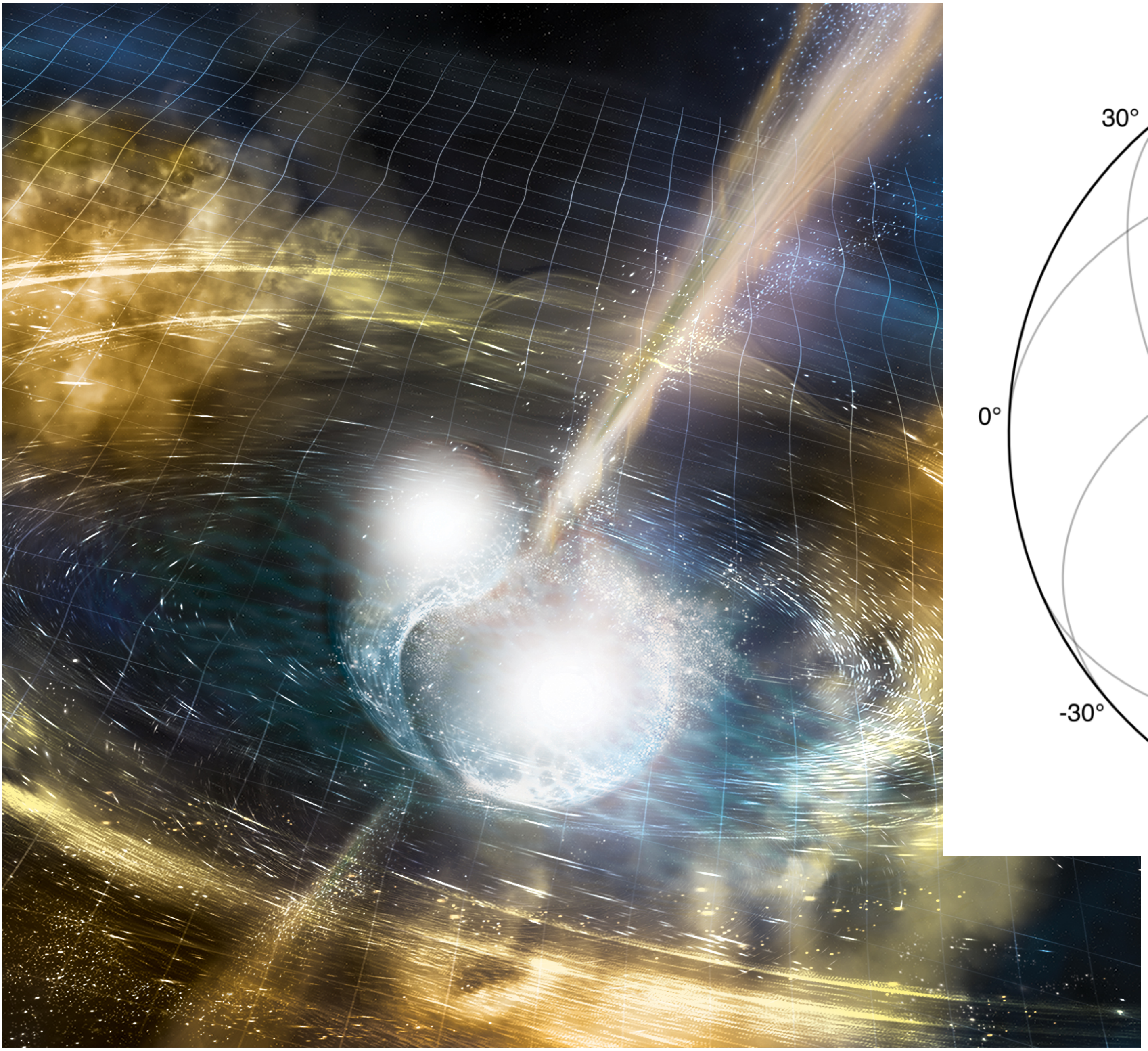
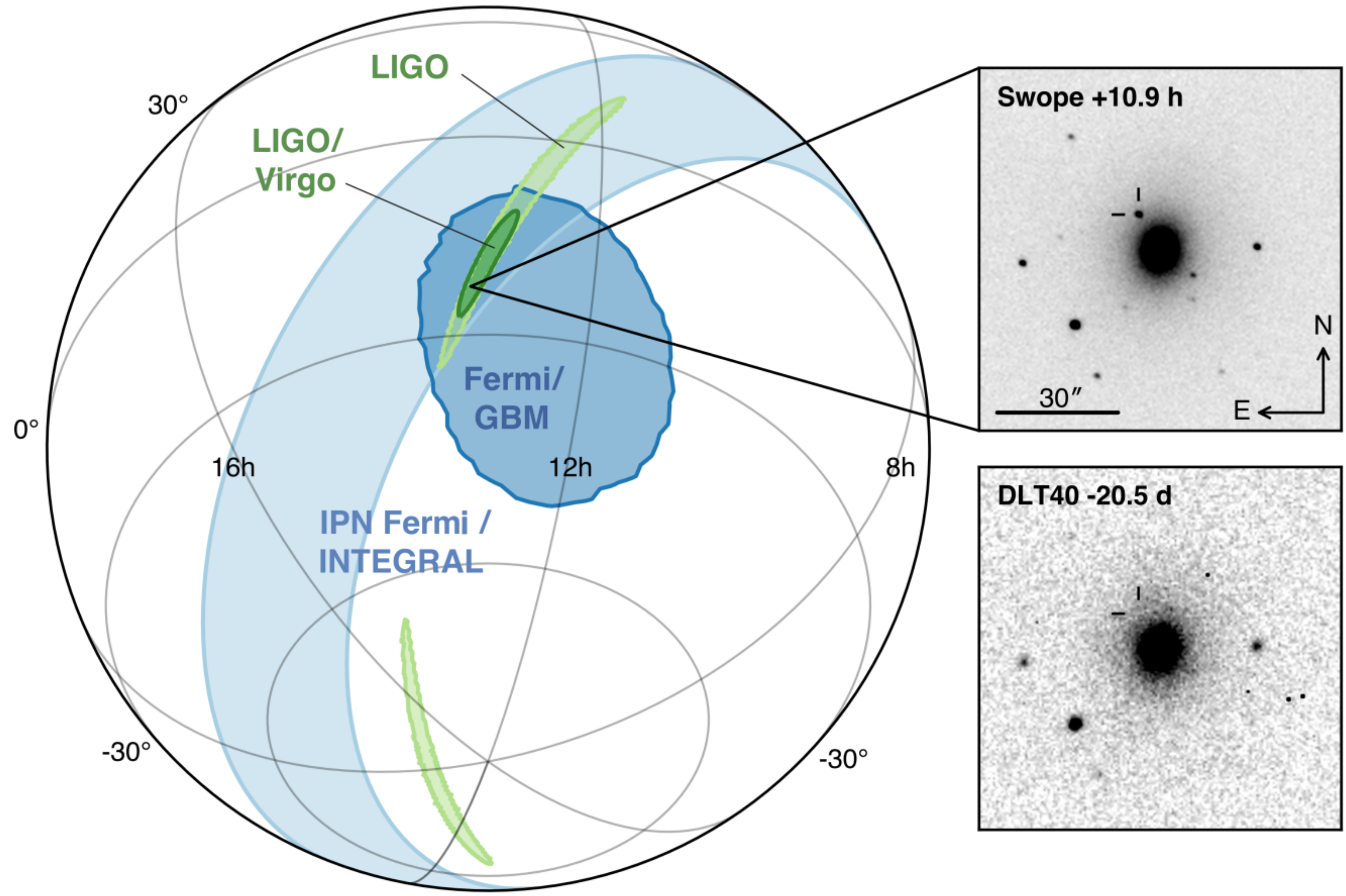


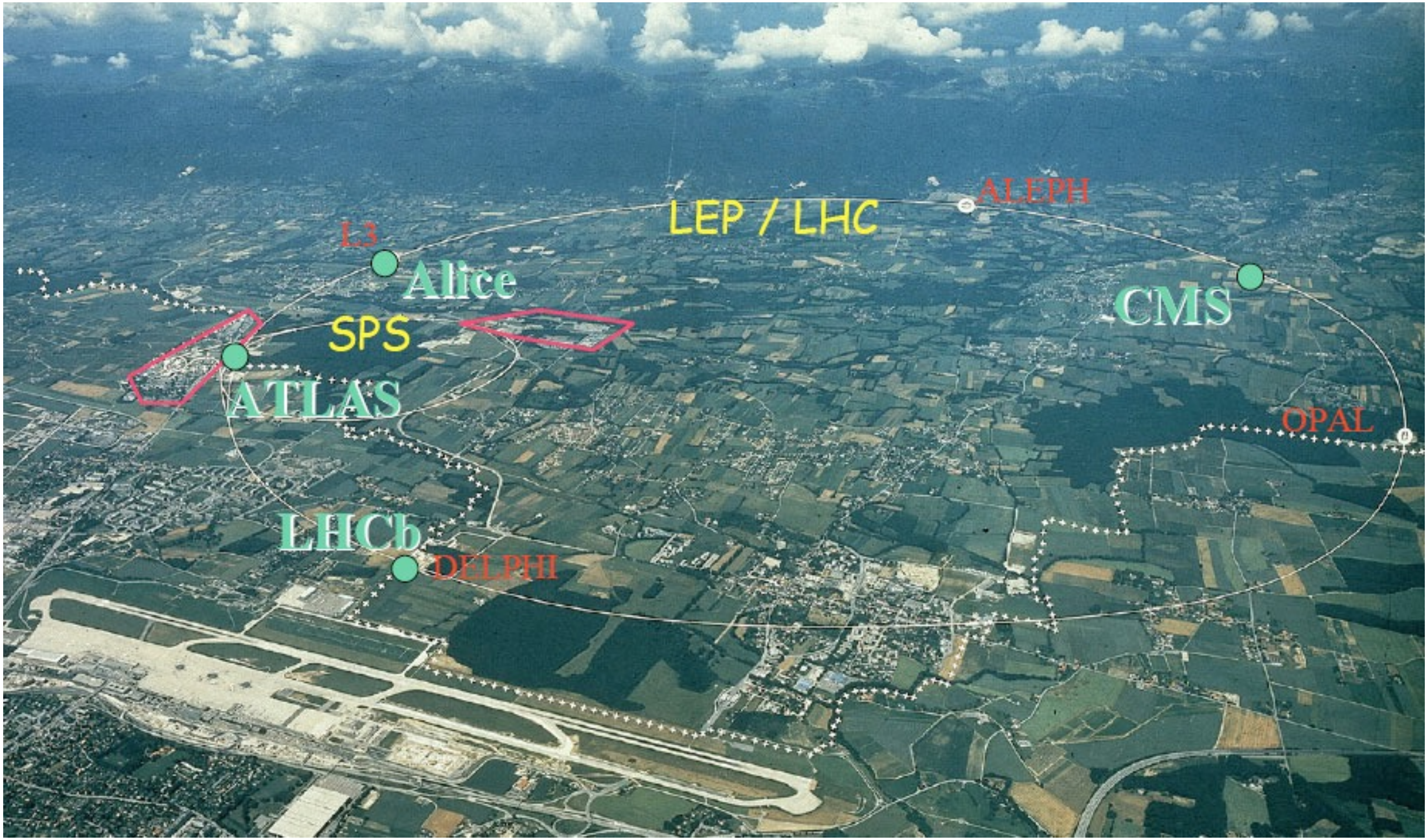
Light and Gravity from one Event

- Spectacular observation last summer: Gamma rays and gravitational waves from a neutron star merger





Accelerators on Earth: LEP/LHC



- Electron-Positron Collider (200 GeV, until 2000),
  now: LHC - with data at 8 TeV, in a few weeks starting again at 13 TeV

LEP: The highest-energy e^+e^- Collider to Date

Foto: CERN

- Circular collider: Magnets keep particles on their track
  - Quadrupole: focussing
  - Dipole: circular orbit

Future Lepton Colliders

- Linear electron-positron colliders to reach energies substantially above those reached by LEP - potentially up to several TeV

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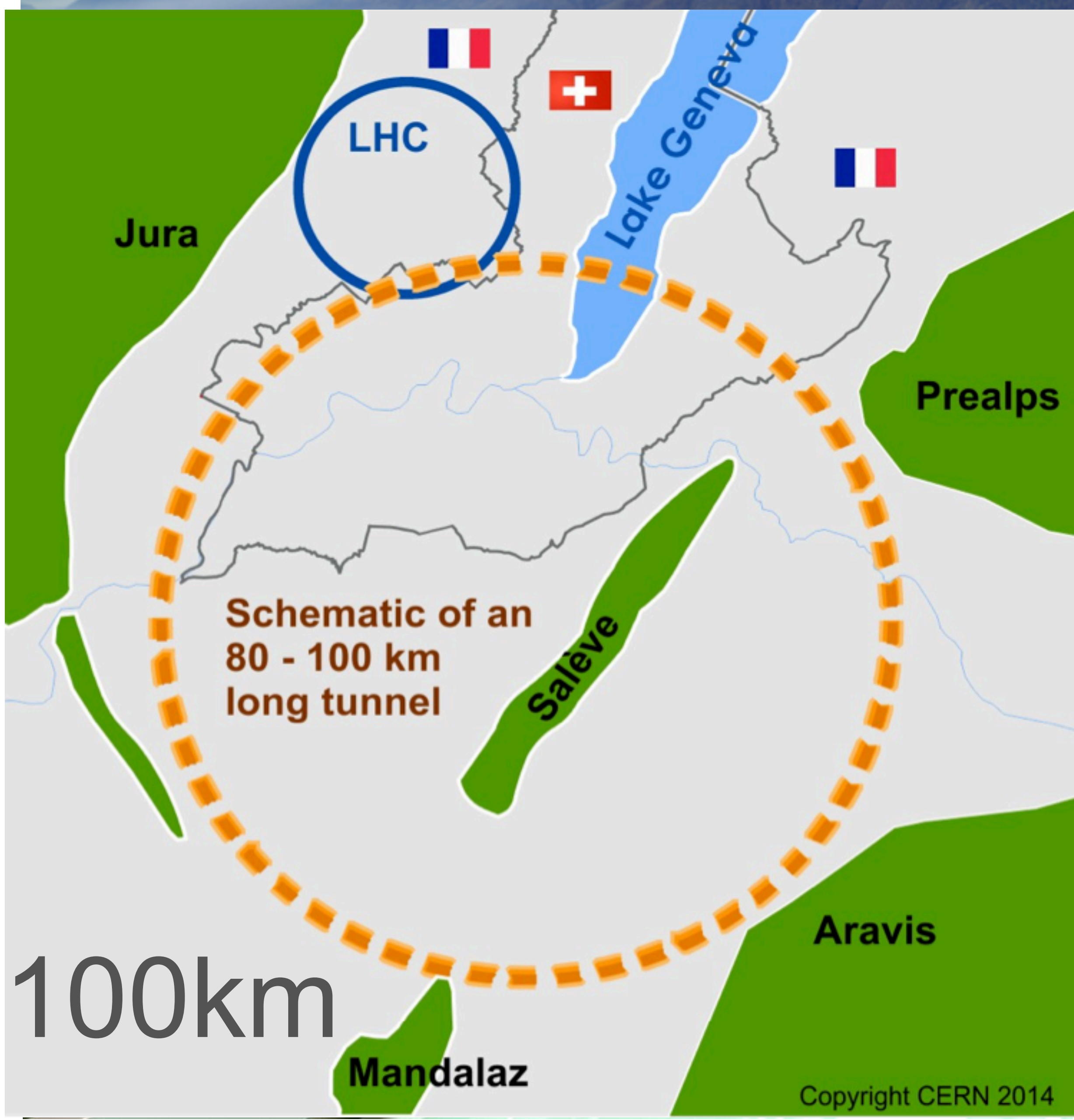

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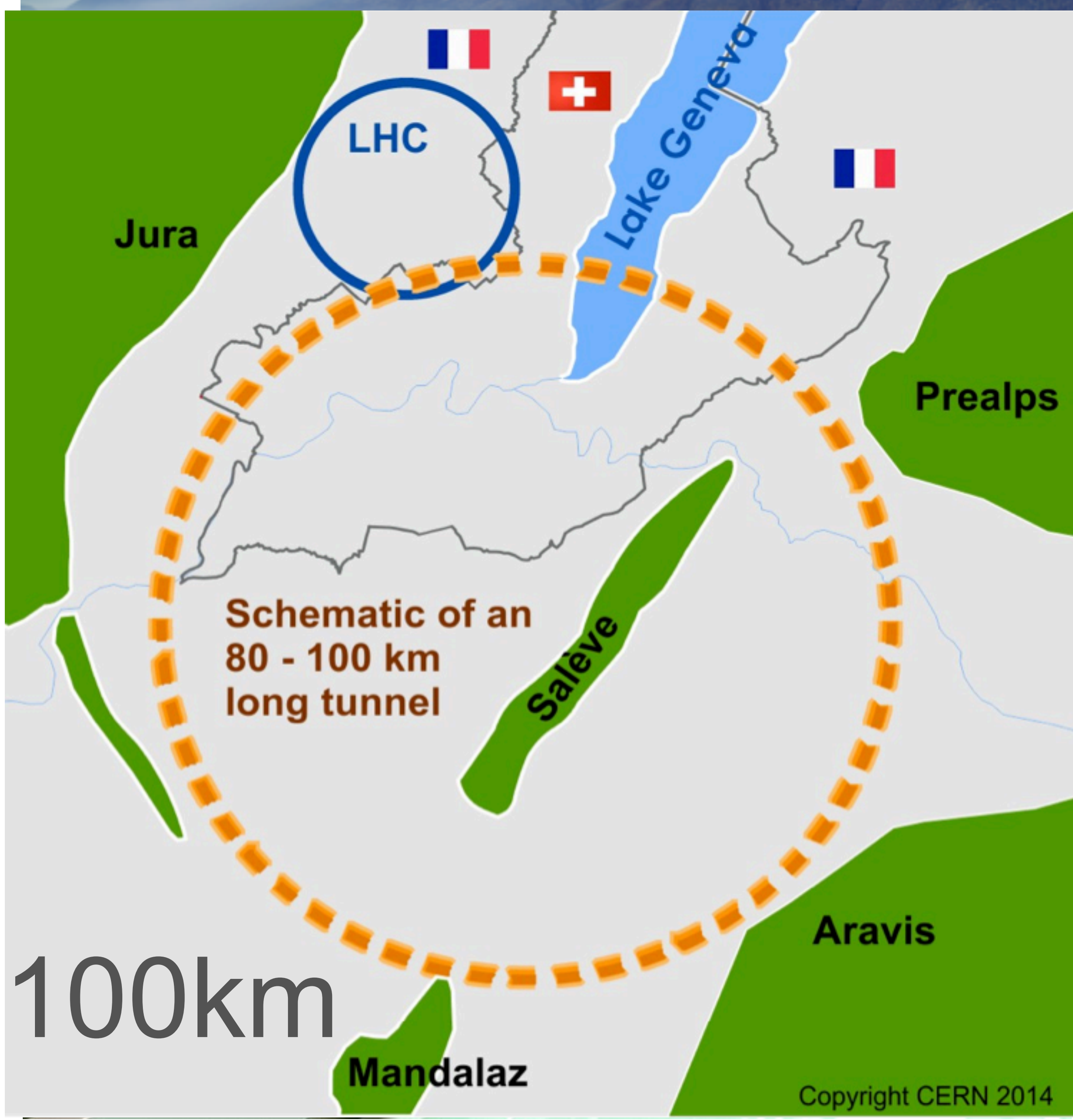

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- As far future project: A muon collider
- Ultimate acceleration gradients for leptons in plasmas - first promising R&D steps

Summary

- Particle physics with accelerators and astroparticle physics are complementary
- Accelerator-based experiments provide detailed understanding of the most fundamental constituents of matter and their interactions
- Highly energetic cosmic particles provide information on violent processes in the universe
    - Where do the particles with the highest energies come from?
    - Photons and neutrinos may point the way to interesting sources
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Next Lecture: 16.04., “Accelerators”, F. Simon