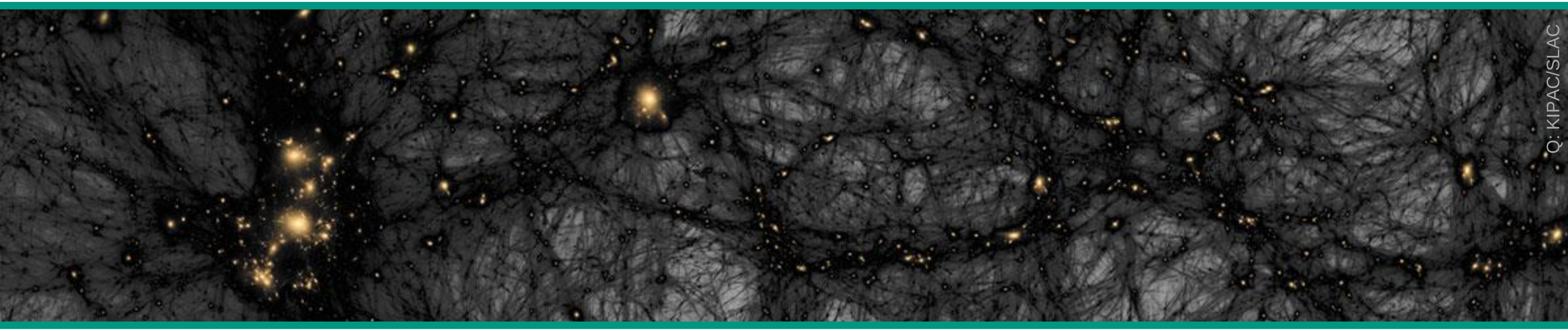
Karlsruhe Institute of Technology

Astroparticle physics I – Dark Matter

WS22/23 Lecture 2 Oct. 27, 2022



Recap of Lecture 1

- **Astroparticle physics - from 3 quarks to the entire cosmos**

  - **Searches for rare processes** from the TeV … sub-eV mass scale:
    dark matter, properties of neutrinos, gravitational waves,…

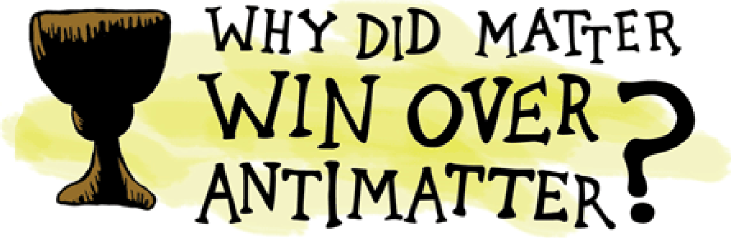
  - **Properties of the high-energy universe** from the TeV … EeV scale:
    charged CR´s, neutrinos, gammas from cosmic super-accelerators

  - **many decades in energy (μeV … ZeV), many sources** :
    neutrinos, gammas, charged cosmic radiation

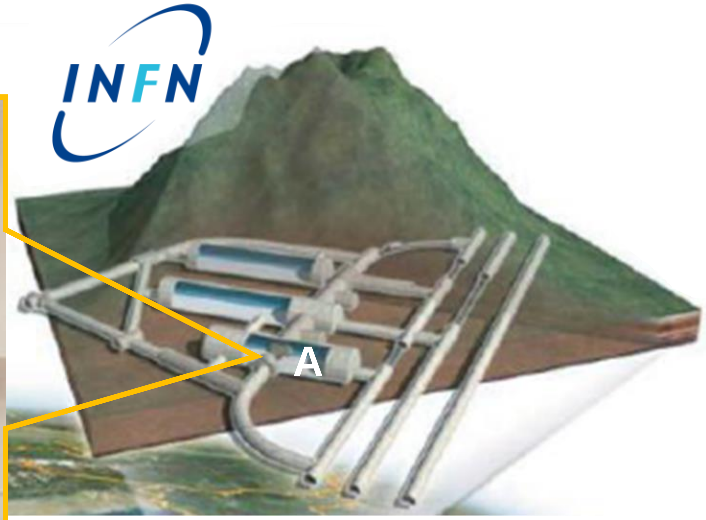
  - **new technologies / detectors & analysis strategies**:
    quasi-background-free detection techniques,…

neutrino studies using enriched detectors

- **search for rare processes at the MeV-scale: Lepton number violation?**

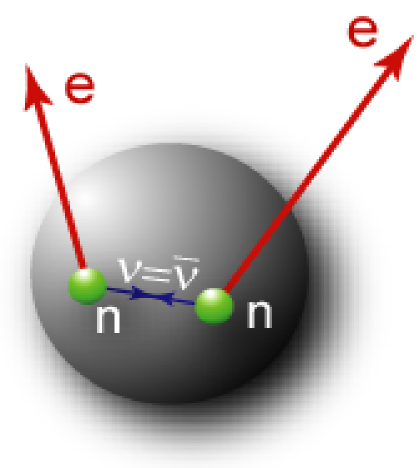


Laboratori Nazionali del Gran Sasso



1.1 Particle Radiation from the Laboratory

- **Electrons in the MeV-range from ßß-decays: Lepton number?**



$\Delta L = 2$

Q: symmetry magazine

Q: MPIK

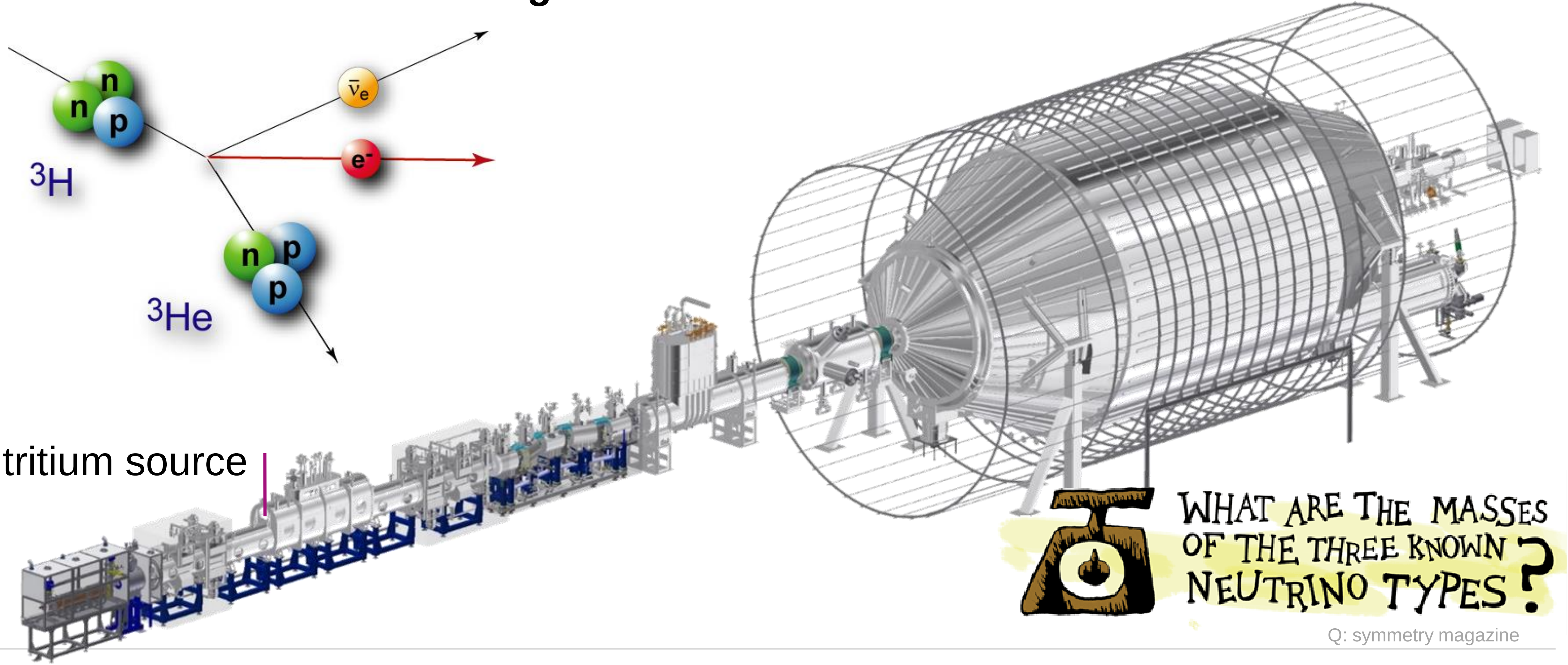
GERDA* experiment at LNGS**

*GErmanium Detector-Array

**Laboratori Nazionali Gran Sasso

KATRIN experiment at KIT

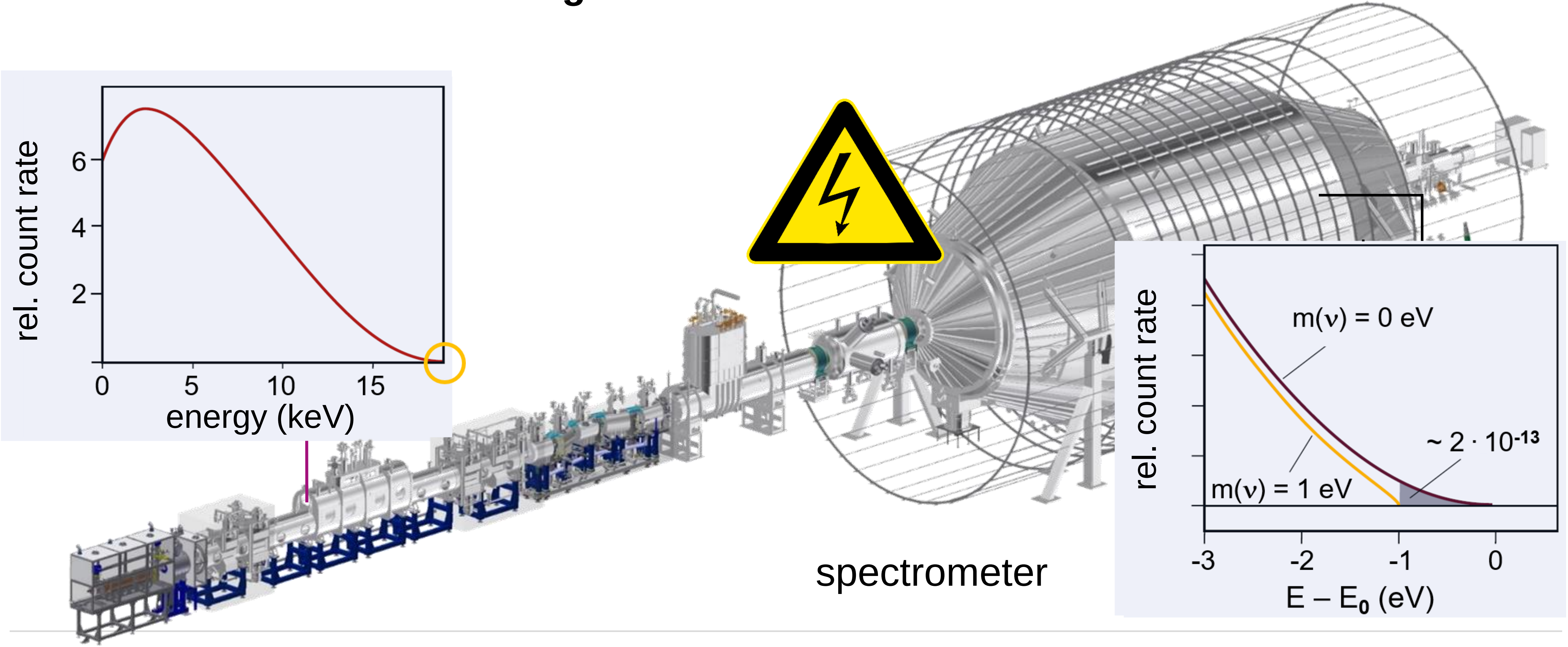
- **Electrons in the keV-range: scale of neutrino mass?**



Q: symmetry magazine

KATRIN experiment at KIT

- **Electrons in the keV-range: scale of neutrino mass?**



Laboratories required for Particle Radiation

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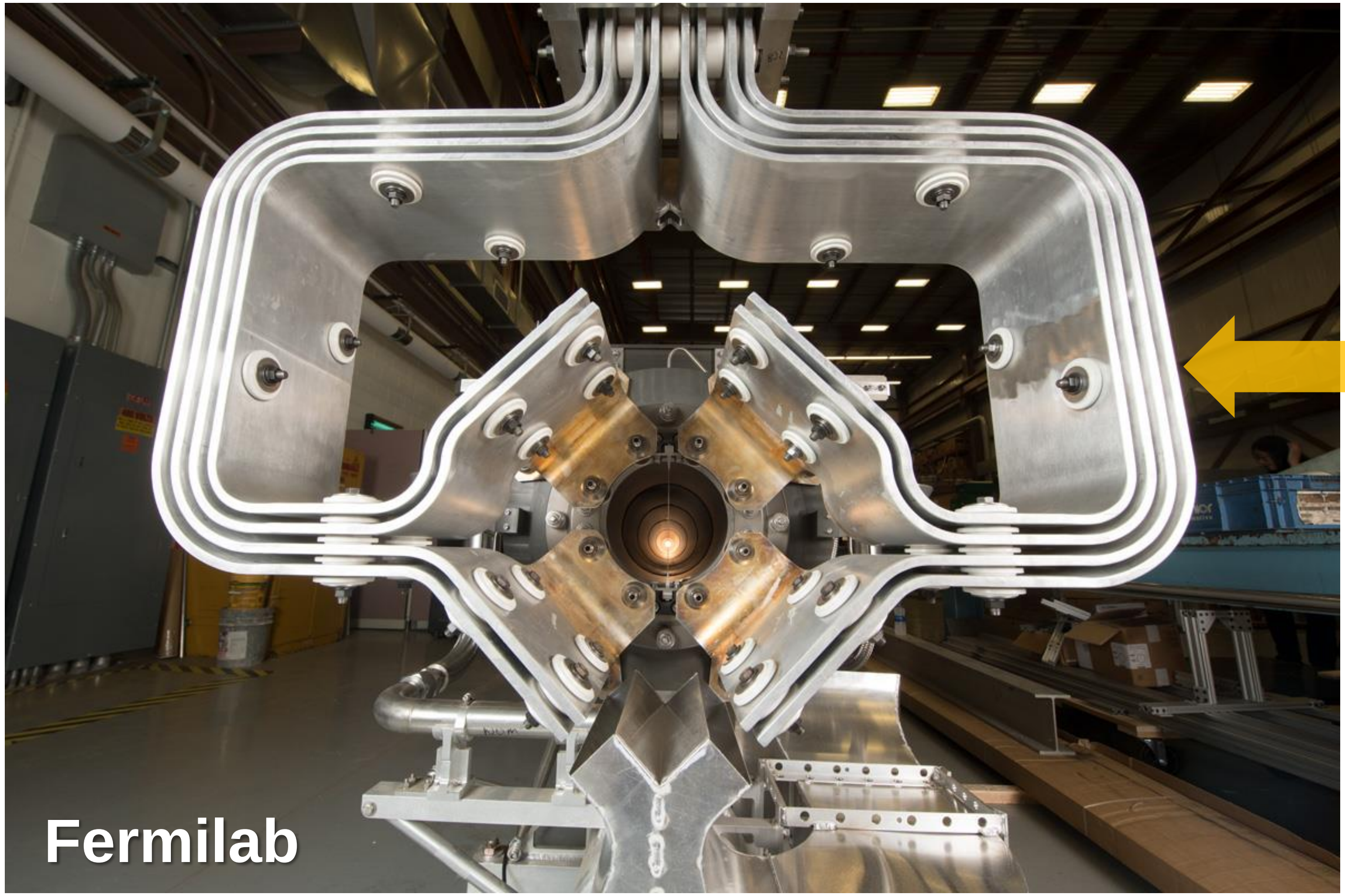
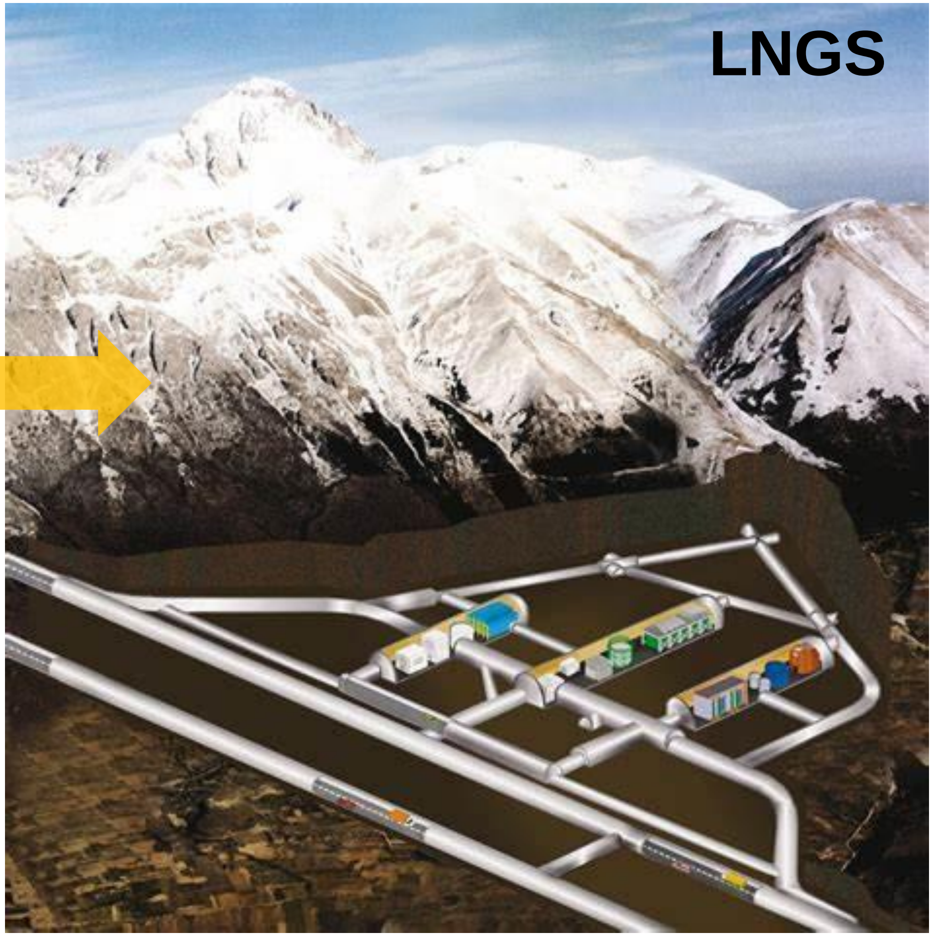
- **Labs**: accelerators, nuclear reactors, TLK*, underground labs (LNGS**)



Q: Fermilab



Q: LNGS

* Tritium Laboratory Karlsruhe **Lab. Nat. di Gran Sasso

1.2 Particle Radiation from the Universe

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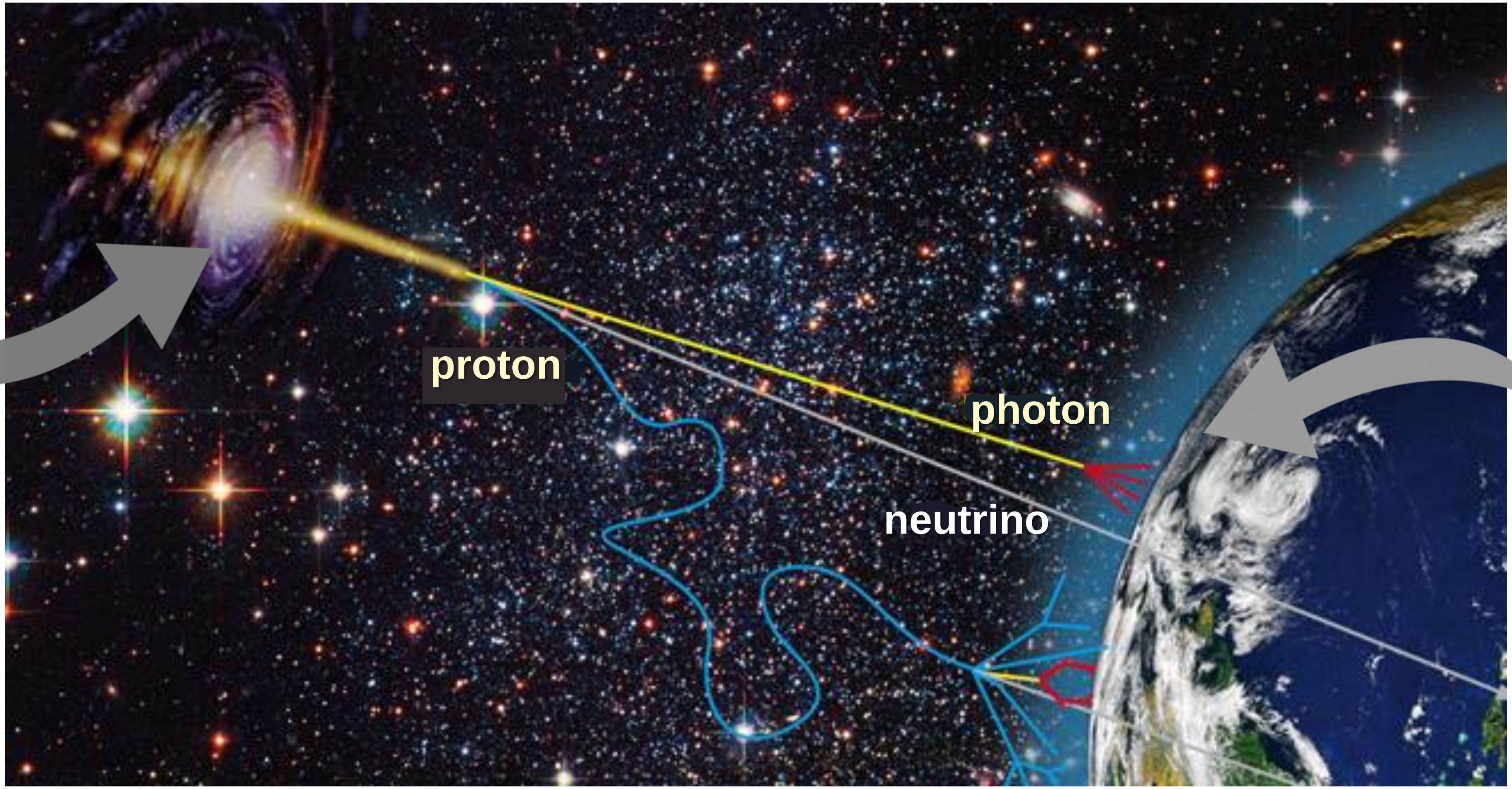
- **multi-messenger approach: news from the hidden, invisible universe**

source of particle radiation - typically a cosmic accelerator (AGN, GRB)



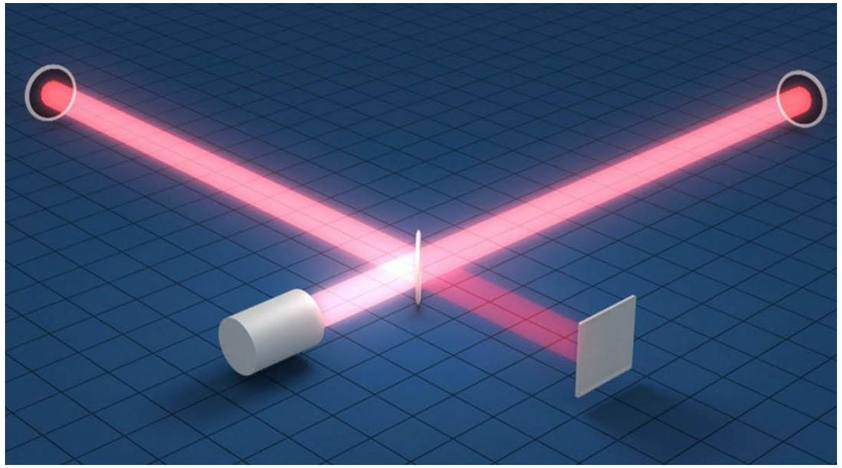
detection of particle radiation

The multi-messenger ansatz: GW & neutrinos

- **news from the hidden universe: examples - massive, compact objects**

black holes, neutron stars,…

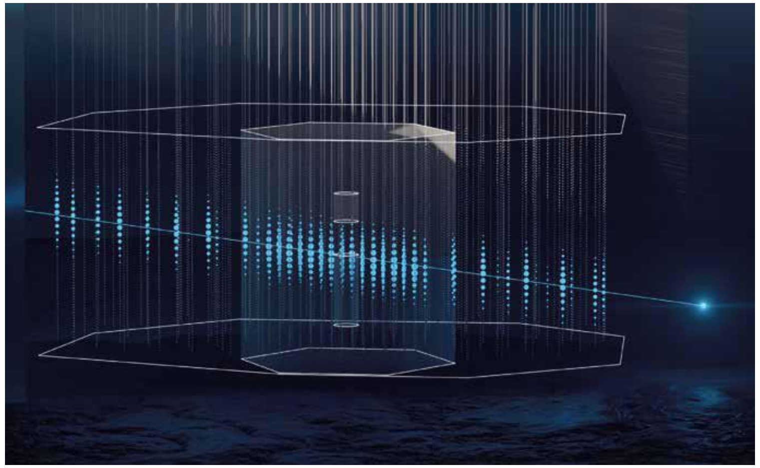
gravitational waves (GW)



Q: APS physics

Q: DESY

UHE* neutrinos



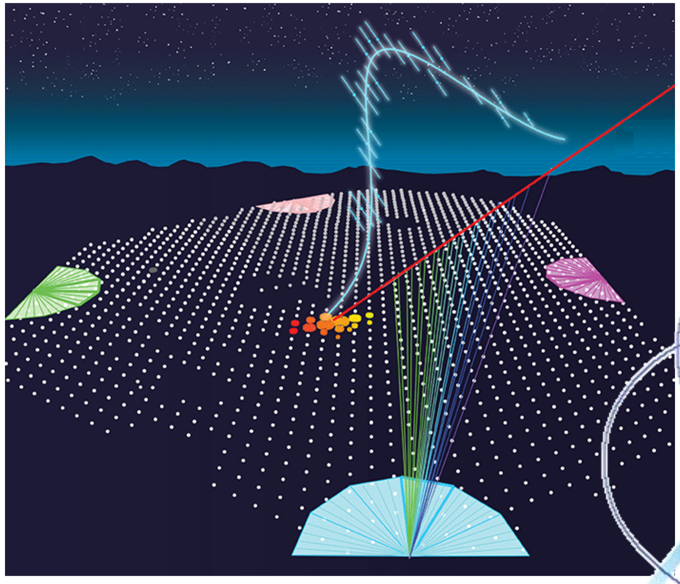
Q: DESY

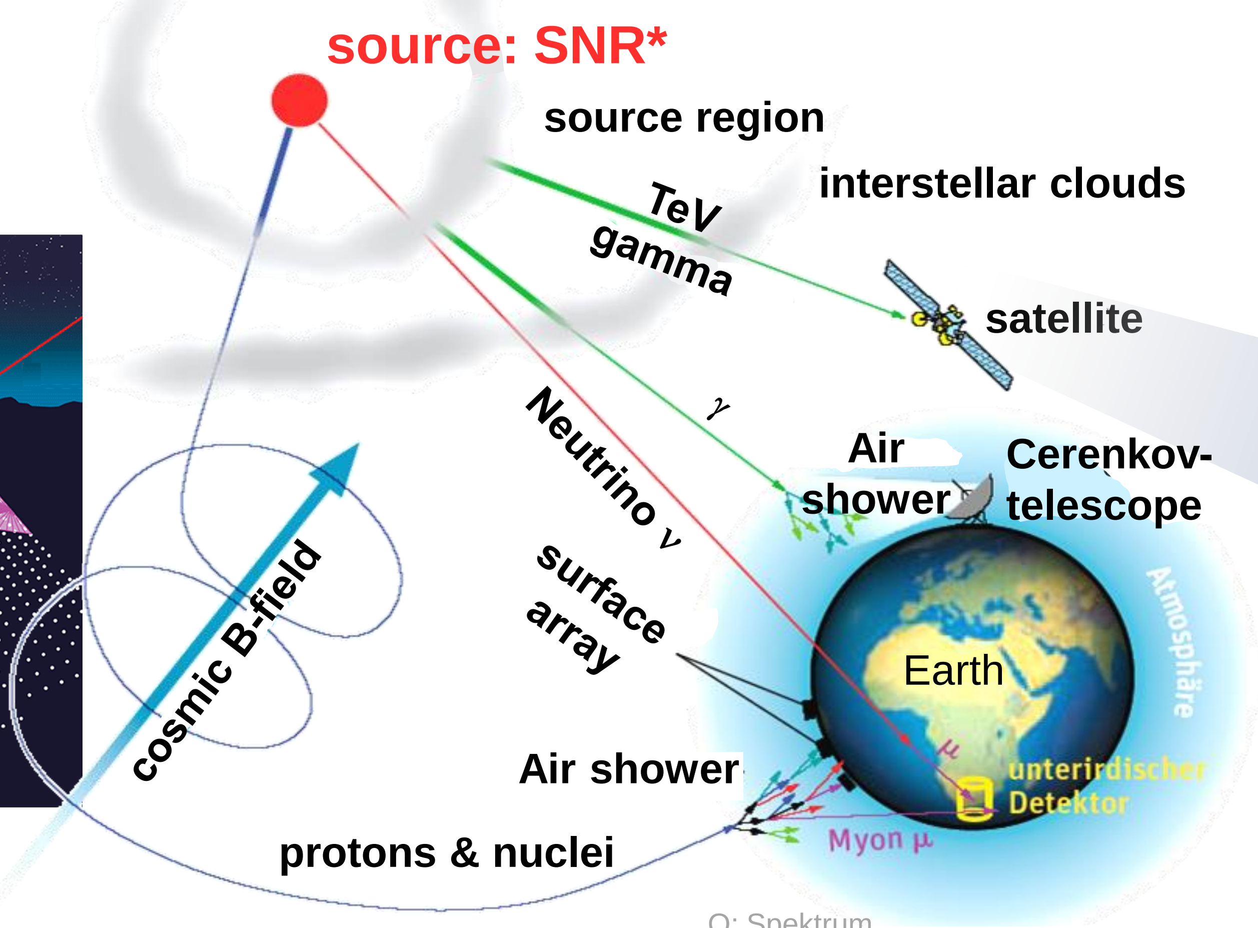
*Ultra-High-Energy

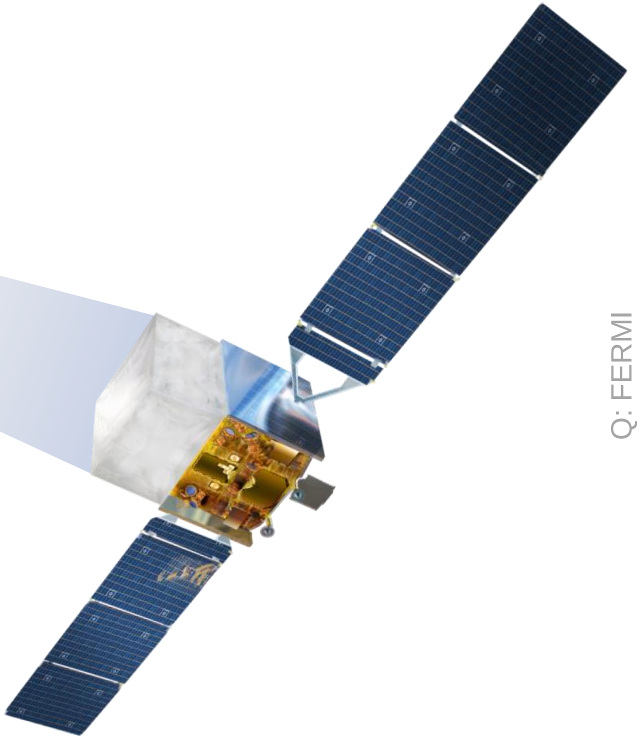
The multi-messenger ansatz: CR´s & Gammas

- news from the hidden universe: example SNR*

Q: APS Physics







charged CR´s

Q: Spektrum

gamma rays

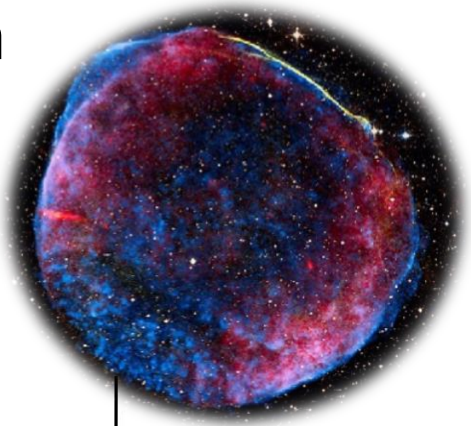
Q: FERMI

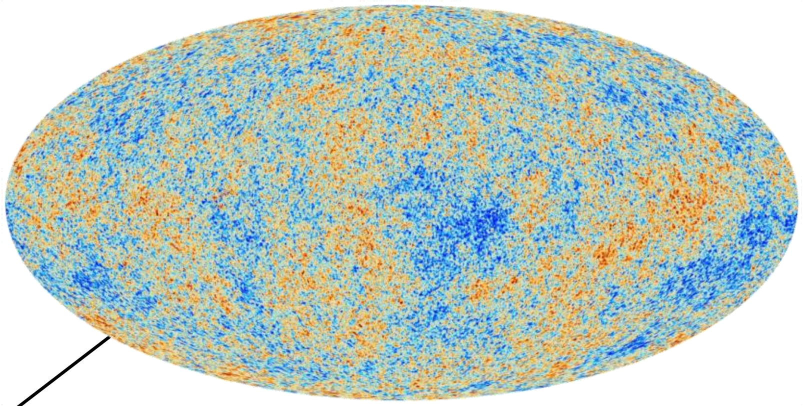
*SNR = SuperNova Remnant

Thermal & non-thermal universe

- **radiation with very different spectral distributions & energy scales**

synchrotron radiation
(non-thermal)

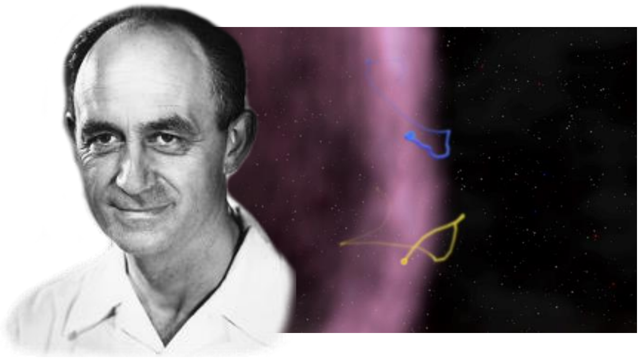


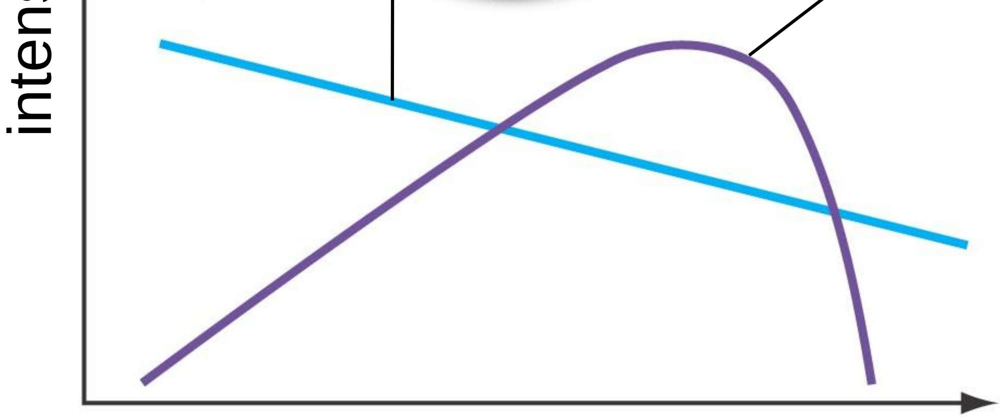


Q: ESA, NASA

thermal radiation

Fermi-
acceleration





Planck
distribution

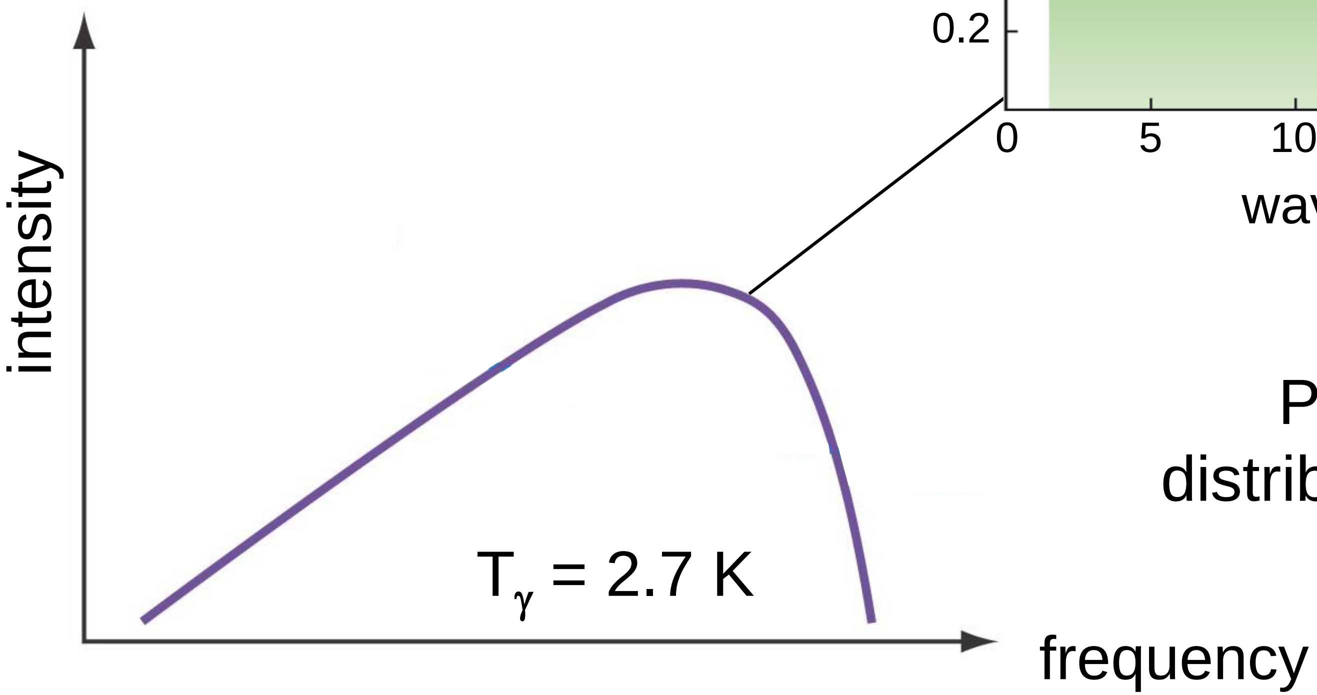
Q: redbubble

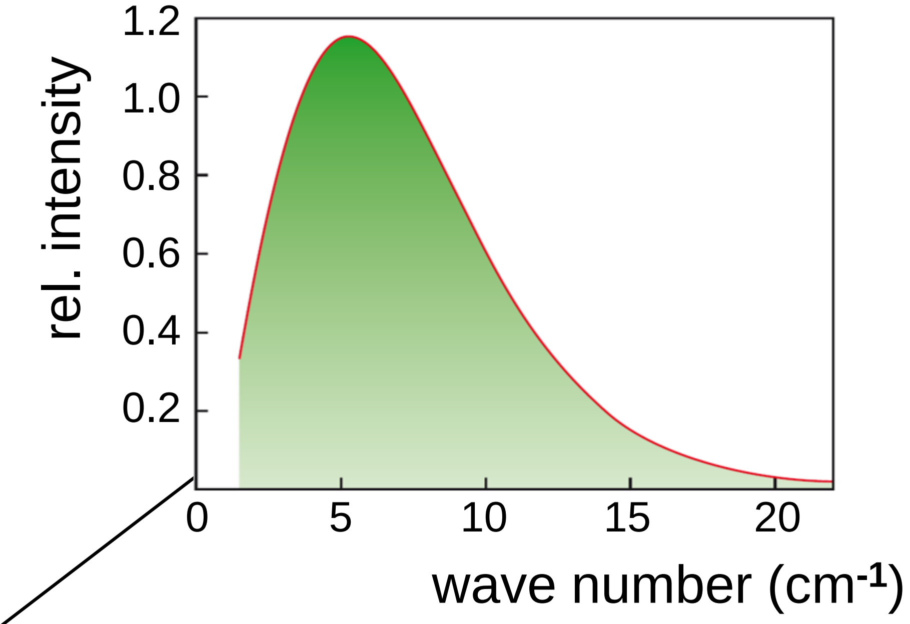
Thermal & non-thermal universe

Karlsruhe Institute of Technology

- **the thermal universe: example CMB***
  - **temperature T** as (sole) **order parameter:** requires a perfect thermal equilibrium

Big Bang: CMB





Planck distribution

***C**osmic **M**icrowave **B**ackground

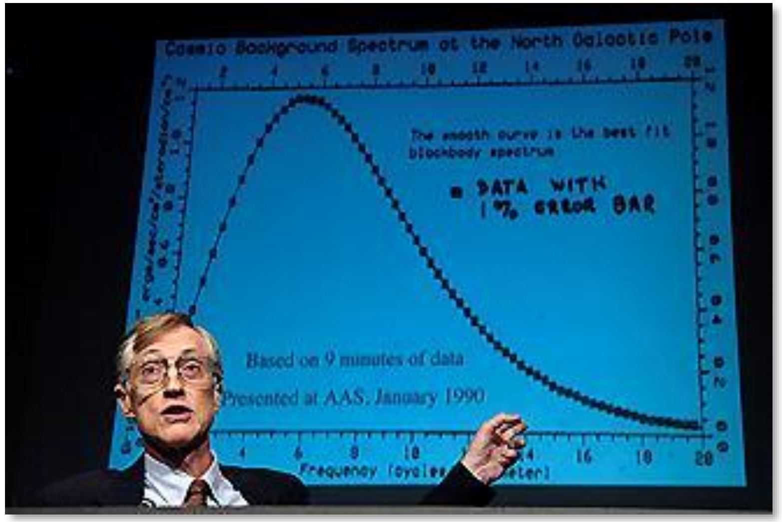
Thermal & non-thermal universe

Karlsruhe Institute of Technology

- **example from thermal universe: CMB**

  - temperature **T** as (sole) **order parameter** requires a perfect thermal equilibrium

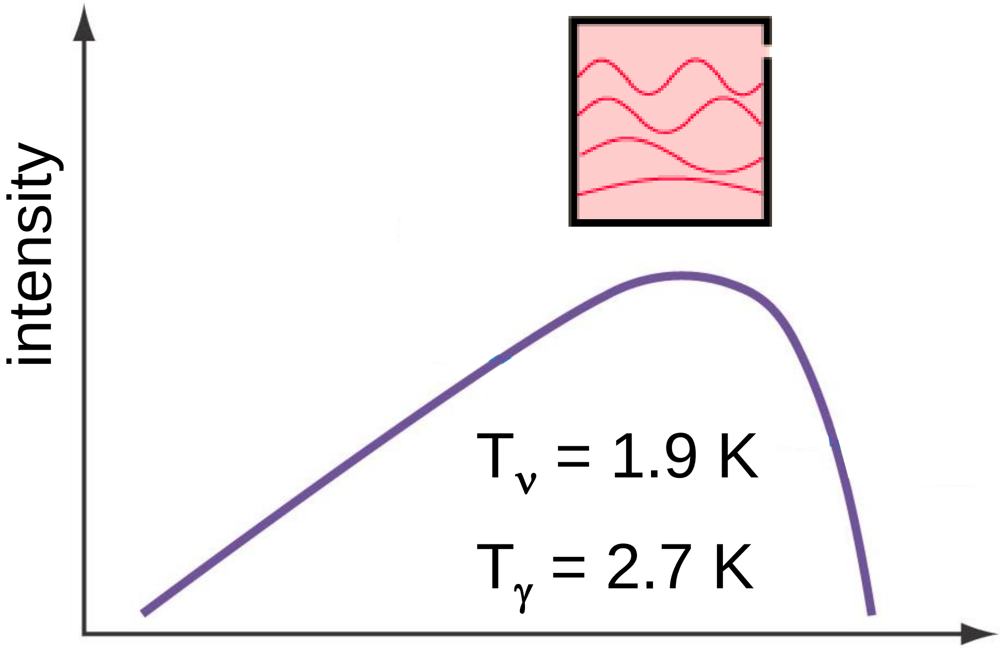
Q: NASA



CMB: the **perfect** black body

Q: symmetry magazine

Big Bang: CMB
CνB*



frequency

Planck distribution

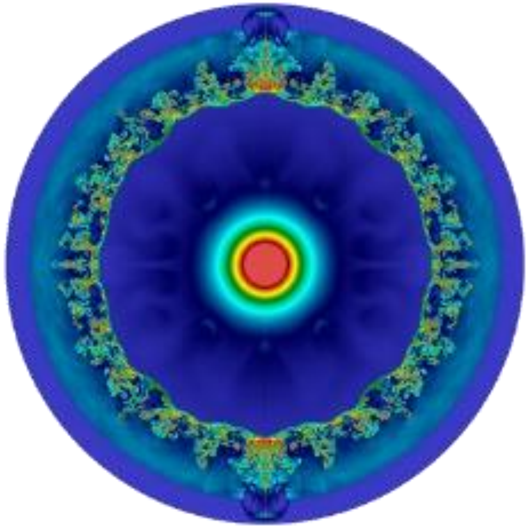
Q: redbubble

*Cosmic Neutrino Background

Thermal & non-thermal universe

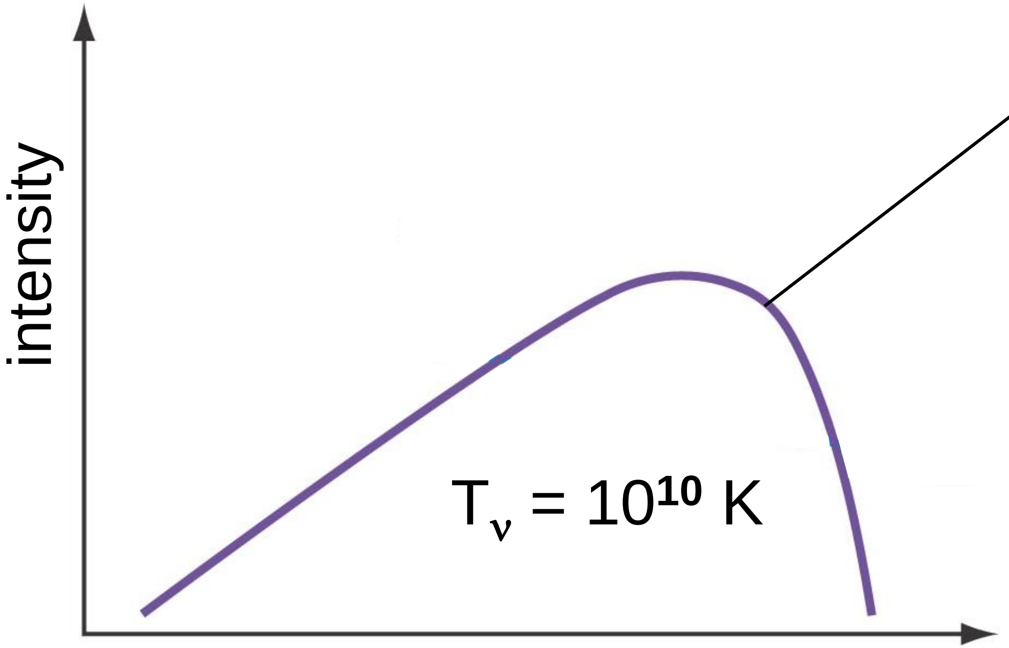
Karlsruhe Institute of Technology

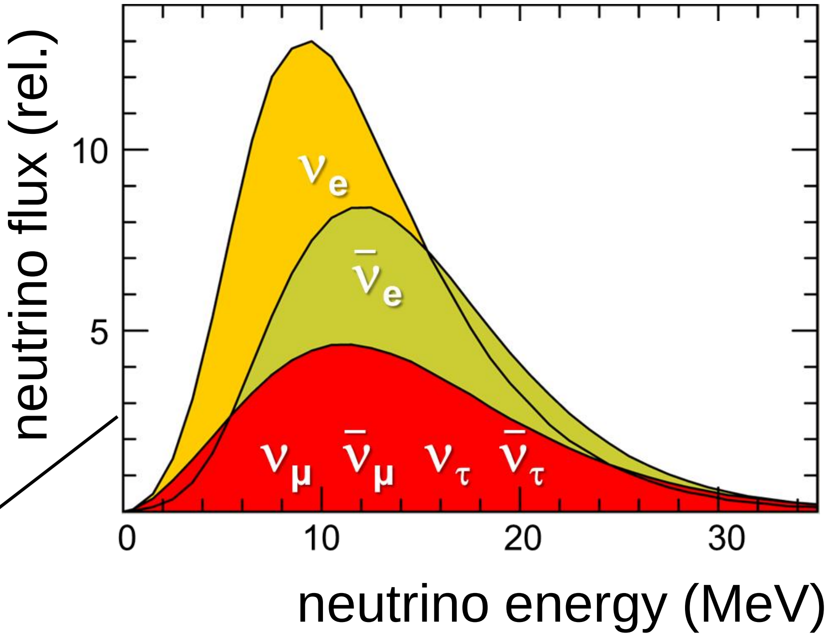
- **example from thermal universe: SN-neutrinos**
  - **S**uper-**N**ova neutrinos are emitted from the extremely hot core of a SN-explosion



Q: ORNL

inside a SN-core: thermal equilibrium



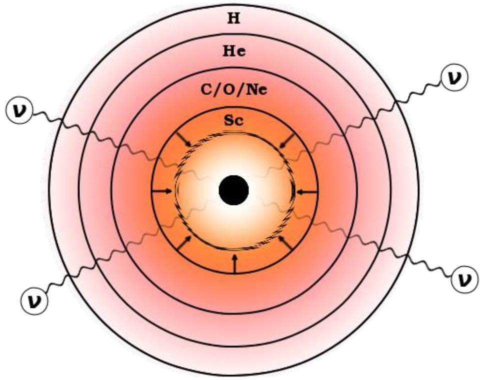


Q: G. Raffelt

Planck distribution

Q: redbubble

Thermal & non-thermal universe



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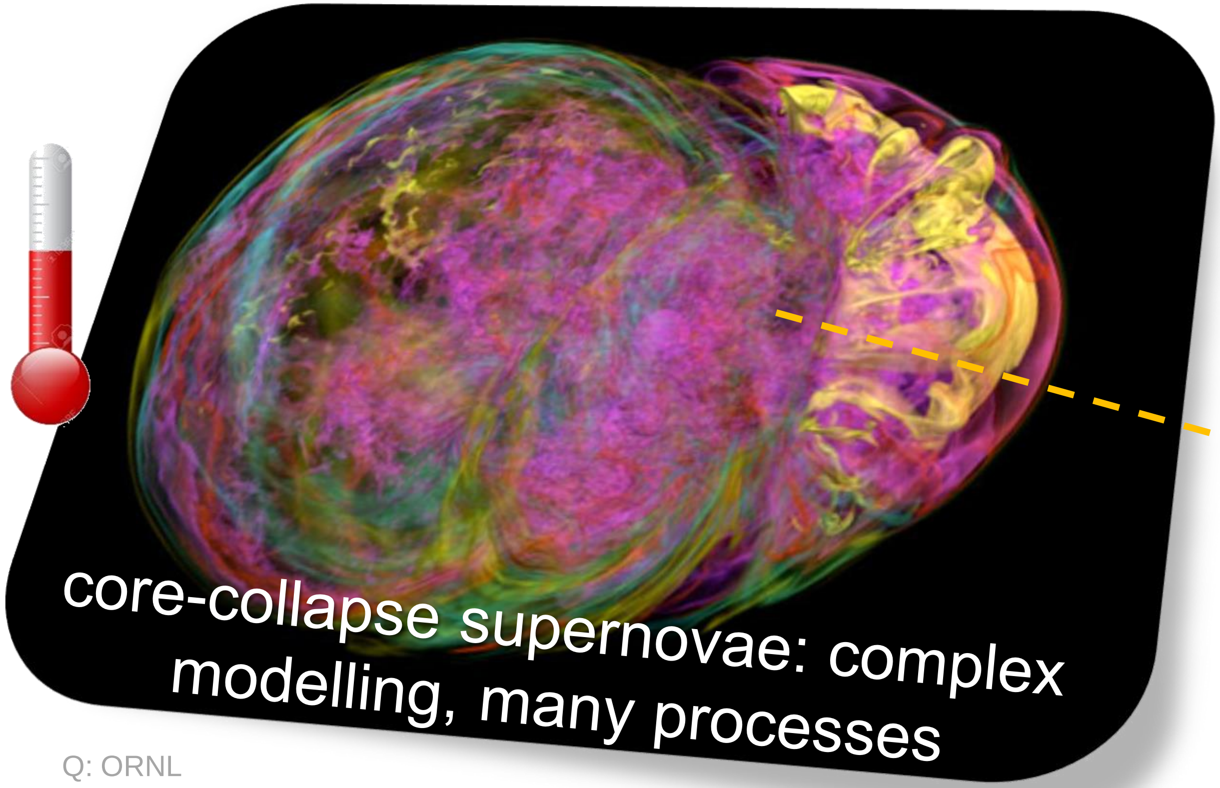
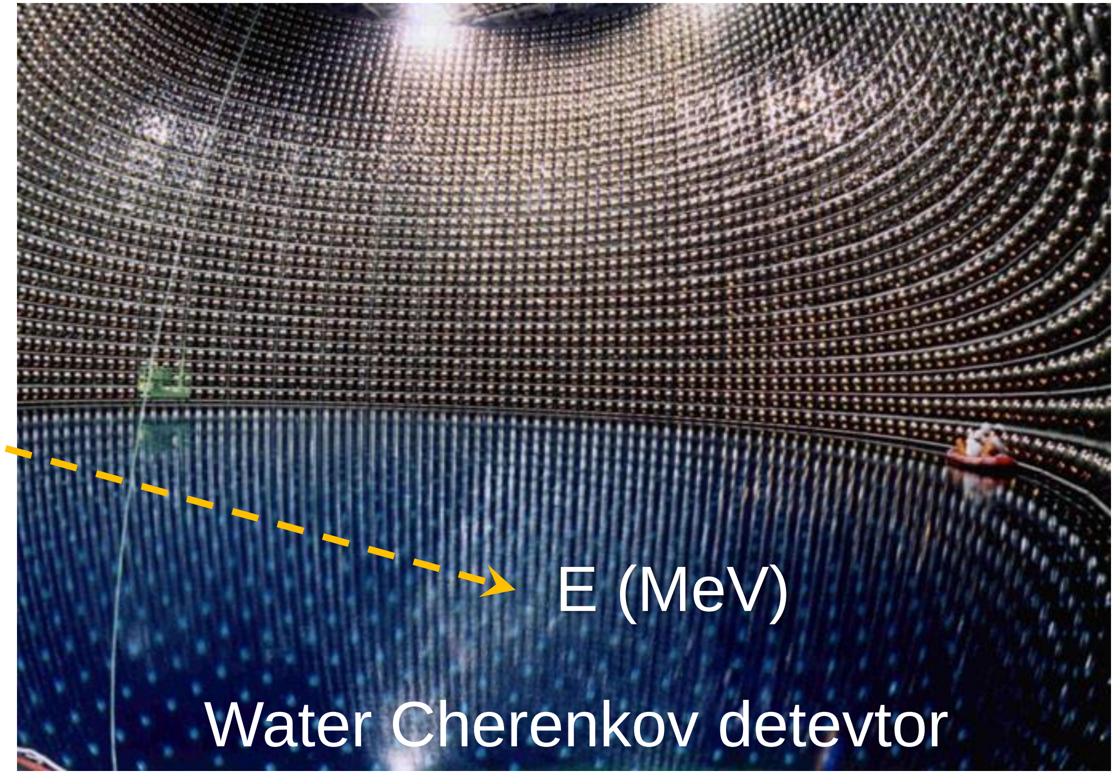
- **example from thermal universe: SN-neutrinos**
  - SN neutrinos have been detected via their interactions in a large water tank: energies match detailed SN-calculations



Q: ORNL



Q: ICRR

Thermal & non-thermal universe

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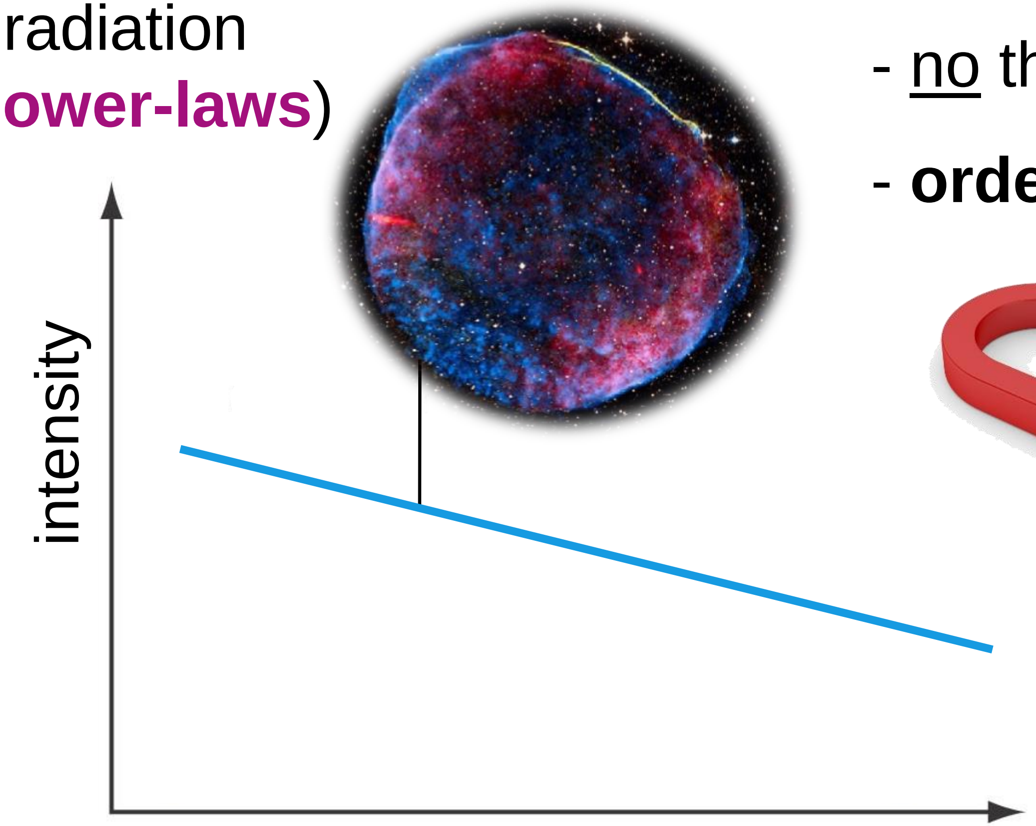
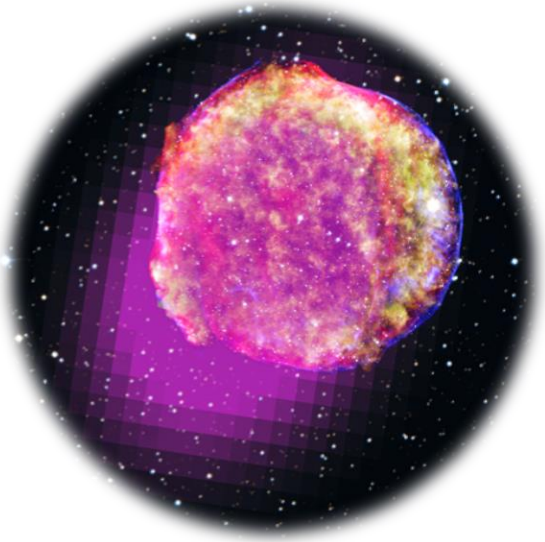
- **example from non-thermal universe: emission of synchrotron- & γ-radiation**

synchrotron radiation
(non-thermal, **power-laws**)

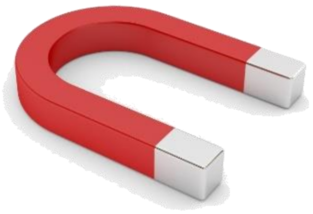




TeV-gammas

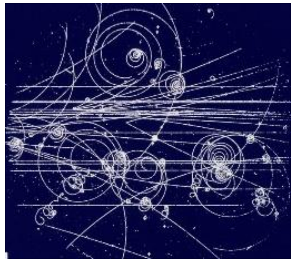
frequency

- no thermodynamical equilibrium
- **order parameters**: **B**, **ρ**, **E_0**



B

density ρ



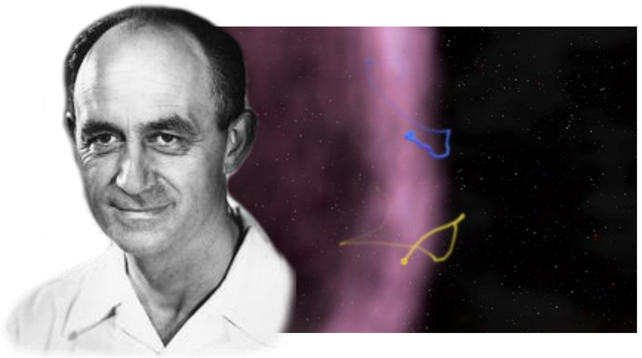
maximum energy **E_0**

Q: ESA, NASA

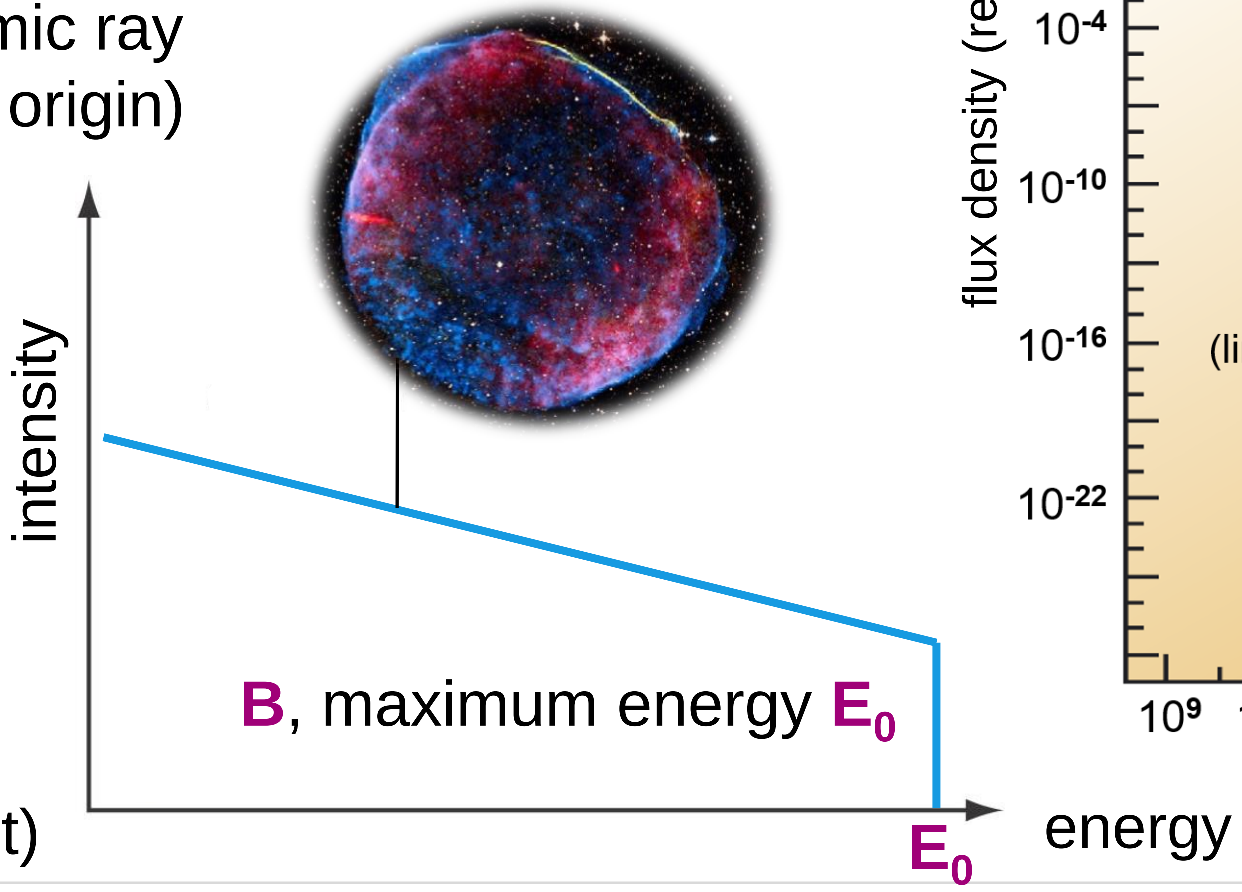
Thermal & non-thermal universe

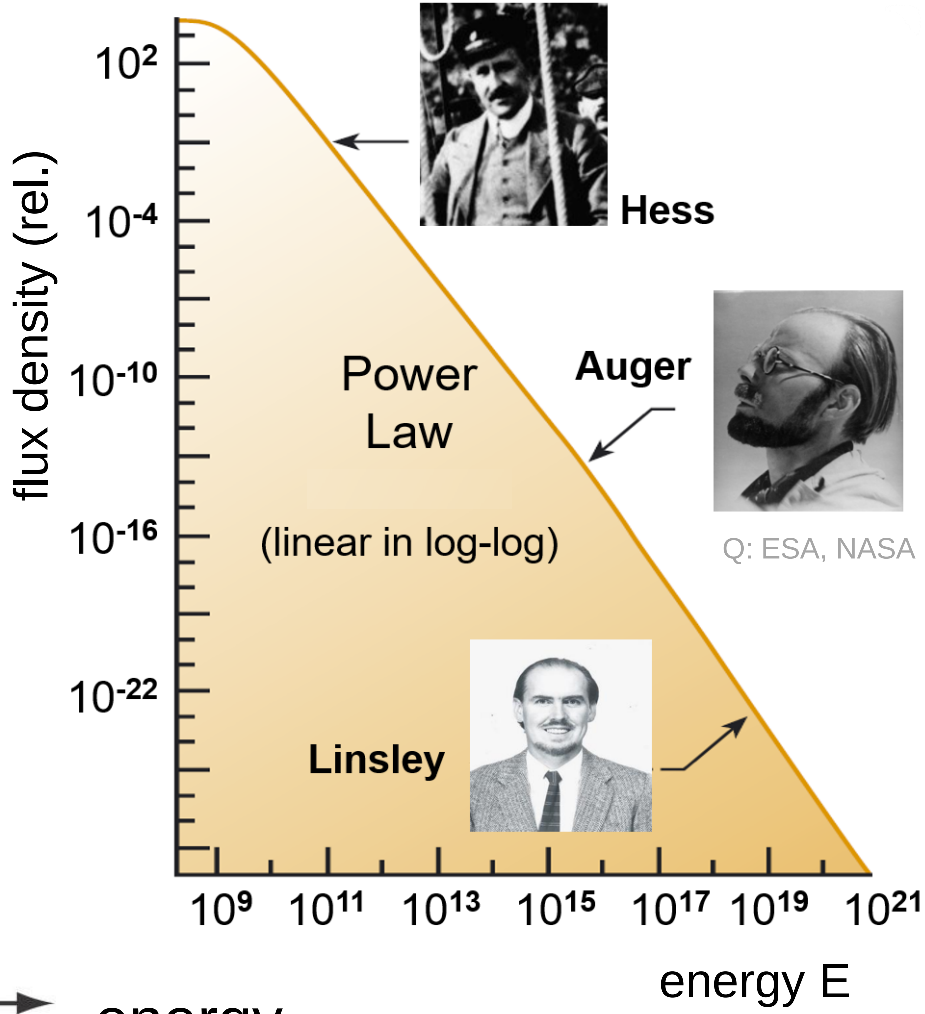
- **example: power law spectrum of cosmic rays**

charged cosmic ray
(non-thermal origin)



Fermi accleration mechanism (Hillas plot)

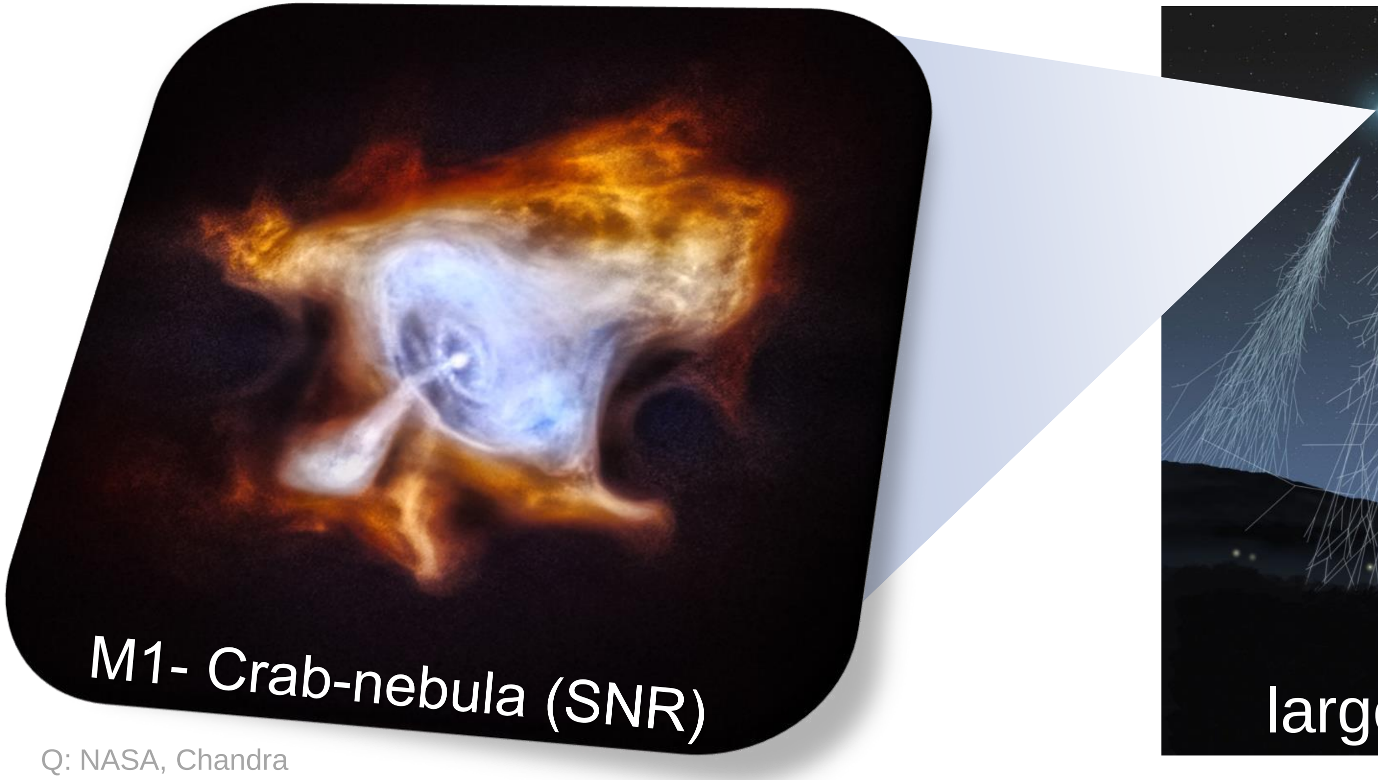




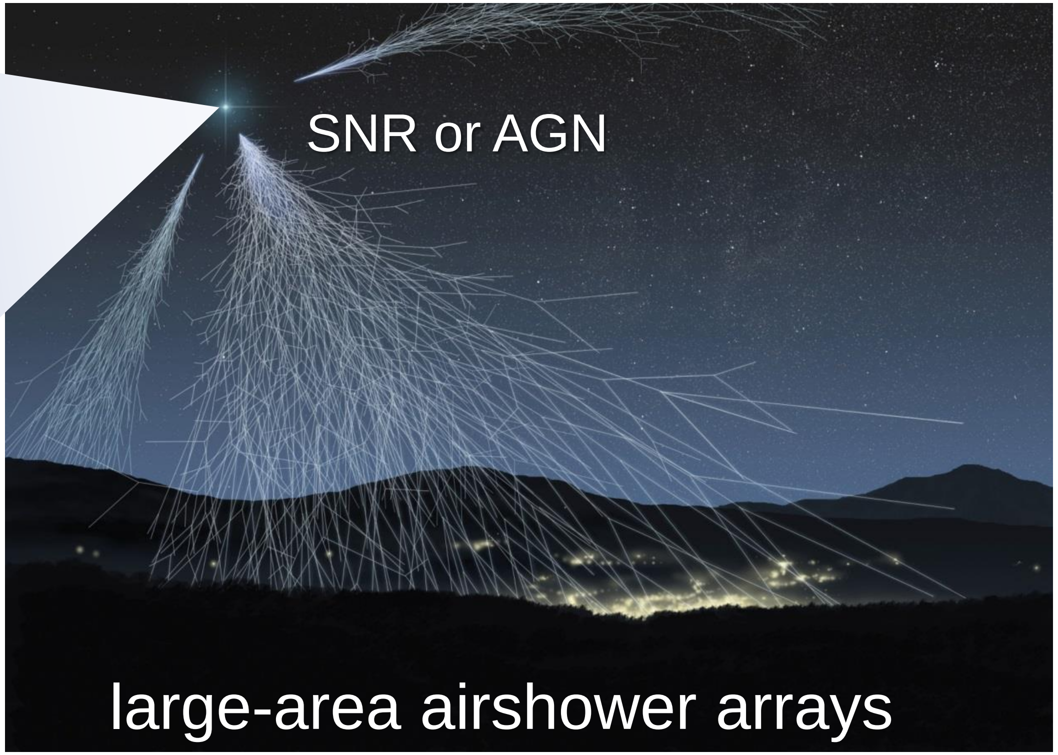
Thermal & non-thermal universe

- **example: air showers induced by charged cosmic rays**

  - sources: cosmic accelerators (galactic, extra-galactic)



Q: NASA, Chandra

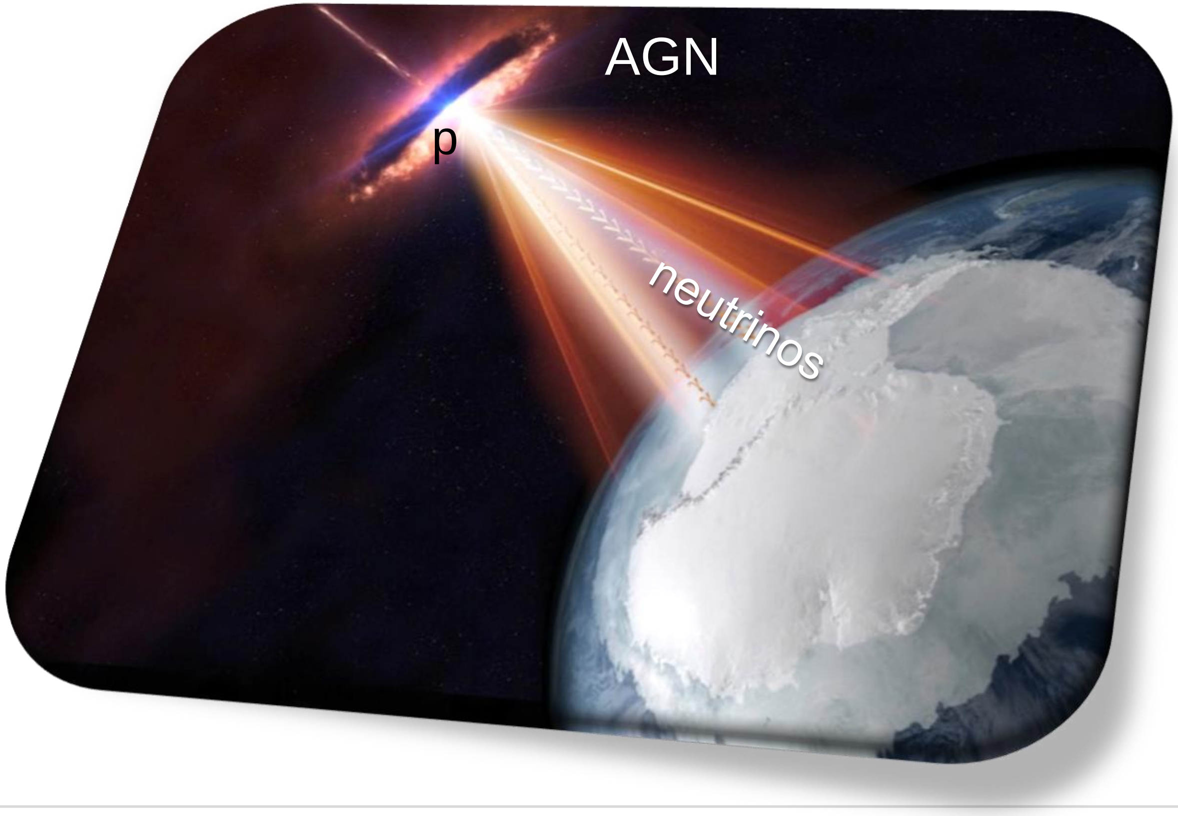


Q: Welt der Physik

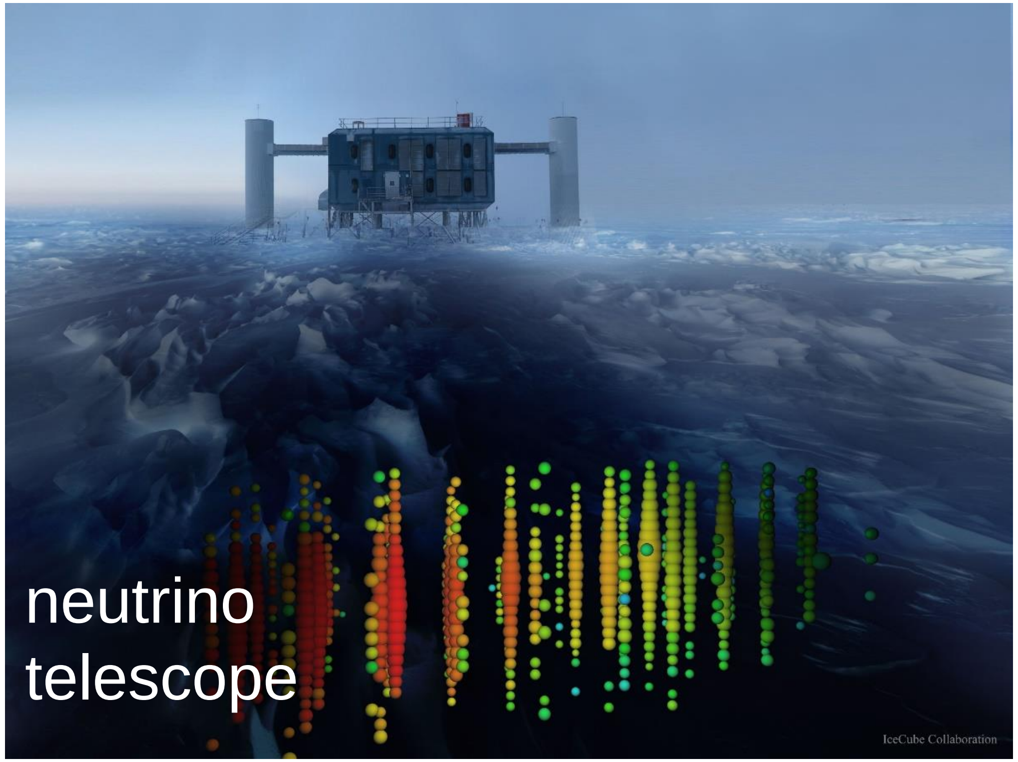
Thermal & non-thermal universe

- **example: Cherenkov light from µ´s induced by ultra-high energy neutrinos**

  - sources: cosmic accelerators (extra-galactic origin)



Q: IceCube, NASA



Q: IceCube, NSF

Thermal & non-thermal universe

- **example: Cherenkov light from showers induced by TeV gamma rays**

  - sources: cosmic accelerators (galactic, extra-galactic)

Q: NASA/Fermi

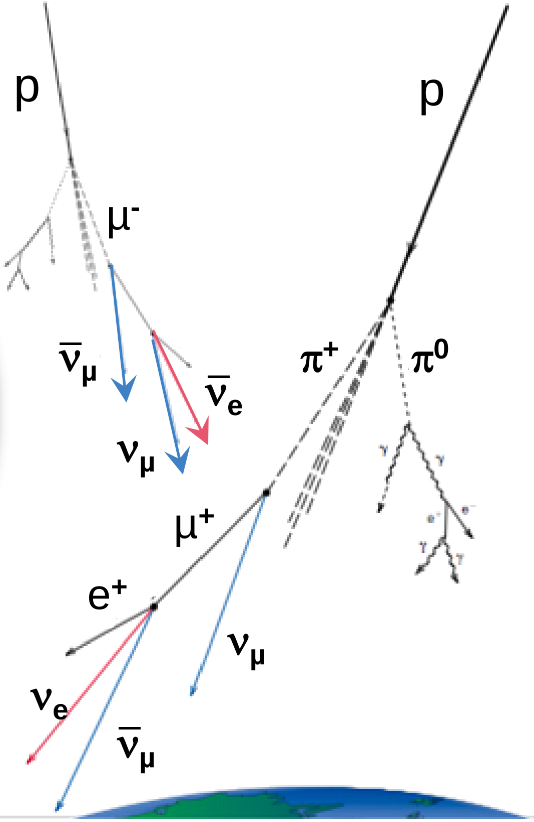
Q: H.E.S.S. Collab.

Thermal & non-thermal universe

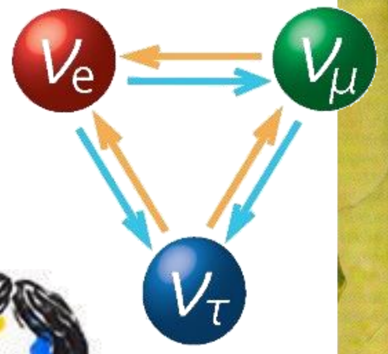
- example: atmospheric ν´s (GeV, TeV) from showers in atmosphere

  - sources: decay sequence of pions during cascades

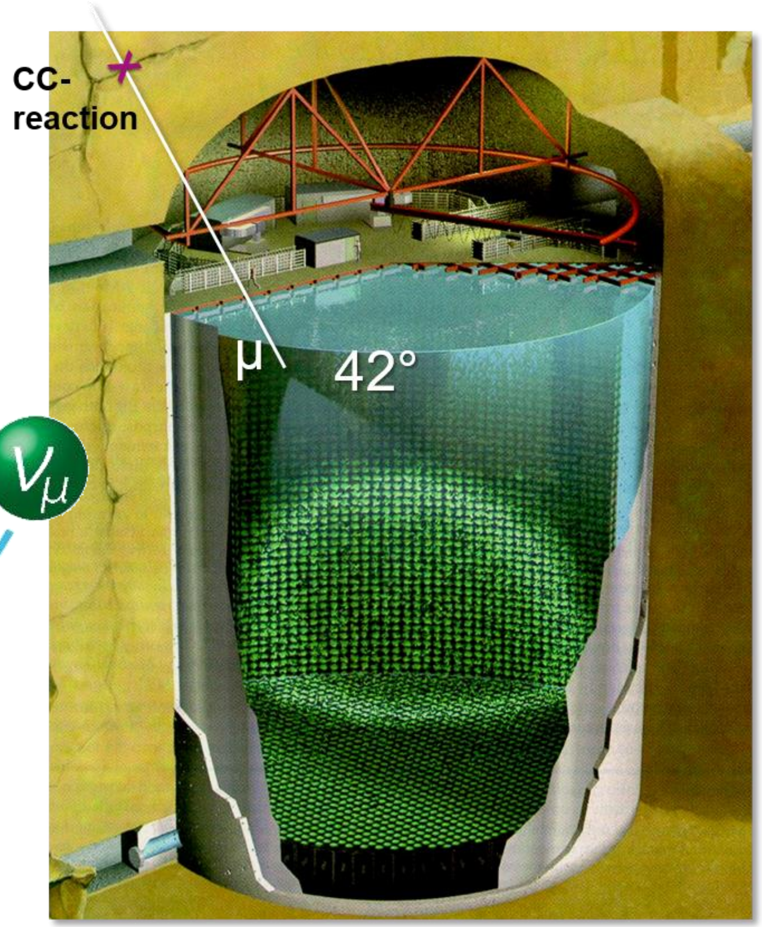
Q: NASA



Q: Los Alamos



T. Kajita

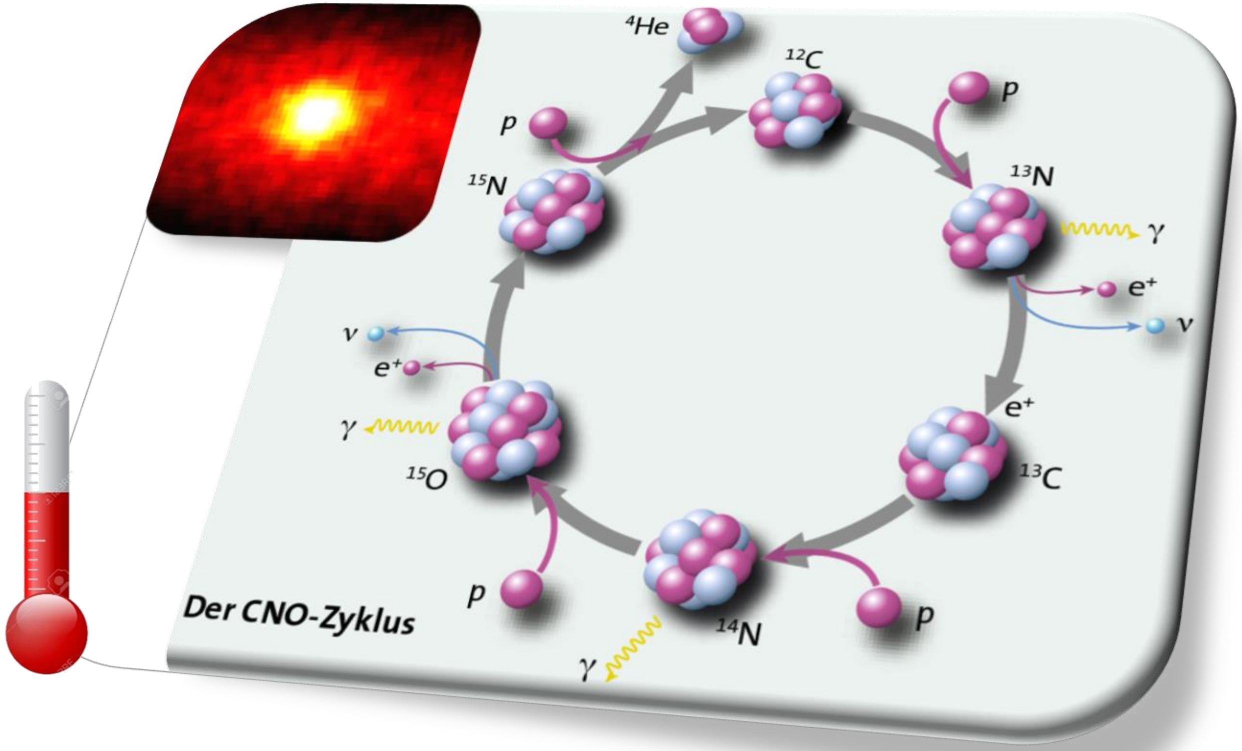


Q: Scientific American

Thermal & non-thermal universe

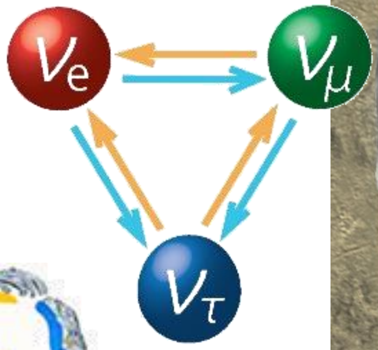
- example: solar ν´s (MeV) from nuclear reaction chains in the core of the sun

- sources: pp & CNO fusion chains

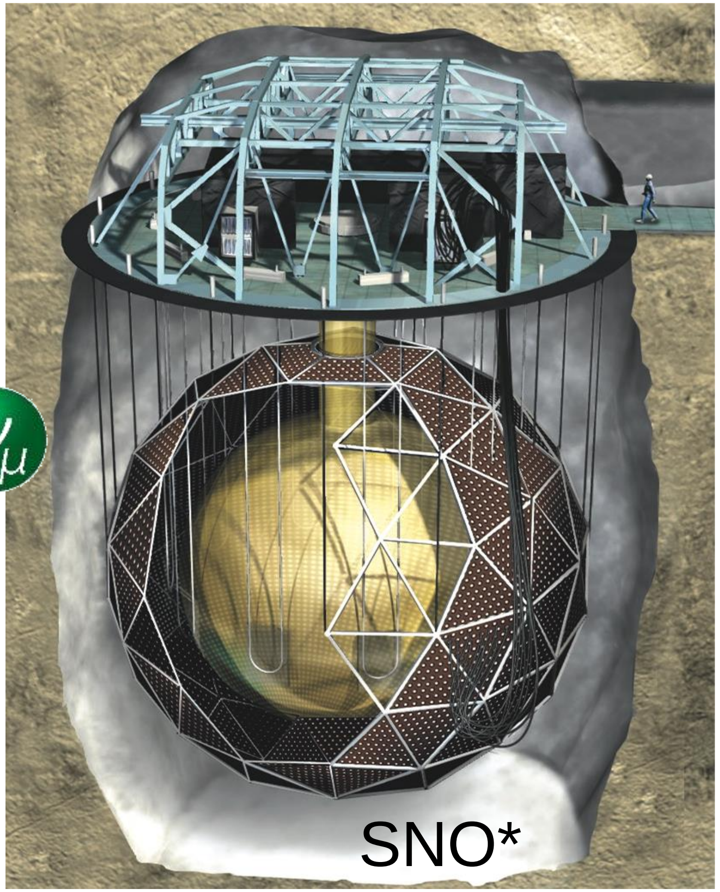


rate depends on T of core

Q: spektrum



A. McDonald



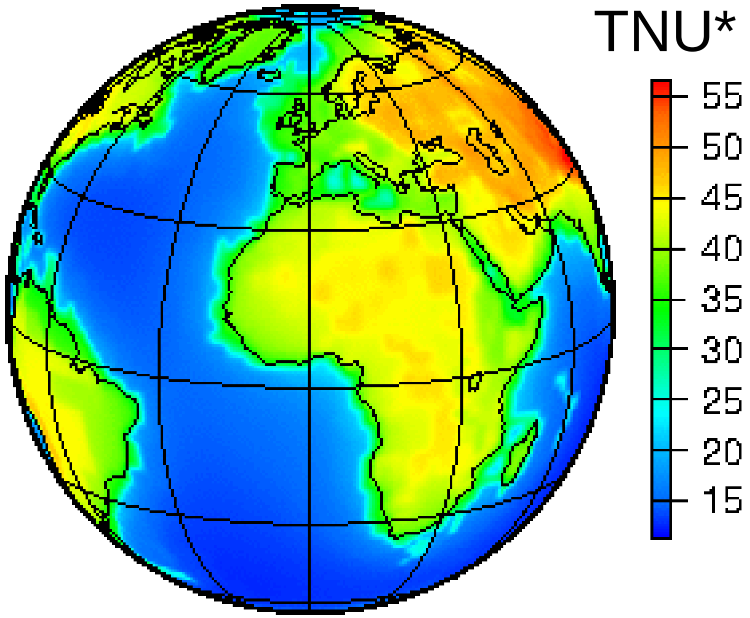
Q: SNO+ Collab.

* **S**udbury **N**eutrino **O**bservatory

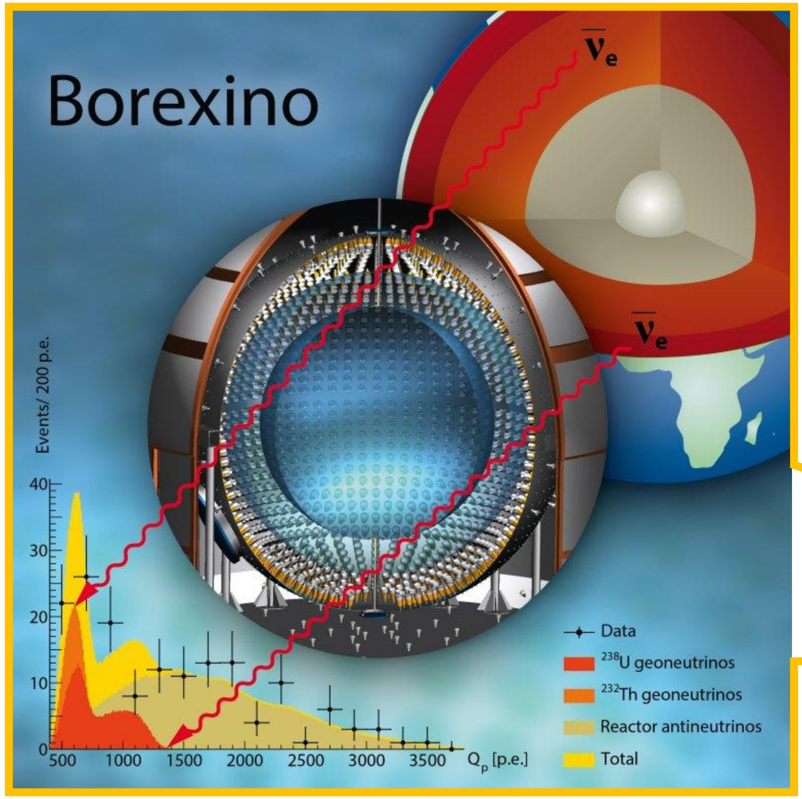
Thermal & non-thermal universe

- **example: geo-ν´s (MeV) from the crust, mantle & core of the earth**

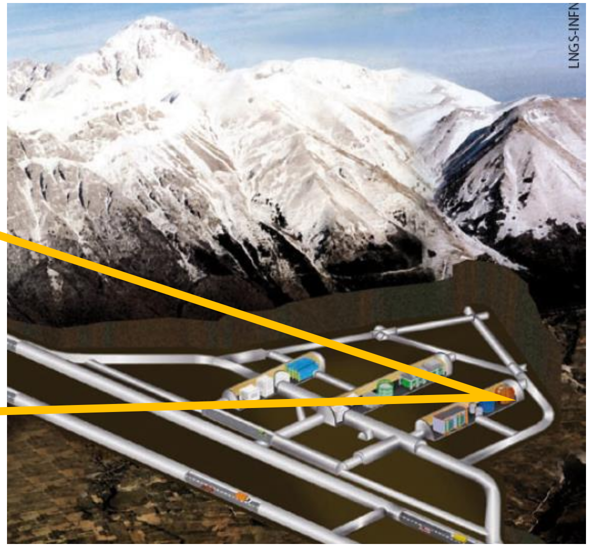
  - source: ß-decays of unstable isotopes (4 long-lived α-decay chains)



Q: O. Šrámek



Q: Borexino Collab.



Q: LNGS

* **T**errestrial **N**eutrino **U**nit

Thermal & non-thermal universe

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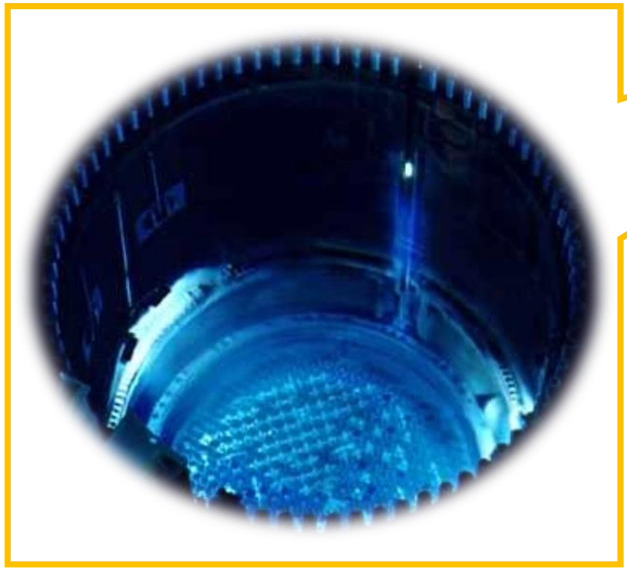
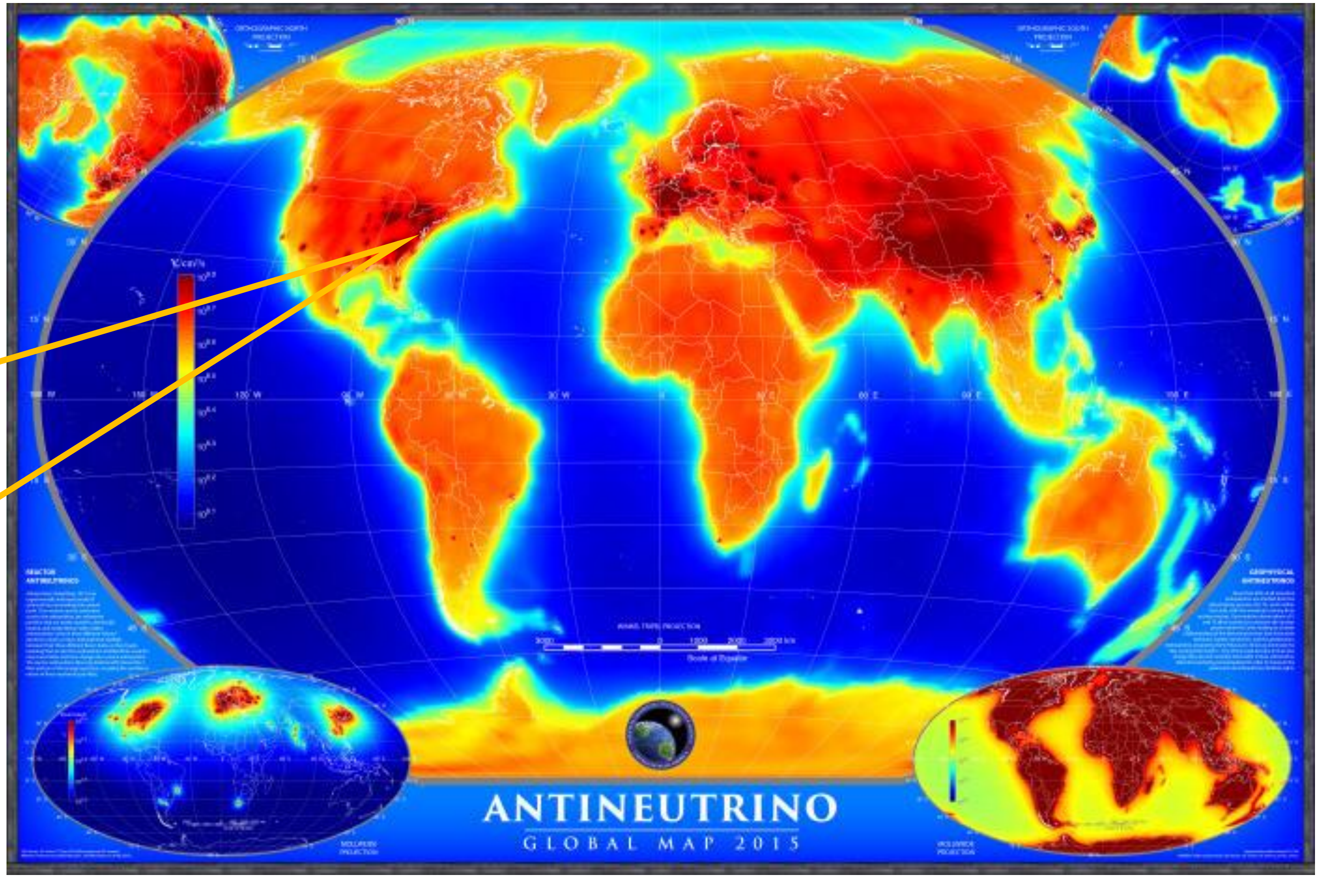
- **example: geo-ν´s & reactor ν´s (MeV) from the earth & nuclear reactors**

  - source: ß-decays of unstable isotopes (long-lived decay chains)

Q: Nature



Q: C. Bell

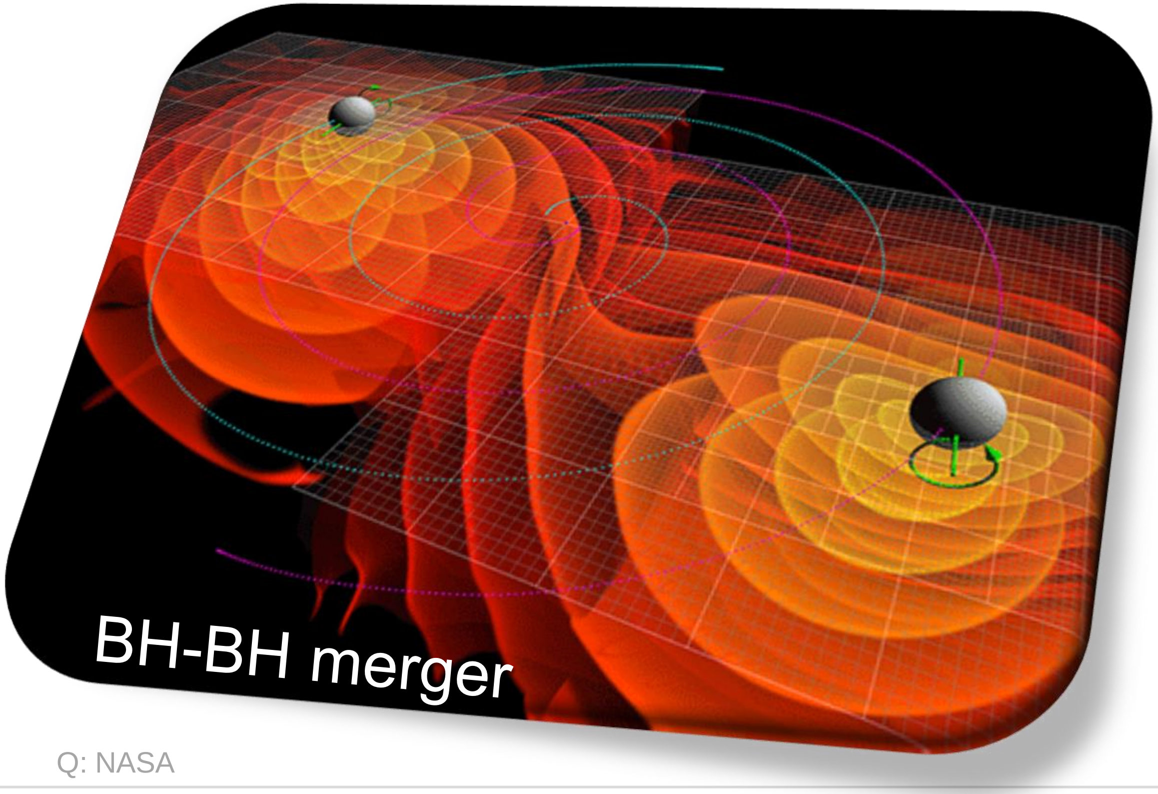


Q: NGA

Thermal & non-thermal universe

- **example: gravitational waves from the merger of compact stellar objects**

  - source: late-phase mergers of compact binary objects (black holes,…)



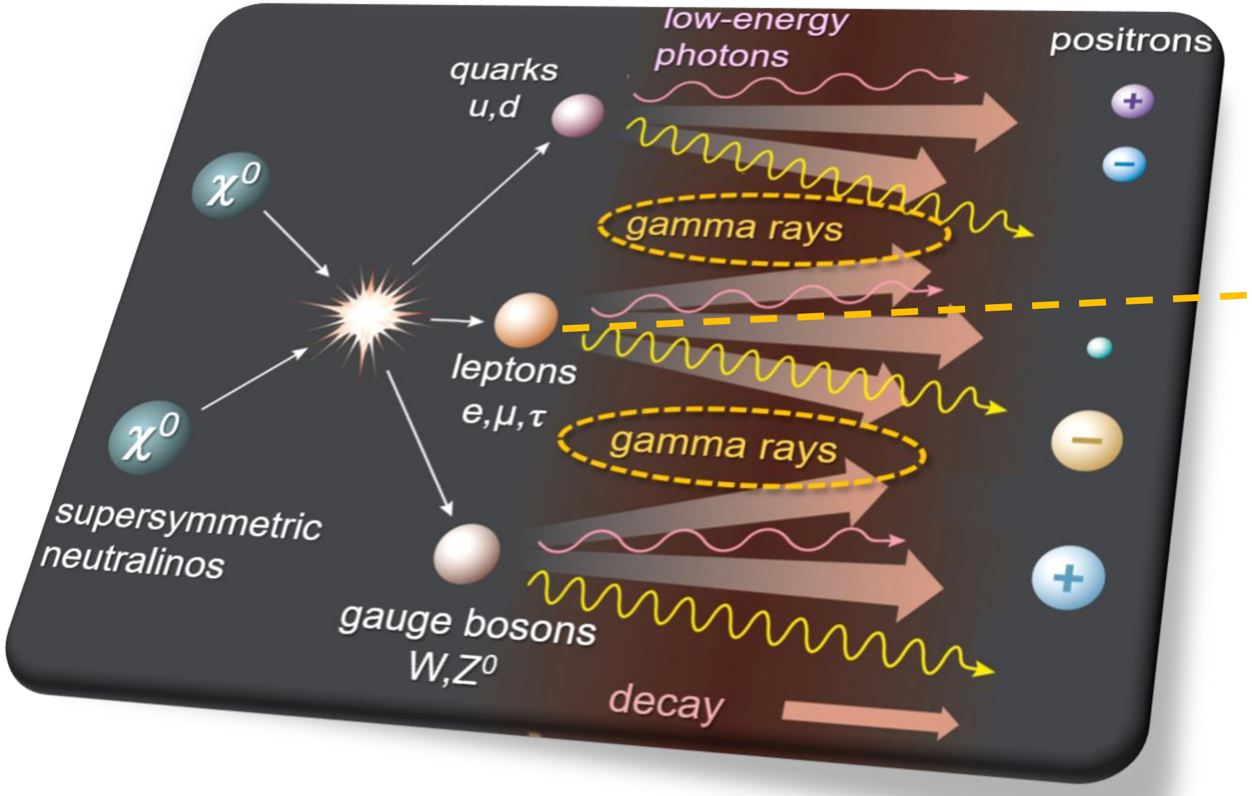
Q: NASA

Q: LIGO

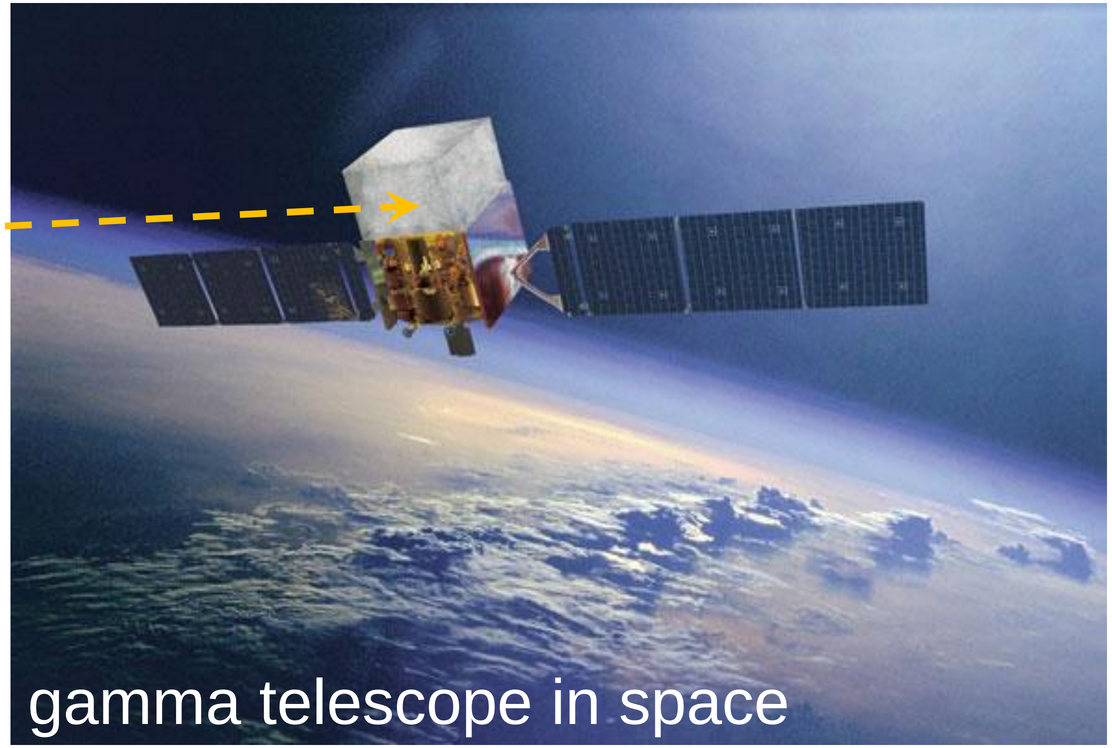
Particle radiation from the dark universe

- **example: messenger particle-radiation from WIMP* annihilation processes**

- source: halo of dark matter particles (GeV, TeV scale) in our galaxy



Q: sky and telescope



gamma telescope in space

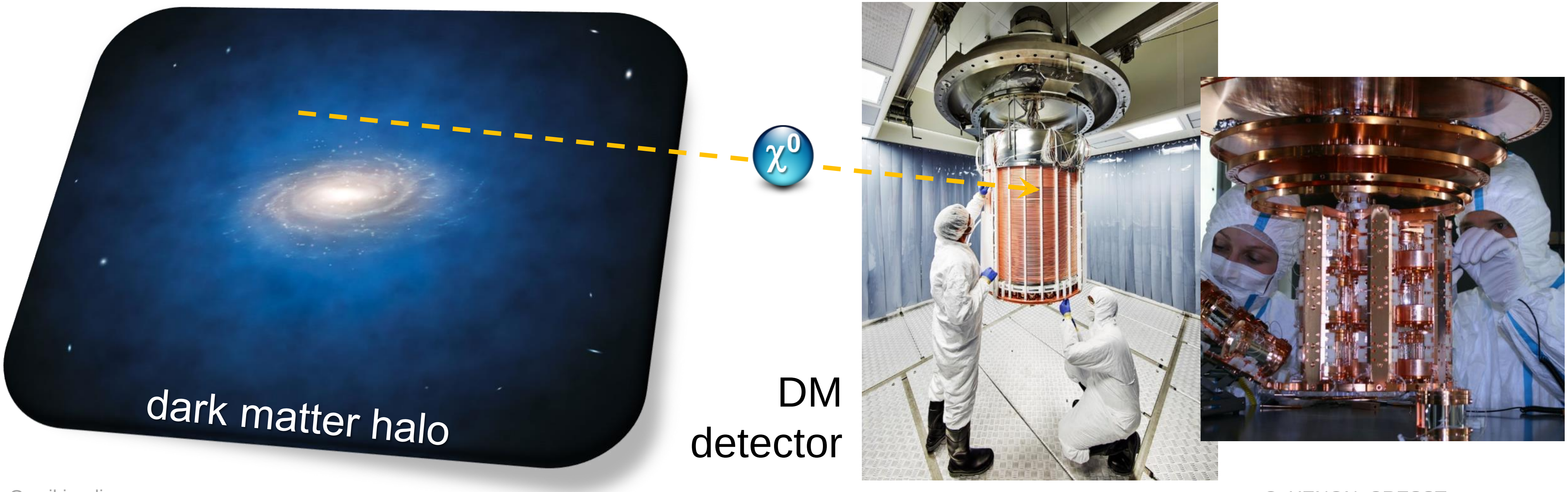
Q: NASA

***WIMP** = **W**eakly **I**nteracting **M**assive **P**article

Particle radiation from the dark universe

- **example: scattering processes of WIMPs (GeV-TeV) in an underground lab**

  - source: dark matter particles from galactic halo, with Earth moving through it



Q: wikipedia

Q: XENON, CRESST

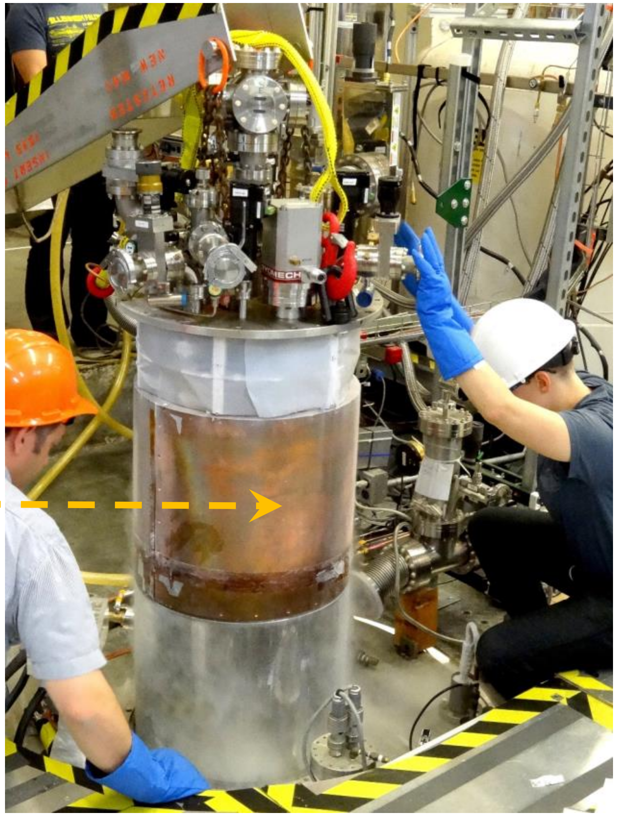
Particle radiation from the dark universe

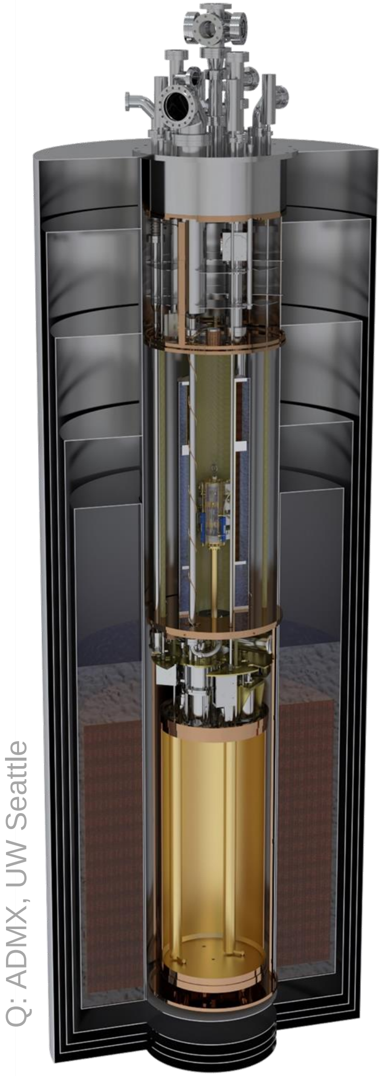
- **example: conversion processes of WISP*s (sub-eV)**

  - source: very light dark matter particles from galactic halo

Q: wikipedia

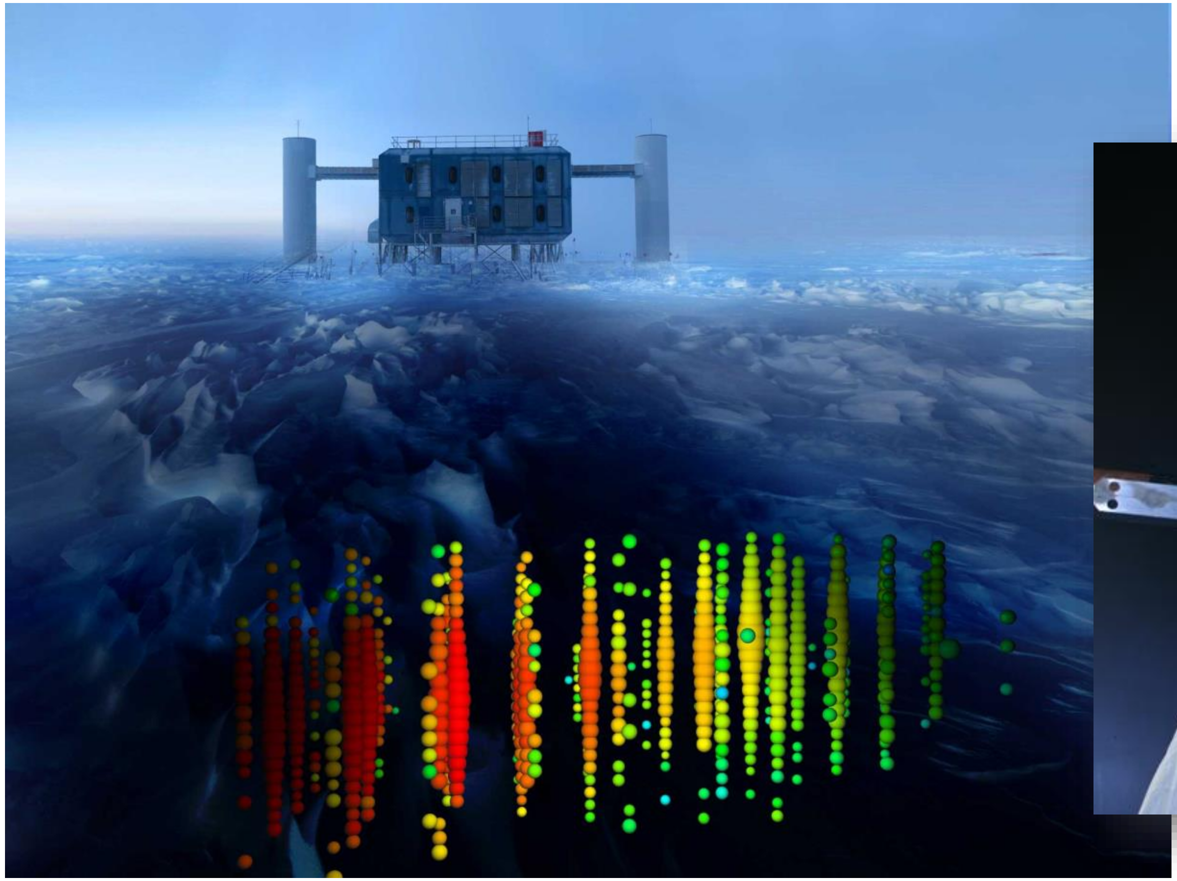
DM detector





Q: ADMX, UW Seattle

*WISP = Weakly Interacting Slim Particle (axions,…)

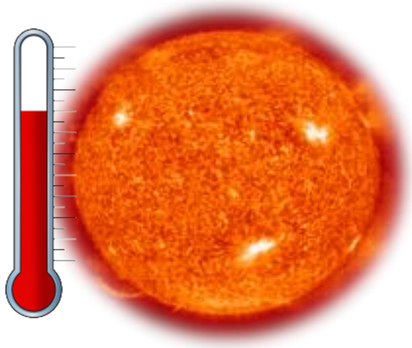


Q: IceCube, CRESST

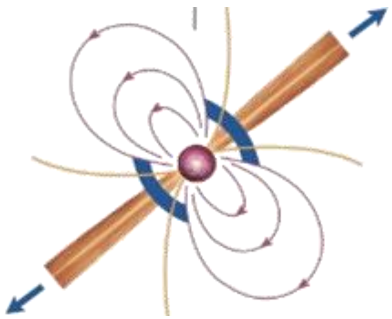
CHAPTER 2 – EXPERIMENTAL METHODS

2.1 Multimessenger methods

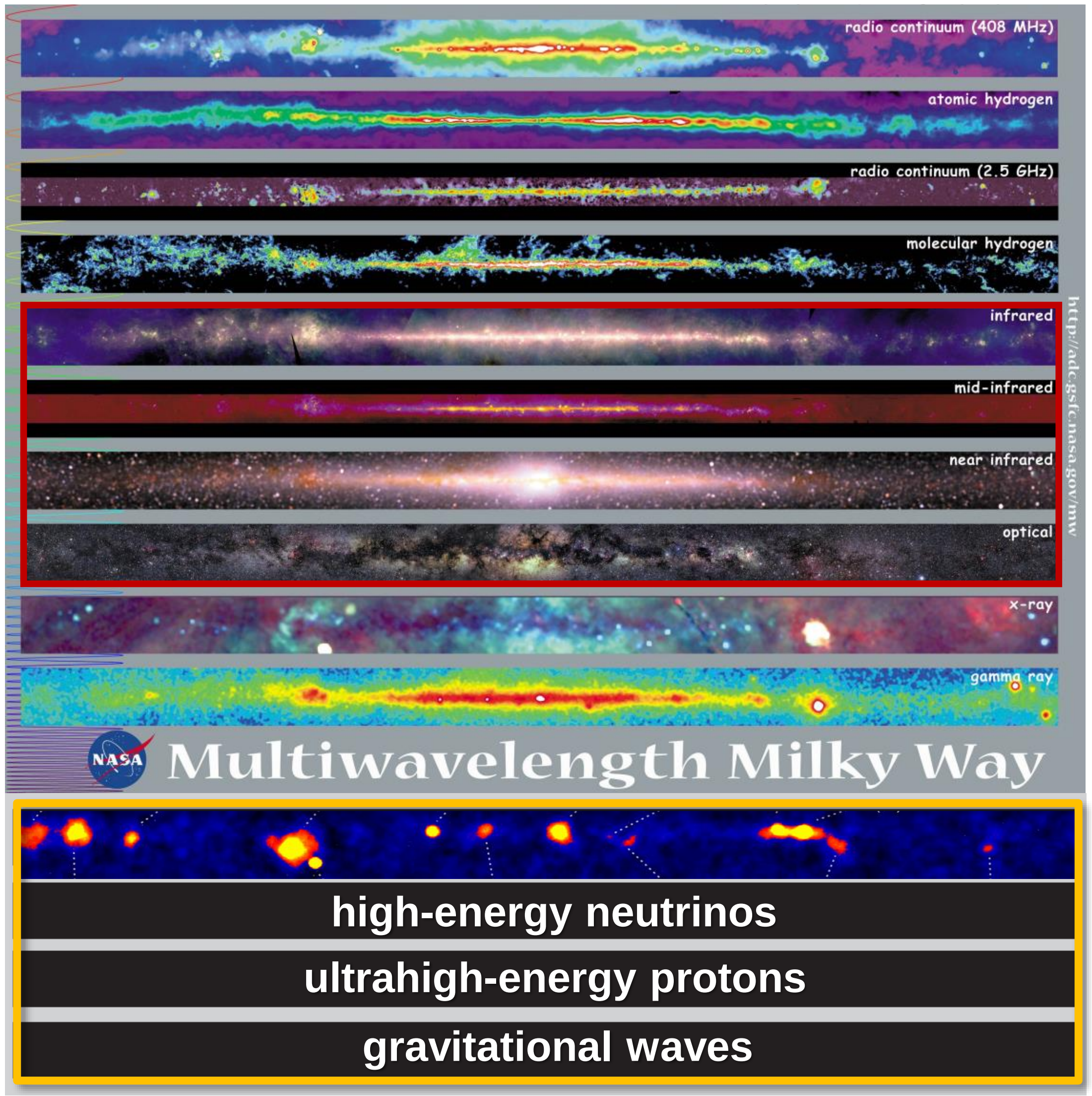
- overview of particle radiation from the universum – from μeV… TeV & beyond



thermal universe:
stars, molecular clouds,
dust (T = 10 – 10^5 K)

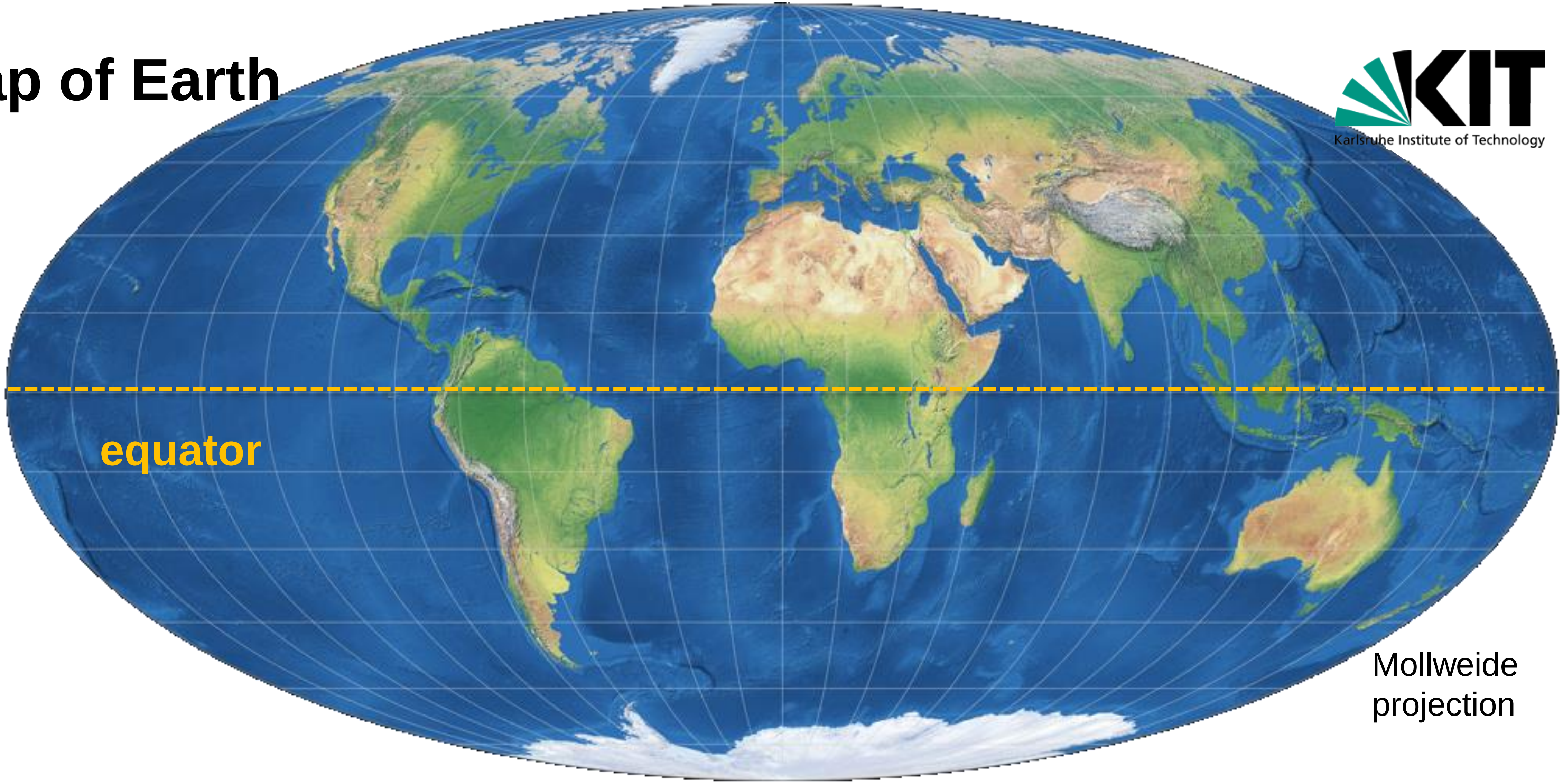


non-thermal universe:
shockfronts of Supernovae,
pulsars, black holes, compact
binary objects, … ?



Q: NASA

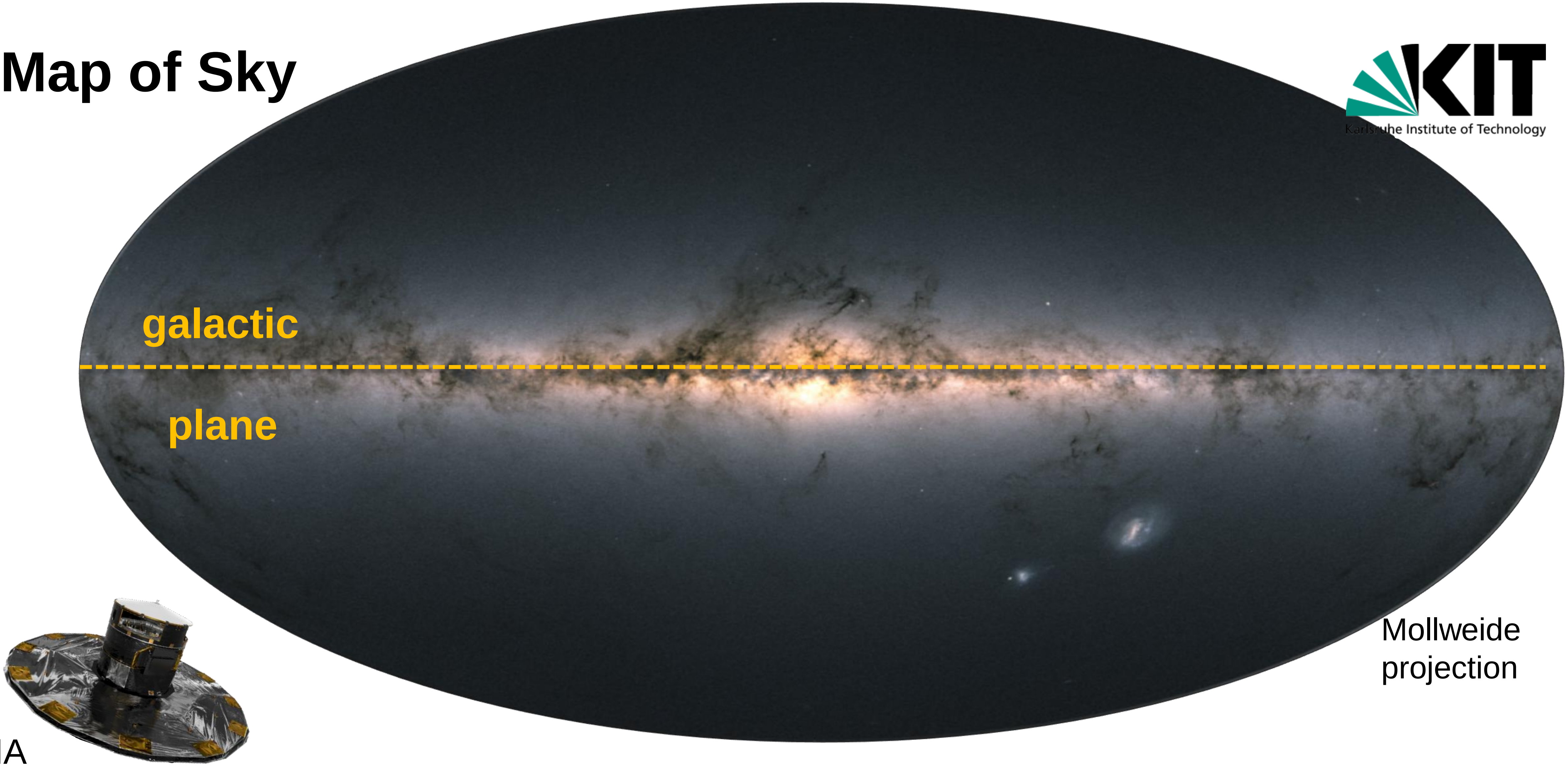
Map of Earth



Display of the sphere of the Earth in a Mollweide projection

Q: map-projections.net

Map of Sky



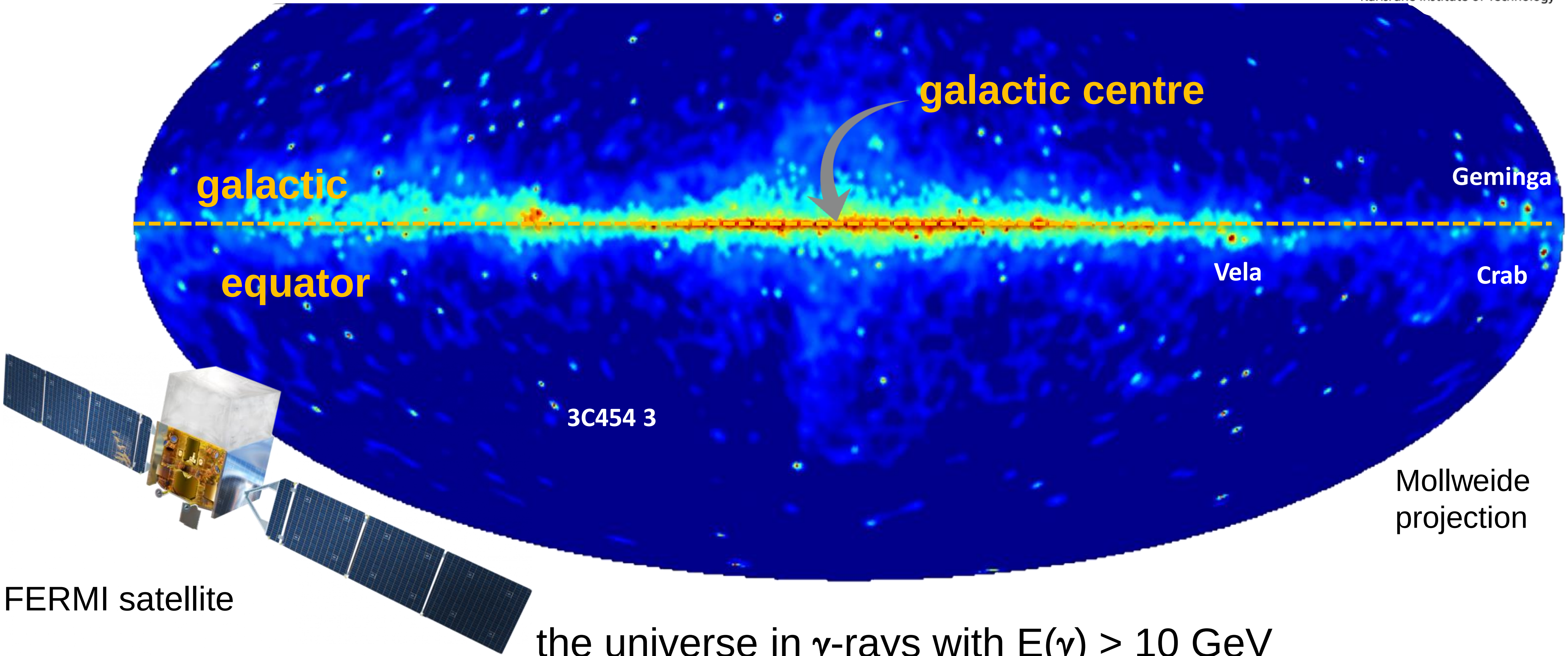
Mollweide projection

GAIA

display of the sky in visible light along the galactic plane

Q: GAIA

High-energy universe: example gamma rays



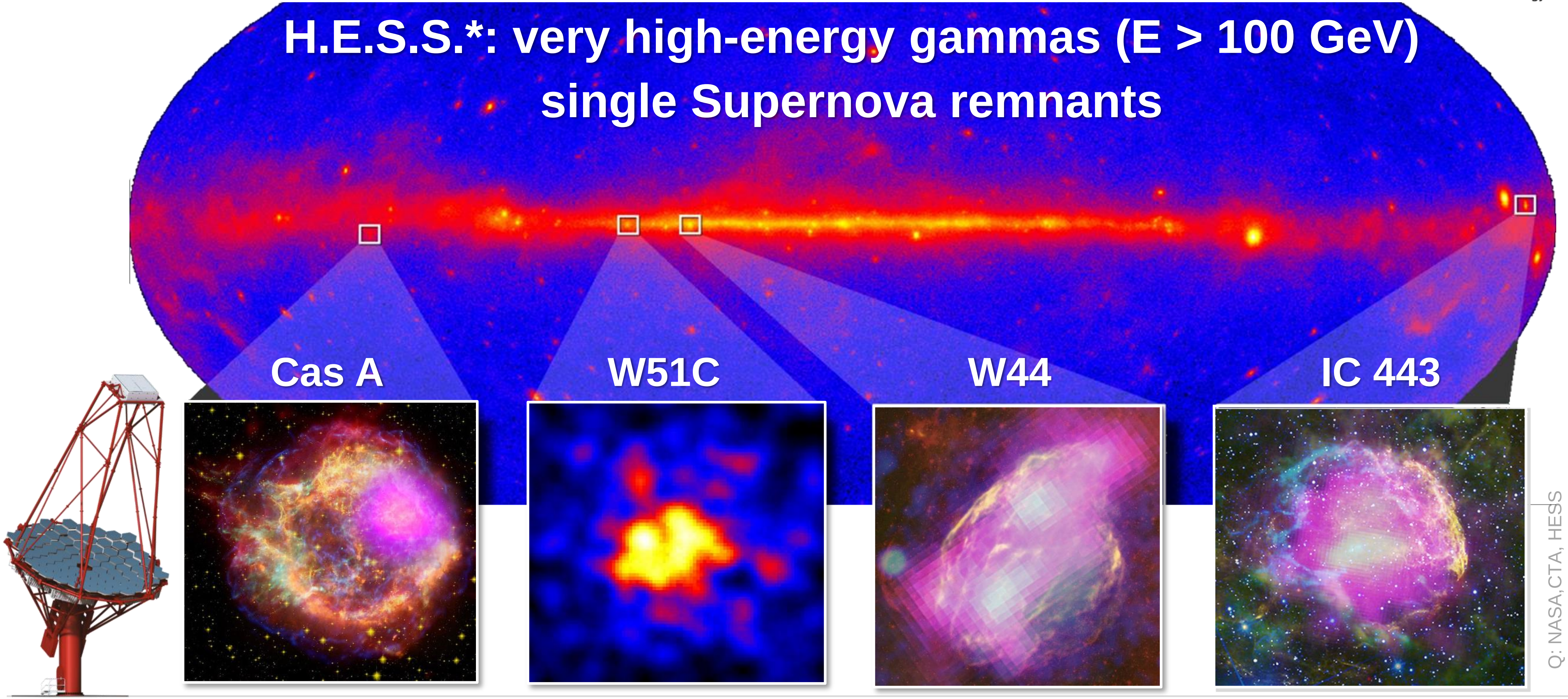
Mollweide projection

FERMI satellite

the universe in γ-rays with $E(\gamma)$ > 10 GeV

Q: NASA

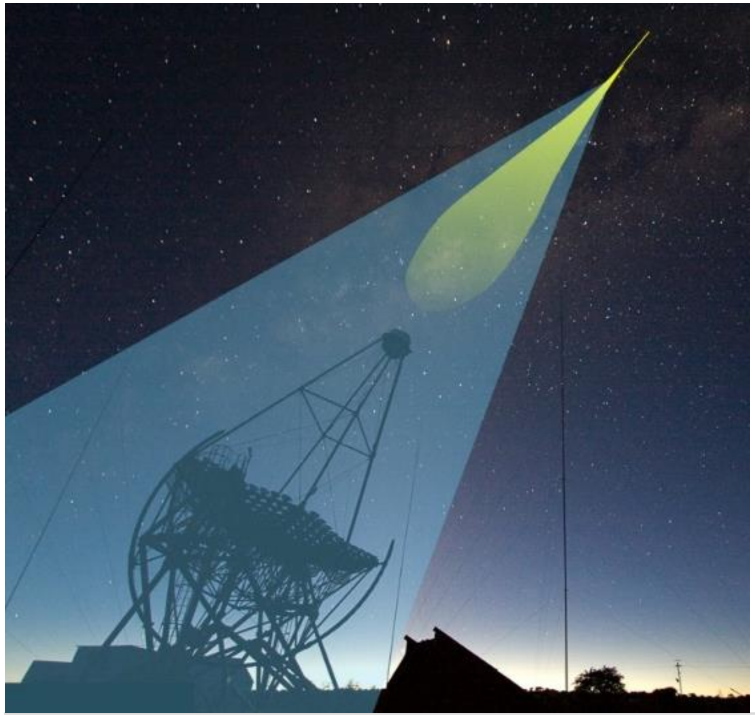
High-energy universe: example gamma rays

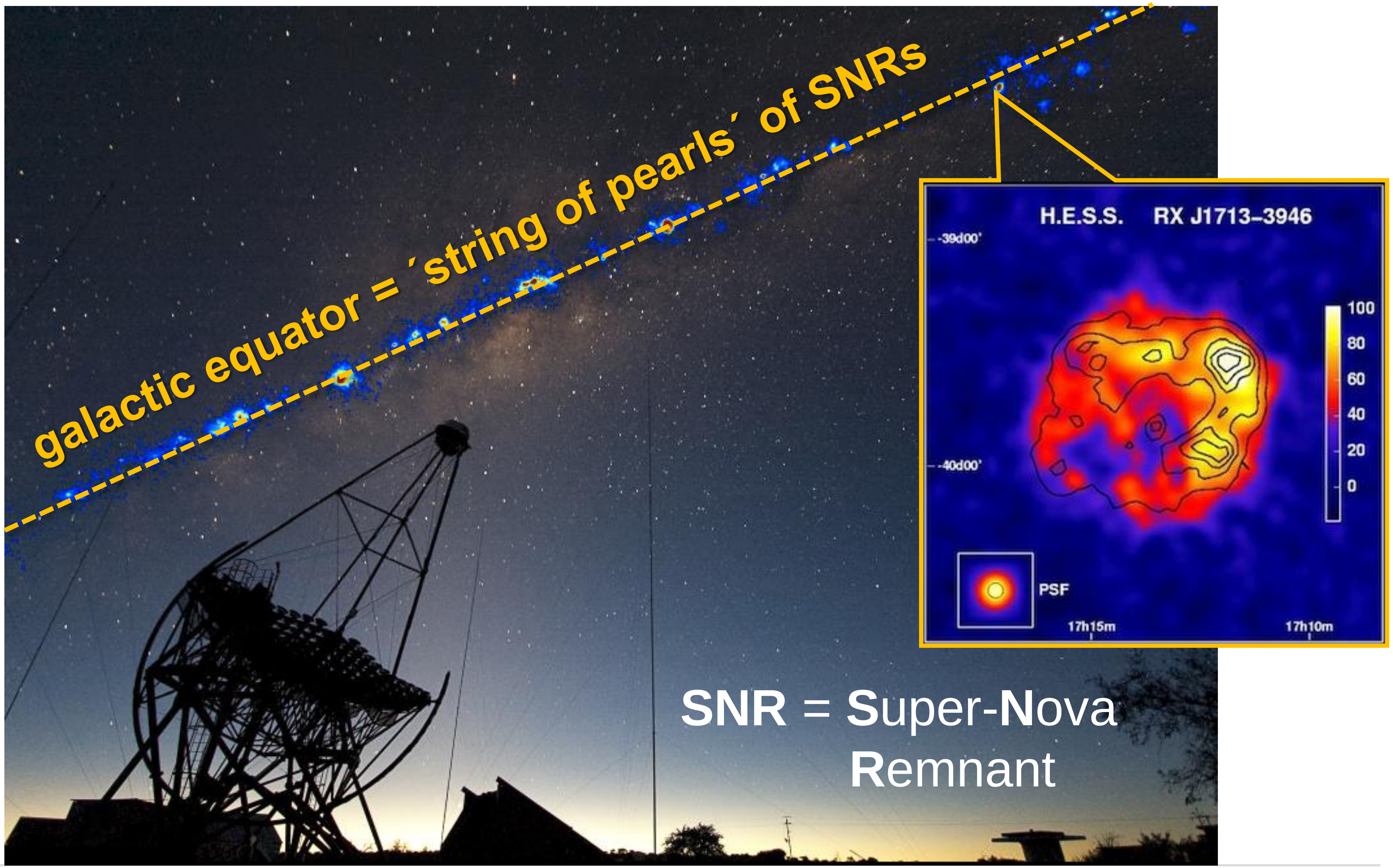


*H.E.S.S. = **H**igh **E**nergy **S**tereoscopic **S**ystem

High-energy universe: Cherenkov telescopes

- γ-telescopes at the surface: HESS, CTA*,…



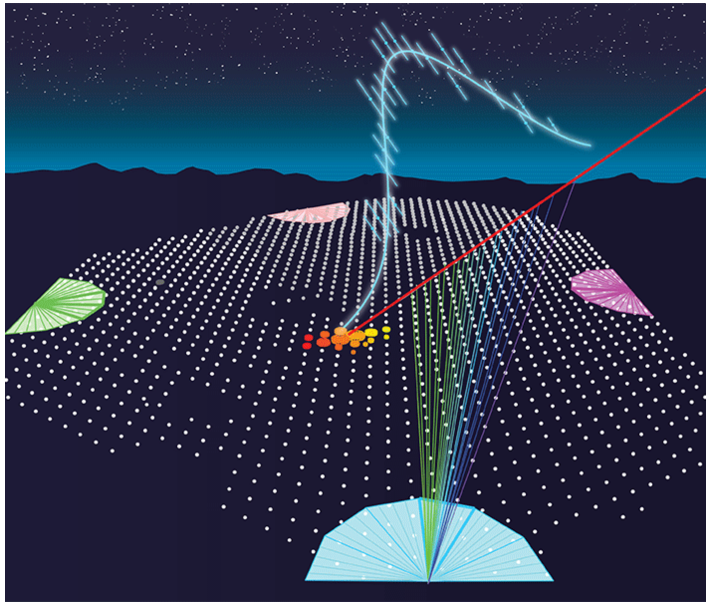


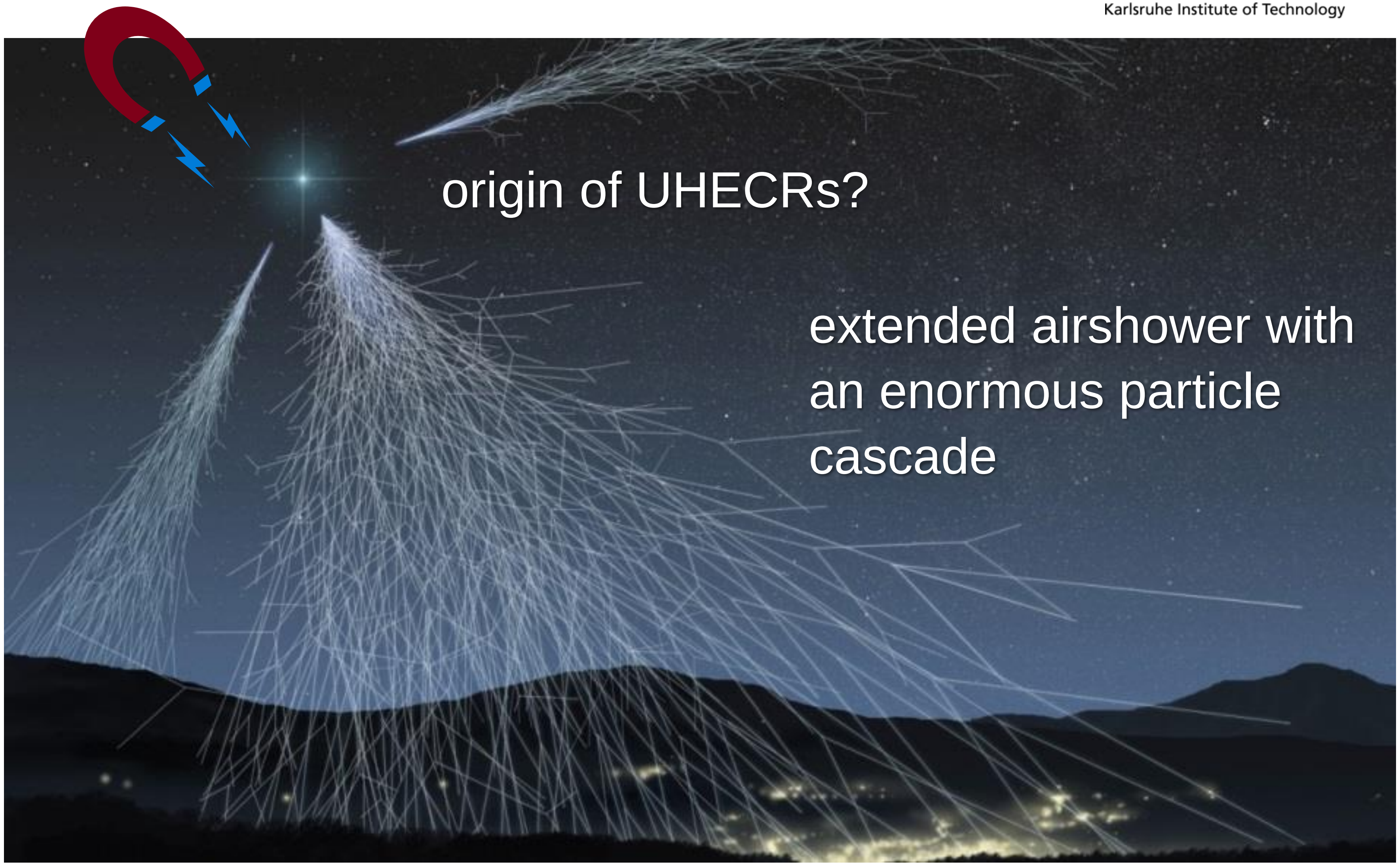
SNR = Super-Nova Remnant

*CTA = Cherenkov Telescope Array

High-energy universe: UHECR*s

- **giant airshower arrays at the Earth´s surface:** Pierre Auger Observatory





Q: APS Physics, APPEC

***UHECR = Ultra High Energy Cosmic Ray**

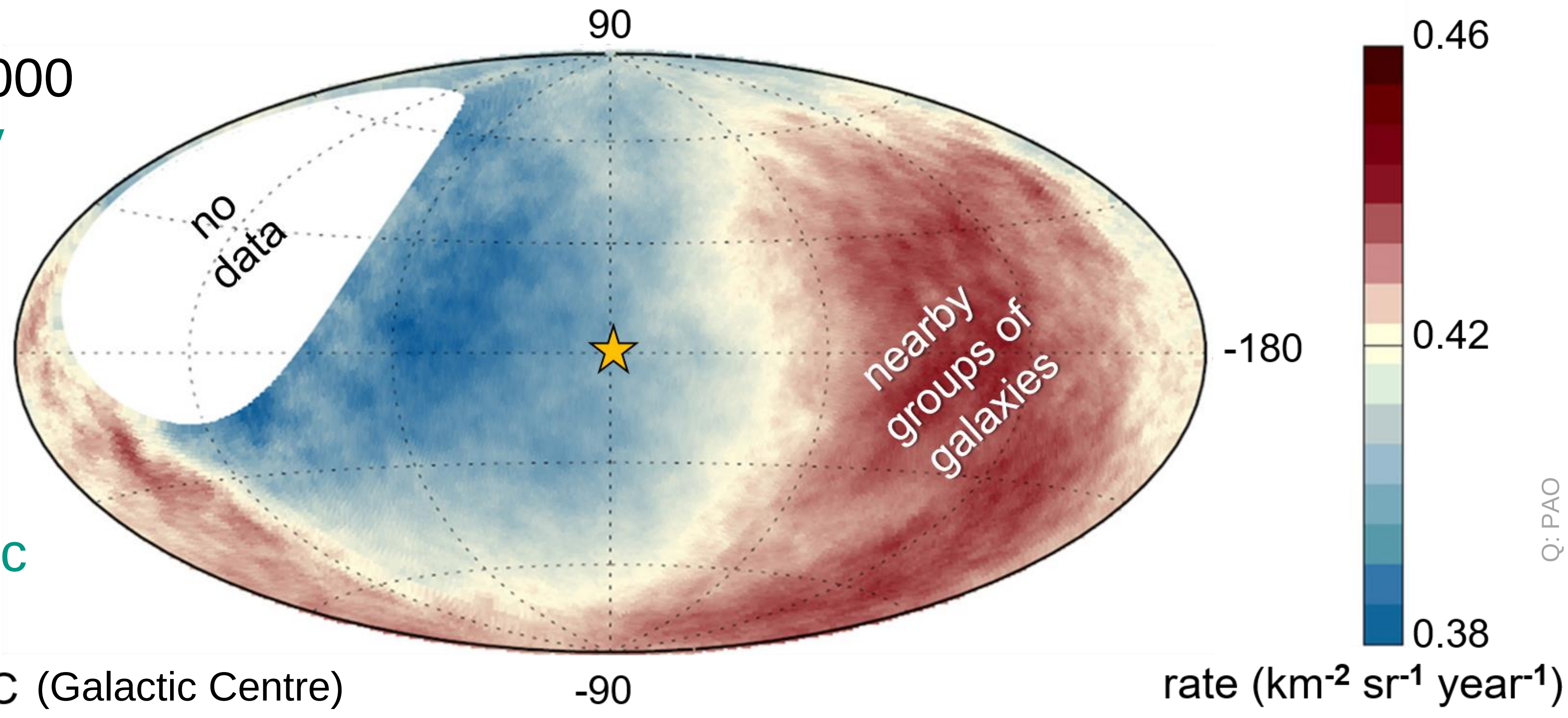
High-energy universe: UHECRs

- **extragalactic origin observed for the highest energies (above a few EeV*!)**

- Auger** observes a dipole anisotropy (~6%), now with stat. significance of **6.6 σ**

- ensemble of 30 0000 **UHECRs > 8 EeV**

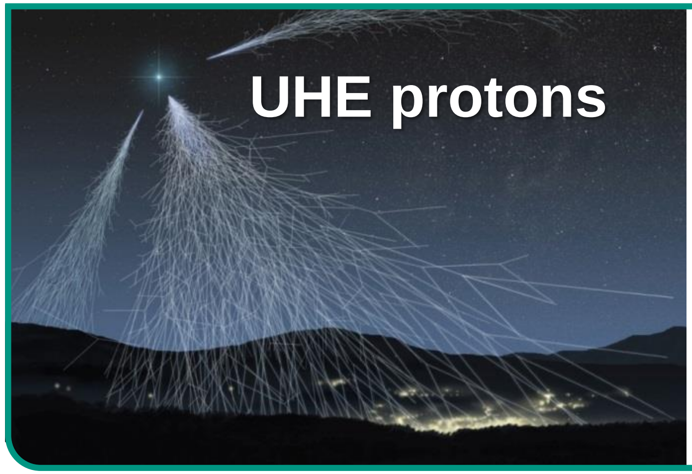
- 120° offset to galactic centre
  ⇨ extra-galactic origin of charged cosmic rays (EeV)



 *EeV = 10^{18} eV **Pierre Auger Observatory, Argent.

Hochenergie-Universum: UHECRs

- **how far can we observe the UHECRs with highest energies (few EeV)?**



interaction with the cosmic microwave background (CMB): resonant generation of a Δ - baryon

interaction with the infrared - bg (IR): resonant generation of e^+e^- pairs

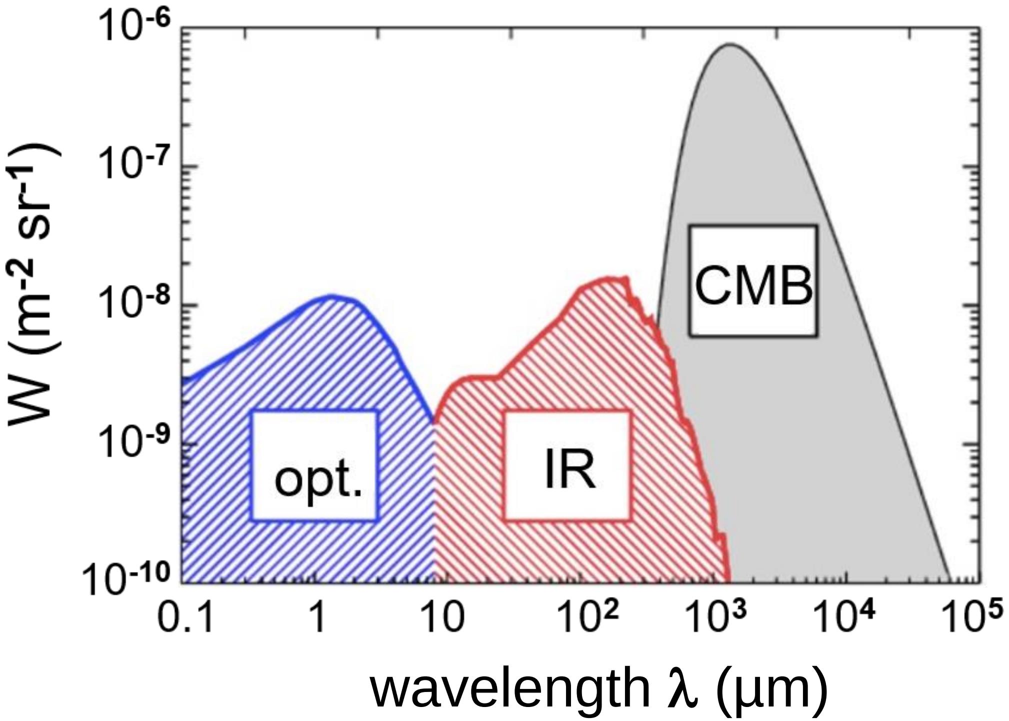
$$\gamma\gamma \rightarrow e^+e^-$$

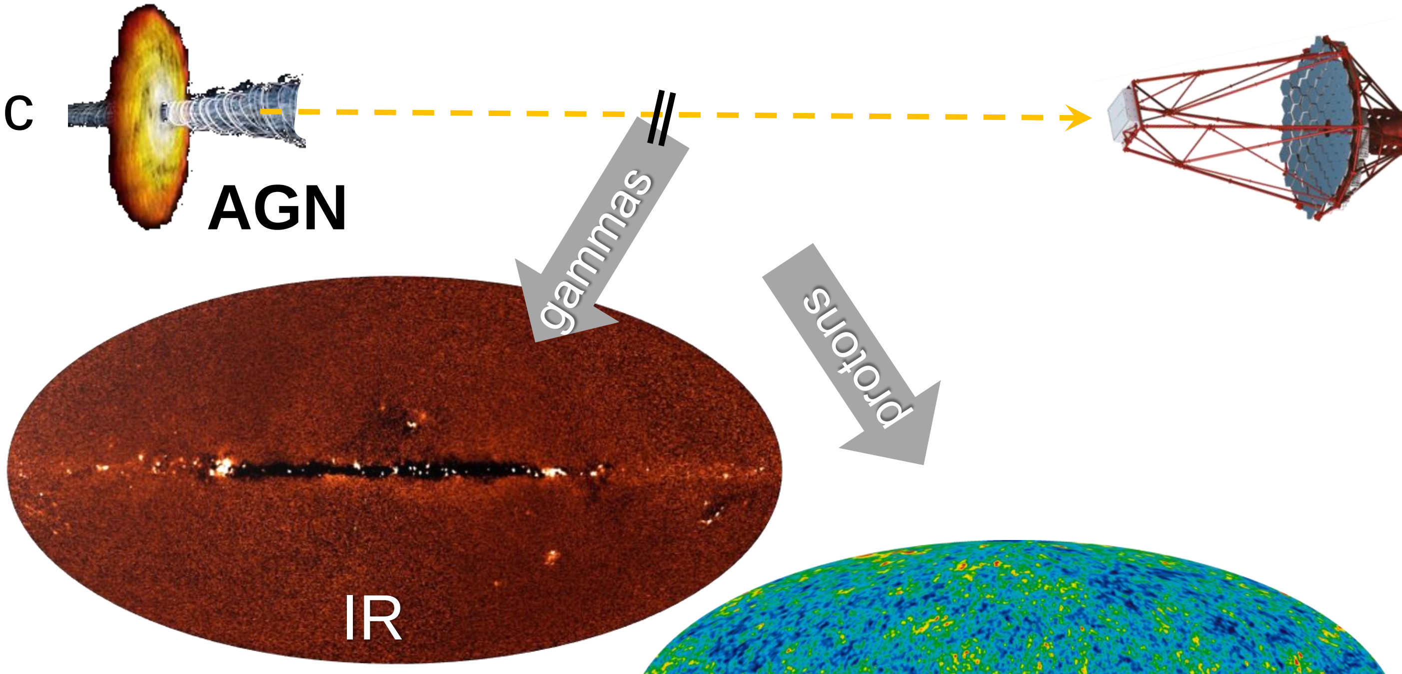
range of high-energy particle radiation

- **interactions with cosmic background fields limit the range of**

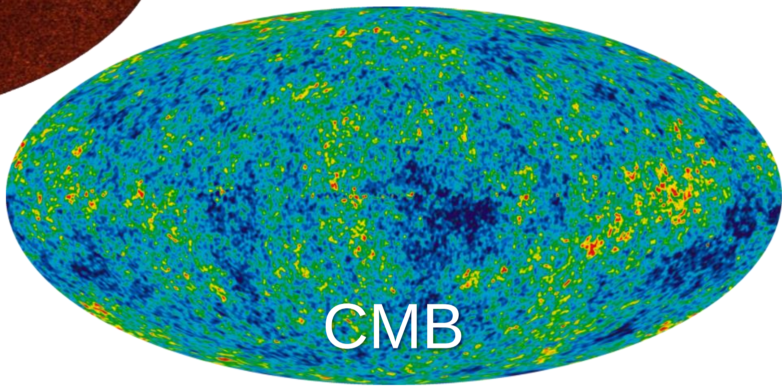
TeV Gammas:
10^{19} eV Protonen:

$d < 100$ Mpc





generation of
resonances via
background fields



Q: NASA

range of gammas and protons

- production of resonances via cosmic background fields of radiation

  - **high-energy gammas (PeV)**

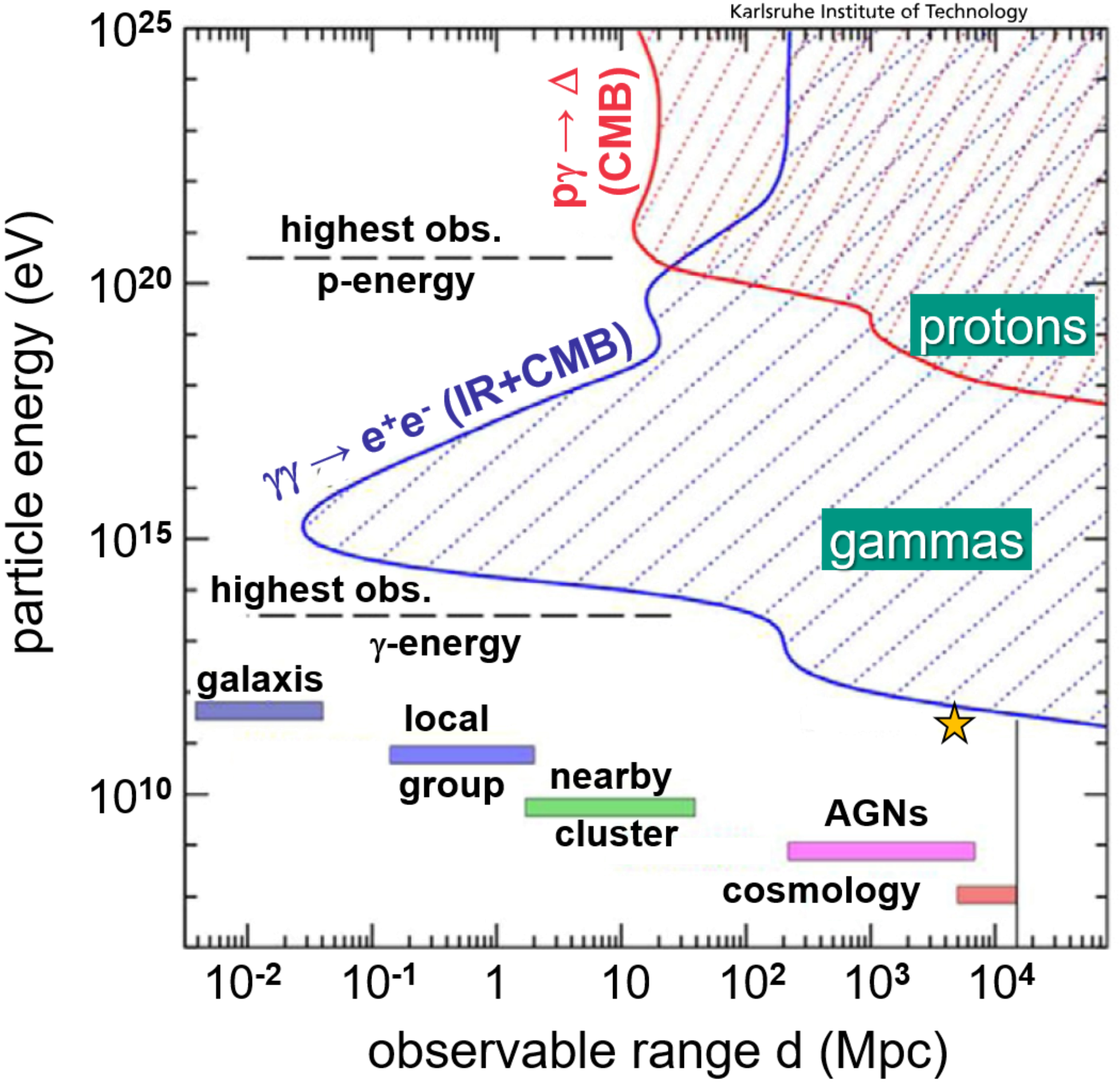
    γ (PeV) + γ (IR) $\rightarrow e^+e^-$ pair

    PeV-atrons* can be observed via γ´s only in our own galaxy

  - **high-energy protons (ZeV)**

    p (ZeV) + γ (CMB) $\rightarrow \Delta^+$ resonance

    ZeV-atrons (for p) only up to 10 Mpc



Q: NA

*named after TeVatron at Fermilab, USA

range of gammas and protons and axions

Karlsruhe Institute of Technology

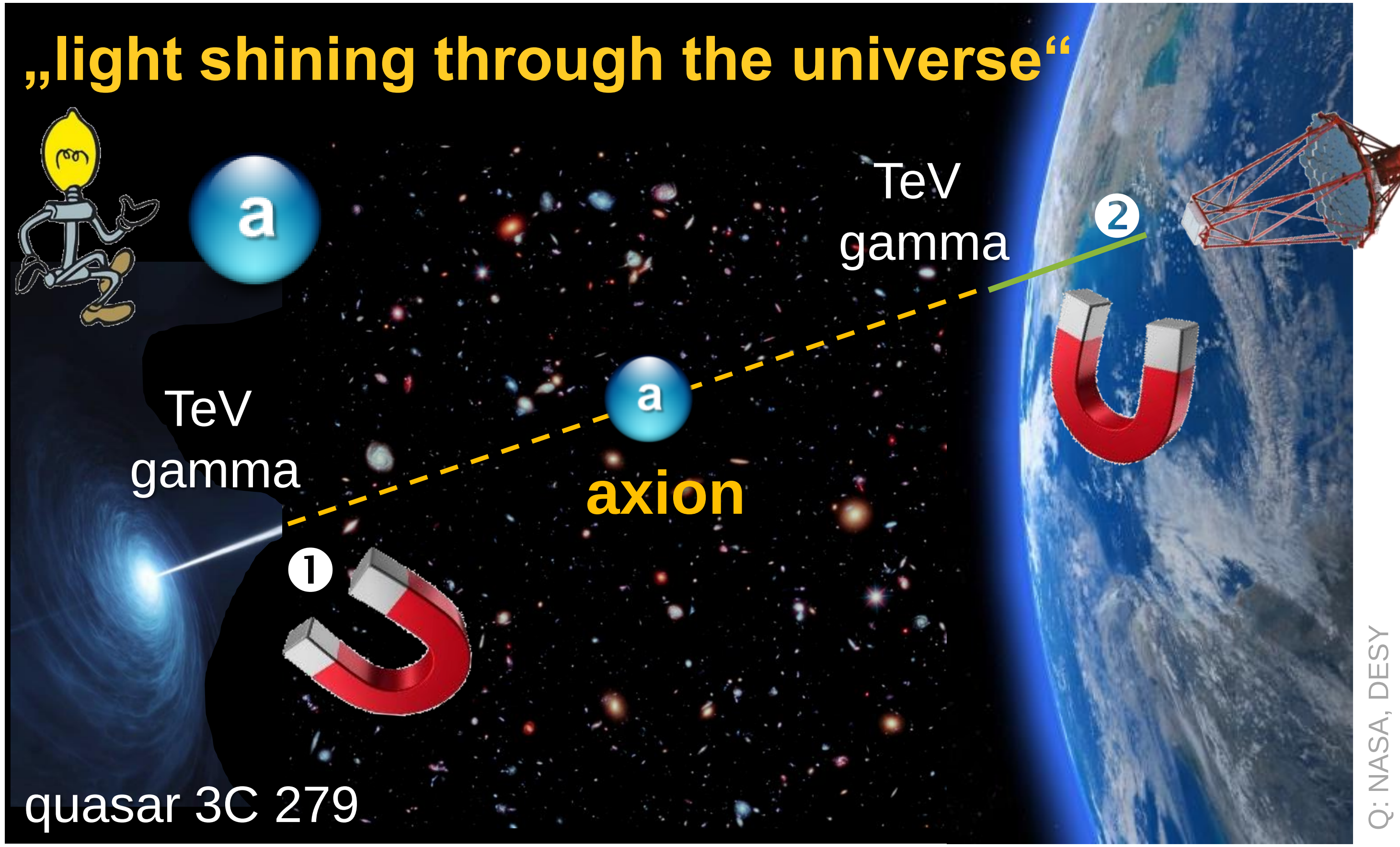
- a tantalizing way to extend γ-range: γ converts to an axion* & back (B-fields)

experimental observation:
universe seemingly is much more transparent for very high-energy gammas than we expect

an intriguing theoretical ansatz:

❶ TeV-γ converts in the B-field close to the source into the hypothetical **axion**, which will propagate over Gpc

❷ axion converts back to γ



Q: NASA, DESY

*see chapter on axions