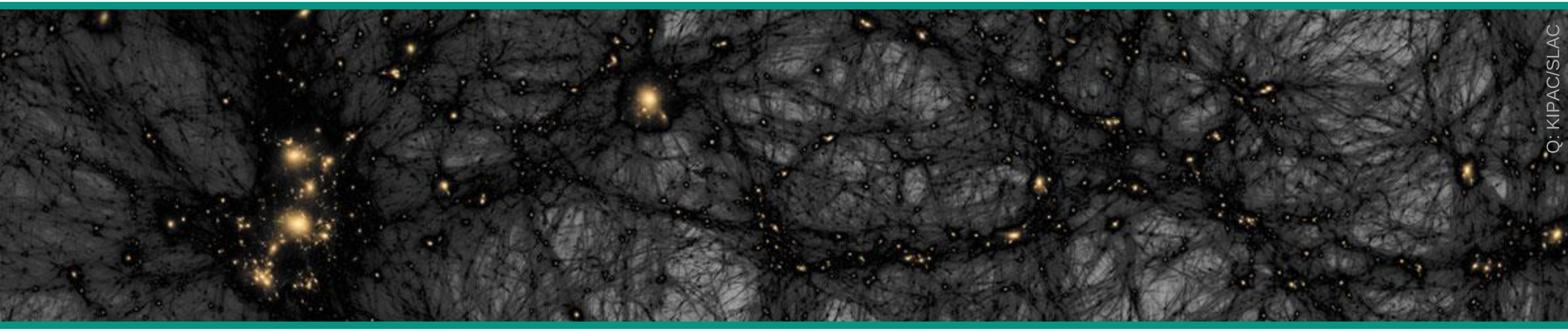
Karlsruhe Institute of Technology

Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 2 Oct. 26, 2023



Recap of Lecture 1

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

  - **searches for rare processes** from the $\boldsymbol{TeV}$ ... $\boldsymbol{sub-eV}$ mass scale:
    dark matter, properties of **neutrinos**, gravitational waves,…

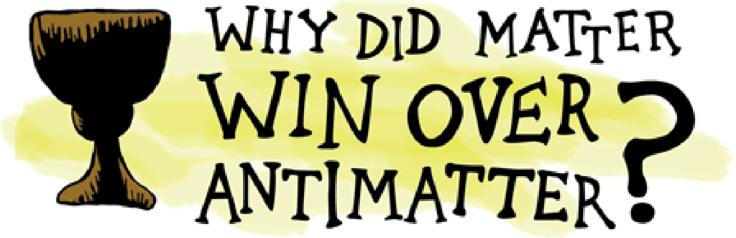
  - **properties of the high–energy universe** from the $\boldsymbol{TeV}$ ... $\boldsymbol{EeV}$ – scale:
    charged $\boldsymbol{CR}$´s, neutrinos, gammas from cosmic super–accelerators

  - **many orders of magnitude in energy ($\boldsymbol{\mu eV}$ ... $\boldsymbol{ZeV}$), specific sources** :
    neutrinos, gammas, charged cosmic radiation ($\boldsymbol{CR}$´s)

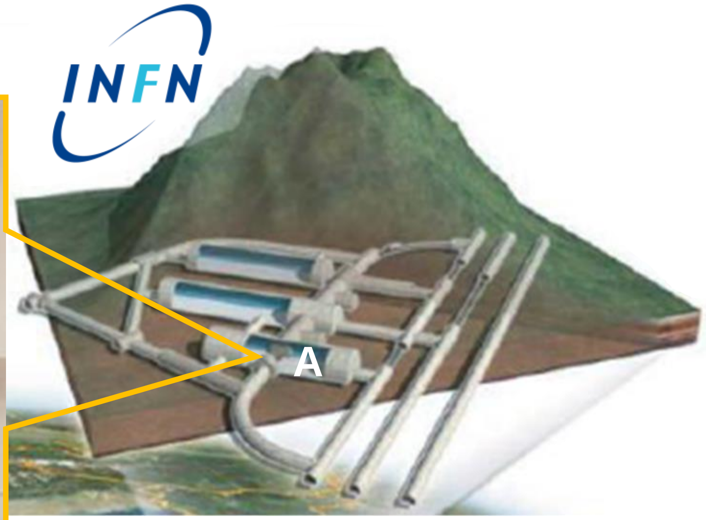
  - **new technologies / detectors & analysis strategies**:
    (quasi–) background–free, novel high–resolution detection techniques, ...

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

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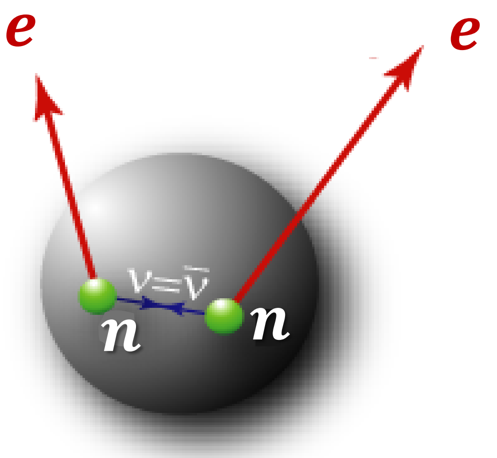
- **Electrons in the MeV – range from $\beta\beta$ – decays: conserved Lepton number?**



$$\Delta L = 2$$

Q: symmetry magazine

*GErmanium Detector–Array

Q: MPIK

$GERDA$* underground experiment at $LNGS$**

**Laboratori Nazionali Gran Sasso

KATRIN experiment at *KIT*

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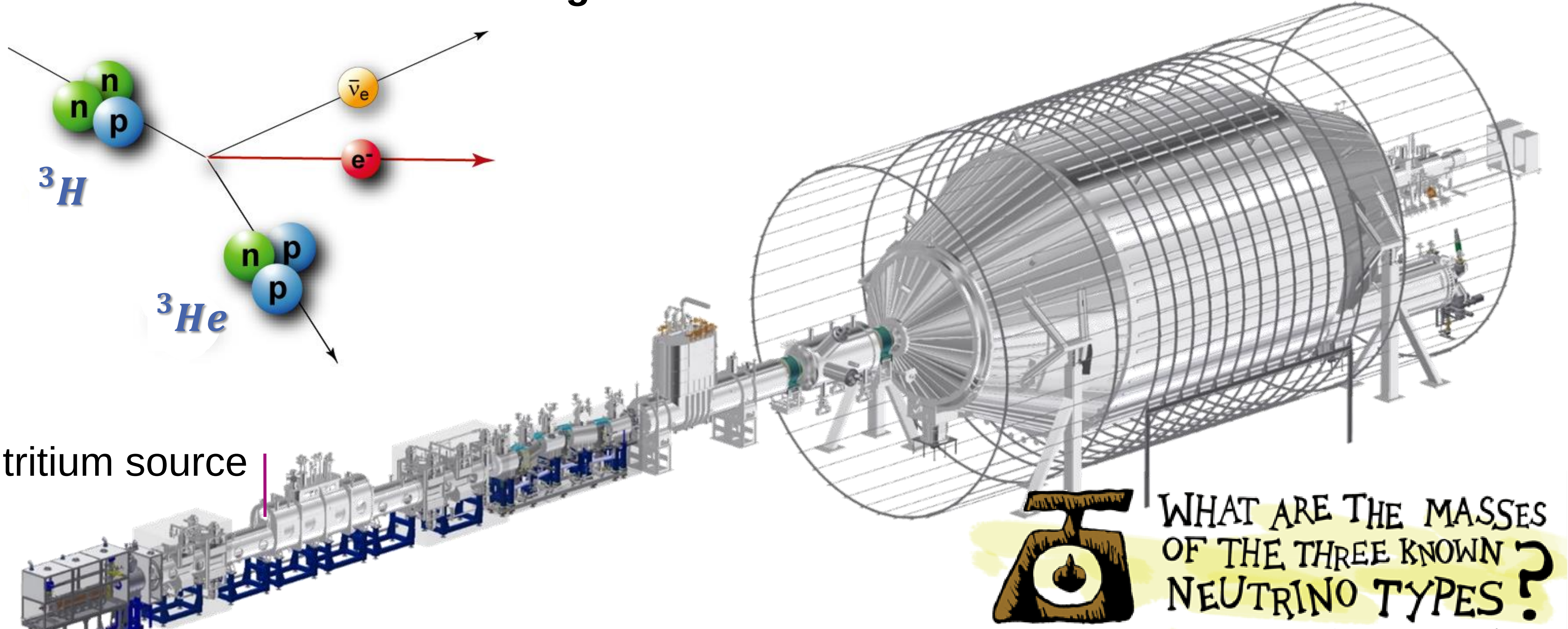
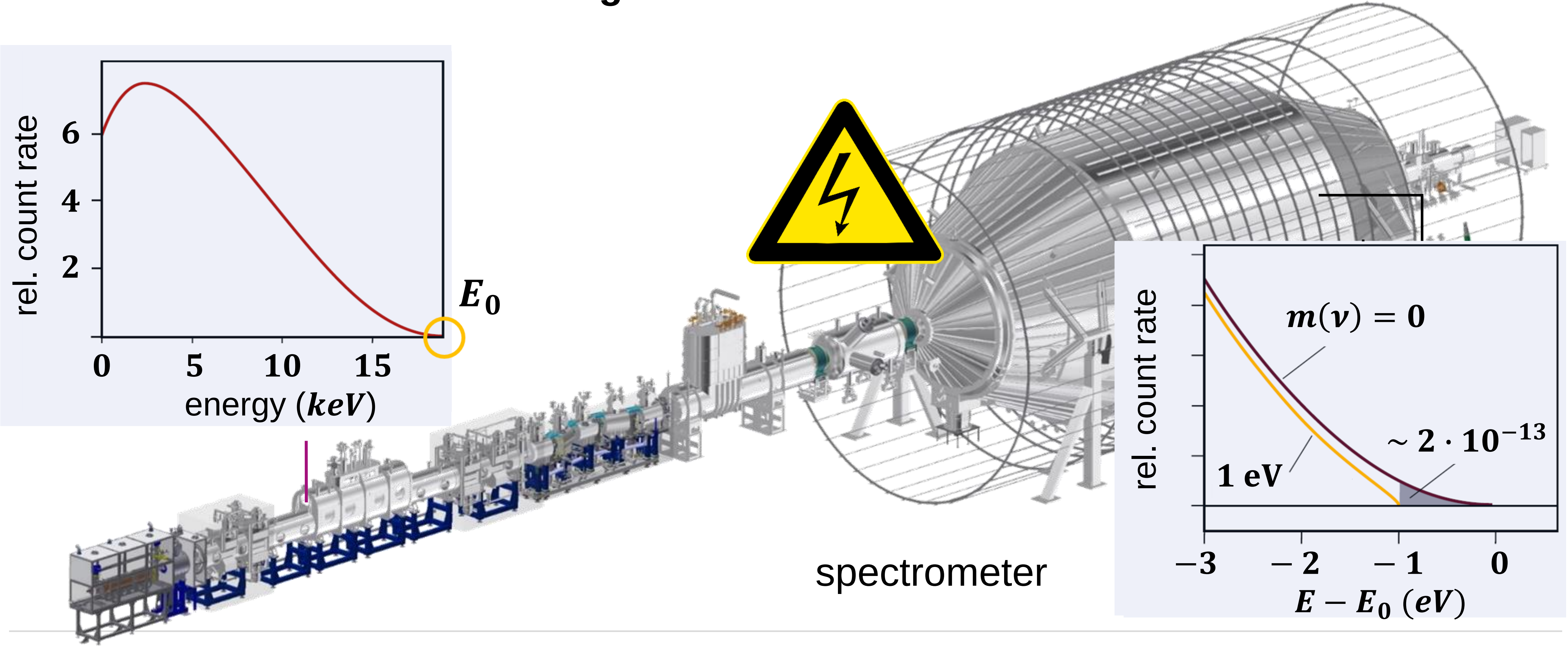
- Electrons in the *keV* – range: absolute scale of neutrino masses?



Q: symmetry magazine

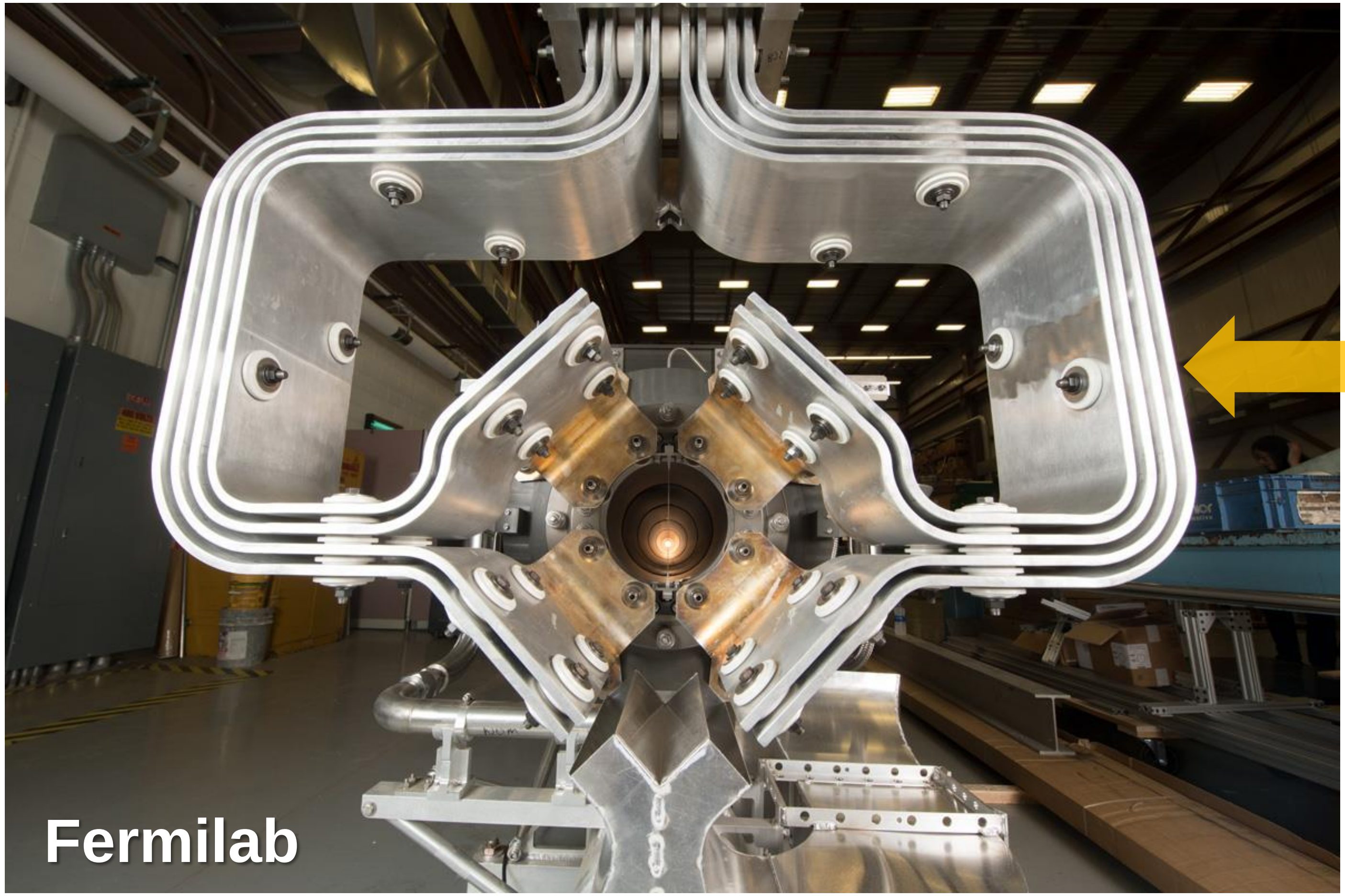
$KATRIN$ experiment at KIT

- **Electrons in the keV – range: absolute scale of neutrino masses?**

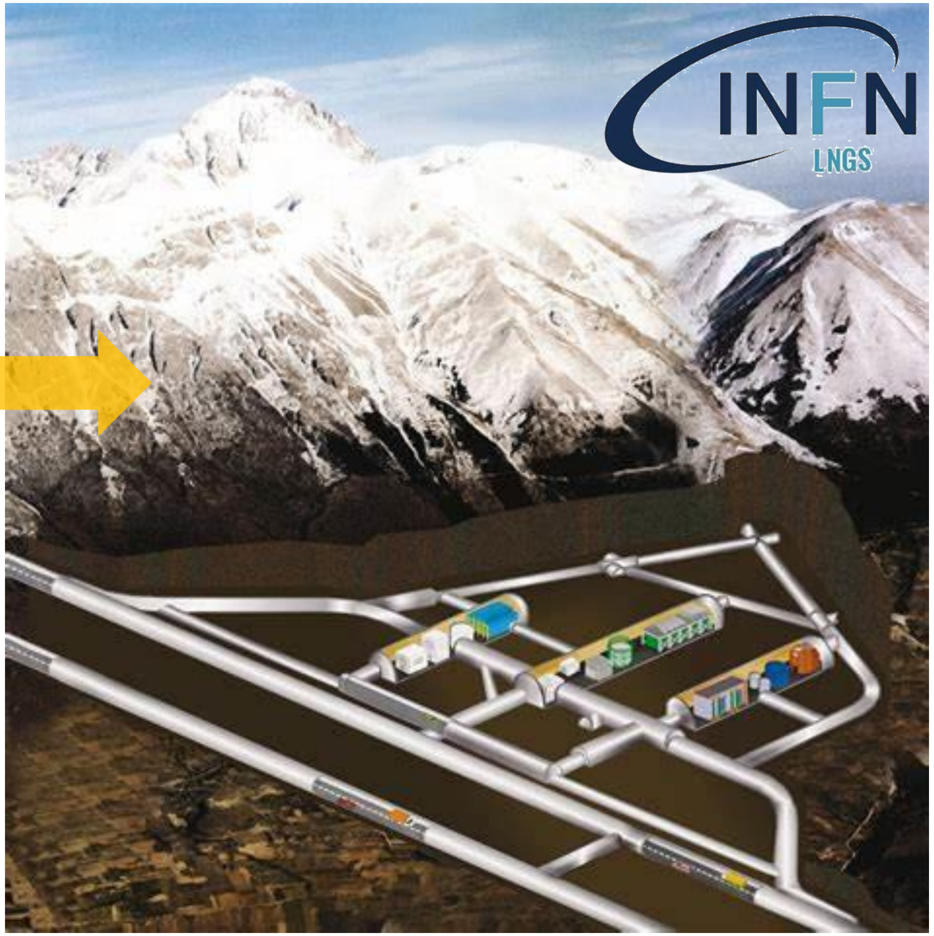


Laboratories required for Particle Radiation

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



Q: Fermilab



Q: LNGS

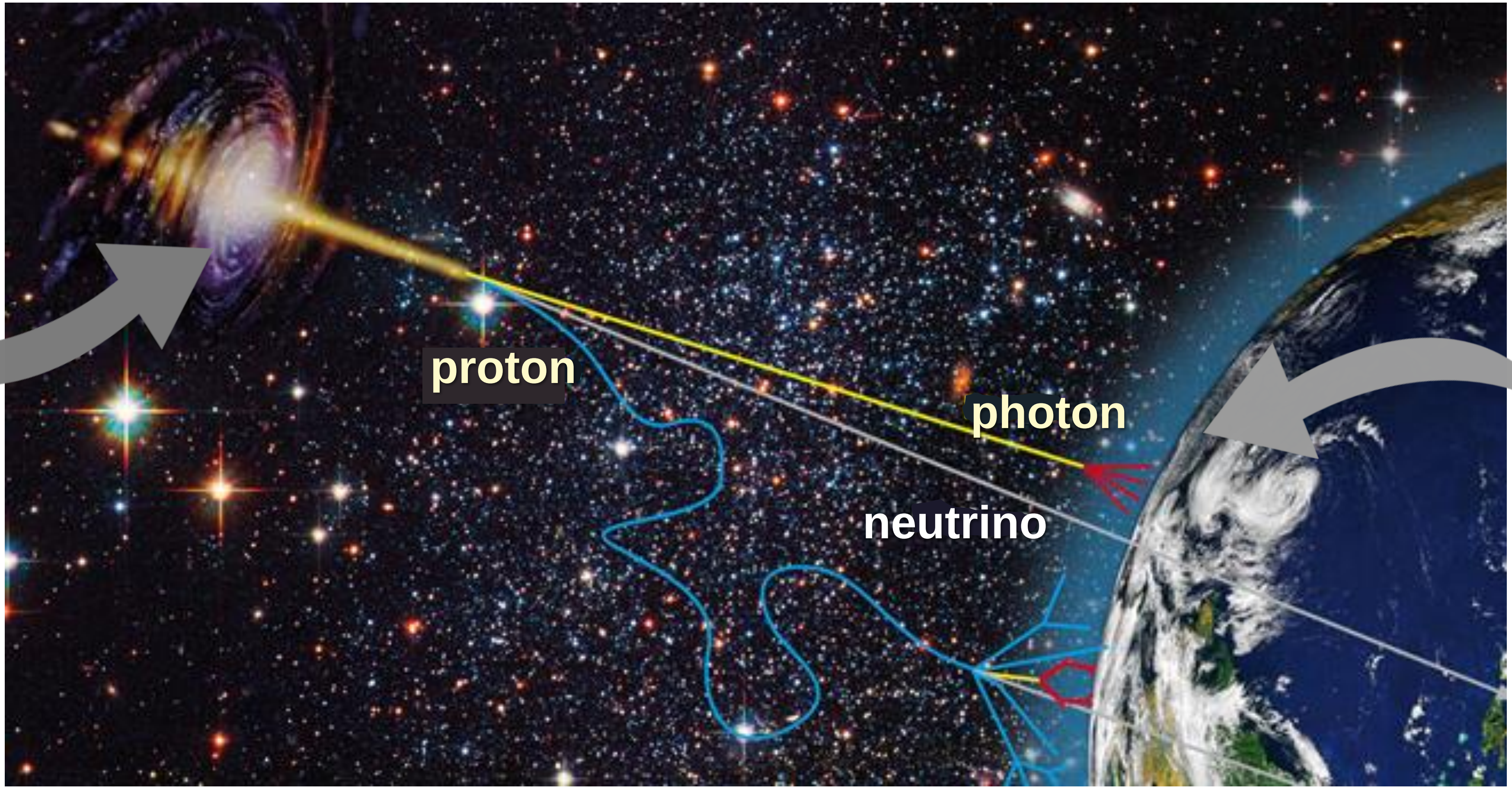
 * *T*ritium *L*aboratory *K*arlsruhe

1.2 Particle Radiation from the Universe

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

source of particle radiation –

typically a **cosmic accelerator** (***AGN***, ***GRB***)*



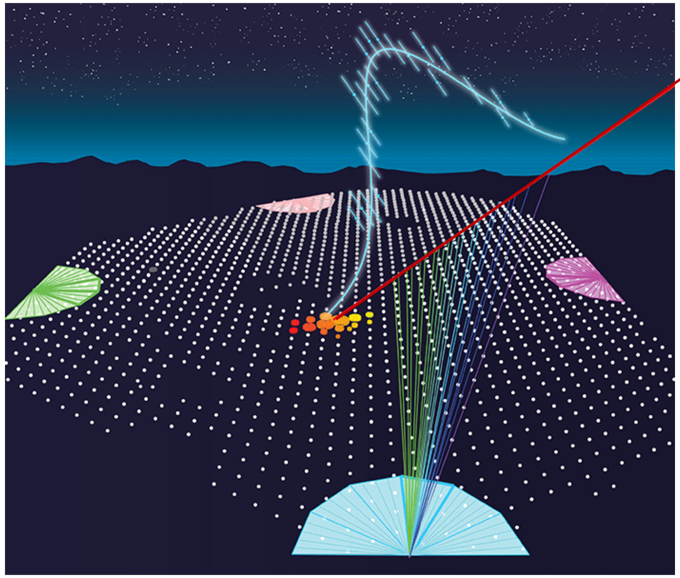
detection of particle radiation

* ***A***ctive ***G***alactic ***N***uclei, ***G***amma ***R***ay ***B***urst

Multi–messenger ansatz: *CR´s*

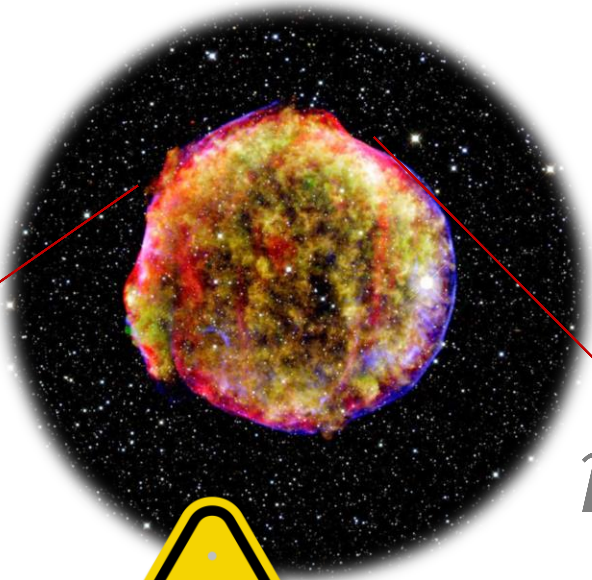
- news from the hidden universe: example *SNR**

Q: APS Physics



charged *CR´s*

p



multi–messenger type #1

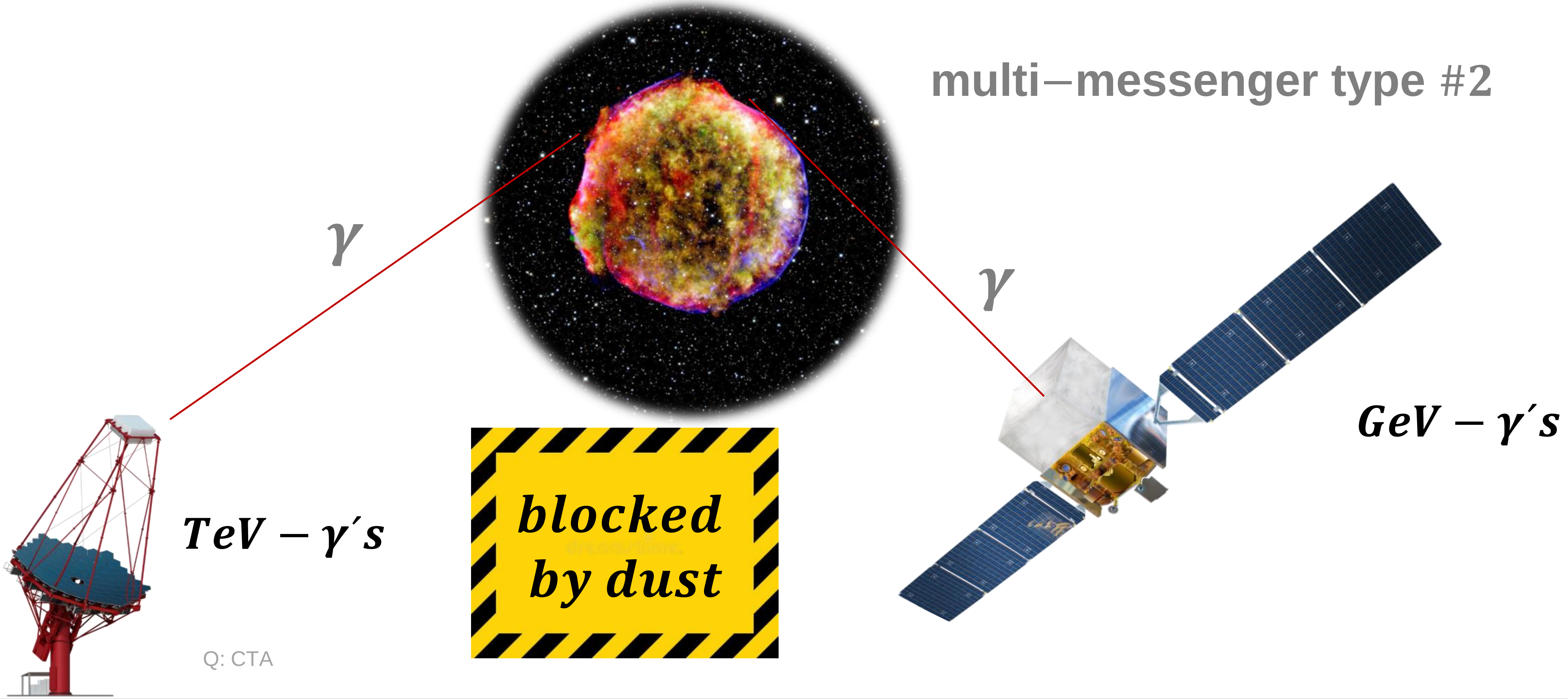
air shower from charged *CR´s*

p

*SuperNova Remnant

Multi–messenger ansatz: energetic γ´s

- news from the hidden universe: example SNR*



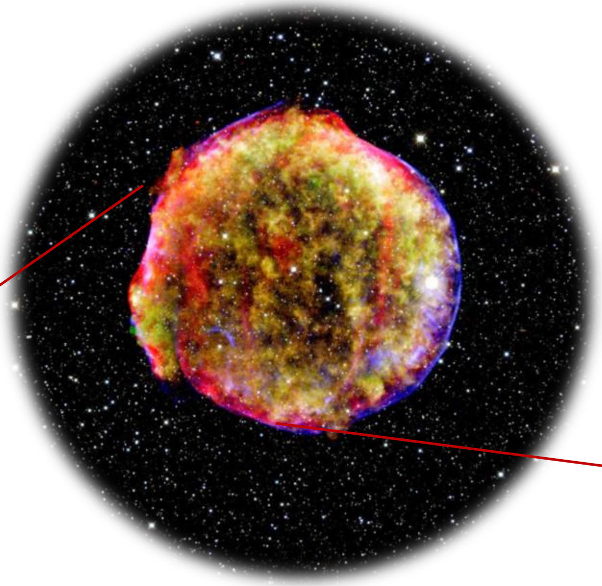
*SuperNova Remnant

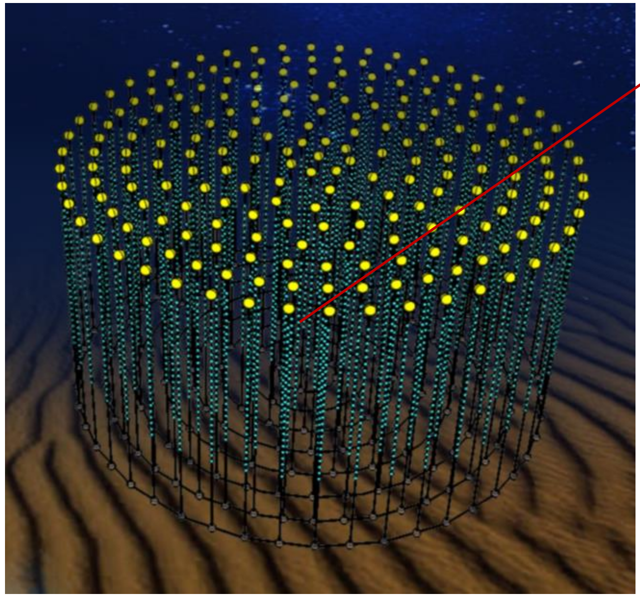
Multi–messenger ansatz: energetic ν´s

- news from the hidden universe: example SNR*

multi–messenger type #3

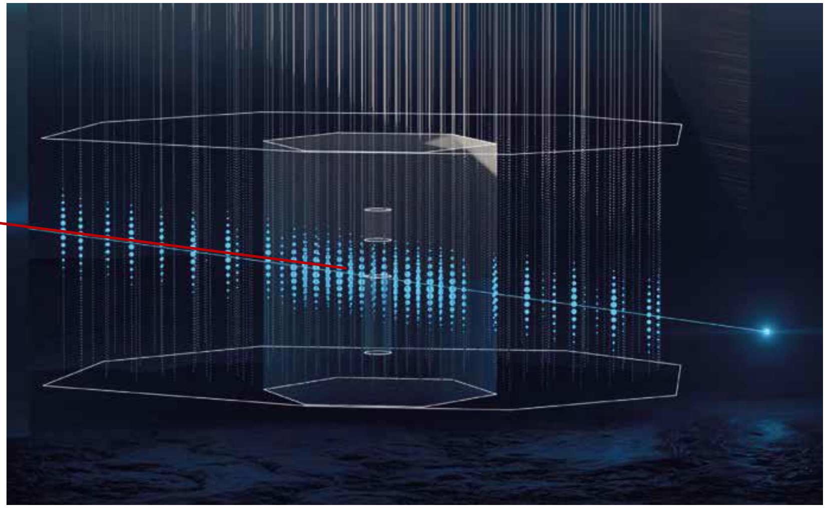
ν





Q: Km3NeT

ν



low
$xsec$

$UHE - \nu$´s

*Super$N$ova Remnant

Multi−messenger ansatz: gravitational waves

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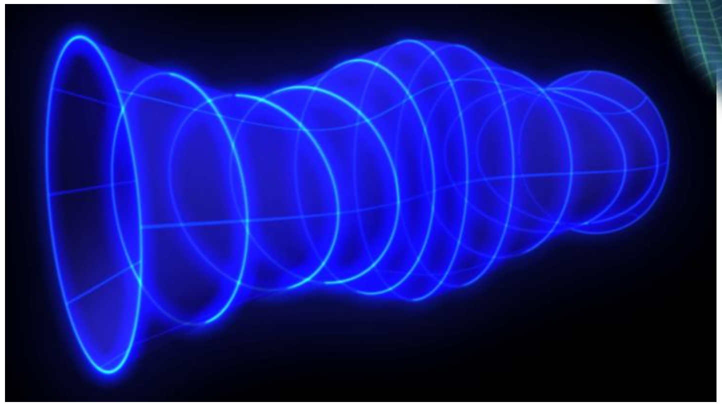
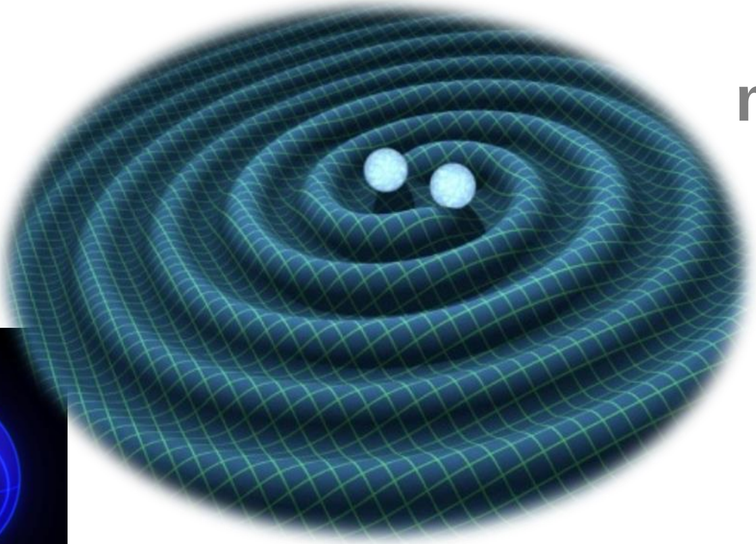
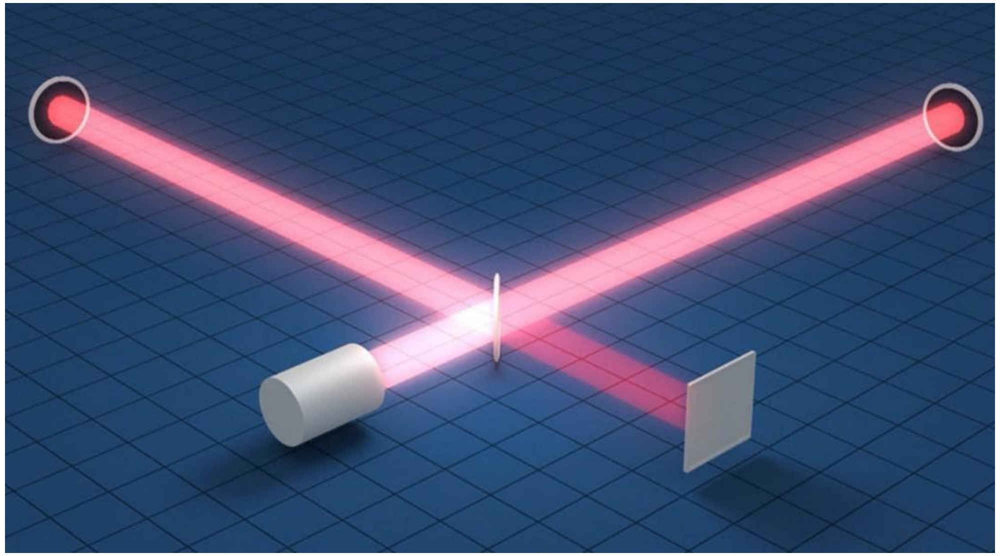
- news from the hidden universe: example $SNIa$*

multi−messenger type #4





$$SN = non - spherical$$



Gravitational Waves (GW)

*merging compact objects

Thermal & non–thermal universe

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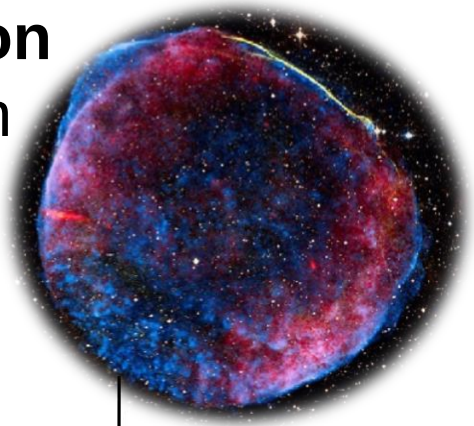
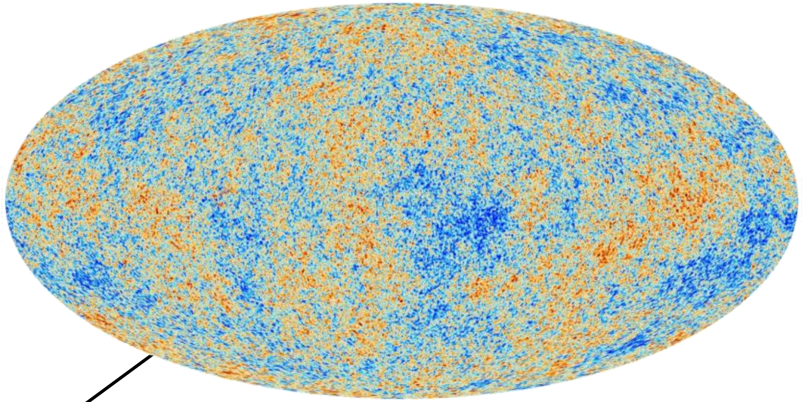
- radiation with very **different spectral distributions** & energy scales

non–thermal radiation
synchrotron emission

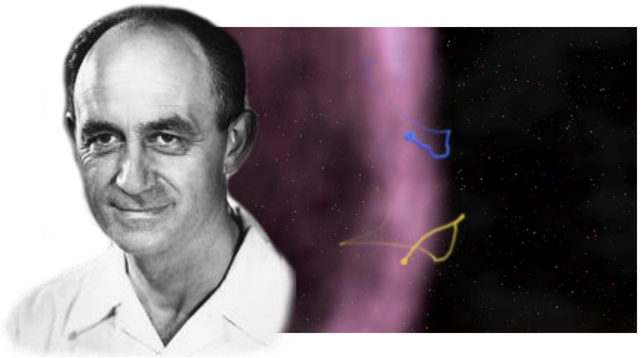


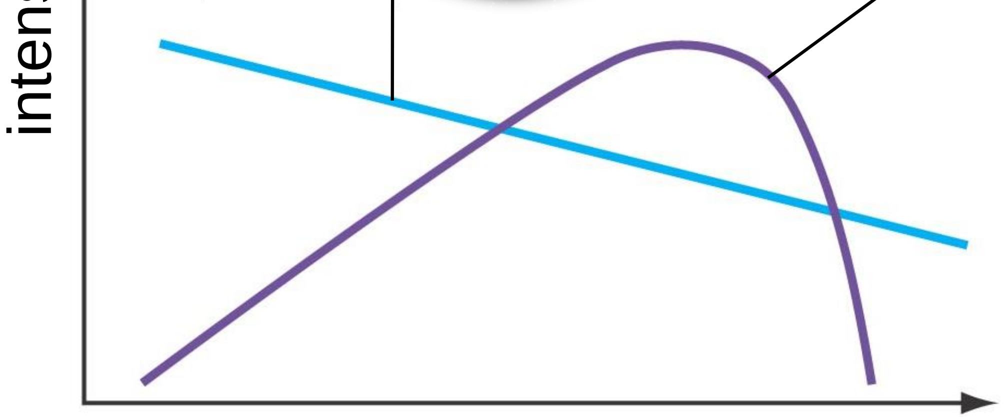


Q: ESA, NASA

thermal radiation

Fermi –
acceleration





Planck –
distribution

Q: redbubble

Thermal & non–thermal universe

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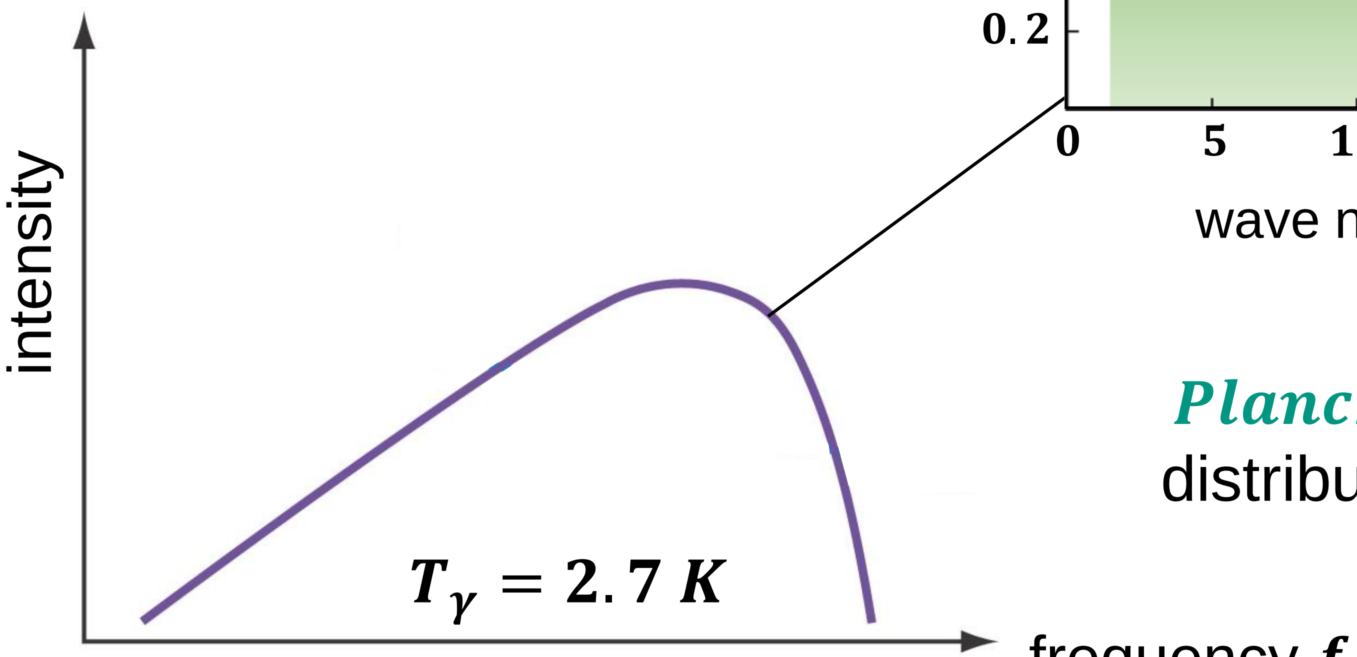
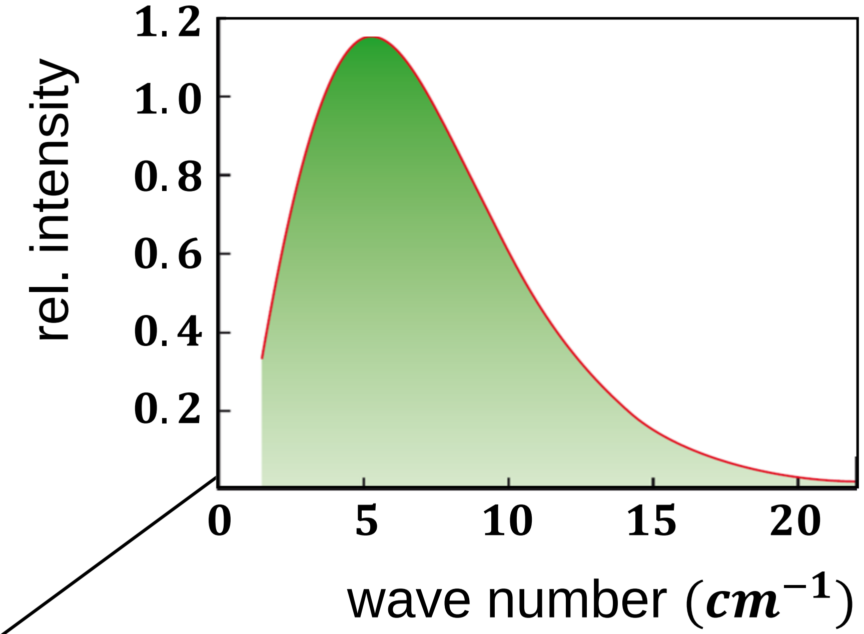
- **the thermal universe: example *CMB****
  - **temperature T** as (sole) **order parameter:** requires a **perfect thermal equilibrium**

Big Bang: *CMB*





***Planck* – distribution**

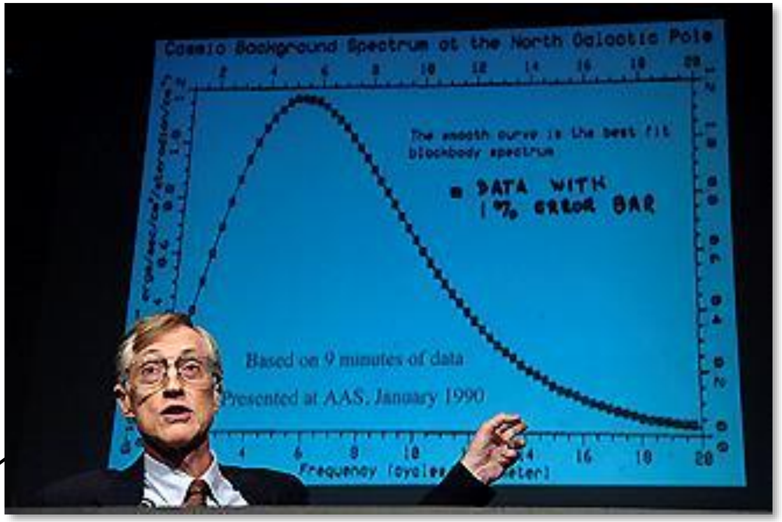
**C*osmic *M*icrowave *B*ackground

Thermal & non–thermal **universe**

- **example from thermal universe:** ***CMB***

- temperature *T* as (sole) **order parameter**
  early universe in **perfect thermal equilibrium**

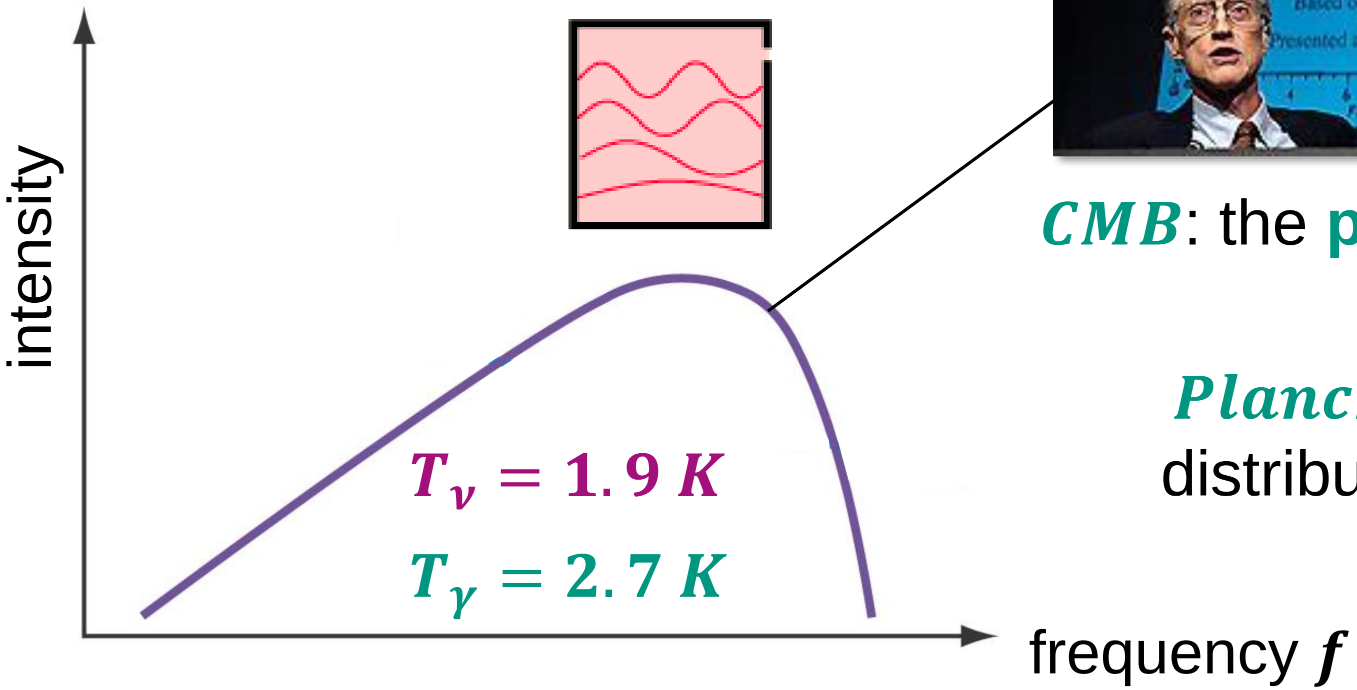
Q: NASA



CMB: the **perfect** black body

Q: symmetry magazine

Big Bang: ***CMB***
CνB*



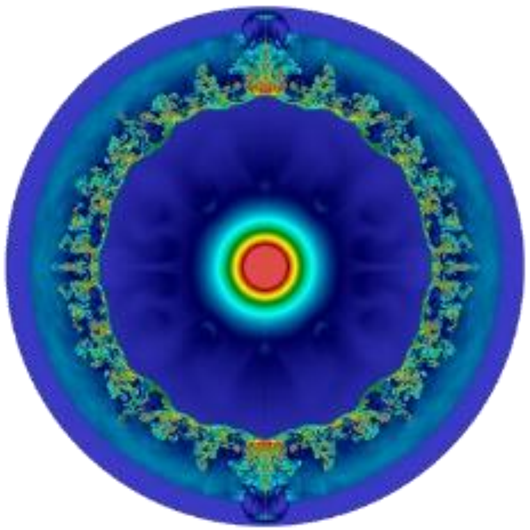
Planck –
distribution

Q: redbubble

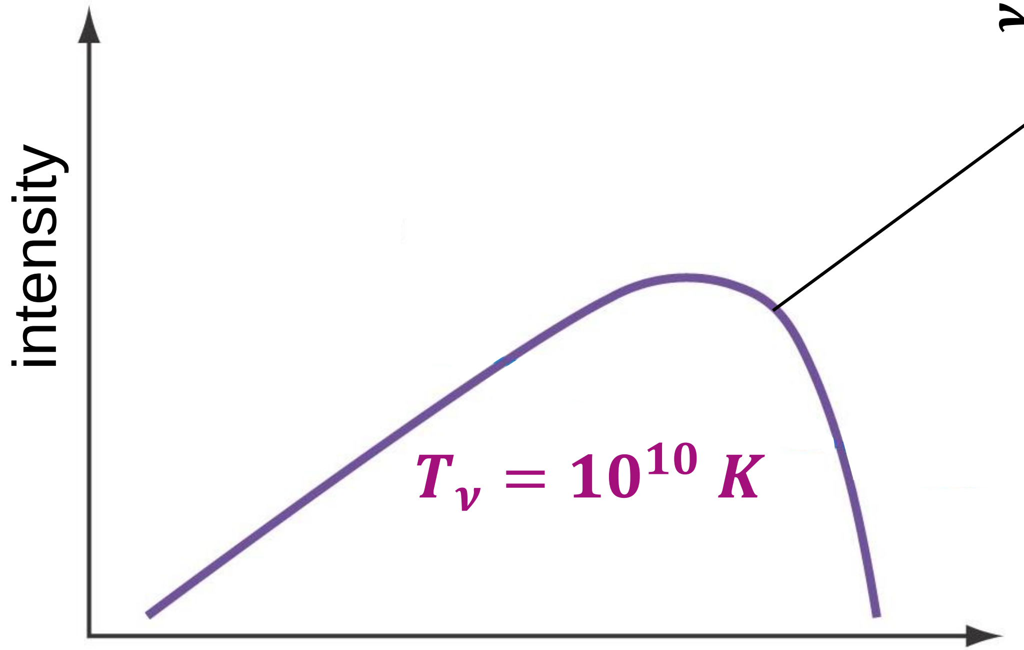
*Cosmic Neutrino Background

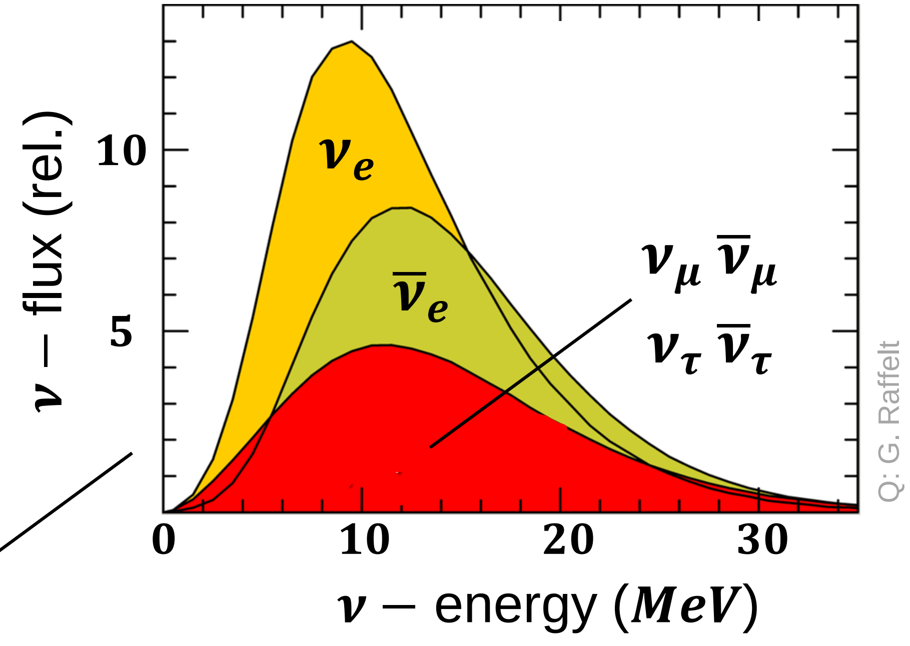
Thermal & non–thermal universe

- **example from thermal universe: SN – neutrinos**
  - MeV –scale neutrinos are emitted from the extremely hot core of a SN –explosion



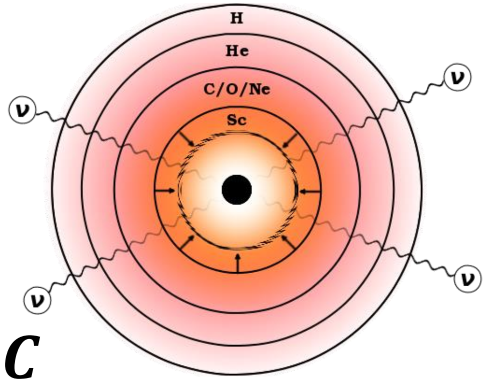
inside a SN – core: thermal equilibrium



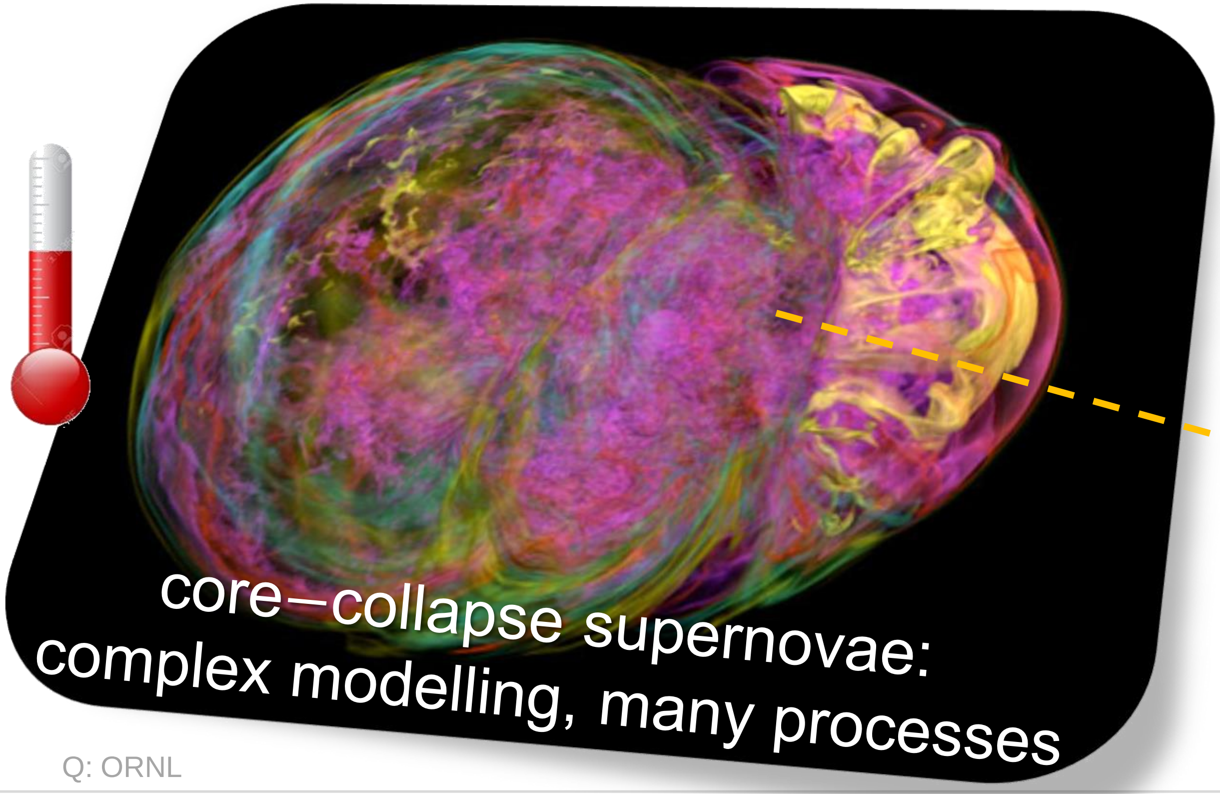


$Planck$ – distribution

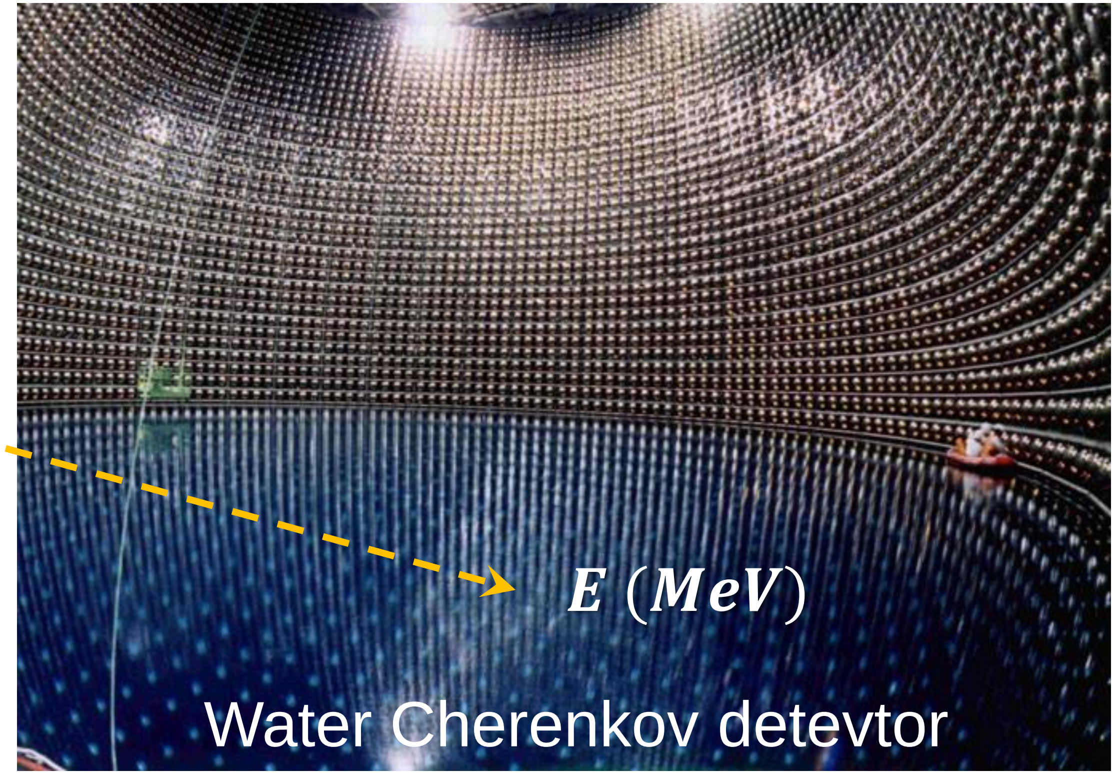
Thermal & non–thermal universe



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



Q: ORNL

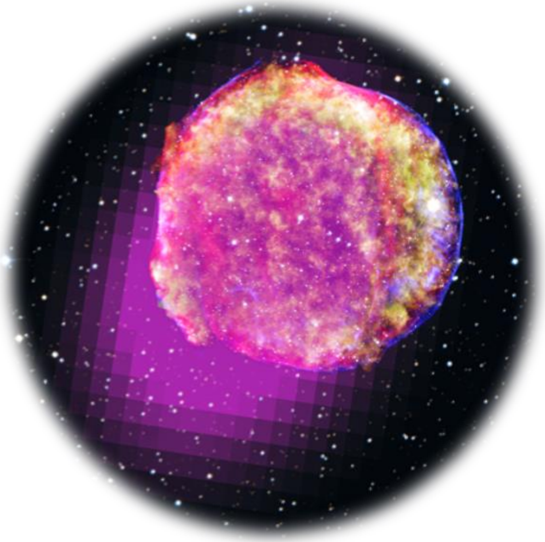


Q: ICRR

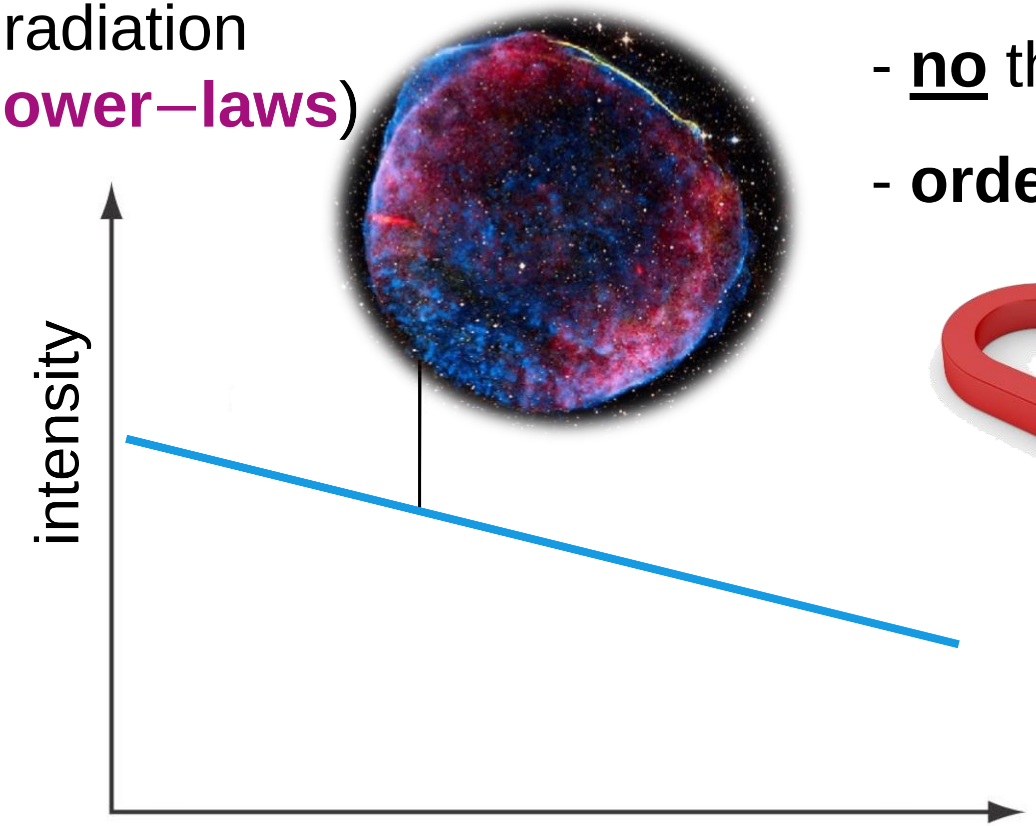
Thermal & non–thermal universe

- **examples from the non–thermal universe: emission of synchrotron– & γ – radiation**

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



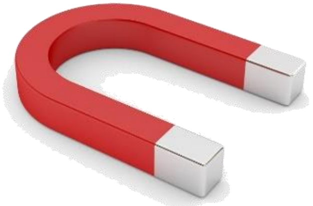
TeV – gammas



frequency f

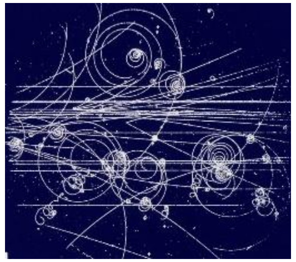
Q: ESA, NASA

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



B

density ρ

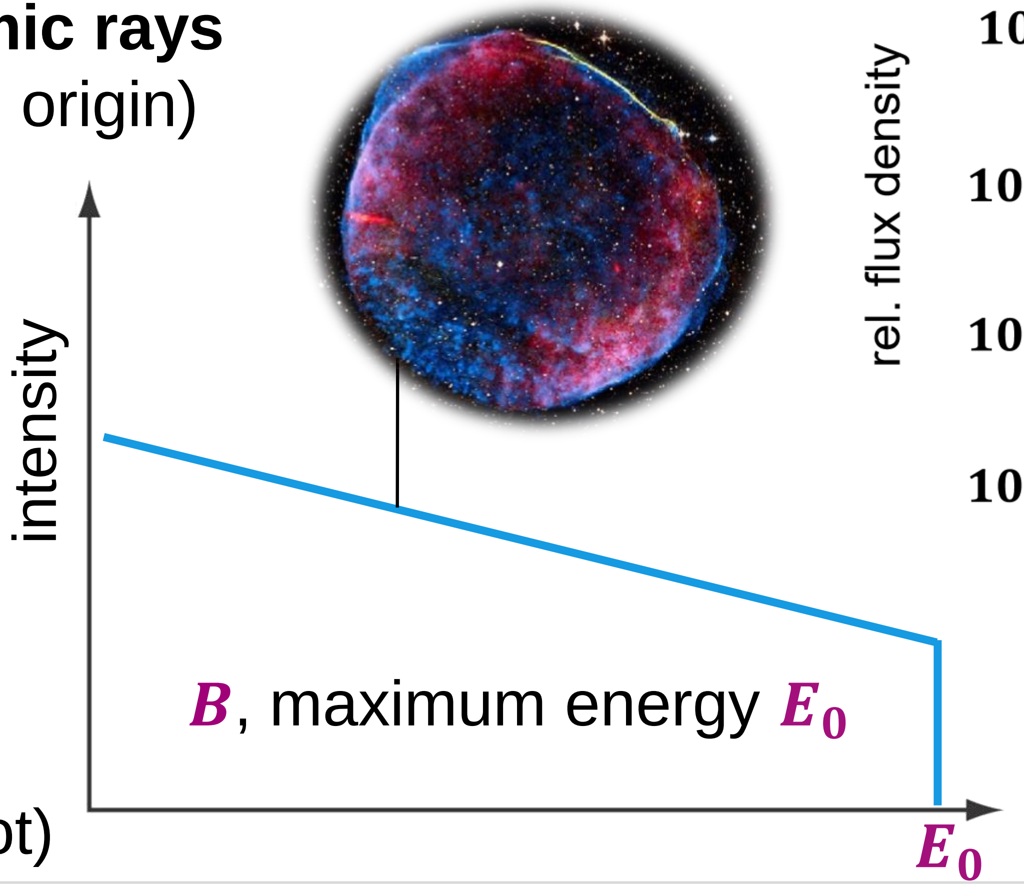


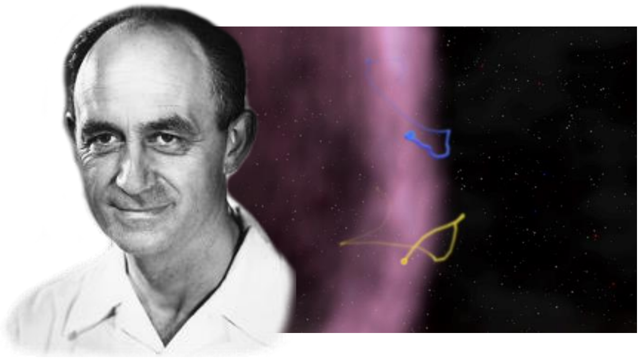
maximum energy E_0

Thermal & non−thermal universe

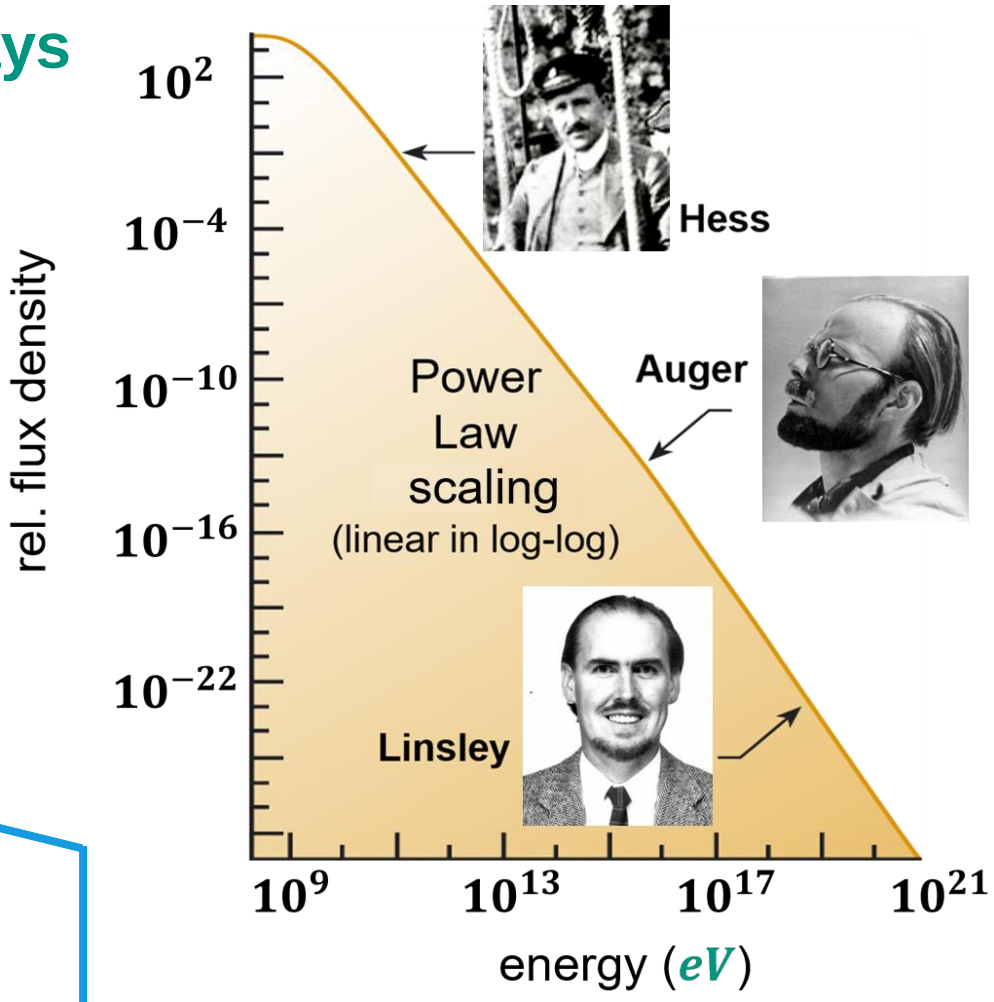
- **example:** power−law spectrum of cosmic rays

charged cosmic rays
(non−thermal origin)





Fermi accleration mechanism (**Hillas** plot)



Thermal & non–thermal universe

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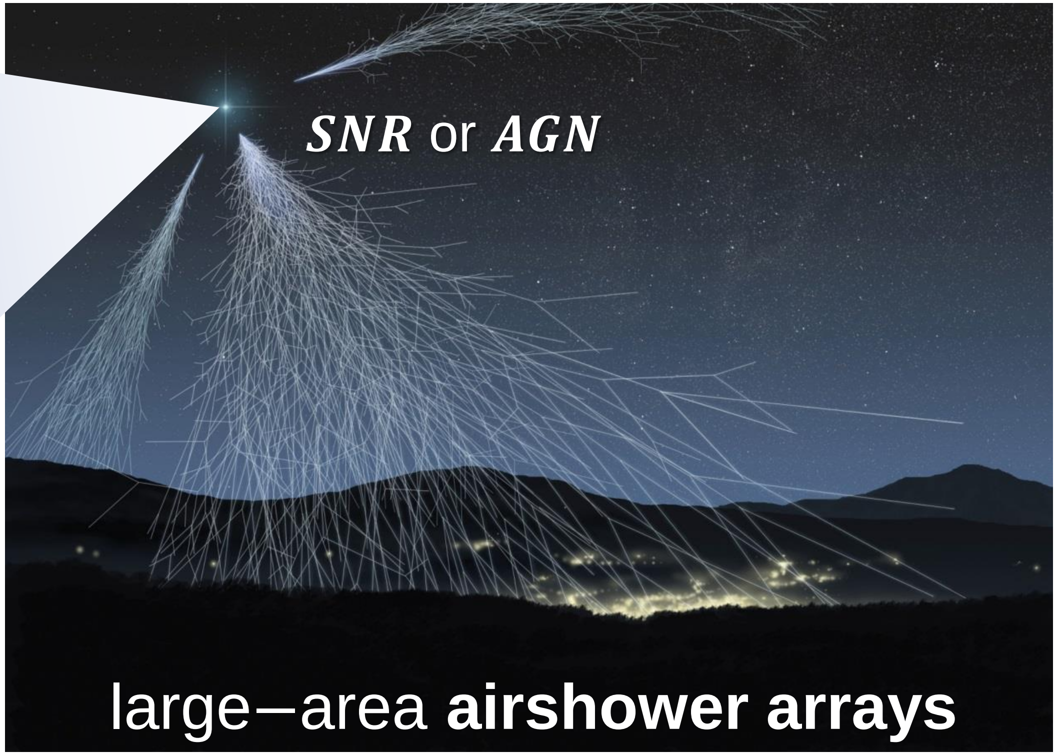
- **example: air showers induced by charged cosmic rays**

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

Q: NASA, Chandra

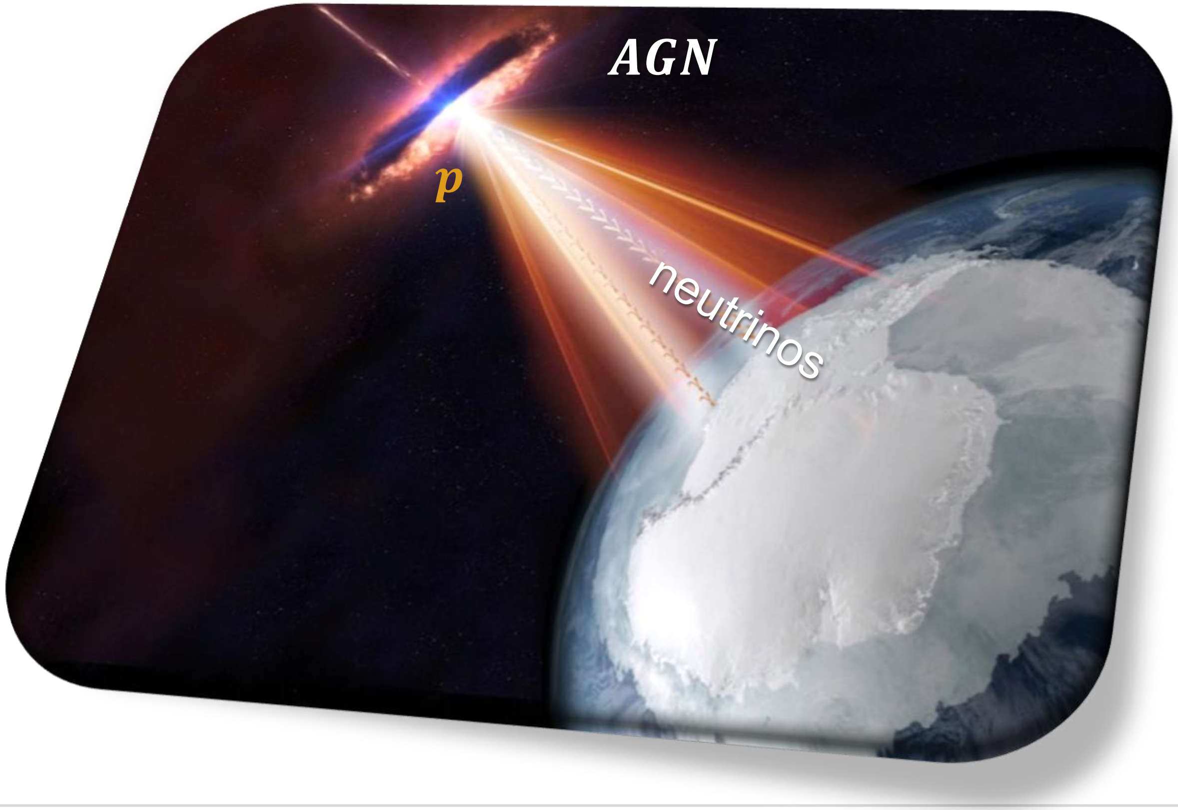


Q: Welt der Physik

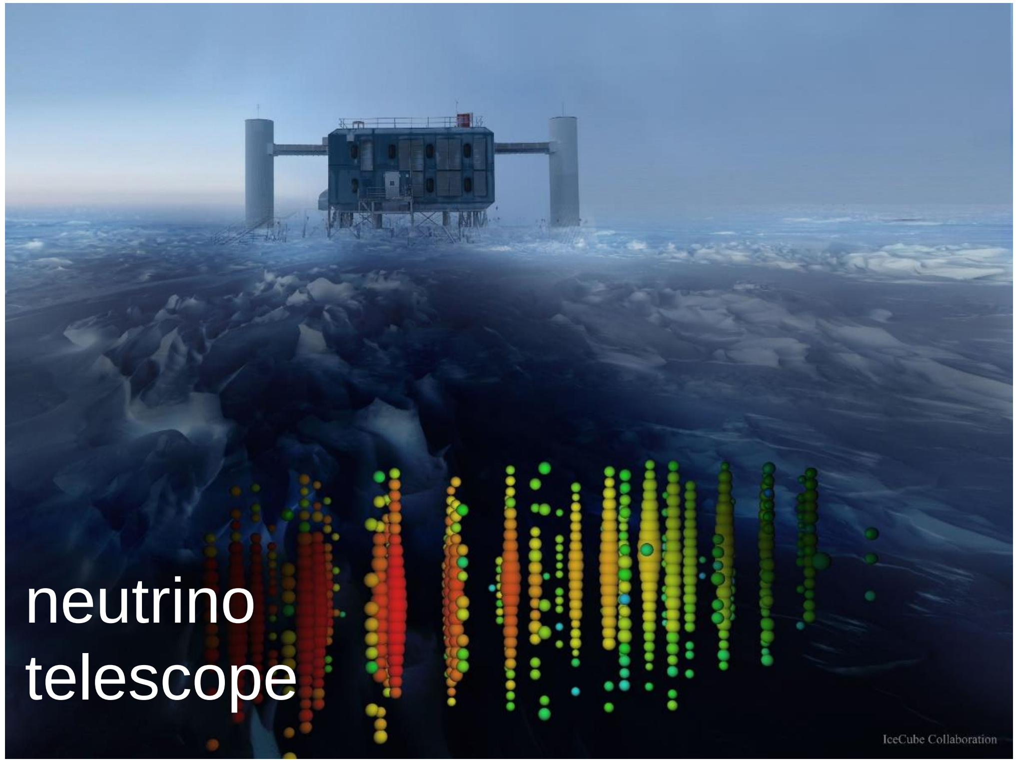
Thermal & non–thermal universe

- **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)

Thermal & non–thermal universe

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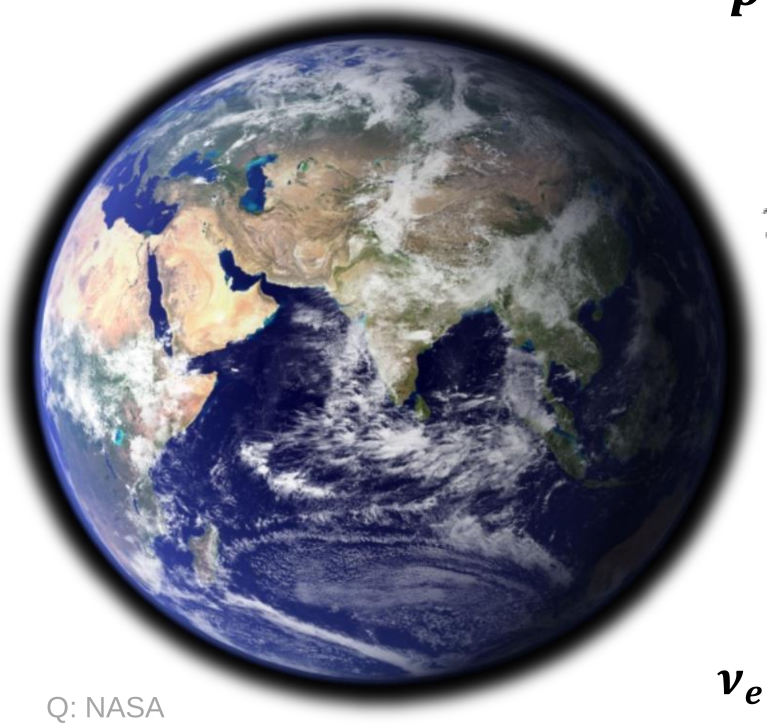
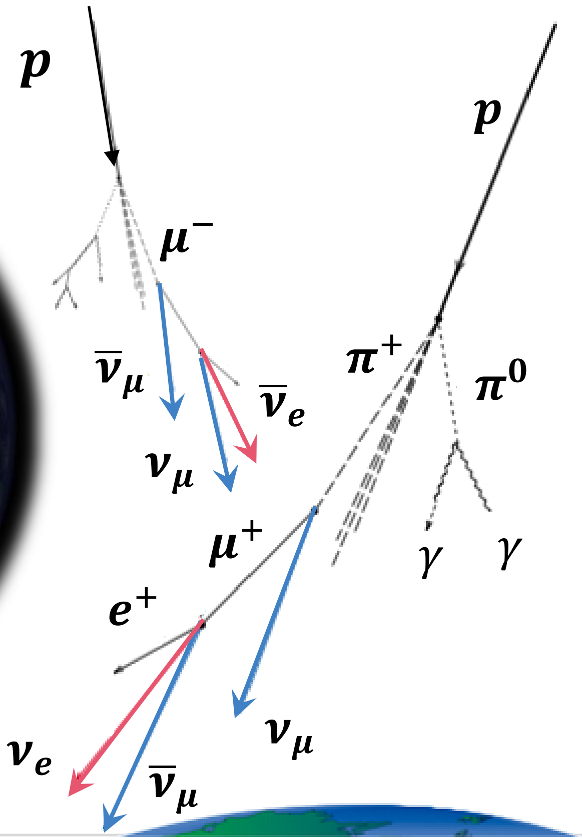
- **example:** atmospheric ν´s (GeV, TeV) **from showers in atmosphere**

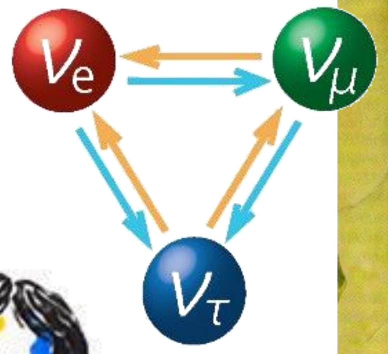
  - sources: **decay sequence** of pions during cascades



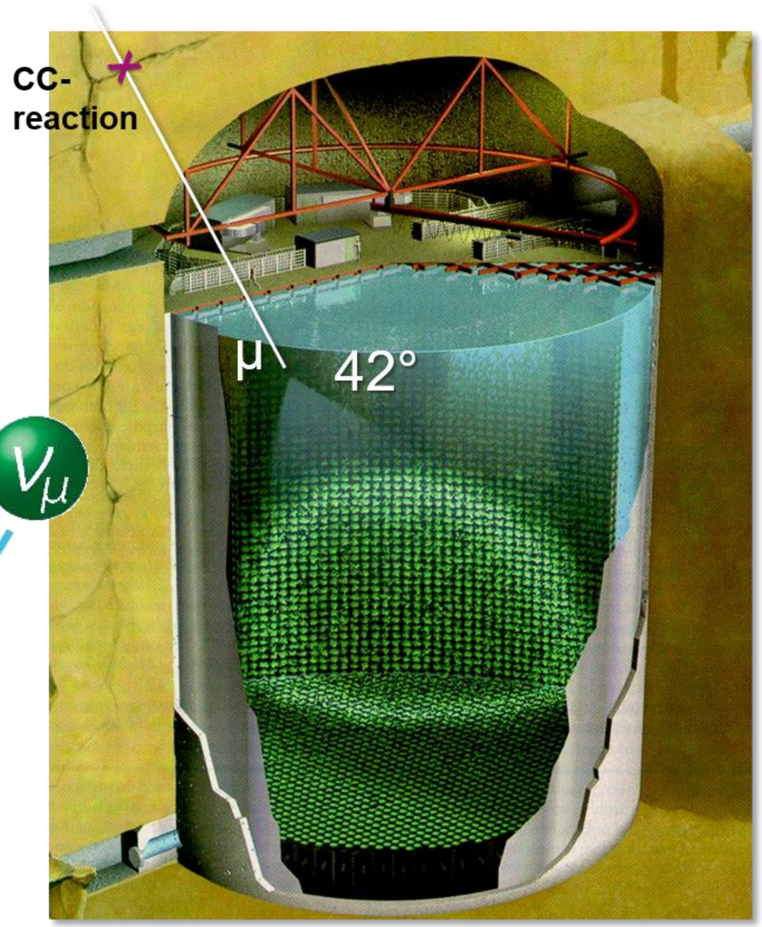
Q: NASA



Q: Los Alamos



T. Kajita

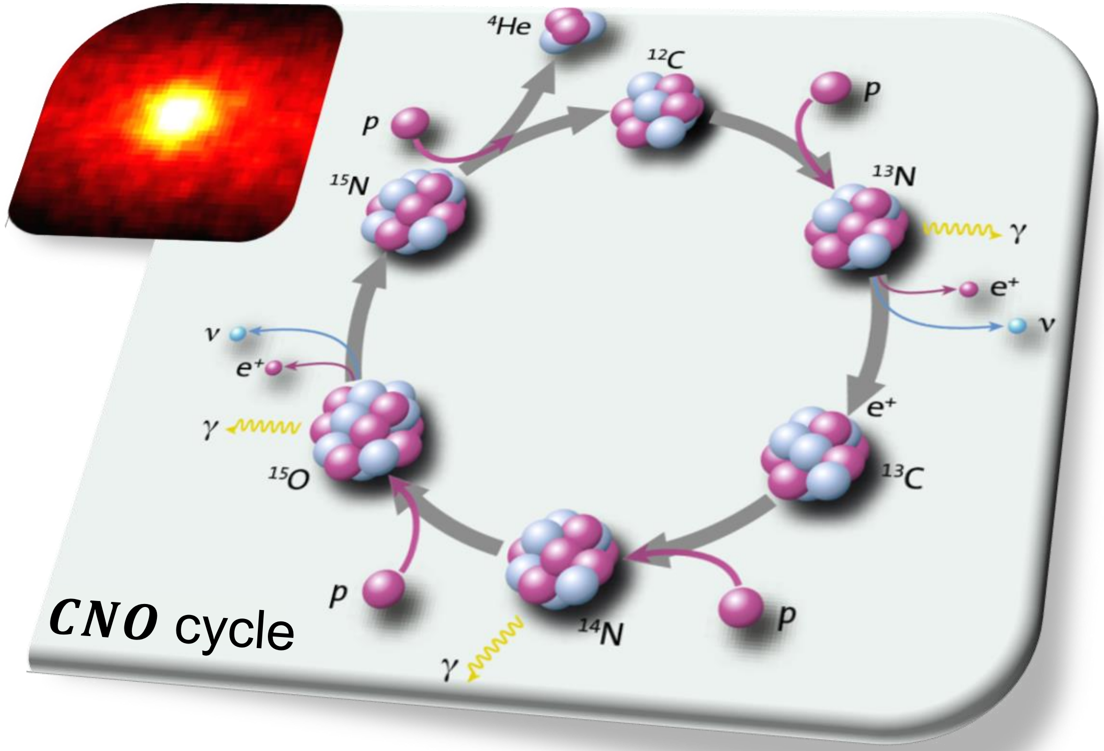


Q: Scientific American

Thermal & non–thermal universe

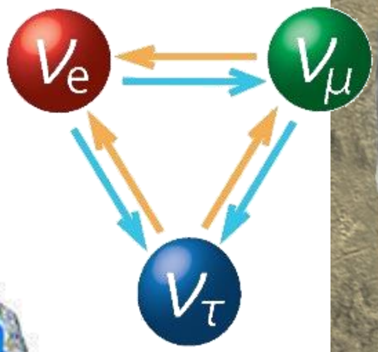
- example: solar ν´s (MeV) from nuclear fusion chains in the solar core

  - sources: pp & CNO chains

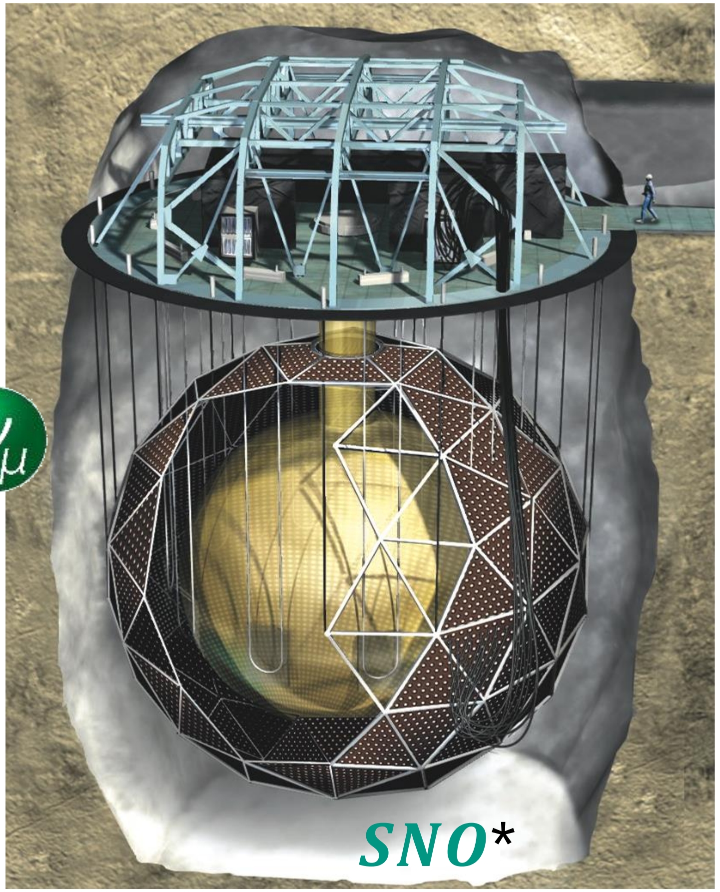


rate depends on T of core

Q: spektrum



A. McDonald



Q: SNO+ Collab.

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

Thermal & non−thermal universe

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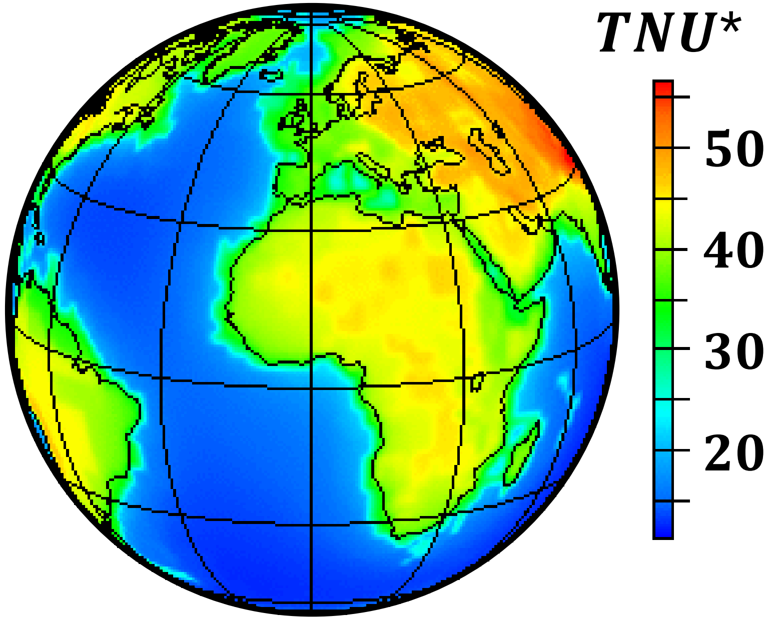
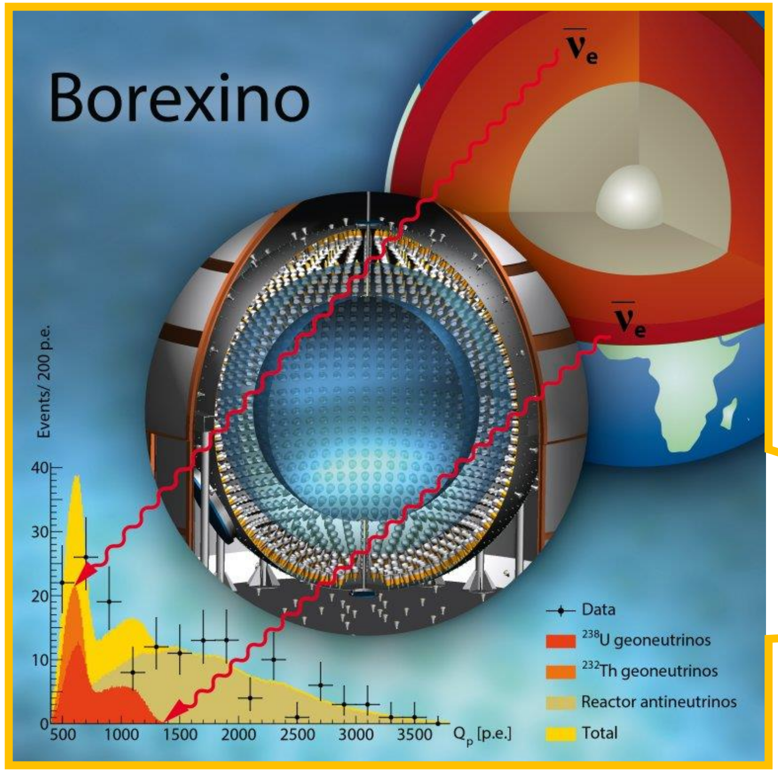
- example: geo−ν´s (MeV) from the crust, mantle & core of the Earth

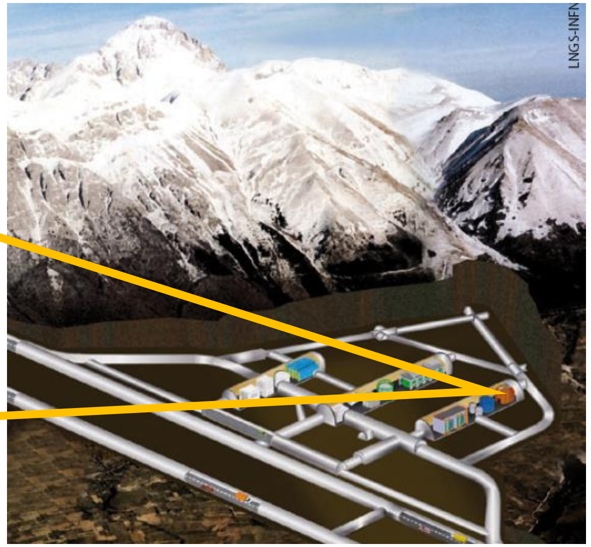
  - source: $\boldsymbol{\beta}$ – decays of unstable isotopes produced as part of $\mathbf{4}$ long−lived $\boldsymbol{\alpha}$ – decay chains



Q: O. Šrámek



Q: Borexino Collab.



Q: LNGS

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

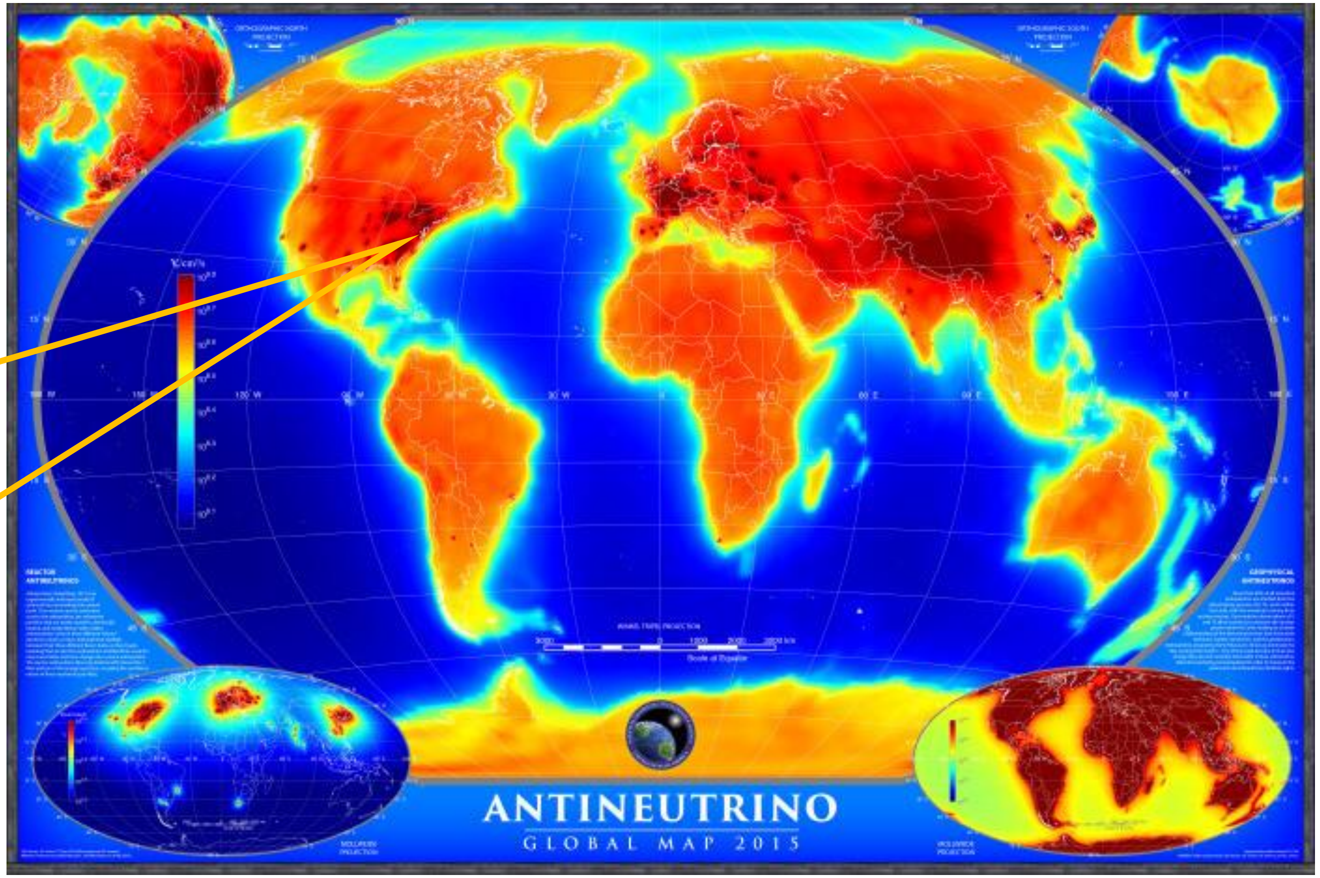
Thermal & non–thermal universe

- **example: reactor–ν´s (MeV) from the core of commercial fission reactors**

  - source: β – decays of unstable isotopes produced in reactor

Q: New Scientist

Q: C. Bell

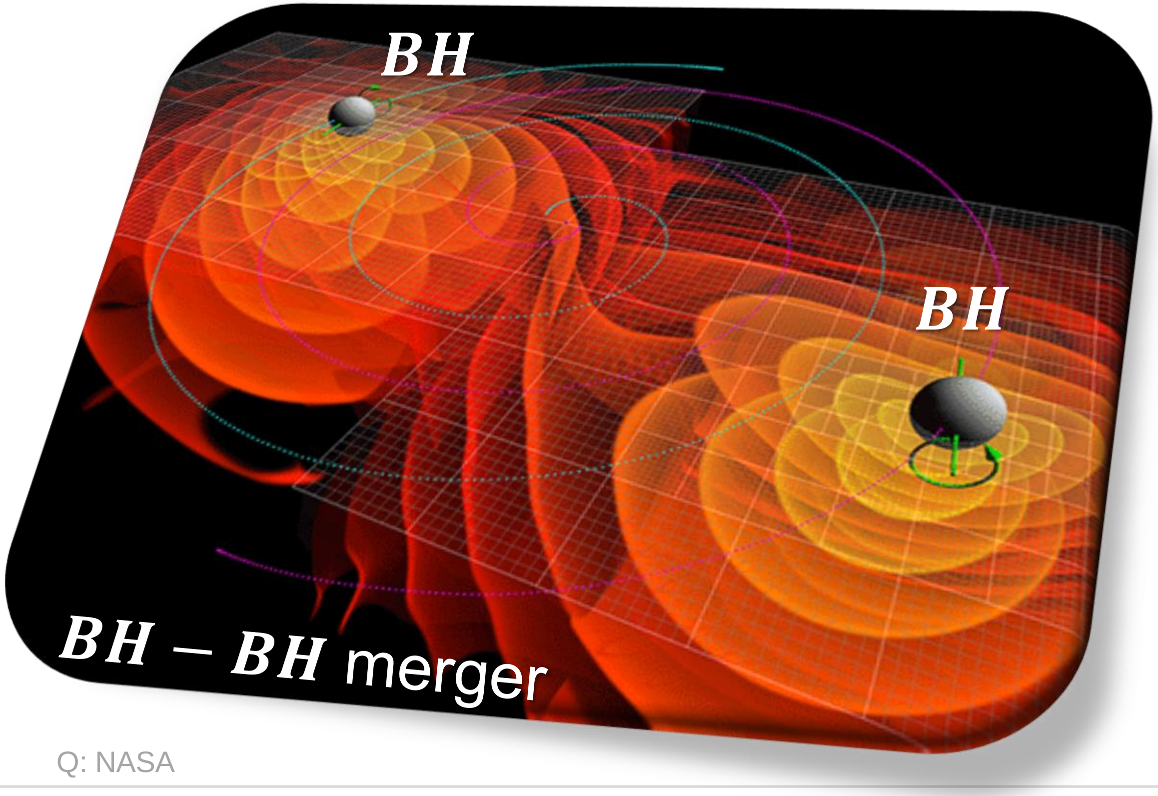


Q: NGA

Thermal & non–thermal universe

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

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



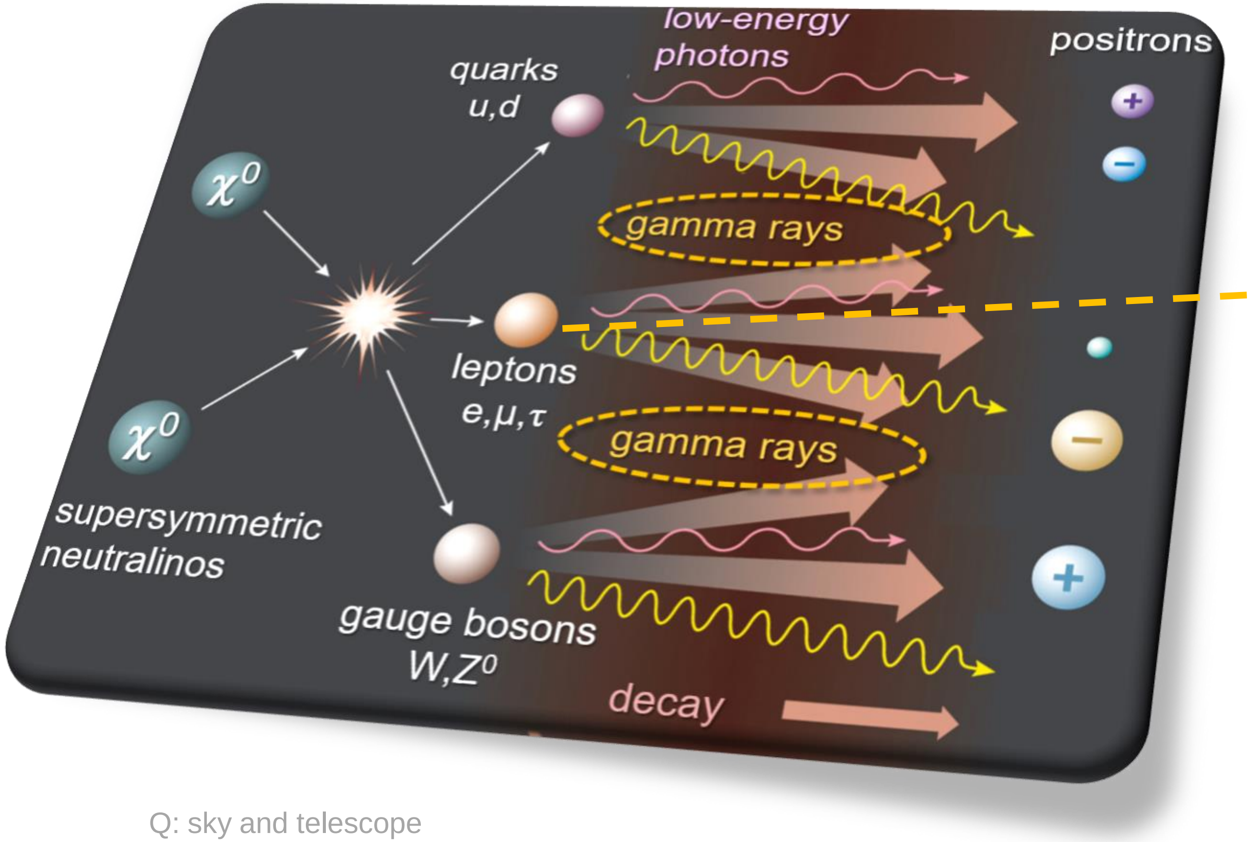
Q: NASA

Q: LIGO

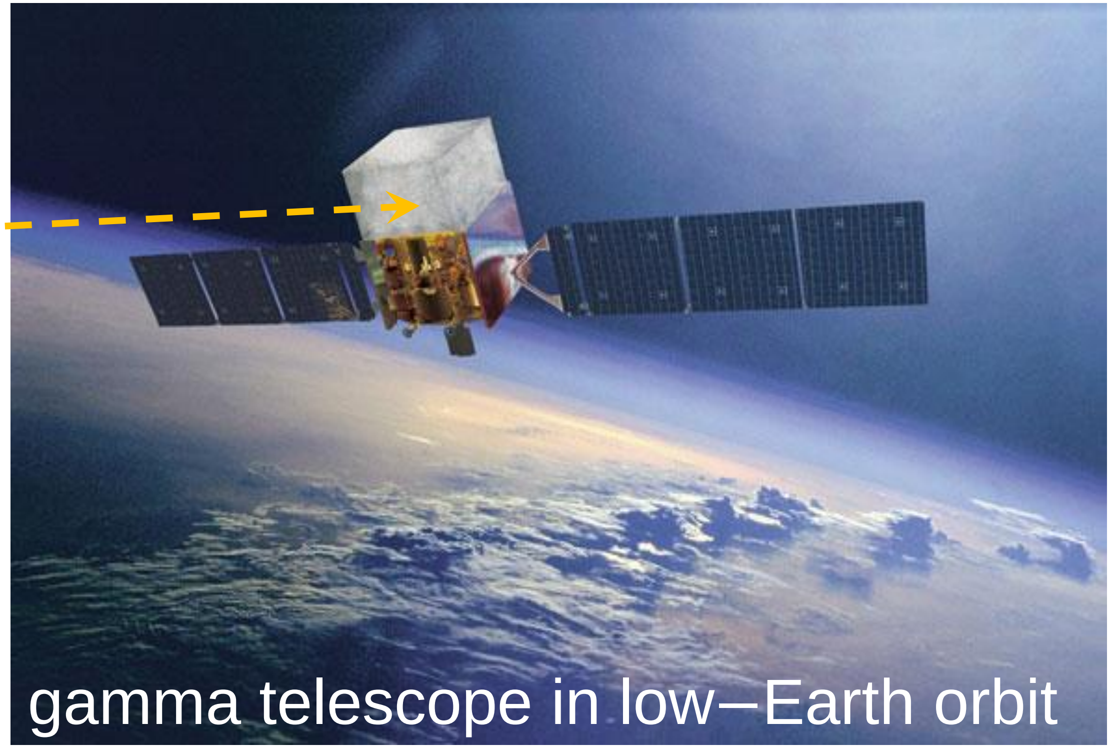
Particle radiation from the dark universe

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

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



Q: sky and telescope



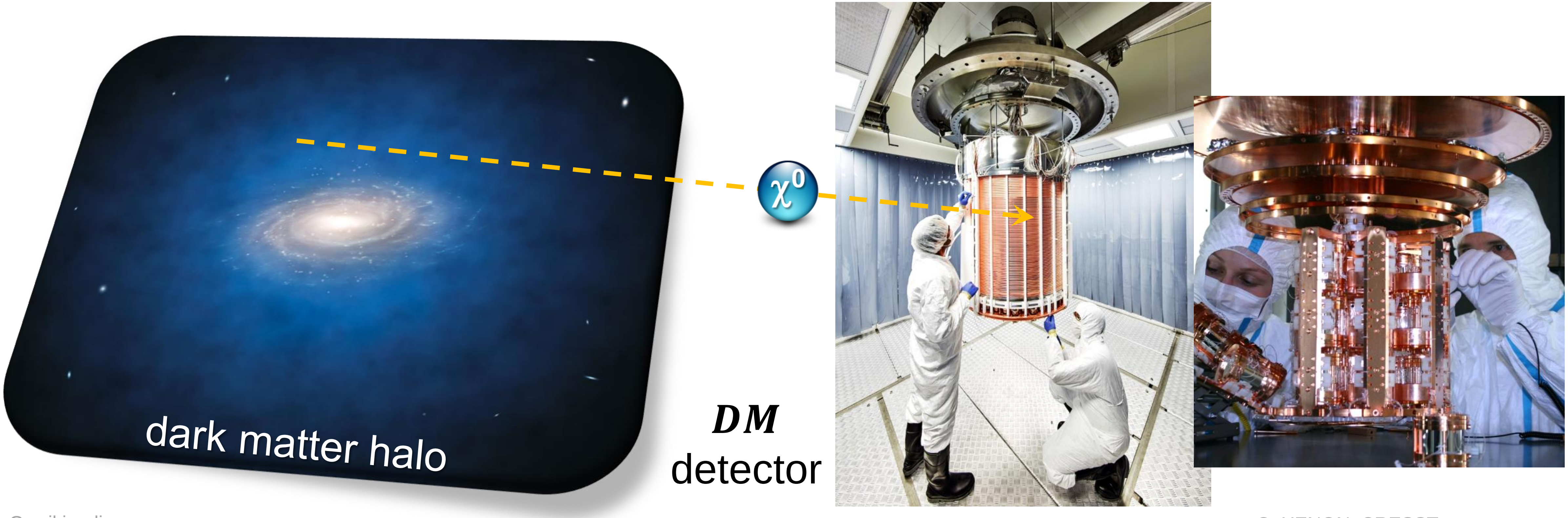
Q: NASA

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

Particle radiation from the dark universe

- **example:** **scattering processes of $WIMPs\ (m = GeV \ldots TeV)$ – 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

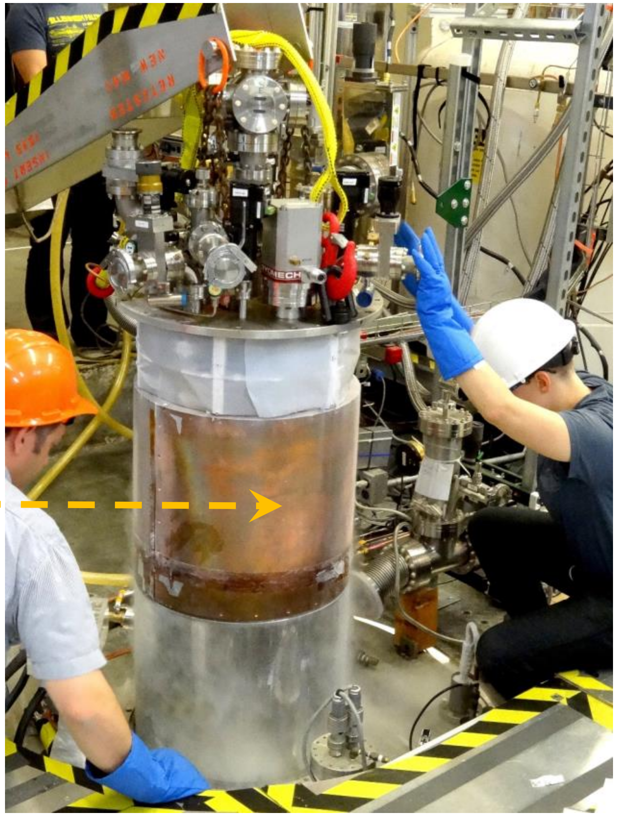
- **example:** conversion processes of $WISPs^{*}$ $(m = sub - eV)$

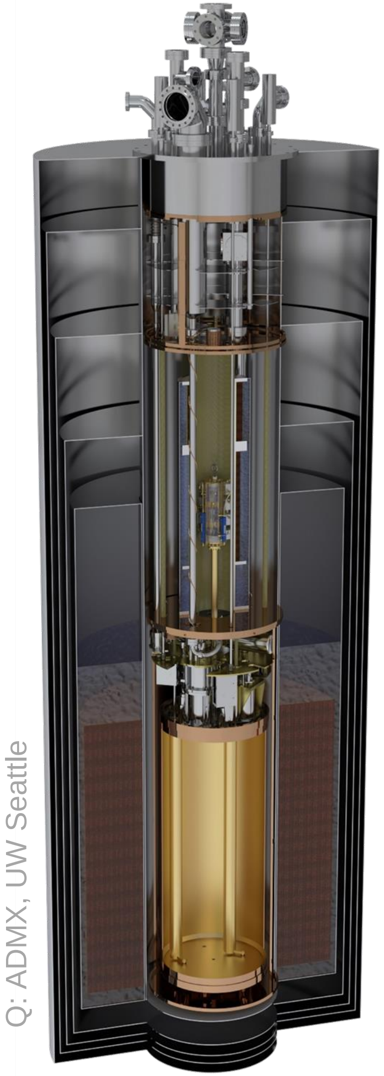
  - source: **very light dark matter** particles from galactic halo

Q: wikipedia

a

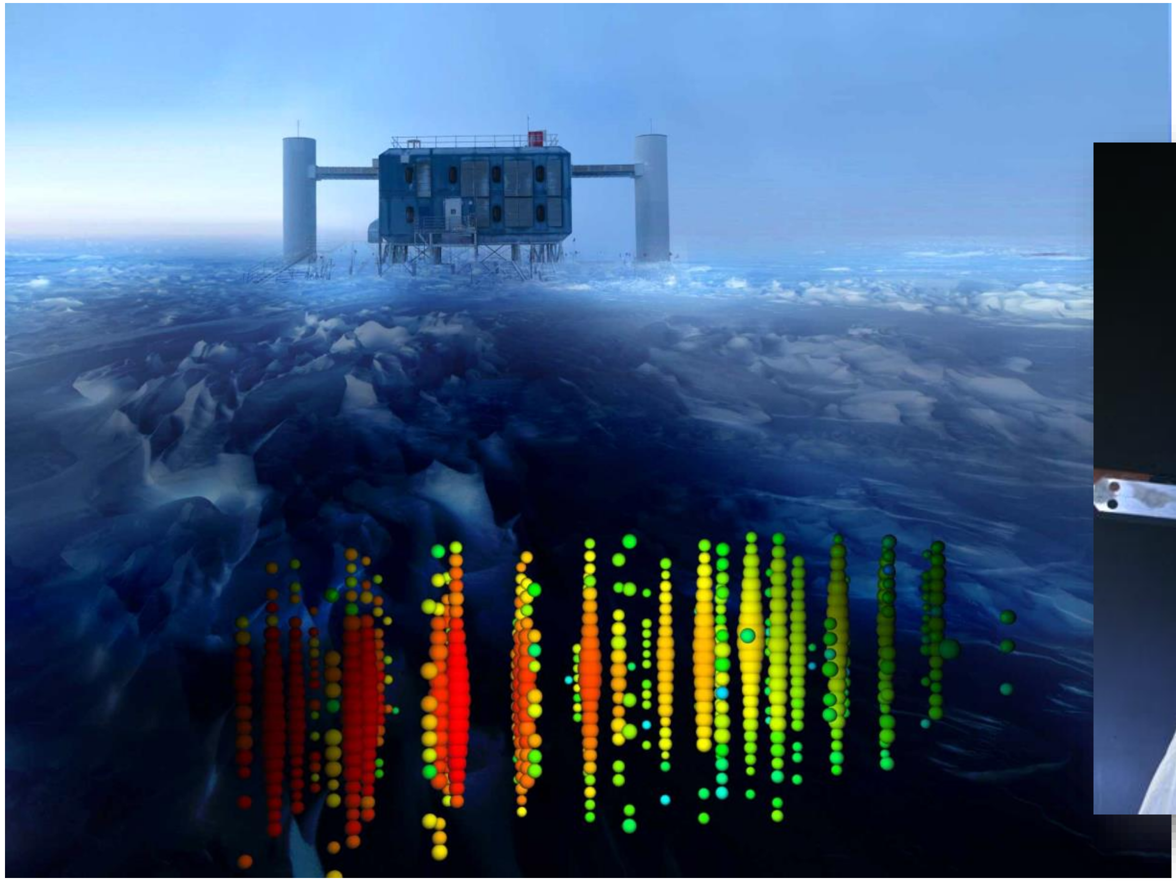
DM
detector





Q: ADMX, UW Seattle

* Weakly Interacting Slim Particle (axions,…)

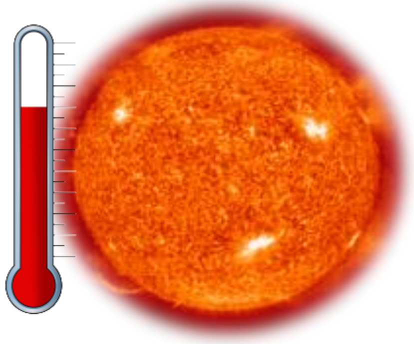


Q: IceCube, CRESST

CHAPTER 2 – EXPERIMENTAL METHODS

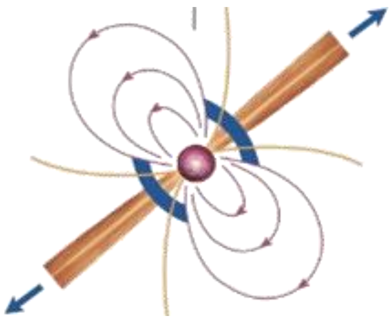
2.1 Multimessenger methods

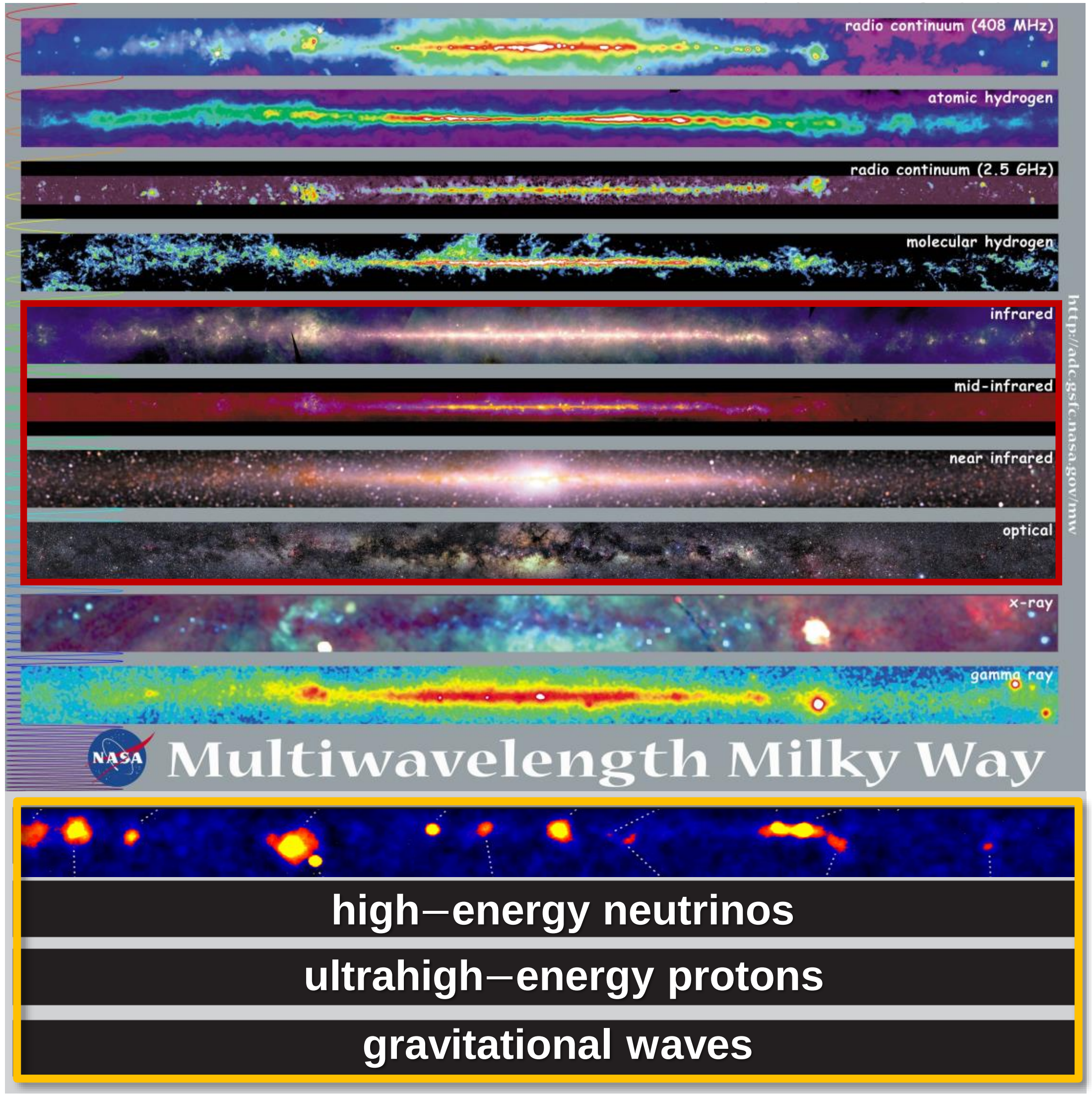
- **overview of particle radiation from the universum – from $\mu eV \ldots TeV$ & beyond**



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

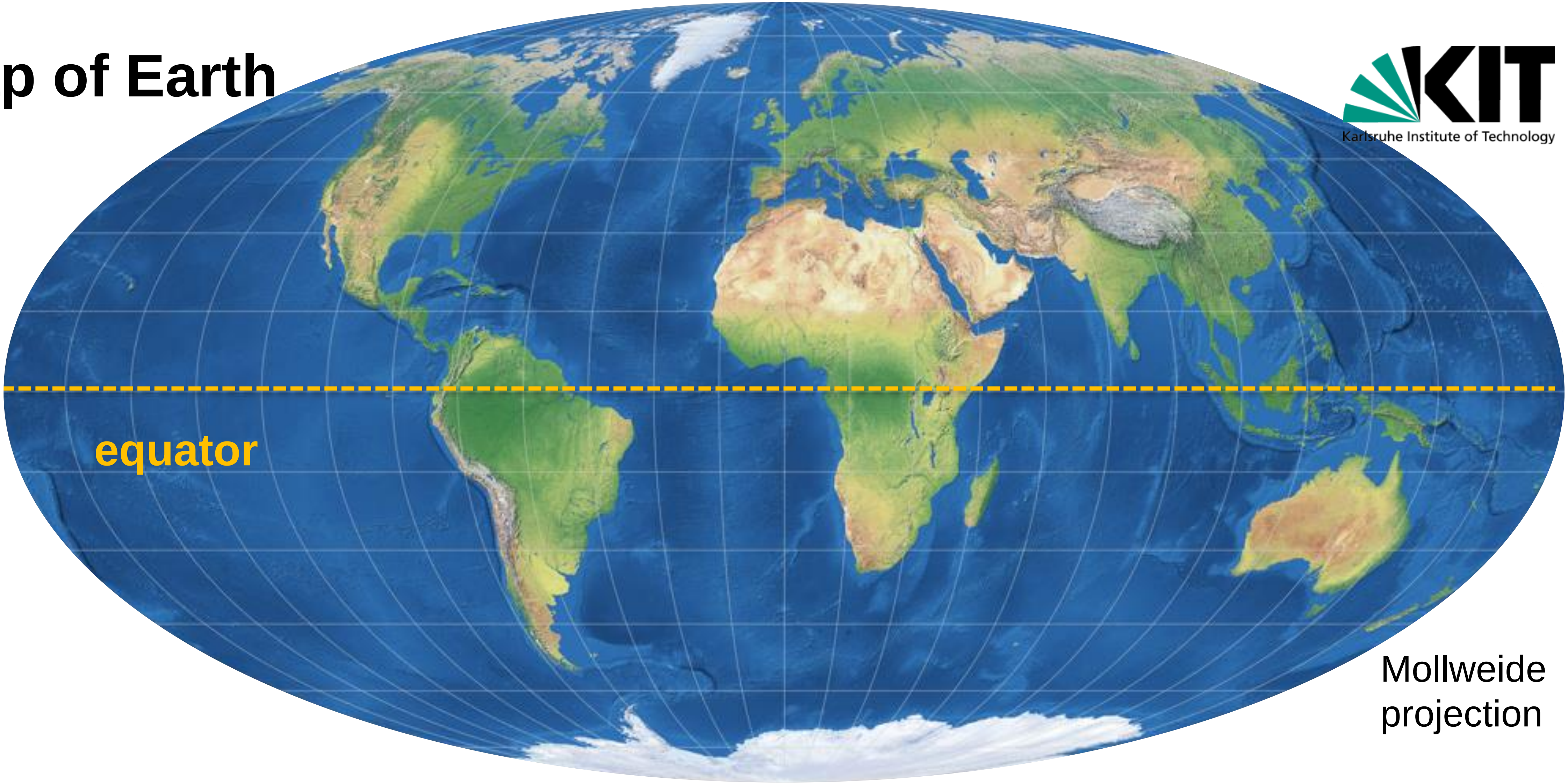
non–thermal universe:
shockfronts of supernovae,
pulsars, black holes,
compact binary objects, ... ?





Q: NASA

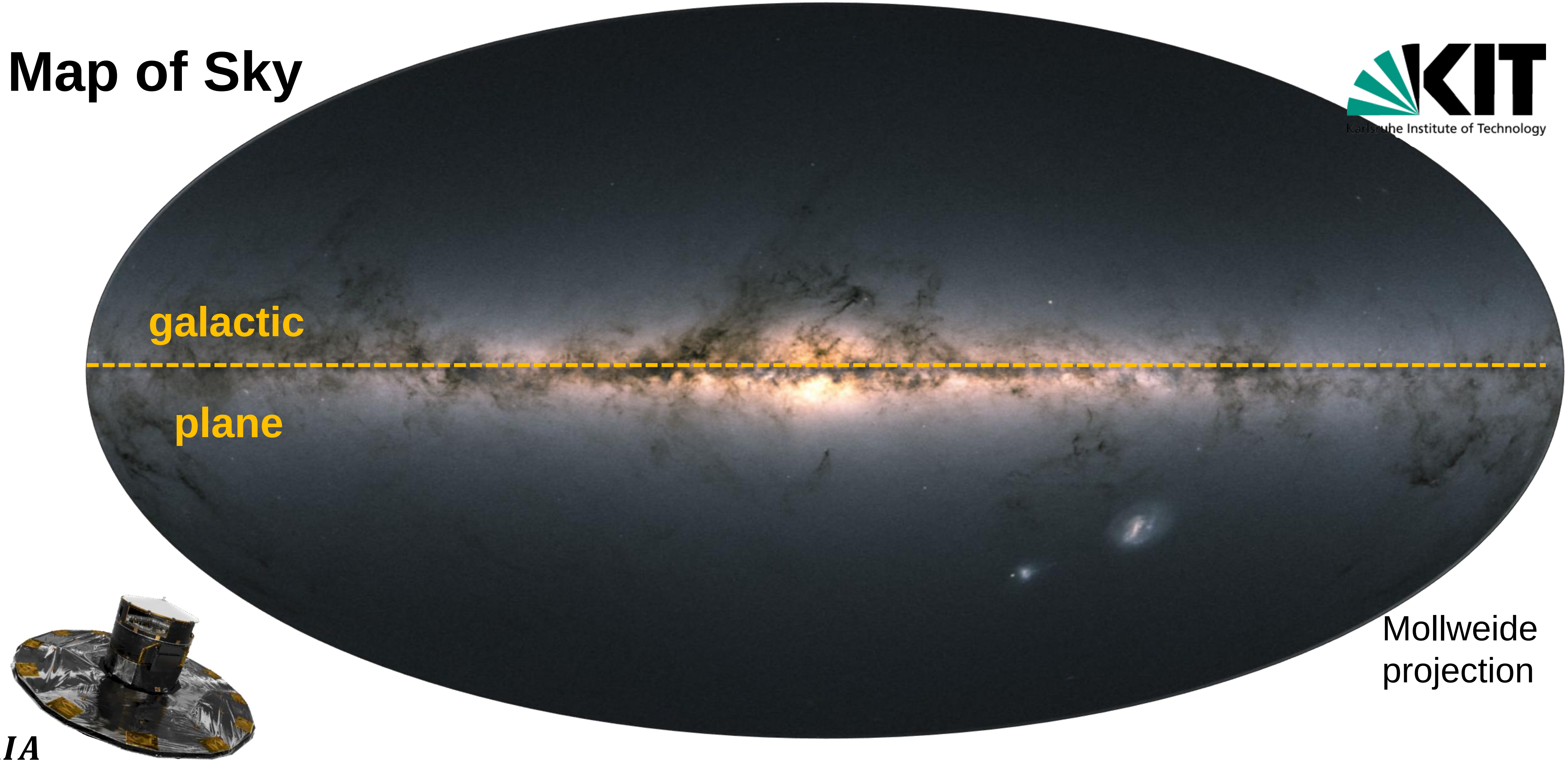
Map of Earth



Display of the sphere of the Earth in a **Mollweide projection**

Q: map-projections.net

Map of Sky



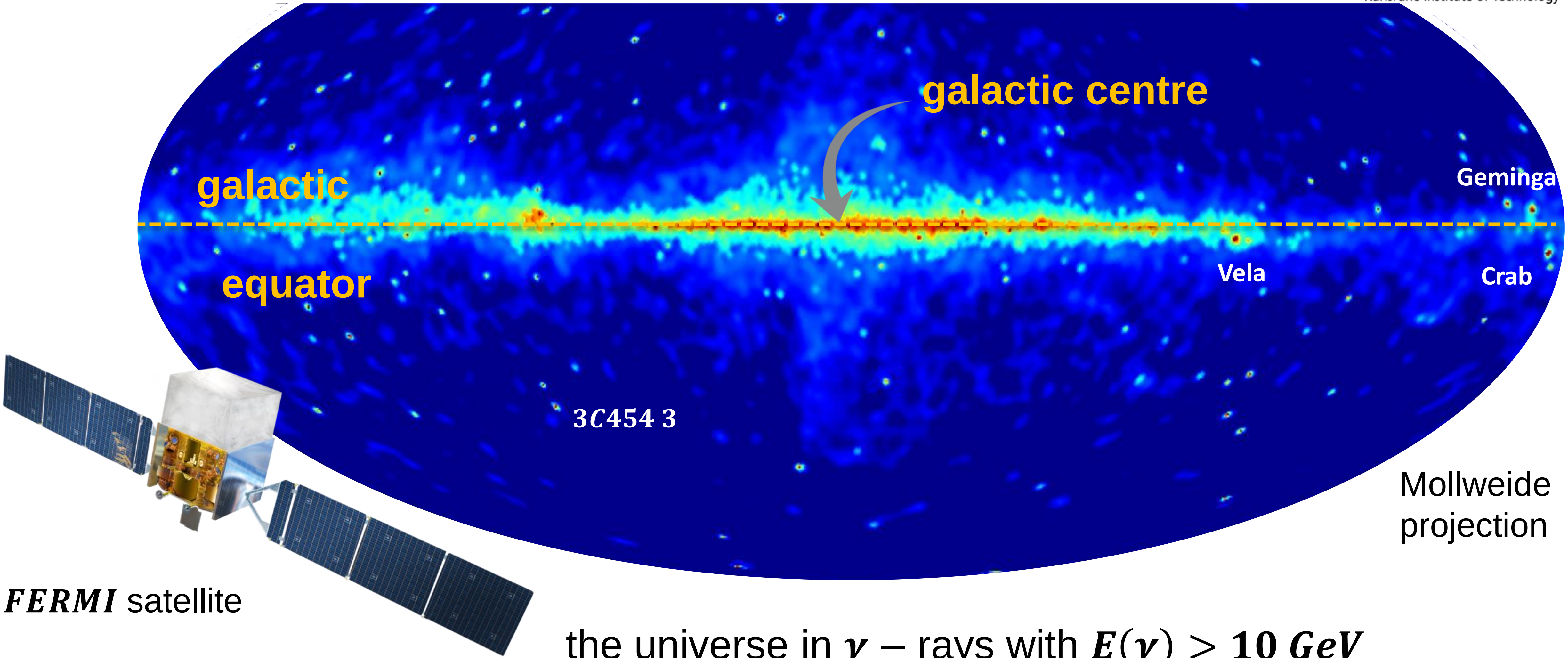
Mollweide
projection

GAIA

display of the sky in visible light along the **galactic plane**

Q: GAIA

High−energy universe: example GeV γ − rays



Mollweide projection

$\boldsymbol{FERMI}$ satellite

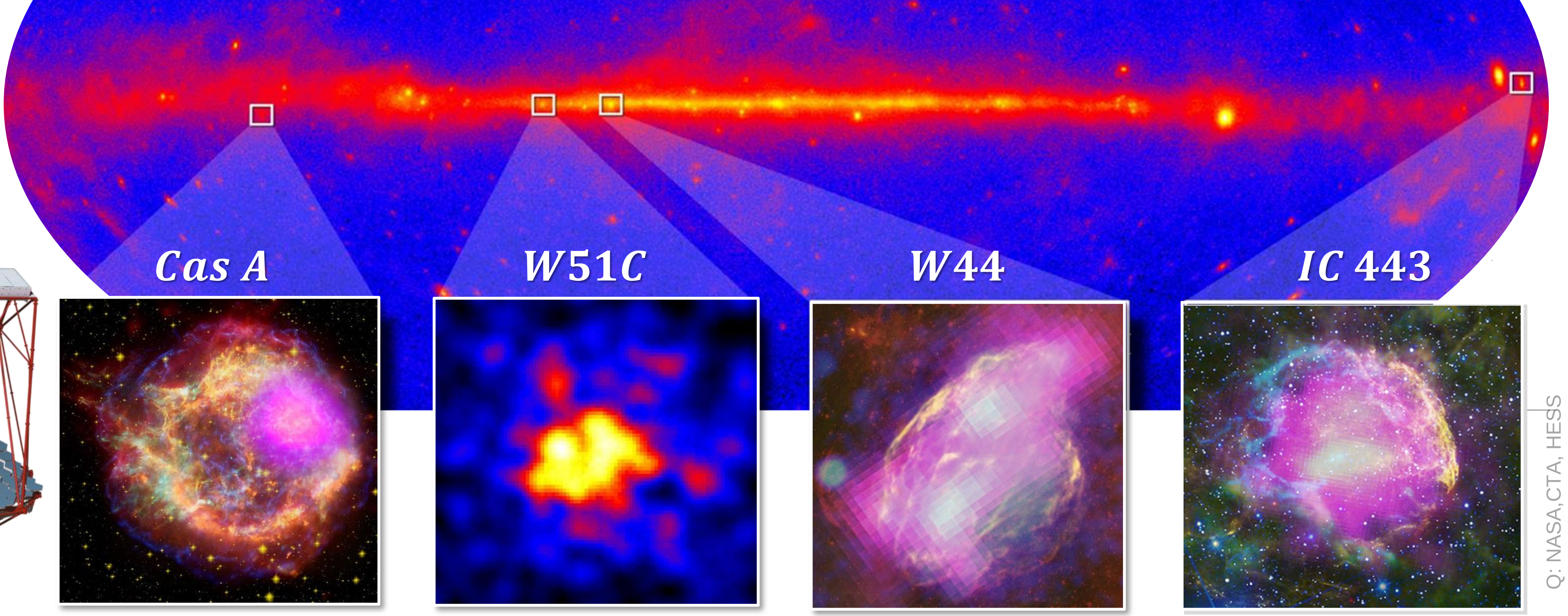
the universe in $\boldsymbol{\gamma}$ – rays with $\boldsymbol{E(\gamma) > 10\ GeV}$

Q: NASA

High–energy universe: example $TeV\ \gamma$ – rays

$HESS.^*$: very high–energy gammas

$(E > 100\ GeV)$ ⇒ specific supernova remnants

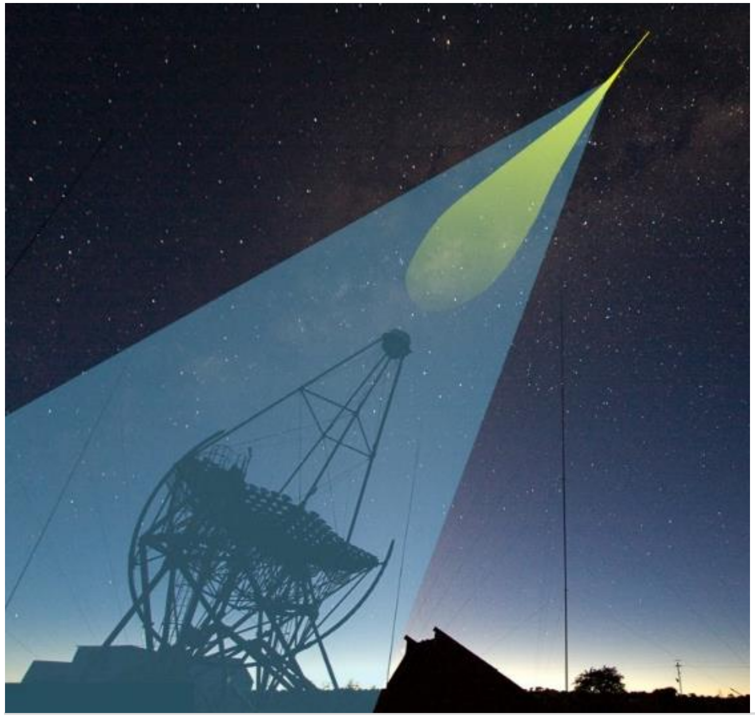


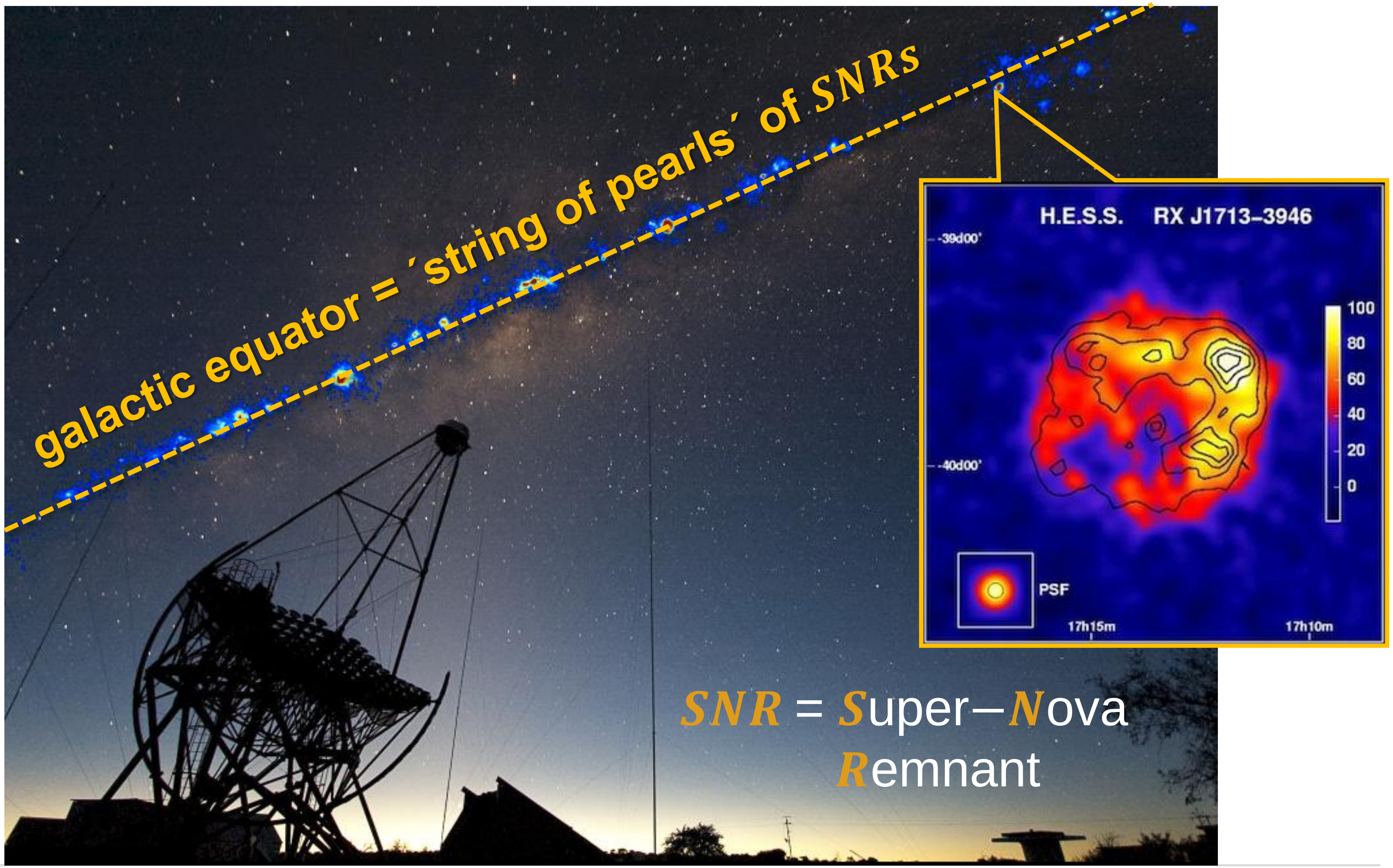
Q: NASA,CTA, HESS

*High Energy Stereoscopic System

High−energy universe: Cherenkov telescopes

- γ − telescopes at the surface: $\boldsymbol{HESS}$, $\boldsymbol{CTA}$*, …



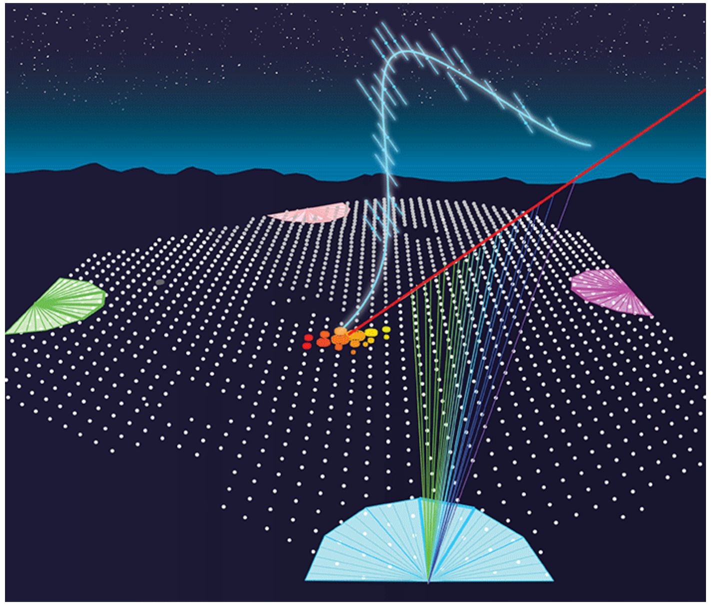


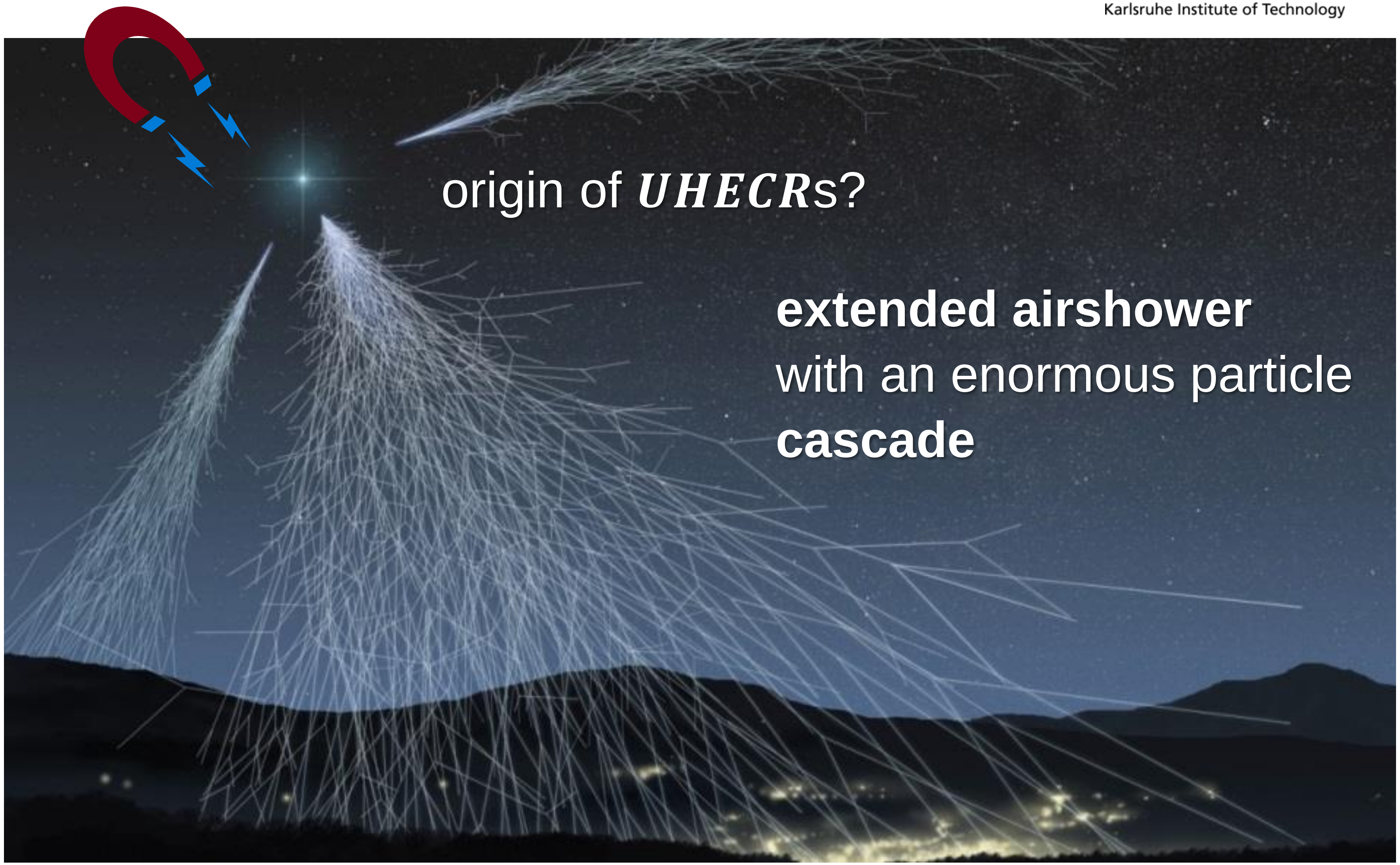
$\boldsymbol{SNR}$ = Super−Nova Remnant

*Cherenkov Telescope Array

High–energy universe: *UHECR*s*

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





Q: APS Physics, APPEC

*Ultra High Energy Cosmic Ray

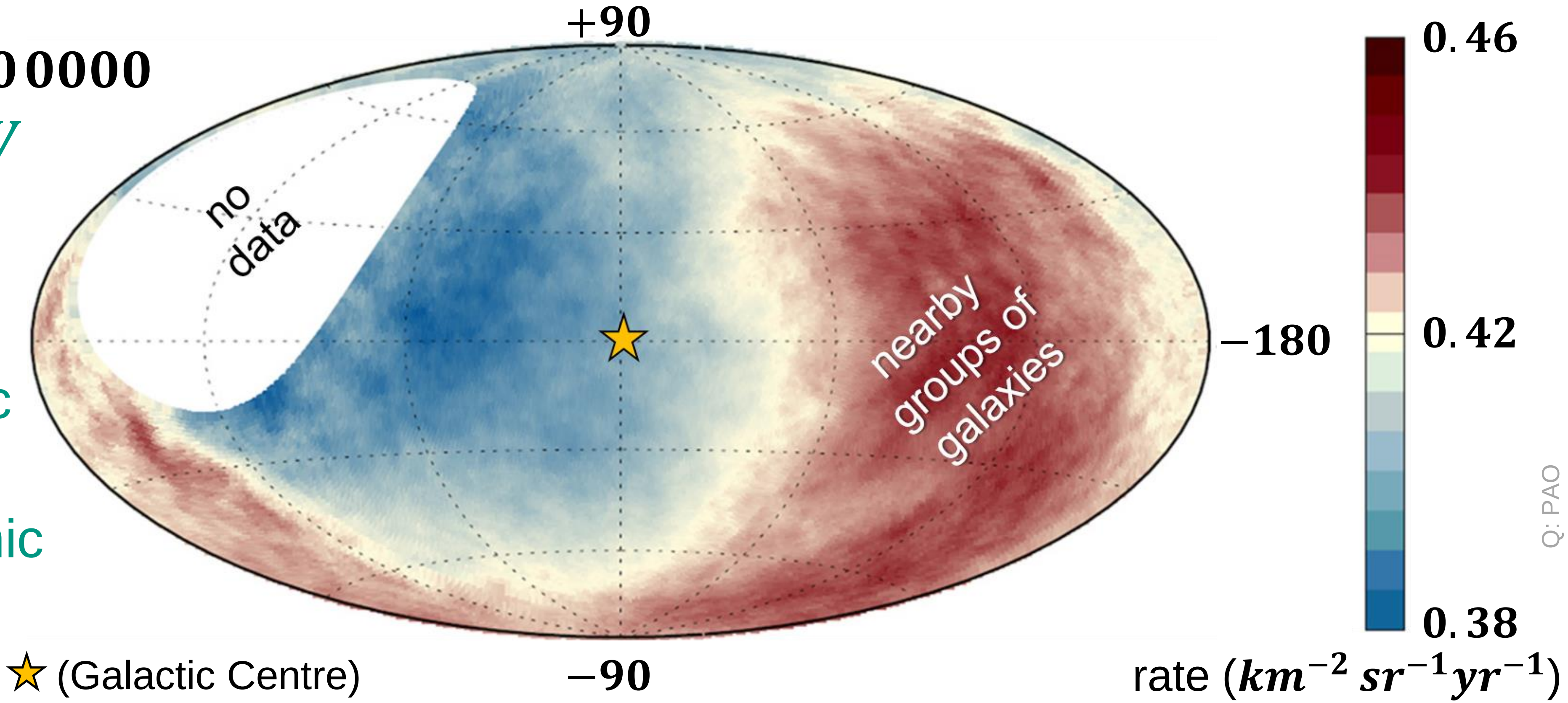
High–energy universe: *UHECRs*

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

- PAO** observes a **dipole anisotropy** ($\sim 6\ \%$): now at stat. significance of $6.6\ \sigma$

- ensemble of ~ 300000 $UHECRs > 8\ EeV$

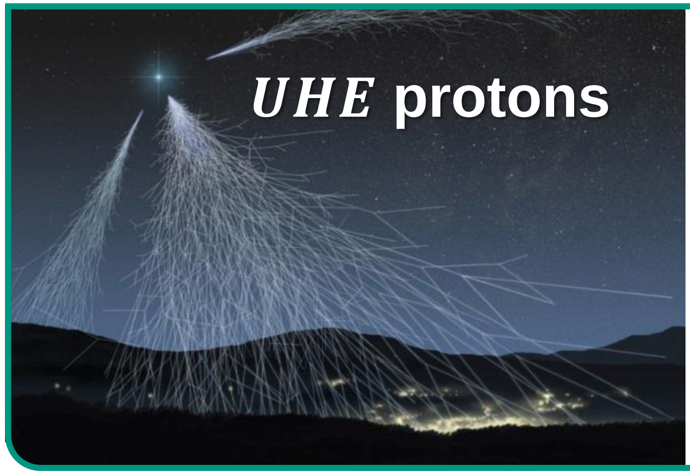
- $120°$ **offset** to galactic centre
  ⇨ extra–galactic origin of charged cosmic rays (EeV)



 *$EeV = 10^{18} eV$ **Pierre Auger Observatory

High–energy universe: $\boldsymbol{UHECRs}$

- **how far can we observe the $\boldsymbol{UHECRs}$ with highest energies (few $\boldsymbol{EeV}$)?**



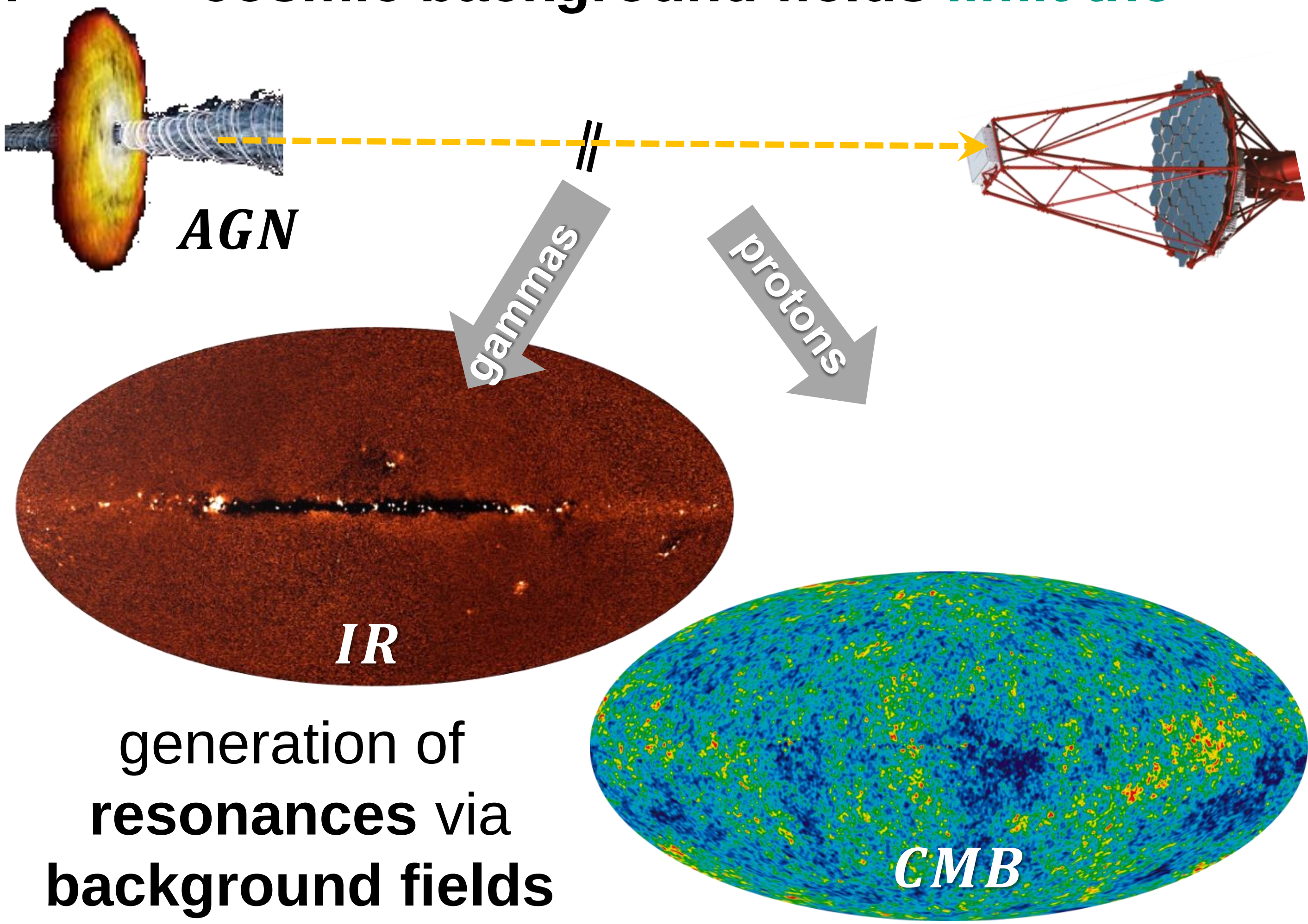
interaction with the cosmic microwave background ($\boldsymbol{CMB}$): resonant generation of a Δ – **baryon**

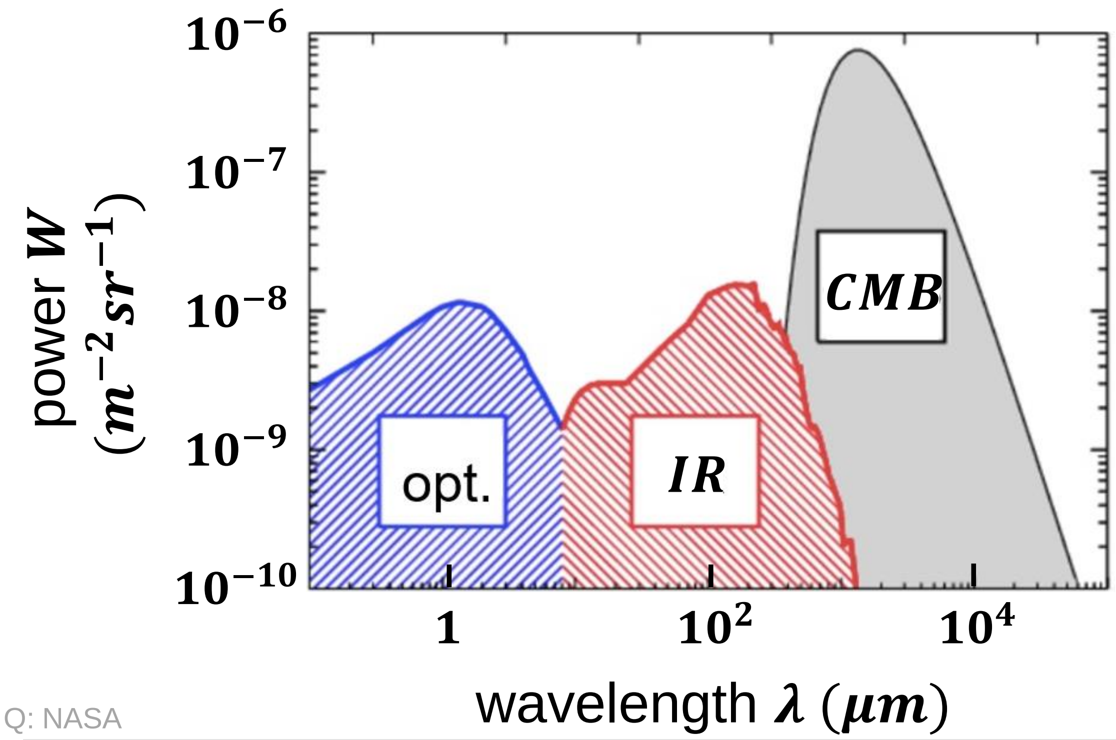
interaction with the infrared – bg ($\boldsymbol{IR}$): resonant generation of $\boldsymbol{e^+e^-}$ pairs

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

range of high−energy particle radiation

- interactions of messengers with cosmic background fields limit the range of $TeV\ \gamma$ / $10^{19} eV\ p$ to $d < 100\ Mpc$





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)

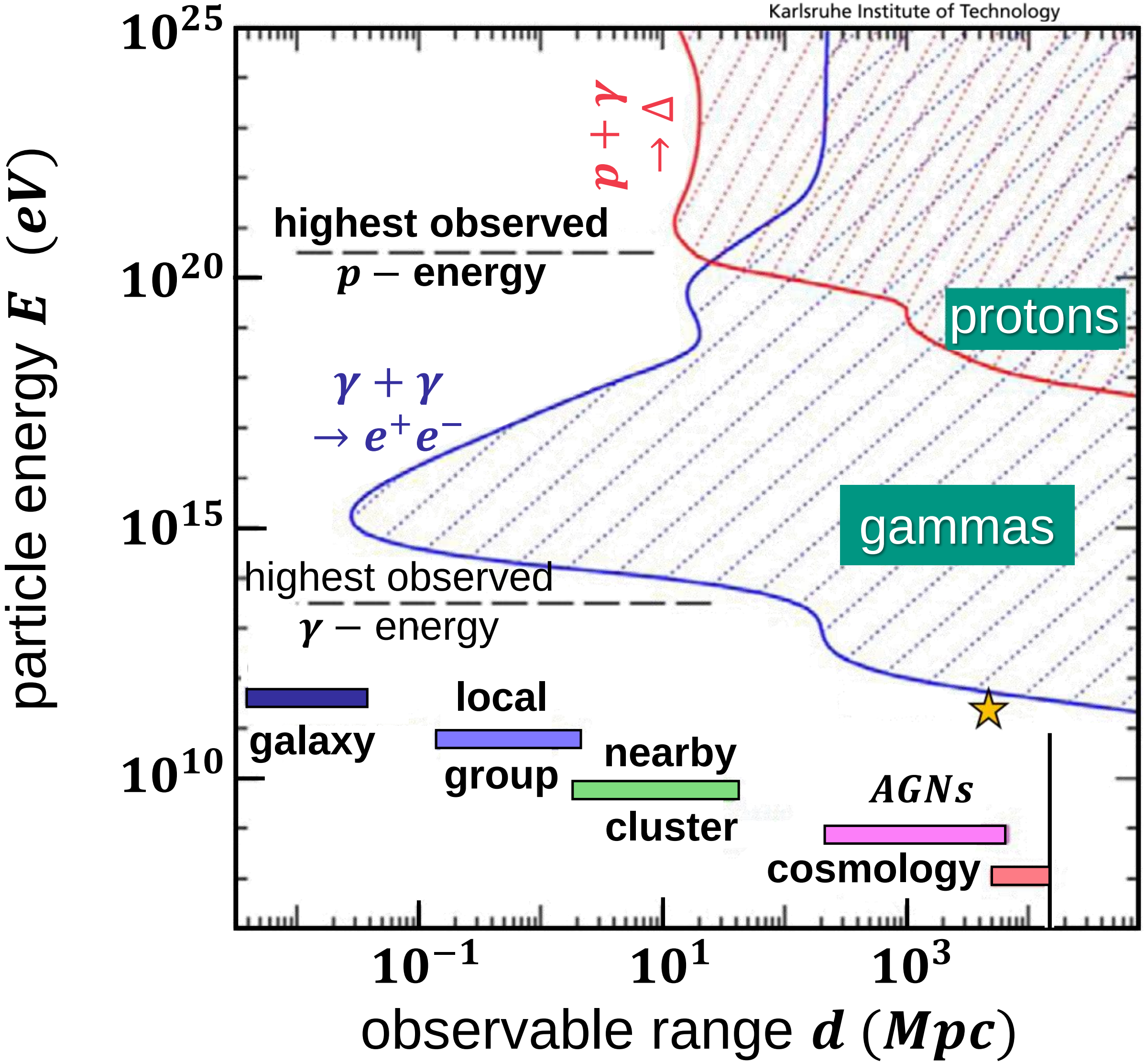
    $\gamma\ (PeV) + \gamma(IR) \ \rightarrow e^+e^-$ pair

    PeVatrons* can be observed via γ´s only in our own **galaxy**

  - high−energy protons (ZeV)

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

    ZeVatrons* (for p) only up to **10 Mpc**



Q: NA

*named after TeVatron at Fermilab, USA

range of gammas: a possible hint for axions ?

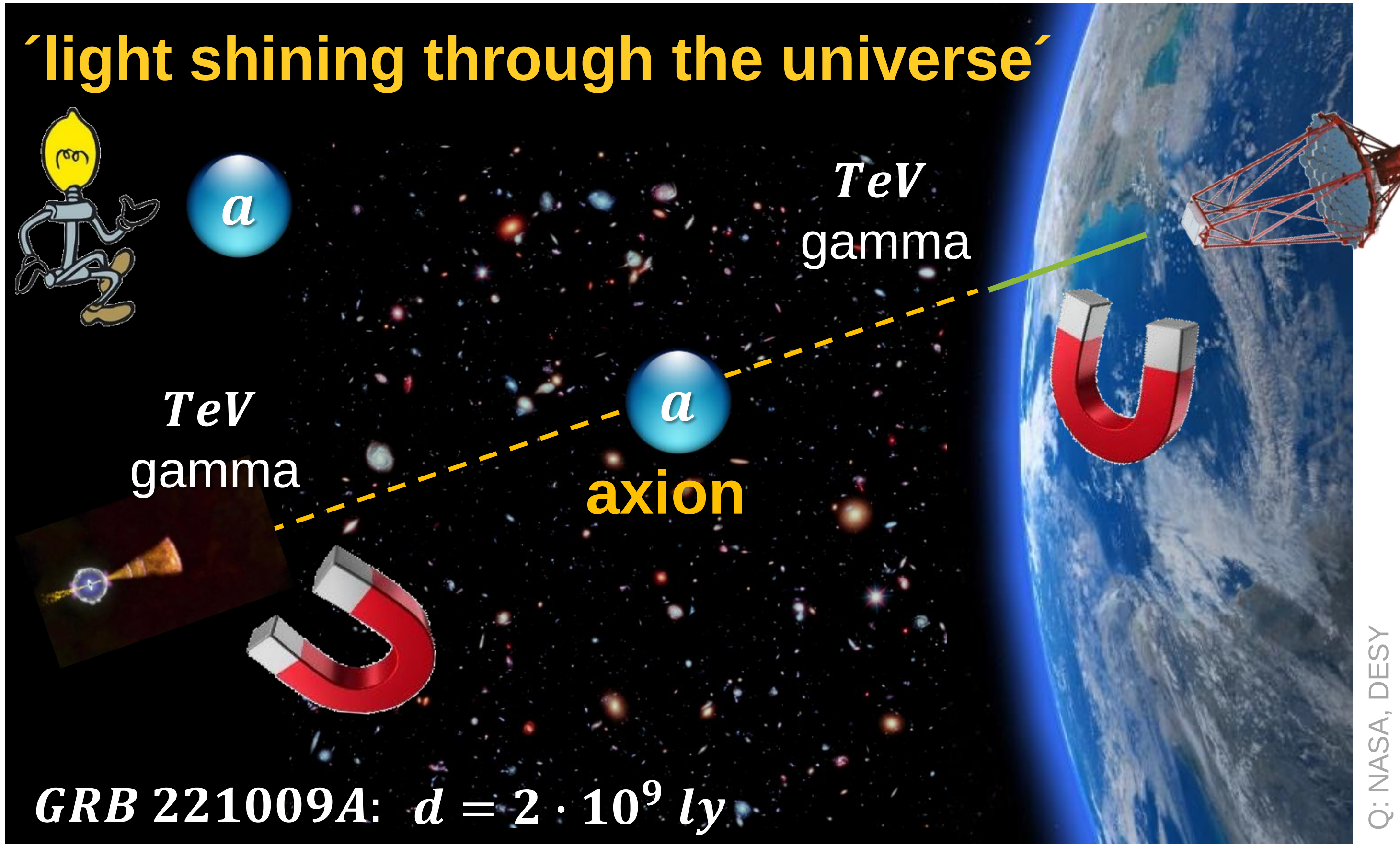
- **tantalizing way to extend γ – range: conversion to axions* & back (B – fields)**

experimental observation:
universe (seemingly) is much **more transparent** for very high–energy γ´s than we expect

an intriguing **theoretical ansatz**:

➊ $TeV - \gamma$ converts in the B – field close to the source into hypothetical **axion**, which will propagate over Gpc

➋ **axion** converts back to γ



Q: NASA, DESY

*see chapter 4.6.1 on axions

range of gammas: a possible hint for axions ?

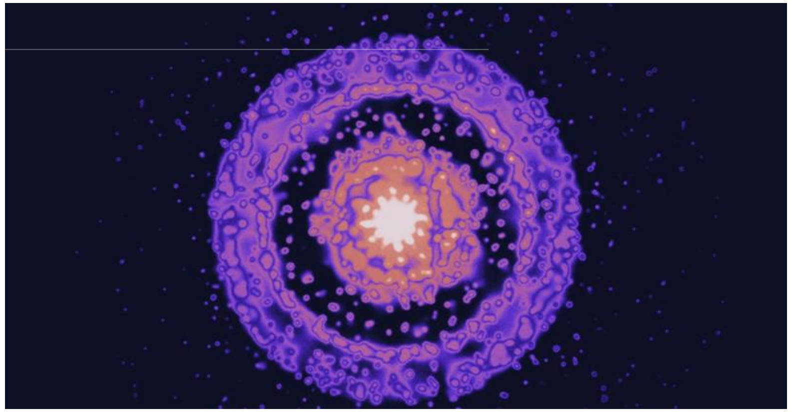
Brightest-Ever Space Explosion Reveals Possible Hints of Dark Matter

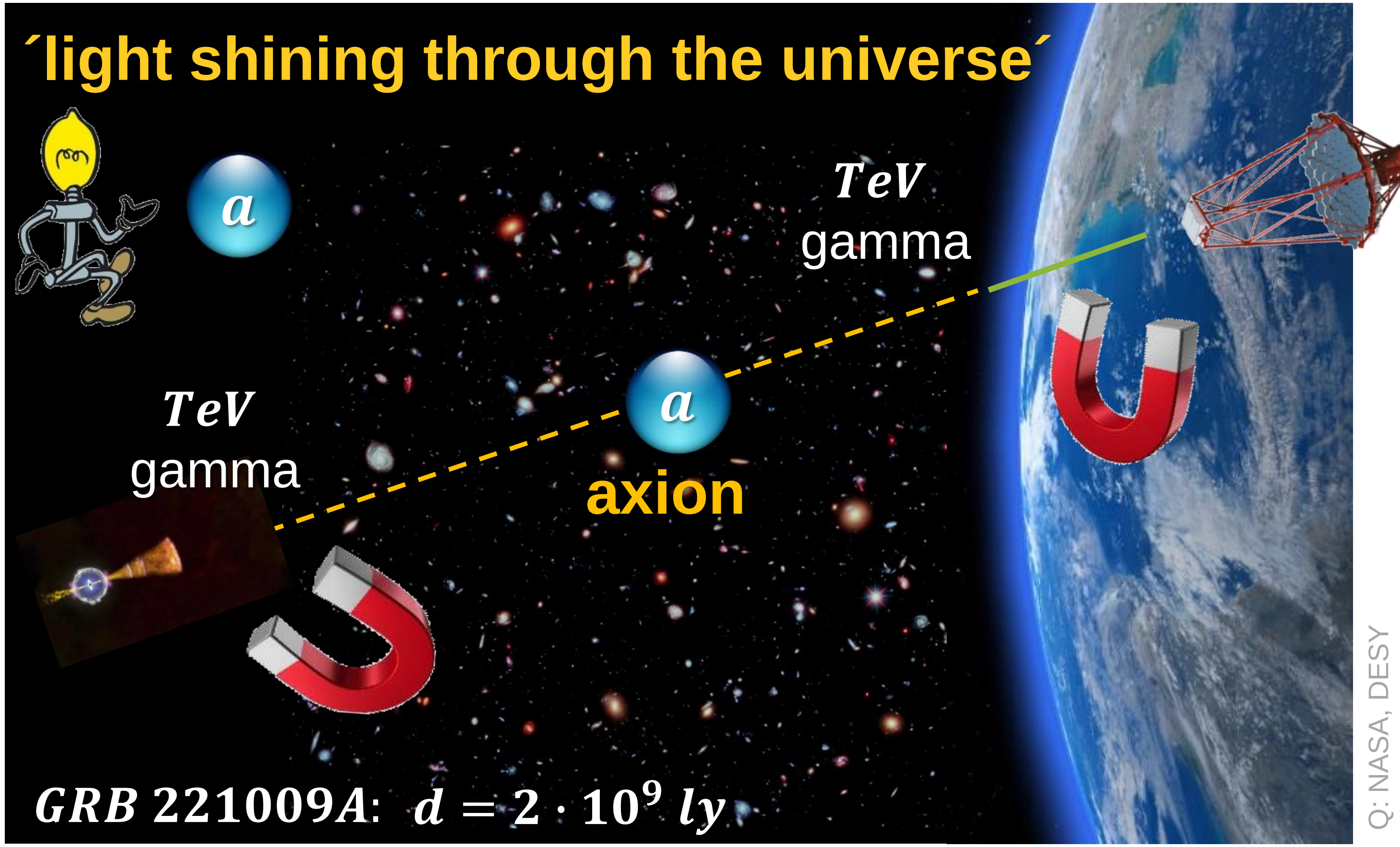
By JONATHAN O'CALLAGHAN

October 26, 2022

A recent gamma-ray burst known as the BOAT — "brightest of all time" — appears to have produced a high-energy particle that shouldn't exist. For some, dark matter provides the explanation.

HOT TOPIC





Q: NASA, DESY

*see chapter **4.6.1** on axions