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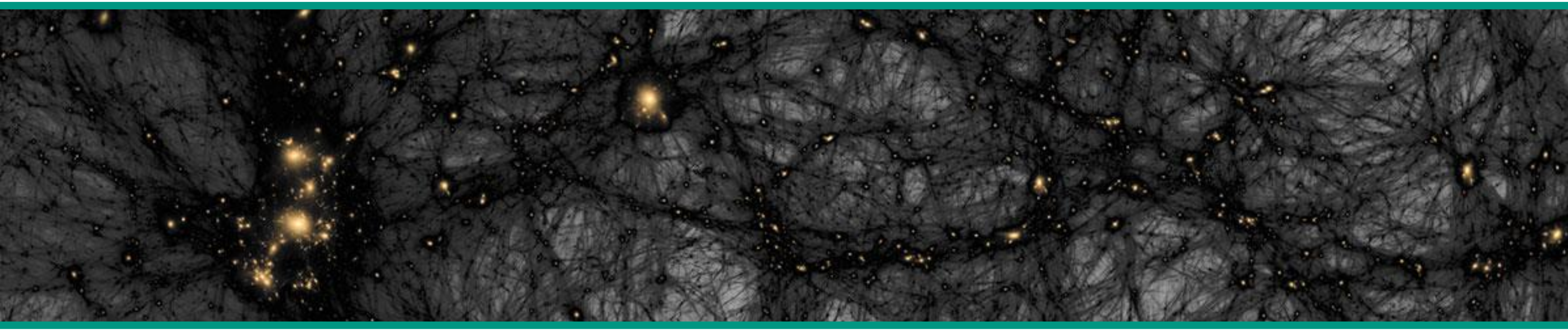
Astroparticle physics I – Dark Matter

WS22/23 Lecture 9 Dec. 1, 2022



Topical: Interesting new article on KM3NeT

- A ´deep dive´ into the Mediterraneans´ dark abyss

HOT TOPIC

NEUTRINOS OUT OF THE BLUE

More than 17,000 photomultipliers for KM3NeT are already transmitting data from the Mediterranean seabed, opening a new vista on the neutrino's properties. Paschal Coyle, Antoine Kouchner and Gwenhaël De Wasseige take a deep dive.

In the dark abysses of the Mediterranean Sea, what promises to be the world's largest neutrino telescope, KM3NeT, is rapidly taking shape. Using transparent seawater as the detection medium, its large three-dimensional arrays of photosensors will instrument a volume of more than one cubic kilometre and detect the faint Cherenkov light induced by the passage of charged particles produced in nearby neutrino interactions. The main physics goals of KM3NeT are to detect high-energy cosmic neutrinos and identify their astrophysical origins, as well as to study the fundamental properties of the neutrino itself.

KM3NeT (the Cubic Kilometre Neutrino Telescope) is the successor to the ANTARES neutrino telescope, which operated continuously from 2008 and has recently been decommissioned (see "The ANTARES legacy" panel, p32). KM3NeT comprises two detectors: ARCA (Astroparticle Research with Cosmics in the Abyss), located at a depth of 3500 m offshore from Sicily, and ORCA (Oscillation Research with Cosmics in the Abyss), located at a depth of 2450 m offshore from southern France. ARCA is a sparse detector of about 1 km^3 that is optimised for the detection of TeV–PeV neutrinos, while ORCA is a 7 Mt-dense detector optimised for sub-TeV neutrinos. The KM3NeT collaboration comprises more than 250 scientists from 16 countries.

The key technology is the digital optical module (DOM) – a pressure-resistant glass sphere hosting 31 three-inch photomutiplier tubes, various calibration devices and the readout electronics (see "Modular" image). A total of 18 DOMs are hosted on a single detection line, and the lines are anchored to the seafloor and held taut by a submerged buoy. The ORCA detector will comprise around 100 lines and the ARCA detector will have twice as many. The bases of the lines are connected via cables on the seafloor to junction boxes, from which electro-optical cables many tens of kilometres long bring the data to shore along optical fibres. Information on every single photon is transmitted to the shore stations, where trigger algorithms are applied to select interesting events for offline analysis.

From the light pattern recorded by the DOMs, the energy and the direction of a neutrino can be estimated. Furthermore, the neutrino flavour can also be distinguished; muon neutrino charged-current (CC) interactions produce an extended track-like signature (see "Subsea shower" image) whereas electron- and tau-neutrino CC interactions, as well as neutral-current interactions, produce more compact shower-like events. By selecting up-going neutrinos, i.e. those that have travelled from the other side of Earth, the large background from down-going

THE AUTHORS

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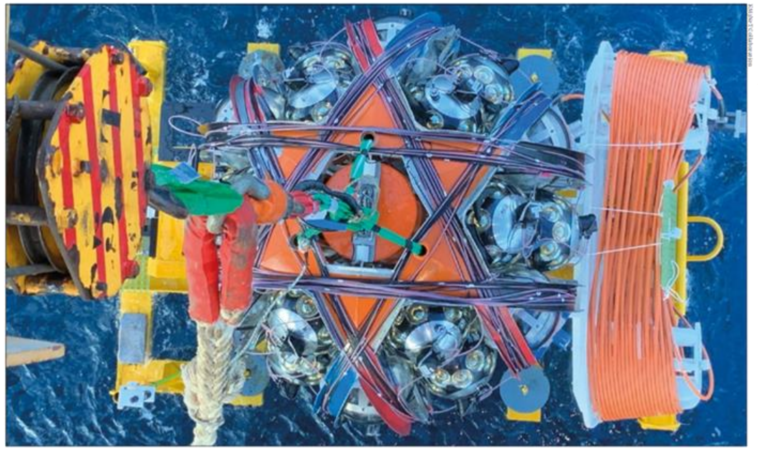

First descent *One of the KM3NeT lines bundled up before being unwound and lowered into position.*

Modular *The assembly room for the KM3NeT optical modules, with a photo of the first prototype module visible as a screen saver.*

atmospheric muons can be rejected and a clean sample of neutrinos obtained.

The first KM3NeT detection line was connected in 2016 and currently a total of 32 lines are operating at the two sites. The first science results with these partial detectors have already been obtained.

Fundamental neutrino properties

Sixty-six years after their discovery, neutrinos remain the most mysterious of the fermions. As they whiz through the universe, barely interacting with any other particles, they have the unique ability to oscillate between their three different types or flavours (electron, muon and tau). The observation of neutrino oscillations in the late 1990s implies that neutrinos have a non-zero mass, contrary to the Standard Model expectation. Understanding the origin and order of the neutrino masses could therefore unlock a path to new physics. Numerous neutrino experiments around the world are closing in on the neutrino's properties, using both artificial (accelerator and reactor) and natural (atmospheric and extraterrestrial) neutrino sources.

Sixty-six years after their discovery, neutrinos remain the most mysterious of the fermions

The KM3NeT/ORCA array is optimised for the detection of atmospheric neutrinos, produced when cosmic rays strike atomic nuclei at an altitude of around 15 km. Such interactions produce a cascade of particles on Earth's surface, mostly pions and kaons, which decay to neutrinos capable of traversing the entire planet. About two thirds of these are muon neutrinos and antineutrinos, and the remainder are electron neutrinos and antineutrinos.

Measuring the directions and energies of the detected atmospheric neutrinos allows the oscillatory behaviour of neutrinos to be studied, and thus elements of the leptonic "PMNS" mixing matrix to be determined. The measured direction is used as a proxy for the distance the atmospheric neutrino has travelled through Earth between its points of production and detection. First preliminary results with six ORCA lines and one year of data clearly show the expected disappearance of muon neutrinos with increasing baseline/energy. The corresponding constraints on θ_{23} (the mixing angle between the m_2 and m_3 states) and Δm^2_{32} (the mass difference of the squared masses) already start to be competitive with multi-year results from the current long-baseline accelerator experiments (see "Physics debut" figure, p33).

A longer-term physics goal of KM3NeT is to determine the neutrino mass ordering, i.e. whether the third neutrino

Recap of Lecture 8

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- **VHE…UHE gammas: source modelling & detection with IACTs**

  - VHE γ – induced showers: **narrow Cherenkov cone** (1°) from relativistic e^+, e^-

  - **shower parameters** to discriminate against showers from charged CRs

  - arrays of IACTs for stereoscopic view & **better gamma sensitivity**

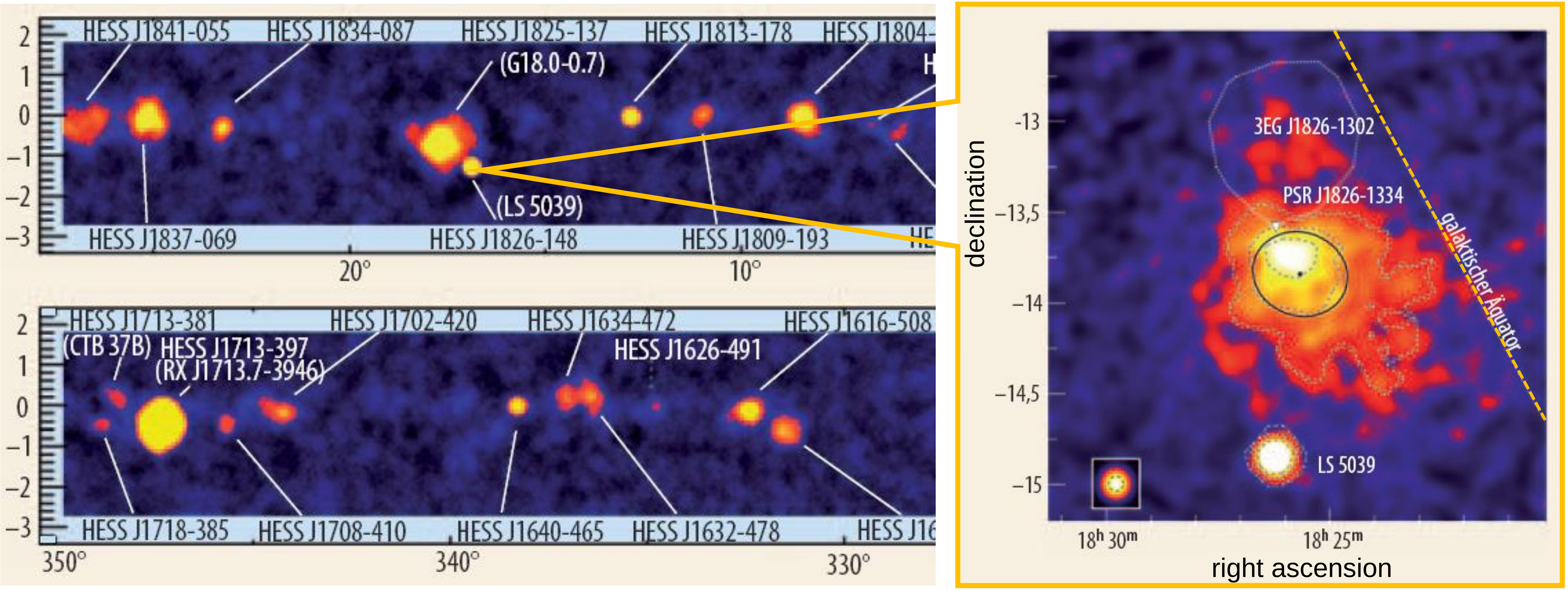
  - source modelling: **hadronic** $(\pi^0 \rightarrow \boldsymbol{\gamma\gamma})$ vs. **leptonic** $(\boldsymbol{e}^- + \gamma \rightarrow \boldsymbol{\gamma} + e^-)$

  - leading observatories: MAGIC (La Palma), H.E.S.S. (Namibia), …

  - scan of the galactic plane: new sources – SNRs, pulsar wind nebulae, …

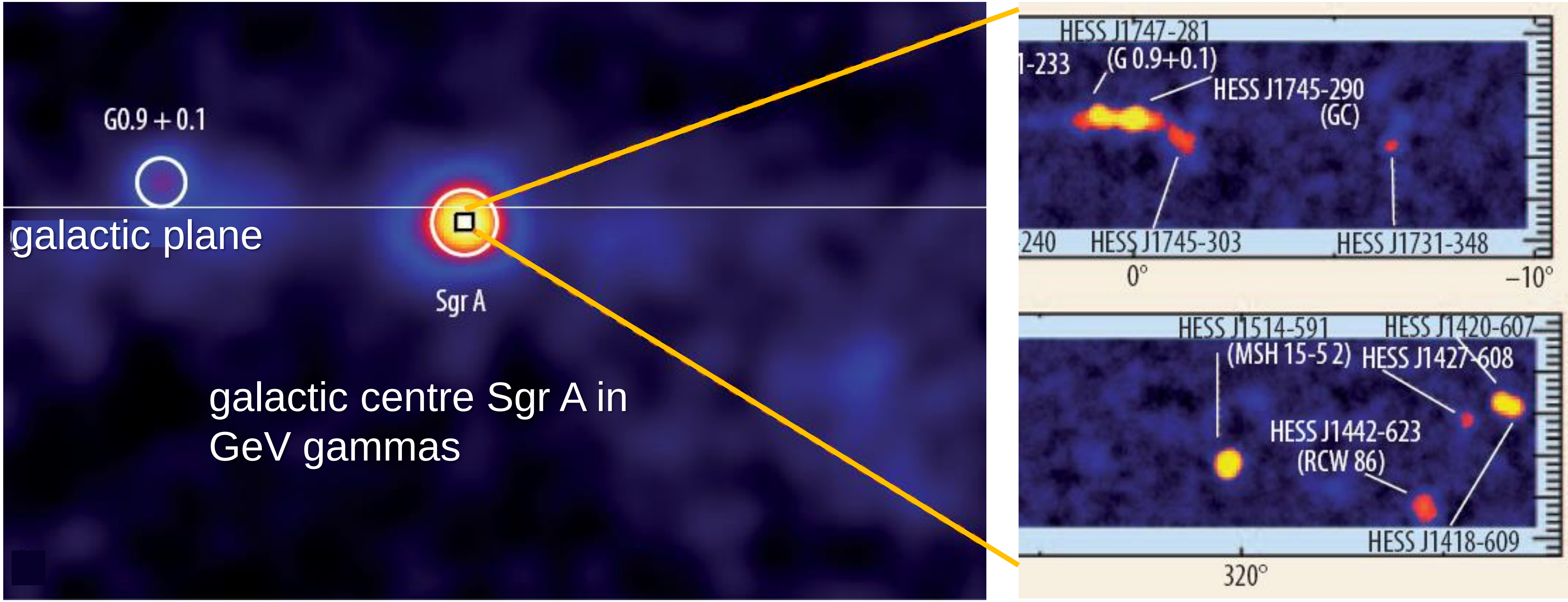
Scanning the galactic plane for UHE gammas

- **2004: first scan with H.E.S.S. over > 600 h – 15 new sources at TeV – scale**



Scanning the galactic plane for UHE gammas

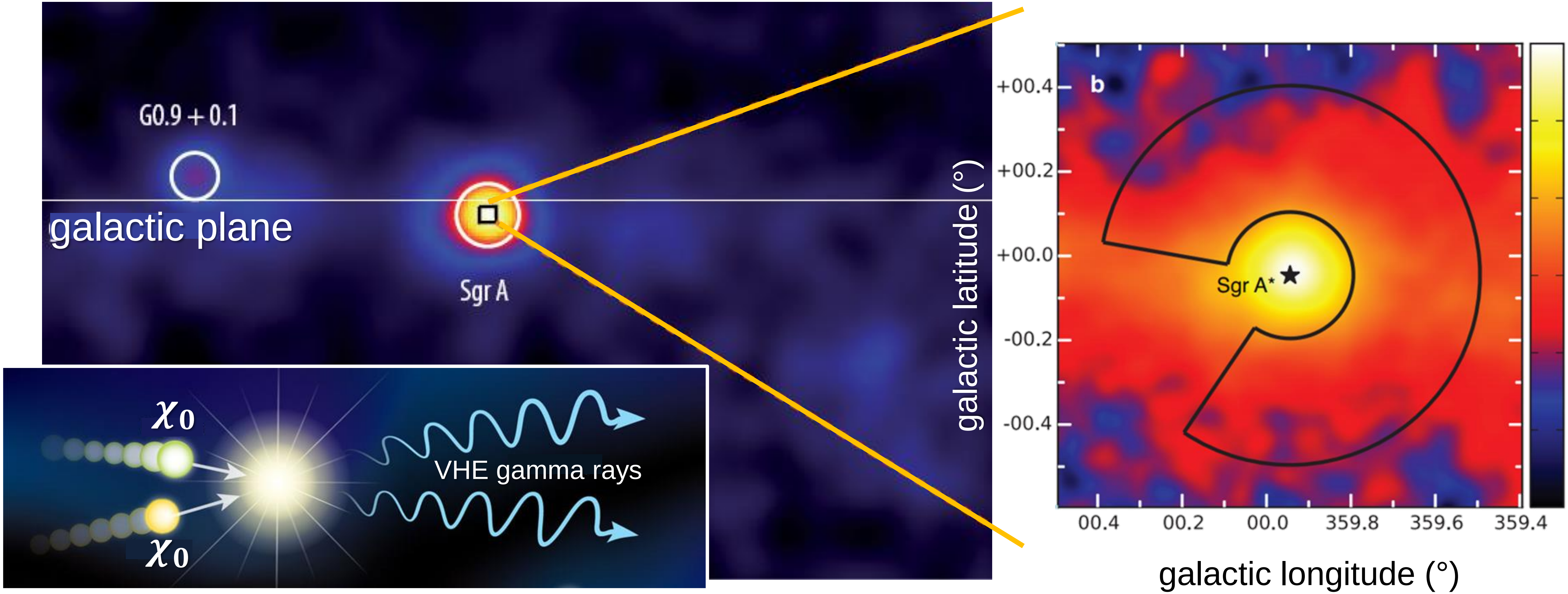
- 2004: strong UHE gamma emission* from the galactic center!



*we will return to Sgr A in our Dark Matter search!

Scanning the galactic plane for UHE gammas

- gamma emission from dark matter annihilation close to galactic center?

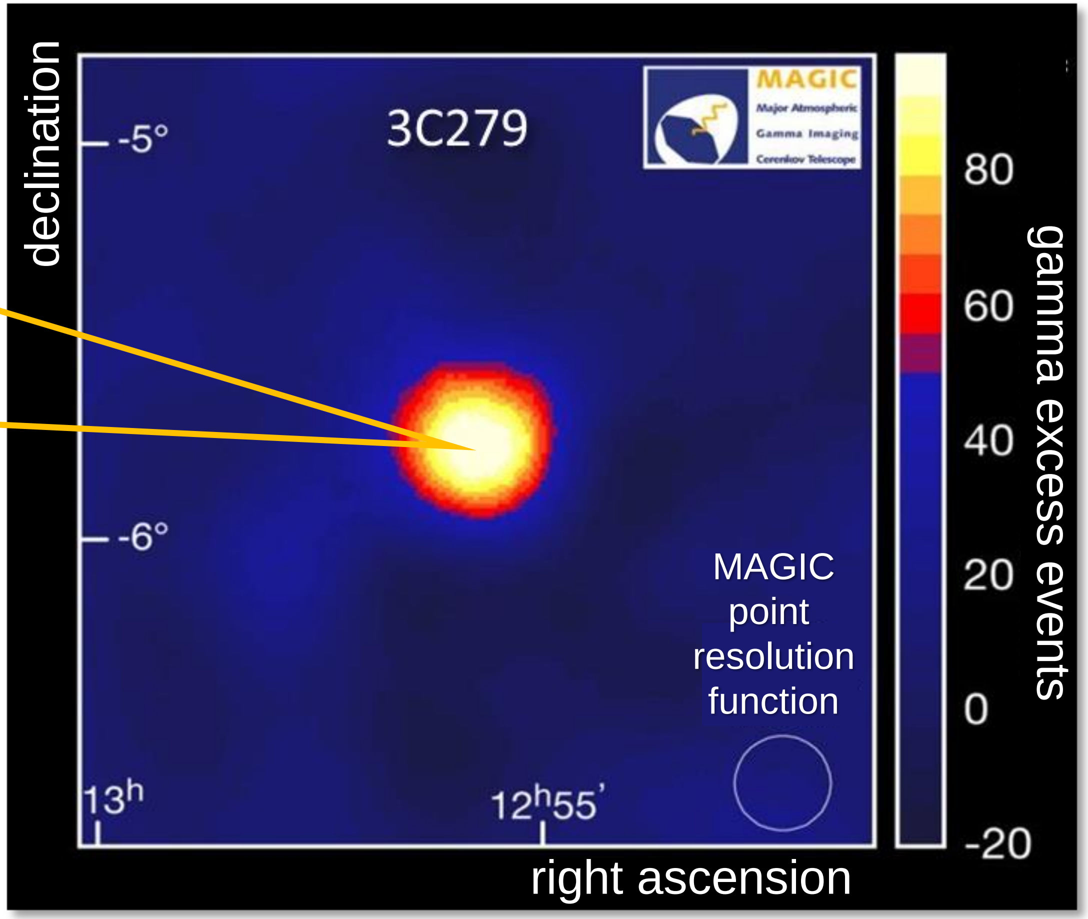


Looking beyond the galactic plane: quasar 3C279

- **First observation at > 50 GeV of a distant quasar at $d = 1.8\ Gpc$ with MAGIC**

- universe more transparent for UHE gammas?*

picture of quasar by Event Horizon Telescope



*see later chapter 4.6.1 on axions

gamma properties and quasar 3C279

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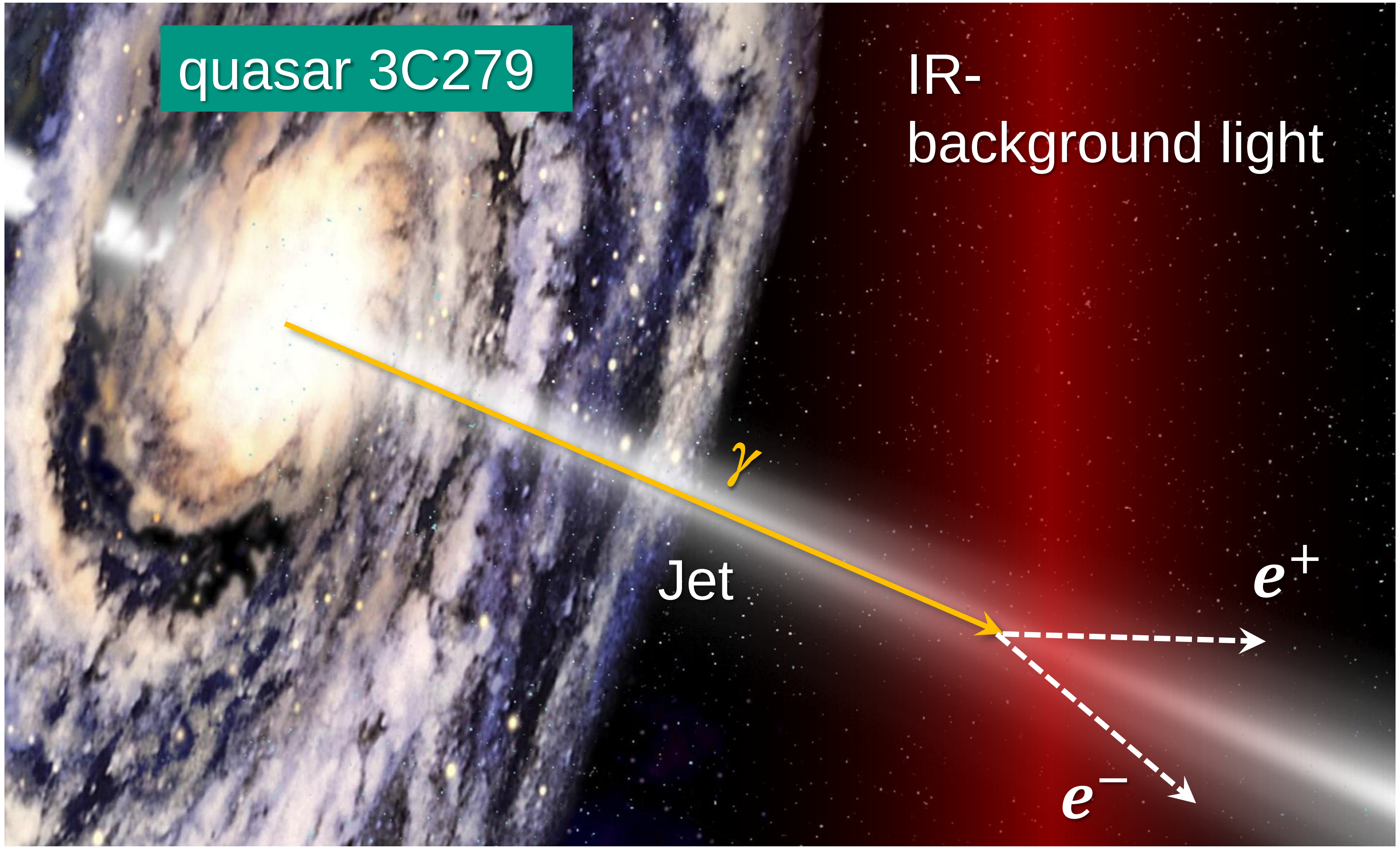
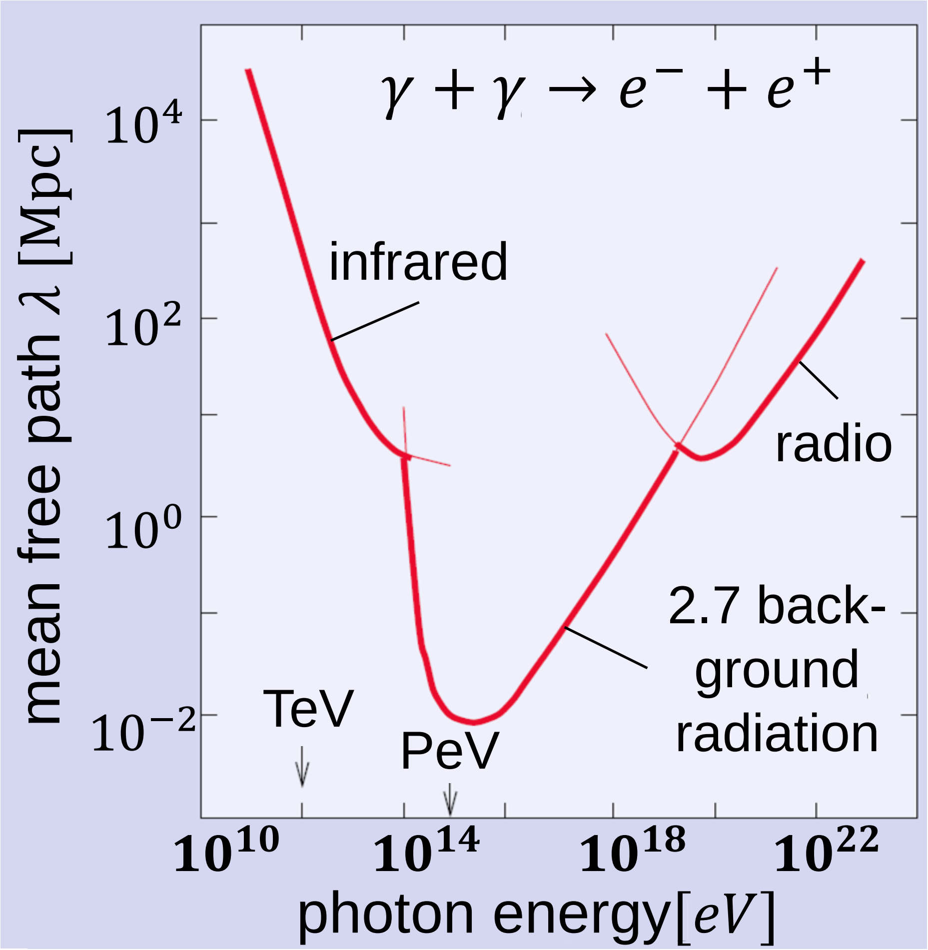
- **Interaction of UHE gammas with extragalactic IR light limits their range!**

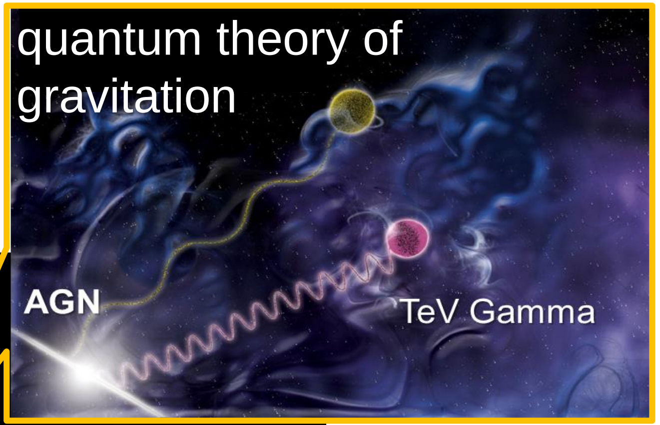


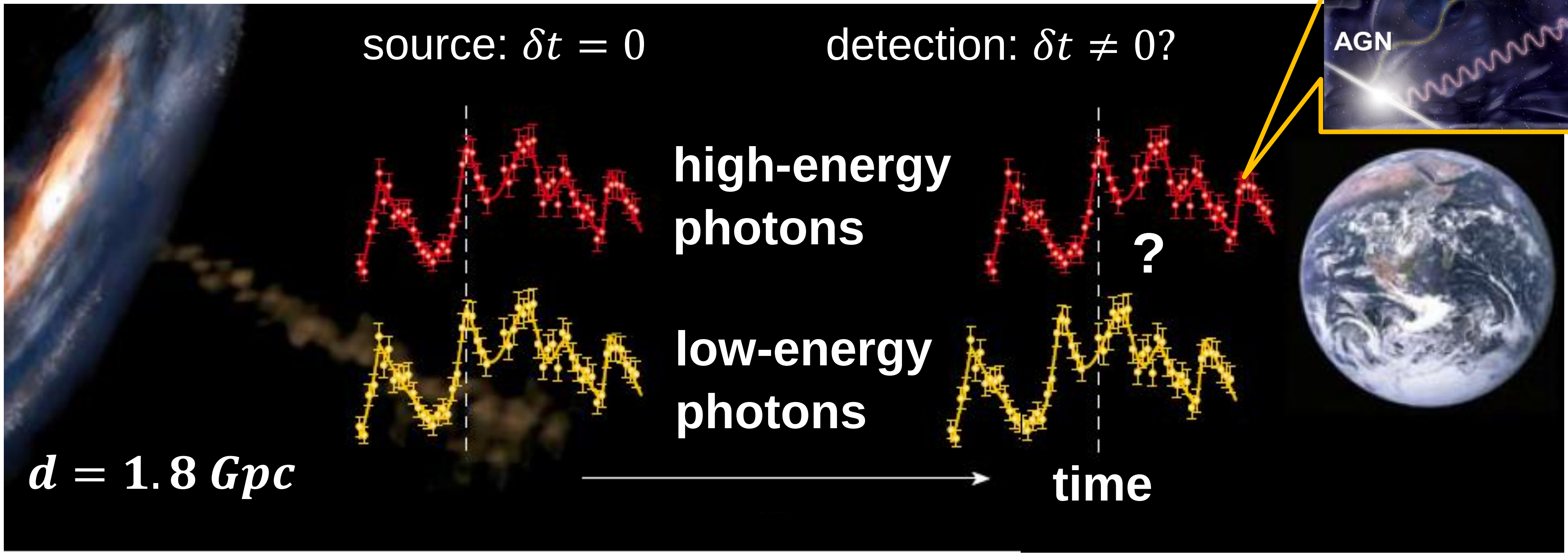


gamma properties and quasar 3C279

- **Search for violations of Lorentz invariance with UHE gammas from a quasar**

  - do UHE gammas of different energies travel faster/ slower? If yes, this would violate Lorentz invariance

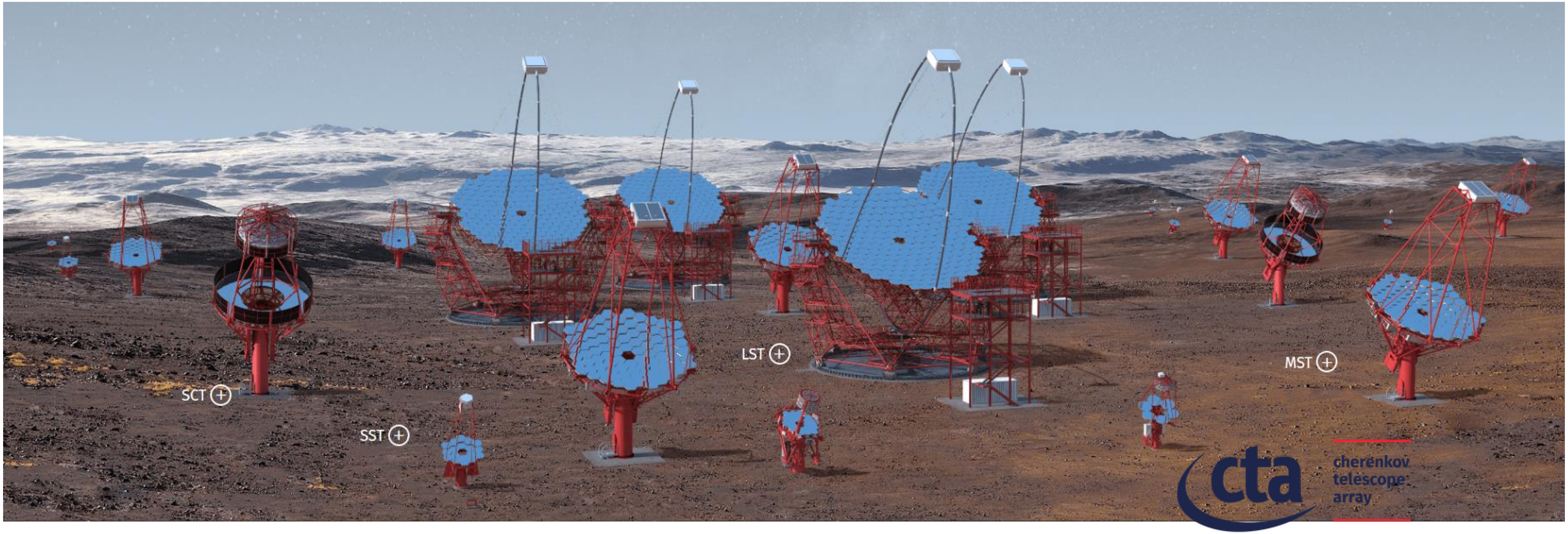




The future of gamma astronomy: CTA observatory

- **Cherenkov Telescope Array (CTA) – 118 telescopes at 2 observation sites**

  - Northern & Southern hemisphere arrays: present status - planning/building stage



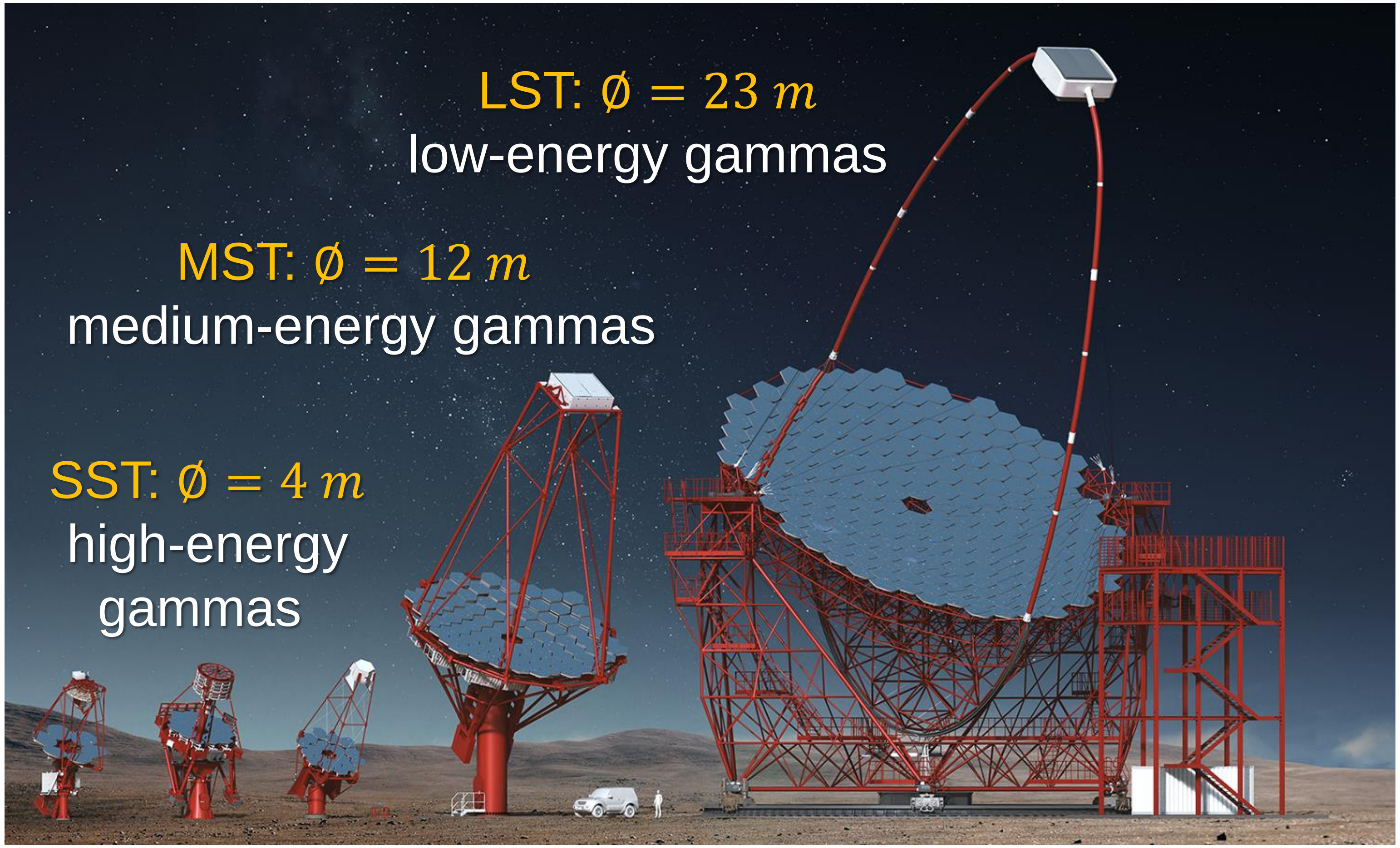
CTA observatory: 3 different telescope sizes

- **From Large (LST) to Medium (MST) to Small (SST) Sized Telescopes**

SST: 70 at southern observatory
1 – 300 TeV

MST: 25 at Southern observatory
15 at Northern
150 GeV – 5 TeV

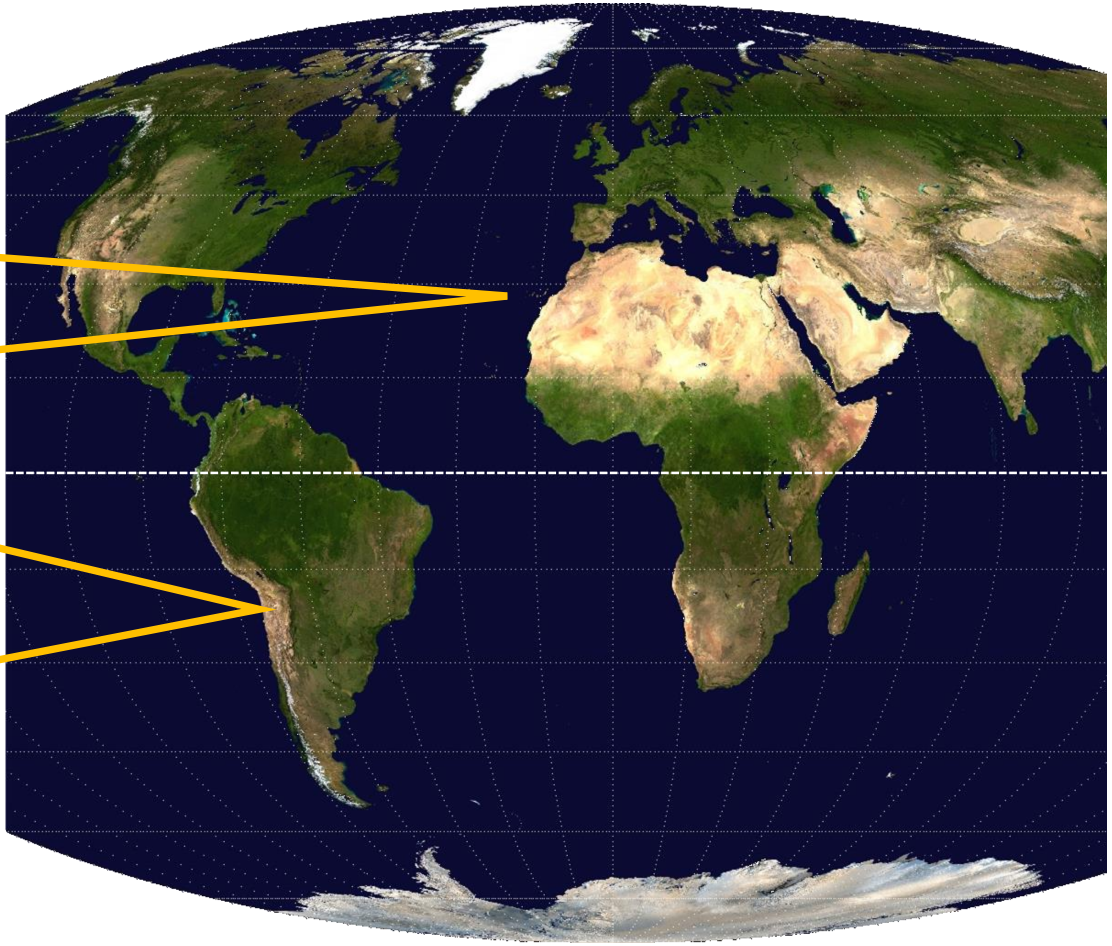
LST: 4 at Southern observatory
4 at Northern
20 – 50 GeV



CTA observatory: 118 telescopes @ 2 different sites

- Exploring VHE…UHE gamma sources of the Northern & Southern sky

virtual reality



CTA observatory: status at the 2 different sites

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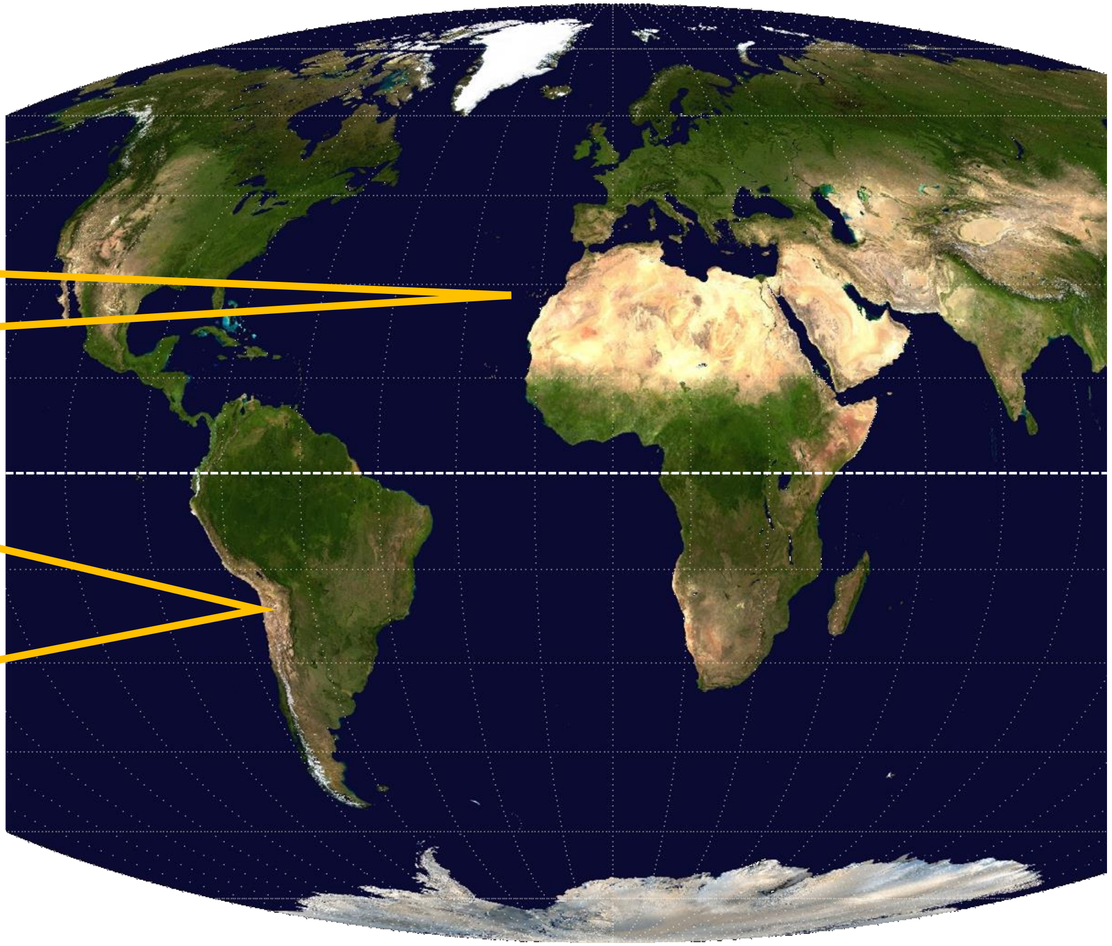
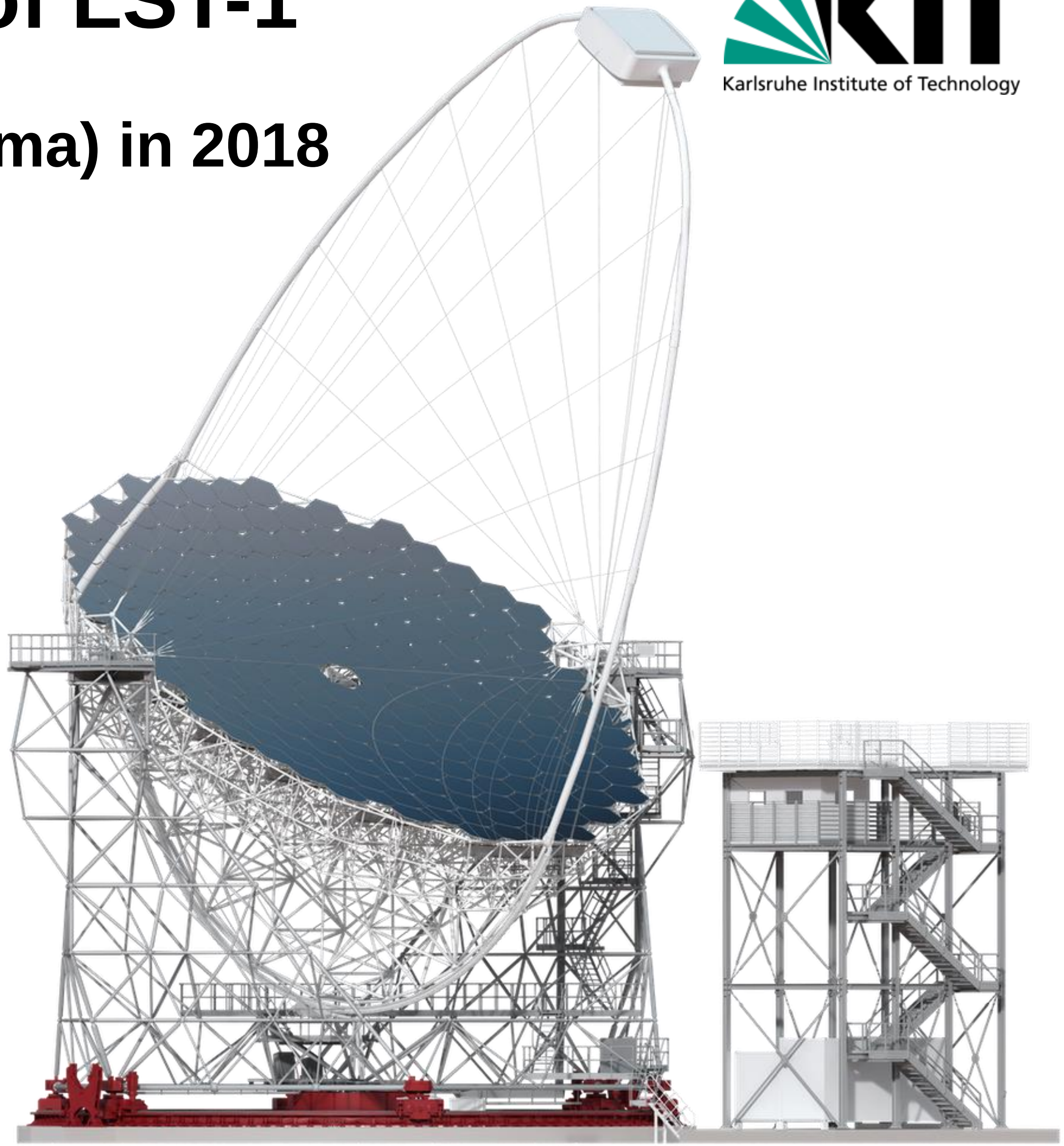
- **Ongoing design & construction works at both sites**

reality until recently



CTA observatory: inauguration of LST-1

- Inauguration ceremony of LST-1 (La Palma) in 2018



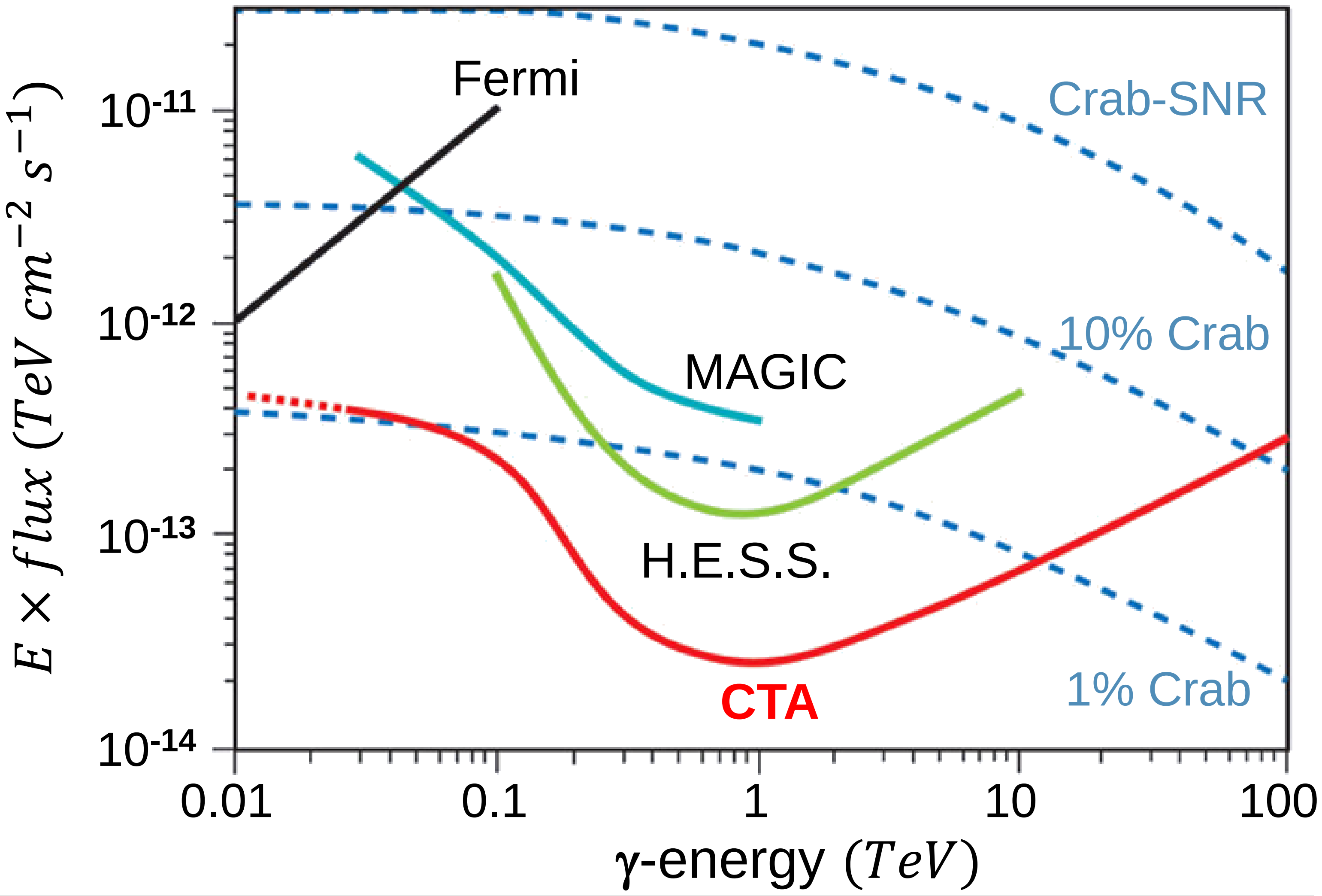
CTA observatory: comparison of sensitivities

Scientific goals of CTA

- search for **new** (fainter) **VHE gamma sources**

- **better discrimination** of hadronic/leptonic scenarios (cosmic LHC or LEP?)

- search for **new physics** (signal from **dark matter annihilation** at galactic center)



CTA observatory: comparison of gamma sources

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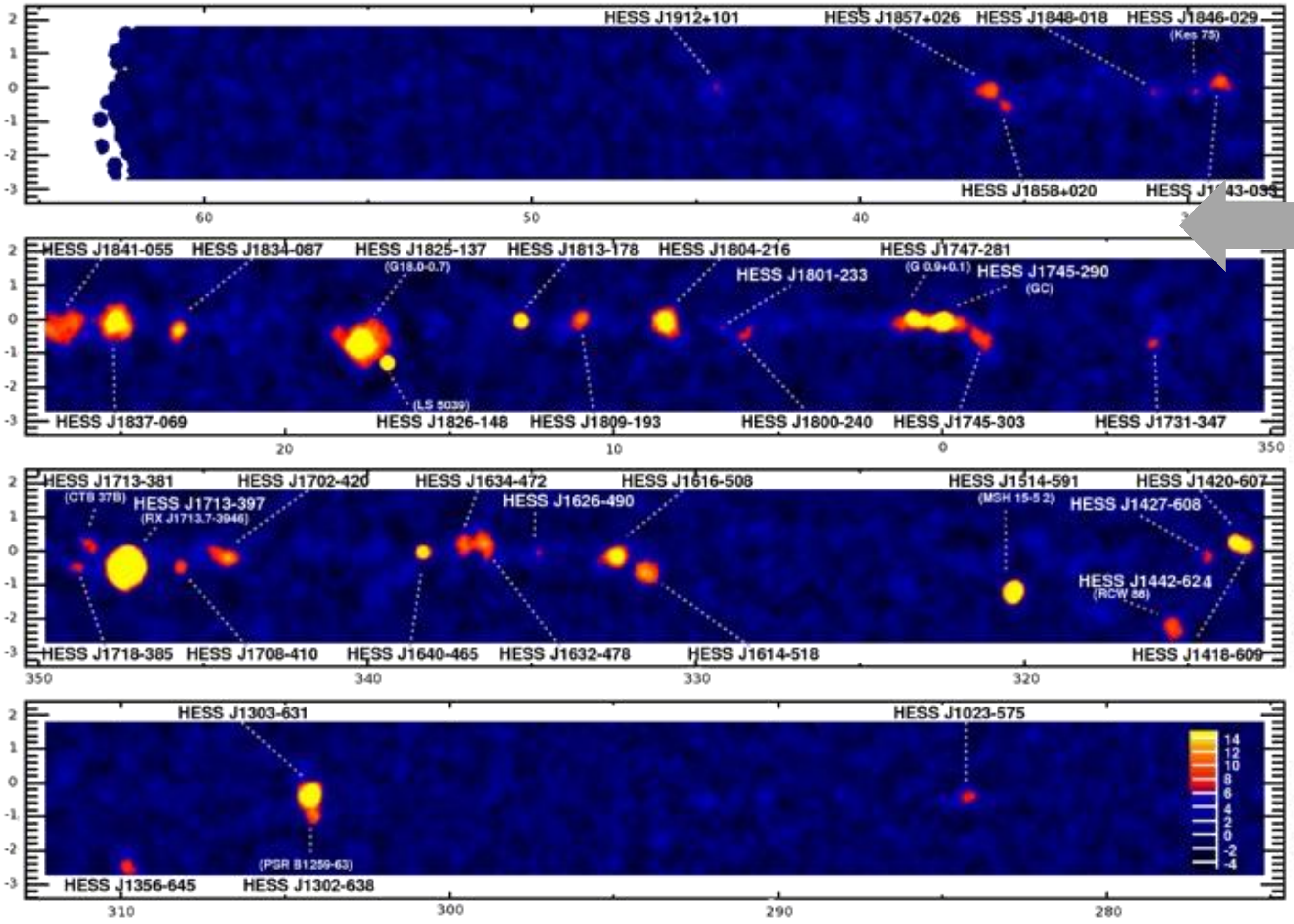
- **Expected CTA sources vs. observed gamma sources with H.E.S.S.**

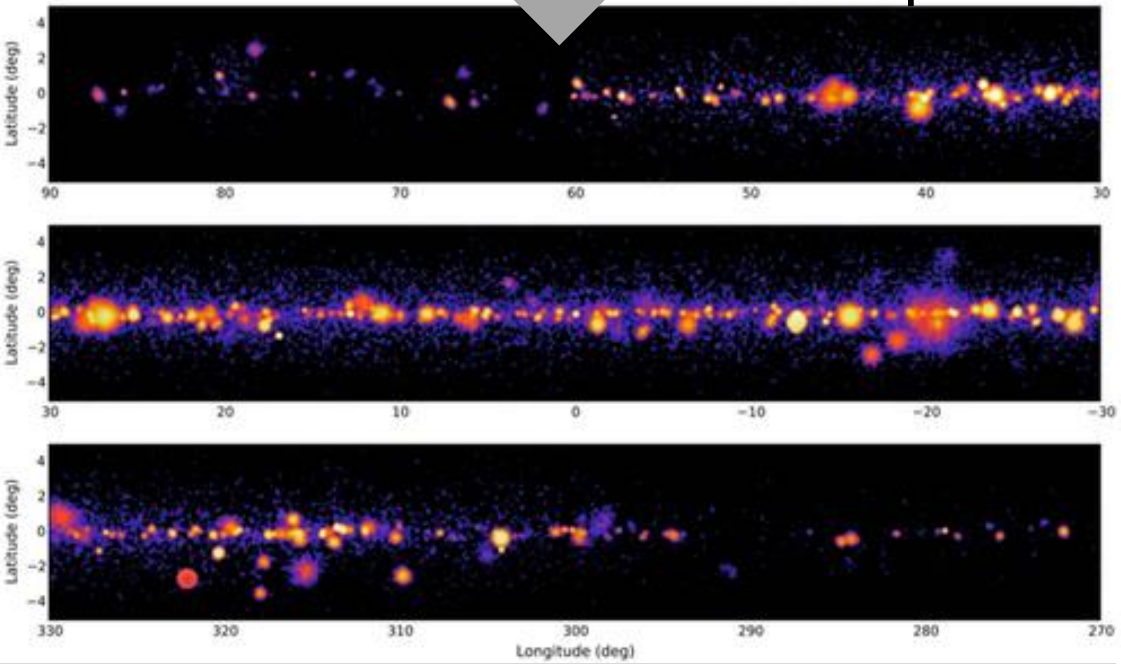


observed

H.E.S.S.

cherenkov telescope array

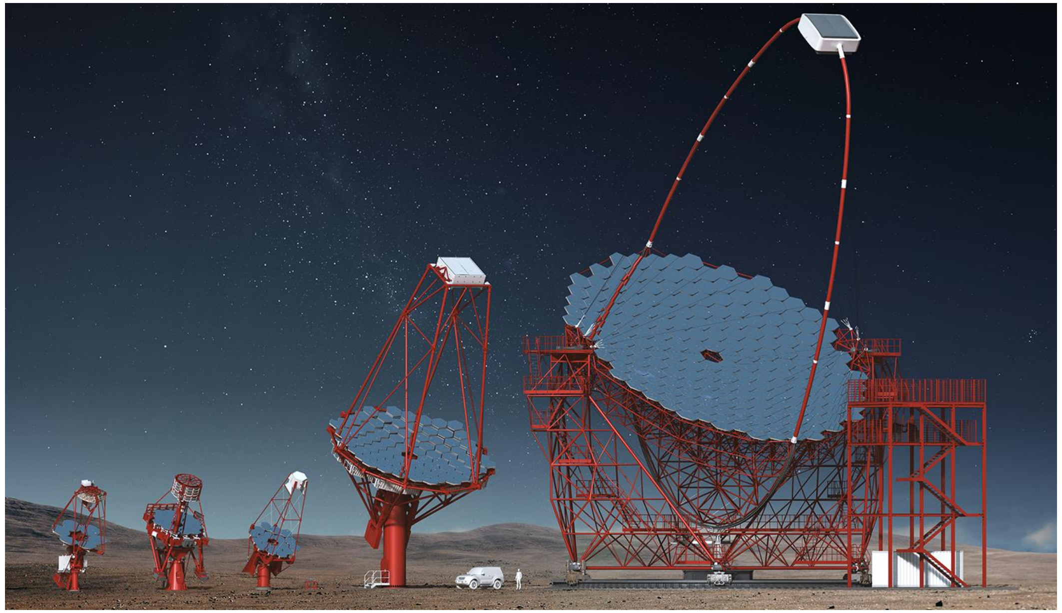
expected



Gamma astronomy: lobbying for CTA funds

- <u>No</u> good argument in VHE/UHE gamma astronomy due to EBL/3K radiation!

cta cherenkov telescope array



2.2 Search for Rare Events

- Searching for **new physics** beyond the Standard Model: ⇨ rare event searches

hunting for dark matter

Rare event searches: principles & technologies

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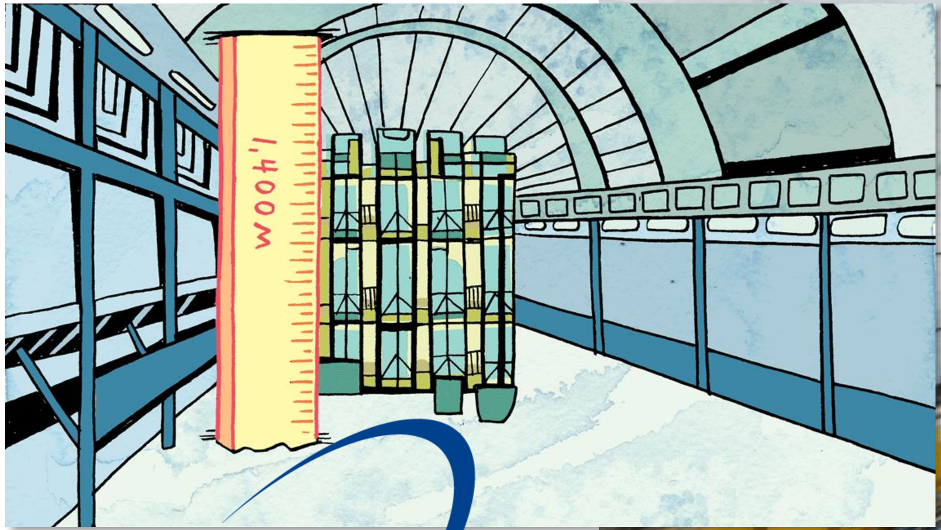
- Why do I need to operate my new detector in an underground laboratory?



INFN

Laboratori Nazionali del Gran Sasso

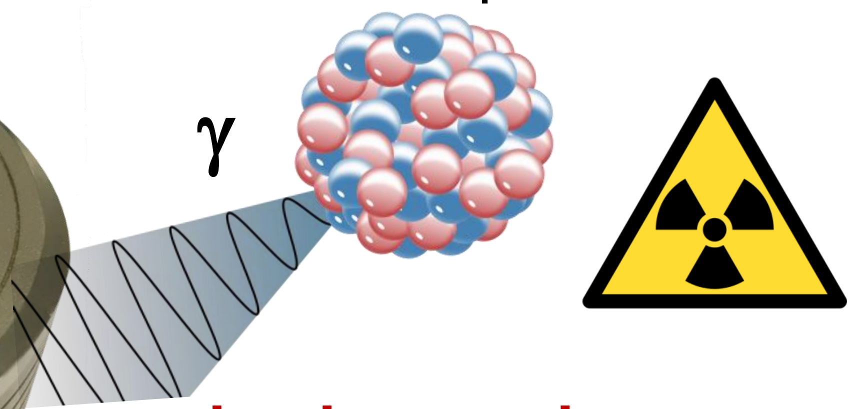
Rare events: how rare is ´rare´? A needle in a …

- How on earth can I detect a signal rate of only $1\ event\ ton^{-1}\ year^{-1}$?

Rare events: Signal compared to background rate

- **There is no shortage of background sources: cosmogenic, radiogenic, …**

  - a few signal events in a few years: huge background reduction required



Ge detector

background rate:

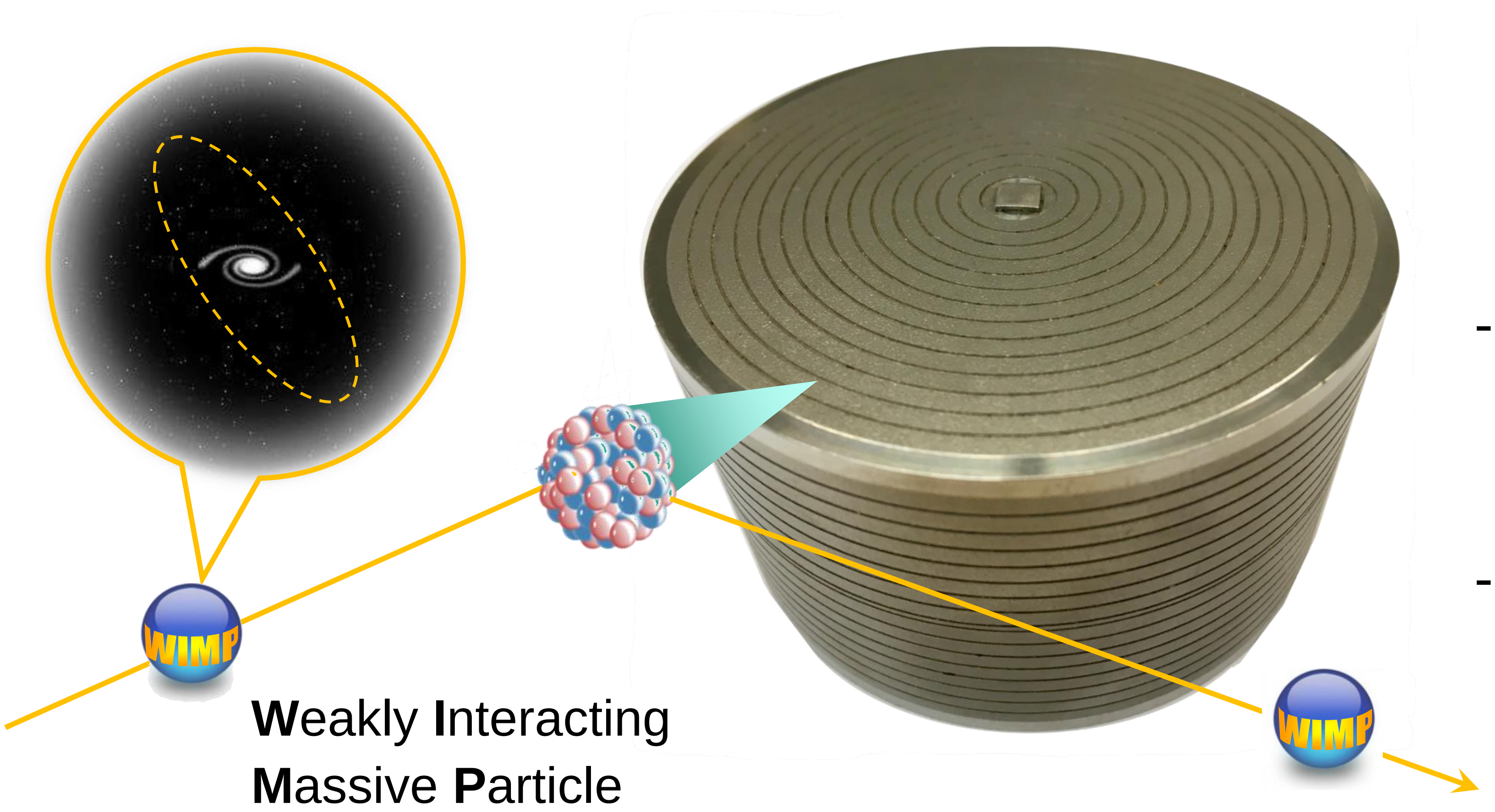
$N_{bg} > 10^{10}\ events\ year^{-1}$

goal:

$N_{bg} < 1\ event\ year^{-1}$

Rare events: example search for Dark Matter (DM)

- **Goal: observe the ´recoil signature´ of a DM particle (here: WIMP)**



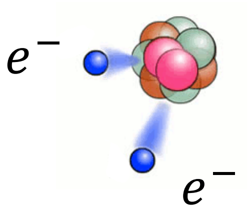
- DM signal detected by **nuclear recoil** with energy $E < 100\ keV$

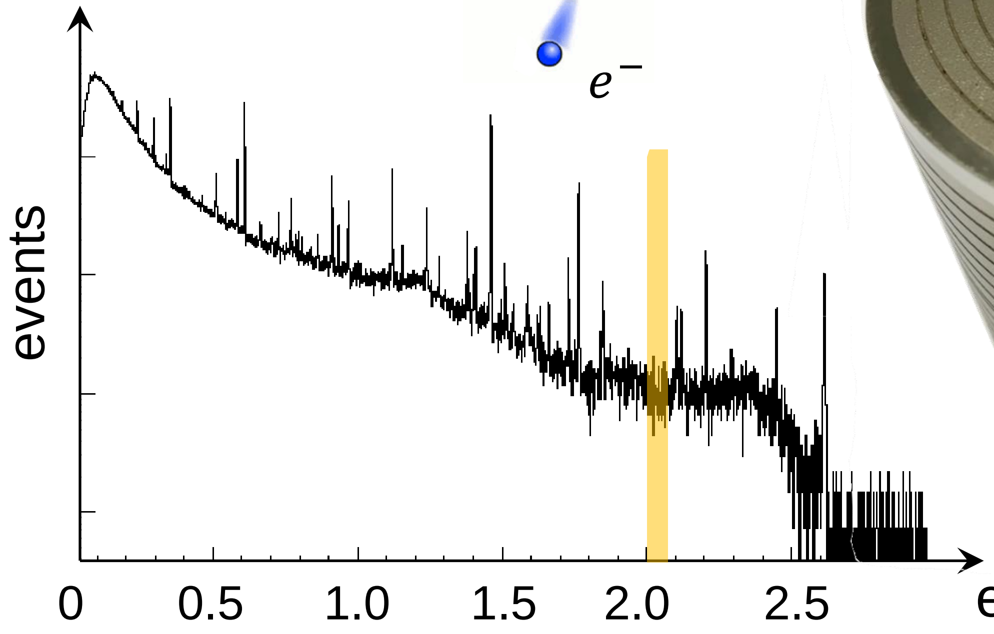
- point-like energy deposition

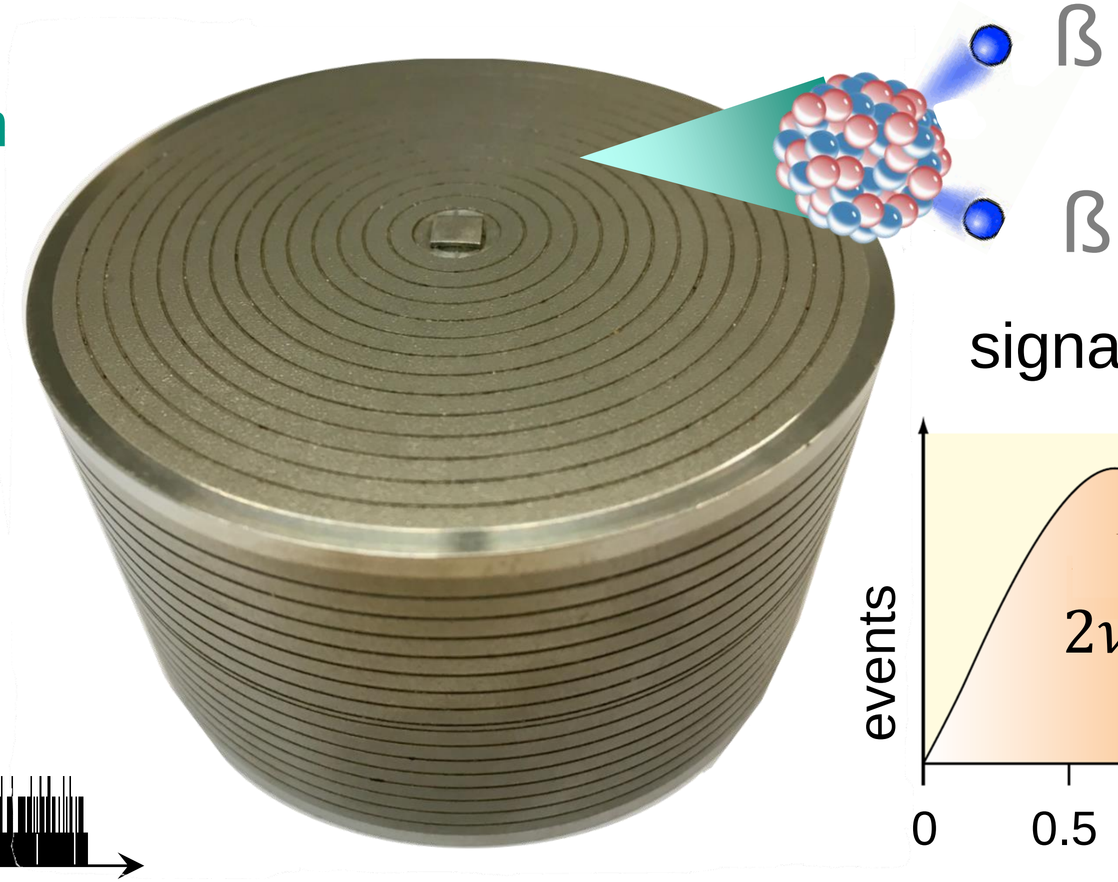
Rare events: example neutrinoless double ß-decay

- **Goal: observe the ´peak´ from $0\nu\beta\beta$ events in an enriched ^{76}Ge detector**

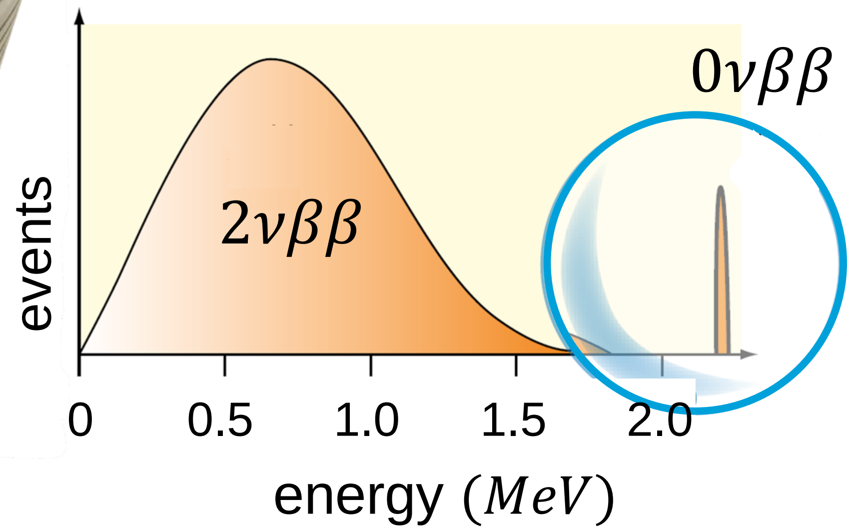
raw experimental spectrum





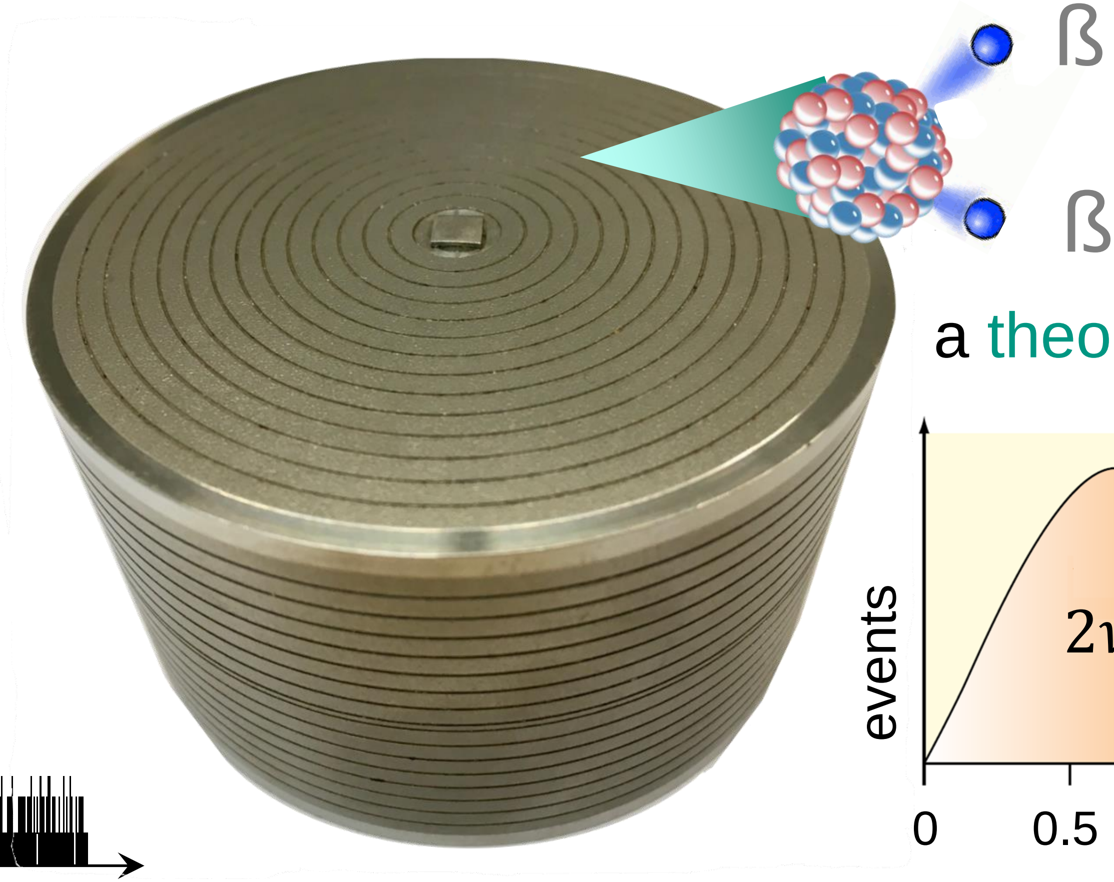


signature of $0\nu\beta\beta$ events

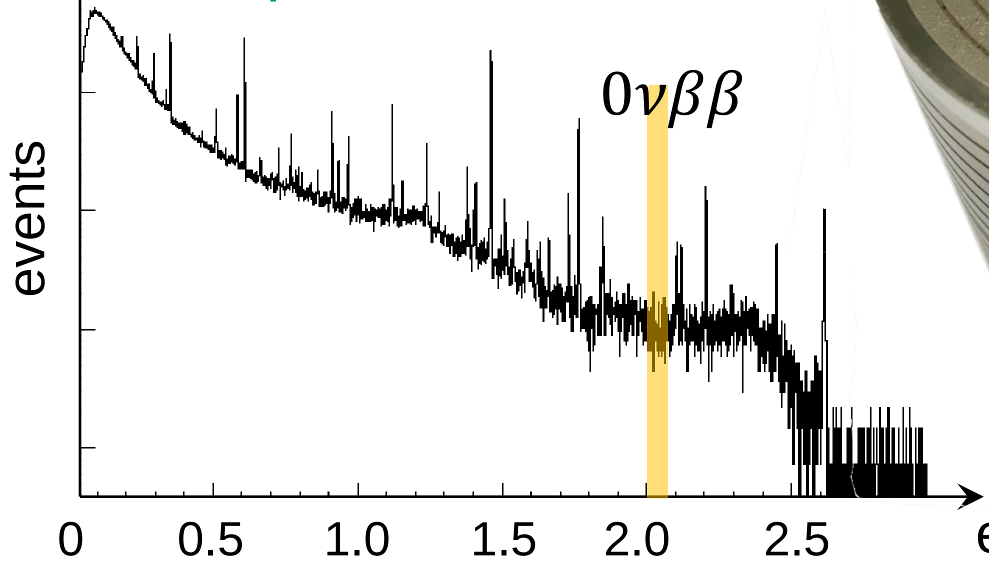


Rare events: example neutrinoless double ß-decay

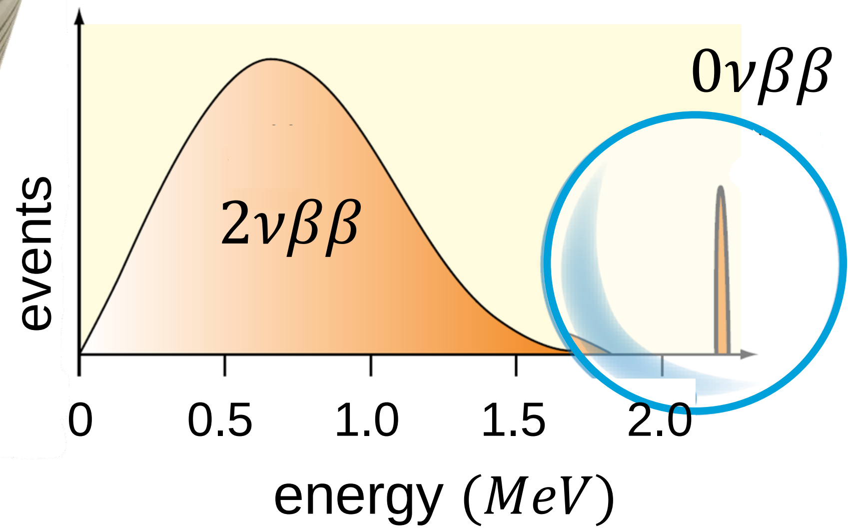
- **Goal: observe the ´peak´ from $0\nu\beta\beta$ events in an enriched ^{76}Ge detector**



an experimentalists´ view



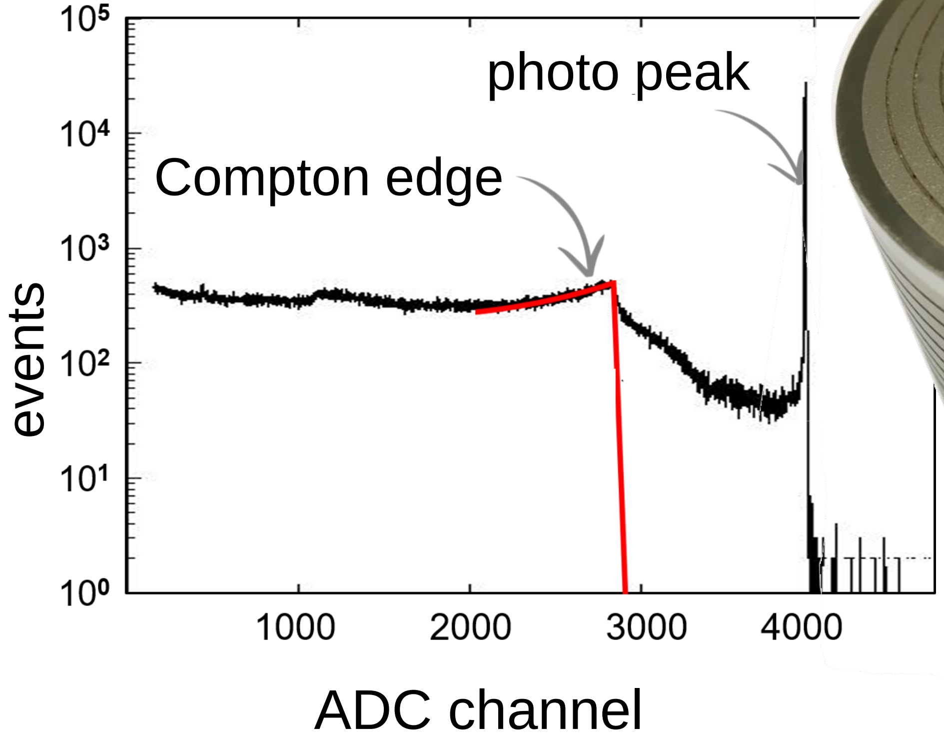
a theorists´ view of $0\nu\beta\beta$



Rare events: example neutrinoless double ß-decay

- **Task: identify & then eliminate each radioactive element in your detector**

raw experimental spectrum
of a _single_ isotope (which?)



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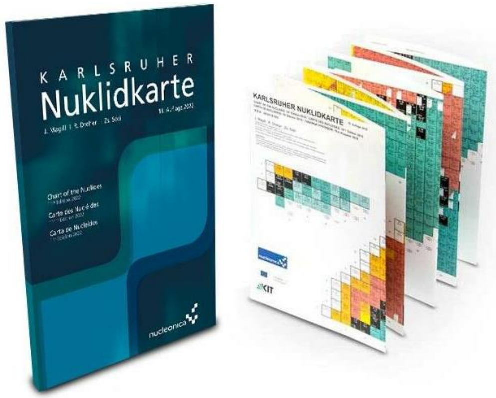
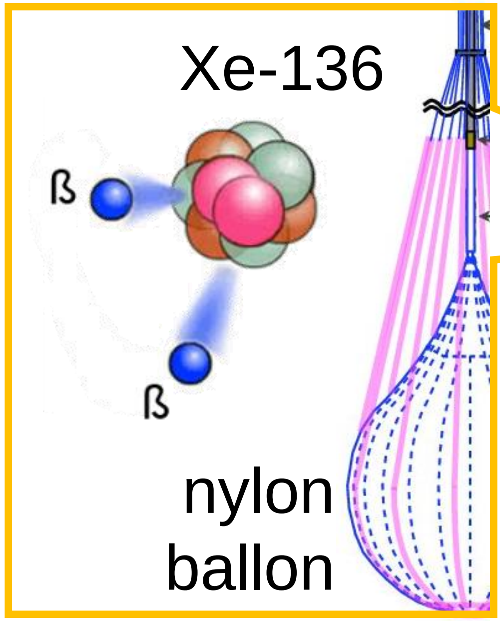
11th ed.,
2022

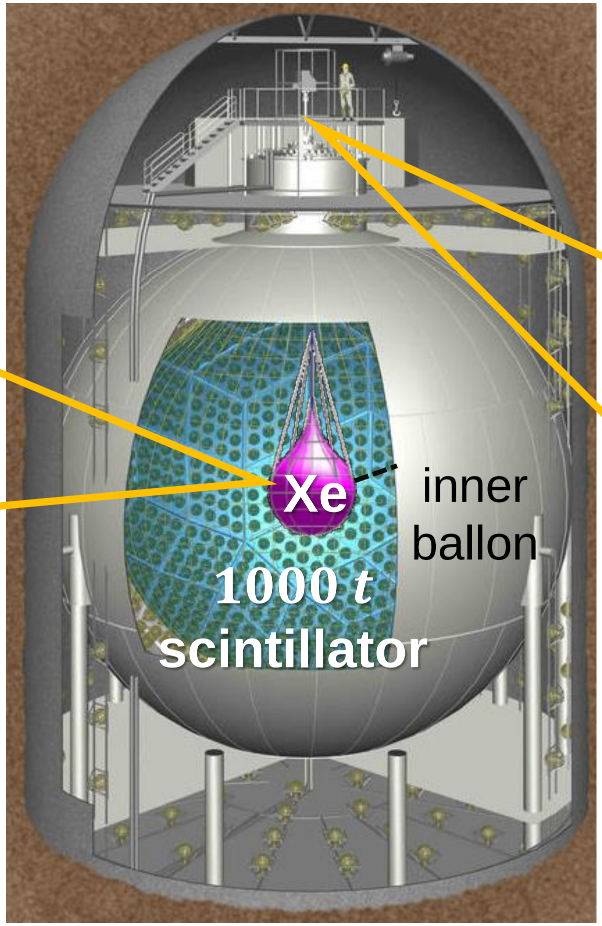


Rare events: example of what can go wrong*

- **Task: install the inner nylon baloon to contain xenon**

  - **KamLAND-Zen** $0\nu\beta\beta$-experiment in Japan





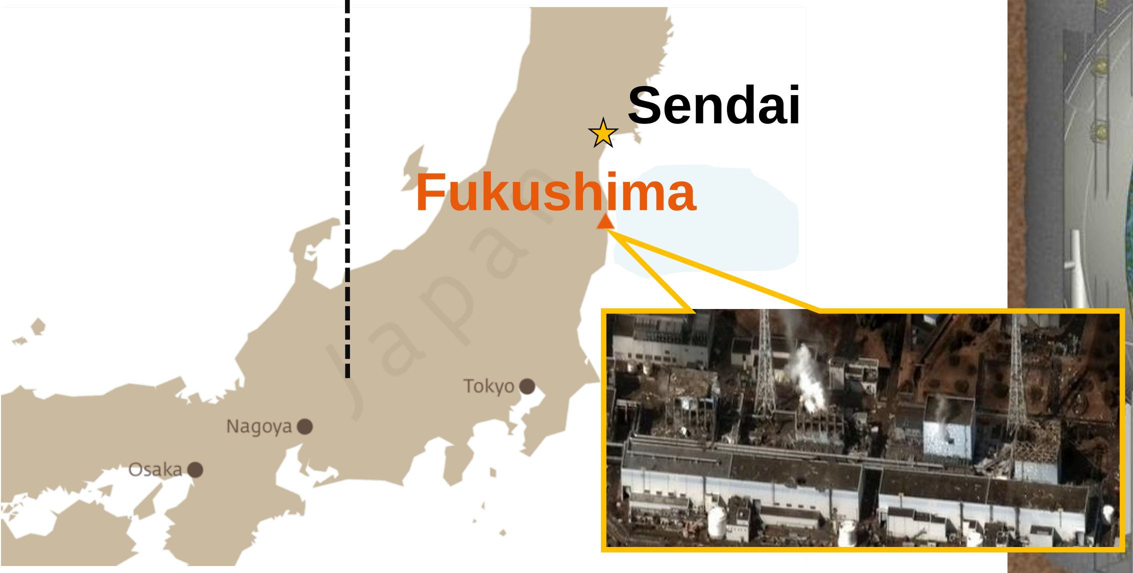
We did it!! And: on time…

*will go wrong

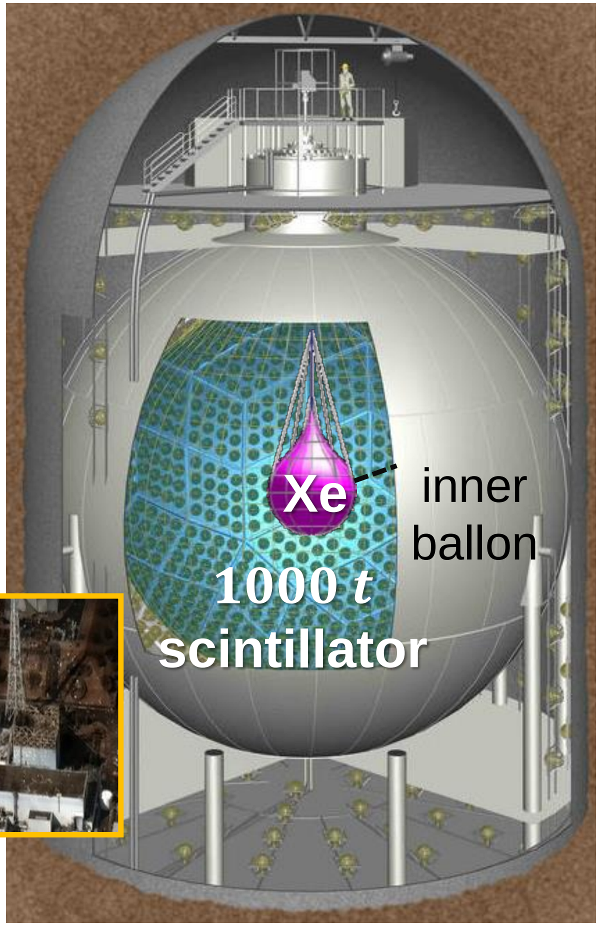
Rare events: example of what can go wrong

- **Impact of ^{134}Cs on inner nylon baloon & background for a $0\nu\beta\beta$ experiment**

- **KamLAND-Zen** $0\nu\beta\beta$-experiment in Japan

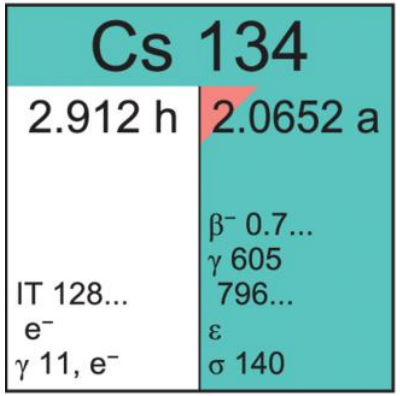


accident of March 11, 2011



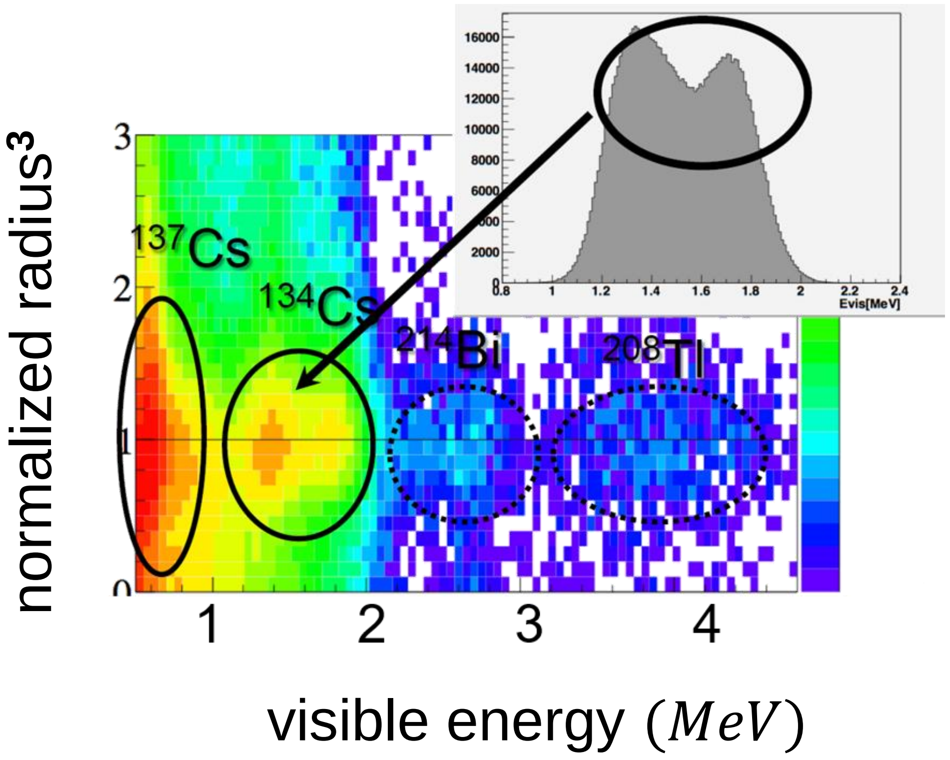
- **Fukushima** nuclear accident: large release of radioactive nuclides such as isotope ^{134}Cs (undergoes β –decay + 2 γ´s)

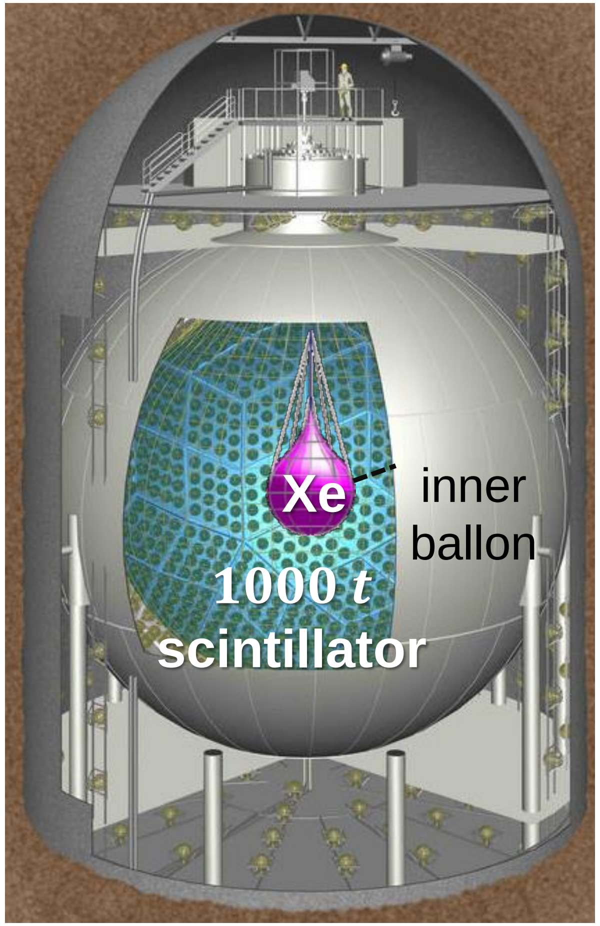
$$Q = 2.06\ MeV$$



Rare events: example of what can go wrong

- **Impact of ^{134}Cs on inner nylon baloon & background for a $0\nu\beta\beta$ experiment**

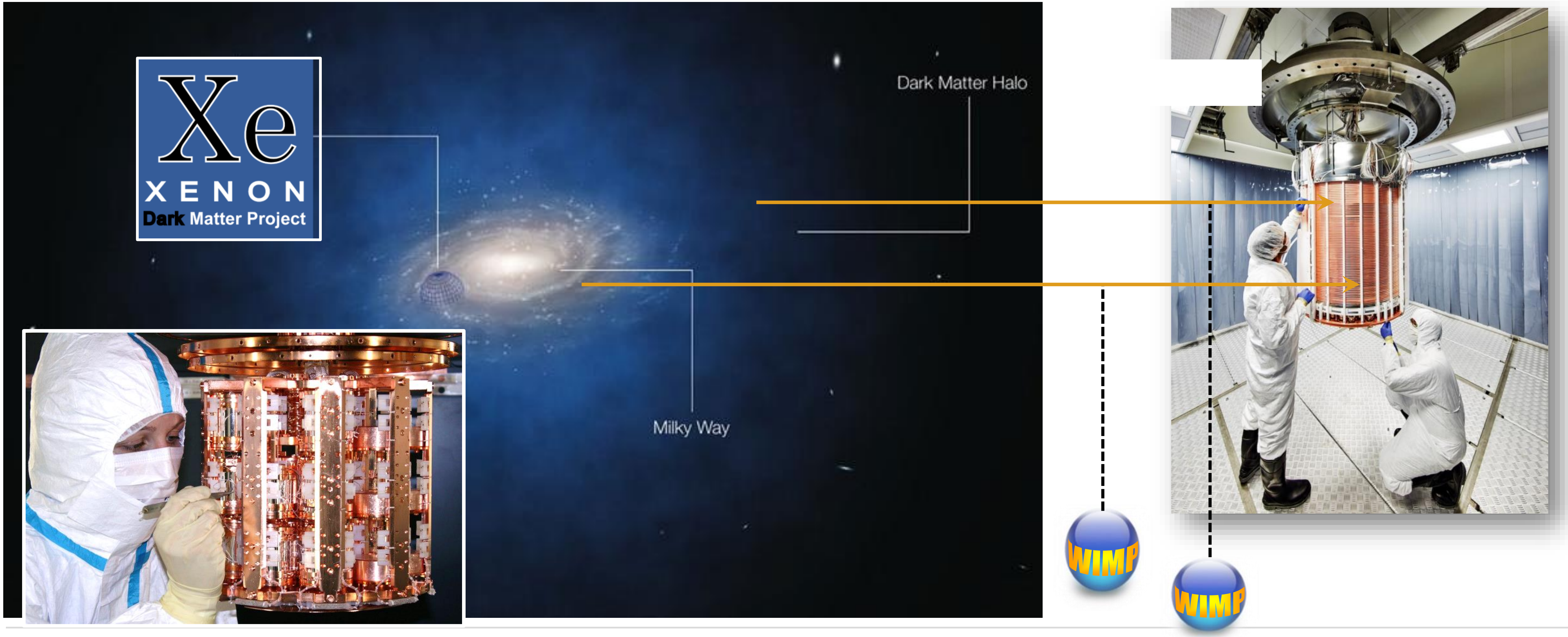




- **Fukushima** nuclear accident: large release of radioactive nuclides such as isotope ^{134}Cs (undergoes β –decay + 2 γ´s)
- inner baloon was produced in nearby Sendai in March 2011: small contamination ^{134}Cs
- result of measurements:
  ⇨ remove contaminated ballon & install a new clean one

How do I calculate the expected signal rate?

- Is the ´beam´ of dark matter particles intense & my detector large enough?



How do I calculate the expected signal rate?

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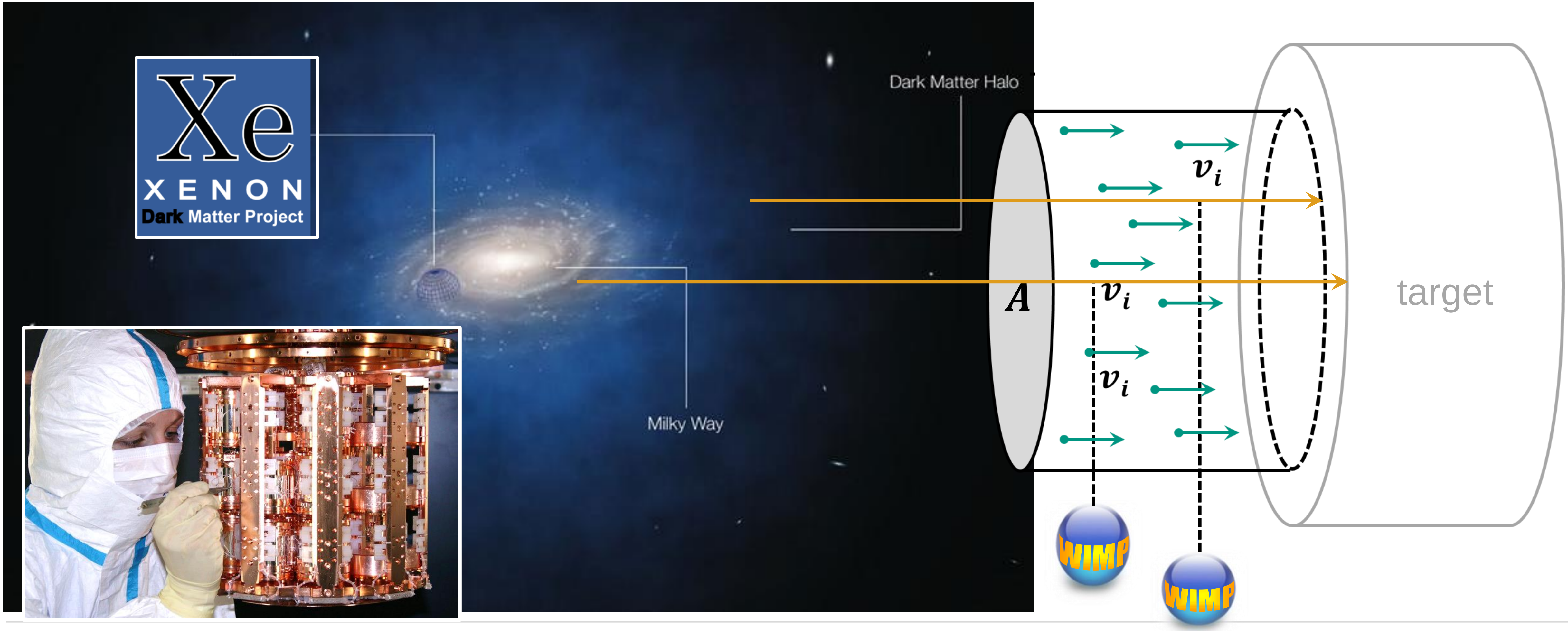


RECAP: how to calculate the expected signal rate

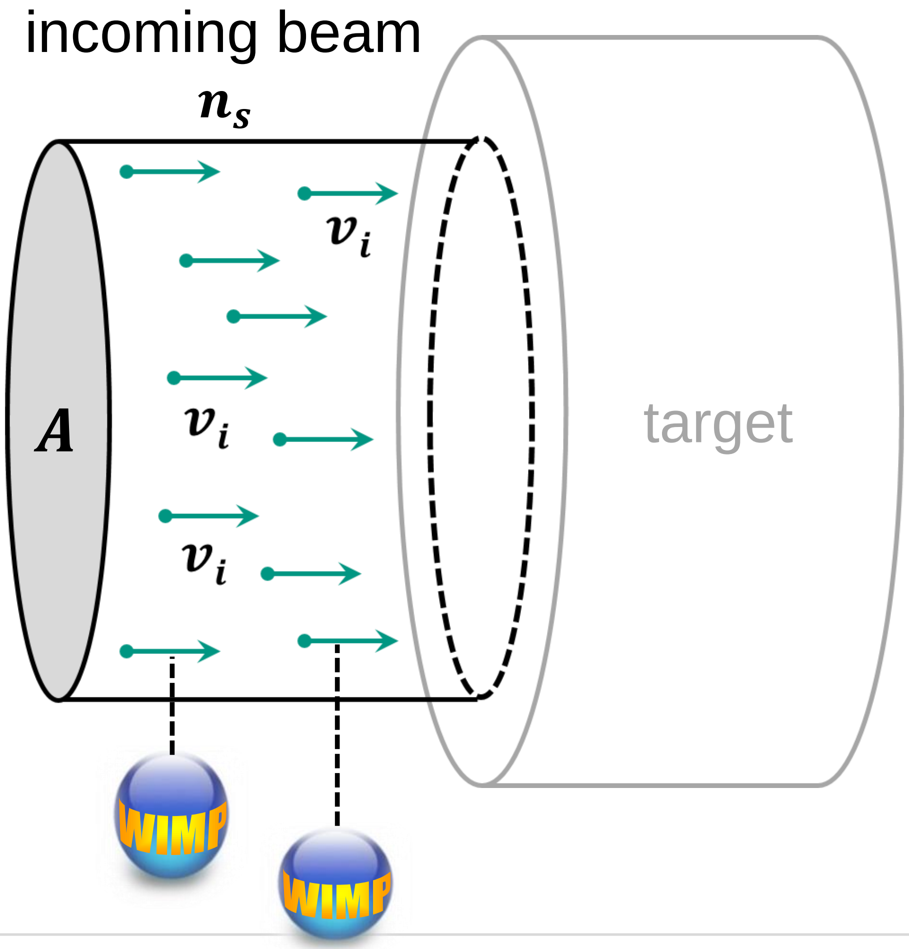
- **Example* of incoming beam of particles (accelerator, dark matter: WIMPs)**

- cross sectional area A $[cm^2]$
- particle velocity v_i $[cm/s]$
- number density n_s $[cm^3]$
- **flux density J** $[cm^{-2}\ s^{-1}]$

$$J = n_S \cdot v_i$$

- **flux** Φ $[s^{-1}]$

$$\Phi = J \cdot A = n_S \cdot v_i \cdot A$$



*see Mod Ex Phys III

RECAP: how to calculate the expected signal rate

- **Example of incoming beam of particles hitting a thin target (single interaction)**

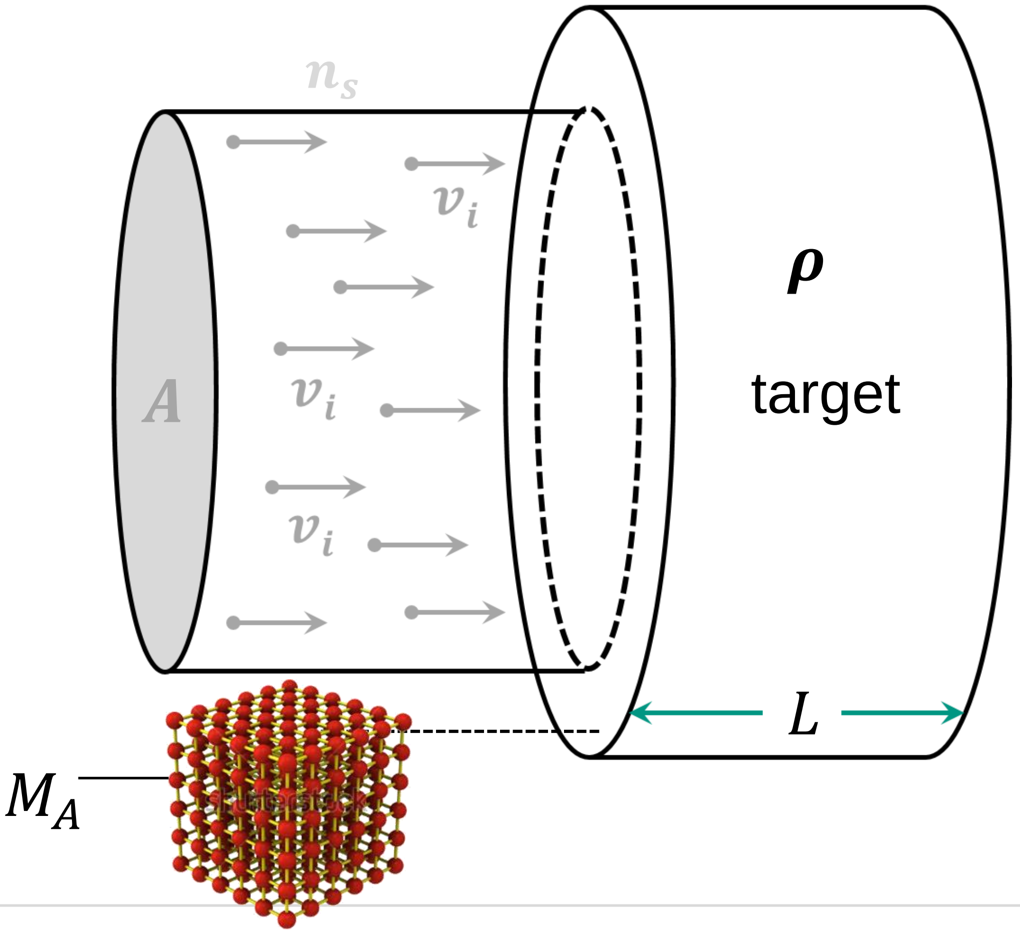
$N_A = 6.022 \cdot 10^{23}$ / mol

- target density $\boldsymbol{\rho}$ $[\boldsymbol{g/cm^3}]$
- target length $\boldsymbol{L}$ $[\boldsymbol{cm}]$
- target atomic mass $\boldsymbol{M_A}$ $[\boldsymbol{u}]$
- **number density** $\boldsymbol{n_t}$ $[\boldsymbol{cm^{-3}}]$

$$\boldsymbol{n_t = \rho \cdot N_A / M_A}$$

- **# of nuclei in beam** $\boldsymbol{N_t}$ [ ]

$$\boldsymbol{N_t = n_t \cdot L \cdot A}$$



$u = 1.6605 \cdot 10^{-27} kg$ (unified atomic mass unit)

RECAP: how to calculate the expected signal rate

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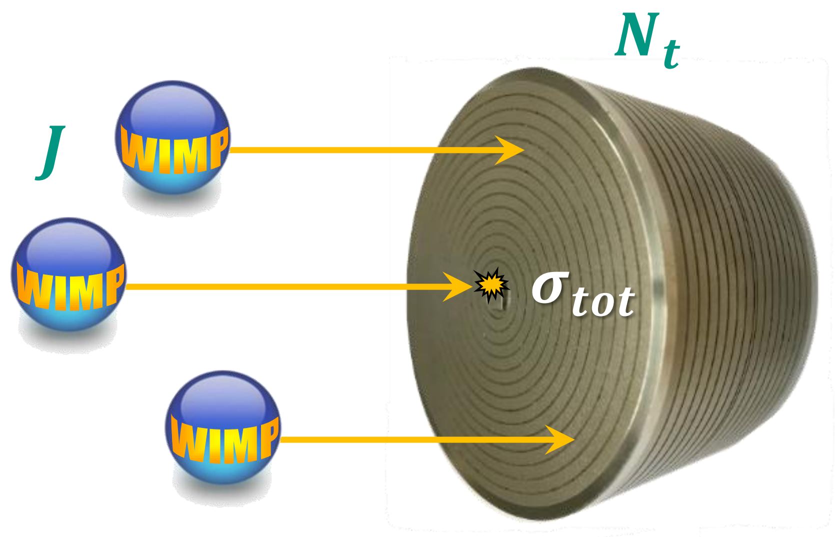
- Interaction rate W_r & # of signal events N_S of incoming WIMPs in a detector

  - total cross section σ_{tot} $[cm^2]$
  - # of targets in beam N_t [ ]
  - WIMP flux density J $[cm^{-2}\ s^{-1}]$
  - # of signal events N_S [ ]
  - **interaction rate** W_r $[s^{-1}]$



$$W_r = dN_S/dt = J \cdot N_t \cdot \sigma_{tot}$$

RECAP: how to calculate the expected signal rate

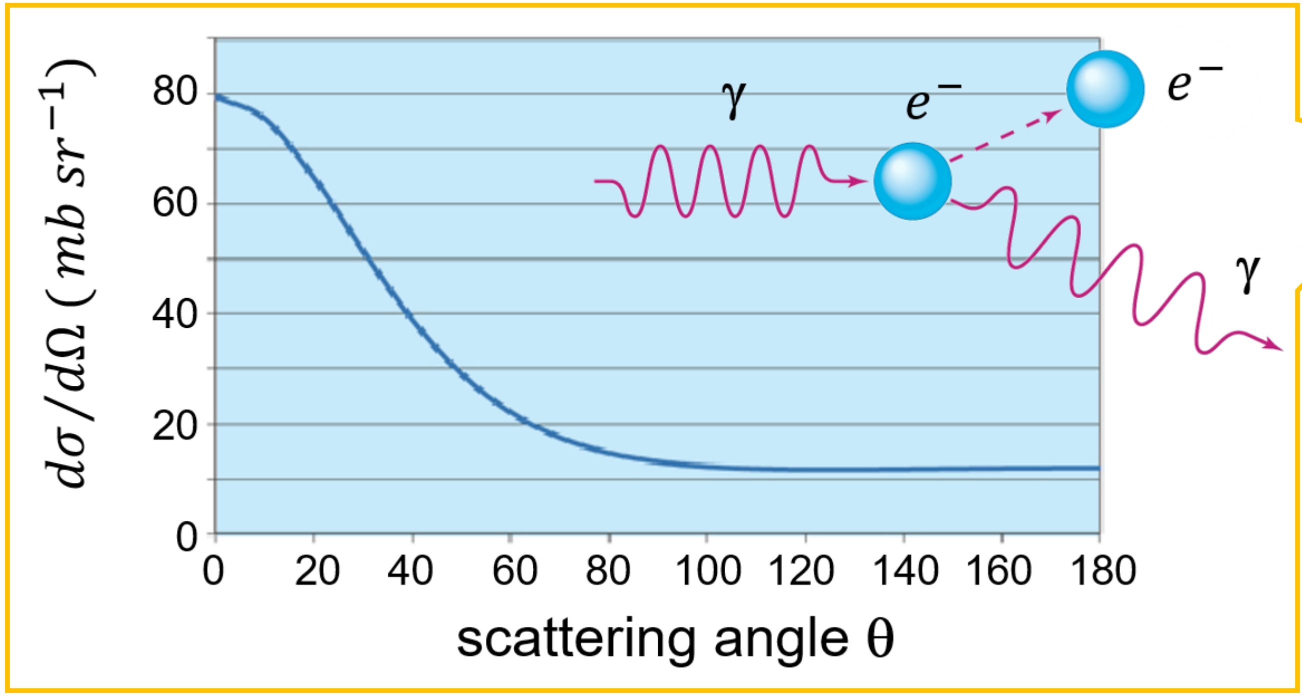
- **background processes in a detector with typical cross section $\sigma_{tot} \sim mb$**

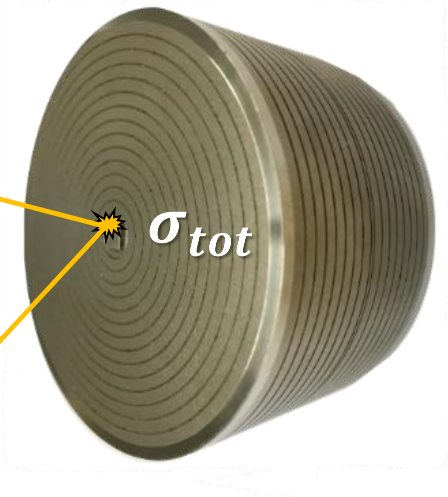
  - unit of total cross section σ_{tot} $[cm^2 \; or \; barn^*]$

$$1\,b = 1\,barn = 10^{-24}\,cm^2$$

*Manhattan project, US

Compton-scattering: $b \ldots mb^{**}$





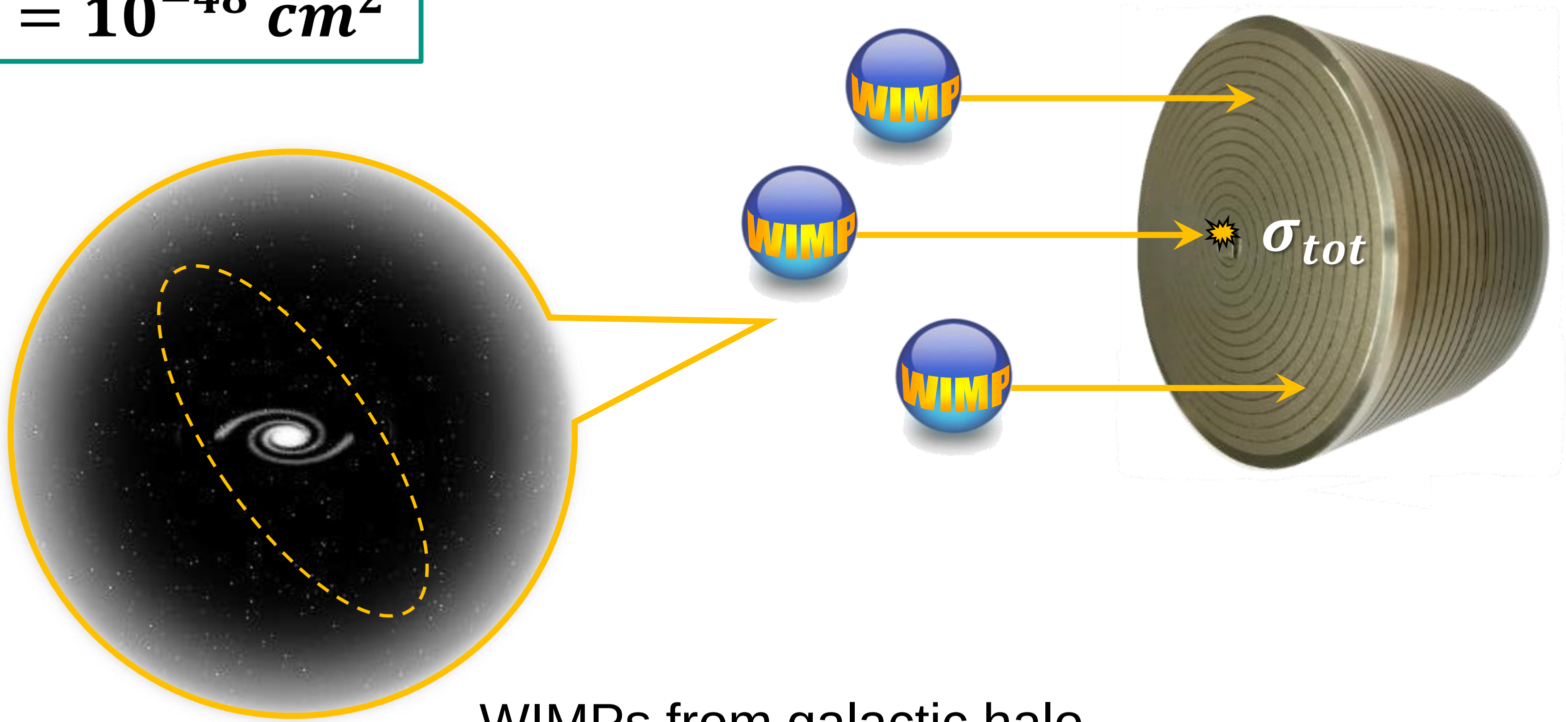
$^{**}mb = milli - barn = 10^{-27} cm^2$

RECAP: how to calculate the expected signal rate

- **WIMP signals in a detector with expected cross section $\sigma_{tot} < 10^{-24}\ b$**

  - exceedingly small expected WIMP cross section σ_{tot}

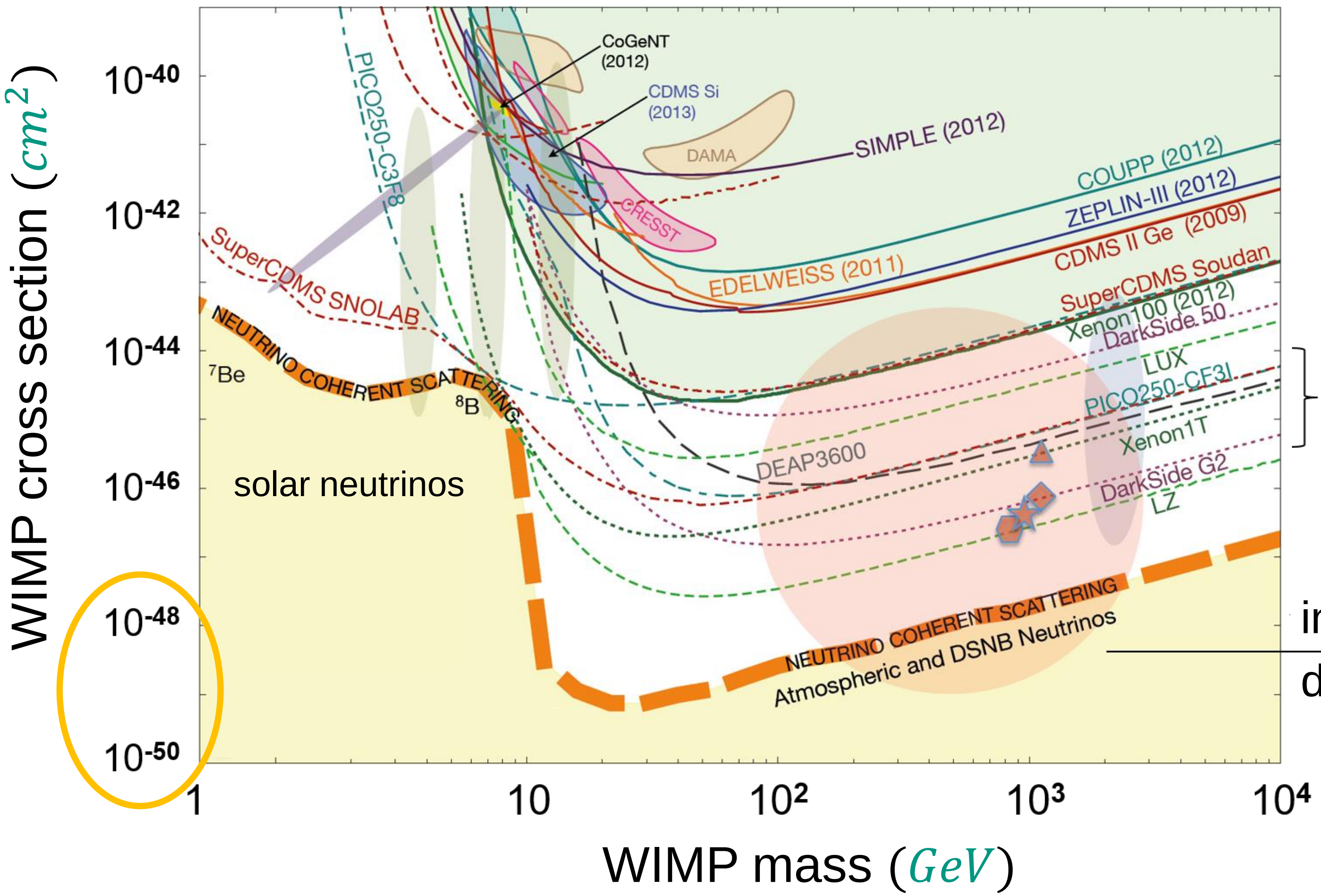
$$1\ yb = 1\ yocto - barn = 10^{-48}\ cm^2$$



WIMPs from galactic halo

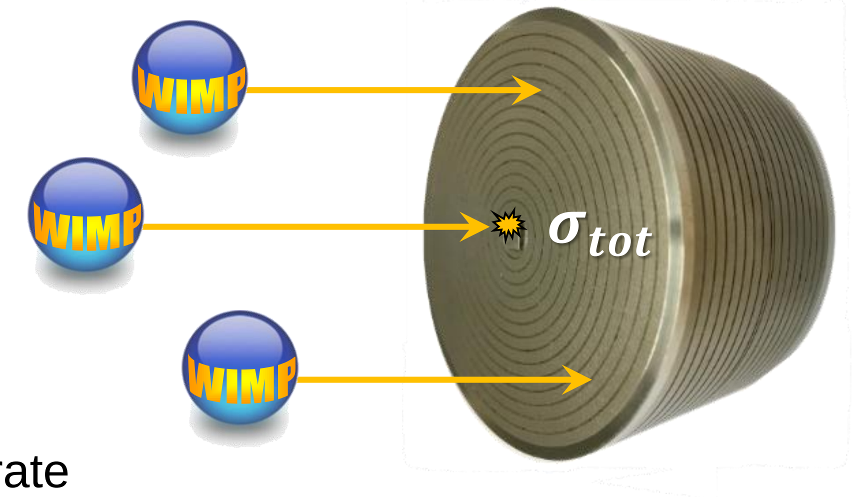
expected signal rates in a dark matter detector

- **WIMP signals in a detector with expected cross section $\sigma_{tot} < 10^{-48}\ cm^2$**



LXe/LAr

interaction rate dominted by ν´s



$10^{-48}\ cm^2$

Signal vs. background: no signal (yet)?

- **Statistical fluctuations of signal & background: confidence intervals**

  - **No signal:** exclusion of parameter interverals at **90 (95) % confidence** level

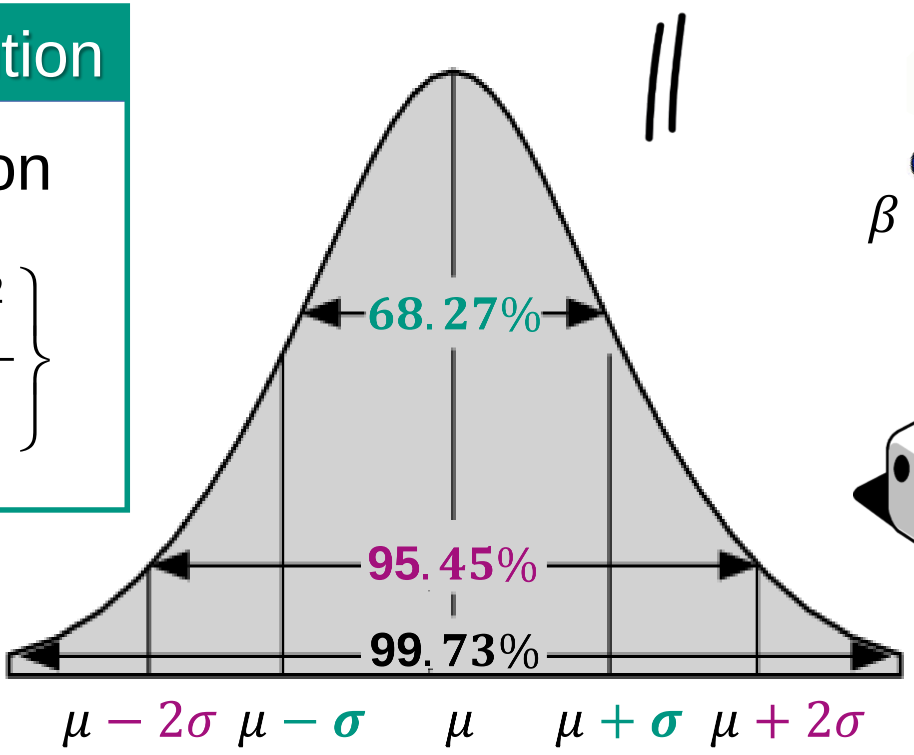
Gaussian (normal) distribution

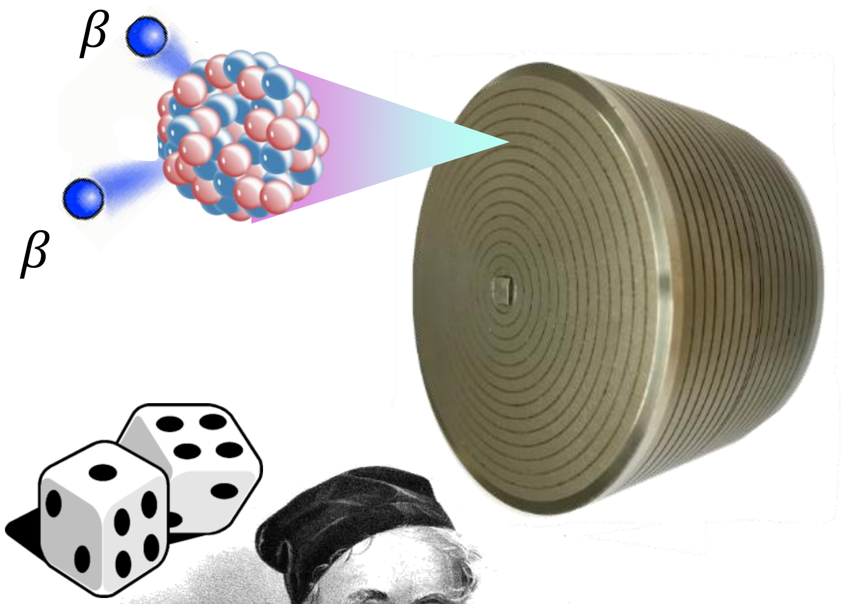
probability density function

$$\frac{1}{\sqrt{2\pi\cdot\sigma^2}}\cdot\exp\left\{-\frac{(x-\mu)^2}{2\sigma^2}\right\}$$

μ: mean of expectation

σ: standard deviation

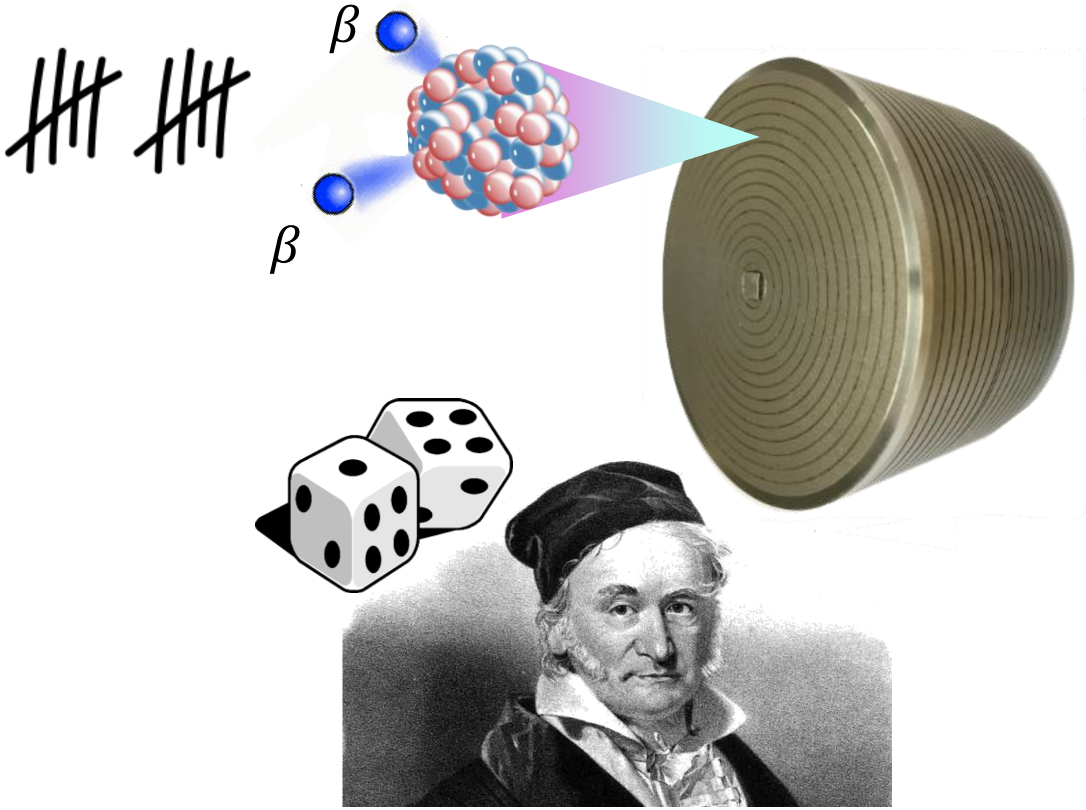




Signal vs. background: is this a detection (yet)?

- **Statistical fluctuations of signal & background: confidence intervals**

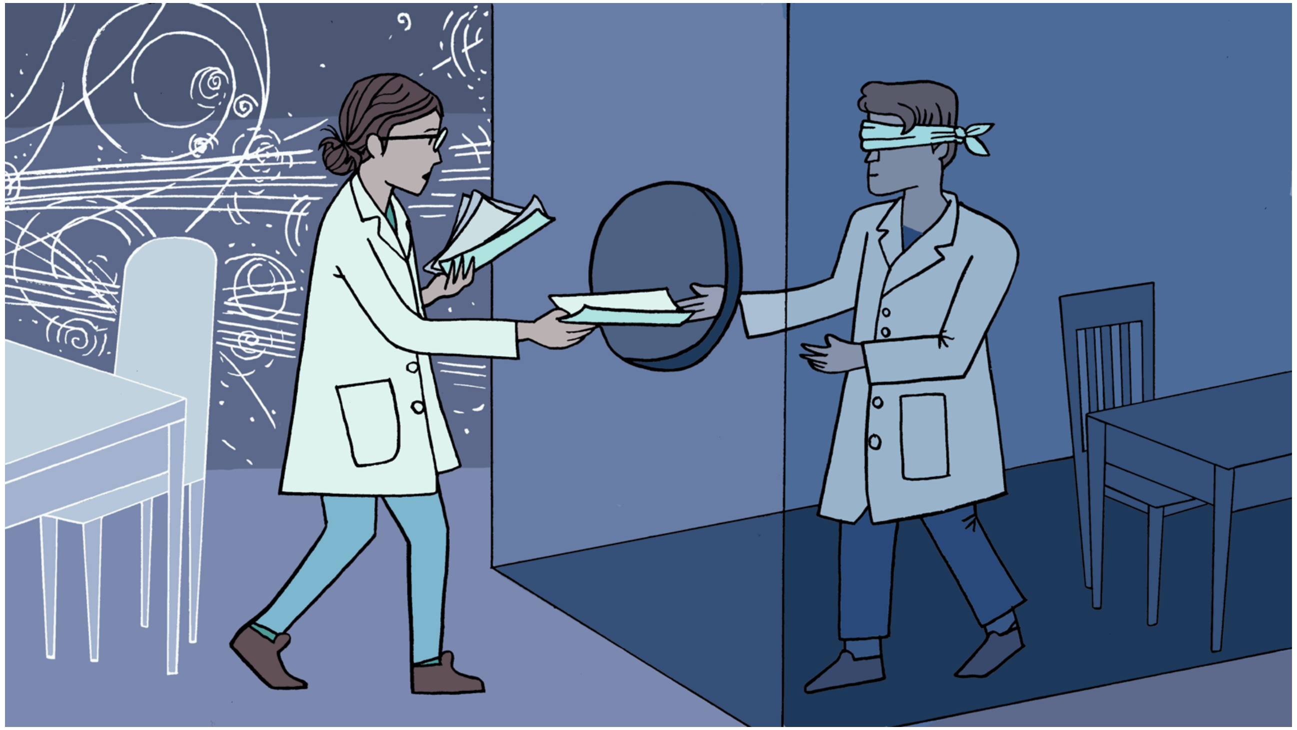
  - **signal:** detection of new physics signal requires > **5 standard deviations**

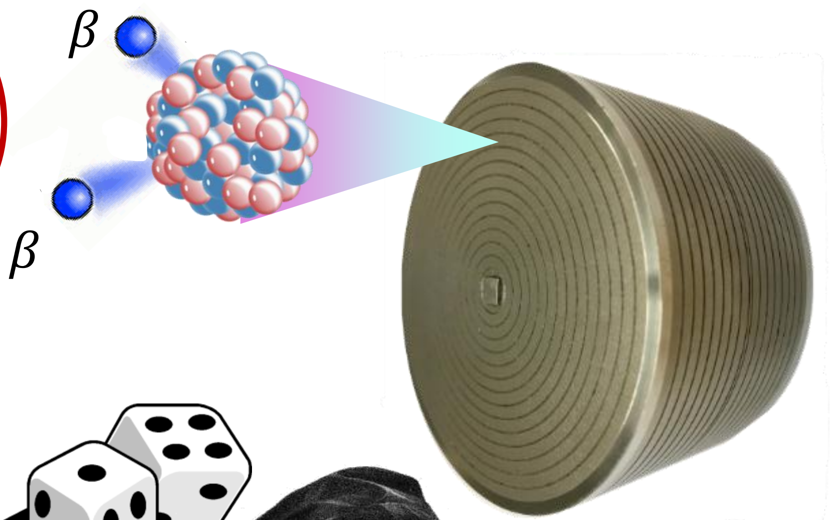


Signal vs. background: is this a detection (yet)?

- **Statistical fluctuations of signal & background: blind analysis**

  - **signal:** region close to it as to be blinded during systematic tests **to avoid any bias in analysis**



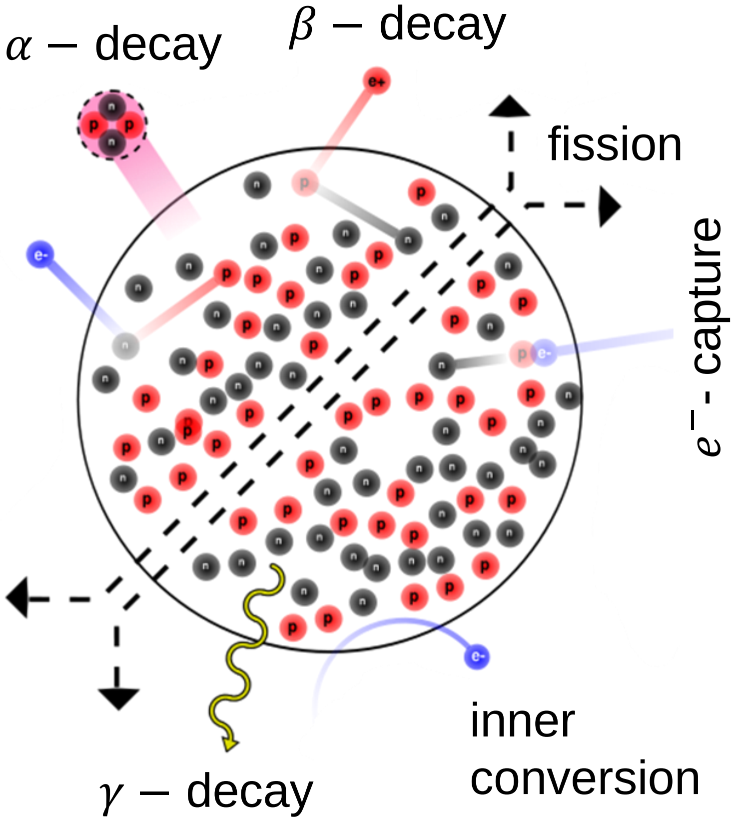


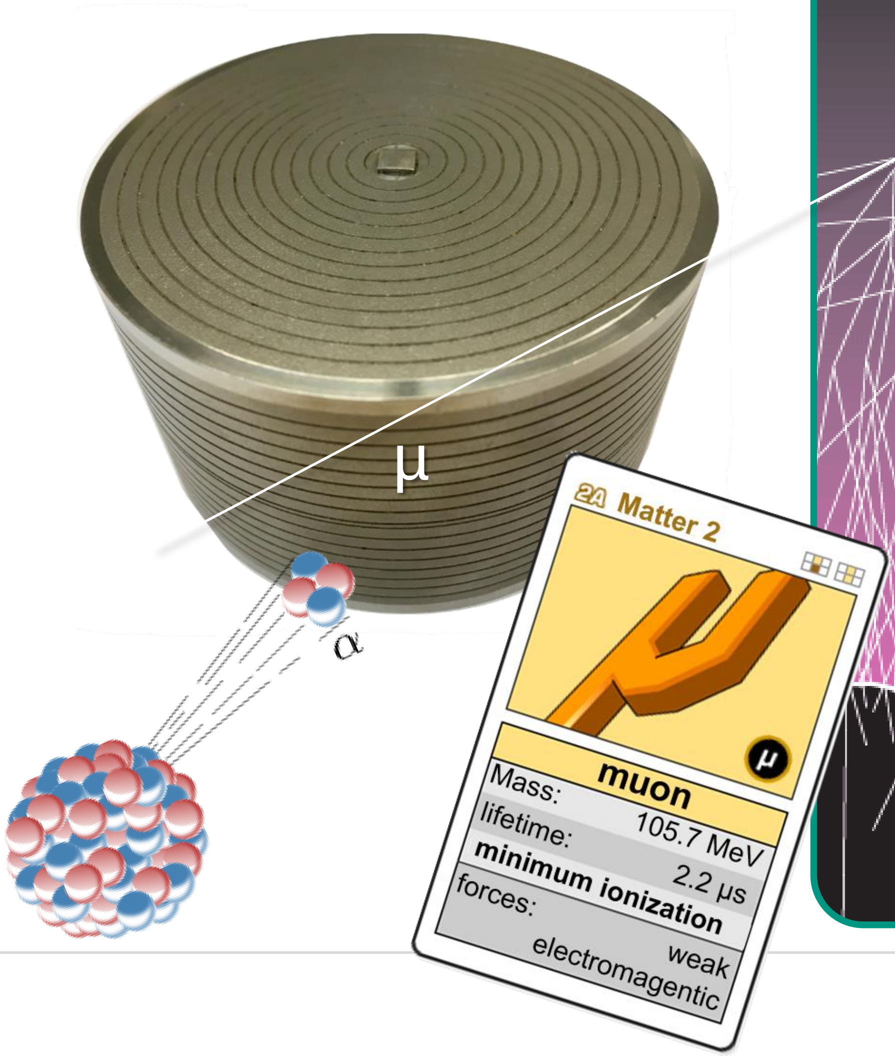
after unblinding:

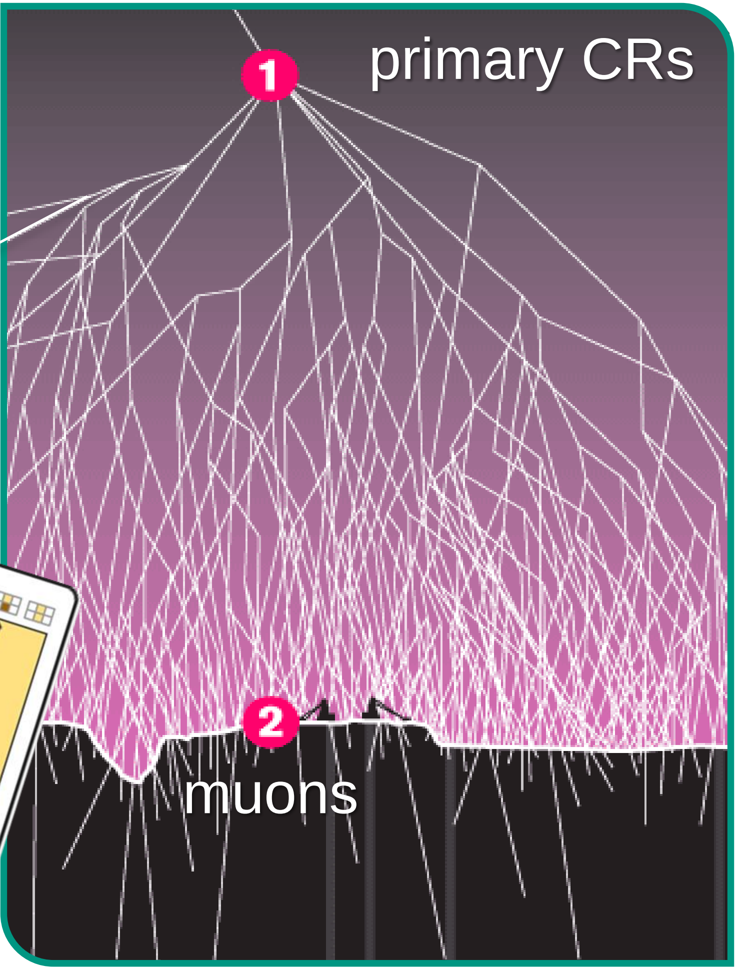
2.2.1 Background processes

- **Dominant background sources:** natural radioactivity & cosmic rays $(\mu´s)$

decay types of nuclei







Background processes – comparison of rates

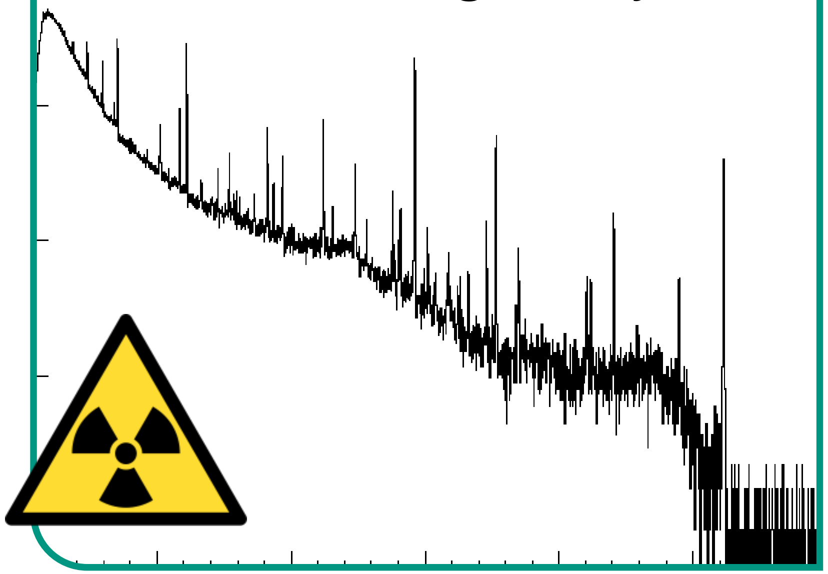
- **Dominant background sources: natural radioactivity & cosmic rays $(\mu' s)$**

natural radioactivity

- rate

100 events $kg^{-1}s^{-1}$

$\mathbf{10^7}$ events $kg^{-1}day^{-1}$



$\mathbf{10^{-3} \ldots 10^{-4}}$ events $kg^{-1}day^{-1}$ in signal region

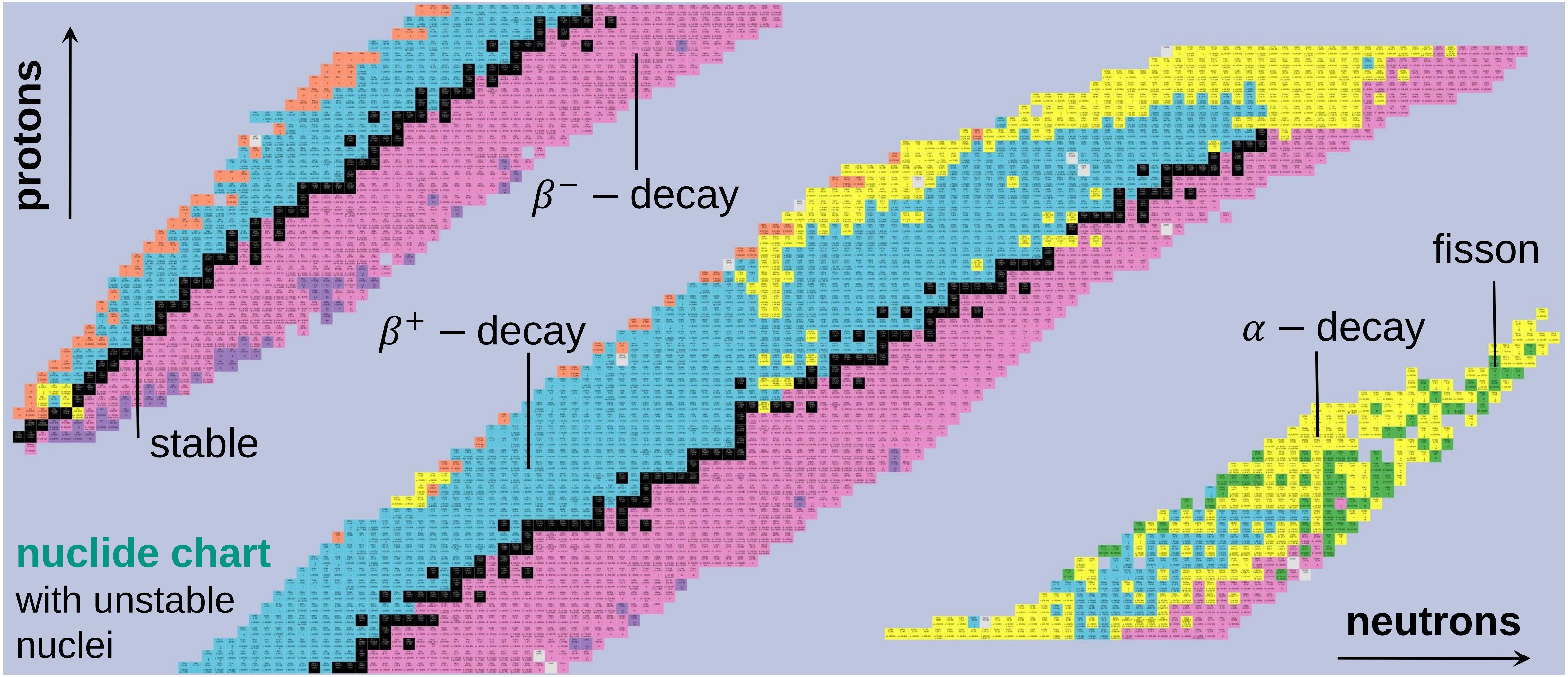
cosmic background

- rate

0.1 events $kg^{-1}s^{-1}$

$\mathbf{10^4}$ events $kg^{-1}day^{-1}$

Decay processes of unstable nuclei: background



nuclide chart
with unstable
nuclei

Decay processes – activity of an isotope

Karlsruhe Institute of Technology

- **Radioactive decay law** and units

- the **activity $A(t)$** of an unstable isotope is…

$$A = \frac{dN}{dt} = -\lambda \cdot N$$

… describing the number dN of decays per unit time dt

… proportional to the decay constant λ (≡ decay probability per unit time* dt)

… *not* a constant, as the ensemble size N decreases over time t
due to decay processes ⇨ activity A of ensemble will decrease

… decreasing exponentially (**decay law**)

$$A(t) = A(0) \cdot e^{-\lambda \cdot t}$$

*for all $dt \ll t_{1/2}$ (i.e. for long $t_{1/2}$: $dt = 1\ s$)

Decay processes – activity of an isotope

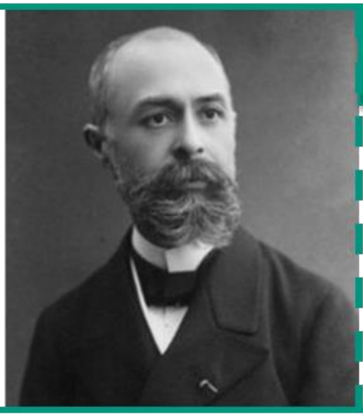
- **Radioactive decay** law and **units**

- the **activity** $A(t)$ of an unstable isotope is measured…

$1\ Becquerel = 1\ decay/s$

$1\ Bq = 2.70 \cdot 10^{-11} Ci$

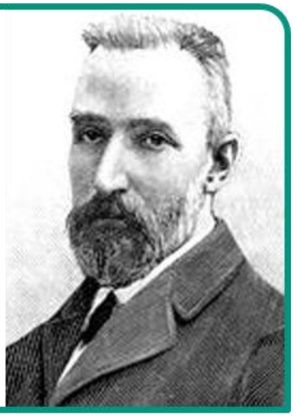
(after Henri Becquerel)



$1\ Curie = 3.7 \cdot 10^{10}\ decays/s$

$1\ Ci \equiv$ activity of $1g$ radium, more specifically ^{226}Ra

(after Pierre Curie)



- … sources vary from $A = \mu Ci$ (KIT lab course) up to $A = MCi$ (radiation lab)

Decay processes – activity of an isotope

■ **Radioactive decay: articifical sources in astroparticle physics**

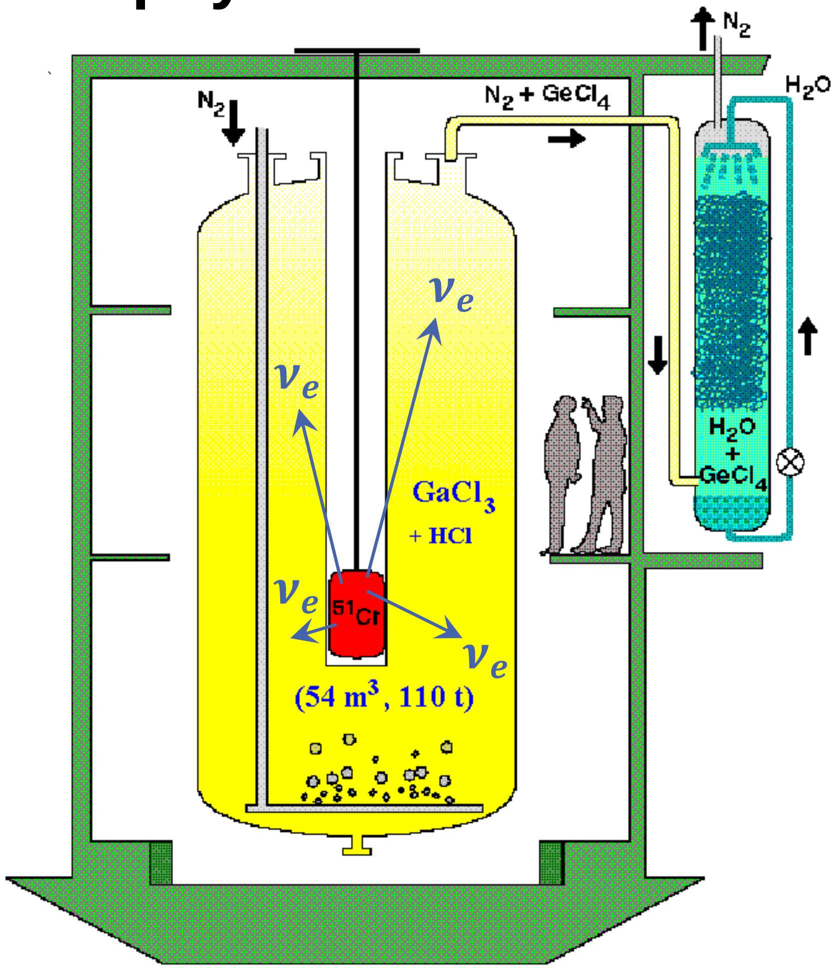
- use of **strong artificial ν-sources**: GALLEX

- ^{51}Cr – source: $\mathbf{A = (1.67 \pm 0.03)\ MCi}$
  decays via e^- - capture process:

$$^{51}Cr + e^- \rightarrow {}^{51}V + \nu_e + \gamma$$

- half-life $t_{1/2} = 27.7\ days$

- calibration of solar neutrino detector GALLEX*



*see ATP-2 summer term 2023

Decay processes – activity of an isotope

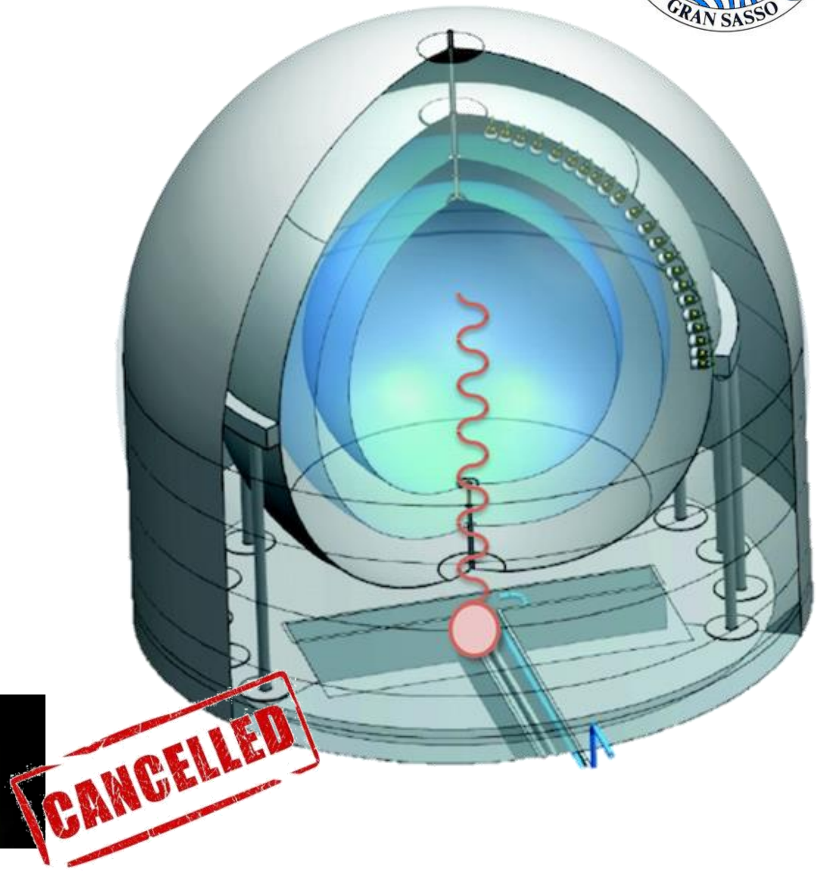
- **Radioactive decay: articifical sources in astroparticle physics**

  - use of **strong artificial ν-sources**: SOX

  - ^{51}Cr – source: $\boldsymbol{A = 5 - 10\ MCi}$
    decays via e^- - capture process:

$$^{51}Cr + e^- \rightarrow {}^{51}V + \boldsymbol{\nu_e} + \gamma$$

  - search for sterile ν´s with BOREXINO detector*



*see ATP-2 summer term 2023

Decay processes – activity of potassium-40

- **Radioactive decay: natural sources in environment**

  - natural radioactivity in organic matter

  - activity of bananas due to ^{40}K

$$^{40}K \rightarrow {}^{40}Ca + \bar{\nu}_e + e^-$$
$$^{40}K + e^- \rightarrow {}^{40}Ar + \nu_e + \gamma$$

  - half-life $t_{½} = 1.2 \cdot 10^9\ yr$

  - unit: **B**anana-**E**quivalent-**D**ose (BED) $= 0.1\ \mu Sv$*

$^*1\ Sievert = 1\ Sv$

Decay processes – activity of human body

- **Is my natural radioactivity measurable & a threat to my rare event search?**

- activity A of a medium-sized human body ?

- my estimate for activity A:

❶ – $A \ll 1\ Bq$

❷ – $A = 10\ Bq$

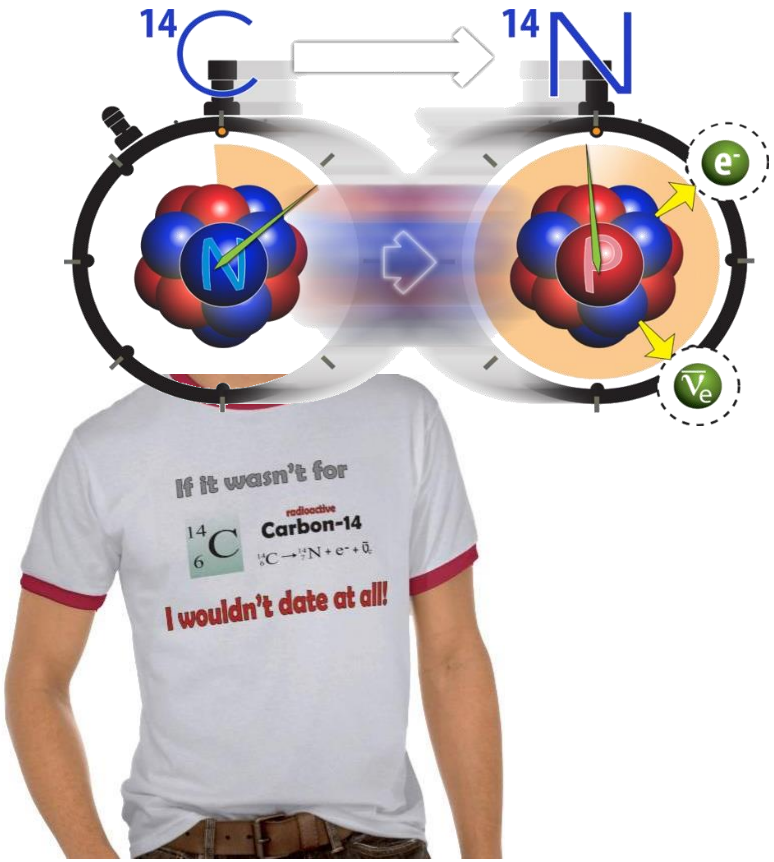
❸ – $A = 1000\ Bq$

❹ – $A = 10^4\ Bq$

Decay processes – activity of human body

Karlsruhe Institute of Technology

- My **natural radioactivity**: dominated by the two isotopes ^{14}C and ^{40}K



see huge noise rate in PMTs of deep-sea-ν-telecopes

Nuklid	Aktivität in Bq
H-3	25
Be-7	25
C-14	3.800
K-40	4.200
Rb-87	650
U-238, Th-234, Pa-234m, U-234	4
Th-230	0,4
Ra-226	1
kurzlebige Rn-222-Zerfallsprodukte	15
Pb-210, Bi-210, Po-210	60
Th-232	0,1
Ra-228, Ac-228, Th-228, Ra-224	1,5
kurzlebige Rn-220-Zerfallsprodukte	30