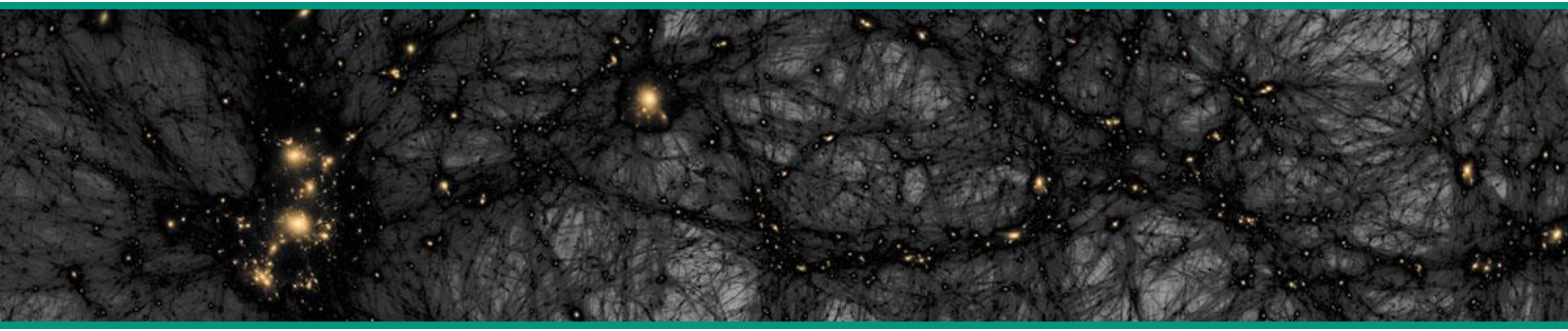
Astroparticle physics *I* – Dark Matter

Winter term 23/24 Lecture 9 Nov. 30, 2023



Recap of Lecture 8

- $VHE \dots UHE$ **gammas: source modelling** & **detection with** $IACTs$

  - $VHE\ \gamma$ – induced showers: **narrow Cherenkov cone** $(1°)$ by relativistic e^+, e^-

  - **shower profile** to discriminate against events from charged CRs

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

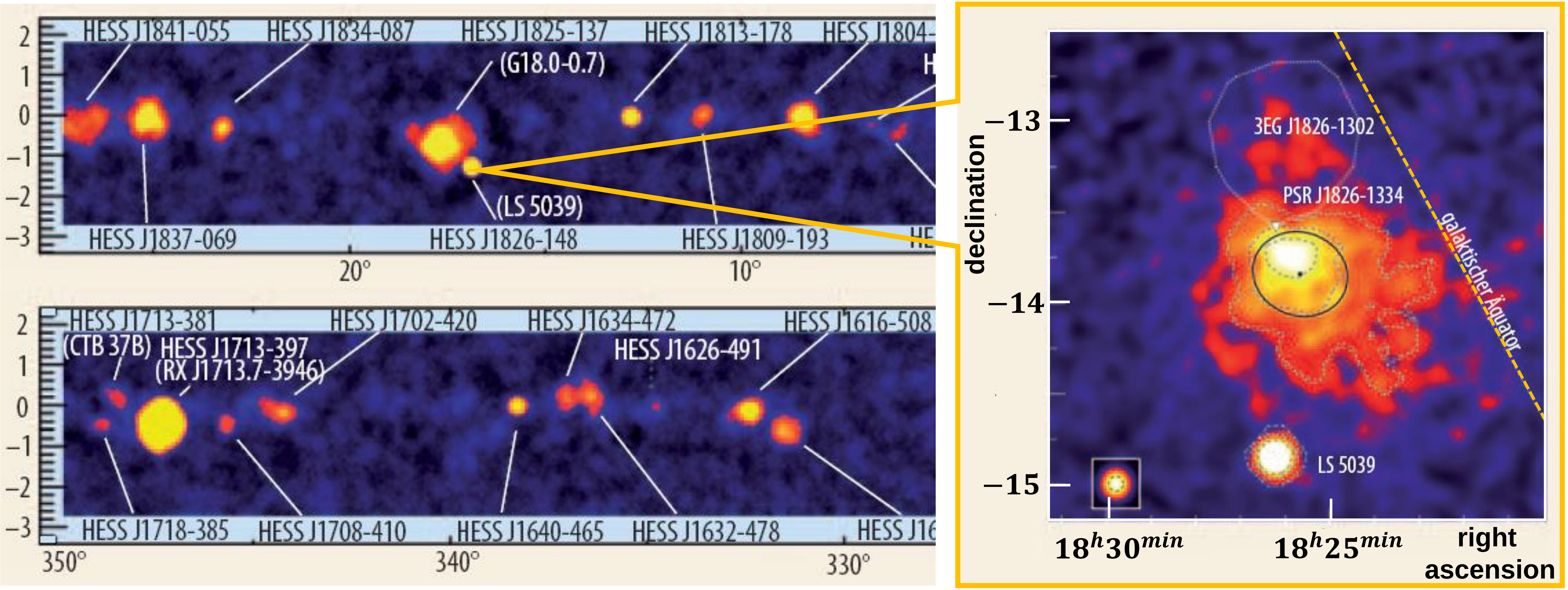
  - source modelling: **hadronic** $(\pi^0 \rightarrow \gamma\gamma)$ *vs.* **leptonic** $(e^- + \gamma \rightarrow \gamma + e^-)$

  - 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

- first scan (2004) with $H.E.S.S.$ over $> 600\ h$: 15 new sources at $TeV -$ scale



Scanning the galactic plane for UHE gammas

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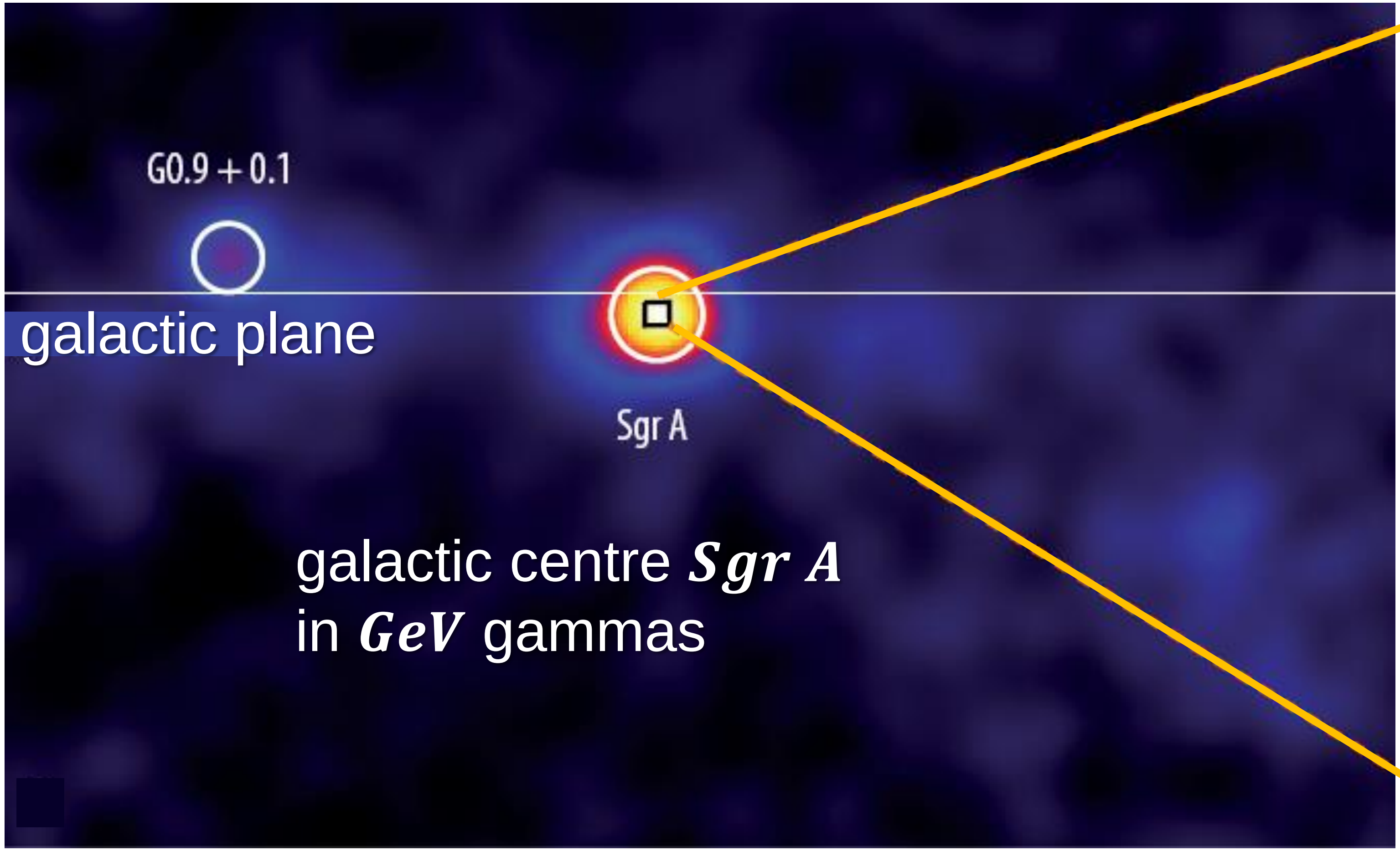
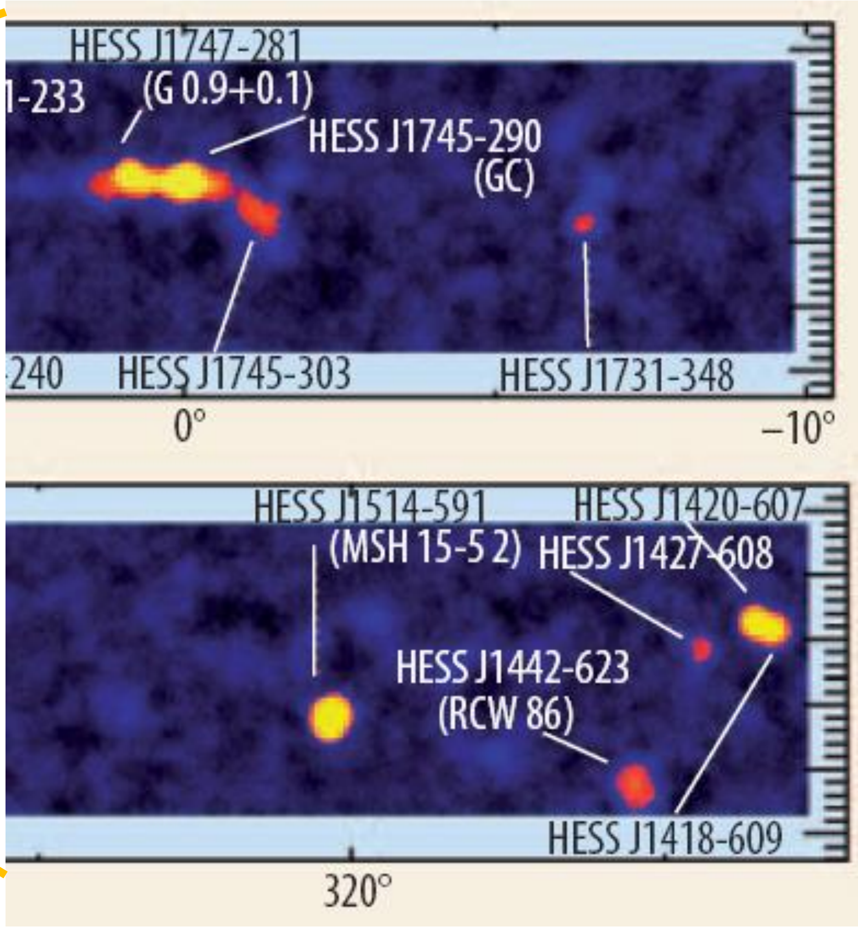
- 2004: strong UHE gamma emission* from the galactic center!

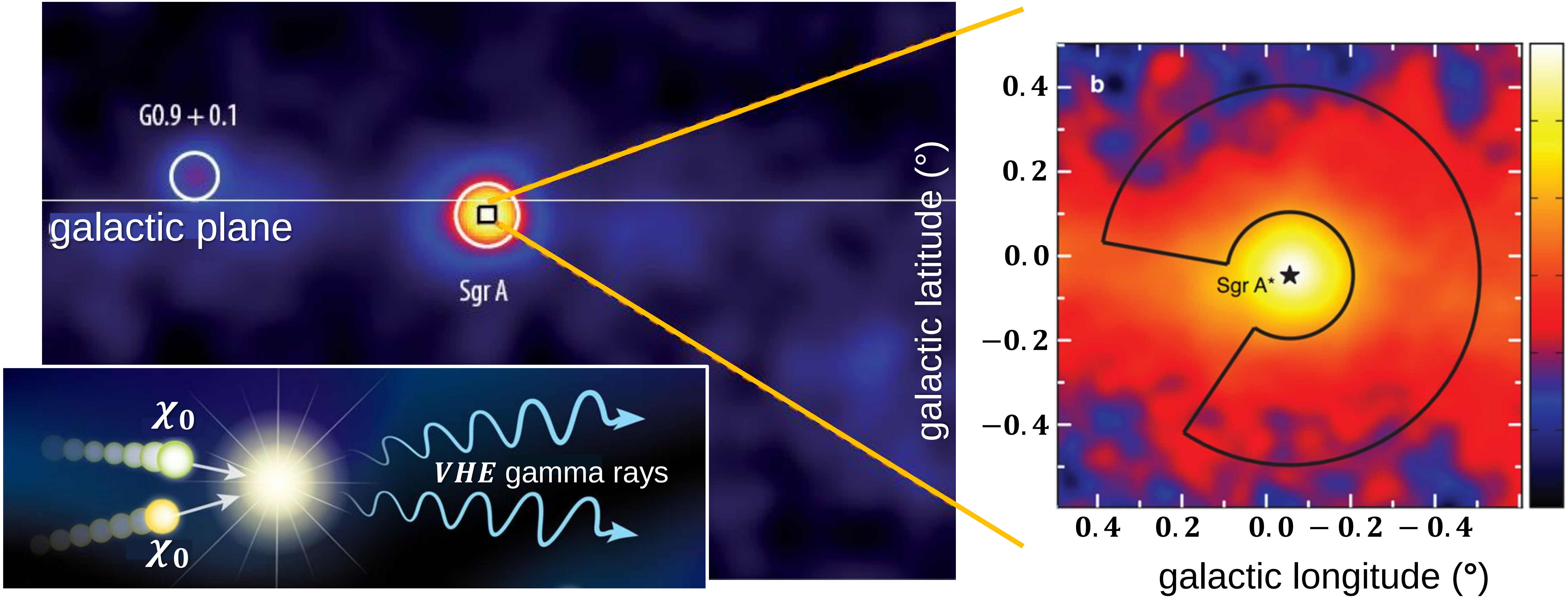




*we will return to $Sgr\ A$ in our Dark Matter search!

Scanning the galactic plane for *UHE* gammas

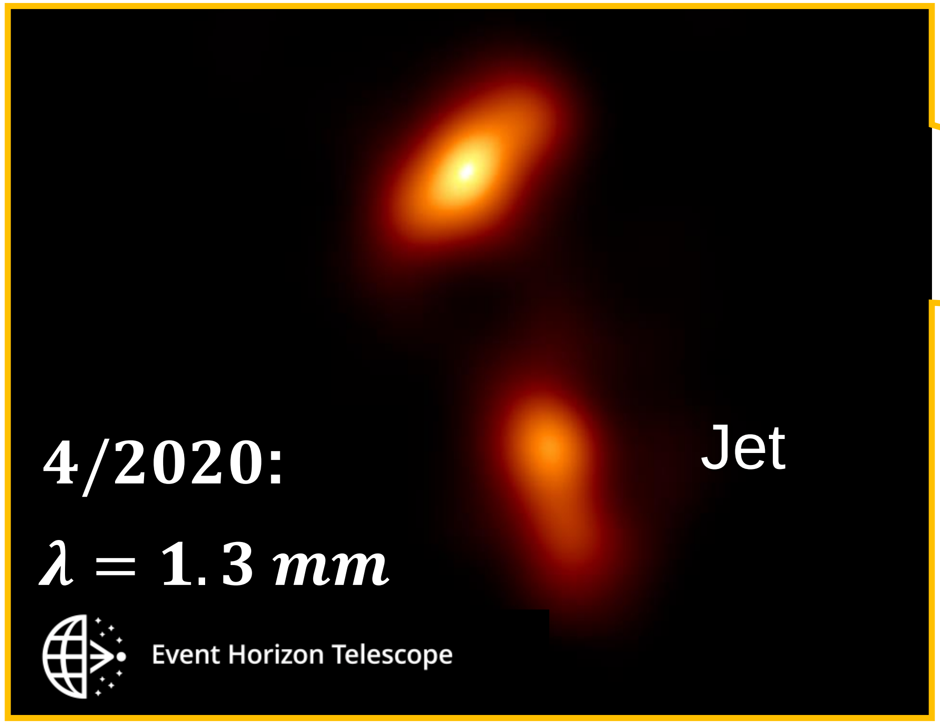
- gamma emission from dark matter annihilation close to galactic center?



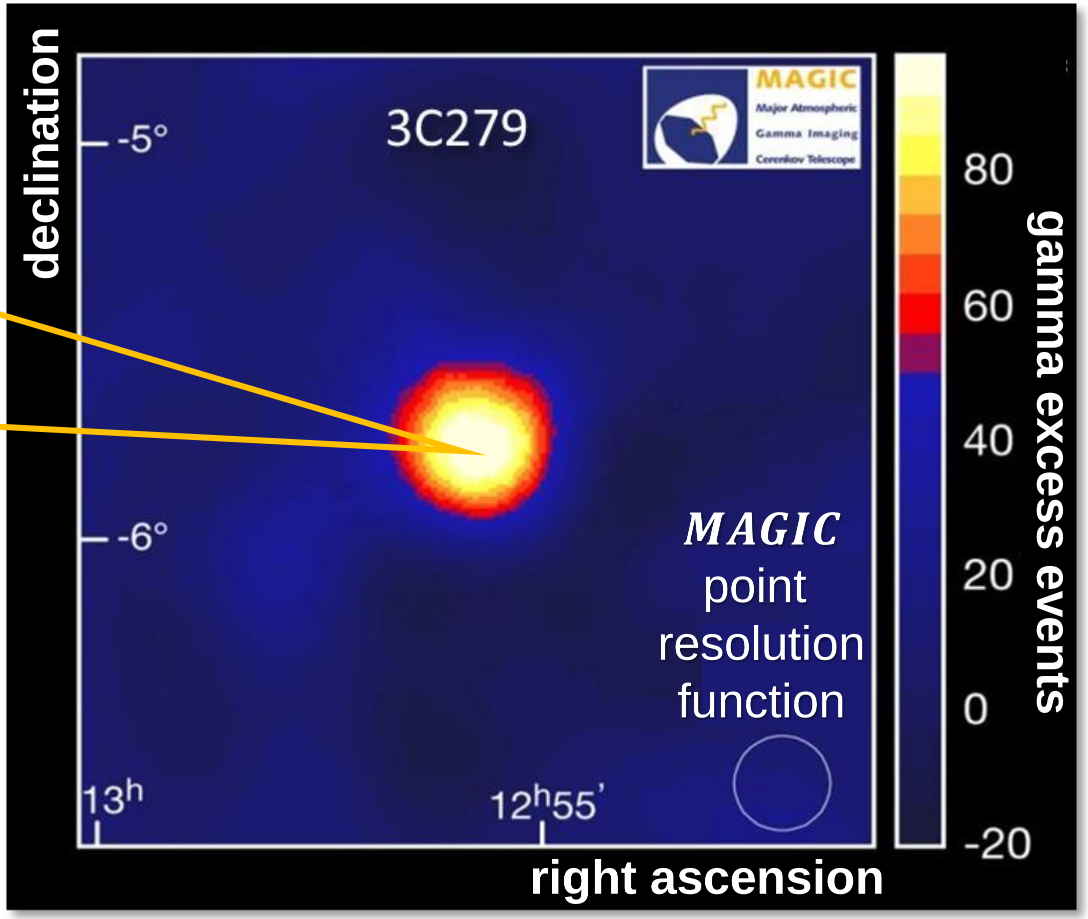
Looking beyond the galactic plane: quasar $3C279$

- $MAGIC$: first observation at $E > 50\ GeV$ of a distant quasar at $d = 1.8\ Gpc$

- universe more transparent for $UHE - \gamma$´s ?*



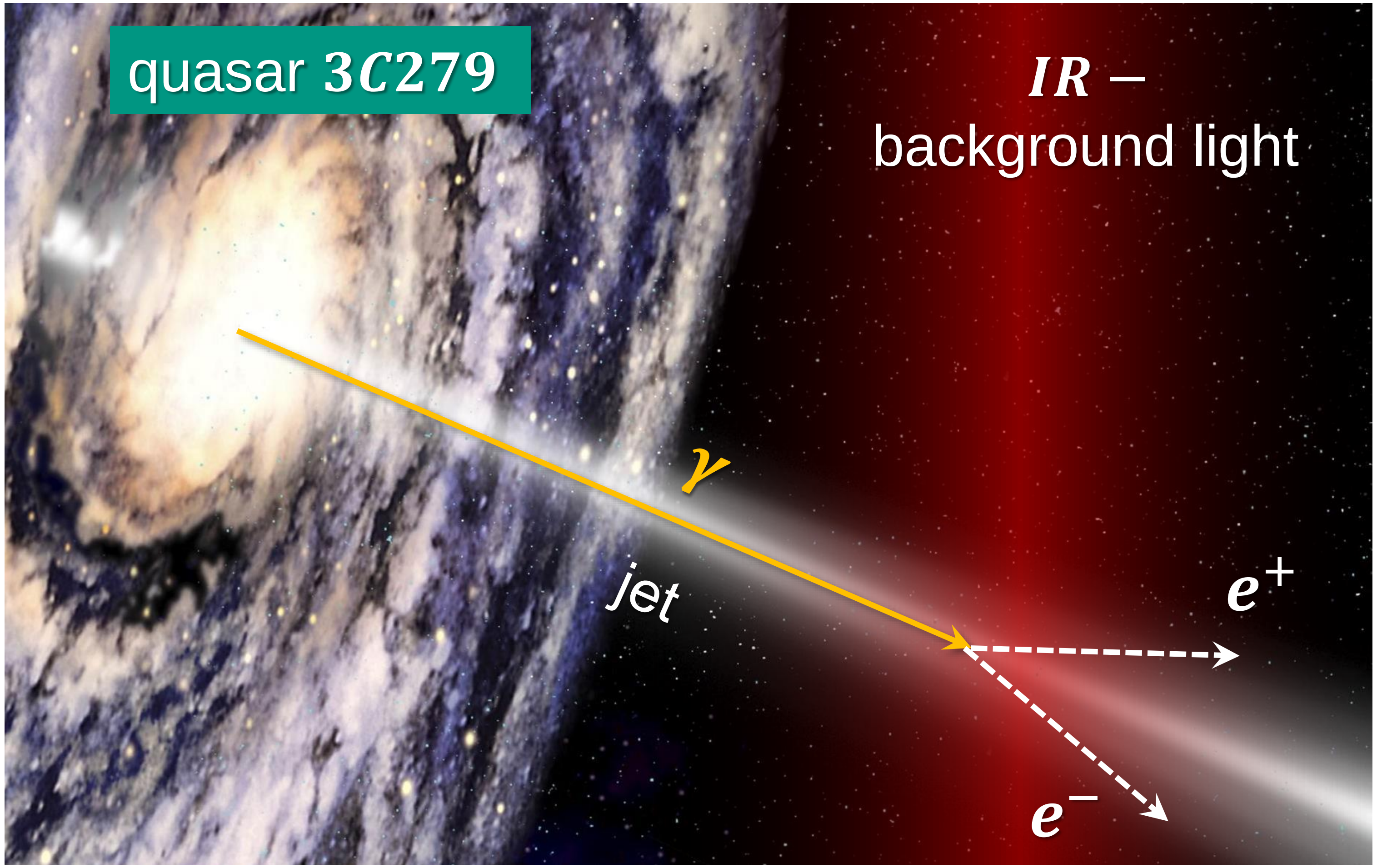
picture of quasar & jet by EHT

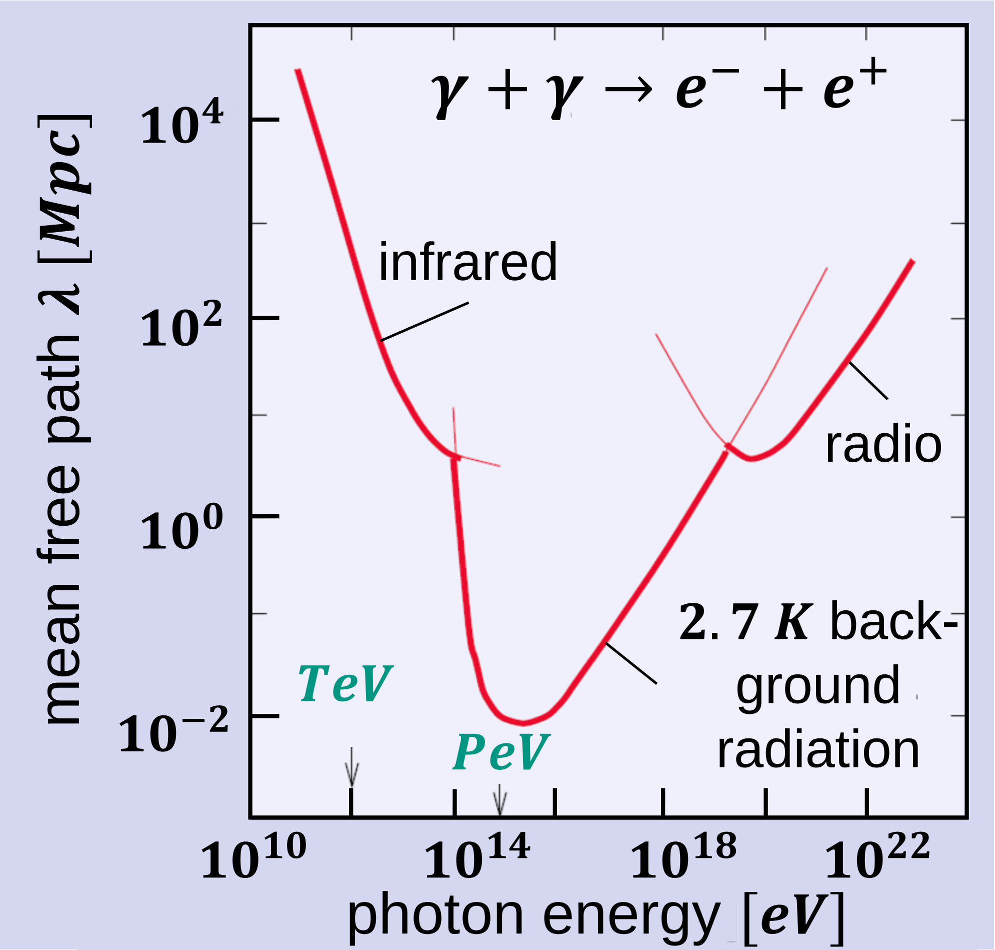


*see Lect. 2 & later chapter $4.6.1$ on axions

gamma properties studies with quasar $3C279$

- **RECAP: limited range of UHE gammas due to extragalactic IR light**

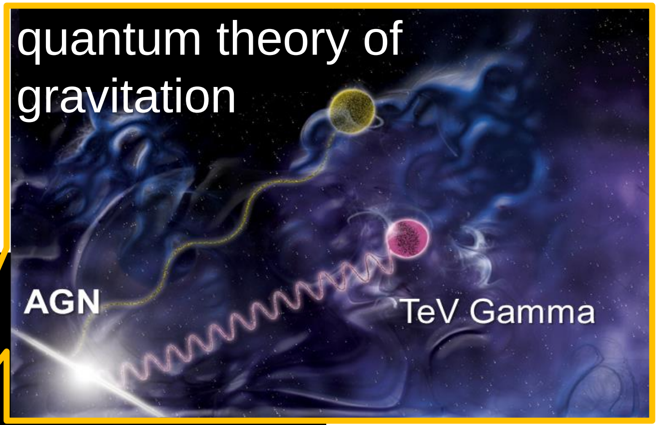


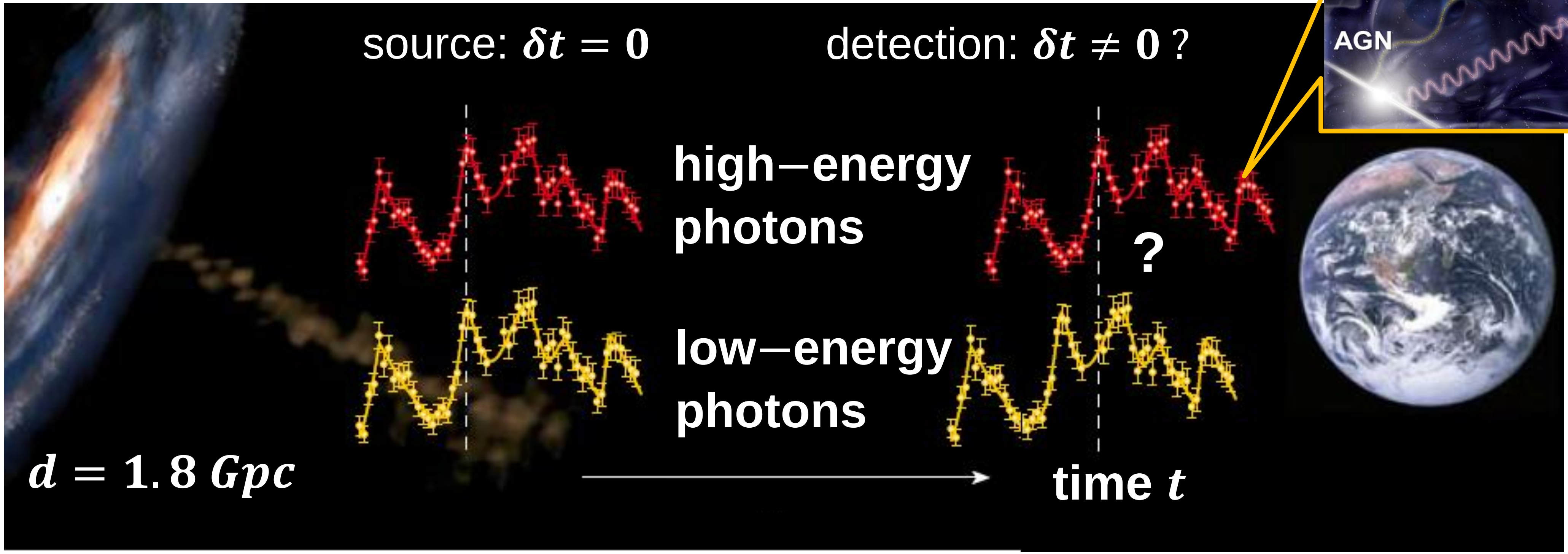


gamma properties studies with quasar $3C279$

- **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**

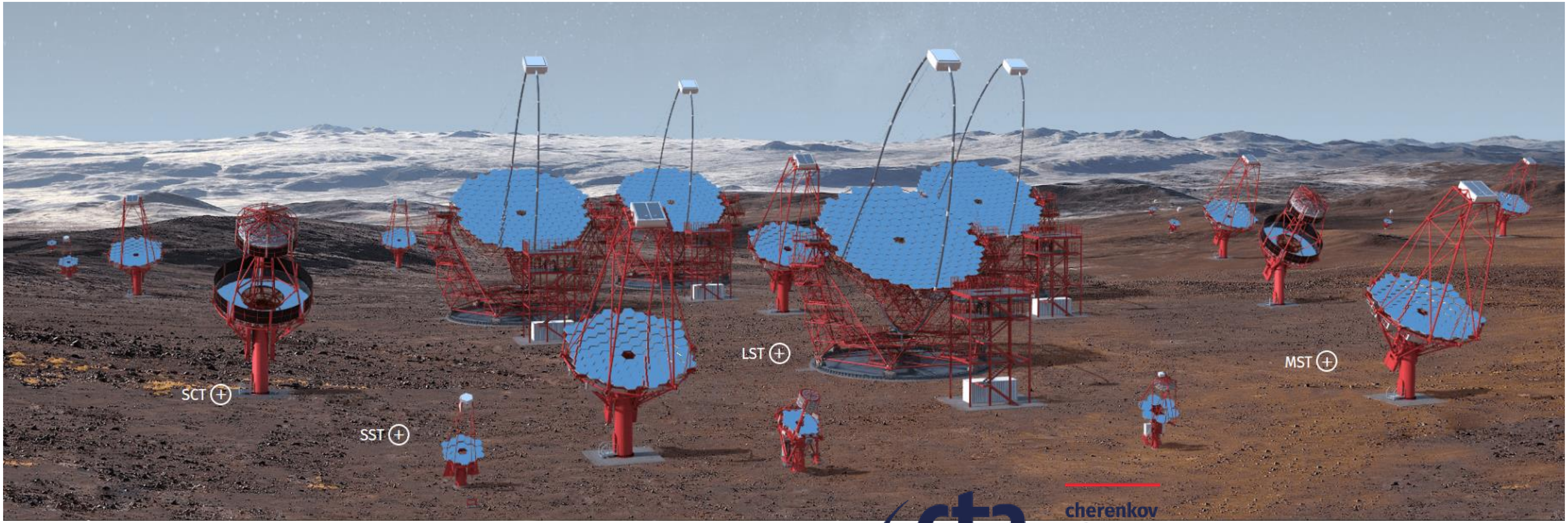




CTA observatory – the future of gamma astronomy

- ***C*herenkov *T*elescope *A*rray (*CTA*) – 118 telescopes at 2 observation sites**

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



cherenkov telescope array

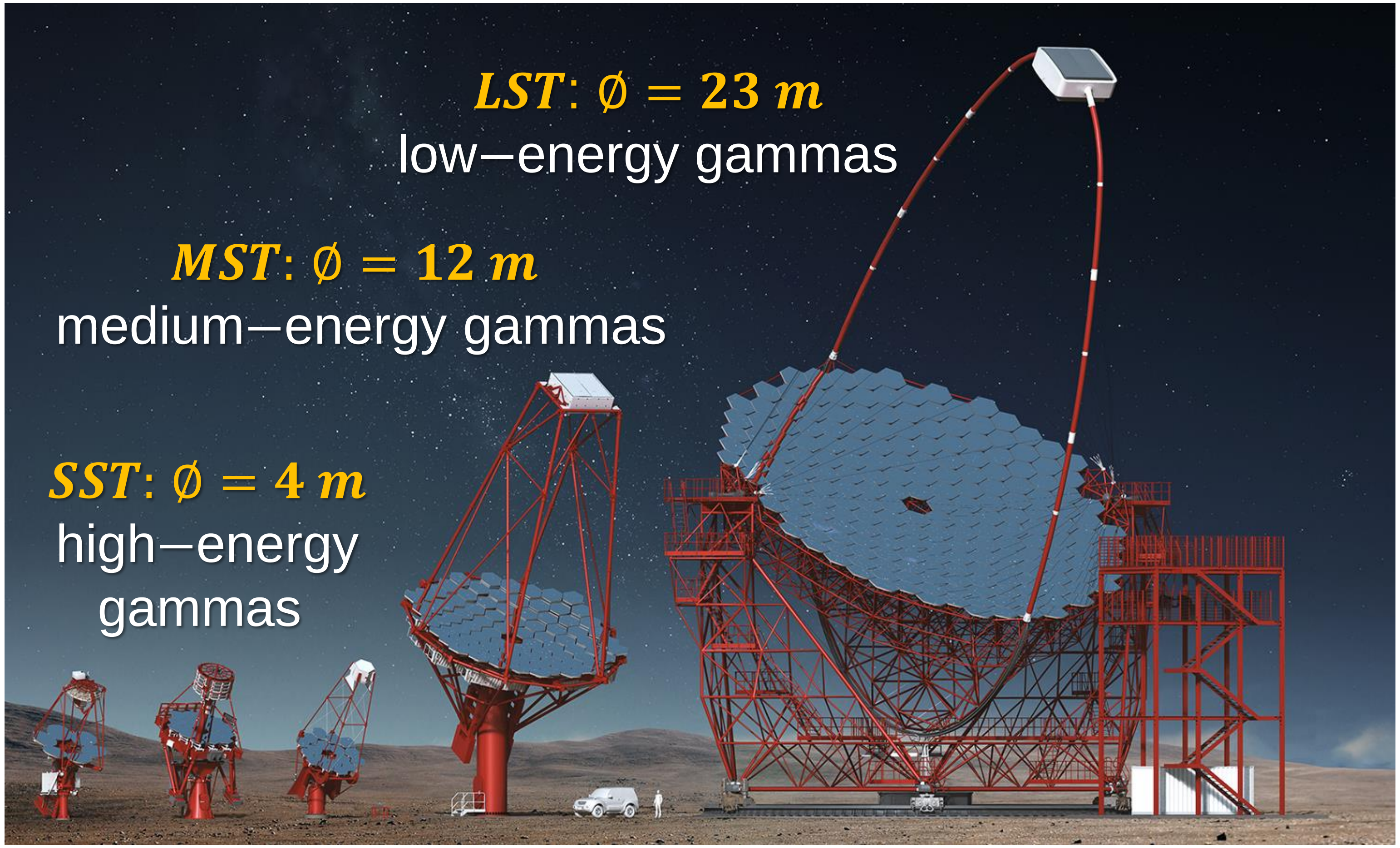
CTA observatory: 3 different telescope sizes

- 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 observatory
150 GeV … 5 TeV

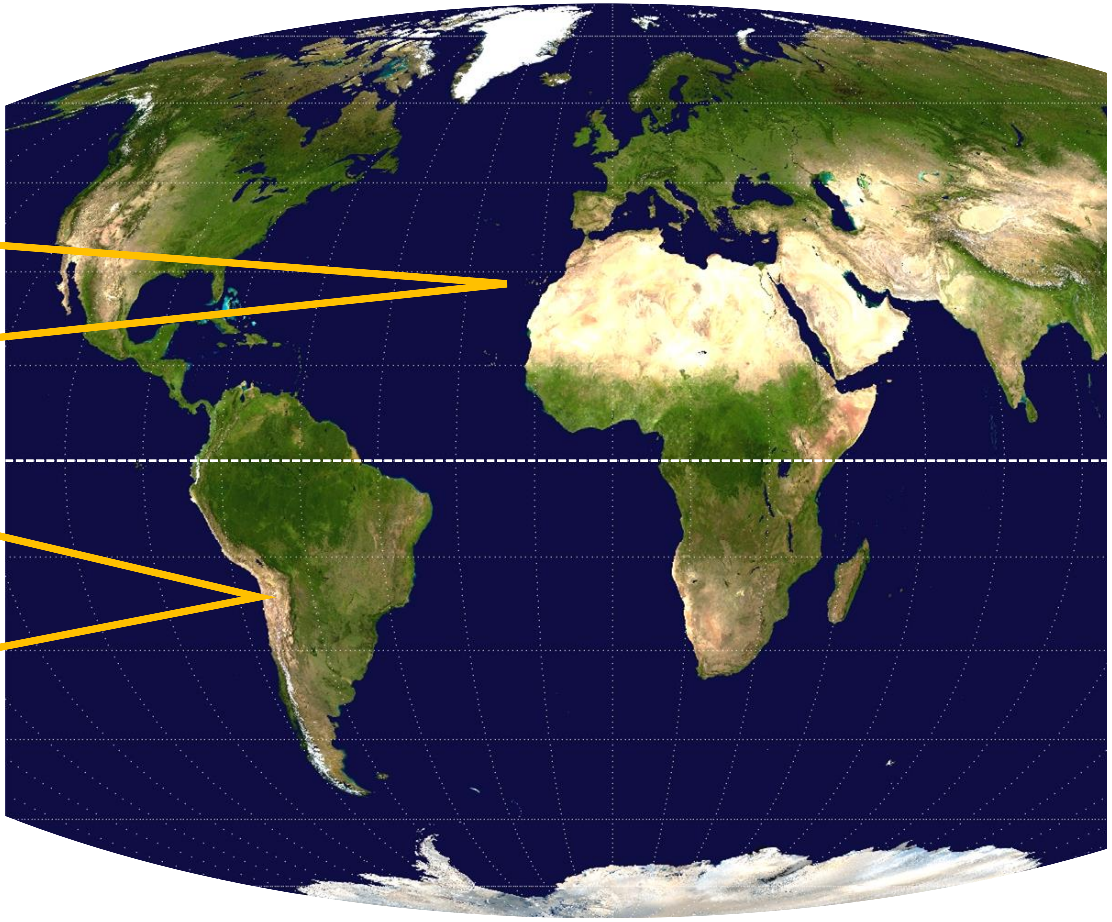
LST: **4** at Southern observatory
4 at Northern observatory
20 … 50 GeV



CTA observatory: 118 telescopes @ 2 sites

- Exploring $VHE \dots UHE$ gamma sources of the Northern & Southern sky

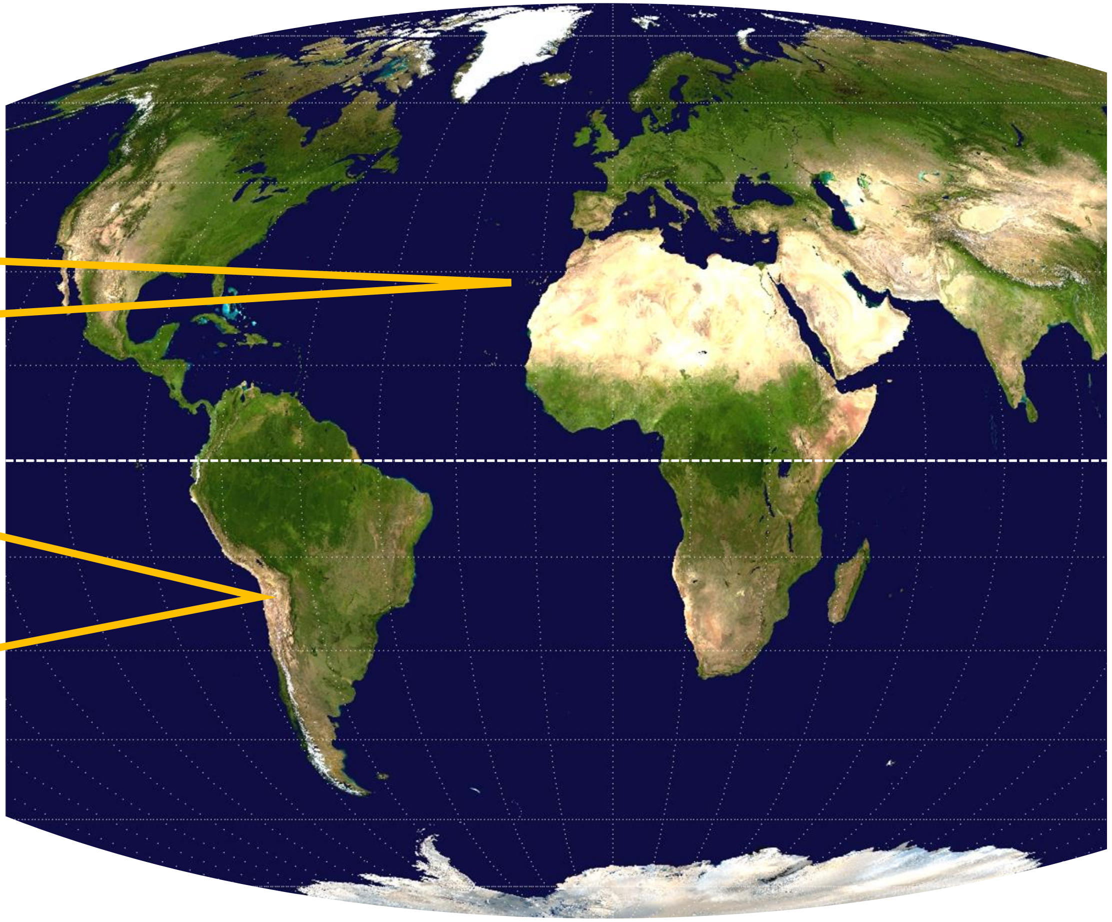
virtual reality



CTA observatory: status at the 2 different sites

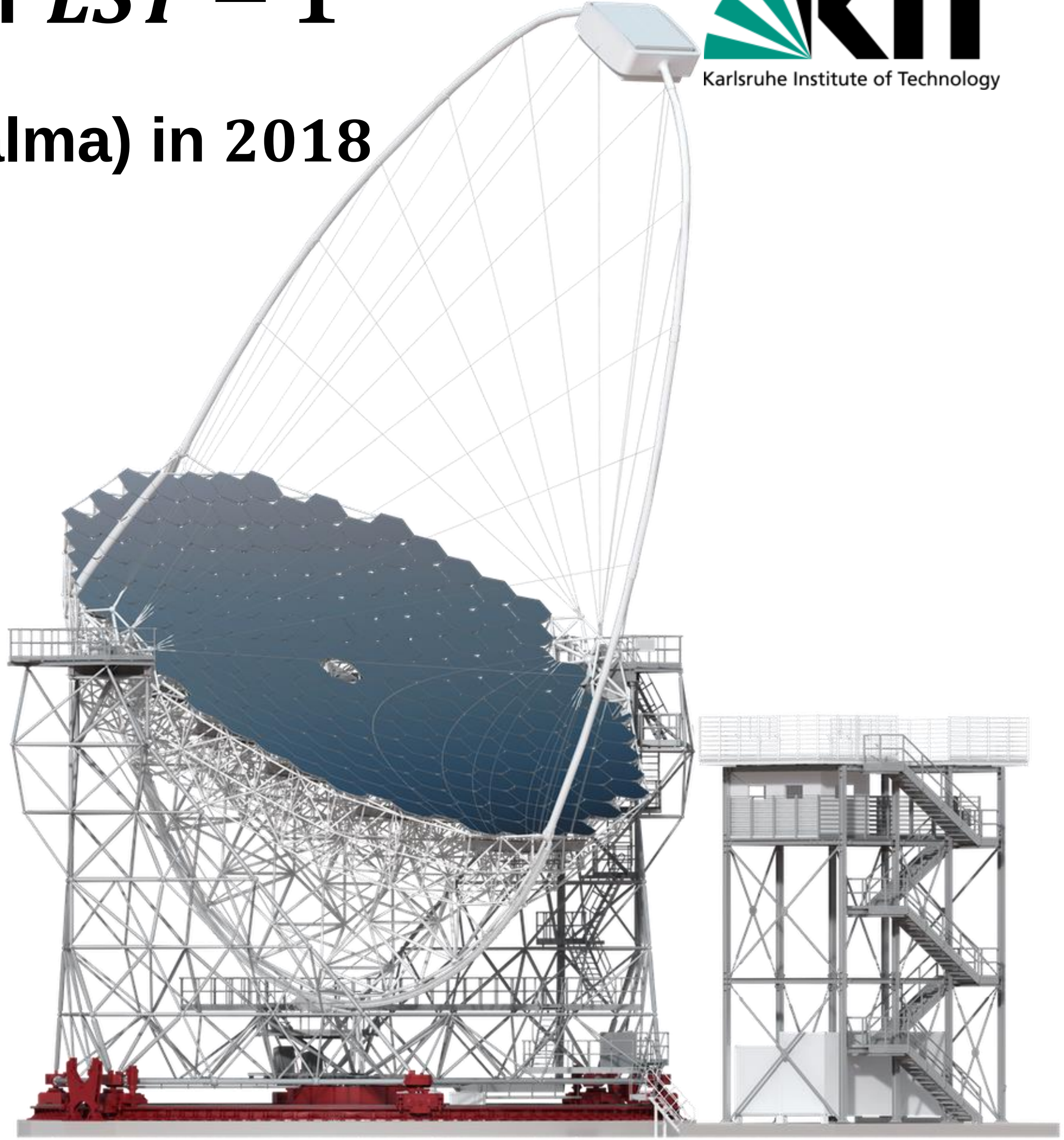
- Ongoing design & construction works at both sites

reality until some time ago



CTA observatory: inauguration of $LST-1$

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



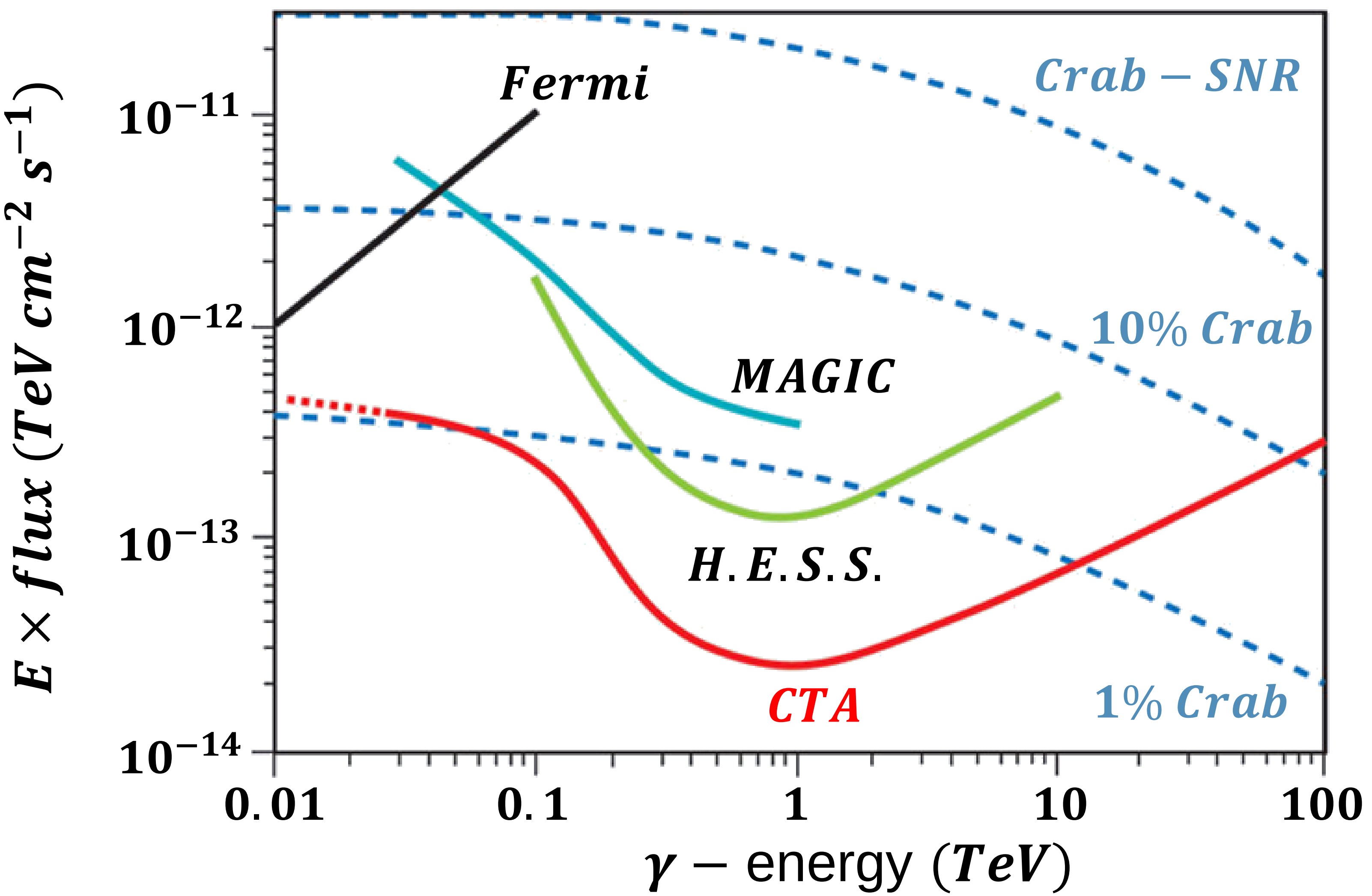
CTA observatory: comparison of sensitivities

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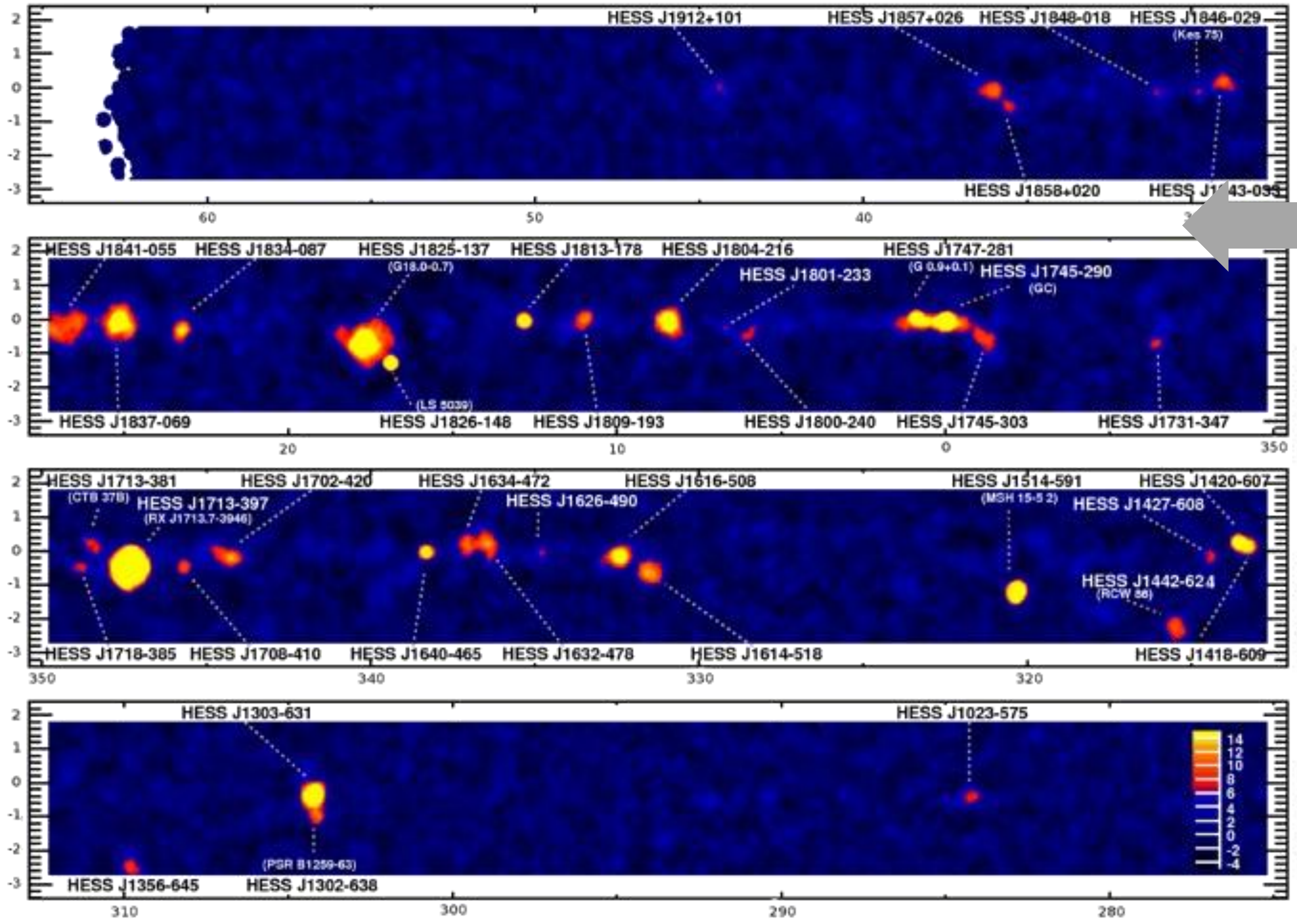
- Expected CTA sources *vs.* observed gamma sources with $H.E.S.S.$

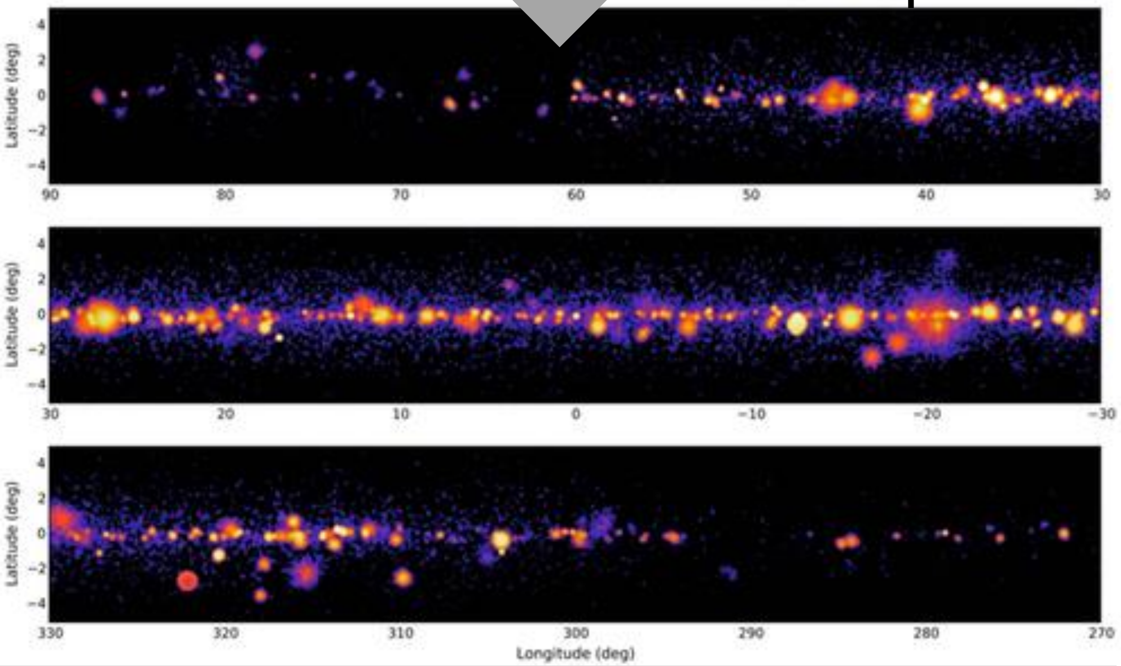
observed

H.E.S.S.



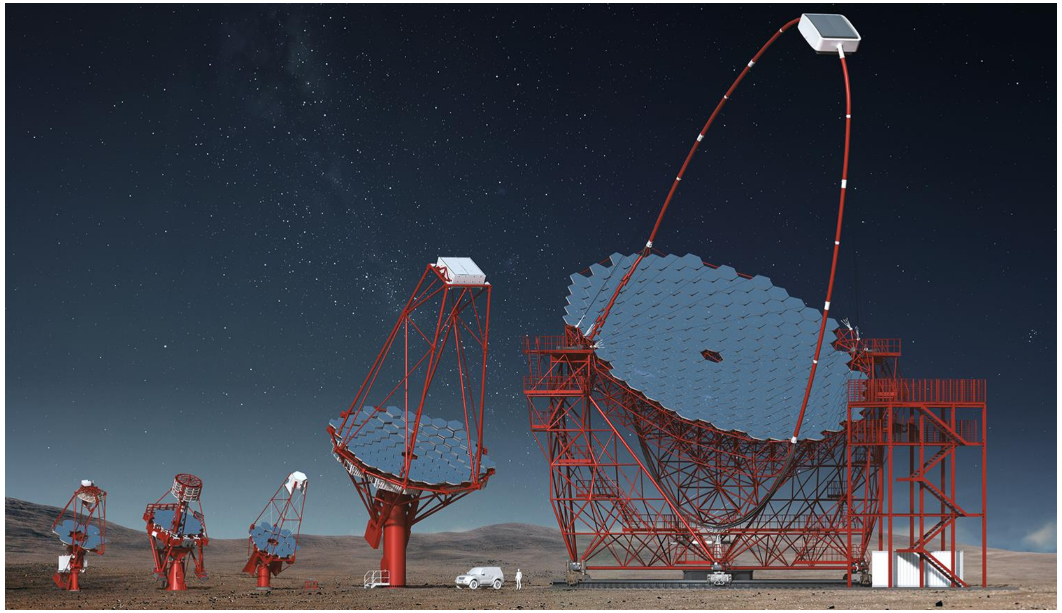
cherenkov telescope array

expected



Gamma astronomy: lobbying for CTA funds…

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



Goodbye, multi–messengers, hello rare events

- **A final, very recent observation in the field of cosmic ray physics**

  - the $\boldsymbol{Telescope\ Array}$ ($\boldsymbol{US}$) experiment announces an event with the second highest energy ever observed (from an empty region without galaxy clusters!)

$$E = 2.4 \cdot 10^{20}\, eV$$

⇨ but: what about $\boldsymbol{GZK}$ – cutoff?

NEWS | 23 November 2023

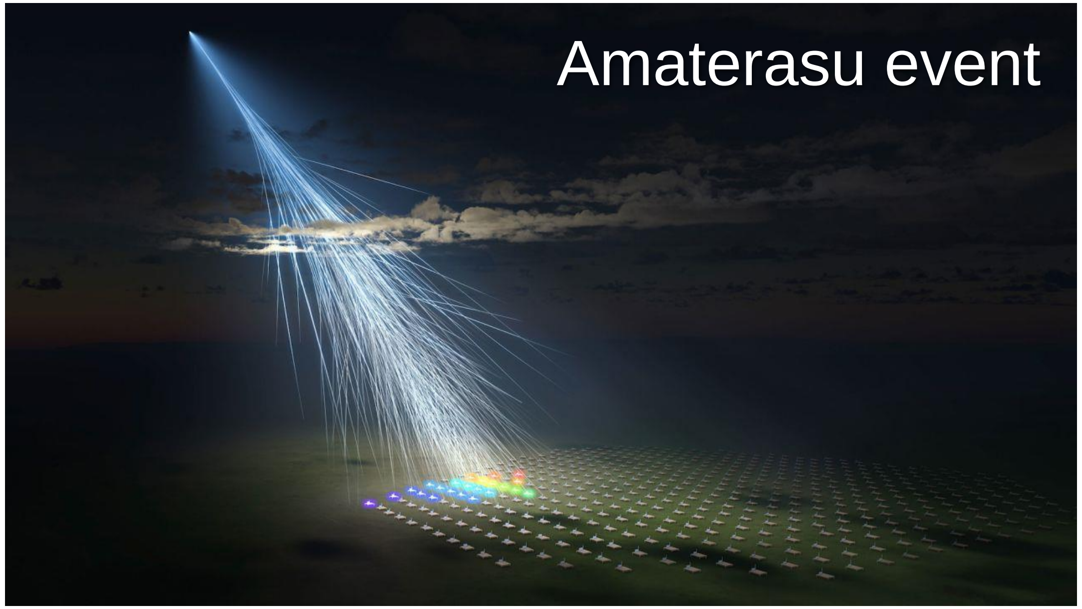
The most powerful cosmic ray since the Oh-My-God particle puzzles scientists

Scientists spot a particle of intense energy, but explaining where it came from might require some new physics.

nature

Scientists detect a cosmic ray that's almost as powerful as the 'Oh-My-God' particle

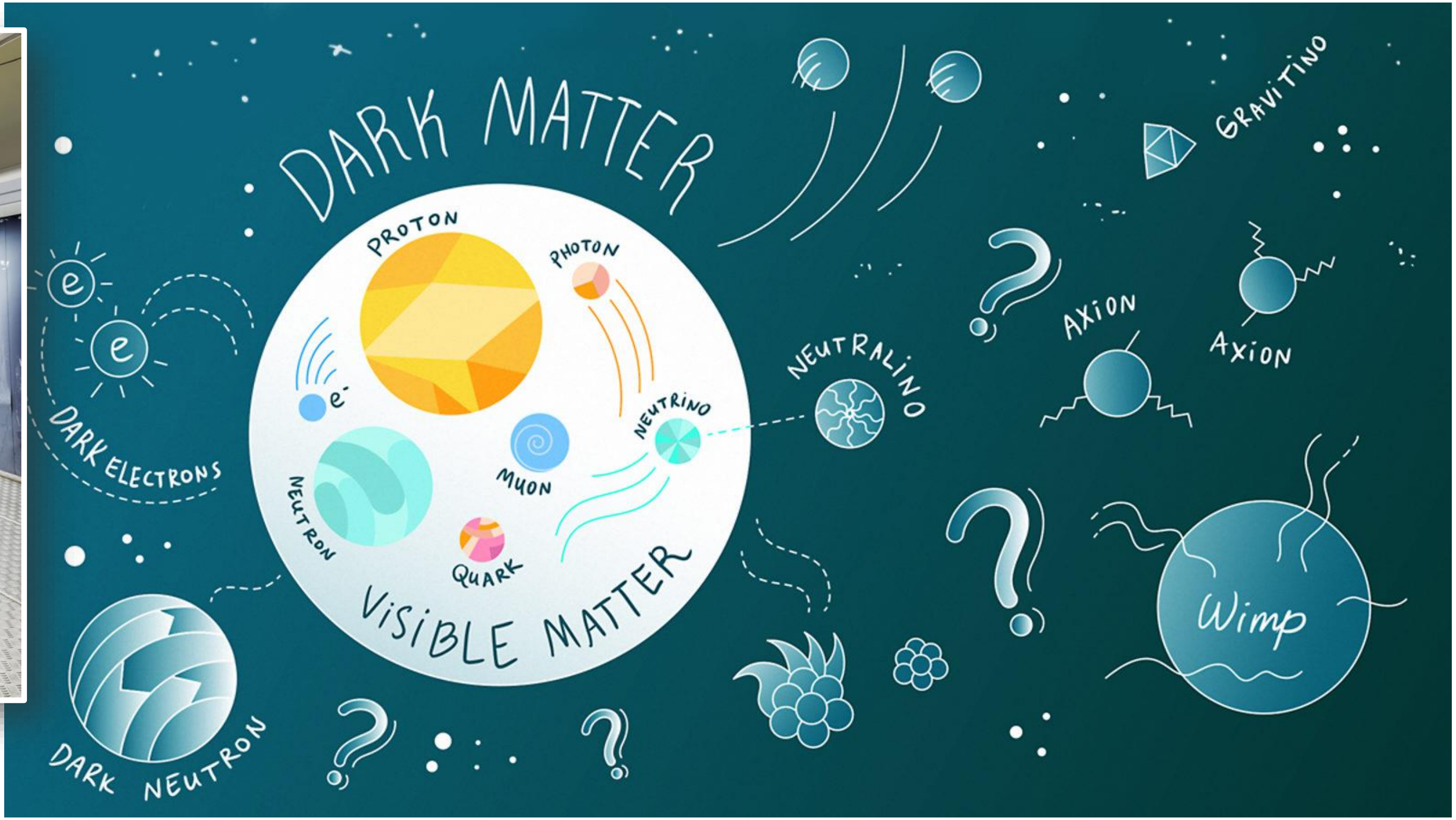
CNN



2.2 Search for Rare Events

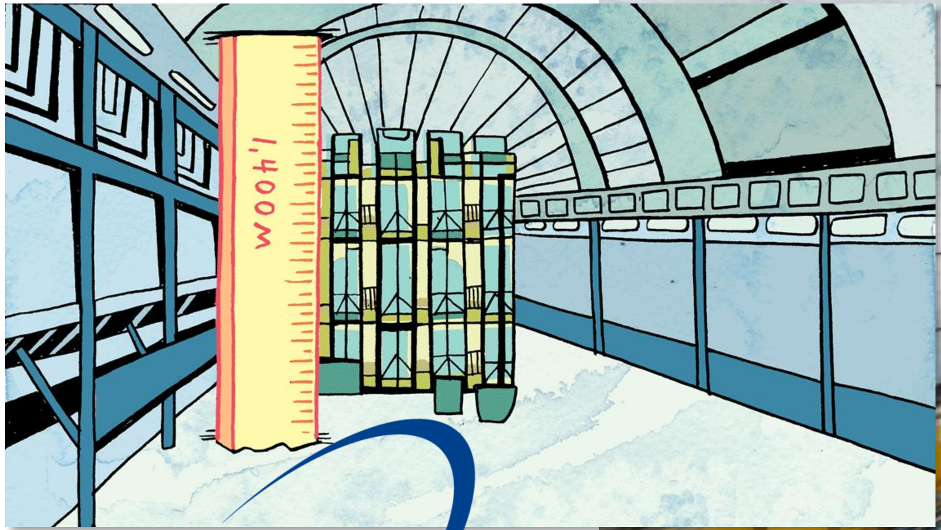
- **Observing novel physics beyond the Standard Model: ⇨ rare event searches**

hunting for dark matter



Rare event searches: principles & technologies

- **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 …

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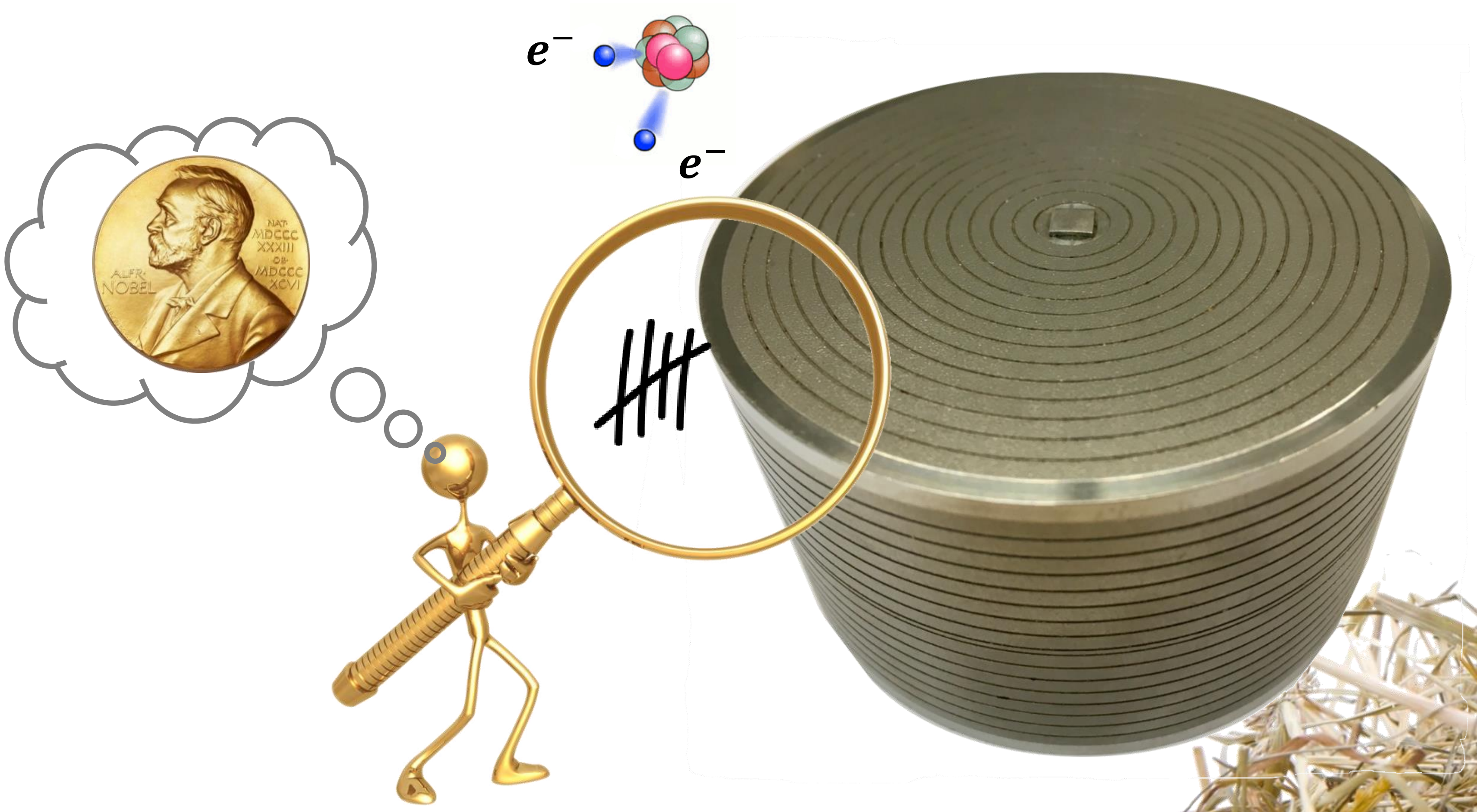
- **How on earth can I detect a signal rate of only $1\ event\ ton^{-1}\ year^{-1}$?**

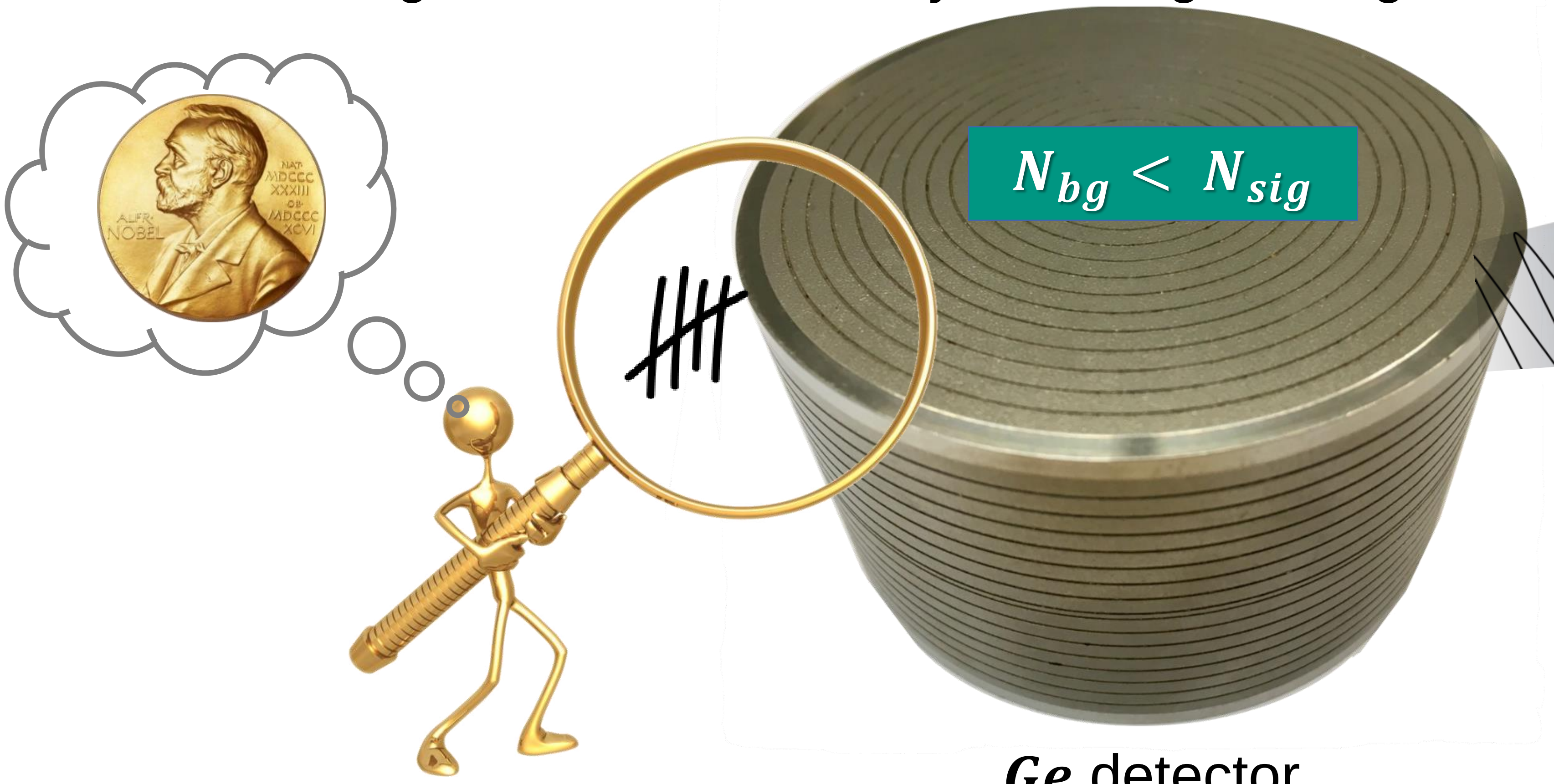


a small needle in
a giant haystack

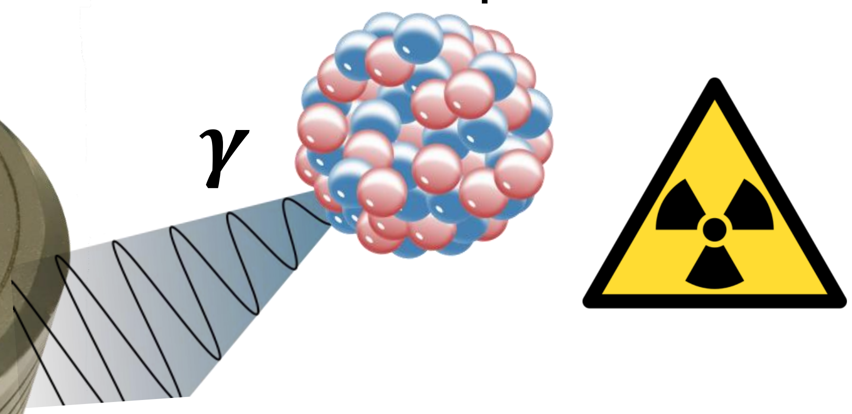
Rare events: Signal compared to background rate

- **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:

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

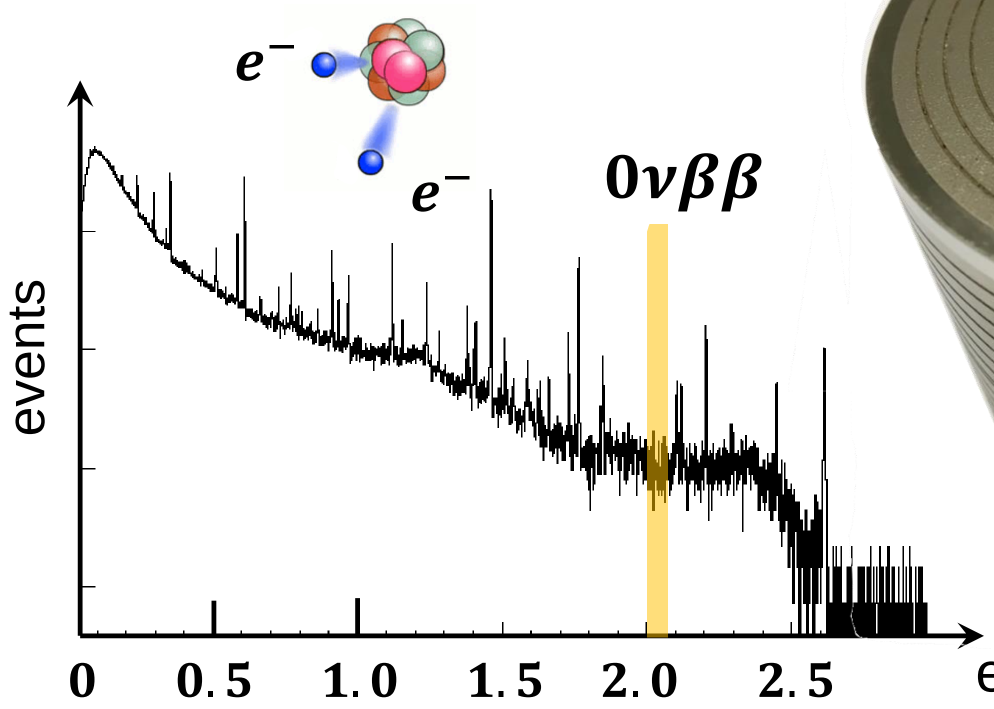
goal:

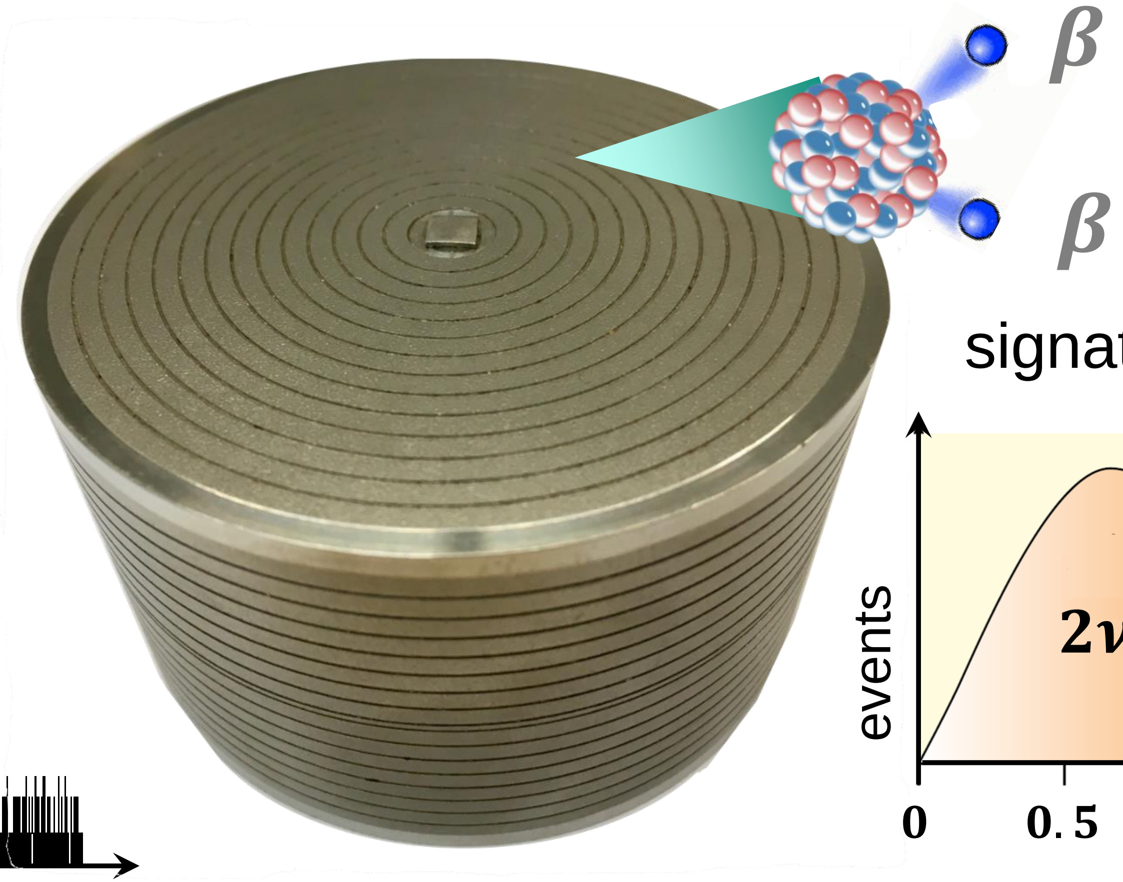
$N_{bg} < 1\ event\ yr^{-1}$

Rare events: example search for $0\nu\beta\beta$ process

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

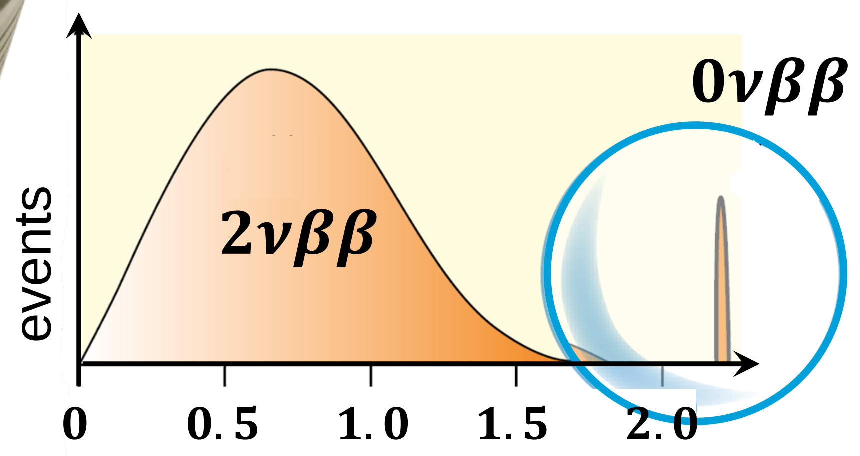
raw experimental spectrum





energy (MeV)

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

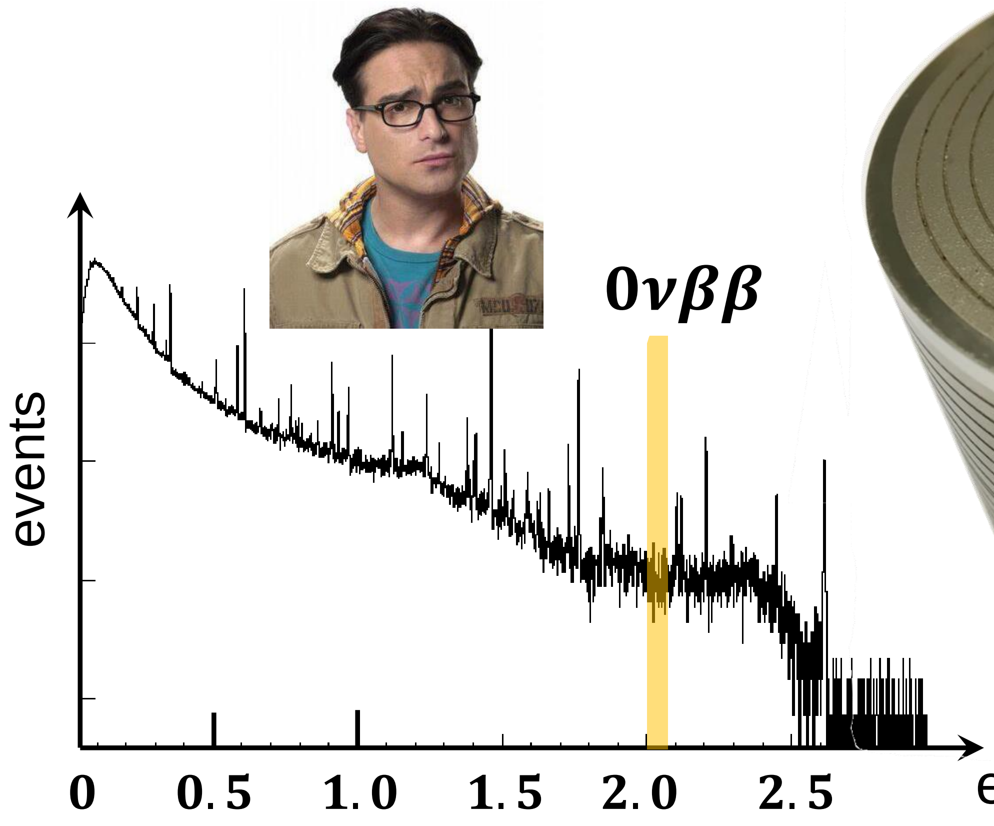


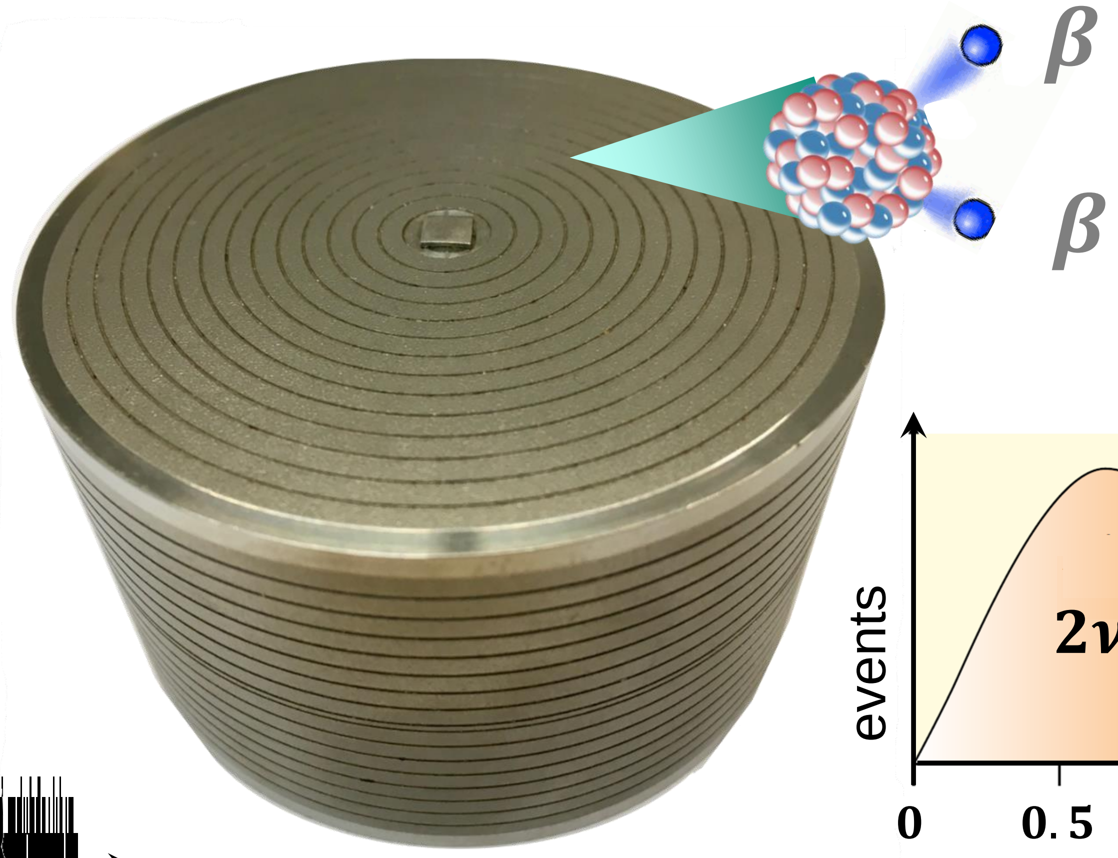
energy (MeV)

Rare events: example search for $0\nu\beta\beta$ process

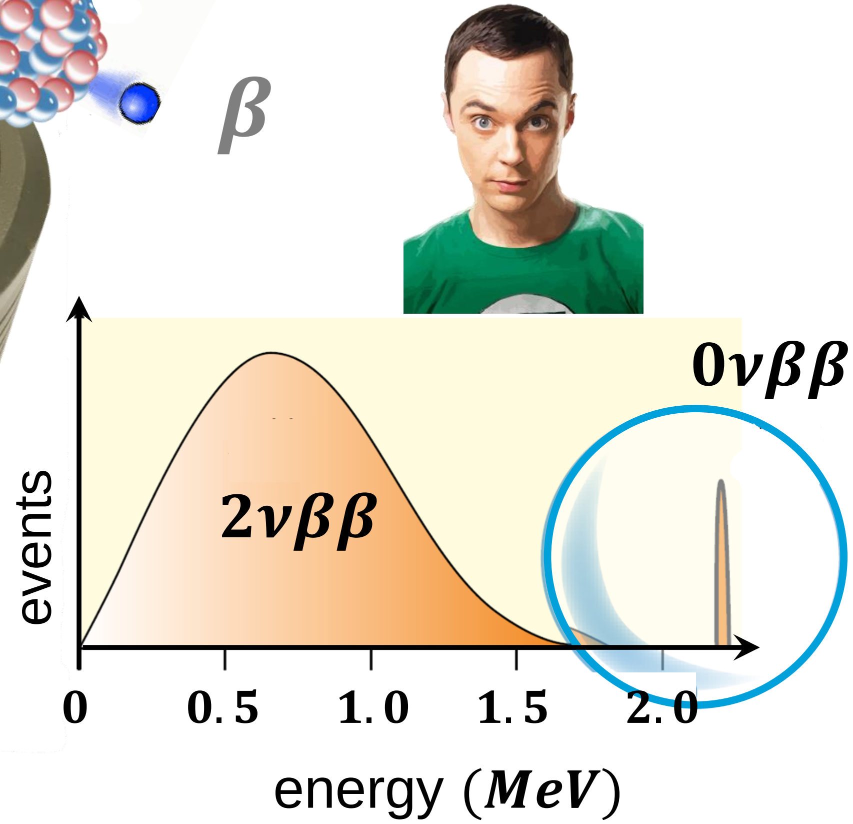
- **Goal: observe the ´peak´ from $0\nu\beta\beta$ events in an enriched ^{76}Ge detector**

an experimentalists´ view





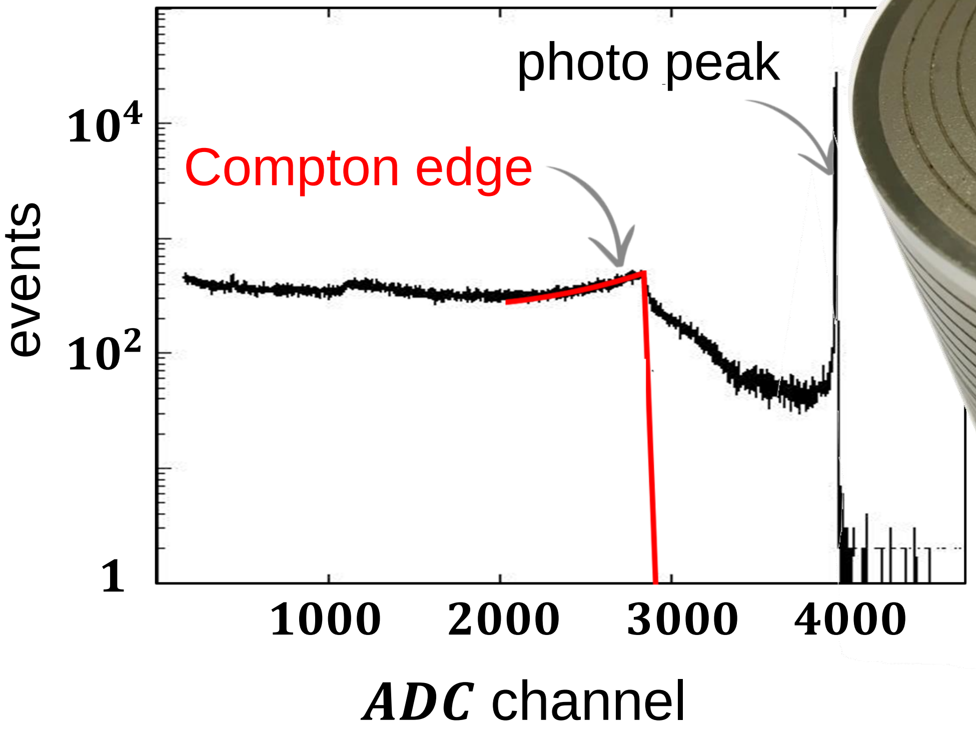
a theorists´ view



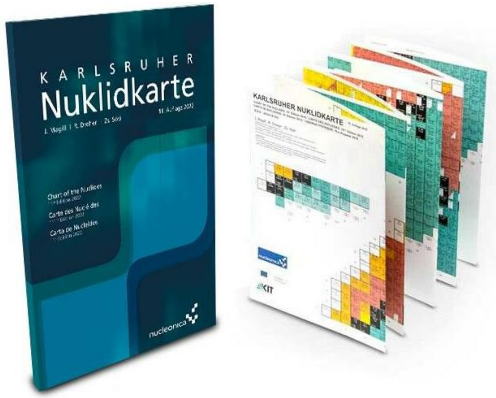
Rare events: example $0\nu\beta\beta$ – decay search

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

raw experimental spectrum
of a *single* isotope (which?)



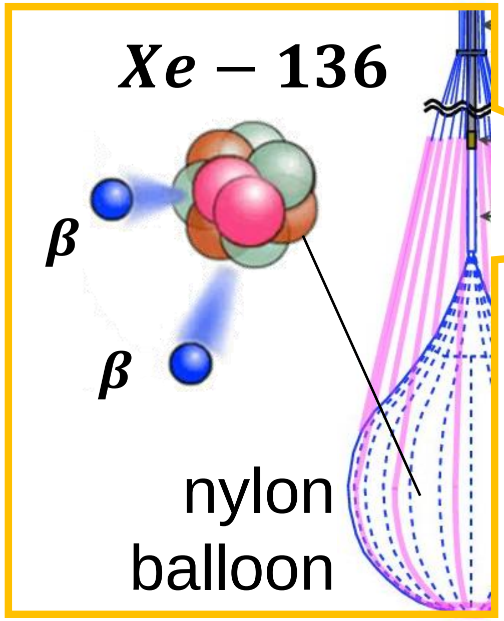
Karlsruhe nuclide chart
11^{th} *ed.*, 2022

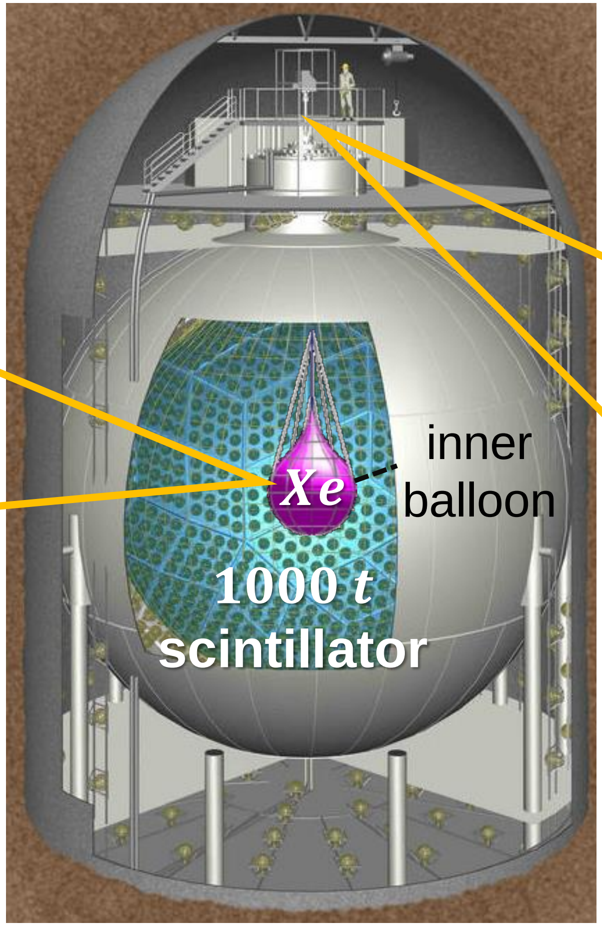


Rare events: example of what can go wrong ...*

- Task: install the inner nylon balloon to contain enriched xenon

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





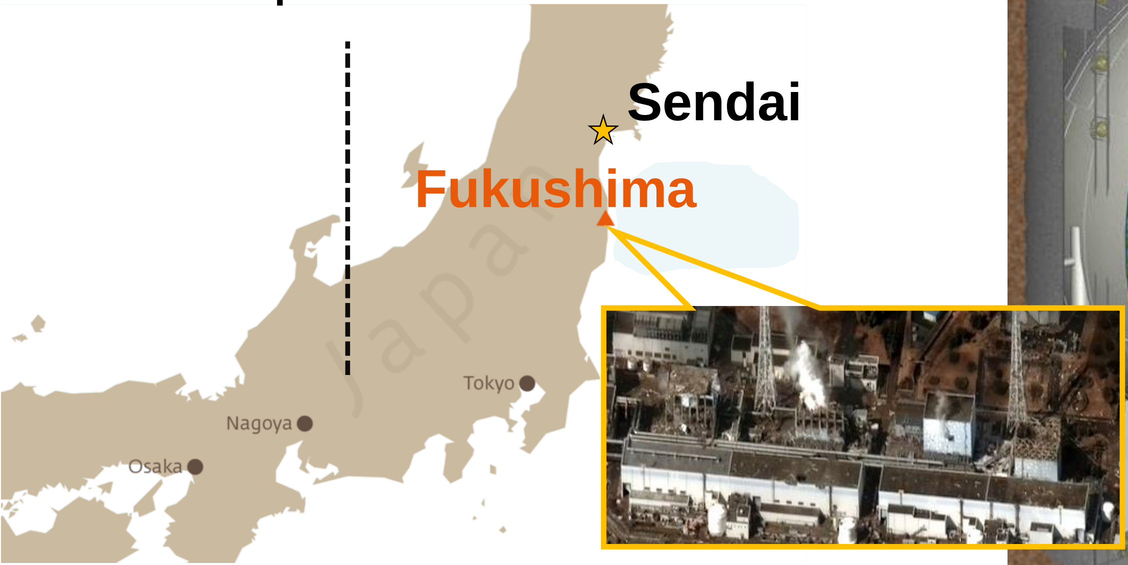
We did it!! And: on time...

*... will go wrong

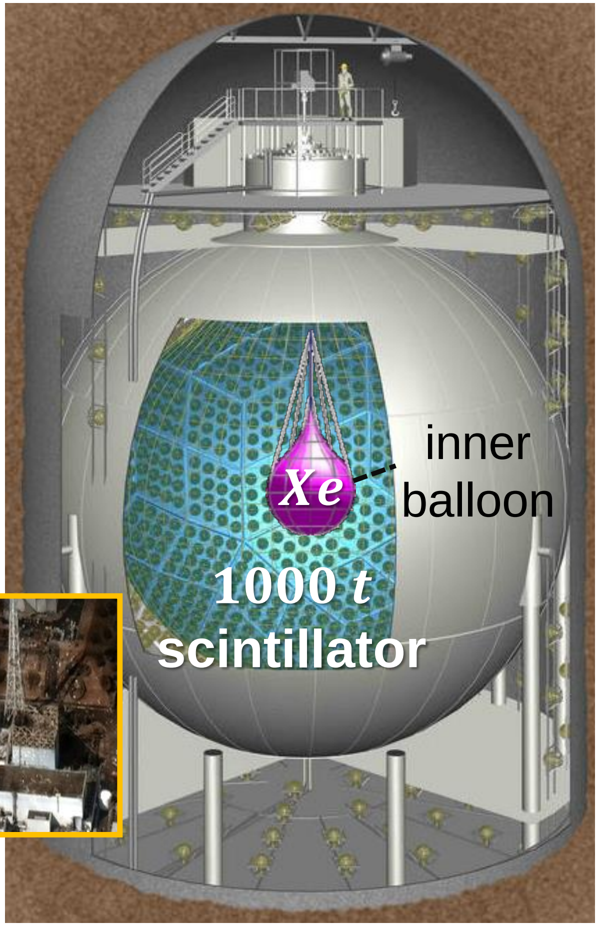
Rare events: example of what can go wrong

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

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

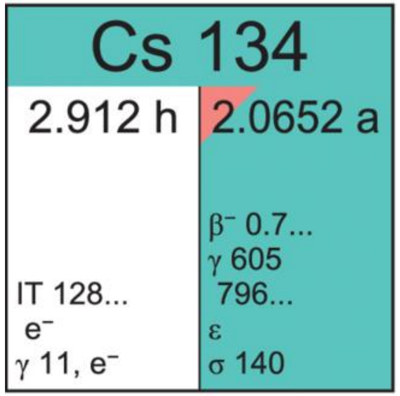


accident* of March $11, 2011$



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

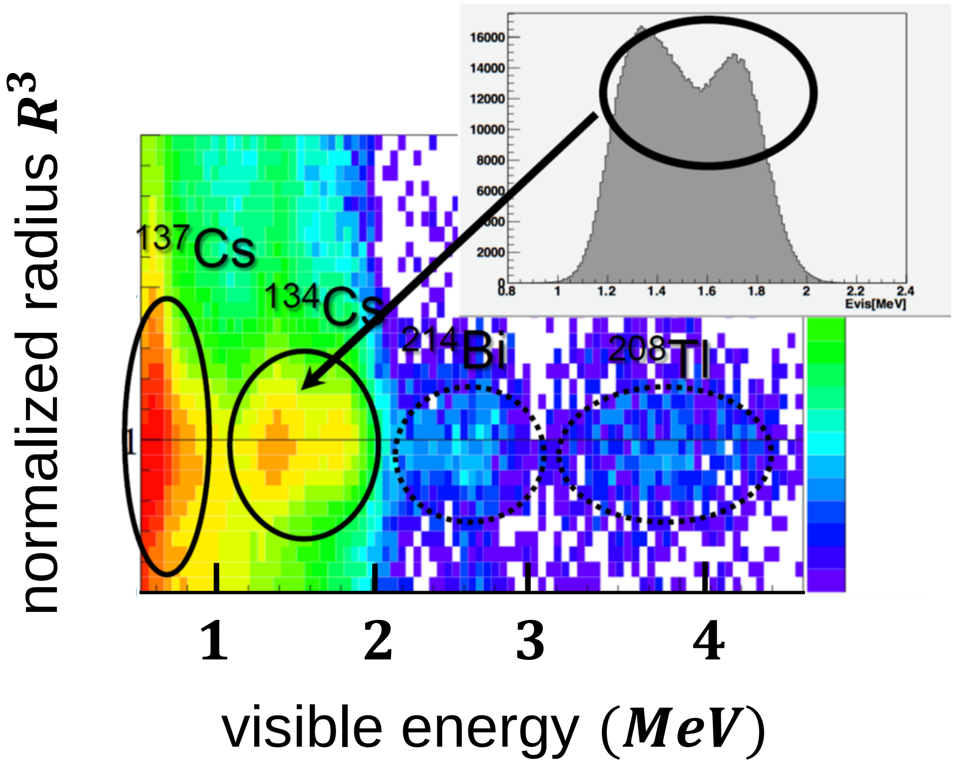
$$Q = 2.06\ MeV$$

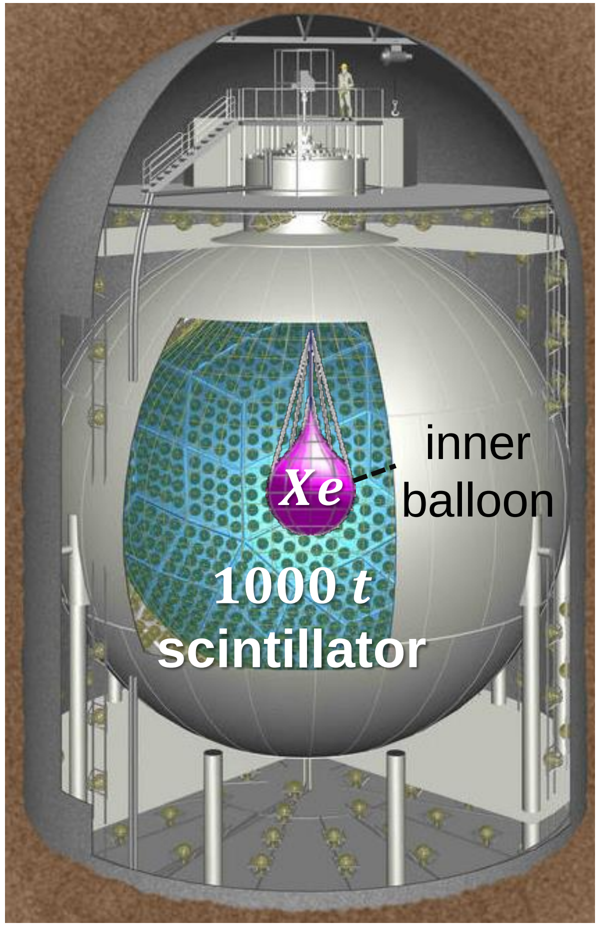


* Fukushima nuclear accident - Wikipedia

Rare events: example of what can go wrong

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





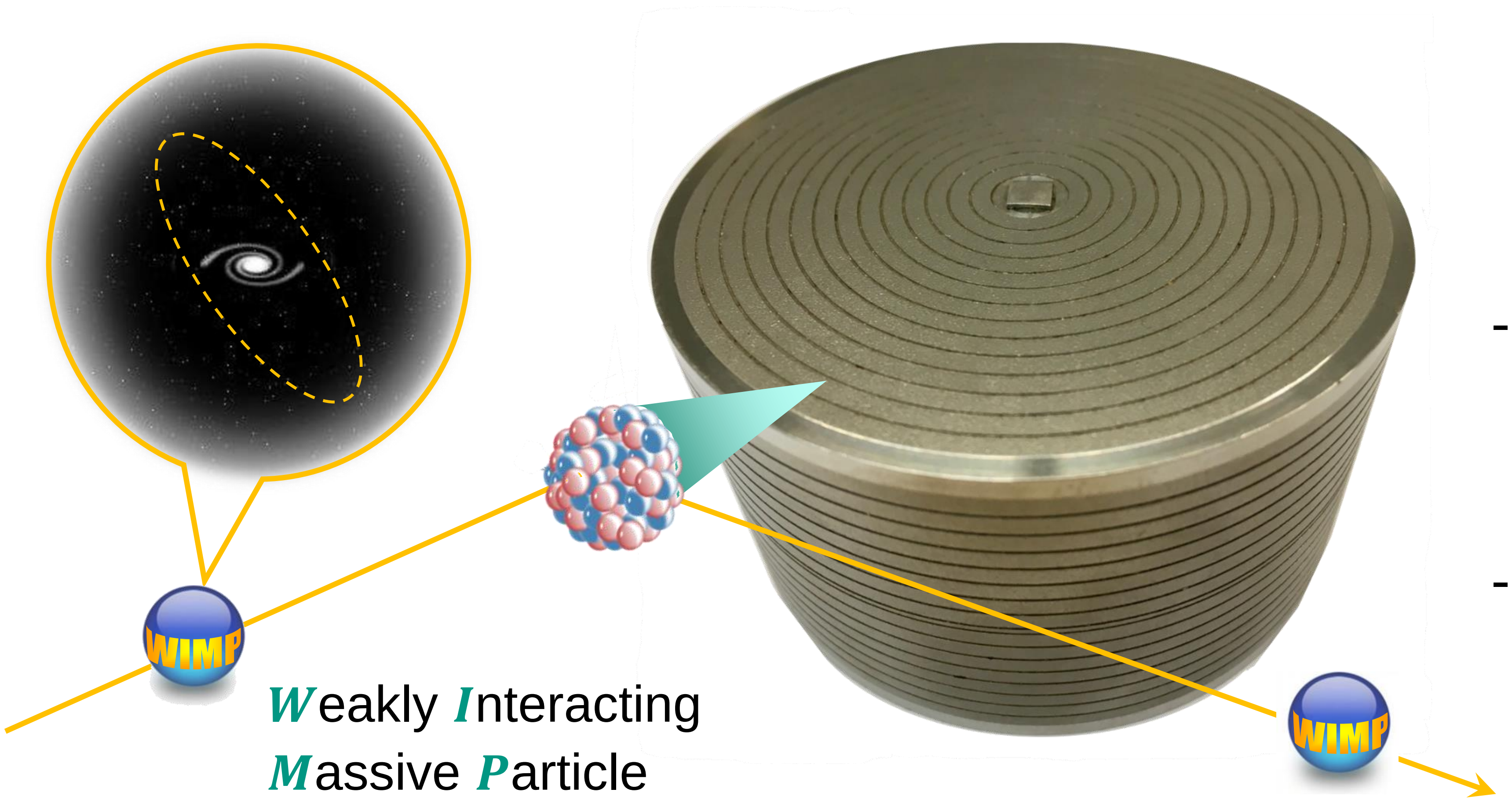
- **Fukushima** nuclear accident: large release of radioactive nuclides such as isotope ^{134}Cs (undergoes β – decay + $2\ \gamma\acute{}s$)

- inner balloon was produced in nearby Sendai in **March 2011**: small contamination with ^{134}Cs

- result of measurements:
  ⇨ remove contaminated nylon & **install a new clean one**

Rare events: example search for Dark Matter (DM)

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

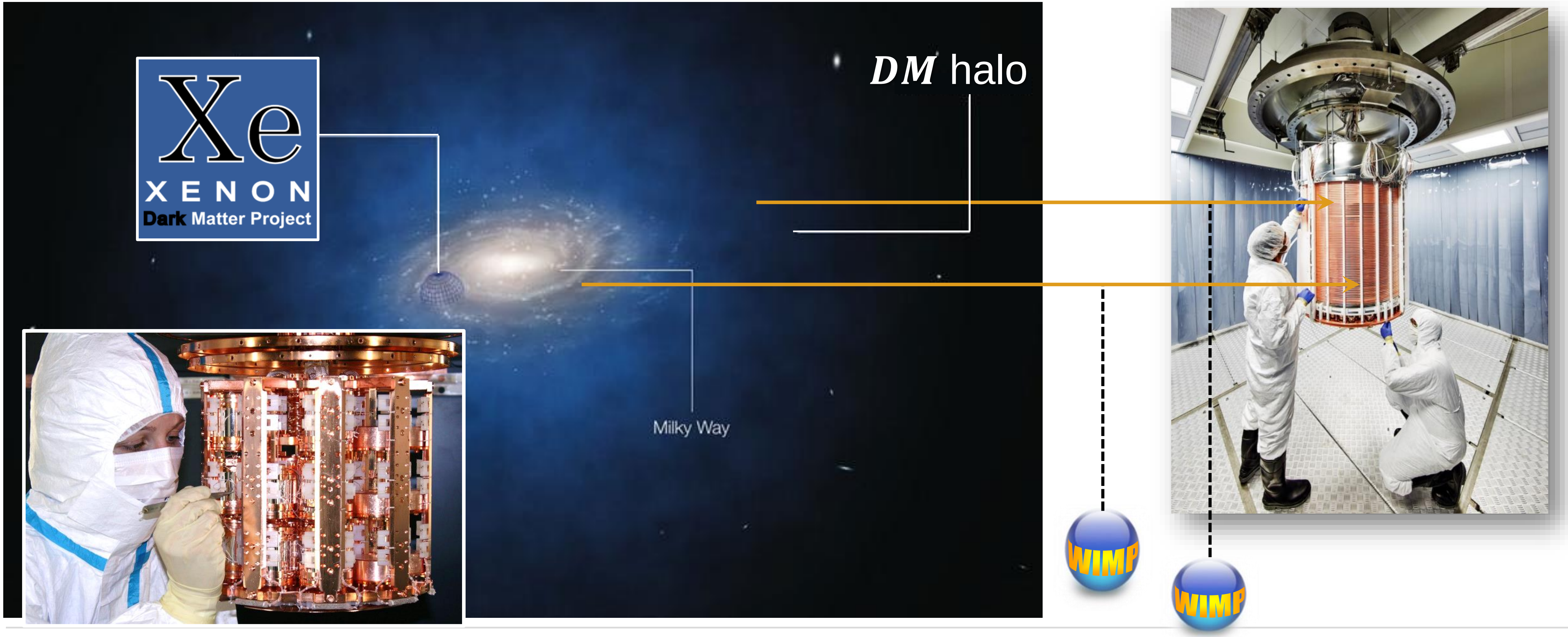


Weakly Interacting
Massive Particle

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

How do I calculate the expected signal rate?

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



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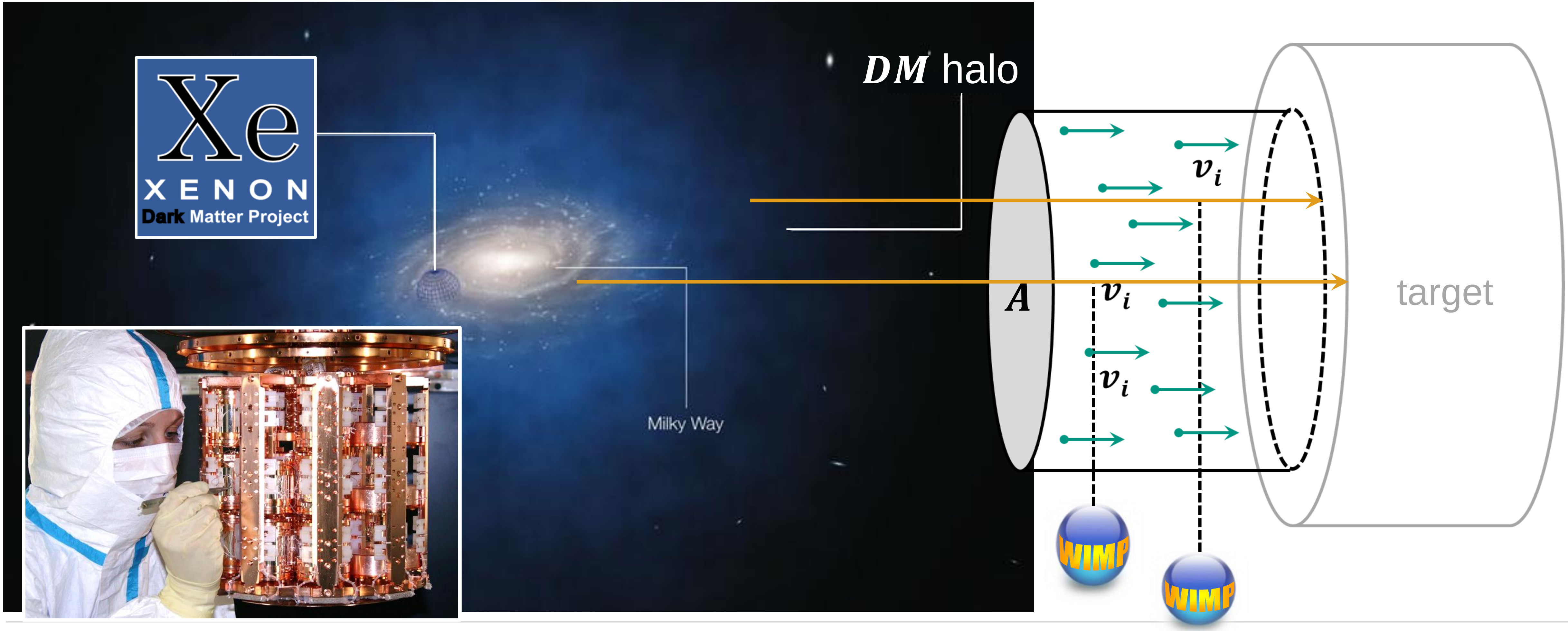

RECAP: how to calculate the expected signal rate

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

- cross sectional area A $[cm^2]$

- particle velocity v_i $[cm/s]$

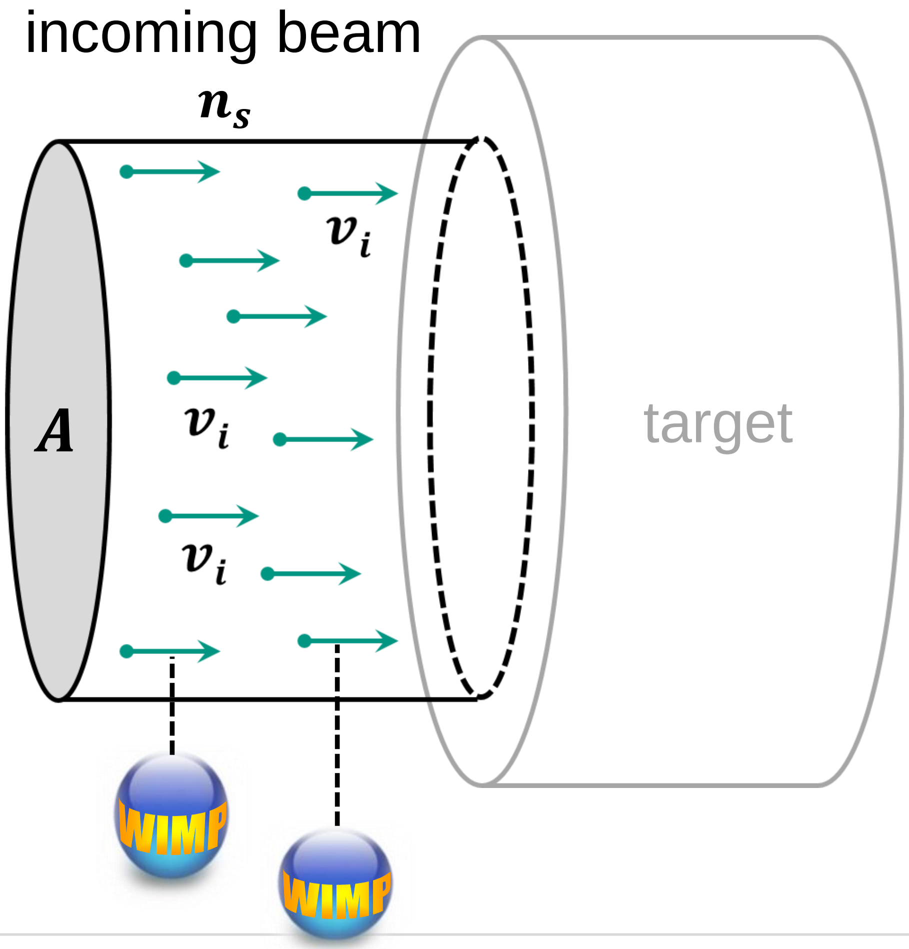
- number density n_s $[cm^3]$

- **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)**

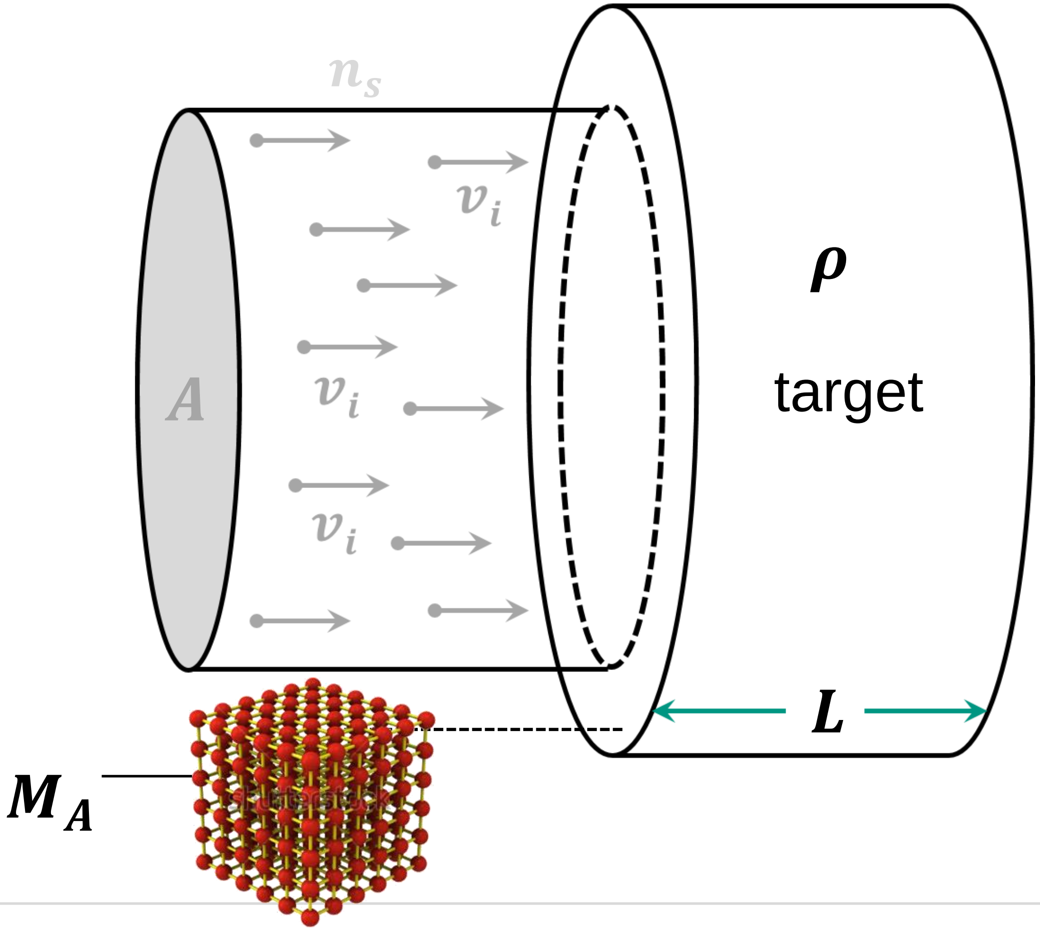
- target density ρ $[g/cm^3]$
- target length L $[cm]$
- target atomic mass M_A $[u]$
- **number density** n_t $[cm^{-3}]$

$$n_t = \rho \cdot N_A / M_A$$

- **# of nuclei in beam** N_t [ ]

$$N_t = n_t \cdot L \cdot A$$

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



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

RECAP: how to calculate the expected signal rate

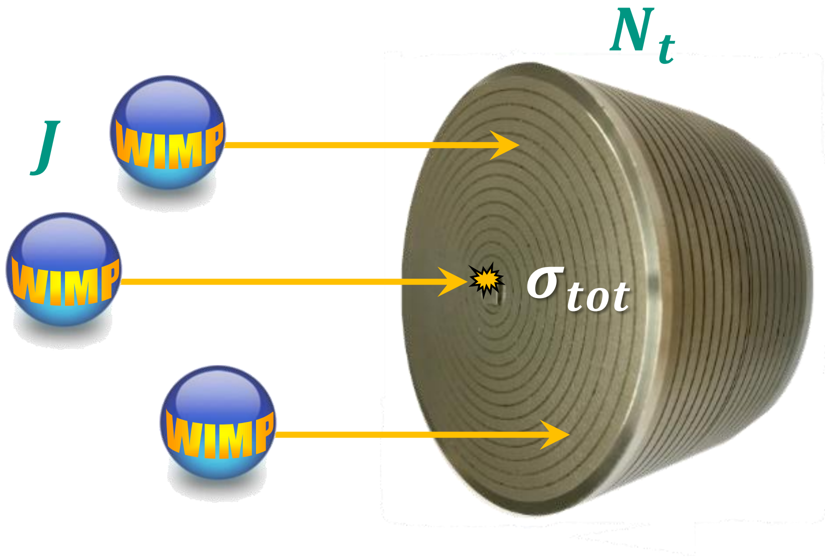
- **Interaction rate W_r & # of signal events N_S of incoming $WIMPs$ in a detector**

- **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** $[s^{-1}]$

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



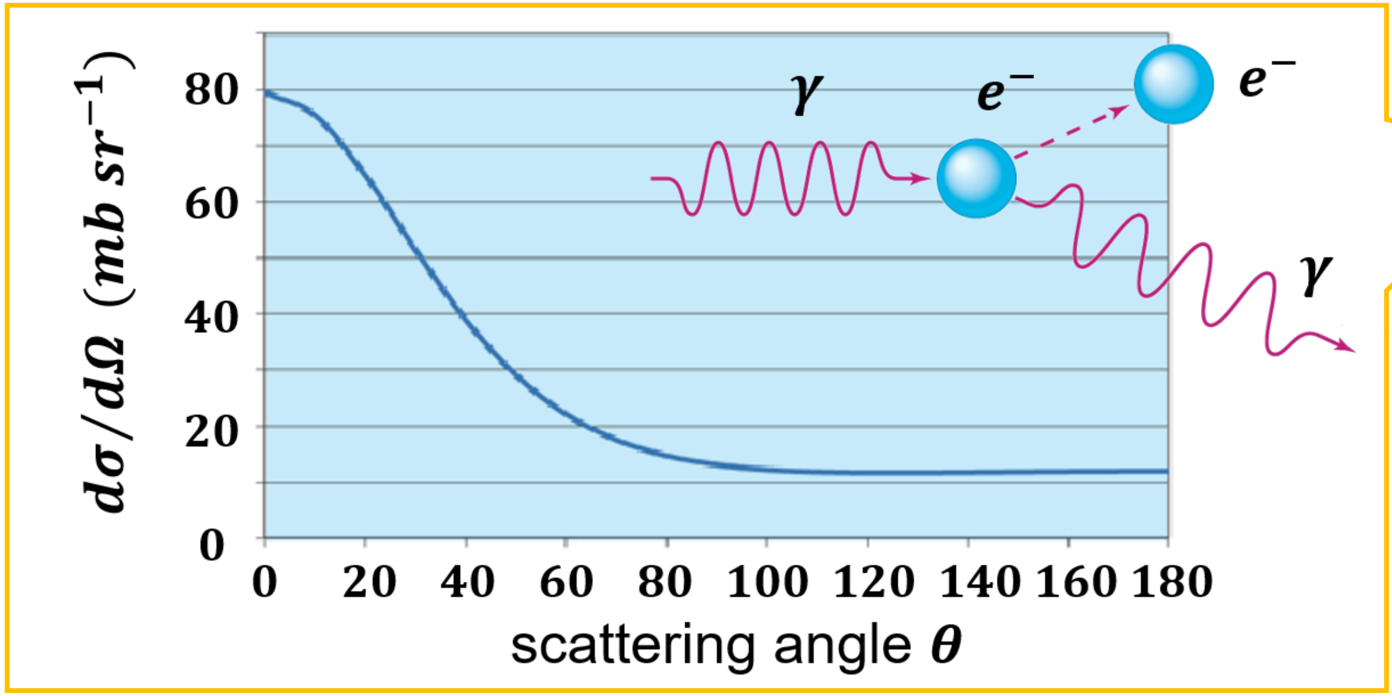
RECAP: how to calculate the expected signal rate

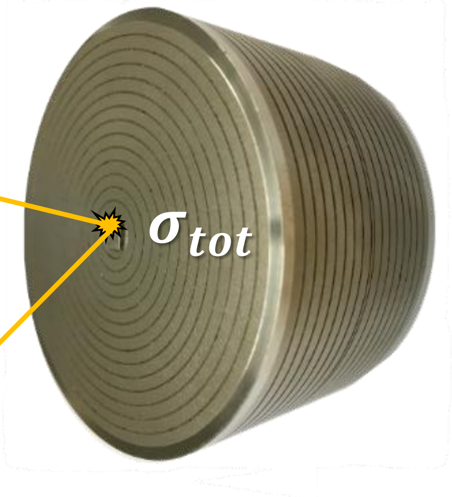
- **background processes in a detector with typical cross section $\sigma_{tot} \sim mb$**

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

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

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





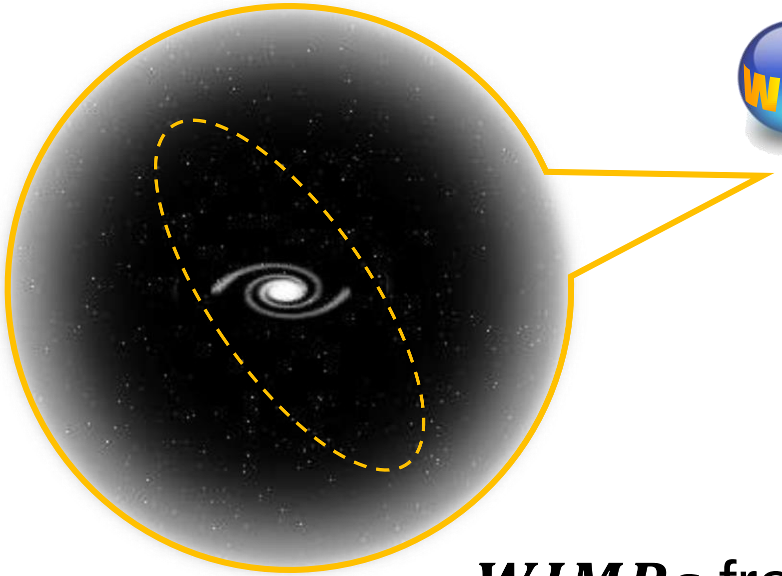
$^{**}mb = milli - barn = 10^{-27} cm^2$

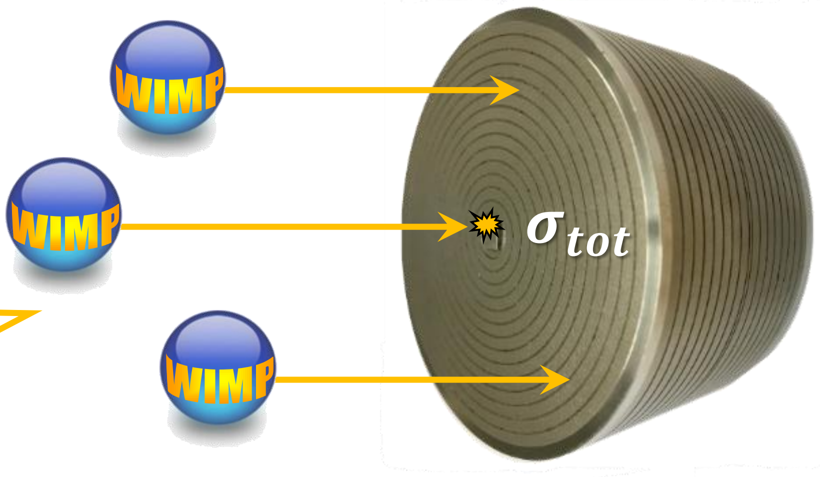
RECAP: how to calculate the expected signal rate

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

  - exceedingly small expected $WIMP$ cross section σ_{tot}

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

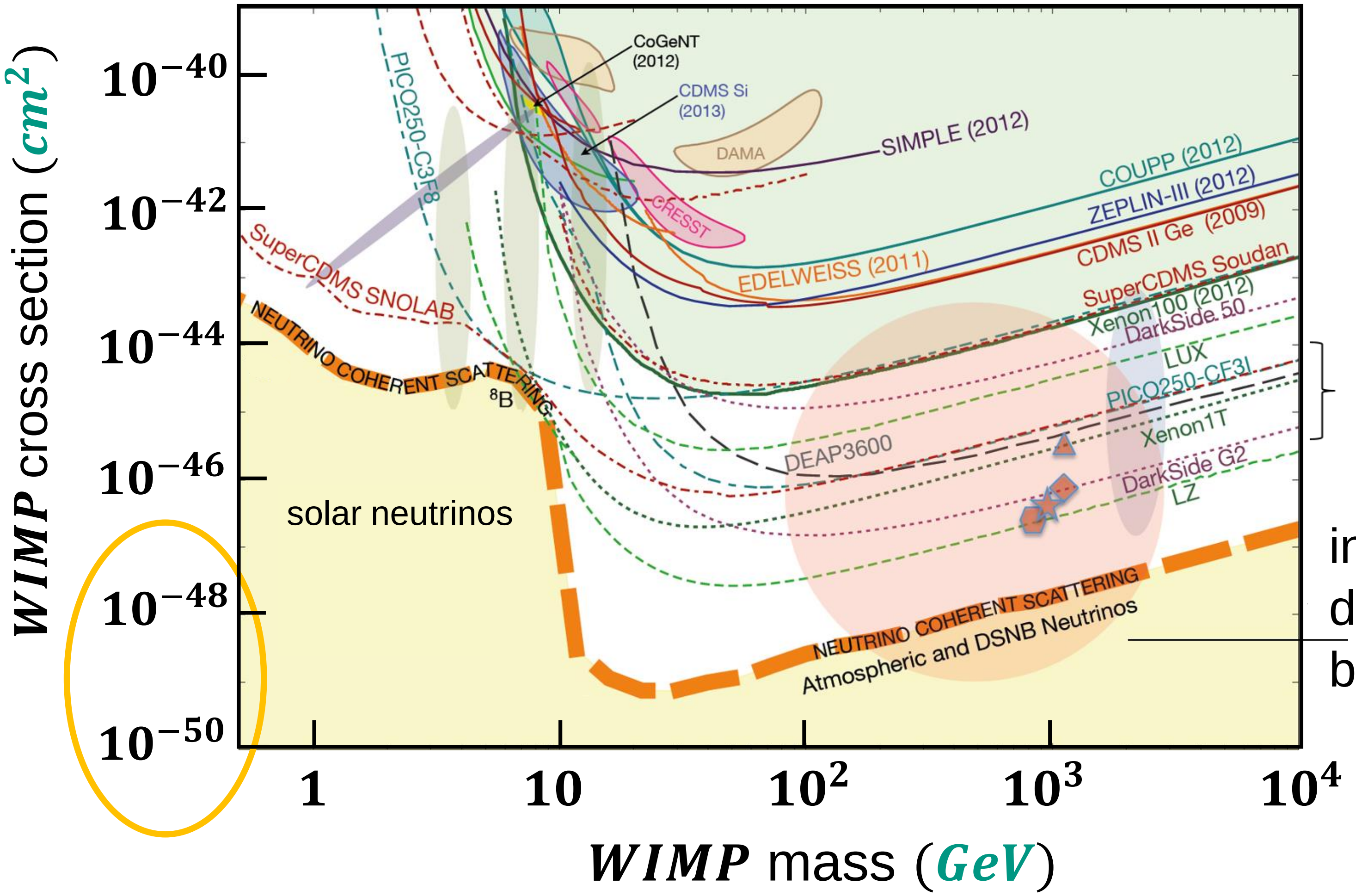




$WIMPs$ from galactic halo

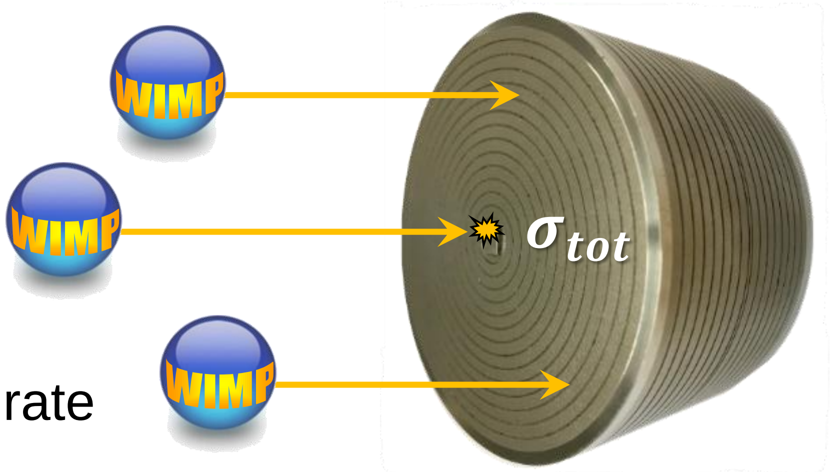
expected signal rates in a dark matter detector

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



LXe
LAr

interaction rate dominated 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

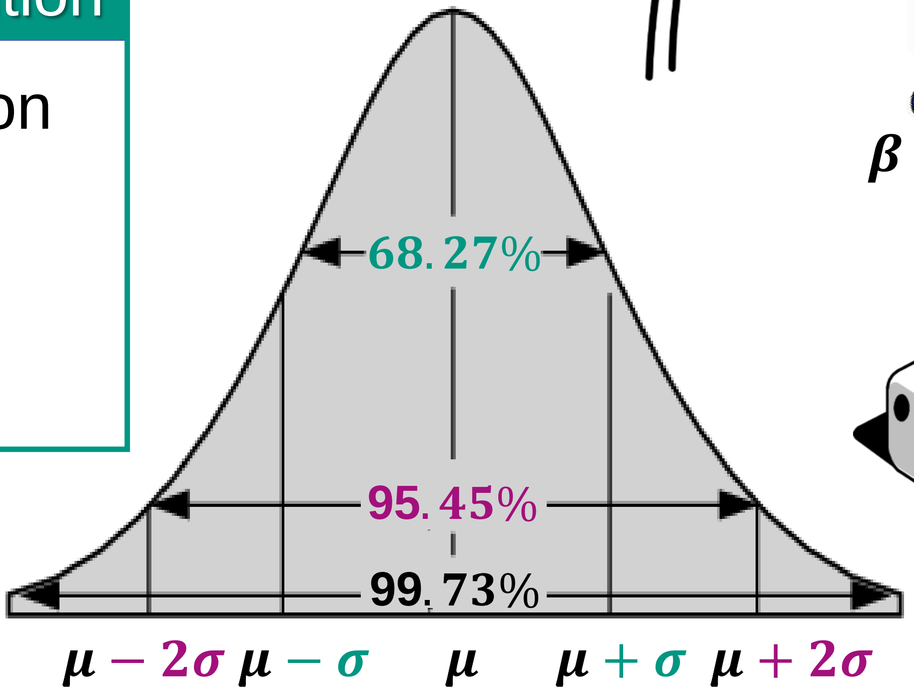
Gaussian (normal) distribution

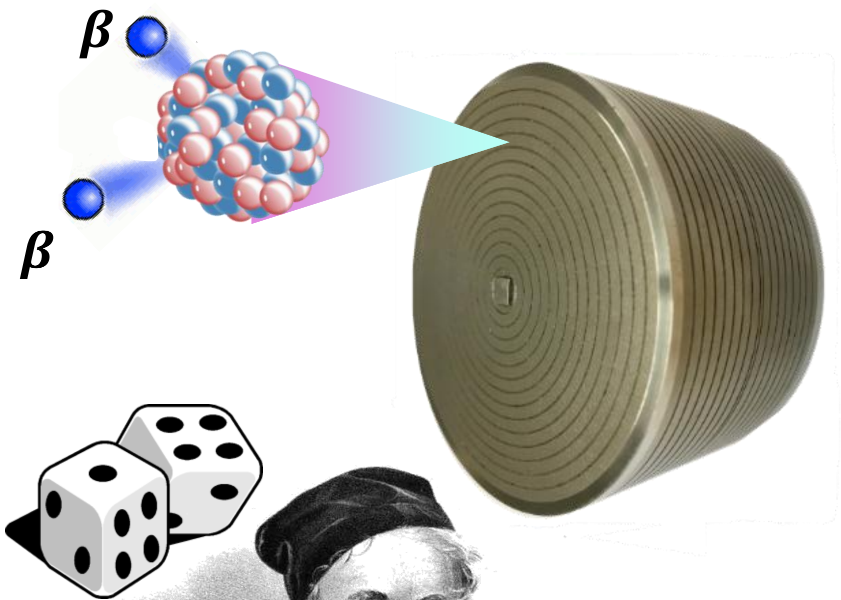
probability density function

$$\frac{1}{\sqrt{2\pi\cdot\sigma^2}}\cdot e^{-\frac{(x-\mu)^2}{2\,\sigma^2}}$$

μ: mean of expectation

σ: standard deviation

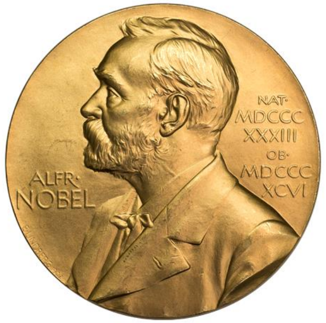


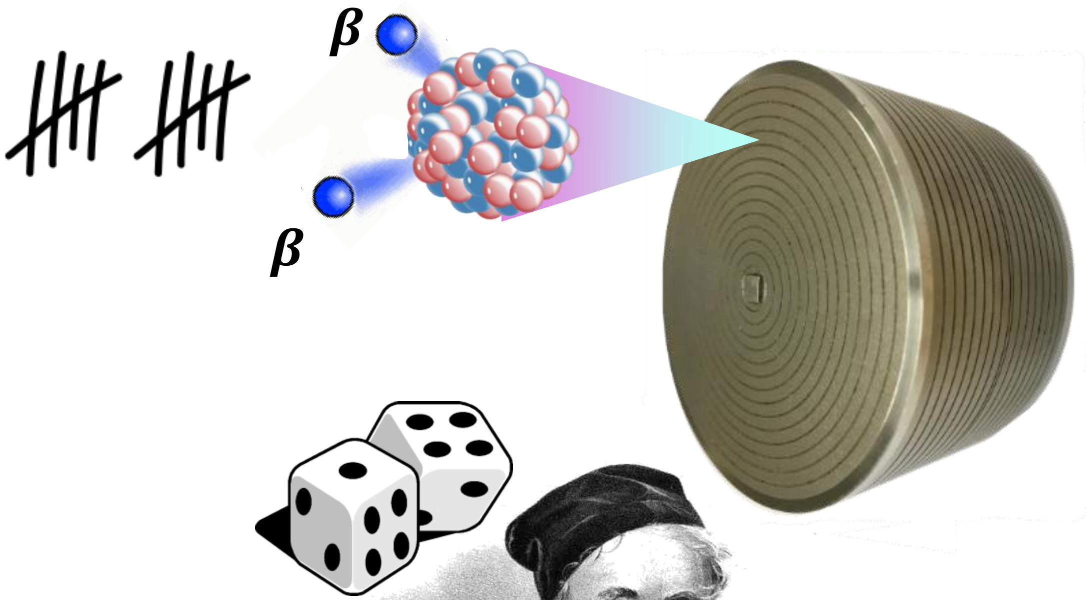


Signal vs. background: is this a detection (yet)?

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

  - **signal:** detection of new physics signal requires $> \mathbf{5\ \sigma}$ **(standard deviations)**

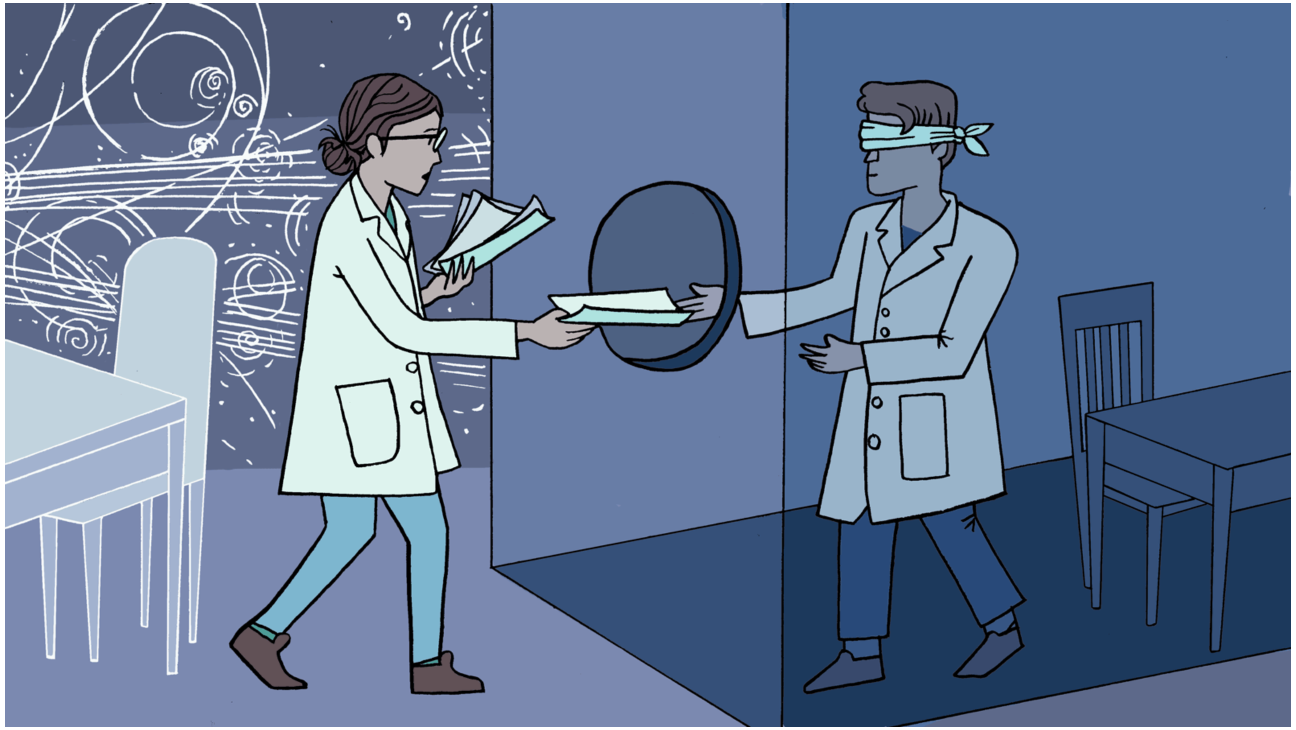


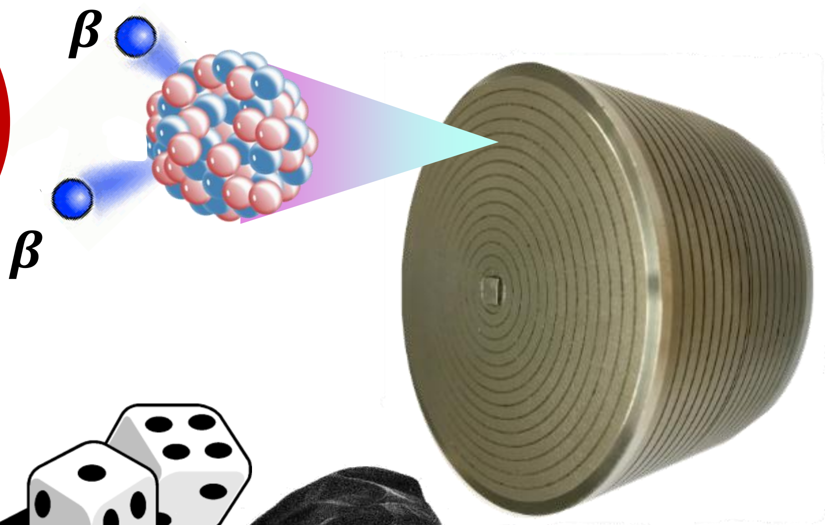


Signal vs. background: is this a detection (yet)?

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

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



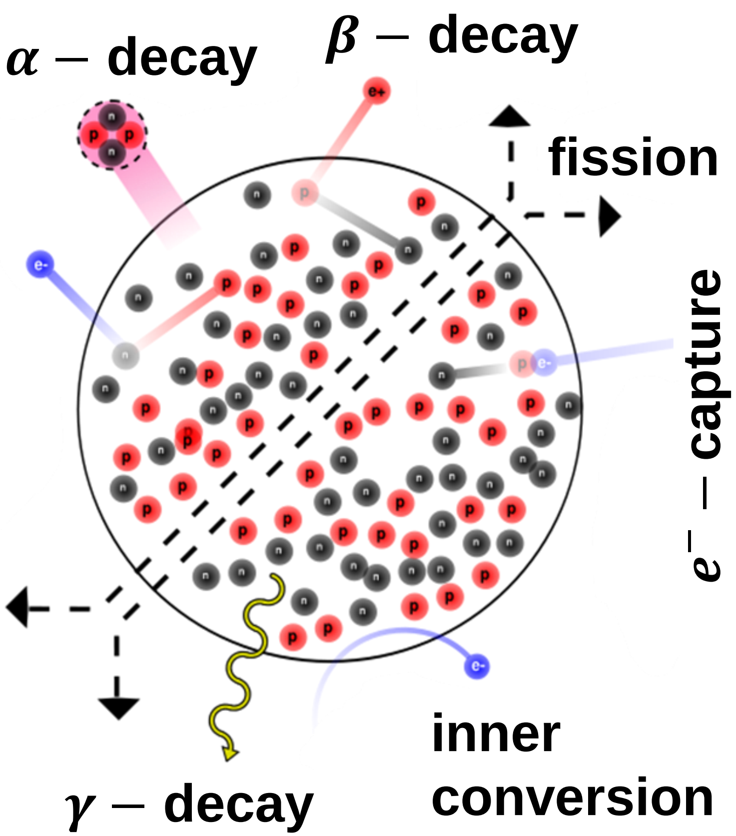


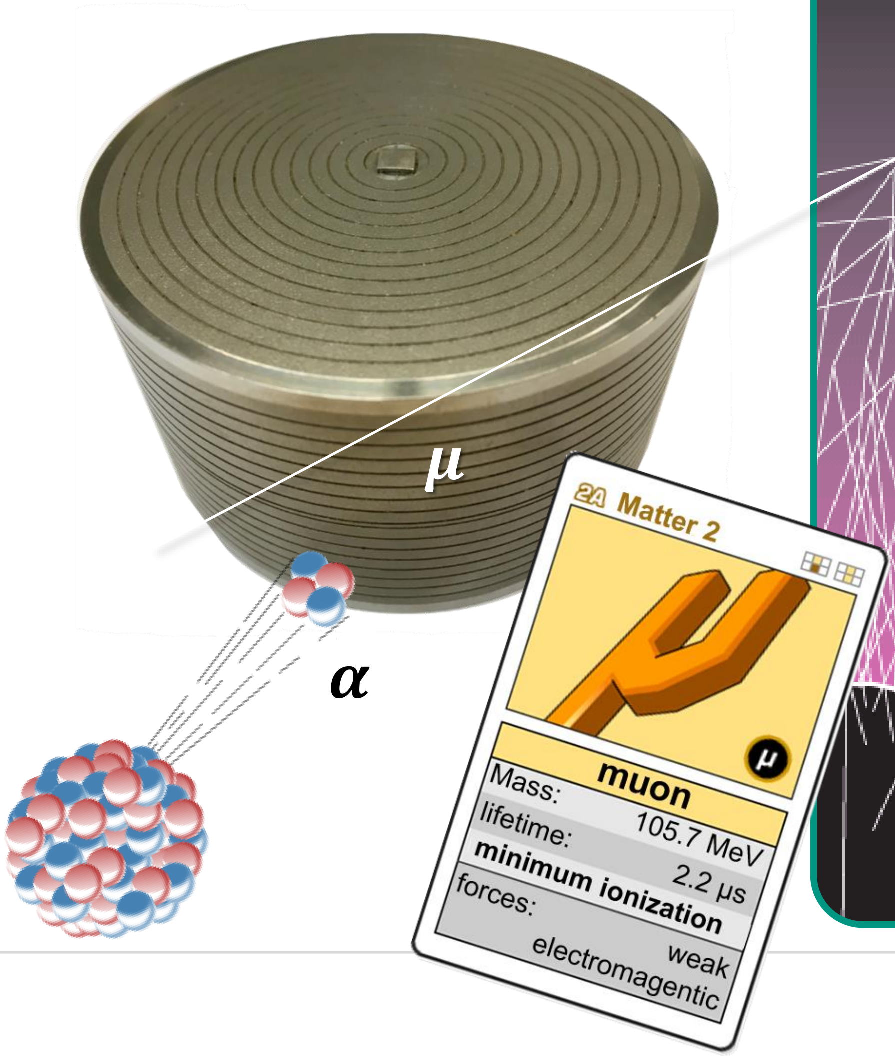
after unblinding:

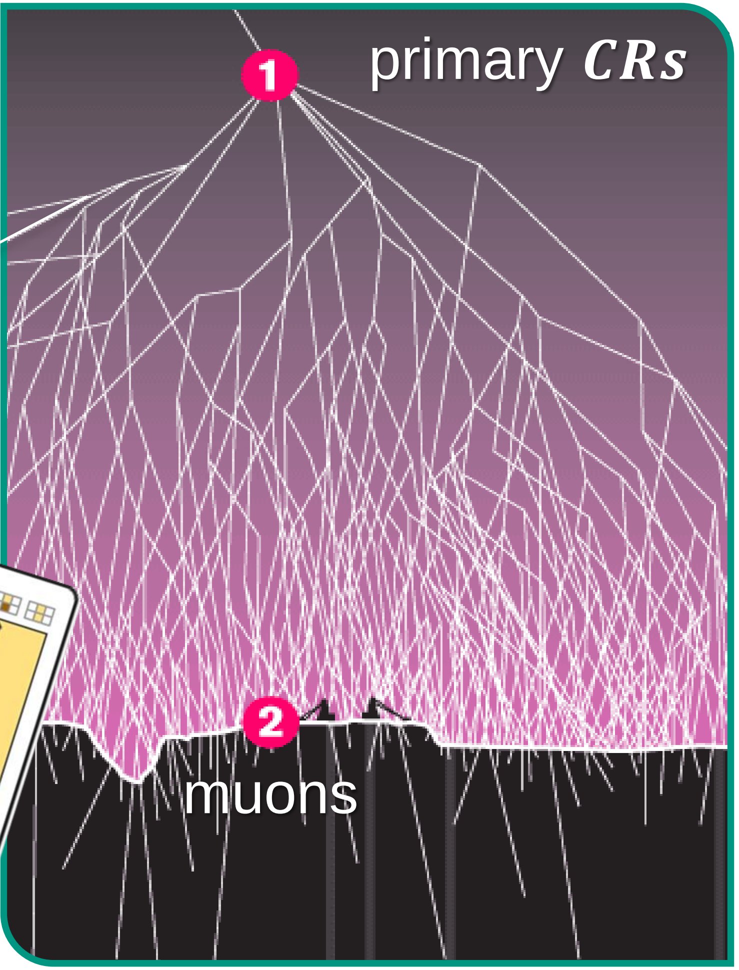
$2.2.1$ Background processes

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

decay types of nuclei







Background processes – comparison of rates

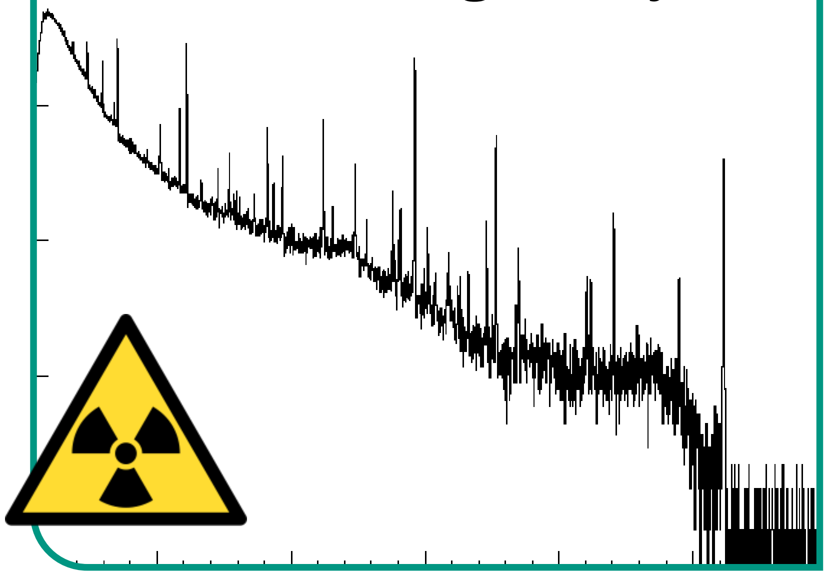
- Dominant background sources: natural radioactivity & cosmic rays (μ´s)

natural radioactivity

- rate:

$\mathbf{100}$ events $\boldsymbol{kg^{-1}s^{-1}}$

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



$\mathbf{10^{-3} \dots 10^{-4}}$ events $\boldsymbol{kg^{-1}day^{-1}}$ for $\boldsymbol{WIMP}$ signal region

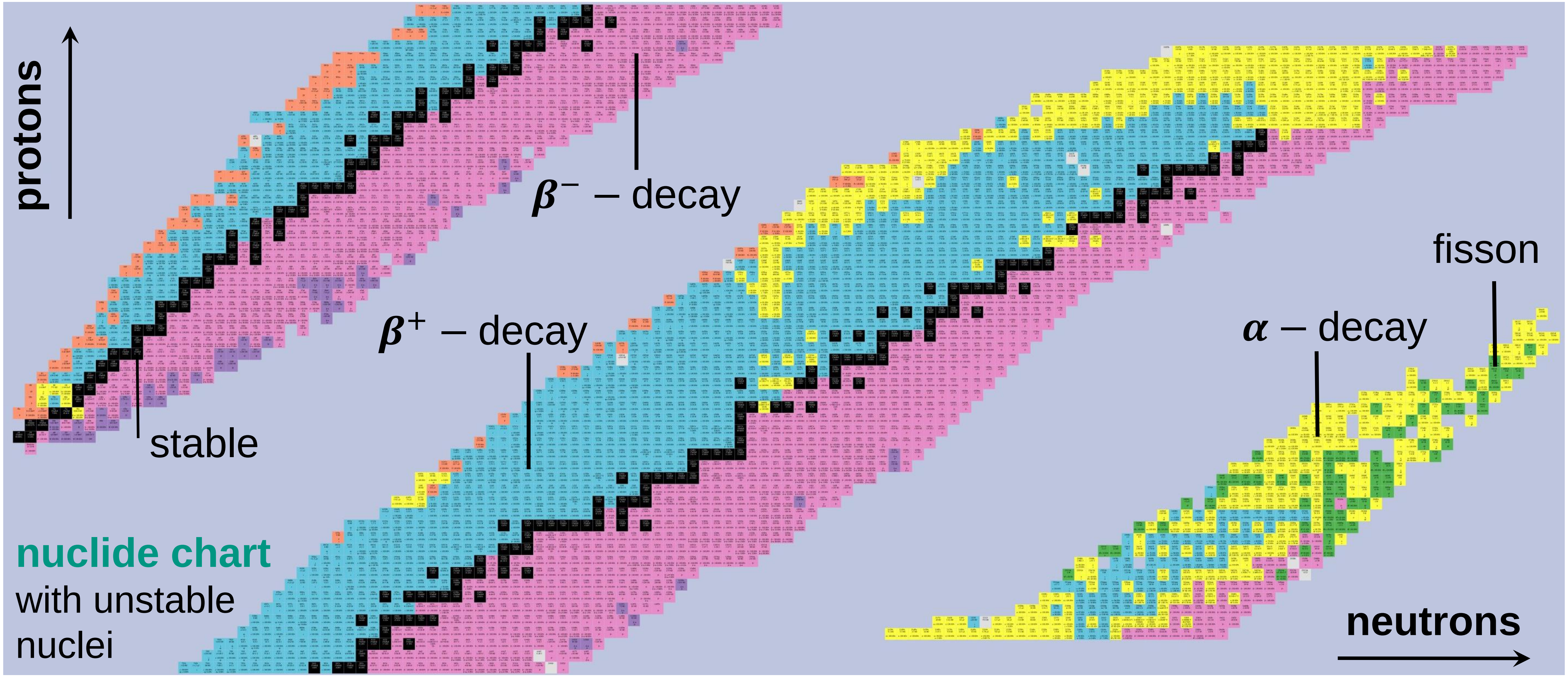
cosmic background

- rate:

$\mathbf{0.1}$ events $\boldsymbol{kg^{-1}s^{-1}}$

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

Decay processes of unstable nuclei: background



Decay processes – activity of an isotope

- **Radioactive decay law** and units

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

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

… 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 is decreasing 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 $dt \ll t_{½}$ (i.e. for long $t_{½}$: $dt = 1\ s$)

Decay processes – activity of an isotope

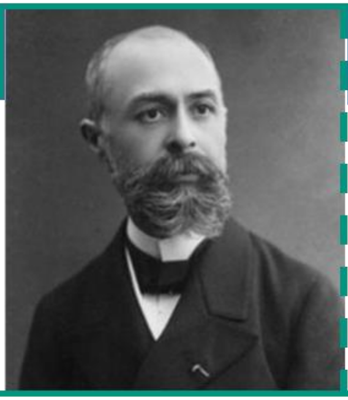
- **Radioactive decay** law and **units**

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

$1\ Bequerel\ =\ 1\ decay/s$

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

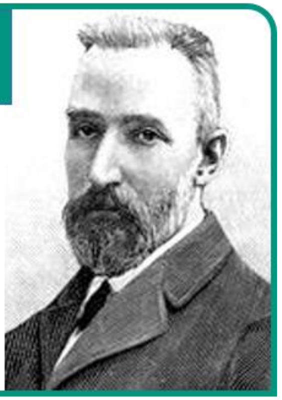
after *Henri Becquerel*)



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

$1\ Ci$ = activity of $1\ g$ radium (^{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**

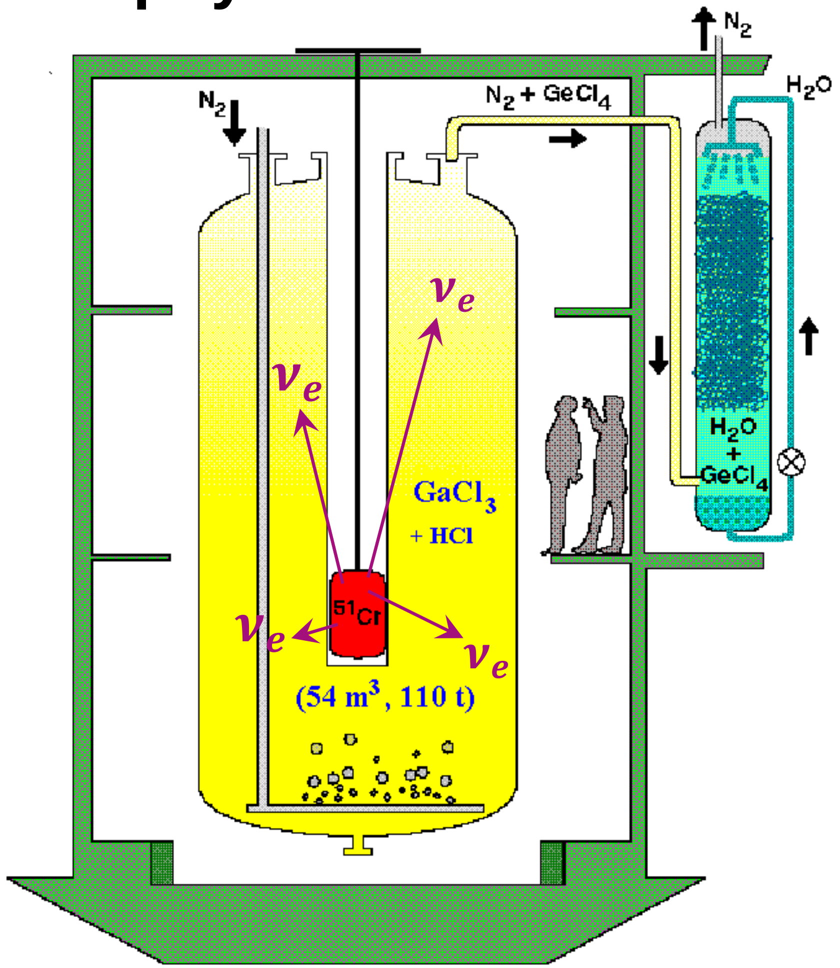
- use of **strong artificial** $\boldsymbol{\nu}$ – **sources**: $\boldsymbol{GALLEX}$

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

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

- half–life $\boldsymbol{t_{½} = 27.7\ days}$

- calibration of solar neutrino detector $\boldsymbol{GALLEX}$*



*see $\boldsymbol{ATP-2}$ summer term $\boldsymbol{2024}$

Decay processes – activity of an isotope

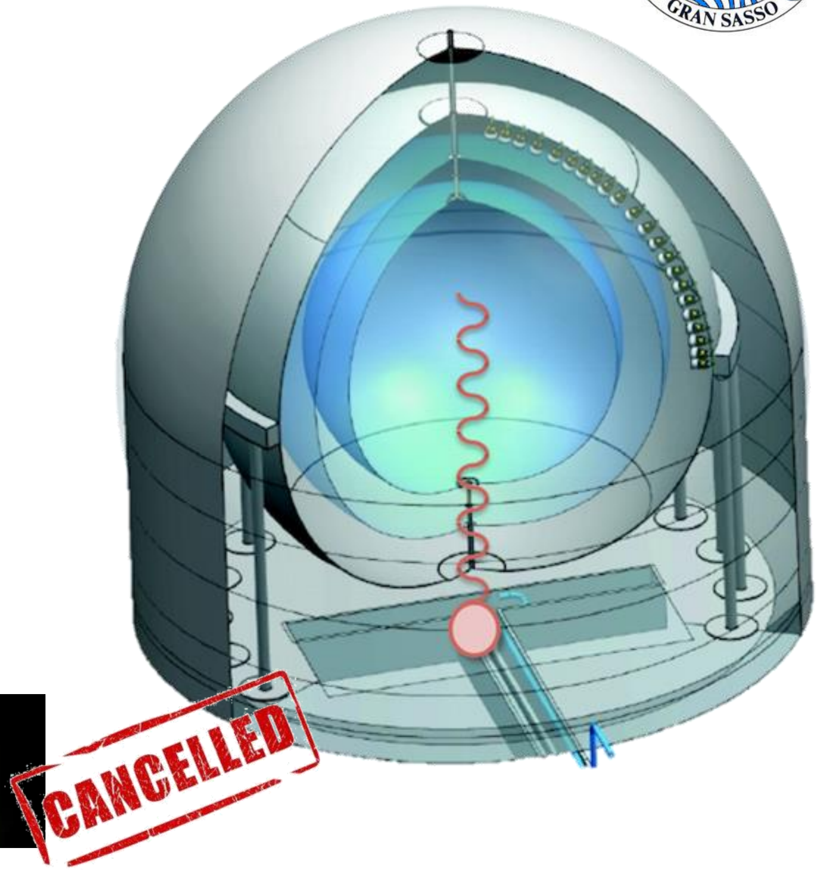
- **Radioactive decay: articifical sources in astroparticle physics**

  - use of **strong artificial $\boldsymbol{\nu}$ – sources**: $\boldsymbol{SOX}$

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

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

  - search for sterile $\boldsymbol{\nu ´s}$ with $\boldsymbol{BOREXINO}$ detector*



*see $\boldsymbol{ATP - 2}$ summer term $\boldsymbol{2024}$

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 $t_{½} = 1.2 \cdot 10^9\ yr$

  - (inofficial) unit: Banana–Equivalent–Dose $(BED) = 0.1\ \mu Sv$*

 $^*1\ Sievert = 1\ Sv$

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 – $A \ll 1\ Bq$

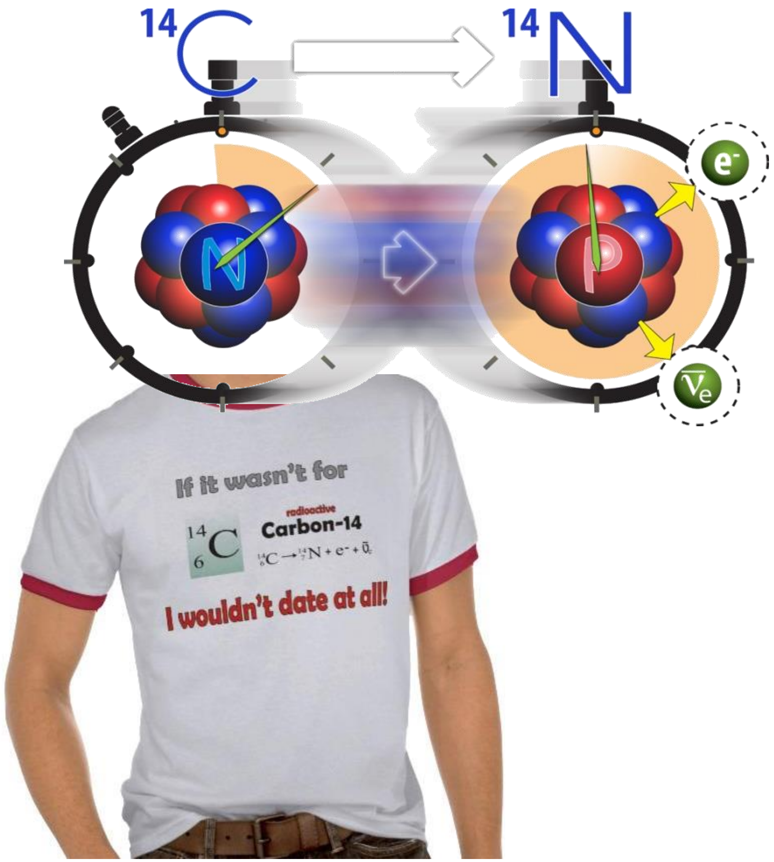
❷ – $A = 10\ Bq$

❸ – $A = 1000\ Bq$

❹ – $A = 10^4\ Bq$

Decay processes – activity of human body

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



nuclide	activity (Bq)
$H-3$	25
$Be-7$	25
$C-14$	3800
$K-40$	4200
$Rb-87$	650
$U-238,234$	4
$Pb-210$	60
$Rn-220$	15
$Rn-220$ daug.	30

huge noise rate* in $PMTs$
of **deep–sea–ν – telecopes**

*see lect. $6\ p.42$