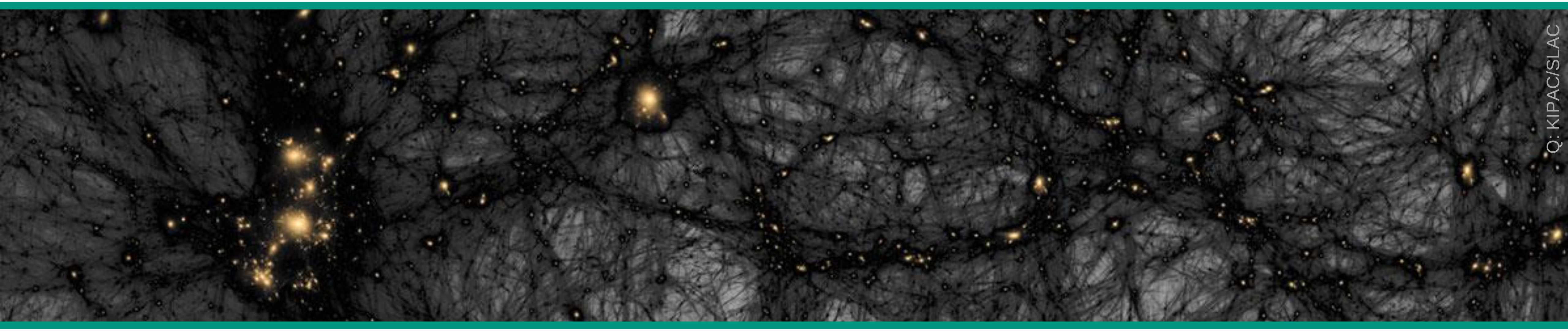
Astroparticle physics I – Dark Matter

Winter term 23/24 Lecture 1 Oct. 25, 2023



*A*stro *P*article *P*hysics – a first overview

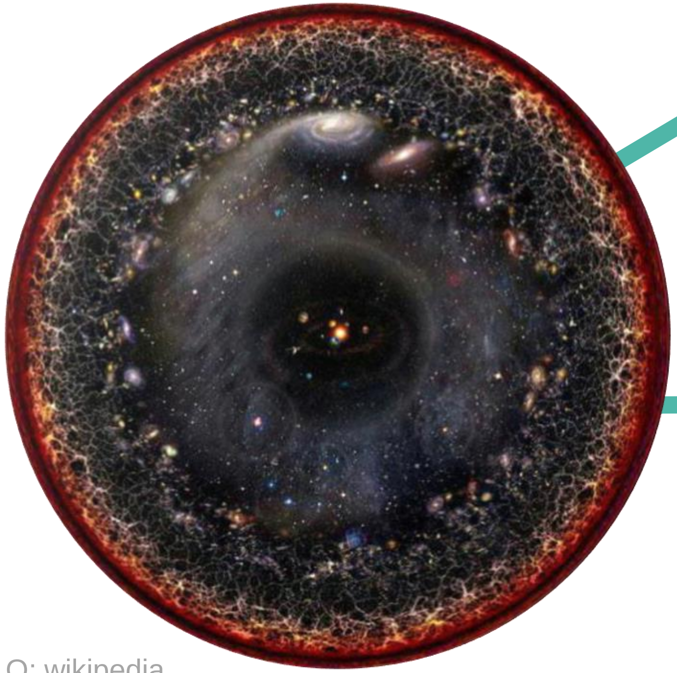
- What are our topics?

particle

physics

Q: Symmetry Magazine

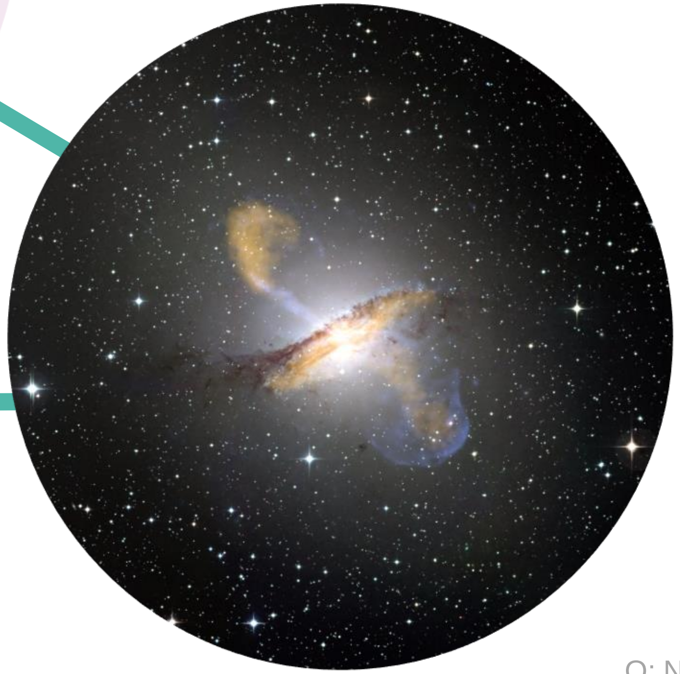
cosmo–
logy



Q: wikipedia

interconnections

astro–
physics



Q: NASA

*A*stro *P*article *P*hysics – a first overview

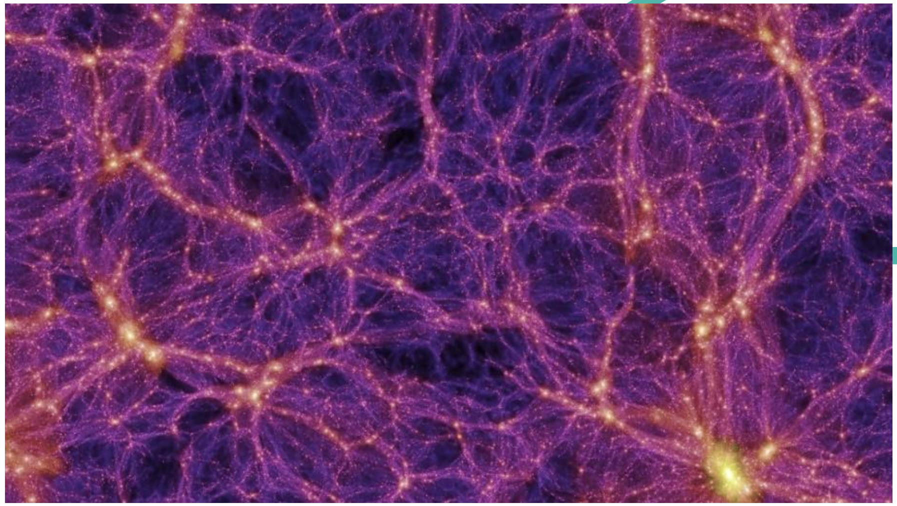
Karlsruhe Institute of Technology

- example: topic *D*ark *M*atter (*DM*)

Q: Symmetry Magazine

DM candidates in particle physics: $\boldsymbol{WIMP}$s, axions, $\boldsymbol{\nu}$´$\boldsymbol{s}$, ...

DM in cosmo– logy



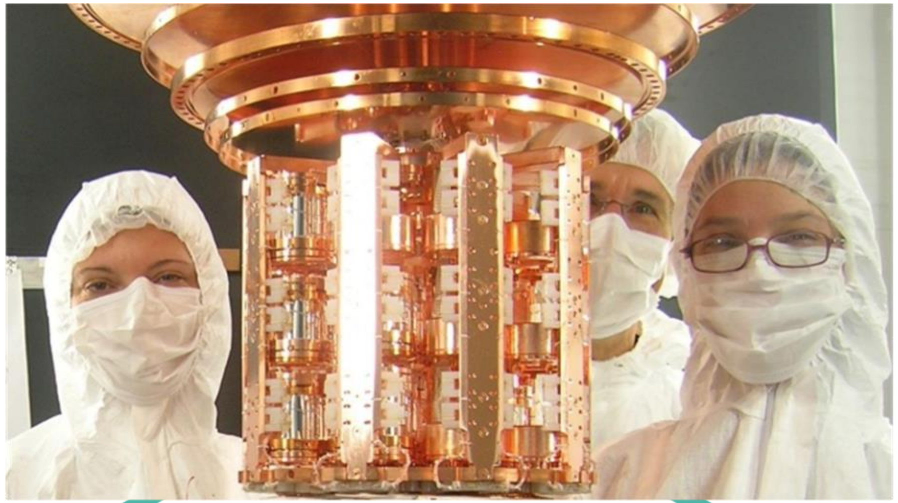
Q: MPG

Q: wikipedia

DM in astro– physics

*A*stro *P*article *P*hysics – a first overview

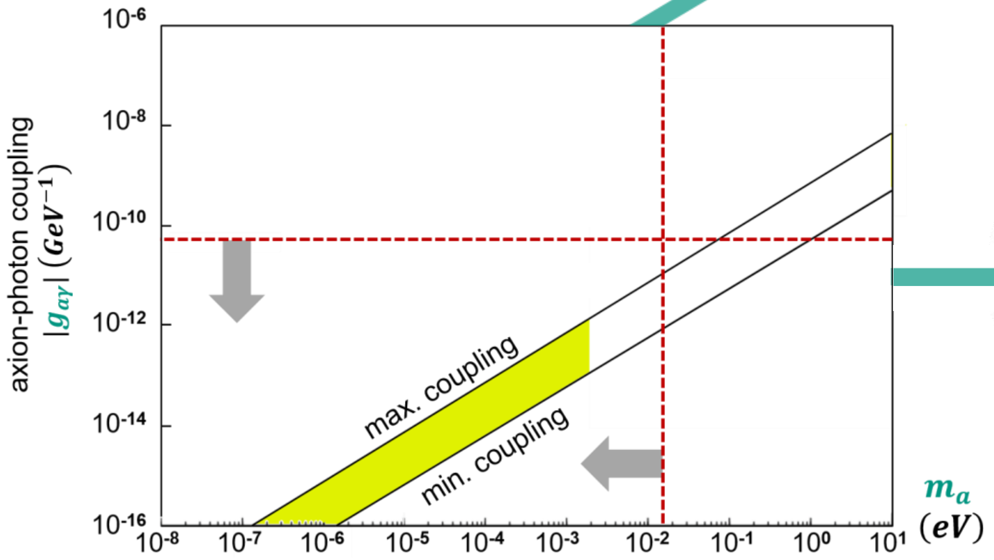
- example: topic
  *D*ark *M*atter
  (*DM*)

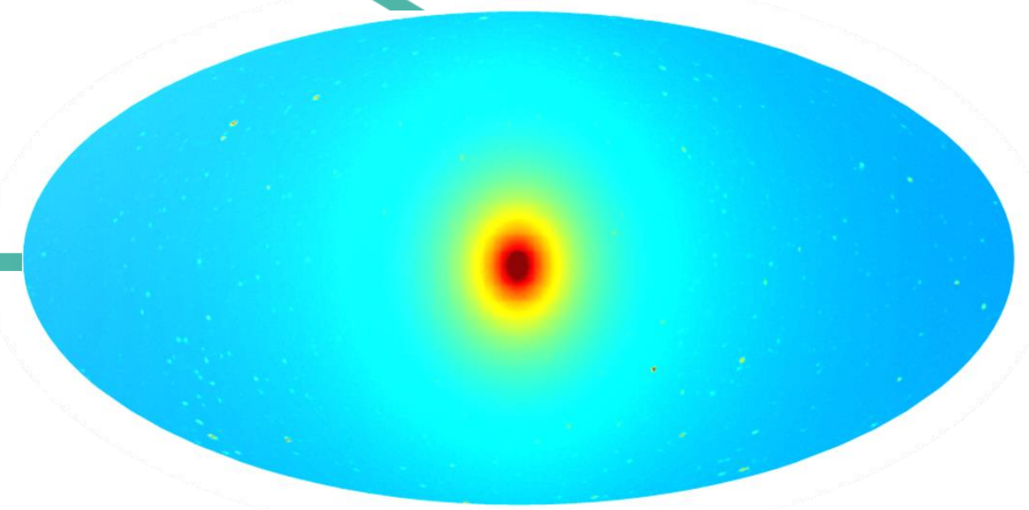


Q: Symmetry Magazine

DM detection
with novel
detectors

DM :
allowed
para-
meters





DM
galactic
halo

Q: wikipedia

*A*stro *P*article *P*hysics – the explosive birth event

- **neutrinos: information on processes during a core−collapse supernova**

$\boldsymbol{SN1987a}$ – February ´**87**

Q: NASA/HST, nobelprize, TIME, SuW

*A*stro *P*article *P*hysics – the central motivation

Karlsruhe Institute of Technology

- *APP*: deciphering the Code of the Universe

*A*stro *P*article *P*hysics – the central motivation

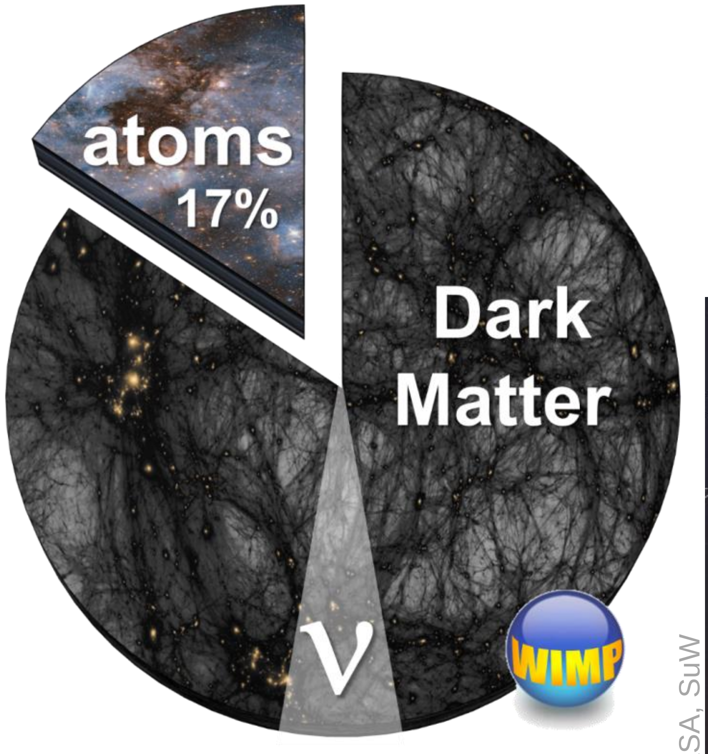
- ***APP***: **deciphering the Code of the Universe – here at *KIT***

KATRIN, IceCube,
Einstein – Telescope
DARWIN, GridKa, …

Auger
XENON – nT

*A*stro *P*article *P*hysics – the central motivation

- **neutrinos & neutralinos: from the Big Bang & the universe**



neutrinos

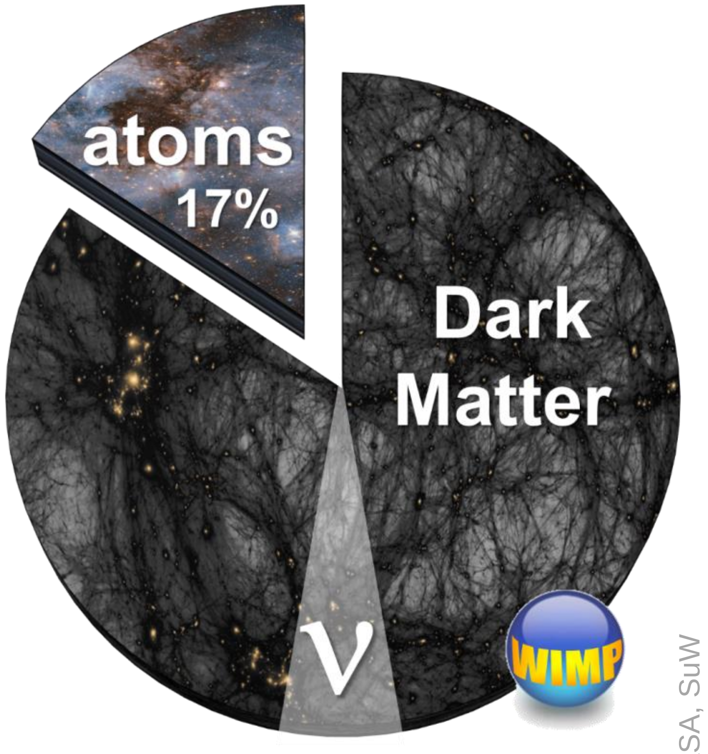
- massive **neutrinos** as
  H*ot *D*ark *M*atter – *HDM
- massive **neutralinos** as
  C*old *D*ark *M*atter – *CDM

Q: NASA, SuW

*A*stro *P*article *P*hysics & Cosmology: perfect match

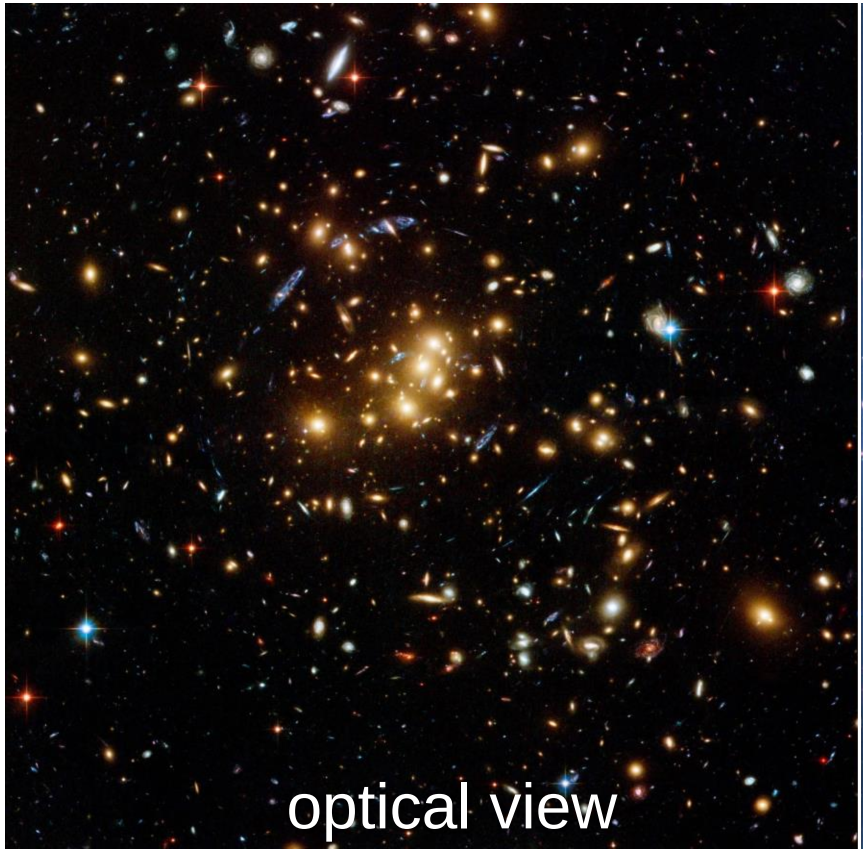
- **Dark Matter: maps by gravitational lenses, see ´Introduction to Cosmology´**

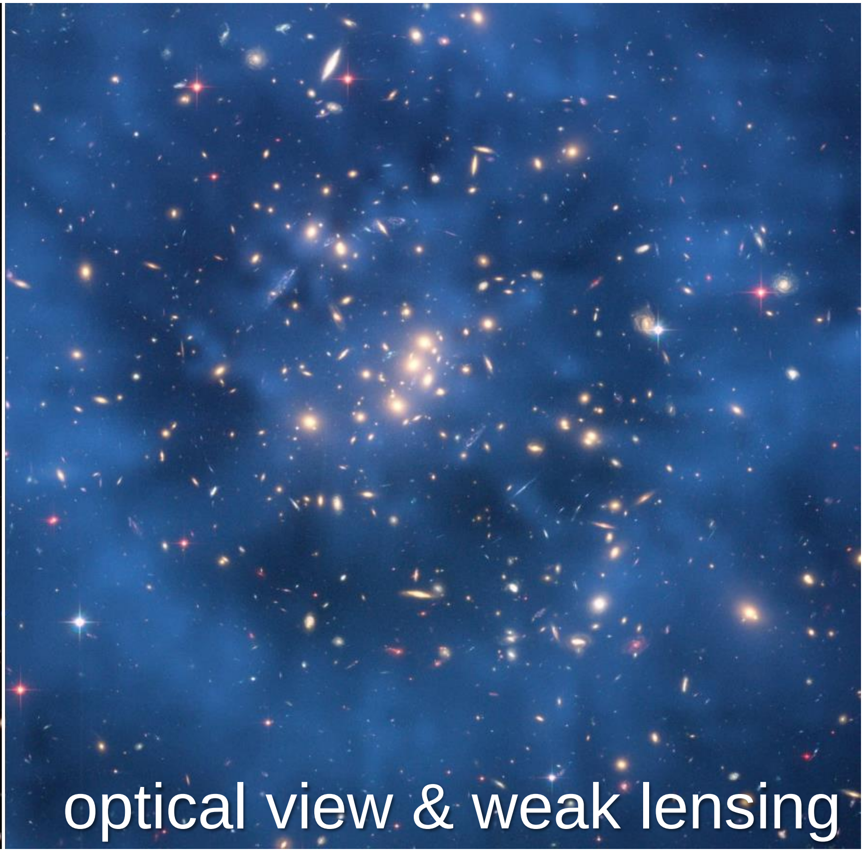
  Cosmology lectures: Tuesdays $11{:}30 - 13{:}00$ *kl. HS. A*



neutrinos

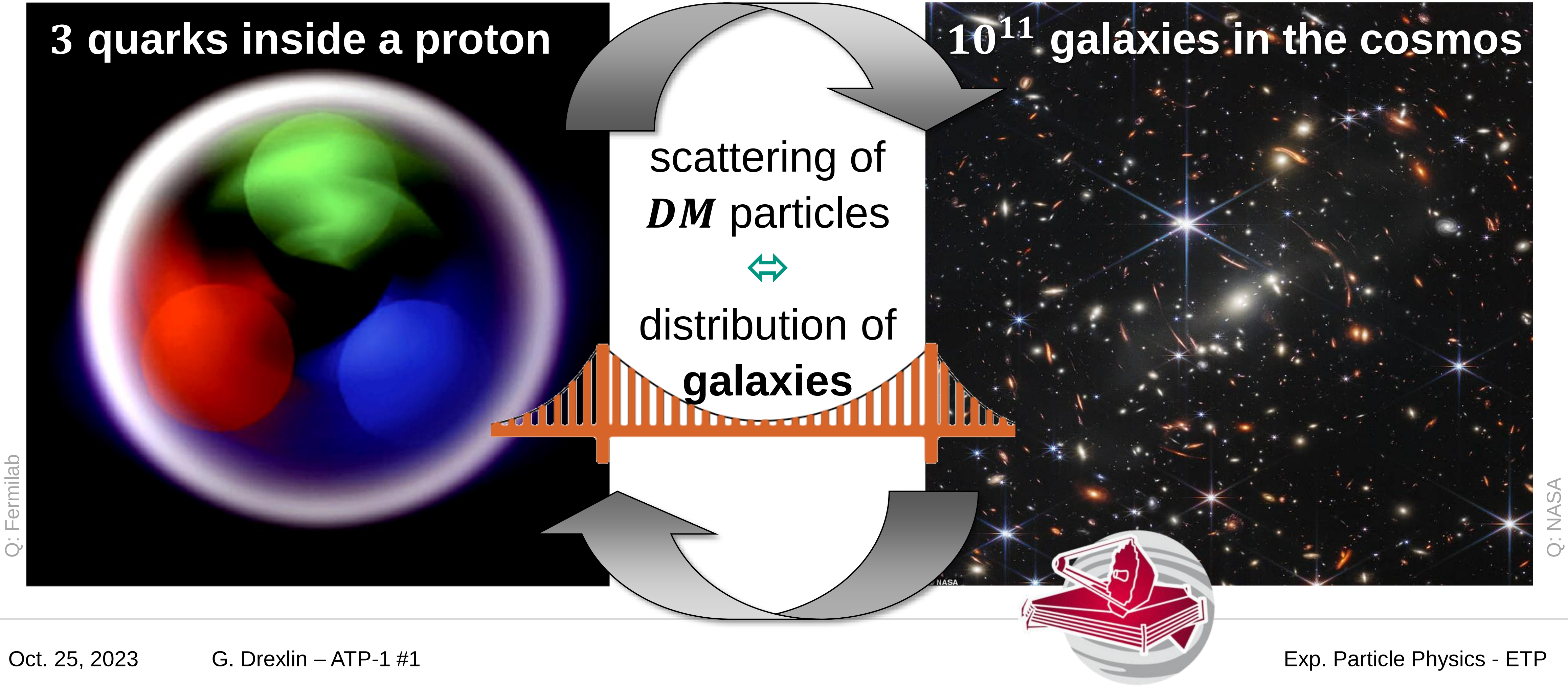
Q: NASA, SuW





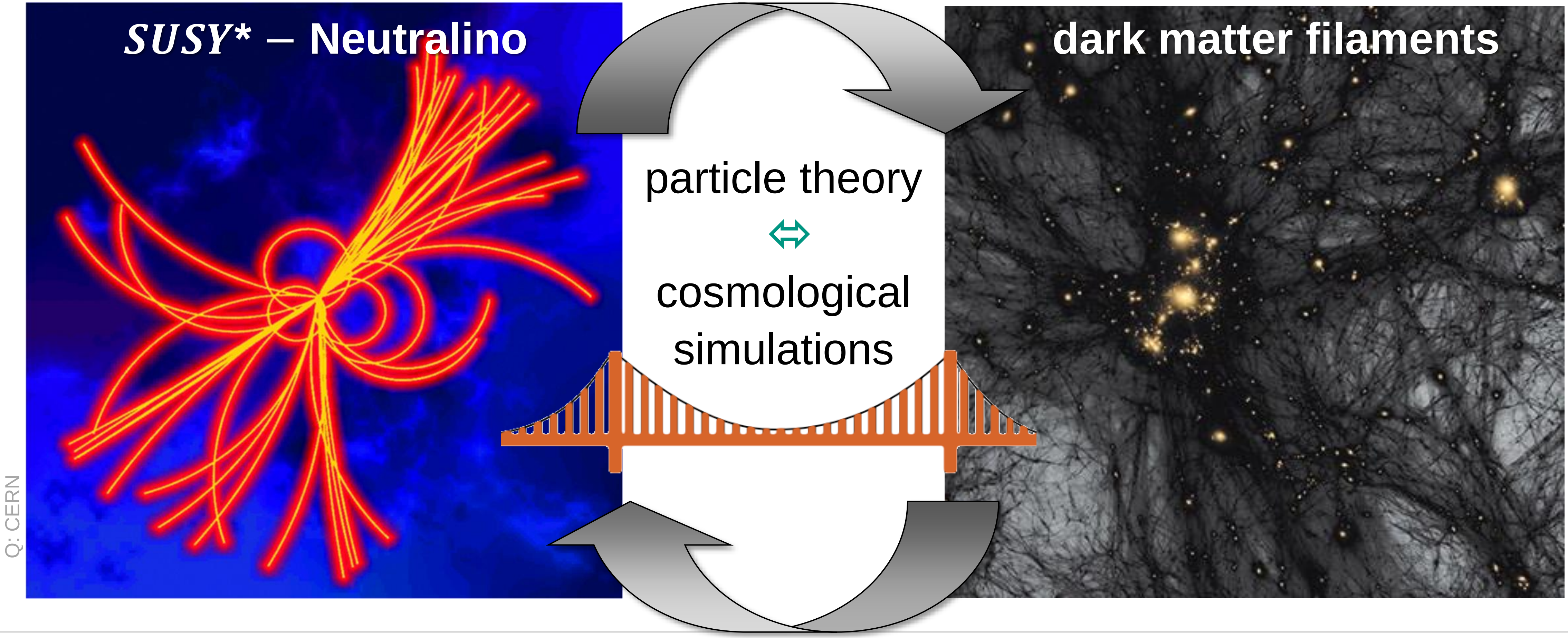
*A*stro *P*article *P*hysics – cross connections #1

- …from the **quark level** to the entire **cosmos**…



*A*stro *P*article *P*hysics – cross connections #2

- **…from neutralinos to dark matter in the cosmos…**

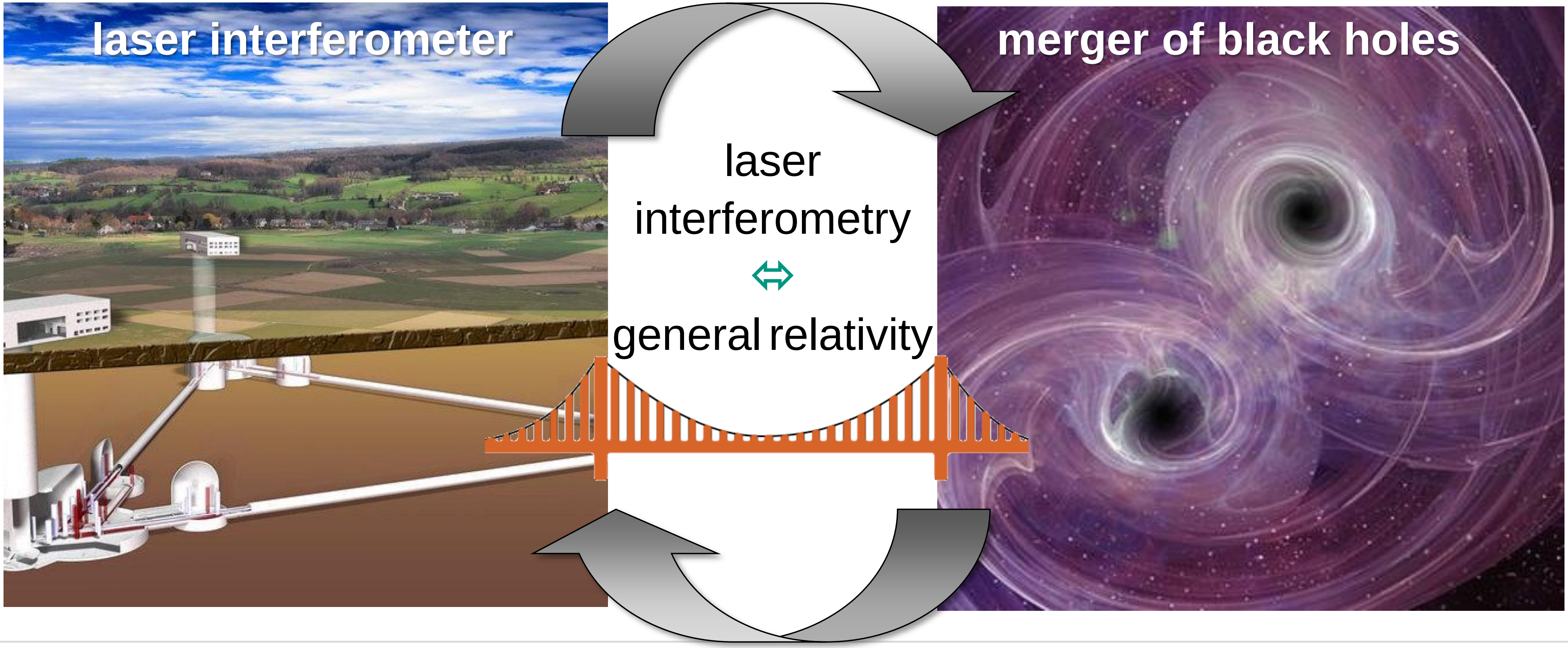


*SUper–SYmmetry

*A*stro *P*article *P*hysics – cross connections #3

- …from **gravitational waves** to **black holes & strong gravity** (*GR**)

Q: NIKHEF, ET

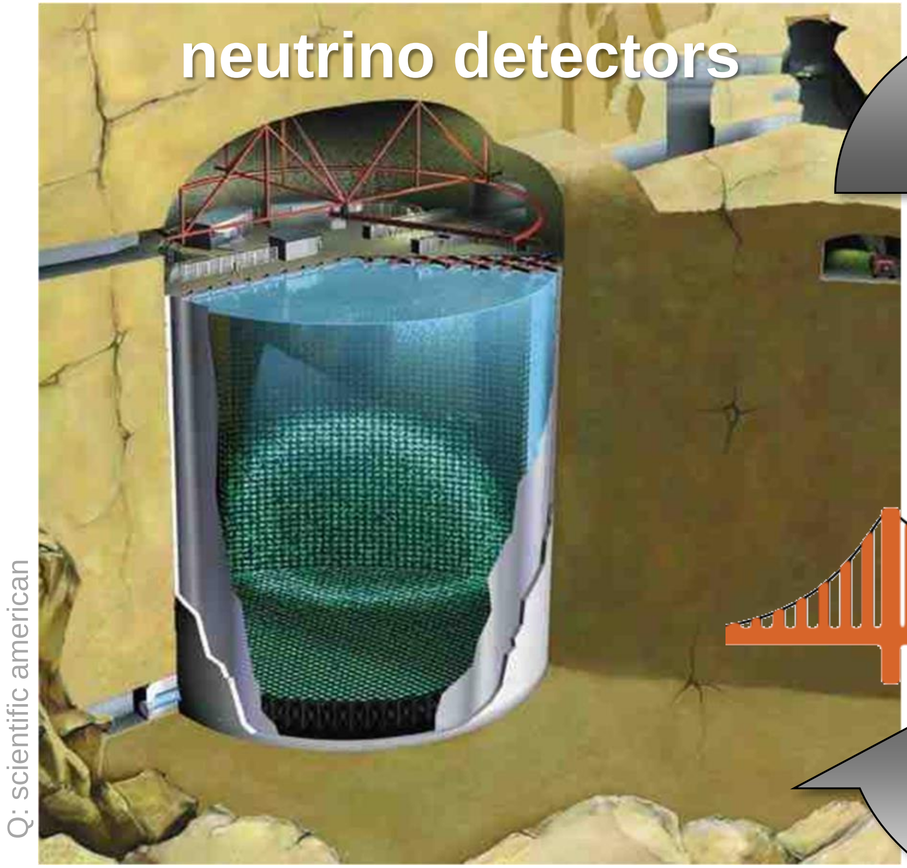


Q: visuals unlimited

**General Relativity*

*A*stro *P*article *P*hysics – cross connections #4

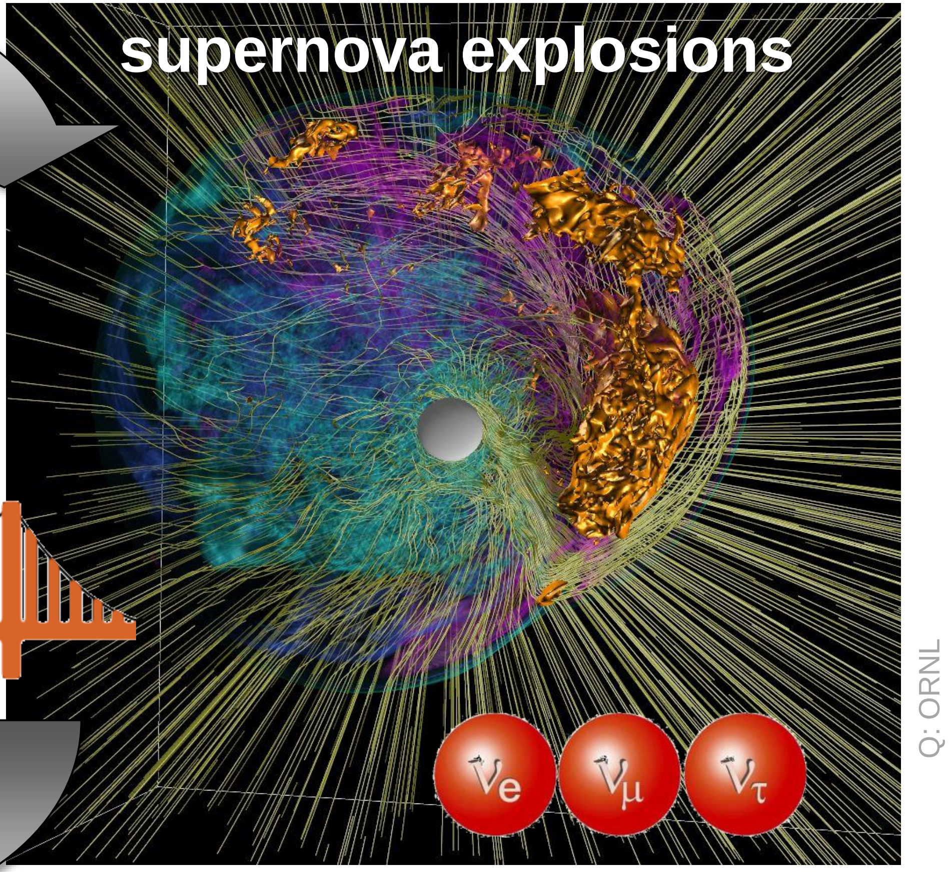
- …from **neutrino detectors** to **core−collapse supernovae**



detection of Cherenkov light

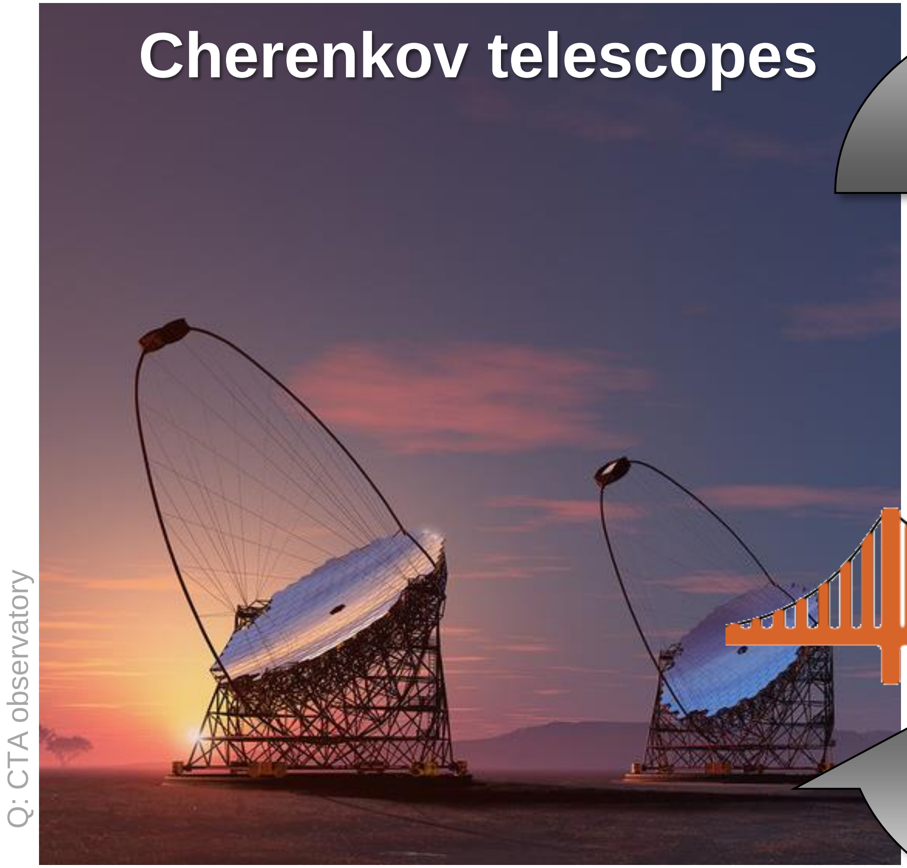
⇔

astrophysics

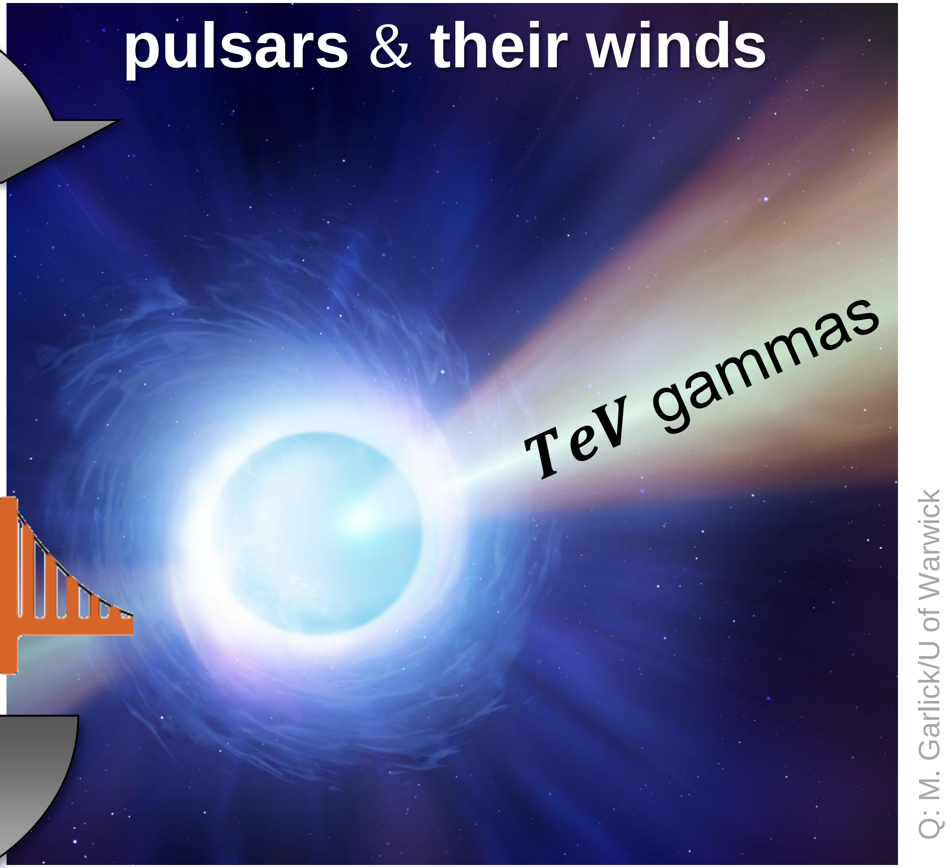


*A*stro *P*article *P*hysics – cross connections #5

- …from TeV – Cherenkov telescopes to pulsar wind nebulae

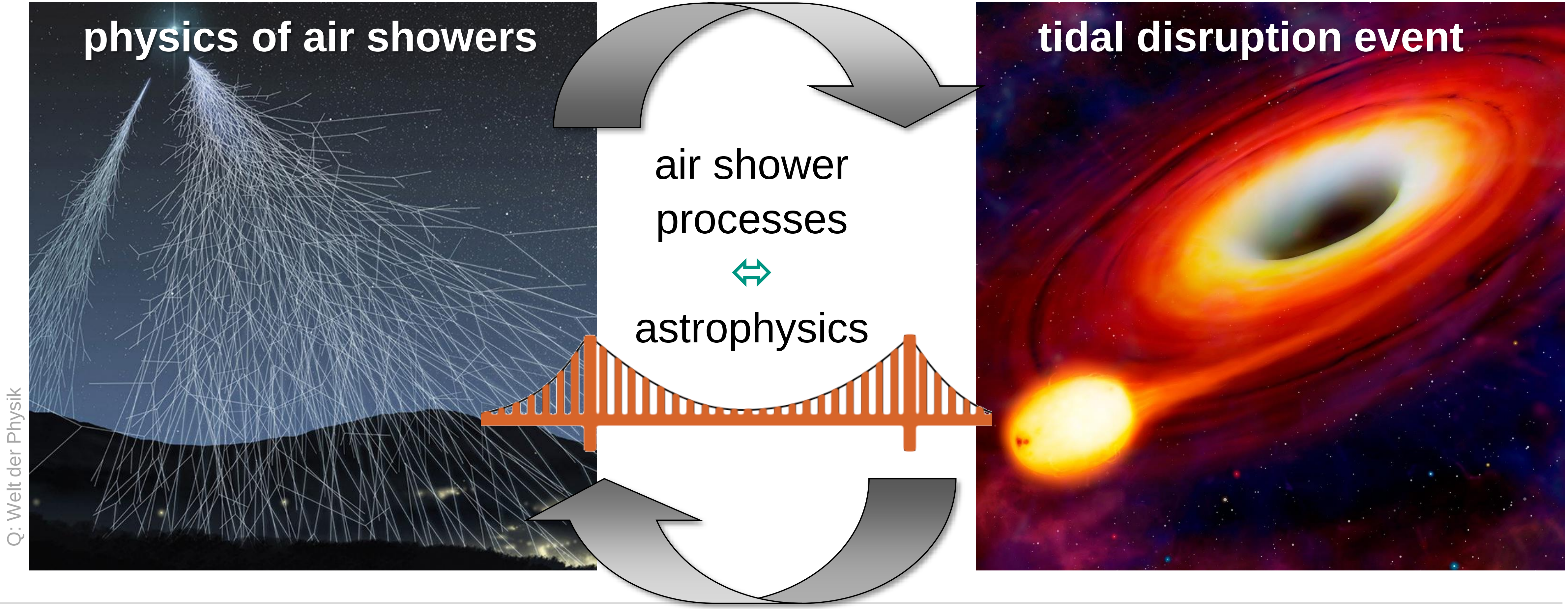


detection of
Cherenkov light
⇔
astrophysics



*A*stro *P*article *P*hysics – cross connections #6

- …from **air shower arrays** to **cosmic super accelerators**



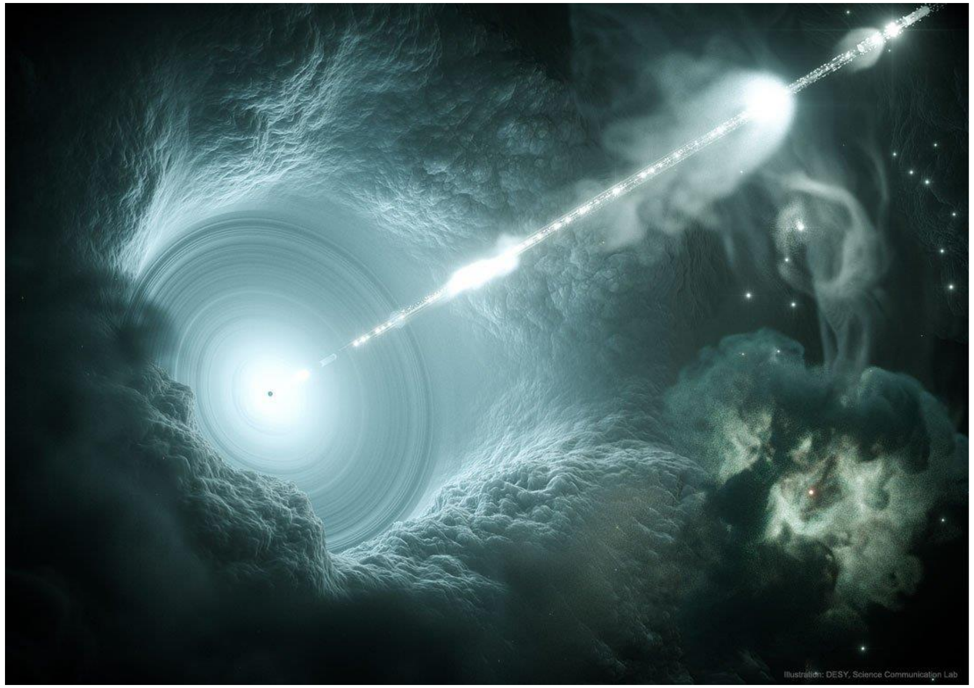
UHECR = *U*ltra–*H*igh *E*nergy *C*osmic *R*ay

Astro Particle Physics – recent breakthroughs

Karlsruhe Institute of Technology

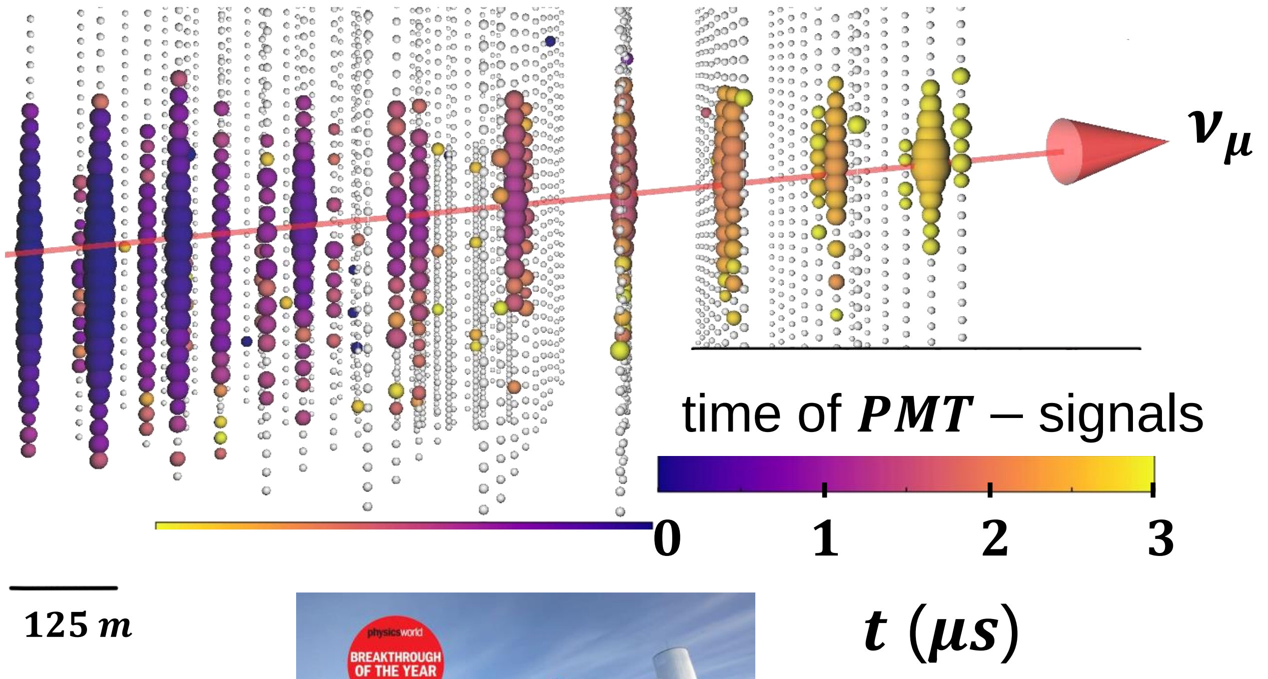
- …from **ultra–high energy neutrinos** to **blazars**…

´$\boldsymbol{Texas}$ source´: $\boldsymbol{TXS\ 0506+056}$
an active supermassive black hole



Blazars as sources for $\boldsymbol{UHE}$* $\boldsymbol{\nu}$´s

Sept. $\mathbf{22, 2017}$: $\boldsymbol{IceCube}$ observes
an event with $\boldsymbol{E = 290\ TeV}$



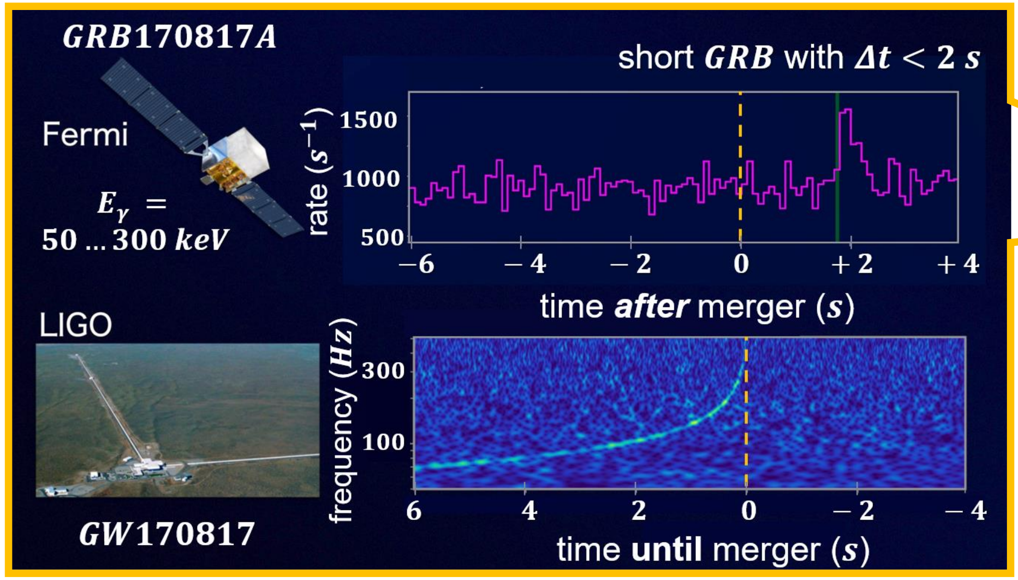
Q: DESY

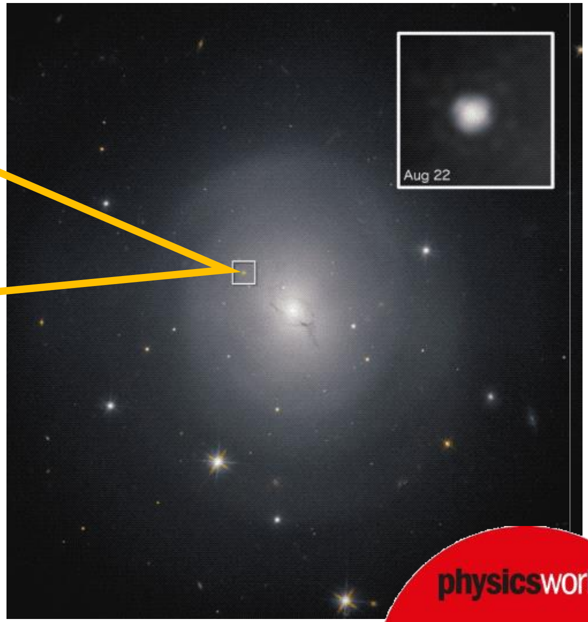
*$\boldsymbol{UHE}$ = $\boldsymbol{U}$ltra–$\boldsymbol{H}$igh $\boldsymbol{E}$nergy

*A*stro *P*article *P*hysics – recent breakthroughs

- …from **gravitational waves** to ***GRB**s**…

merger process of two neutron stars observed ***live***





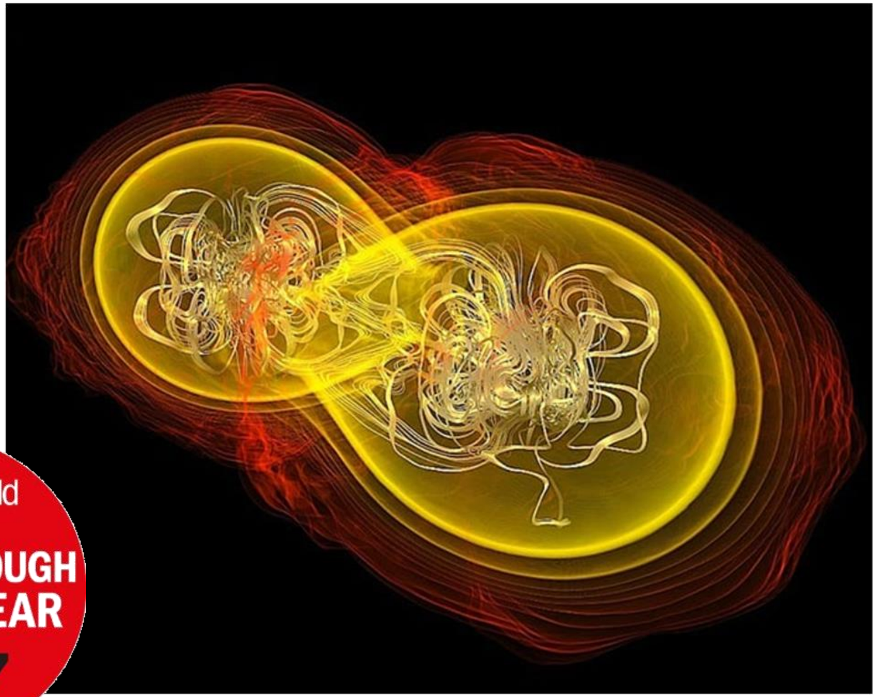
Q: HST, Fermi, Ligo

ASTRONOMY AND SPACE | NEWS

First multimessenger observation of a neutron-star merger is Physics World 2017 Breakthrough of the Year

11 Dec 2017 Hamish Johnston

The *Physics World* 2017 Breakthrough of the Year goes to the international team of astronomers and astrophysicists that ushered in a new era of astronomy by making the first ever multimessenger observation involving gravitational waves. Nine other achievements are highly commended and cover topics ranging from topological physics to Egyptology and more.



…hrouded in mystery: artist's impression of merging neutron stars

Q: physics world

news on the origin of ***heavy elements***

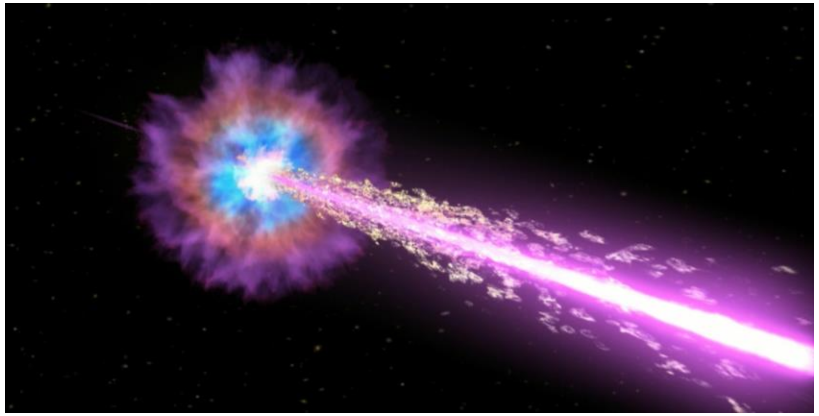
**GRB* = *G*amma *R*ay *B*urst

$\mathcal{A}$stro $\mathcal{P}$article $\mathcal{P}$hysics – a recent observation

- …a unique record−breaking GRB occured $\sim 1\ year\ (Oct.\,9,\,2022)$ ago…

  - collapse of a massive star to a black hole

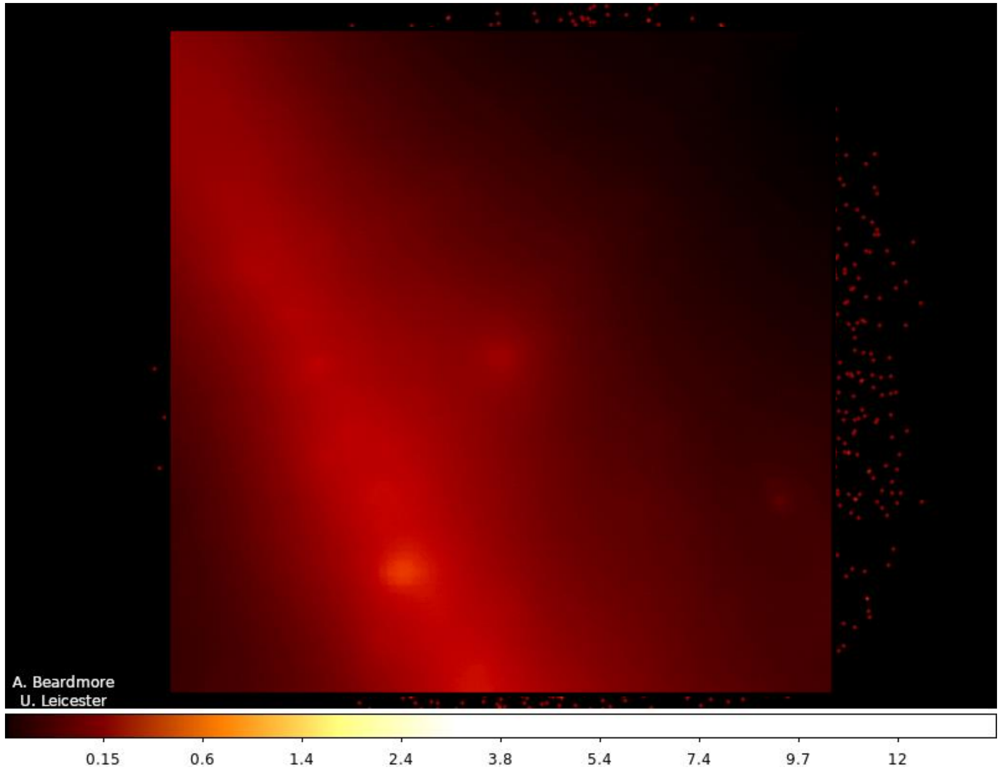
generation of a very long burst ($\sim 10\ h$) of gamma rays with peak energies up to $14\ TeV$



GRB occured at a distance $D = 2\ Gpc$
here: light reflection at dust grains in between

OCTOBER 15, 2022

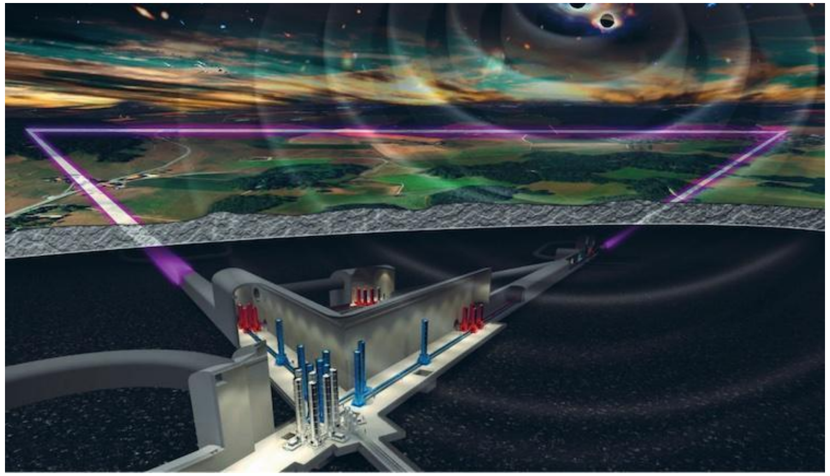
Record-breaking gamma-ray burst possibly most powerful explosion ever recorded

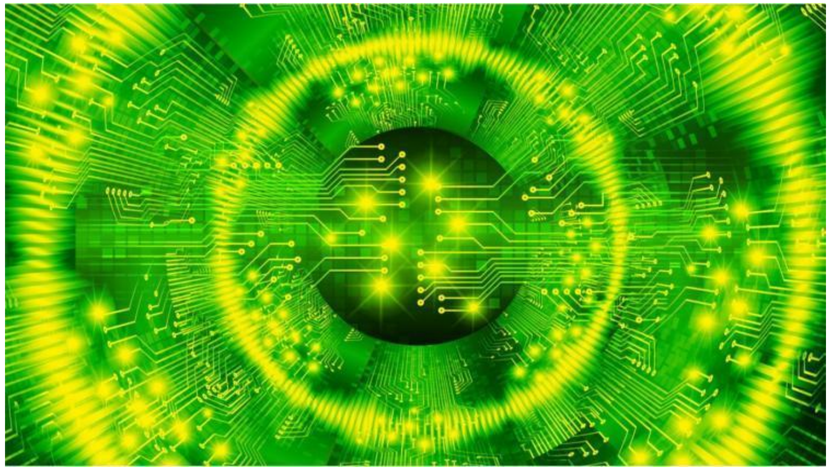


*A*stro *P*article *P*hysics – future breakthroughs

Karlsruhe Institute of Technology

- ***DZA*** **– *D*eutsches *Z*entrum für *A*strophysik: a new *APP* centre in the Lausitz**

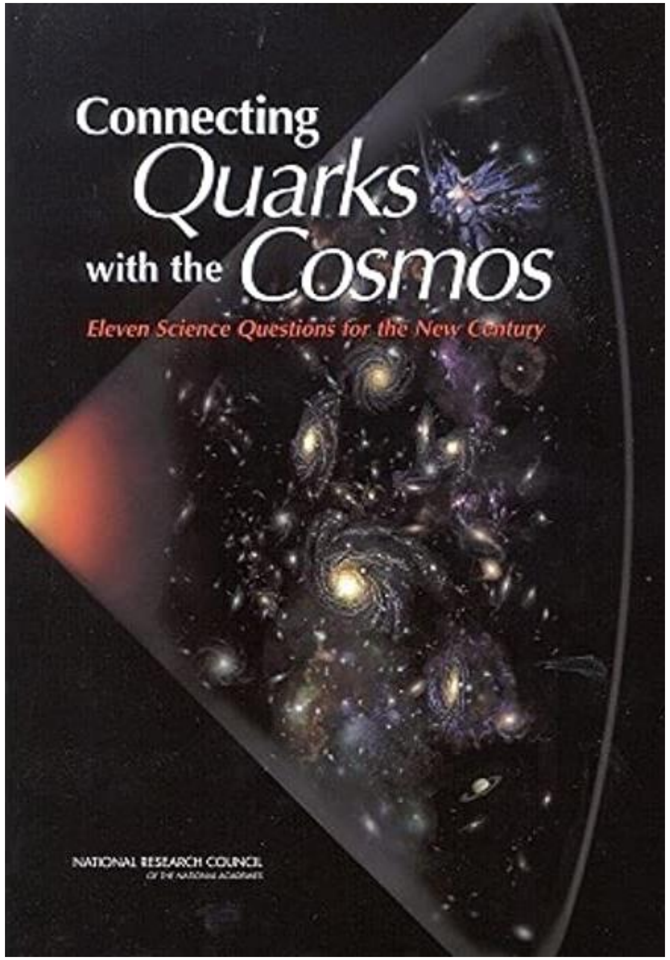


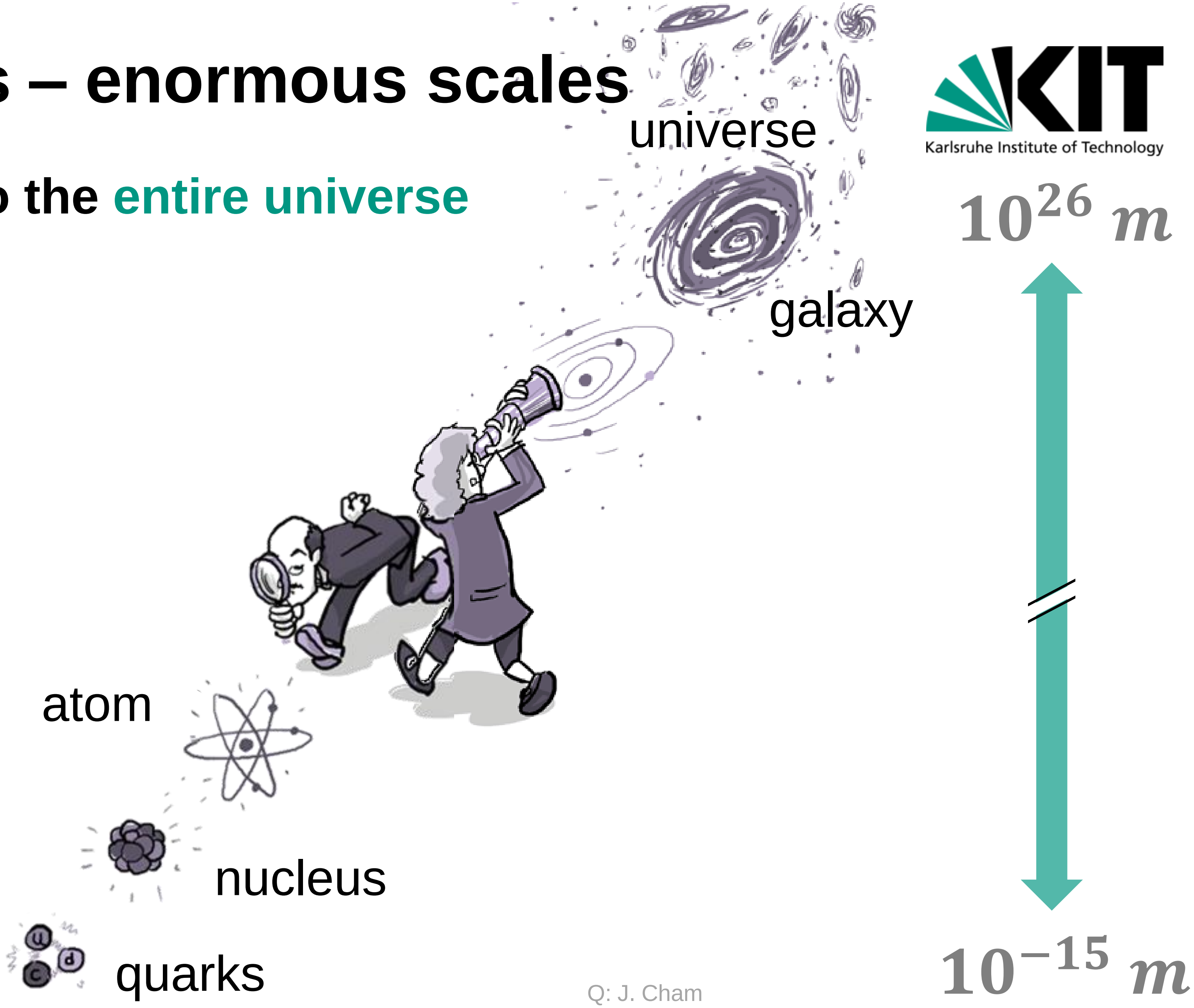


- bundling the activities of **German astroparticle physics**

*A*stro *P*article *P*hysics – enormous scales

- **from the quark scale … to the entire universe**

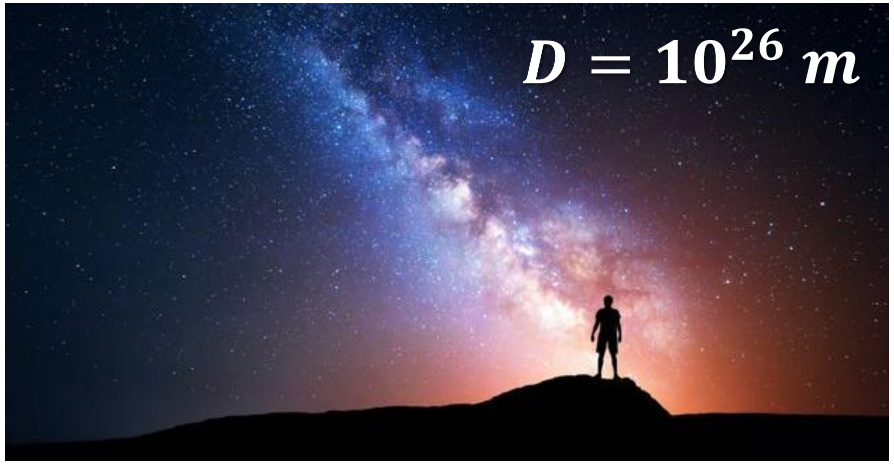


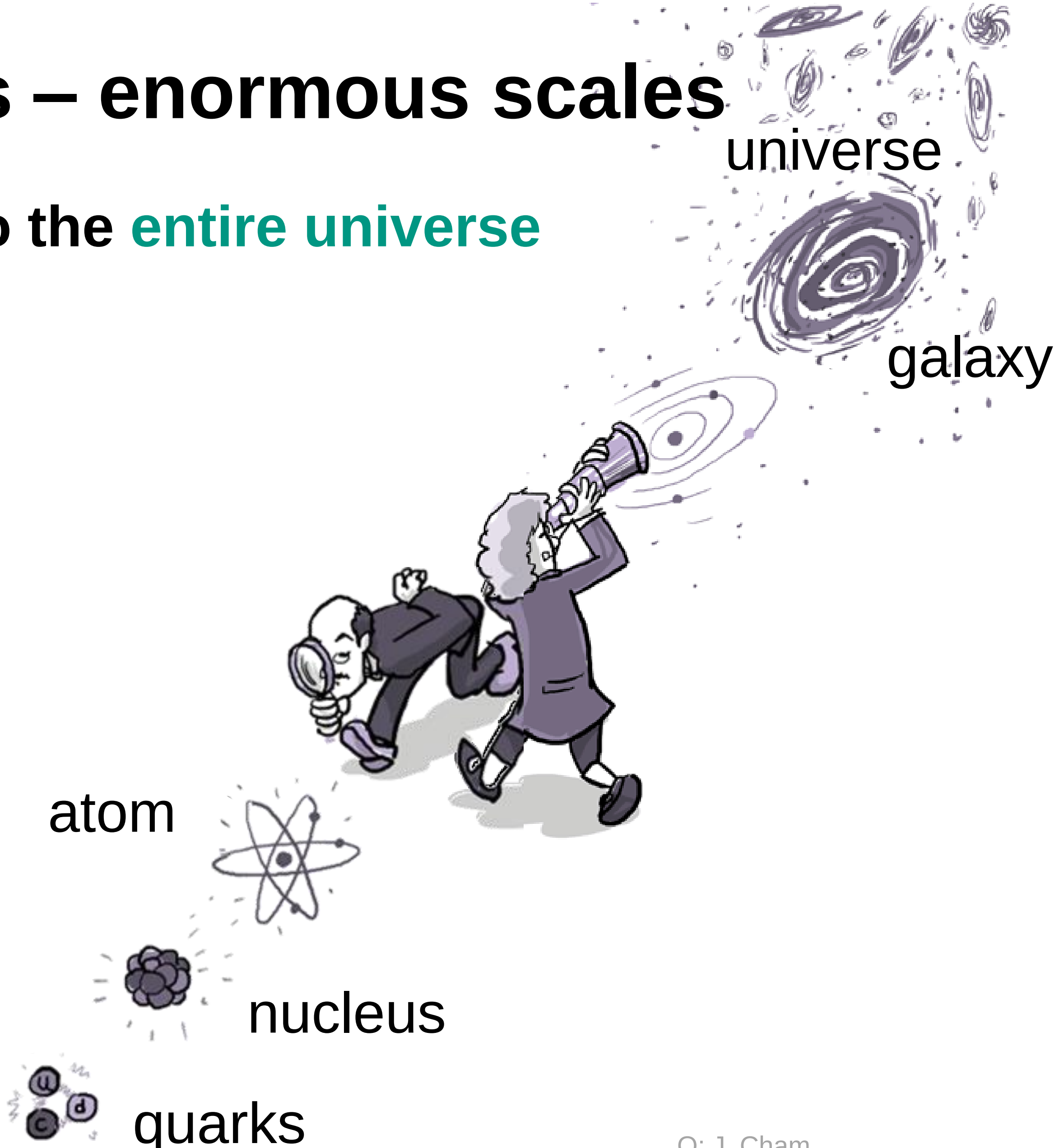


Q: J. Cham

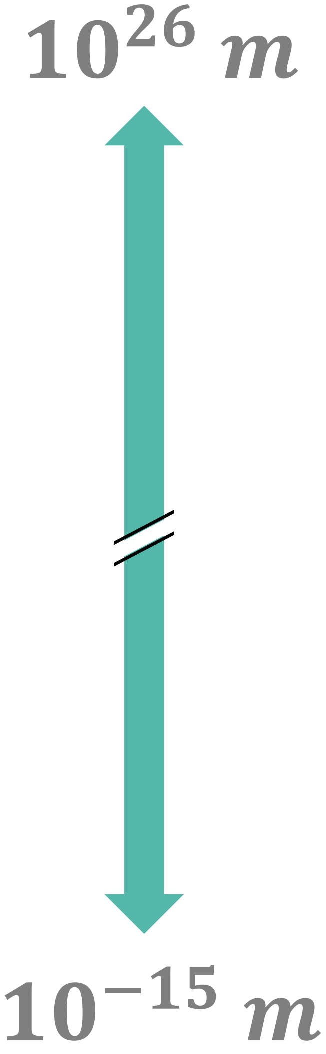
*A*stro *P*article *P*hysics – enormous scales

- **from the quark scale … to the entire universe**





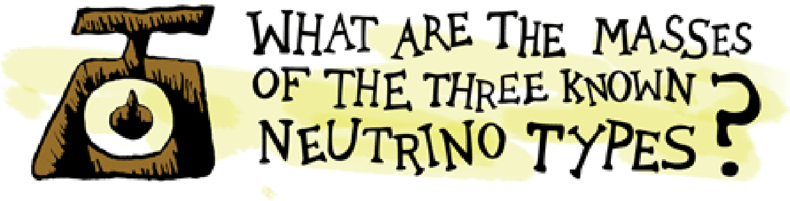
Q: J. Cham

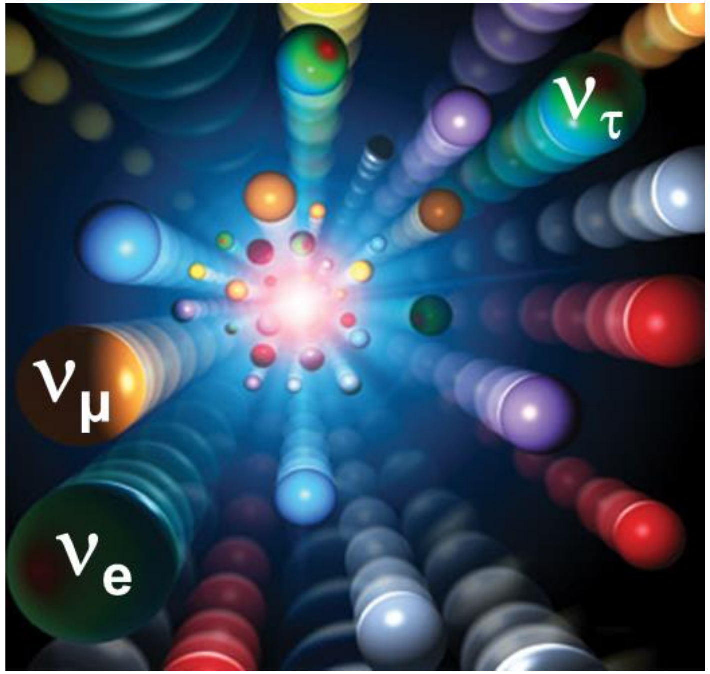


*A*stro *P*article *P*hysics – open questions

- **what is the fundamental nature of neutrinos?**

- we can find out by **observing their role** in the cosmos!





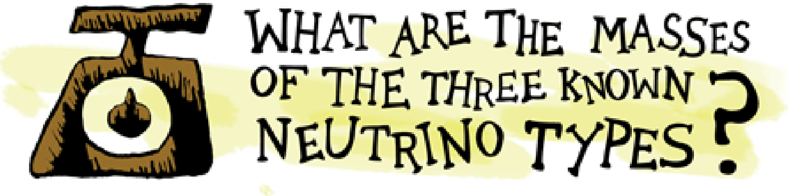
- using our knowledge of cosmic evolution / galaxy formation

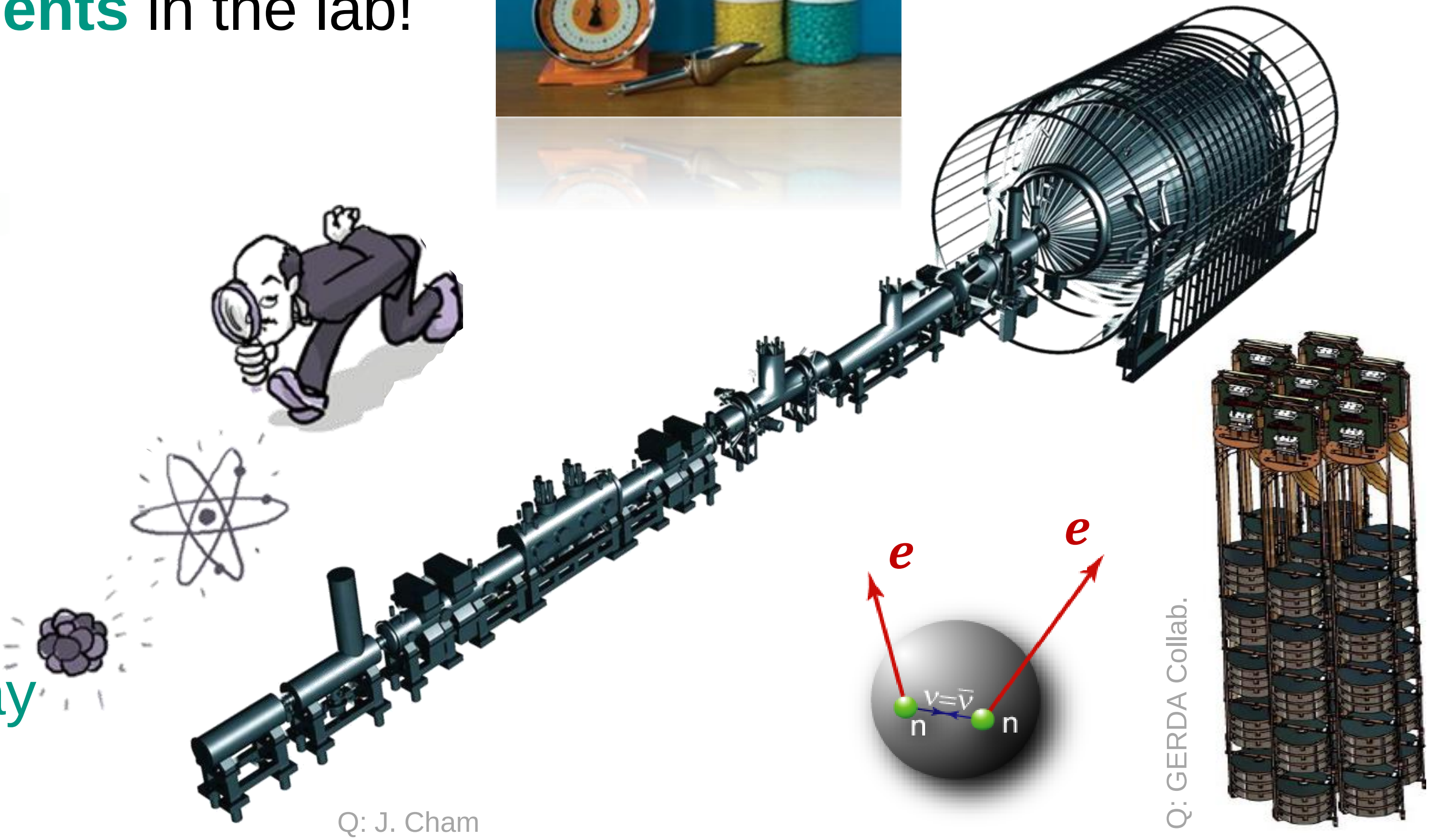
Q: J. Cham

*A*stro *P*article *P*hysics – open questions

- **what is the fundamental nature of neutrinos?**

- we can find out by doing **experiments** in the lab!





- using our knowledge of β – decay theory

Q: J. Cham

Q: GERDA Collab.

*A*stro *P*article *P*hysics – open questions

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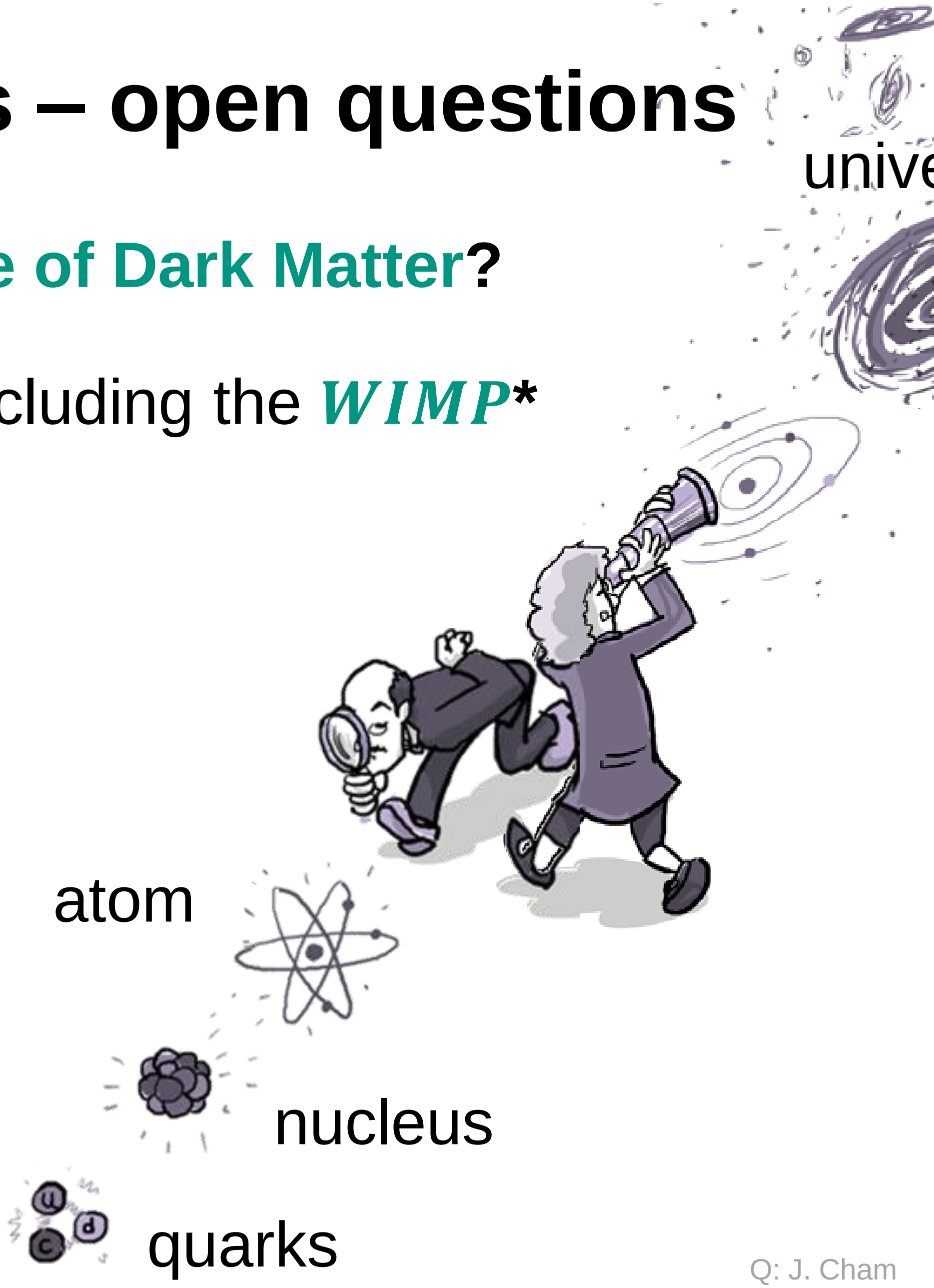
■ **what is the particle nature of Dark Matter?**

- there are many candidates, including the ***WIMP****



*

dark halo

scattering process

- how can we detect them?

- how to measure their mass?

Q: J. Cham

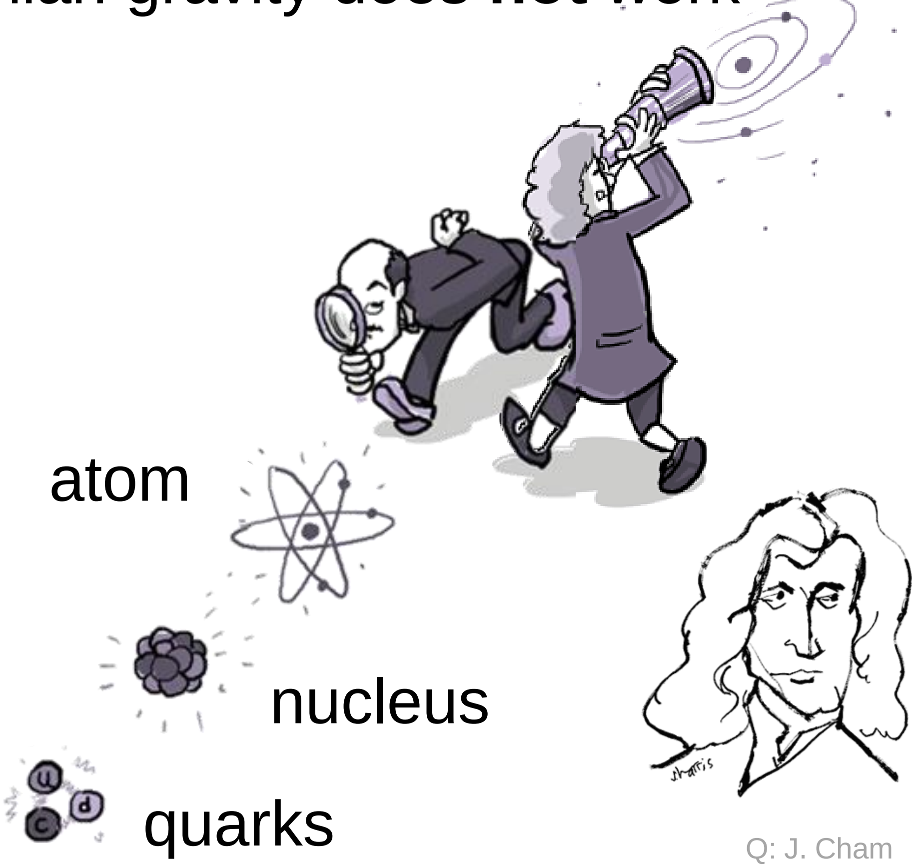
* ***W***eakly ***I***nteracting ***M***assive ***P***article

*A*stro *P*article *P*hysics – open questions

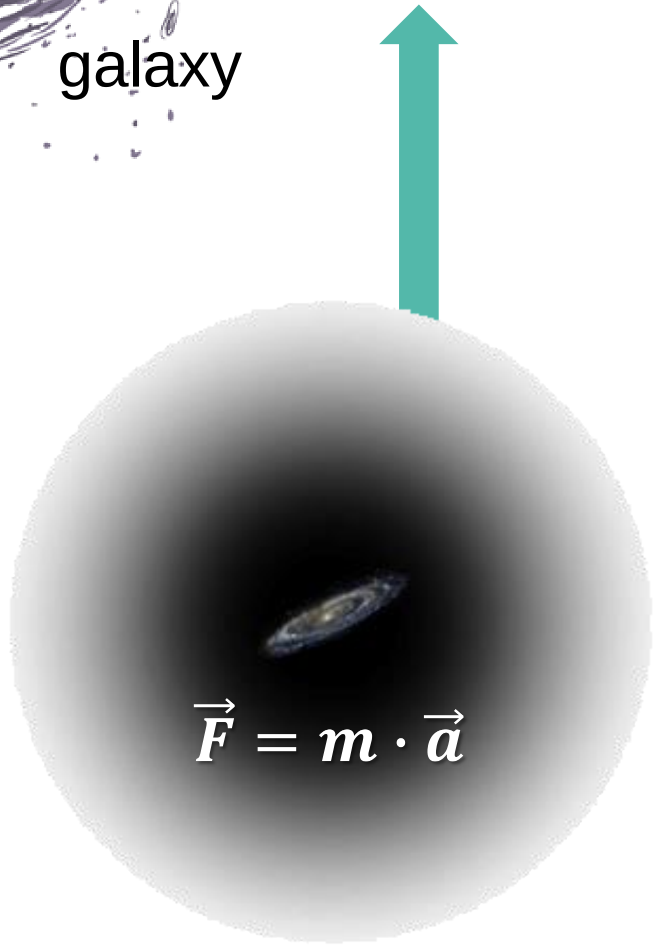
■ **Are we certain Dark Matter exists?**

- **yes**, we are! To modify Newtonian gravity does **not** work

- Dark matter halos surround all galaxies, plus other evidences



Q: J. Cham

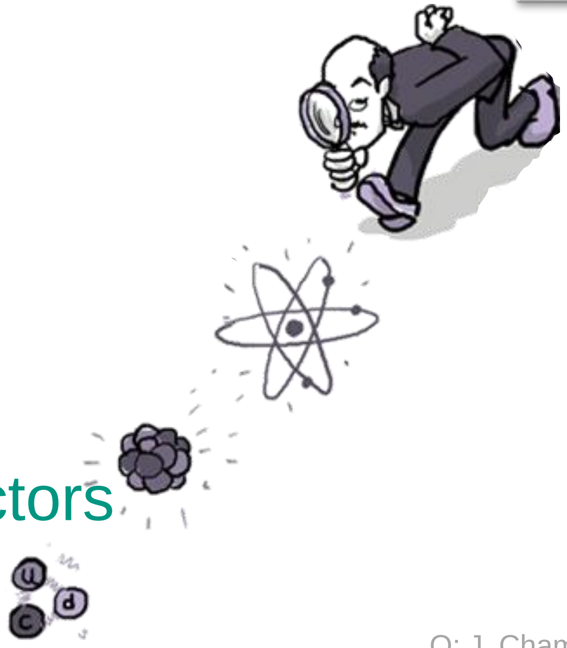


*A*stro *P*article *P*hysics – open questions

- **what is the particle nature of Dark Matter?**

\- we can find out via **detecting it here on Earth**!

Q: CRESST



Q: J. Cham

Q: XENON/DARWIN

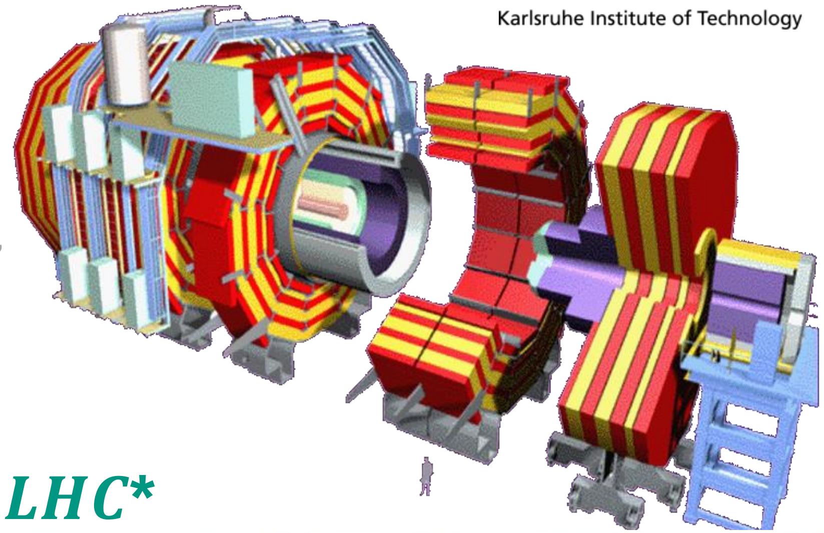
\- by using novel advanced detectors

\- by bg – reduction methods

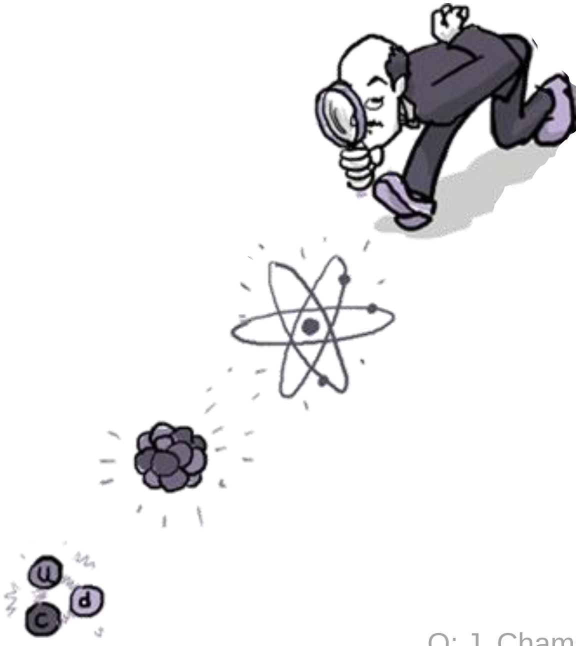
*A*stro *P*article *P*hysics – open questions

- **what is the particle nature of Dark Matter?**

- we can find out by **producing it** via an accelerator!

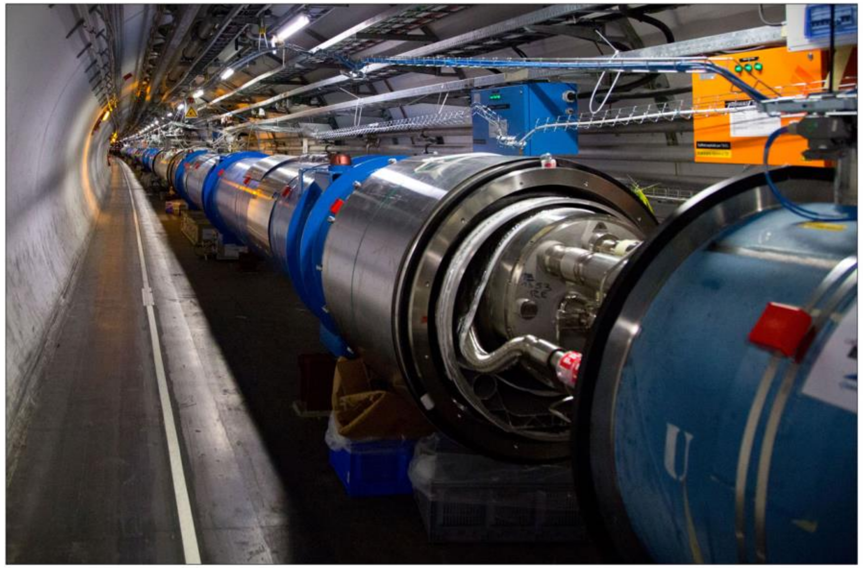


Q: CMS



Q: J. Cham, CERN

LHC*



- using our knowledge of ***SUSY***

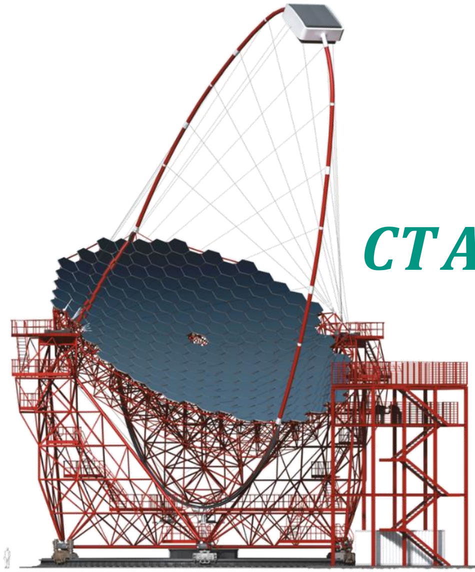
- using our knowledge of ***LHC***

**Large Hadron Collider (CERN)*

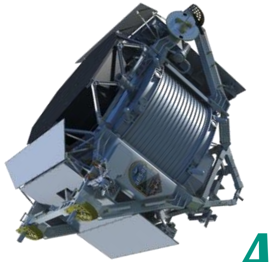
*A*stro *P*article *P*hysics – open questions

- **what is the particle nature of Dark Matter?**

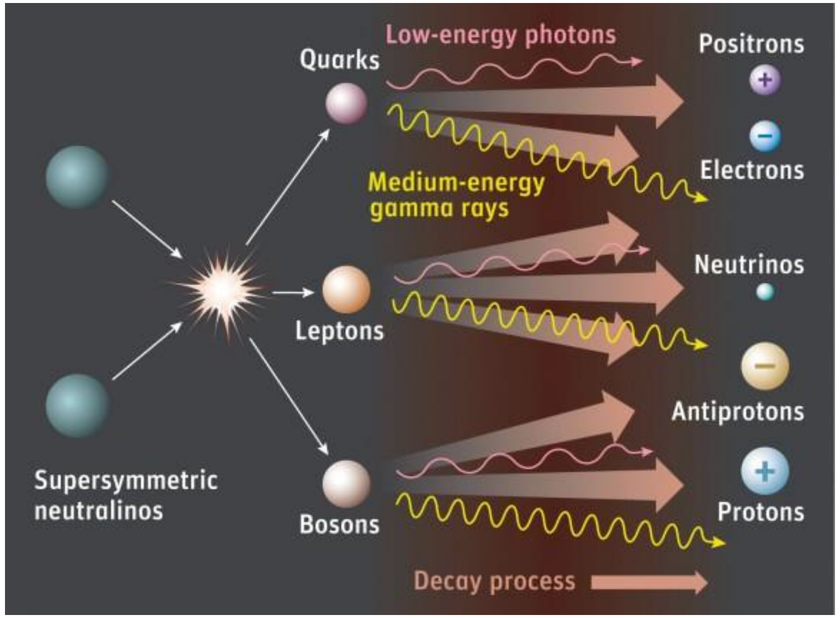
- we can find out by **observing its decay** in the cosmos!



CTA*



AMS**



- using our knowledge of theory (***SUSY***)

- using our knowledge of cosmic accelerators

Q: J. Cham

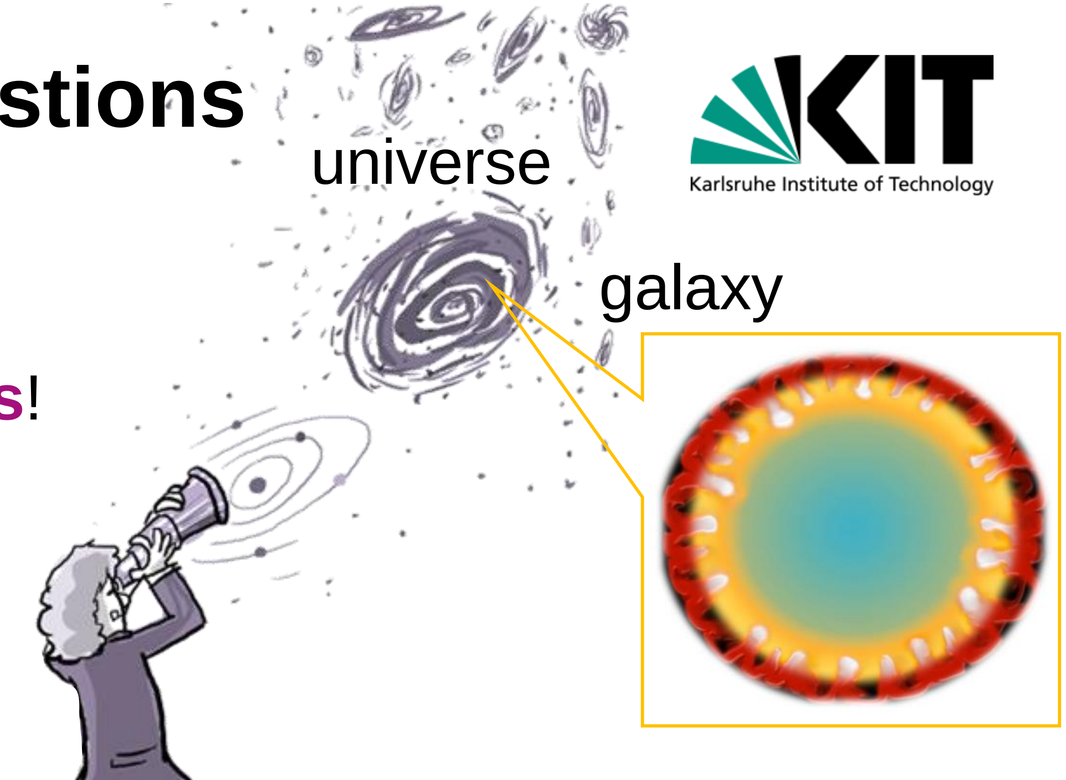
* ***C***herenkov ***T***elescope ***A***rray

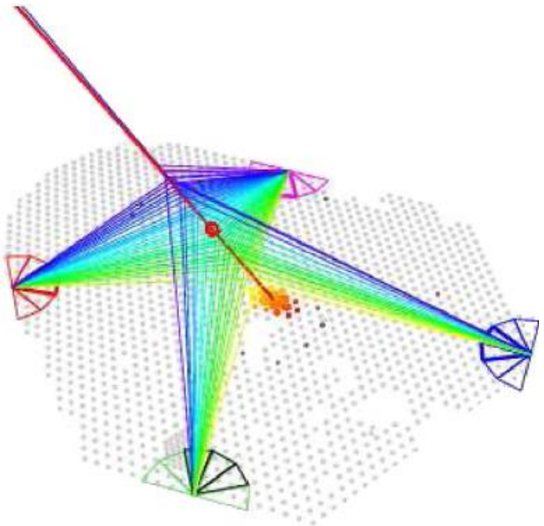
** ***A***lpha ***M***agnetic ***S***pectrometer

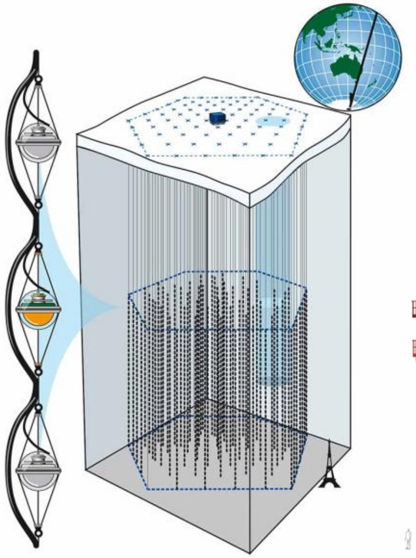
*A*stro *P*article *P*hysics – open questions

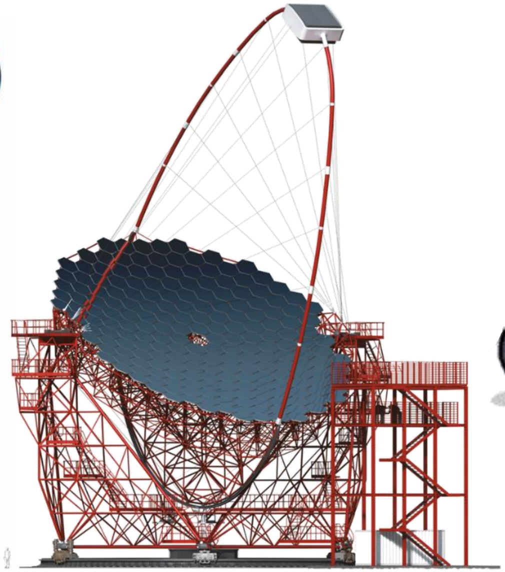
- **what is the nature of cosmic rays?**

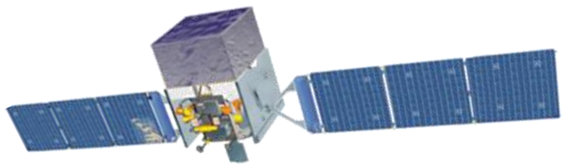
- we can find out by **using different messengers**!











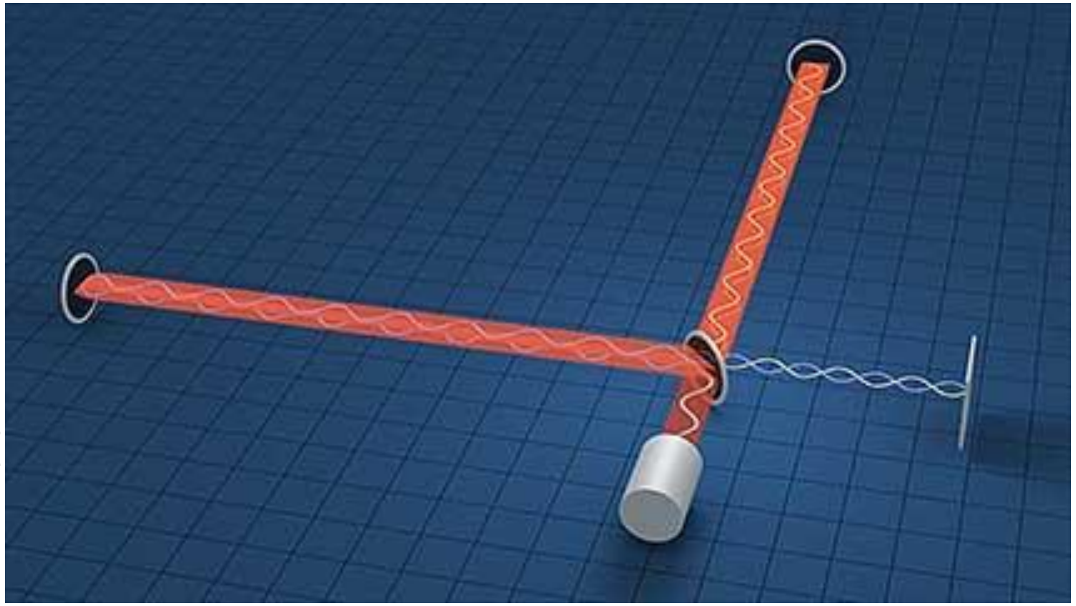
- combing our knowledge of each **messenger**: gammas, neutrinos, protons & nuclei

- using our knowledge of astrophysical **magnetic fields**

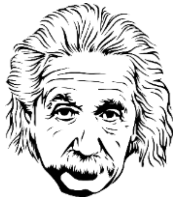
*A*stro *P*article *P*hysics – open questions

- **what is the nature of gravitational waves?**

- we can find out by **using laser interferometers**!

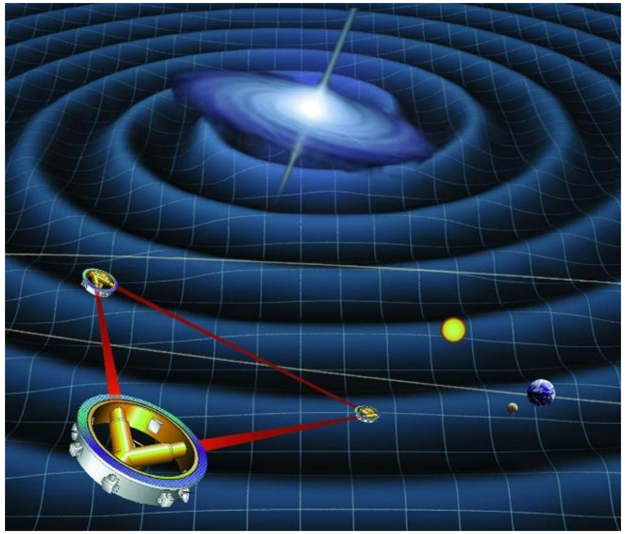


Q: APS physics



- using our knowledge of general relativity

- combining data from surface of **earth** & **in space**

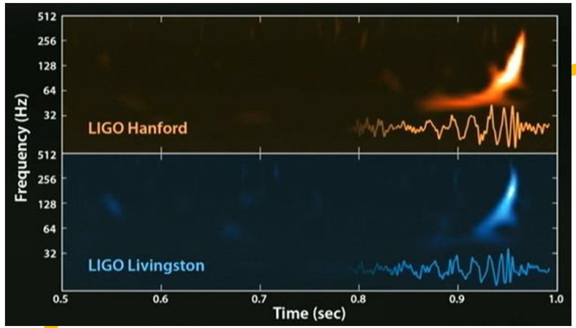


Q: NASA/LISA

*A*stro *P*article *P*hysics – skills

Karlsruhe Institute of Technology

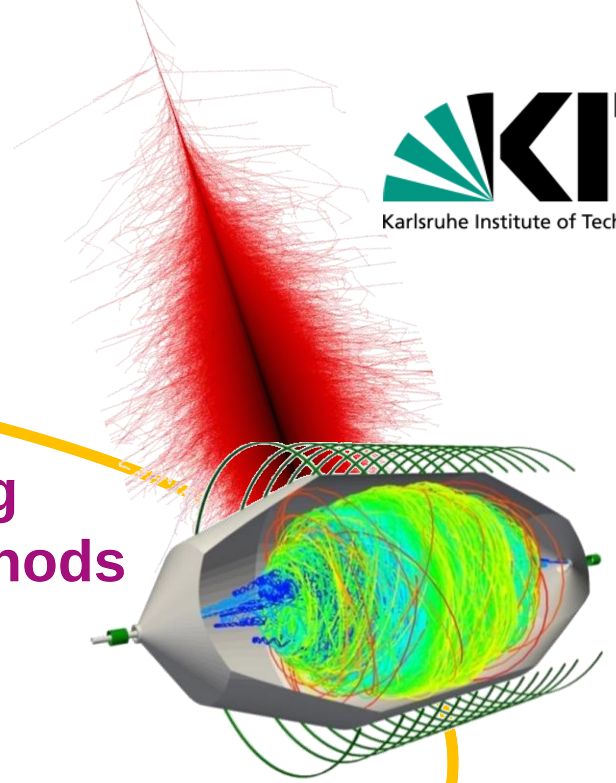
- what **skills** do I learn in this lecture series?



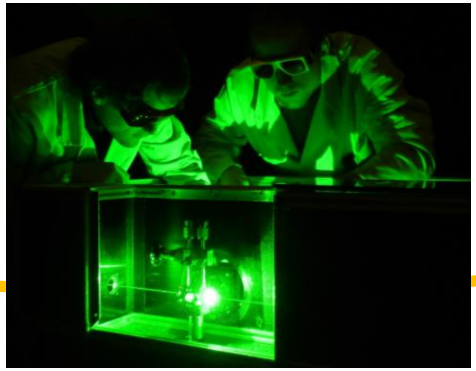
Q: LIGO

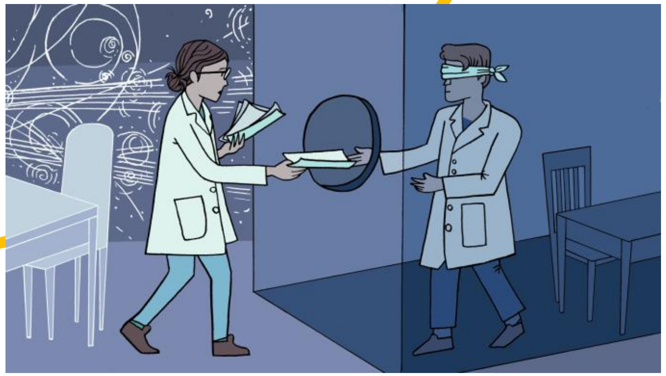
HOT TOPIC

hands-on
TRAINING



leading
$MC -$ methods





modern detectors

advanced technologies

analysis techniques

*A*stro *P*article *P*hysics – topics

Karlsruhe Institute of Technology

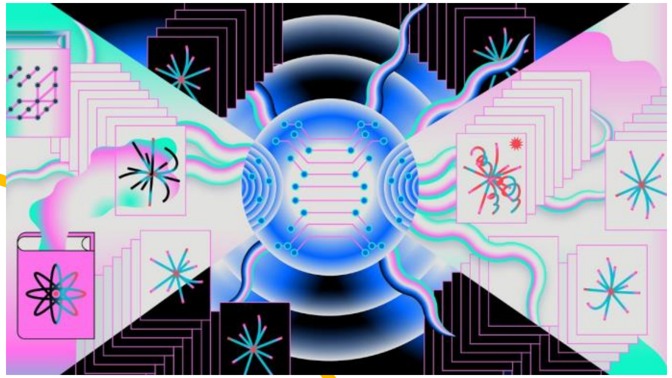
- what **topics** do I follow in this lecture series?

arXiv

HOT TOPIC

hands-on TRAINING

modern electronics



Q: symmetry magazine (2)

Q: wikipedia

modern astrophysics

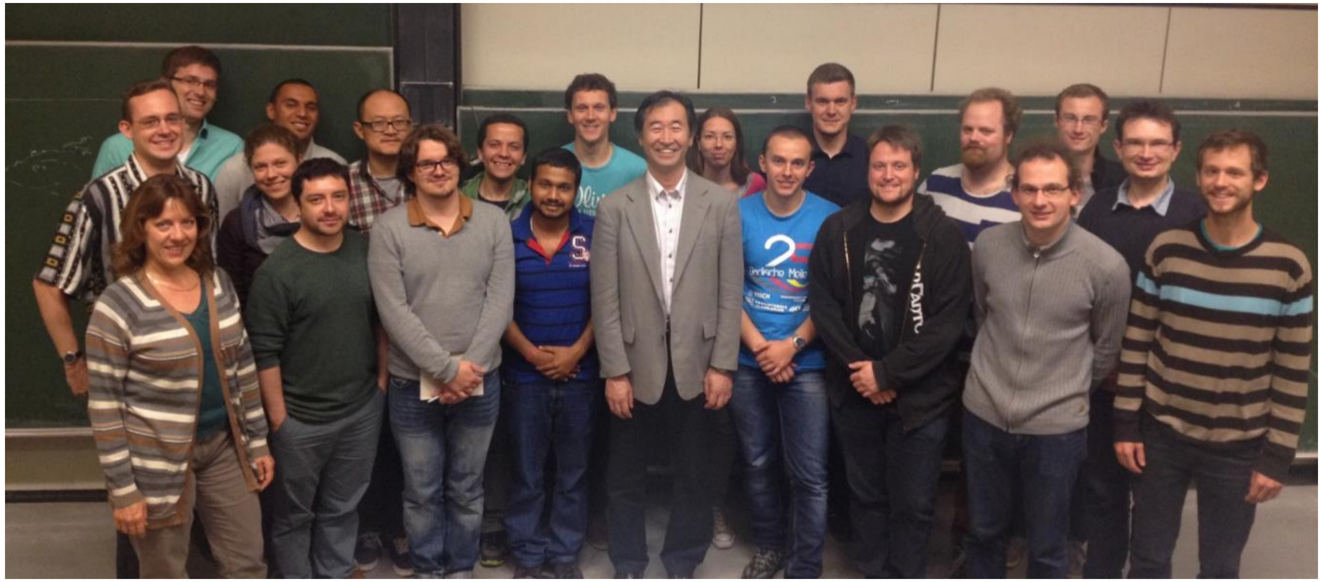
latest particle theory models

*A*stro *P*article *P*hysics – science network

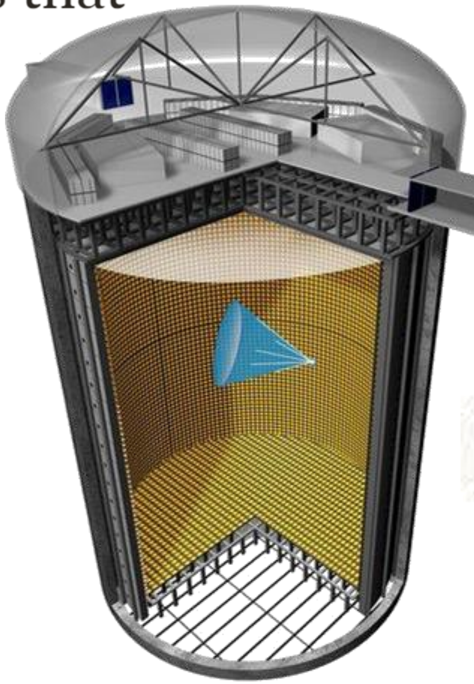
Karlsruhe Institute of Technology

- **What connections does *APP* provide? Meet and greet … a Nobel Laureate**

The Nobel Prize in Physics 2015 was awarded jointly to Takaaki Kajita and Arthur B. McDonald "for the discovery of neutrino oscillations, which shows that neutrinos have mass."



July 10, 2014 – ***Takaaki Kajita @ kl. HS A***



Nobelprize.org
The Official Web Site of the Nobel Prize

Takaaki Kajita

*A*stro *P*article *P*hysics – science network

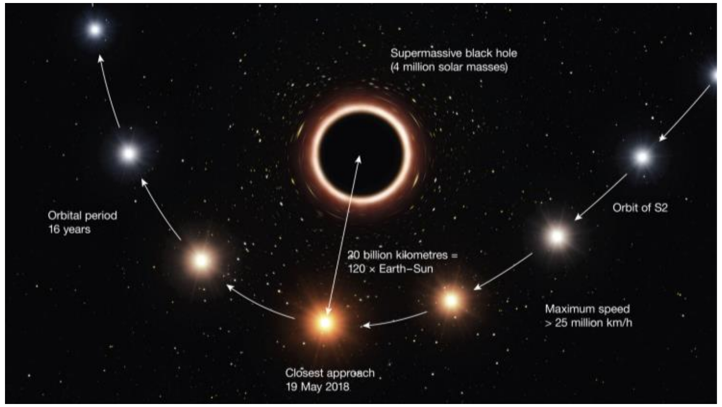
- **What connections does *APP* provide? Meet and greet … a Nobel Laureate**

The Nobel Prize in Physics 2020 was divided, the other half

jointly to Reinhard Genzel and Andrea Ghez "for the discovery of a supermassive compact object at the centre of our galaxy"

October 4/5, 2022 – ***R. Genzel @ KIT / KATRIN***

Nobelprize.org
The Official Web Site of the Nobel Prize



Reinhard Genzel

*A*stro *P*article *P*hysics – recent breakthroughs

Karlsruhe Institute of Technology

- **and the winner is…**

Einstein's waves win Nobel Prize in physics

By Paul Rincon and Jonathan Amos
BBC Science News

© Nobel Media. Ill. N. Elmehed
Rainer Weiss

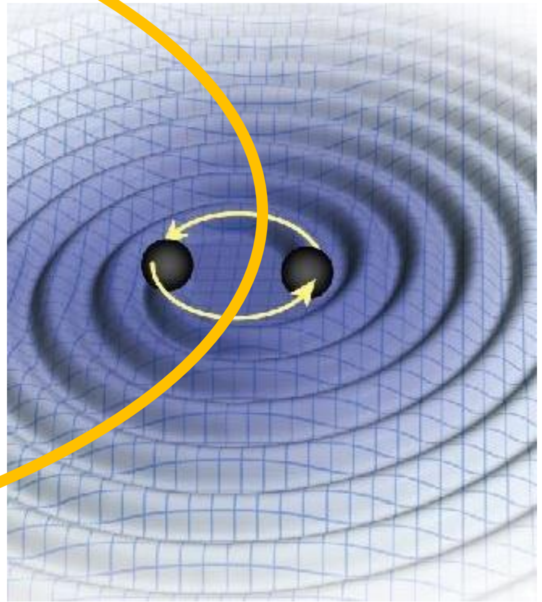
© Nobel Media. Ill. N. Elmehed
Barry C. Barish

© Nobel Media. Ill. N. Elmehed
Kip S. Thorne

Nobel Prize in Physics 2017

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne *"for decisive contributions to the LIGO detector and the observation of gravitational waves"*.

Nobelprize.org
The Official Web Site of the Nobel Prize



Q: BBC

*A*stro *P*article *P*hysics – topic events (2021 *ed.*)

- what was new in this lecture series? Interruption of $TeV -$ gamma views…

Q: MAGIC

direct view from $\boldsymbol{MAGIC}$ to volcanic eruption at the Cumbre Vieja (Santa Cruz de Tenerife)

*A*stro *P*article *P*hysics – topic events (2022 *ed.*)

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■ what was **new** in this lecture series?

arXiv

arXiv:2207.03764v2 [hep-ex] 18 Jul 2022

First Dark Matter Search Results from the LUX-ZEPLIN (LZ) Experiment

J. Aalbers,[1,2] D.S. Akerib,[1,2] C.W. Akerlof,[3] A.K. Al Musalhi,[4] F. Alder,[5] A. Alqahtani,[6] S.K. Alsum,[7] C.S. Amarasinghe,[3] A. Ames,[1,2] T.J. Anderson,[1,2] N. Angelides,[5,8] H.M. Araújo,[8] J.E. Armstrong,[9] M. Arthurs,[3] S. Azadi,[10] A.J. Bailey,[8] A. Baker,[8] J. Balajthy,[11] S. Balashov,[12] J. Bang,[6] J.W. Bargemann,[10] M.J. Barry,[13] J. Barthel,[14] D. Bauer,[8] A. Baxter,[15] K. Beattie,[13] J. Belle,[16] P. Beltrame,[5,17] J. Bensinger,[18] T. Benson,[7] E.P. Bernard,[13,19] A. Bhatti,[9] A. Biekert,[13,19] T.P. Biesiadzinski,[1,2] H.J. Birch,[3,15] B. Birrittella,[7] G.M. Blockinger,[20] K.E. Boast,[4] B. Boxer,[11,15] R. Bramante,[1,2] C.A.J. Brew,[12] P. Brás,[21] J.H. Buckley,[22] V.V. Bugaev,[22] S. Burdin,[15] J.K. Busenitz,[23] M. Buuck,[1,2] R. Cabrita,[21] C. Carels,[4] D.L. Carlsmith,[7] B. Carlson,[14] M.C. Carmona-Benitez,[24] M. Cascella,[5] C. Chan,[6] A. Chawla,[25] H. Chen,[13] J.J. Cherwinka,[7] N.I. Chott,[26] A. Cole,[13] J. Coleman,[13] M.V. Converse,[27] A. Cottle,[4,16] G. Cox,[14,24] W.W. Craddock,[1] O. Creaner,[13] D. Curran,[14] A. Currie,[8] J.E. Cutter,[11] C.E. Dahl,[16,28] A. David,[5] J. Davis,[14] T.J.R. Davison,[17] J. Delgaudio,[14] S. Dey,[4] L. de Viveiros,[24] A. Dobi,[13] J.E.Y. Dobson,[5] E. Druszkiewicz,[27] A. Dushkin,[18] T.K. Edberg,[9] W.R. Edwards,[13] M.M. Elnimr,[23] W.T. Emmet,[29] S.R. Eriksen,[30] C.H. Faham,[13] A. Fan,[1,2,*] S. Fayer,[8] N.M. Fearon,[4] S. Fiorucci,[13] H. Flaecher,[30] P. Ford,[12] V.B. Francis,[12] E.D. Fraser,[15] T. Fruth,[4,5] R.J. Gaitskell,[6] N.J. Gantos,[13] D. Garcia,[6] A. Geffre,[14] V.M. Gehman,[13] J. Genovesi,[26] C. Ghag,[5] R. Gibbons,[13,19] E. Gibson,[4] M.G.D. Gilchriese,[13] S. Gokhale,[31] B. Gomber,[7] J. Green,[4] A. Greenall,[15] S. Greenwood,[8] M.G.D.van der Grinten,[12] C.B. Gwilliam,[15] C.R. Hall,[9] S. Hans,[31] K. Hanzel,[13] A. Harrison,[26] E. Hartigan-O'Connor,[6] S.J. Haselschwardt,[13] S.A. Hertel,[32] G. Heuermann,[3] C. Hjemfelt,[26] M.D. Hoff,[13] E. Holtom,[12] J.Y-K. Hor,[23] M. Horn,[14] D.Q. Huang,[3,6] D. Hunt,[4] C.M. Ignarra,[1,2] R.G. Jacobsen,[13,19] O. Jahangir,[5] R.S. James,[5] S.N. Jeffery,[12] W. Ji,[1,2] J. Johnson,[11] A.C. Kaboth,[12,25,†] A.C. Kamaha,[20,33] K. Kamdin,[13,19] V. Kasey,[8] K. Kazkaz,[34] J. Keefner,[14] D. Khaitan,[27] M. Khaleeq,[8] A. Khazov,[12] I. Khurana,[5] Y.D. Kim,[35] C.D. Kocher,[6] D. Kodroff,[24] L. Korley,[3,18] E.V. Korolkova,[36] J. Kras,[7] H. Kraus,[4] S. Kravitz,[13] H.J. Krebs,[1] L. Kreczko,[30] B. Krikler,[30] V.A. Kudryavtsev,[36] S. Kyre,[10] B. Landerud,[7] E.A. Leason,[17] C. Lee,[1,2] J. Lee,[35] D.S. Leonard,[35] R. Leonard,[26] K.T. Lesko,[13] C. Levy,[20] J. Li,[35] F.-T. Liao,[4] J. Liao,[6] J. Lin,[4,13,19] A. Lindote,[21] R. Linehan,[1,2] W.H. Lippincott,[10,16] R. Liu,[6] X. Liu,[17] Y. Liu,[7] C. Loniewski,[27] M.I. Lopes,[21] E. Lopez Asamar,[21] B. López Paredes,[8] W. Lorenzon,[3] D. Lucero,[14] S. Luitz,[1] J.M. 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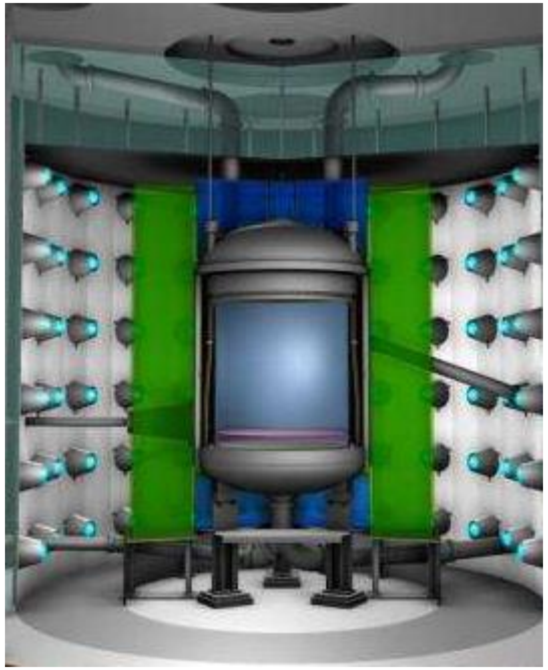
Piepke,[23] J. Podczerwinski,[7] D. Porzio,[21,‡] S. Powell,[15] R.M. Preece,[12] K. Pushkin,[3] Y. Qie,[27] B.N. Ratcliff,[1] J. Reichenbacher,[26] L. Reichhart,[5] C.A. Rhyne,[6] A. Richards,[8] Q. Riffard,[13,19] G.R.C. Rischbieter,[20] J.P. Rodrigues,[21] A. Rodriguez,[38] H.J. Rose,[15] R. Rosero,[31] P. Rossiter,[36] T. Rushton,[36] G. Rutherford,[6] D. Rynders,[14] J.S. Saba,[13] D. Santone,[25] A.B.M.R. Sazzad,[23] R.W. Schnee,[26] P.R. Scovell,[4,12] D. Seymour,[6] S. Shaw,[10] T. Shutt,[1,2] J.J. Silk,[9] C. Silva,[21] G. Sinev,[26] K. Skarpaas,[1] W. Skulski,[27] R. Smith,[13,19] M. Solmaz,[10] V.N. Solovov,[21] P. Sorensen,[13] J. Soria,[13,19] I. Stancu,[23] M.R. Stark,[26] A. Stevens,[4,5,8] T.M. Stiegler,[39] K. Stifter,[1,2,16] R. Studley,[18] B. Suerfu,[13,19] T.J. Sumner,[8] P. Sutcliffe,[15] N. Swanson,[6] M. Szydagis,[20] M. Tan,[4] D.J. Taylor,[14] R. Taylor,[8] W.C. Taylor,[6] D.J. Temples,[28] B.P. Tennyson,[29] P.A. Terman,[39] K.J. Thomas,[13] D.R. Tiedt,[9,14,26] M. Timalsina,[26] W.H. To,[1,2] A. Tomás,[8] Z. Tong,[8] D.R. Tovey,[36] J. Tranter,[36] M. Trask,[10] M. Tripathi,[11] D.R. Tronstad,[26] C.E. Tull,[13] W. Turner,[15] L. Tvrznikova,[19,29,34] U. Utku,[5] J. Va'vra,[1] A. Vacheret,[8] A.C. Vaitkus,[6] J.R. Verbus,[6] E. Voirin,[16] W.L. Waldron,[13] A. Wang,[1,2] B. Wang,[23] J.J. Wang,[23] W. Wang,[7,32] Y. Wang,[13,19] J.R. Watson,[13,19] R.C. Webb,[39] A. White,[6] D.T. White,[10] J.T. White,[39,‡] R.G. White,[1,2] T.J. Whitis,[1,10] M. Williams,[3,18] W.J. Wisniewski,[1] M.S. Witherell,[13,19] F.L.H. Wolfs,[27] J.D. Wolfs,[27] S. Woodford,[15] D. Woodward,[24,§] S.D. Worm,[12] C.J. Wright,[30] Q. Xia,[13] X. Xiang,[6,31] Q. Xiao,[7] J. Xu,[34] M. Yeh,[31] J. Yin,[27] I. Young,[16] P. Zarzhitsky,[23] A. Zuckerman,[6] and E.A. Zweig[33]
(The LUX-ZEPLIN (LZ) Collaboration)

new results on *WIMP* Dark Matter

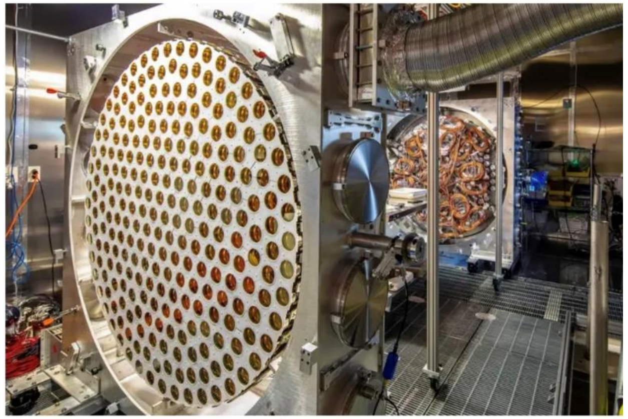


World's most sensitive dark matter detector tested for the first time

A brief test has proven that the new LUX-ZEPLIN dark matter detector is the most sensitive ever. It may be our best bet for finally finding dark matter particles

PHYSICS 7 July 2022

By Leah Crane

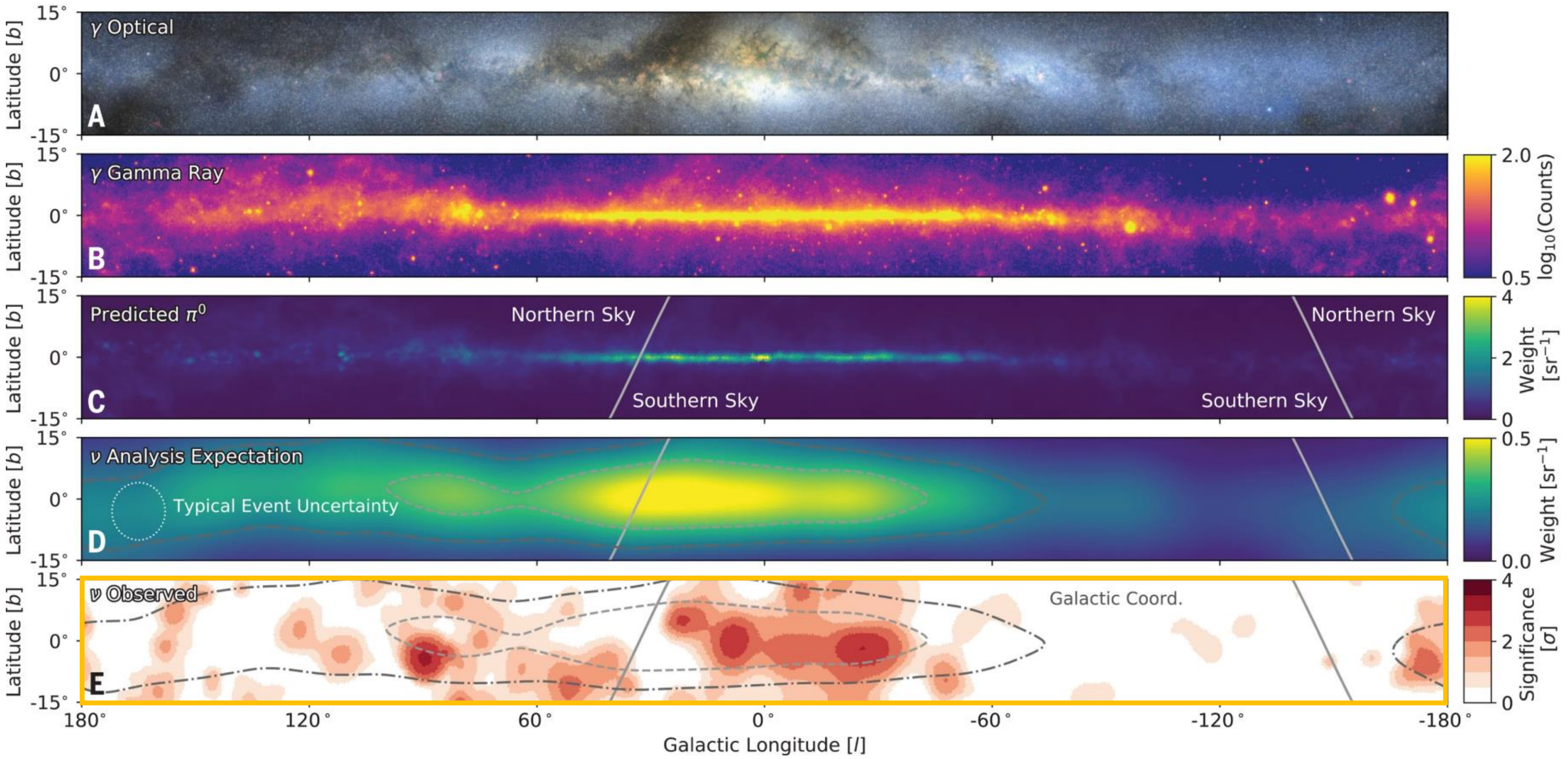


The LUX-ZEPLIN dark matter detector at the Sanford Undergroun
Research Facility in South Dakota is the most sensitive ever

*A*stro *P*article *P*hysics – topic events (2023 *ed.*)

- what is **new** this semester in this lecture series?

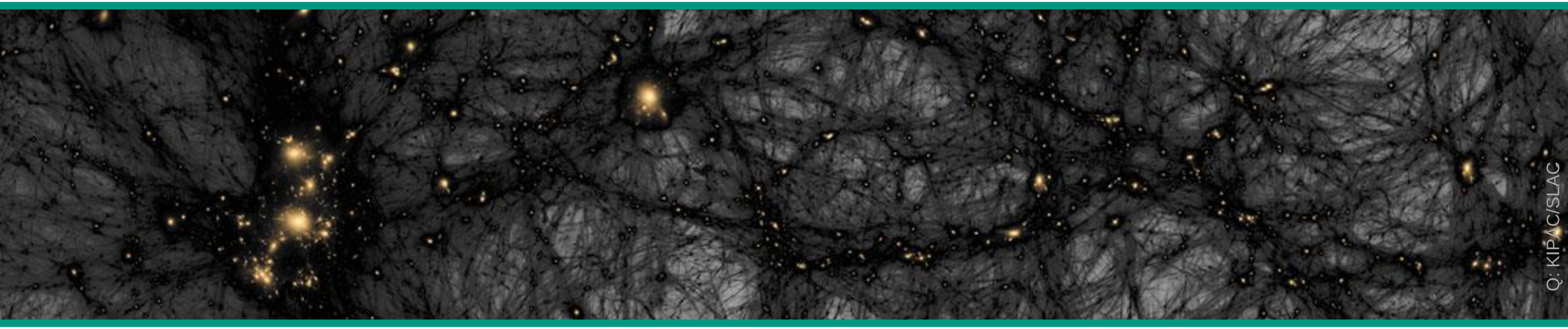
  - 6/2023: our galaxy in the light of $UHE - \nu's$



IceCube and NANOGrav open new windows onto the universe

08/01/23 | Madeleine O'Keefe

New results from a neutrino telescope and a gravitational-wave observatory show how astronomers use different forms of messengers to study the cosmos.



OUTLINE

Astroparticle Physics – 1: Outline

Karlsruhe Institute of Technology

1. Introduction

1.1 Particle Radiation from the Laboratory

1.2 Particle Radiation from the Universe

2. Experimental Methods

2.1 Multi–Messenger Methods

2.1.1 Air Shower Experiments

2.1.2 Neutrino Telescopes

2.1.3 Gamma Telescopes

Astroparticle Physics – 1: Outline

2.2 Search for Rare Events

2.2.1 Background processes
2.2.2 Shielding methods
2.2.3 Primordial decay chains

3. Neutrinos

3.1 Introduction

3.2 kinematic determination of the neutrino mass

3.3 Search for $0\nu\beta\beta$ processes

Astroparticle Physics – 1: Outline

Karlsruhe Institute of Technology

4. Dark Matter

4.1 Introduction

4.2 DM Candidates

4.3 $WIMP$ searches at the LHC

4.4 indirect $WIMP$ detection methods

4.4.1 Gammas and positrons

4.4.2 Neutrinos

Astroparticle Physics – 1: Outline

Karlsruhe Institute of Technology

4.5 direct detection methods for $WIMPs$

$4.5.1$ reaction kinematics

$4.5.2$ cryogenic bolometers

$4.5.3$ liquid noble gas detectors

$4.5.4$ future projects & outlook

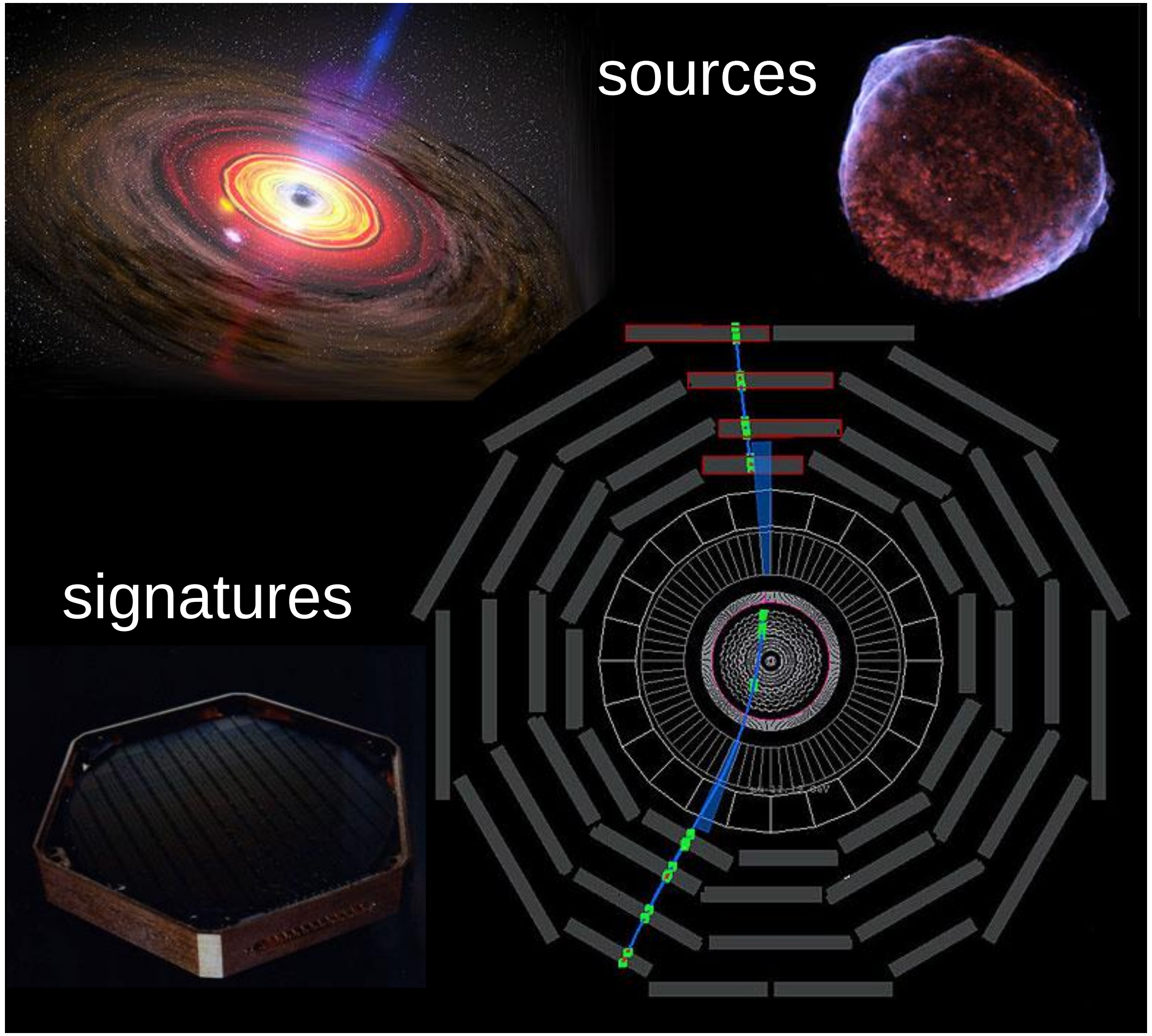
4.6 non$-$thermal DM candidates

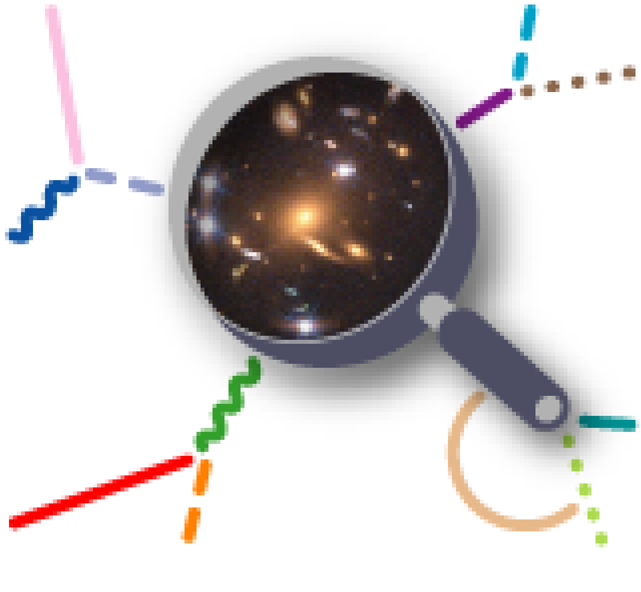
$4.6.1$ axions

$4.6.2$ keV – neutrinos

1. INTRODUCTION

- **Particle radiation from the Laboratory and from the Universe**

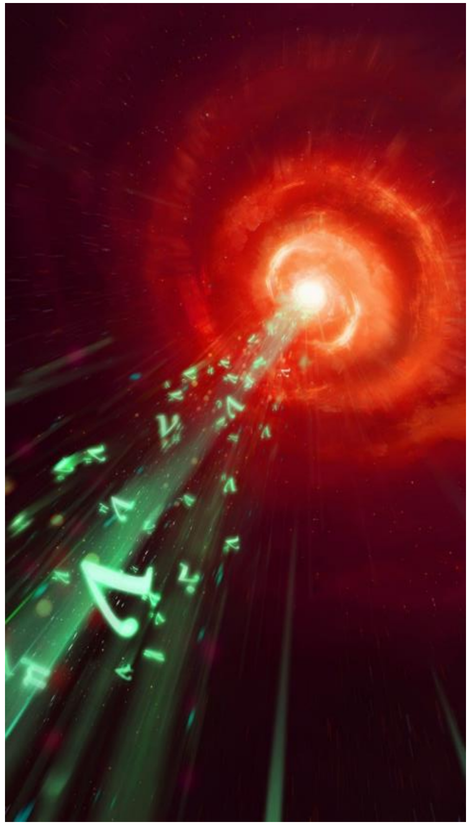


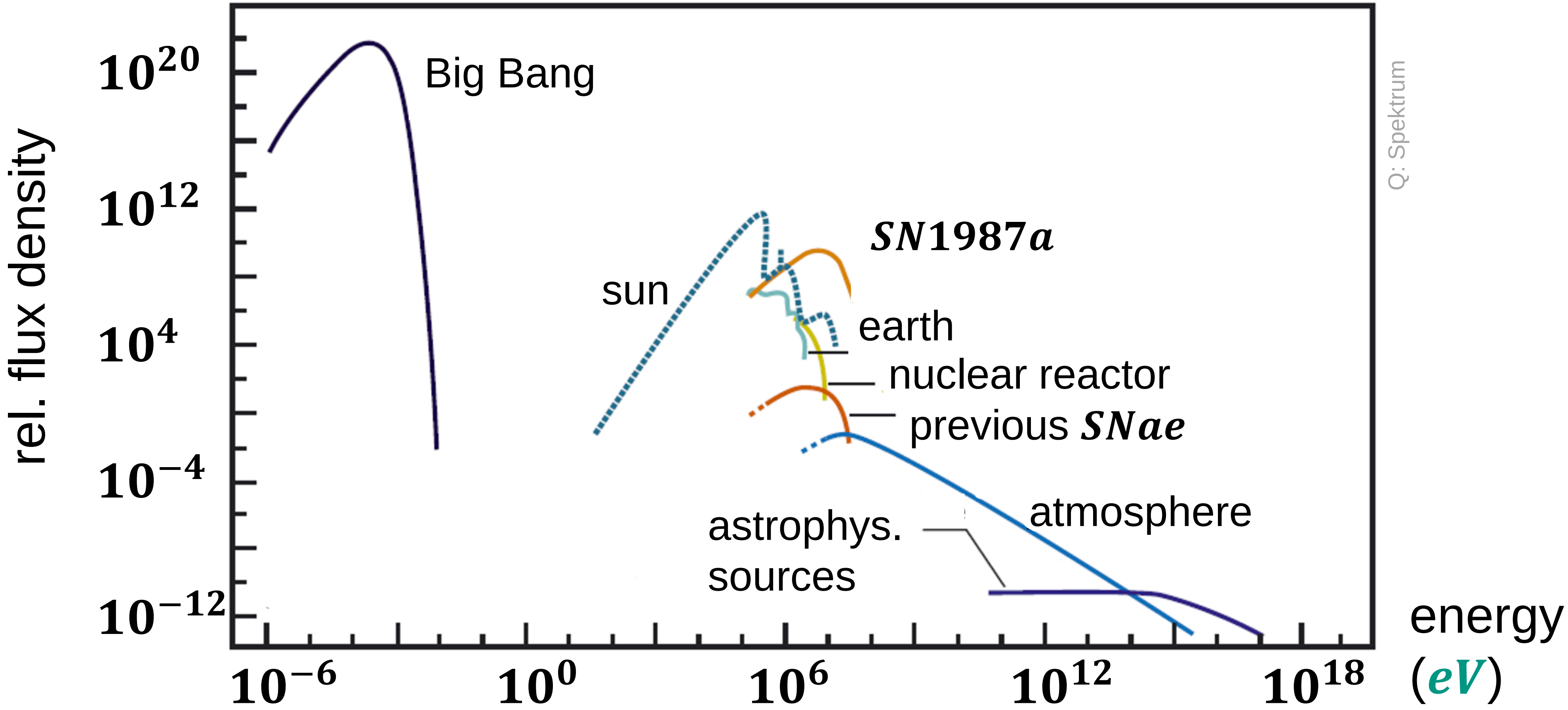


Q: NASA, CMS, CDMS

Example: neutrinos from the earth & beyond

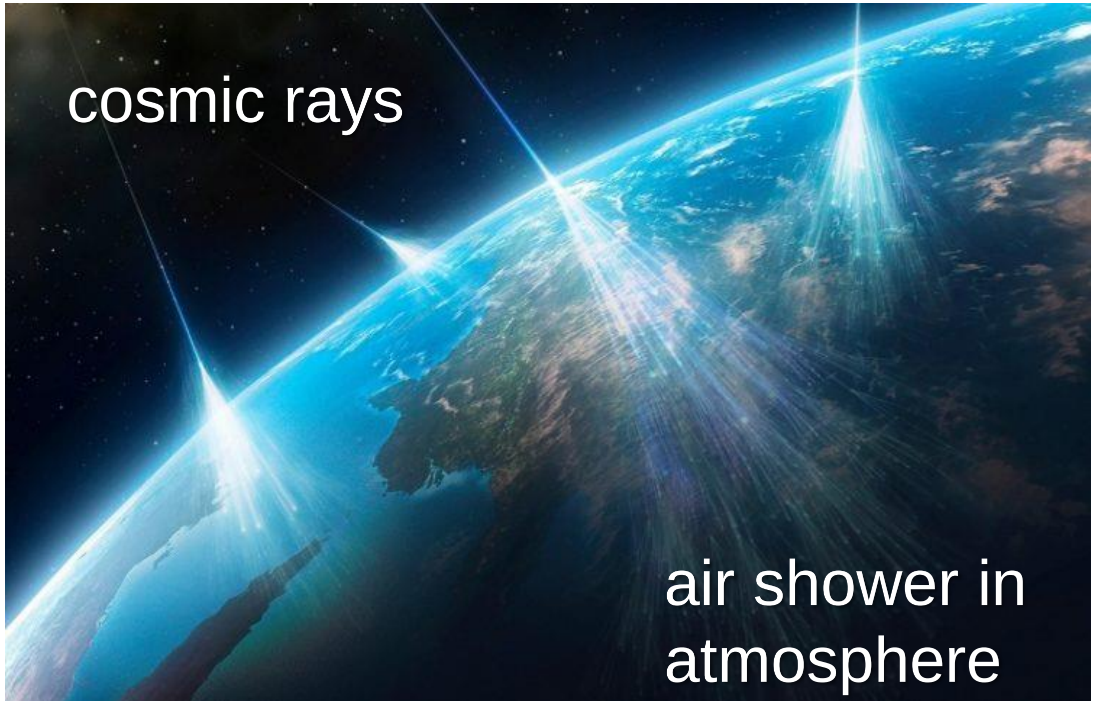
- extremely broad energy region, comprising many sources



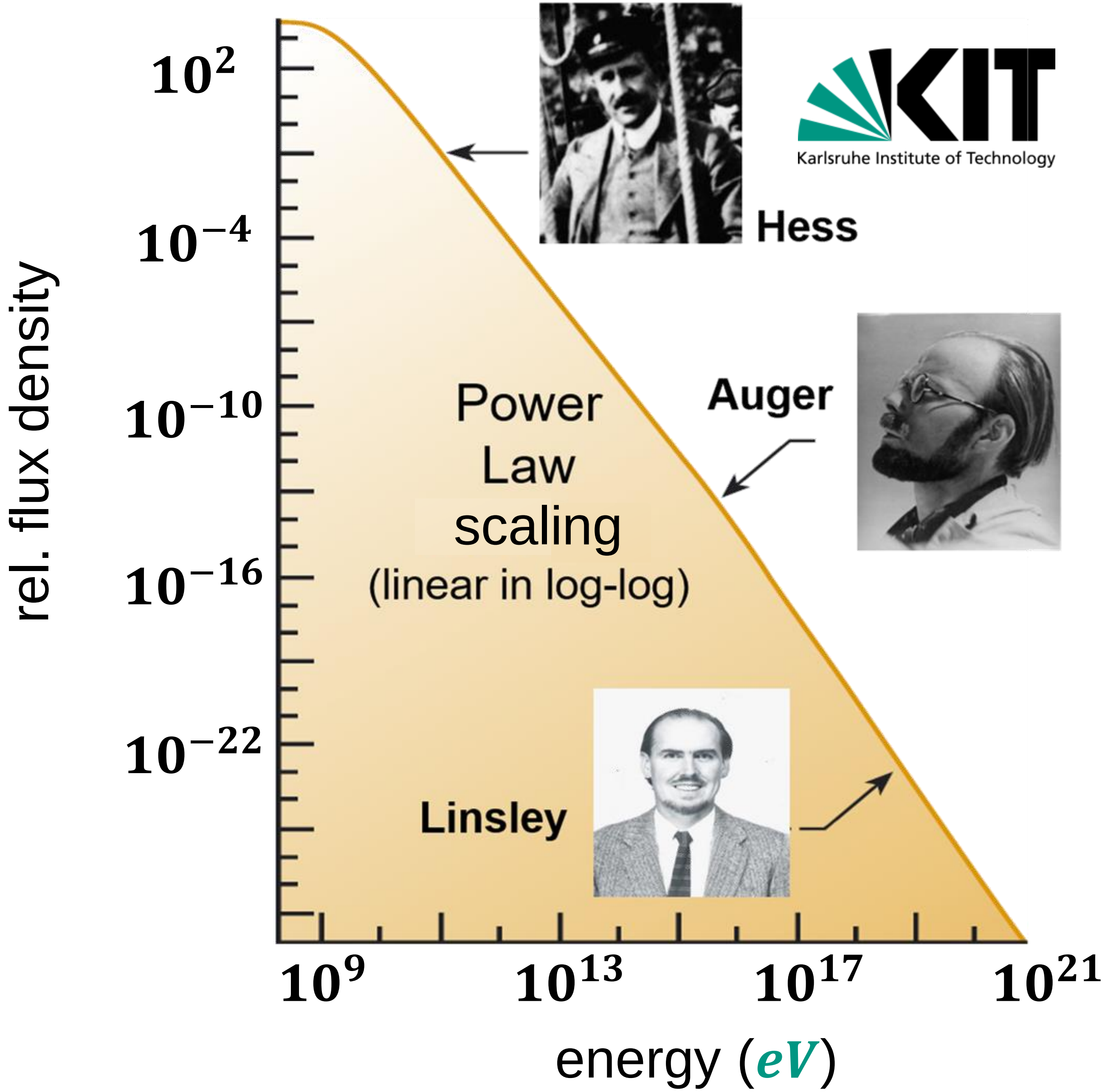


Example: cosmic rays

- extremely broad energy region, from many individual sources



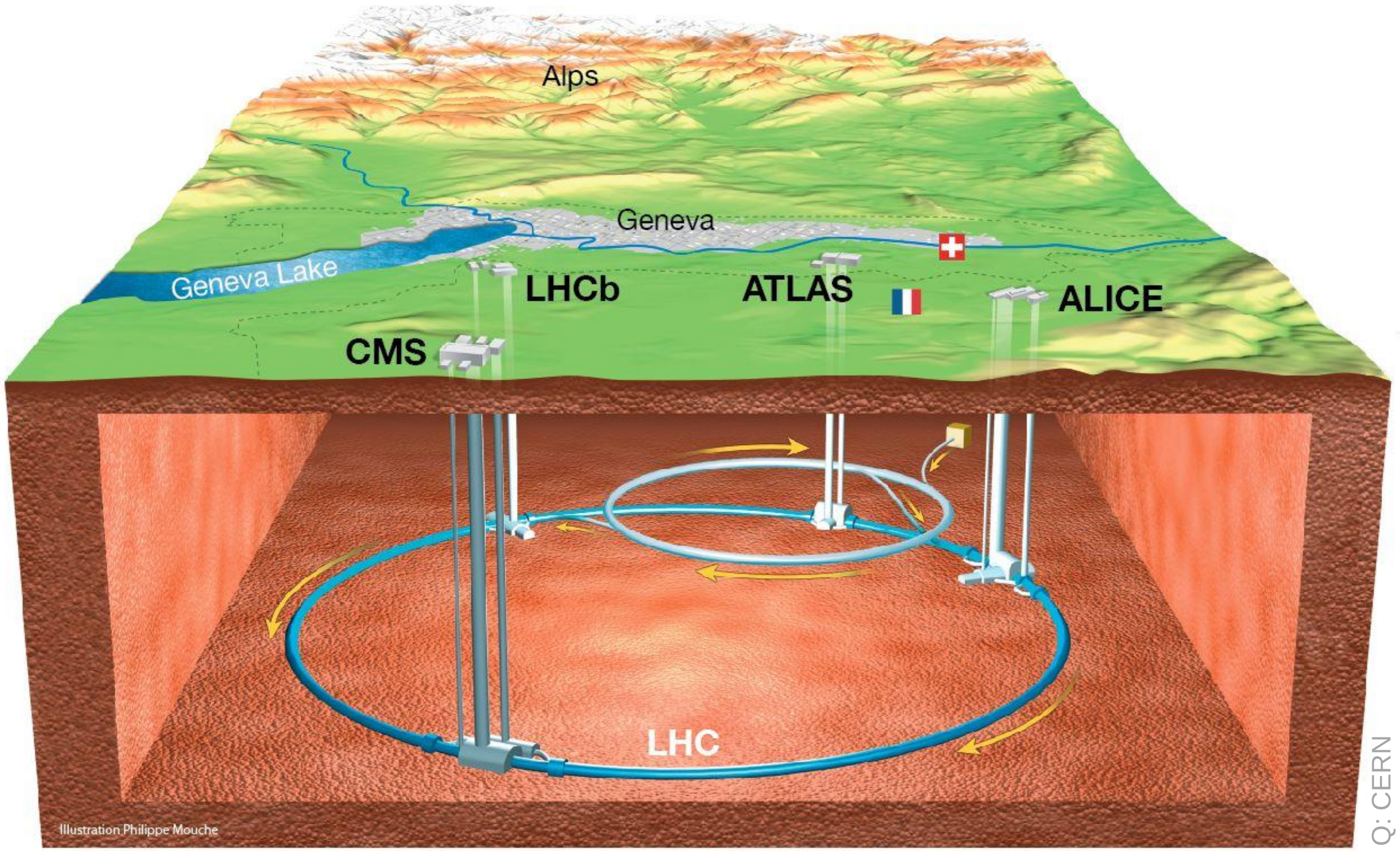
Q: electroverse.net



Karlsruhe Institute of Technology

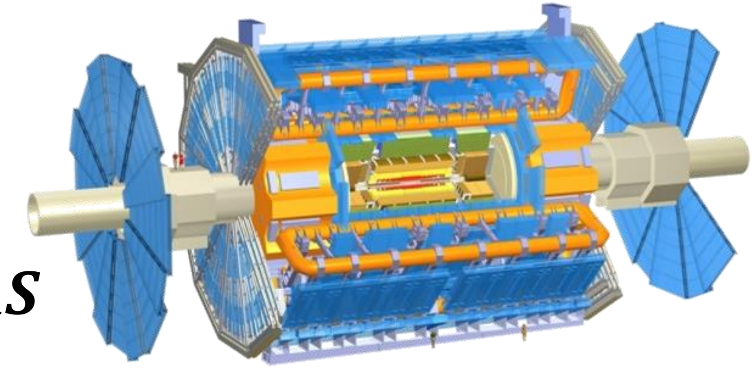
1. 1 particle radiation from the laboratory

- accelerators at TeV – scale: searches for $SUSY$

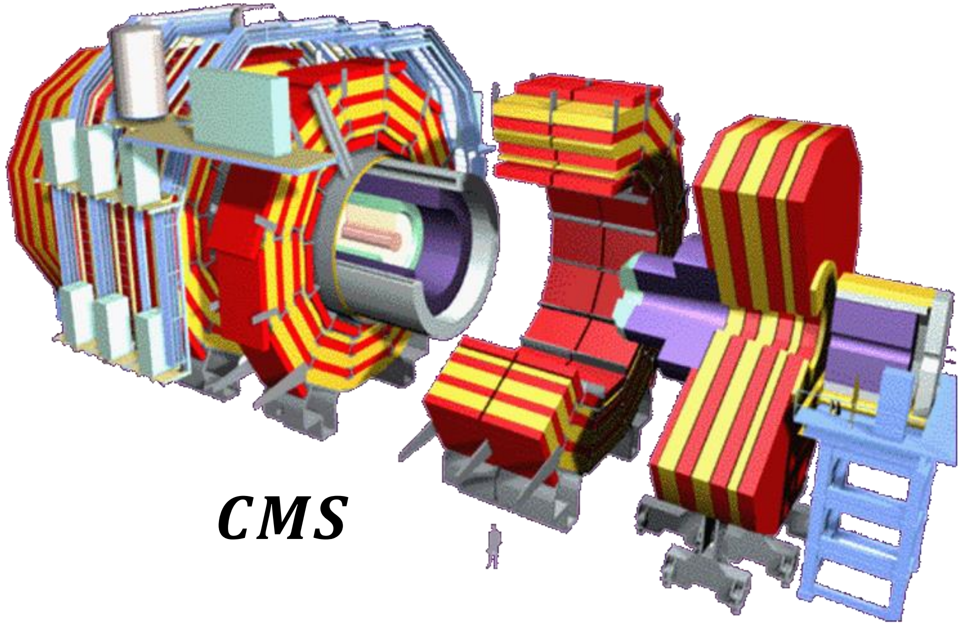


Q: CERN

$ATLAS$



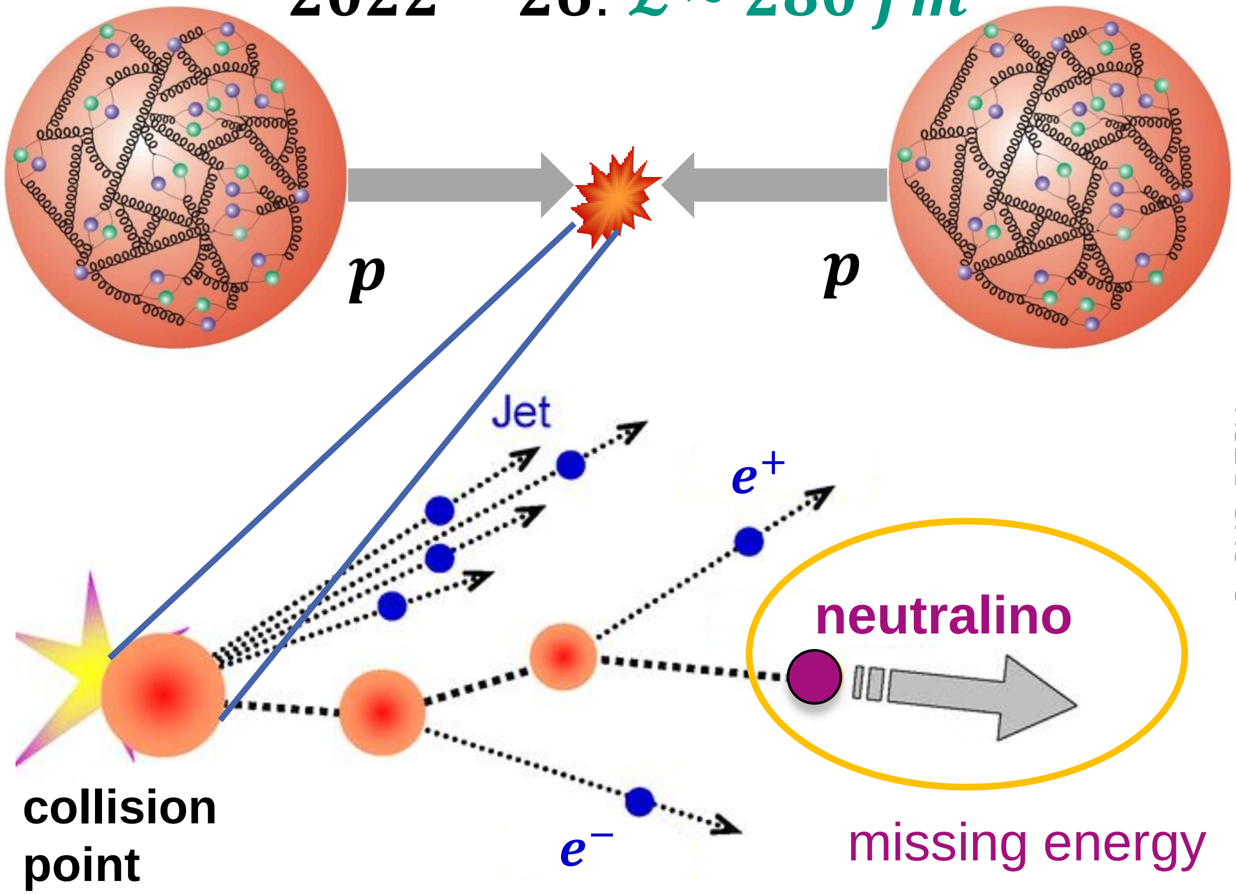
CMS

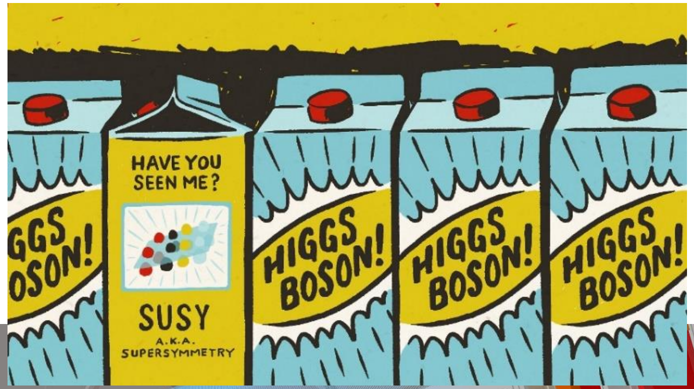


Accelerator–based $SUSY$ – searches at LHC

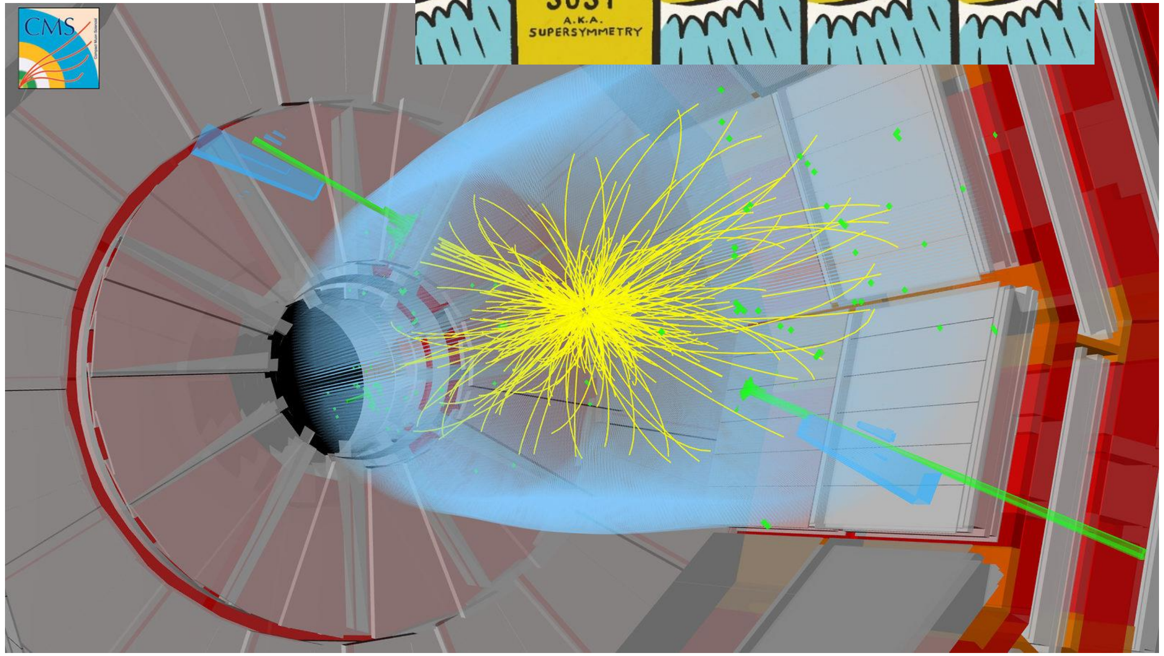
- **Run 3: proton–proton collisions at $\sqrt{s} = 13.6\ TeV$**

$2022 - 26$: $\mathcal{L} \sim 280\ fm^{-1}$





Q: symmetry magazine



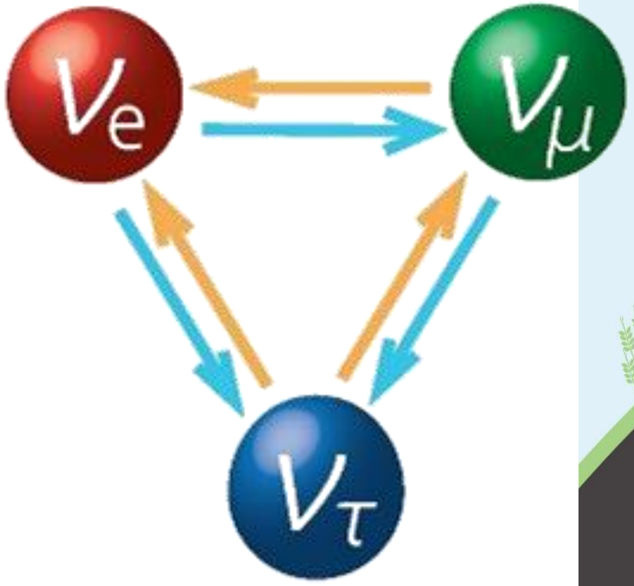
Q: CMS, DESY

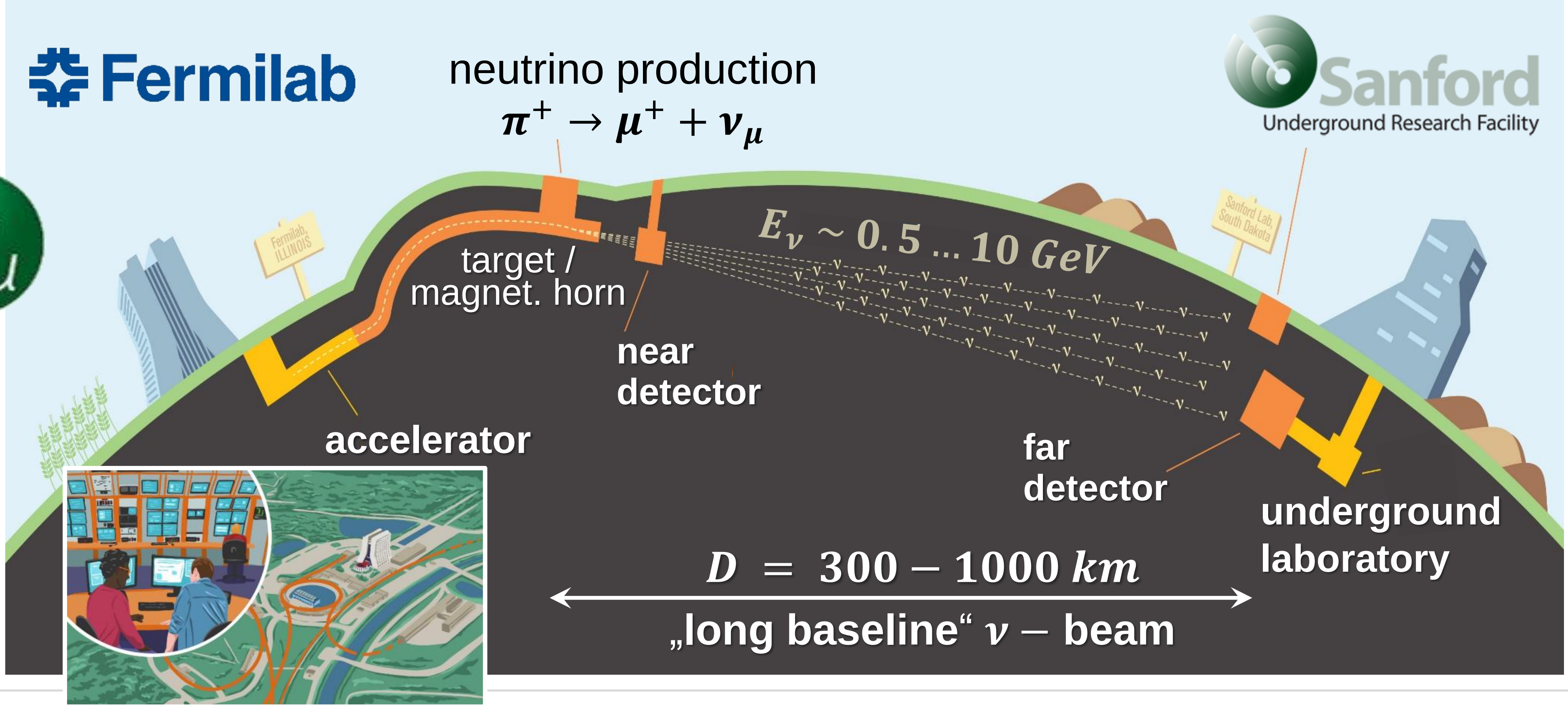
missing transversal energy/momentum

Accelerator–based neutrino oscillation studies

- **long–baseline (LBL) ν – beams at the GeV – scale: mixing properties, CP**

  - set–up of an $LBL - \nu$ – experiment: accelerator, magn. horn, near/far detectors

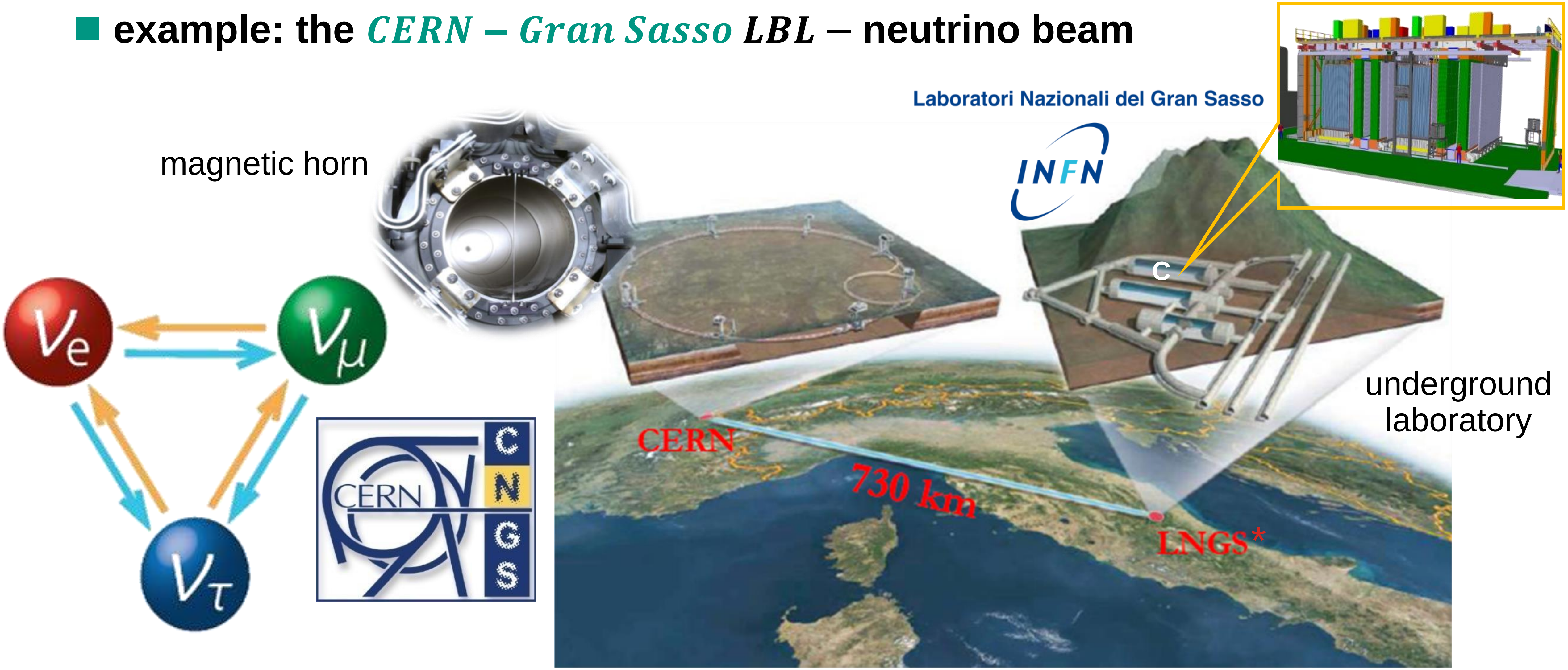




Q: Fermilab

Accelerator–based neutrino oscillation studies

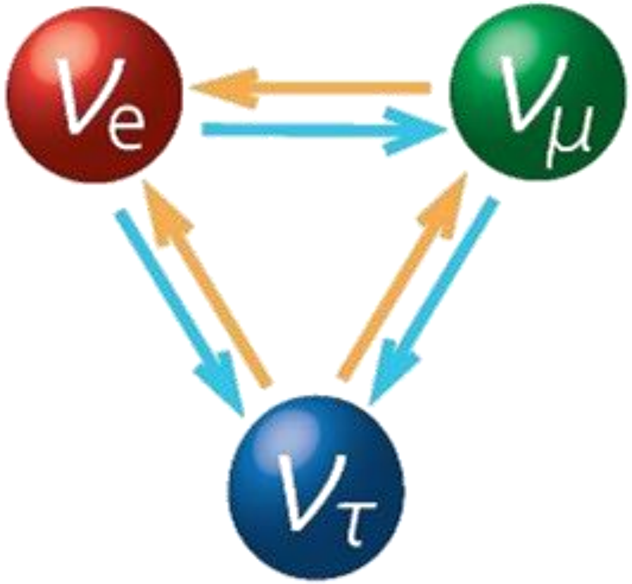
- example: the $CERN - Gran\ Sasso\ LBL$ – neutrino beam

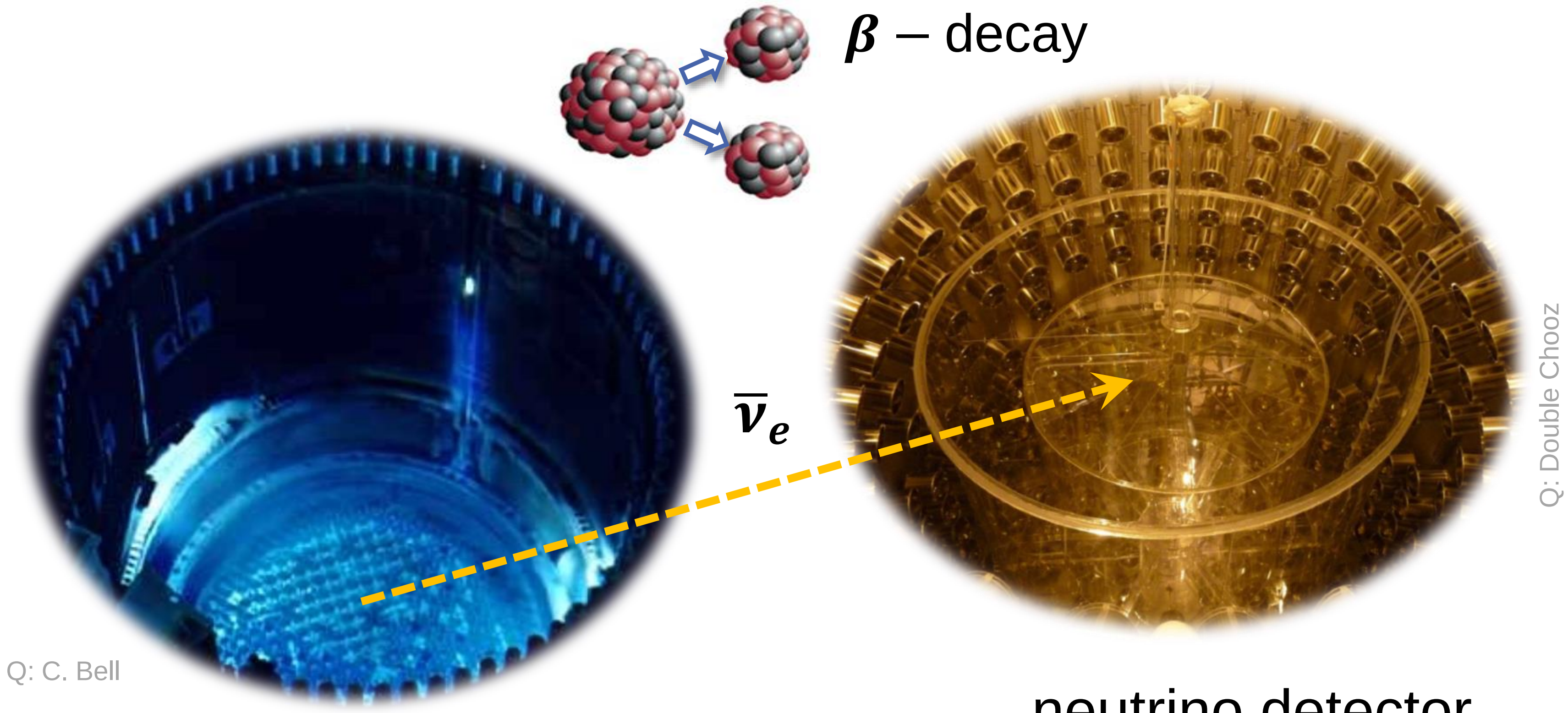


*Laboratori Nazionali Gran Sasso

reactor–based neutrino oscillation studies

- **long–baseline neutrino beams at the MeV – scale: mixing properties, CP**



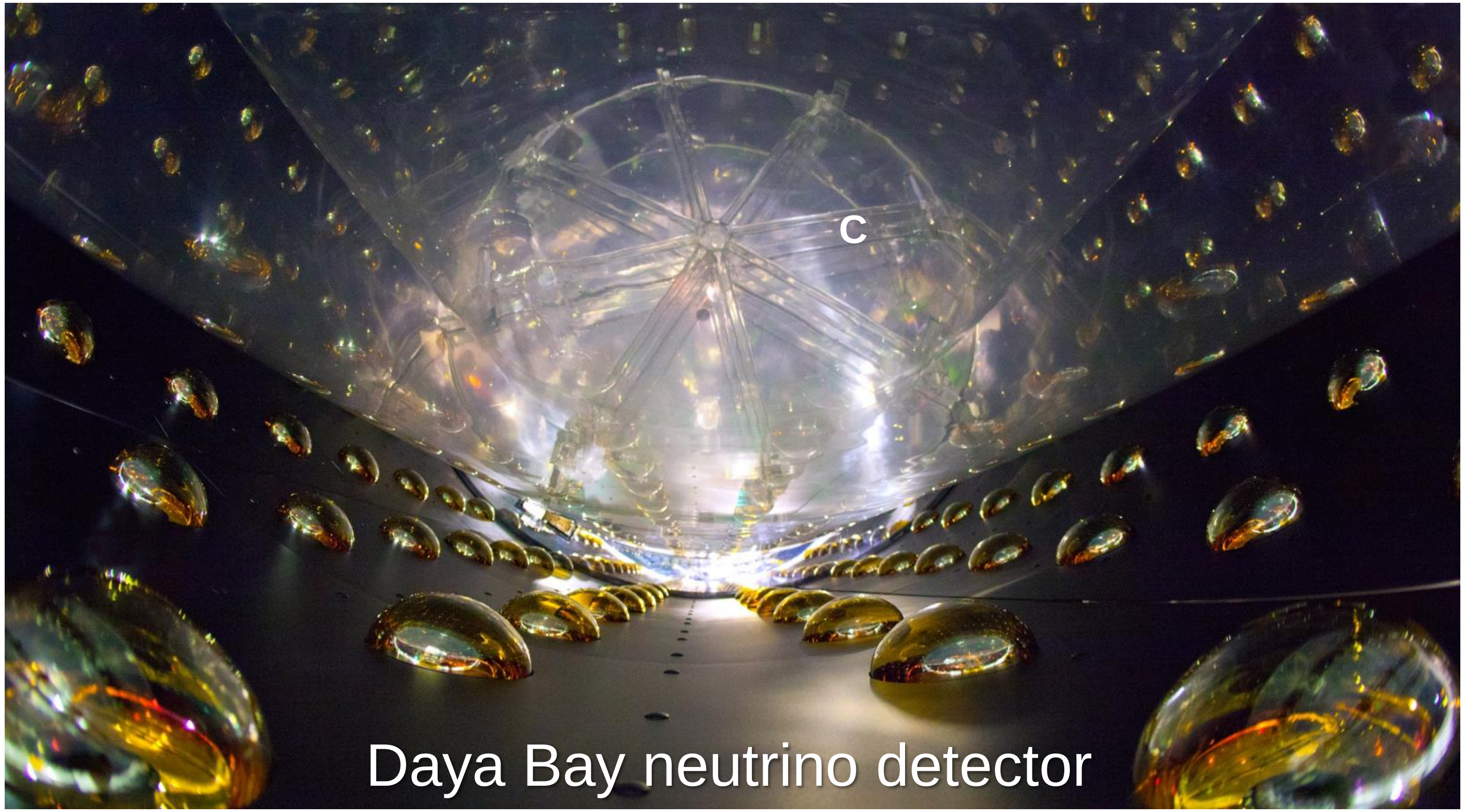


nuclear reactor

neutrino detector

reactor–based neutrino oscillation studies

- example: the **Daya Bay** neutrino–oscillation experiment in China

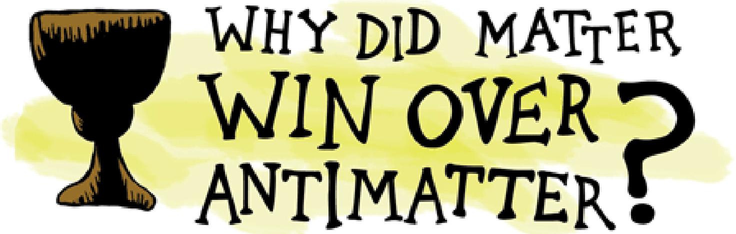


Q: Daya Bay

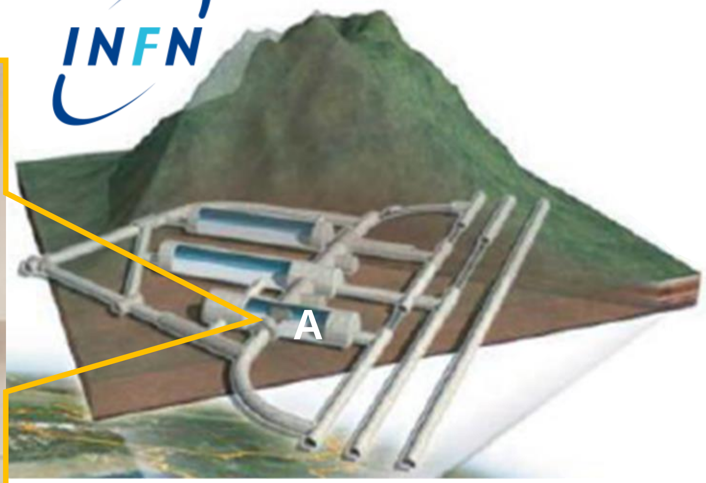
neutrino studies using enriched detector materials

Karlsruhe Institute of Technology

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

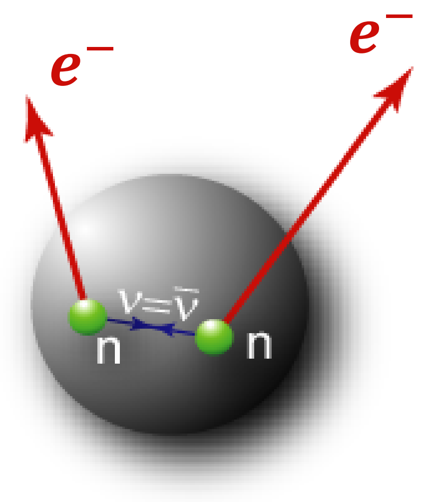


Laboratori Nazionali del Gran Sasso

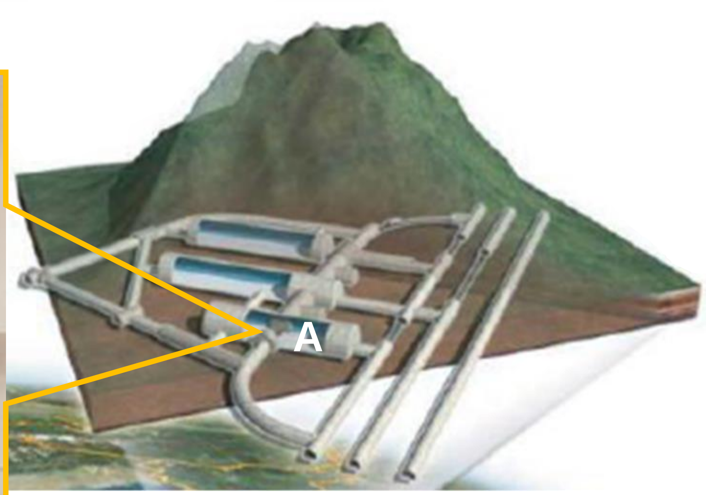


neutrino studies using enriched detector materials

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



$$\Delta L = 2$$

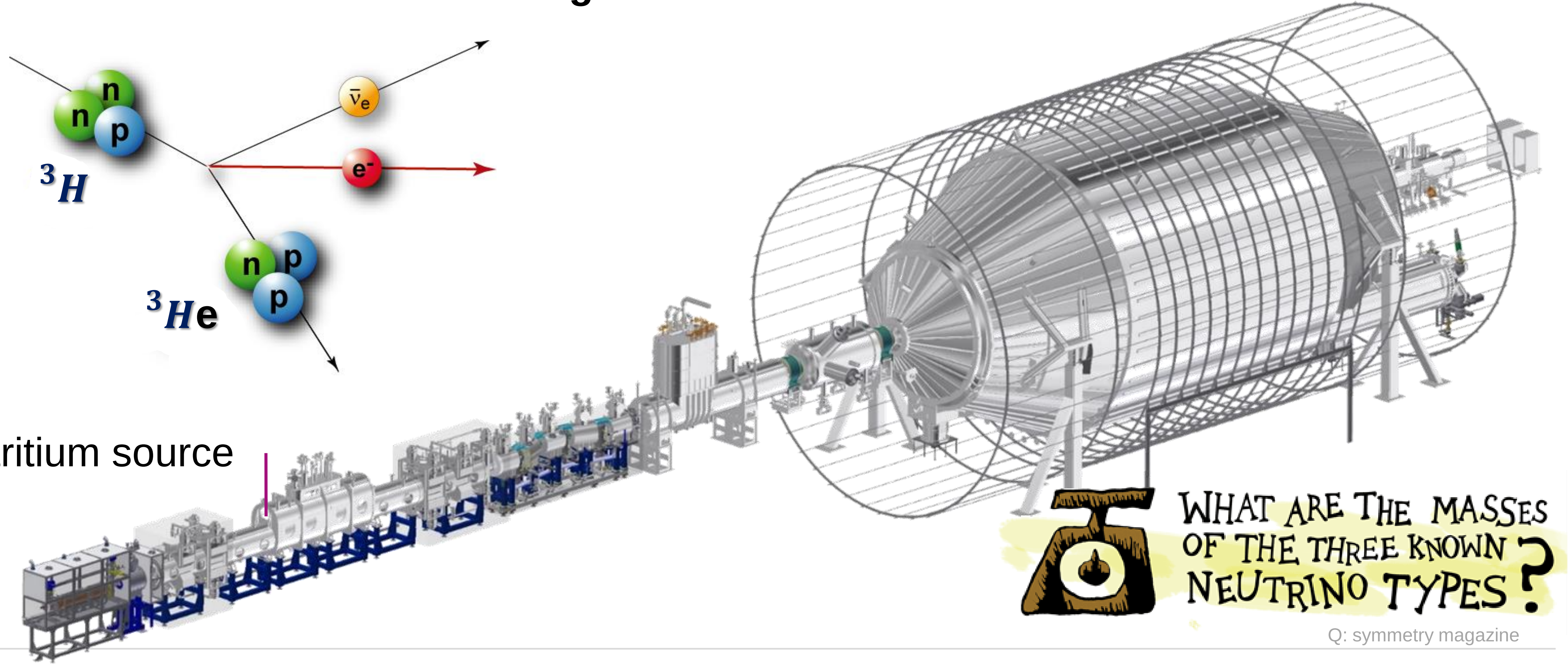


$GERDA$* experiment at $LNGS$

*GERmanium Detector–Array

$KATRIN$ experiment at KIT

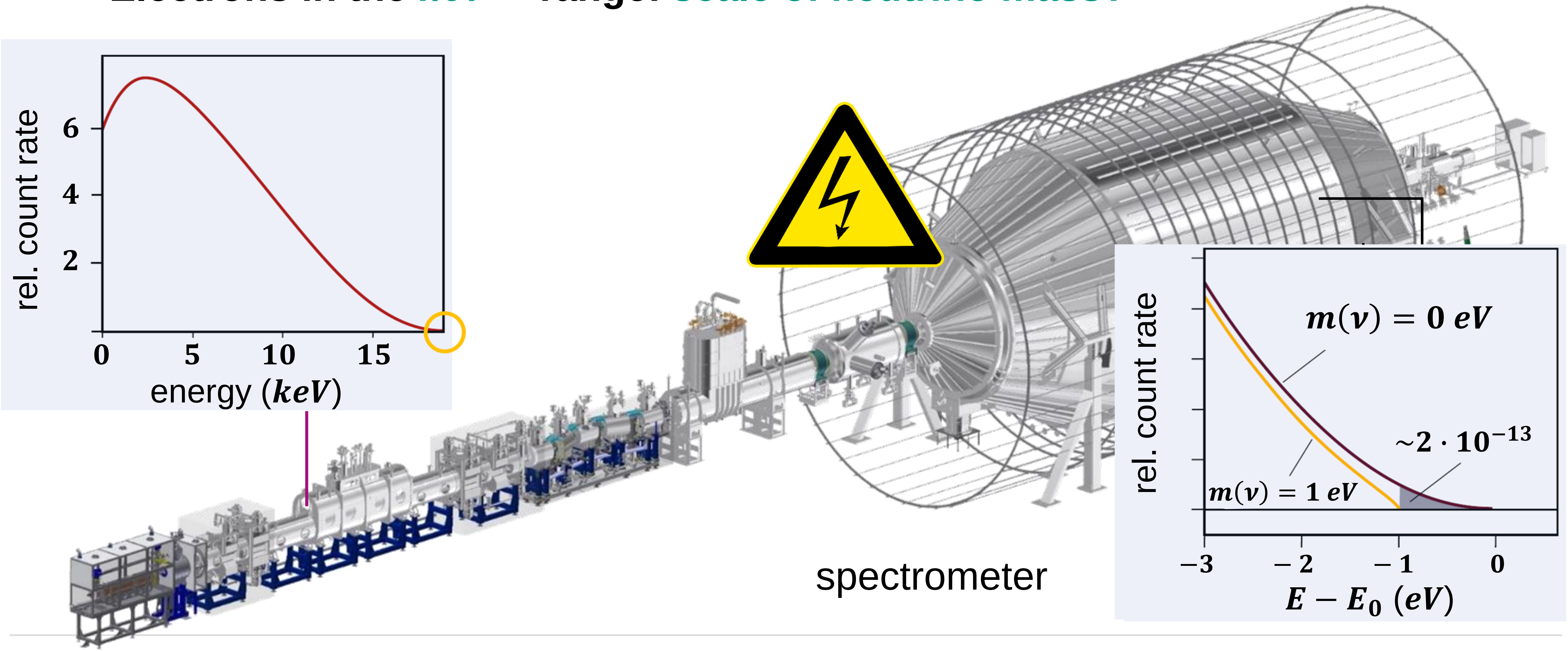
- **Electrons in the keV – range: scale of neutrino mass?**



Q: symmetry magazine

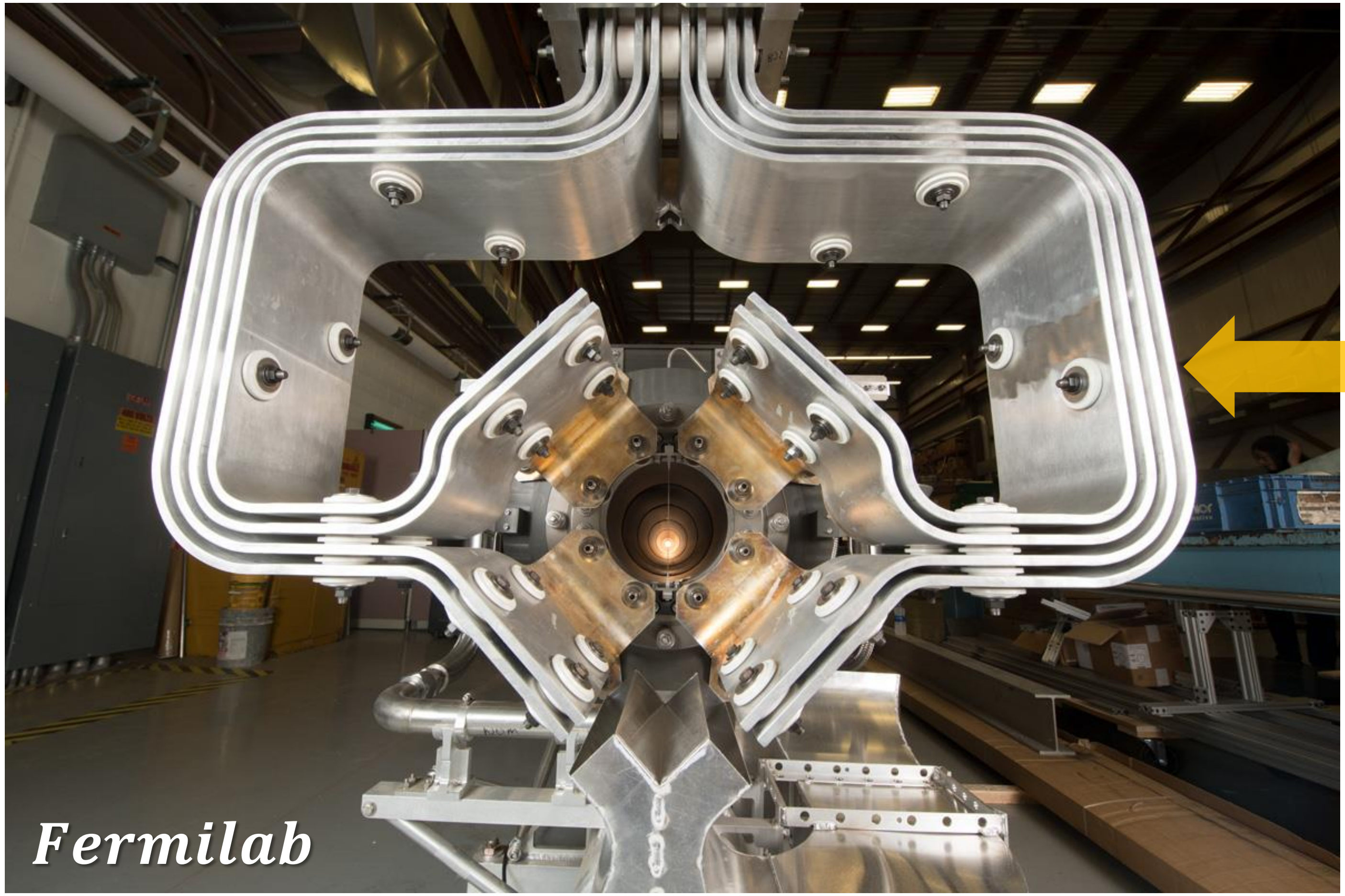
$KATRIN$ experiment at KIT

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

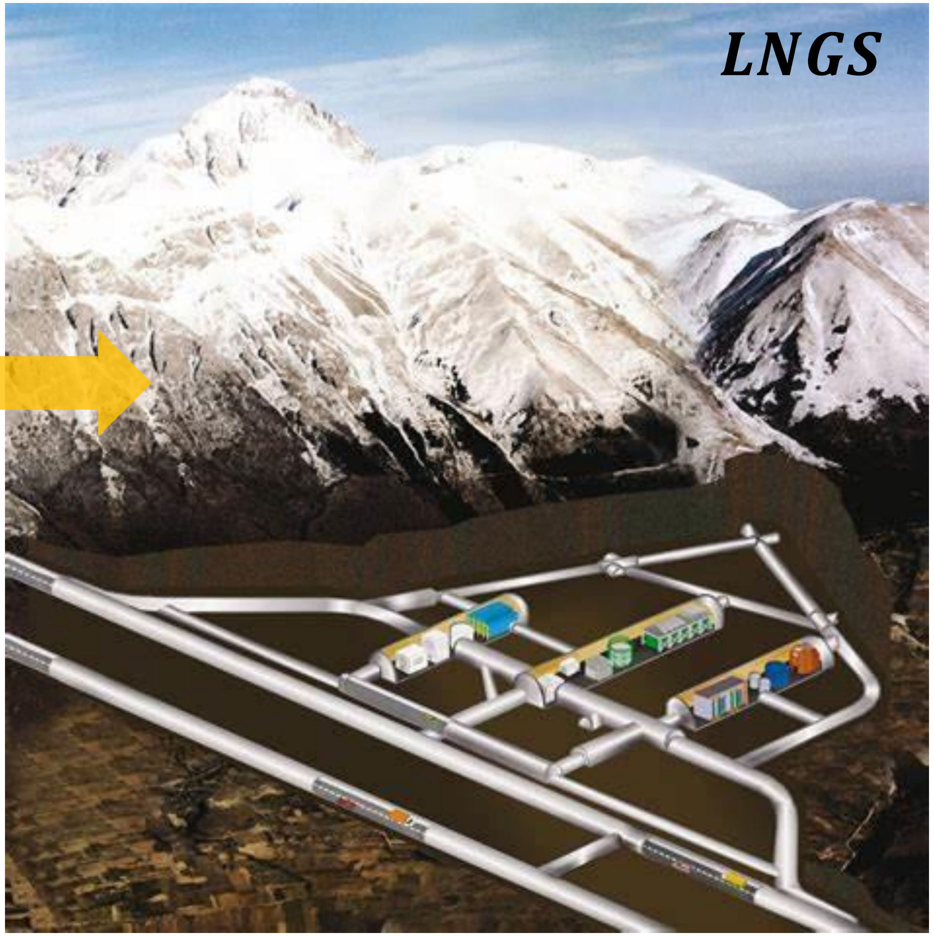


Laboratories required for Particle Radiation

- **Labs**: accelerators, nuclear reactors, underground labs,…



Q: Fermilab



Q: LNGS