University of Zurich^UZH

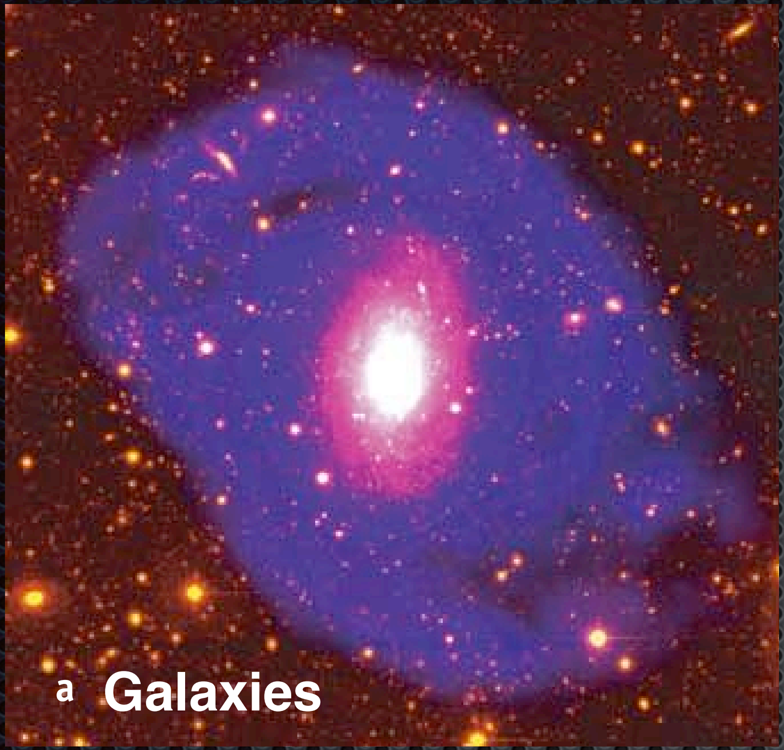
Illuminating the dark - searches for dark matter with XENON

Miller Institute for Basic
Research in Science

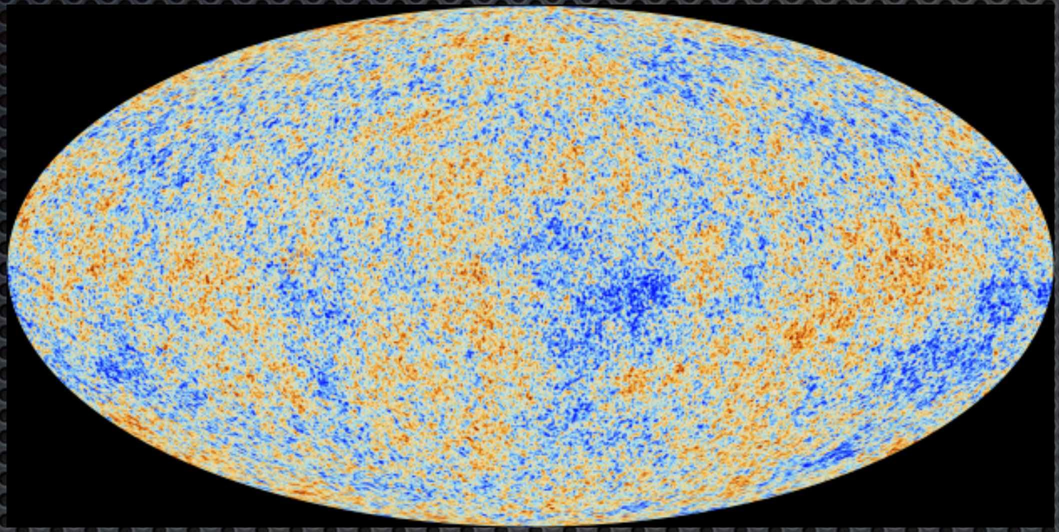
UC Berkeley
March 17, 2020

Laura Baudis
University of Zurich

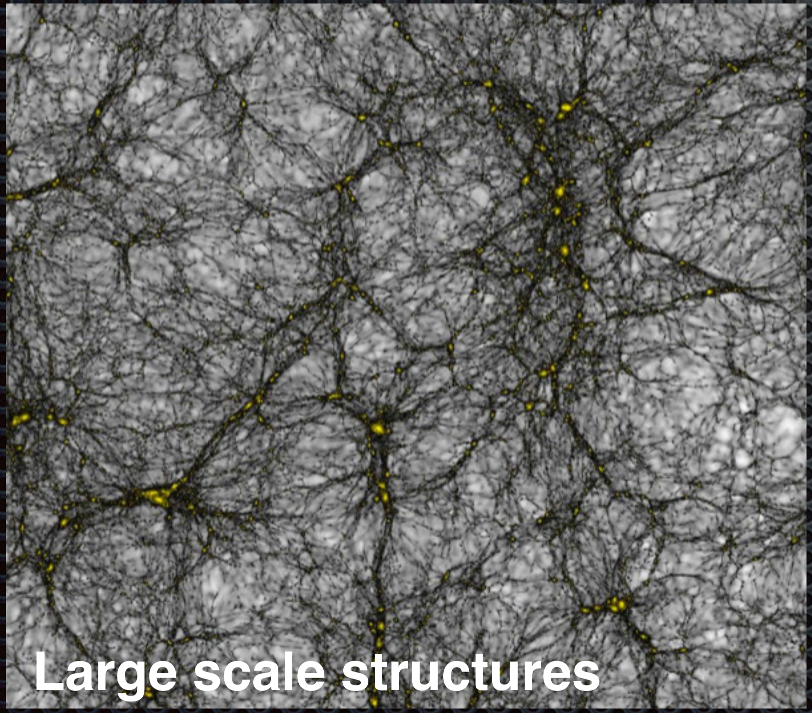
Our Universe today



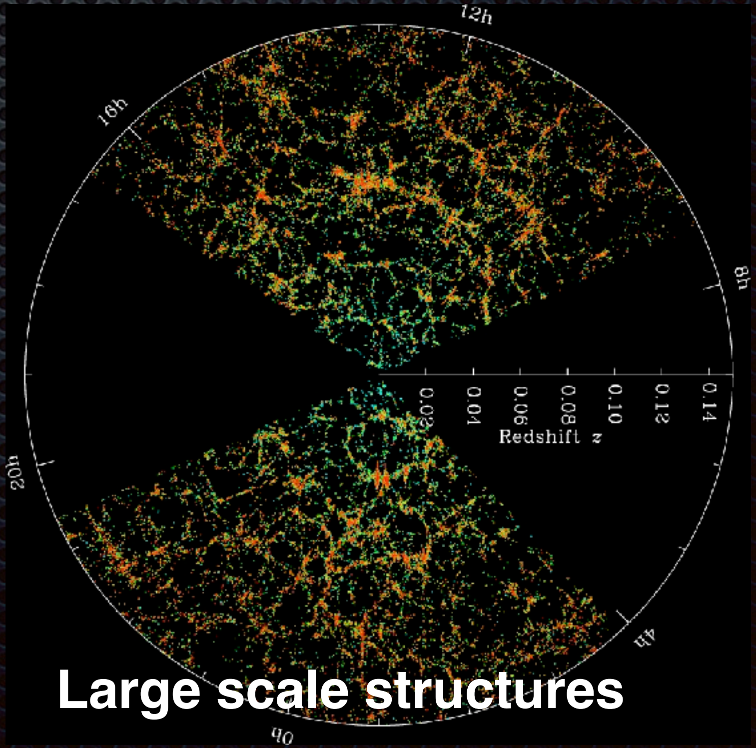
Galaxies


Cosmic microwave background


Clusters of galaxies

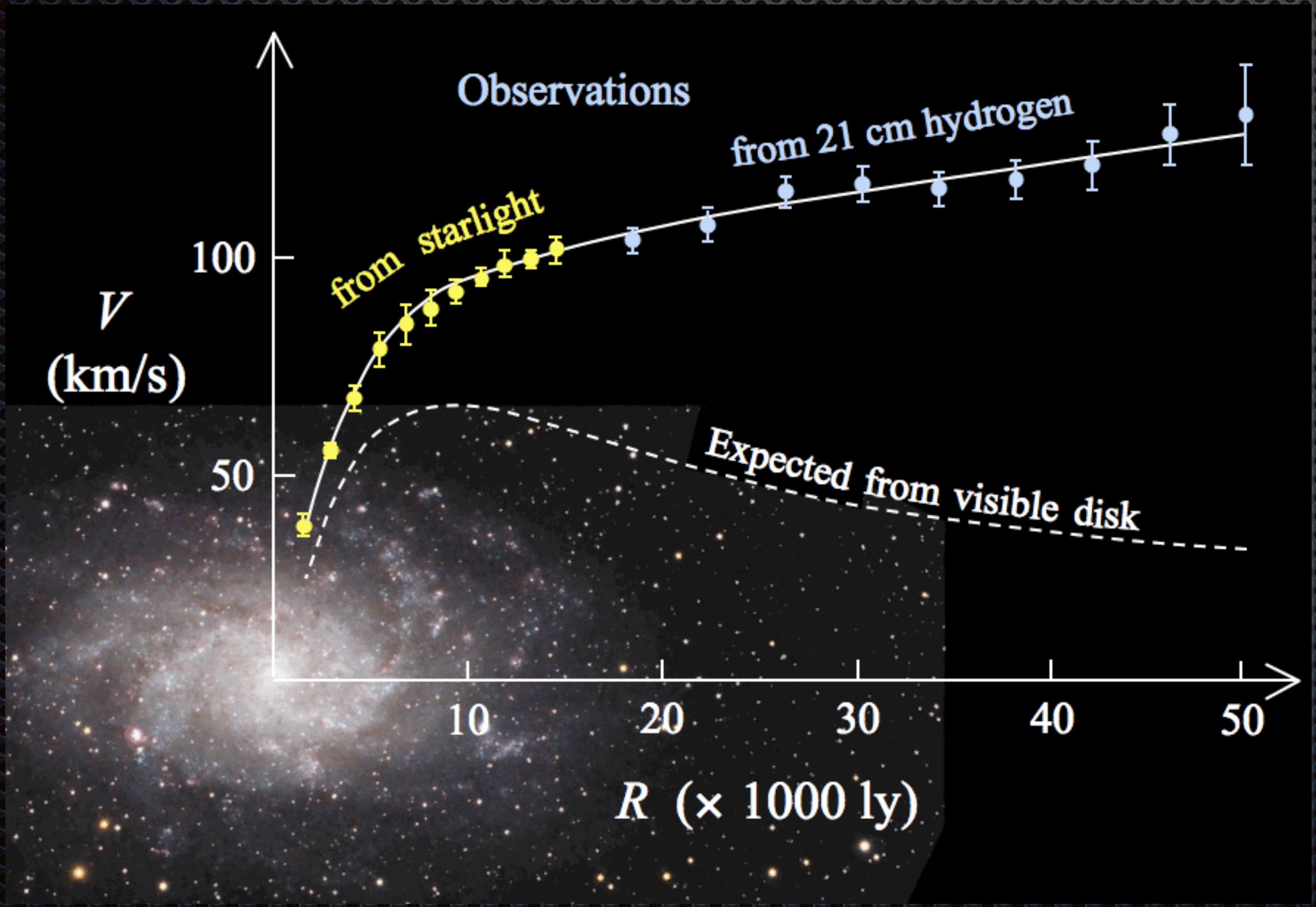

Large scale structures

85% of the matter content is non-luminous, or dark



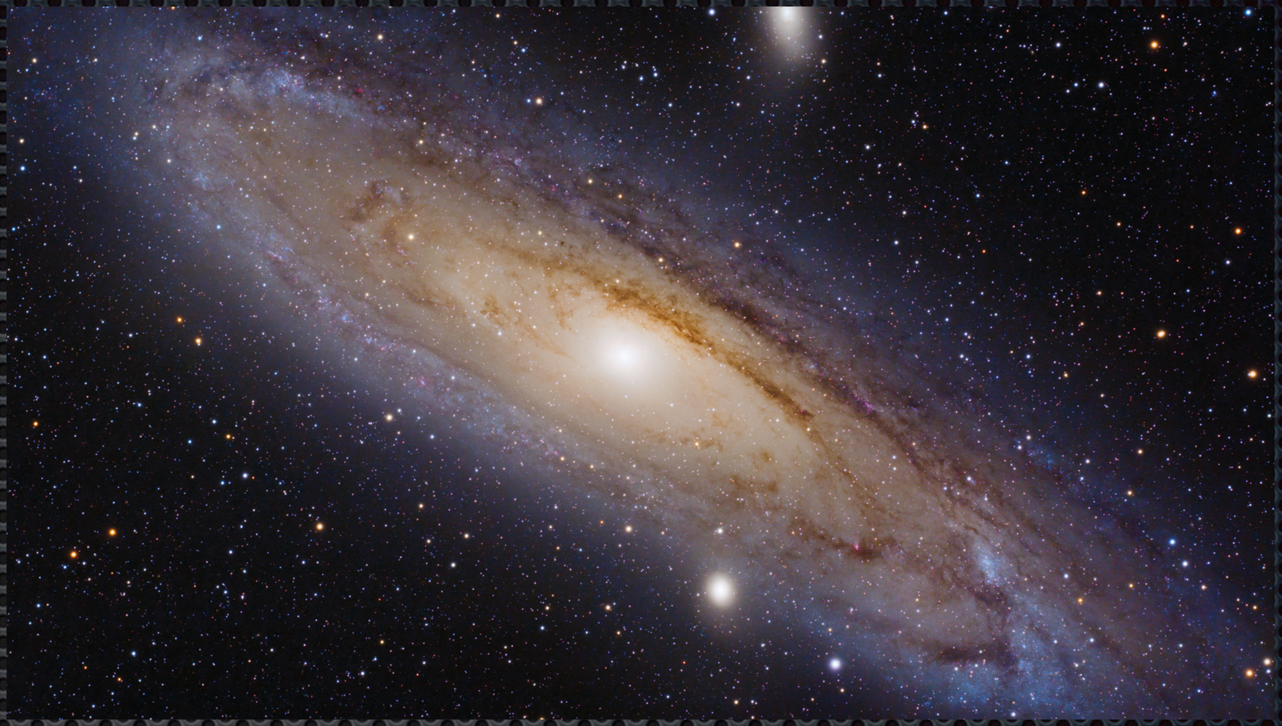
Large scale structures

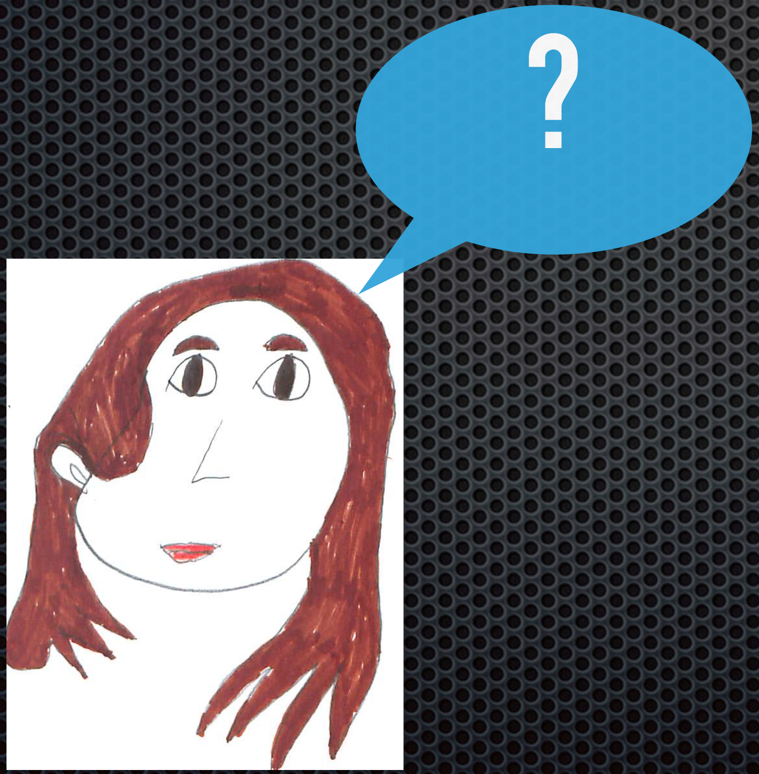
Dark Matter in Galaxies



Vera Rubin in the 70s

Dark matter forms the structures we observe in the Universe today, in particular also galaxies





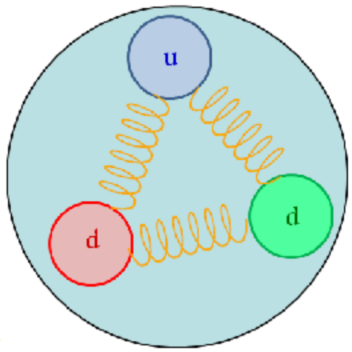
But:

what is it made of?

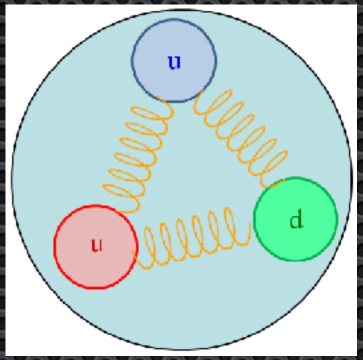
First:

what is normal matter made of?

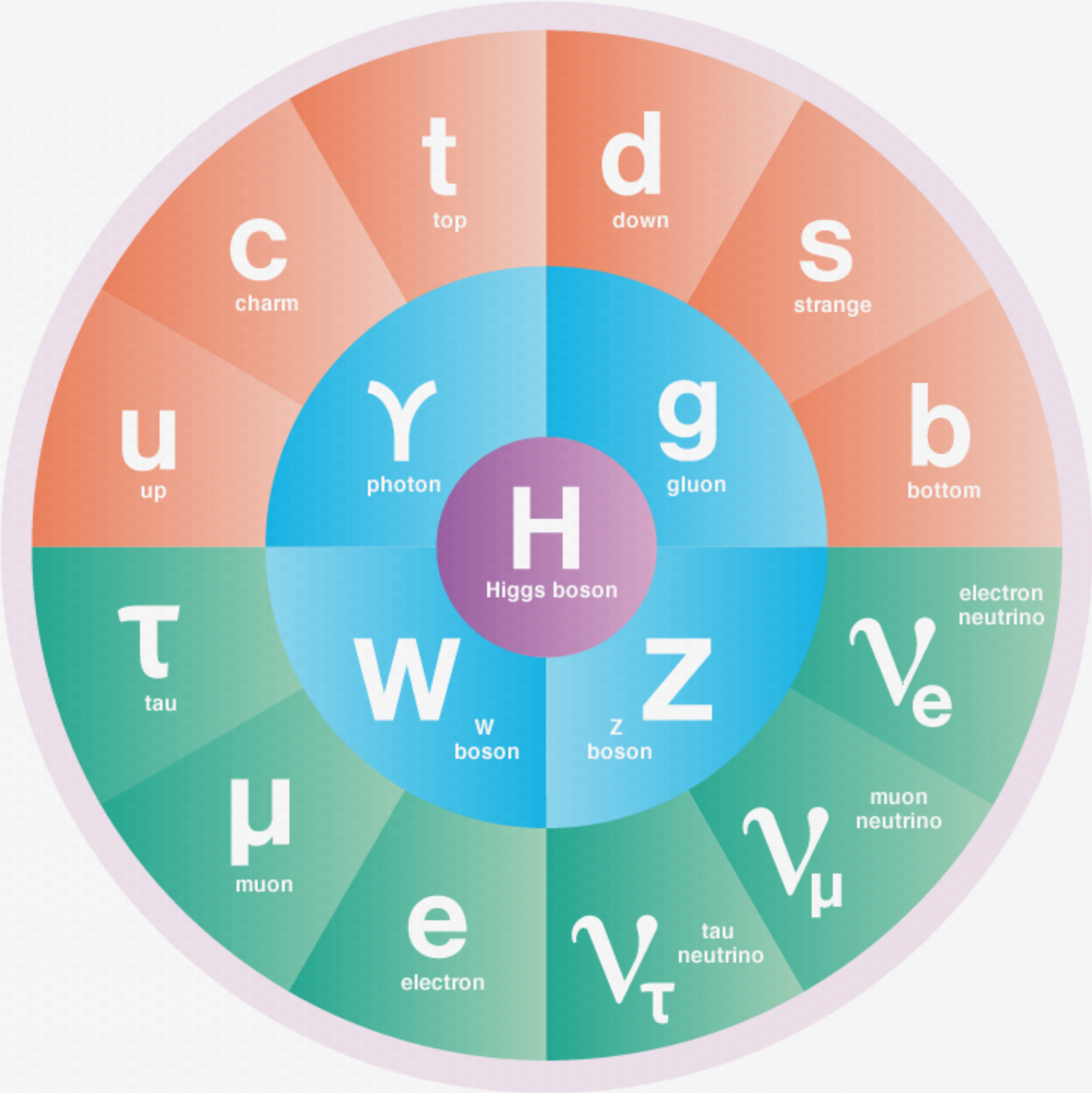
Neutron



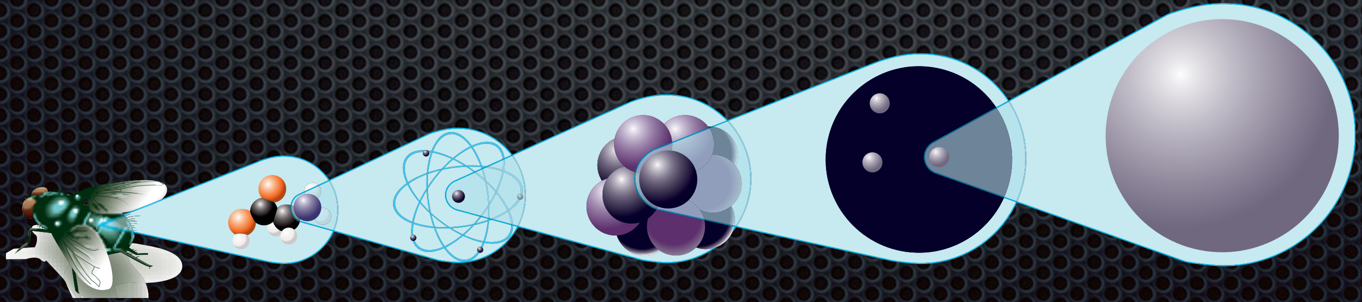
Proton



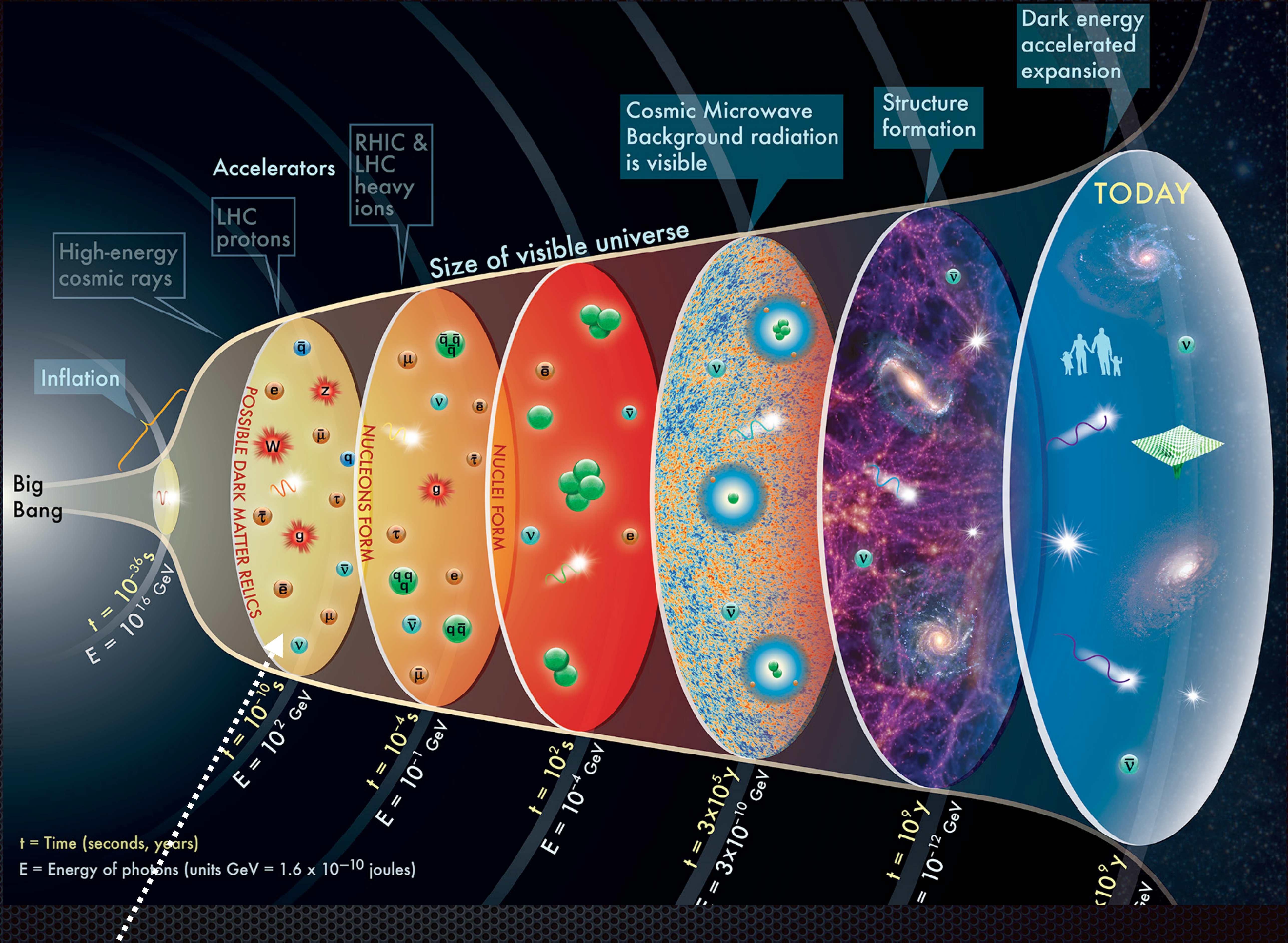
Electron



http://www.symmetrymagazine.org



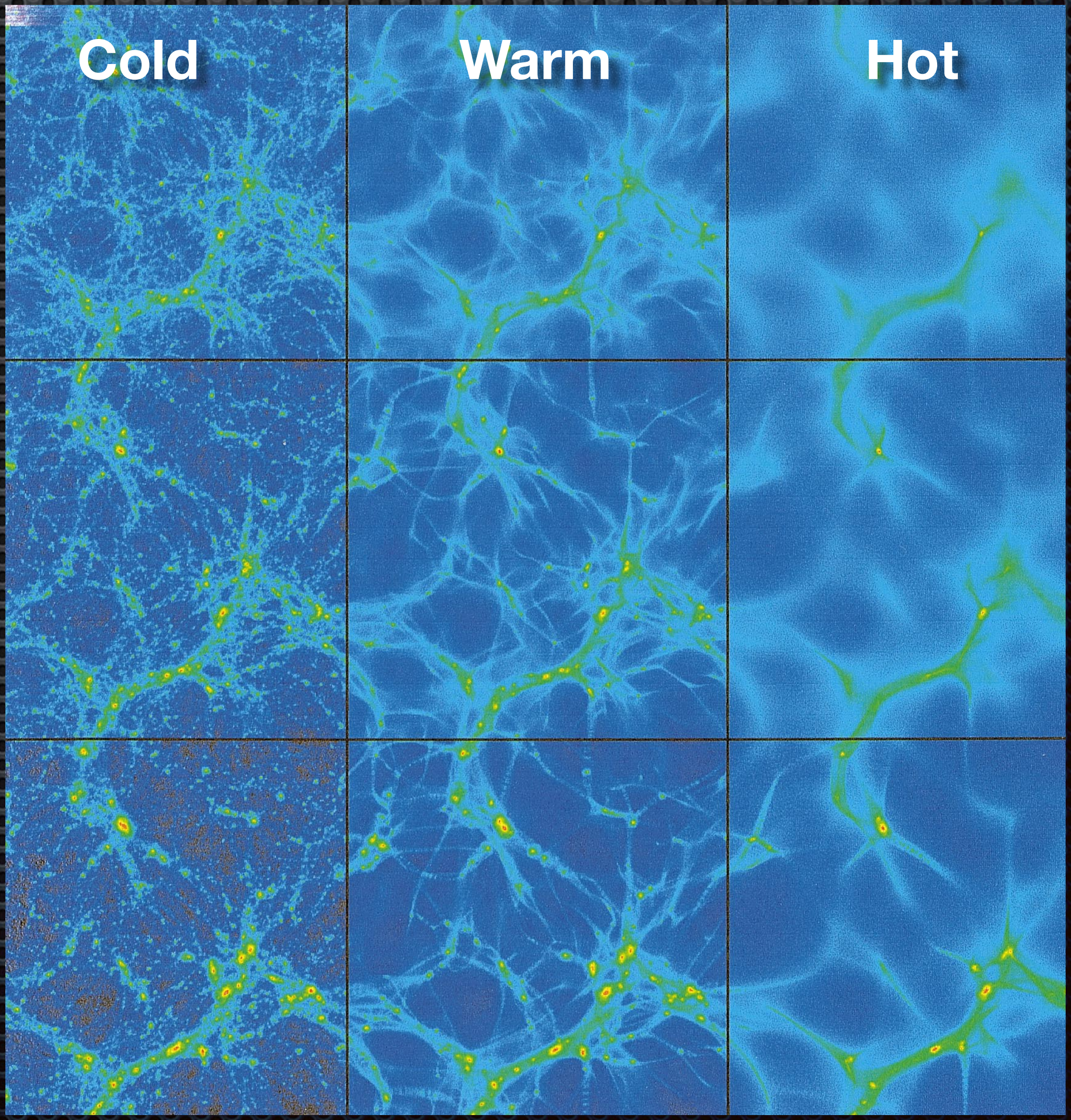
galaxies, stars, planets, people, polenta…



Particles from a *very early phase* of our Universe

What do we know about the dark matter particles?

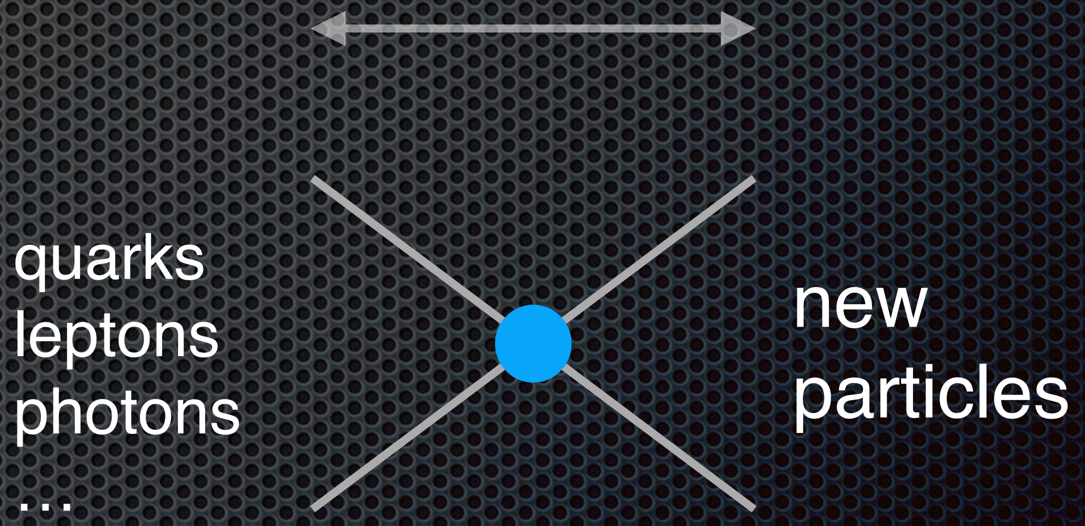
- Exist today and in the early Universe
- Constraints from astrophysical measurements and from searches for new particles:
  - No electric charge
  - No strong interaction
  - Slow-moving (non-relativistic, or Cold) as large-scale structure were forming
- Stable, or very long-lived



Probing dark matter through gravity

Weakly interacting massive particles (WIMPs)

- One of the leading hypotheses for Cold Dark Matter
- A thermal relic from an early phase
- We can calculate its density today
  - and it matches the observations



WIMPs could make up the halo of our Milky Way

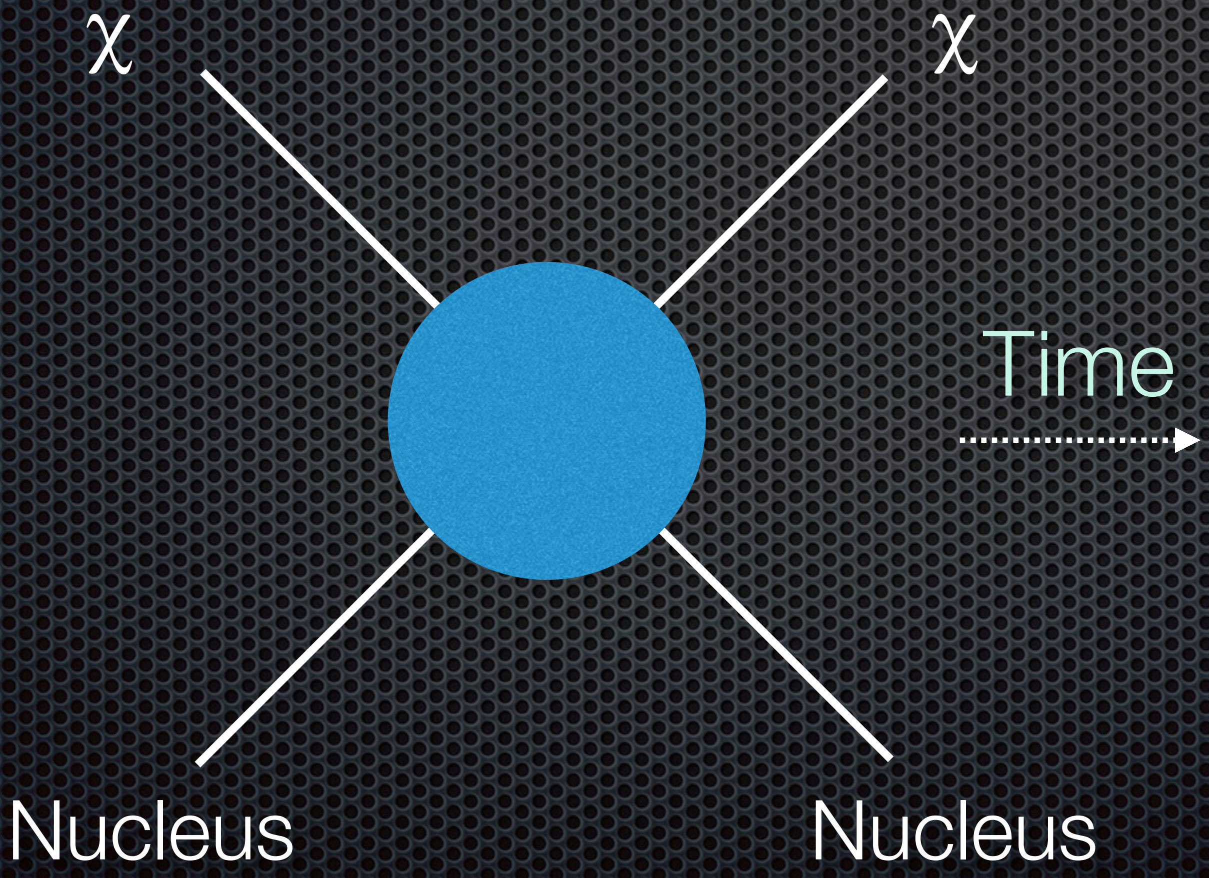
Dark matter

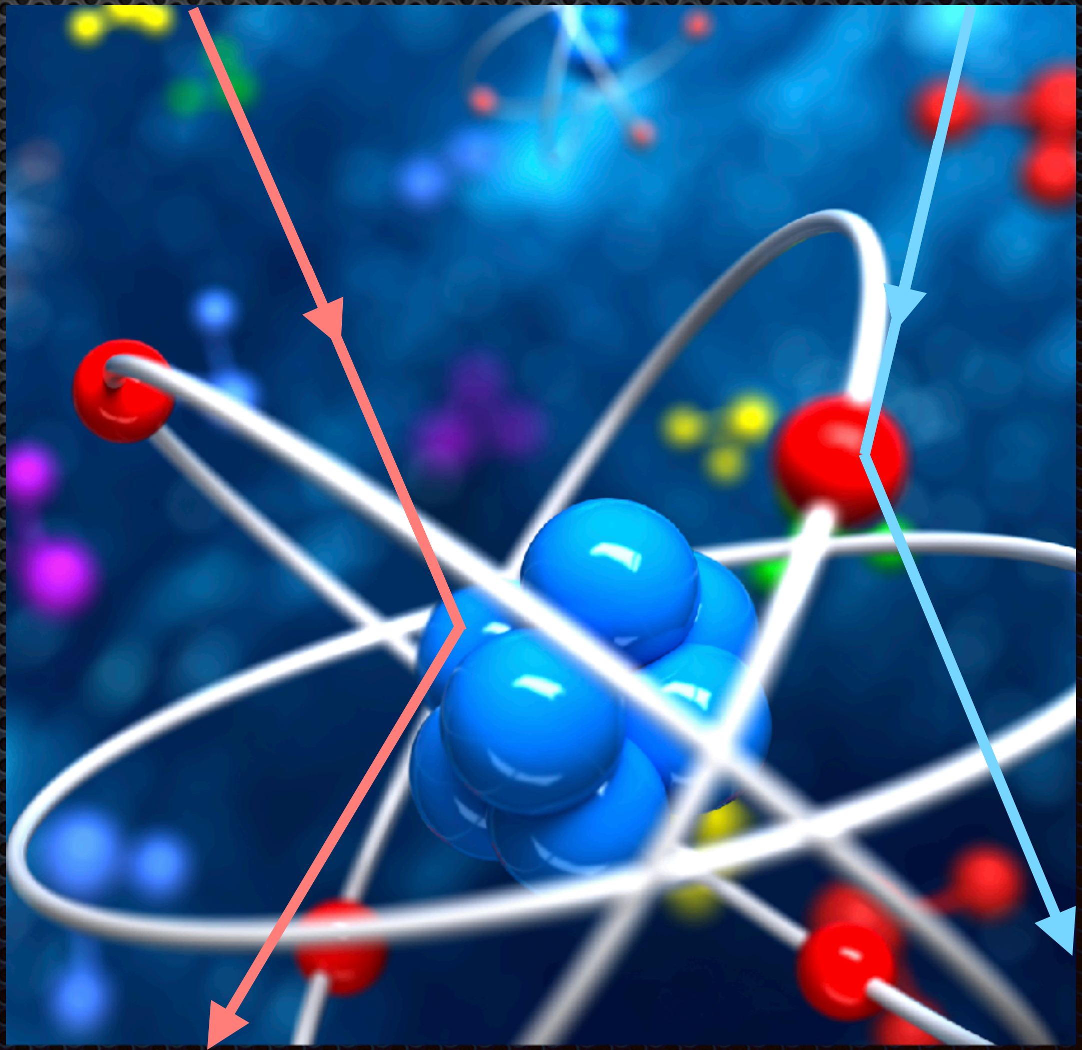
=

A new particle, which does not emit nor absorb light

How to make these dark matter particles visible?

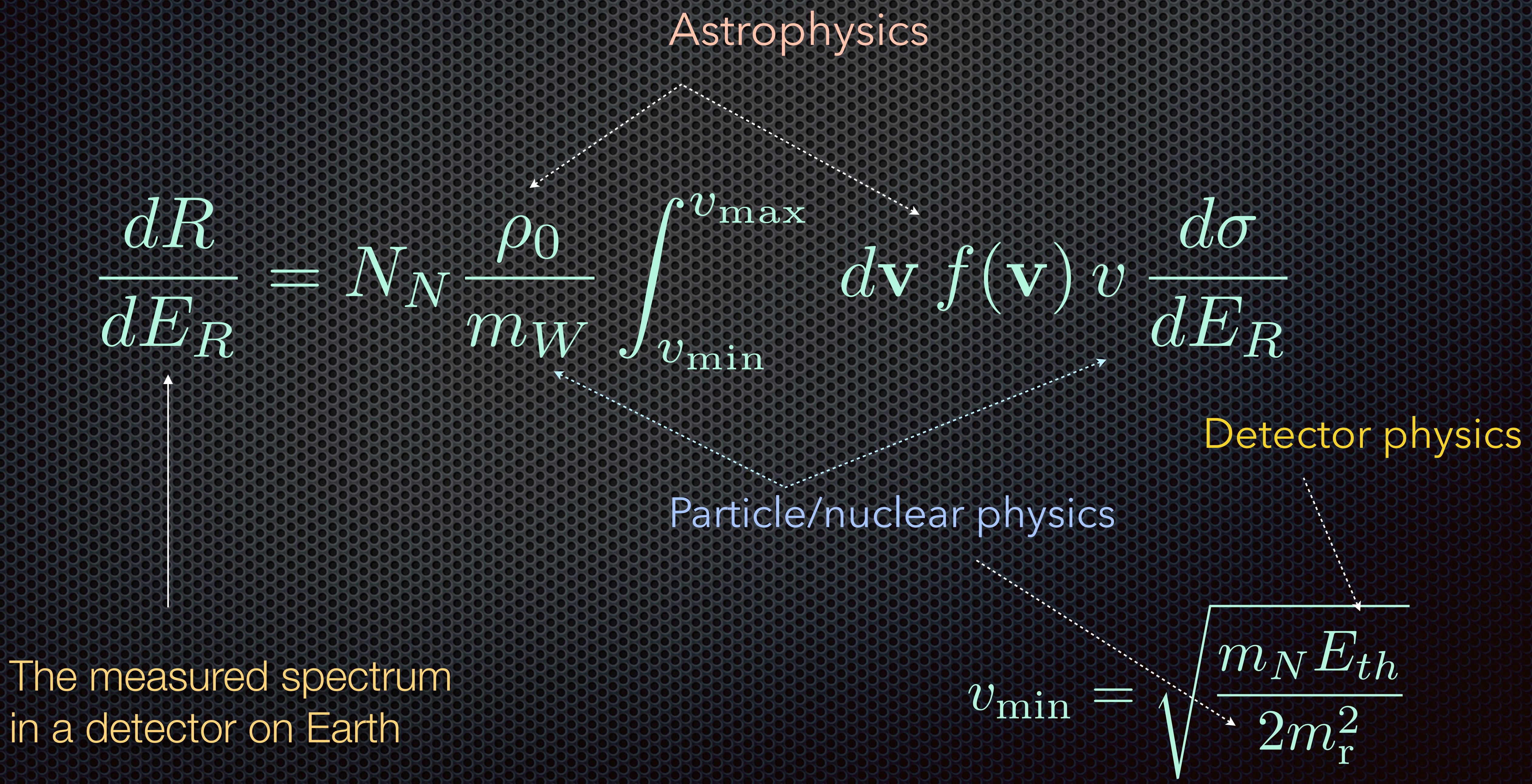
Look for *very rare* collisions of such particles with atomic nuclei





What do we expect in a detector?

- Input from: particle physics, nuclear physics, astrophysics and detector physics



Astrophysics

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{v_{\min}}^{v_{\max}} d\mathbf{v}\, f(\mathbf{v})\, v\, \frac{d\sigma}{dE_R}$$

Detector physics

Particle/nuclear physics

$$v_{\min} = \sqrt{\frac{m_N E_{th}}{2 m_{\mathrm{r}}^2}}$$

The measured spectrum
in a detector on Earth

Flux of dark matter particles:

$\phi = \frac{\rho_{dm}}{m_{dm}} \times \langle v \rangle$

- From the measured local dark matter density
- About 10 Millions through your hand, every second

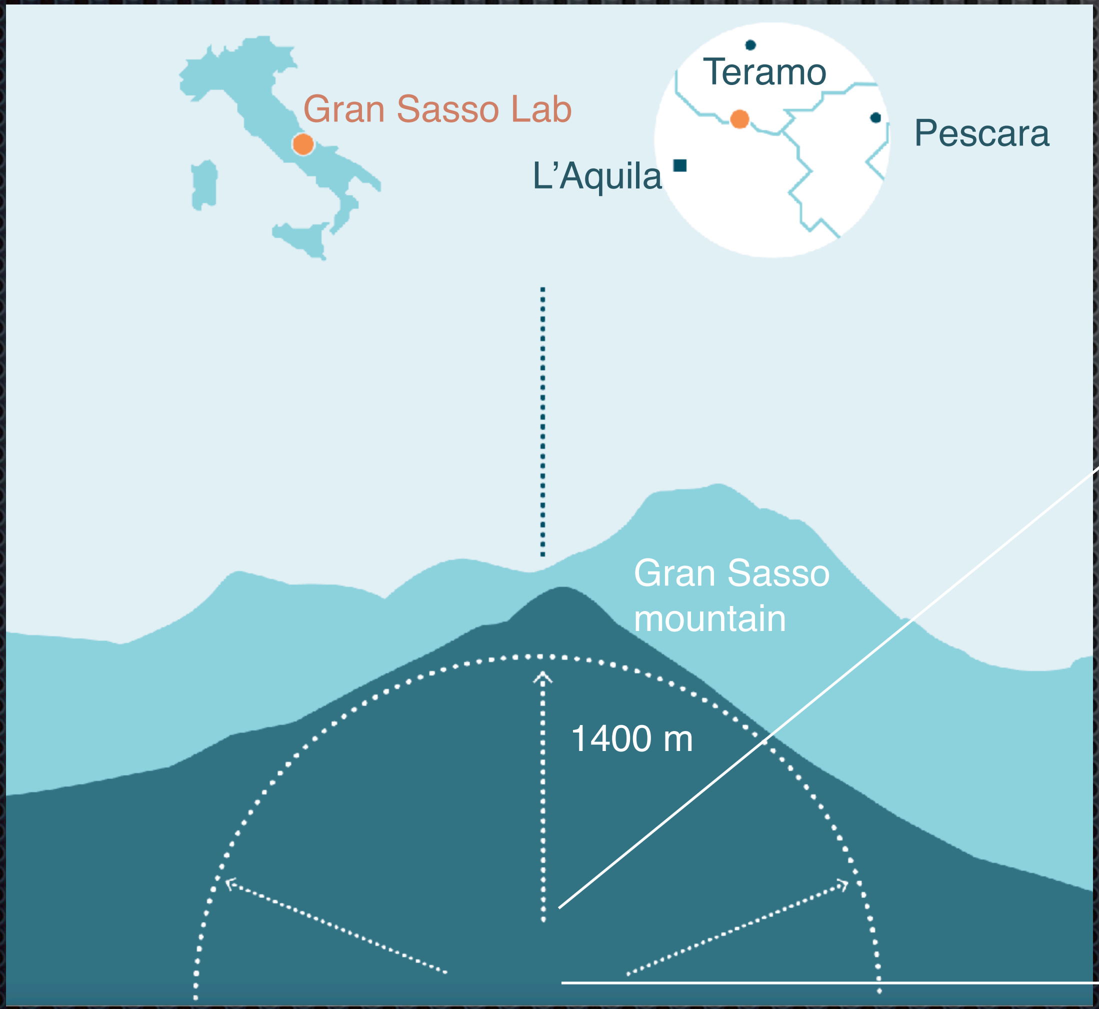
Gaia mission: data from 1.4×10^9 stars

Backgrounds: cosmic rays

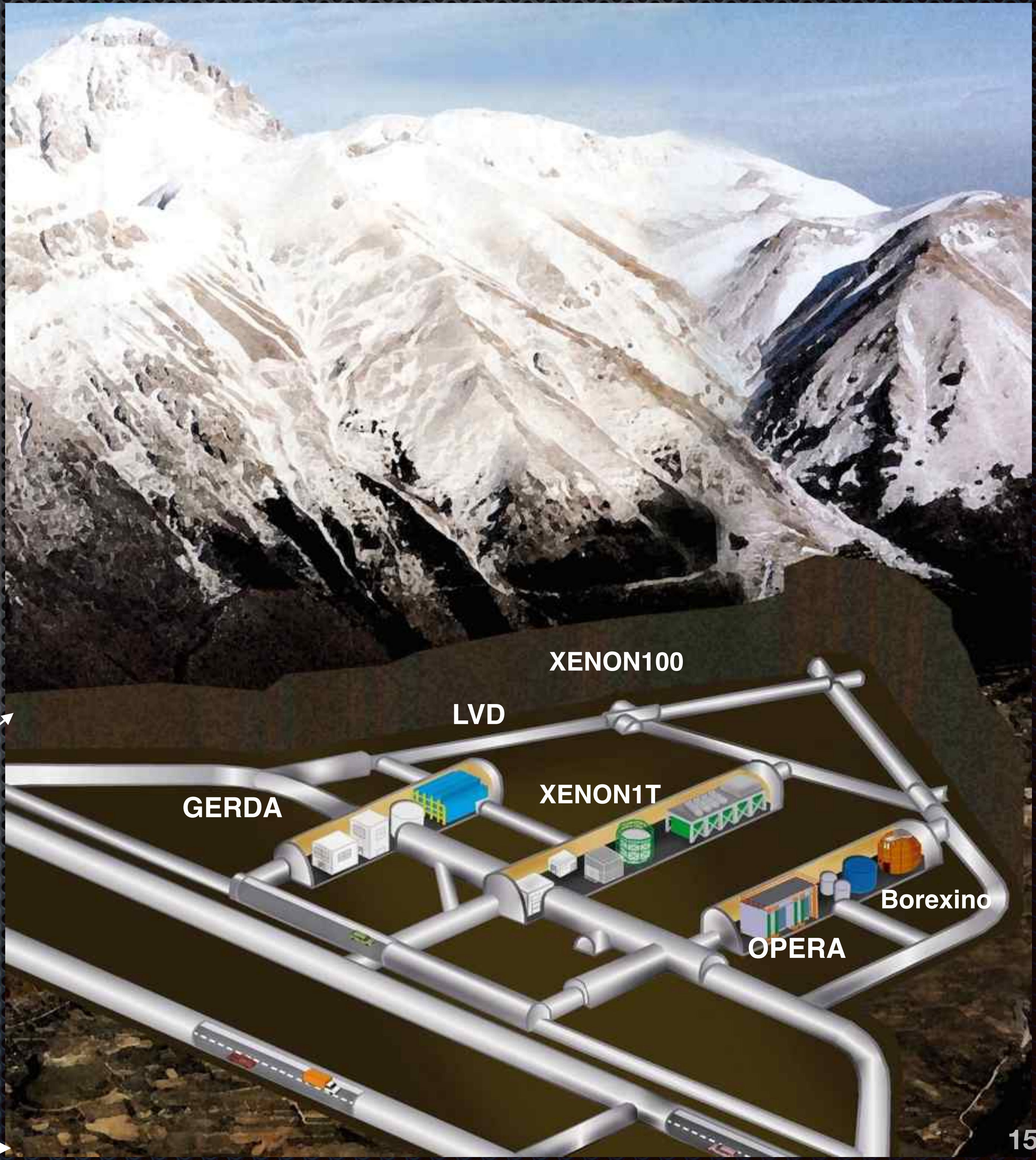
=> much higher interaction rates than expected from dark matter particles!

Backgrounds

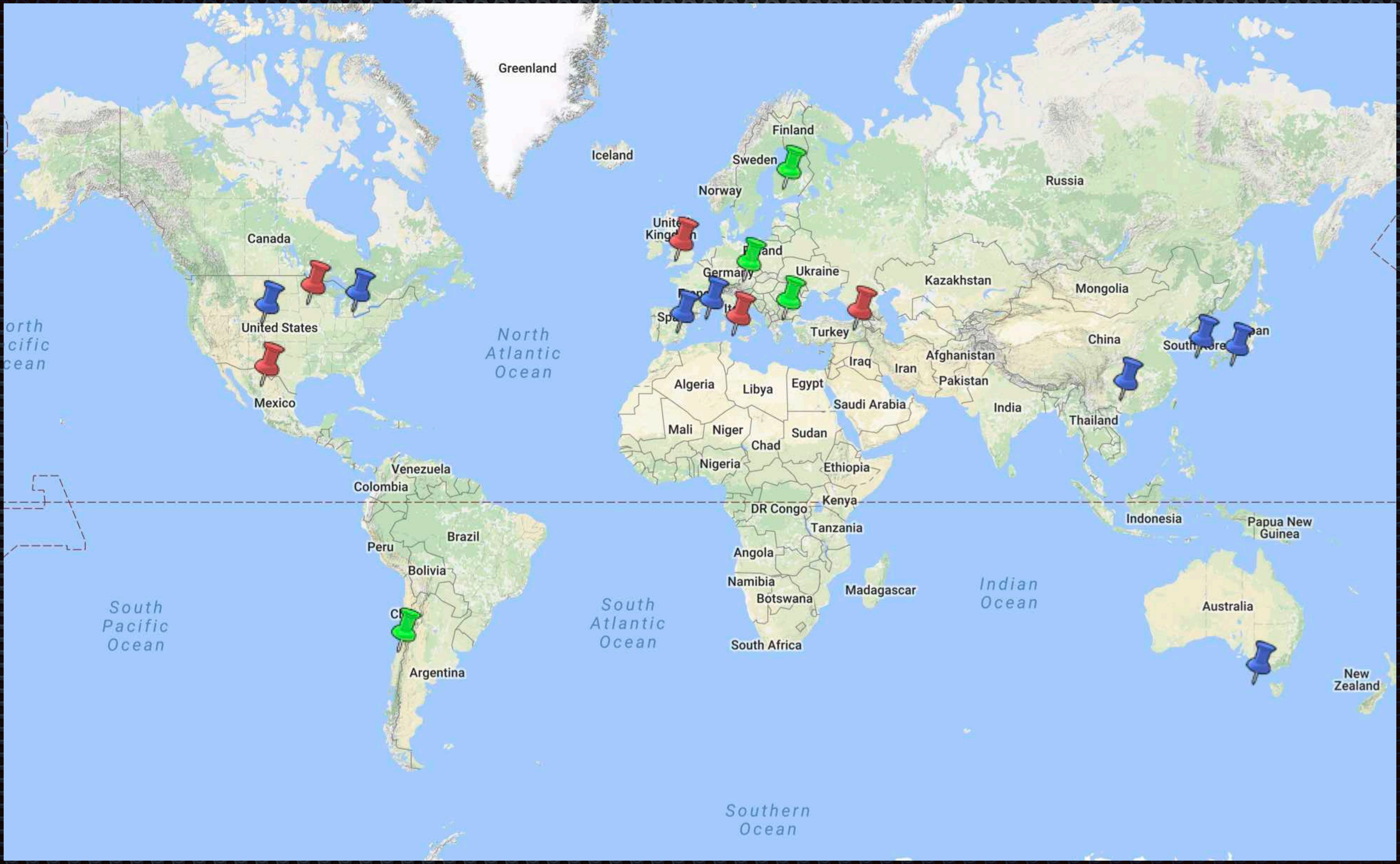
- Dark matter experiments are deep underground
- To shield from cosmic rays and their secondary particle



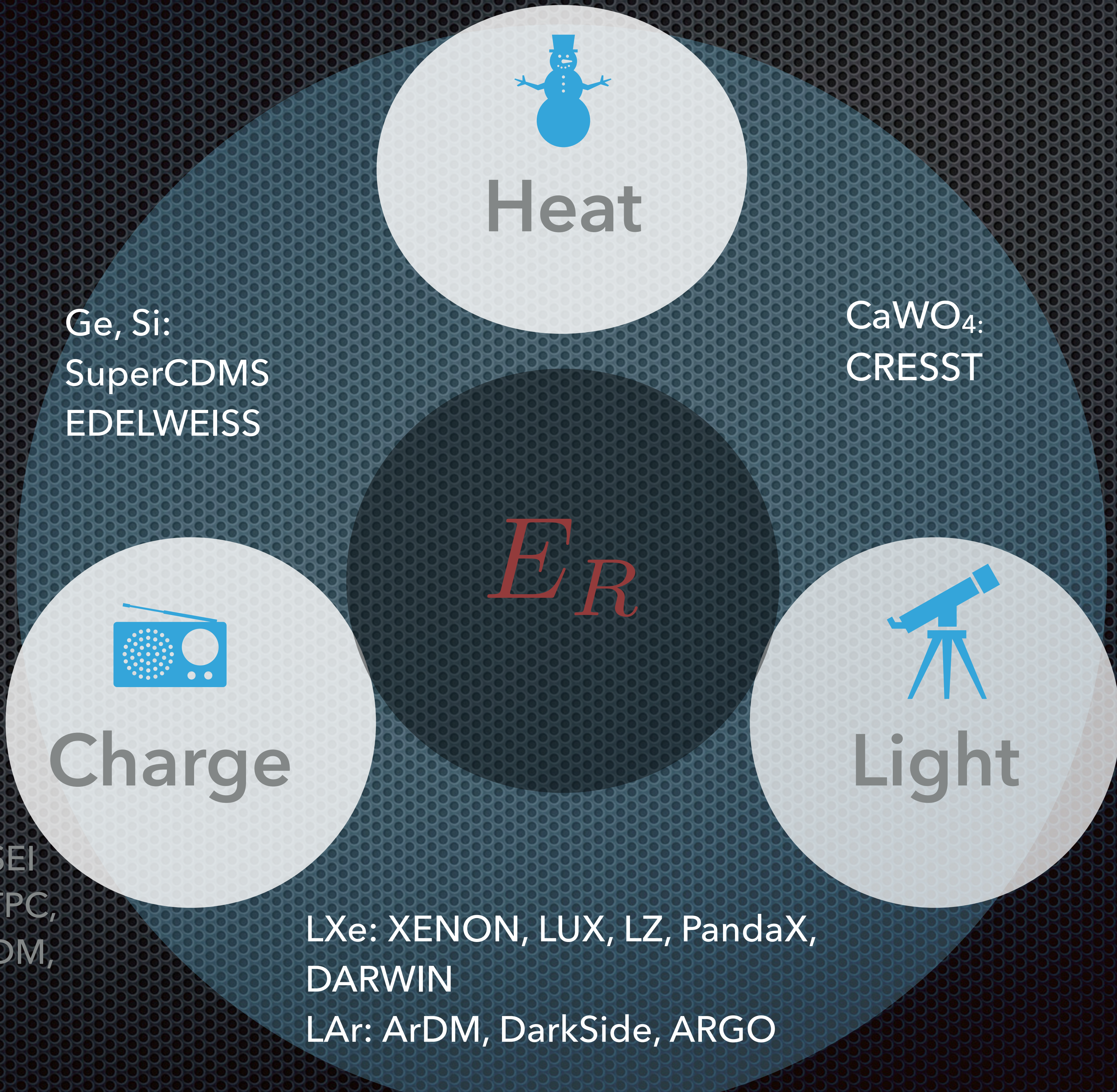
The Gran Sasso Laboratory in Italy



Underground laboratories



Direct detection signals



Ge, Si:
SuperCDMS
EDELWEISS

$CaWO_4$:
CRESST

C_3F_8, CF_3I: PICO
Ge: CDEX
Si: DAMIC, SENSEI
CF_4: DRIFT, DMTPC, MIMAC, NEWS-DM, NEWS-G

LXe: XENON, LUX, LZ, PandaX, DARWIN
LAr: ArDM, DarkSide, ARGO

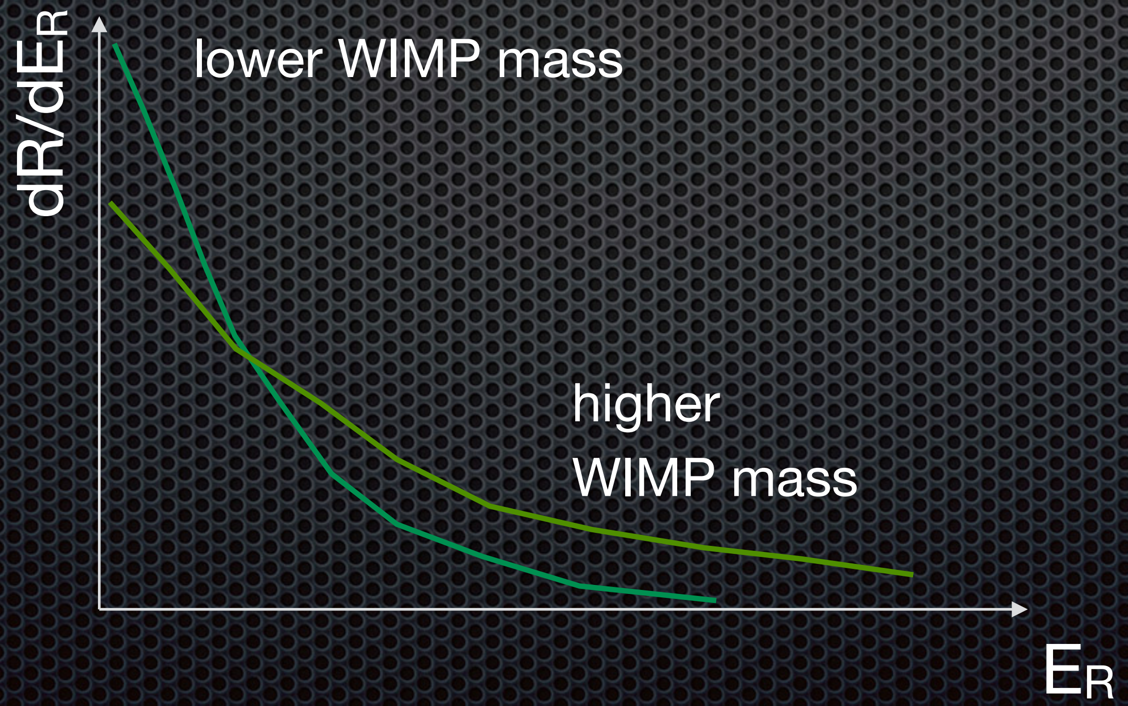
LXe: XMASS
LAr: DEAP-3600
CsI: KIMS
NaI: ANAIS
DAMA/LIBRA, COSINE, SABRE

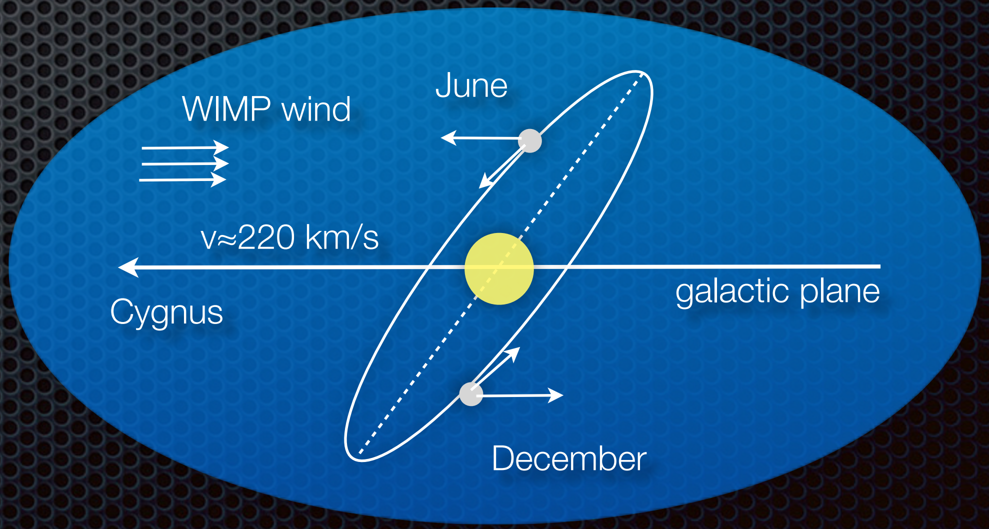
The experimental challenge

- Observe a signal which is:
  - very small (few keV - tens of keV)
  - extremely rare (<1 per ton of detector material per year)
  - embedded in a background that is millions of times higher

The experimental challenge

- Specific dark matter signatures
    - rate and shape of recoil spectrum depend on target material
    - motion of the Earth cause a
        - temporal variation in the rate (“annual modulation”)
        - directional dependance

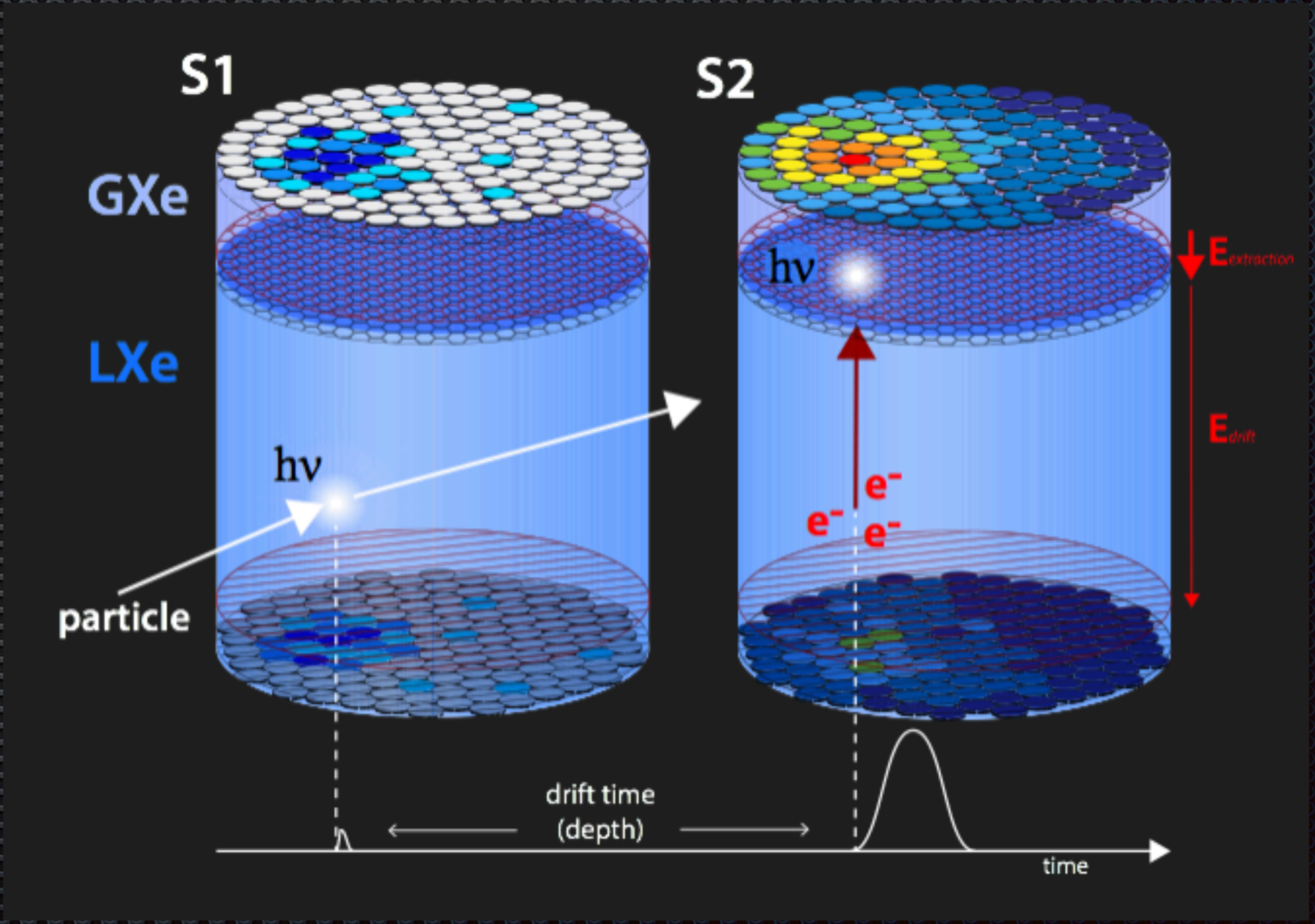




Detectors using xenon

- Measure VUV light and charge
- 3D position of an interaction
- Example: 3.2 t of liquid xenon at -100°C

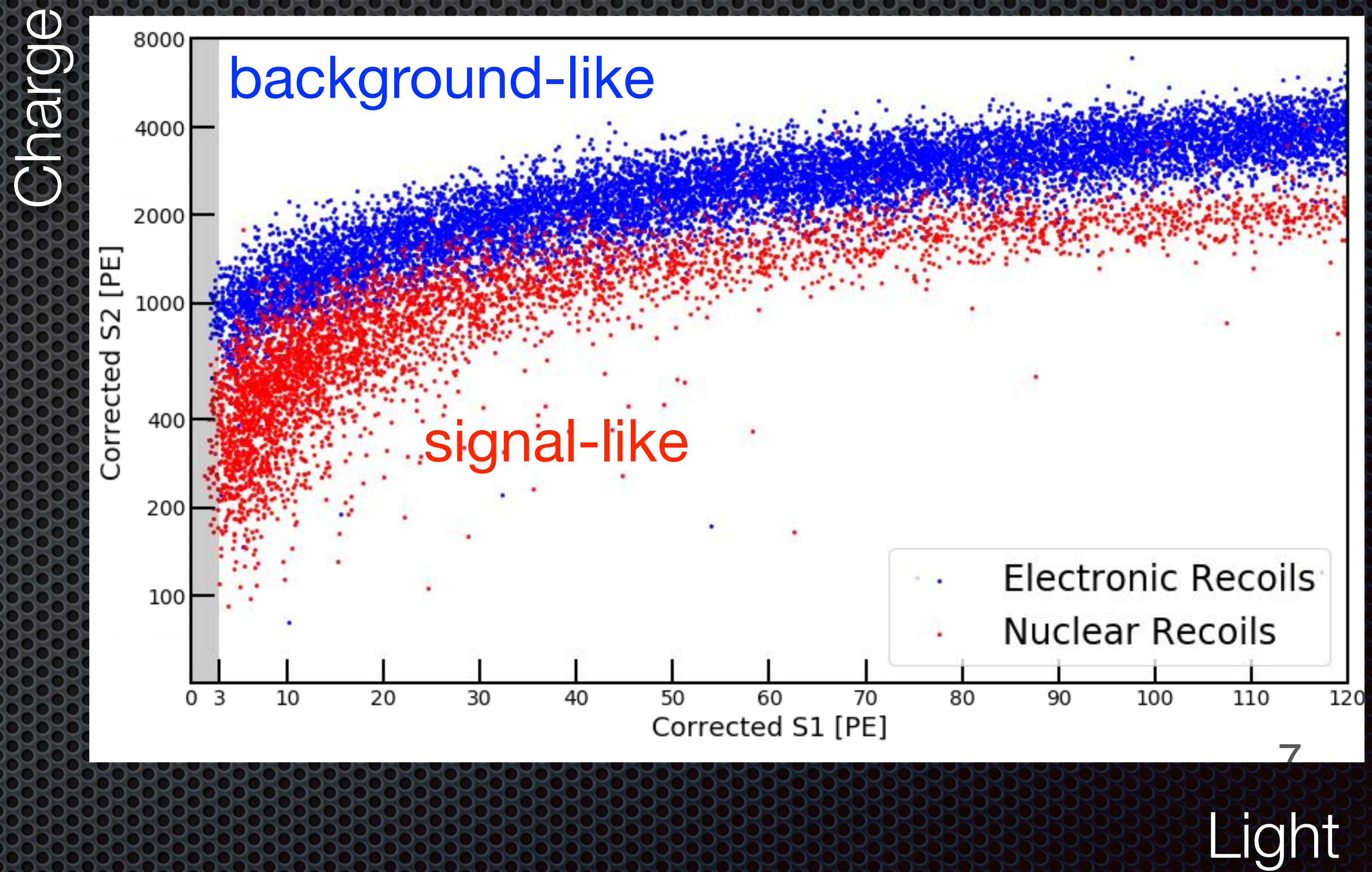
Light at λ=175 nm



Time

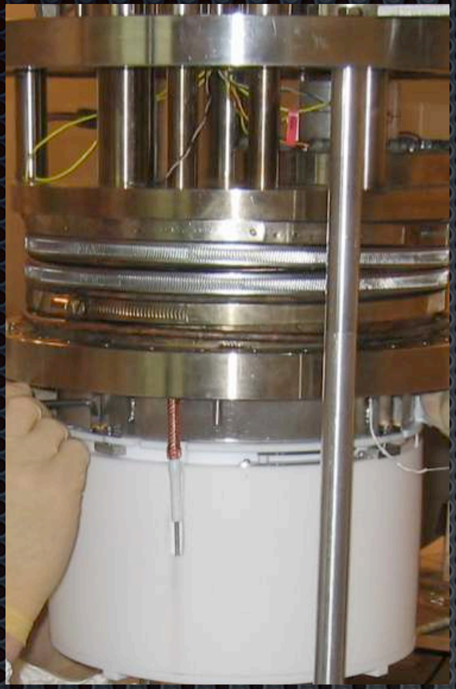
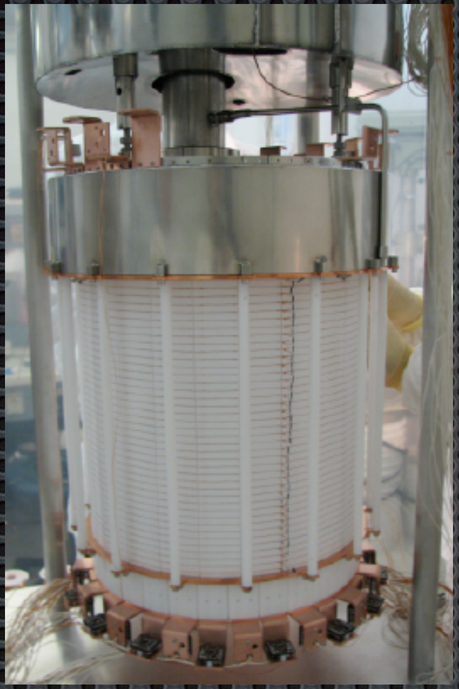
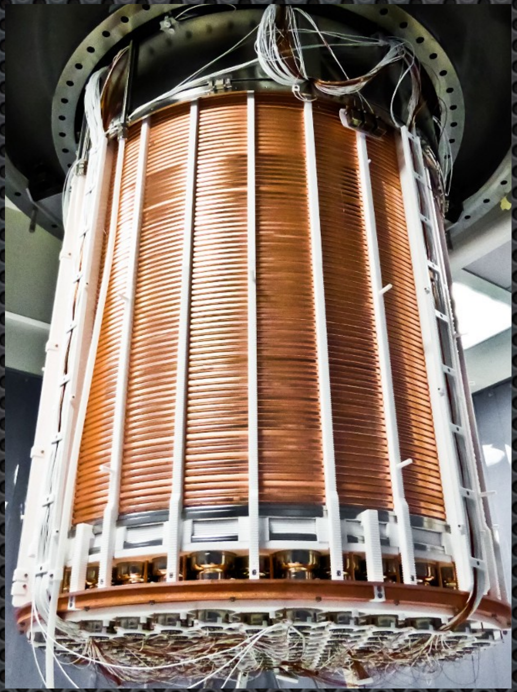
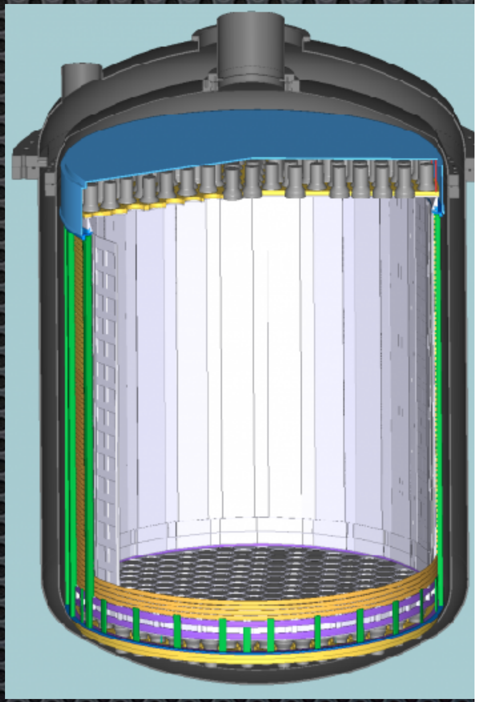
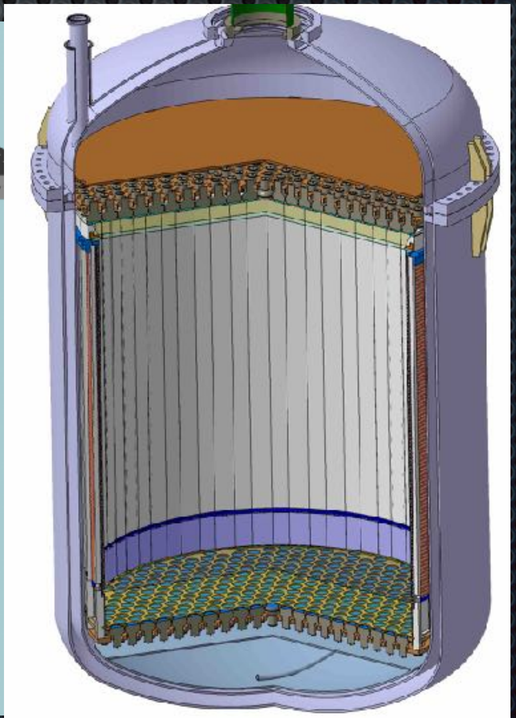
Detectors using xenon

- Measure VUV light and charge
- 3D position of an interaction
- Example: 3.2 t of liquid xenon at -100ºC



Time

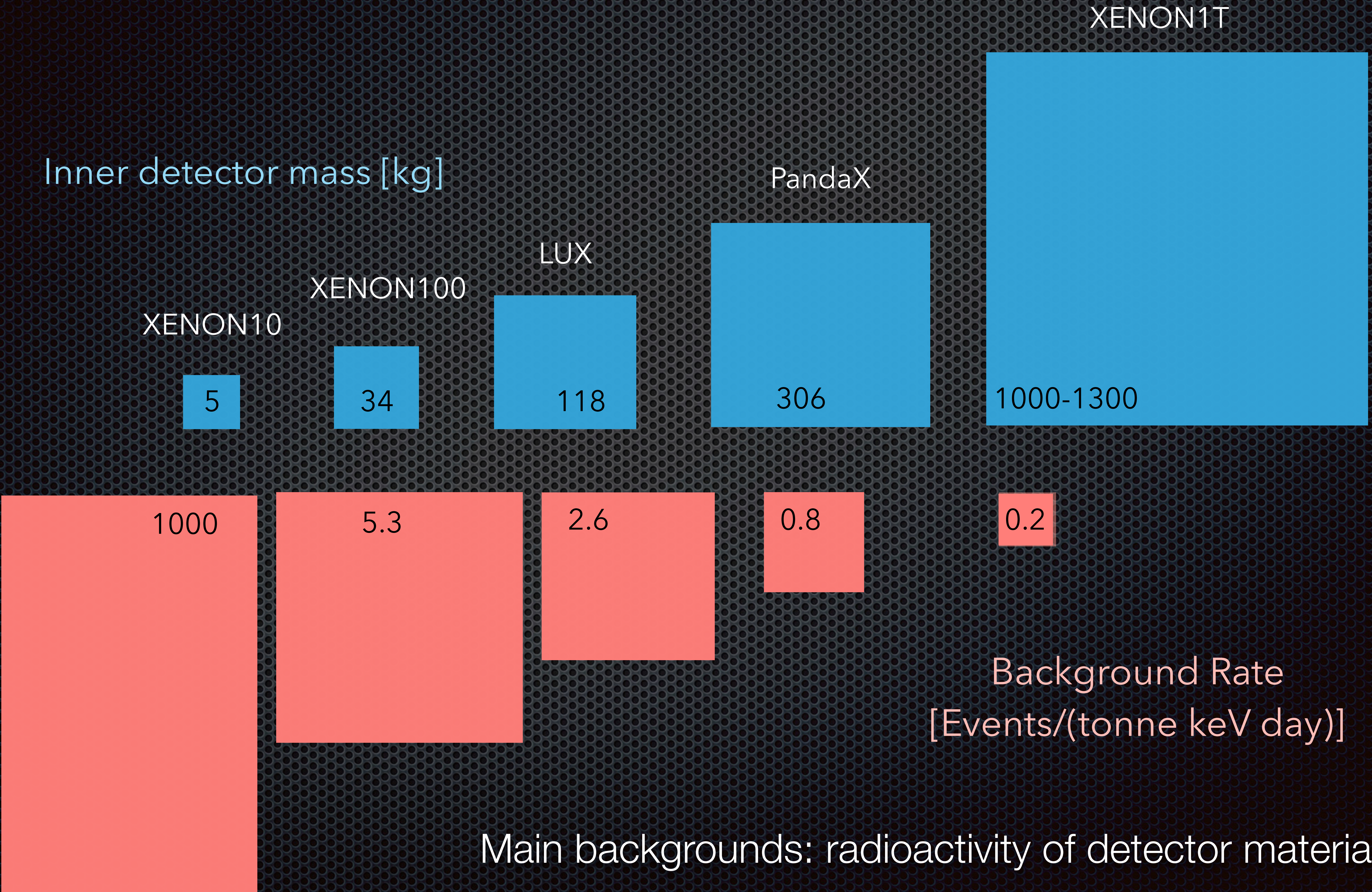
The XENON and DARWIN timelines

XENON10	XENON100	XENON1T	XENONnT	DARWIN
15 cm	30 cm	1 m	1.3 m	2.6 m
2005-2007	2008-2016	2012-2019	2020-2024	2024++
15 kg	161 kg	3200 kg	8200 kg	50 tonnes
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2	~10^{-49} cm^2

*detector pictures not to scale

Size and backgrounds



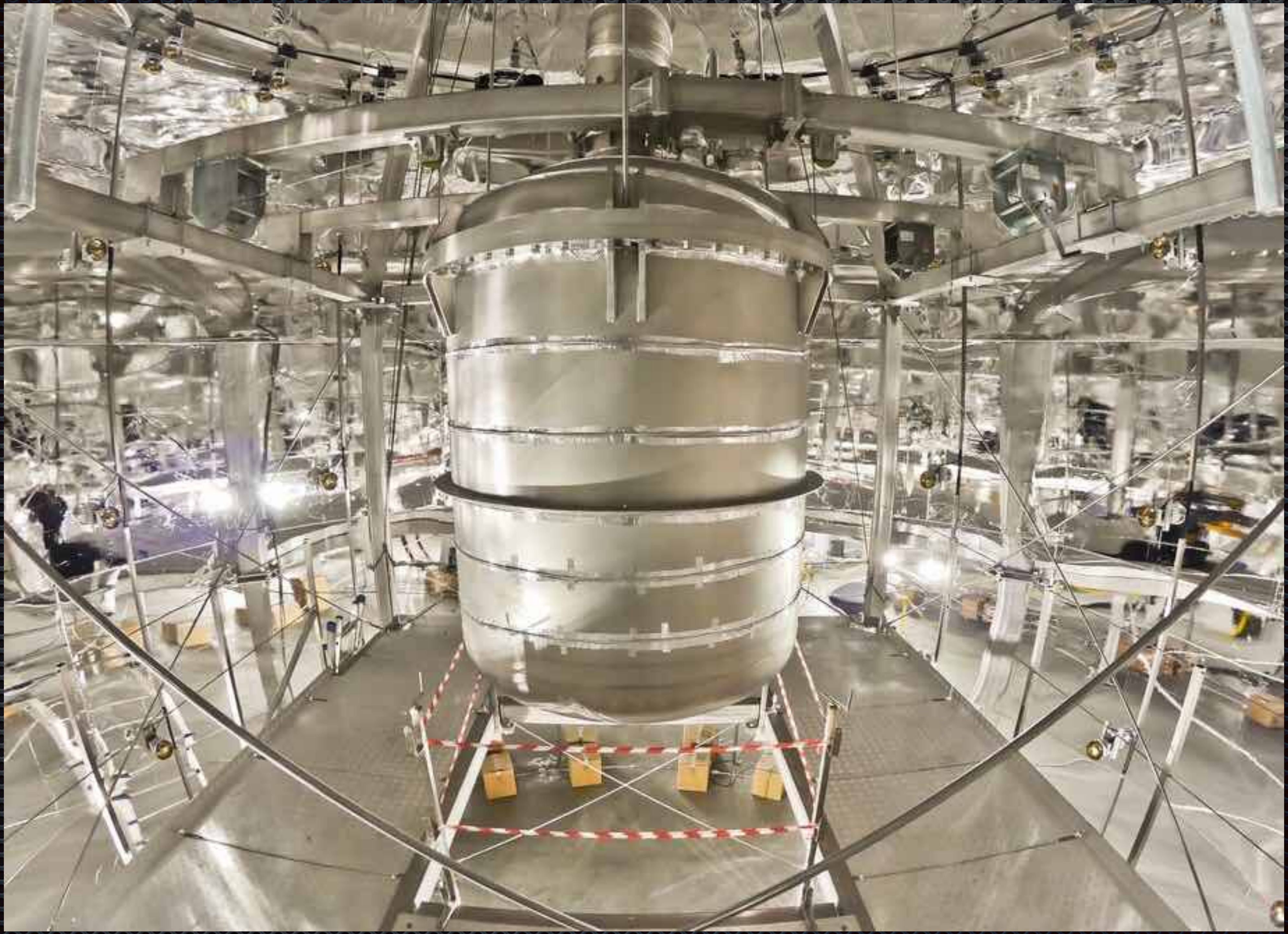
	Inner detector mass [kg]	Background Rate [Events/(tonne keV day)]
XENON10	5	1000
XENON100	34	5.3
LUX	118	2.6
PandaX	306	0.8
XENON1T	1000-1300	0.2

Main backgrounds: radioactivity of detector materials

XENON Collaboration, EPJ-C 77 (2017) 12

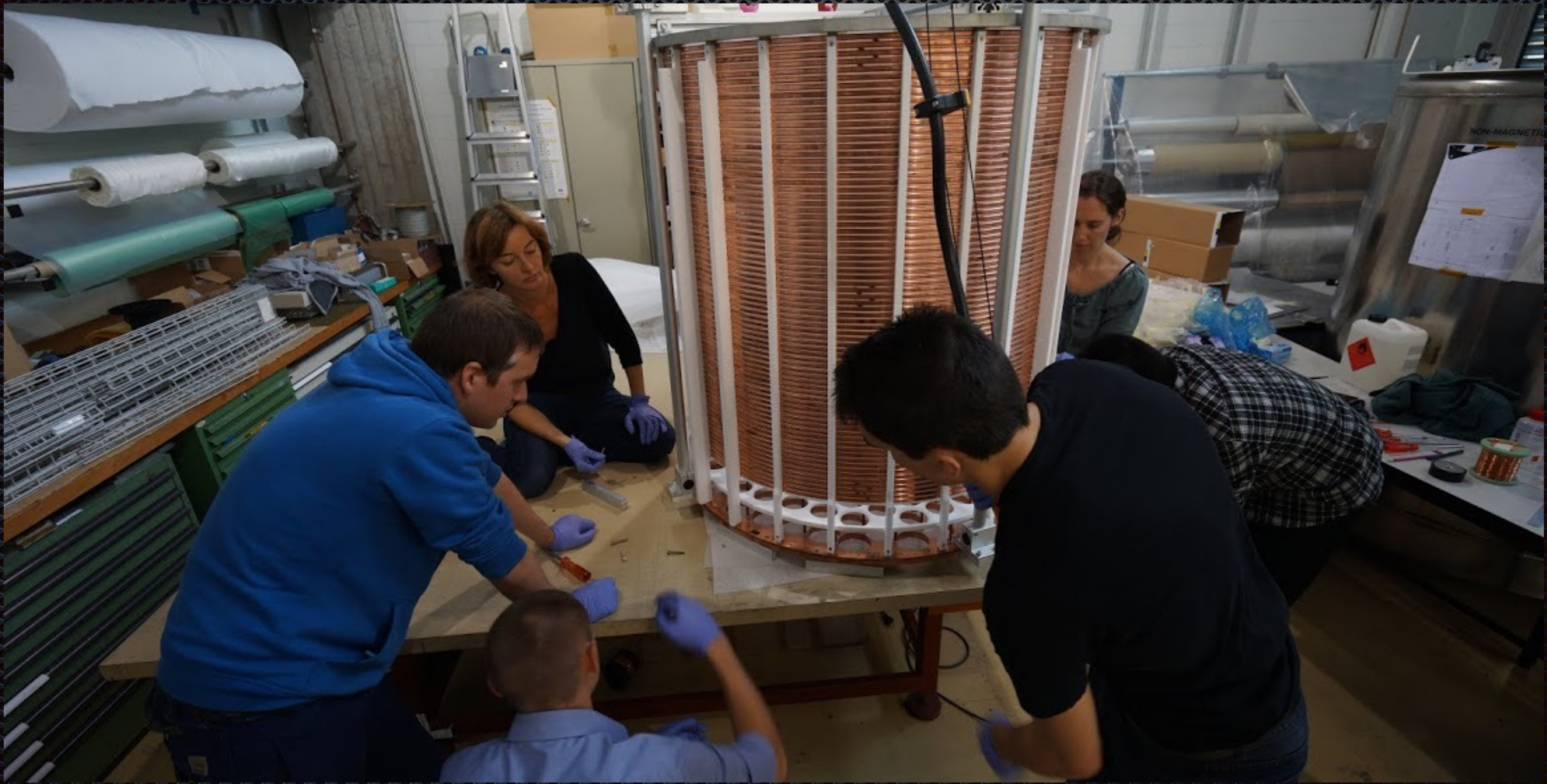
XENON1T at Gran Sasso

XENON1T at the Gran Sasso Lab



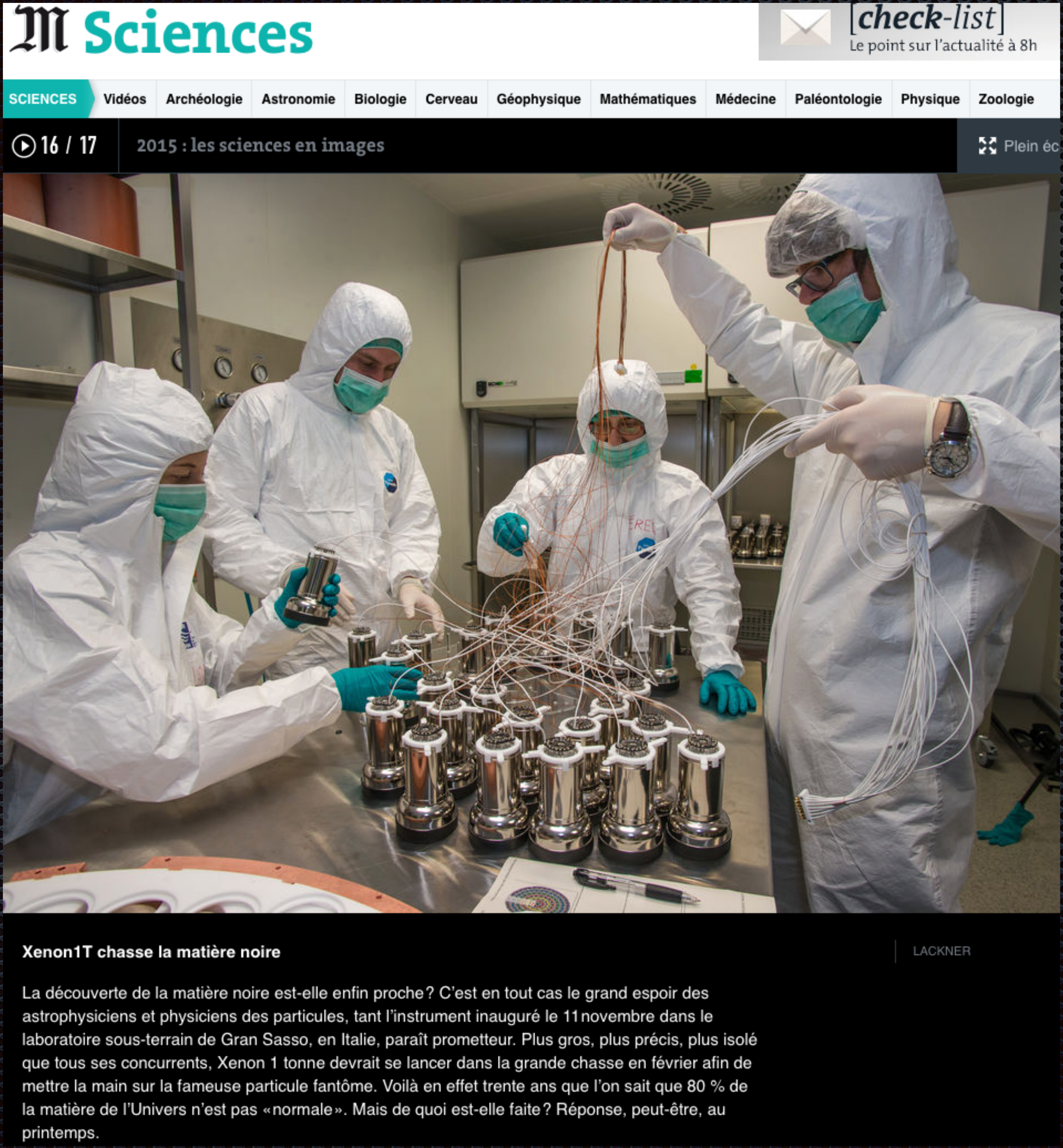
Stainless steel cryostat and outer water shield

Inner detector tests in Zurich



Le Monde

Les Sciences en Images



2015 : les sciences en images

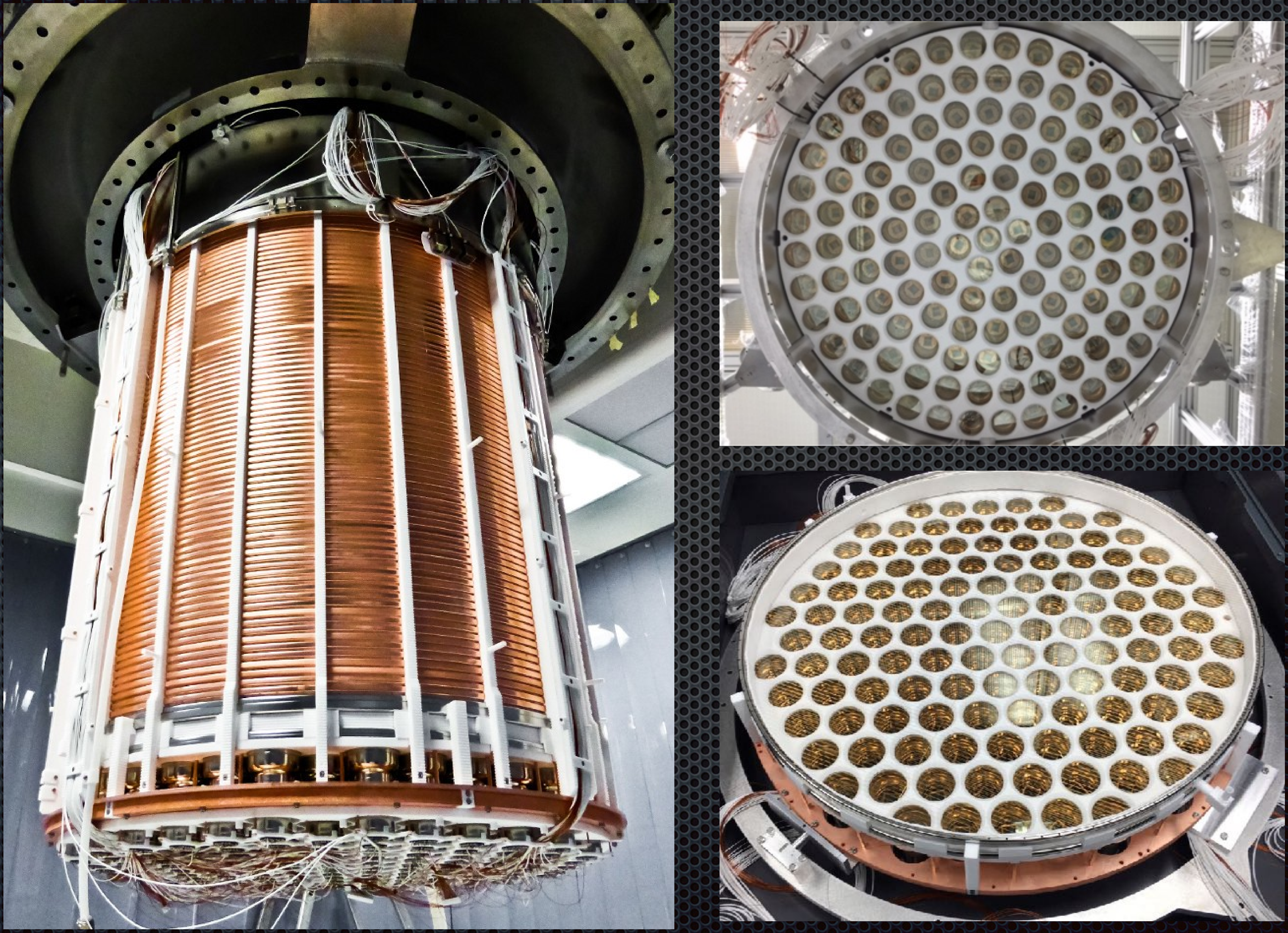
Xenon1T chasse la matière noire

LACKNER

La découverte de la matière noire est-elle enfin proche? C'est en tout cas le grand espoir des astrophysiciens et physiciens des particules, tant l'instrument inauguré le 11 novembre dans le laboratoire sous-terrain de Gran Sasso, en Italie, paraît prometteur. Plus gros, plus précis, plus isolé que tous ses concurrents, Xenon 1 tonne devrait se lancer dans la grande chasse en février afin de mettre la main sur la fameuse particule fantôme. Voilà en effet trente ans que l'on sait que 80 % de la matière de l'Univers n'est pas «normale». Mais de quoi est-elle faite? Réponse, peut-être, au printemps.

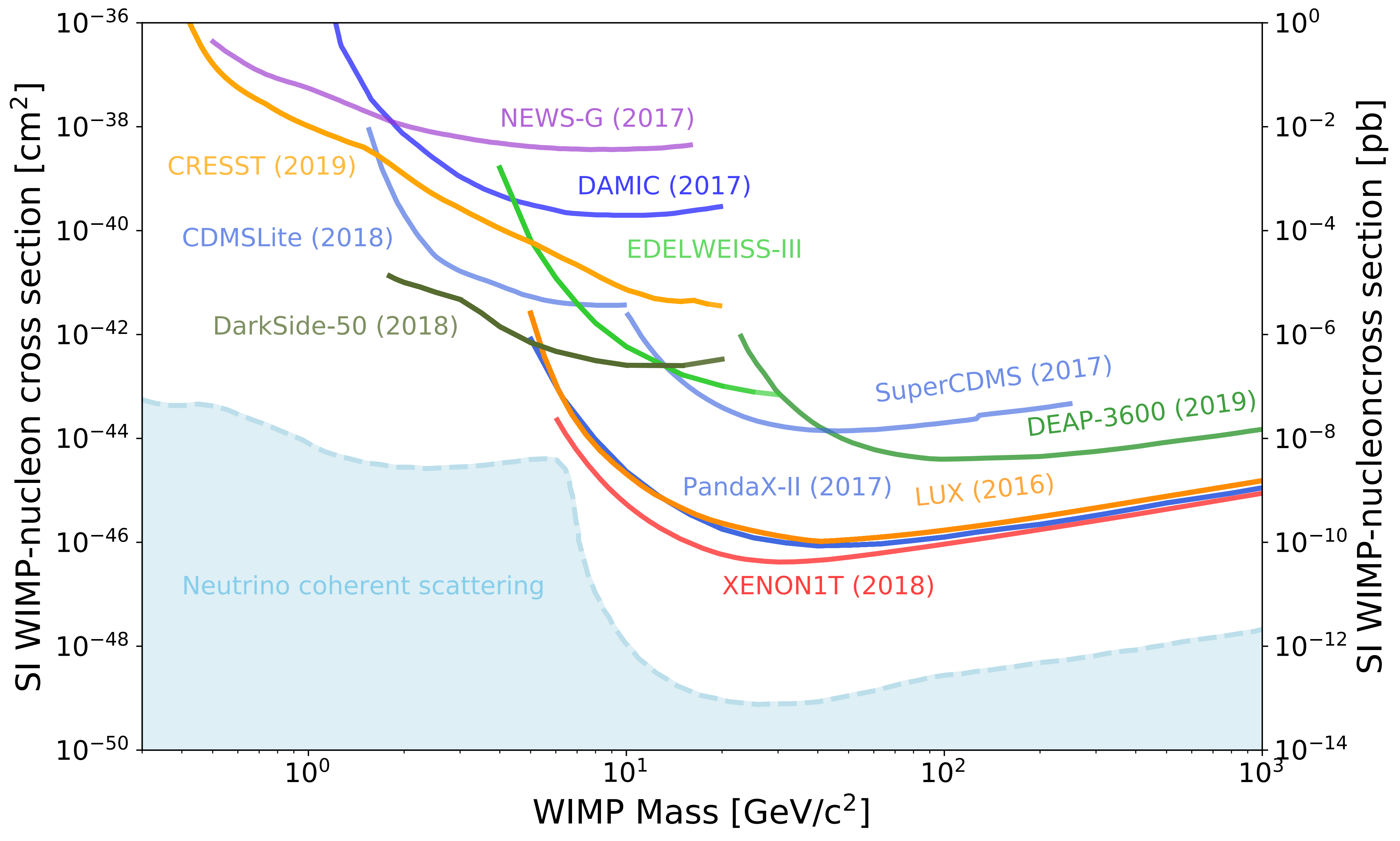
Inner detector in the cleanroom

XENON1T at Gran Sasso



No dark matter signal (so far)

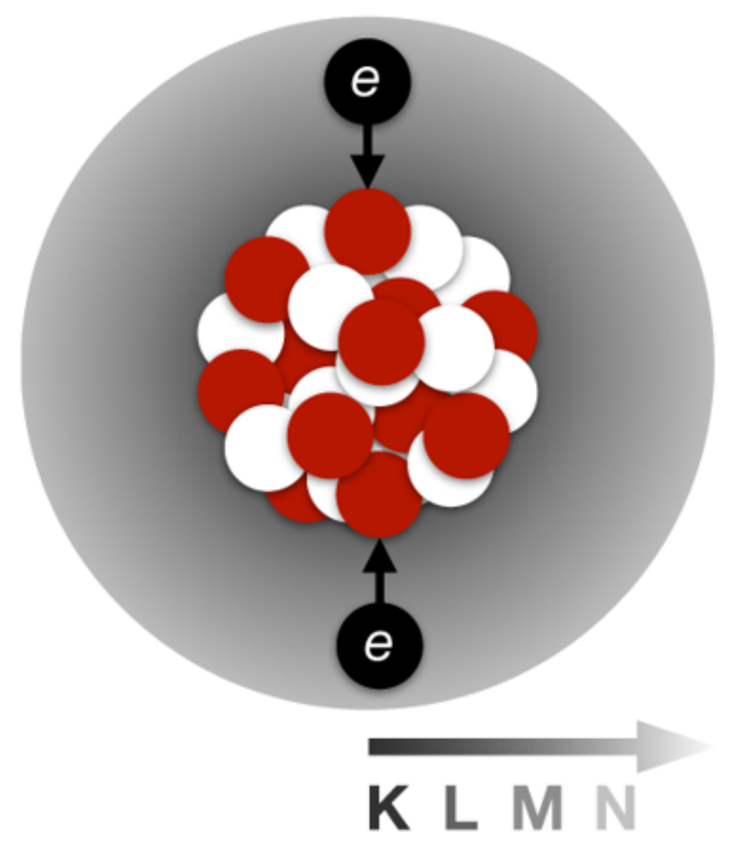
L. Baudis. S. Profumo, PDG2019



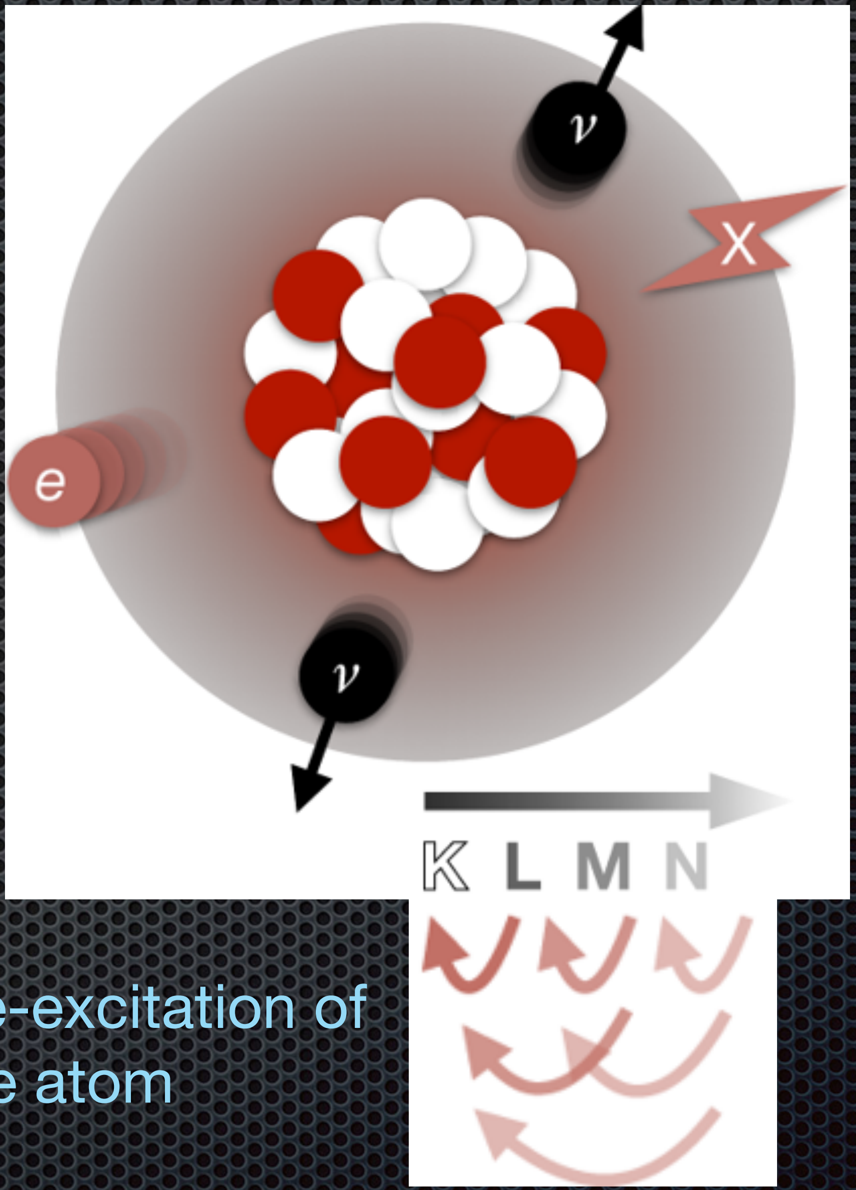
XENON collaboration, Nature 568, April 25, 2019

Observation of DEC in ^{124}Xe

$$^{124}\mathrm{Xe} + 2\mathrm{e}^- \rightarrow {}^{124}\mathrm{Te} + 2\nu_e$$



2 electrons are captured from the atomic shell



De-excitation of the atom

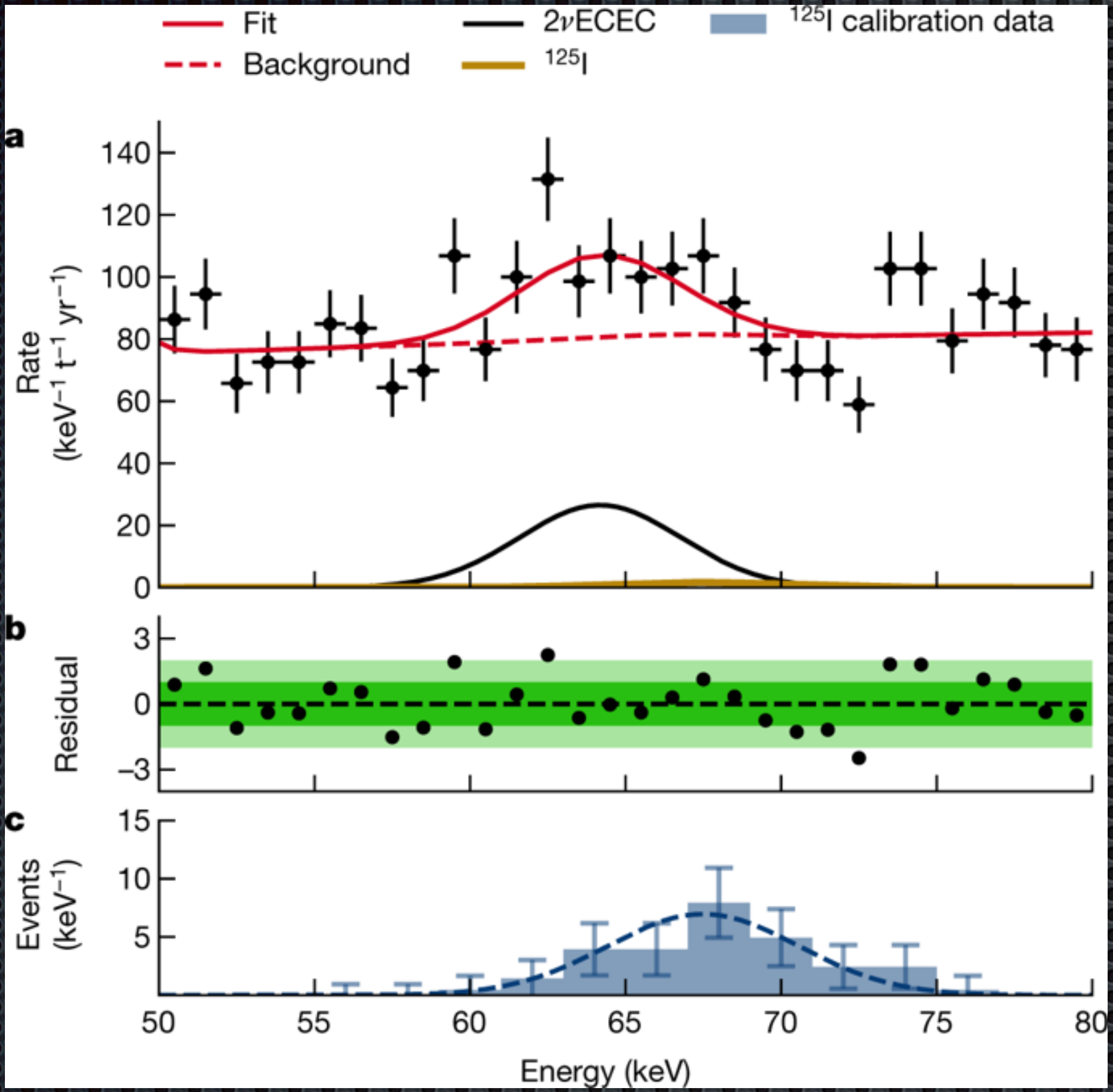
The 2 neutrinos leave the detectors unnoticed

X-rays with at ~ 64 keV are observed

The rarest decay process ever measured in the Universe

XENON collaboration, Nature 568, April 25, 2019

Observation of DEC in ^{124}Xe



$$T_{1/2} = 1.8 \times 10^{22}\ a$$

25. April, 2019

nature

THE INTERNATIONAL WEEKLY JOURNAL OF SCIENCE

CAUGHT IN THE ACT

Dark-matter detector captures elusive nuclear decay in xenon PAGES 462 & 532

SEX AND GENDER

TRANSITIONAL INSIGHTS

The world's largest study of transgender people

PAGE 446

ENVIRONMENT

IN THE DARK

How high-rise living deprives urban centres of natural light

PAGE 451

NEUROSCIENCE

SPEECH SYNTHESIZER

Implant gives voice to brain signals that control movement

PAGES 466 & 493

NATURE.COM

25 April 2019

Vol. 568, No. 7753

Next step: XENONnT

In construction at LNGS
Start in 2020

- 8.4 tonnes of liquid xenon
- New inner detector, photosensor arrays
- Gd-doped water neutron shield

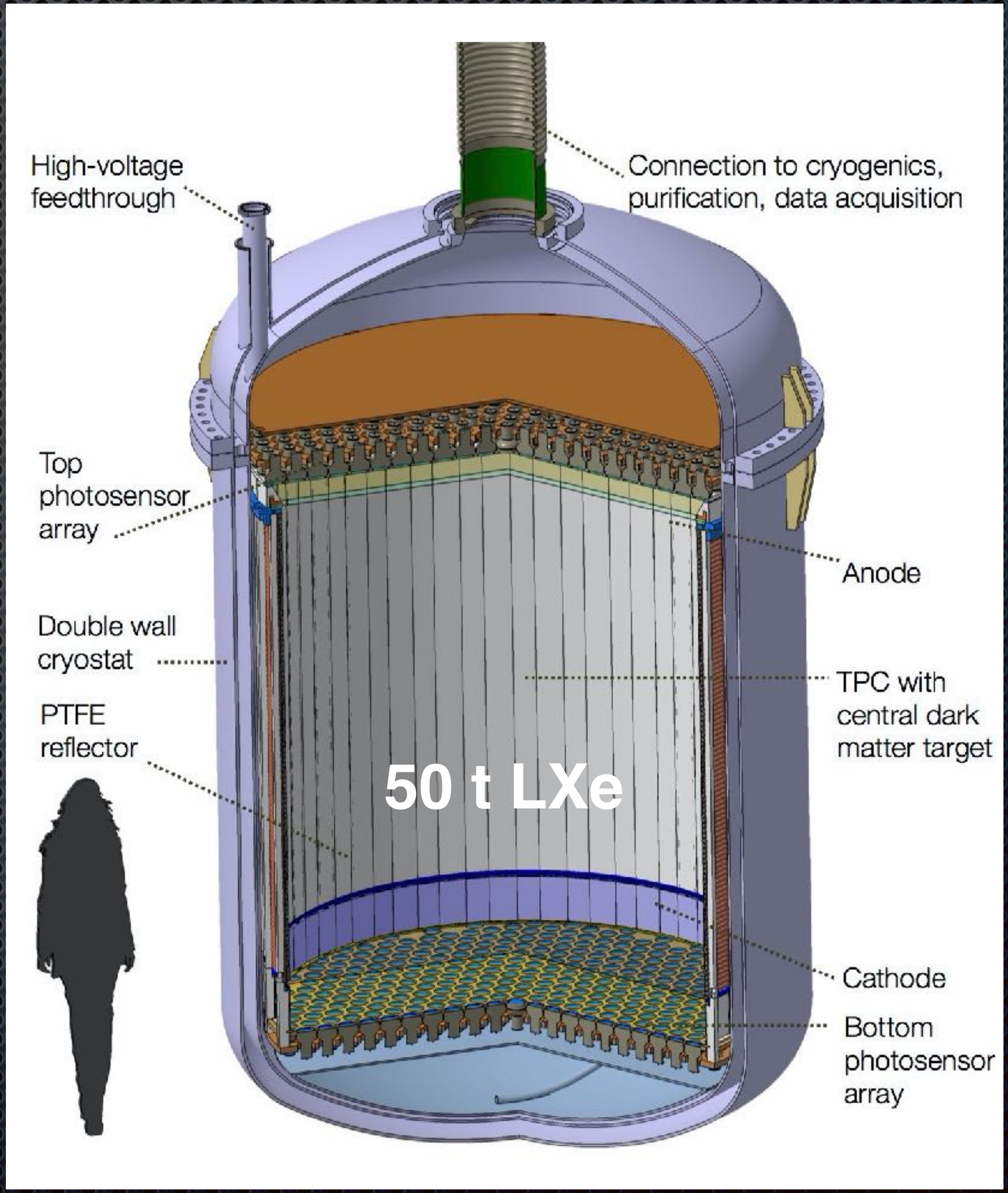
The XENON collaboration

- 165 scientists, 25 institutions, 11 countries

The DARWIN Observatory

- Ultimate dark matter detector
- 50 tons liquid xenon
- Probe the experimentally accessible parameter space for WIMP dark matter (before the neutrino background will dominate)

darwin-observatory.org



DARWIN Collaboration, JCAP 1611 (2016) 017 darwin-observatory.org

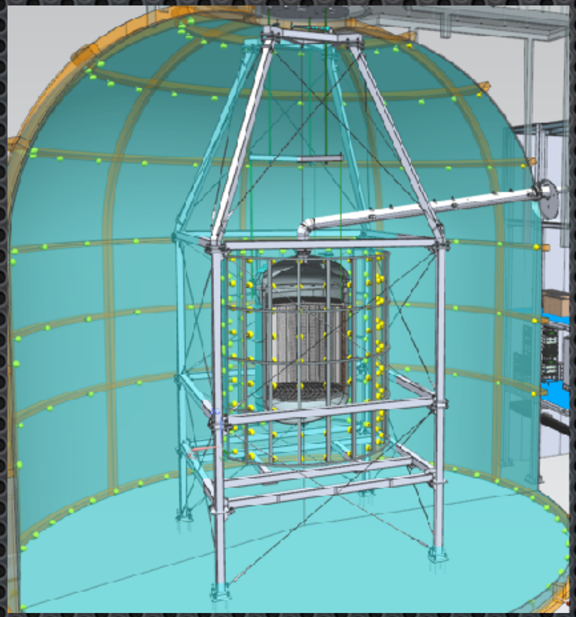
@DarwinObserv

DARWIN physics

DIRECT DARK MATTER DETECTION

SOLAR AXIONS

NEUTRINOLESS DOUBLE BETA DECAY ^{136}XE



GALACTIC ALPS, DARK PHOTONS

LOW-ENERGY SOLAR NEUTRINOS

COHERENT NEUTRINO NUCLEUS SCATTERS

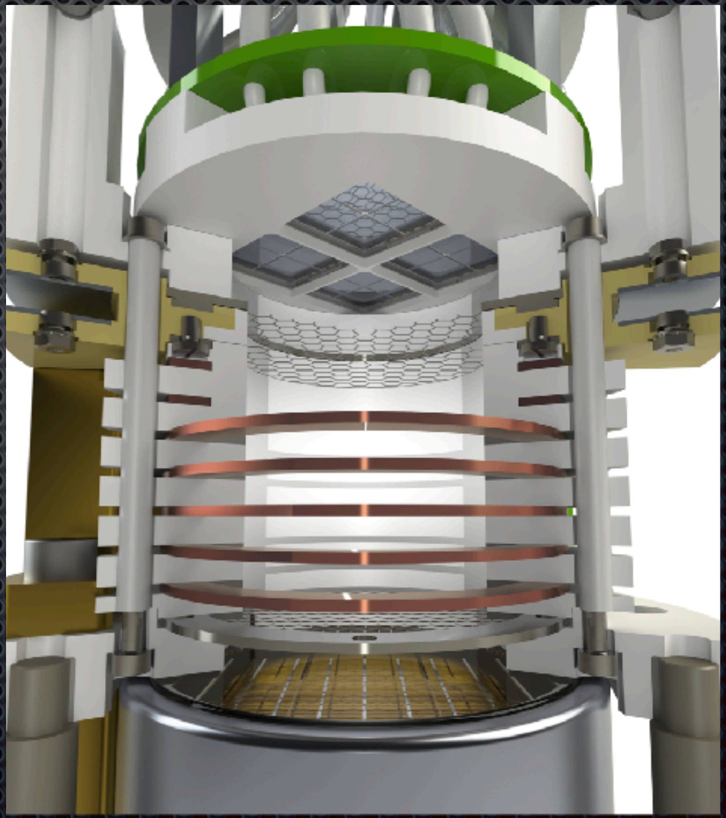
SUPERNOVA NEUTRINOS

European Research Council
Established by the European Commission

DARWIN Demonstrator

- In construction at UZH (ERC grant Xenoscope)
- Small detector for photosensor R&D (Xurich)

Darwin demonstrator in our lab at UZH



L. Baudis et al., arXiv:2003.01731

Xurich detector

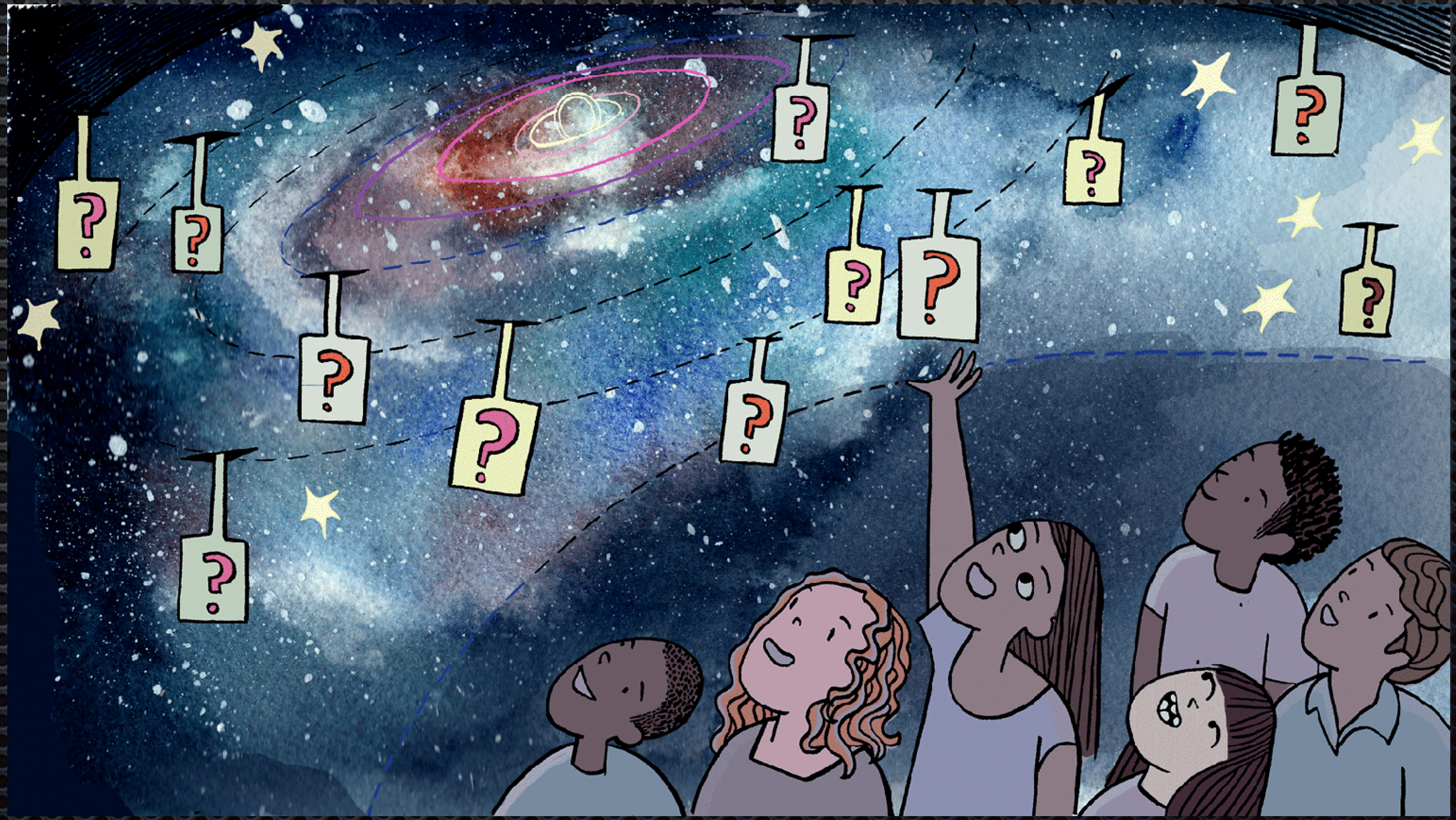
Many open questions…

Is the DM really made of new, weakly interacting massive particles?

What are the properties of these particles?

Are there more than one type of dark matter particles?

What is their detailed distribution in the Milky Way?



http://www.symmetrymagazine.org

Thank you

The Adolph C. and Mary Sprague
MILLER INSTITUTE
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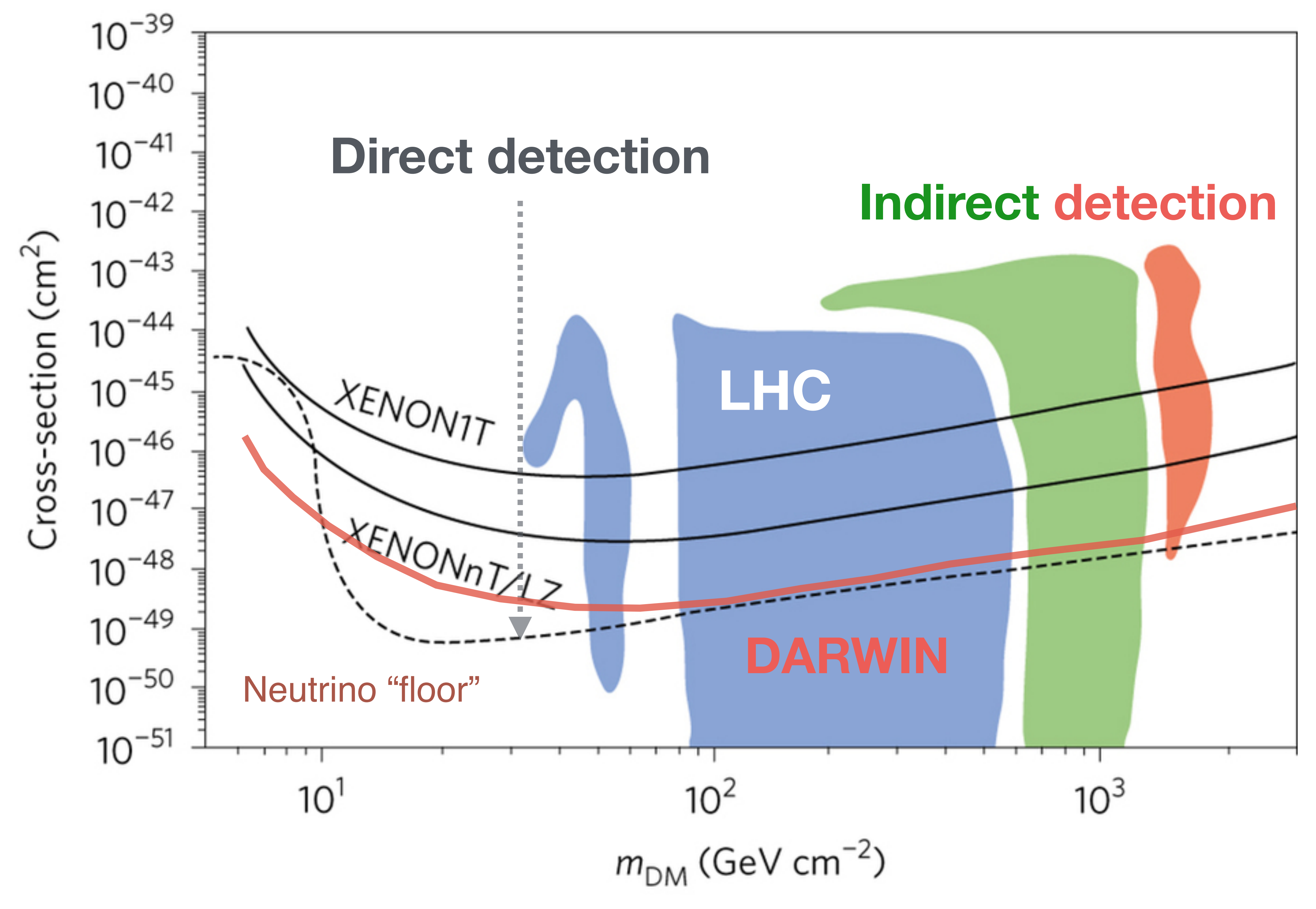
Hilary Jacobsen
Donata Huber
Emily Birman

Hosts at UCB and LBNL:
Yury Kolomensky
Alan Poon

Coaches: Nikhil Bhatla, Louis Kang

The End

Direct, indirect & LHC

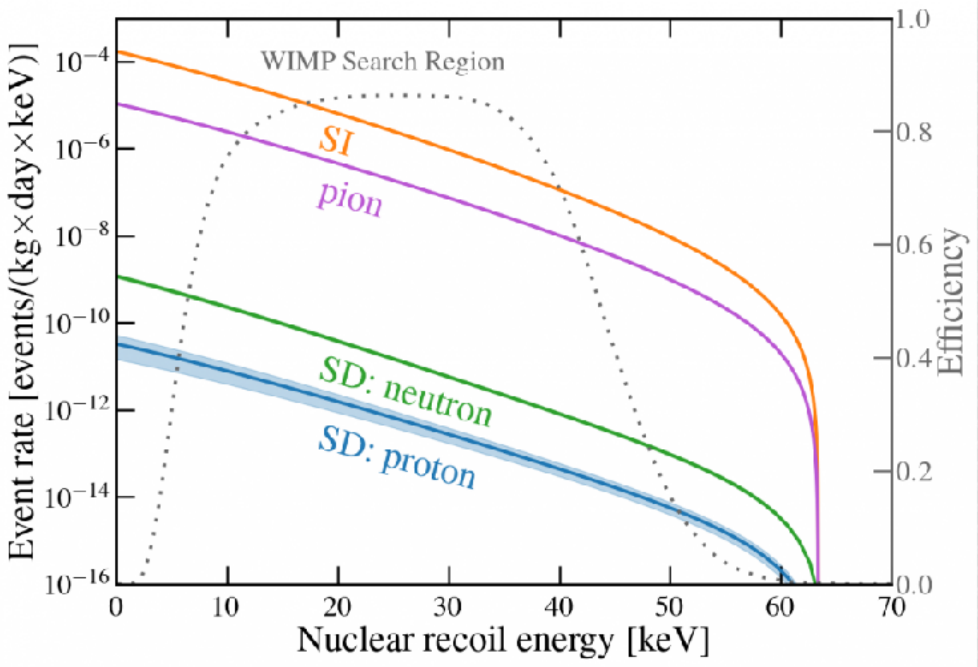


After Nature physics, March 2017

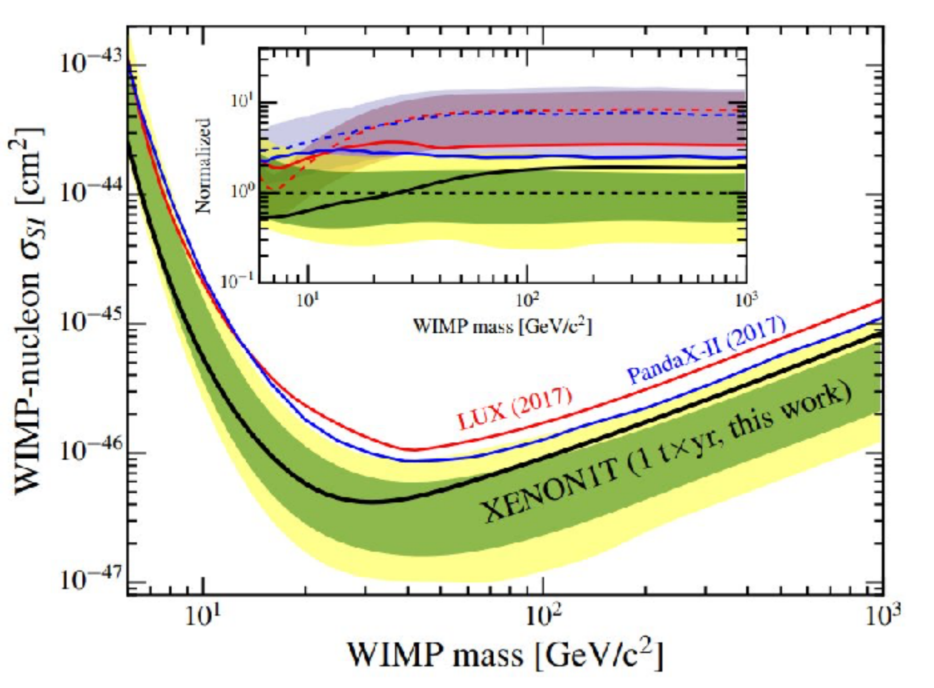
Dark matter results

XENON, PRL 122, 2019

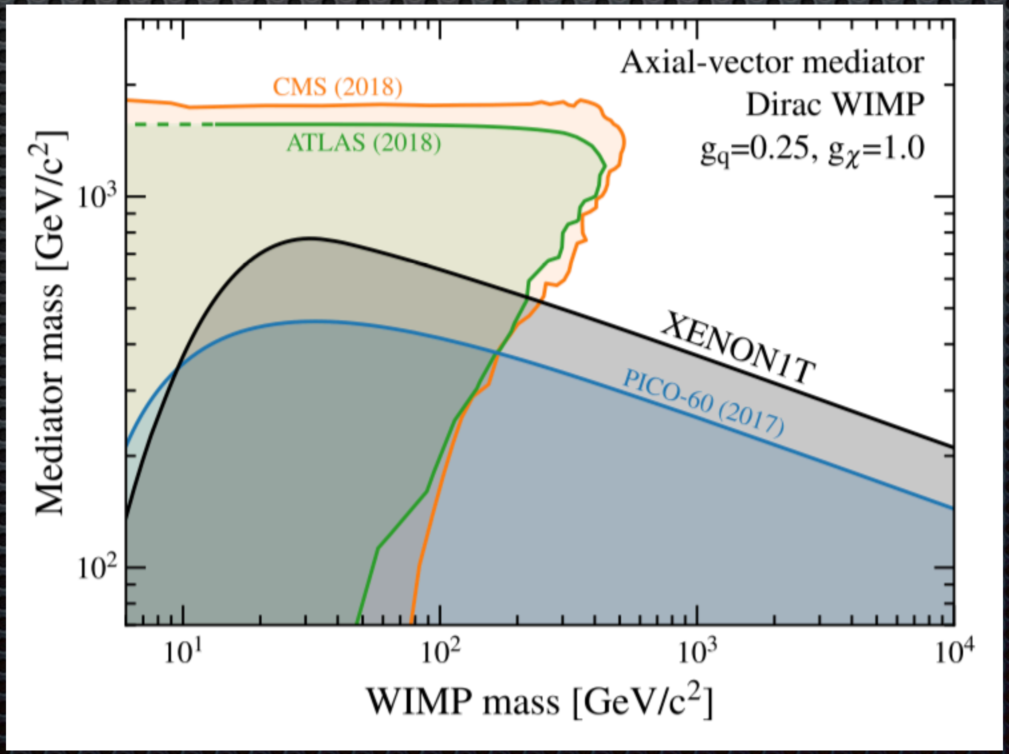
30 GeV WIMP, σ=1x10^{-45} cm^2



$\sigma_{\rm SI} < 4.1 \times 10^{-47}{\rm cm}^2$ at $30\,{\rm GeV/c}^2$



Axial-vector mediator and a Dirac WIMP, with fixed mediator-quark and mediator-WIMP coupling

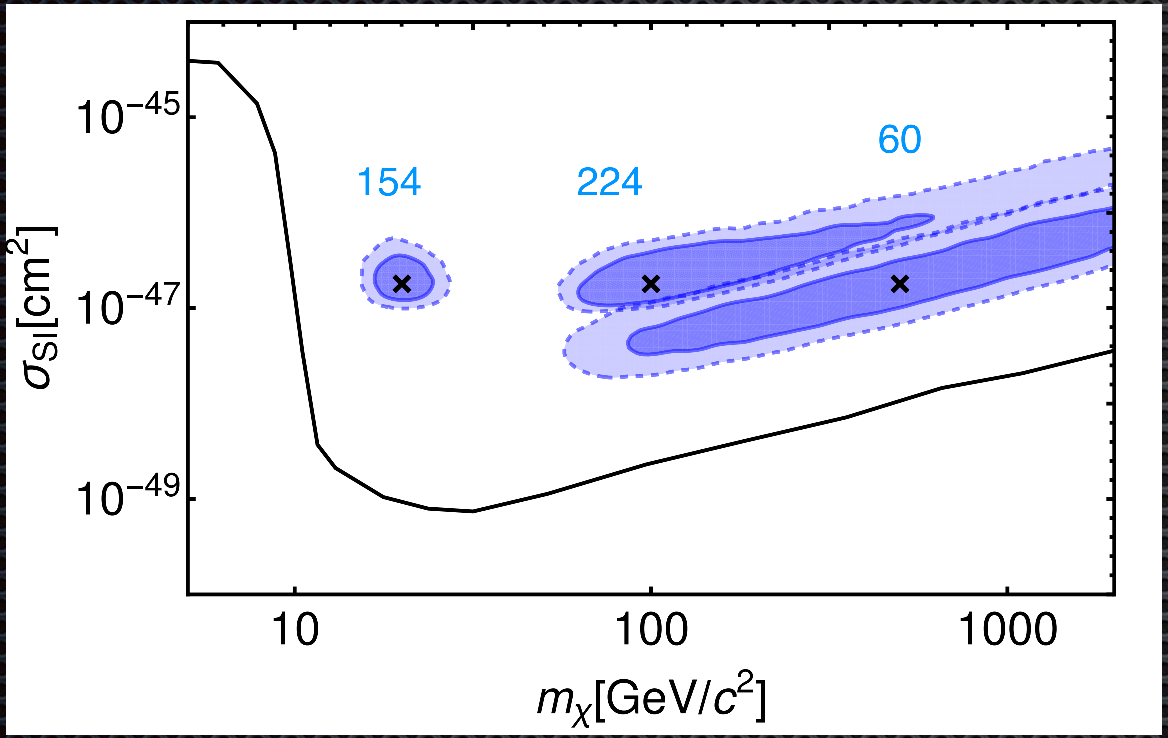


XENON, PRL 122, 2019

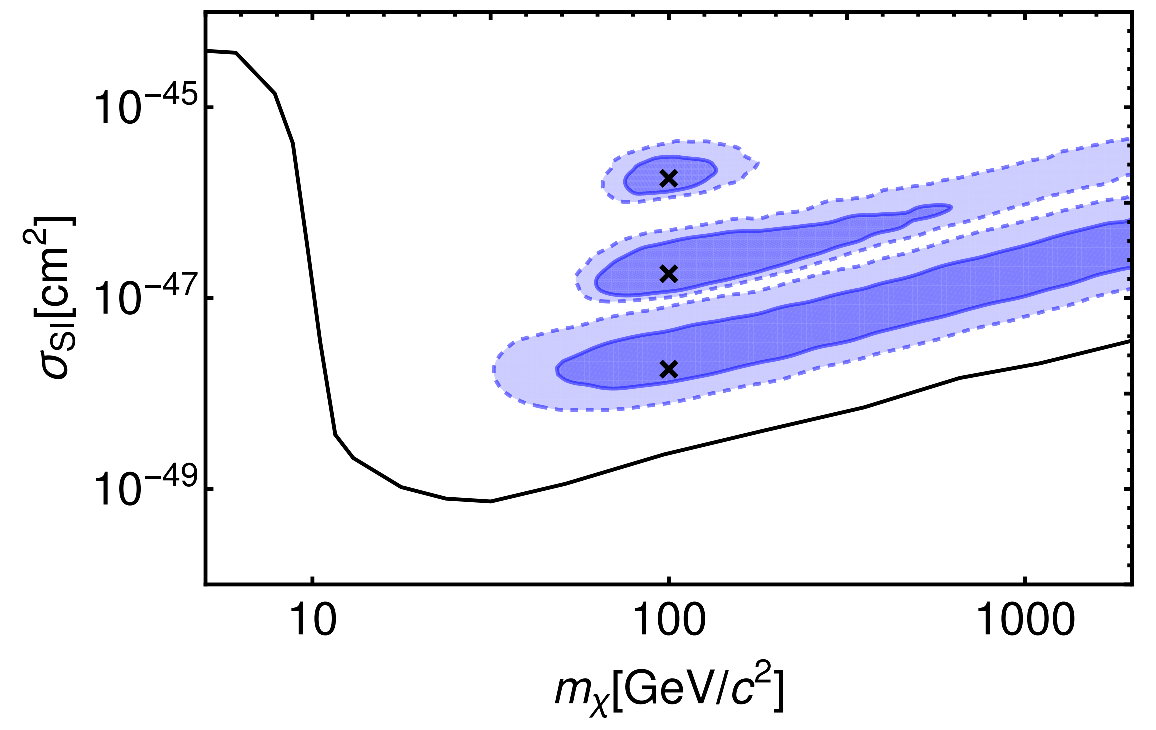
Dark matter spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses - here 20, 100, 500 GeV/c^2 -

Exposure: 200 t y



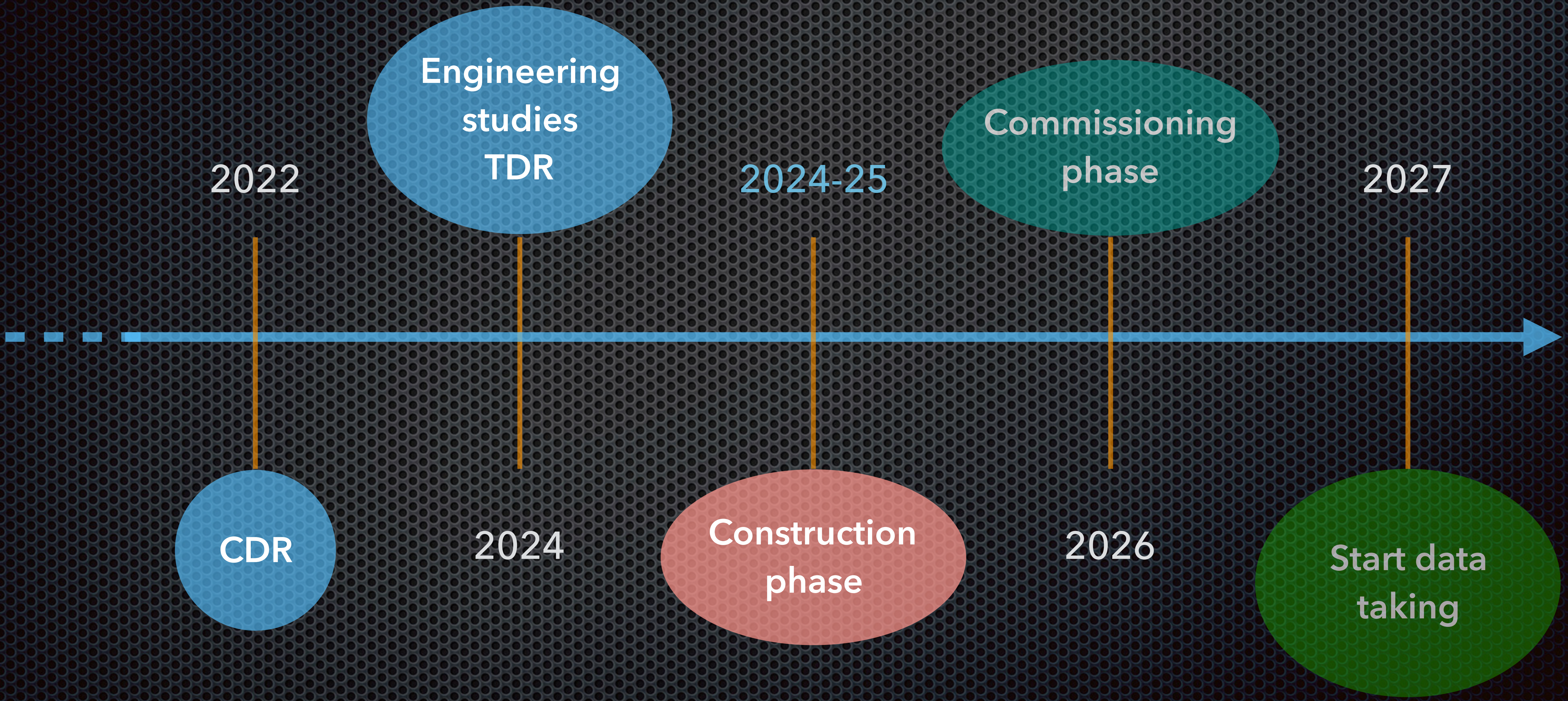
Exposure: 200 t y



1 and 2 sigma credible regions after marginalising the posterior probability distribution over:

Update: Newstead et al., PRD D 88, 076011 (2013) darwin-observatory.org

The timescale for DARWIN



2022

CDR

Engineering studies TDR

2024

2024-25

Construction phase

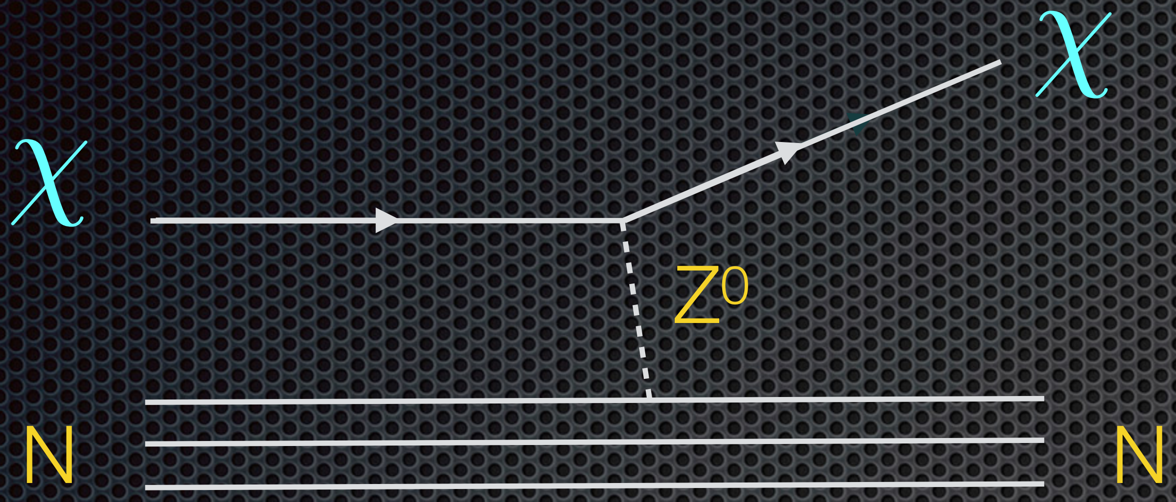
Commissioning phase

2026

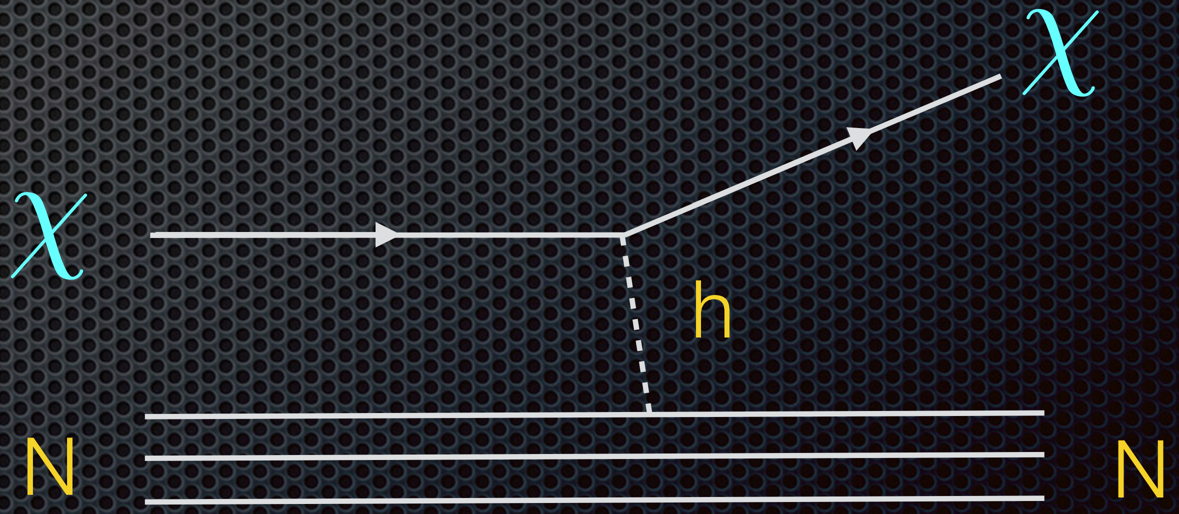
2027

Start data taking

Example cross sections



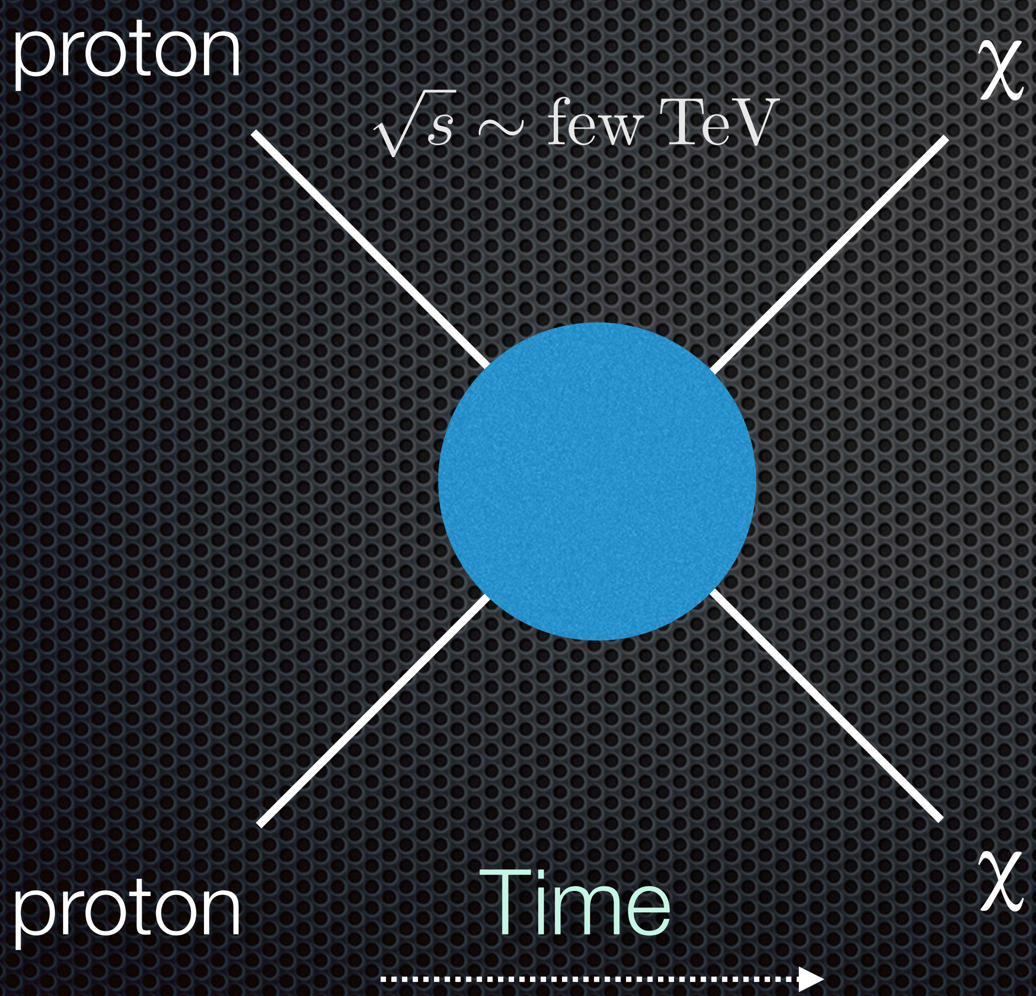
$$\sigma_0 \sim 10^{-39} \mathrm{cm}^2$$

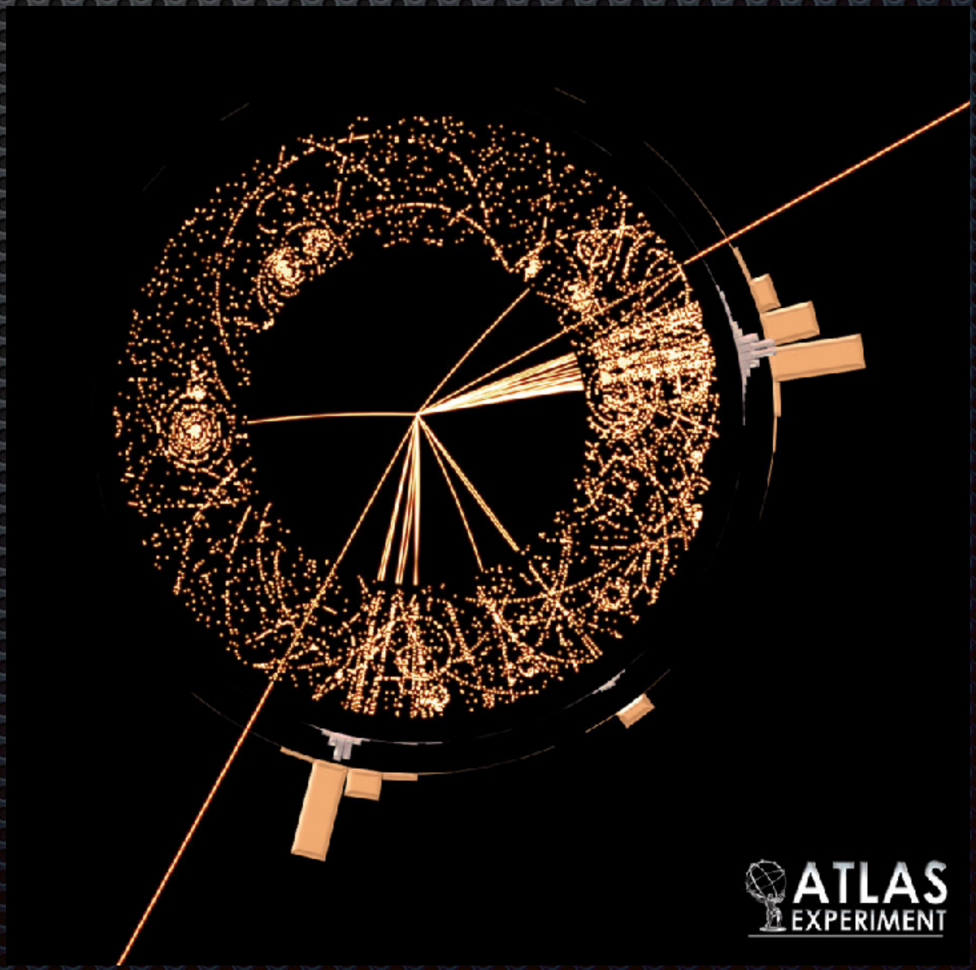


$$\sigma_0 \sim 10^{-44} - 10^{-47}\, \mathrm{cm}^2$$

How to make them visible?

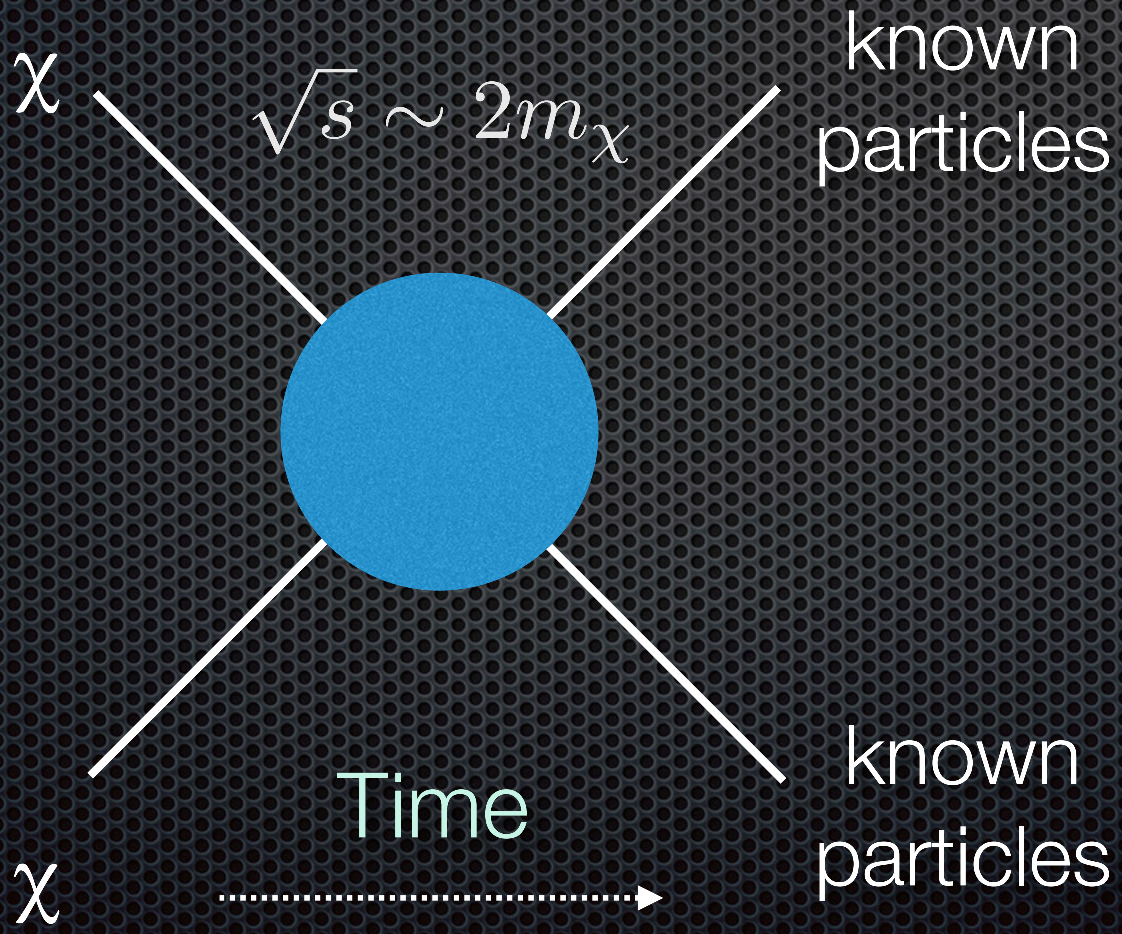
Produce such new particles at the LHC, in p-p collisions





How to make them visible?

Look for their *annihilation products* in the Galactic Halo, Galactic Centre or in the Sun



χ

$\sqrt{s} \sim 2m_\chi$

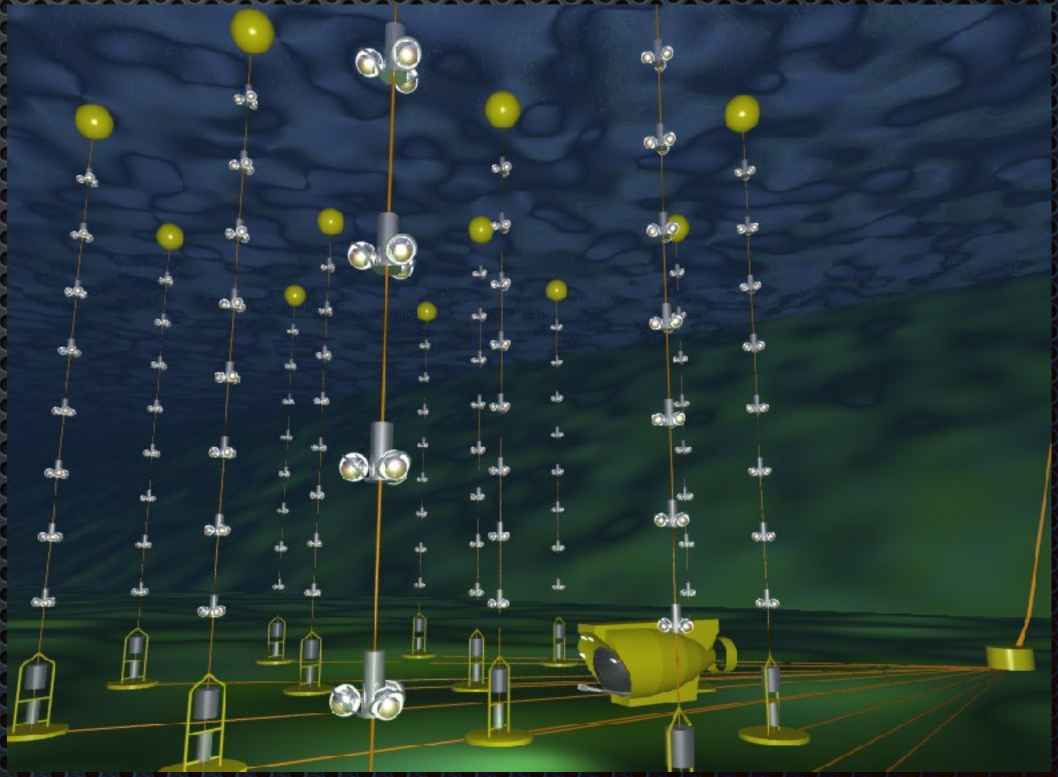
known particles

χ

Time

known particles

The AMS experiment on the ISS

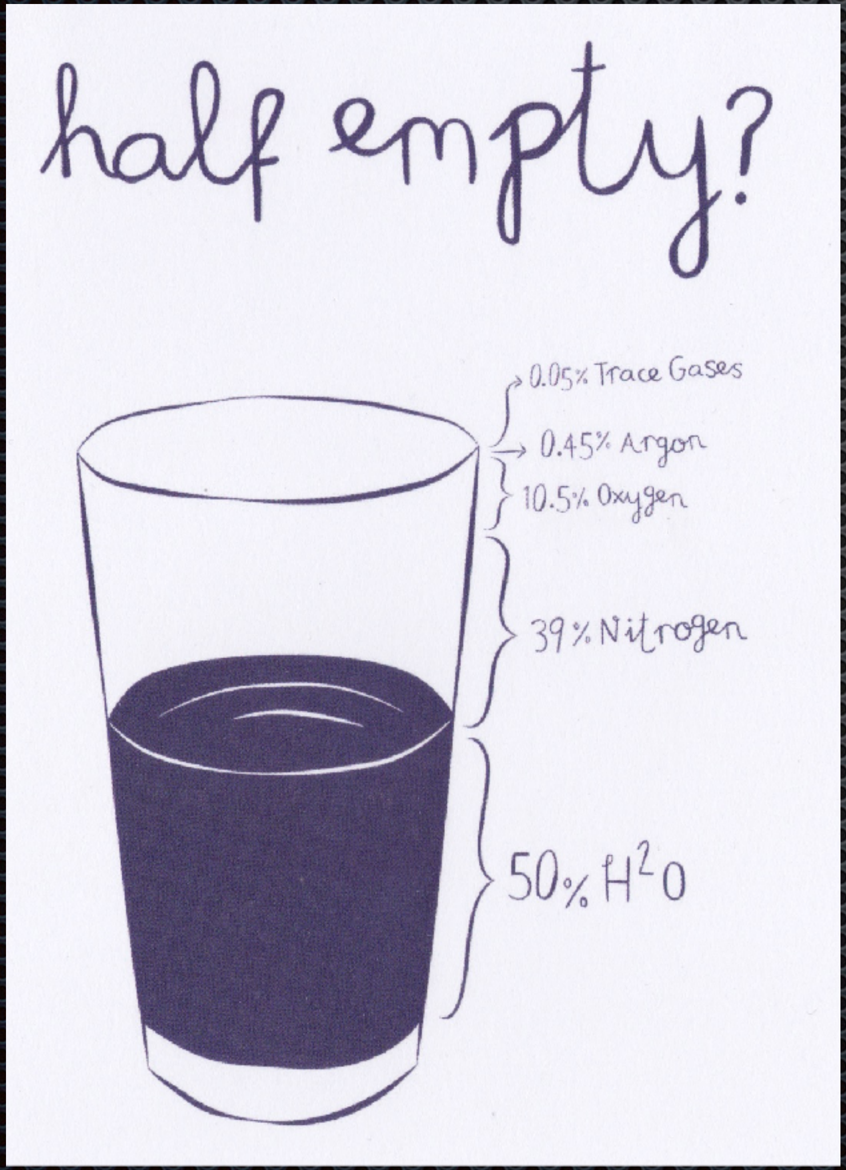


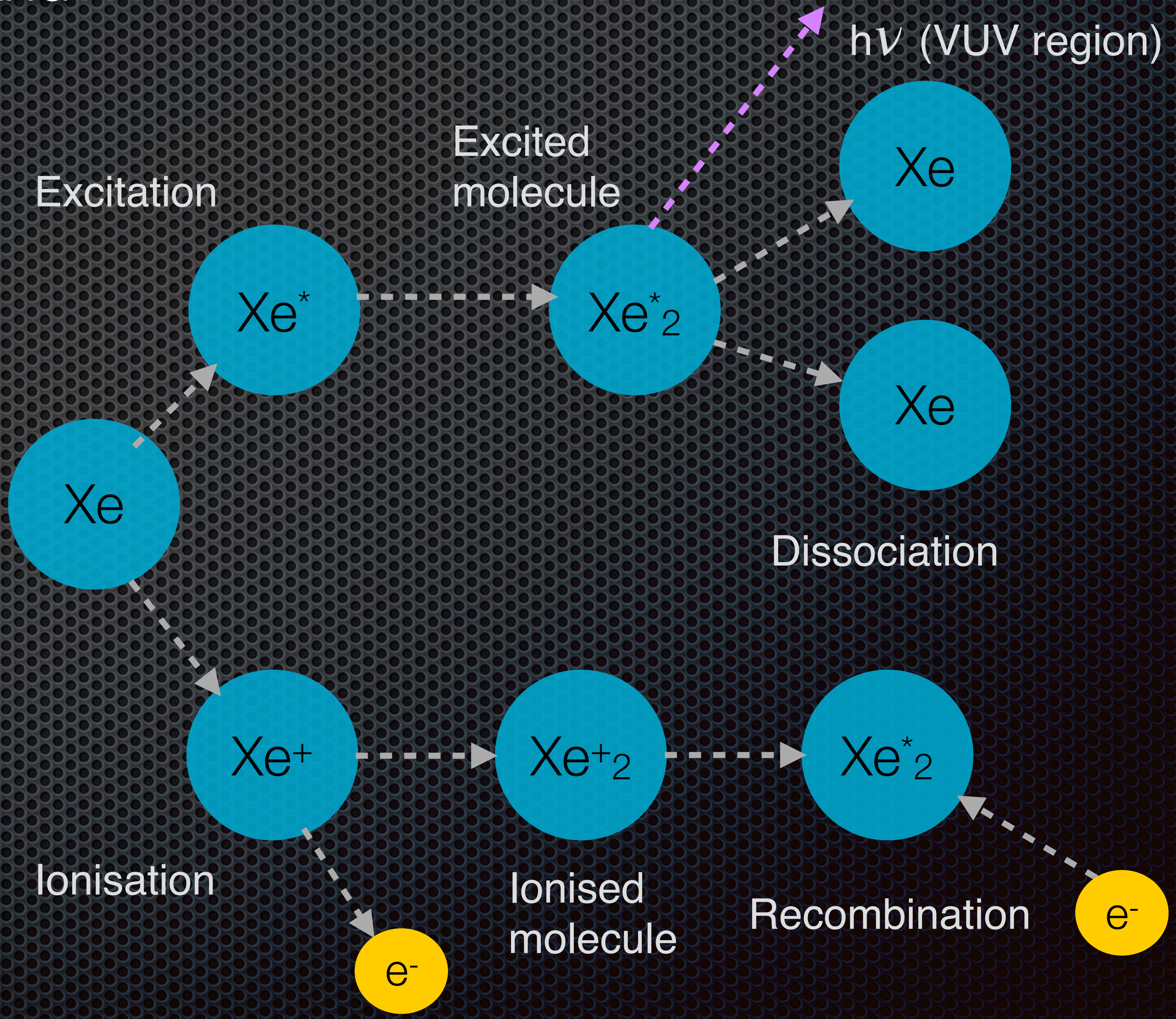
The Antares experiment in the Mediterranean sea

Ar 18 Xe 54

Liquified noble gases

- Xenon (“the strange one”) and argon (“the inactive one”)





Excitation

Excited molecule

$h\nu$ (VUV region)

Xe

Xe^*

Xe^*_2

Xe

Xe

Dissociation

Xe^+

Ionisation

e^-

Xe^+_2

Ionised molecule

Xe^*_2

Recombination

e^-