Universität Zürich[UZH]

# Illuminating the dark: direct searches for cold dark matter in the Milky Way

Laura Baudis
University of Zurich

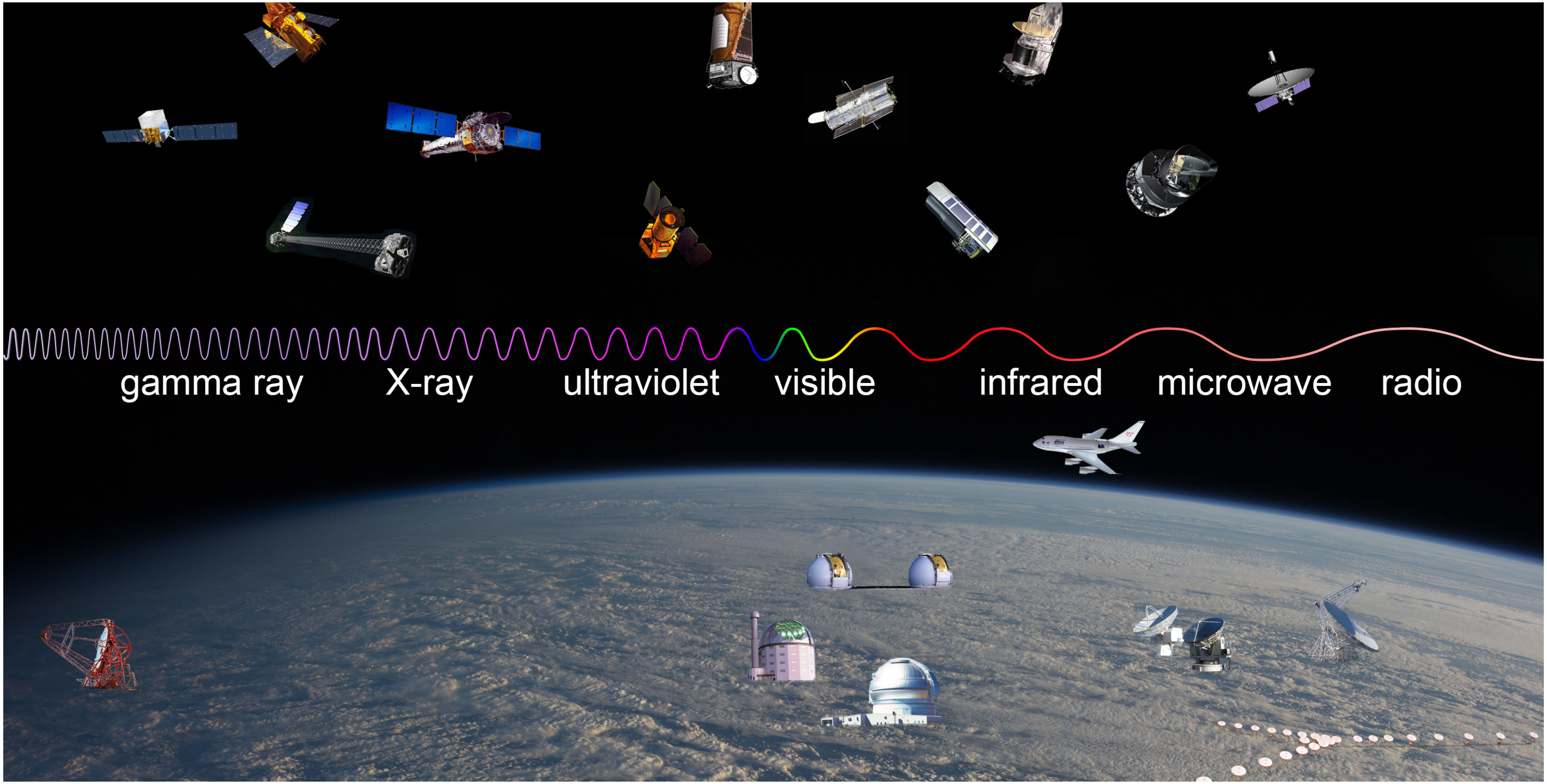
Elizabeth Spreadbury Lecture
UCL, March 14, 2018

ESA/Gaia 2015

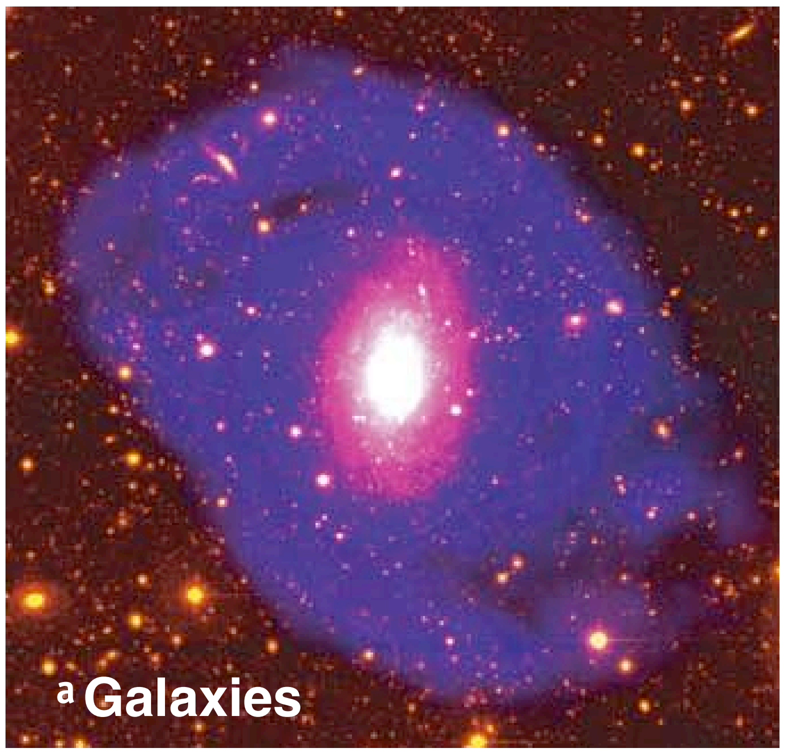
# When you look at the sky in a dark, clear night….

# Andromeda, our neighbour, 2 million light years away…

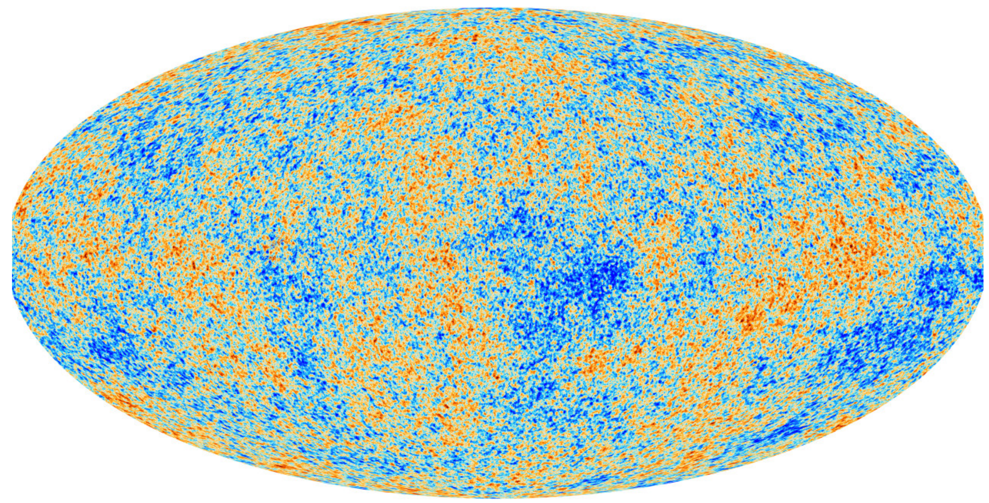
# Mapping the visible Universe

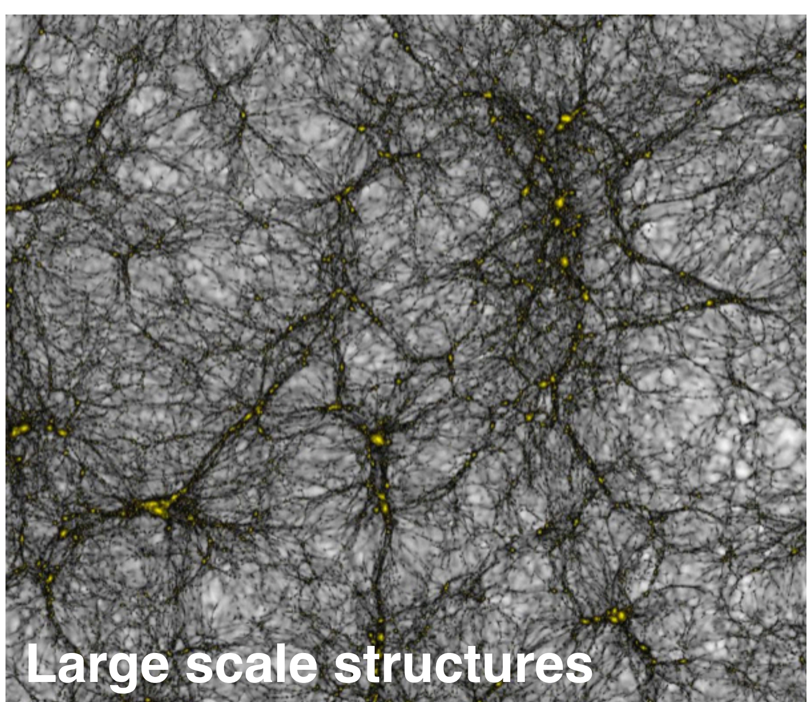


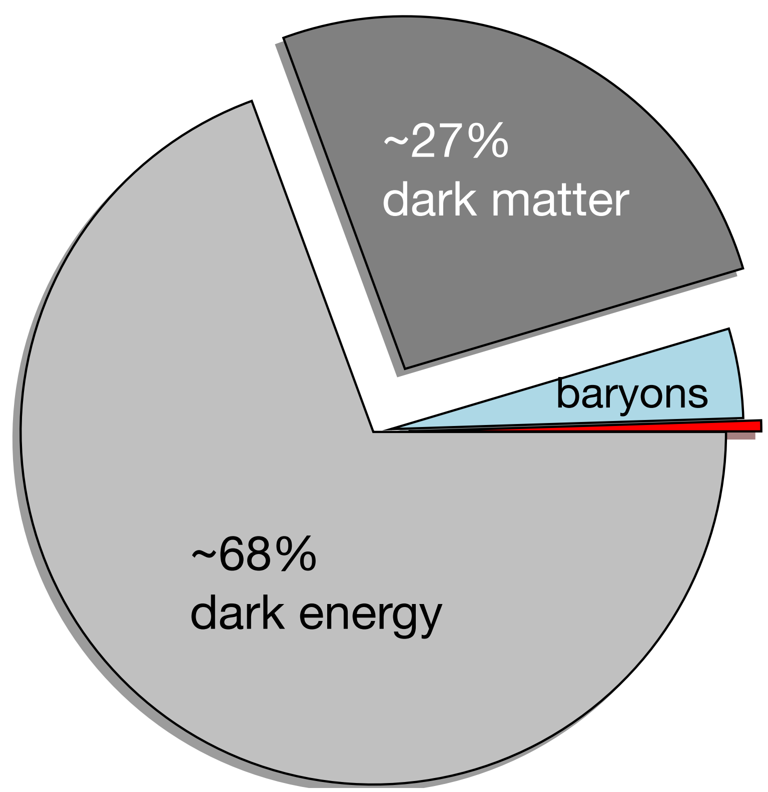
# Our Universe today: apparently consistent picture from an impressive number of observations

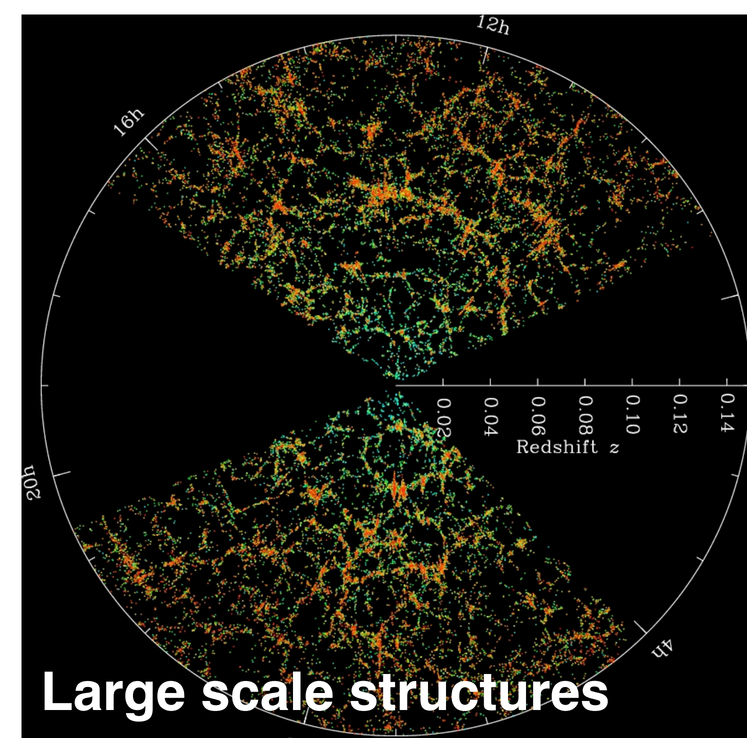



Cosmic microwave background



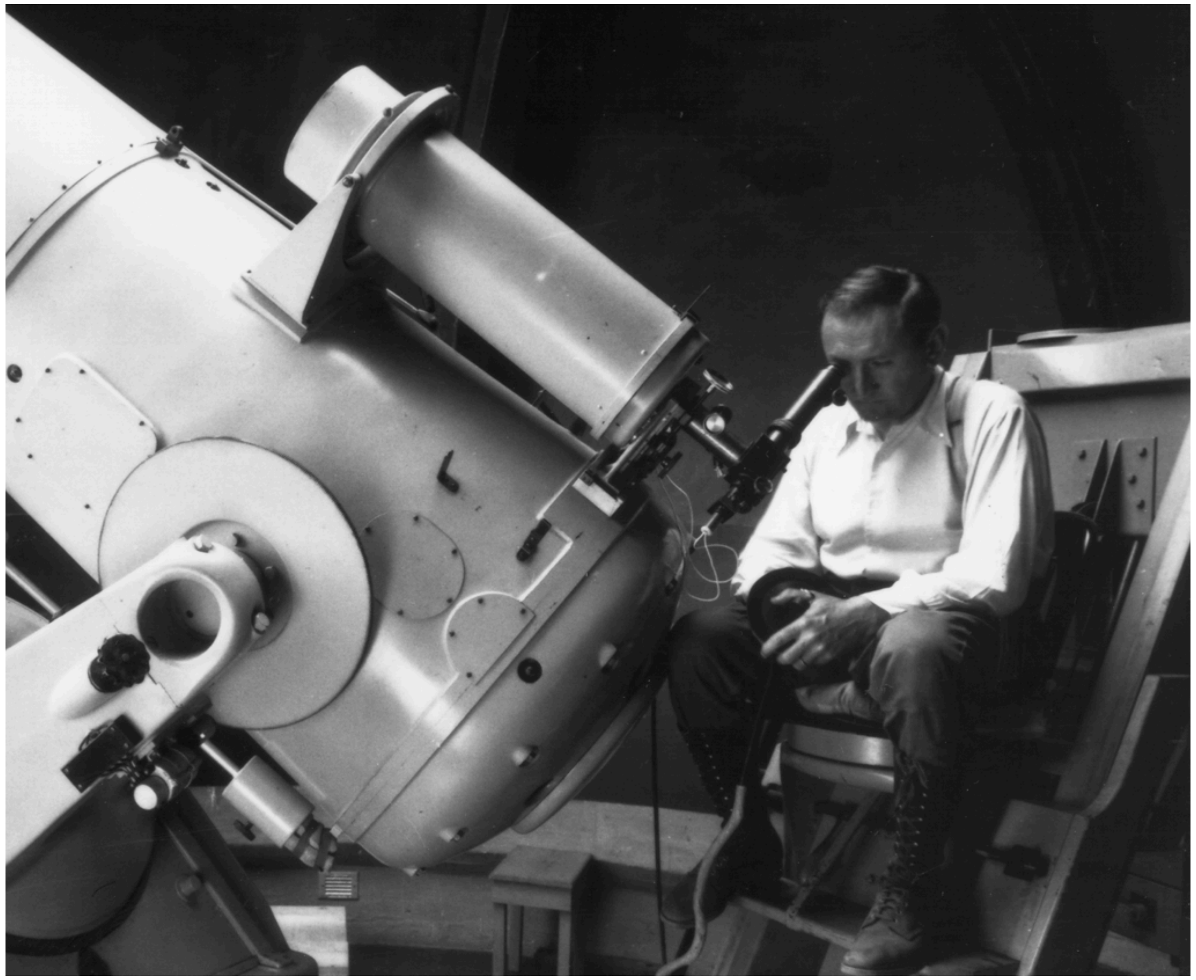



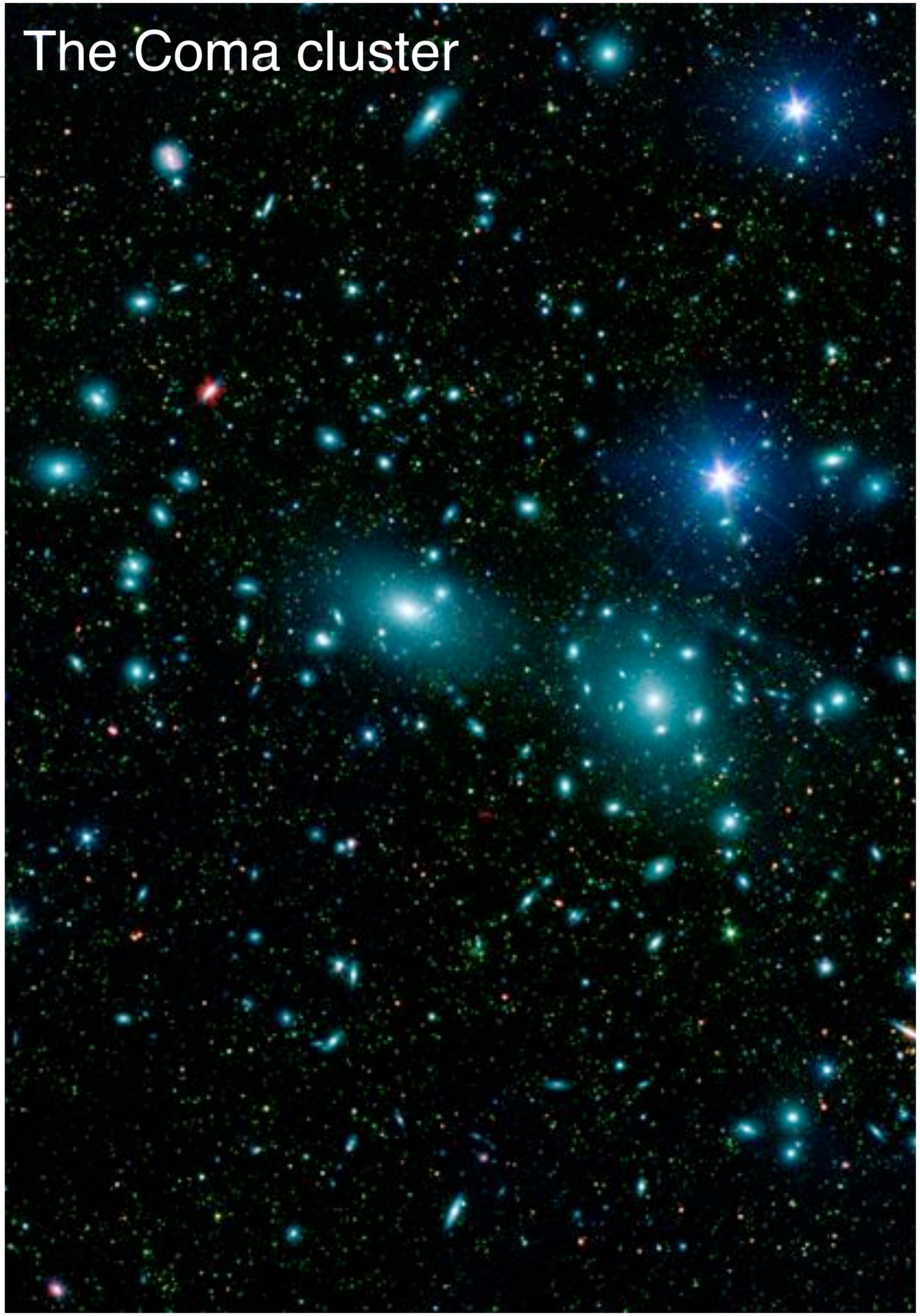



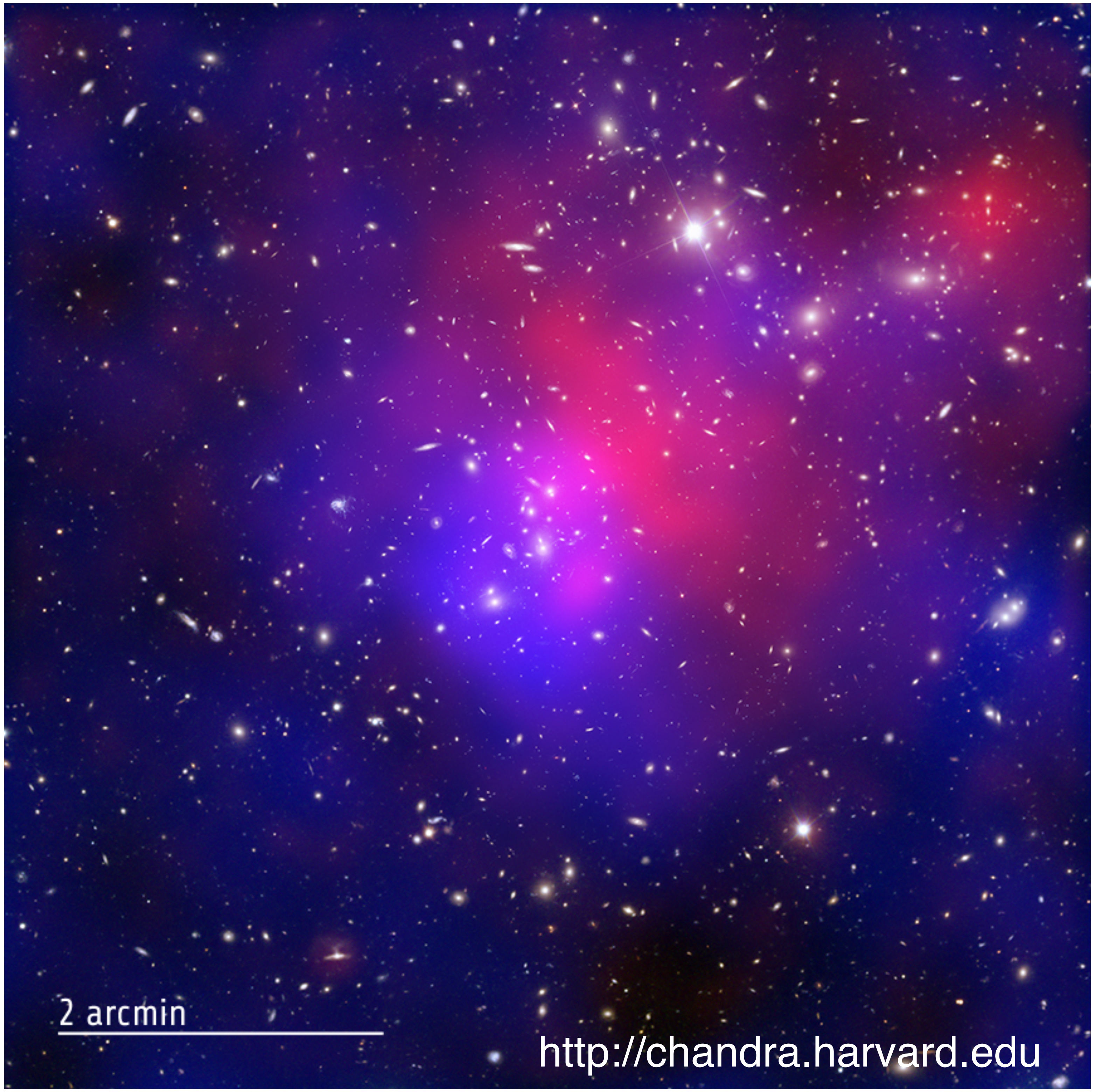
# Dark matter in galaxy clusters

Fritz Zwicky, 1933





# Dark matter in clusters of galaxies

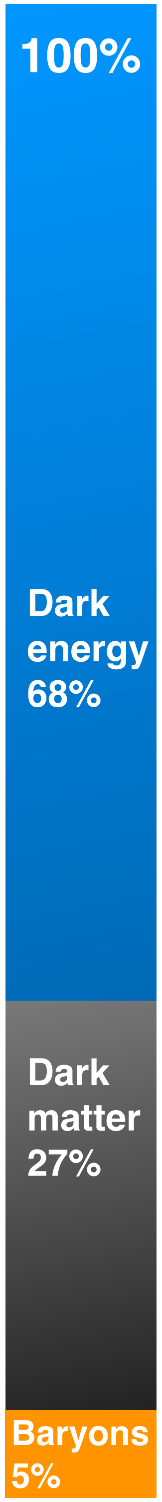



Pandora's Cluster
(Abell 2744)

3.5 billion light years from Earth

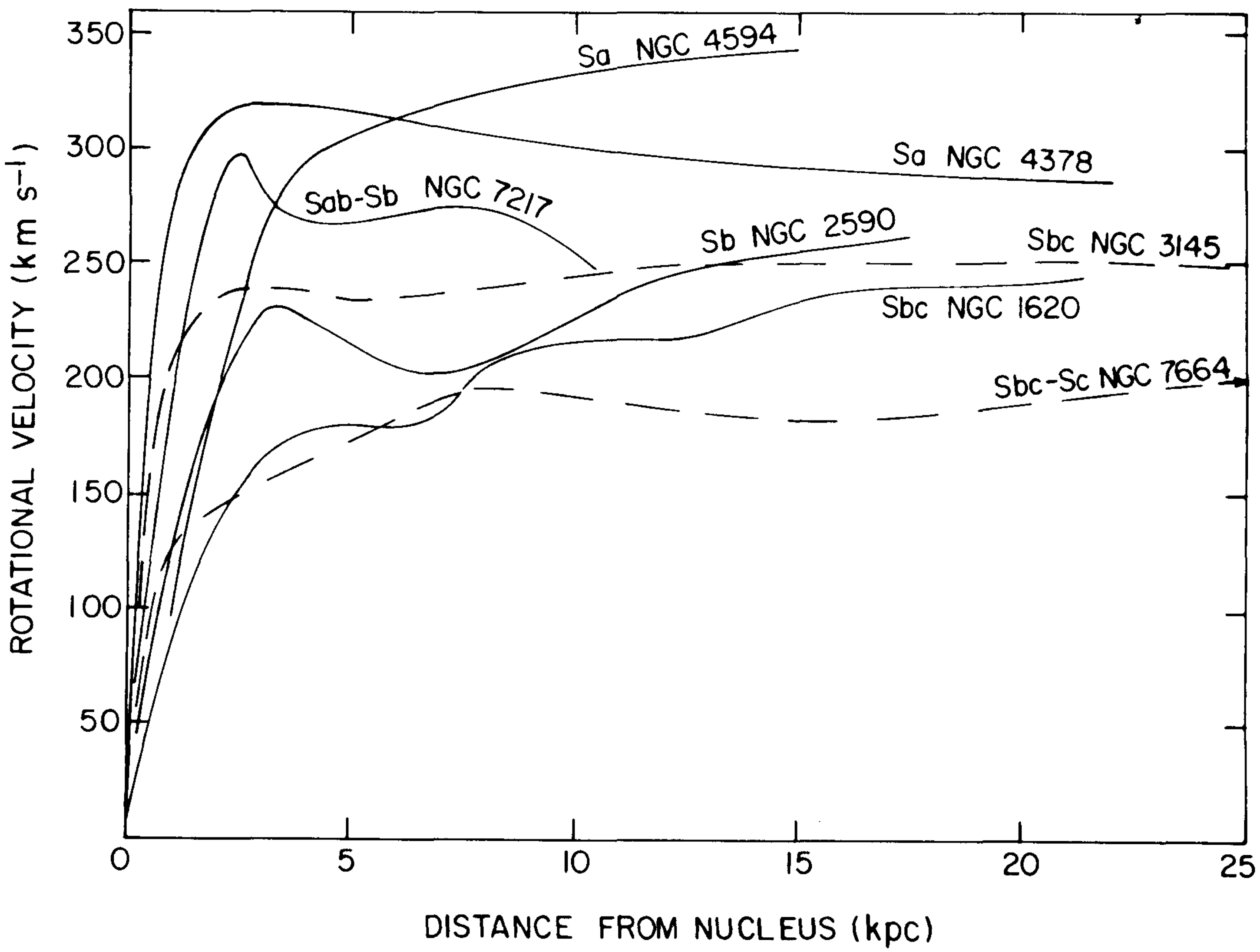
Blue: dark matter
Red: hot X-ray gas
**Optical: galaxies**
**< 5% of the total mass**

*At least 4 galaxy clusters were involved in the collision*



# Dark matter in spiral galaxies

Vera Rubin, Kent Ford, Norbert Thonnard, The Astrophysical Journal 1978

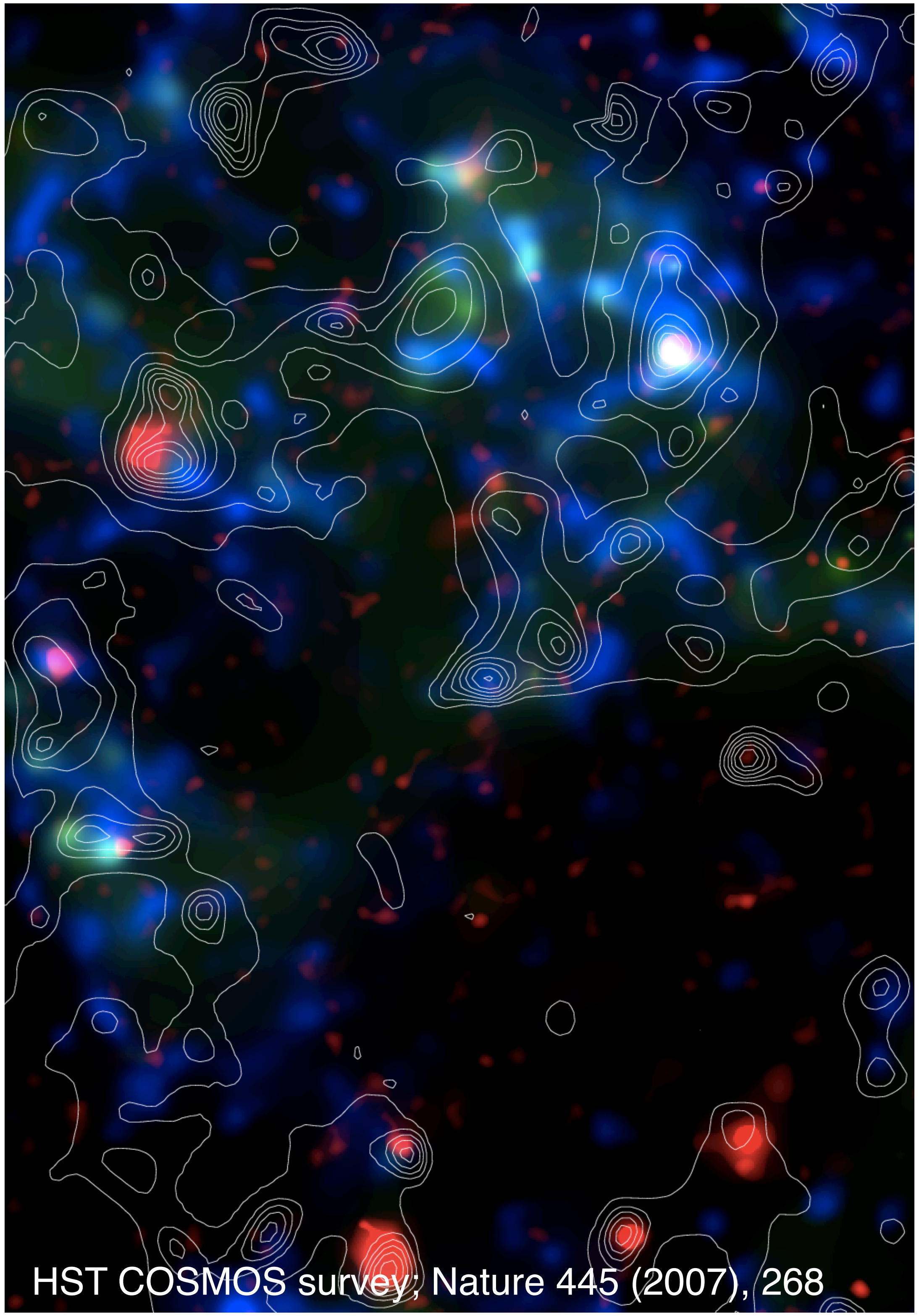



Vera Rubin:

”In a spiral galaxy, *the ratio of dark-to-light matter is about a factor of 10*. That's probably a good number for the ratio of our ignorance-to-knowledge. *We're out of kindergarten, but only in about third grade.*"

# The dark matter puzzle

Large scale distribution of dark matter, probed through gravitational lensing




The dark matter puzzle is *fundamental*: dark matter is *matter* - **it leads to the formation of structure and galaxies in our universe**

We have a standard model of cold dark matter (CDM), from ‘precision cosmology’ (CMB, LSS): however, *measurement ≠ understanding*

**For ~85% of matter in the universe is of unknown nature**

# What do we know about the dark matter?

**Exists today and in the early Universe**

**Constraints from astrophysics and searches for new particles:**

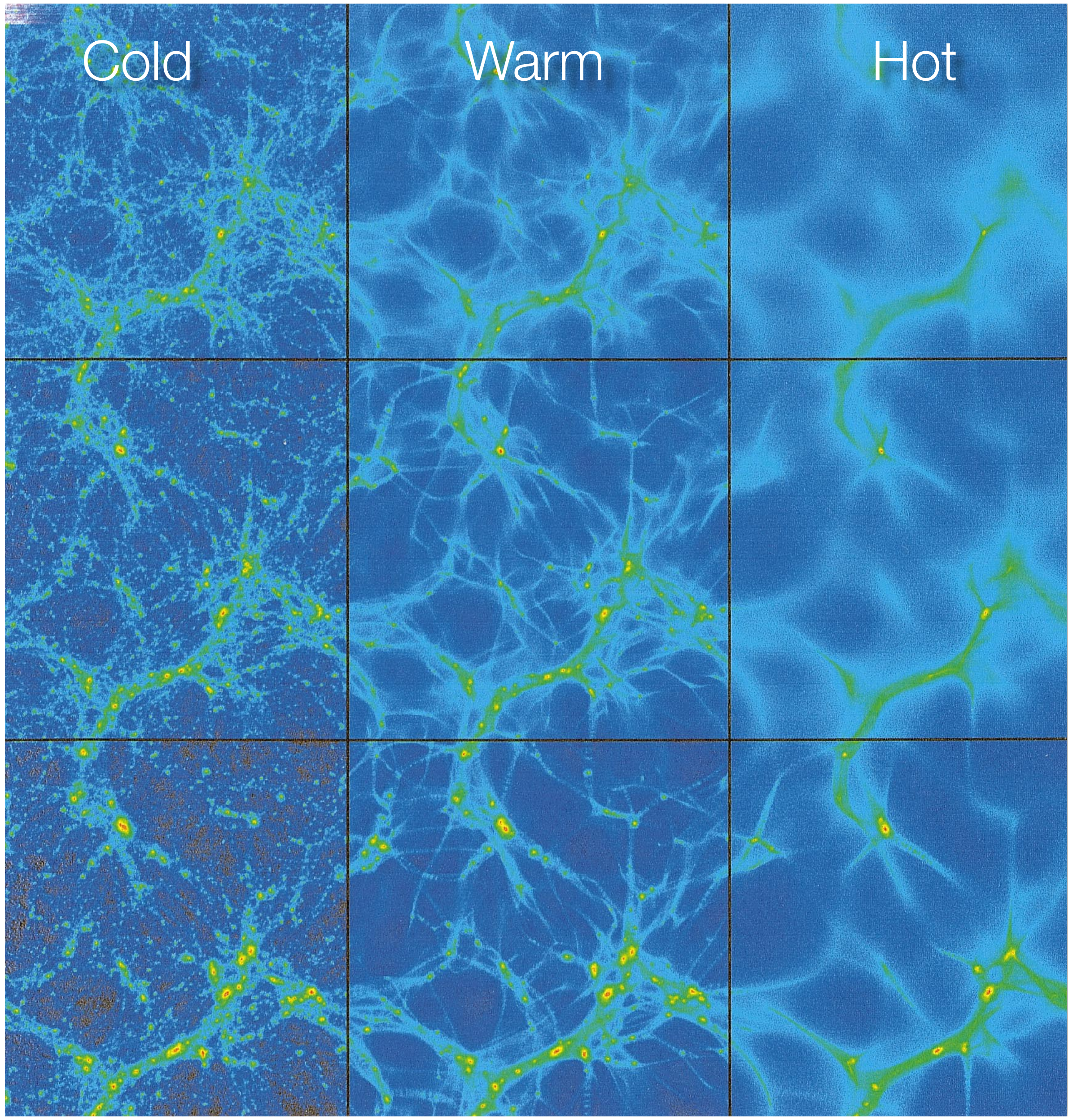
No colour charge

No electric charge

No strong self-interaction

Was slow-moving (non-relativistic) as large-scale structures were forming

**Stable, or very long-lived**



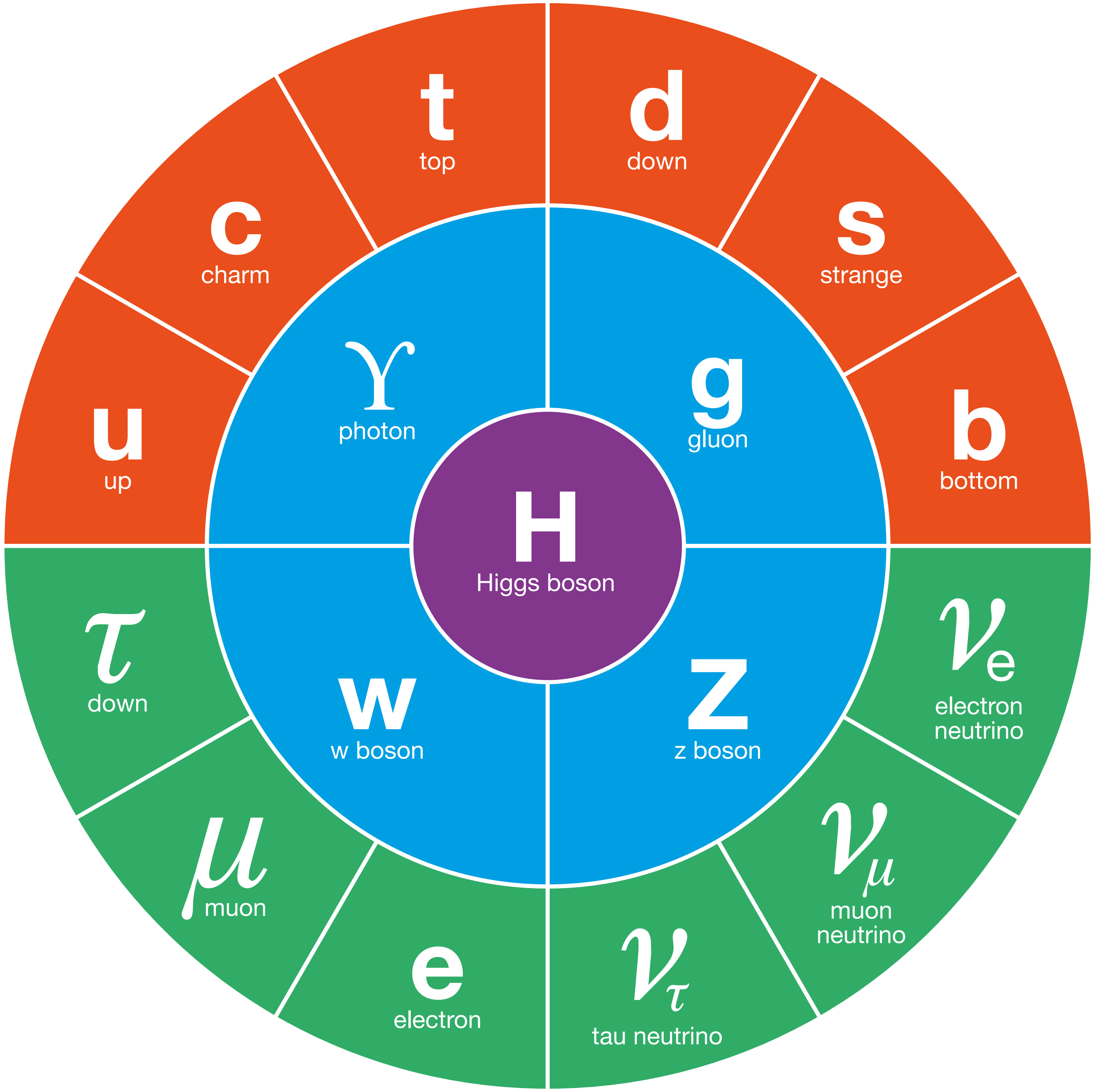

Probing dark matter through gravity

# The Standard Model of Particle Physics

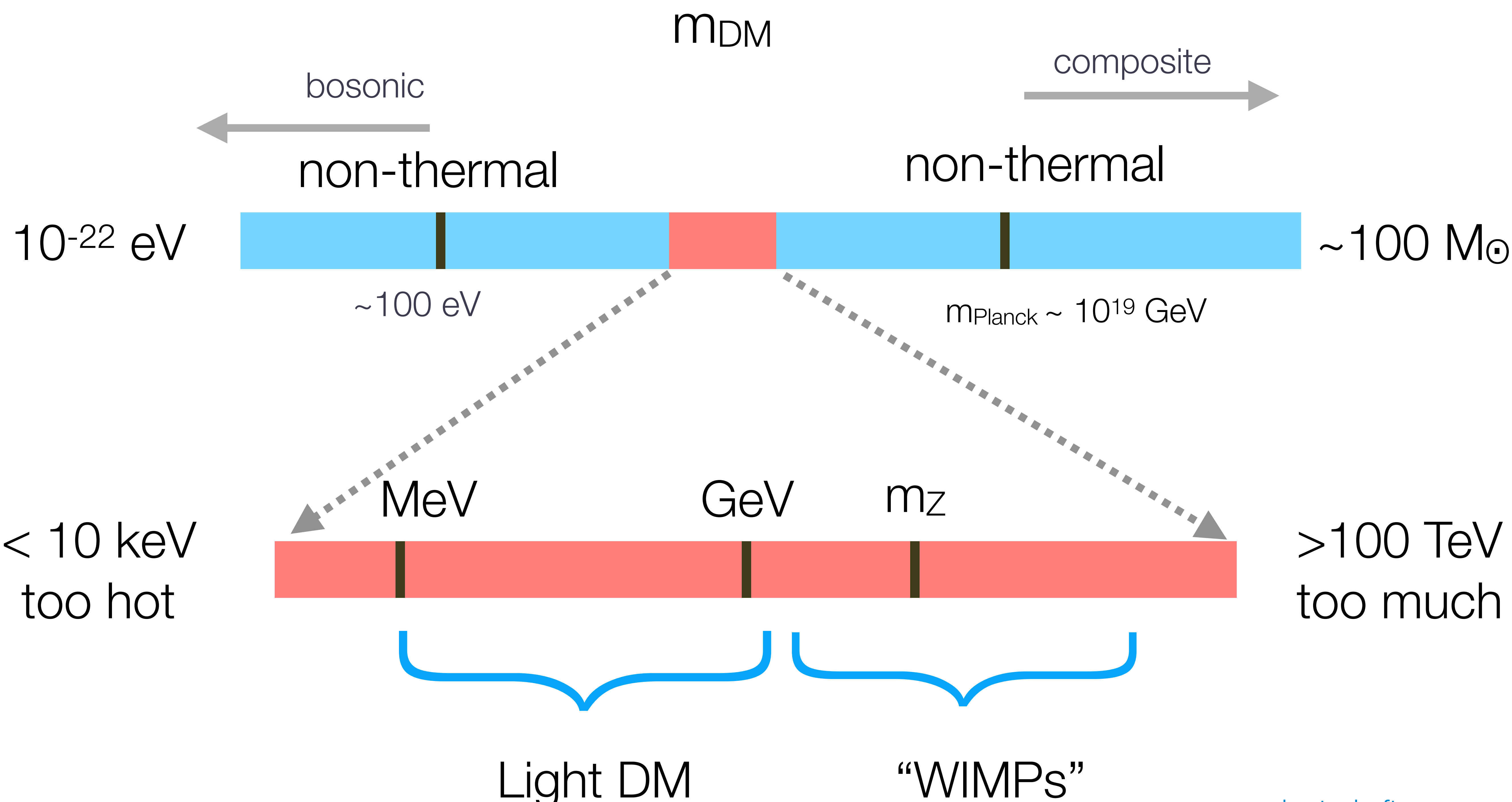
Only an “effective” theory at low energies

We expect new particles and new phenomena as well probe higher energies (e.g. at the LHC)

In particular, no particle of the Standard Model is a good dark matter candidate



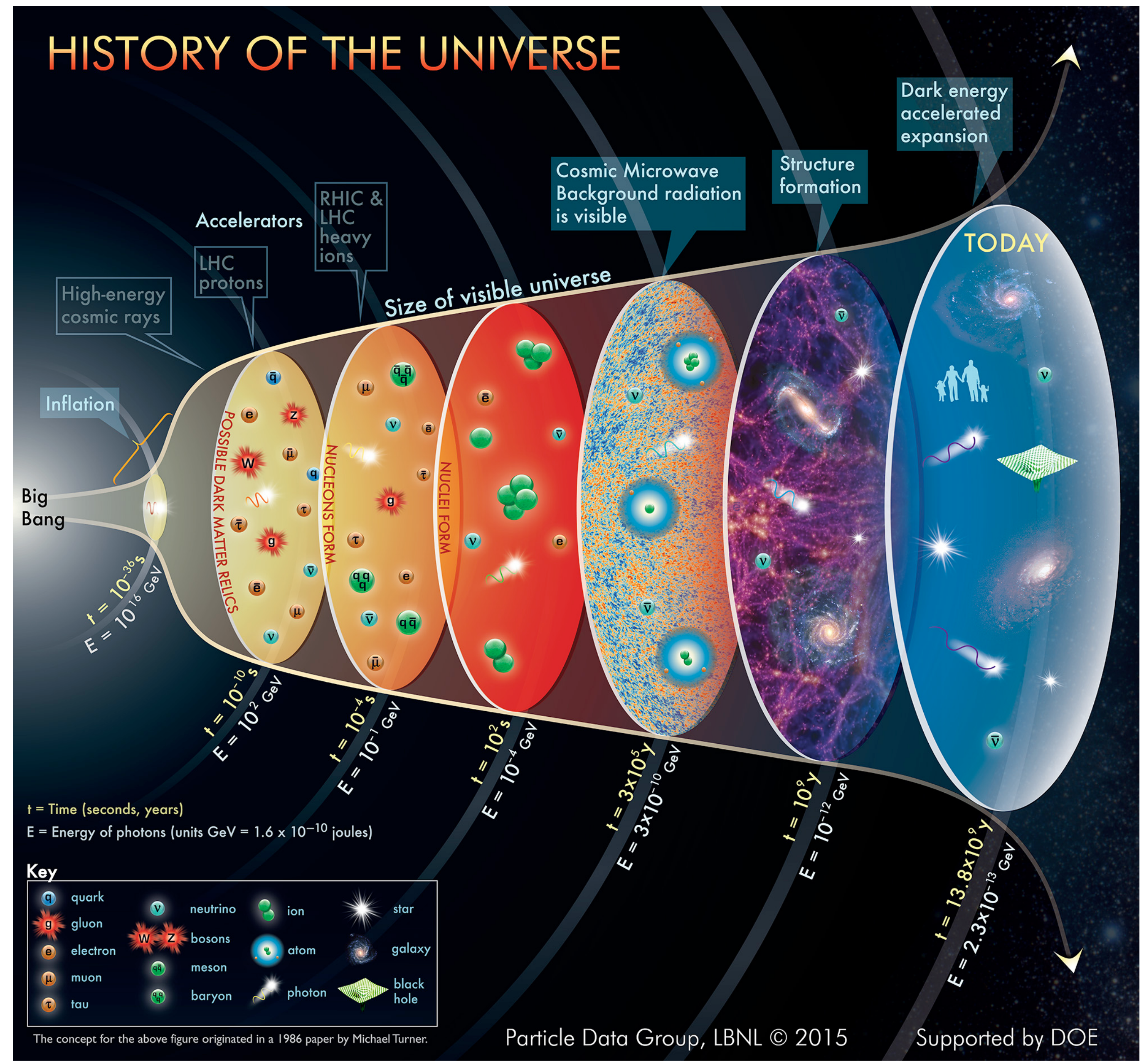
# Dark Matter Candidates



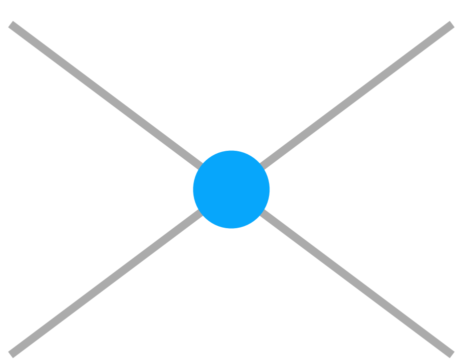

adapted after Brian Batell, Invisibles2017

# A Thermal Relic

- One of the leading hypotheses: a ‘thermal relic’ from an early period in our Universe
- when the average temperature was T ~ $10^{15}$ K ~ 100 GeV
- and *our young Universe was hot enough to create new, massive particles:*



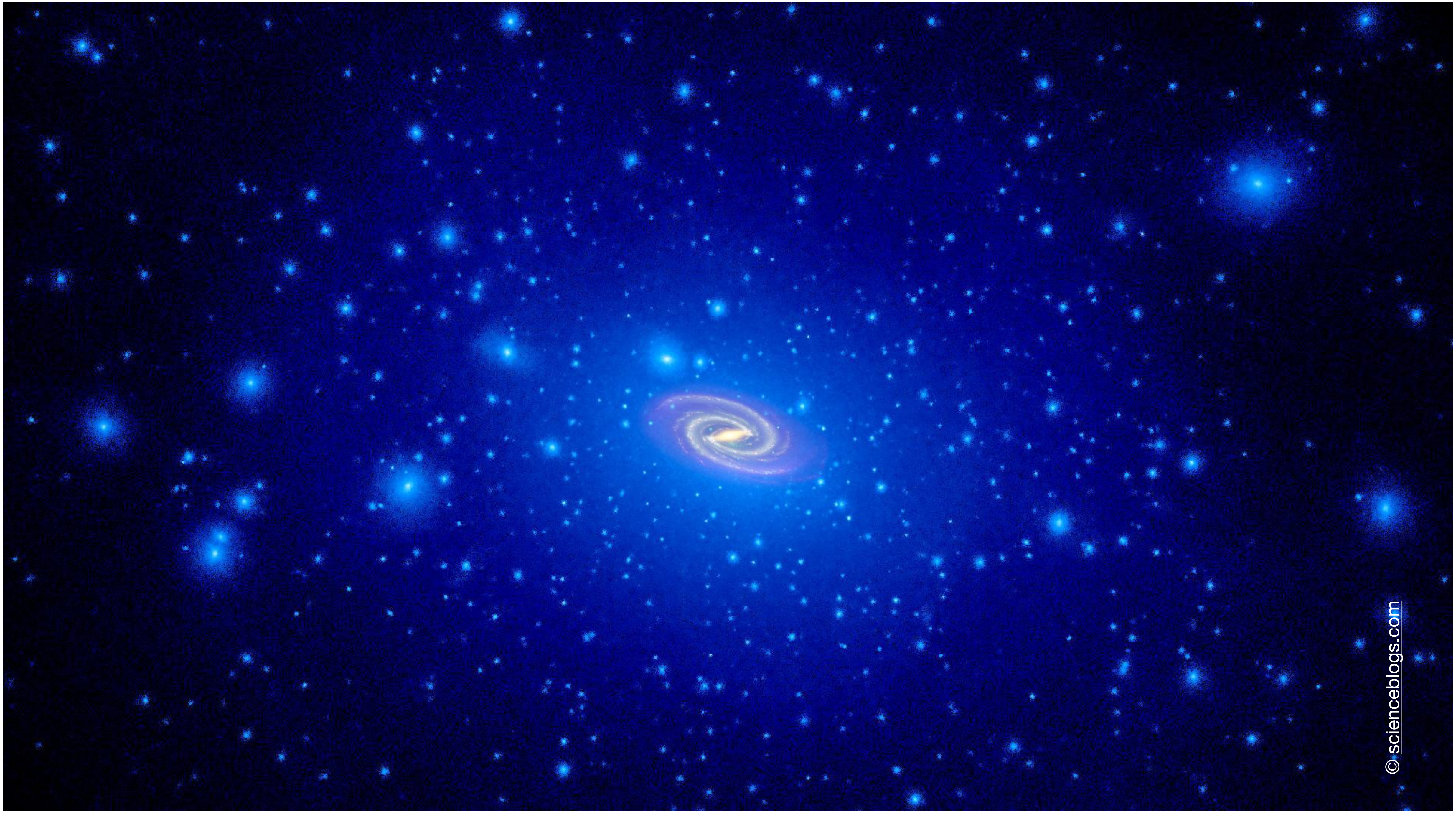

quarks
leptons
photons
...



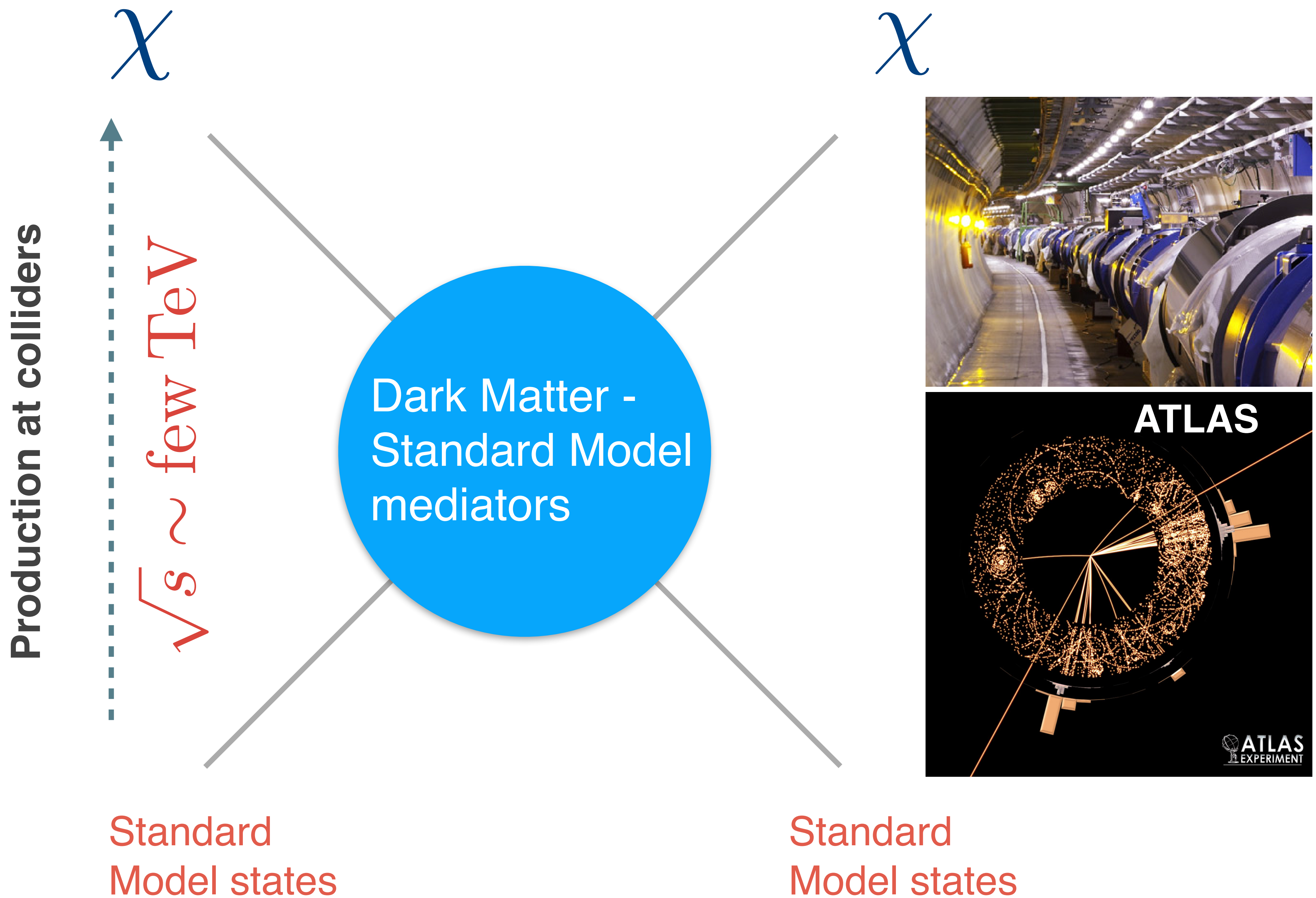
new particles

# Dark matter in the Milky Way

- If these particles are stable, they could form the halo of our Milky Way



# How to see in the dark?



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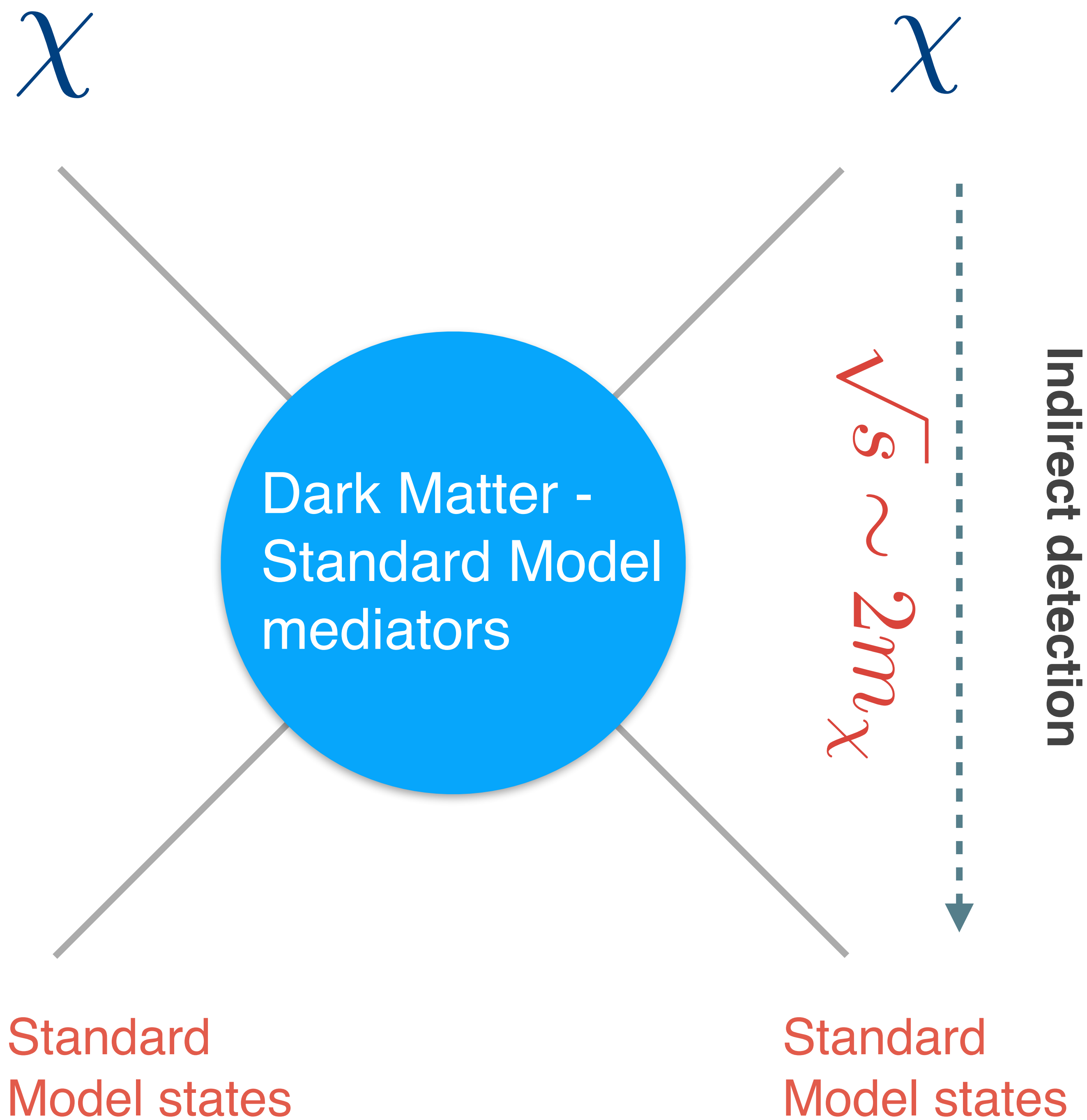


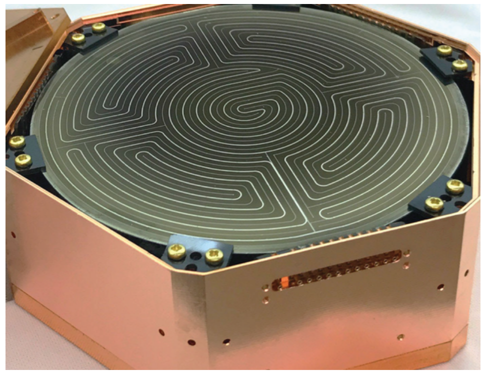
# How to see in the dark?

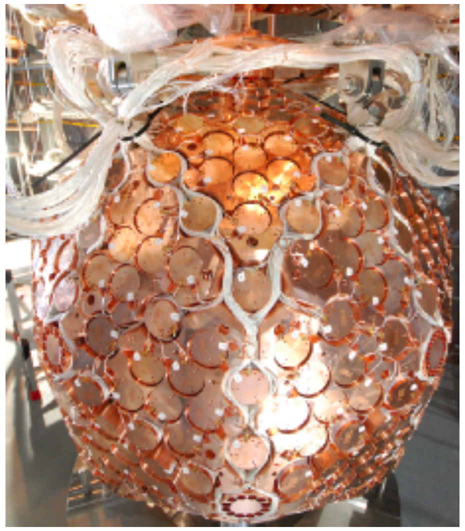
$\chi$ Direct detection $\chi$

$q \leq 10\mathrm{s\,MeV}$

$$E_R = \frac{q^2}{2m_{Xe}} < 30\,\mathrm{keV}$$

Dark Matter - Standard Model mediators

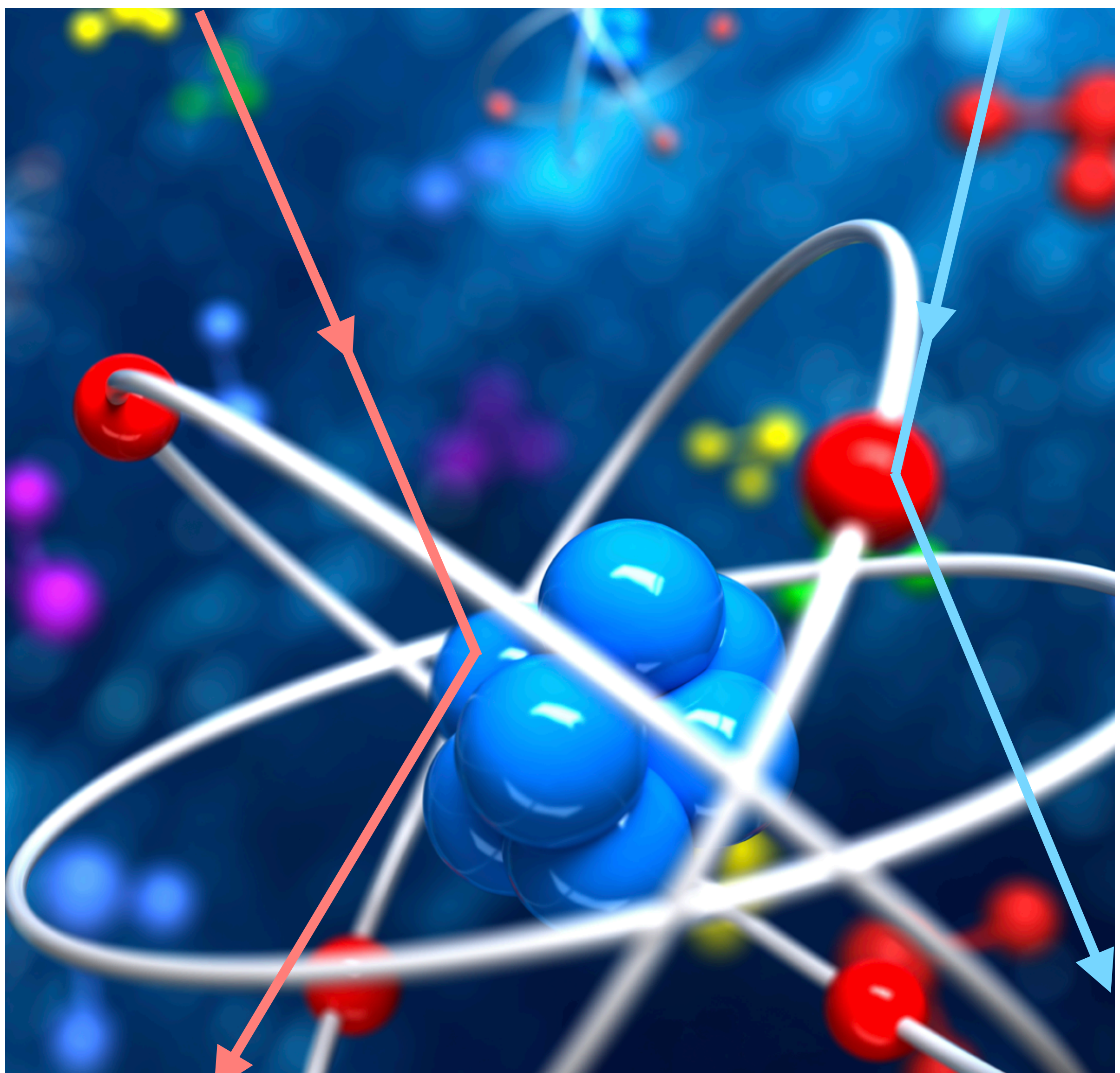




Standard Model states

Standard Model states

# Direct detection principle




**Collisions of invisibles particles with atomic nuclei**

REVIEW D VOLUME 31, NUMBER 12

## Detectability of certain dark-matter candidates

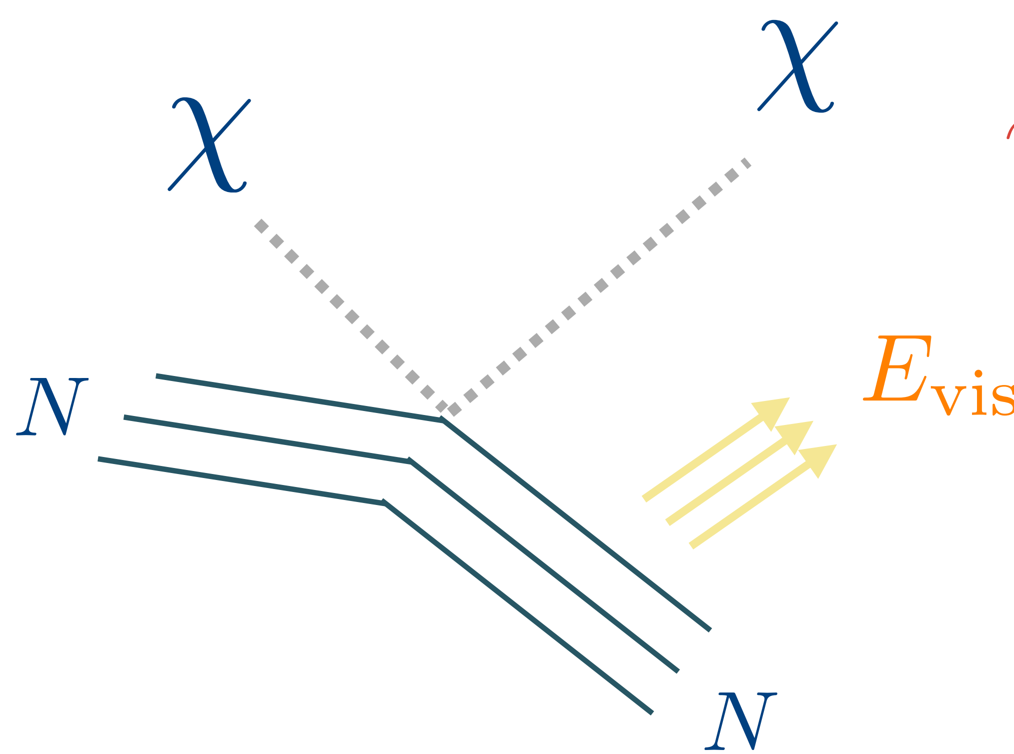
Mark W. Goodman and Edward Witten
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544*
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

# Direct detection principle

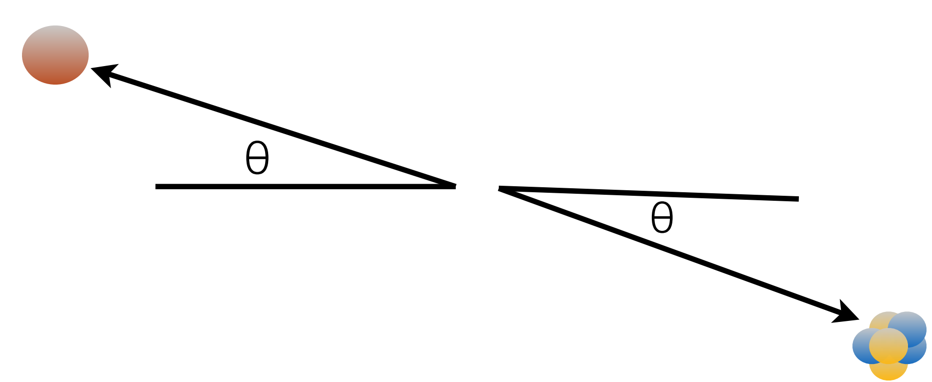
Momentum transfer **~ few tens of MeV**

Energy deposited in the detector **~ few keV - tens of keV**




$$v/c \sim 0.75 \times 10^{-3}$$

$$E_R = \frac{q^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta)$$



# What to expect in an Earth-bound detector?

$$\frac{dR}{dE_R} = N_N \frac{\rho_0}{m_W} \int_{\sqrt{(m_N E_{th})/(2\mu^2)}}^{v_{max}} dv f(v) v \frac{d\sigma}{dE_R}$$

**Detector physics**

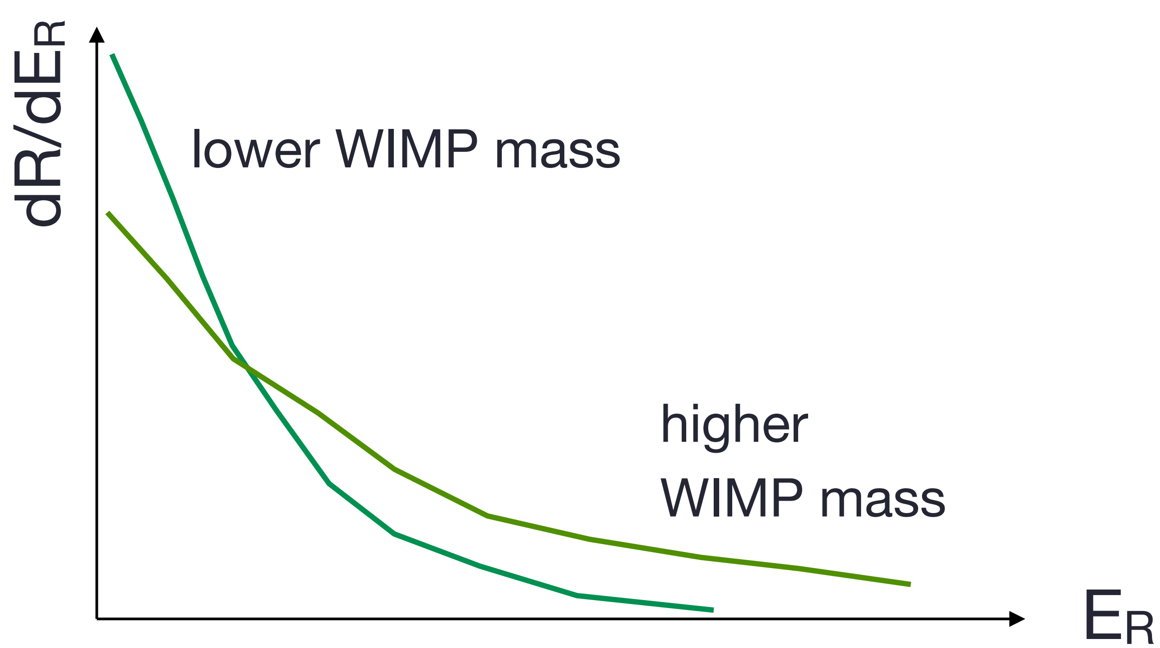
$N_N, E_{th}$

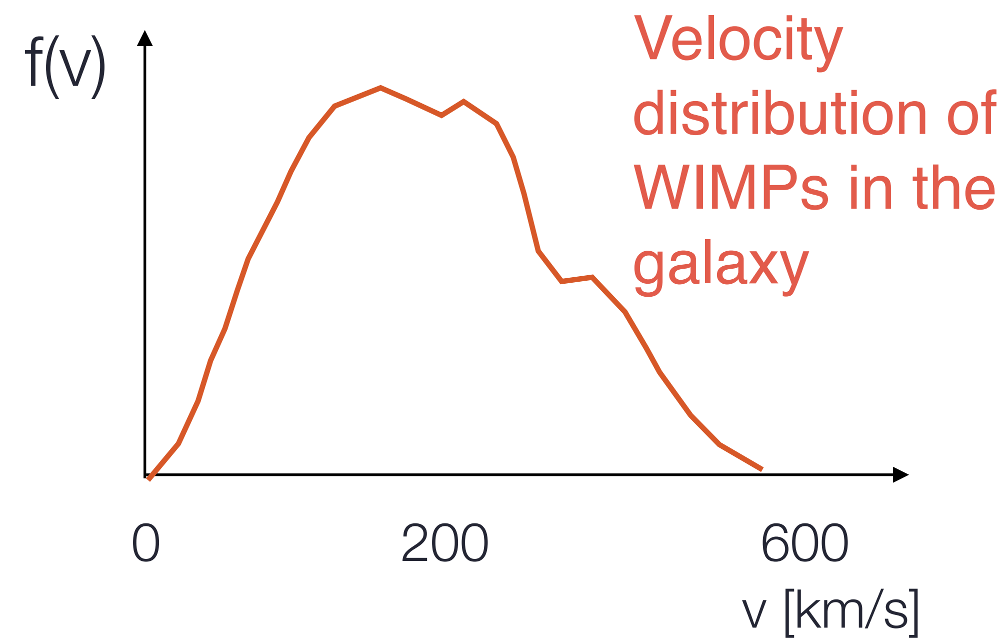
**Particle/nuclear physics**

$m_W, d\sigma/dE_R$

**Astrophysics**

$\rho_0, f(v)$



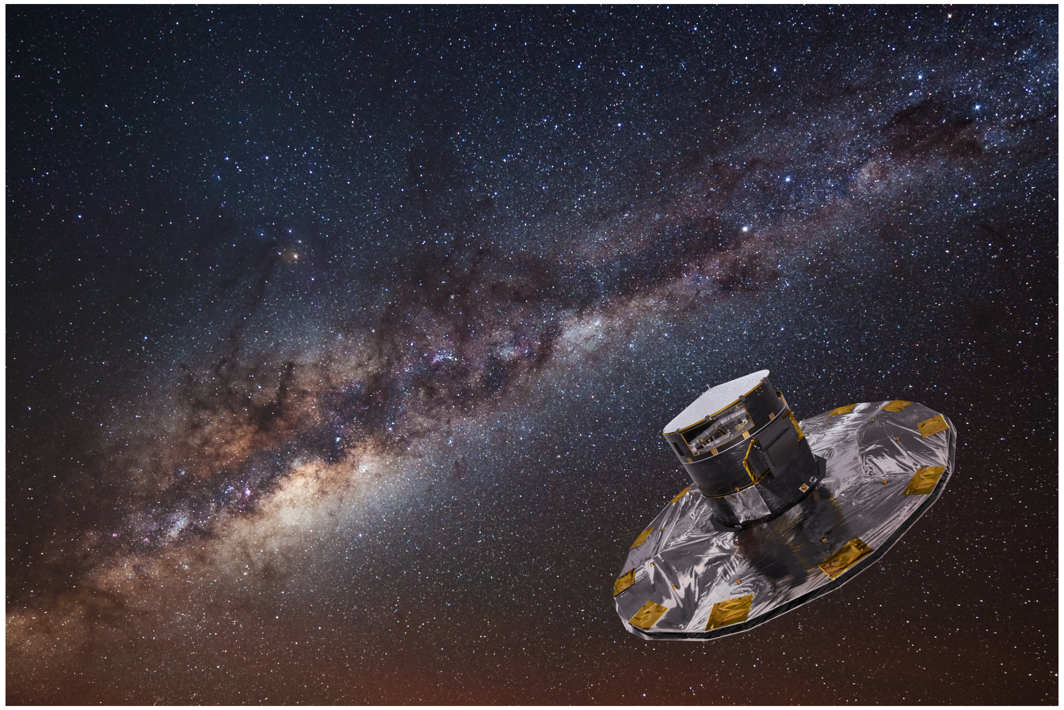



# Astrophysics

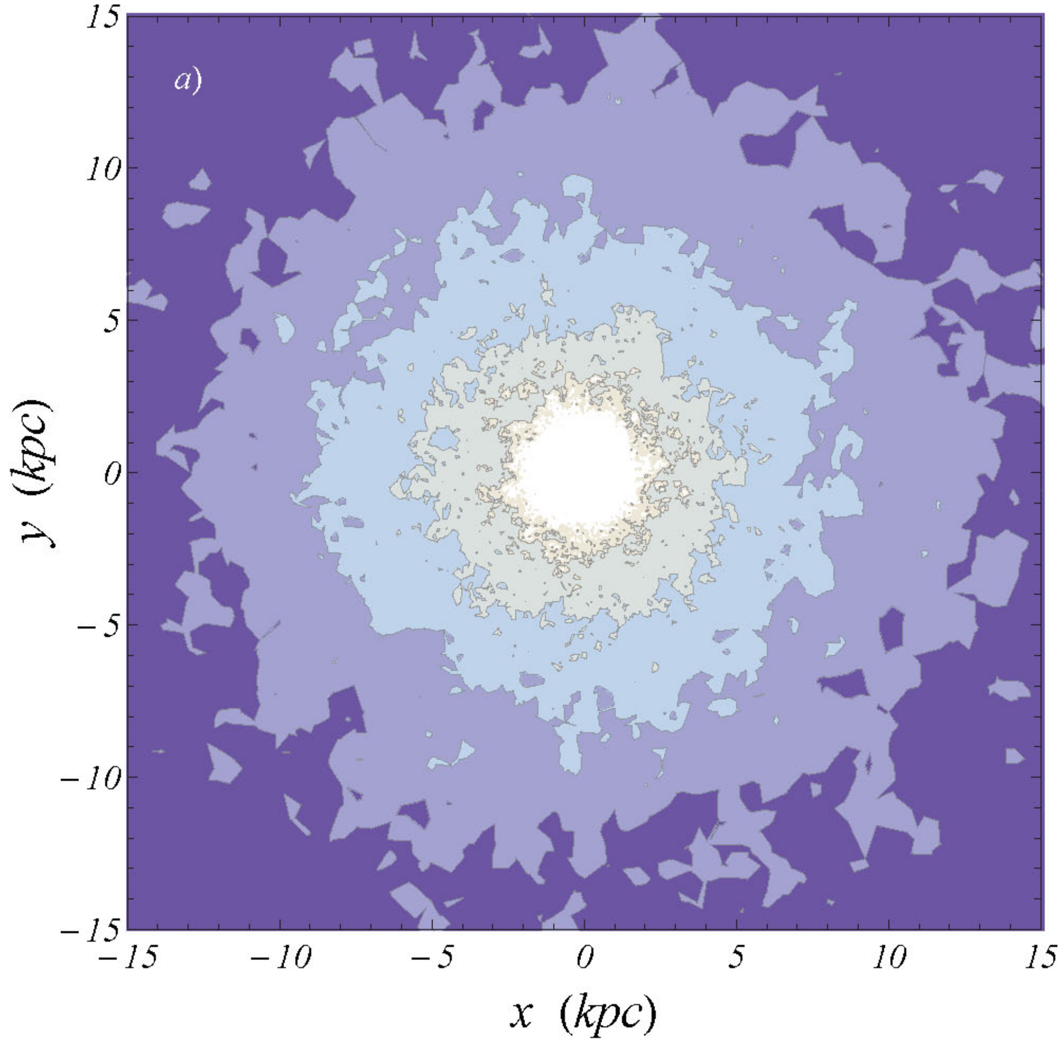
## Local density (at $R_0$ ~ 8 kpc)

**local measures:** vertical kinematics of stars near the Sun as 'tracers' (smaller error bars, stronger assumptions about the halo shape)

**global measures:** extrapolate the density from the rotation curve (larger errors, fewer assumptions)



Density map of the dark matter halo
rho = [0.1, 0.3, 1.0, 3.0] GeV $cm^{-3}$




High-resolution cosmological simulation with baryons: F.S. Ling et al, JCAP02 (2010) 012

Gaia mission: April 25 to release data from 1.3 billion stars

# What is the WIMP flux on Earth?

$$\rho(R_0) = 0.2 - 0.56\,\mathrm{GeV\,cm^{-3}} = 0.005 - 0.015\,\mathrm{M_\odot\,pc^{-3}}$$

Justin Read, Journal of Phys. G41 (2014) 063101


=> **WIMP flux on Earth: ~$10^5$ $cm^{-2}s^{-1}$** ($M_W$=100 GeV, for 0.3 GeV $cm^{-3}$)

# How to deal with the particle physics?

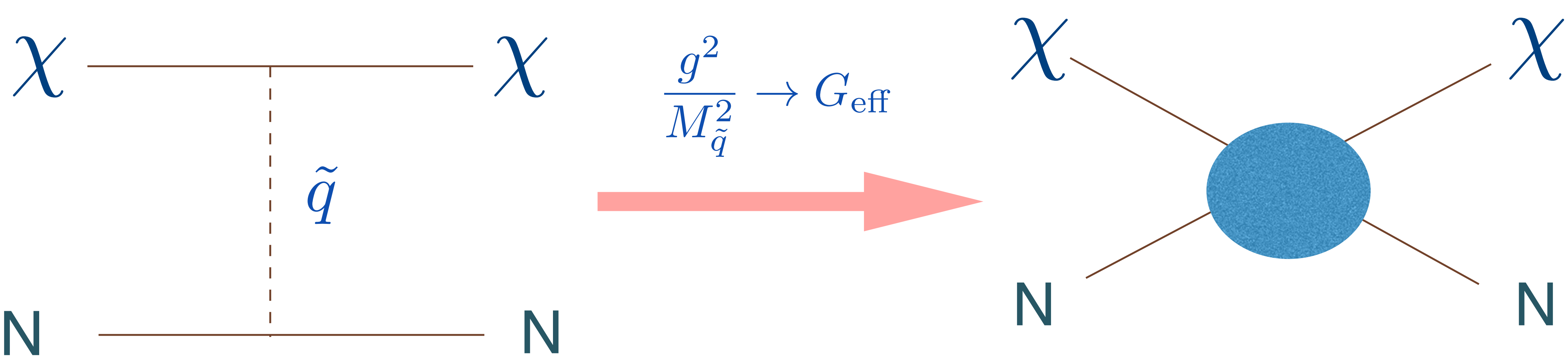
## Use effective operators to describe WIMP-quark interactions

- Example: vector mediator

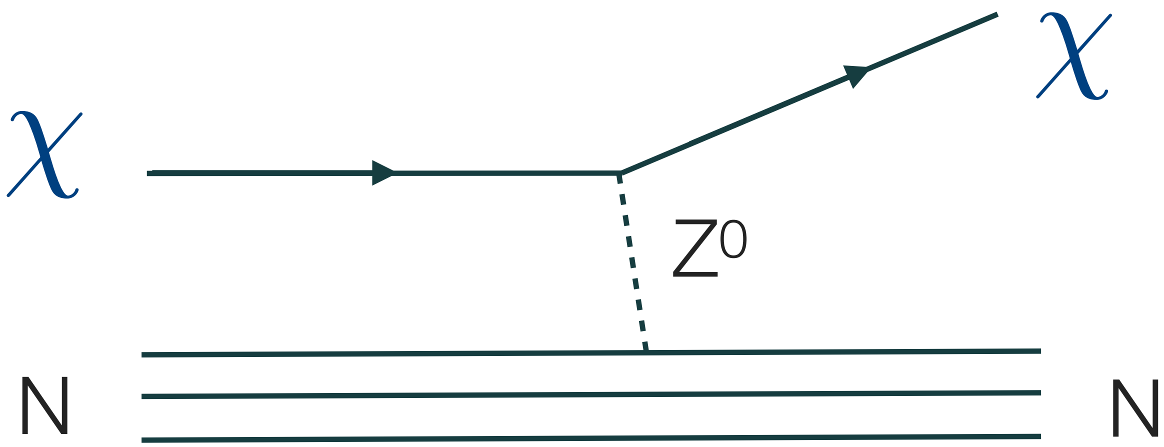
contact interaction scale

$$\mathcal{L}_{\chi}^{\text{eff}} = \frac{1}{\Lambda^2}\bar{\chi}\gamma_{\mu}\chi\bar{q}\gamma^{\mu}q \qquad \Lambda = \frac{M}{\sqrt{g_q g_{\chi}}} \Rightarrow \sigma_{\text{tot}} \propto \Lambda^{-4}$$

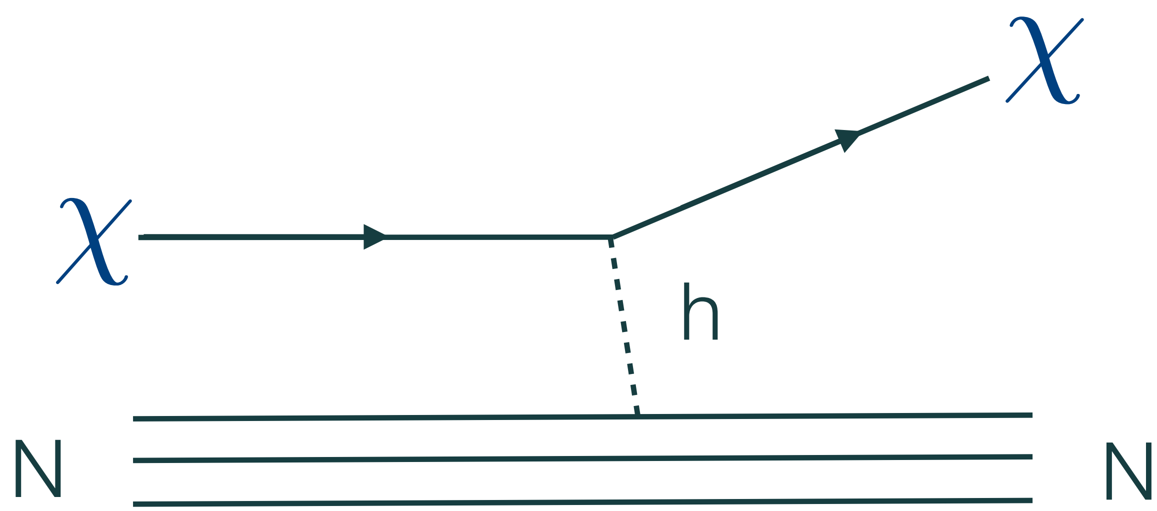
- The effective operator arises from "integrating out" the mediator with mass M and couplings $g_q$ and $g_{\chi}$ to the quark and the WIMP



# WIMP-nucleus cross section: examples



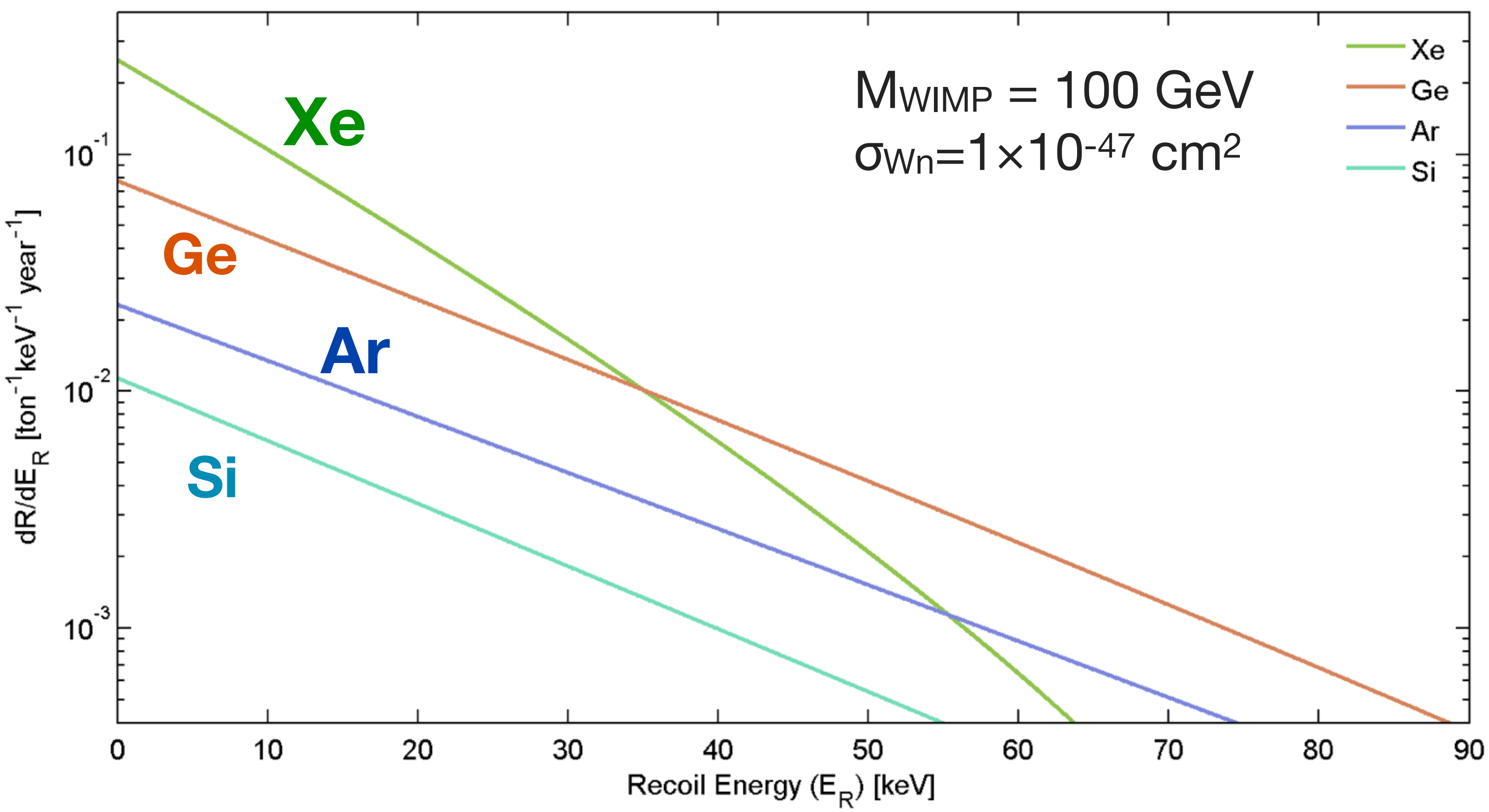

$$\sigma_0 \sim 10^{-39}\mathrm{cm}^2$$

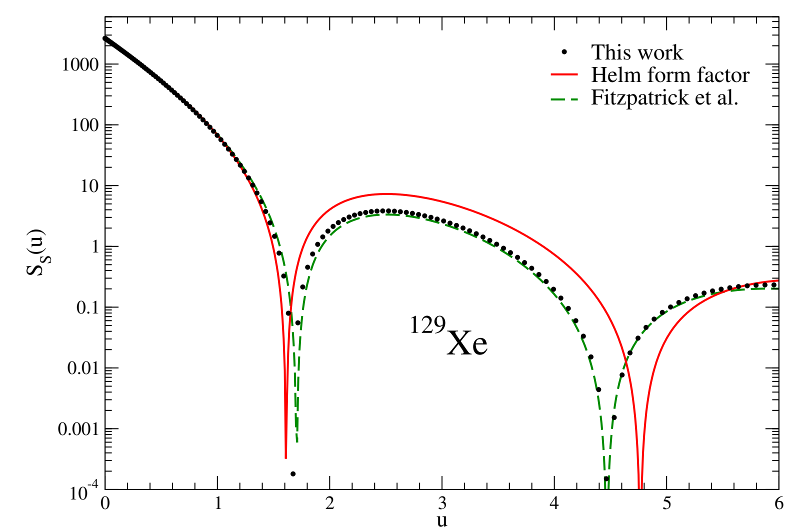



$$\sigma_0 \sim 10^{-44} - 10^{-47}\,\mathrm{cm}^2$$

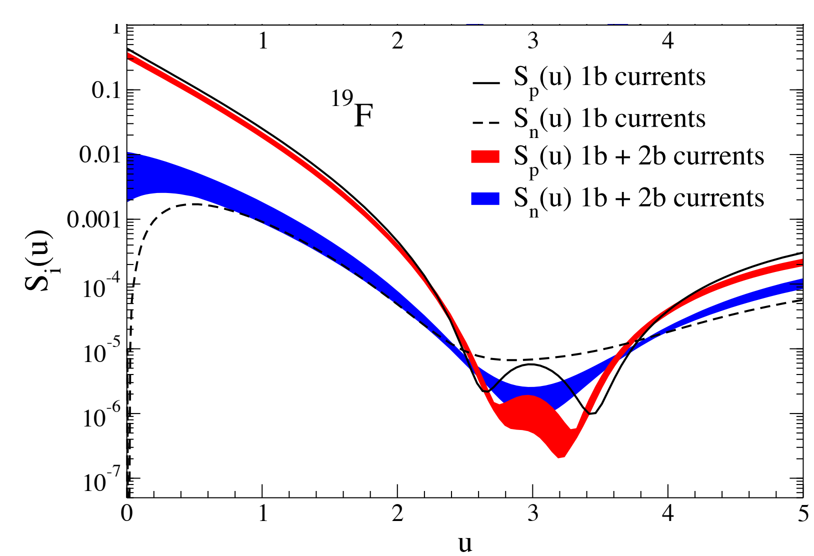
# Expected nuclear recoil spectrum

$$R \sim 0.13 \, \frac{\text{events}}{\text{kg year}} \left[ \frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\text{cm}^{-3}} \right]$$




SI

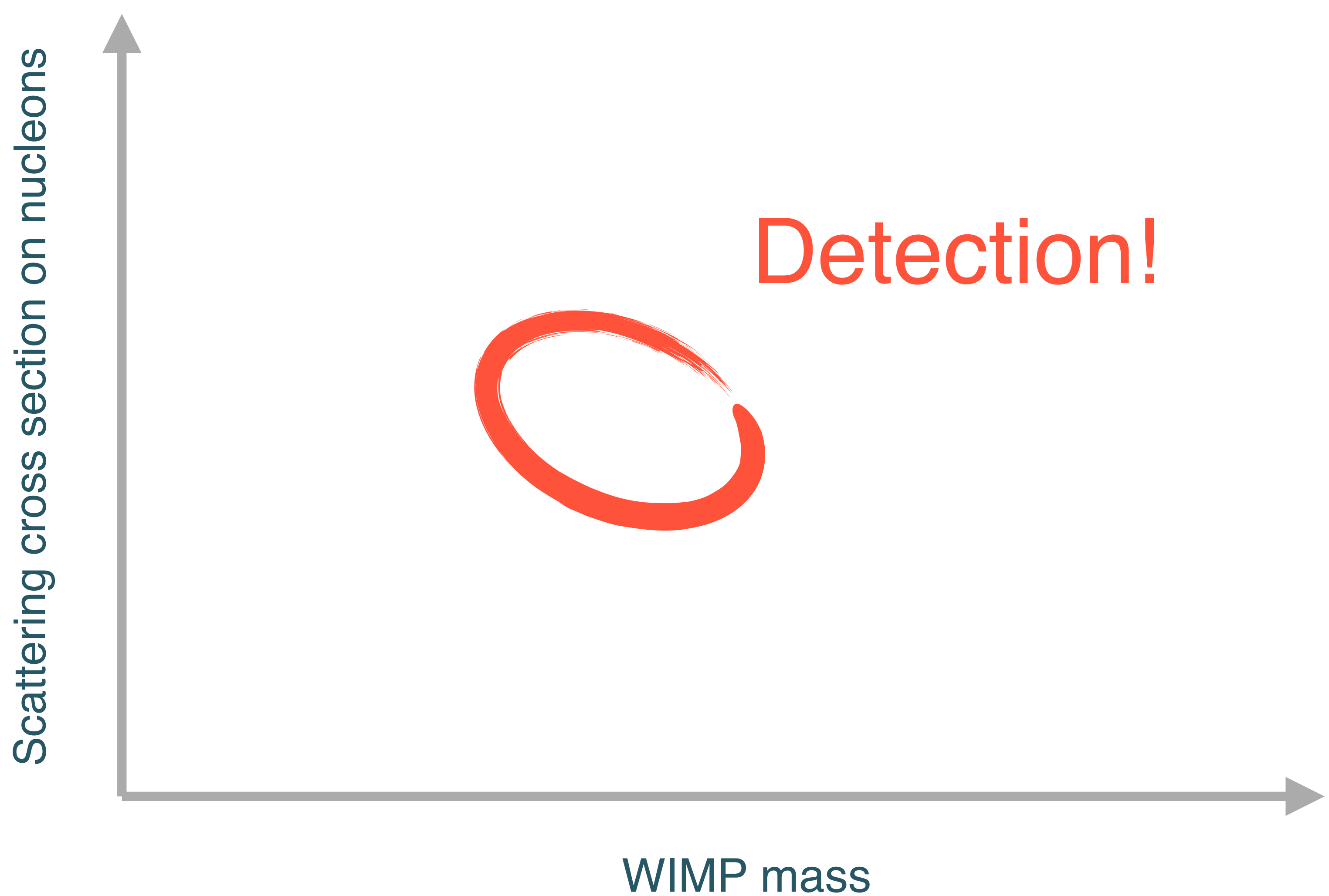


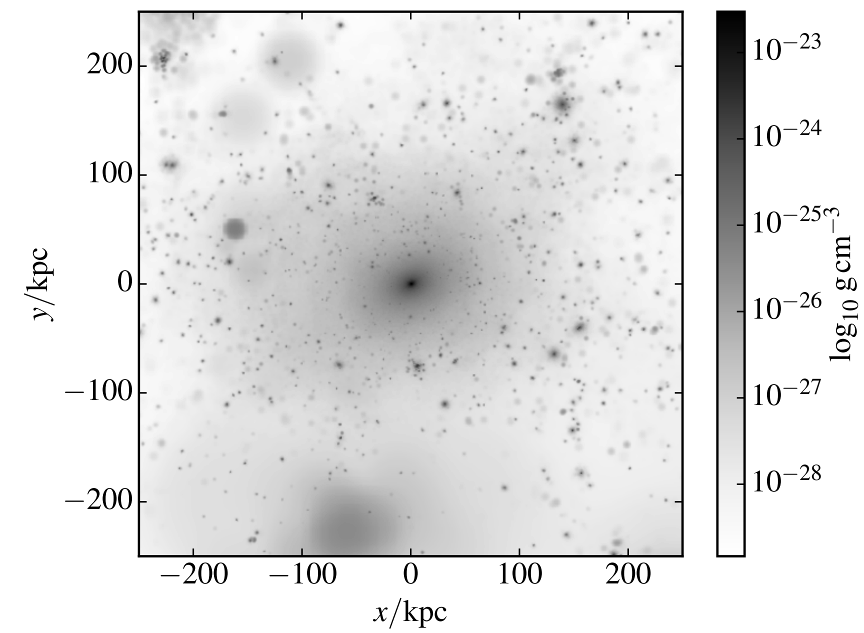

SD

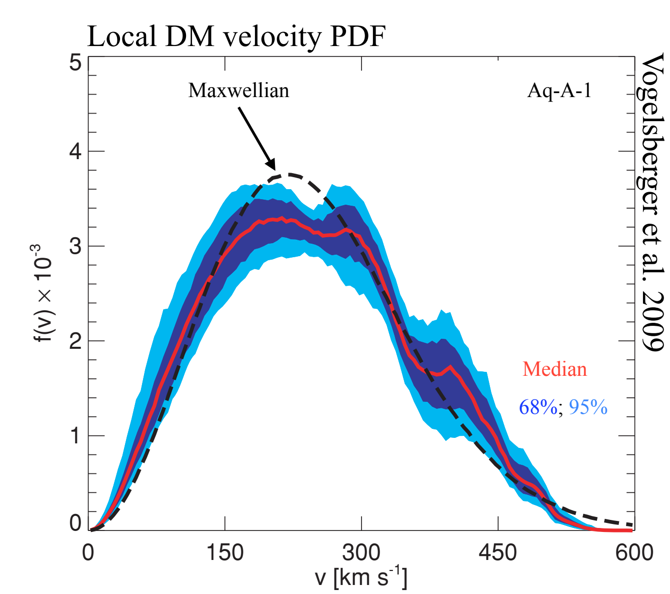
# What can we learn about WIMPs?

- Constraints on the mass and scattering cross section

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



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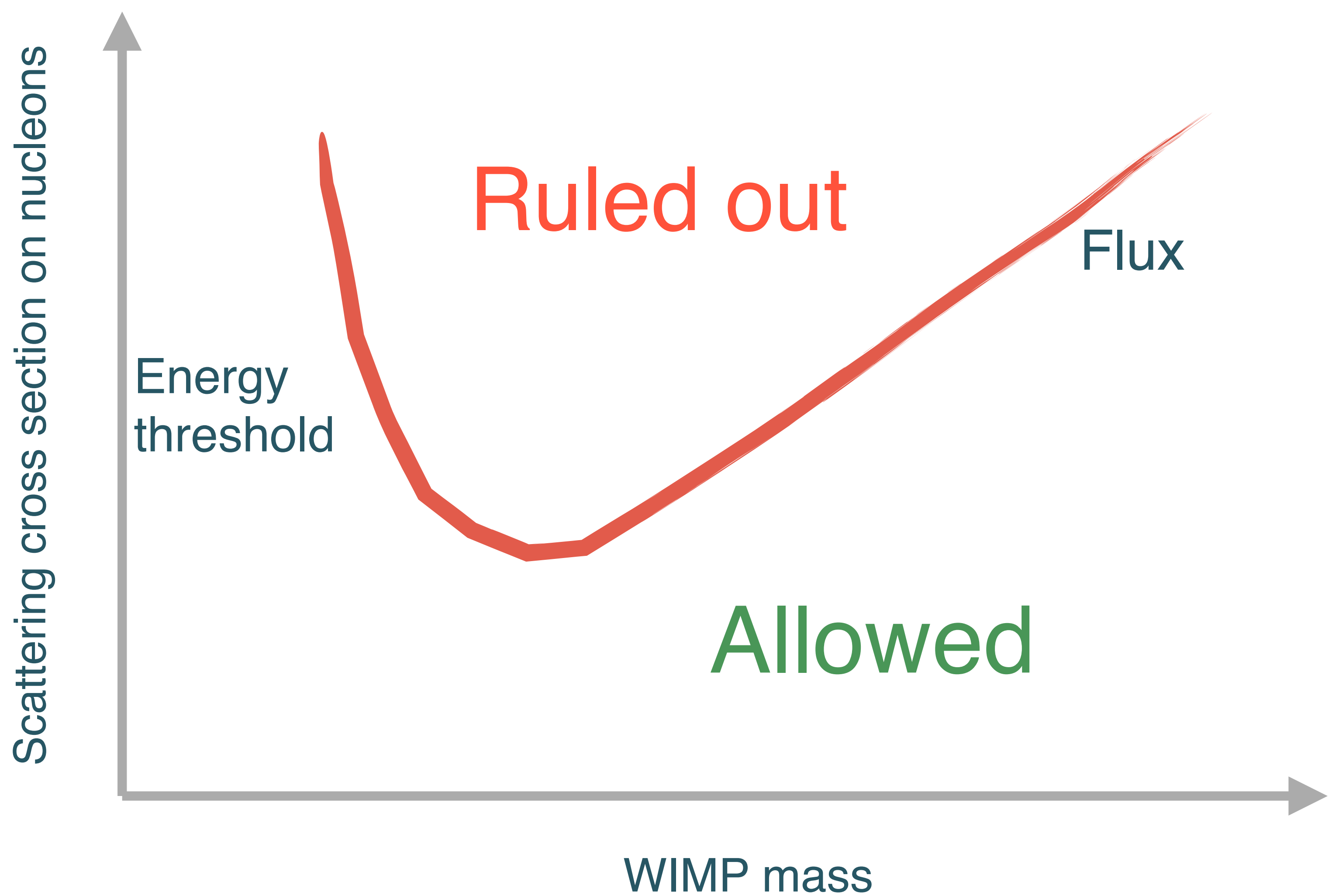
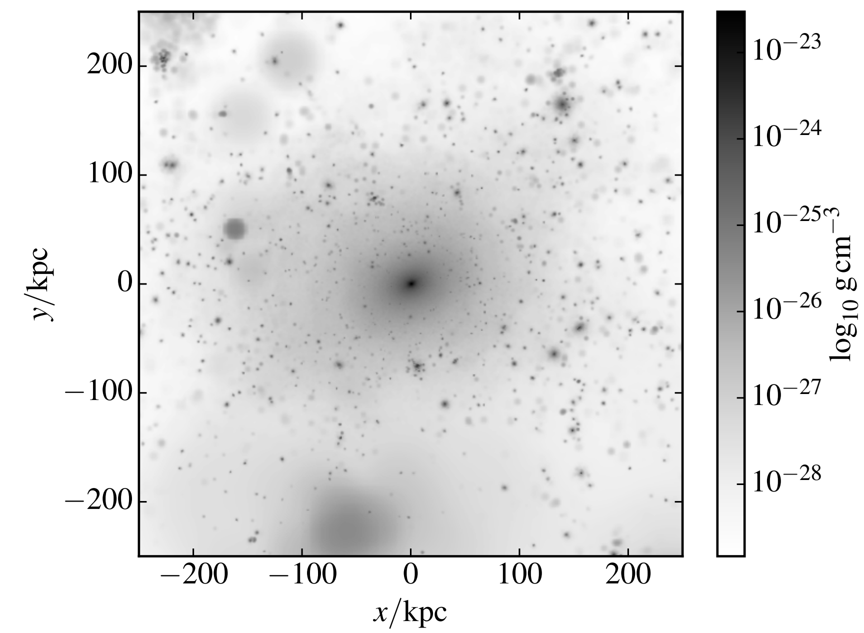
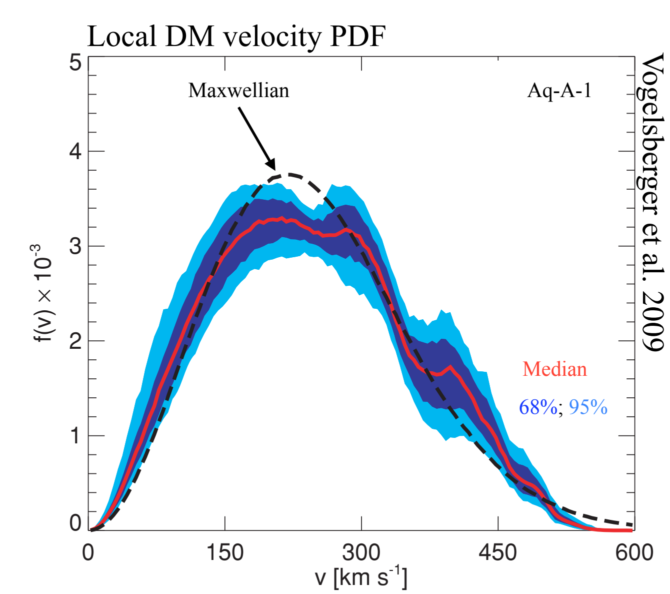
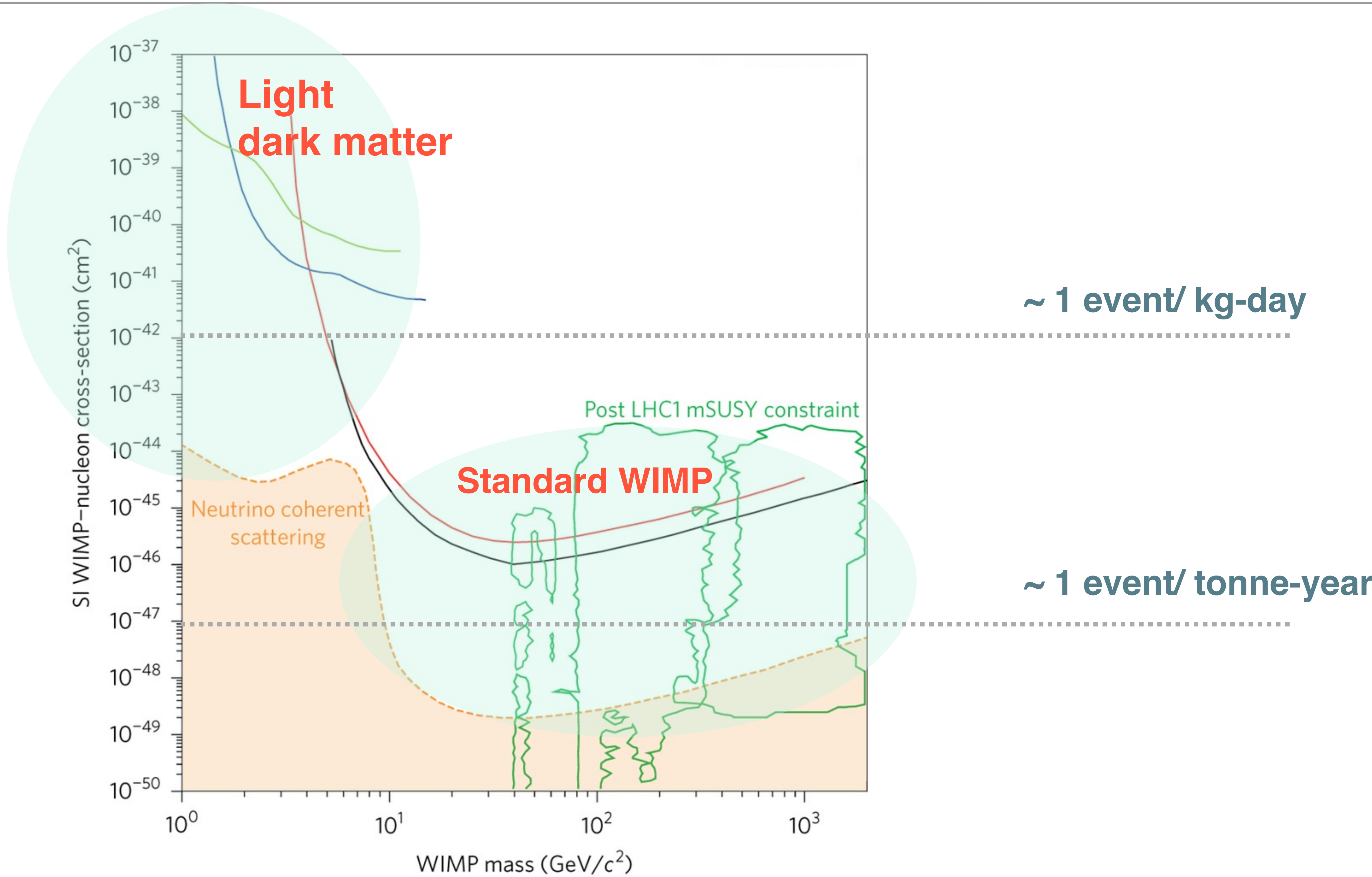


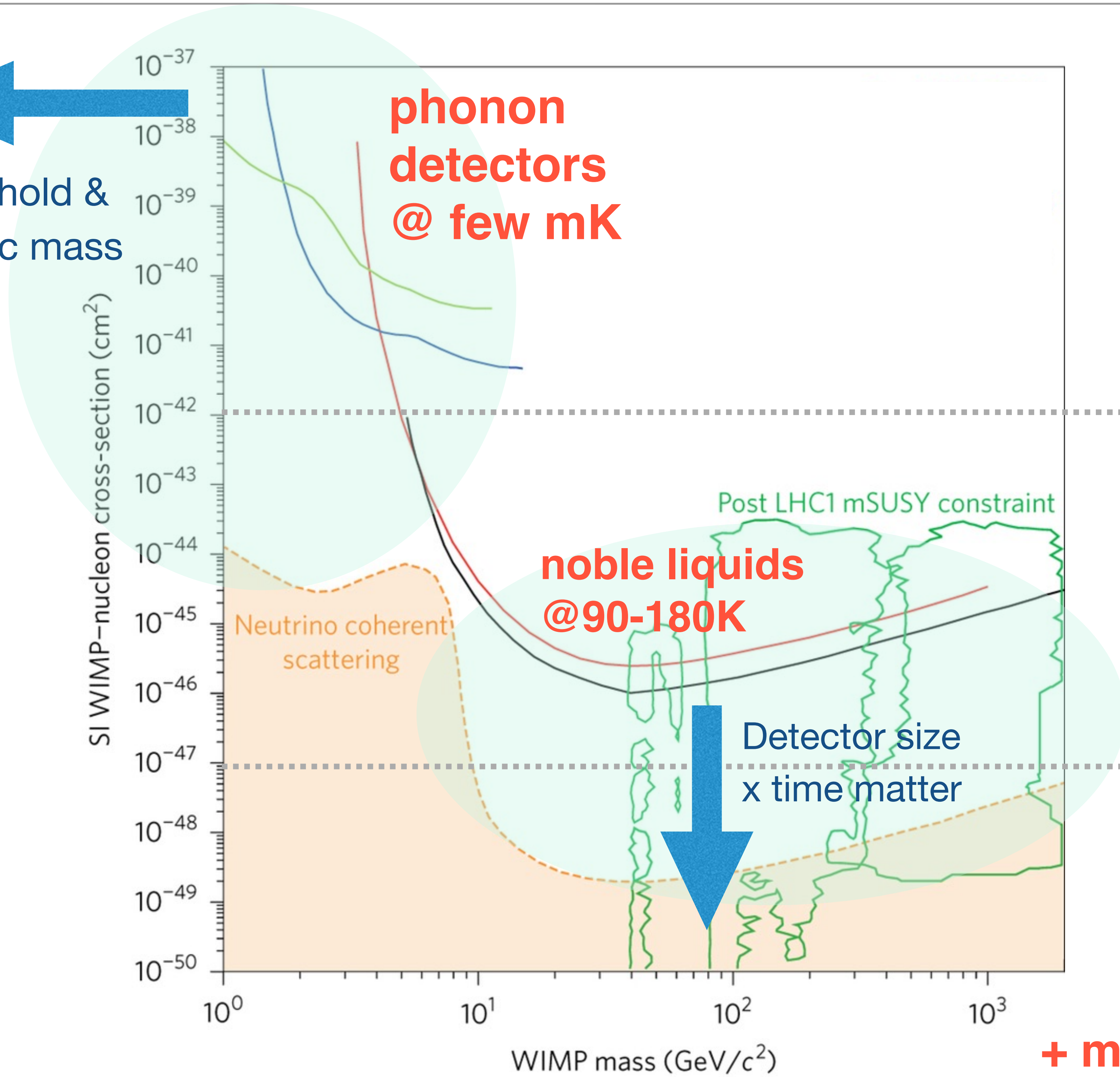
# The WIMP landscape ~one year ago




Nature physics, March 2017

# The WIMP landscape ~one year ago

Threshold & atomic mass



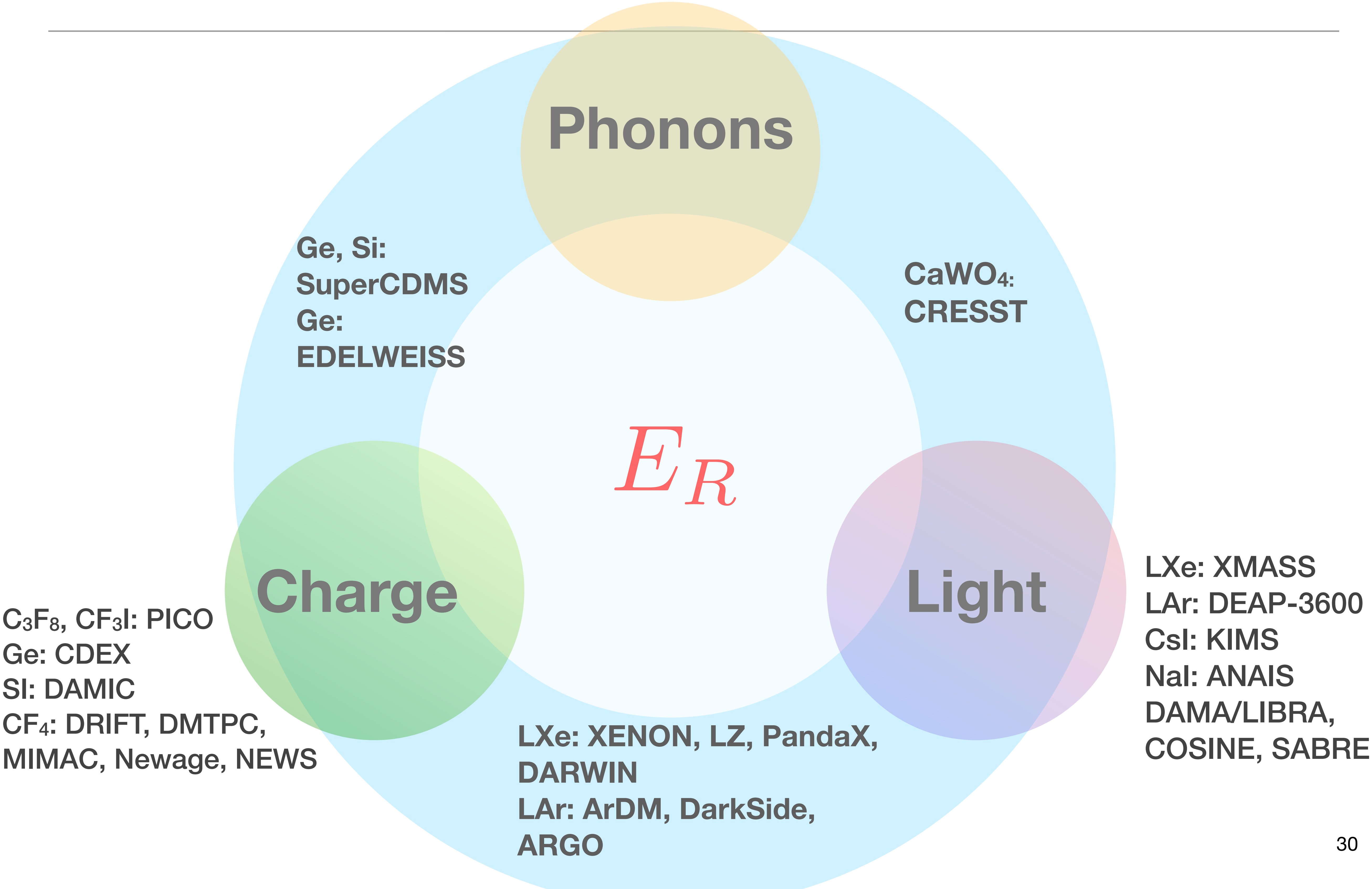

**~ 1 event/ kg-day**

**~ 1 event/ tonne-year**

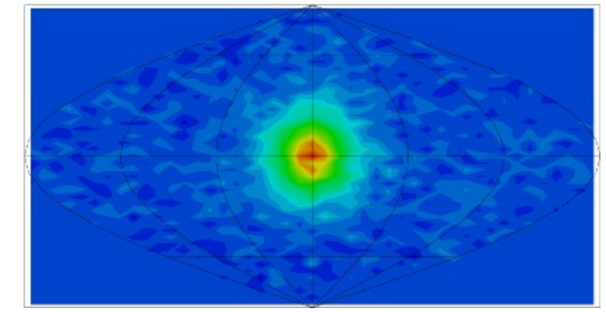
**+ many other technologies!**

Nature physics, March 2017

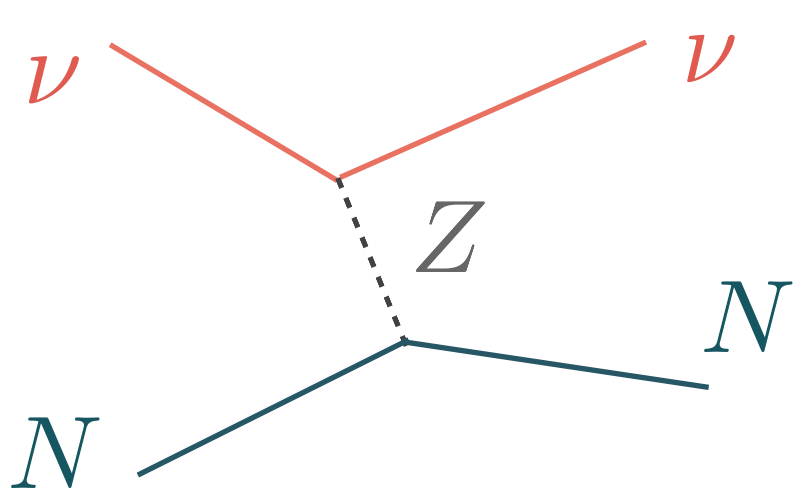
# Direct Detection Zoo

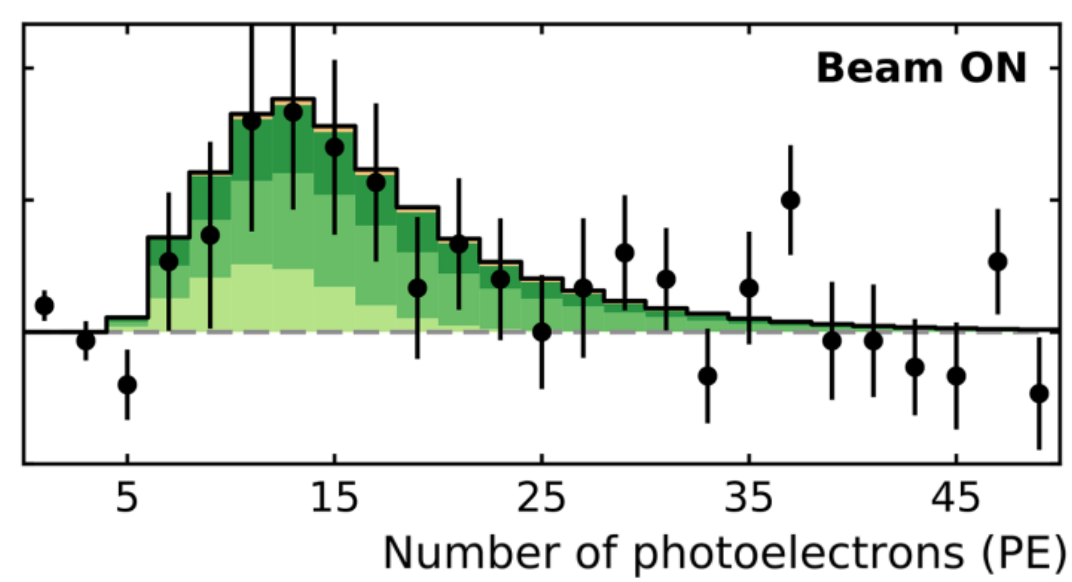


# Backgrounds

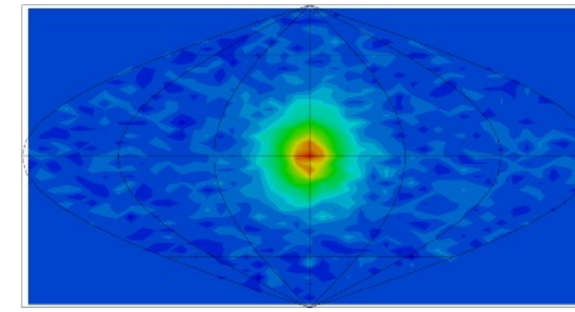


- Must be below the expected signal (< 1 event/exposure)
  - Muons & associated showers; cosmogenic activation of detector materials
  - Natural and anthropogenic radioactivity
  - Neutrinos! *Coherent neutrino-nucleus scattering exists*




COHERENT, Science, August 3, 2017



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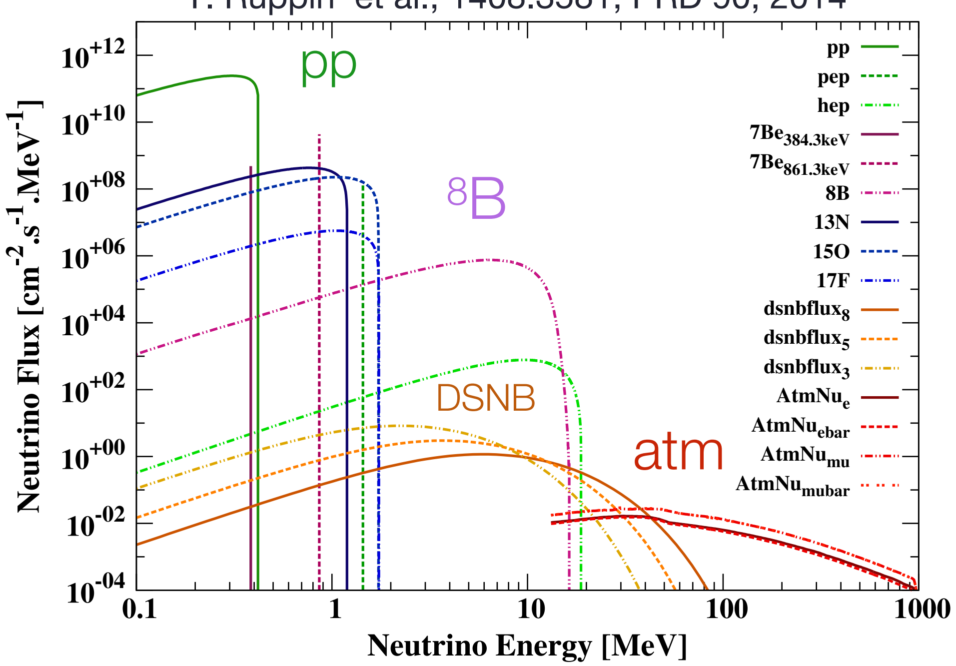
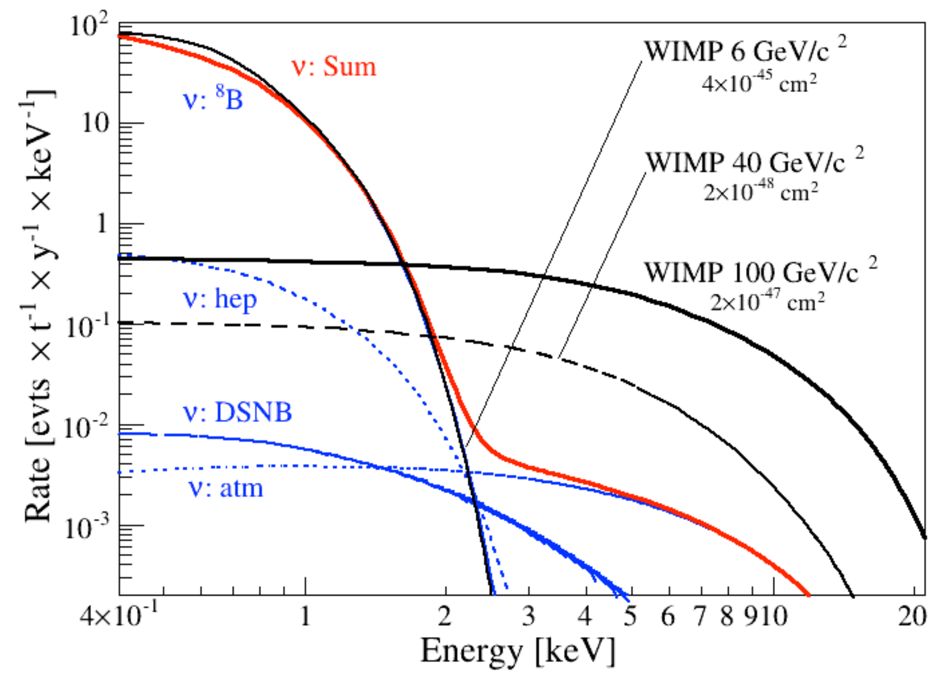
F. Ruppin et al., 1408.3581, PRD 90, 2014

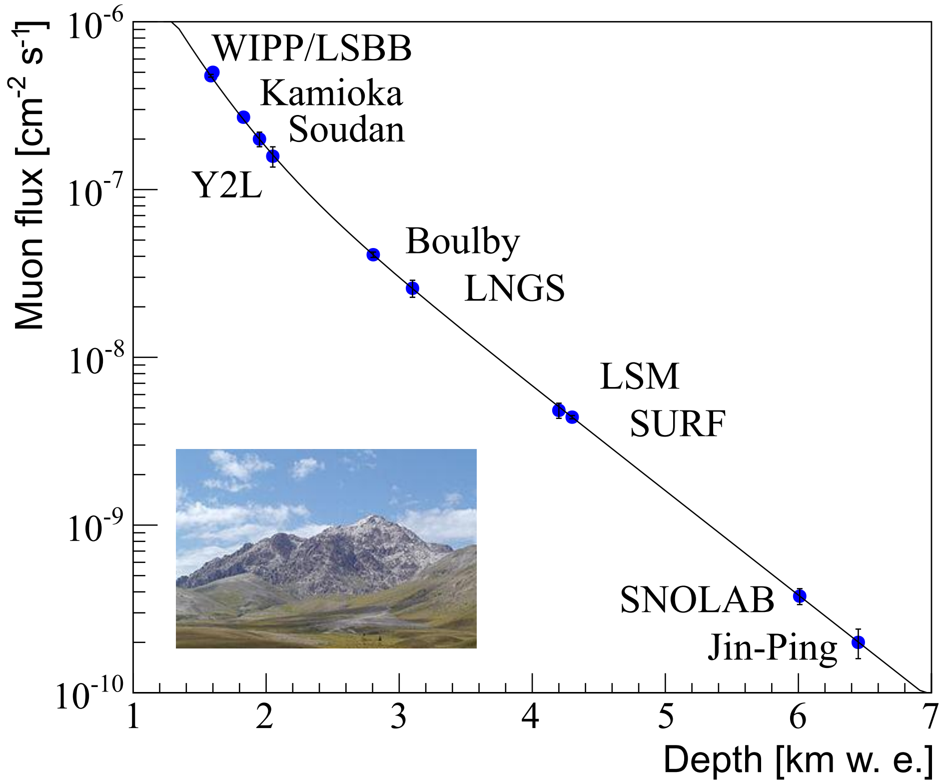



LB et al., JCAP01 (2014) 044

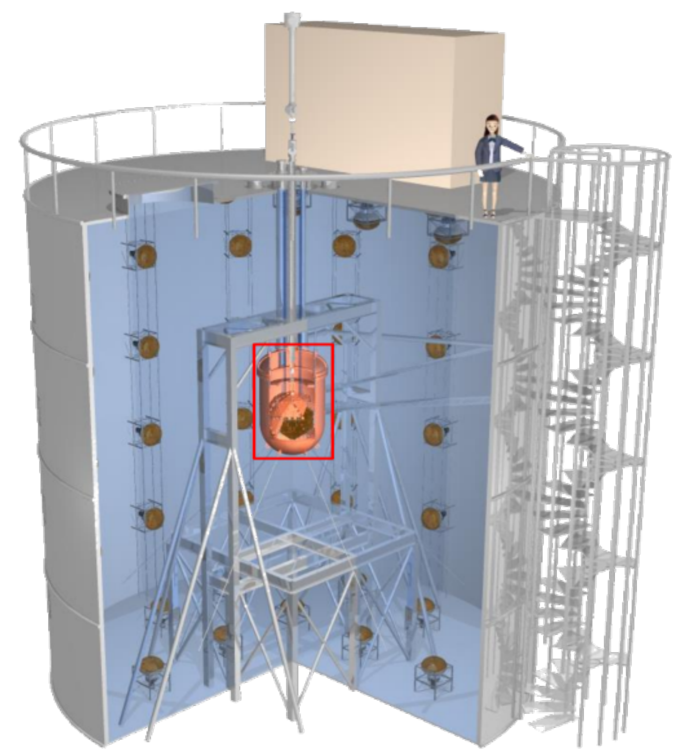


# How to deal with backgrounds?

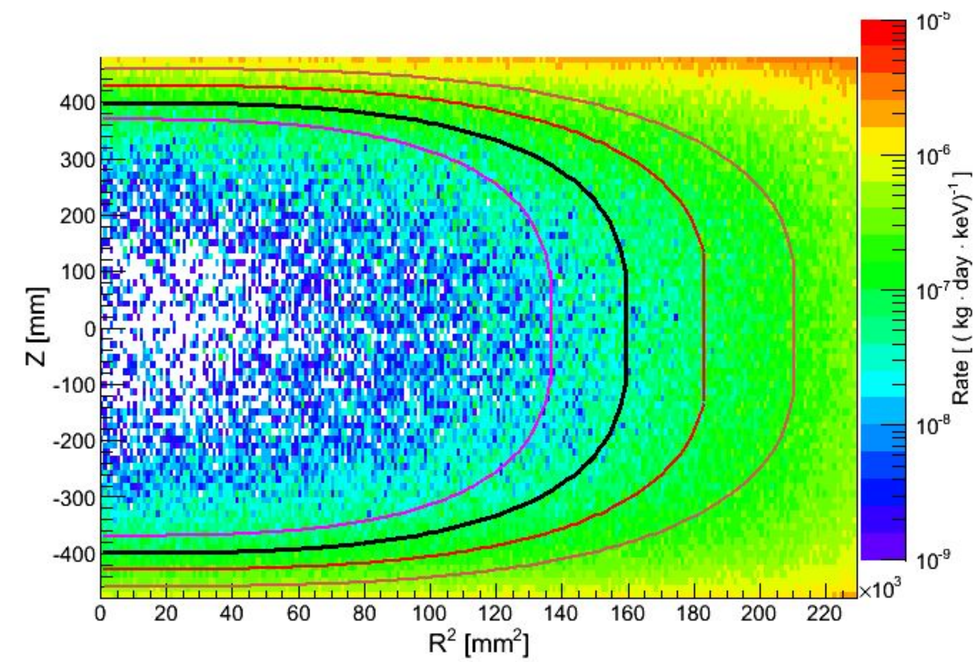
- Go deep underground



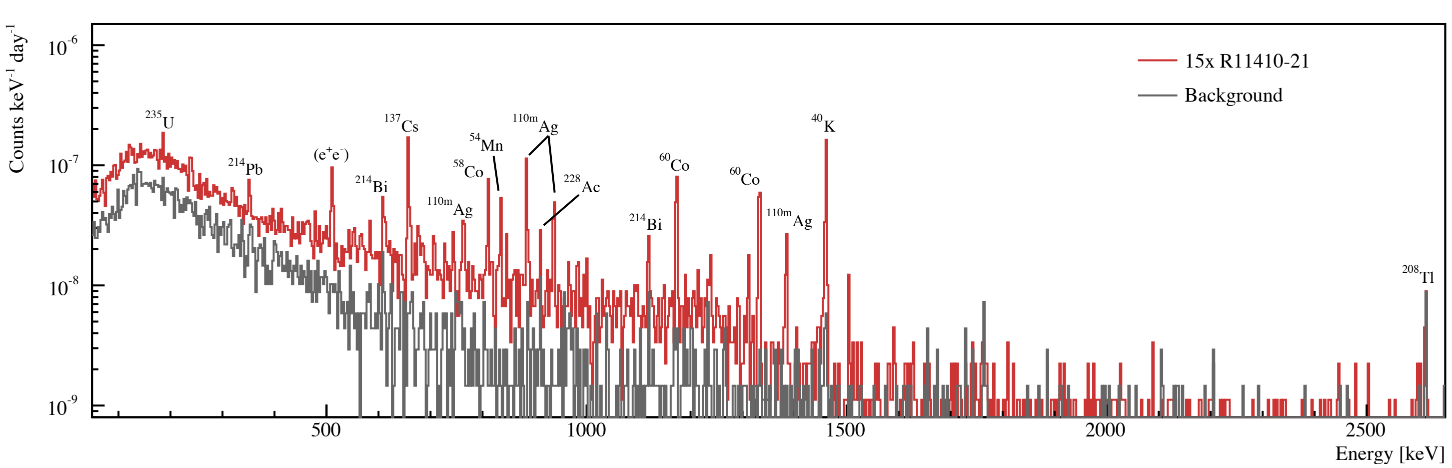

- Use active shields



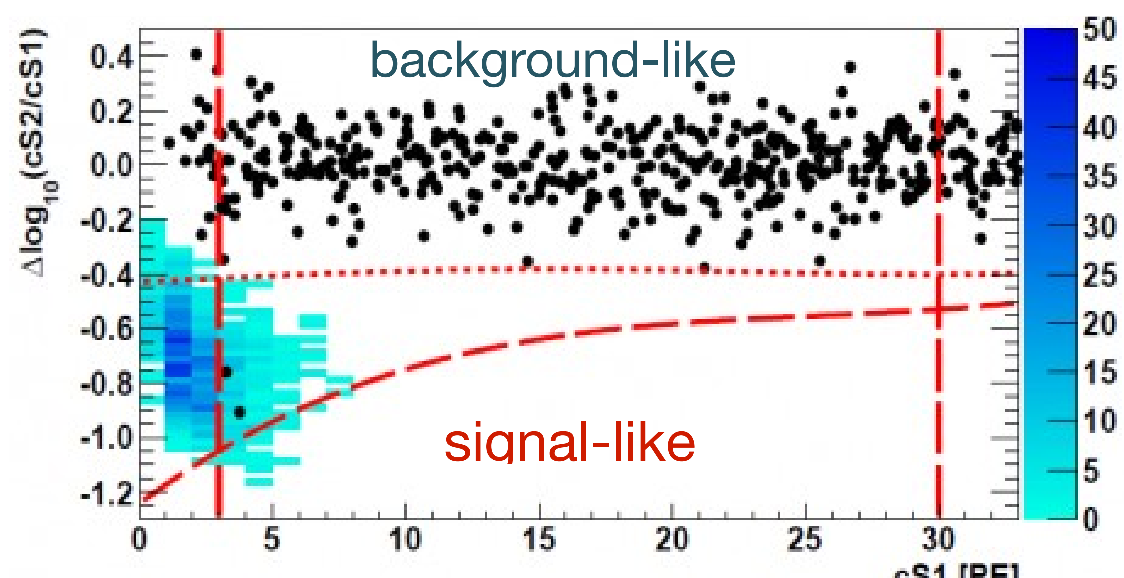
- Fiducialize



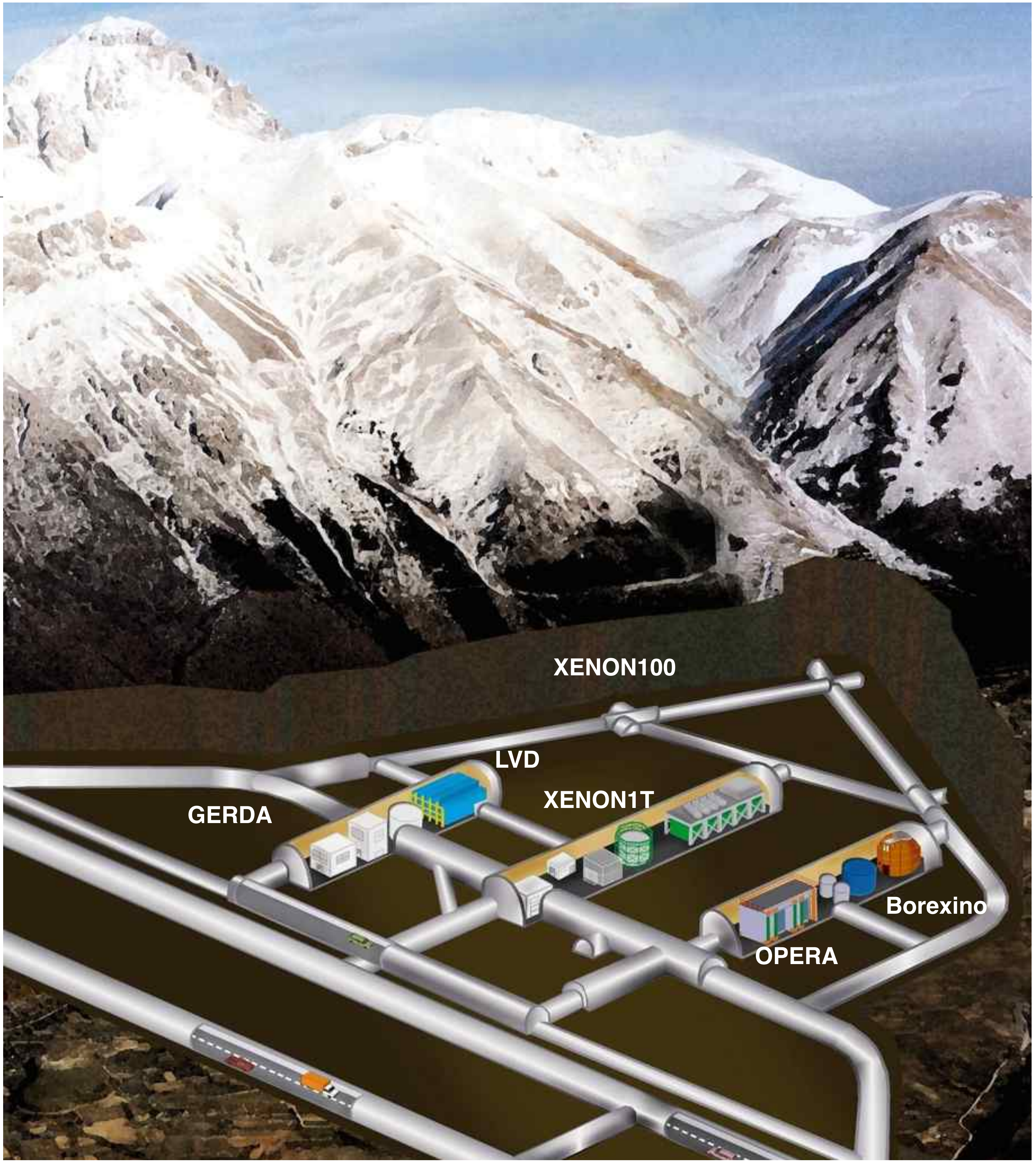

- Select low-radioactivity materials




- Discriminate

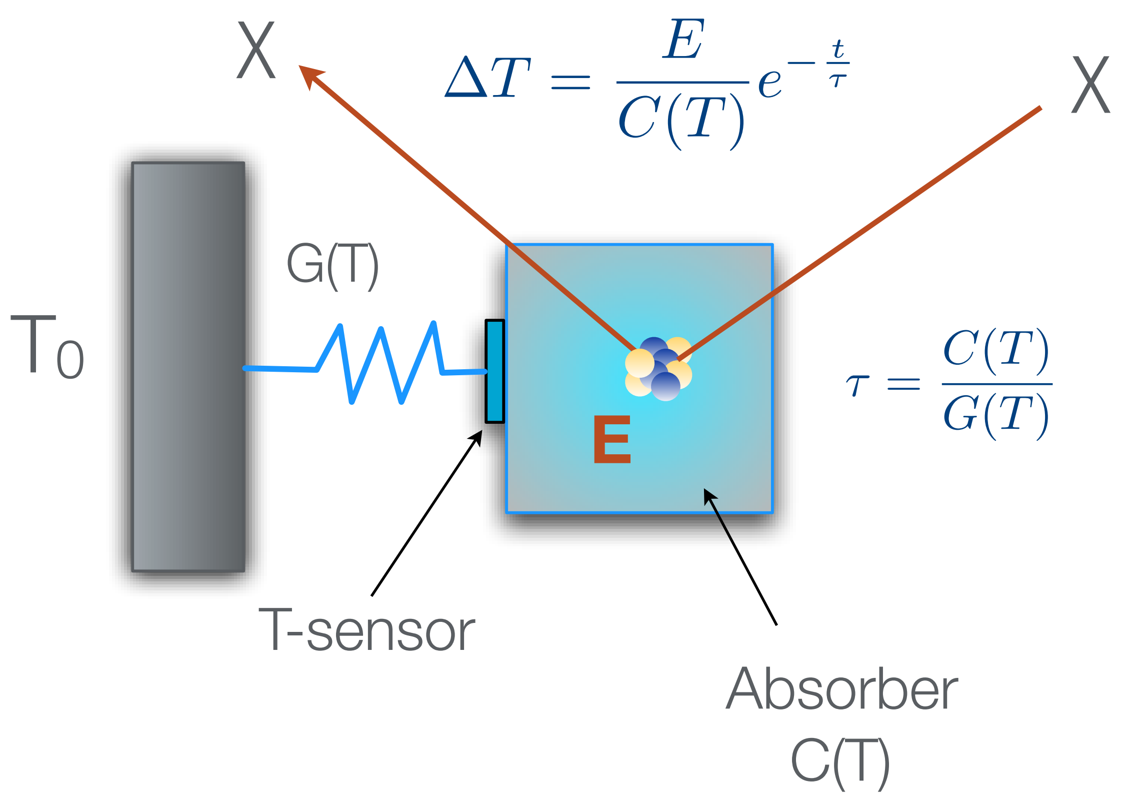


# The Gran Sasso Laboratory



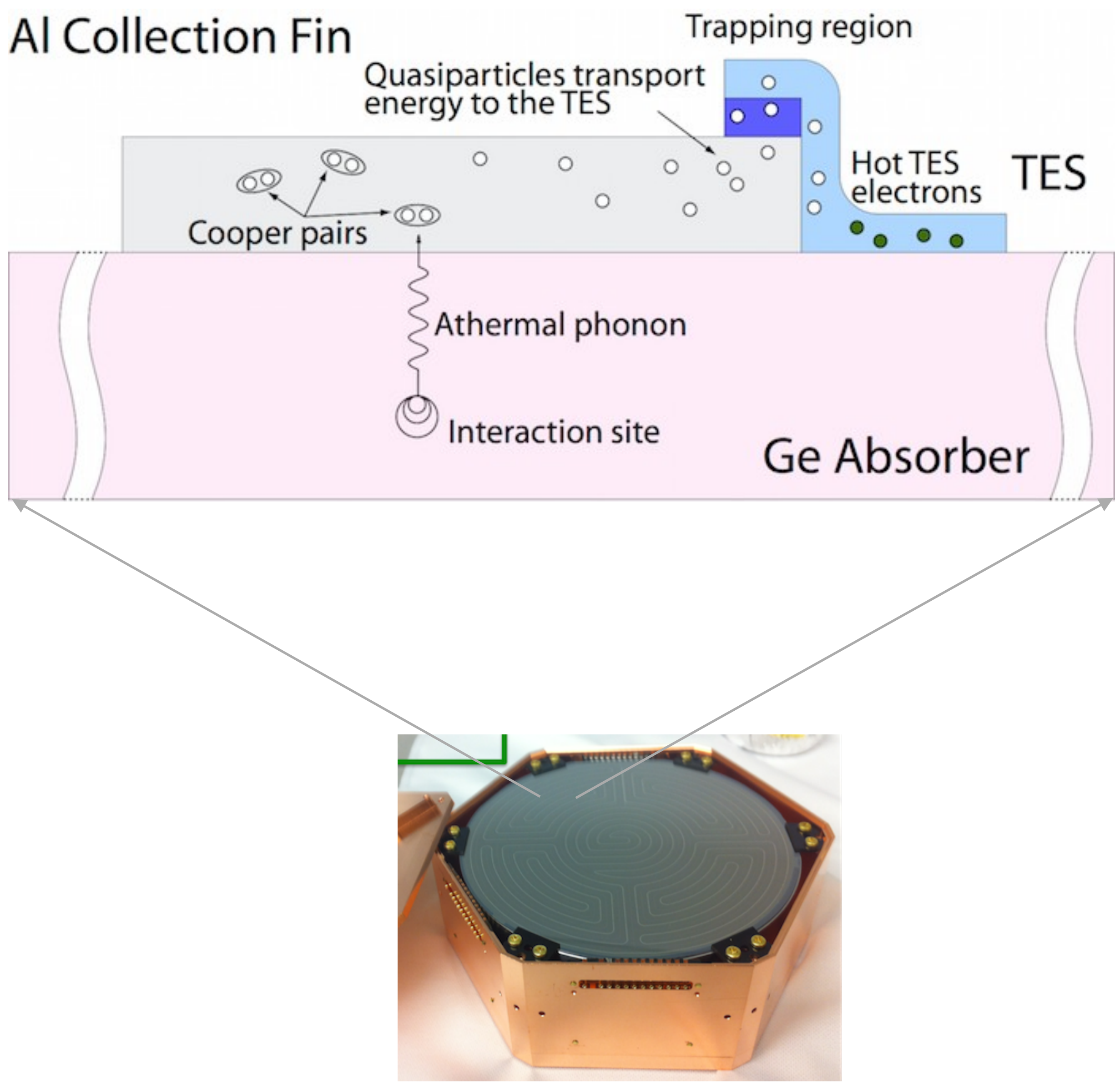
# Phonon detectors at T ~ mK

- Detect *a temperature increase* after a particle interacts in an absorber




$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$

$$\tau = \frac{C(T)}{G(T)}$$

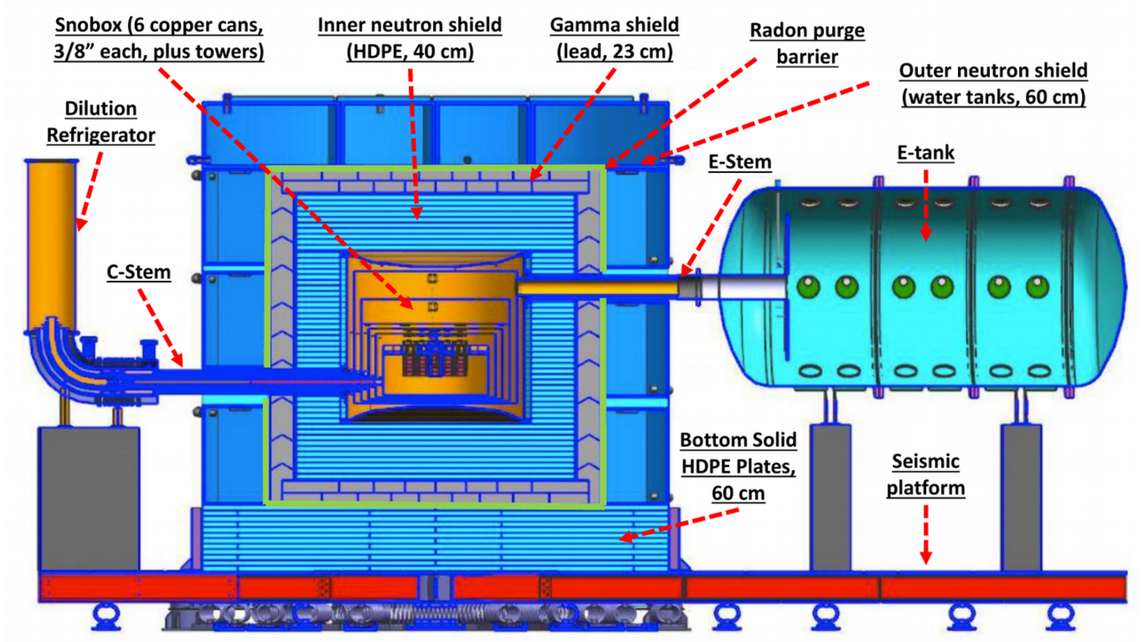



SuperCDMS: Ge, Si

# Phonon detectors at T ~ mK

CREST-III: 10 modules, 24 g each
Energy threshold ~ 100 eV

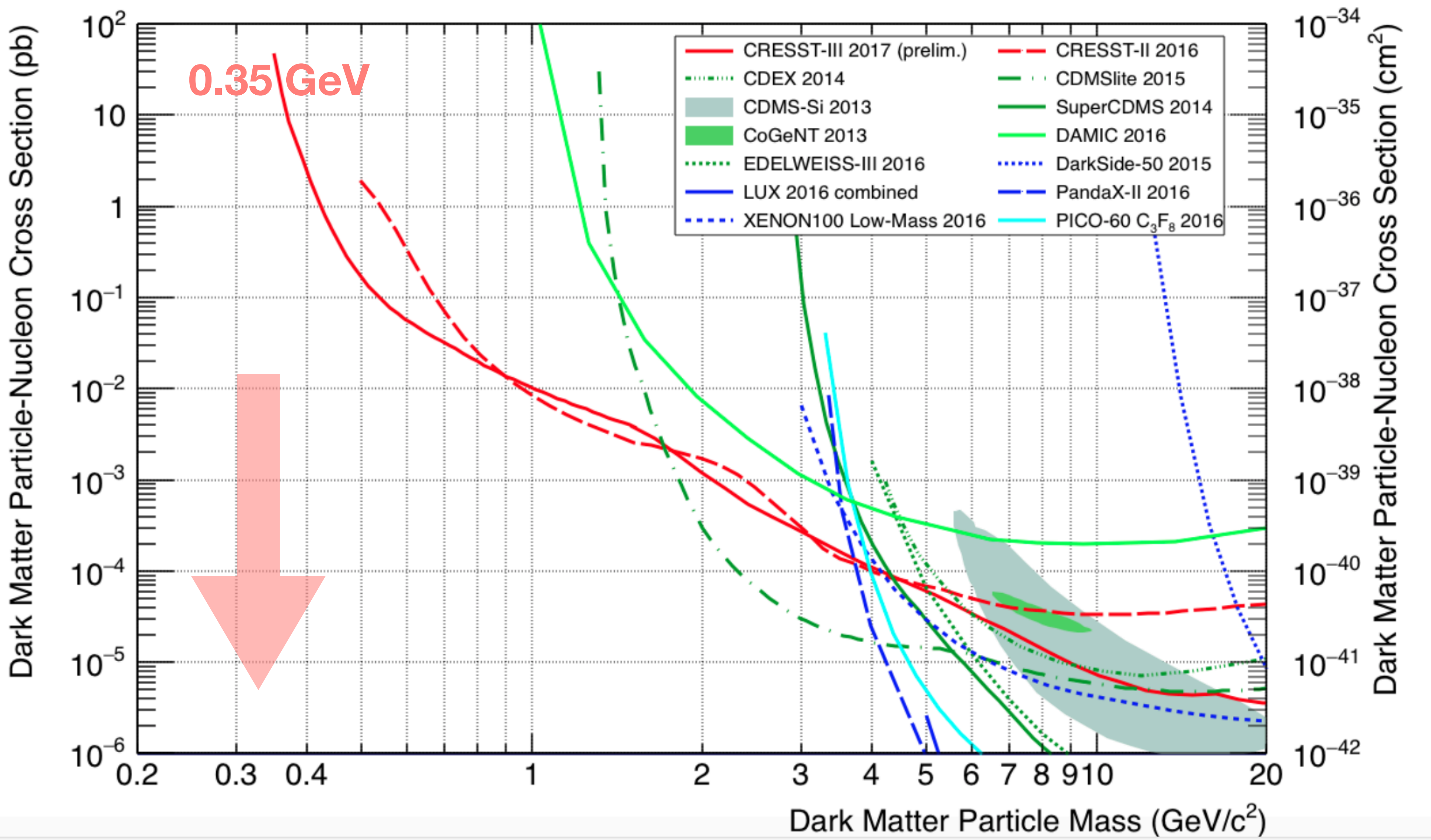
## SuperCDMS @SNOLAB




- 4 detector towers with 18 Ge (à 1.4 kg) and 6 Si (à 0.5 kg) crystals in total
- reduce ER background by factor 200
- improve energy resolution (TES design, improved electronics)
- start operation in 2020

# Phonon detectors at T ~ mK

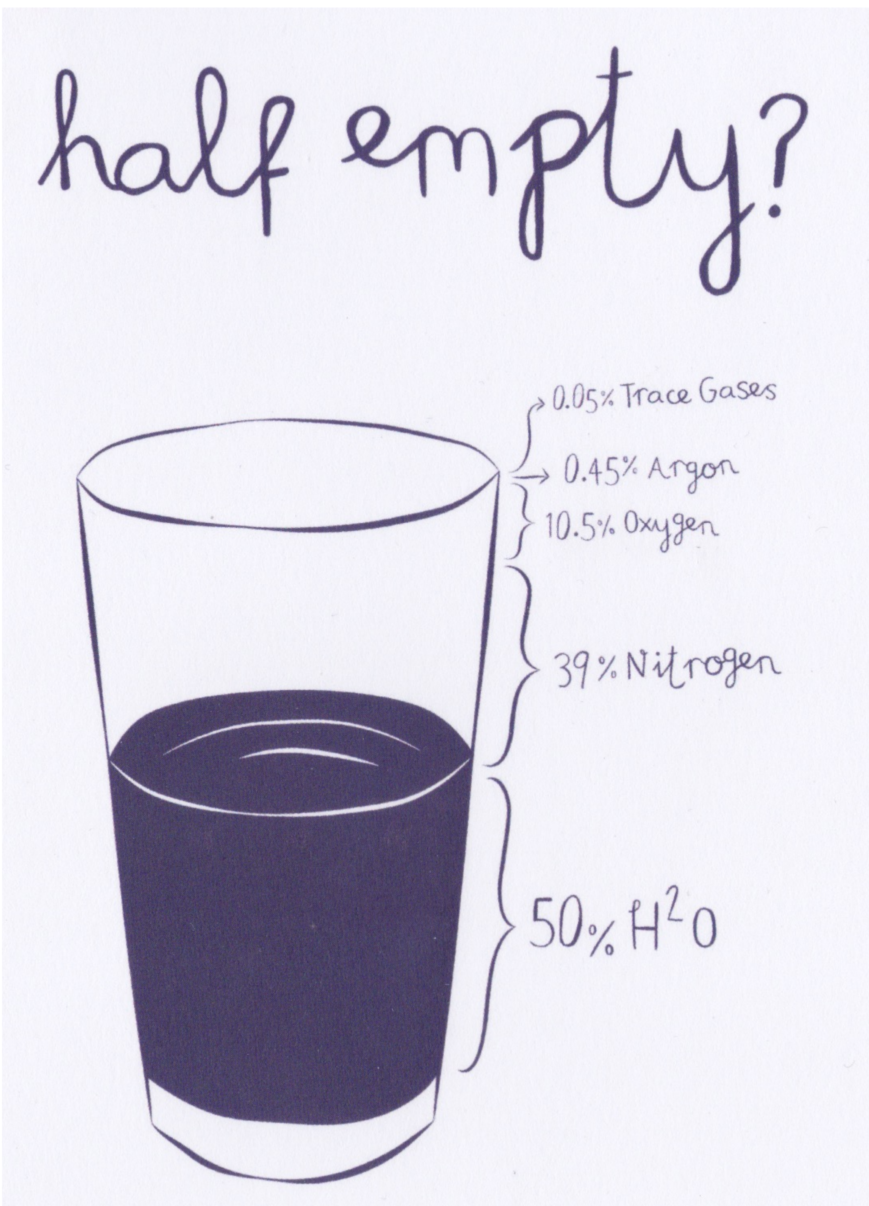
- Reached energy thresholds ~ 100 eV
- Probe low-mass WIMP region (sub-GeV to few GeV)

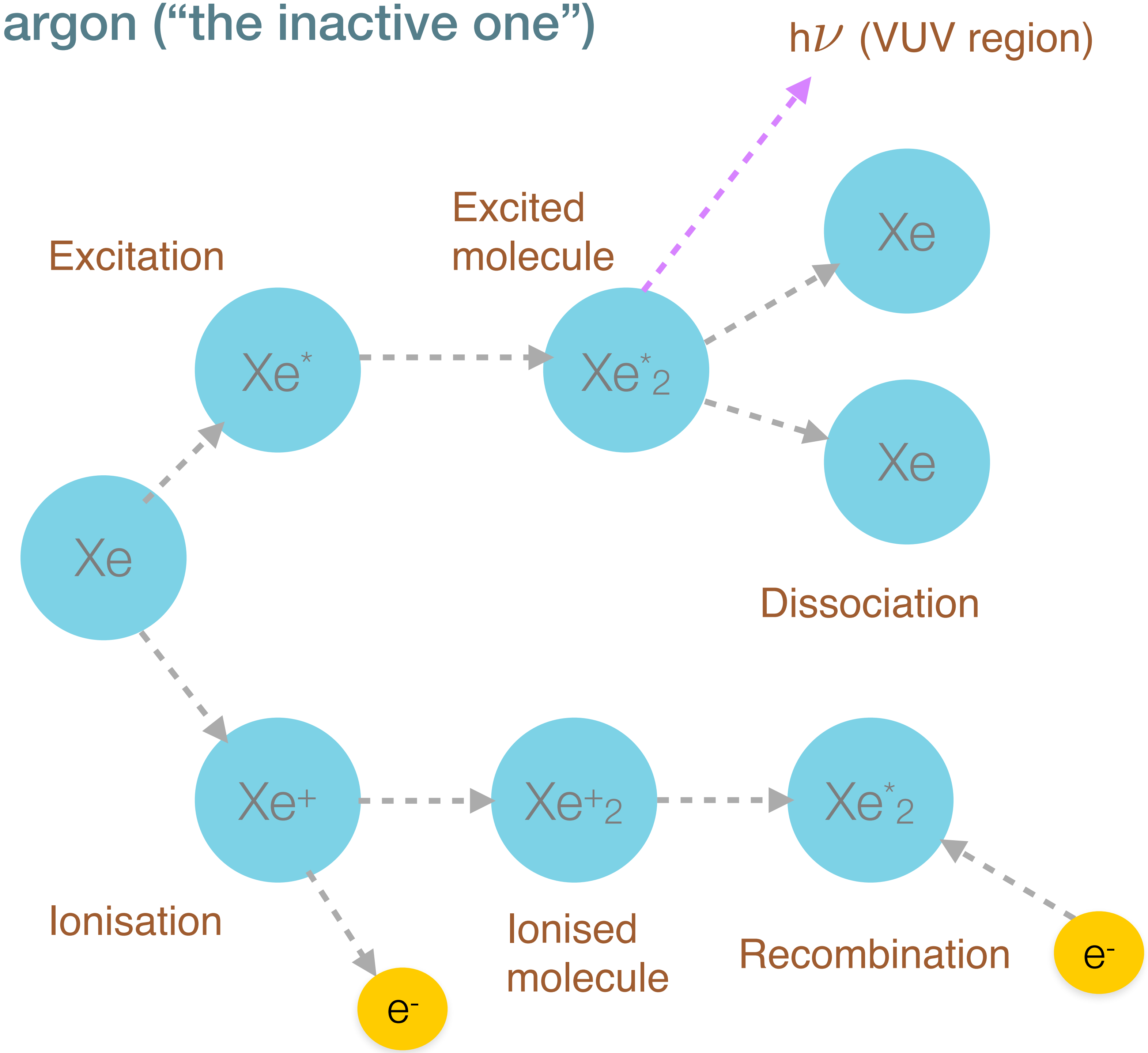



CRESST, at TAUP2017

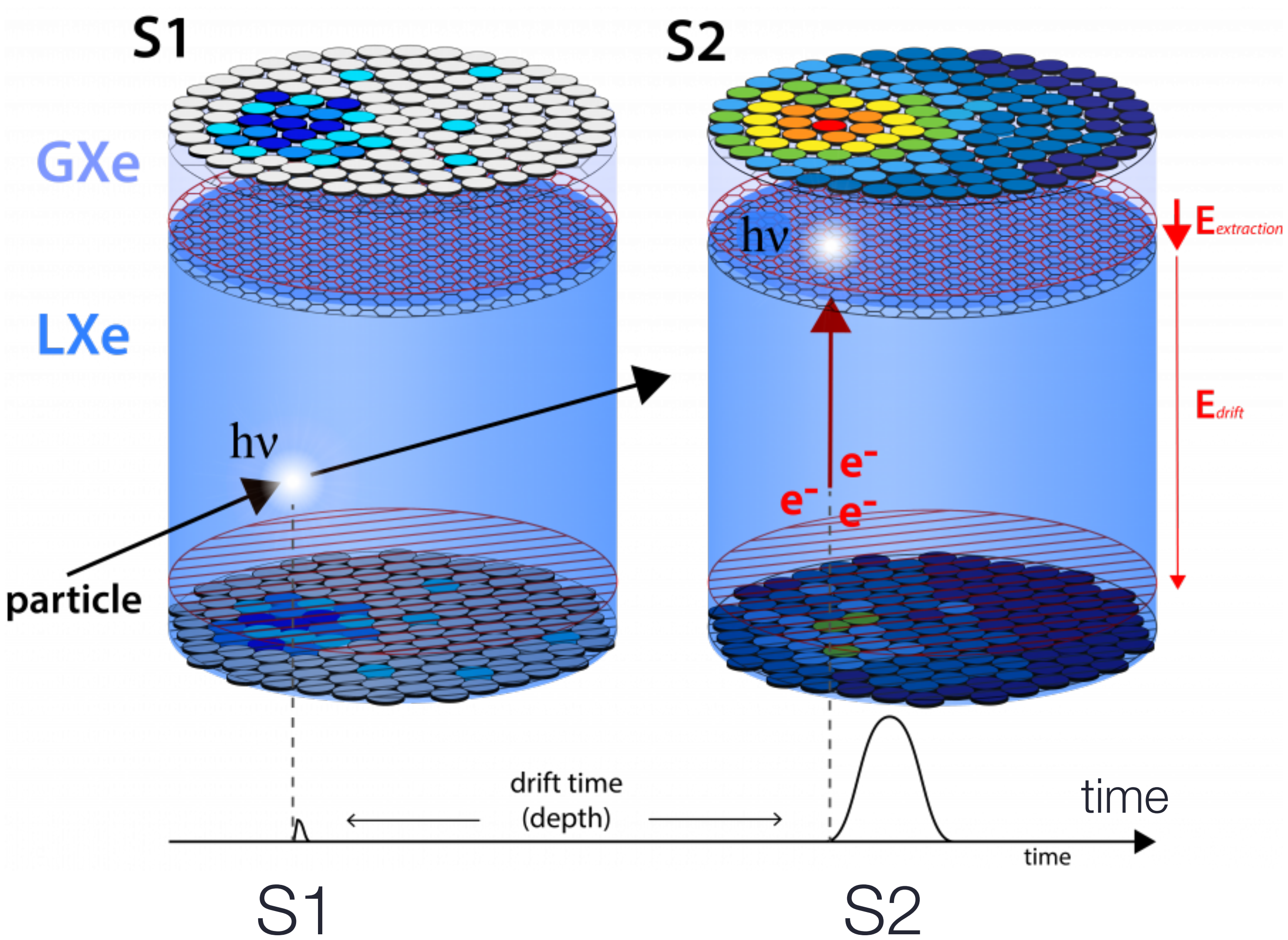
# Liquefied noble gases

- Xenon ("the strange one") and argon ("the inactive one")



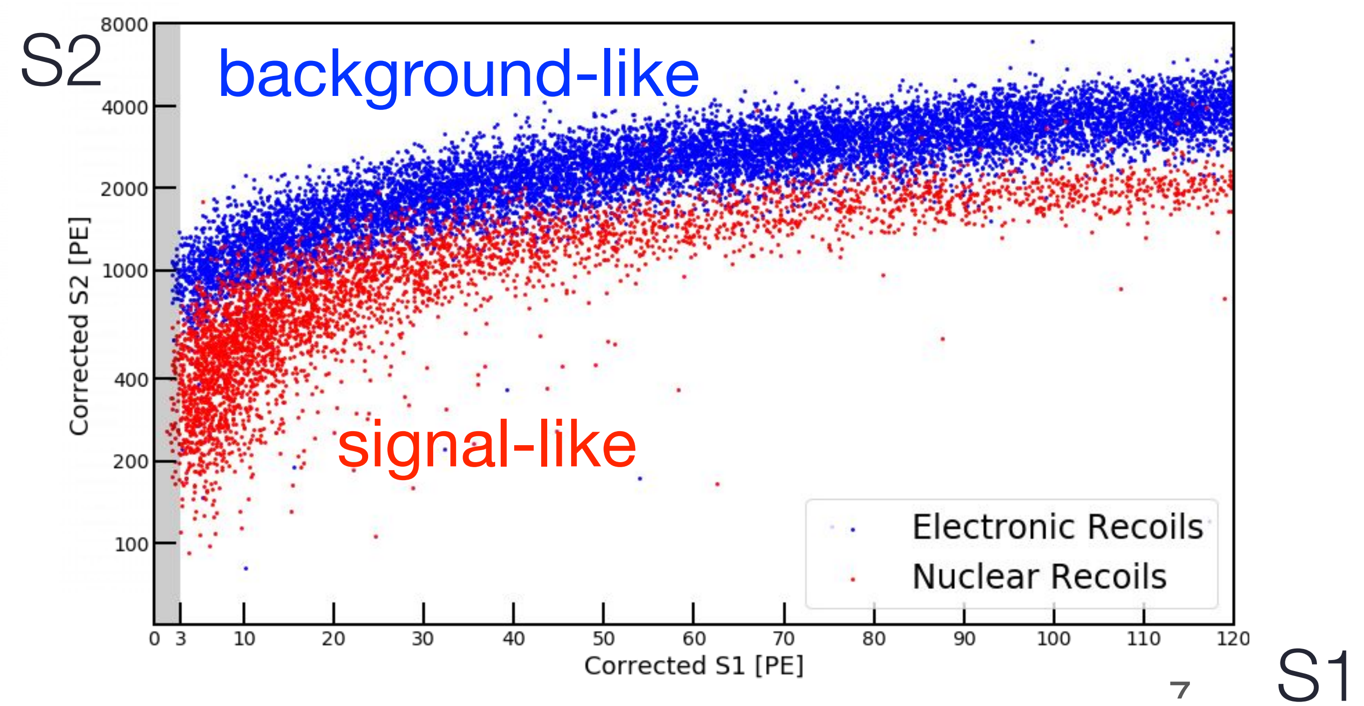
# Two-phase xenon projection chambers




XENON100

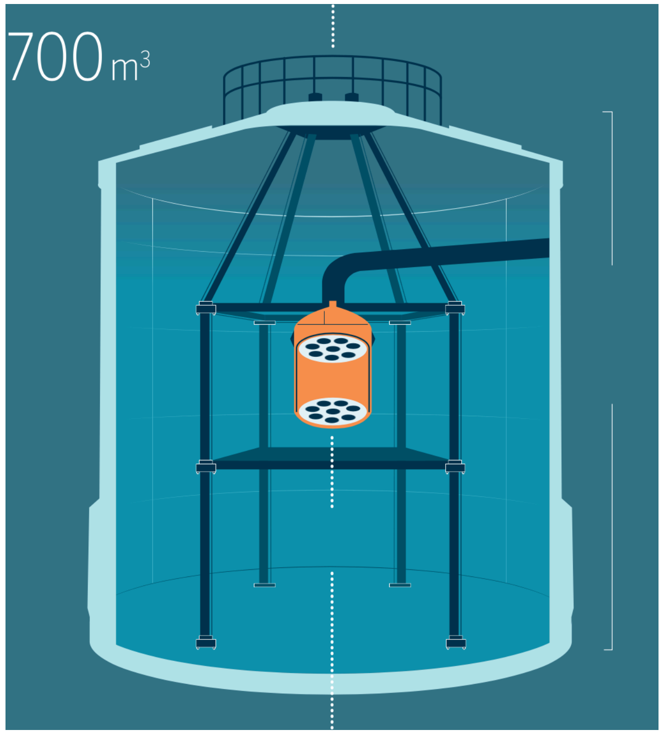
LUX

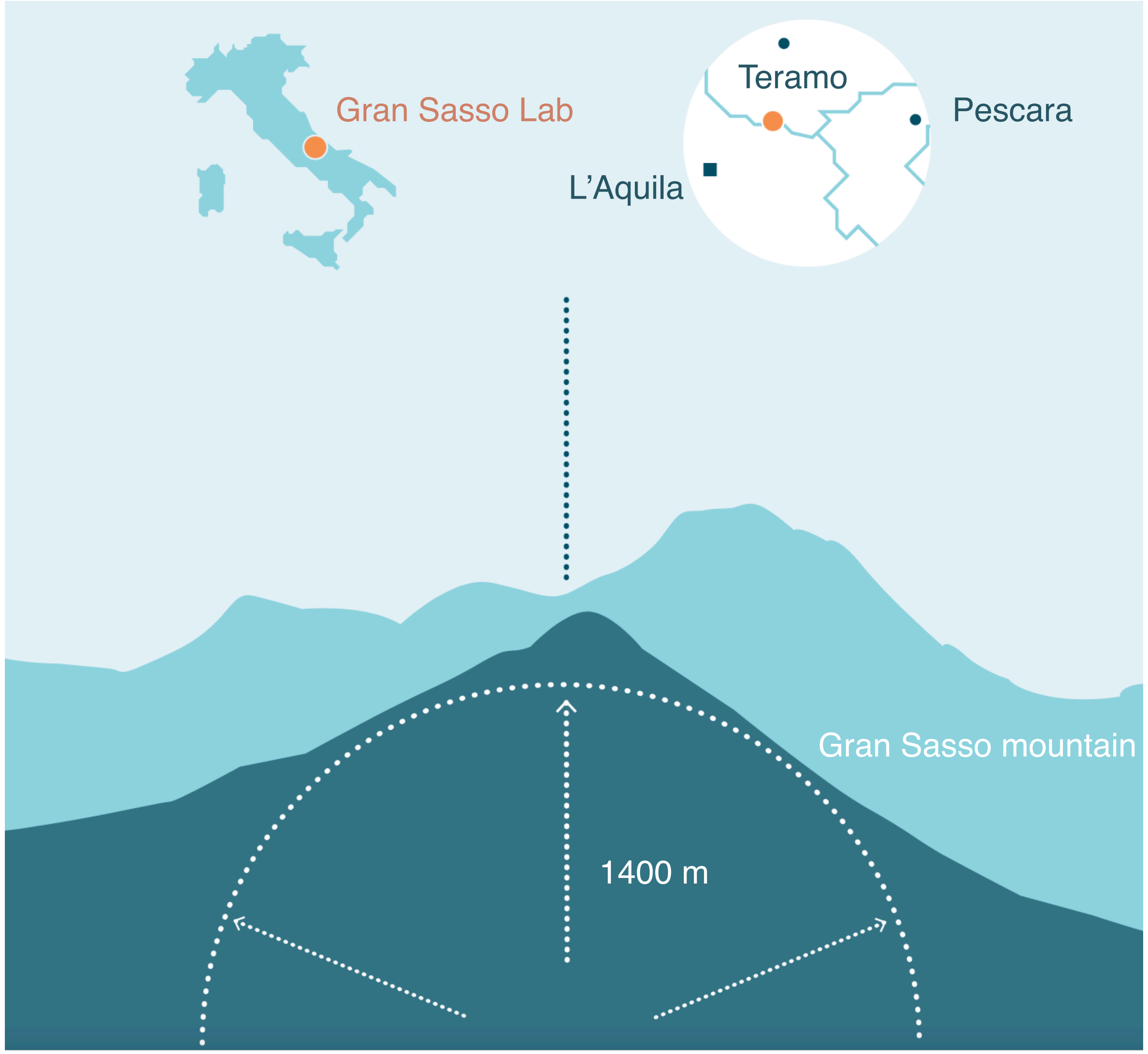
PandaX

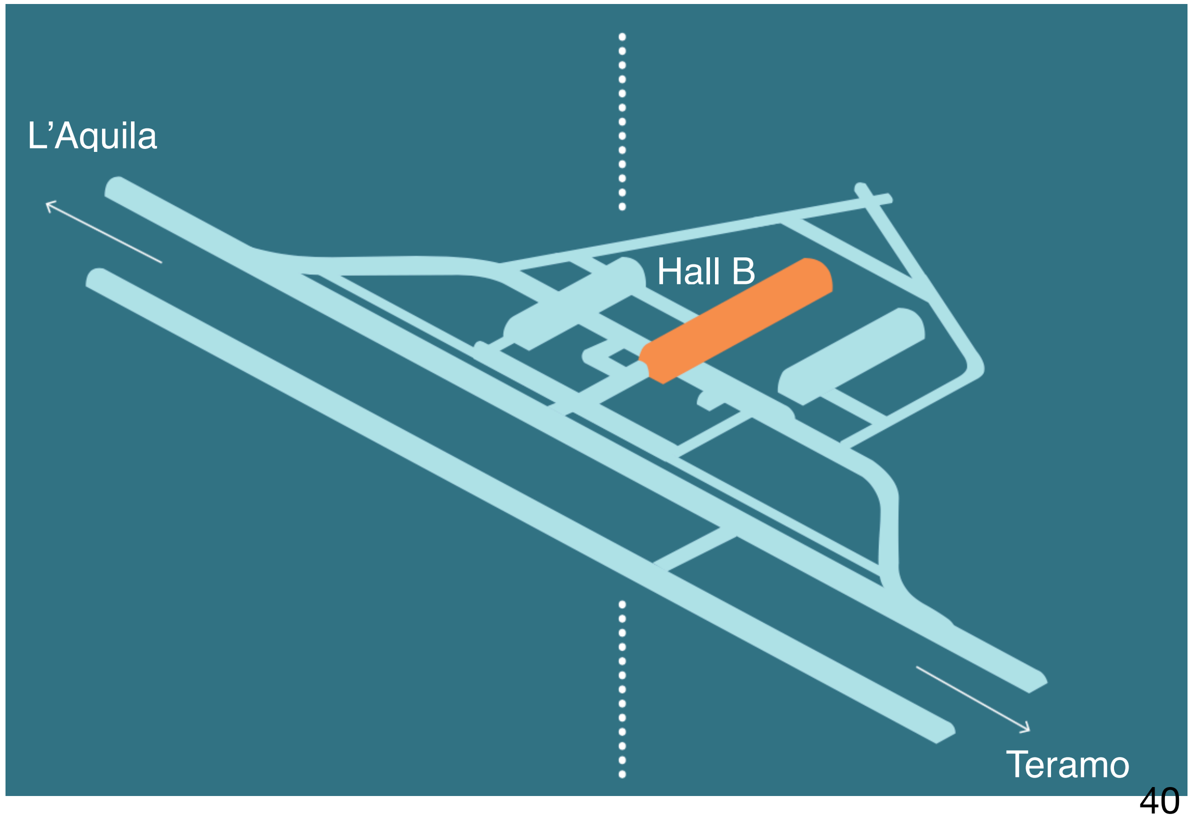


# XENON1T at LNGS

- Total (active) LXe mass: 3.2 t (2 t), 1 m electron drift
- 248 3-inch PMTs in two arrays




Tagesanzeiger December 2016

# XENON1T at LNGS

Water tank and
Cherenkov muon veto

Cryostat and support
structure for TPC

Time projection
chamber

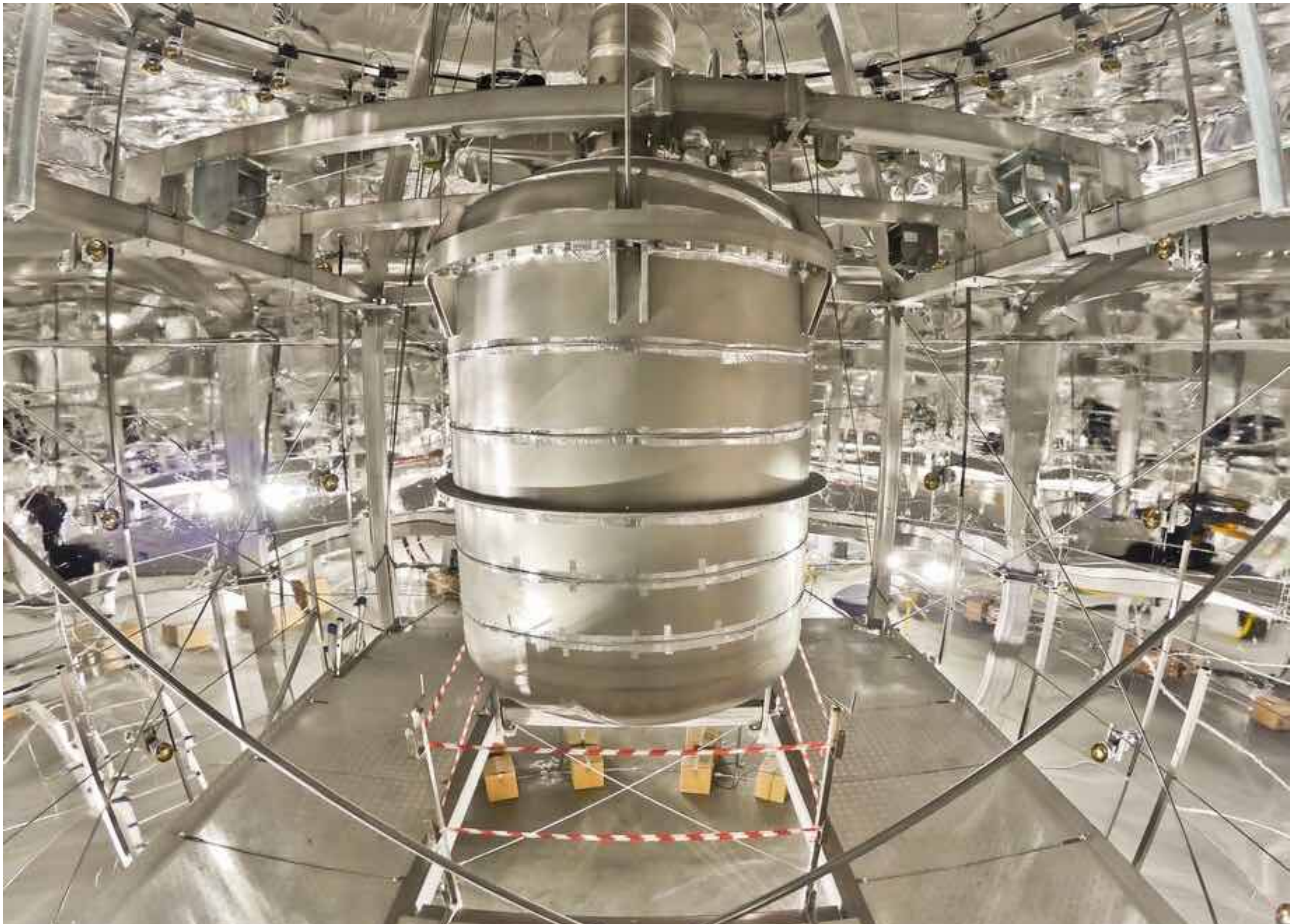
Umbilical pipe
(cables, xenon)


Cryogenics and
purification

Data acquisition and
slow control

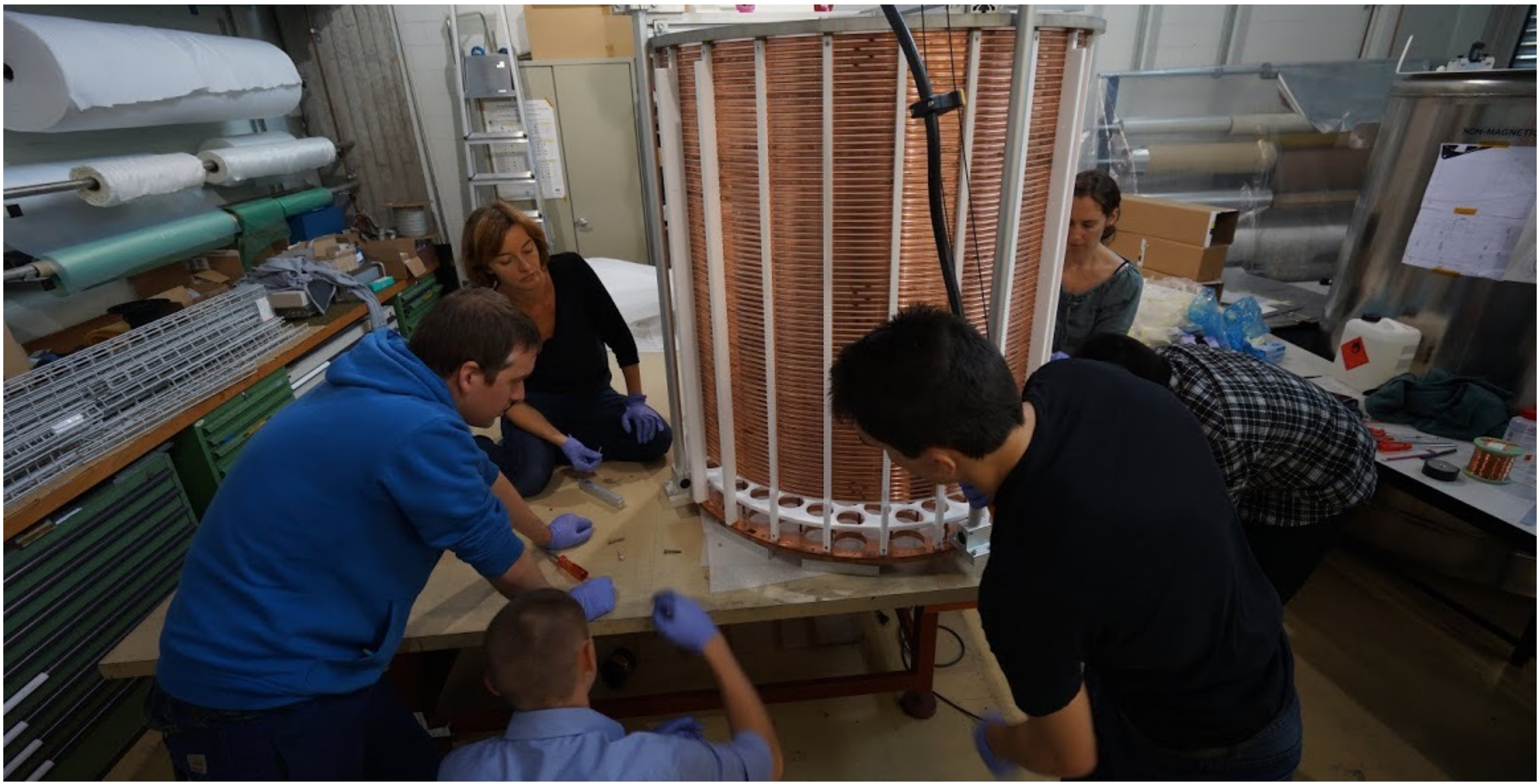
Xenon storage,
handling and
distillation column

# The XENON1T Cryostat and Water Shield



# The XENON1T Cryostat and Water Shield

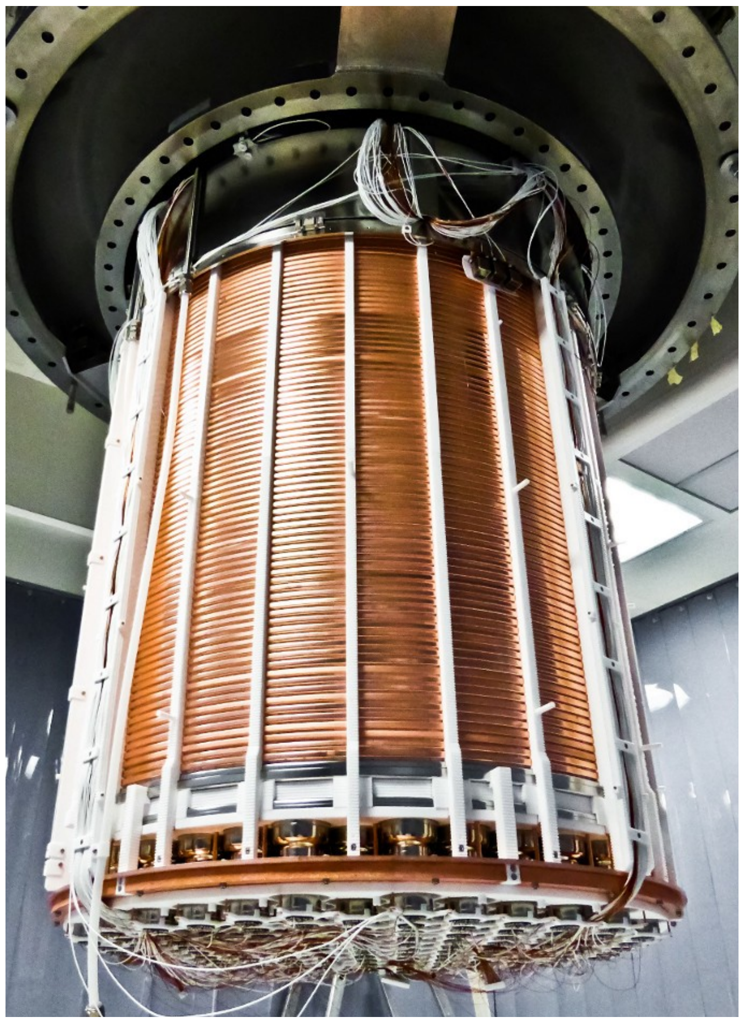
# The time projection chamber: first assembly



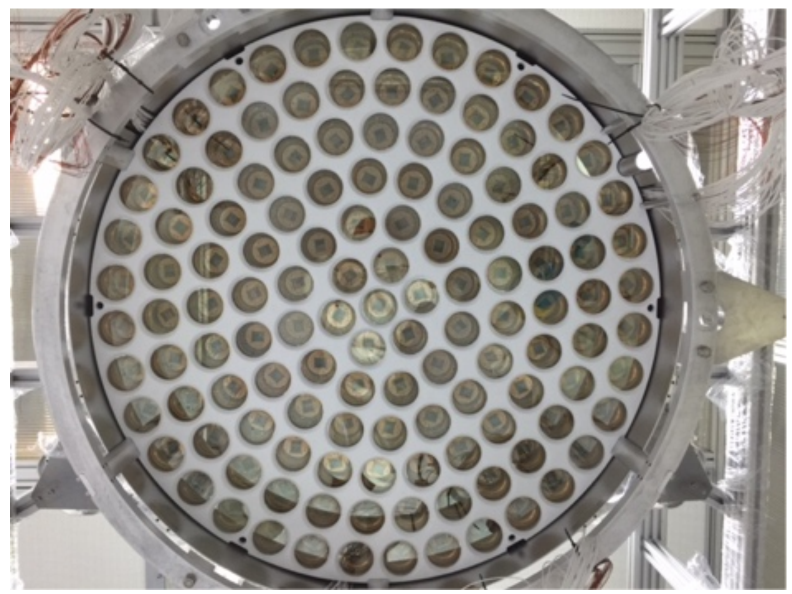
# The time projection chamber underground

# The Time Projection Chamber

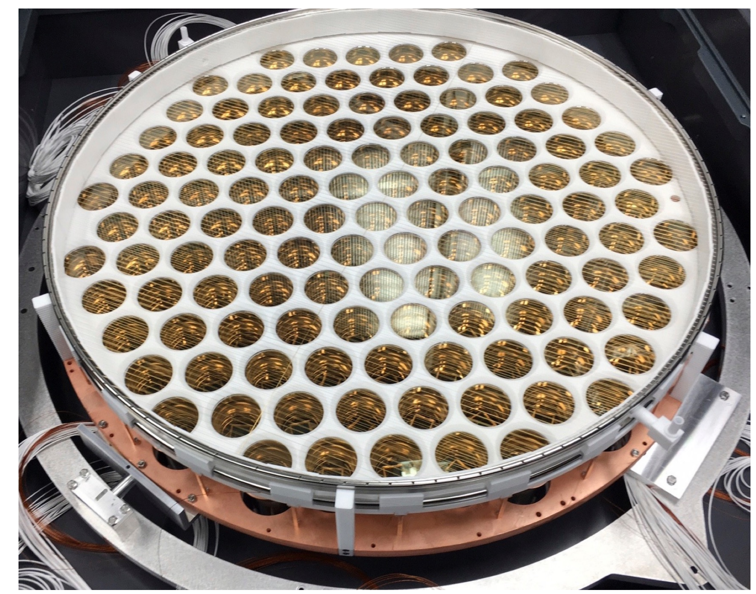
- The 248 3-inch, low-radioactivity PMTs are arranged in two arrays



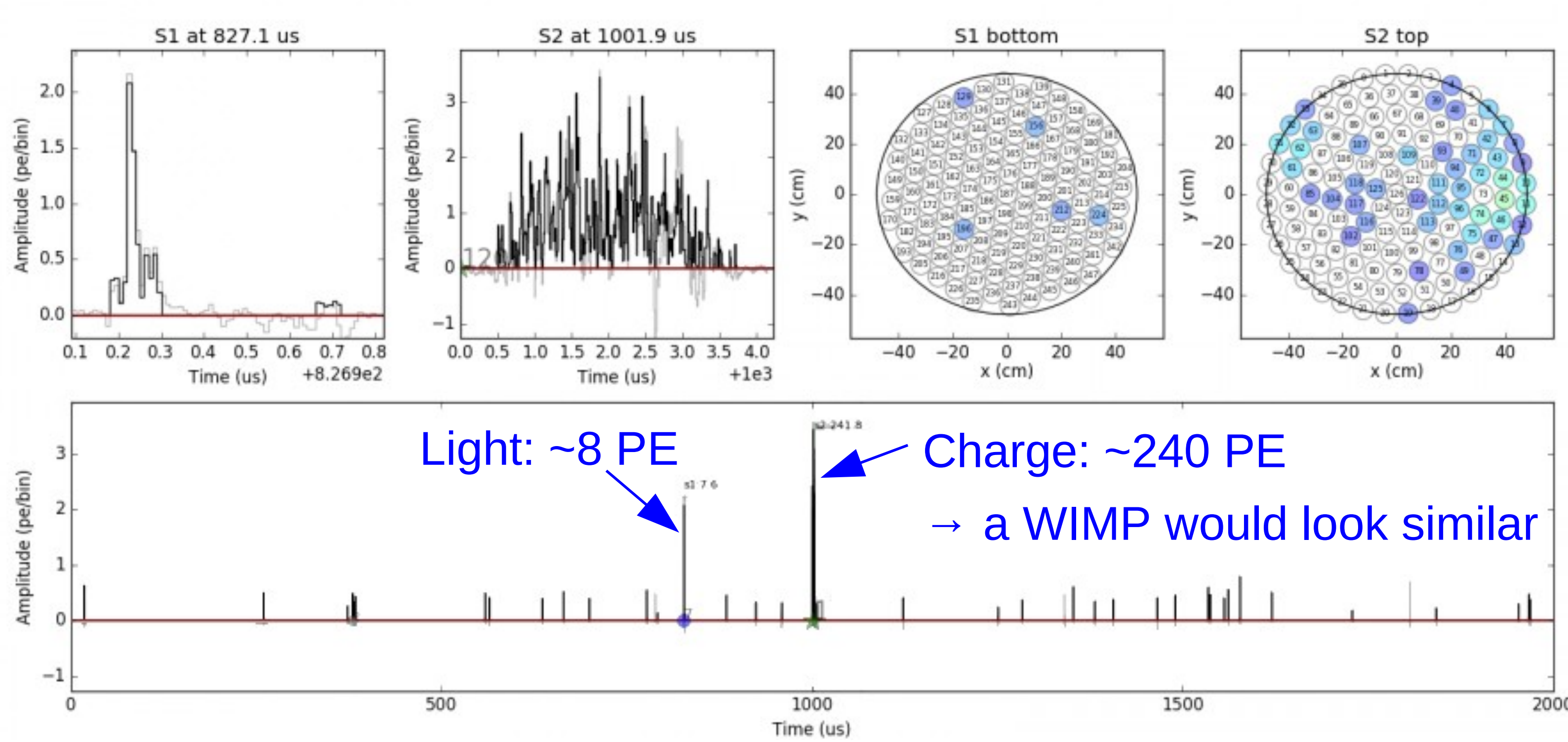
3.2 t LXe @180 K



127 PMTs in the top array



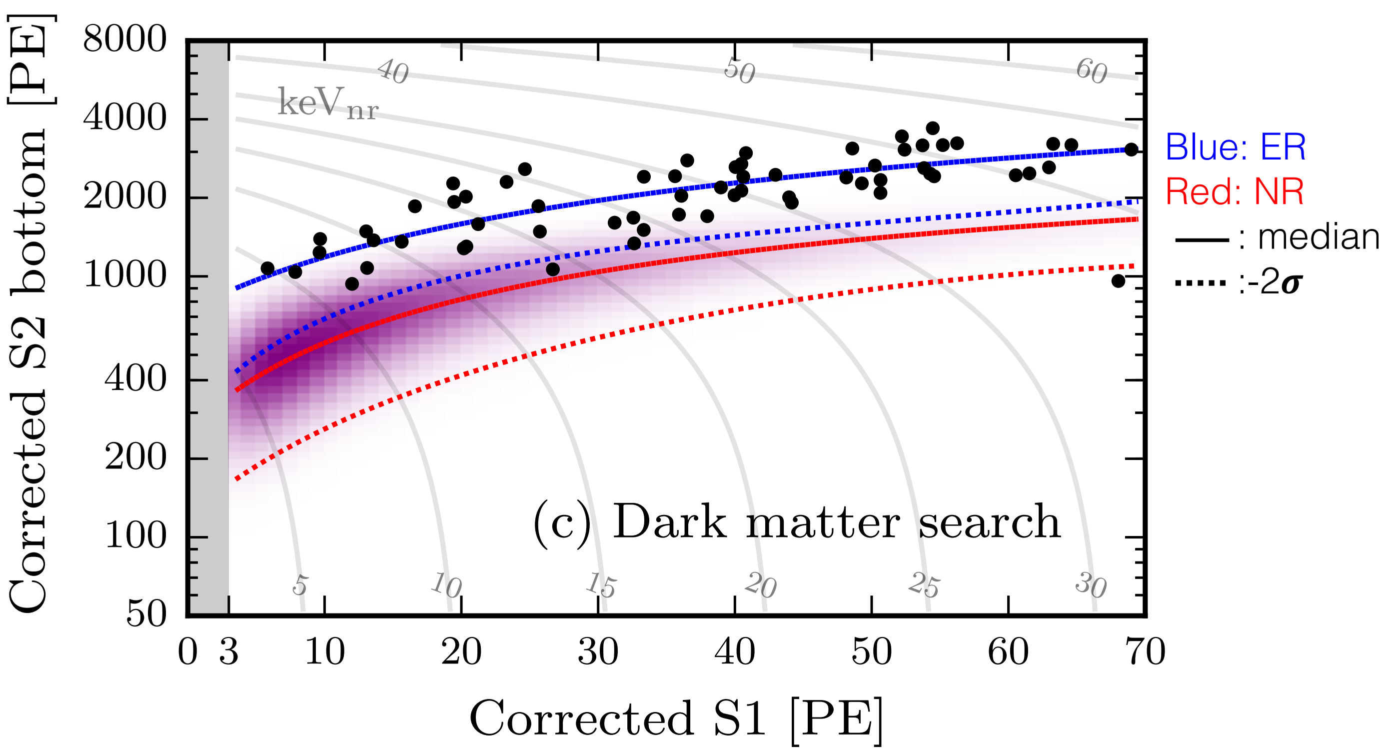
121 PMTs in the bottom array

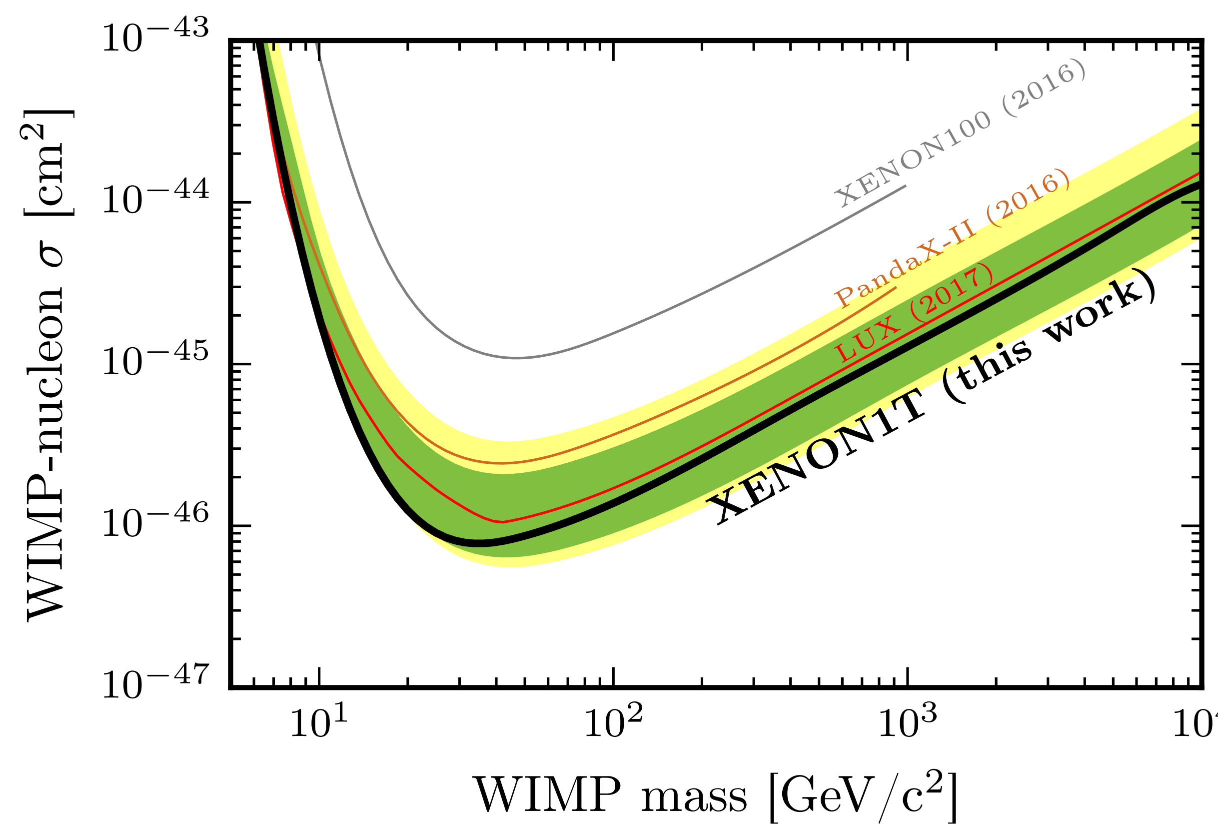


# XENON1T first results

- 34.2 live days dark matter exposure Oct 2016 - Jan 2017
- No evidence for a signal -> upper limit

Phys. Rev. Lett. **119**, 181301, 2017

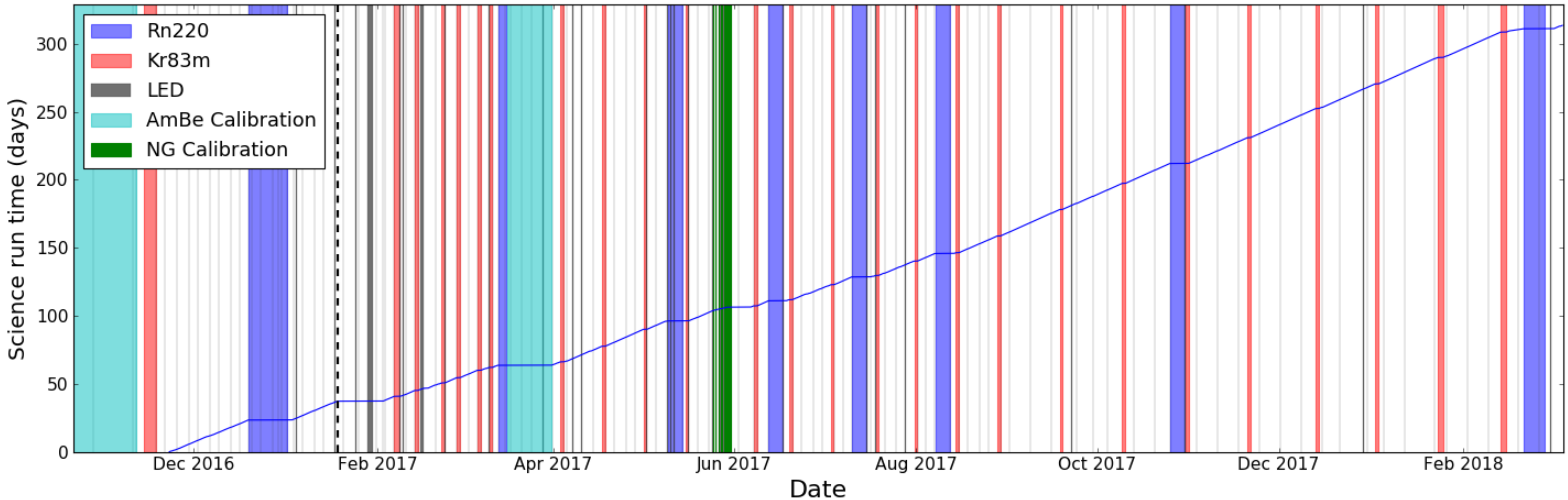



$$7.8 \times 10^{-47}\,\mathrm{cm}^2 \text{ at } 35\,\mathrm{GeV/c^2}$$

# Science and calibration data overview

- **First science run: Oct 2016 - Jan 2017 (34.2 live days)**
- Second science run proceedings smoothly (~ 250 live days)
- Unblinding very soon… and new results this spring

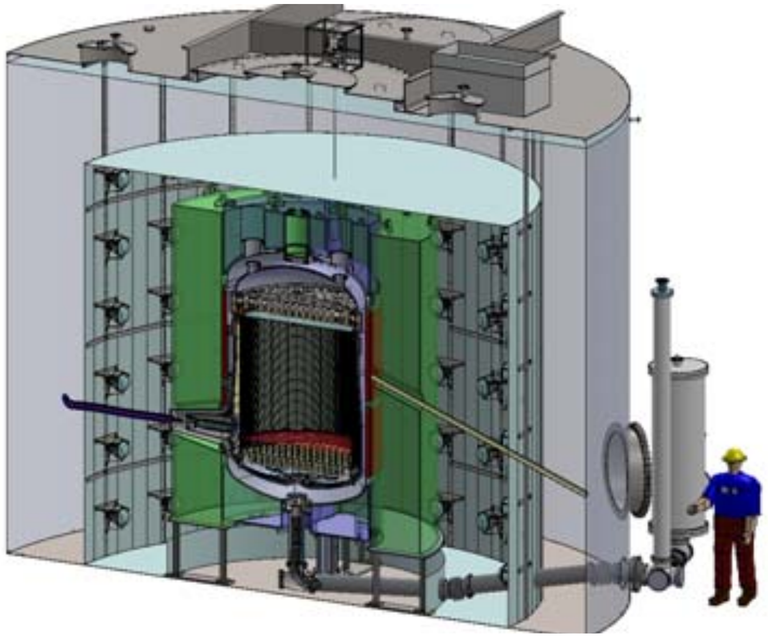



**SR0**
**~34 live days**

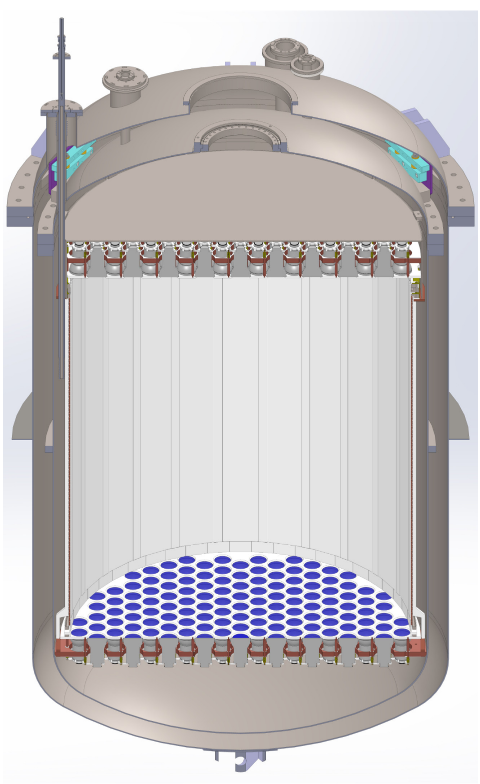
**SR1**
**~ 250 live days**

# Future noble liquid detectors

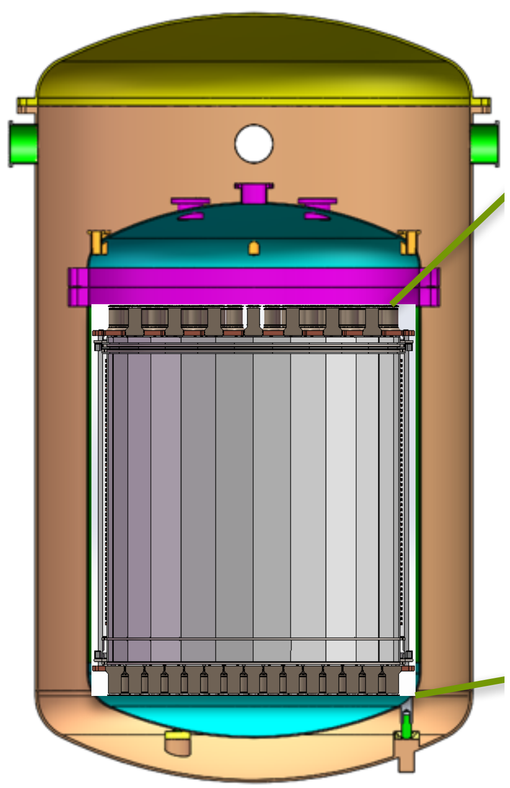
- In construction LXe & LAr:
  - LUX-ZEPLIN, XENONnT, DarkSide-20k, PandaX-4t
- Next-generation, design & R&D phase:
  - DARWIN 50 t LXe; ARGO 300 t LAr



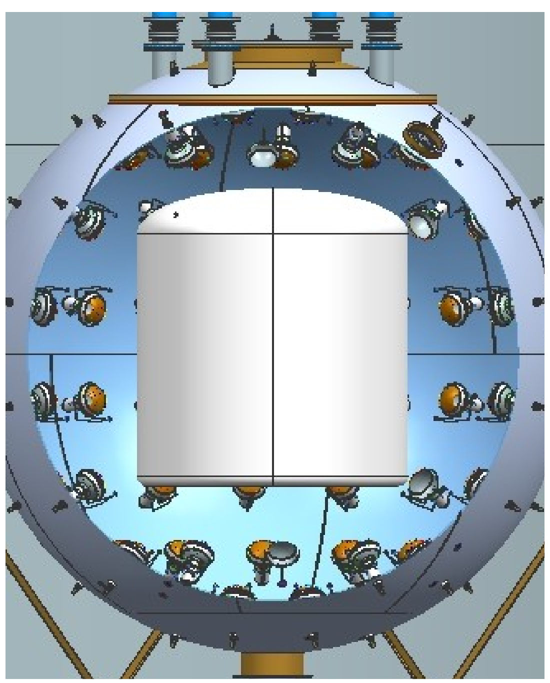
LUX-ZEPLIN: 8 t LXe



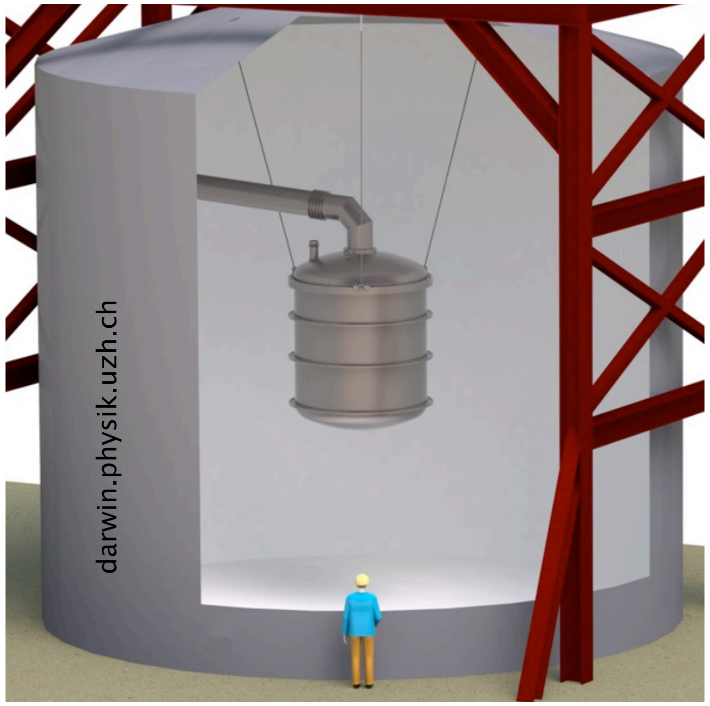
XENONnT: 8t LXe



PandaX-4t LXe



DarkSide: 20 t LAr




DARWIN: 50 t LXe

DARWIN

European Research Council

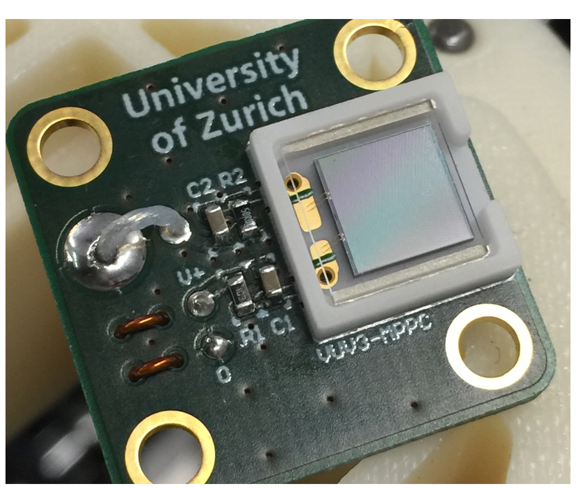
Established by the European Commission

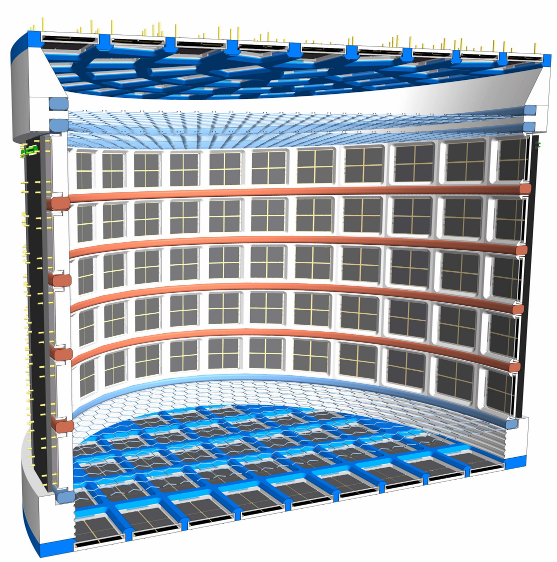
# darwin-observatory.org

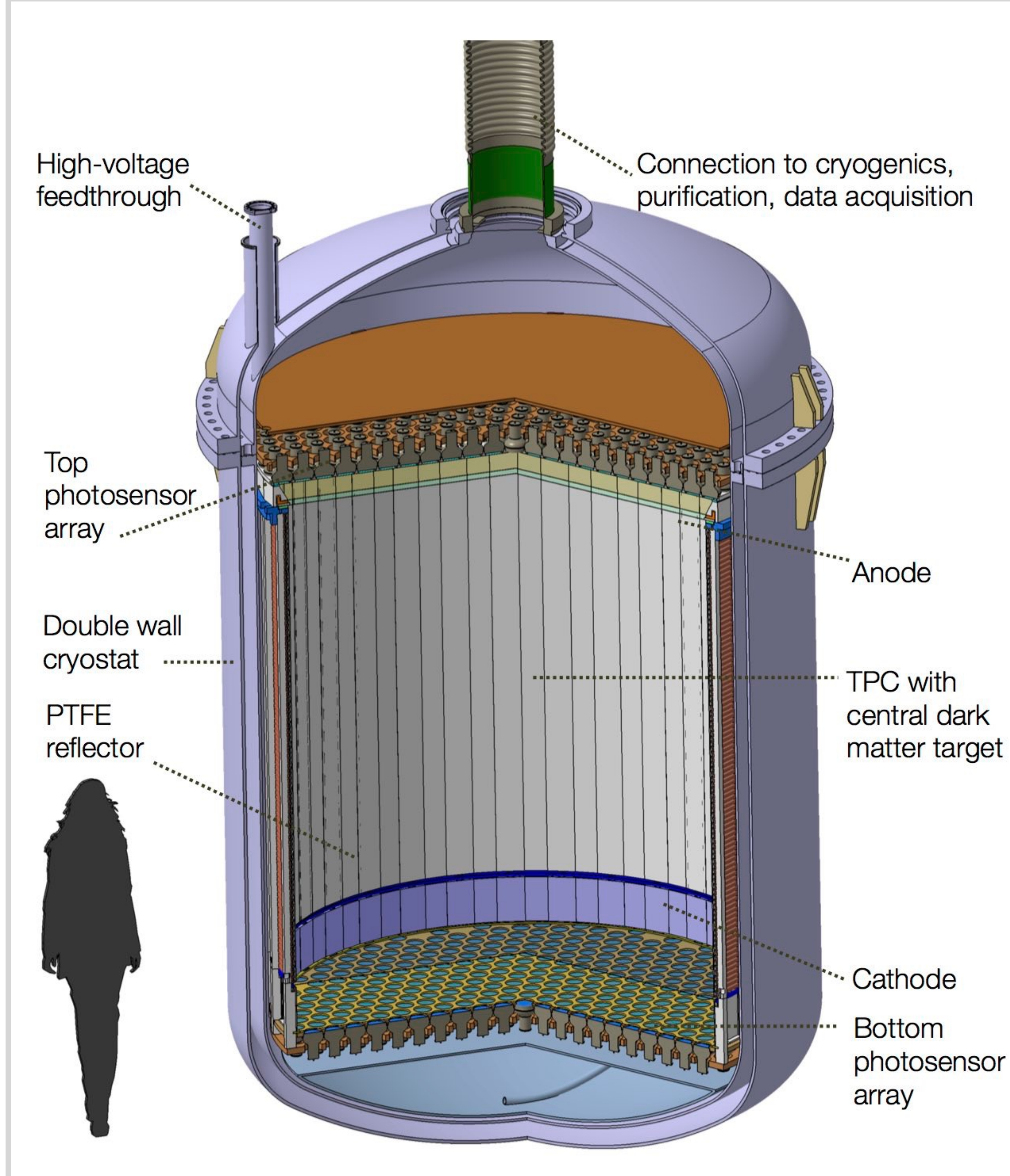
## “Ultimate” WIMP detector

50 tonnes liquid xenon

R&D and prototypes supported by two ERC grants: Ultimate (Freiburg) and Xenoscope (Zürich)



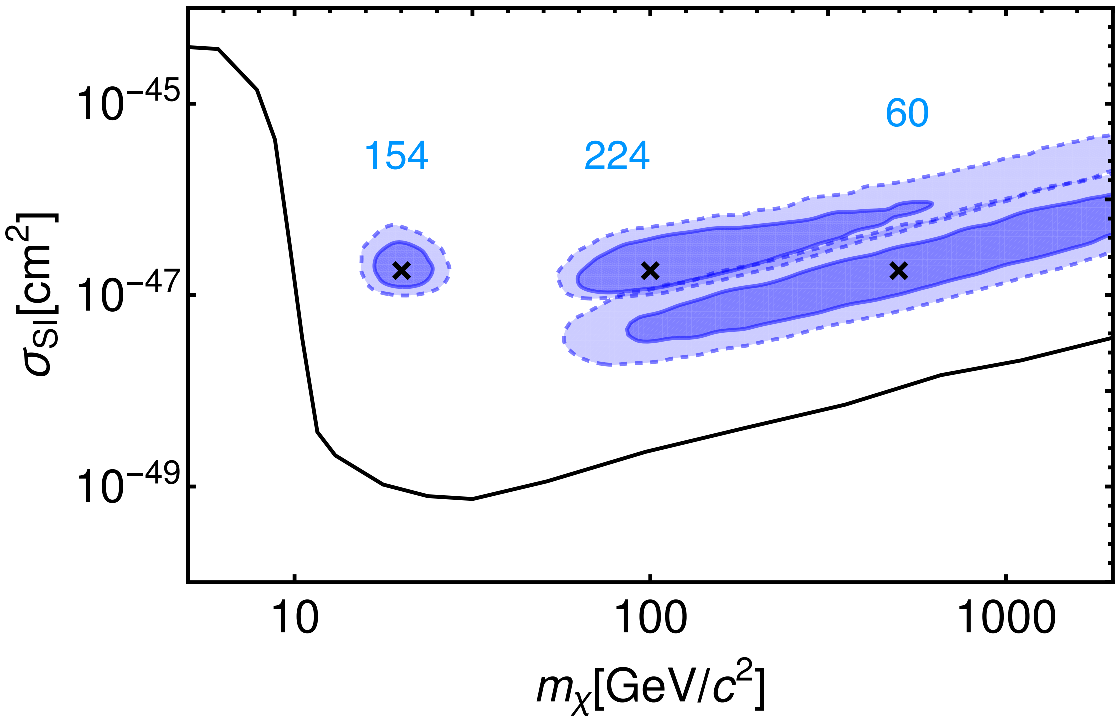





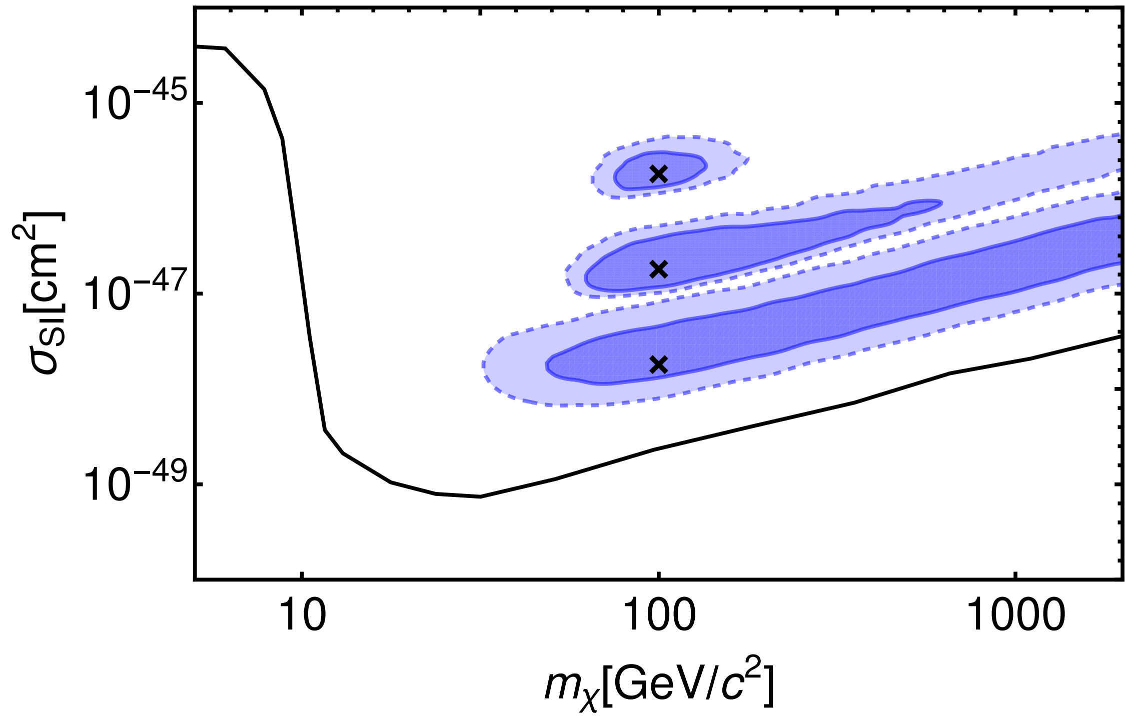
# Dark matter spectroscopy

- Capability to reconstruct the WIMP mass and cross section for various masses (**20, 100, 500 GeV/c²**) and cross sections

**Exposure: 200 t y**




**Exposure: 200 t y**




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

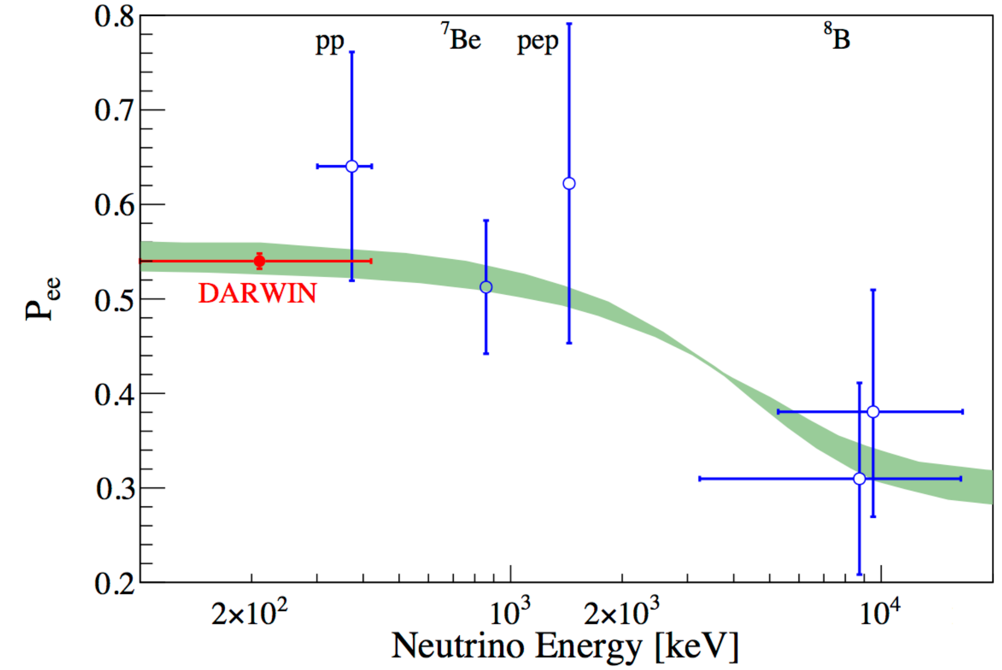
$$v_{esc} = 544 \pm 40\,\mathrm{km/s}$$

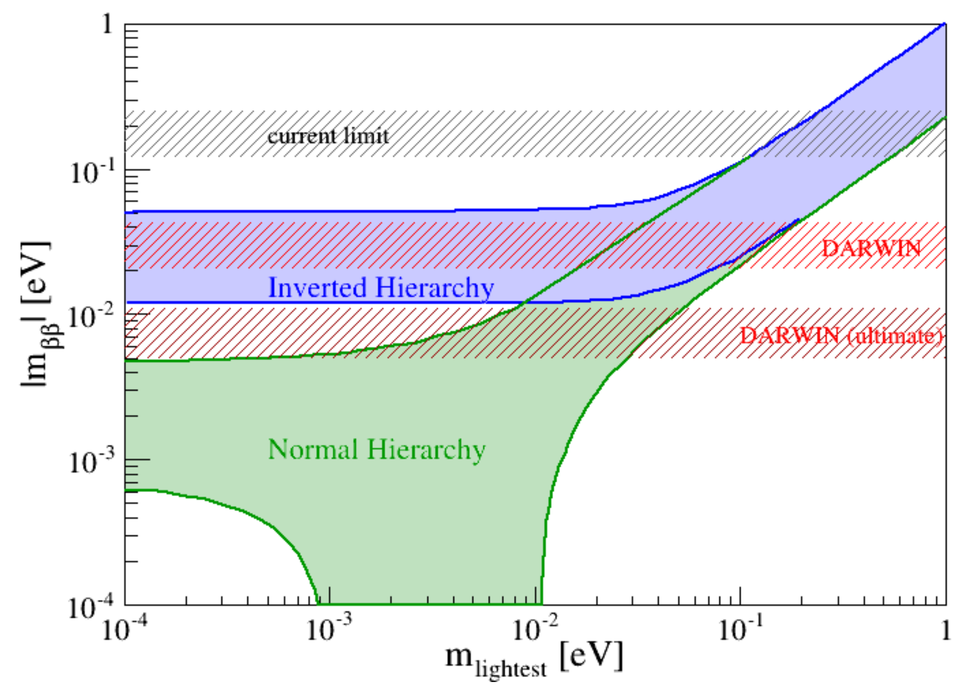
$$v_0 = 220 \pm 20\,\mathrm{km/s}$$

$$\rho_\chi = 0.3 \pm 0.1\,\mathrm{GeV/cm^3}$$

# Non-WIMP Physics: a non-exhaustive list

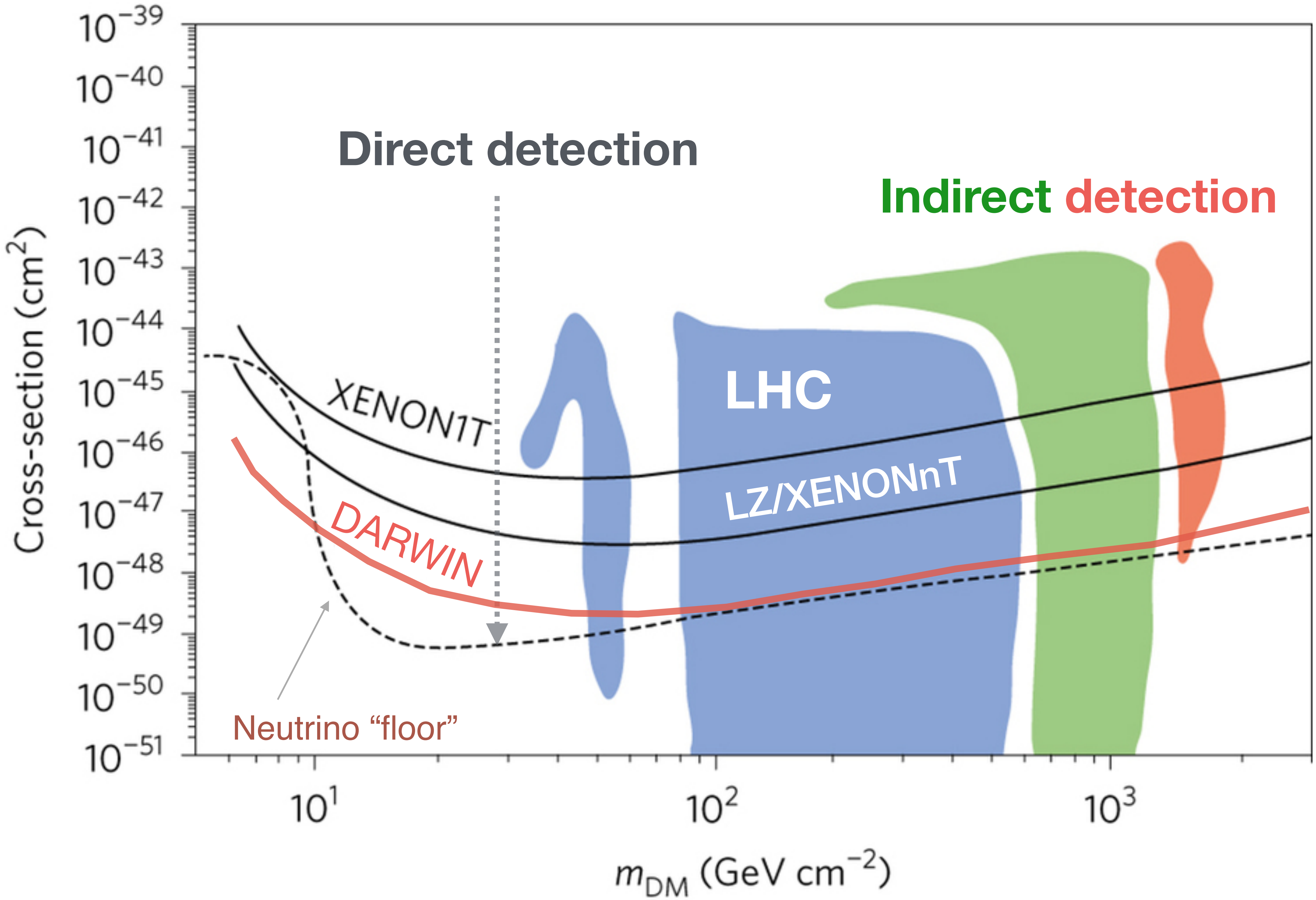
- DM scattering off electrons (leptophilic models)
- pp solar neutrinos (ν-e⁻ scattering) to ~1%
- Coherent ν-nucleus scattering ($^{8}$B and SN neutrinos)
- Neutrinoless double beta decay in $^{136}$Xe
- Double electron capture in $^{124}$Xe
- Solar axions and axion-like particles (via axio-electric effect)
- Heavy sterile neutrinos (masses in the > 10 keV range)
- Bosonic SuperWIMPs (via absorption by Xe atoms)




DARWIN collaboration, JCAP 1611 (2016) 017

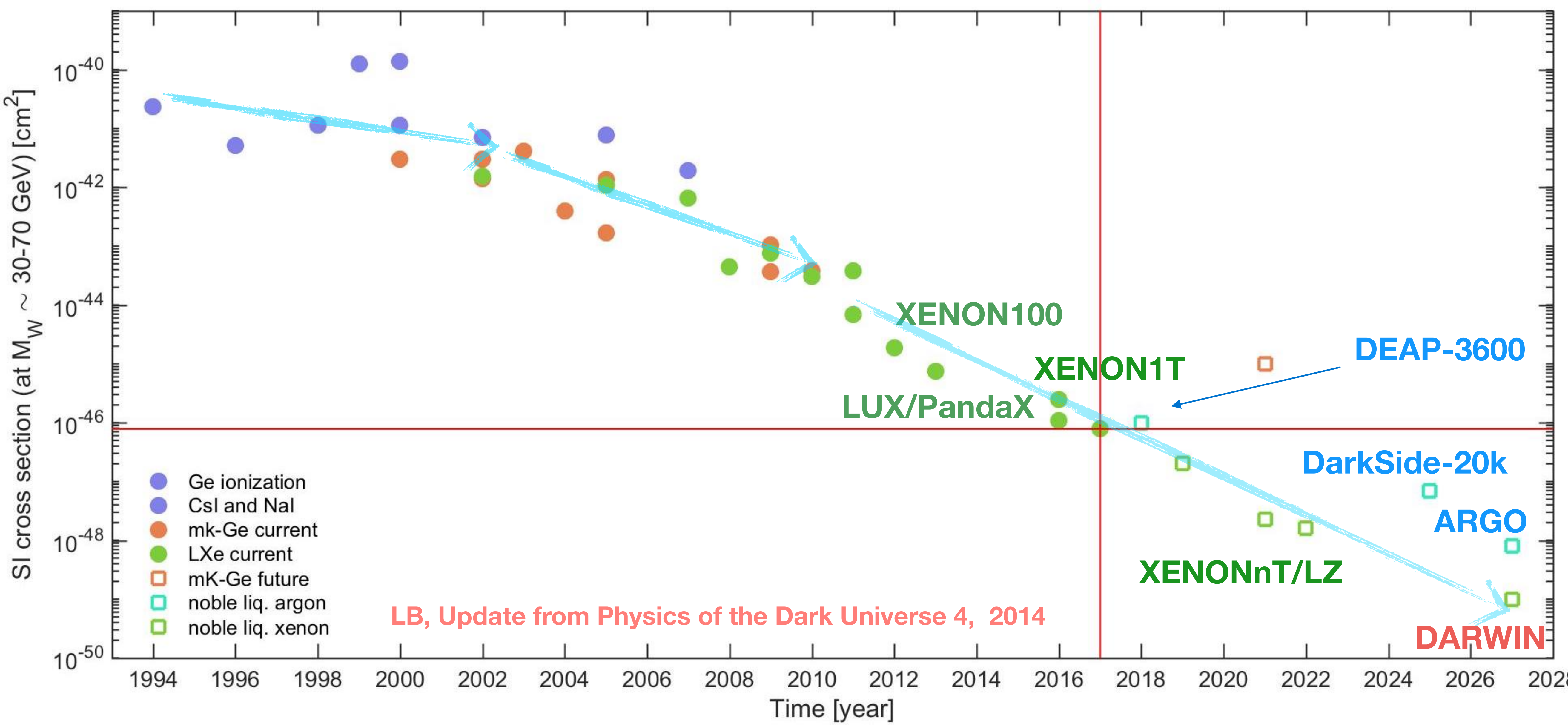
# WIMP Physics: Direct, indirect detection, and LHC




After Nature physics, March 2017

# Direct detection versus time

- Sensitivity: about a factor of 10 increase every ~ 2 years



# Summary & Outlook

Cold dark matter is (still) a viable paradigm that explains all cosmological & astrophysical observations

It could be made WIMPs - thermal relics from an early phase of our Universe

- this hypothesis is testable: direct detection, indirect detection, accelerators

- so far, no convincing detection of a dark matter particle in the laboratory

But: direct detection experiments offer excellent prospects for discovery

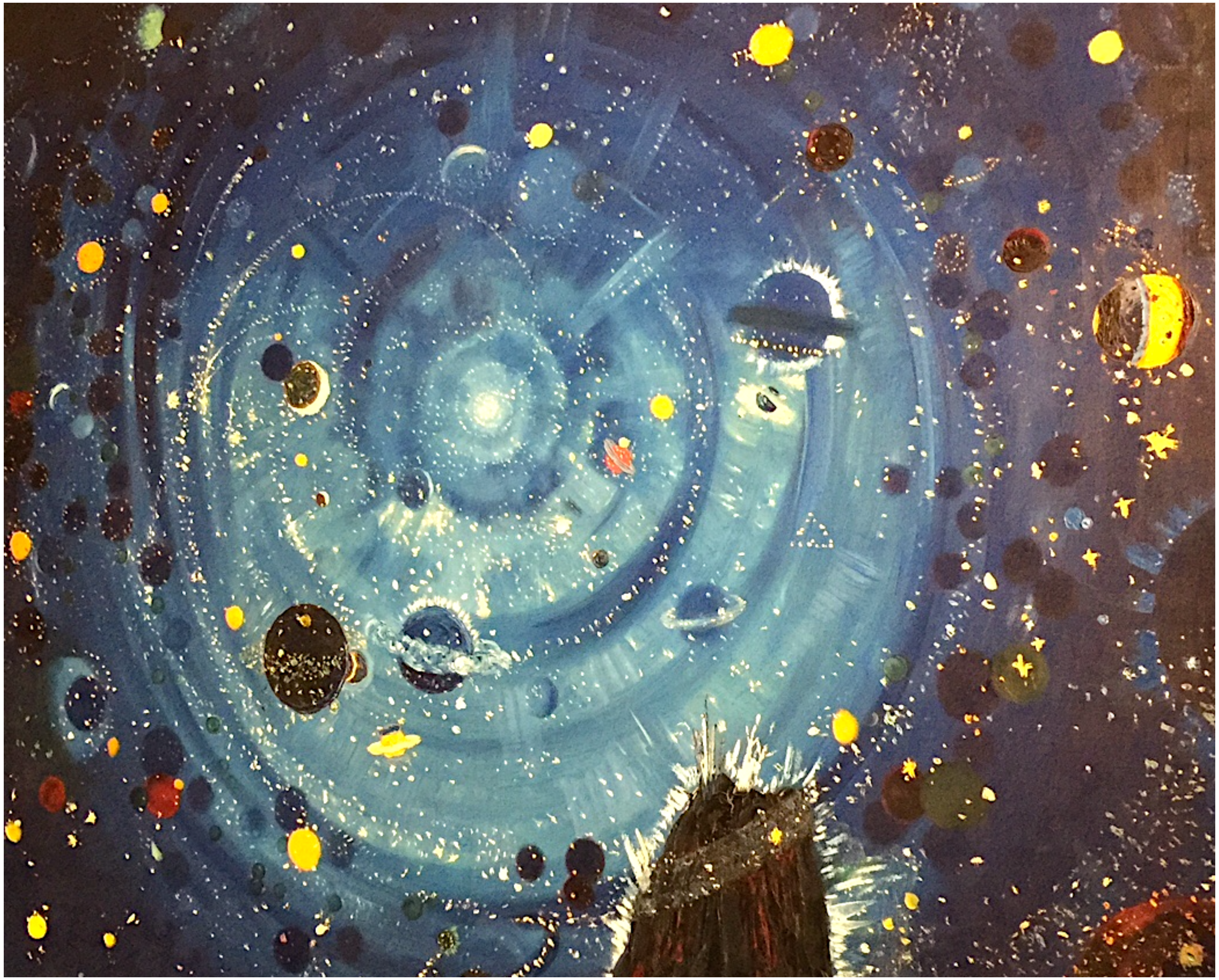
increase in WIMP sensitivity by 2 orders of magnitude in the next few years

reach neutrino background *(and measure neutrino-nucleus coherent scattering from solar/atm/SN neutrinos!)* this & next decade

high complementarity with indirect searches (AMS, IceCube, CTA, Fermi…) & with the HL-LHC

## Of course, “the probability of success is difficult to estimate, but if we never search, the chance of success is zero”

G. Cocconi & P. Morrison, Nature, 1959

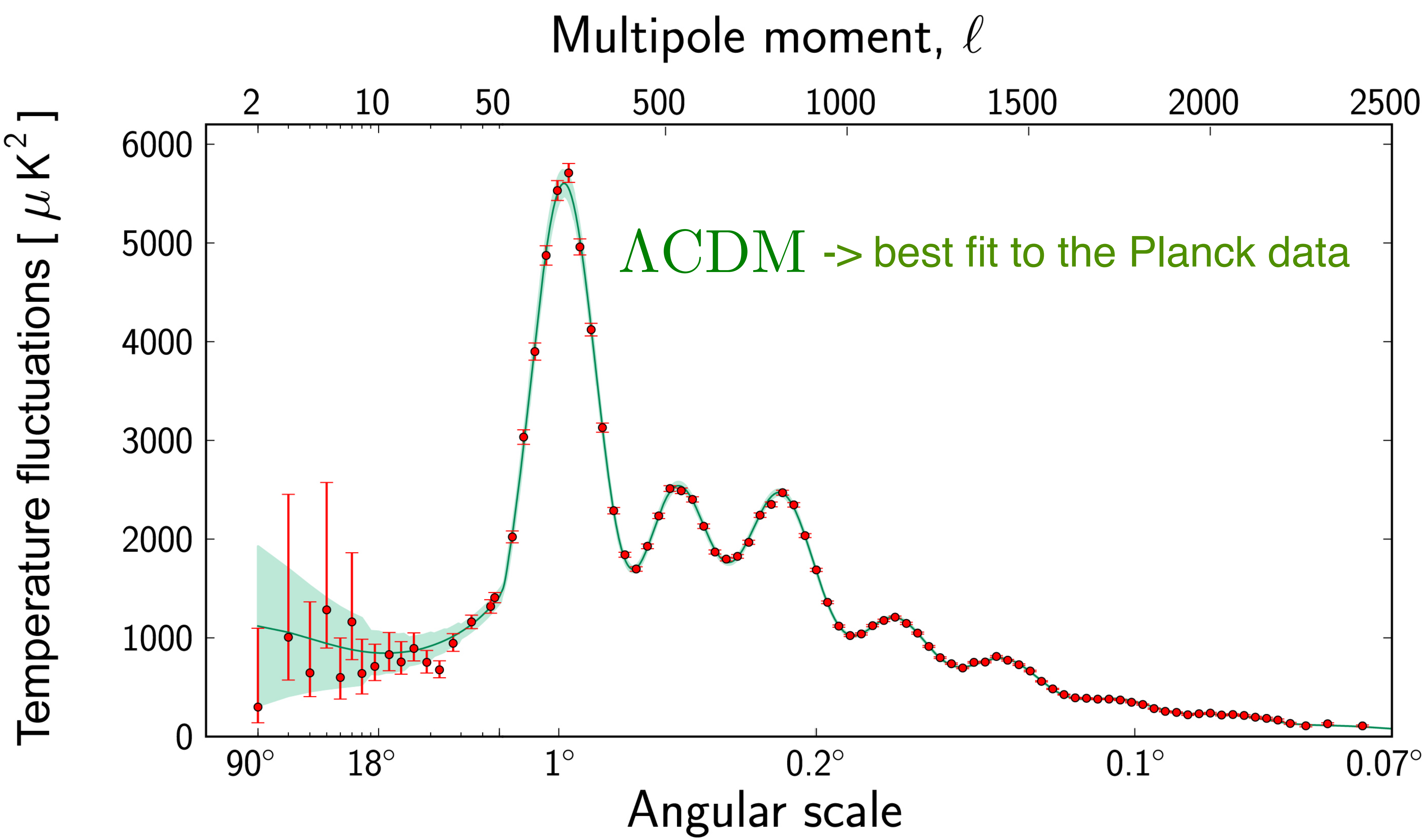


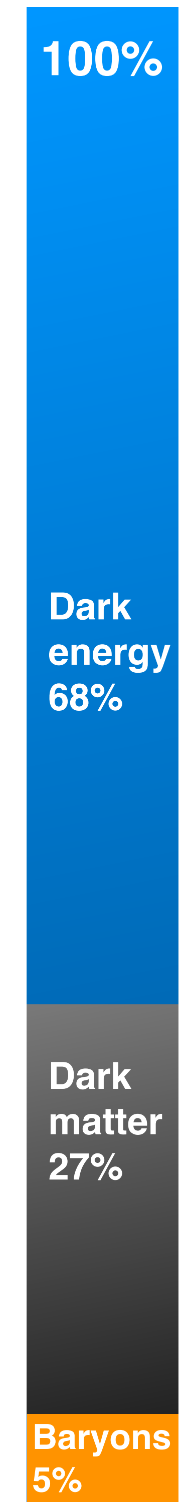
W. Hablick, Sternenhimmel

# Extra slides

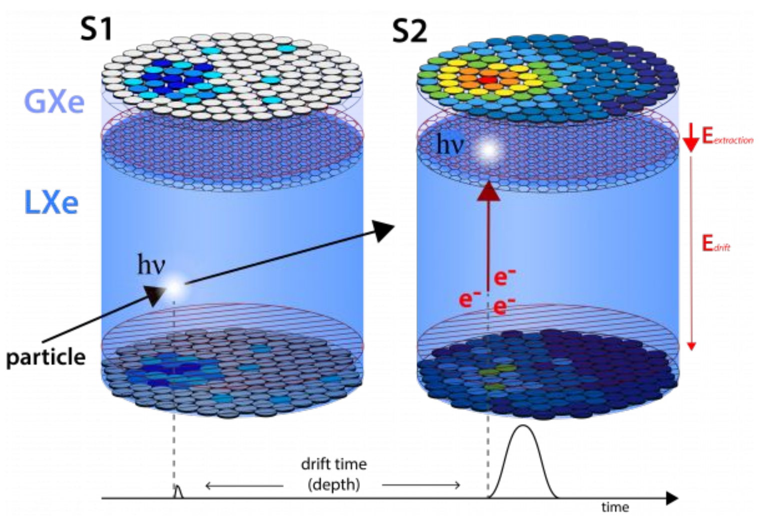
# Dark matter and the CMB

ΛCDM: excellent description of the cosmic microwave background spectrum



# Energy scale in XENON1T

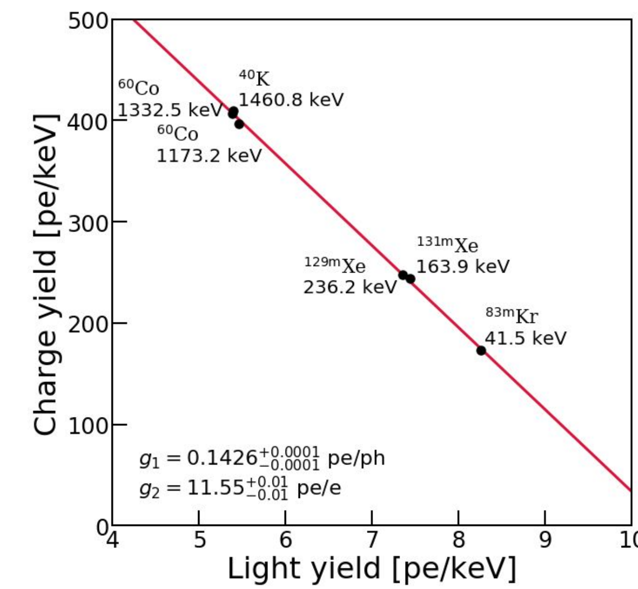



Energy loss to *either* light or charge channel
→ S1/S2 anticorrelation

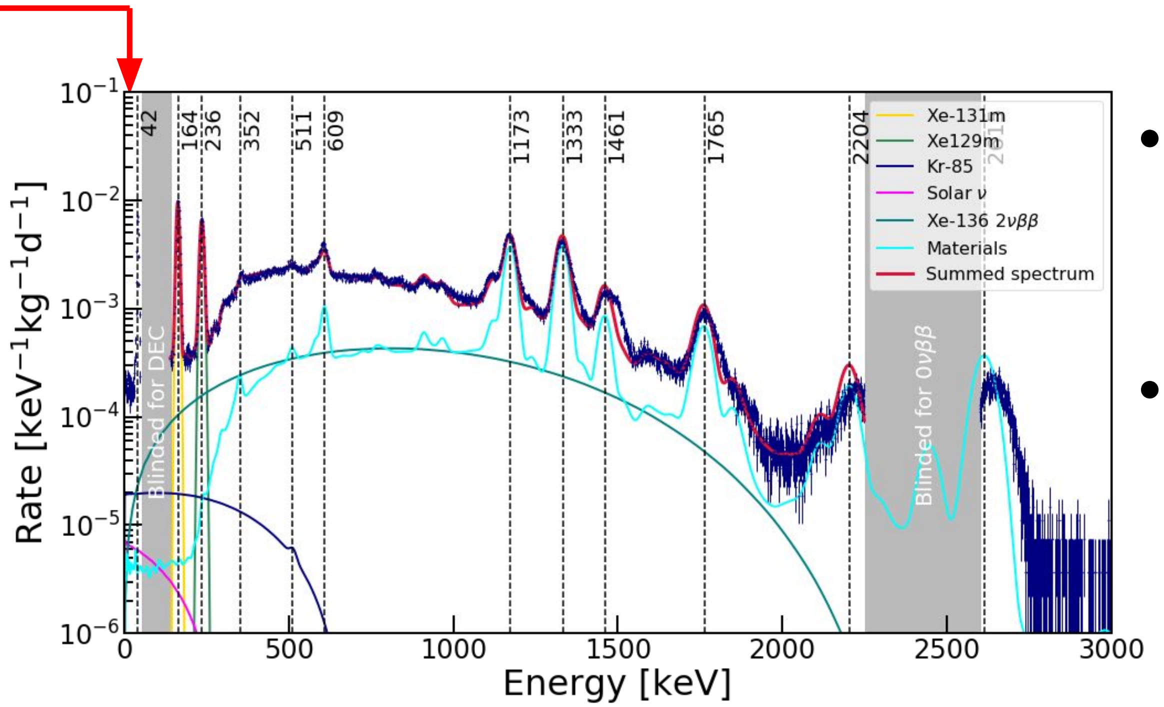
$$\frac{S1}{E} = \frac{n_\gamma}{n_e + n_\gamma} \times \frac{g1}{W}$$

$$\frac{S2}{E} = \frac{n_e}{n_e + n_\gamma} \times \frac{g2}{W}$$

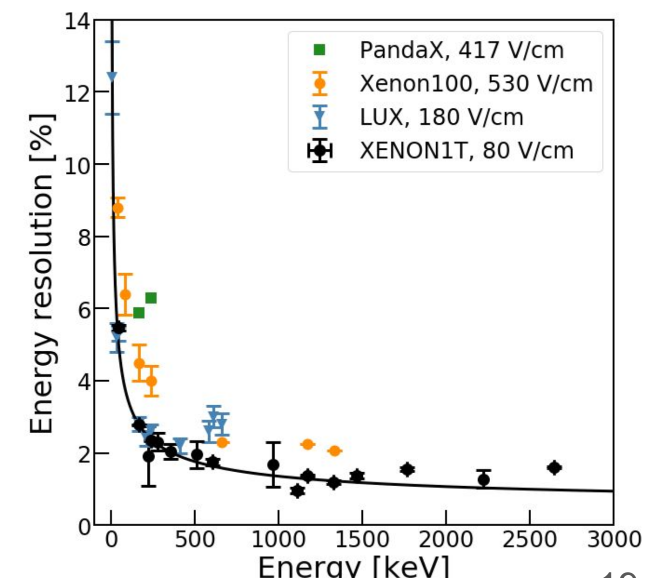
"Doke plot" → linear fit to calibration isotopes




ROI for WIMP search up to ~30 keV




- Solve the above for E for combined energy reconstruction
- Excellent resolution across a broad energy range



# XENON1T calibration and science data