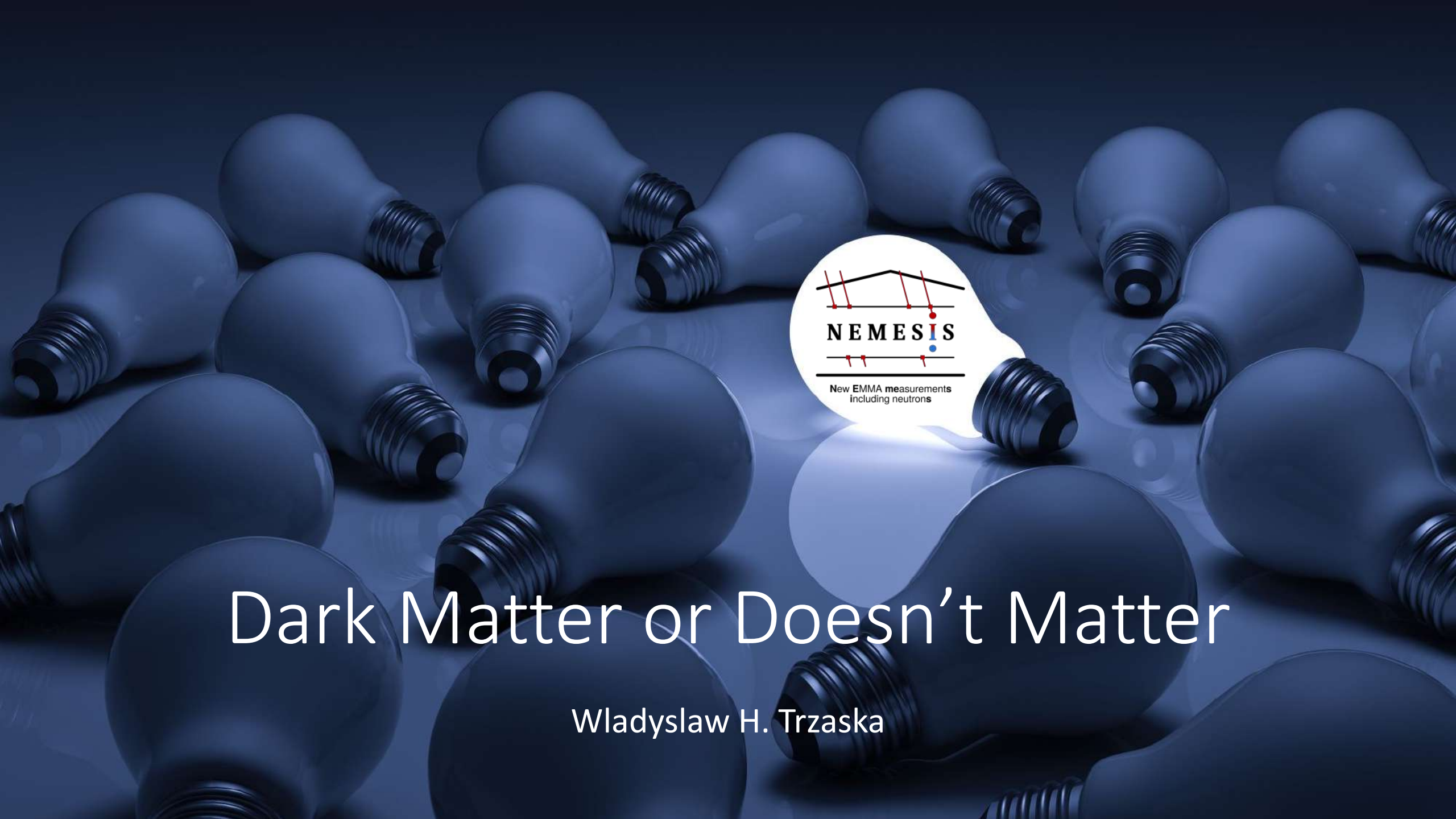
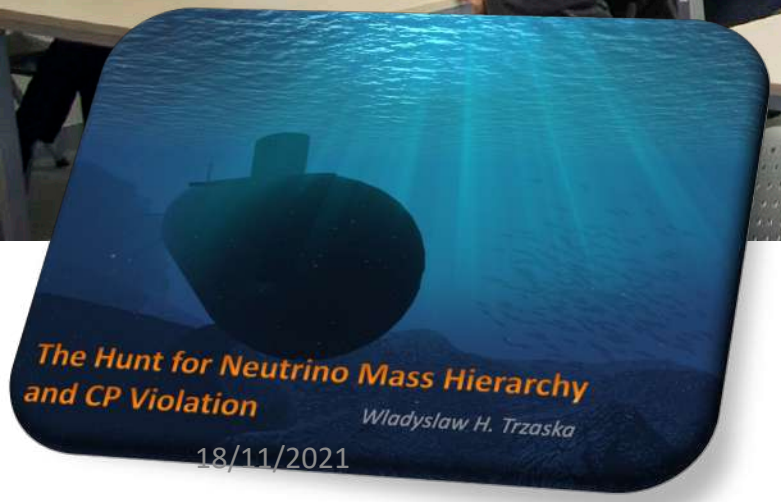


Dark Matter or Doesn’t Matter

Wladyslaw H. Trzaska

Thank you for the invitation!
It is nice to be back!

NEMESIS
New EMMA measurements including neutrons



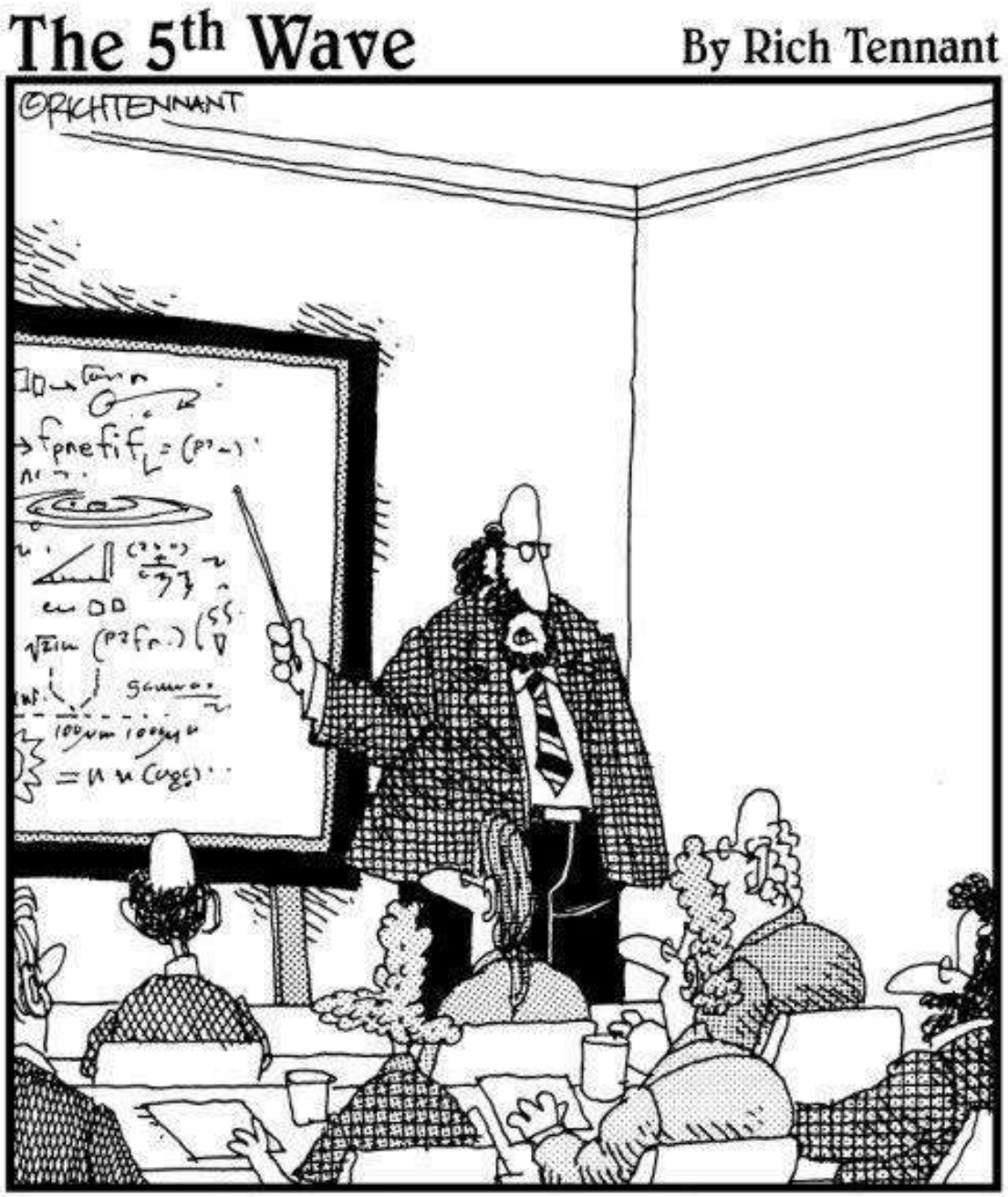
On 5 November 2015, I talked to you on

The Hunt for Neutrino Mass Hierarchy and CP Violation

Why the title:

Dark Matter or Doesn't Matter

Along with **Antimatter**,
and **Dark Matter**
we've recently discovered
Doesn't Matter
which appears to have no effect
on the universe whatsoever



The main points

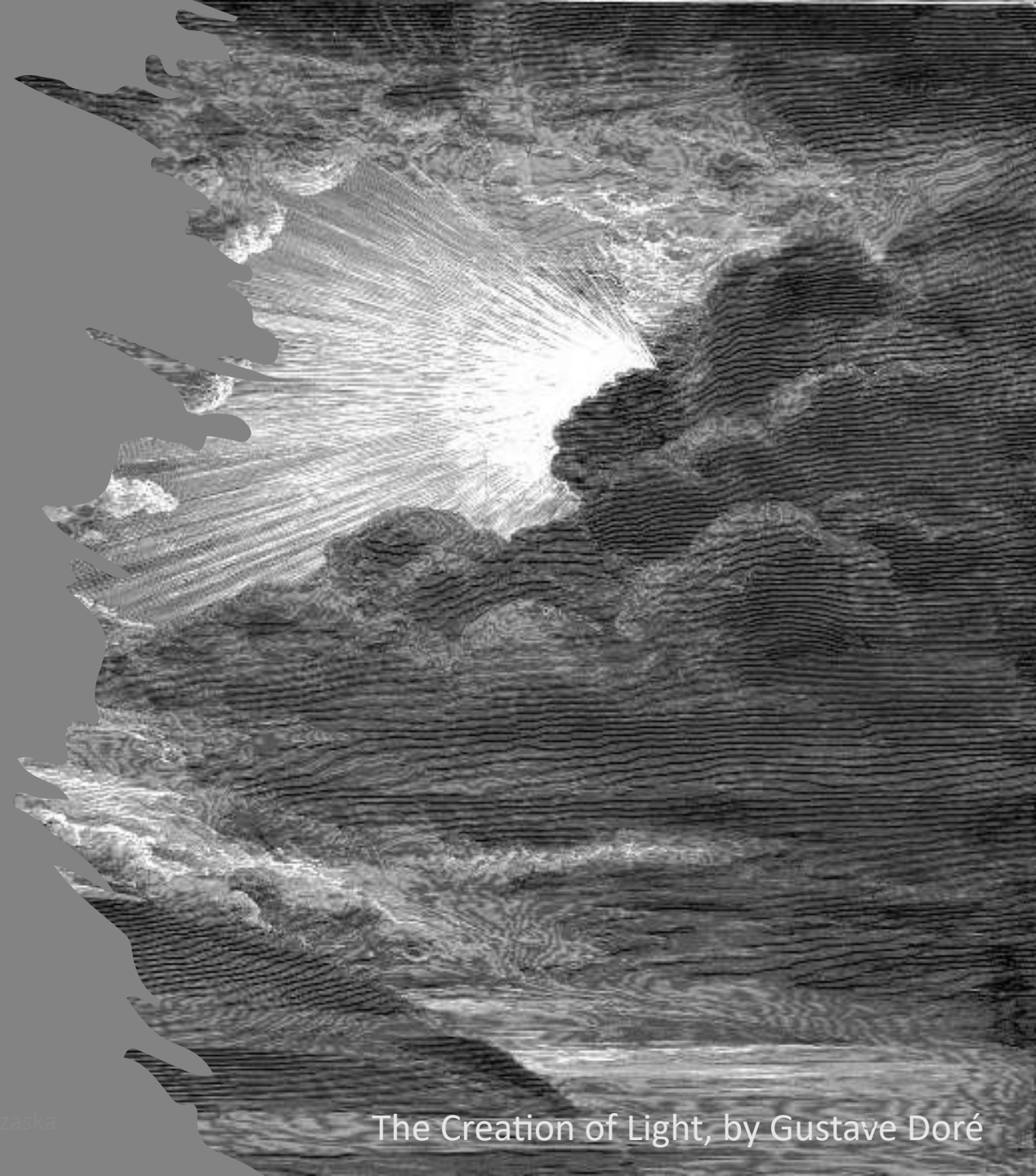
NEMESIS
New EMMA measurements including neutrons

- A brief **Dark Matter** reminder
- The **puzzling outcome** of the new analysis of the neutron multiplicity spectra obtained by **3 underground experiments**
  - Different groups, different depth, different equipment
- Possible **connection with Dark Matter**
  - If confirmed, this will be the long-awaited breakthrough
  - If not, Dark Matter will remain dark for the time being
- Summary and outlook

Dark Matter

reminder

an oversimplified view



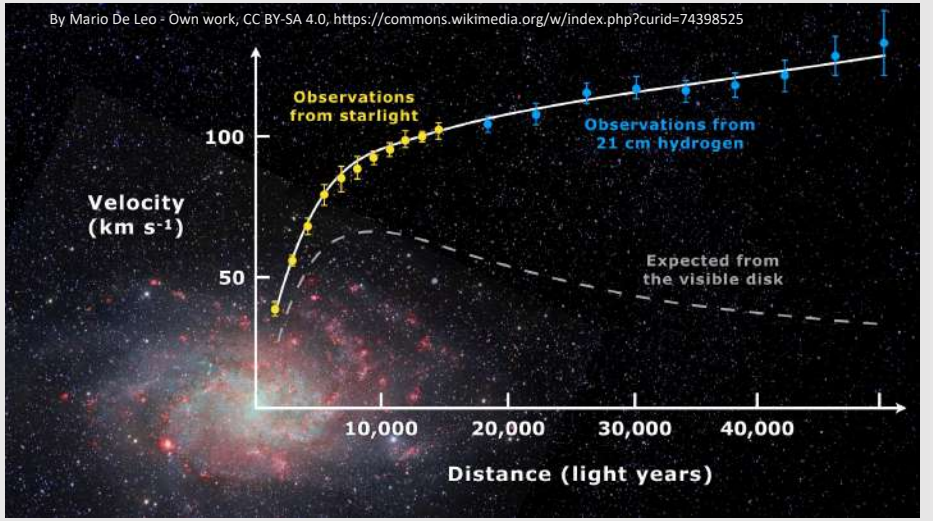
The Creation of Light, by Gustave Doré

NEMESIS
New EMMA measurements including neutrons

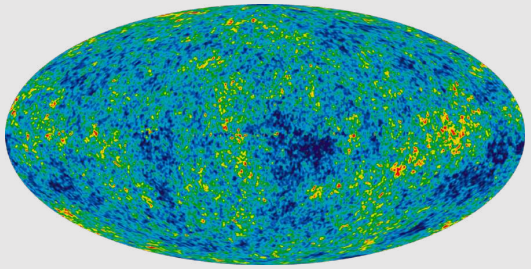
Simple Q&A

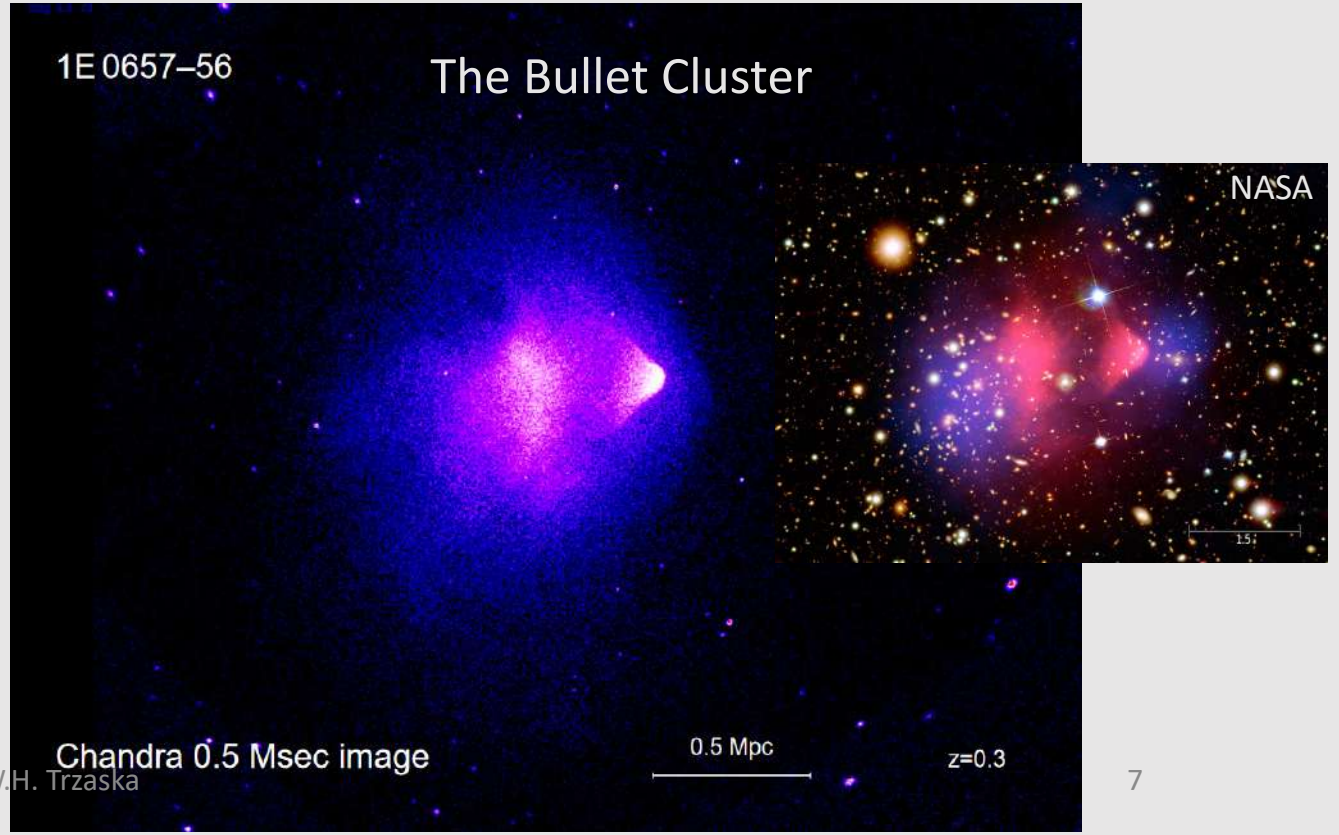
- What is Dark Matter? Nobody knows!
  But, we develop models!
- Does it exist? Nobody knows!
  But, we believe it does!
- How to detect it? Nobody knows!
  But, we have ideas!
- Is it important?
  Yes, very important!
  - We can account only for ~5% of the Universe!
  - What is the missing 95%? Nobody knows!
    Probably, ~1/3 is DM and ~2/3 is Dark Energy.
    What is Dark Energy? Nobody knows!

Gravity is the main argument for DM



- DM explains galactic rotation, stellar velocity dispersion, mass of galactic clusters, etc.
- DM is consistent with the observed gravitational lensing
- DM fits cosmologically

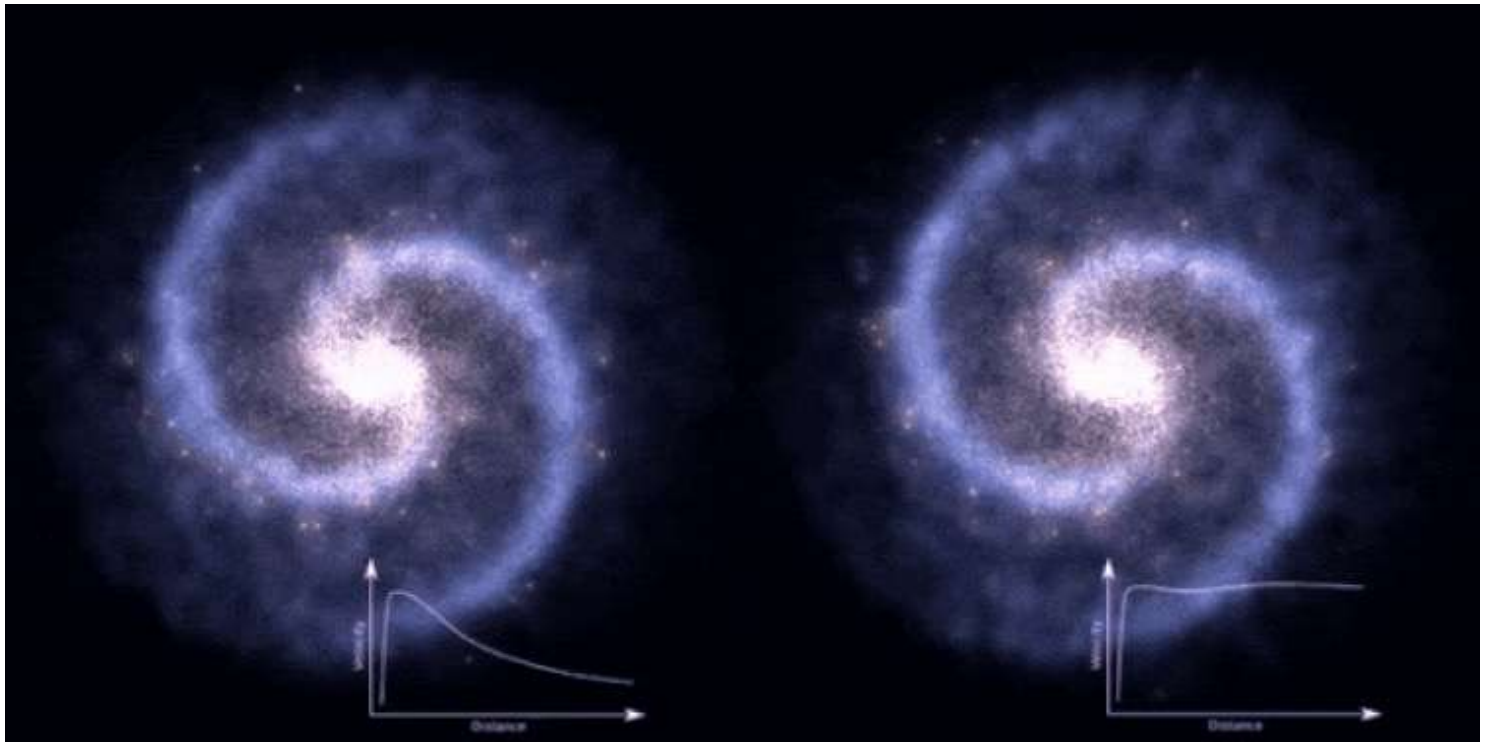




Evidence for Dark Matter

1. Rotation of galaxy clusters (and galaxies)

WIKIMEDIA COMMONS



In 1933, Fitz Zwicky* (1898 – 1974) was the first to use the virial theorem to infer the existence of unseen dark matter, describing it as "dunkle (kalte) Materie"

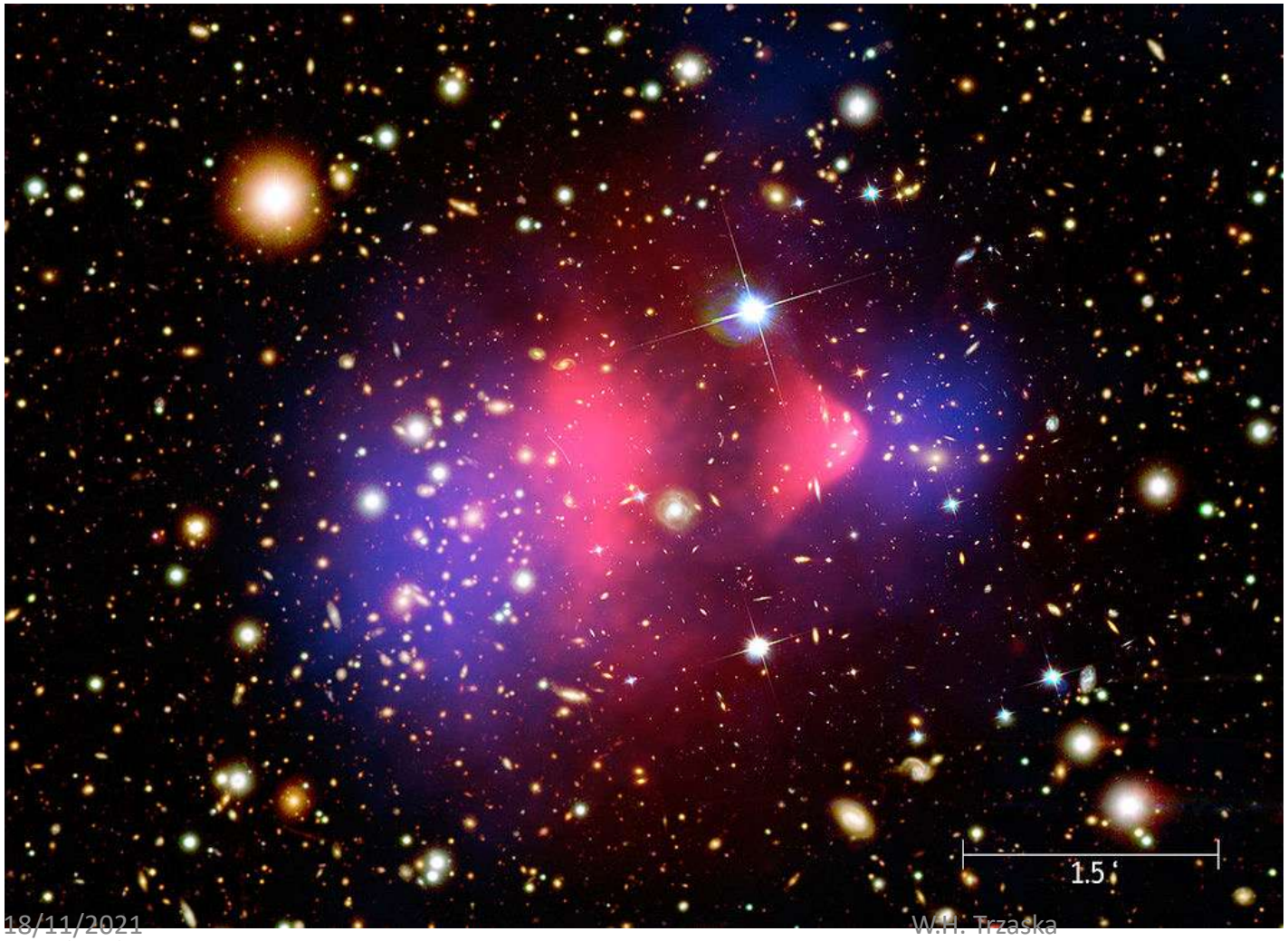
*Born in Bulgaria, to a Swiss father and Czech mother. Since 1924 in the US (Caltech, Mount Wilson, and Palomar Observatory)

To explain the rotation of the Coma Cluster, he needed 400 times the visible mass.

A 40 000% correction!

Evidence for Dark Matter

2. Gravitational lensing



NASA/CXC/M. Weiss - Chandra X-Ray Observatory: 1E 0657-56

- **Visible** light image (galaxies)
- **X-ray** image (pink)
- **Gravitational** matter distribution calculated from gravitational lensing (blue)

Bullet Galaxy Cluster

- The best evidence for Dark Matter
- 8σ evidence against Modified Newtonian Dynamics (MOND)

ΛCDM (Lambda cold dark matter) model

the standard model of Big Bang cosmology

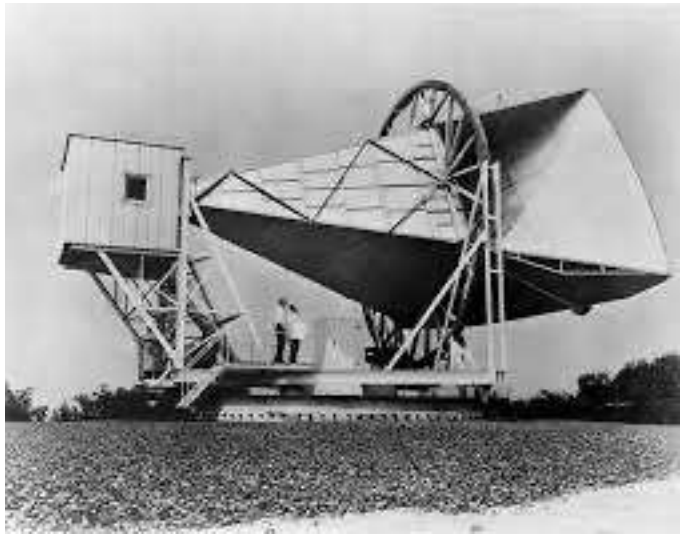
NEMESIS
New EMMA measurements including neutrons

Parameterization using three major components

- a cosmological constant (Λ) associated with dark energy
- the postulated cold dark matter (CDM)
- ordinary matter

The simplest model accounting for

- CMB (cosmic microwave background) existence and structure
- Galaxy distribution structures
- Hydrogen, deuterium, helium, and lithium abundances
- Accelerating expansion of the universe

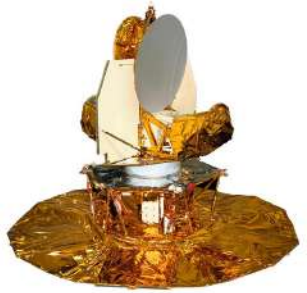


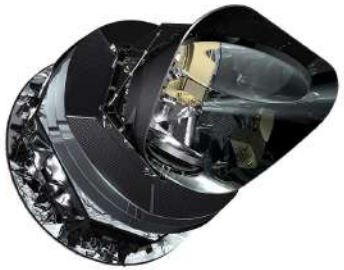
2.7 K

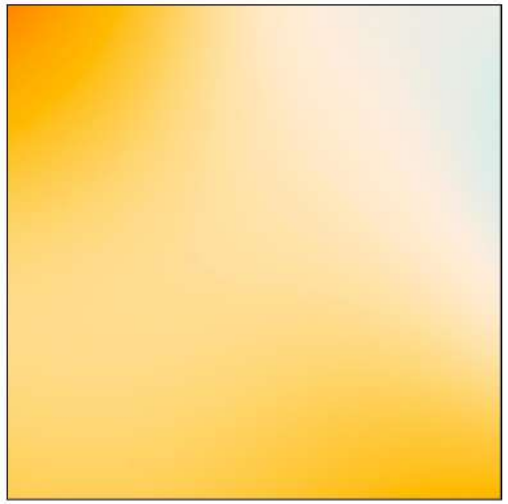
Penzias & Wilson
1964

CMB discovery

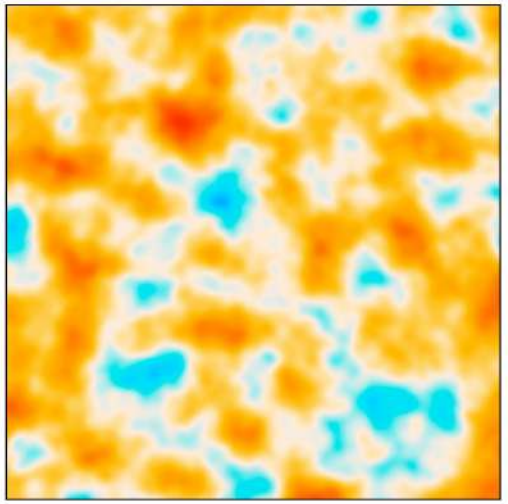
Cosmic Microwave Background anisotropy



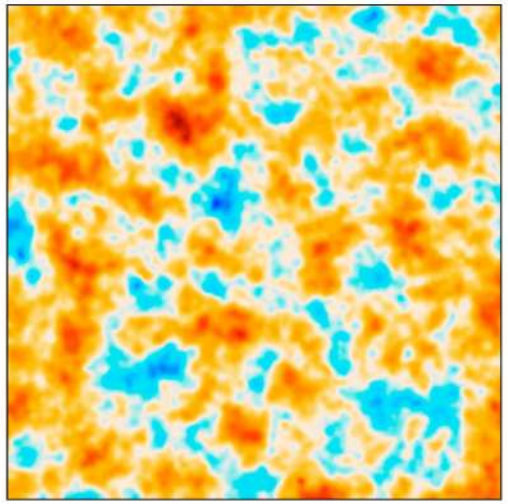




COBE



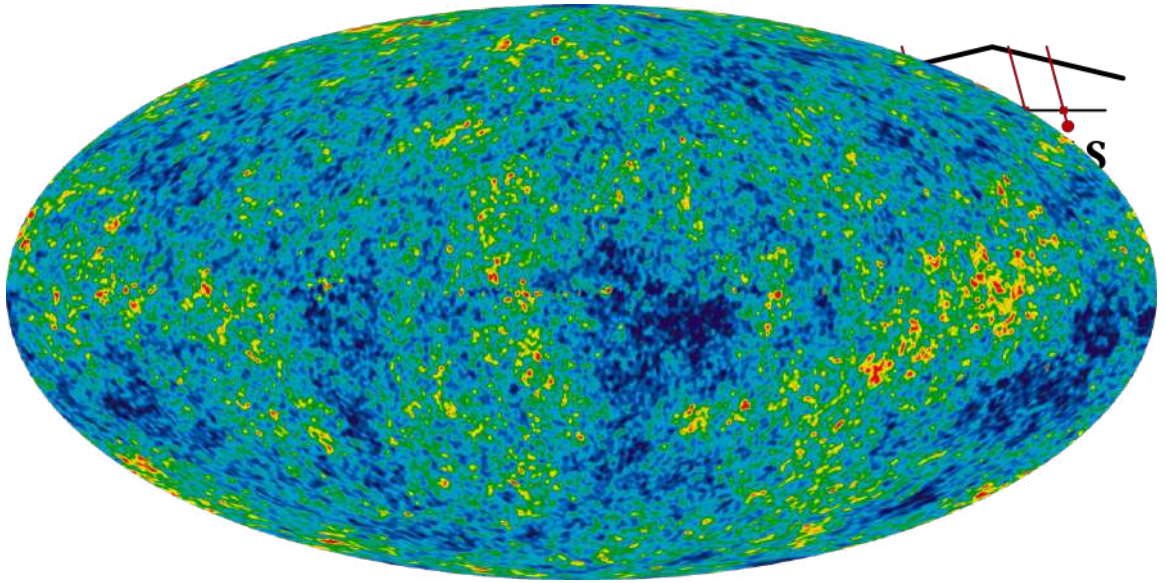
WMAP



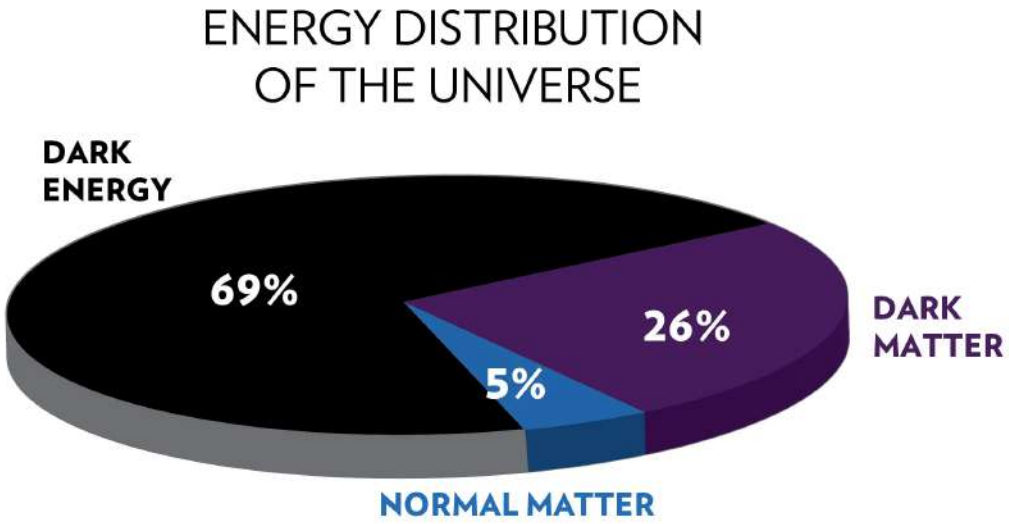
Planck

$\Delta T/T \sim 10^{-6}$

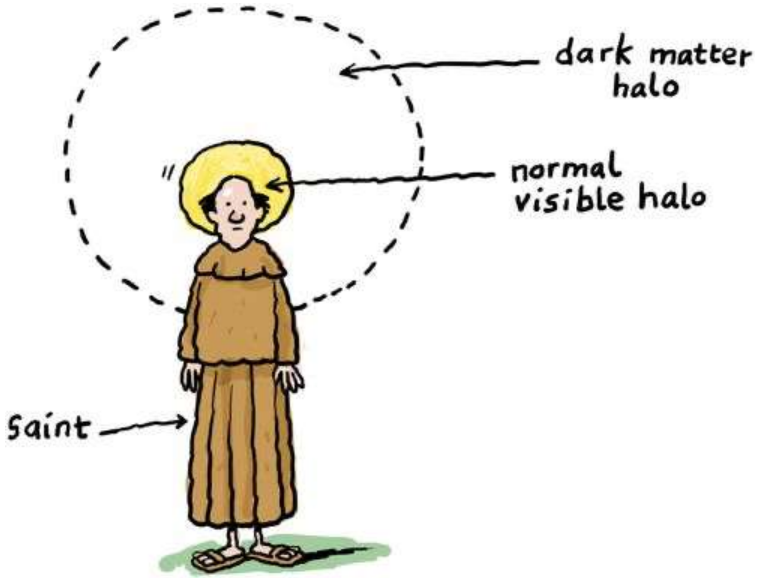
Planck spacecraft
→ CMB map



CMB map + **ΛCDM** model analysis →



How big is DM halo?



By Ellis Nadler

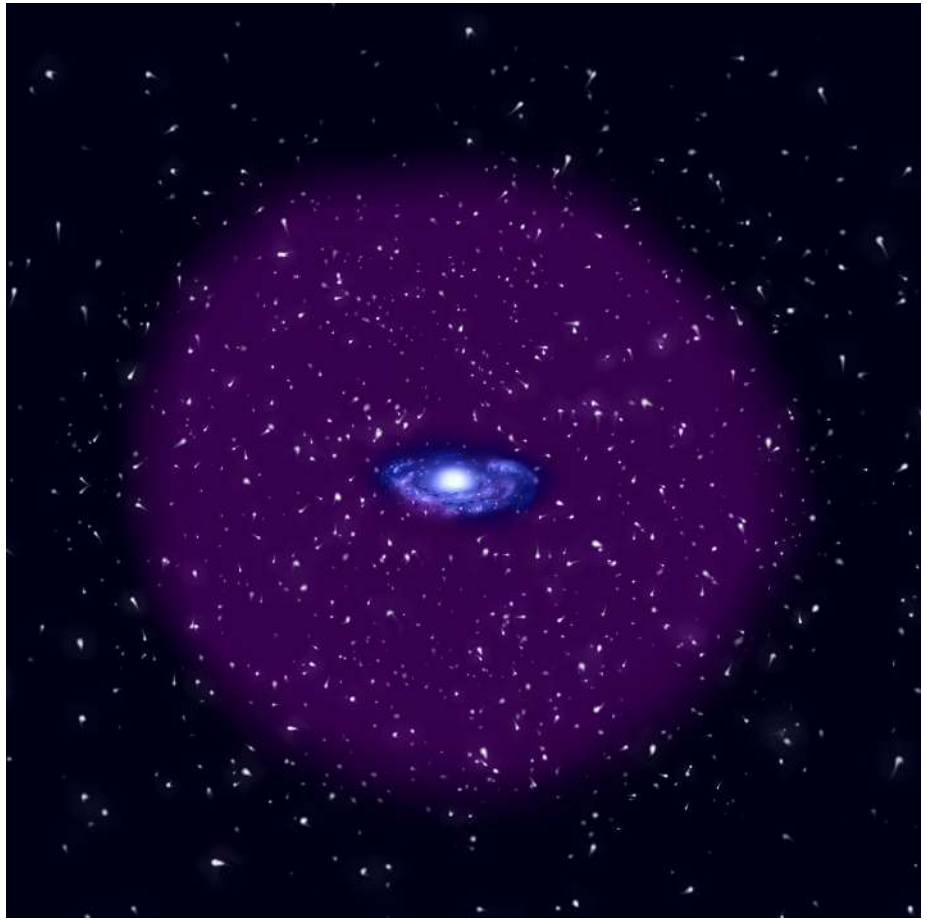
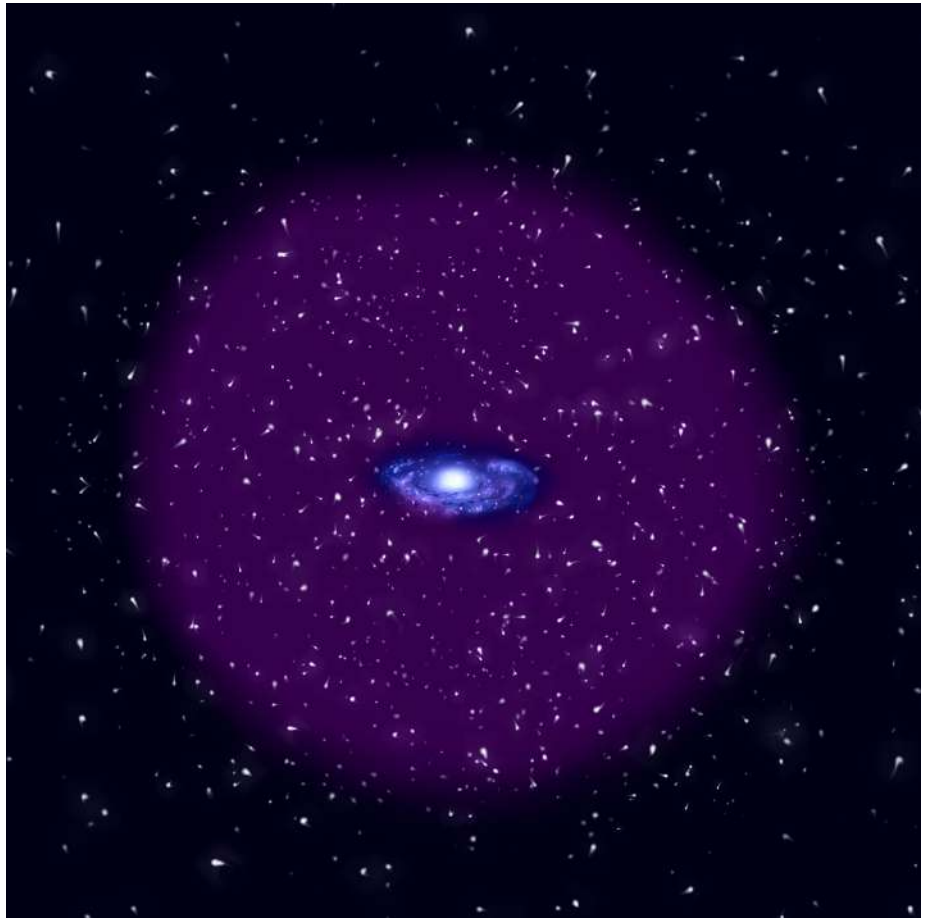


Illustration by Abagail Burrus

How big is DM halo?

- Just like galaxies, DM halos must rotate to avoid gravitational collapse
- DM and visible matter rotate at different speed
- Earth, Sun, and other planets experience a DM wind



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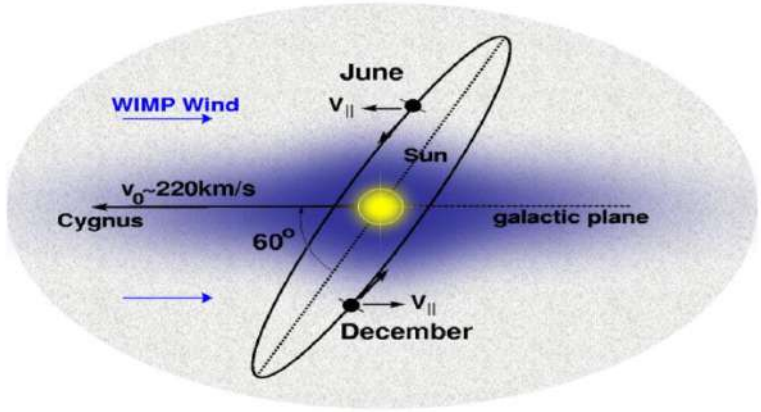


Parameter	Value	Unit
DM velocity dispersion (v_0)	220	km/s
Galactic escape velocity (v_{esc})	544	km/s
Galactic rotation ($\underline{u}_r$)	(0, 235, 0)	km/s
Solar proper motion ($\underline{u}_S$)	(9, 12, 7)	km/s
Earth mean orbital speed ($\langle u_E \rangle$)	30	km/s
DM density (ρ_{DM})	0.3	GeV/cm^3

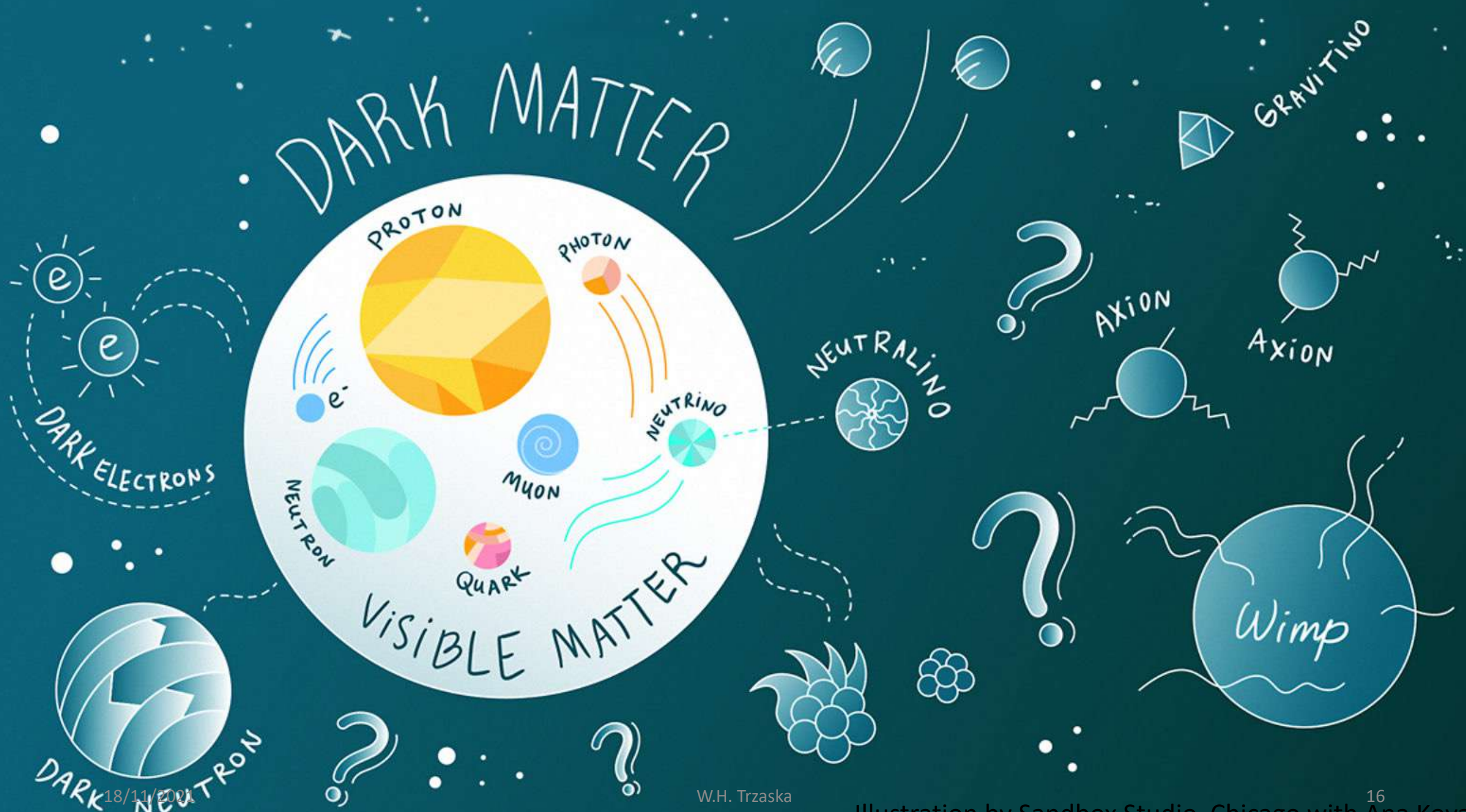


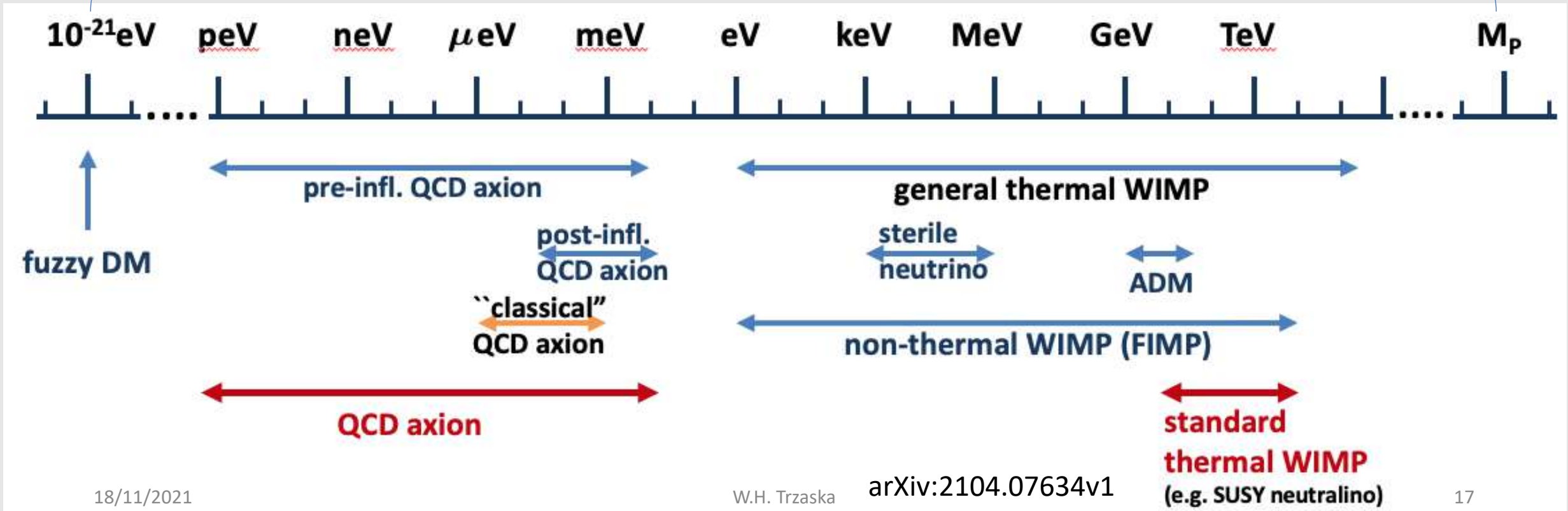
Illustration by Sandbox Studio, Chicago with Ana Kova

Are there DM particles? Nobody knows!
What's their mass? Nobody knows!

NEMESIS
New EMMA measurements including neutrons

WIMP <==> Weakly Interacting Massive Particle

We are guessing over 65 orders of magnitude!



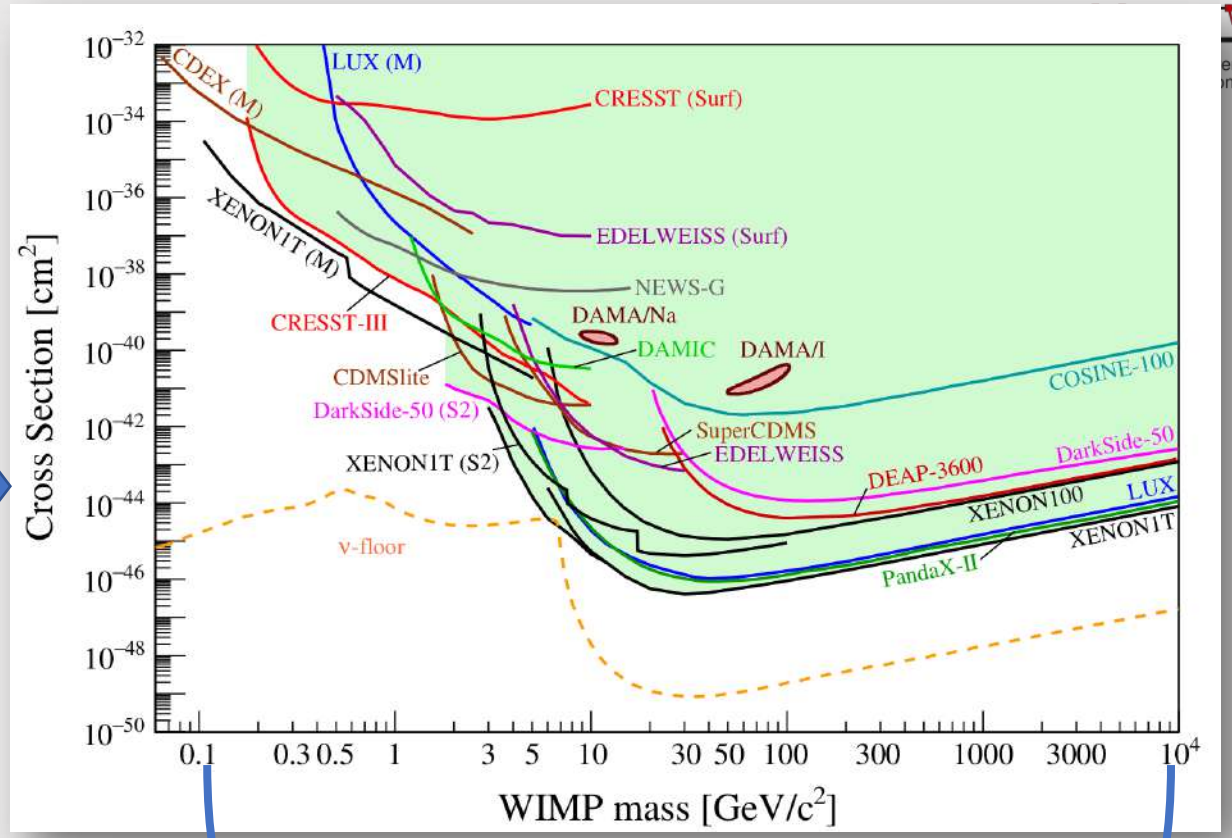
arXiv:2104.07634v1

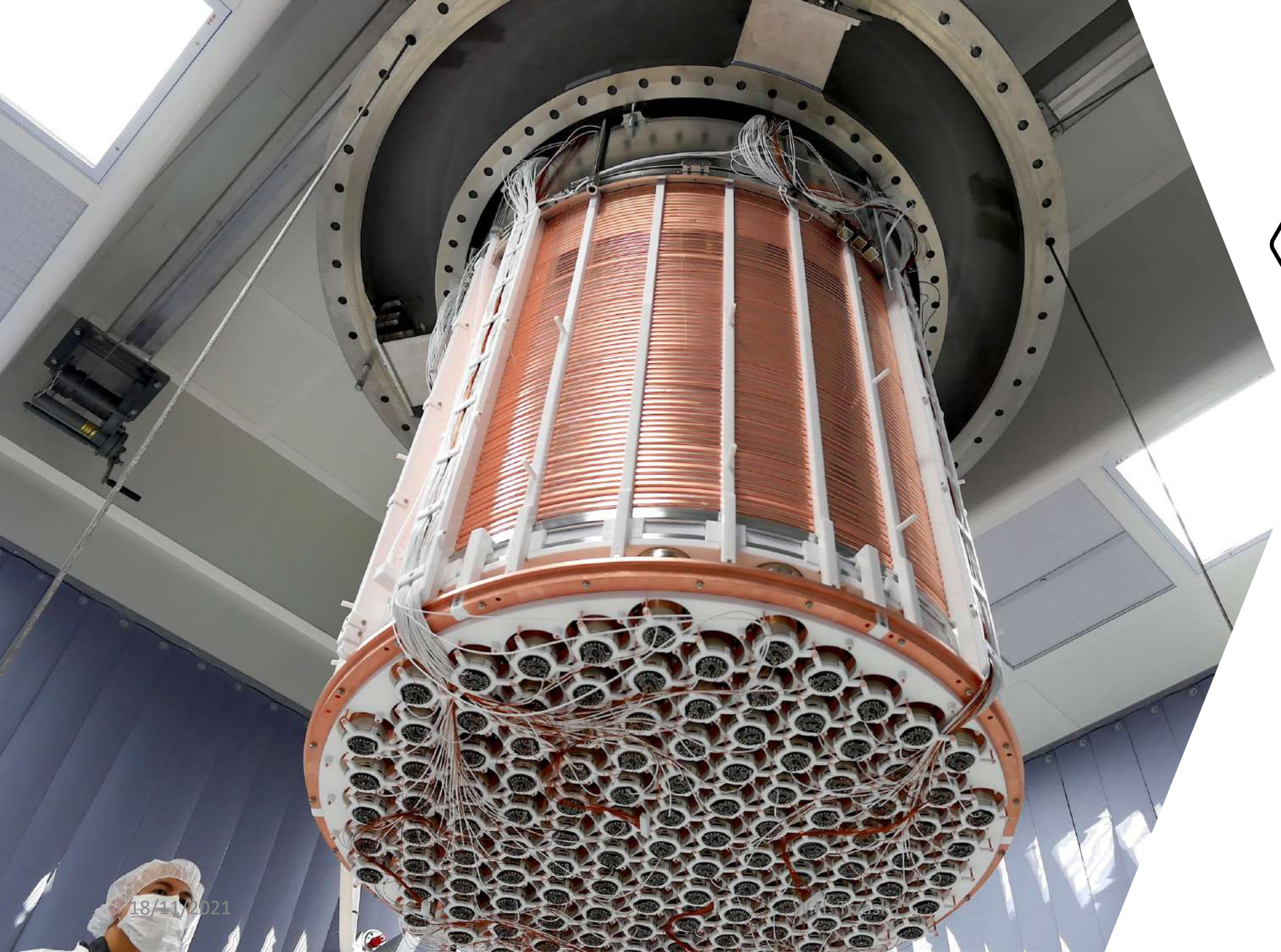
arXiv:2104.07634v1 [hep-ex] 15 Apr 2021

How to look for DM particles?

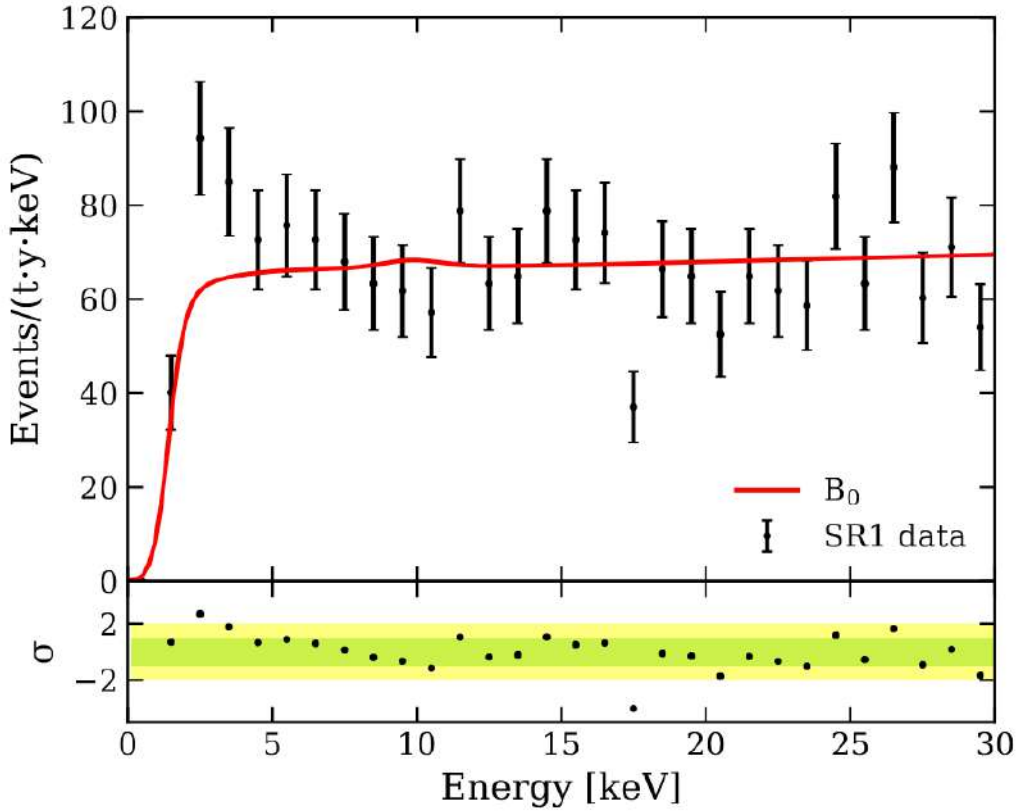
Nobody knows,
but we are trying!

Current (April 2021) status of searches for SI elastic WIMP-nucleus scattering





XENON1T



The most exciting outcome of XENON1T

The excess observed in XENON1T in the electronic recoil background at low energies, compared to the level expected from known backgrounds indicated as the red line.

NEMESIS idea

Look for high-multiplicity neutron spectra underground!

NEMESIS
New EMMA measurements including neutrons

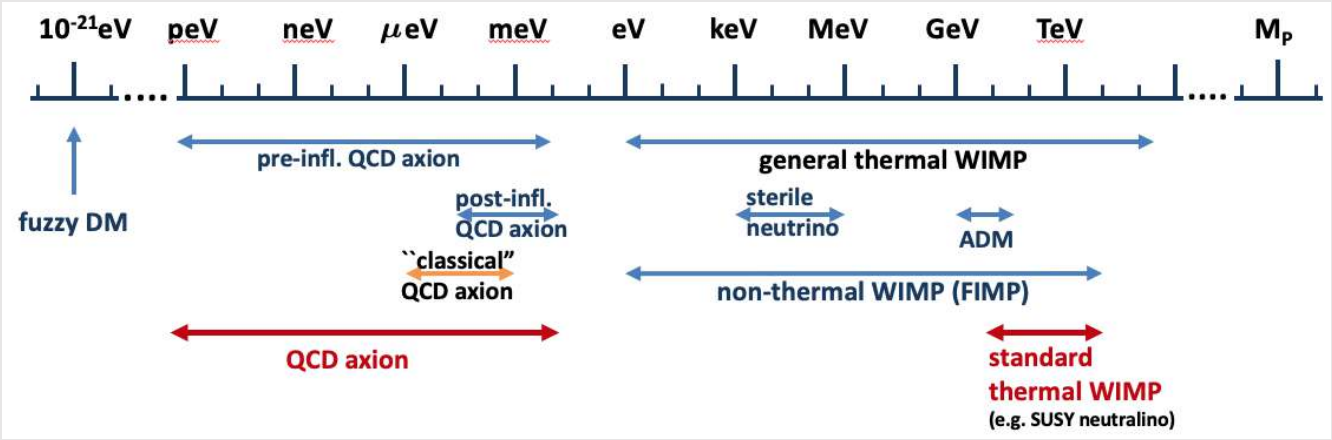
Why neutron spectra?

- If WIMPs exist, upon contact with matter, they may **self-annihilate/disintegrate** into known (SM) particles
- Such event would resemble **particle-induced spallation** leading to neutron emission from the target
- These **neutrons are relatively easy to detect**
- From the spallation studies and our model assumptions, we expect **~8 neutrons per GeV**
- If we detect a “bump” at a certain multiplicity, we will have a good estimate of **WIMP’s mass**:

$$\mathbf{M_{WIMP}[GeV] \approx Neutron\_multiplicity / 8}$$

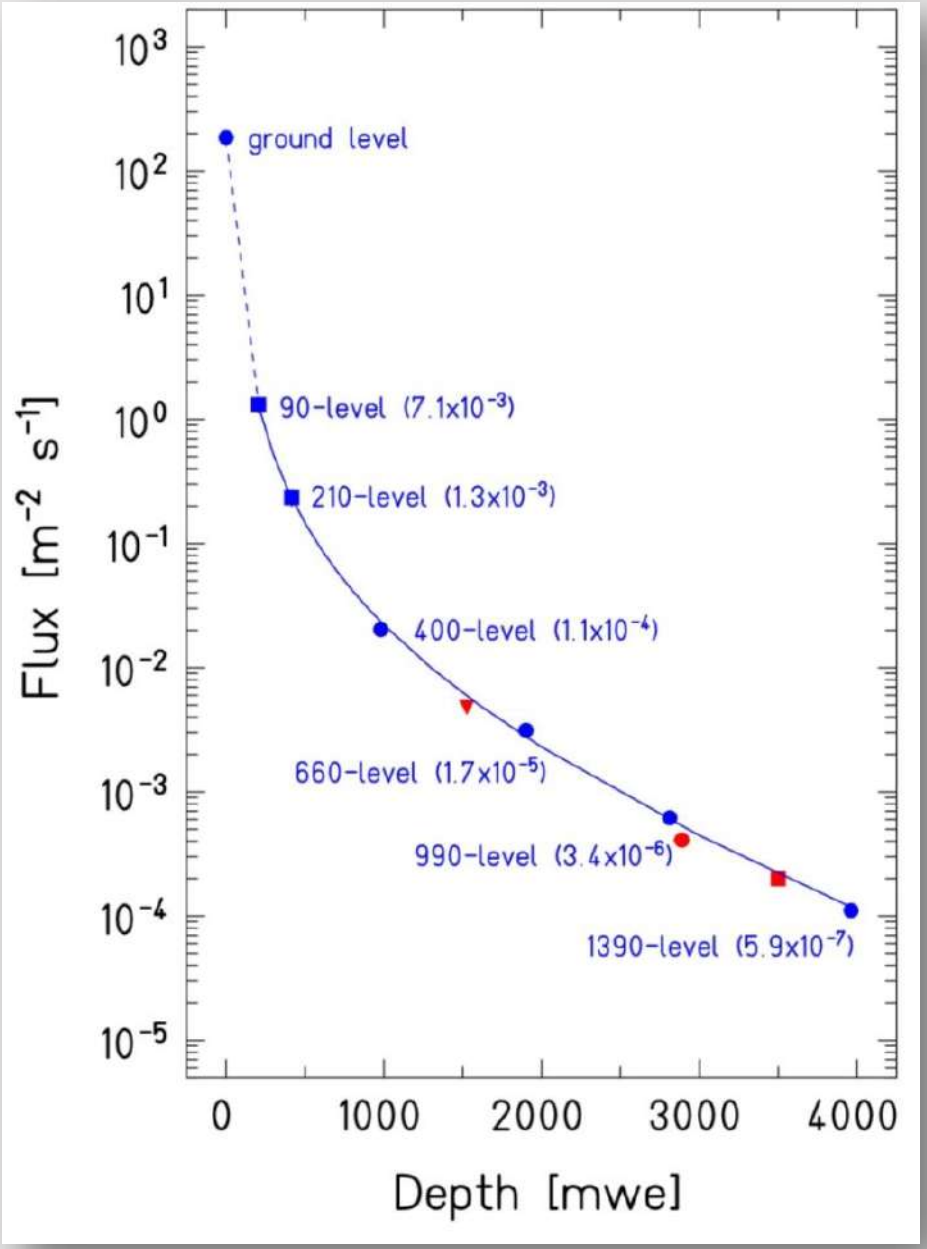
Basic assumptions*

*justifying experimental WIMP searches



Dark Matter consists of Weakly Interacting Massive Particles

- WIMP is either a new type of particle (non SM) or
- Composite of known Standard Model particles ←
  - Must interact gravitationally and weakly (weak nuclear force)
  - Very strongly bound (let's assume a GeV-scale)
  - Interaction with a nucleus would destabilize WIMP and cause its self-annihilation
  - The released energy would obliterate the target nucleus as well
    - Emission of large amount of particles and gamma-rays
    - Only neutrons and energetic leptons would come out of a thick, dense target (Pb)
- Look for high-multiplicity neutron events underground



https://callio.info/facilities/conditions-of-environment/

Why underground?

NEMESIS
New EMMA measurements including neutrons

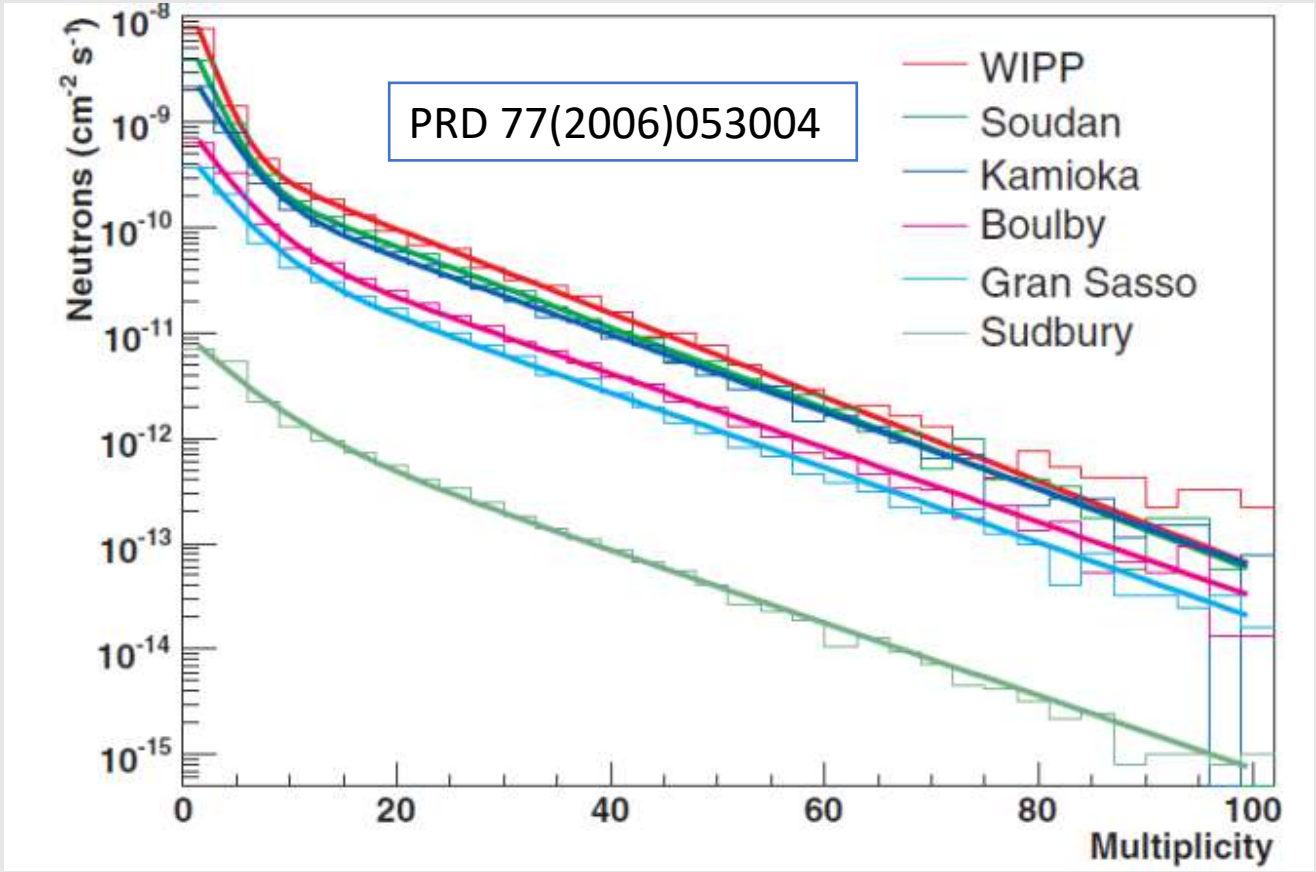
- **To reduce neutron background** induced by Cosmic Ray (atmospheric) muons

  ← measured muon flux underground in the Pyhäsalmi mine

- We expect a very weak signal, comparable or smaller than neutrino cross sections

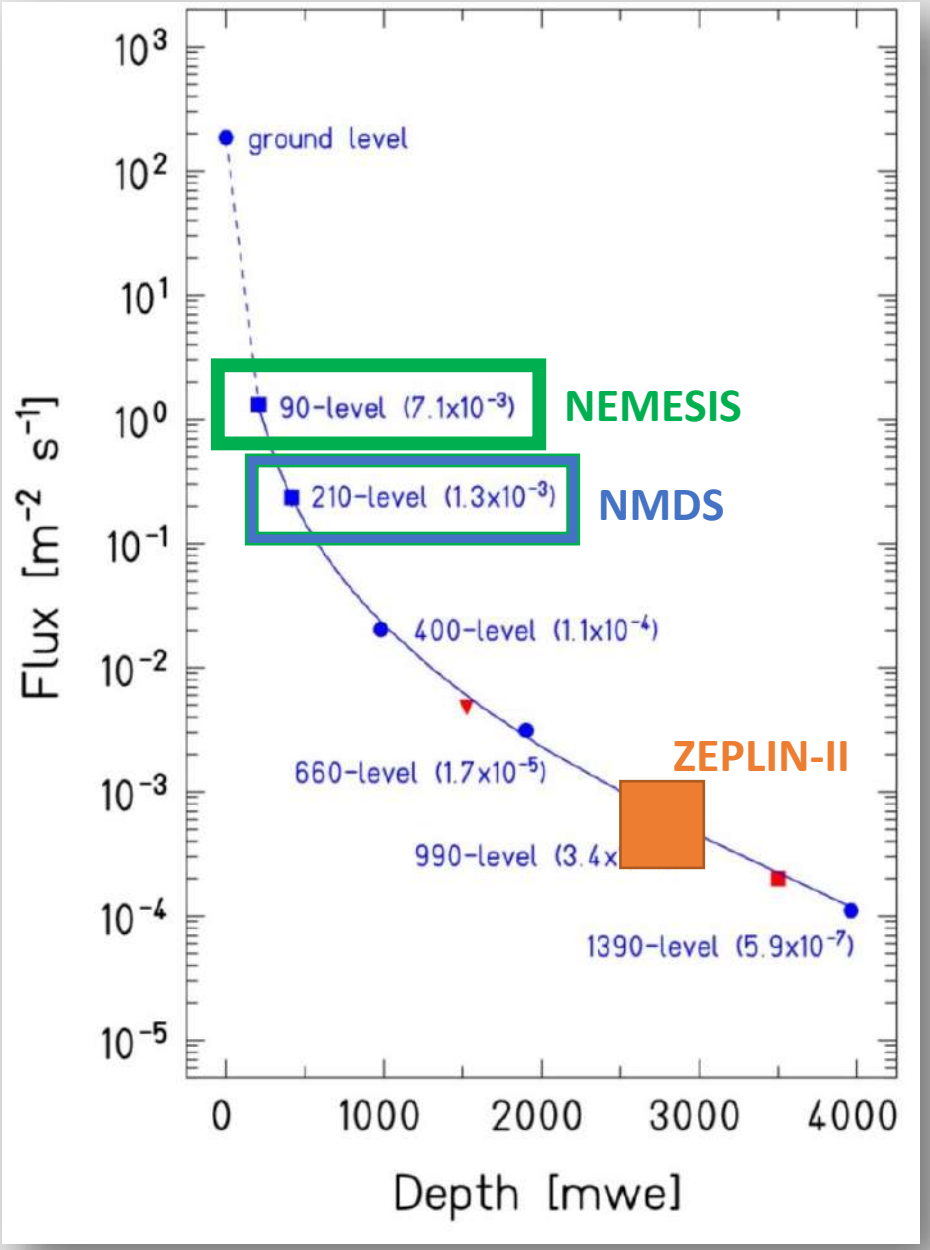
What to expect: smooth, exponential neutron multiplicity spectra from μ-induced reactions

- FLUKA calculations based on experimental databases →
- Intensity drops with depth
- Simulated slopes stay the same and are exponential (linear in the log-lin scale)
- WIMP signal, if exists, would be on top of an exponential background



Calculated neutron multiplicity at different experimental sites

How deep underground?



https://callio.info/facilities/conditions-of-environment/

← From the background point of view, **the deeper, the better**

- However, muon-induced neutron spectra help you to **setup, monitor, and calibrate** your detection system

- Budget-limitted experiment can't be too picky → **use what is available**

<u>Solution</u> → **moderate depth + muon veto**

NEMESIS
New EMMA measurements including neutrons

Experimental evidence

for anomalous, high-multiplicity events in neutron multiplicity spectra, measured underground by **NEMESIS**, **NMDS**, **ZEPLIN-II**, and HALO experiments


Our short video is available at
https://youtu.be/0UcEdJje4ms
NEMESIS
New EMMA measurements
including neutrons
TAUP
2021 VALENCIA

Our venue:

CallioLAB

in the Pyhäsalmi mine, Finland

NEMESIS

New EMMA measurements including neutrons

NEMESIS

New **E**MMA **me**asurement**s** **i**ncluding neutron**s**

Emmaville – infrastructure from the EMMA experiment

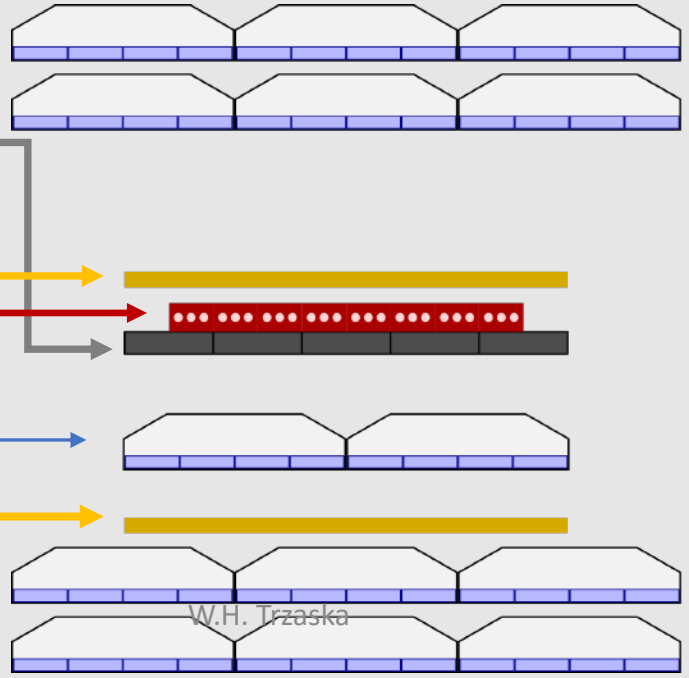
NEMESIS

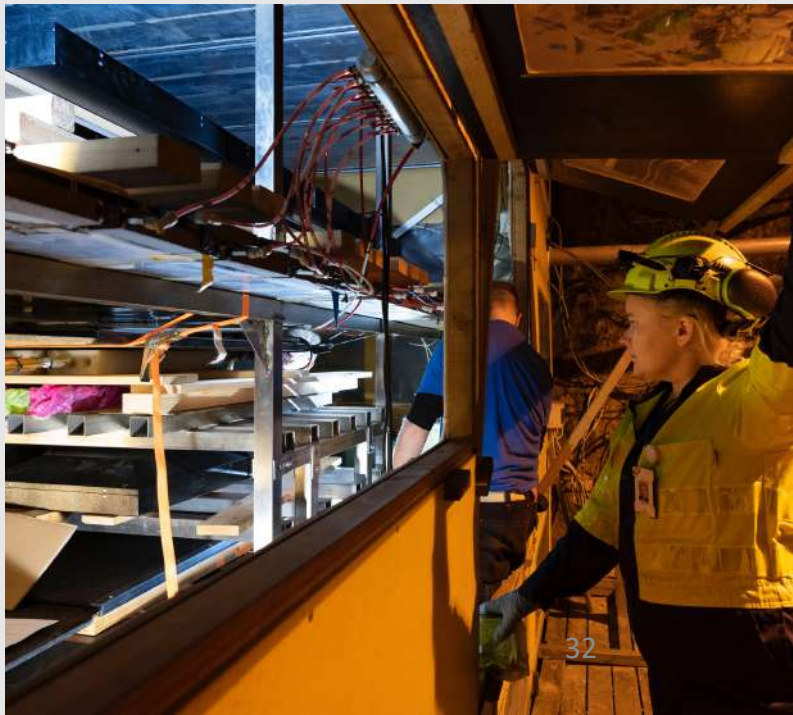
New EMMA measurements including neutrons

Our experiment

at the depth of 210 m.w.e.

- 349-day 565 kg Pb target run
- 166-day background run
- 736-pixel tracking detectors
- 14 ^{3}He neutron detectors
- 2 large-area scintillators

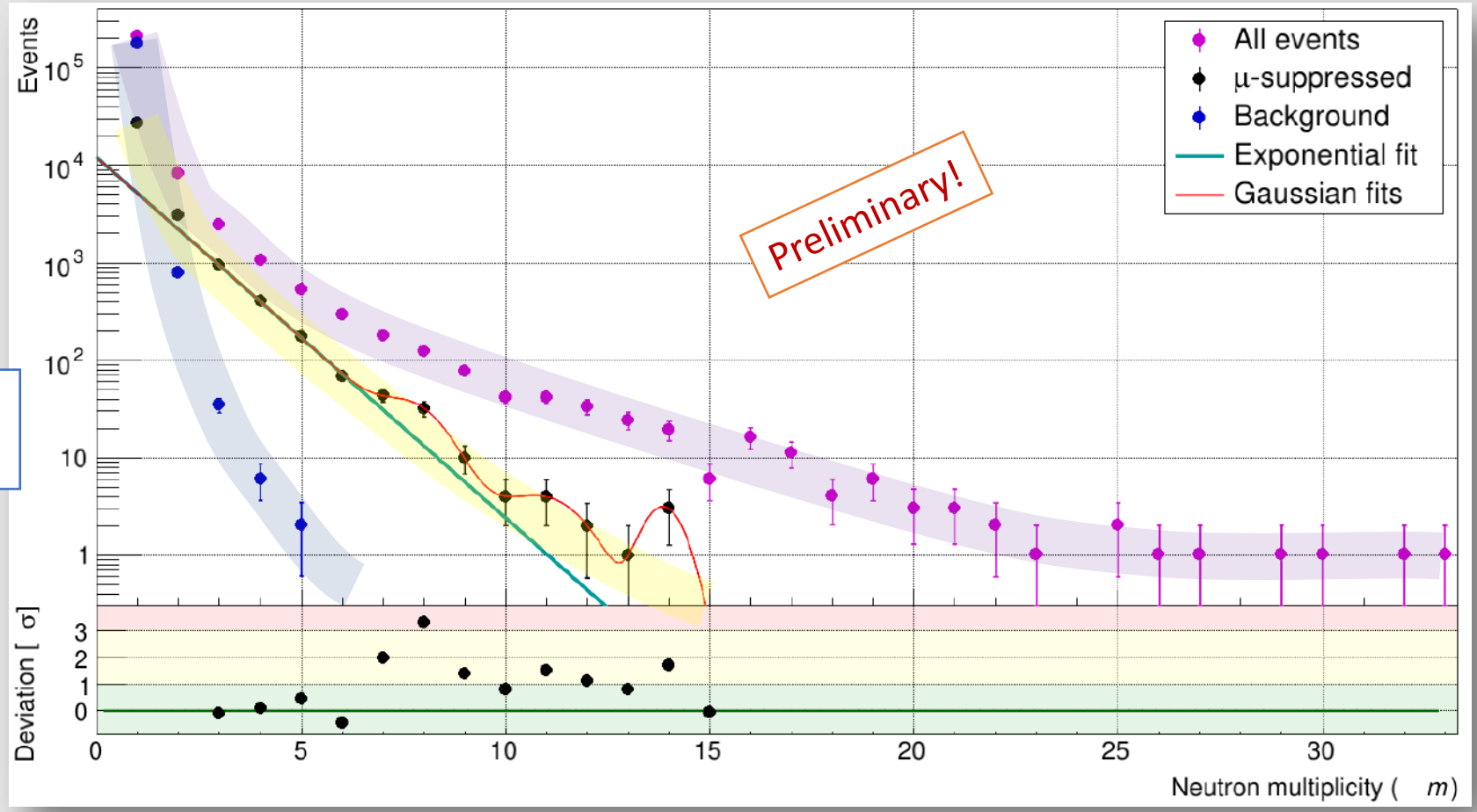




Neutrons from Pb in anti-coincidence with traversing CR μ

Neutron multiplicity spectra

New EMMA measurements including neutrons

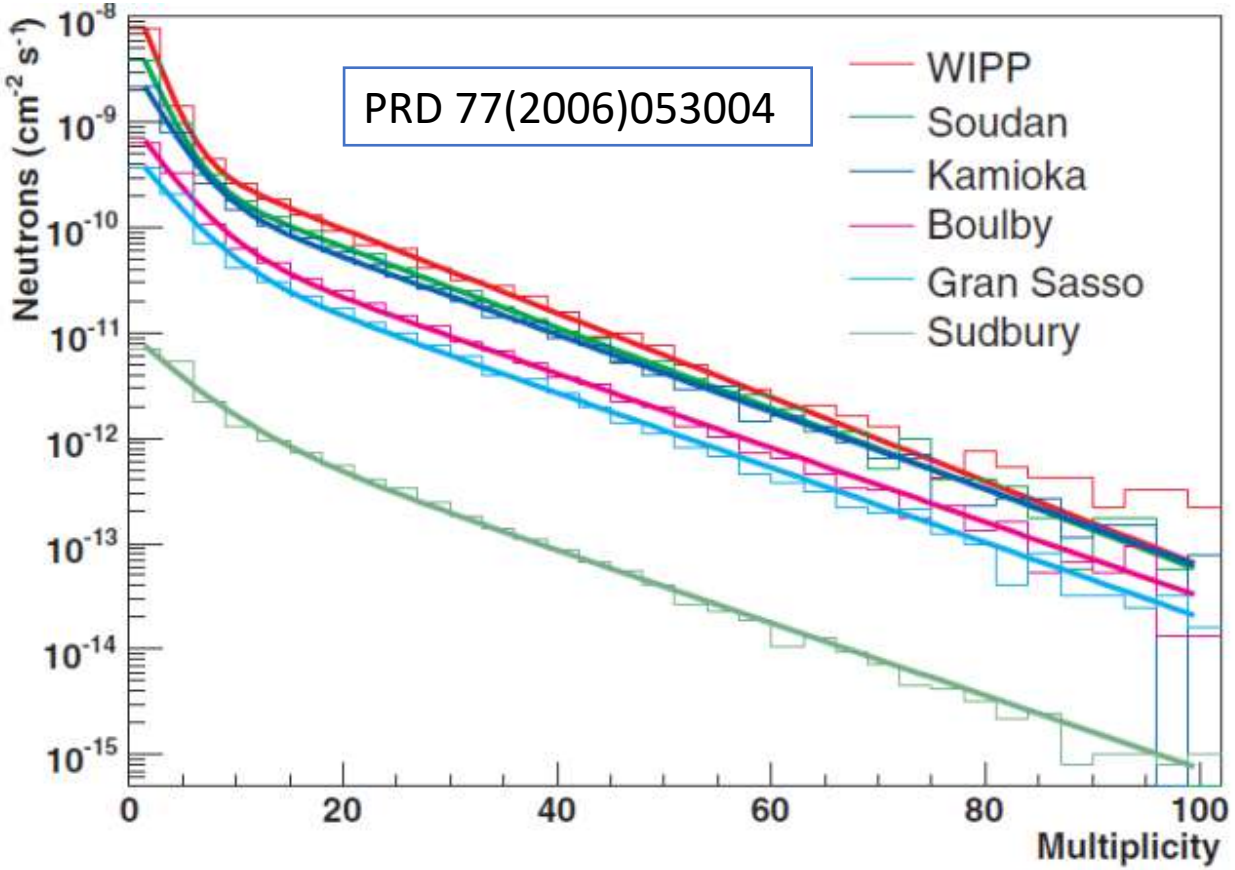


Bgd neutrons no target

Pb target all neutron events

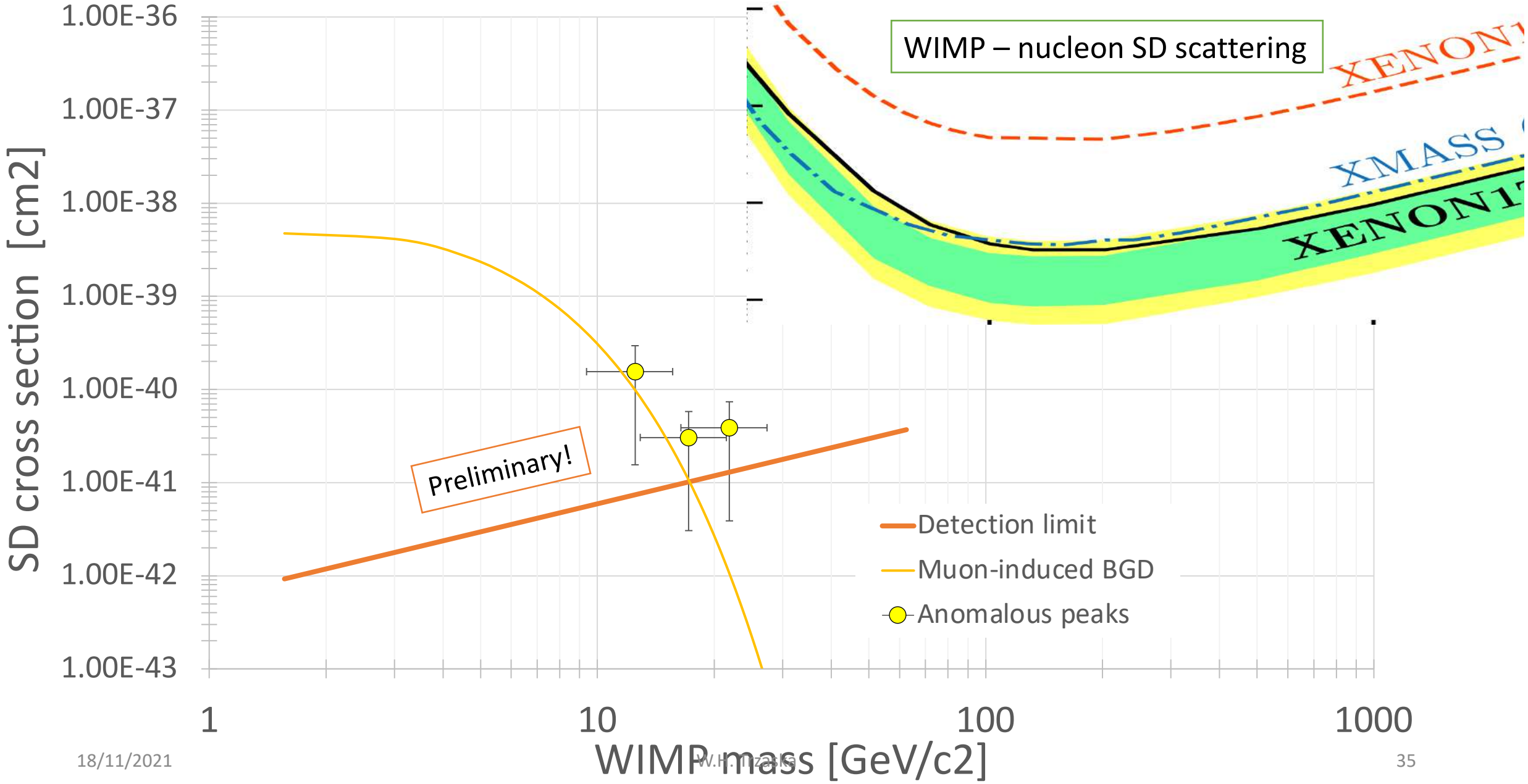
Is an exponential fit of the neutron multiplicity background justified? YES, it is!

- FLUKA calculations based on experimental databases →
- Figure from D-M Mei and A. Hime, et. al. PRD 77, 053004 (2006)
- As expected, intensity drops with depth
- However, the simulated slopes stay the same and are exponential (linear in the log-lin scale)



Calculated neutron multiplicity at different experimental sites

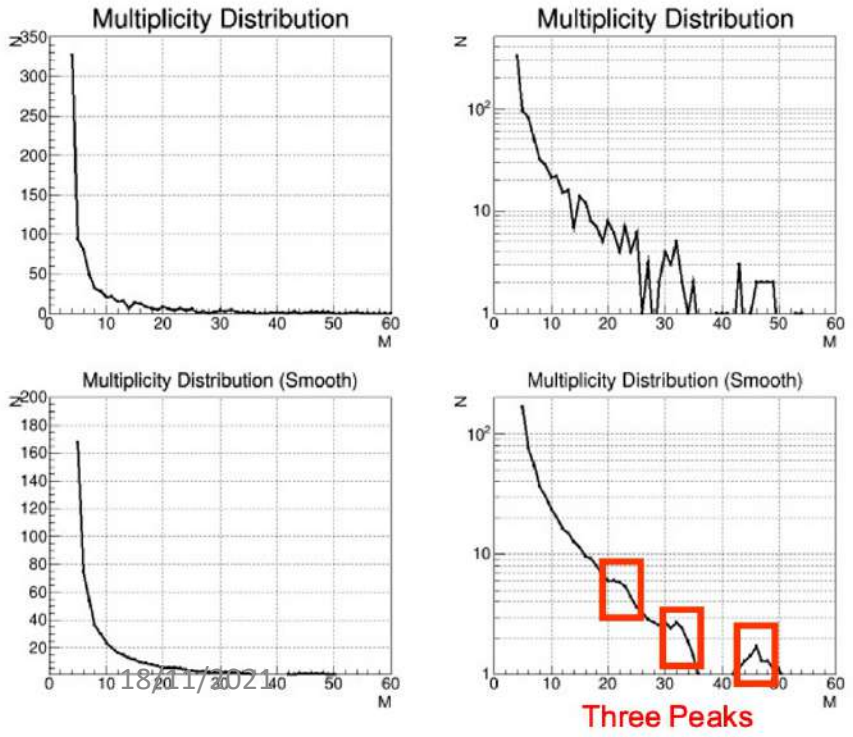
NEMESIS Spin Dependent results vs PRD 103, 063028 (2021)



Do NEMESIS results fit with the rest?

Where such measurements conducted before?

before and after Smoothing



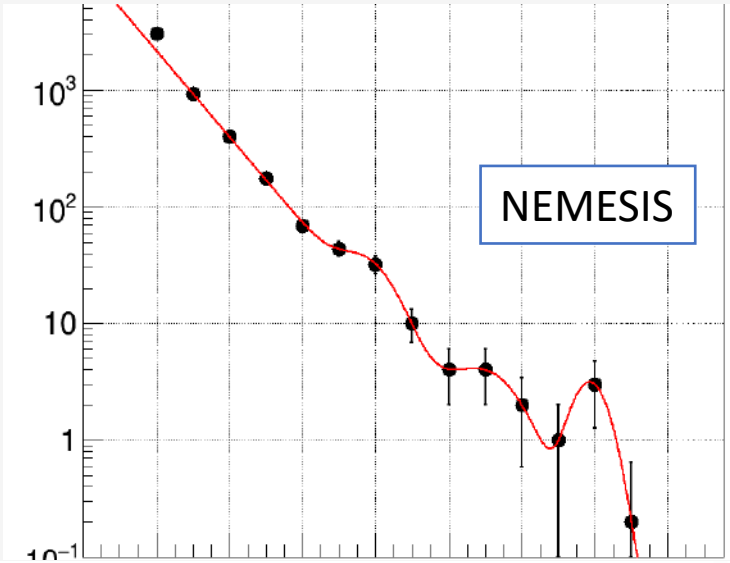
- Yes, in 2001-2002 a group of Russian and US scientists performed a similar search using **Neutron Multiplicity Detector System** (NMDS) designed and constructed in the Khloplin Radium Institute in St. Petersburg, Russia.
- The 271-day measurement, conducted at 583 m.w.e. depth, yielded no conclusive results. However, there were **three small anomalies** discerned in the data

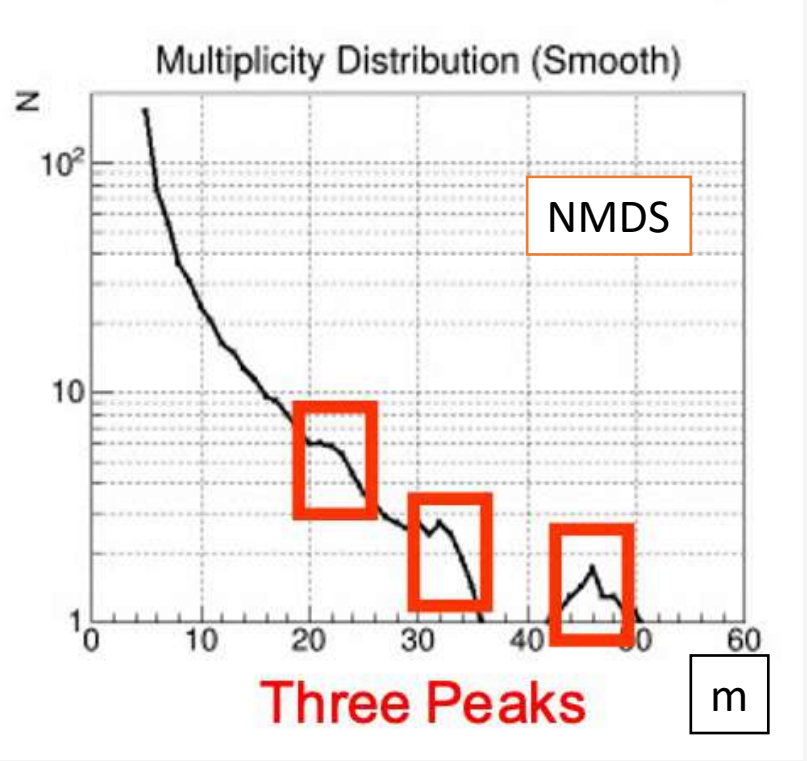
How to compare the outcome of both experiments?

- If the detected anomalies/peaks are real (correspond to some physics process or interaction), their multiplicities should match!
- Since *M* – the actual multiplicity is related to the measured multiplicity *m* by Eff – the efficiency of the detection system:

  $M = m / Eff$ and $m = M \times Eff$
- hence, the measured multiplicity ratio must equal the efficiency ratio:

$$m_{NMDS} / m_{NEMESIS} = Eff_{NMDS} / Eff_{NEMESIS}$$





See our ICRC 2021 proceedings: https://pos.sissa.it/395/514/pdf

NEMESIS vs NMDS

Perfect match!

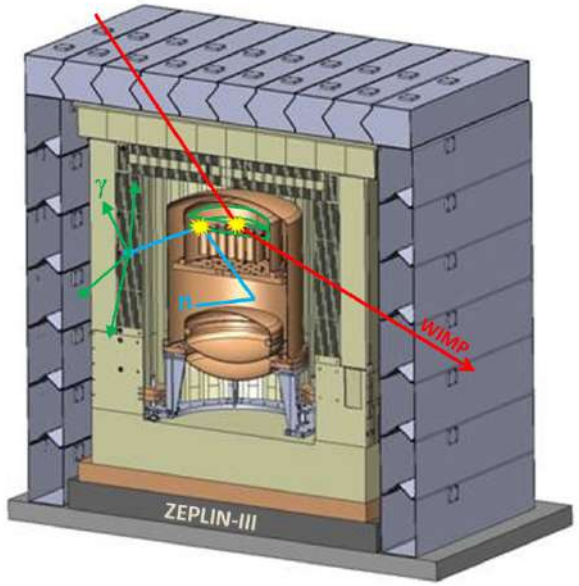
New EMMA measurements including neutrons

NMDS 2002			NEMESIS 2021				Efficiency ratio
Efficiency = 23.2(2)%			Efficiency = 8(2)%				2.9(7)
Neutron multiplicity		WIMP mass* GeV/c^2	Statistical significance (σ)	Neutron multiplicity		WIMP mass* GeV/c^2	Multiplicity ratio
Measured	Actual			Measured	Actual		
23(1)	99(4)	~12	3.6	7.7(3)	102(26)	~13	3.0(2)
33(2)	140(9)	~18	1.5	11.0(6)	146(36)	~18	3.0(2)
47(3)	202(13)	~25	1.8	14.0(4)	185(46)	~23	3.4(3)

*T. Ward, "Radiation Gauge Theory in an Extended Standard Model: Dark Matter, Dark Energy and Higgs Sectors", in preparation

ZEPLIN-II in Boulby (2005-2008)

(ZonEd Proportional scintillation in LIquid Noble gases)



ZEPLIN-III (pictured) reused the ZEPLIN-II Pb shield

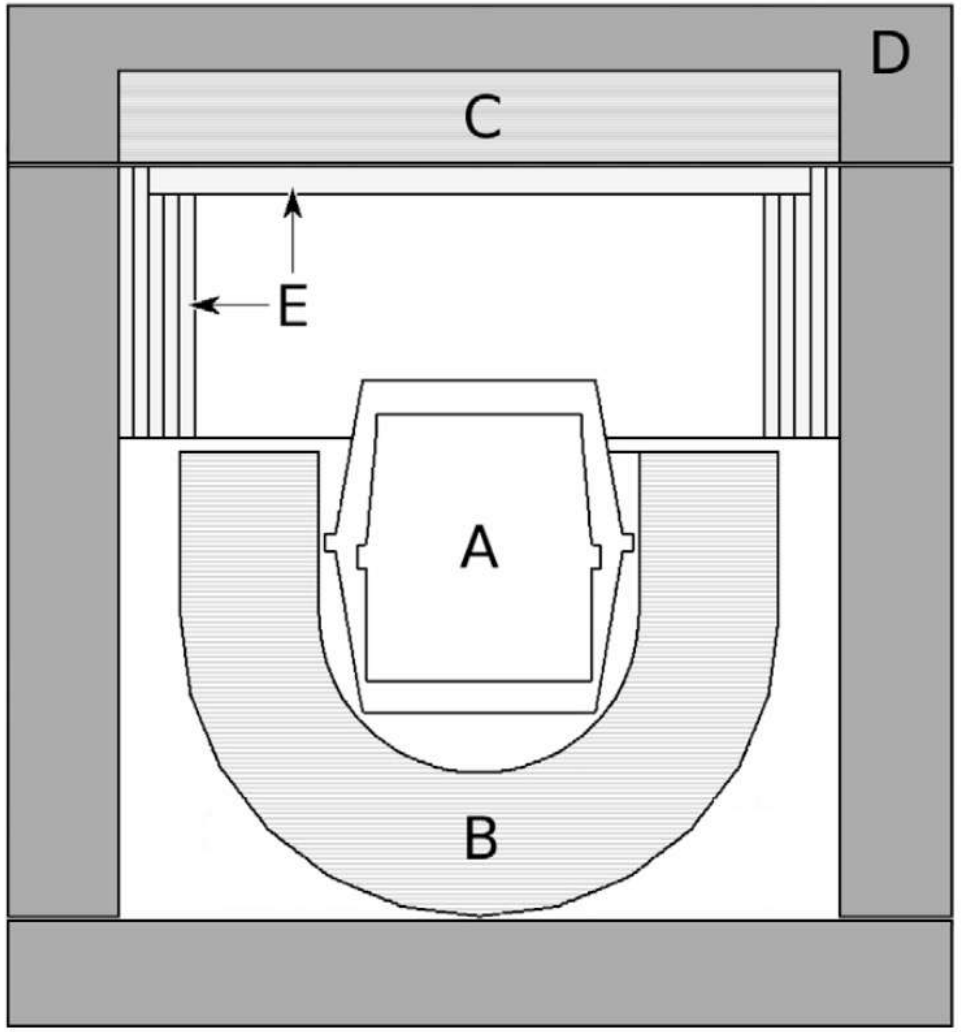
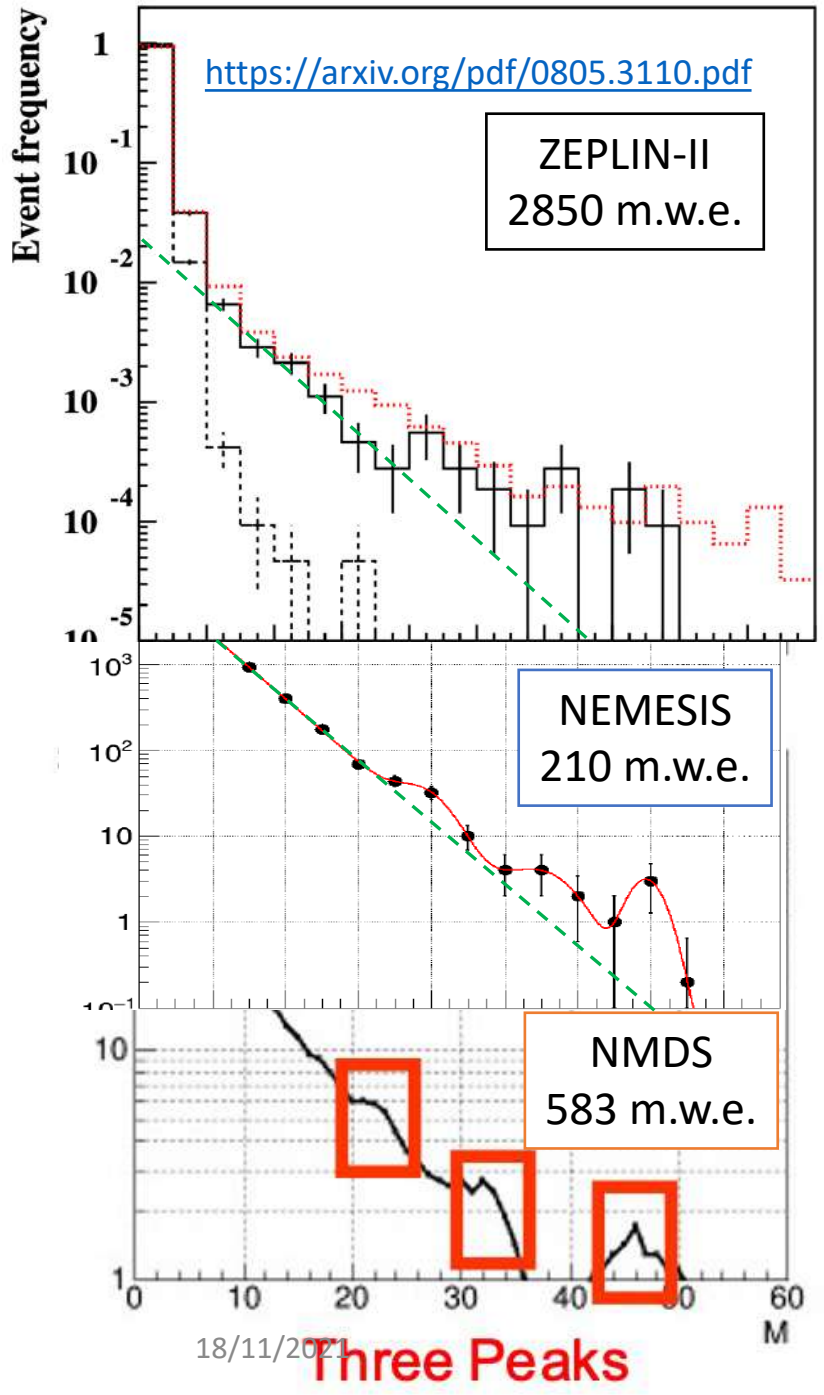


Fig. 10. Vertical cut of the geometry model used in the GEANT4 simulation: A – ZEPLIN-II detector, B – liquid scintillator detector (veto), C – Gd-loaded wax, D – lead castle, E – polypropylene sheets which make up the passive neutron shielding (vertical slabs are interleaved with Gd-loaded resin). Details of the ZEPLIN-II detector were removed from this figure for simplicity.

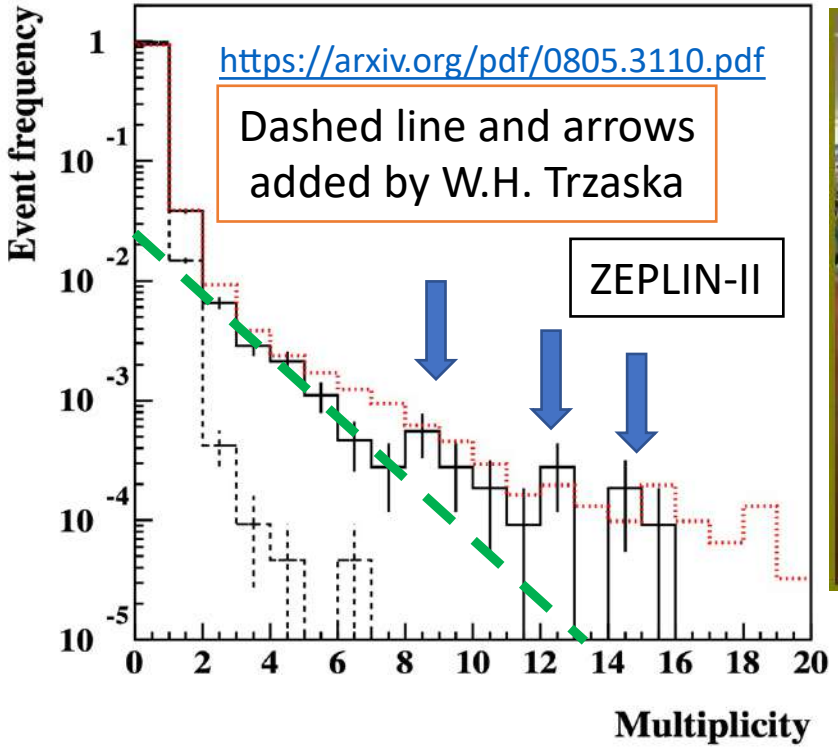
APP 31(2009)366

Neutron spectra (background) available on arxiv:

https://arxiv.org/pdf/0805.3110.pdf

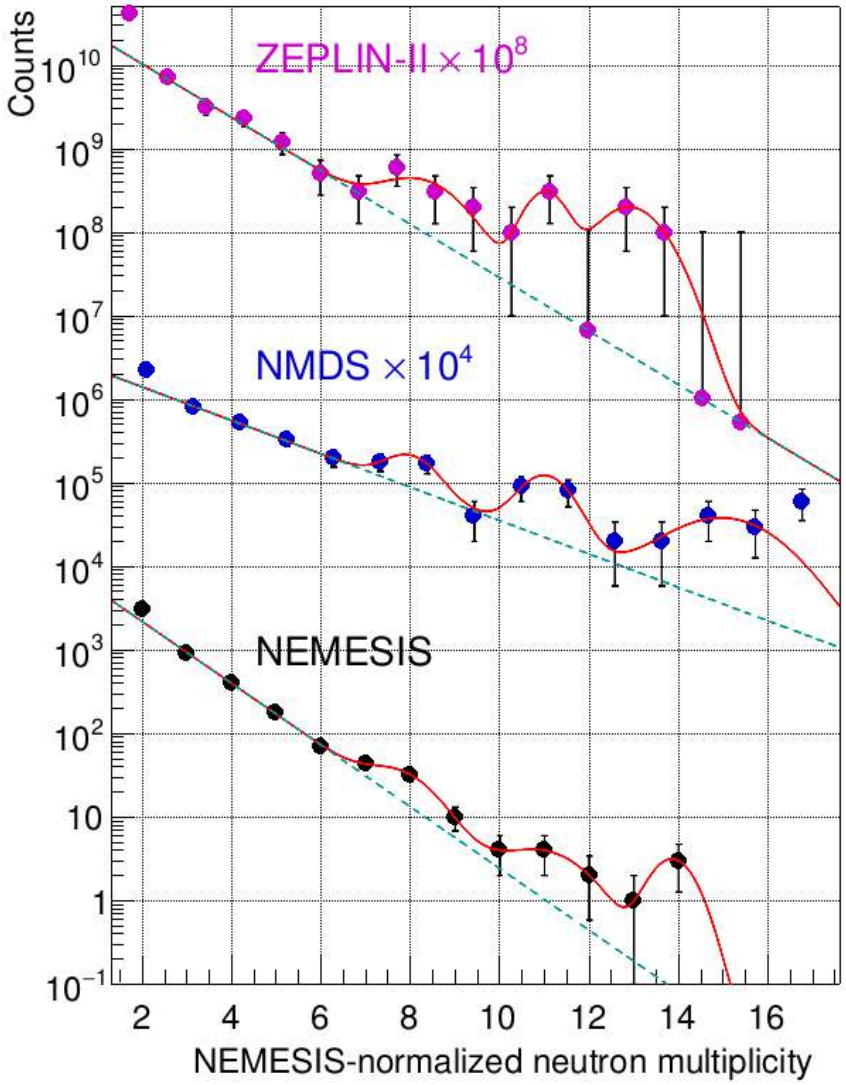


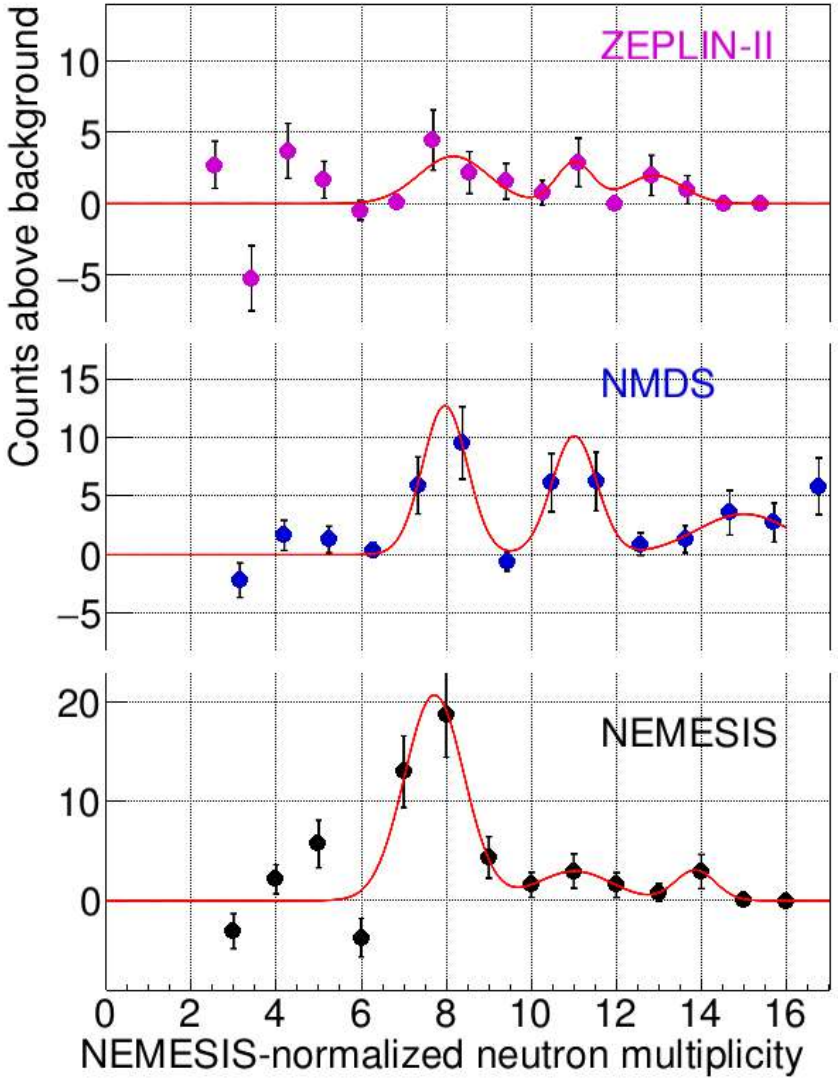
There are similar structures in the multiplicity spectrum collected by **ZEPLIN-II** in the Boulby Underground Lab at a depth of 2850 m.w.e.



← Probability of a statistical fluke **~ 1** in **50 000 000**

W.H. Trzaska et al., TAUP 2021 proceedings, in print





ZEPLIN-II

The DAQ time window was 200 microseconds with data accumulated in the (40-190) microsecond time-period which is only 42% of the neutron exponential die-away time.

Required correction x 2.38

Summary of evidence for WIMP annihilation

NEMESIS
New EMMA measurements including neutrons

We have small but consistent (in multiplicity and estimated cross section) anomalous peaks in neutron multiplicity spectra taken deep underground or with muon suppression

- NEMESIS (210 m.w.e. μ-suppressed)
- NMDS (583 m.w.e.)
- ZEPLIN-II (2850 m.w.e.)

Sufficient to justify further simulations and search

To cross the 5-σ discovery threshold **we need**

- NEMESIS upgrade (210 m.w.e. μ-suppressed)
- HALO data analysis (6000 m.w.e.)

Work in progress

Confirmation
of the observed anomalies
at above 5σ level

New EMMA measurements including neutrons

The next step

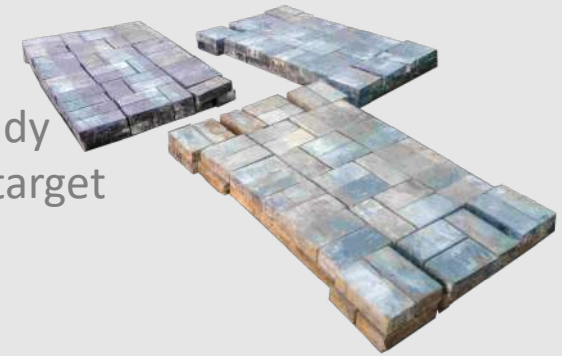
What

How

When

NEMESIS upgrade

- Larger targets (Pb and Cu)
- More neutron detectors
- Better muon suppression
- Better scintillator coverage



3t of Pb bricks ready
for NEMESIS-DM target

Seeking funding
and new collaborators

Possible explanations

- Instrumental artefact
  - Not likely to appear in 4 different experimental setups
- CR muon-induced effect
  - Not likely since the flux changes by 4 orders of magnitude while the yields remain comparable
- Error in data analysis
  - Not likely as the analysis is very straightforward and can be done even directly on the plot
- Dark Matter
  - But why SuperK didn't report anything?
- Something else
  - But what?

"It's not Dark Matter,
you've got the lens cap on."

NEMESIS at international conferences

- **ICRC 2021** 12-23 July 2021
  - New NEMESIS results https://doi.org/10.22323/1.395.0514
  - High-multiplicity neutron events registered by NEMESIS experiment https://doi.org/10.22323/1.395.0497

- **TAUP 2021** 26 Aug – 3 Sep 2021
  - DM-like anomaly in neutron multiplicity spectra
  - Proceedings: http://doi.org/10.1088/1742-6596/2156/1/012029
  - YouTube video (https://youtu.be/0UcEdJje4ms)

- **JUNO Europe meeting** 13 – 14 Sep 2021

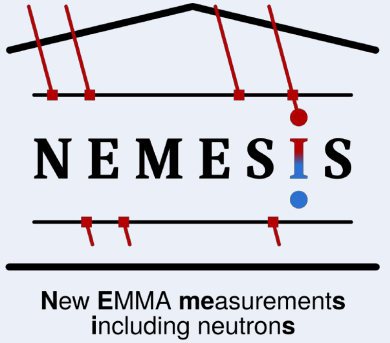
- **VCI 2022** 21 – 25 Feb 2022
  - https://indico.cern.ch/event/1044975/contributions/4663815/

- **NDM 2022** 15 – 21 May 2022
  - https://indico.phy.ornl.gov/event/142/contributions/740/
  - https://indico.phy.ornl.gov/event/142/contributions/828/

NEMESIS

New EMMA measurements including neutrons

Thank you for your attention!



W.H. Trzaska,[a,e,*] T. Enqvist,[a] K. Jędrzejczak,[b] J. Joutsenvaara,[d] M. Kasztelan,[b] O. Kotavaara,[d] P. Kuusiniemi,[a] K. K. Loo,[f] J. Orzechowski,[b] J. Puputti,[d] M. Slupecki,[e] J. Szabelski,[b] I. Usoskin[c], T. E. Ward[g,h], and A. Barzilov[i]

* email: trzaska@jyu.fi

[a]*Department of Physics, University of Jyväskylä, P.O. Box 35, FI-40014 University of Jyväskylä, Finland*
[b]*Cosmic Ray Laboratory, National Centre for Nuclear Research (NCBJ), 28 Pułku Strzelców Kaniowskich 69, 90-558 Łódź, Poland*
[c]*University of Oulu, Sodankylä Geophysical Observatory, P.O. Box 3000, FIN-99600 Sodankylä, Finland*
[d]*University of Oulu, Kerttu Saalasti Institute, Pajatie 5, 85500 Nivala, Finland*
[e]*Helsinki Institute of Physics (HIP), P.O. Box 64, 00014 University of Helsinki, Finland*
[f]*Institut für Physik (IPH), Johannes Gutenberg-Universität Mainz (JGU), Staudingerweg 7, 55128 Mainz, Germany*
[g]*Office of Nuclear Energy, DOE 1000 Independence Ave., SW, Washington, D.C., 20585, United States*
[h]*TechSource, Santa Fe, NM, United States*
[i] *University of Nevada Las Vegas, Department of Mechanical Engineering, Nevada 89154-4027, United States*