

DIRECT SEARCH FOR DARK MATTER

DEEP UNDERGROUND

STATUS AND NEXT STEPS

Gravity, Strings and
Supersymmetry breaking

April, 3-5 2025

Palazzo della Carovana, Pisa, Italy

Karoline Schöffner

MPP, Garching, Germany

kschaeff@mpp.mpg.de



MAX-PLANCK-INSTITUT
FÜR PHYSIK

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DIRECT SEARCH FOR DARK MATTER

DEEP UNDERGROUND

STATUS AND NEXT STEPS
FROM THE PERSPECTIVE OF AN EXPERIMENTALIST



Gravity, Strings and
Supersymmetry breaking

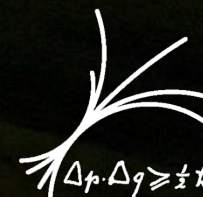
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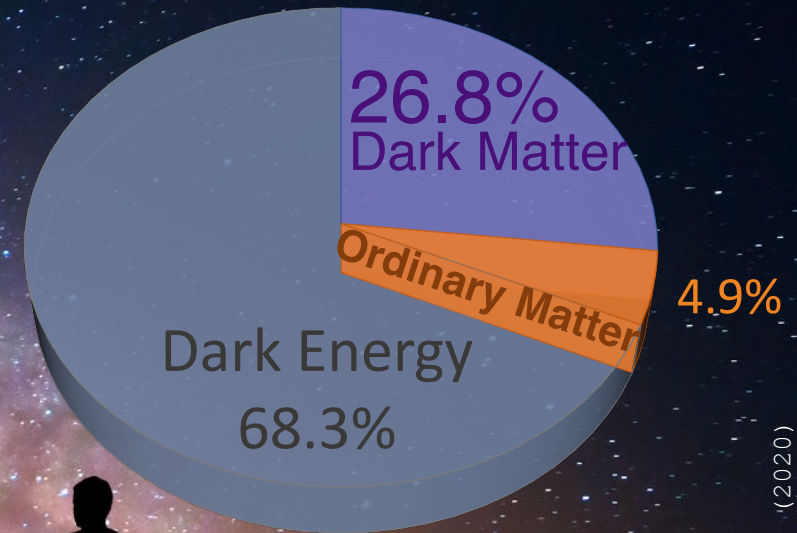
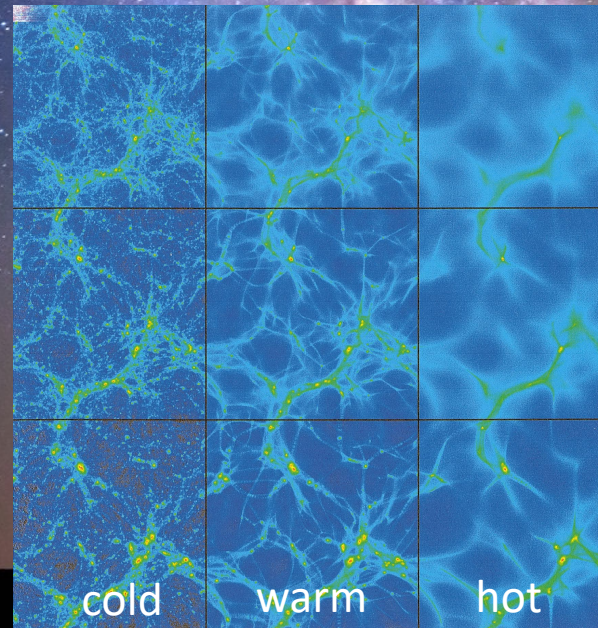
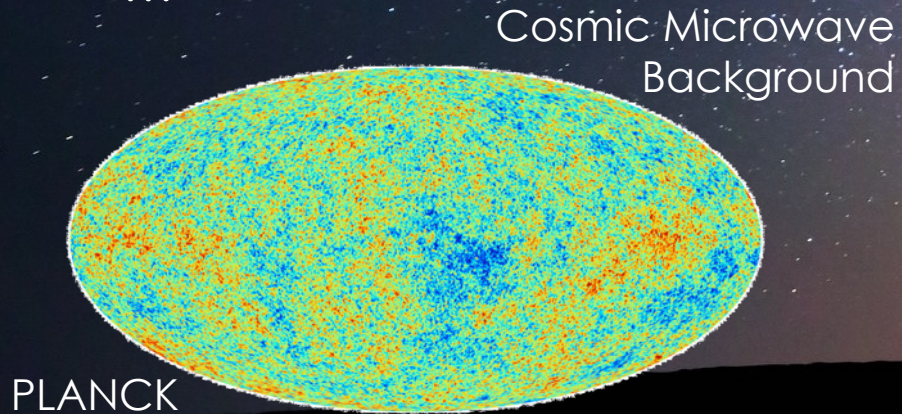
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MOST OF THE UNIVERSE IS INVISIBLE

The evidence for dark matter today is **overwhelming** and present on all length scales

- Early and late cosmology (CMB, LSS)
- Clusters of galaxies
- Galactic rotation curves
- Big Bang Nucleosynthesis
- ...



CHALLENGE FOR DM DETECTION

Gravity is universal:

no chance for particle identification

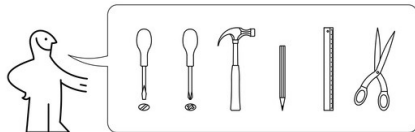
Particle physics framework:

evidence via other channels is mandatory
e.g. weak interaction or beyond

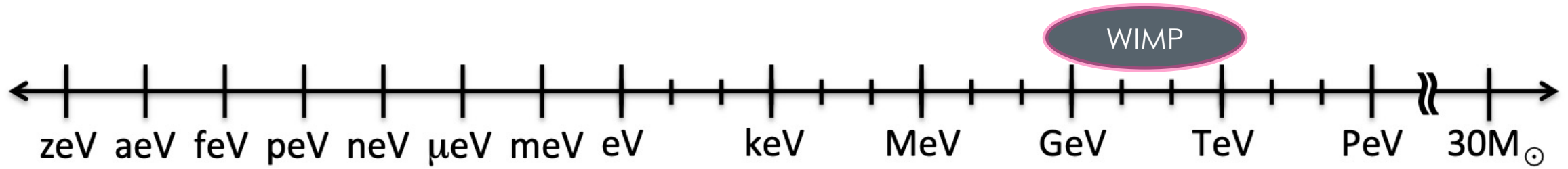
BUT:

→ What you search for is **model-dependent!**

→ (*hardest part*: other channel is **not** guaranteed, DM could also be only gravitationally coupled to Standard Model particles ect.)



THE “ALLOWABLE” MASS RANGE



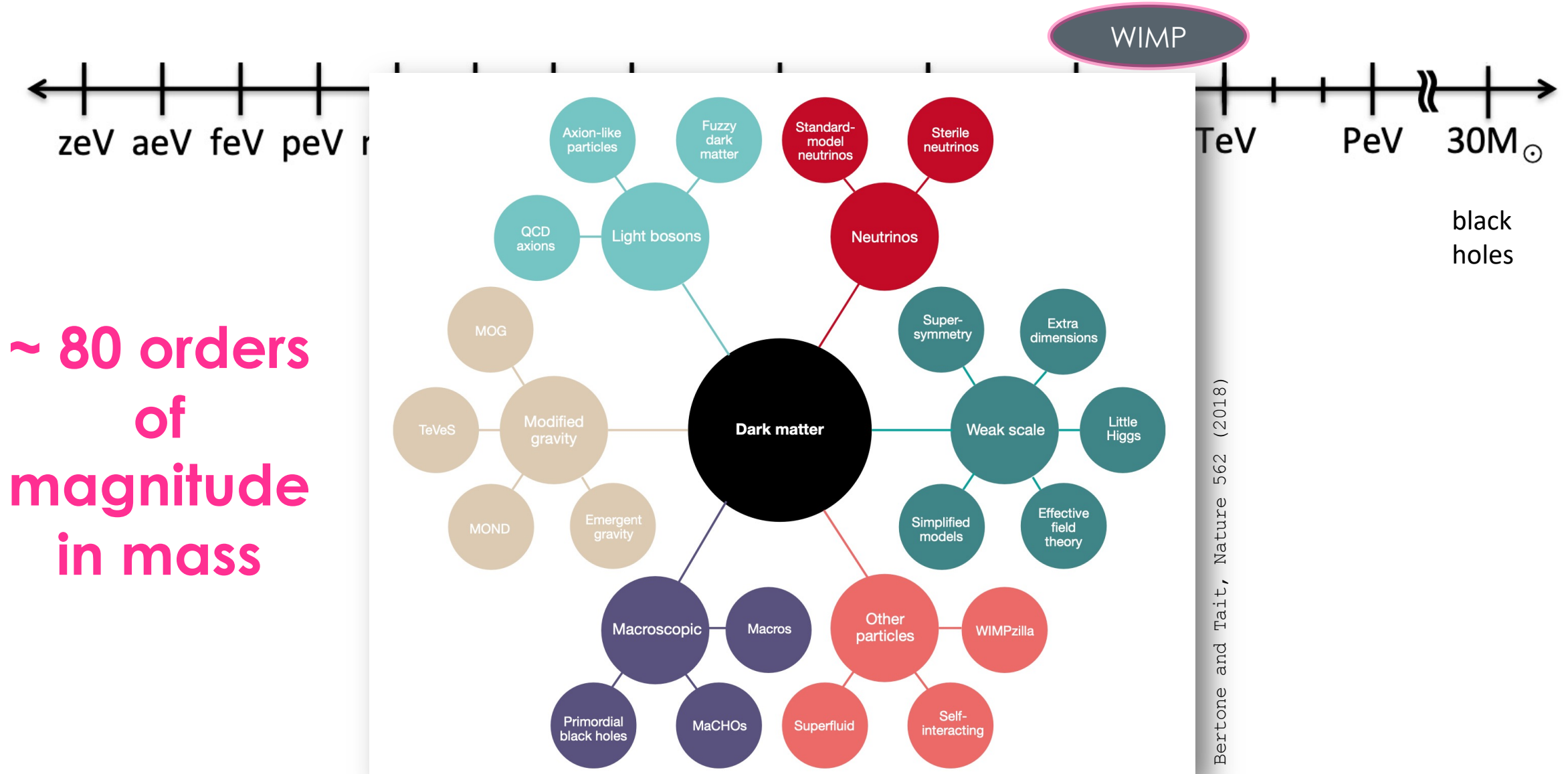
“wave-like” dark matter

“particle-like” dark matter

black
holes

talk by F. Januschek

THE “ALLOWABLE” MASS RANGE



HUNT FOR DARK MATTER

INDIRECT

annihilation

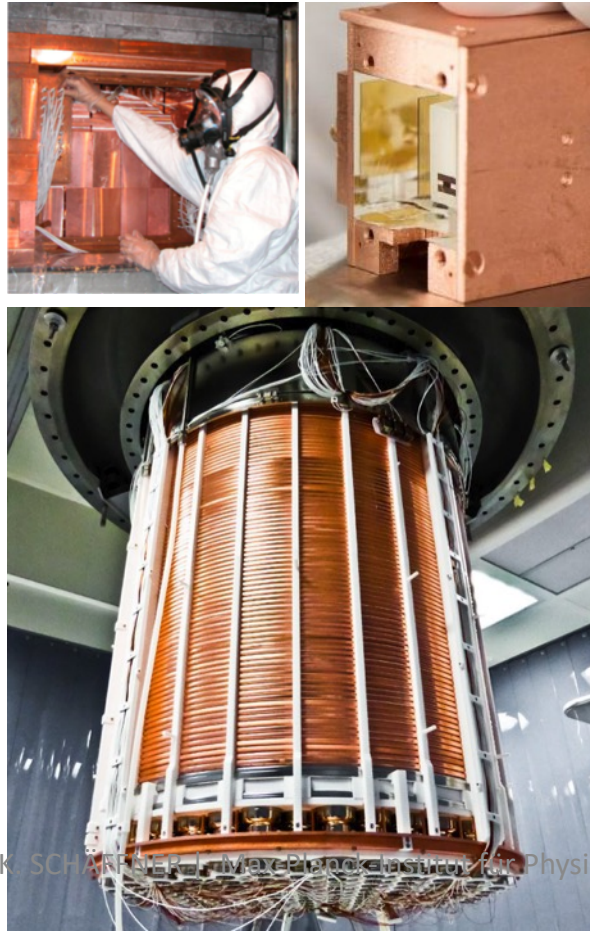
$$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \dots$$



DIRECT

scattering

$$\chi N \rightarrow \chi N$$



COLLIDERS

production

$$p + p \rightarrow \chi\bar{\chi} + \text{products}$$



talk by M. Kado

HUNT FOR DARK MATTER

INDIRECT

annihilation

$$\chi\bar{\chi} \rightarrow \gamma\gamma, q\bar{q}, \dots$$



05.07.25

DIRECT

scattering

$$\chi N \rightarrow \chi N$$

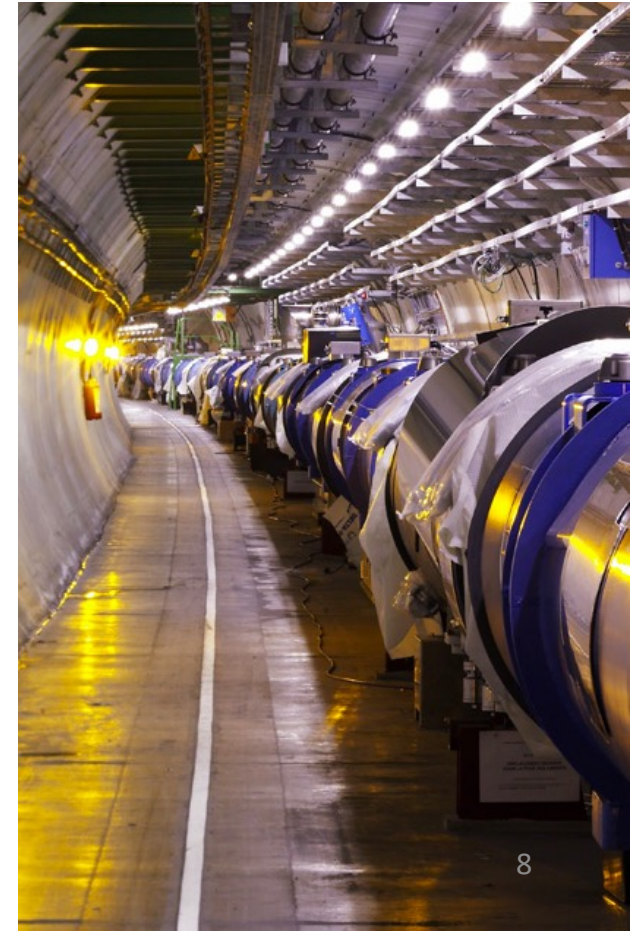


K. SCHÄNBERG, Max-Planck-Institut für Physik

COLLIDERS

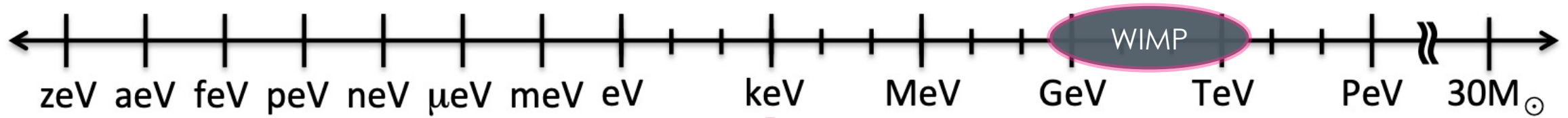
production

$$p + p \rightarrow \chi\bar{\chi} + \text{products}$$



8

THE “ALLOWABLE” MASS RANGE

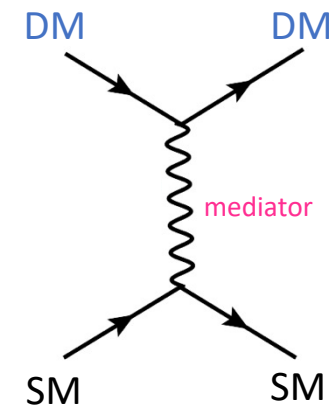


“wave-like” dark matter

“particle-like” dark matter

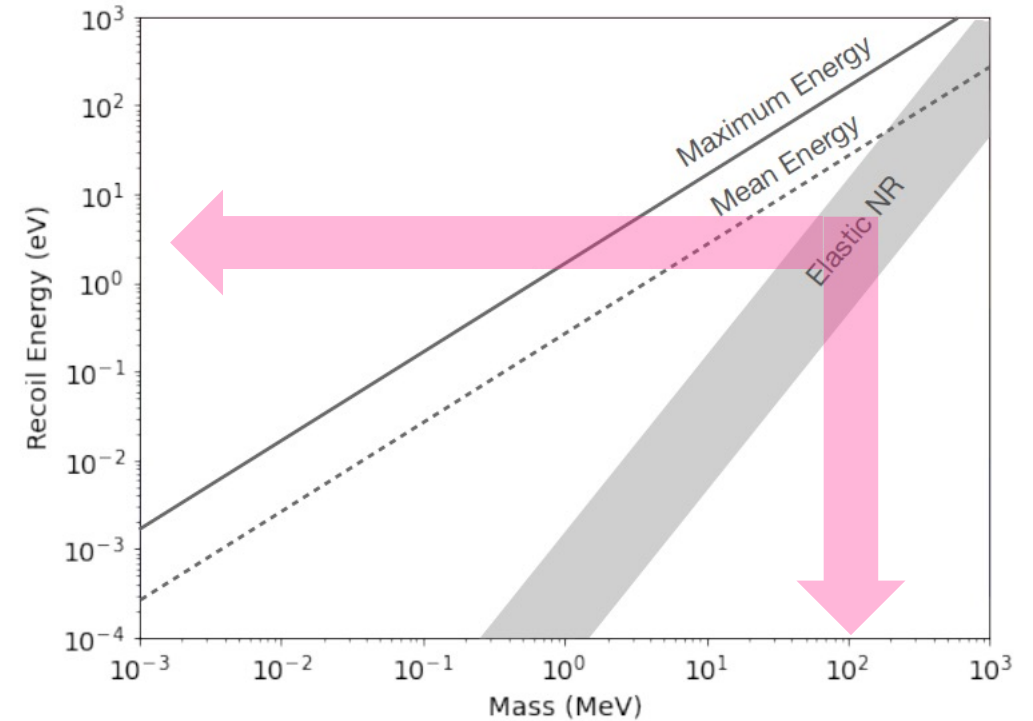
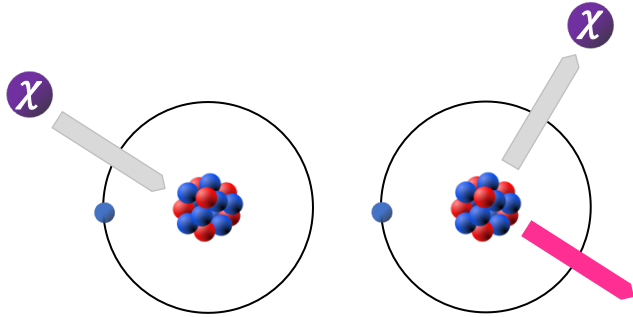
black
holes

DM scattering



DARK MATTER INTERACTIONS AND SIGNALS

- elastic DM – nucleus scattering (NR)

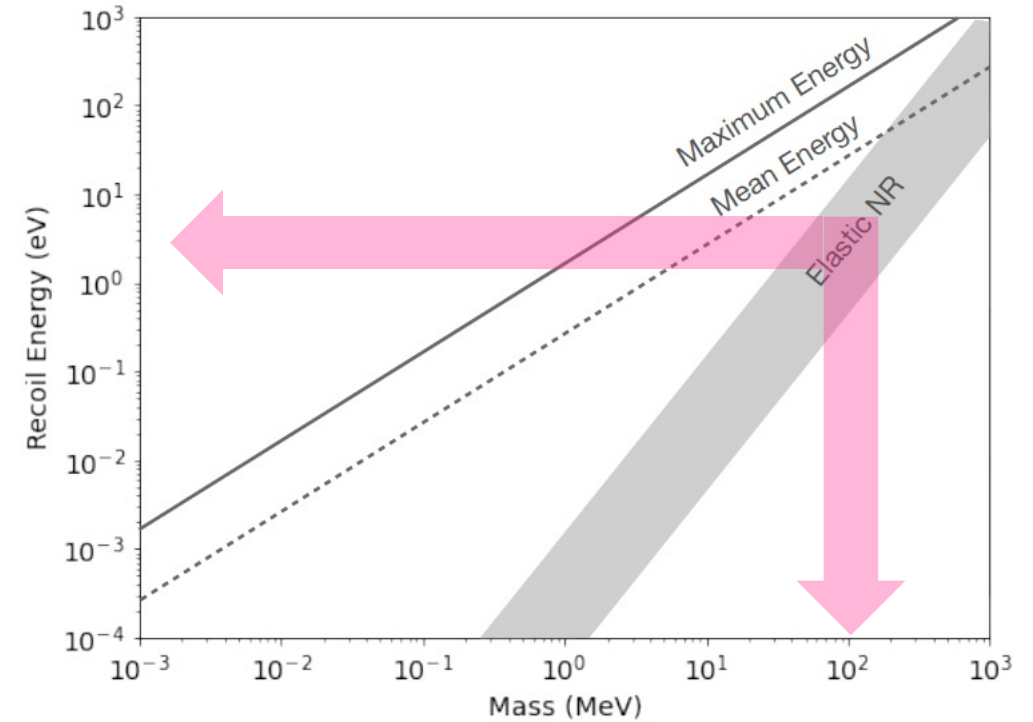
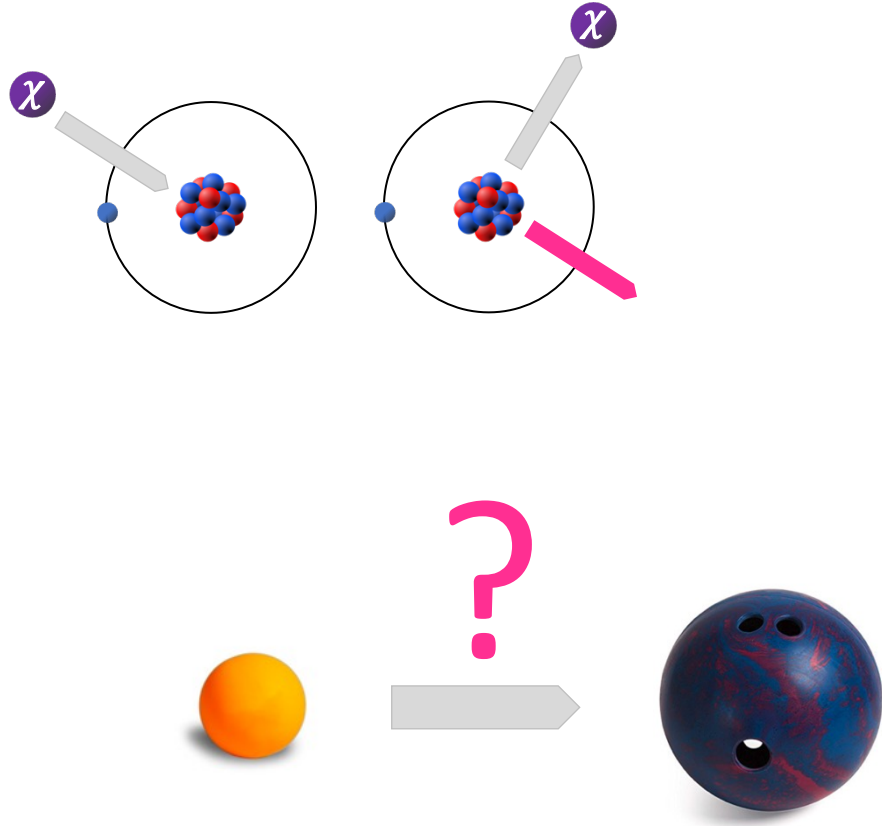


Elastic NR for H and Xe

Credit: R. Essig, modified arXiv: 2203.08297

DARK MATTER INTERACTIONS AND SIGNALS

- elastic DM – nucleus scattering (NR)

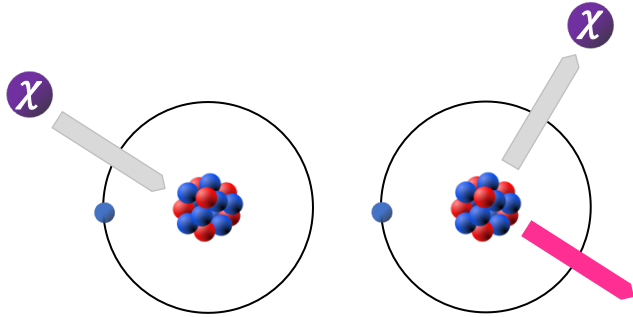


Elastic NR for H and Xe

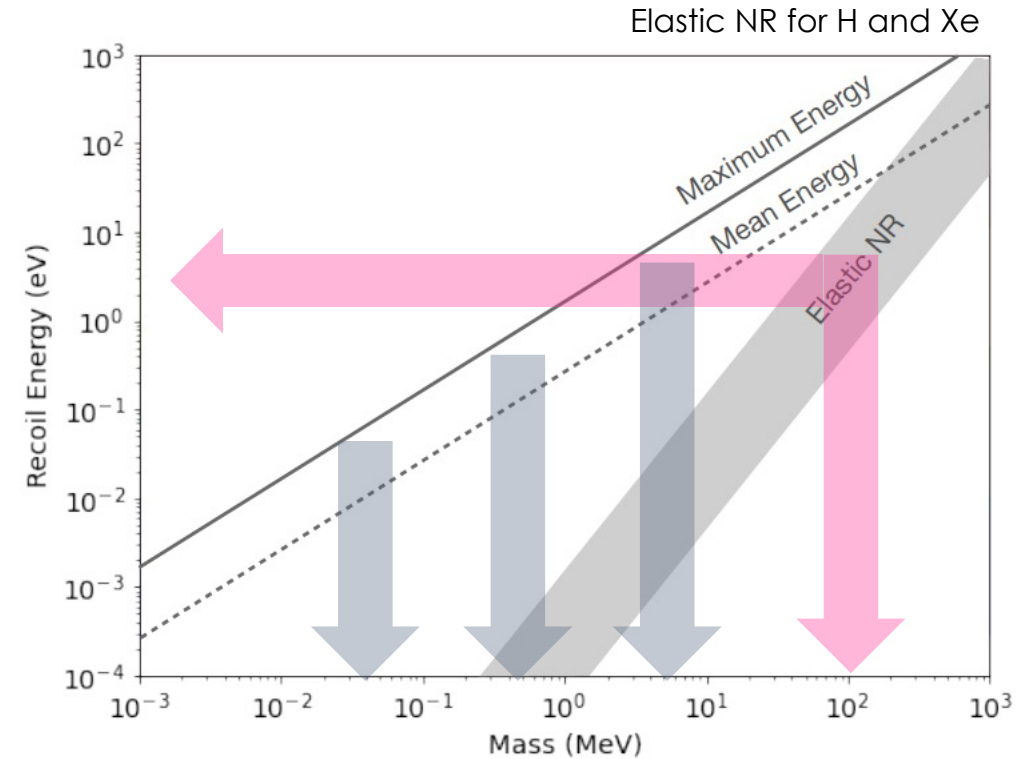
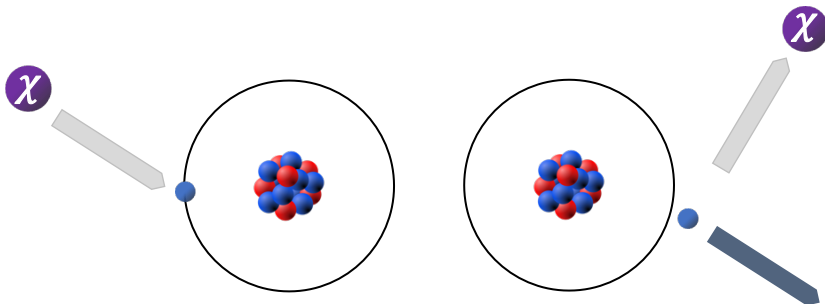
Credit: R. Essig, modified arXiv: 2203.08297

DARK MATTER INTERACTIONS AND SIGNALS

- elastic DM – nucleus scattering (NR)



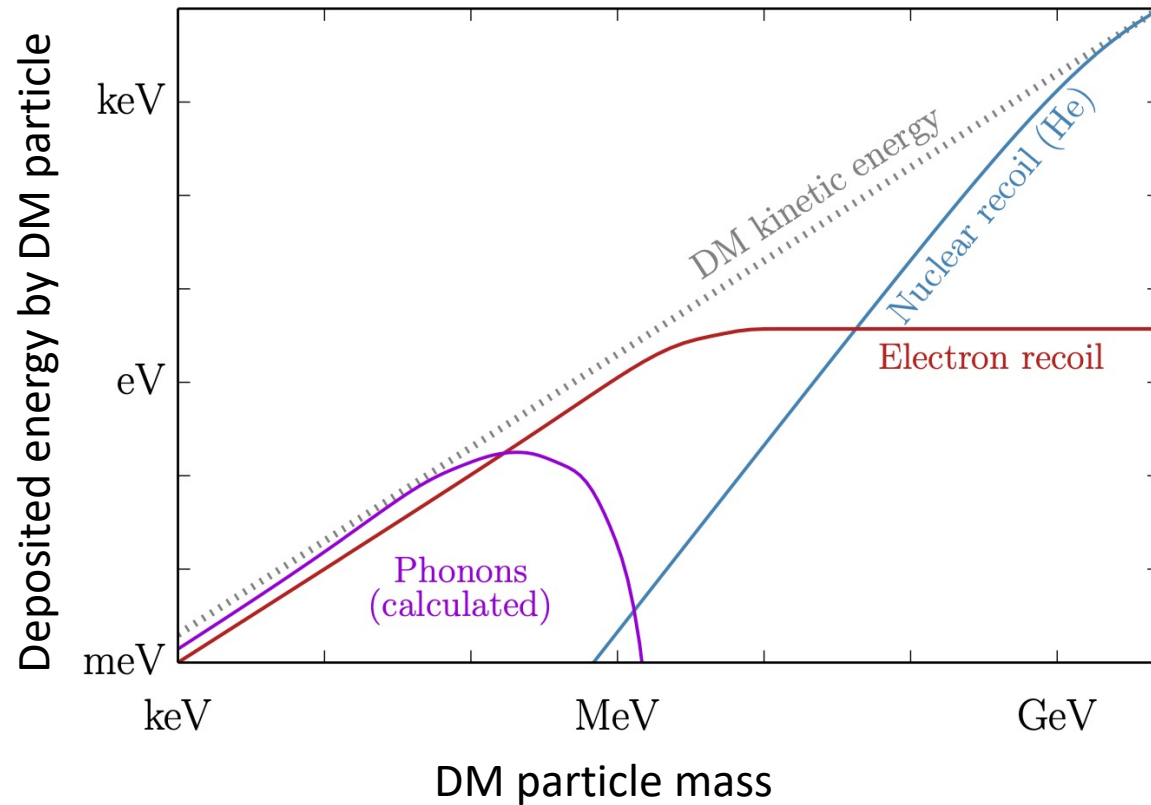
- also:
DM – electron – scattering (ER) (inelastic)



Credit: R. Essig, modified arXiv: 2203.08297

KINEMATICS – THE DM PARTICLE MASS MATTERS

*except for LHe

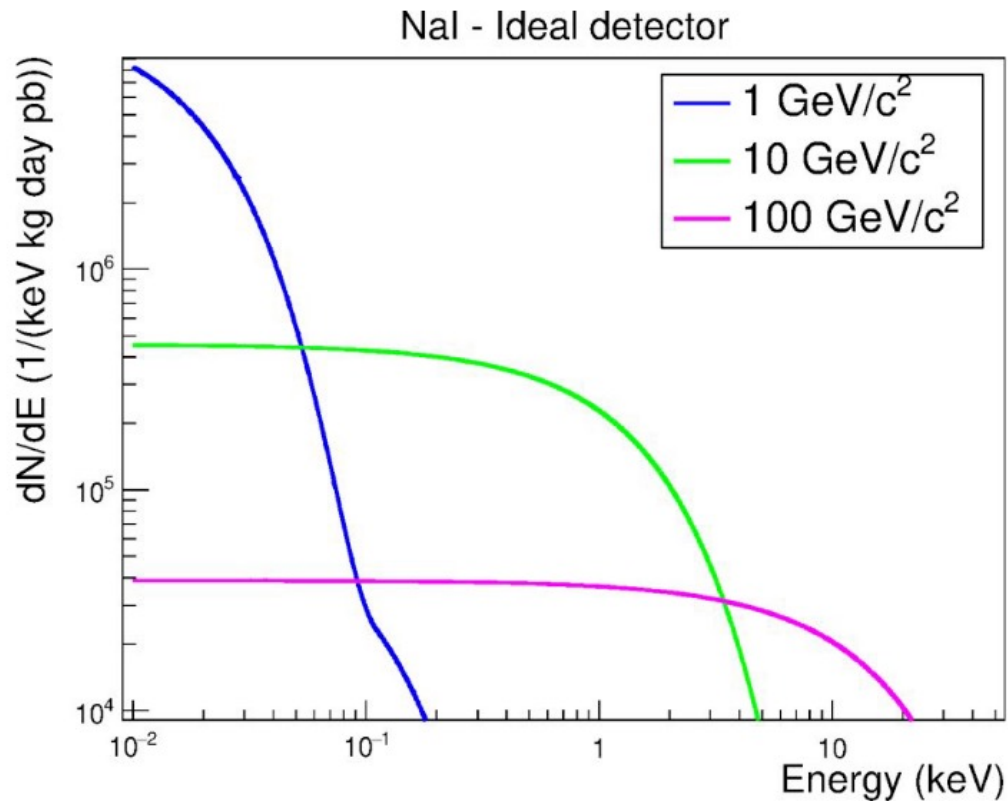


- free NRs down to $\mathcal{O}(10)$ eV*
- in liquid nobles: free ERs down to ~ 20 eV
- in semiconductors: free ERs down to ~ 1 eV
- in exotic materials: free ERs down to ~ 1 meV
- in superconductors: free ERs down to 0.1 meV
- below above limits $\rightarrow$ phonon-only

Figure: Tongyan Lin, TASI lectures on DM models and direct detection, arXiv:1904.07915

OBSERVABLE: DIFFERENTIAL RECOIL SPECTRUM

rate and shape of differential recoil spectrum depend on target material



→ small recoil energies of few ~ **eV to keV range**

→ flat and **featureless** spectrum !!

→ extremely rare interaction rate
< 1 event / (kg y) at low masses
< 1 event / (tonne y) at higher masses

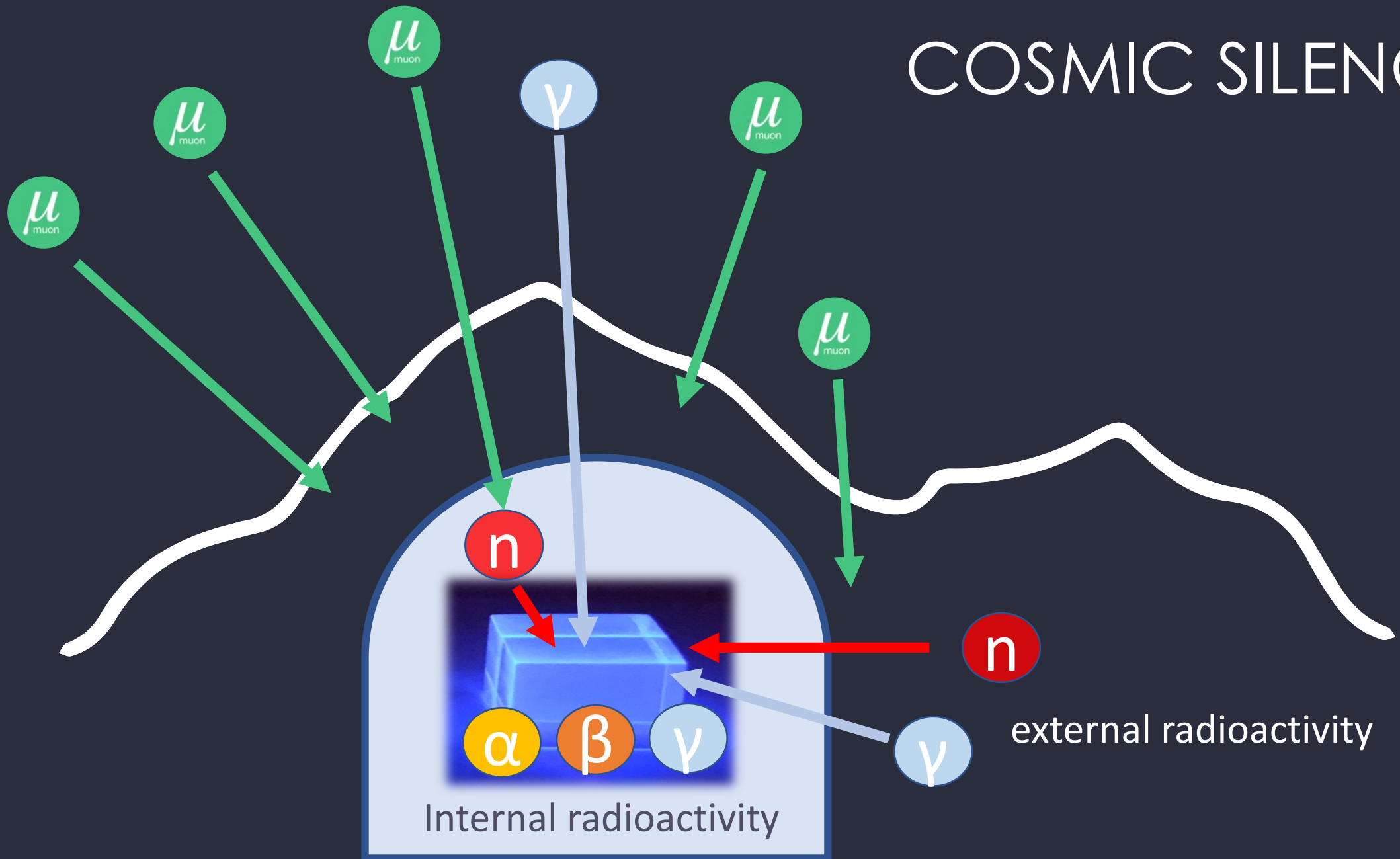
DIRECT SEARCH FOR DARK MATTER

DEEP UNDERGROUND

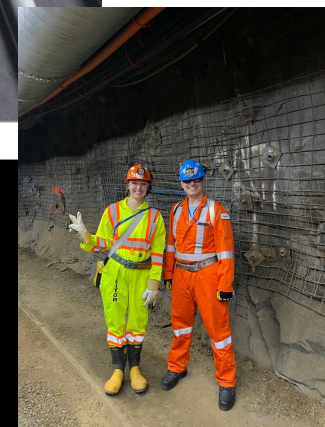
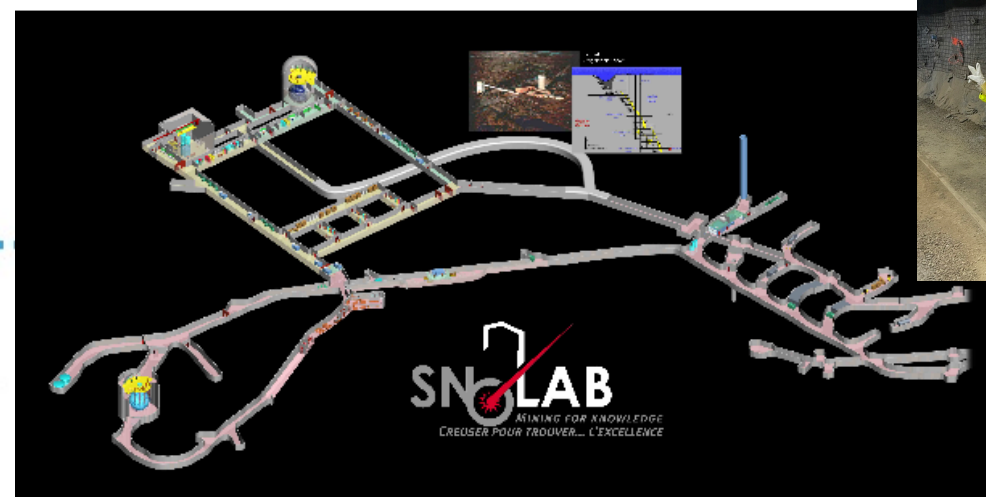
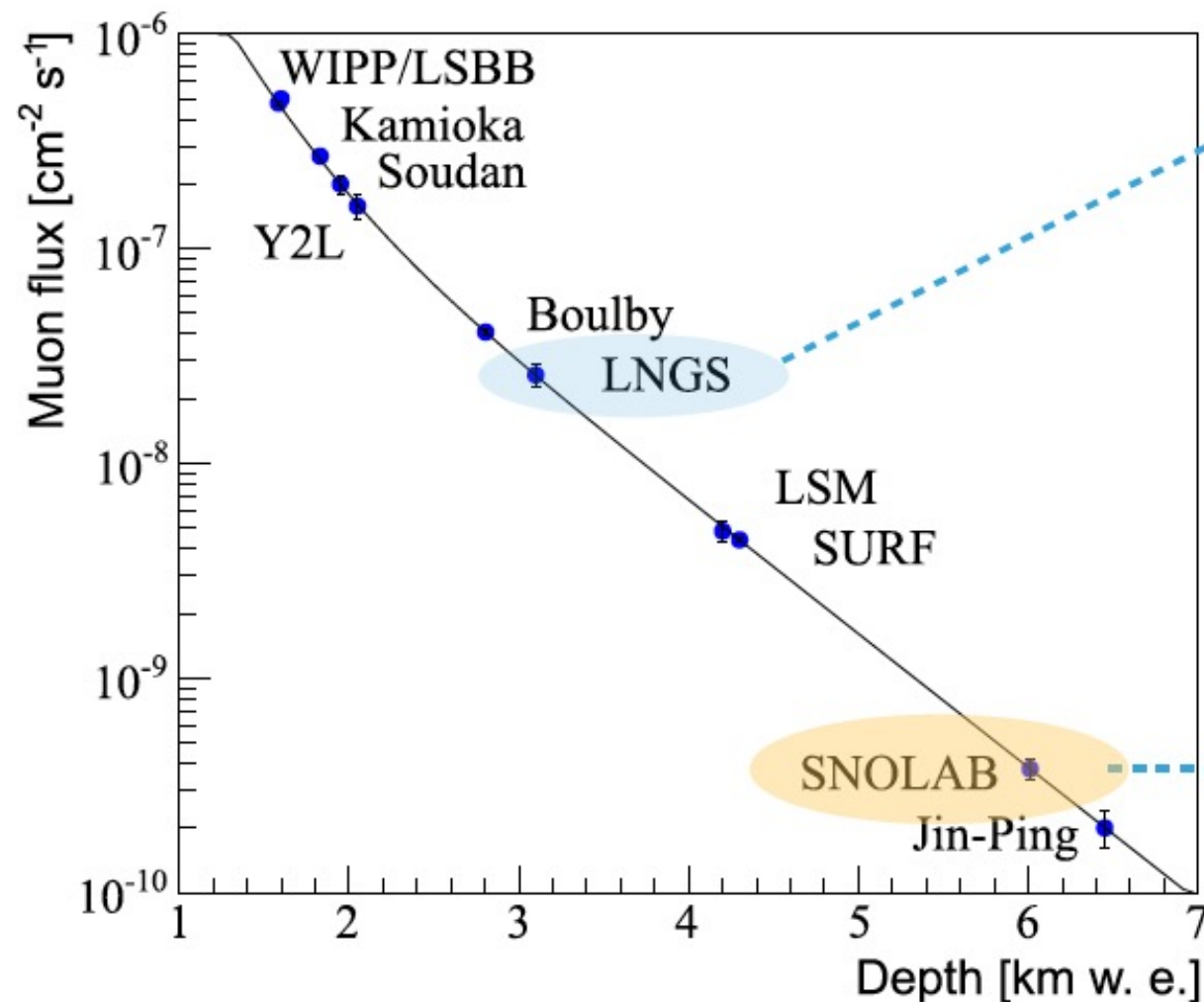
STATUS AND NEXT STEPS

WHY GO DEEP for
direct detection
experiments?

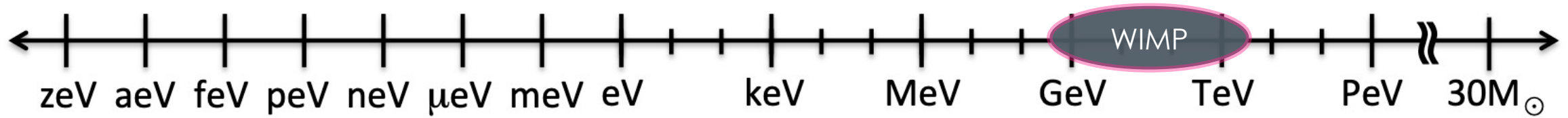
COSMIC SILENCE



UNDERGROUND SITES IN THE WORLD



3 RESEARCH LINES



“wave-like” dark matter

“particle-like” dark matter

black
holes

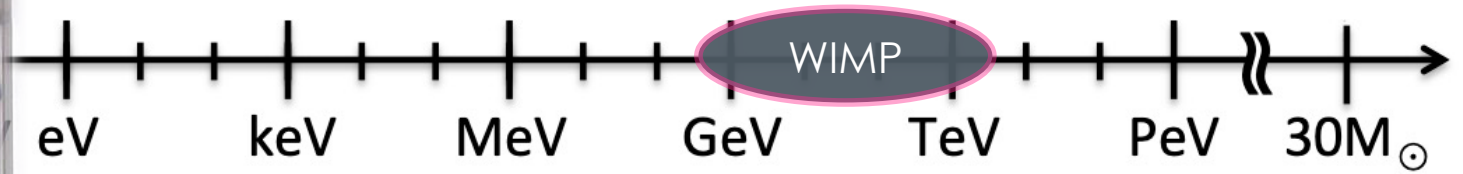
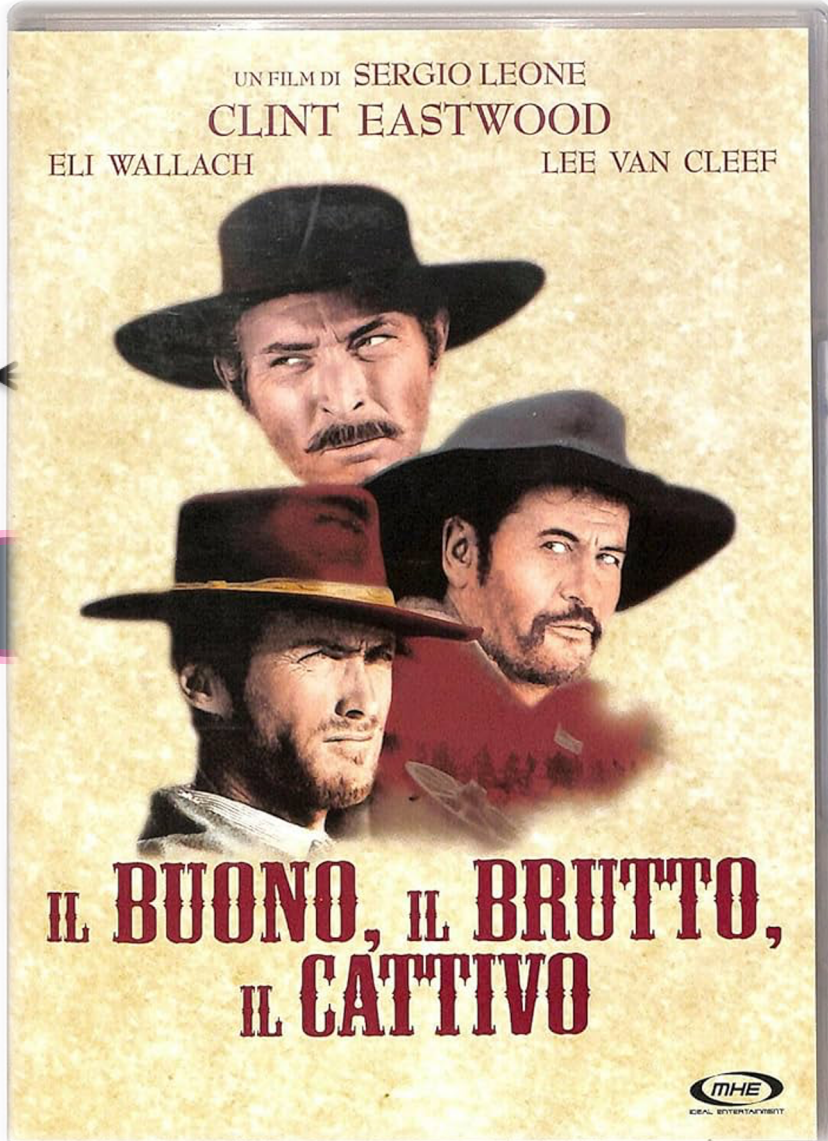
low-mass DM
“dark sector”
 $< 1\text{GeV}/c^2$

Vanilla WIMP
 $1\text{-}1000\text{ GeV}/c^2$



DAMA/LIBRA claim

3



“particle-like” dark matter

black
holes

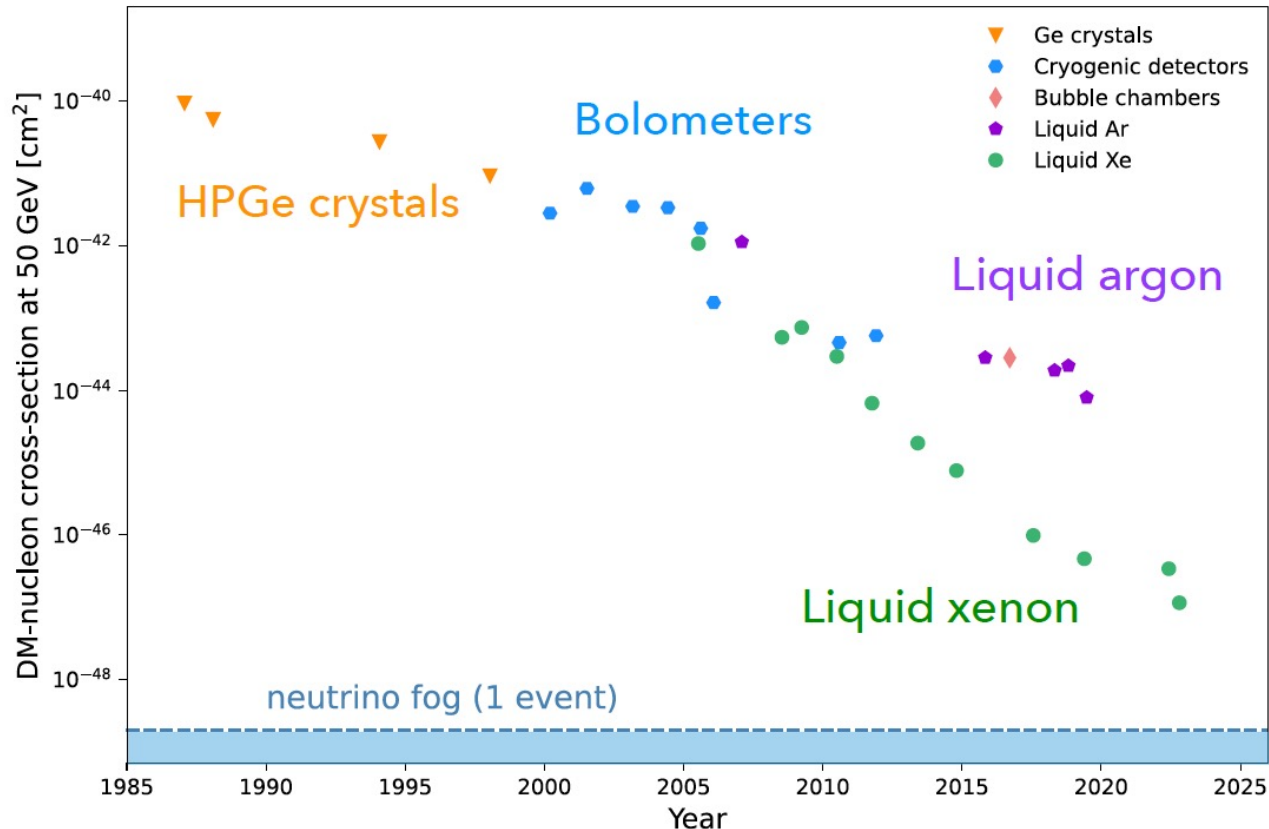
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DAMA/LIBRA claim

SEARCHING for “the” **WIMP** for 40 years



Plot from L. Baudis

Protagonists: 1990 - 2000

semiconductors and cryogenic detectors proof technological feasibility and are the “starters” of the WIMP hunt

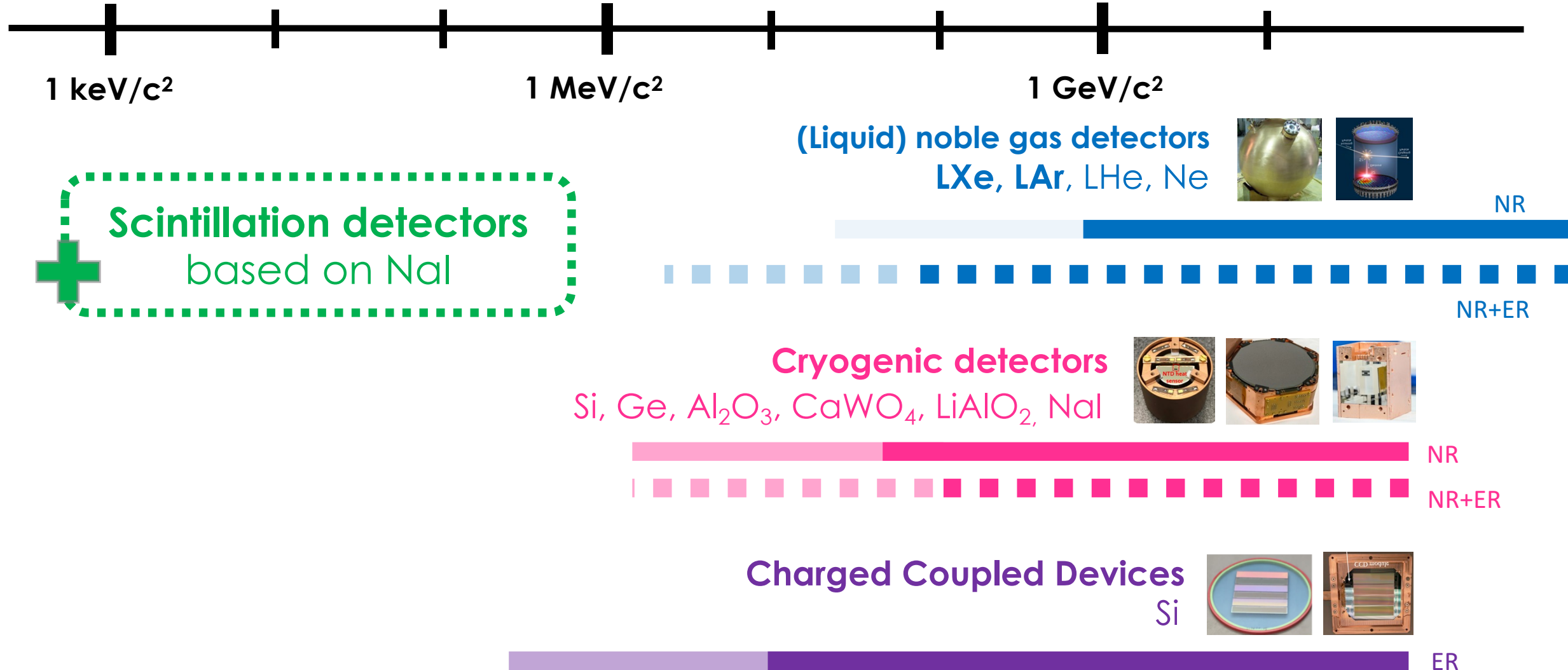
Background discrimination: 2005-2007

cryogenic detectors provide particle identification → a breakthrough!
Liquid noble gas detectors enter the field

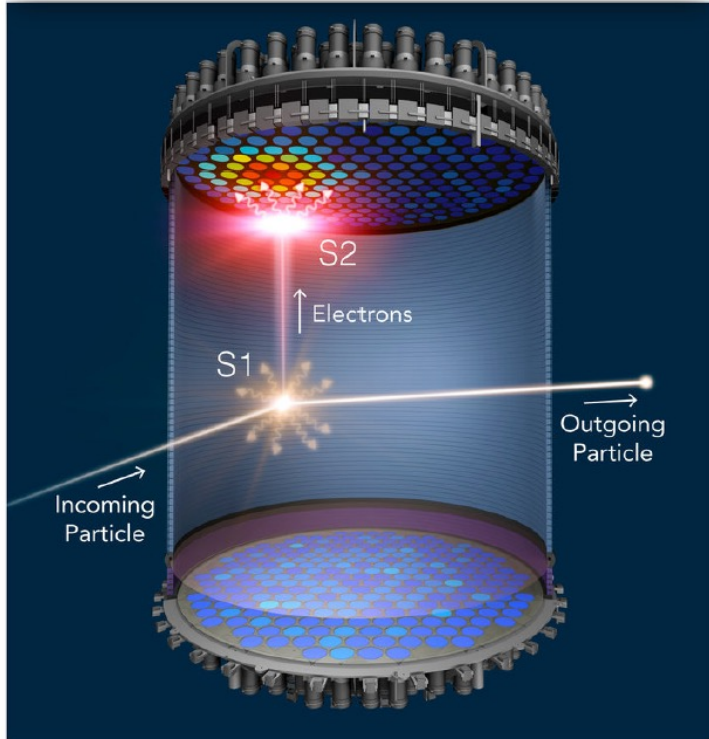
Scalability: > 2010

liquid noble gas detectors take the lead in the run for the classical WIMP

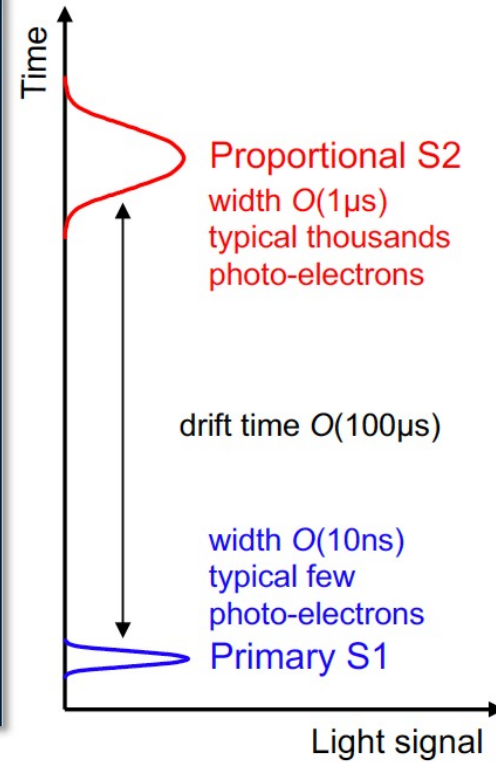
DETECTION TECHNIQUE and TARGETS



LIQUID NOBLE GAS TPCs for Xe, Ar

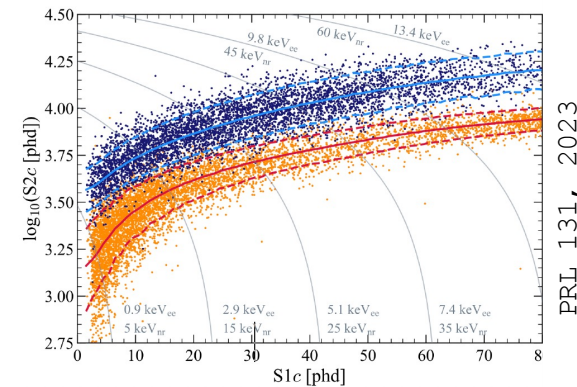


Credit: LZ collaboration SLAC



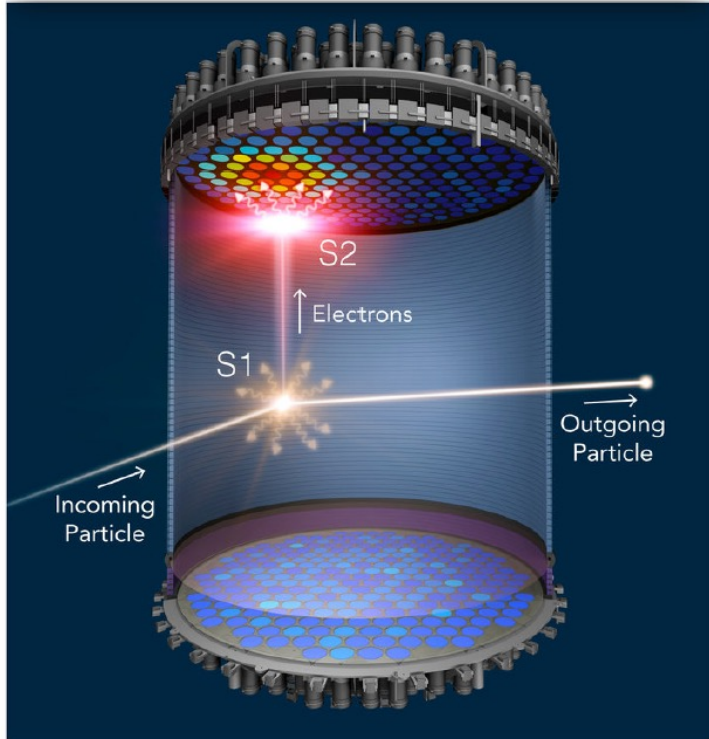
Dual-phase time projection chambers

- primary scintillation signal S1
- ionisation electrons via secondary scintillation S2 in the gas
- particle identification via ratio S2/S1

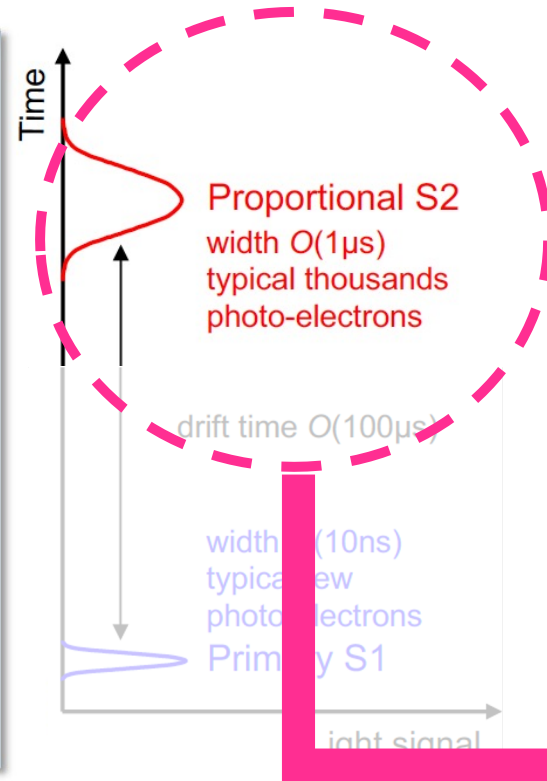


- position reconstruction
- multi-scatter rejection
- + in Ar: pulse shape discrimination

LIQUID NOBLE GAS TPCs for Xe, Ar



Credit: LZ collaboration SLAC



Dual-phase time projection chambers

- primary scintillation signal S1
- ionisation electrons via secondary scintillation S2 in the gas
- particle identification via ratio S2/S1
- reconstruction of the interaction position
- multi-scatter rejection
- + in Ar: pulse shape discrimination

Light production less efficient than ionization

S2 only-mode

- sensitive to single extracted electrons
- lower energy thresholds
e.g. XENON1T: $\sim 5 \text{ keV}_{\text{nr}}$ versus $\sim 1.5 \text{ keV}_{\text{nr}}$

XENONnT

@LNGS, 8.6 (5.9) t



data taking will soon end
→ upgrade TPC

LUX-ZEPLIN

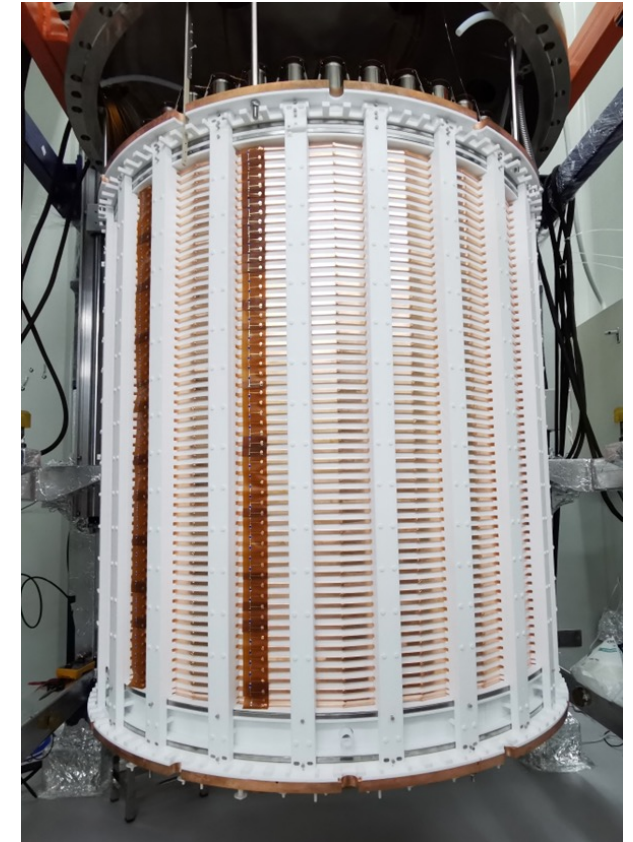
@SURF, 10 (7 t)



data taking ongoing

PandaX-4T

@Jin-Ping, 5.6 (3.7)t



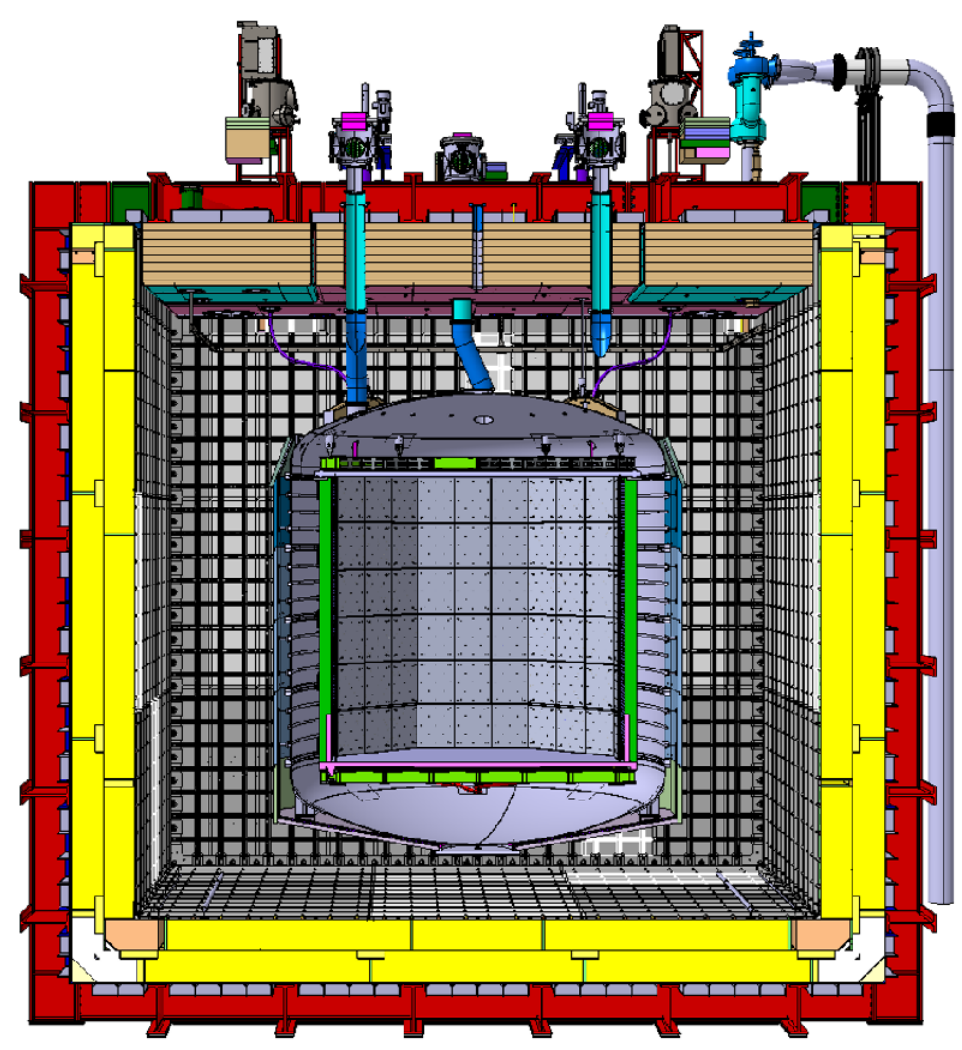
data taking ongoing
since 12/2023

images borrowed from E. Aprile

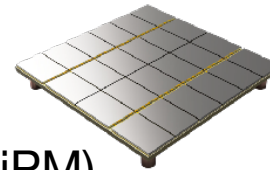
DarkSide-20k

→ in construction @LNGS, UAr 32 t

images borrowed from C. Galbiati

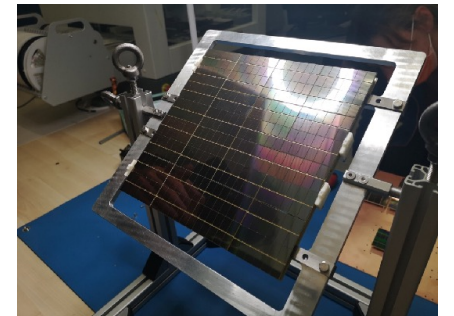


- pulse shape discrimination
- custom SiPM-based photosensors
- DUNE-like cryostat for shielding
- underground argon for pile-up avoidance:
 - produced at URANIA Site Cortex, CO USA
 - about 300 kg/day
 - purified at ARIA in Sardegna, Italy
 - $\mathcal{O}(1 \text{ tonne/day})$ 99.999%

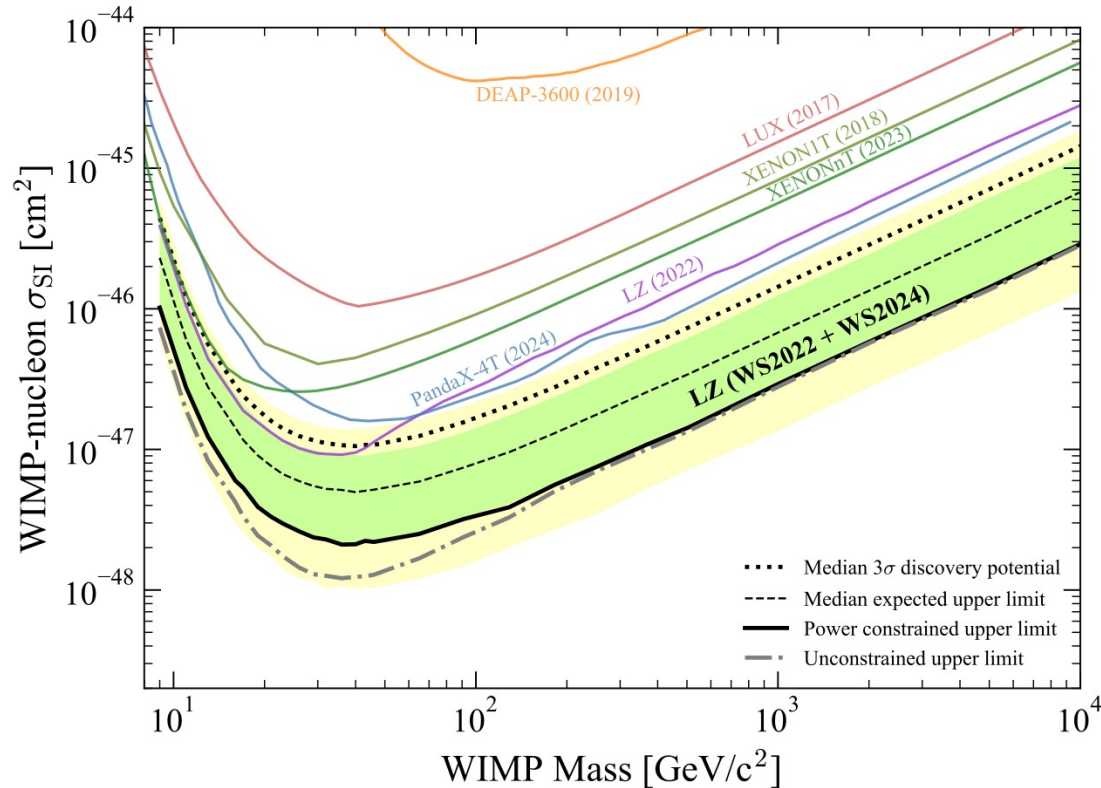


Tile (24 SiPM)
5 × 5 cm²

PDU (16 Tiles)
20 × 20 cm²



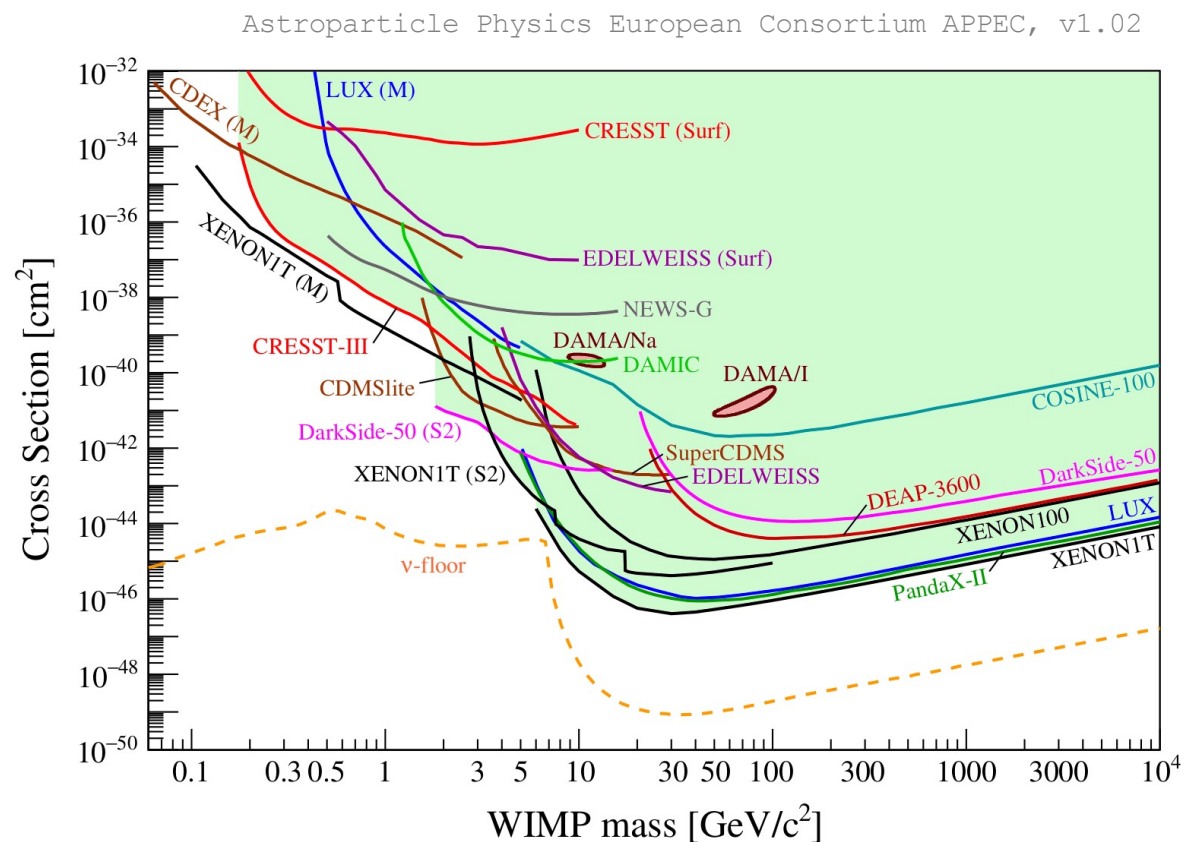
CURRENT STATUS of “WIMP” SEARCHES



~ 10 – 1000 GeV/c² with liquid nobles

- world-wide effort with enormous technological progress in last decades
- LXe tonne-scale experiments with extremely rare interaction rate
current limits: $\mathcal{O}(0.01)$ cts/(keV tonne year)

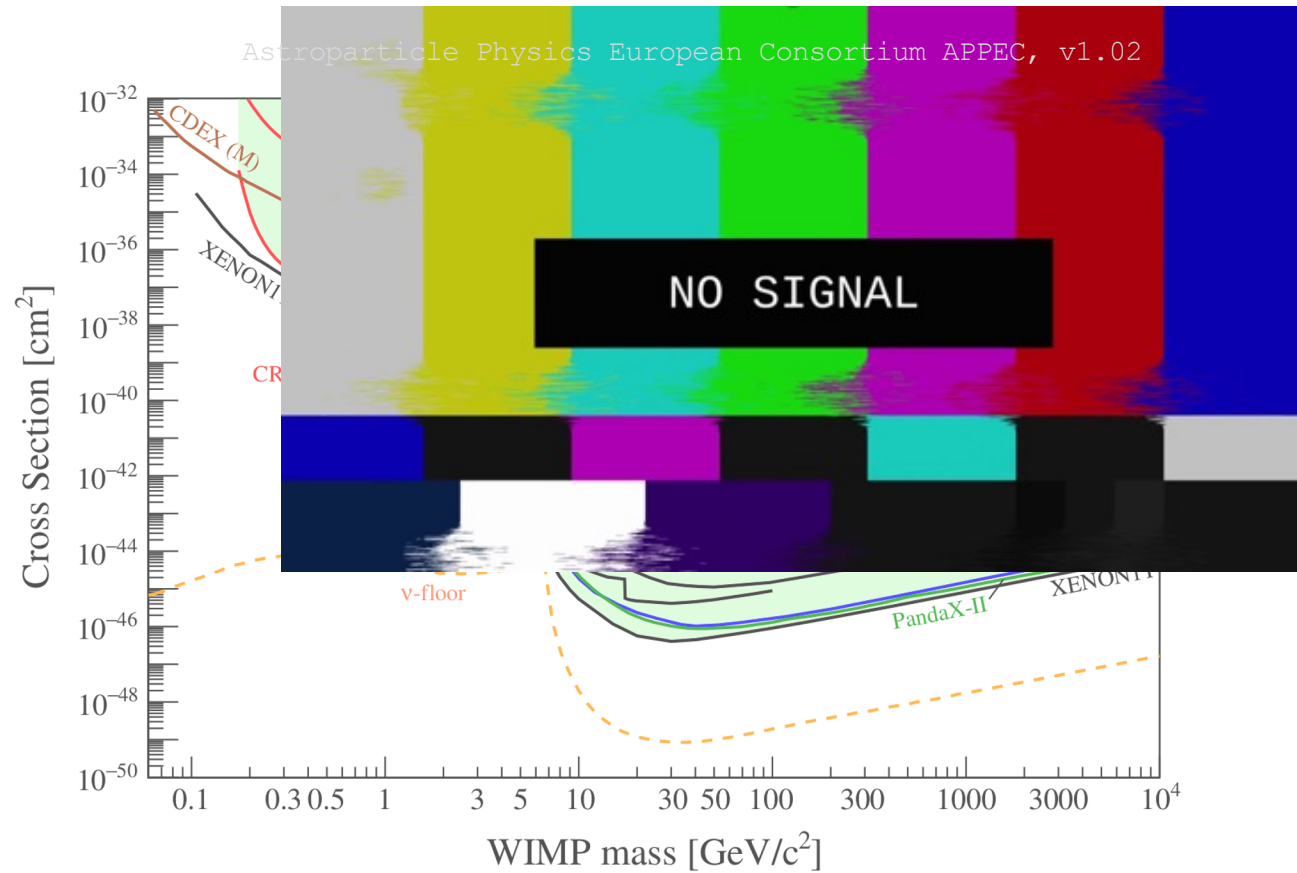
CURRENT STATUS of “WIMP” SEARCHES



$\sim 10 - 1000 \text{ GeV}/c^2$ with liquid nobles

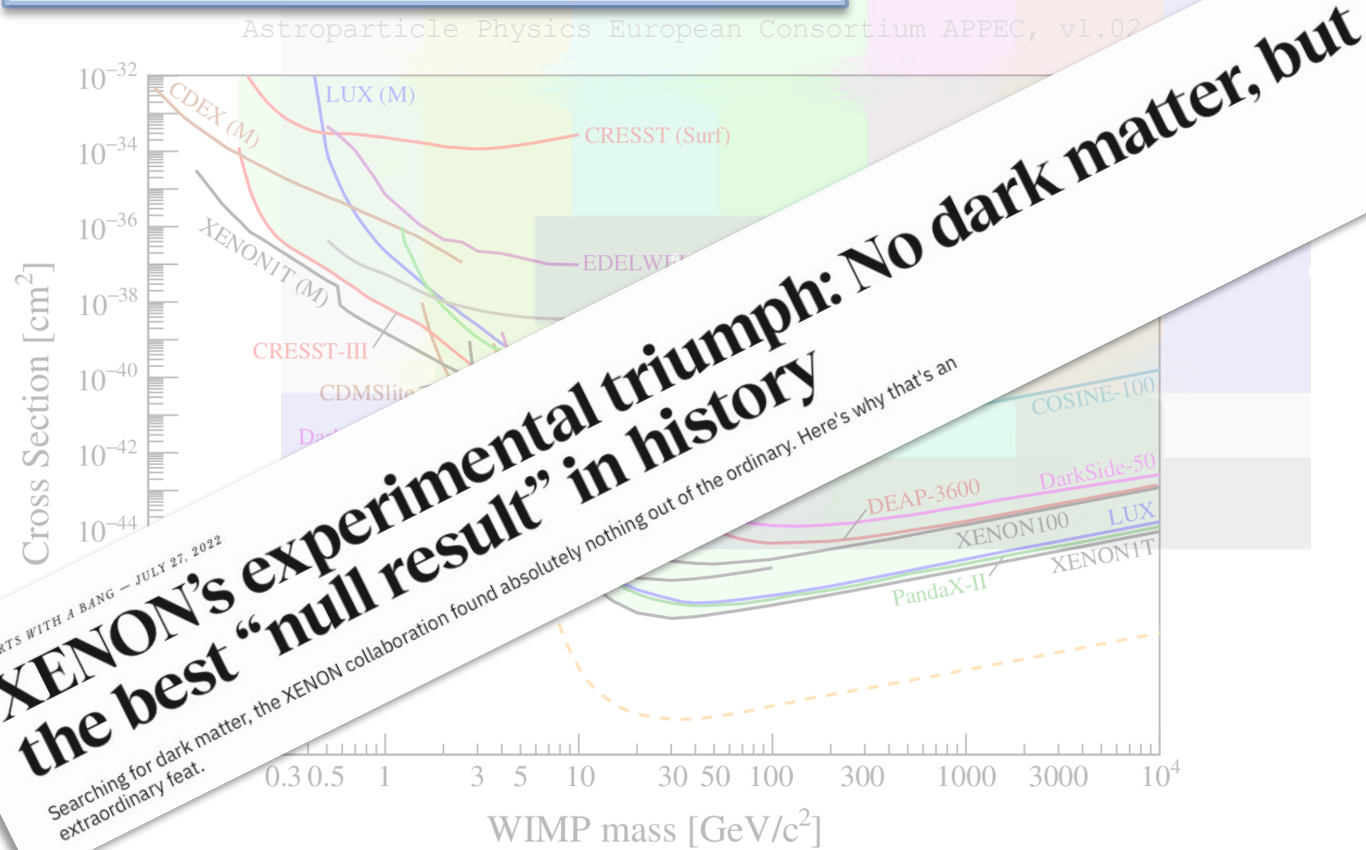
- world-wide effort with enormous technological progress in last decades
- LXe tonne-scale experiments with extremely rare interaction rate
current limits: $\mathcal{O}(0.01)$ cts/(keV tonne year)
- DarkSide-50 with LAr:
 - sensitivity down to $\sim 1 \text{ GeV}$ via S2
 - DarkSide-20k aims to catch up with LXe experiments

STATUS of DIRECT DARK MATTER SEARCHES



→ no discovery !

Highlight of the year 2022



Highlight

of the year 2022

**Highlight
of the year 2024**

Editors' Suggestion

Featured in Physics

PHYSICAL REVIEW LETTERS 133, 191001 (2024)

**First Indication of Solar ^8B Neutrinos through Coherent Elastic
Neutrino-Nucleus Scattering in PandaX-4T**

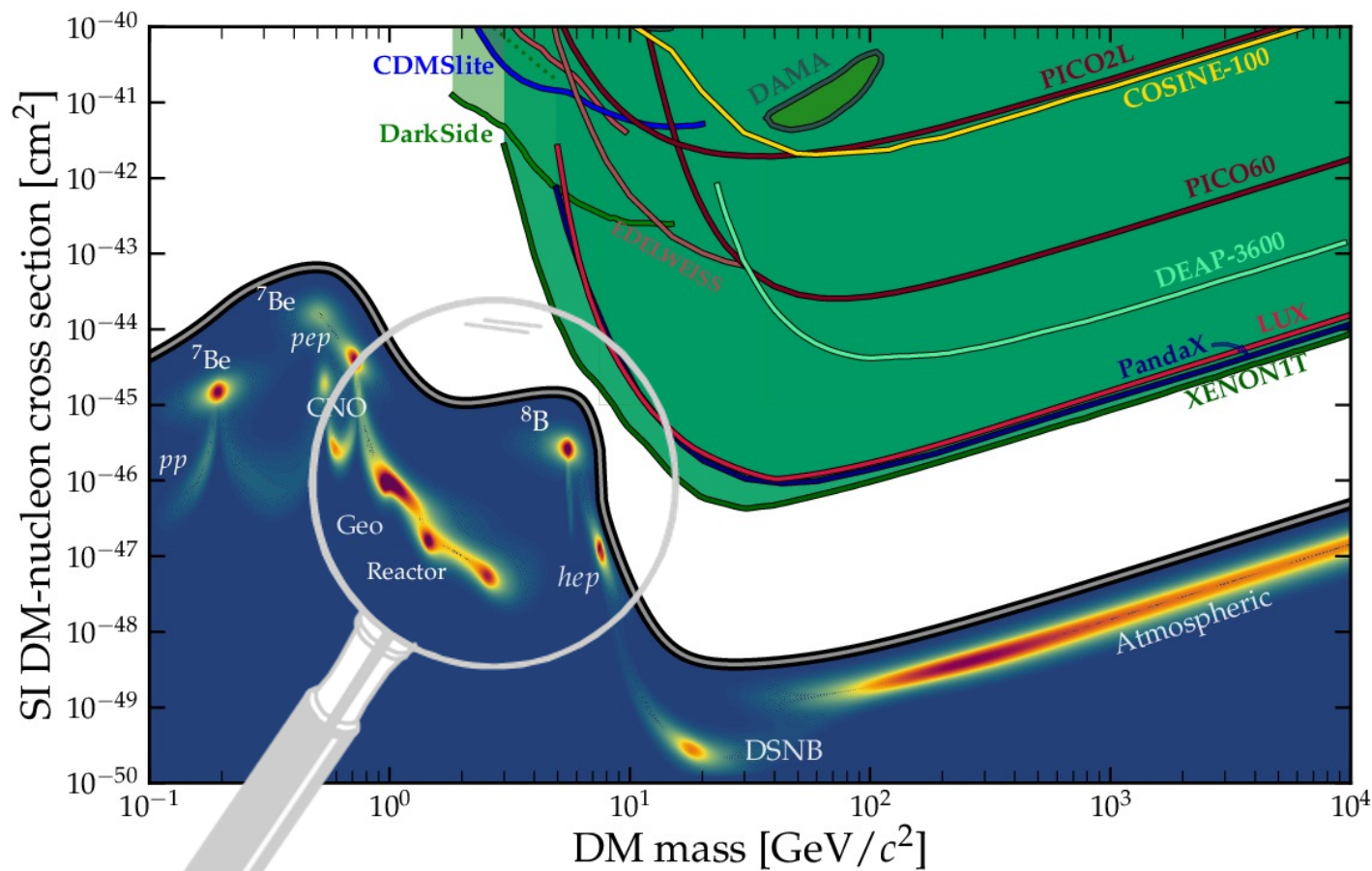
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**First Indication of Solar ^8B Neutrinos via Coherent Elastic Neutrino-Nucleus
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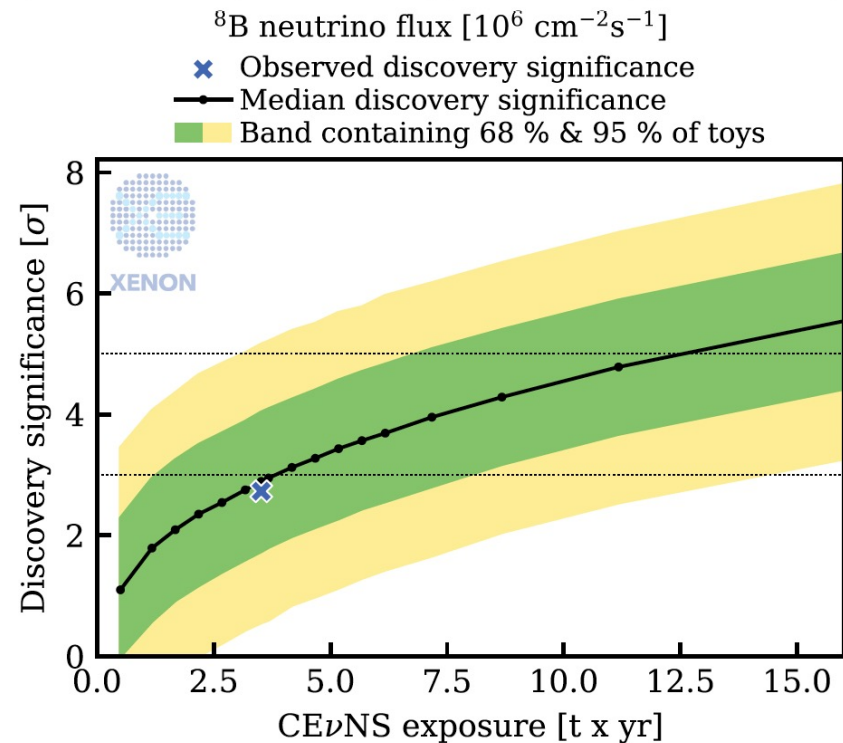
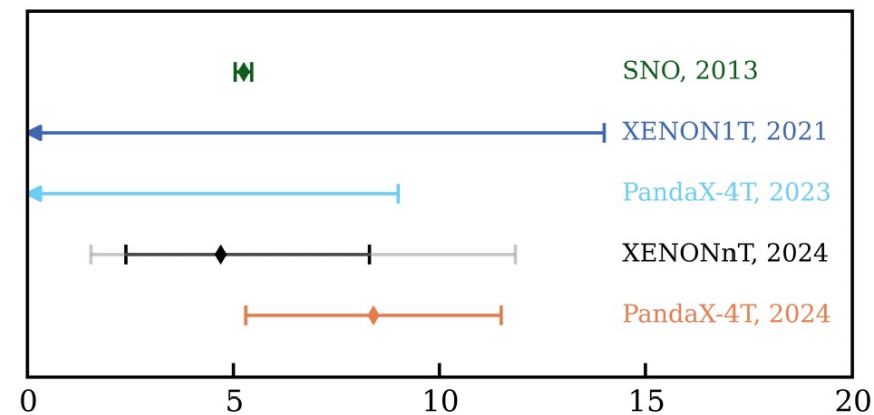
FIRST “STEP” IN THE NEUTRINO FOG



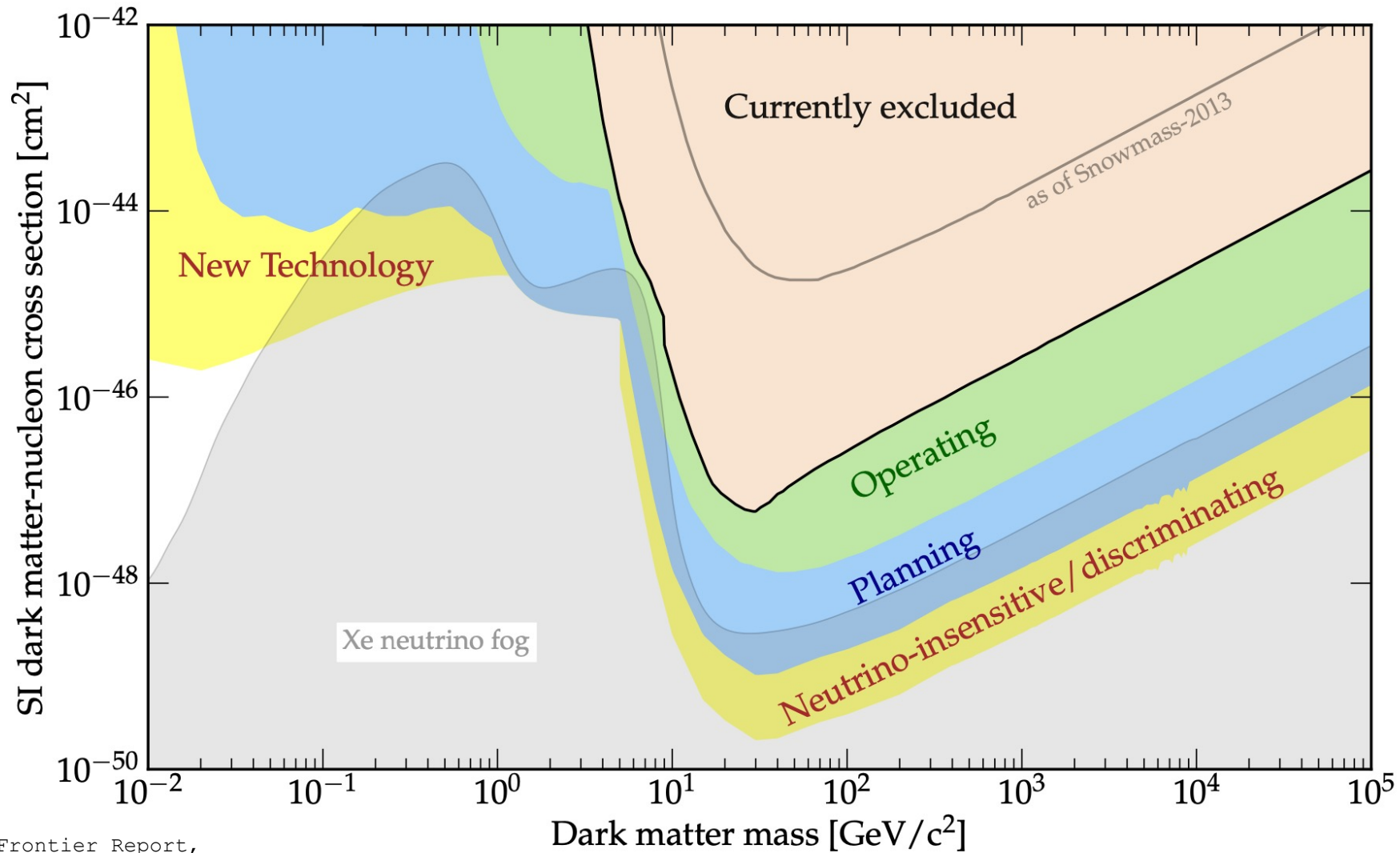
PRL 133, 191002 2024

05.04.25

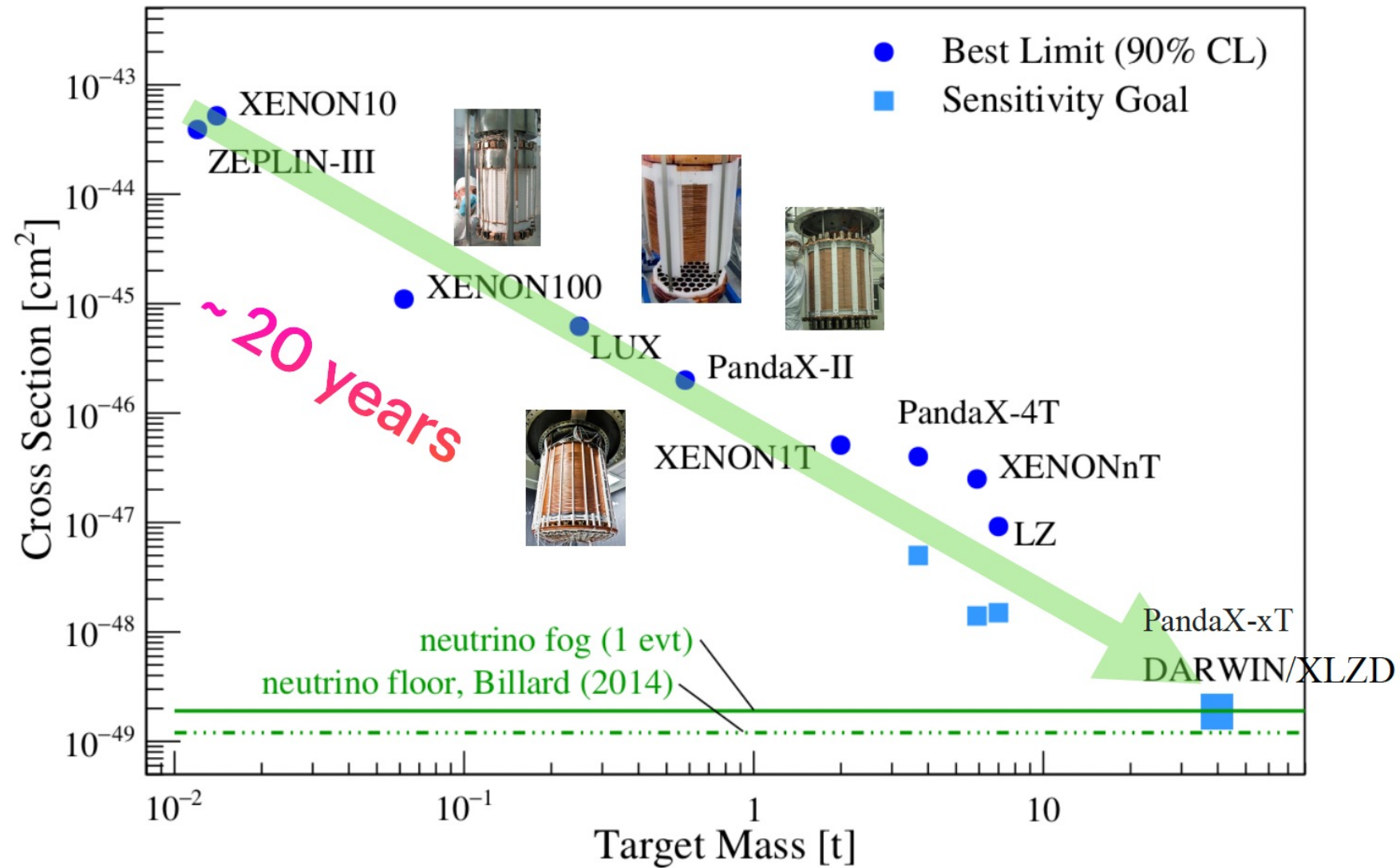
K. SCHÄFFNER | Max-Planck-Institut für Physik



TOWARDS THE NEUTRINO FOG



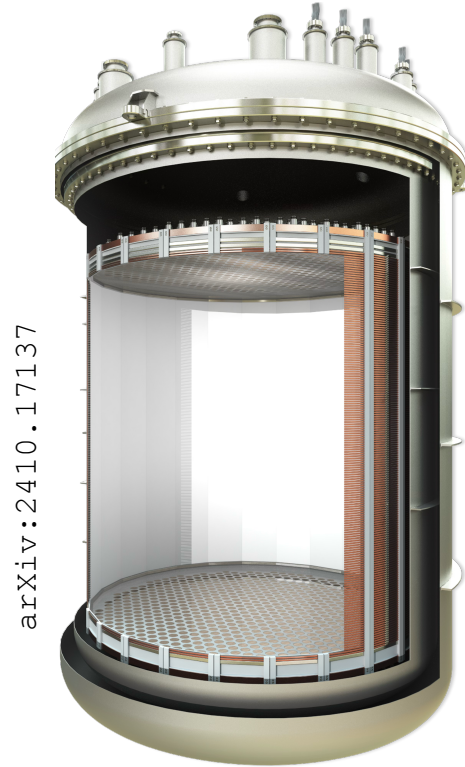
Snowmass, Cosmic Frontier Report,
arXiv: 2211.09978



[Snowmass 2021, arXiv:2203.08084, adapted by Baudis 2024]

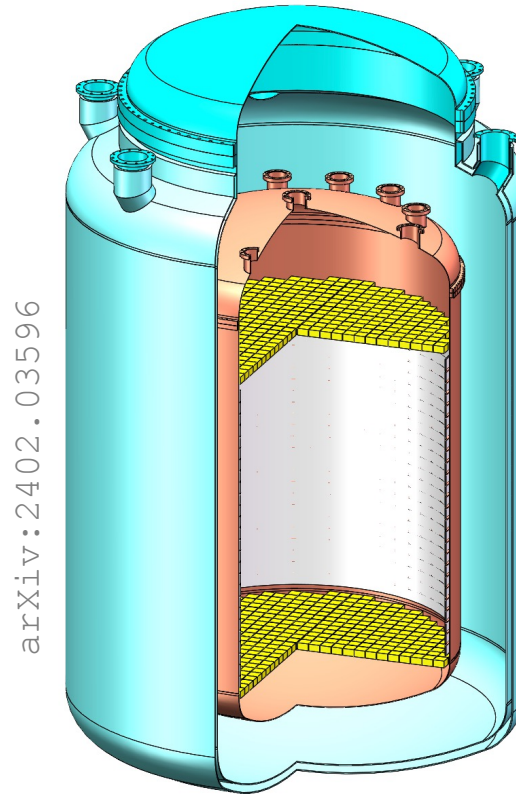
XLZD

Xenon-LZ-DARWIN



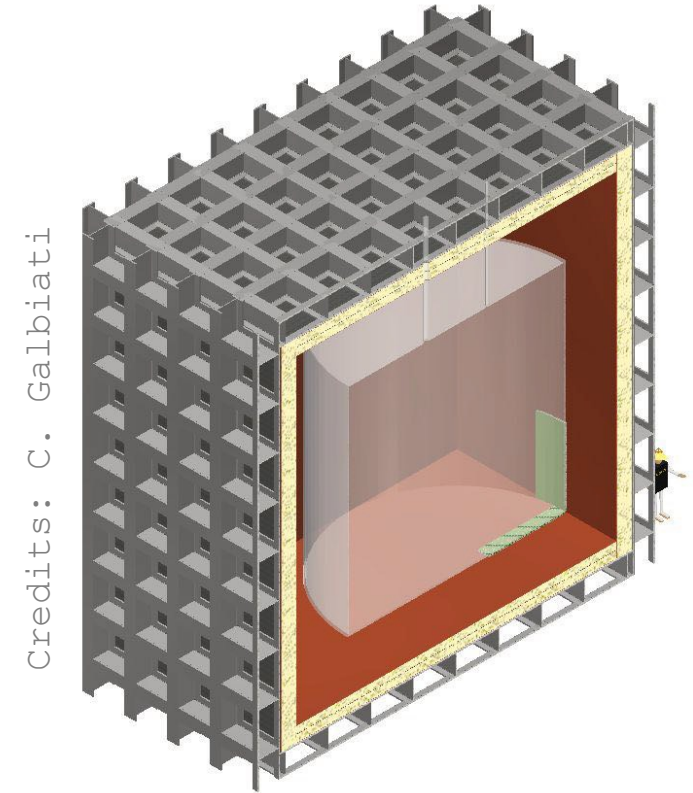
- 60-80 t active LXe target
- 2 arrays of 3-inch PMTs
- intermediate step:
→ under study

PANDAnT



- 40 t active LXe target
- 2 arrays of 2-inch PMTs
- intermediate step:
→ PandaX-20T by 2027

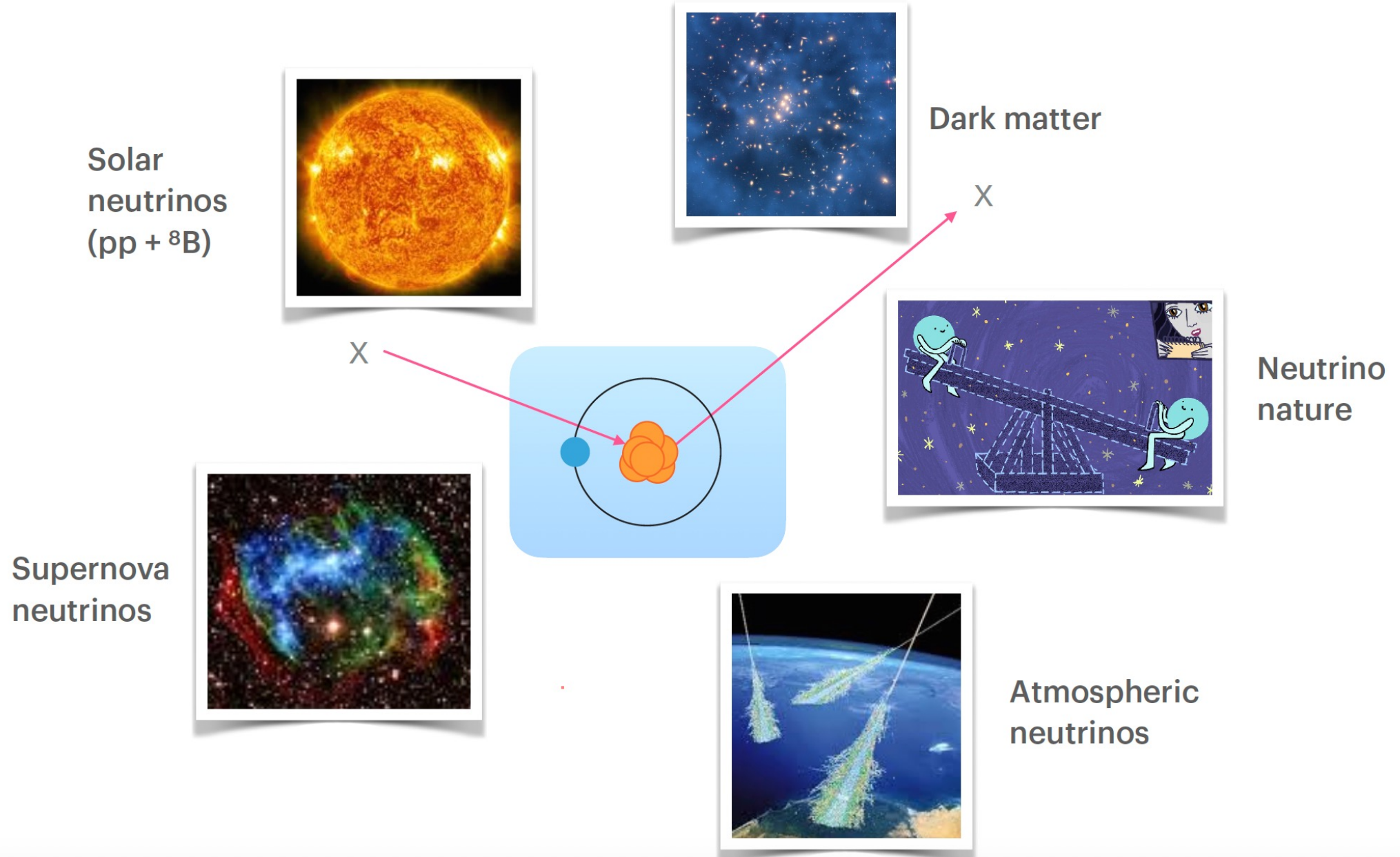
ARGO



- 300 t active LXe target
- SiPMs as pixelated photo-detectors

NEW TOOLS, NEW DISCOVERIES (?) – OBSERVATORIES FOR RARE EVENTS

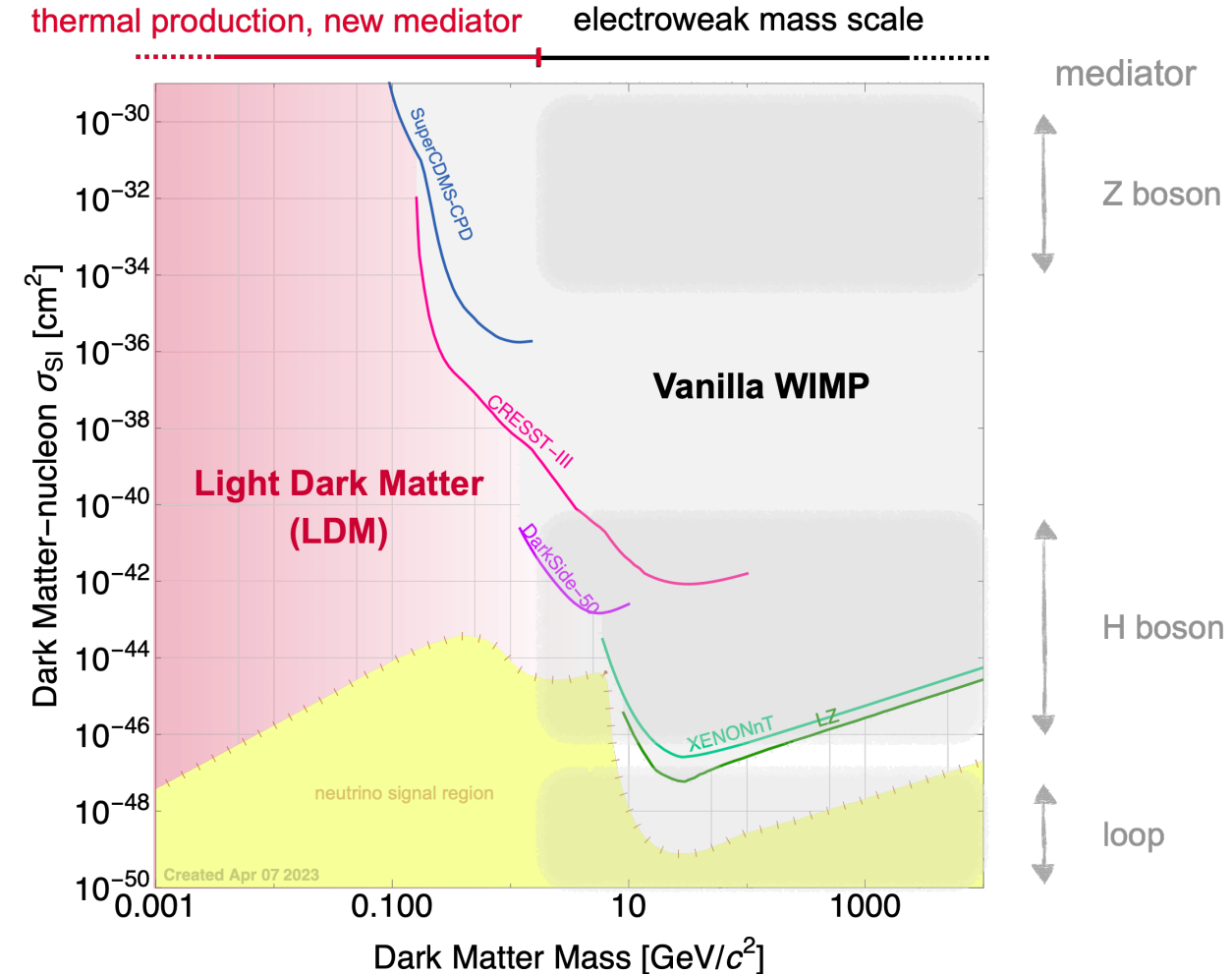
slide borrowed from L. Baudis



LOW MASS DARK MATTER

plot borrowed from B. von Krosigk

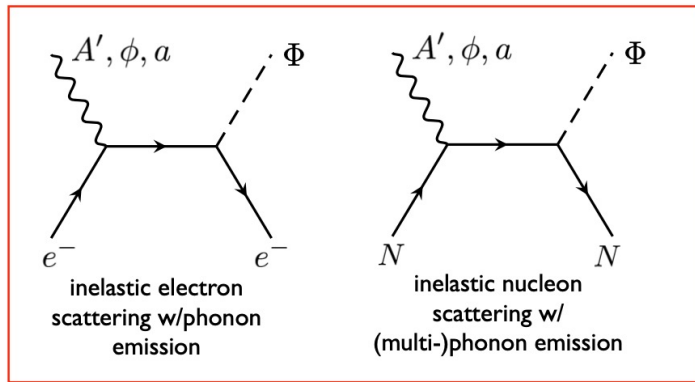
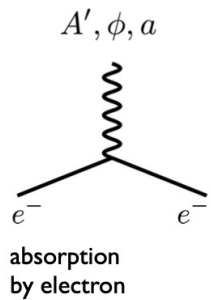
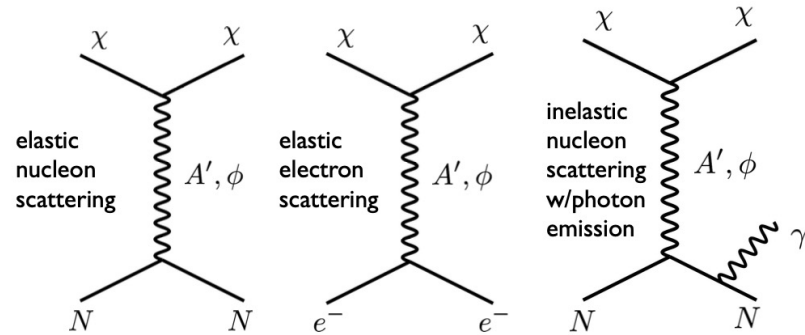
- Vanilla-WIMP searches mostly rely on elastic scattering of DM off nuclei
- for light DM exist well-motivated models:
 - „hidden sector“ DM candidates are completely neutral under Standard Model forces but interact through a new force lighter than the mass of a proton ($< 1 \text{ GeV}/c^2$)



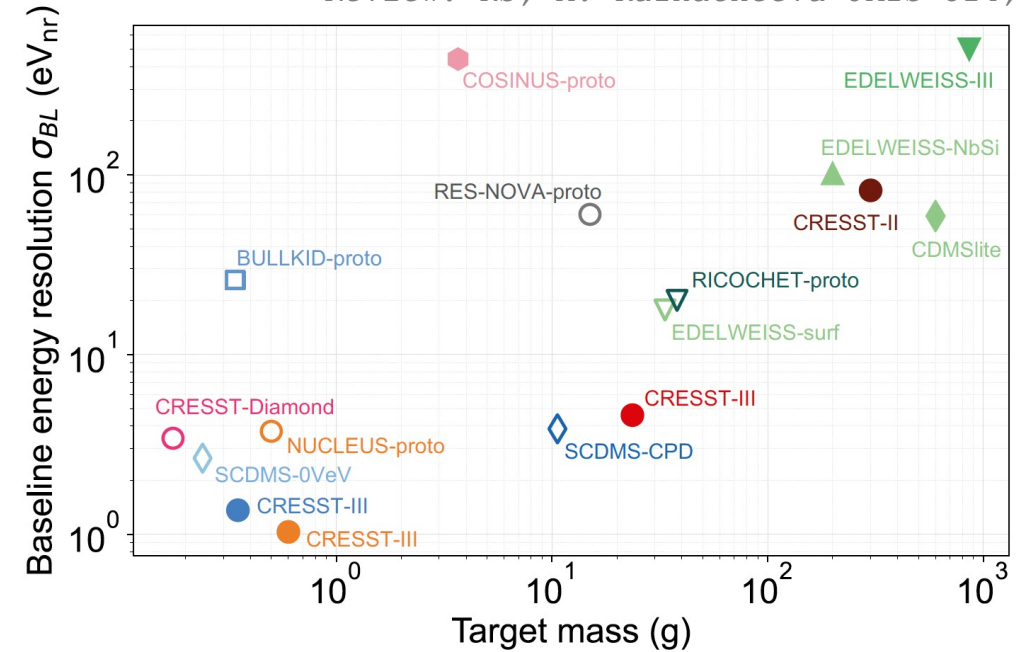
LOW MASS DM DIRECT DETECTION

Review: KS, M. Kaznacheeva JAIS-514, 2024

Many possible DM couplings...
Nearly *all* are testable via phonons.
Some are *only* testable via phonons.



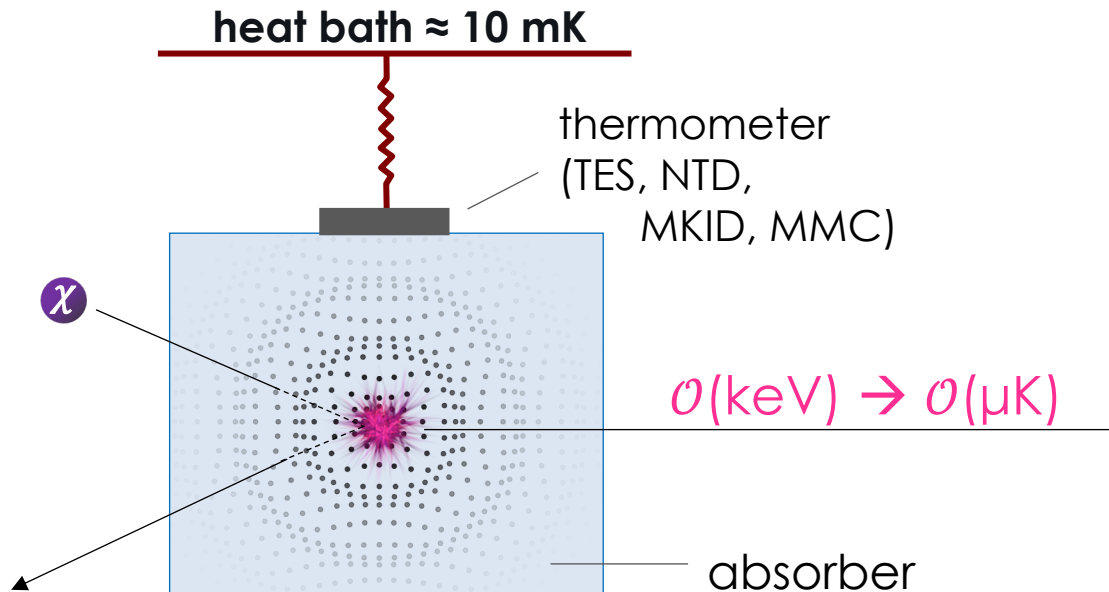
Direct phonon production only accessible to cryogenic solid-state detectors



Cryogenic detectors:

- energy threshold at eV-scale
→ R&D is pushing towards meV-scale
- small arrays with kg-day exposure can explore new parameter space

CRYOGENIC DETECTORS



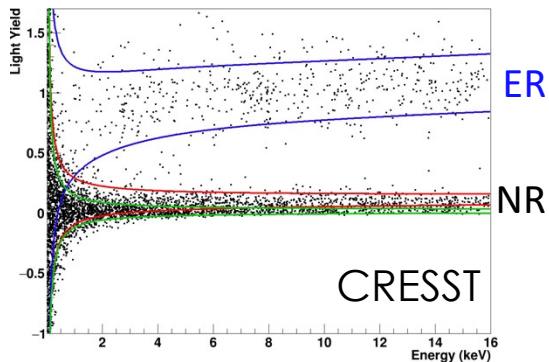
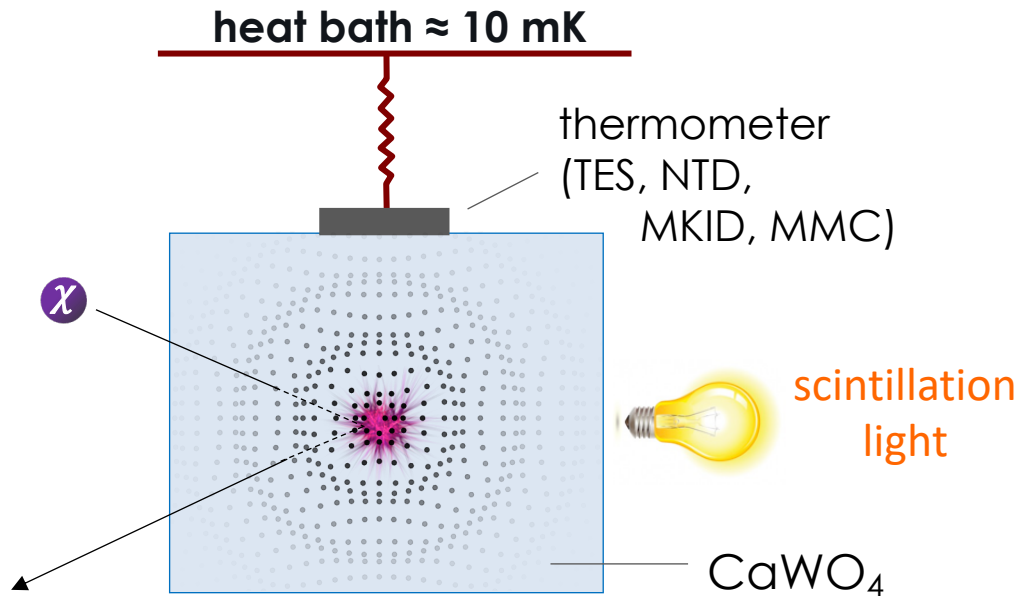
Primary signal:

dark matter creates **phonons / heat**

→ temperature increase measured by thermometer

→ precise measurement of (almost) full deposited energy

“CLASSIC” CRYOGENIC DETECTORS I



Primary signal:

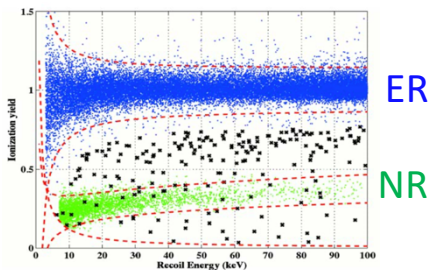
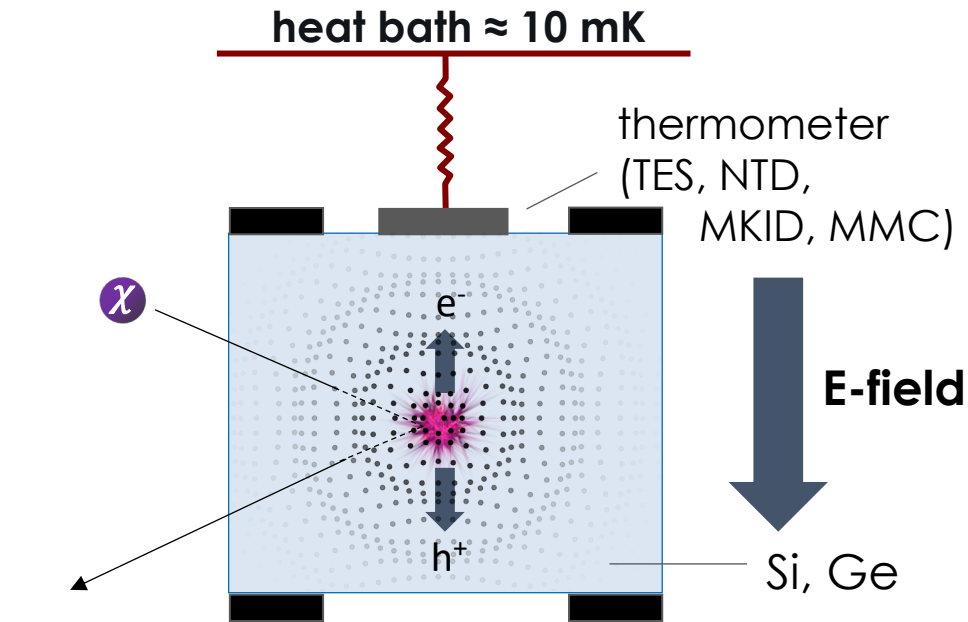
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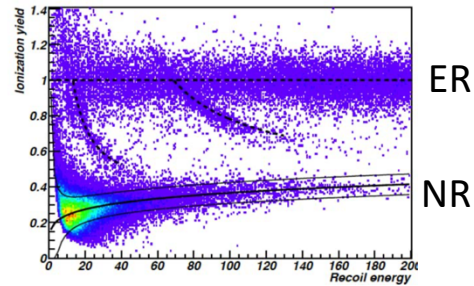
Secondary signal: scintillating target

- separate cryogenic detector for light signal
- particle identification via ratio of light to primary phonon

“CLASSIC” CRYOGENIC DETECTORS II



SuperCDMS



EDELWEISS

Primary signal:

dark matter creates **phonons / heat**

- temperature increase measured by thermometer
- precise measurement of (almost) full deposited energy

Secondary signal: scintillating target

- separate cryogenic detector for light signal
- particle identification via ratio of light to primary phonon

Secondary signal: semiconducting target

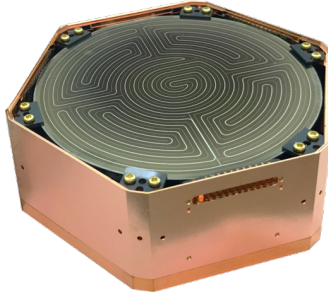
- phonon and charge sensors on target
- particle identification via ratio of ionization to primary phonon
- surface event rejection via ID electrodes

SuperCDMS @ SNOLAB

iZIP detector (6 V):

Ge of 1.4 kg with TESs

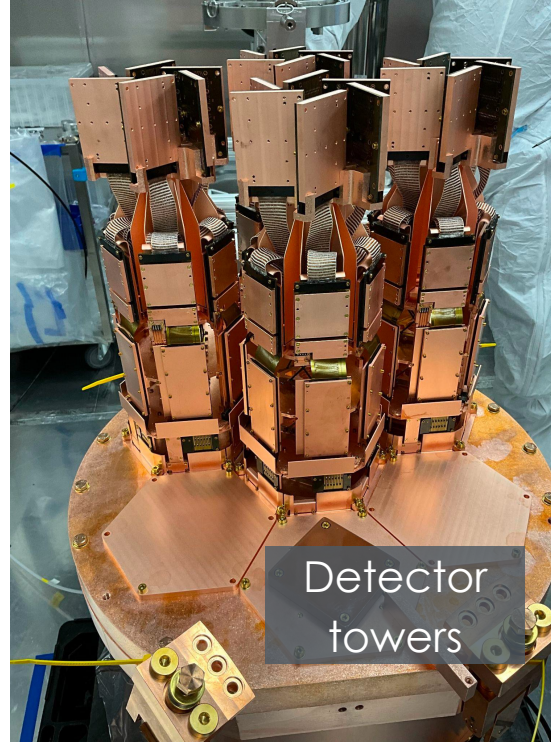
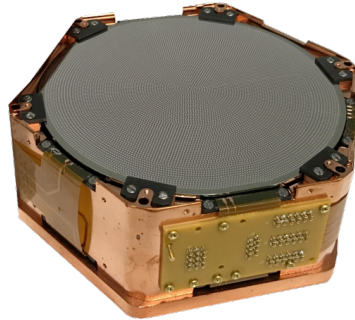
$E_{th} \sim 150 \text{ eV}_{nr}$



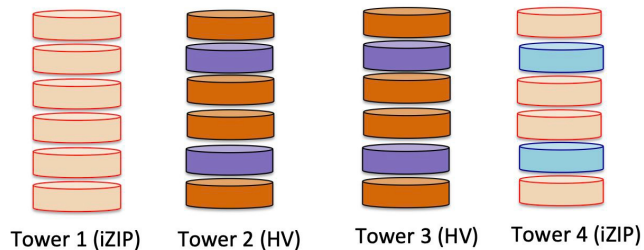
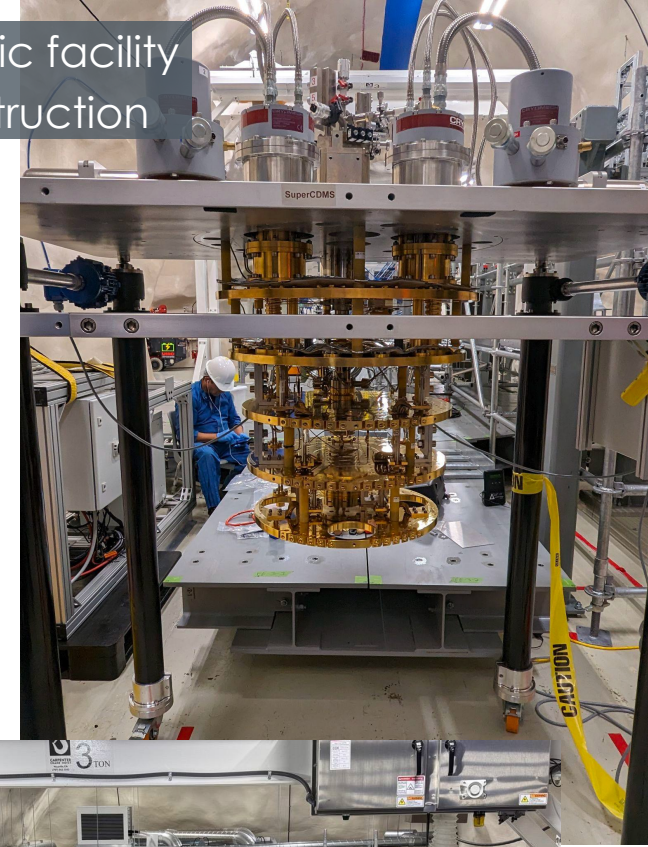
HV detector (100 V):

Si of 0.6 kg with TESs

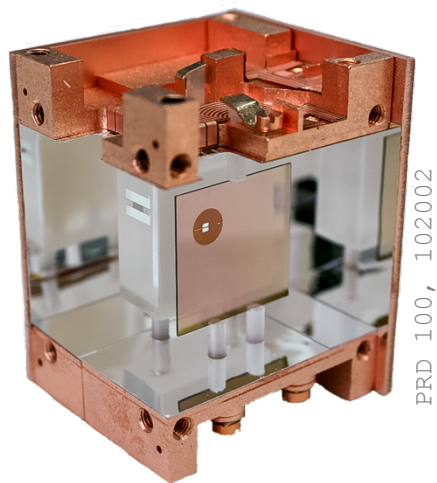
$E_{th} \sim 60 \text{ eV}_{nr}$



Cryogenic facility
in construction

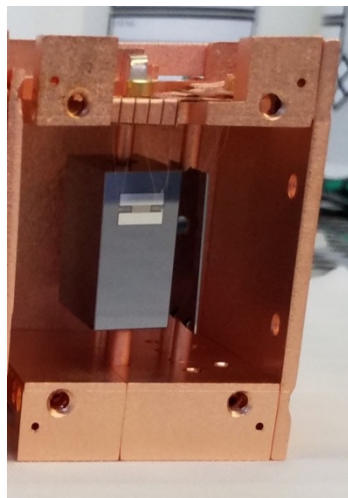


CRESST-III @ LNGS



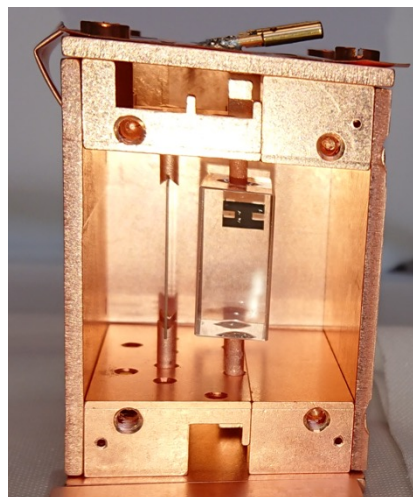
PRD 100, 102002

Detector A - CaWO_4 :
23.6 g
exposure: 5.698 kgd
 $E_{\text{th}} = 30.1 \text{ eV}_{\text{NR}}$



PRD 107, 122003

Si wafer detector:
0.35 g
exposure: 55.06 gd
 $E_{\text{th}} = 10.0 \text{ eV}_{\text{NR}}$



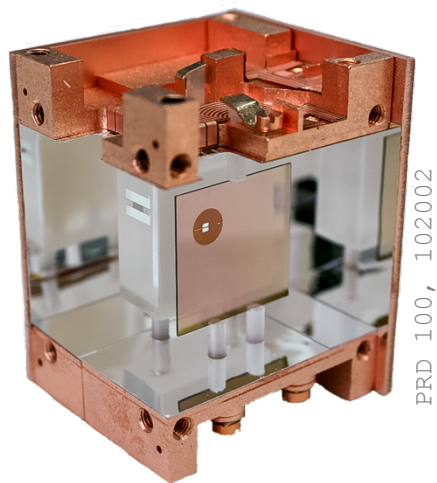
arXiv:2405.06527

Al_2O_3 wafer detector:
0.6 g
exposure: 0.14 kgd
 $E_{\text{th}} = 6.7 \text{ eV}_{\text{NR}}$

different target materials in two modi:

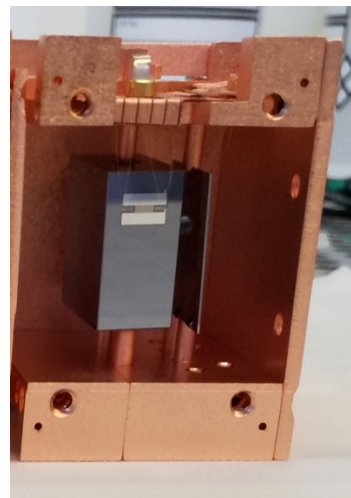
- phonons + scintillation (NR/ER discrimination)
- phonons only

CRESST-III @ LNGS



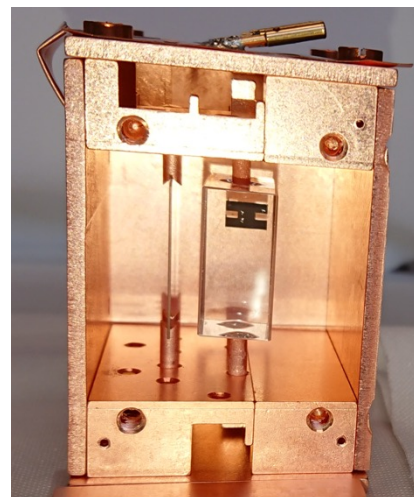
PRD 100, 102002

Detector A - CaWO_4 :
23.6 g
exposure: 5.698 kgd
 $E_{\text{th}} = 30.1 \text{ eV}_{\text{NR}}$



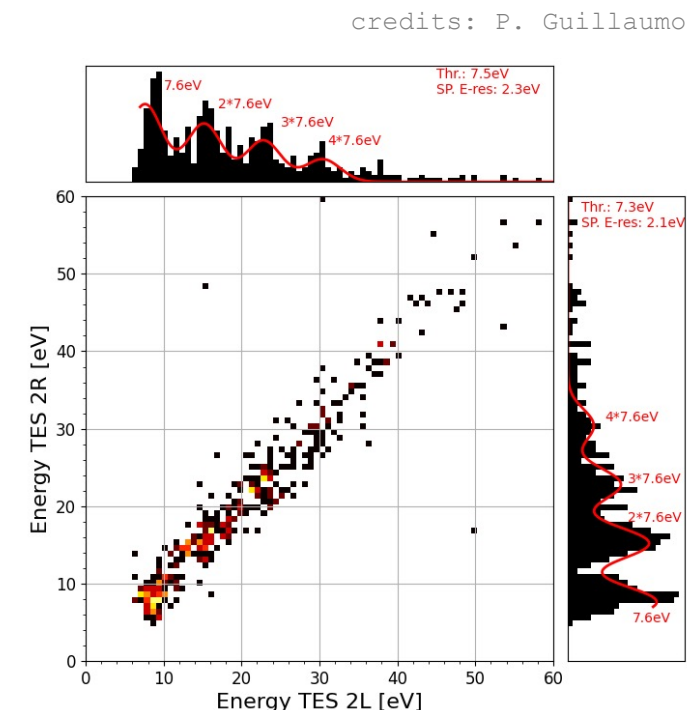
PRD 107, 122003

Si wafer detector:
0.35 g
exposure: 55.06 gd
 $E_{\text{th}} = 10.0 \text{ eV}_{\text{NR}}$



arXiv:2405.06527

Al_2O_3 wafer detector:
0.6 g
exposure: 0.14 kgd
 $E_{\text{th}} = 6.7 \text{ eV}_{\text{NR}}$



„stack detector“ with double TES:

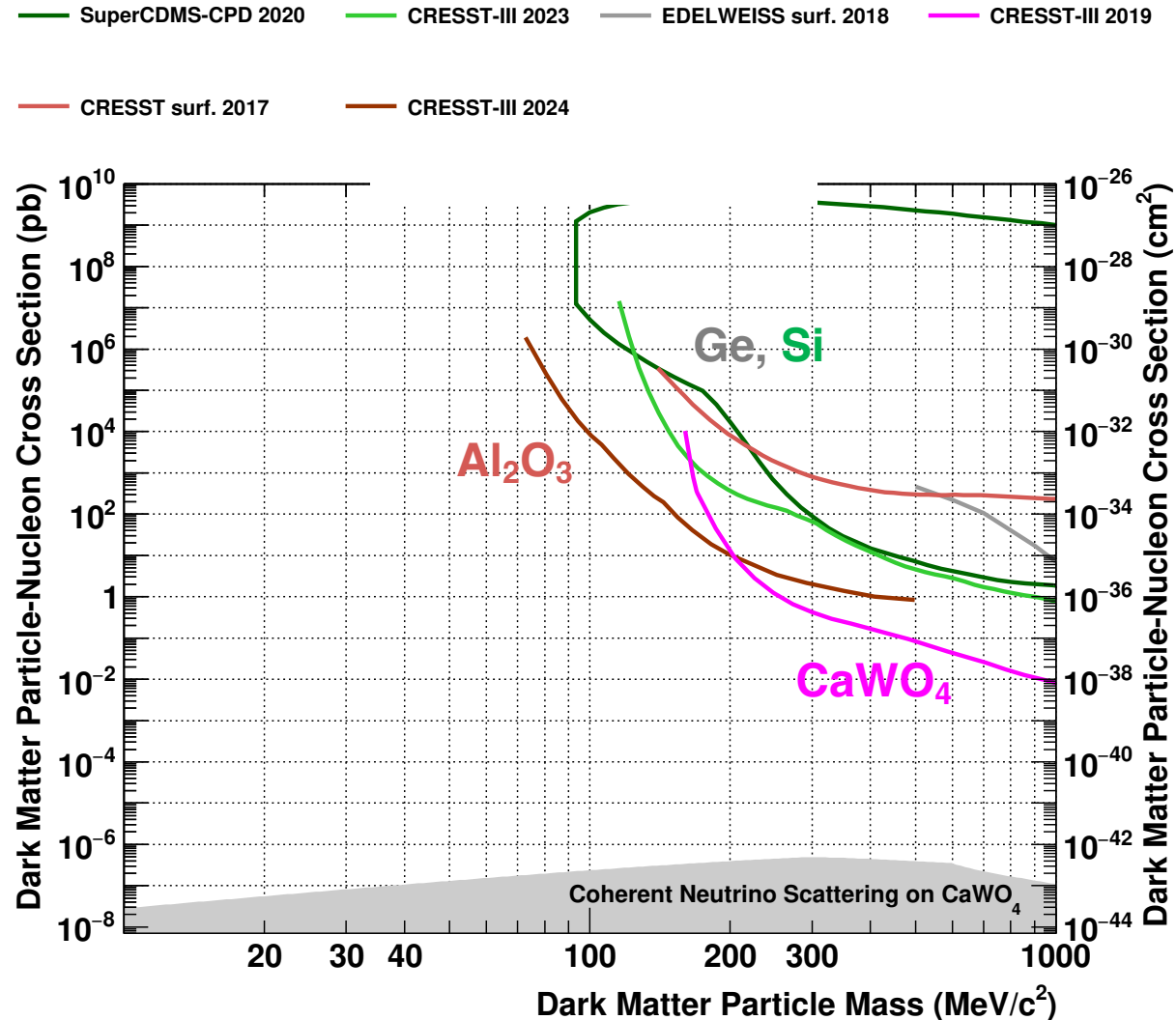
- baseline resolution: $\sim 1 \text{ eV}$
- analysis threshold: $\sim 7.5 \text{ eV}$
- single photon detection

different target materials in two modi:

- phonons + scintillation (NR/ER discrimination)
- phonons only

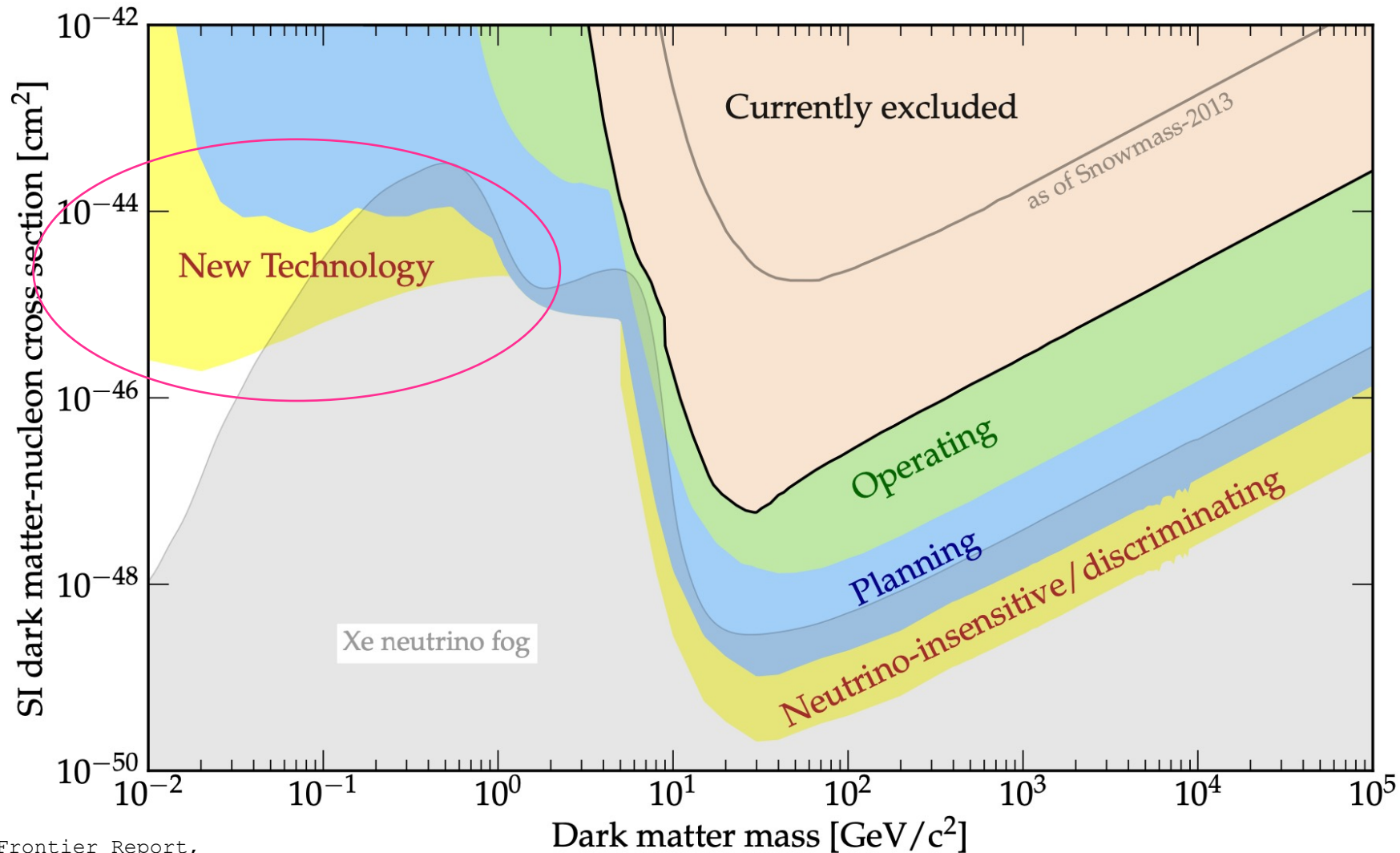
DM-NUCLEUS SCATTERING LANDSCAPE

MIGDAL



cryogenic solid-state detectors lead
the field in the sub-GeV particle-like
DM mass region

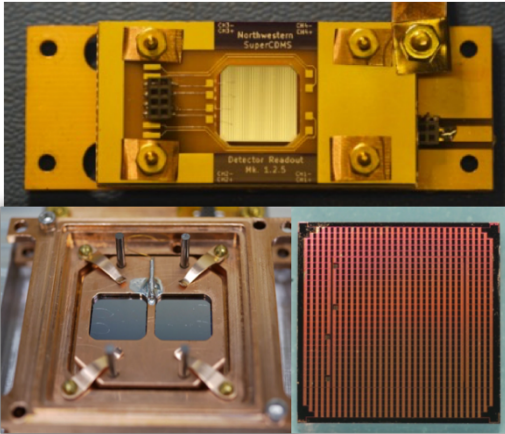
TOWARDS THE NEUTRINO FOG $\ll 1 \text{ GeV}/c^2$



Snowmass, Cosmic Frontier Report,
arXiv: 2211.09978

SuperCDMS @ SURFACE

HVeV detector Run 1-4: Si wafer of 1cm² x 4 mm

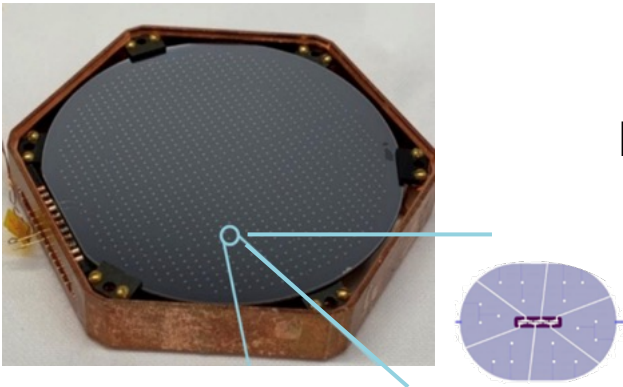


Single e-h resolution
Si wafer with 0.93 g

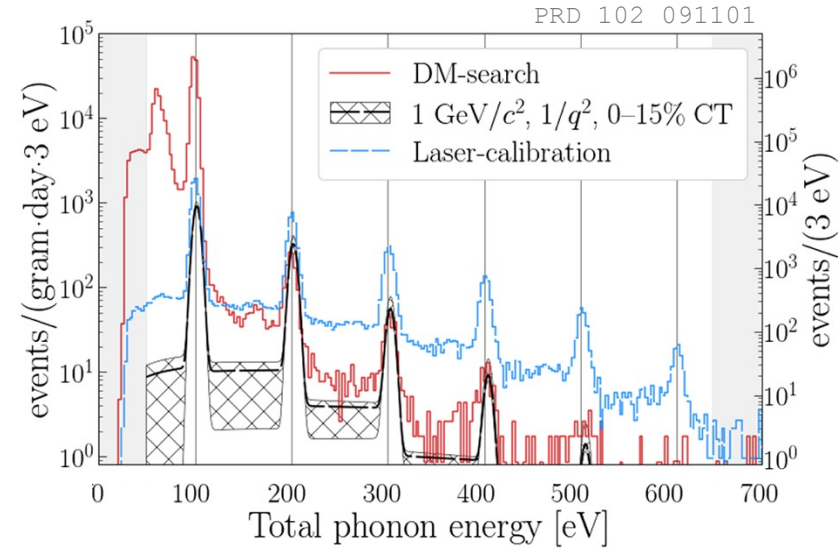
$$\sigma = 2.7 \text{ eV}_{ee}$$

$$E_{th} = 9.2 \text{ eV}$$

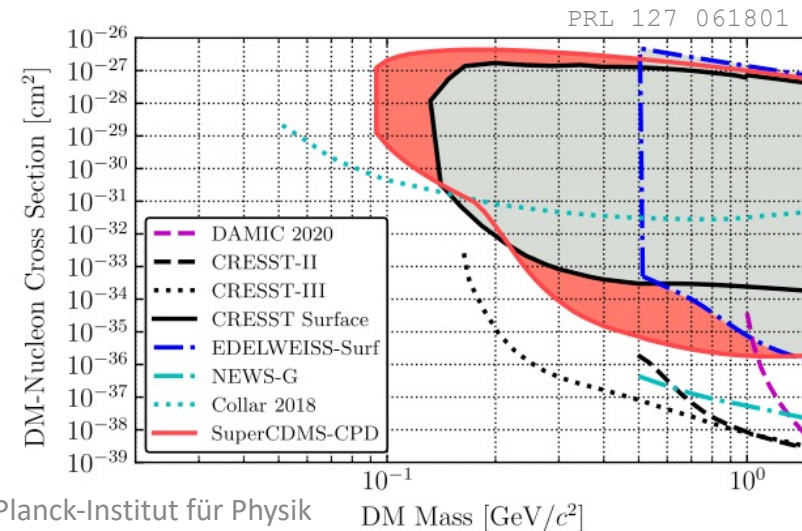
0V detector (aka CPD) : Si wafer of 10.6 g

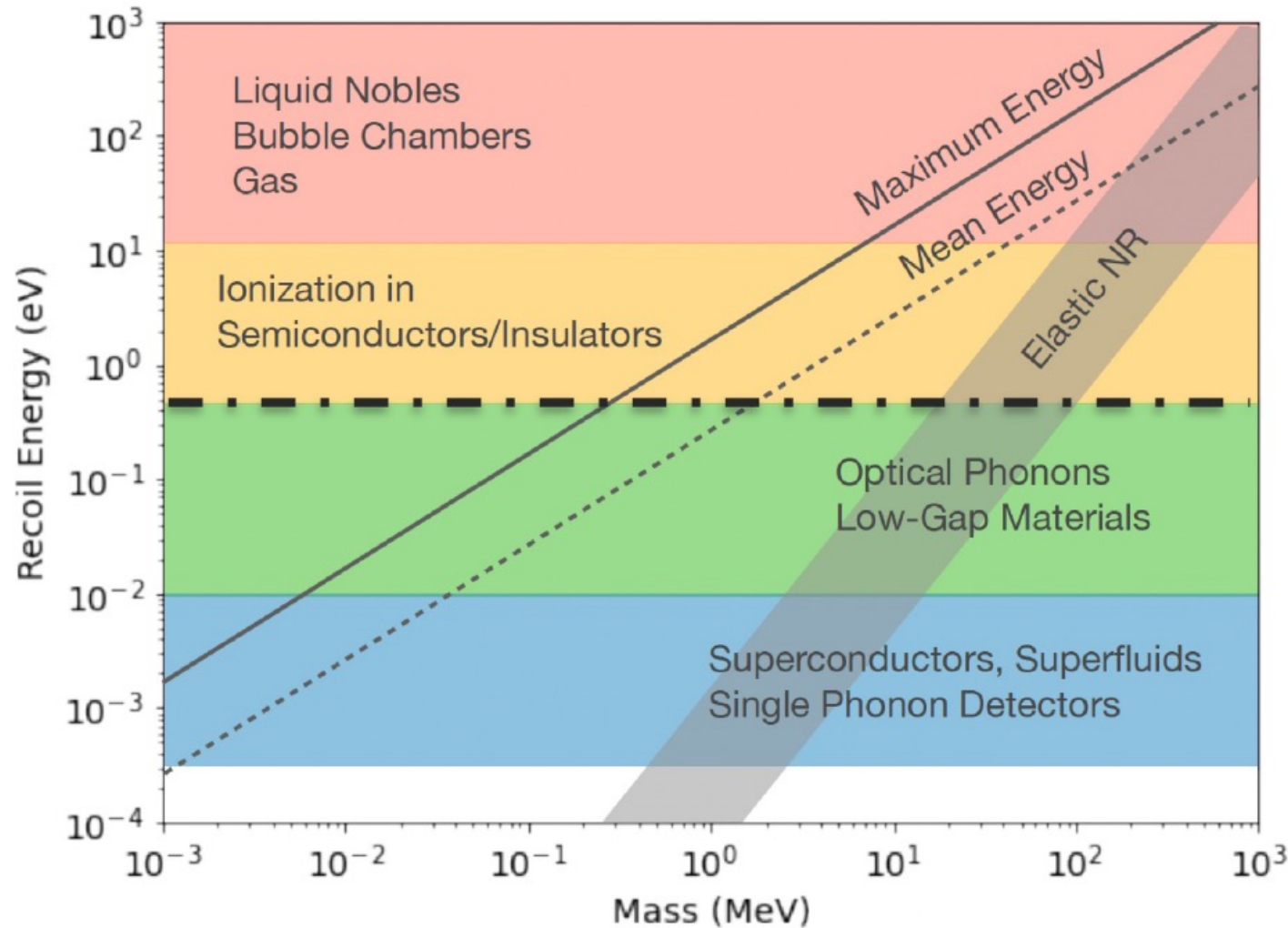


$$E_{th} = 16.3 \text{ eV}_{nr}$$



@NEXUS
at Fermilab
(300 m.w.e.)





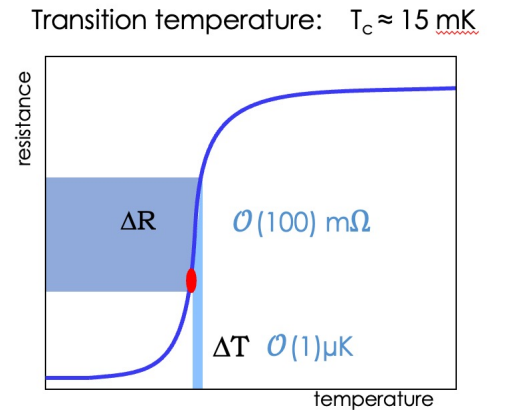
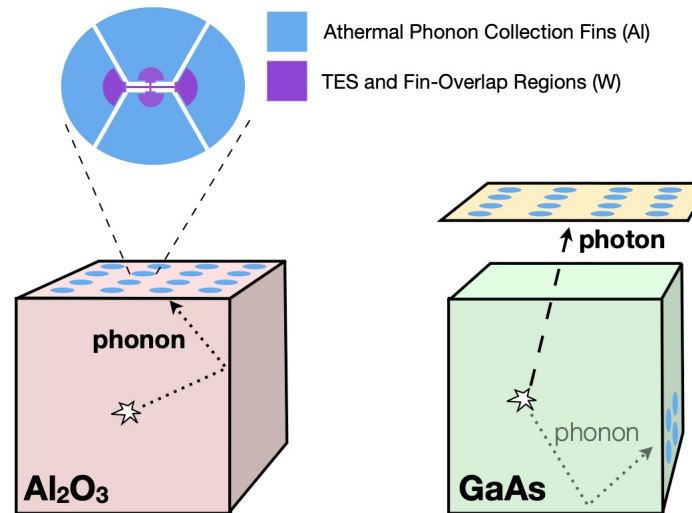
$\Delta E \sim 10 - 100 \text{ meV}$
 e.g. GaAs, sapphire, Dirac materials, doped s/c, ...

$\Delta E \sim 1 \text{ meV}$
 e.g. superfluids, superconductors

Essig et al, Snowmass CF1 WP2 (2022) [arXiv:2203.08297]

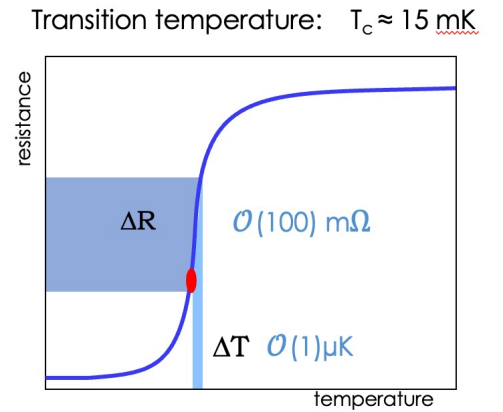
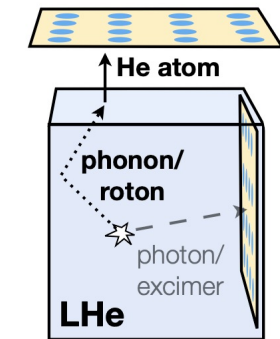
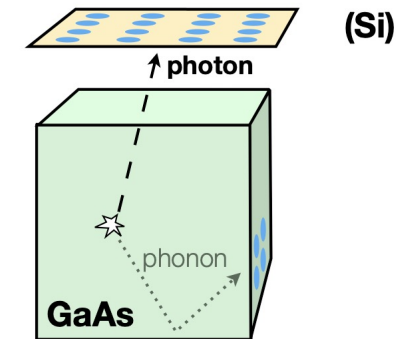
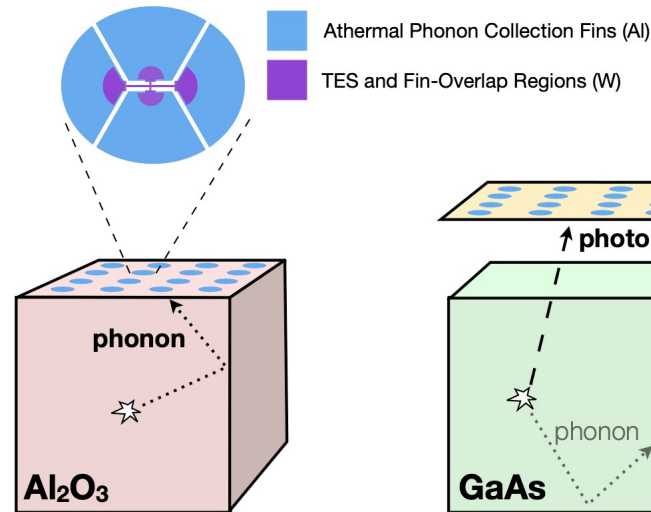
NEW and OPTIMIZED TECHNOLOGIES

- TES-based detectors
 - CRESST-III
 - TESSERACT $\text{Al}_2\text{O}_3/\text{GaAs}$



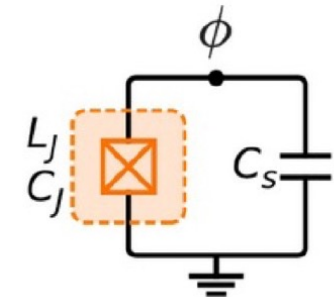
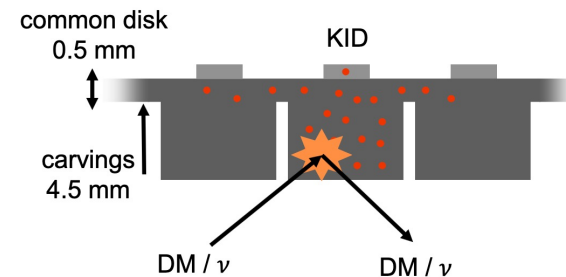
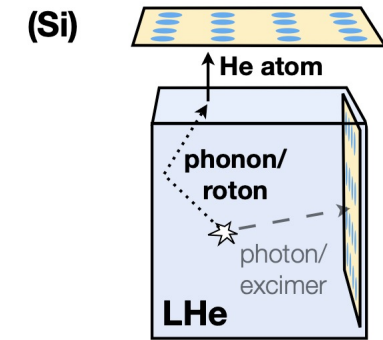
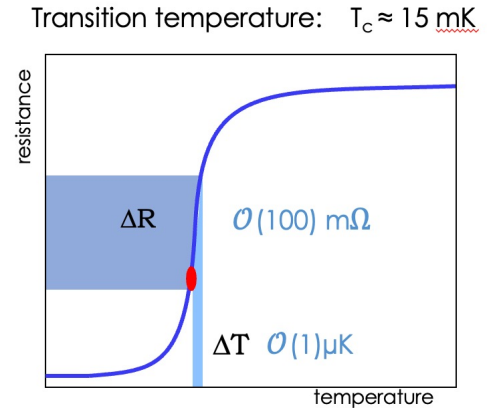
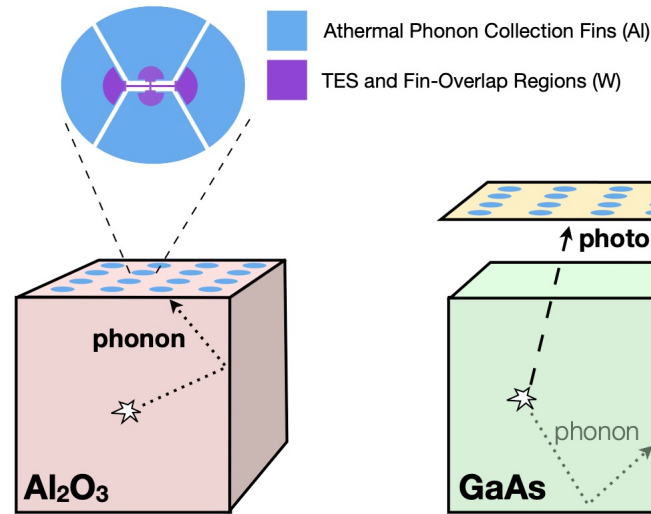
NEW and OPTIMIZED TECHNOLOGIES

- TES-based detectors
 - CRESST-III
 - TESSERACT $\text{Al}_2\text{O}_3/\text{GaAs}$
- Superfluid helium detectors
 - TESSERACT (HeRALD)
 - DELight



NEW and OPTIMIZED TECHNOLOGIES

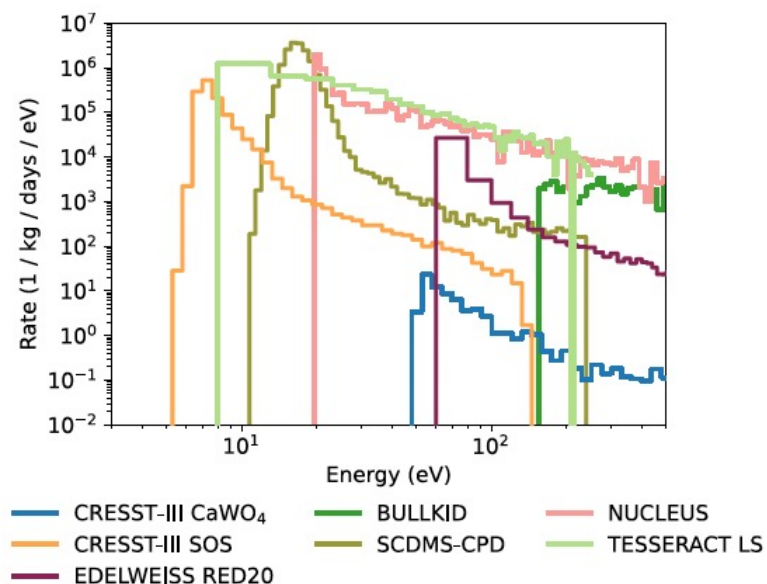
- TES-based detectors
 - CRESST-III
 - TESSERACT $\text{Al}_2\text{O}_3/\text{GaAs}$
- Superfluid helium detectors
 - TESSERACT (HeRALD)
 - DELight
- MKID-based detectors
 - BULLKID
- Superconducting Qubit sensors
 - Cosmic Quantum (CosmiQ)
 - SQUATs



PHONON-ONLY LOW ENERGY EXCESS (LEE)

arXiv:2503.08859

SciPost Phys. Proc. 9, 001 (2022)



steeply rising background towards lower energies

→ Low Energy Excesses

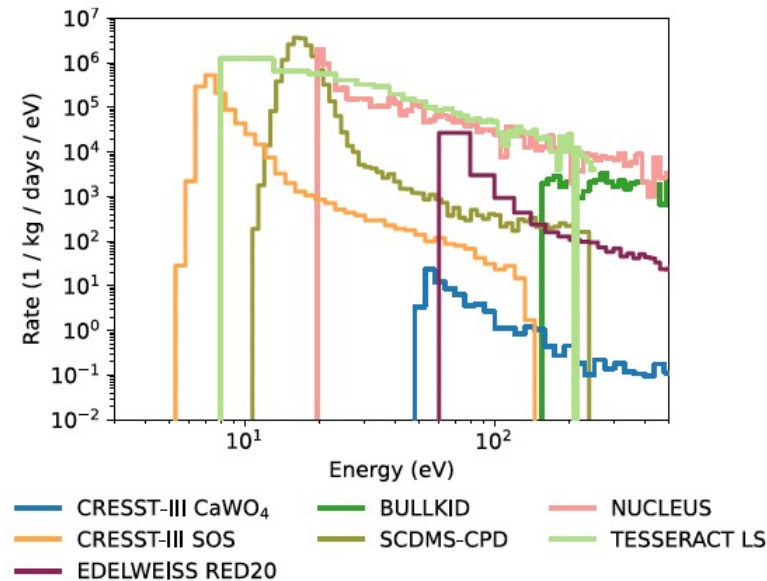
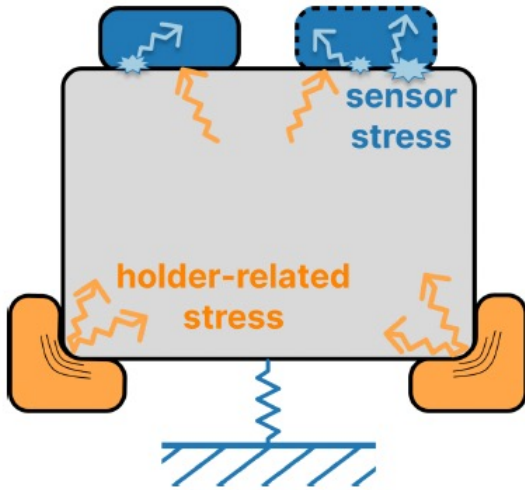
→ LEE has significant impact on DM sensitivity

→ active community to solve LEE

PHONON-ONLY LOW ENERGY EXCESS (LEE)

arXiv:2503.08859

SciPost Phys. Proc. 9, 001 (2022)



steeply rising background towards lower energies

→ Low Energy Excesses

→ LEE has significant impact on DM sensitivity

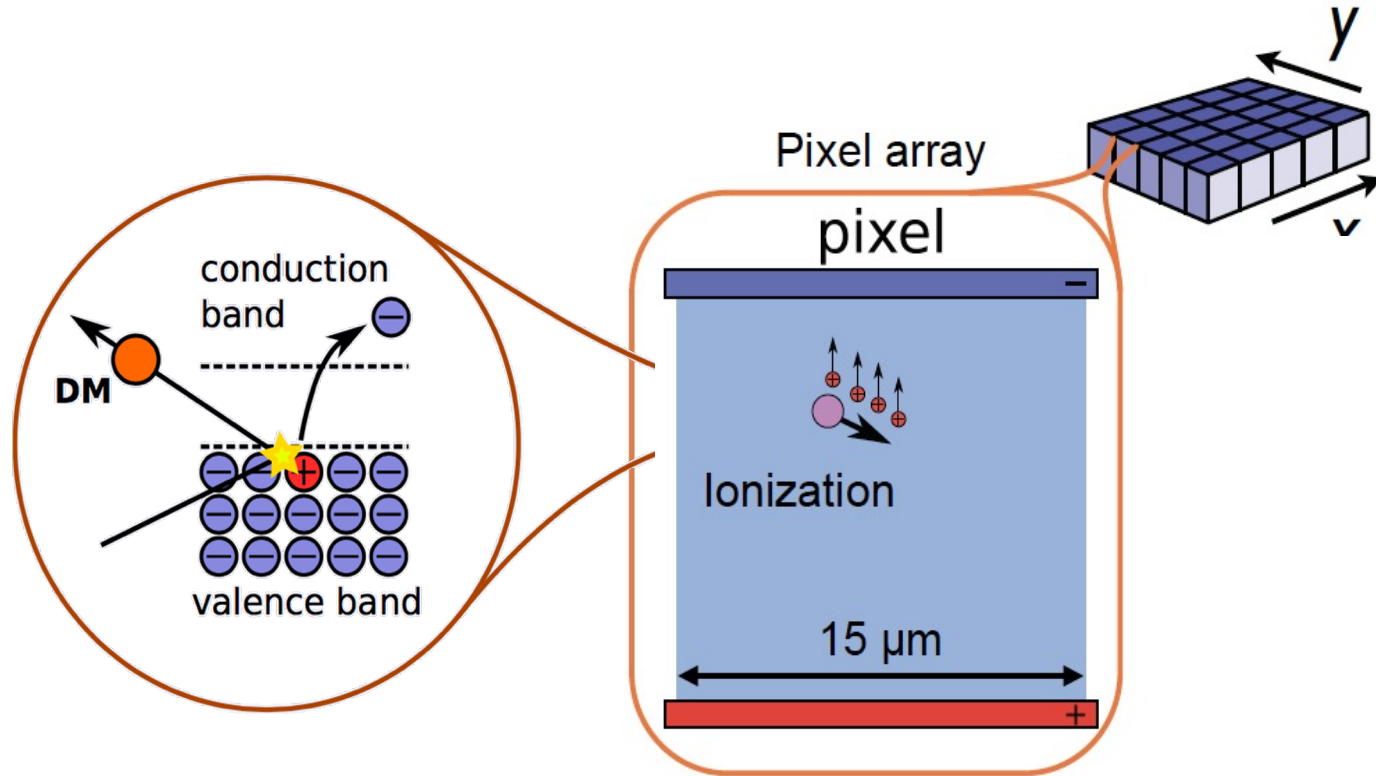
→ active community to solve LEE

Origin(s) still unclear / mitigation strategies under investigation:

- mounting stress / holder related stress
- sensor film relaxation (can be vetoed using more sensors on same target)
- intrinsic to substrate / targets (stress/defects from growth process)
- inconsistencies among different experiments → physics may be different...

Silicon-Charged Coupled Devices (CCDs)

Tiffenberg et.al. 2017



dark matter creates **one or a few electrons** in a pixel

- repeatedly measure charge
- sub-electron readout noise

excellent spatial resolution:

SENSEI: ~ 20 mm x 100 mm, 5.4 Mpixel

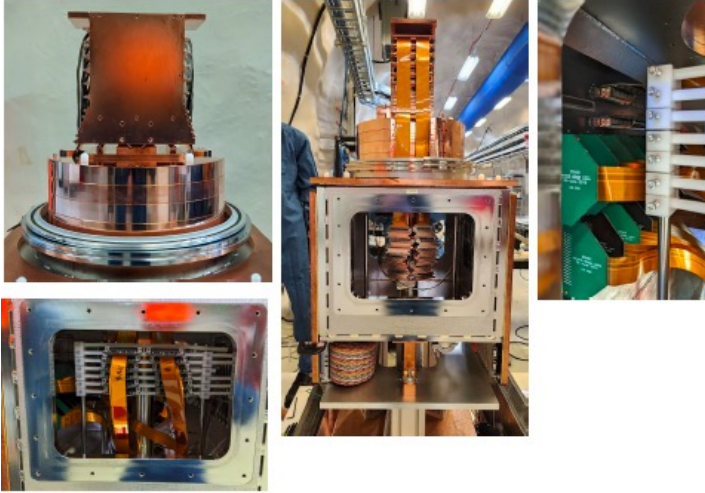


- particle identification
- surface background rejection

$$E_{\text{kin}} = \frac{1}{2} m_{\text{DM}} v_{\text{DM}}^2 \sim 1 \text{ eV} \left(\frac{m_{\text{DM}}}{1 \text{ MeV}} \right)$$

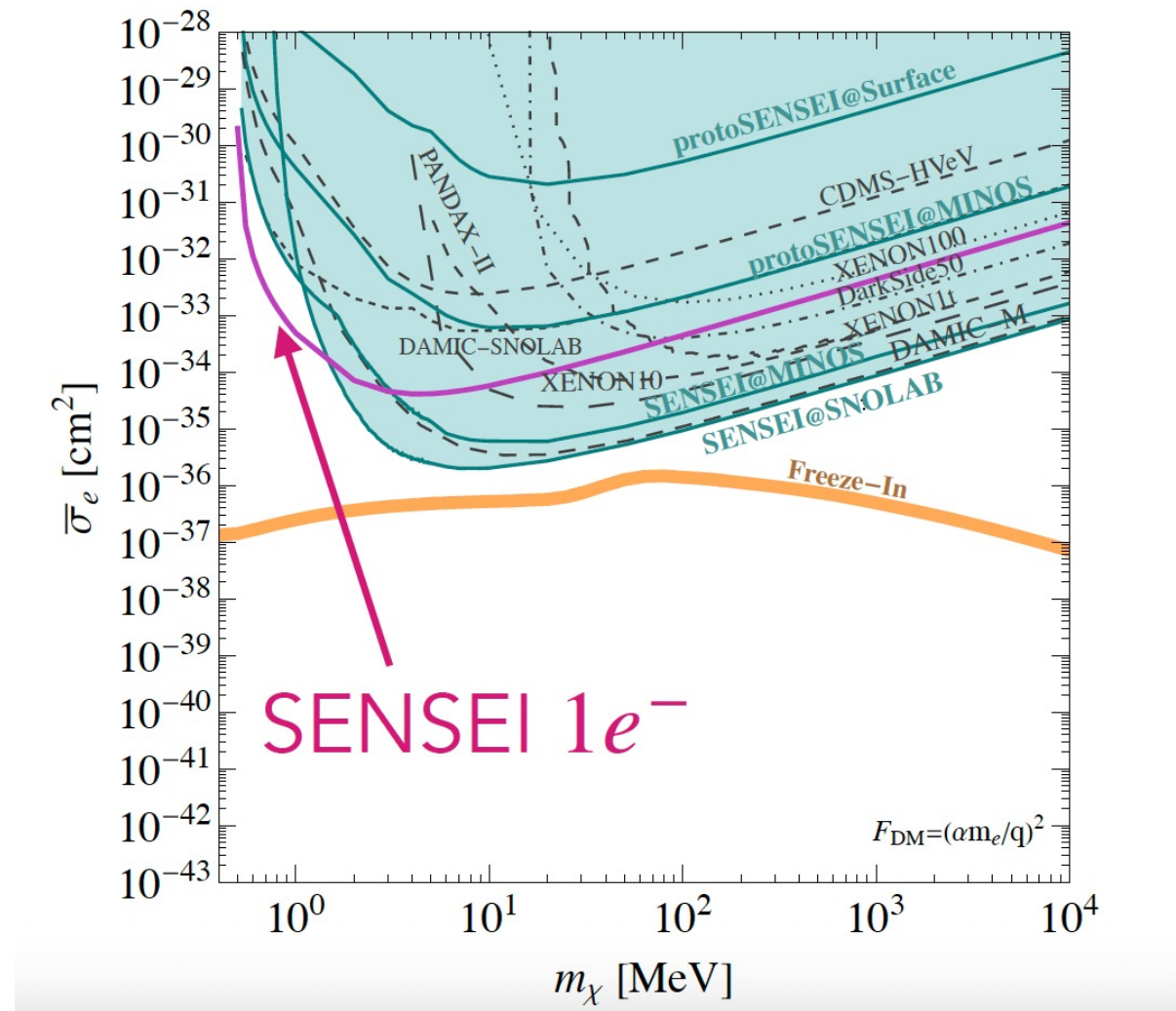
SENSEI @ SNOLAB

RUN2/3



- 5.4 Mpix
- 19 CCDs: mass ~ 40 g
- used new Cu trays to reduce background

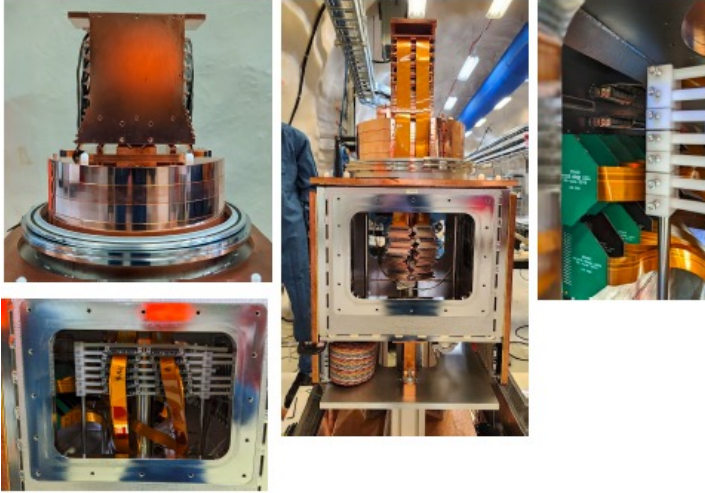
arXiv:2410.18716
PRL



This means about 1e-/pix/200 years!

SENSEI @ SNOLAB

RUN2/3



- 5.4 Mpix
- 19 CCDs: mass ~ 40 g
- used new Cu trays to reduce background

arXiv:2410.18716
PRL

DAMIC @ SNOLAB

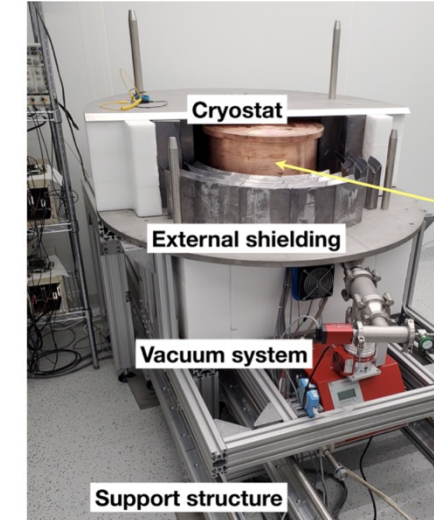


credits: R. Essig

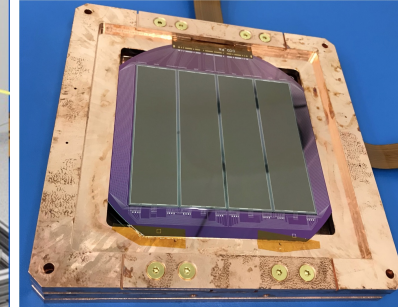
- 16 Mpix of 15 μm
- 7 CCDs: mass ~6 g
- background shielding
- $T \sim 140 \text{ K}$
- ~10 dru

PRL123 181802 (2019)
PRL125 241803 (2020)
PRD105 062003 (2022)

DAMIC-M @ LSM



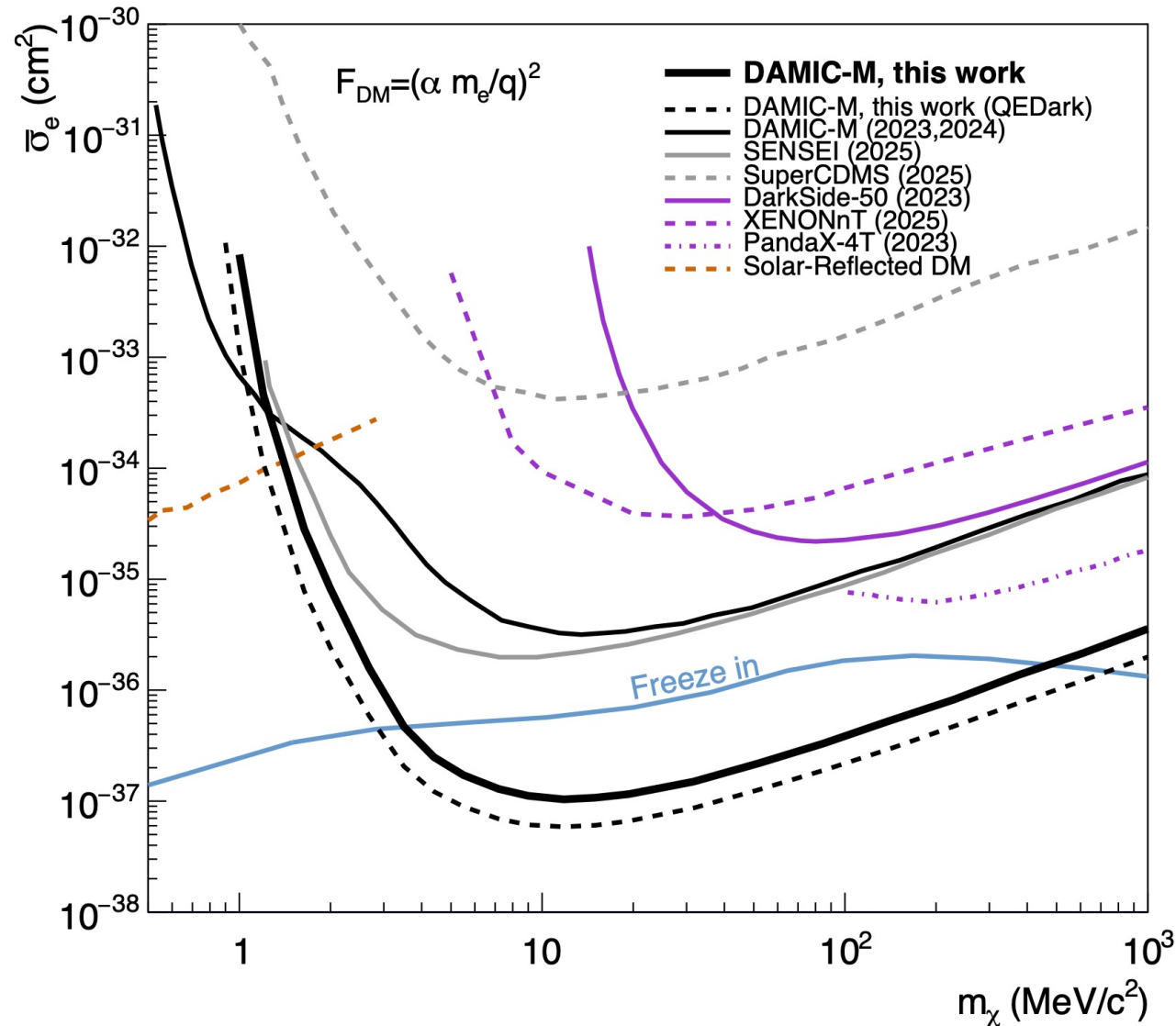
credits: P. Privitera



- 9 Mpix of 15 μm
- 2 CCDs: mass ~ 26.4 g
- low background shielding
- $T \sim 140 \text{ K}$
- exposure ~1.3 kg-day

2407.17872
2302.02372, PRL

DM-ELECTRON SCATTERING LANDSCAPE



arXiv:2503.14617

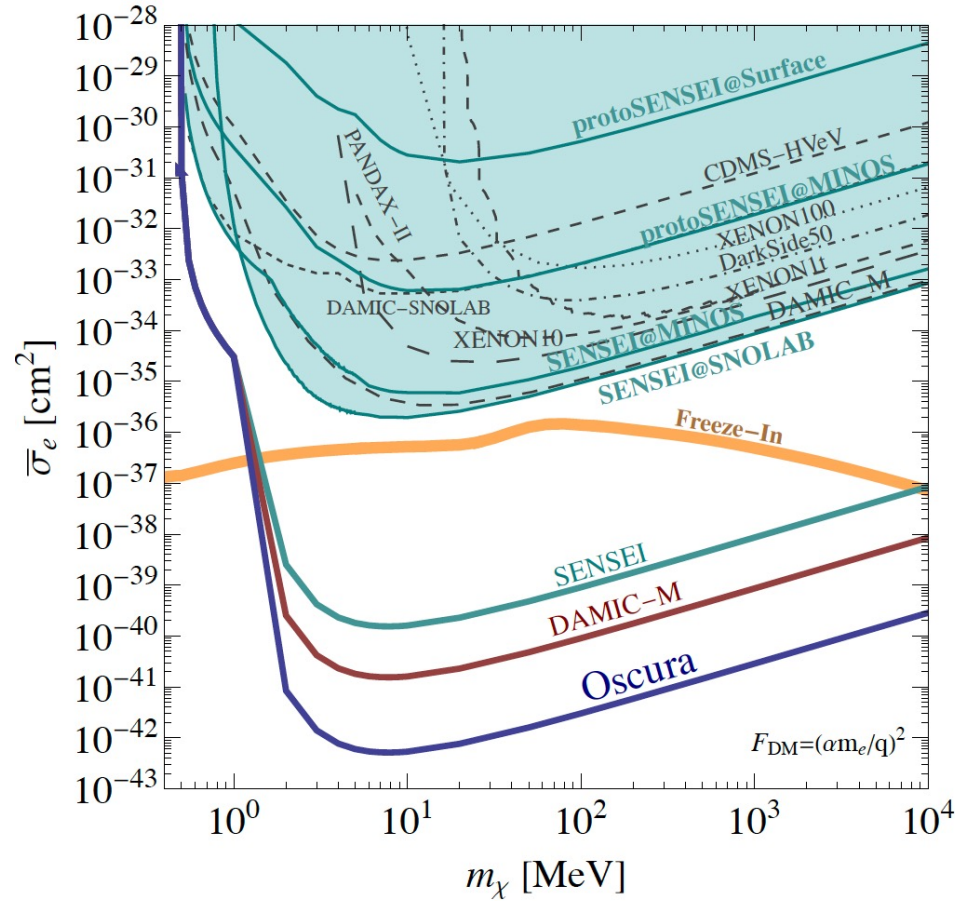
Liquid nobles via S2-only

first bounds on sub-GeV
freeze-in DM

strong bounds on
various other models

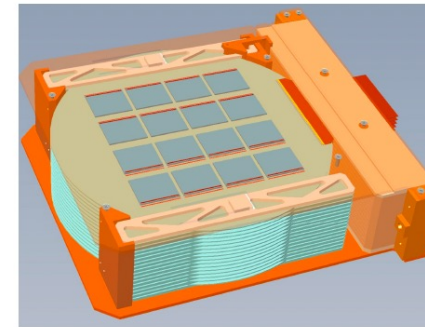
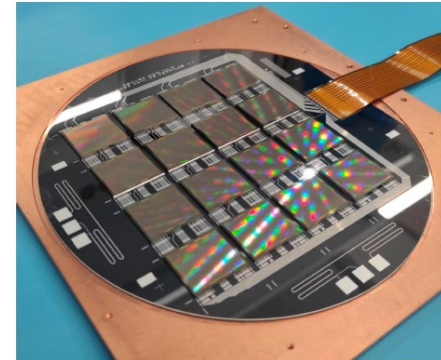
Oscura: ultimate Skipper-CCD DM experiment

Slide borrowed from R. Essig, UCLA DM 25



[current bounds outdated!]

- Goal: 10 kg
- R&D funded by DOE DMNI
- Sufficient resources for 1 kg prototype to test R&D

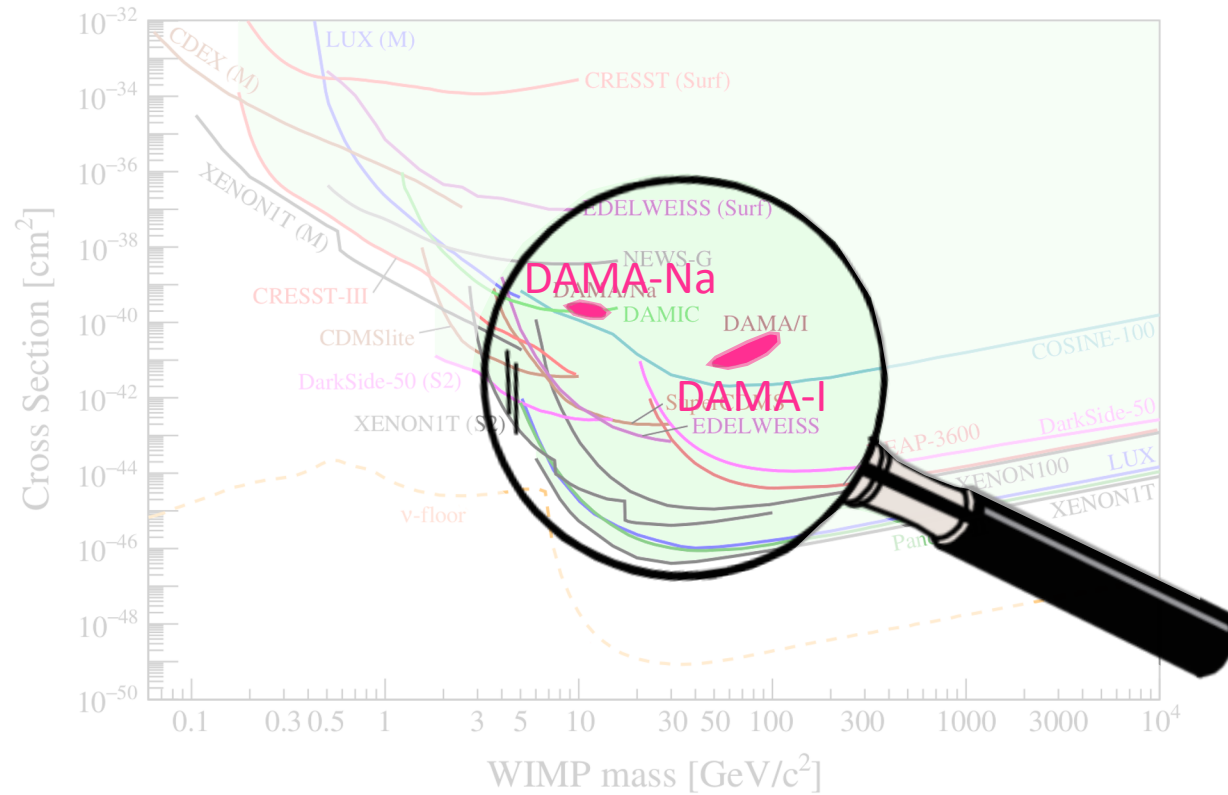


Can probe e.g. freeze-in benchmark for DM masses > 1 MeV

CLAIM BY DAMA/LIBRA



Astroparticle Physics European Consortium APPEC, v1.02



positive evidence reported by
DAMA/LIBRA

REACTION vs. SCIENTIFIC AGE

Professor:

Ahh, those were the good old days, when we were still excited about DAMA. I was there, you know?

Postdoc:

I. DON'T. WANT. TO. HEAR. ANOTHER. WORD. ABOUT. DAMA

Grad student:

What is DAMA?



Professor

PostDocs

Grad students

Credits to F. Kahlhoefer

DAMA/LIBRA experiment

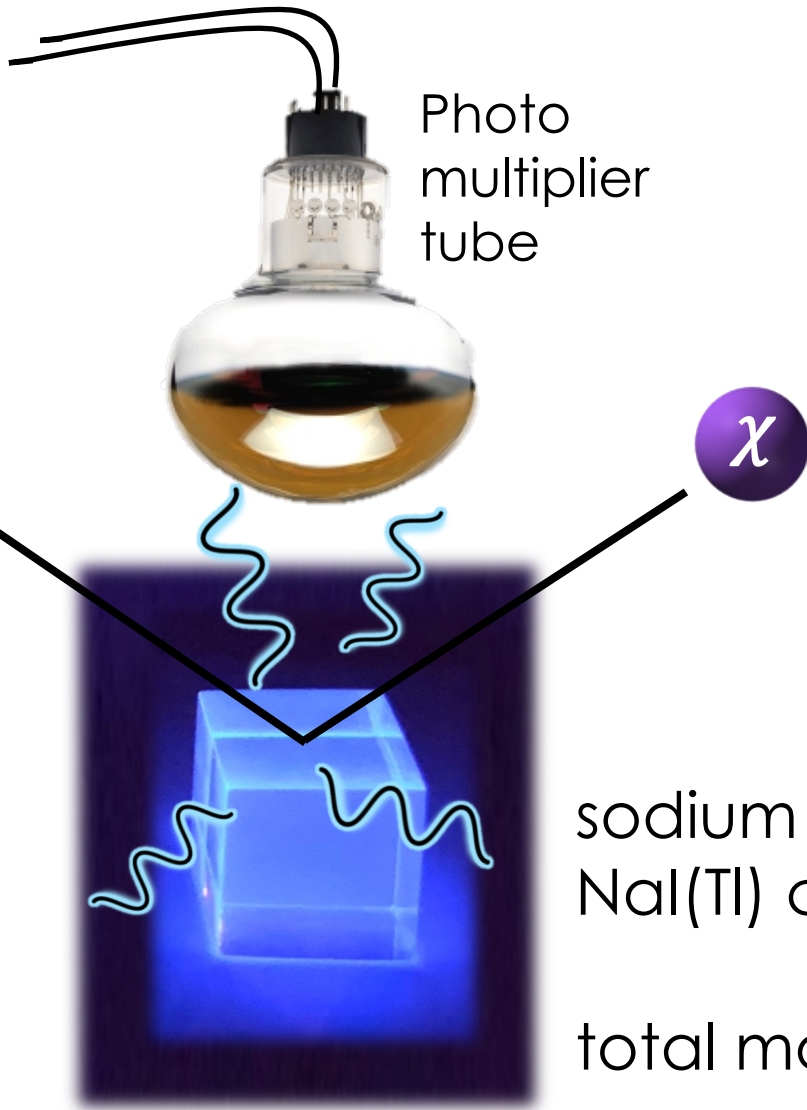
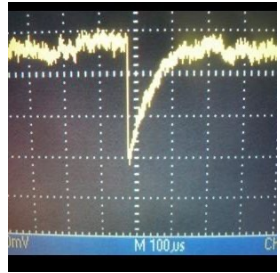
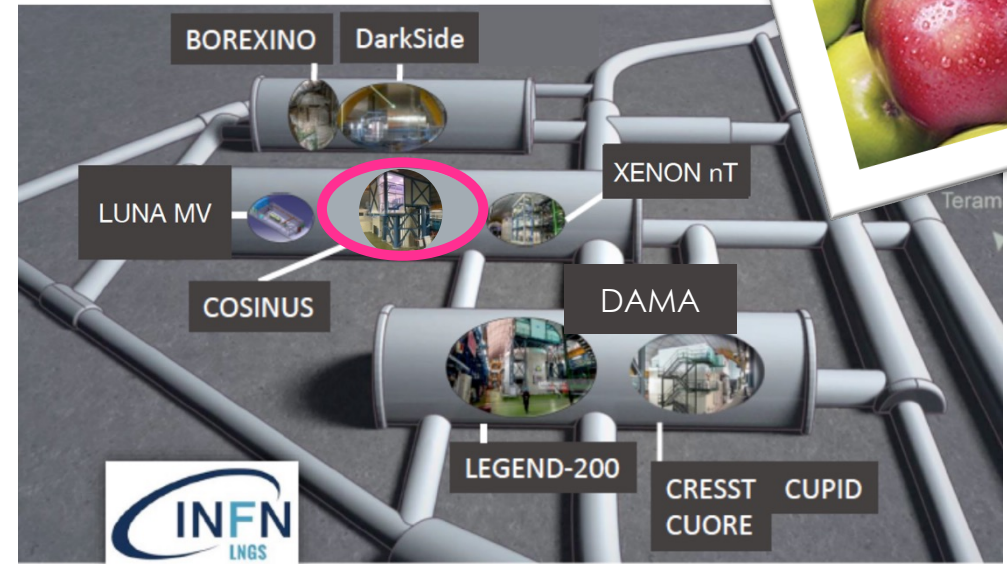


Photo multiplier tube

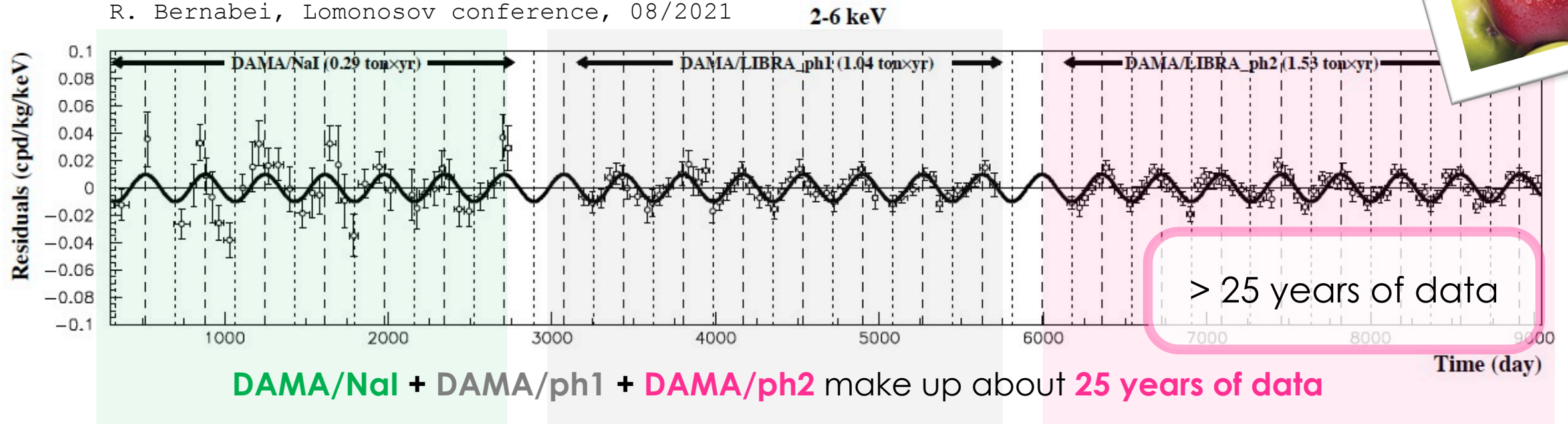
sodium iodide
NaI(Tl) crystals

total mass: 250 kg



DAMA/LIBRA RESULT

R. Bernabei, Lomonosov conference, 08/2021



total exposure:

2.86 tonne years

statistical significance:

13.7σ

energy region:

2-6 keV_{ee} → ee = electron equivalent

claim: positive evidence for the presence of DM particles in the galactic halo



THE SMOKING GUN EVIDENCE?

statistics: 13.7σ ✓

period: 0.99834 ± 0.00067 years * ✓

phase: 22th May +/- 4 days ✓
(cosine peaking June 2nd)

convincing non-DM explanation ✗

*in (2-6) keV_{ee} interval



WHAT TO CONCLUDE ?

If the DAMA signal is due to dark matter we have **fundamental problems** in **understanding its astrophysical distribution and fundamental interactions**.

→ same-target experiments offer test without need for assumptions!

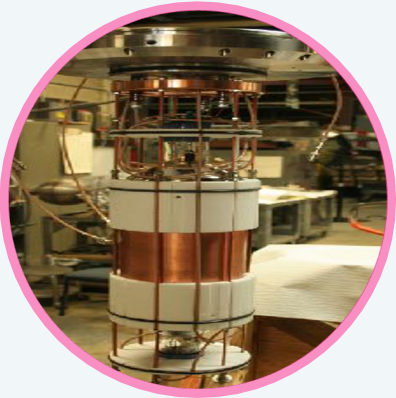
APPEC Recommendation:

*“The long-standing claim from DAMA/LIBRA [...] needs to be independently verified using **the same target material**.”*

$$\frac{dR}{dE_r} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{min}}^{v_{esc}} d^3 v f(v) v \frac{d\sigma(v, E_r)}{dE_r}$$

NaI EXPERIMENTS à la DAMA

* not complete list



DM-Ice

South Pole
2200 m.w.e of ice

17 kg

4 keV_{ee}

3.5 y of data

DATA TAKING



COSINE-100

Korea @Y2L

106 kg

1 keV_{ee}

6.0 y of data



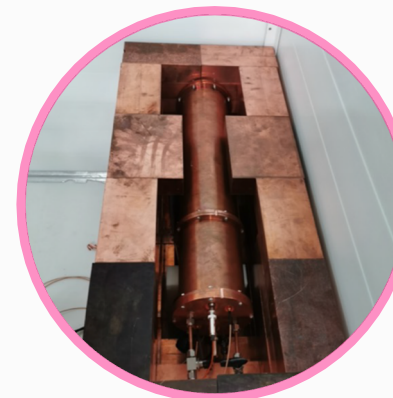
ANAIIS-112

Spain @ LSC

112 kg

<1 keV_{ee}

since 2017
7 y of data



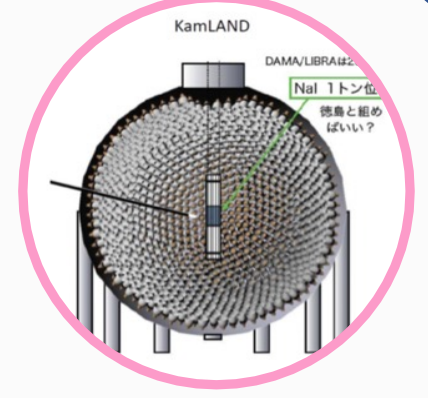
SABRE

Italy @ LNGS
Australia @ Stallwell

30-50 kg

PoP 2021

in construction/
commissioning



PicoLON

Japan @ Kamland

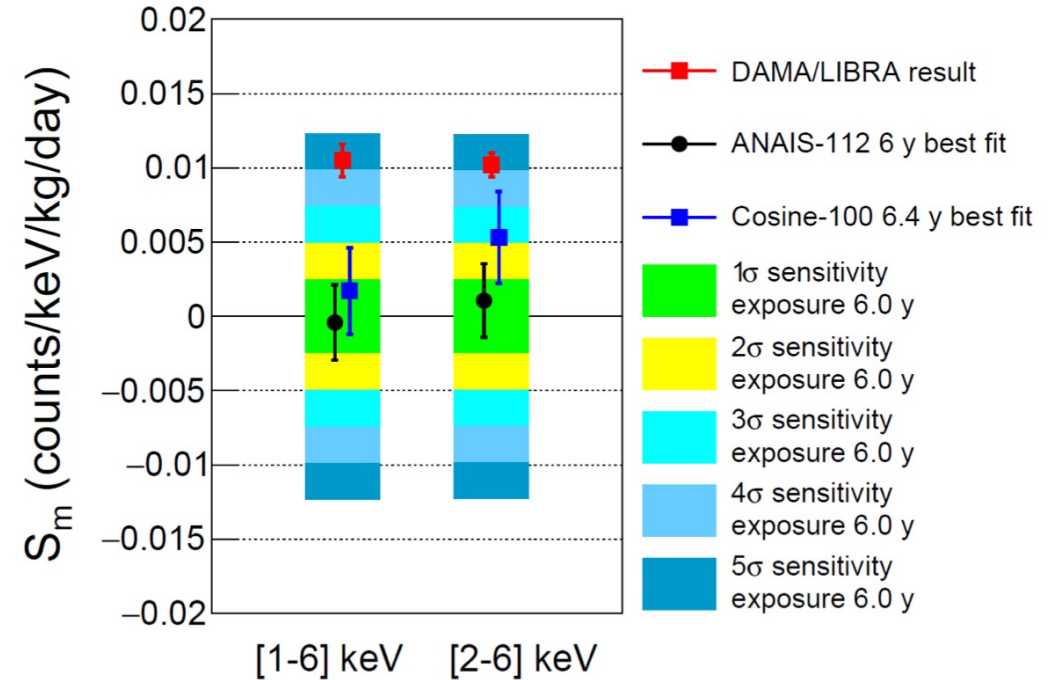
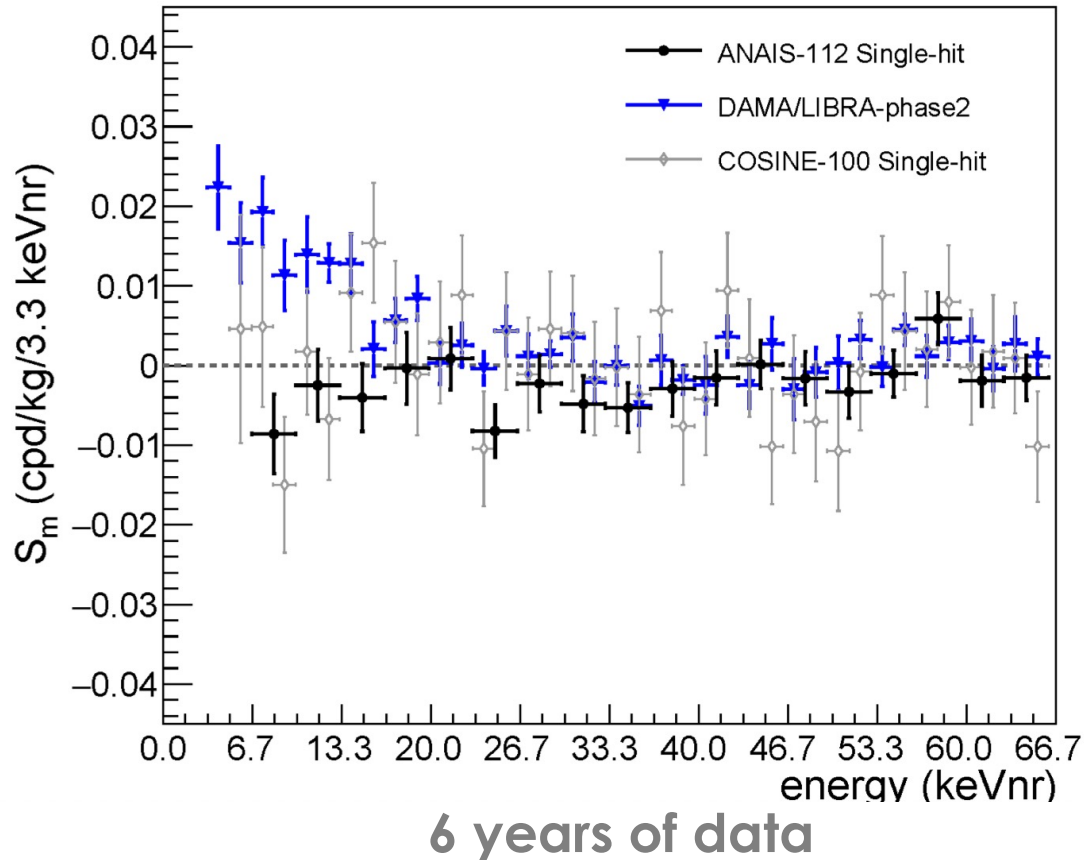
staged approach
54→250→1000 kg

planning phase

IN MAKING

ANAIS-112 LATEST RESULTS

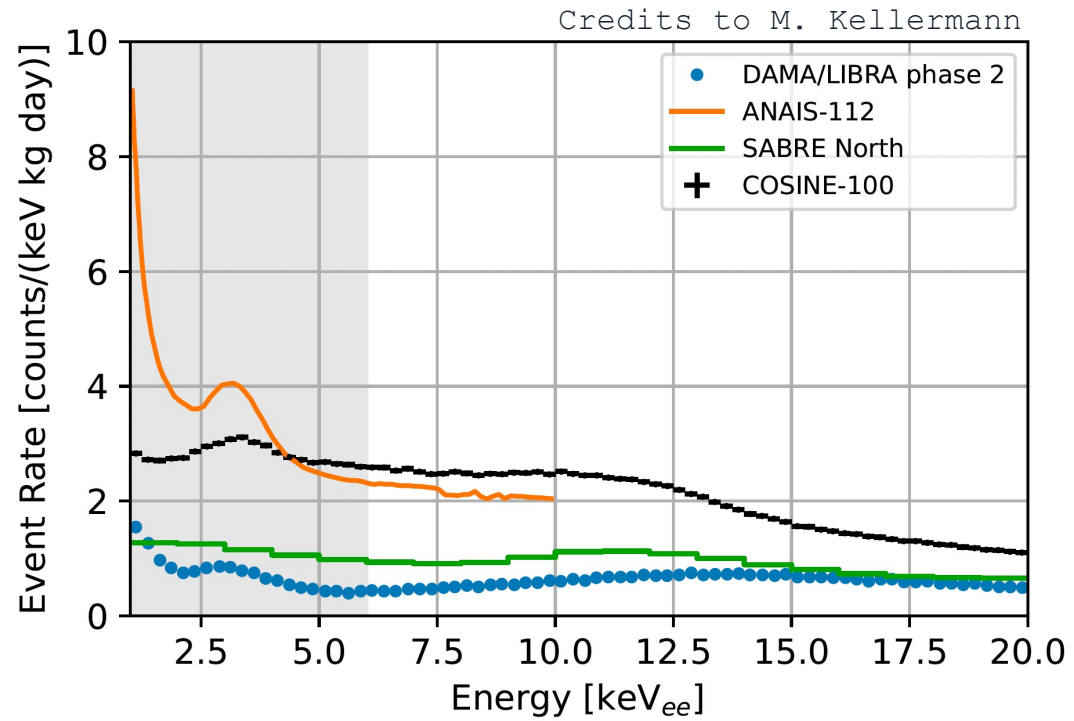
[arxiv: 2502.01542](https://arxiv.org/abs/2502.01542)



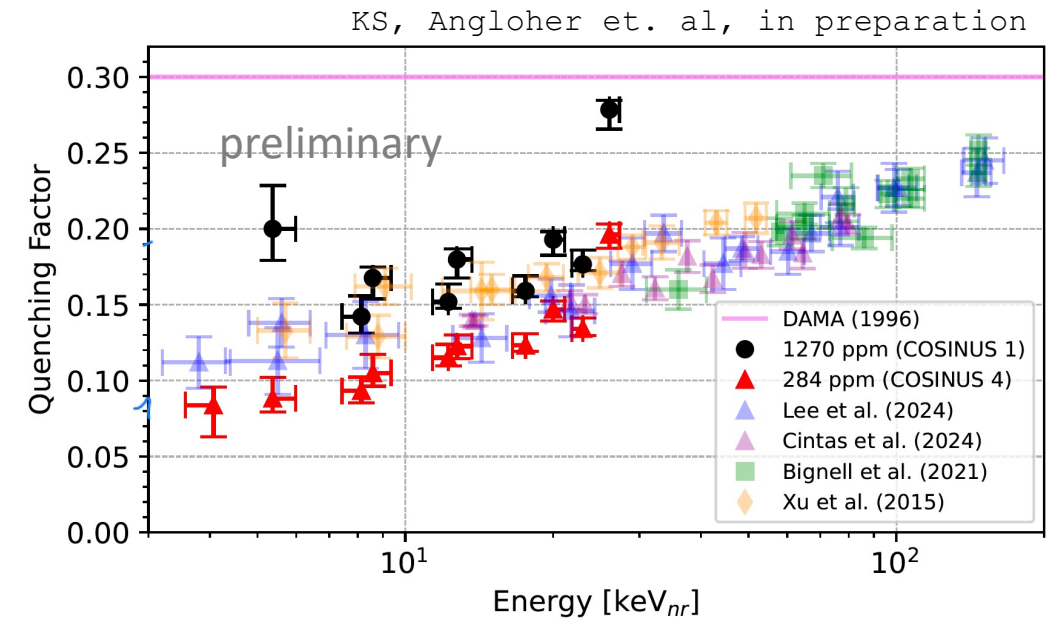
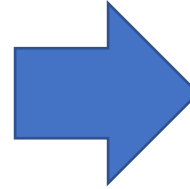
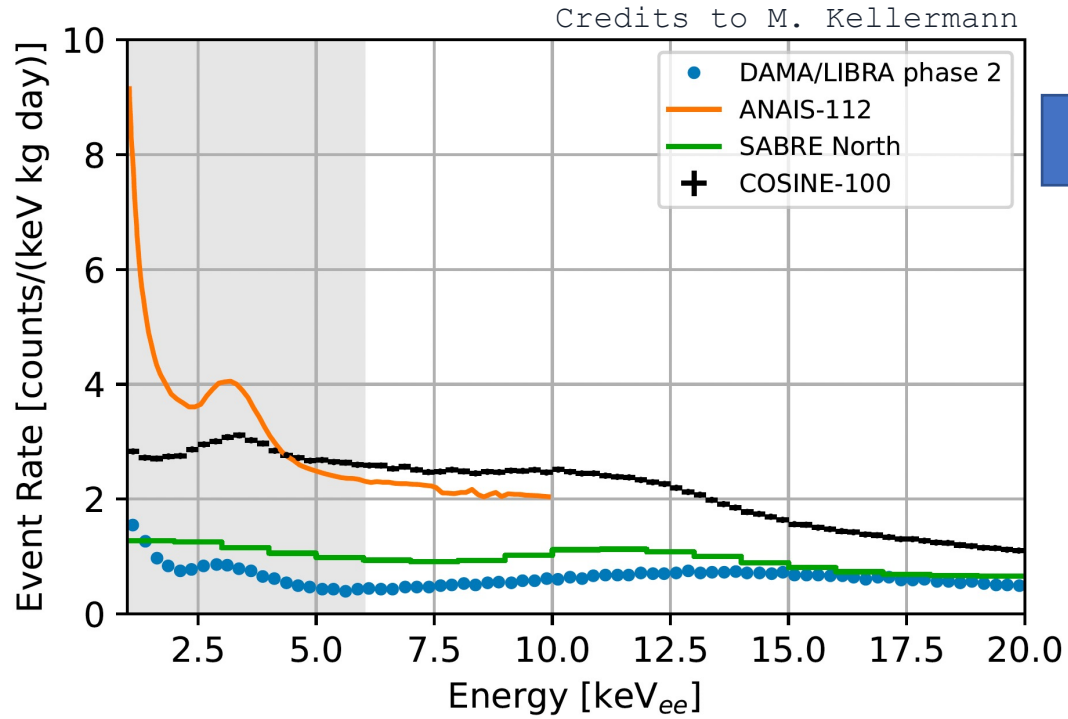
→ incompatible with DAMA/LIBRA result at **4.0 and 3.5 σ** in [1-6]keV and [2-6] keV

→ **5 σ exclusion at reach in late 2025 / 2026**

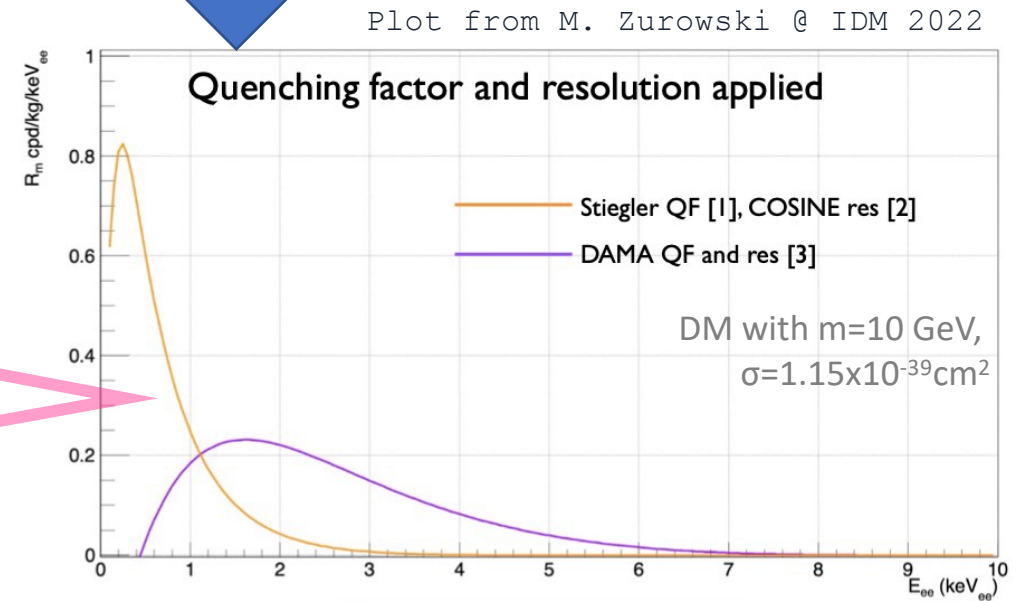
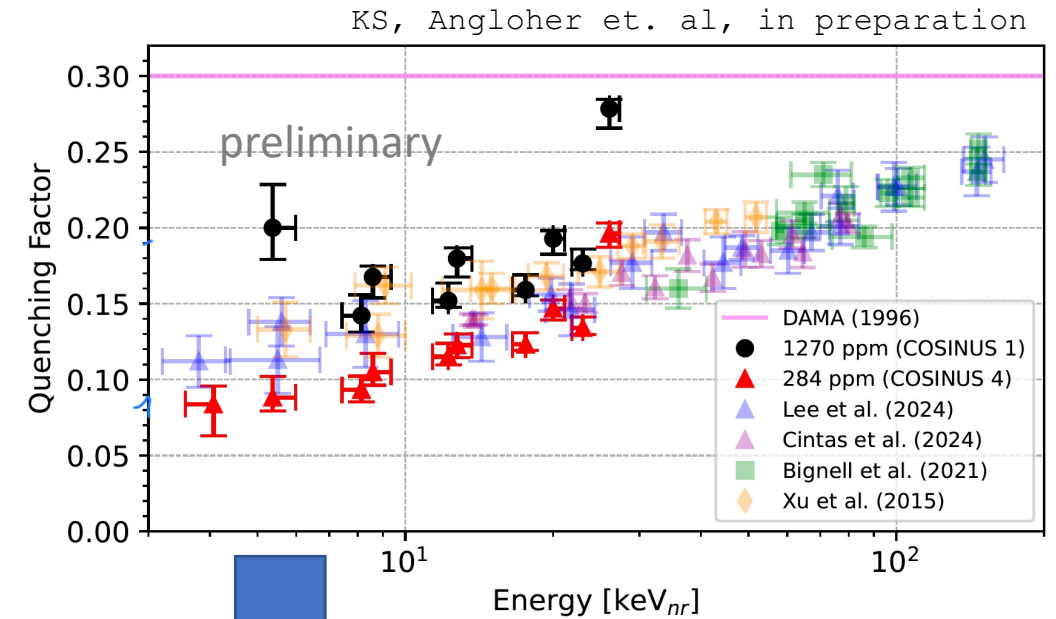
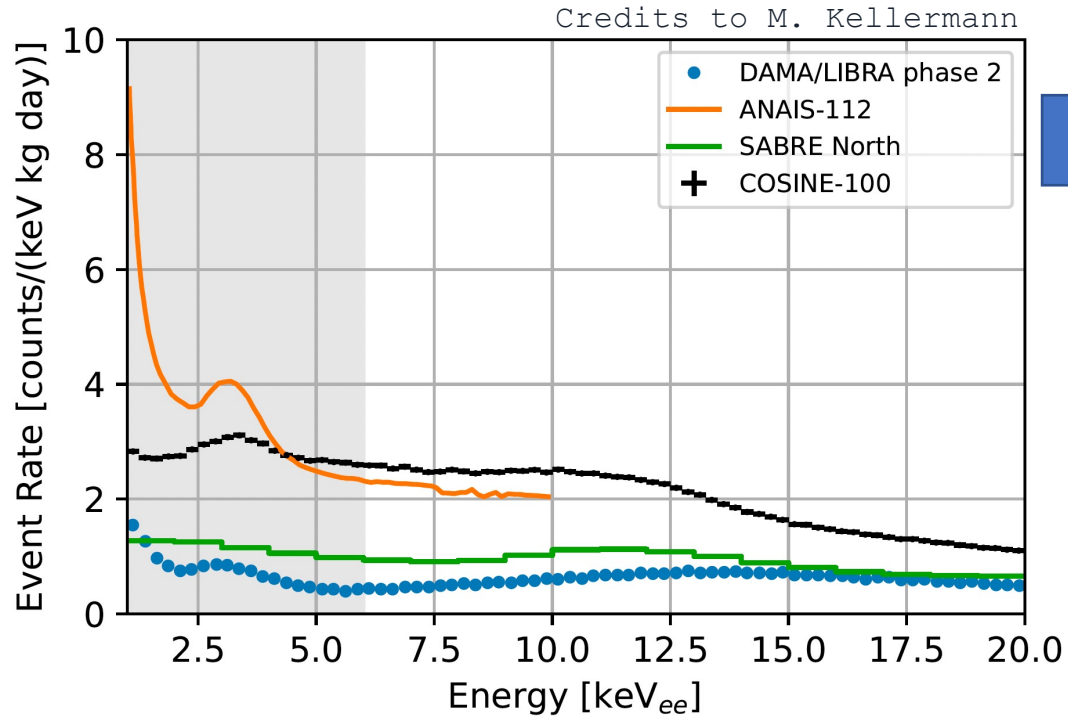
SYSTEMATICS (!!!)



SYSTEMATICS (!!!)



SYSTEMATICS (!!!)



quenching factors are uncertain:

- uncertainty on the nuclear recoil energy scale
- comparison of results **not solid**

One more thing

SAME, SAME BUT DIFFERENT

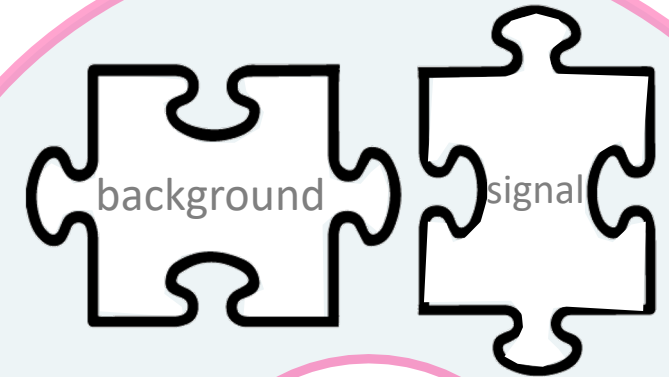
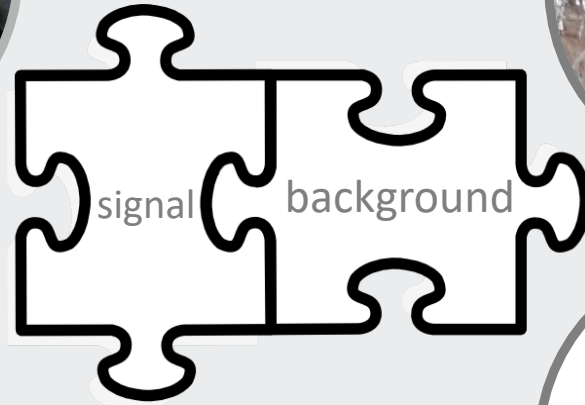
DAMA/LIBRA



ANAIS-112

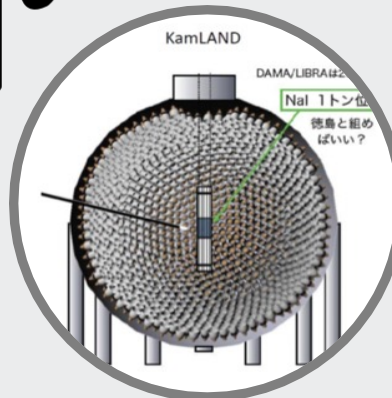
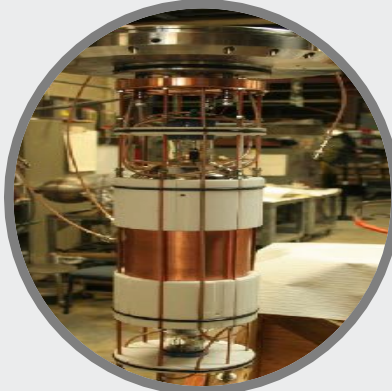


COSINE-100

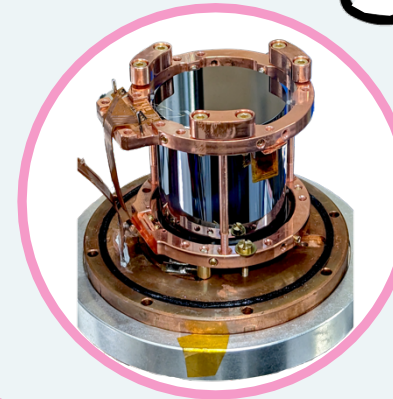


SABRE

DM-Ice



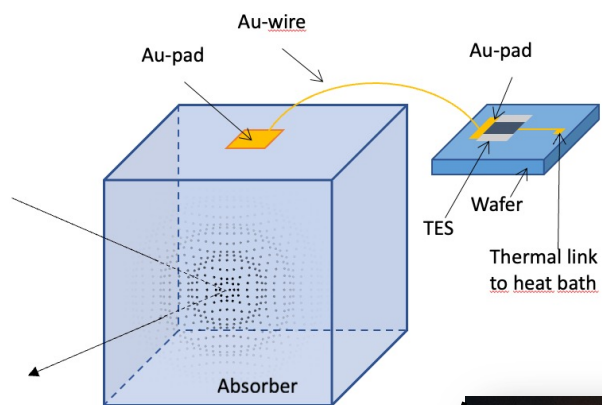
PicoLON



COSINUS

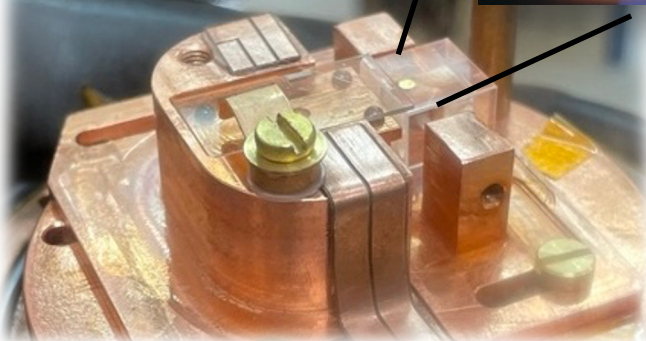
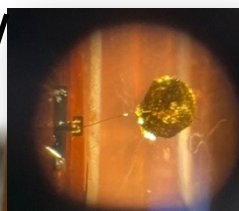
COSINUS – the “cold” DAMA-check

remoTES readout for NaI



NIM A1045 167532

NaI remoTES

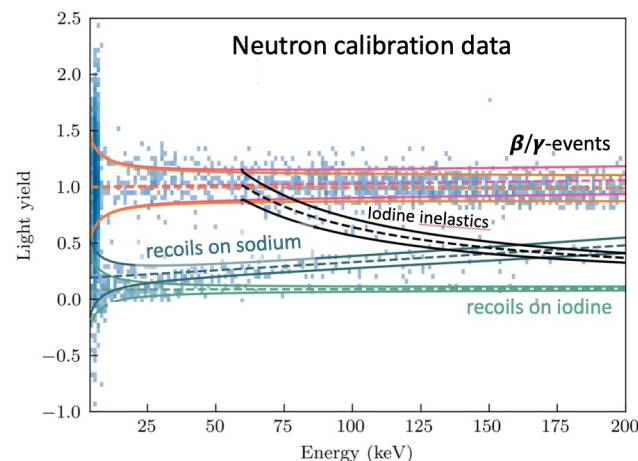


05.04.25

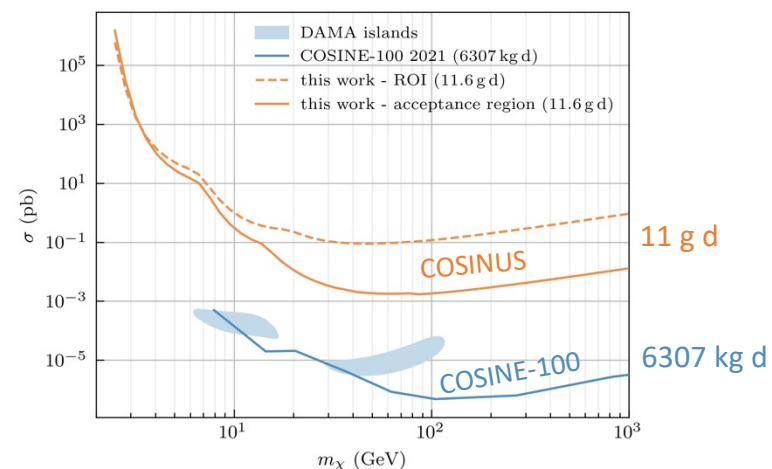
K. SCHAFFNER | MAX-PLANCK-INSTITUT FÜR PHYSIK

first physics results

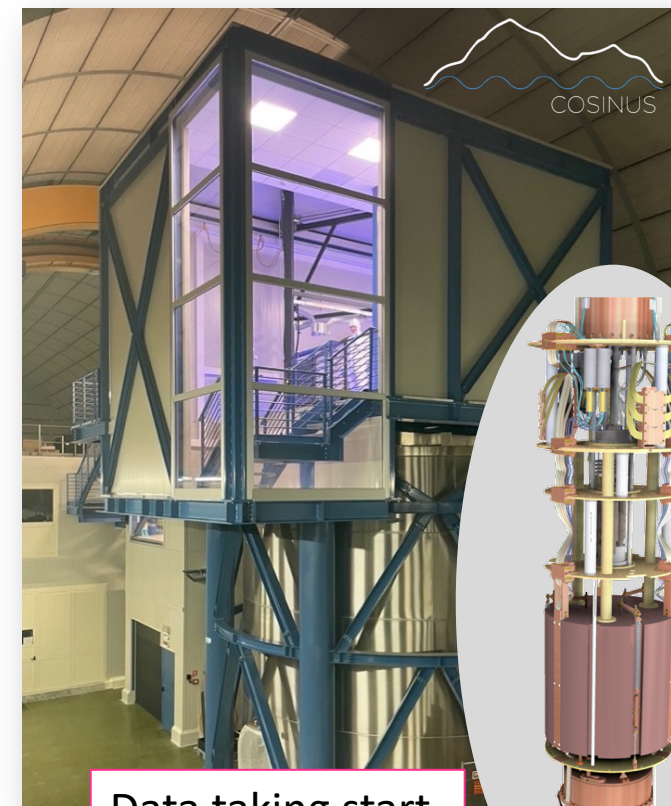
PRD 110, 043010, 2024



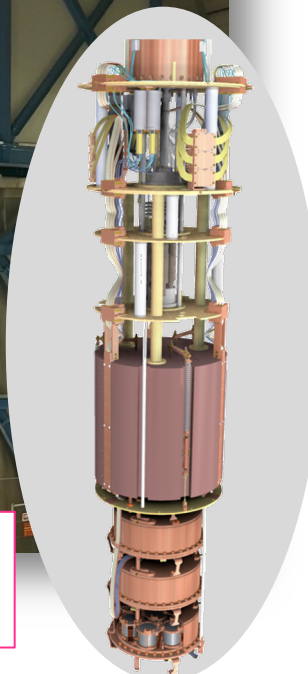
$$\sigma(\text{NaI}) = (0.441 \pm 0.011) \text{ keV}$$



cryogenic low background facility in hall B @LNGS



Data taking start
in late 2025



CONCLUSION

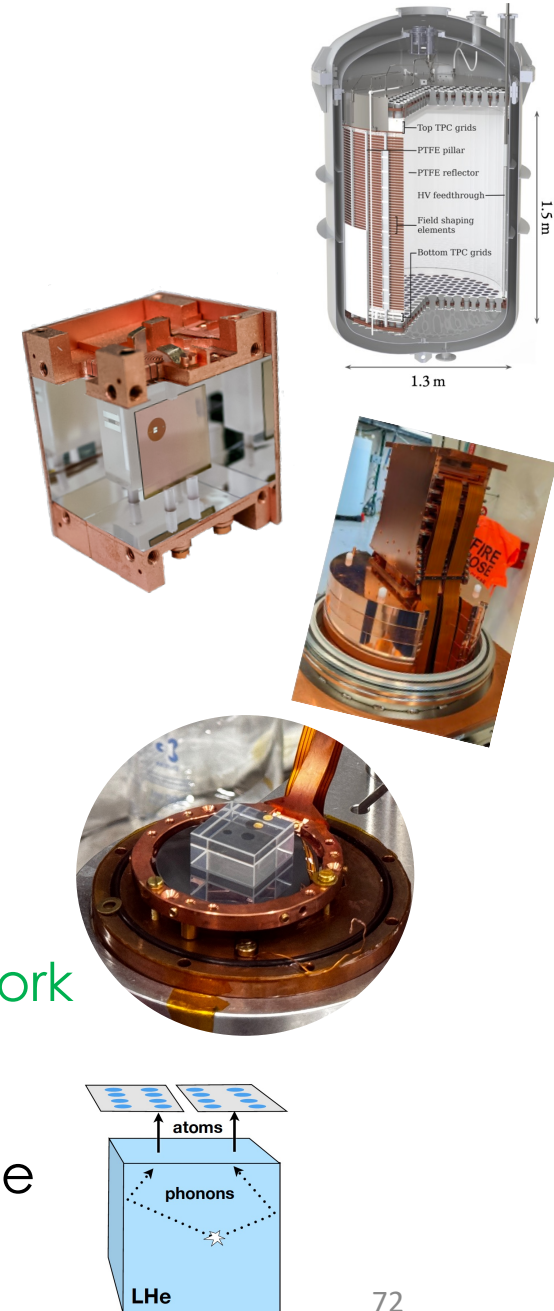
- unveiling the nature of DM is (almost) an 100 years challenge now
- **liquid Noble Gas detectors** have been at the forefront since 2007 for dark matter masses $> 10 \text{ GeV}/c^2$

✓ **ACTION REQUIRED** *scale-up towards the neutrino fog necessary
+ further background reduction*

- **low-temperature detectors and CCDs** probe new parameter space with small-scale detectors for both NR and ER - DM interactions

✓ **ACTION REQUIRED** *solve the Low Energy Excess (LEE)
+ sub-eV resolutions + reduced background level*

- COSINUS is the **first NaI detector with particle identification** and will work on finally solving the DAMA puzzle
- **new technologies** are a MUST – we need to cover an enormous range in dark matter masses and cross sections



Be an optimist, and be prepared for discoveries and/or new puzzles!

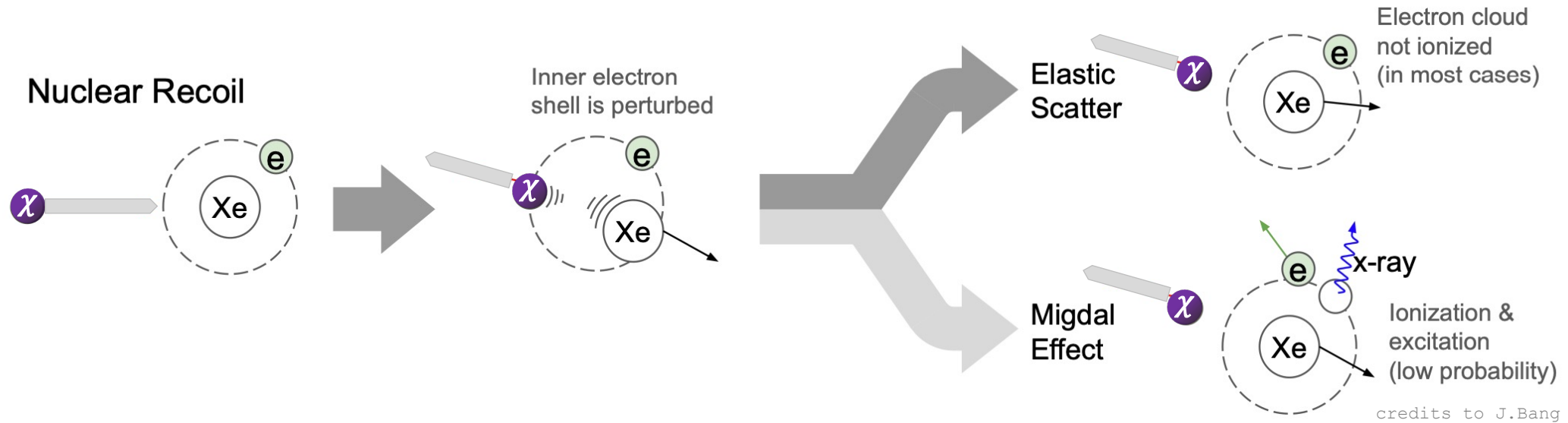




THANK YOU FOR YOUR ATTENTION

EXTRA MATERIAL

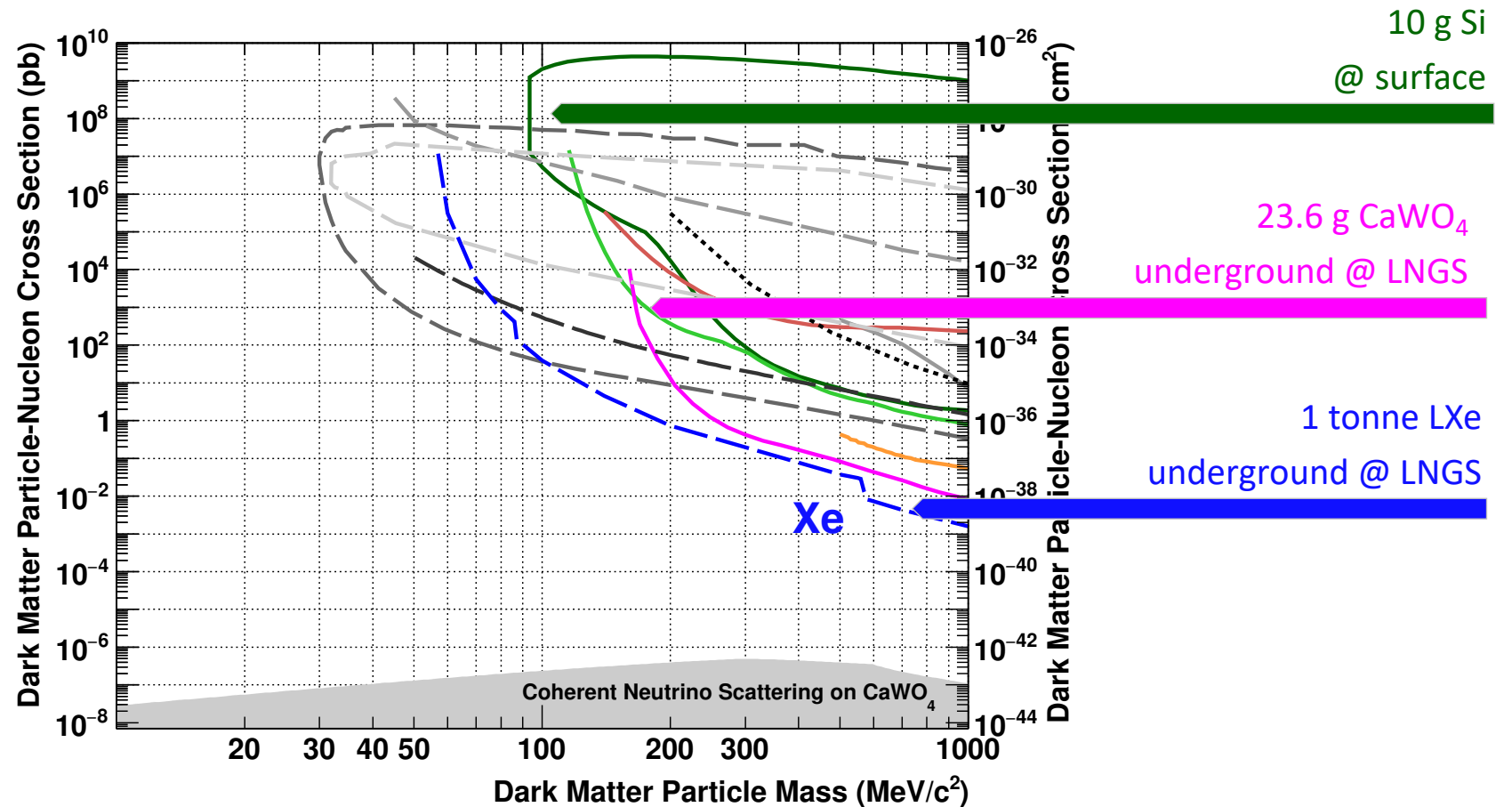
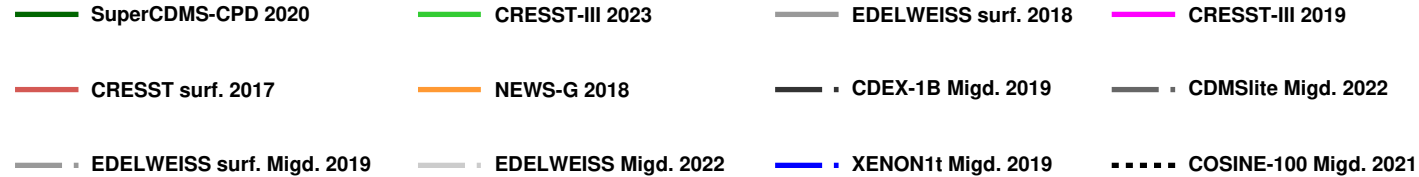
MIGDAL EFFECT – promising avenue



change in the Coulomb field felt by the electrons results in an energy transfer from DM to the electrons
→ readjustment of the electron cloud can spit out an electron of a few hundred eV = **ionisation signal**

BUT there is a penalty to pay → signal rates are suppressed

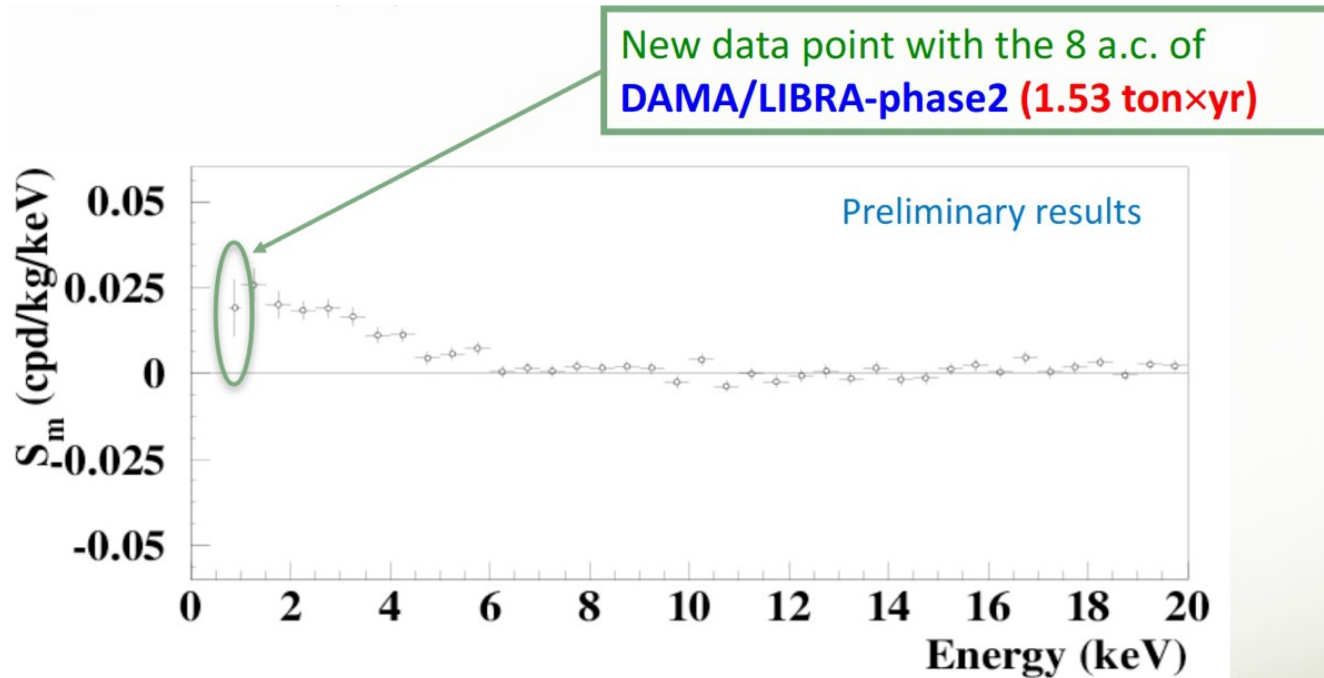
DM-NUCLEUS SCATTERING LANDSCAPE



Migdal strongly pushes sensitivity of liquid noble gas detector

cryogenic detectors achieve competitive sensitivity with far less exposure

WHAT'S NEW – LOWER ENERGY THRESHOLD



Credit: P. Belli at UCLA Dark Matter, LA, US - April 2023

Phase 2 upgrade(s):

2010:

new PMTs with higher Q.E.
→ 1keV_{ee} software threshold

2021:

new electronics and digitizers
→ < 0.75keV_{ee} software threshold
→ data taking since 12/2021

2024: switched off

→ DAMA released results after 3
annual cycles → early 2025 ?

DARK MATTER RATE

Total rate:

$$R = \frac{M_{target}}{m_N} \cdot \frac{\rho_\chi}{m_\chi} \cdot v \cdot \sigma(v)$$

$$\frac{dR}{dE_r} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{min}}^{v_{esc}} d^3 v \, f(\vec{v}) \, v \, \frac{d\sigma(\vec{v}, E_r)}{dE_r}$$

galactic escape velocity

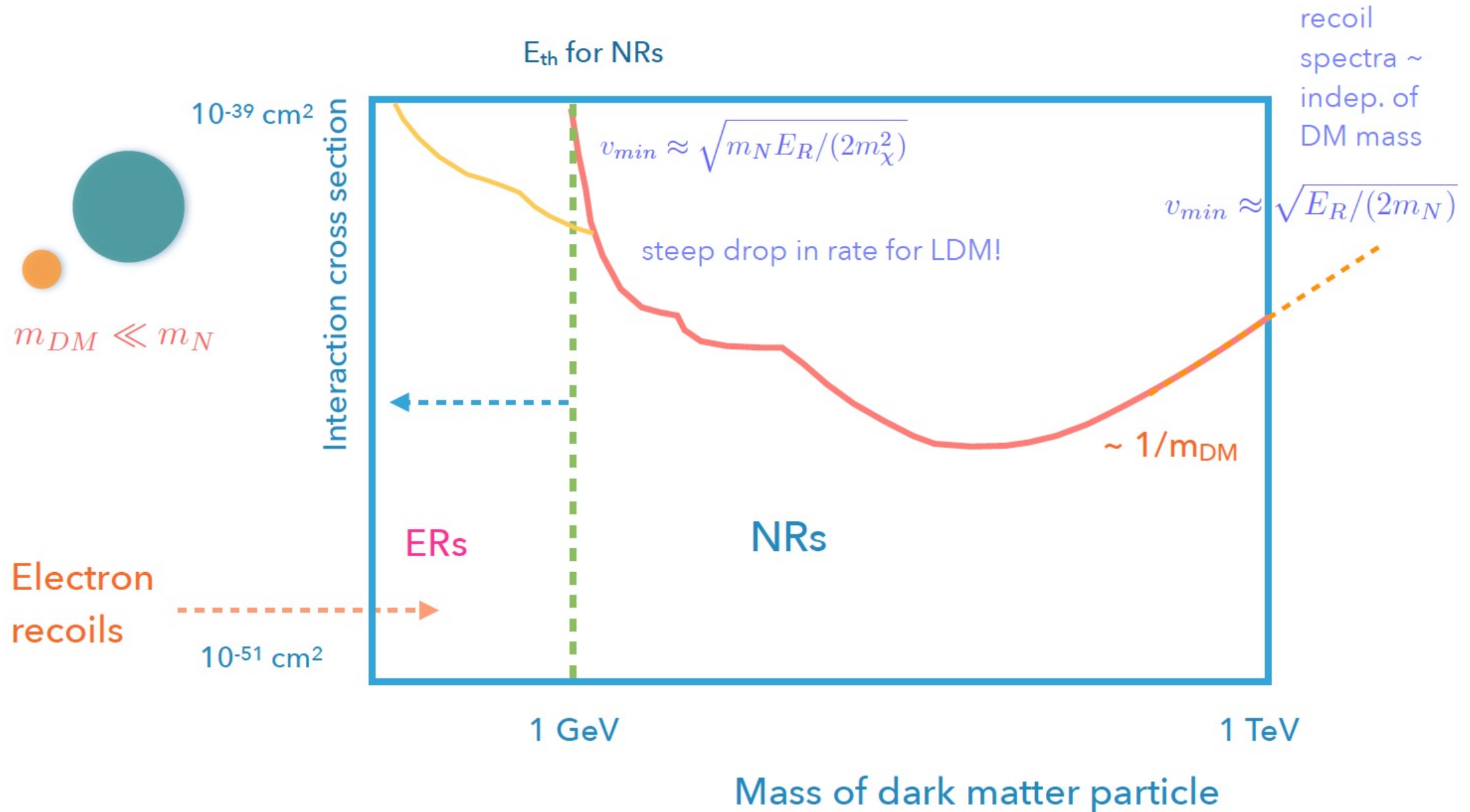
velocity distribution

DM-nucleus cross-section

minimal velocity to produce a recoil of energy E_r

$\sim A^2$
 $\sim$ form factor

INTERACTION CROSS SECTION VS MASS



RATE vs. MODULATION AMPLITUDE

F. Kahlhöfer, KS et al., JCAP 1805 (2018) no.05, 074

Central idea: modulation amplitude
cannot be larger than (average) absolute rate:

$$\bar{R} \geq S$$

COSINUS

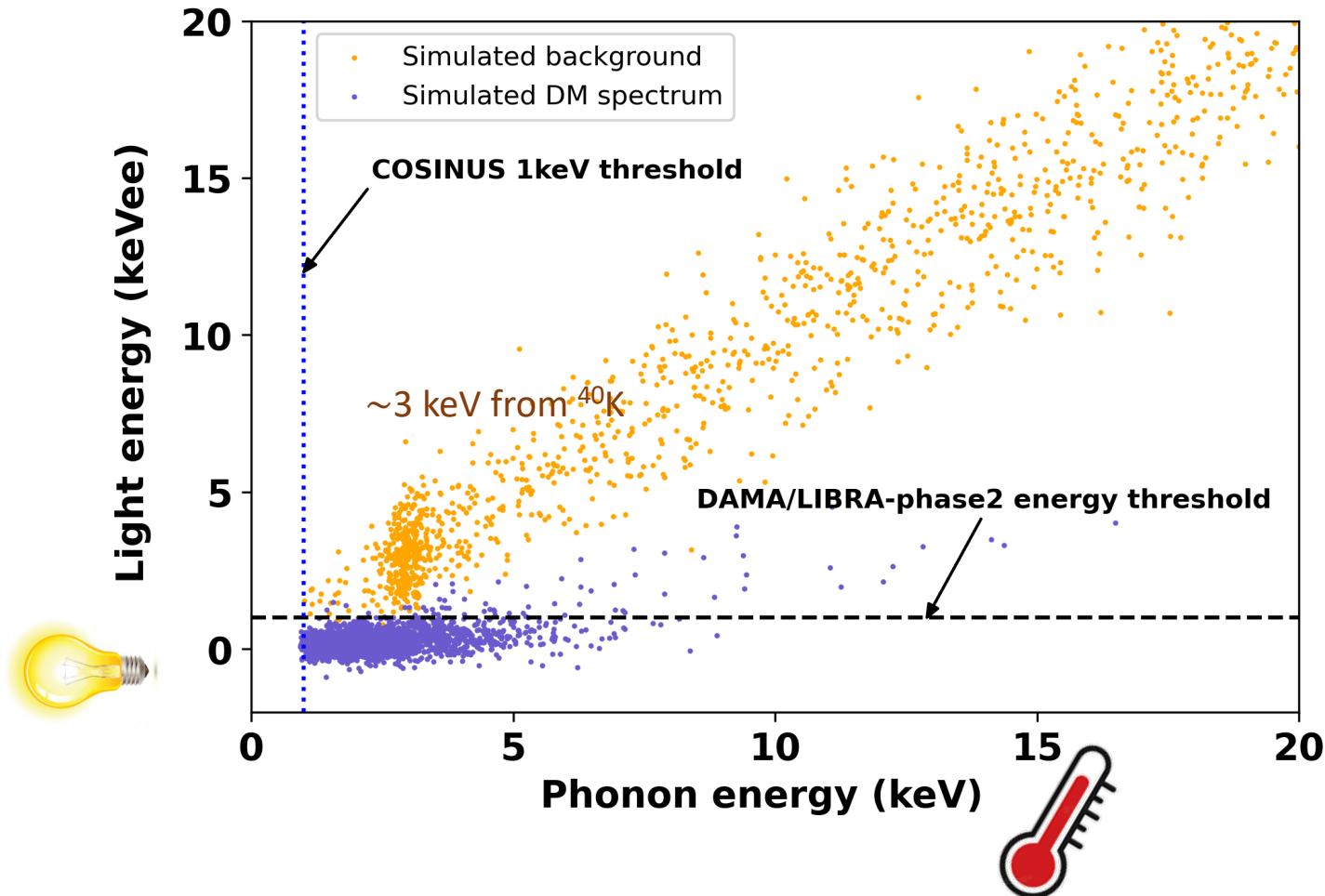
Mean rate $\bar{R} = \frac{1}{2} [R(t = \text{June } 1^{\text{st}}) + R(t = \text{Dec. } 1^{\text{st}})]$

DAMA

Modulation Amplitude $S = \frac{1}{2} [R(t = \text{June } 1^{\text{st}}) - R(t = \text{Dec. } 1^{\text{st}})]$

→ low background condition makes it possible to test DAMA
in a single annual cycle

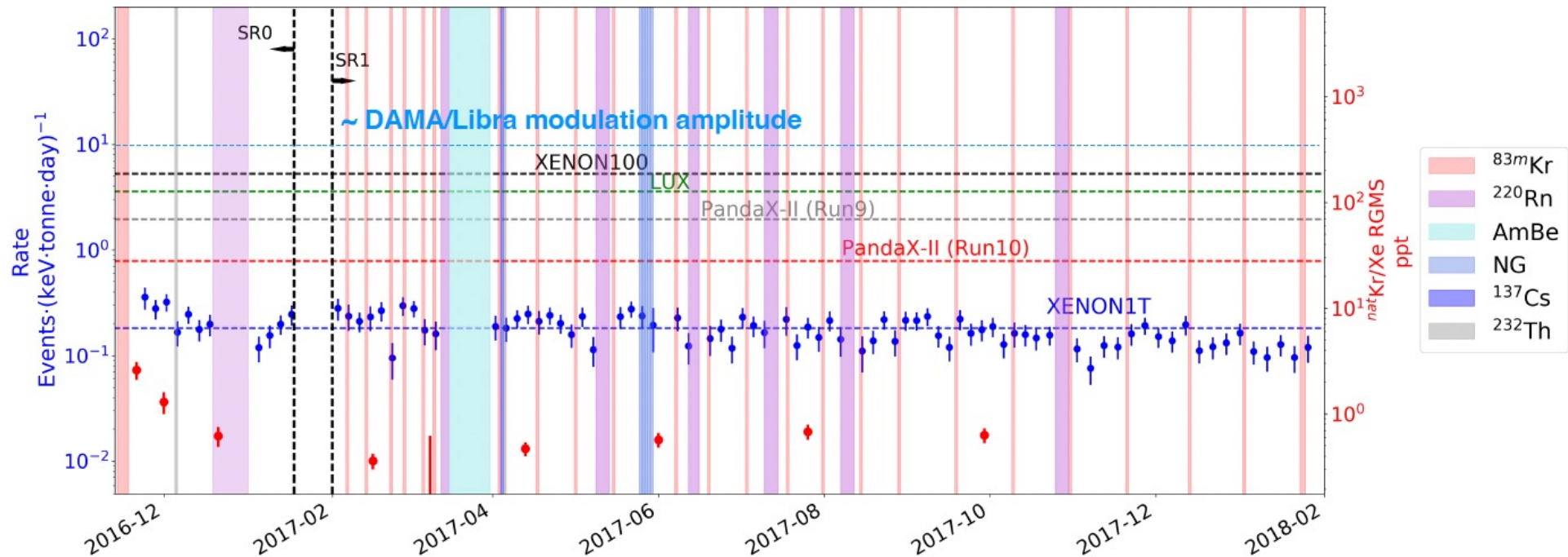
SIMULATED DATA FOR 100 kg days (gross-exposure)



- 1keV nuclear recoil threshold
- flat background: $1 / (\text{keV kg d})$
+ ^{40}K background: $600 \mu\text{Bq/kg}$
- dark matter spectrum:
 $10 \text{ GeV}/c^2$, $2 \times 10^{-4} \text{ pb}$
- **values for quenching factors** from:
Tretyak, Astropart. Phys. 33, 40 (2010)

Eur. Phys. J. C (2016) 76:441
DOI 10.1140/epjc/s10052-016-4278-3

XENON1T Background



(82 ± 5) events / (t × yr × keV_{ee}) below 25 keV_{ee}

Lowest ER background achieved in a DM detector

Dominated by Pb214 from Rn222 (~ 10 uBq/kg)

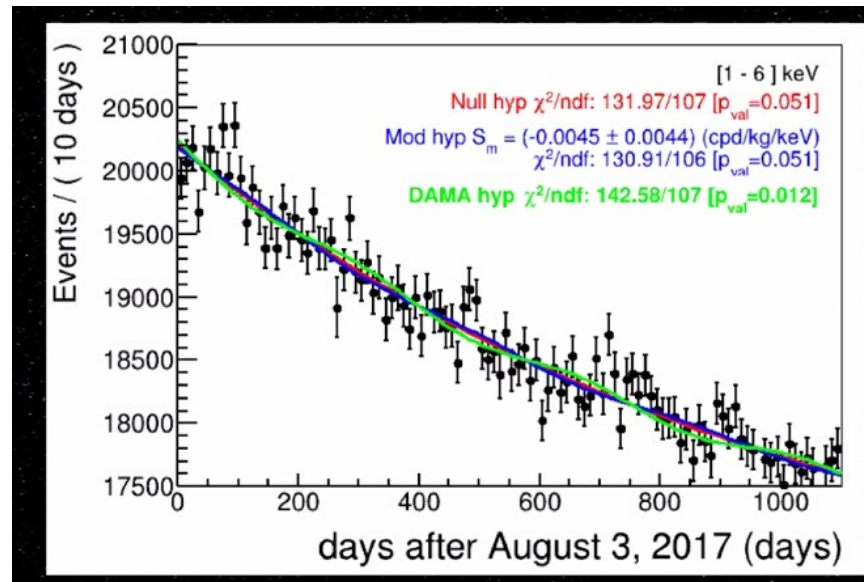
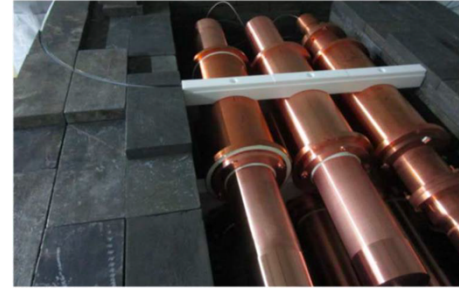
ANAIS-112



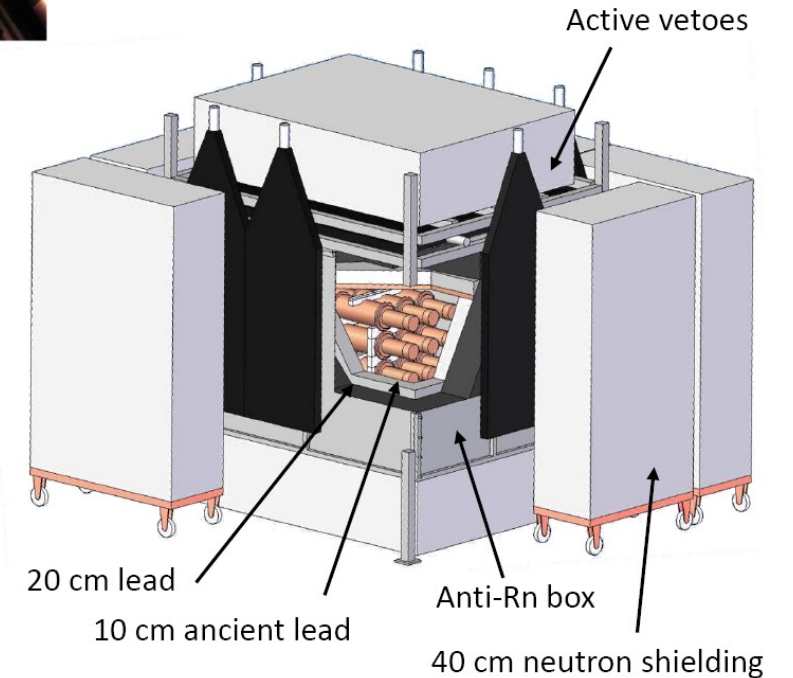
112 kg of pure NaI
@ Canfranc, Spain



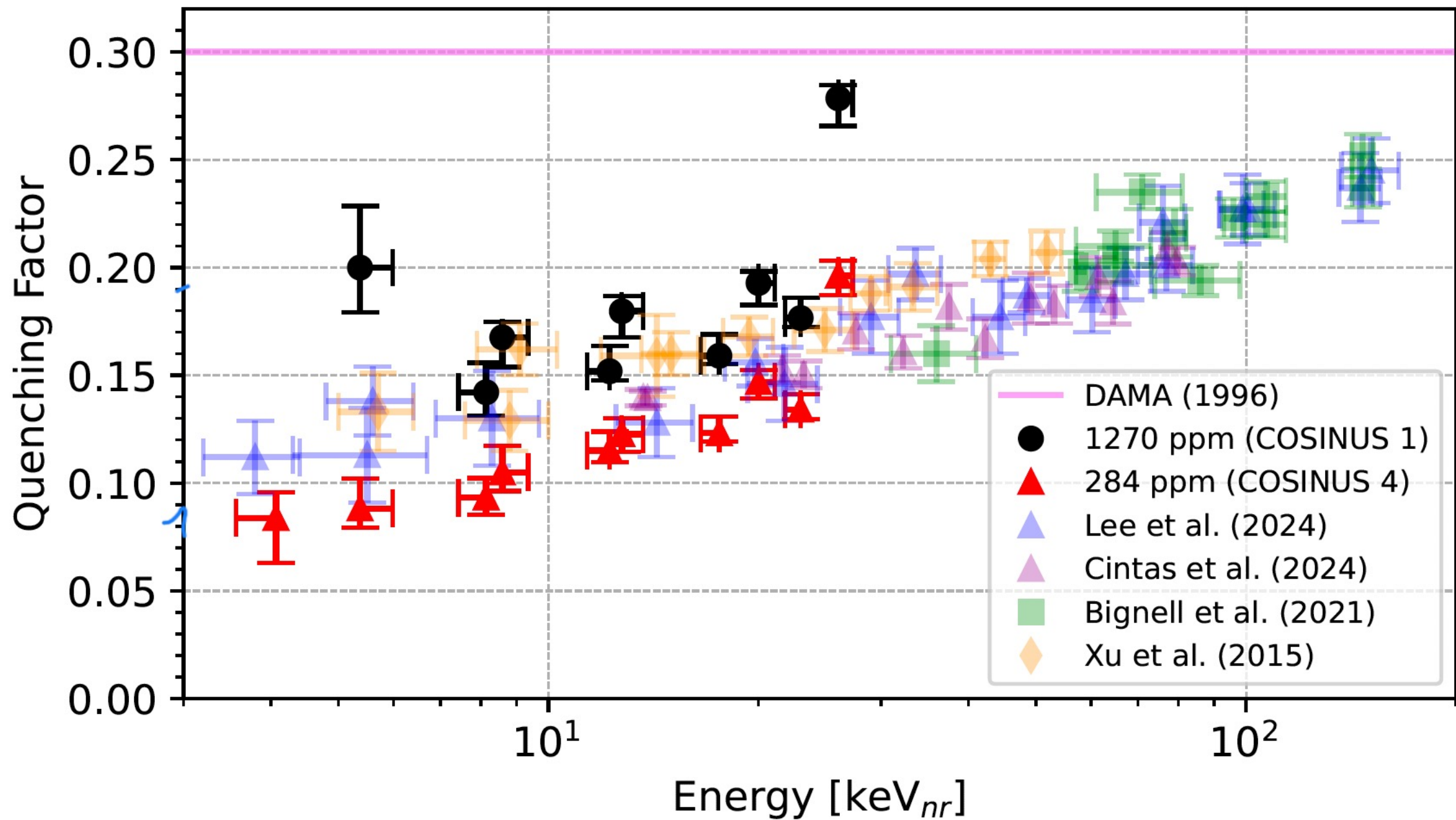
- operation since Aug, 2017
- 9 crystals in 3x3 array, 112.5 kg total
- **+ muon veto**



Moriond 2021: M.L. Sarsa



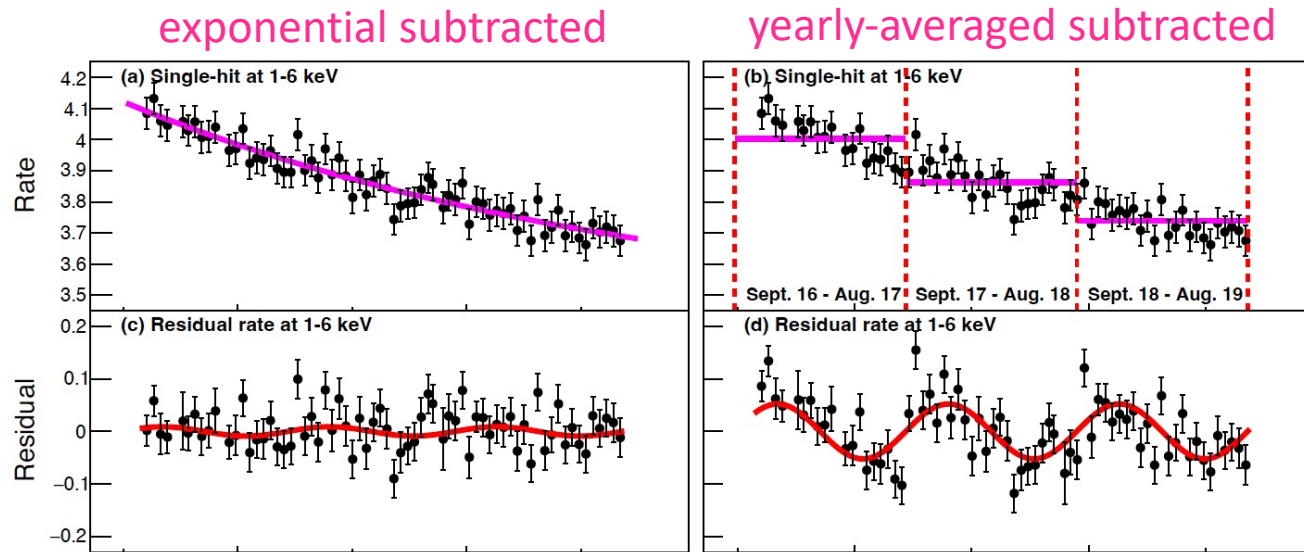
credits to M. Martinez



CHALLENGE - ANALYSIS TECHNIQUES

Rate in detector is: $R(t) = R_0(t) + A \cos\left(\frac{2\pi}{T}t - \varphi\right) \rightarrow$ DAMA-strategy: subtract average / dataset

COSINE-100 case study: *Sci. Rep. 13 (2023) 4676*



58

$\rightarrow$ high modulation amplitude (4 x DAMA) at 7σ C.L.

BUT

- 1) DAMA claims constant bckg. (but does not show rate vs. time)
- 2) wrong by 1π (= sign)
- 3) comparison to the correct model (sawtooth-like)

