

INTRODUCTION TO DIRECT DARK MATTER DETECTION

AND THE COSINUS EXPERIMENT

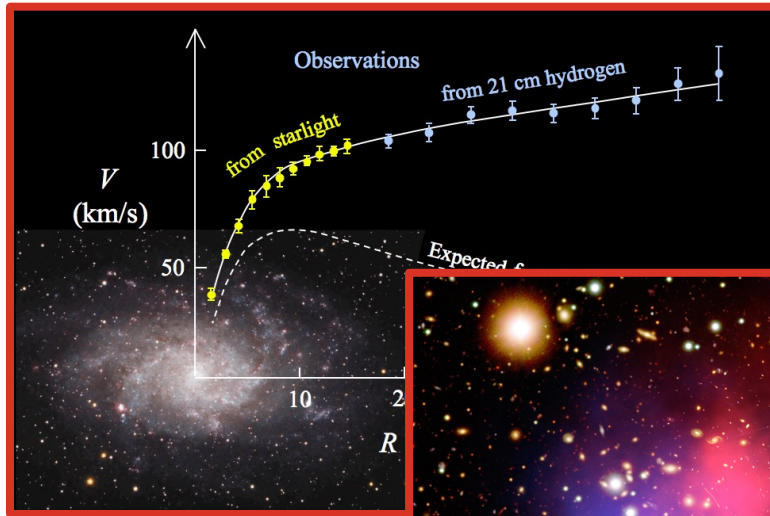


28. June 2022

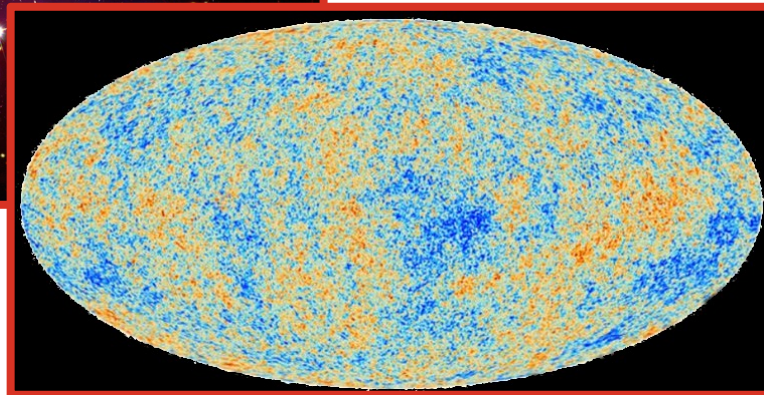
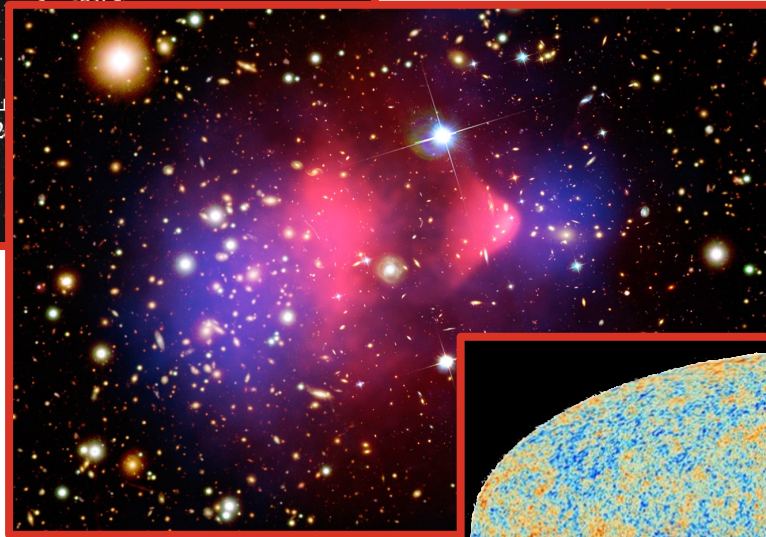
Humboldt Kolleg, Kitzbühel

Florian Reindl HEPHY & TU Vienna

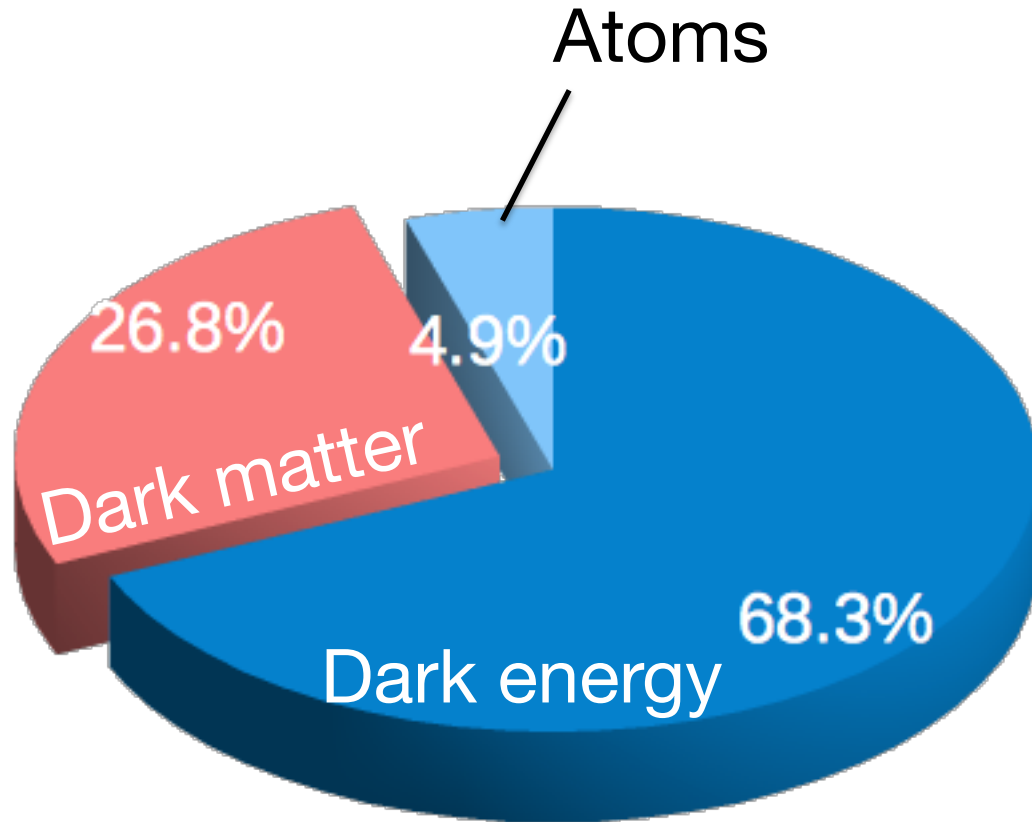
EVIDENCE FOR DARK MATTER



Compelling evidence for dark matter on various cosmological scales



DARK MATTER



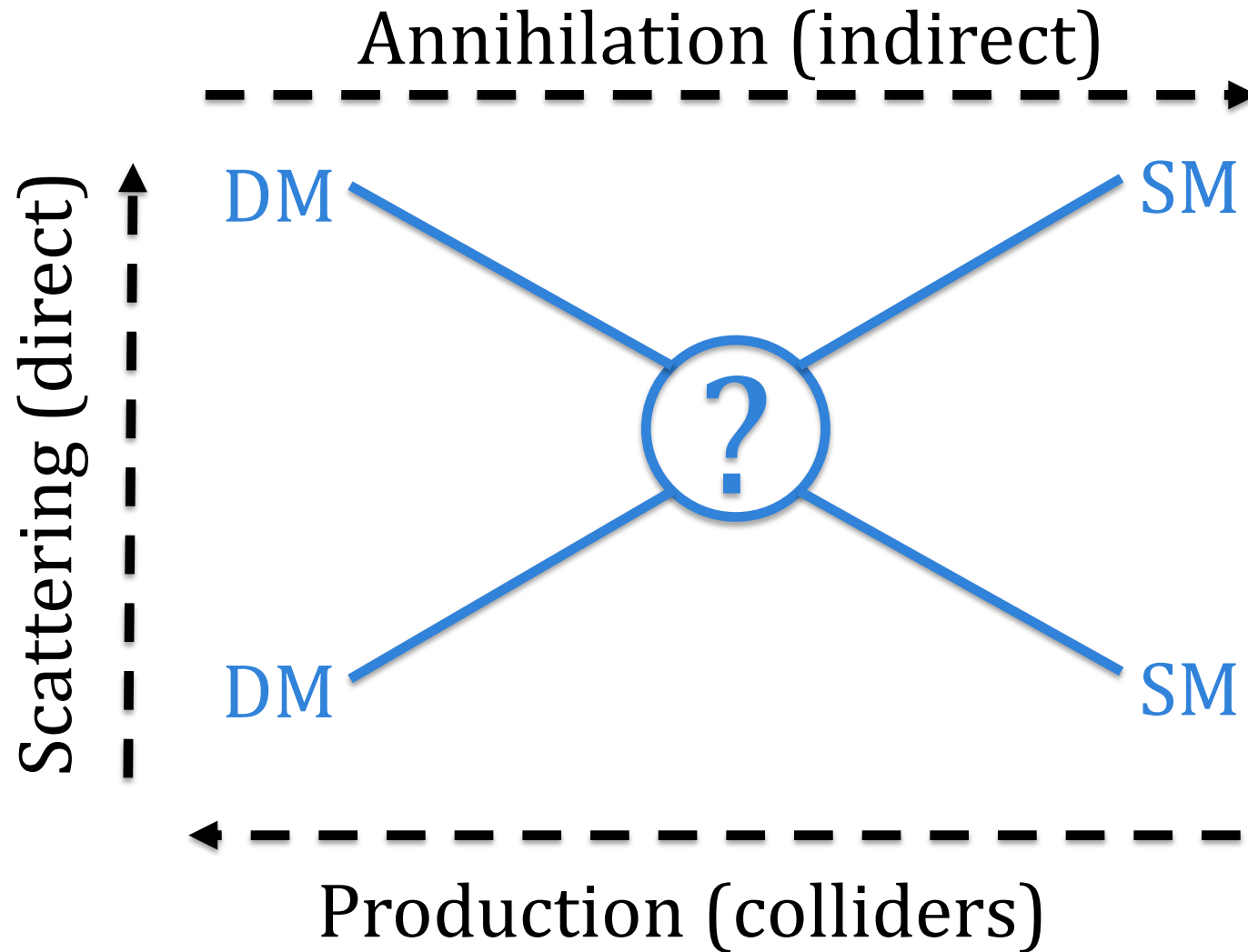
Astronomy

There is a lot of dark matter in the Universe!

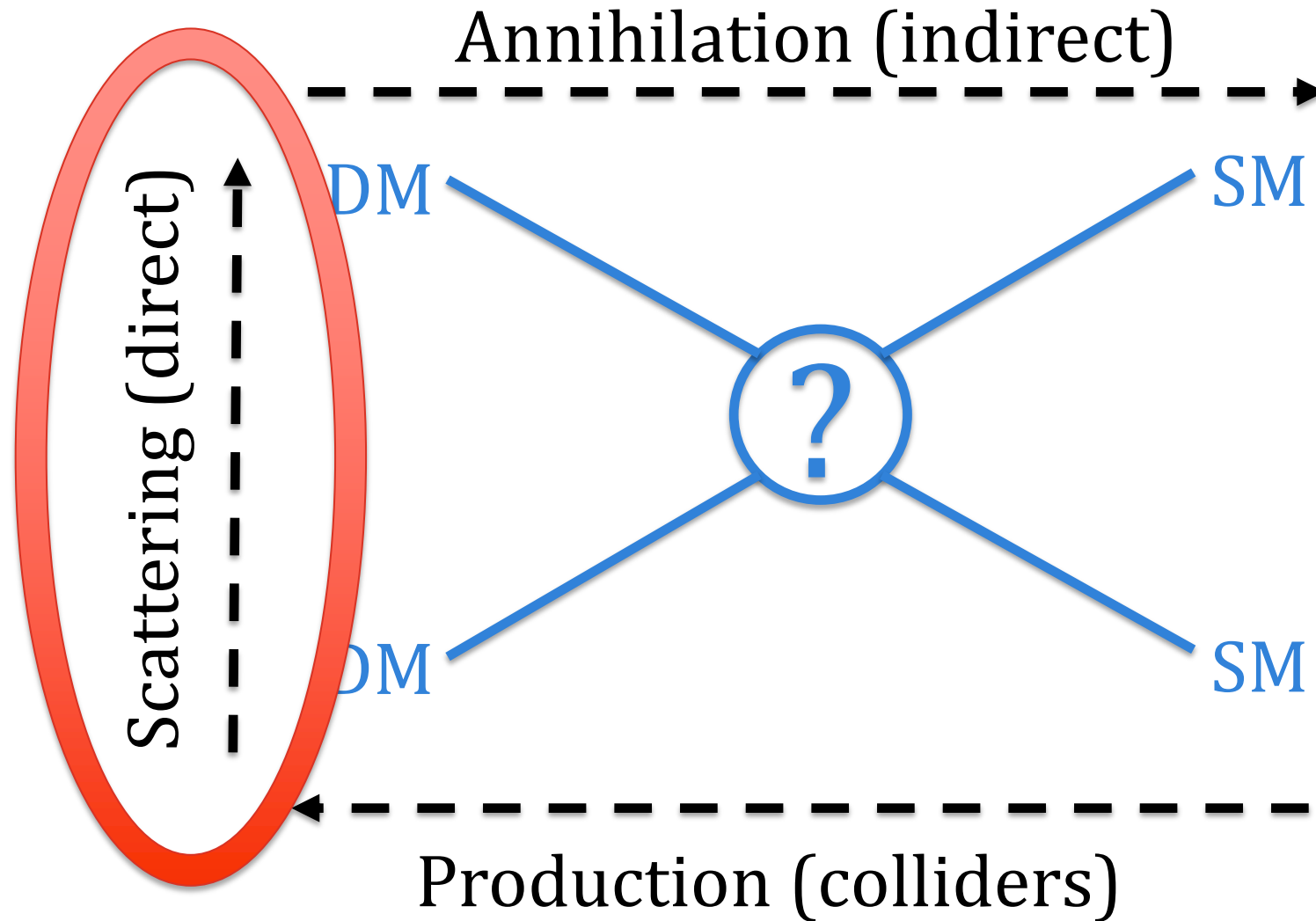
(Astro-) Particle Physics

What is it made of?

DETECTION CHANNELS



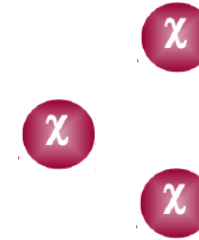
DETECTION CHANNELS



DIRECT DETECTION OF DARK MATTER

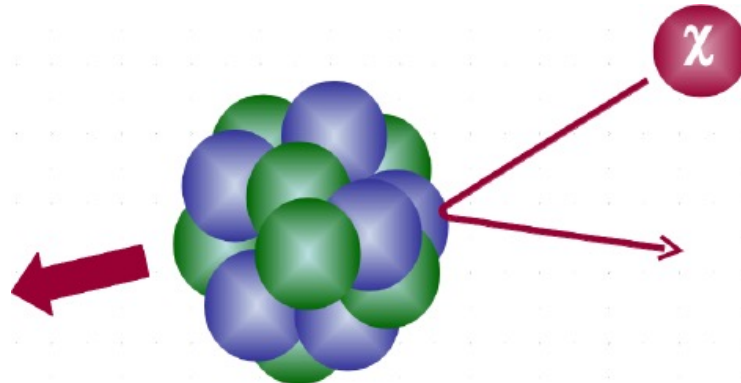
Basic idea

Dark matter is made of particles which interact with Standard Model particles

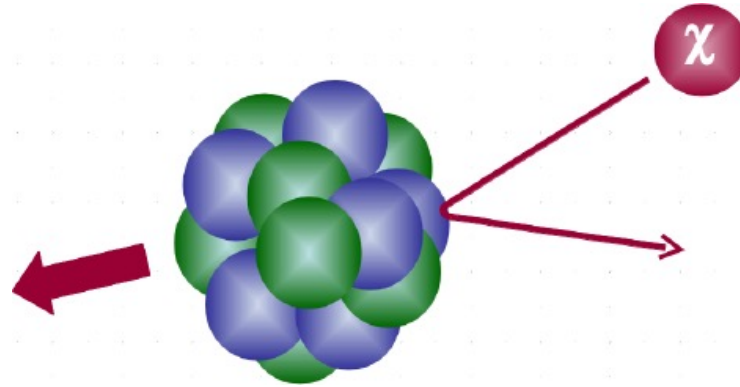


Most common

Dark matter particles induce nuclear recoils



DIRECT DARK MATTER DETECTION – DM-NUCLEUS SCATTERING



Astro physics

Dark matter halo \leftrightarrow

Velocity distribution

Particle physics

Interaction mechanism

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

galactic escape velocity

velocity distribution

WIMP-nucleon cross section

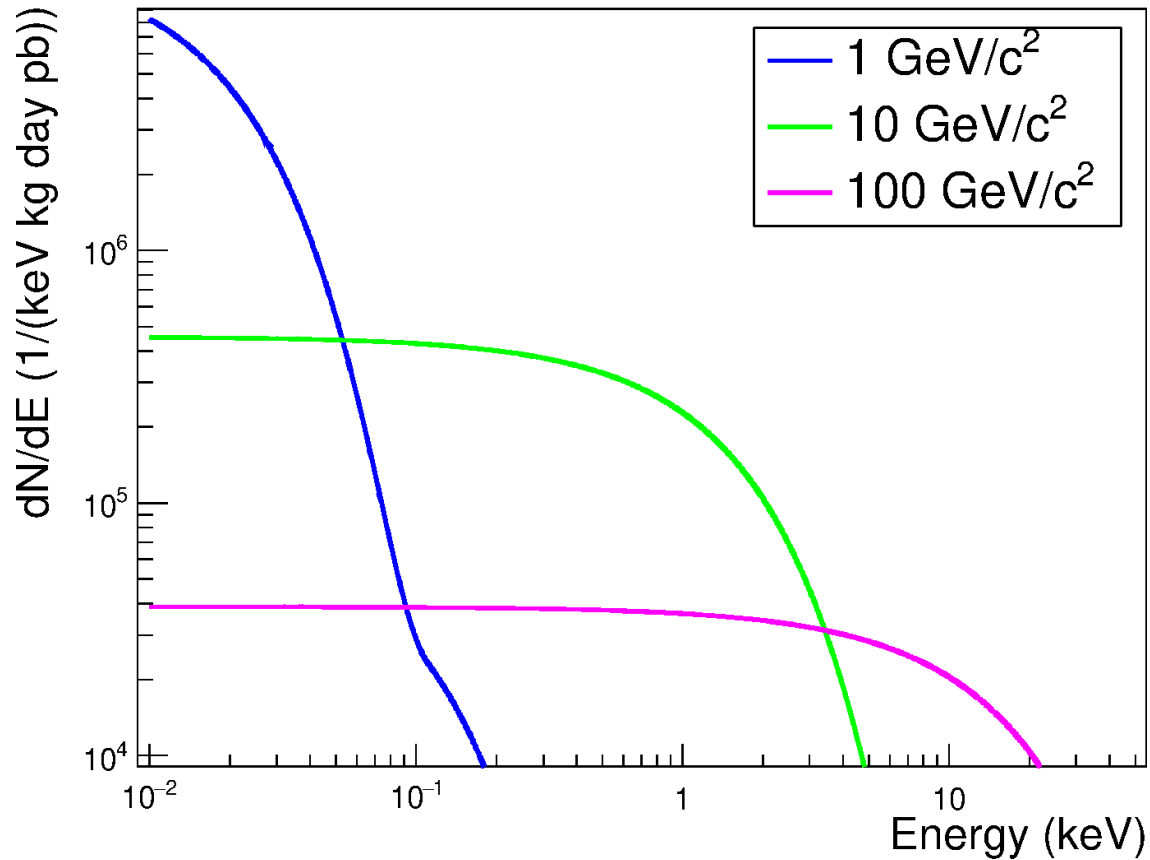
minimal velocity to produce a recoil above E_R

$\sim A^2$
 \sim form factor

EXPERIMENTAL CHALLENGES (DM-NUCLEUS SCATTERING)

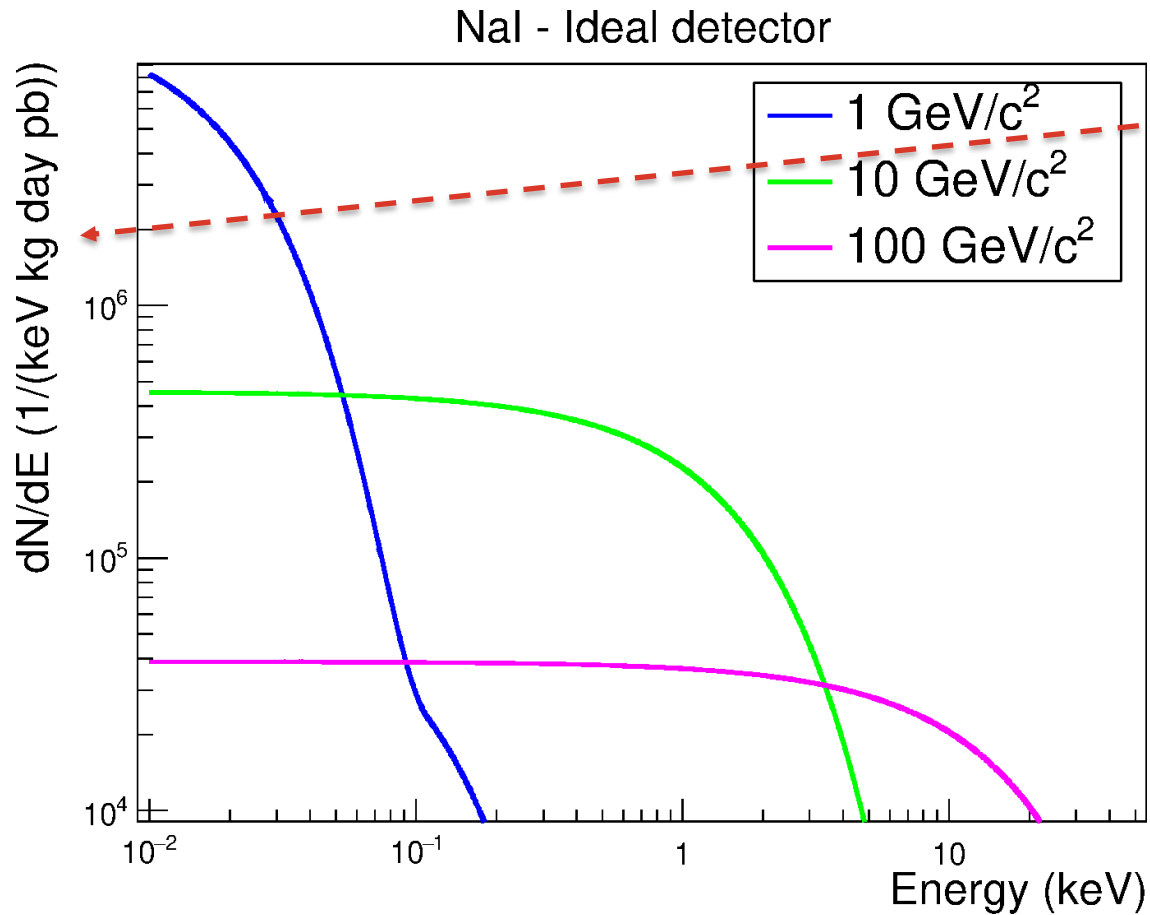
THE DARK MATTER RECOIL SPECTRUM

NaI - Ideal detector



EXPERIMENTAL CHALLENGES (DM-NUCLEUS SCATTERING)

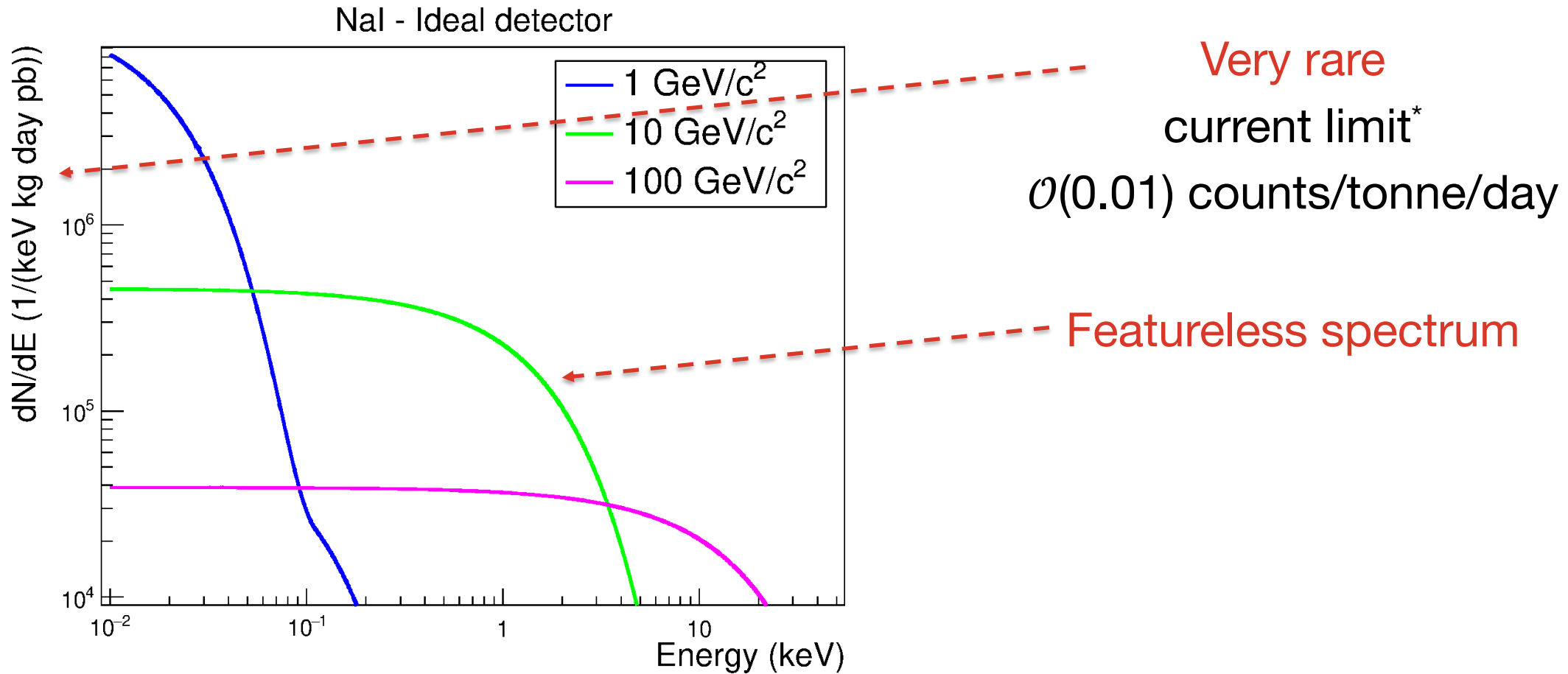
THE DARK MATTER RECOIL SPECTRUM



Very rare
current limit*
 $\mathcal{O}(0.01)$ counts/tonne/day

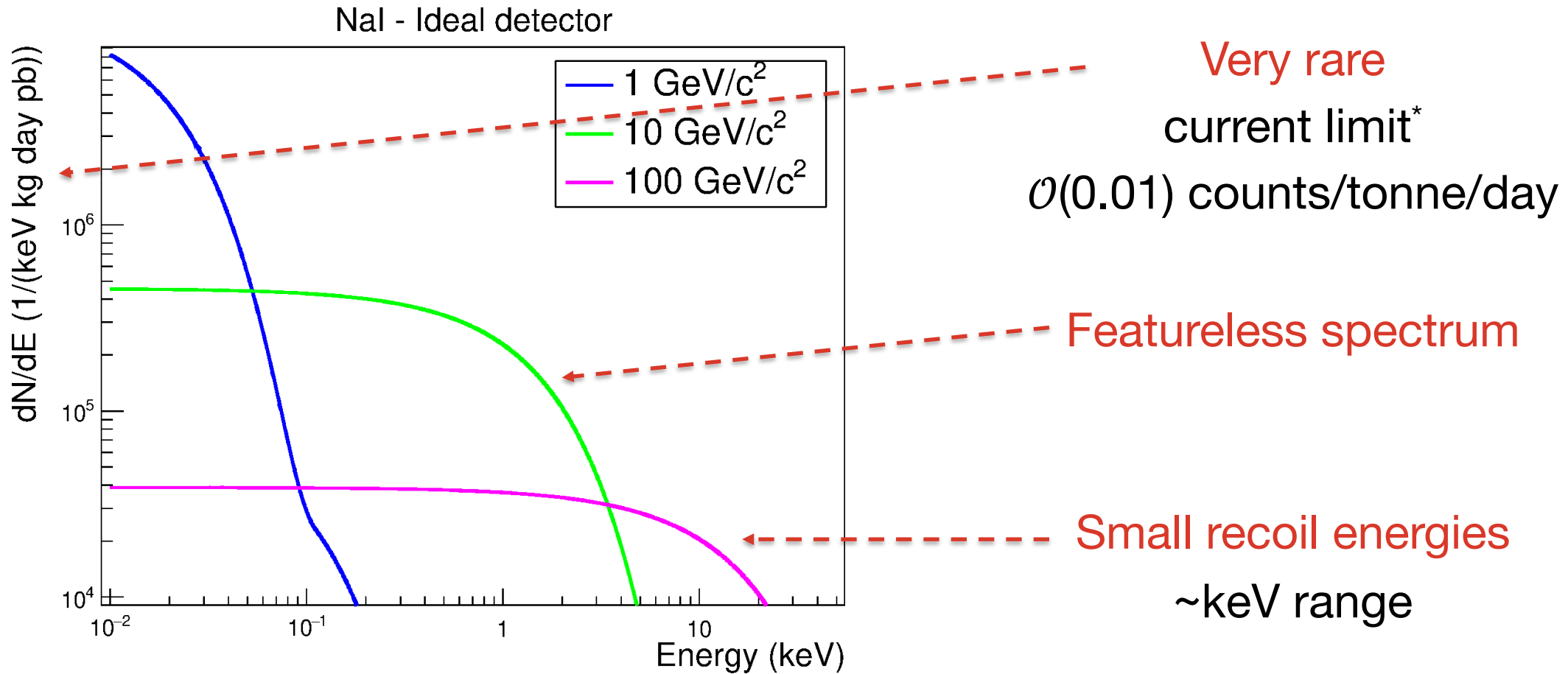
EXPERIMENTAL CHALLENGES (DM-NUCLEUS SCATTERING)

THE DARK MATTER RECOIL SPECTRUM

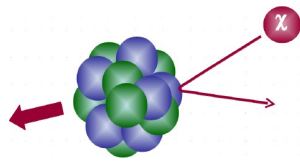


EXPERIMENTAL CHALLENGES (DM-NUCLEUS SCATTERING)

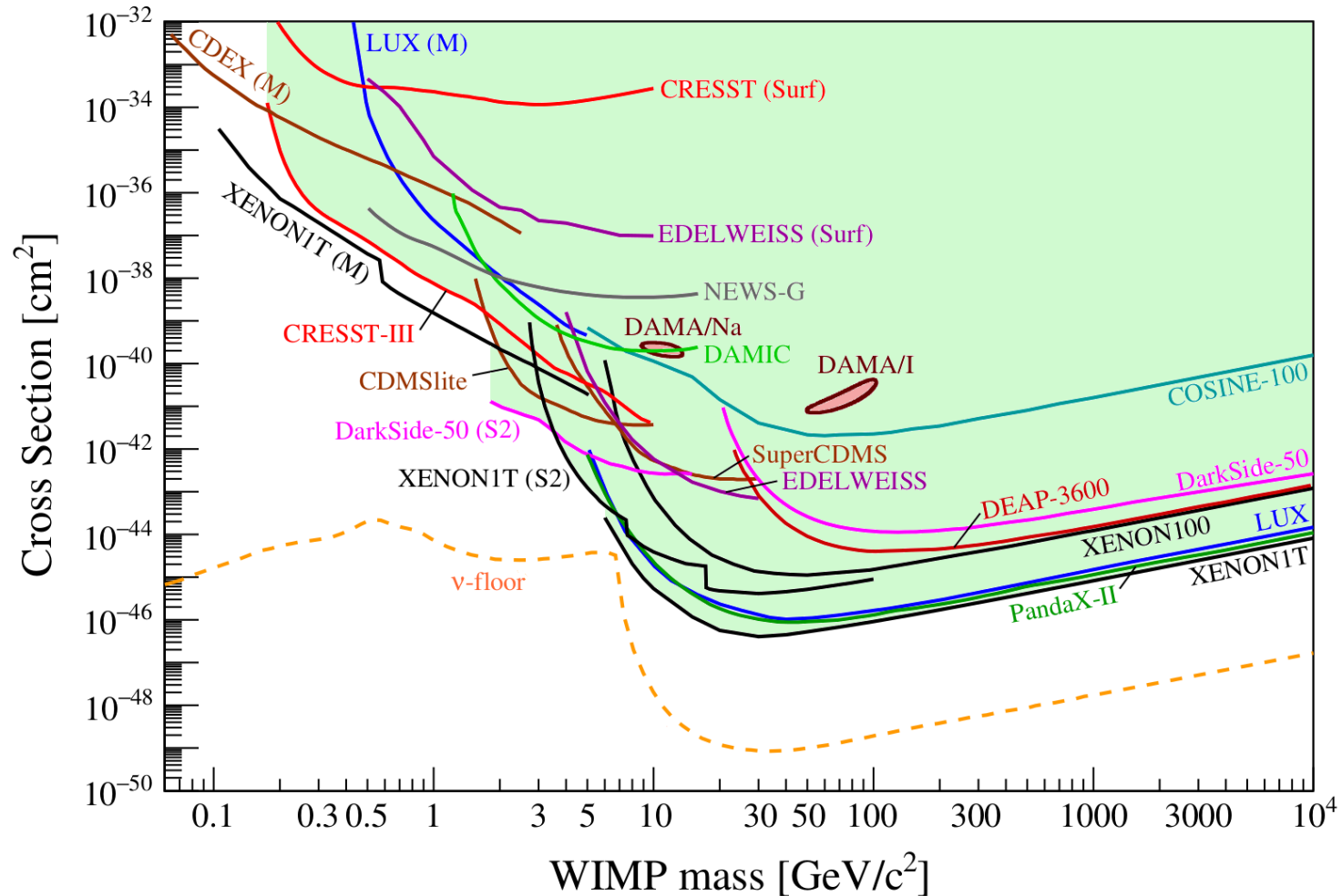
THE DARK MATTER RECOIL SPECTRUM



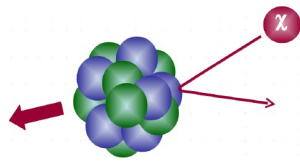
STATUS DIRECT DARK MATTER DETECTION



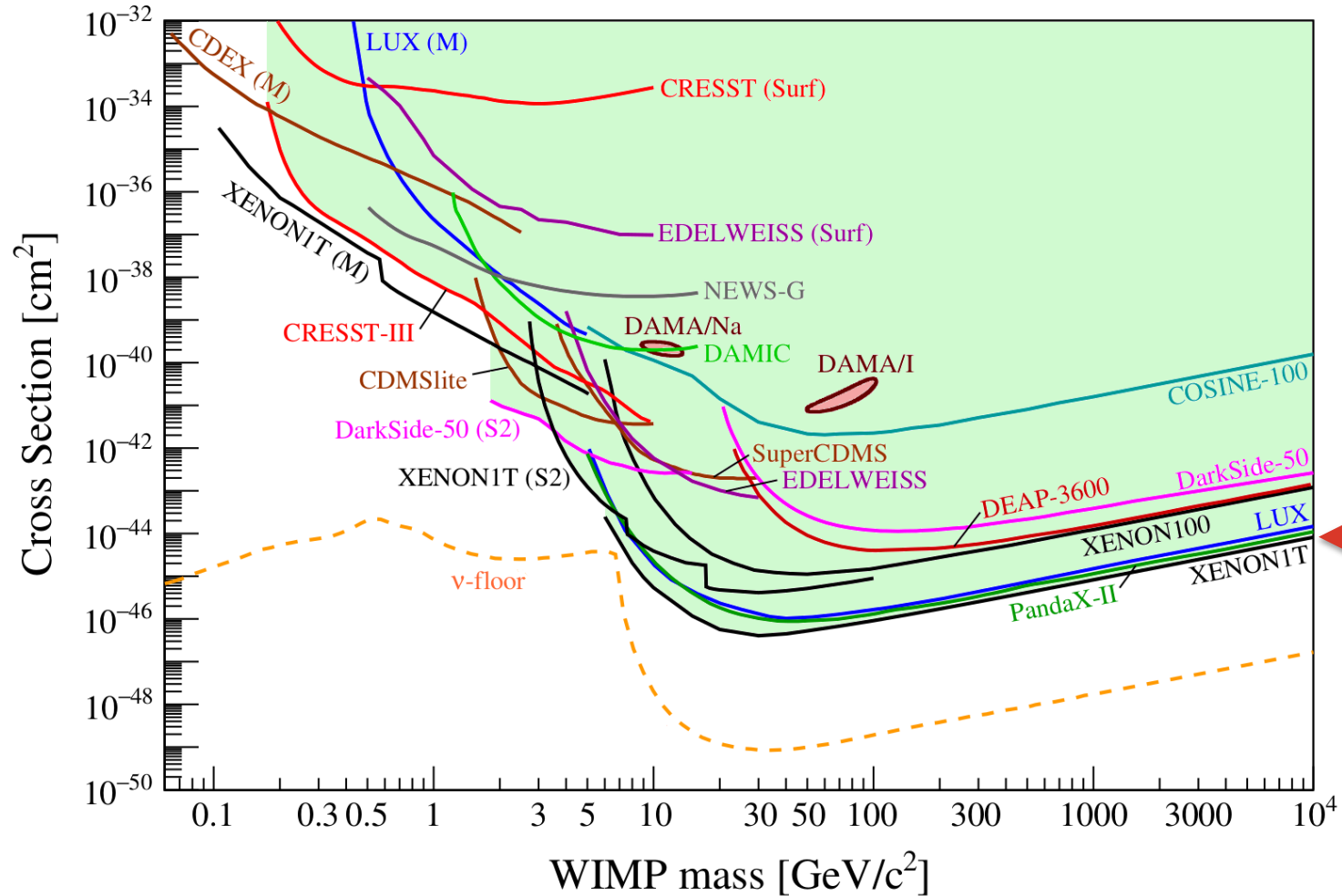
Astroparticle Physics European Consortium APPEC, v1.02, [arXiv:2104.07634](https://arxiv.org/abs/2104.07634)



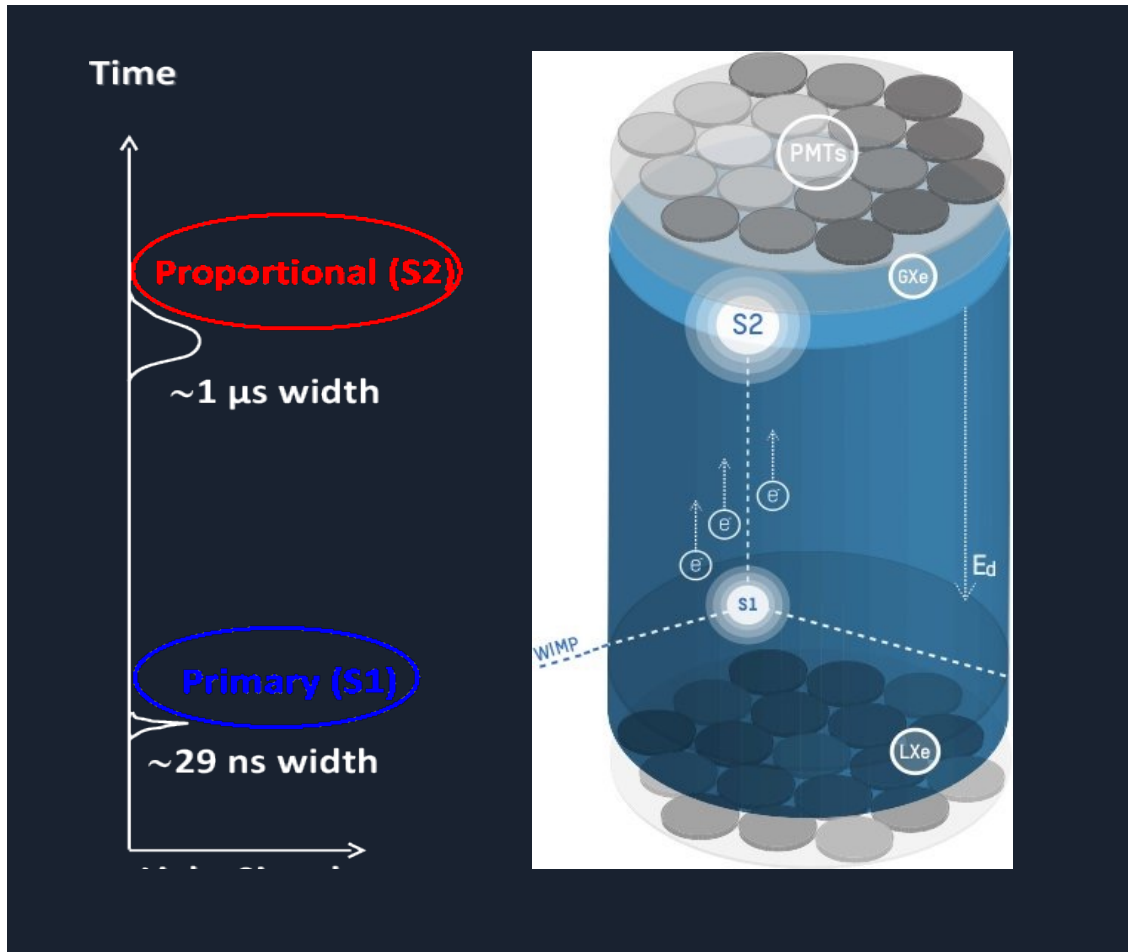
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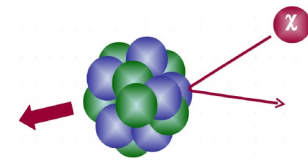


LIQUID NOBLE GAS DETECTORS – THE “CLASSIC WIMP” EXPLORER

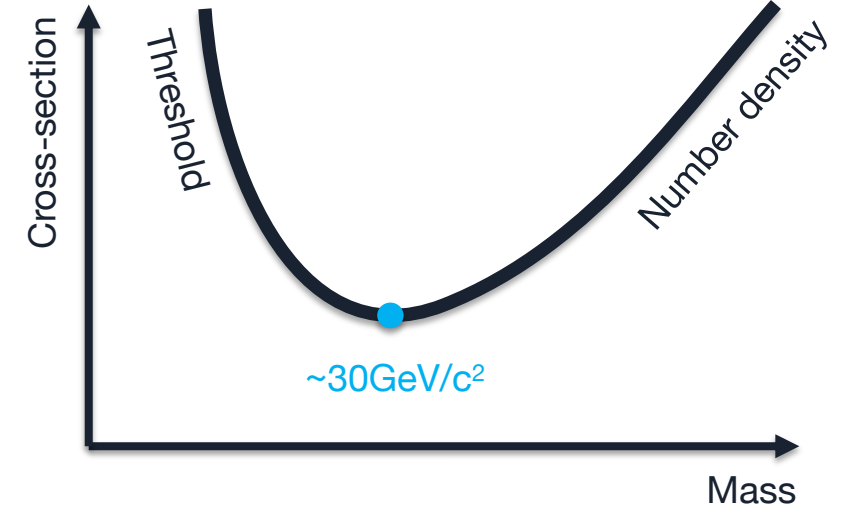
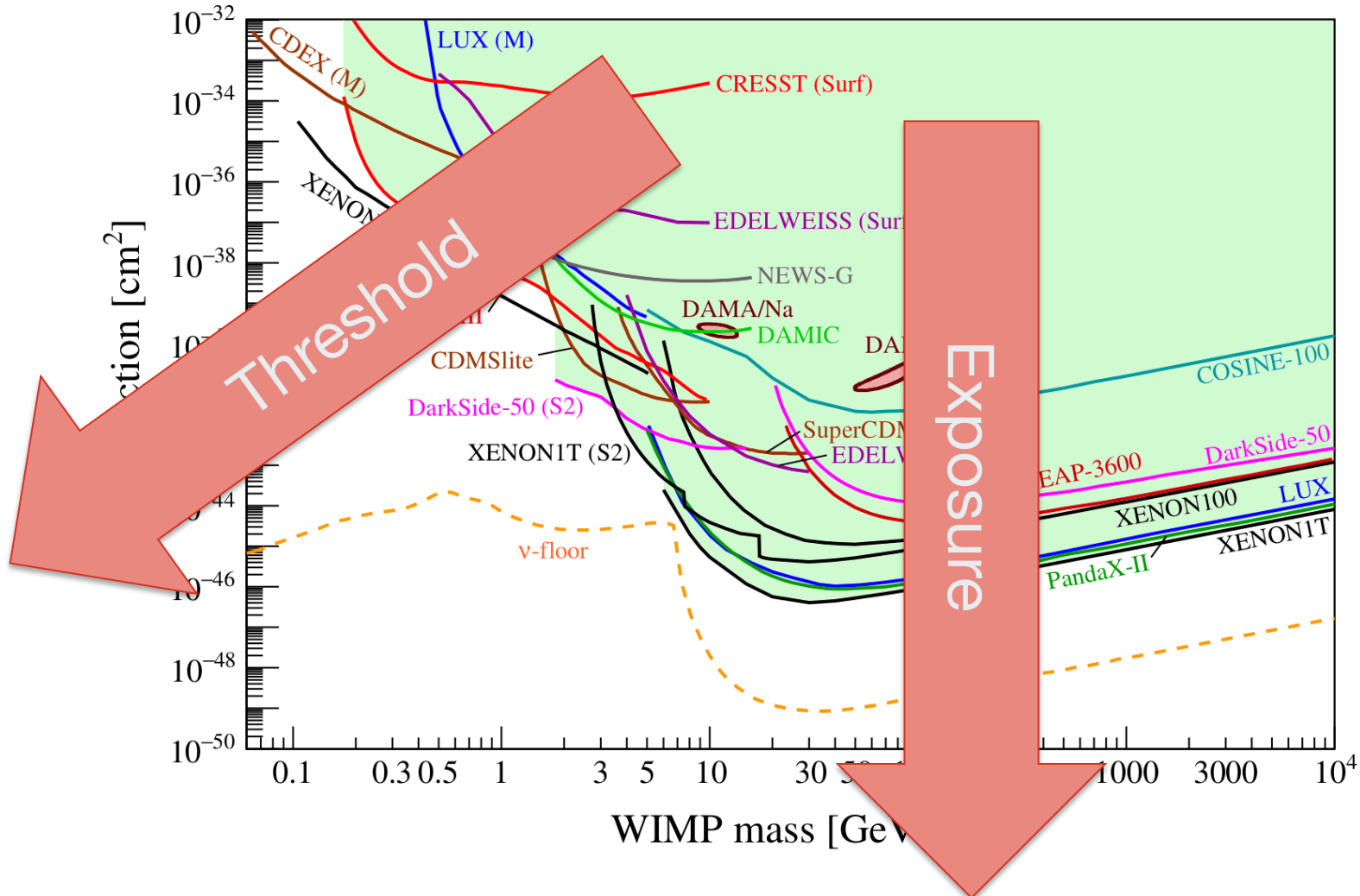


- Fiducialization - Self-shielding
 - Constant purification
 - Scalable to large target masses (up to 20tonnes)
 - Experiments
Xe: LUX/LZ, XENON/Darwin, PandaX ...
Ar: DarkSide
- Low background + high target mass
the ideal DM detector?

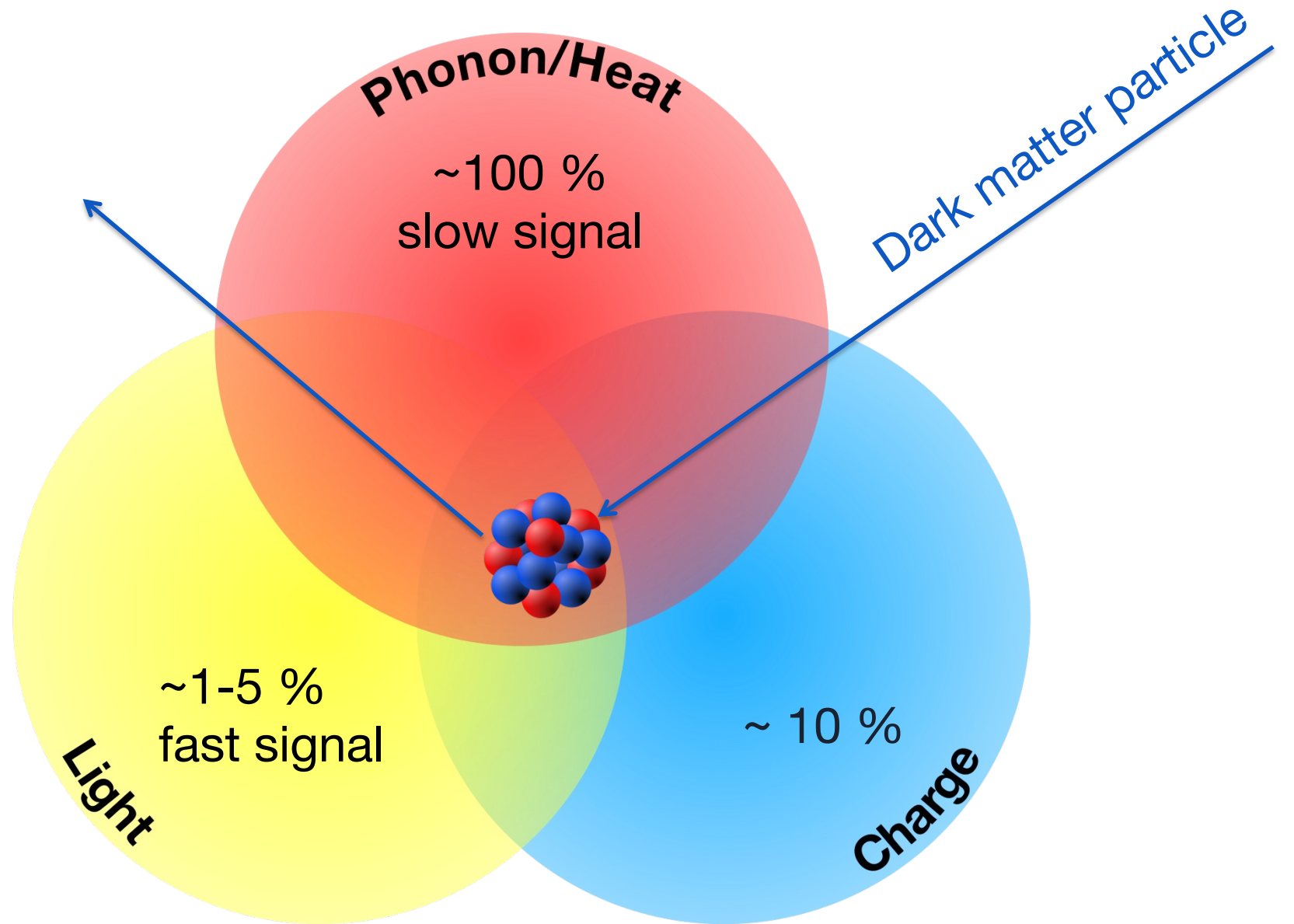
STATUS DIRECT DARK MATTER DETECTION



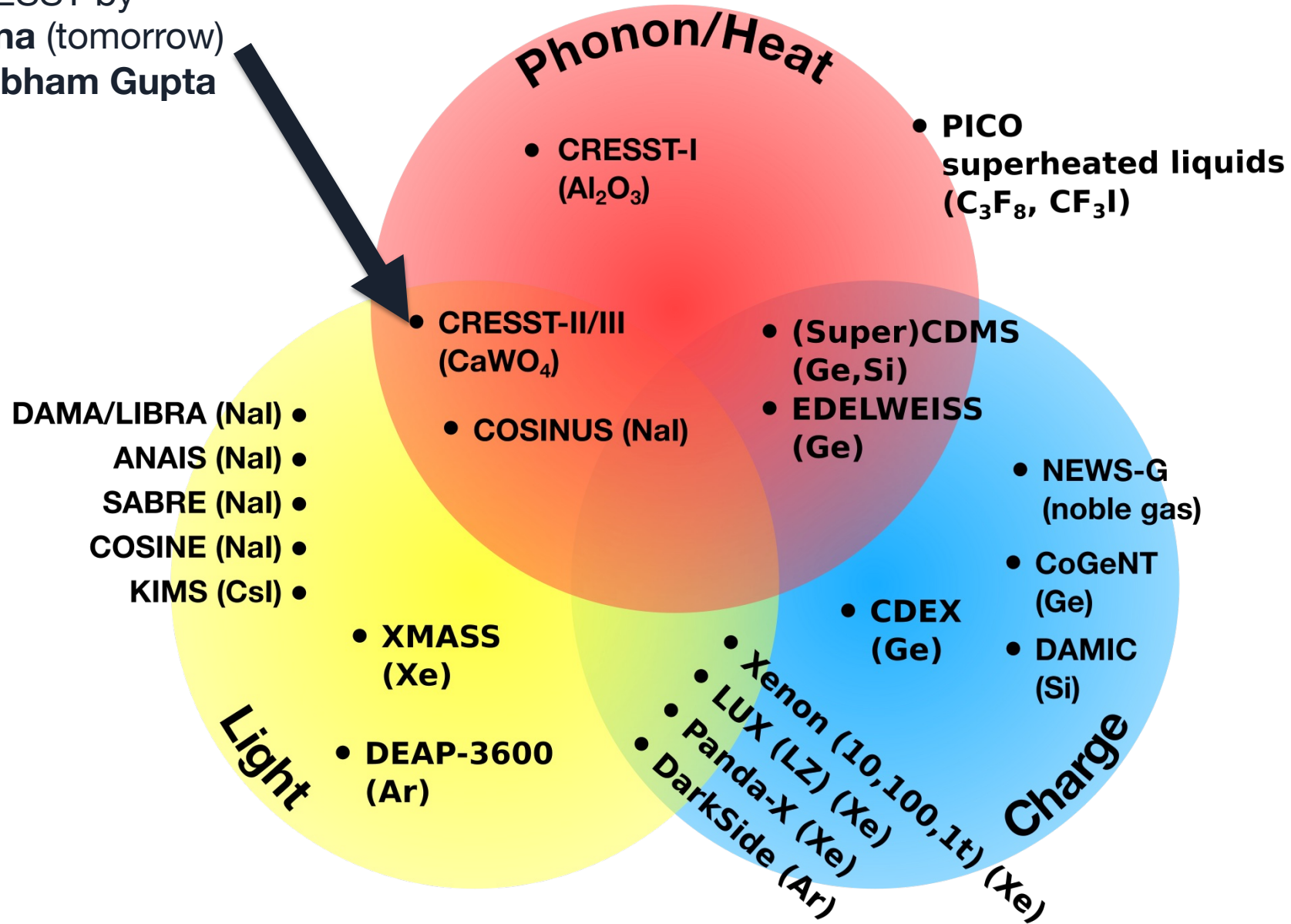
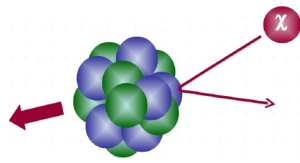
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DIRECT DETECTION CHANNELS

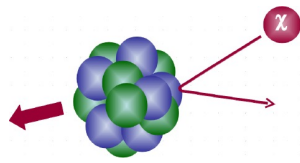
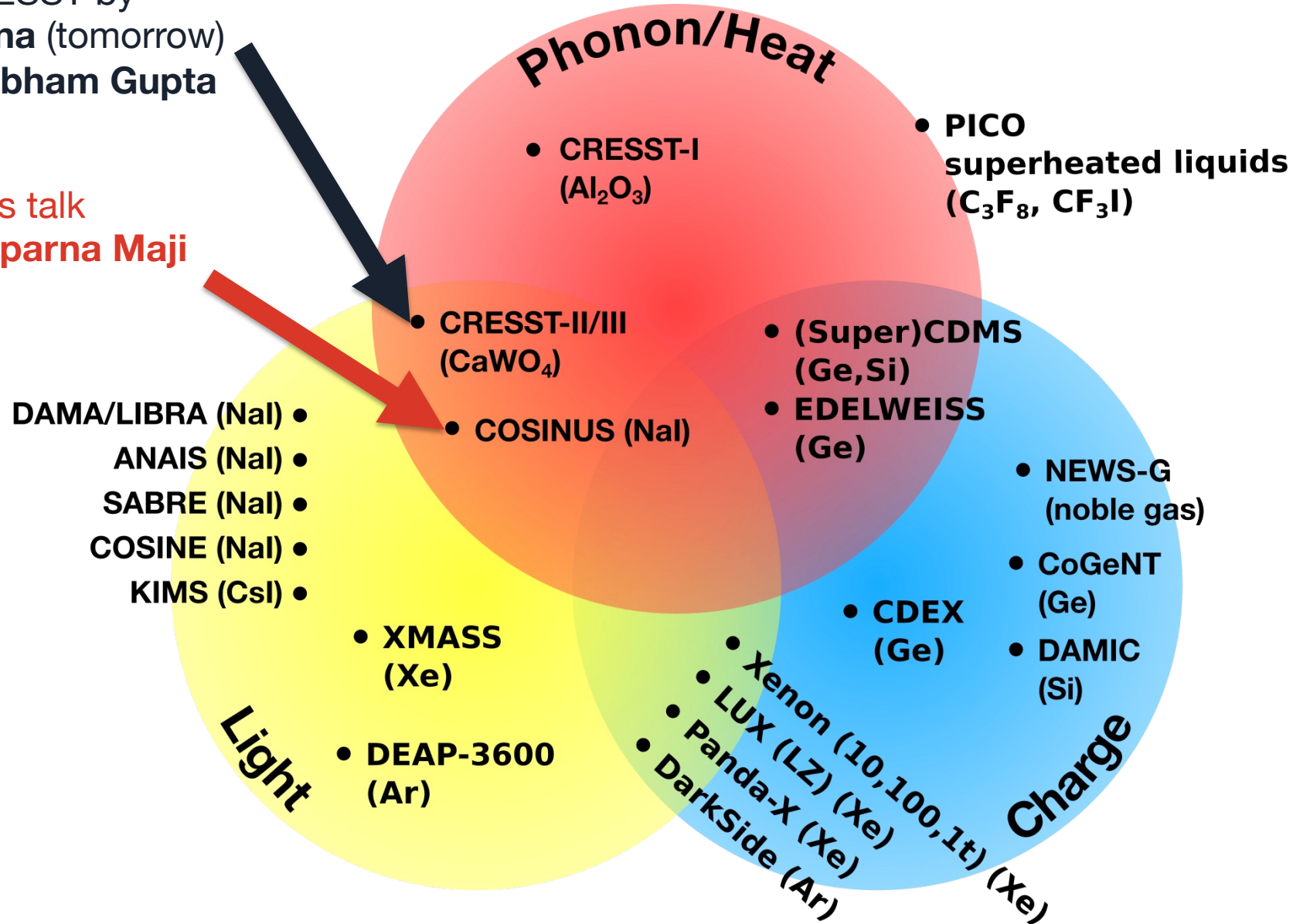


Talk on CRESST by
Valentyna Mokina (tomorrow)
+ Poster by **Shubham Gupta**

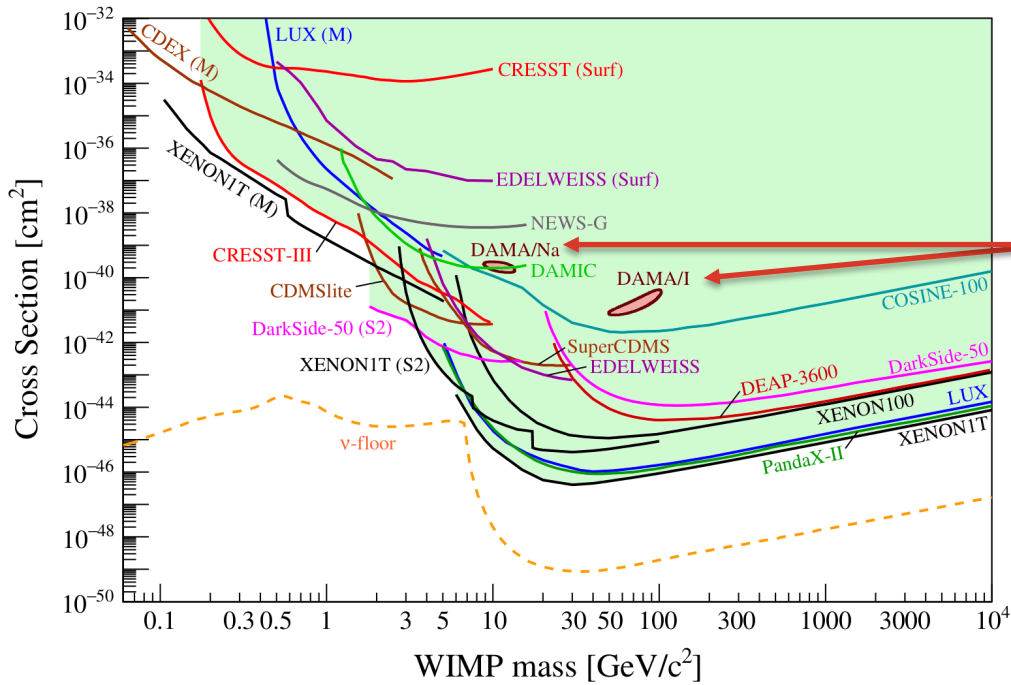


Talk on CRESST by
Valentyna Mokina (tomorrow)
+ Poster by **Shubham Gupta**

Rest of this talk
+ Poster by **Rituparna Maji**



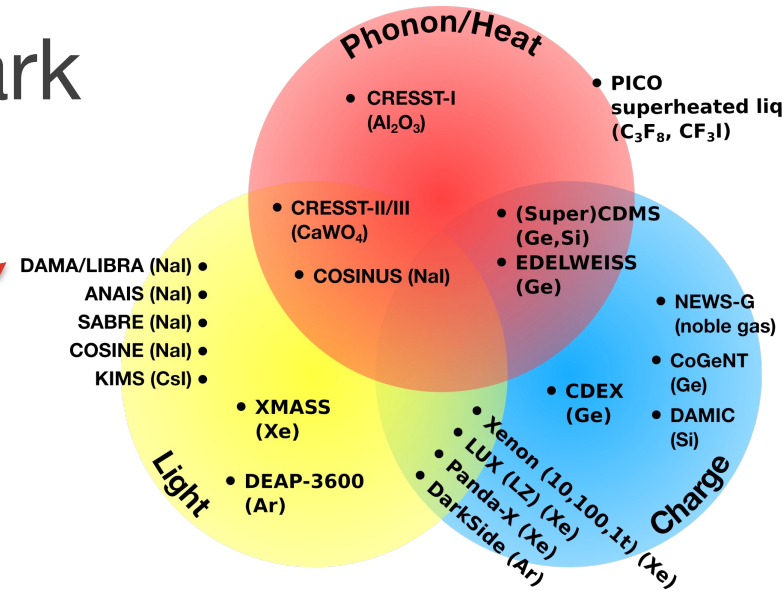
STATUS IN DIRECT DARK MATTER DETECTION



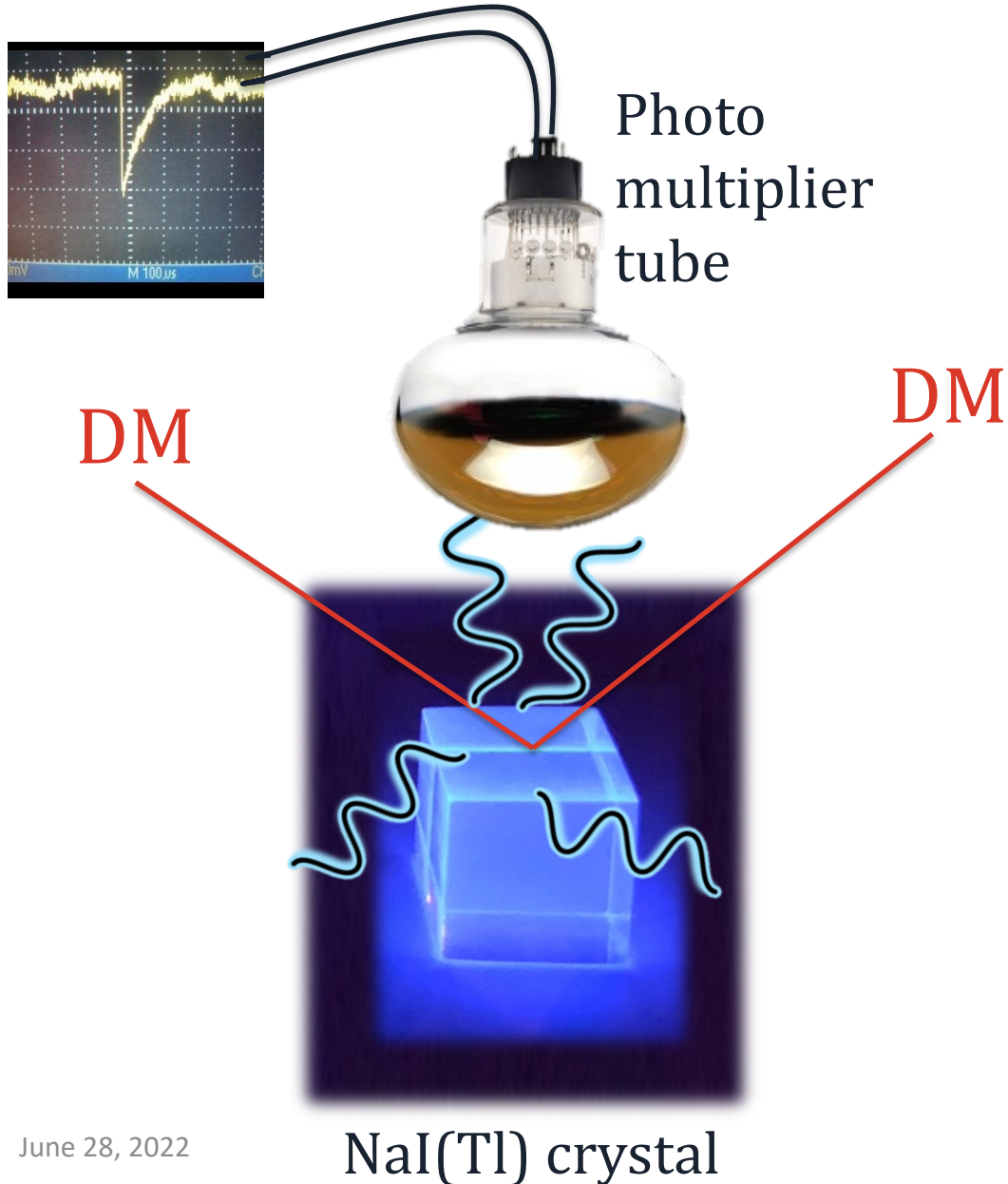
DAMA/LIBRA

The only strong dark matter claim

Single-channel
(light only)

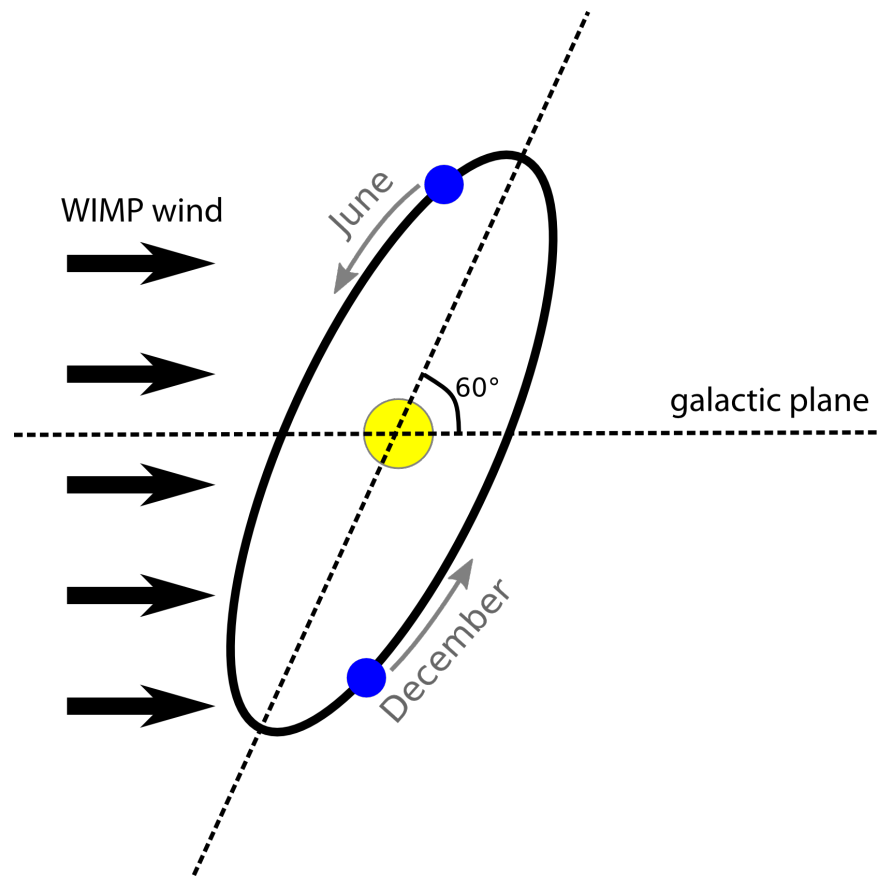


DAMA – WORKING PRINCIPLE



- Single channel: Scintillation light
- Electron-equivalent energy scale
- No event-by-event discrimination between electron recoils and nuclear recoils off Na and I

THE RELATIVE VELOCITY MODULATES AND SO SHOULD THE INTERACTION RATE



The smoking gun
evidence?

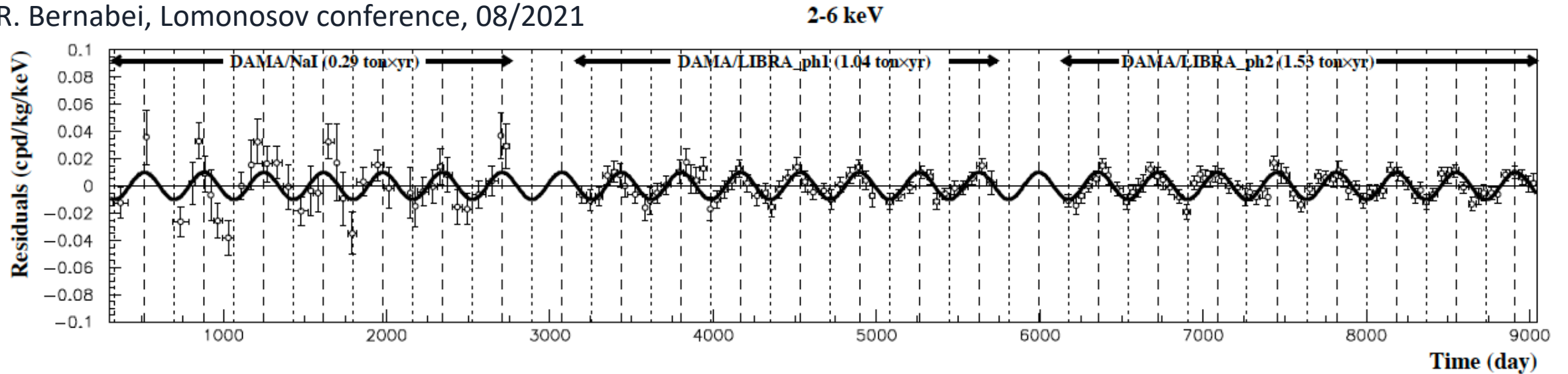


Period: 1 year
Phase: cosine peaking June 2nd

DAMA/LIBRA MODULATION SIGNAL

TIME DISTRIBUTION

R. Bernabei, Lomonosov conference, 08/2021



~25years of data
2.86 tonne years exposure
 13.7σ statistical significance

A DARK MATTER SIGNAL?

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)keVee interval

A DARK MATTER SIGNAL?

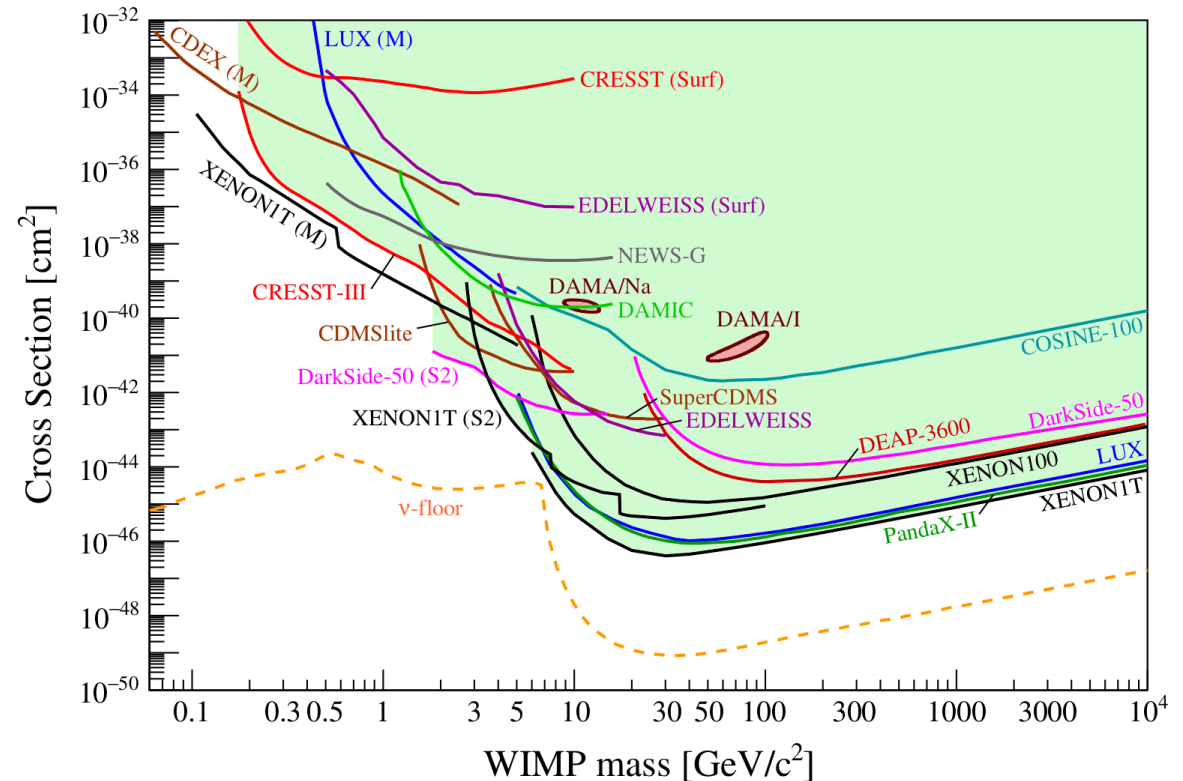
Statistics: 13.7σ ✓

Period: (0.99834 ± 0.00067) years* ✓

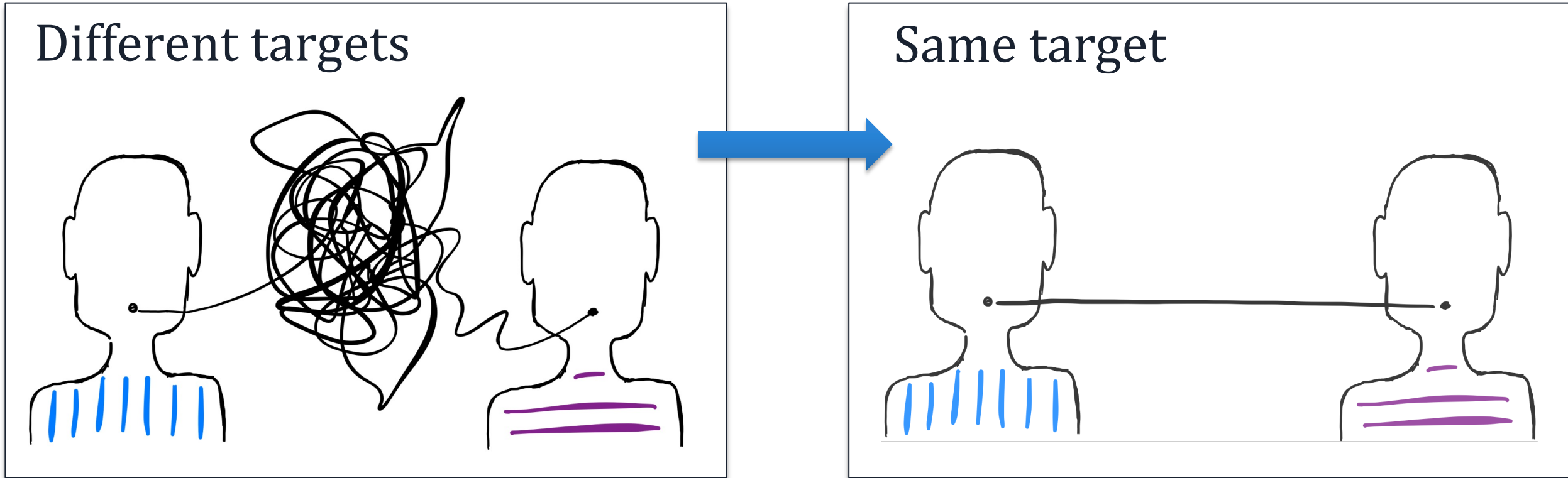
Phase: 22^{th} May \pm 4 days* ✓
(cosine peaking June 2nd)

Convincing non-DM explanation ✗

*in (2-6)keVee interval



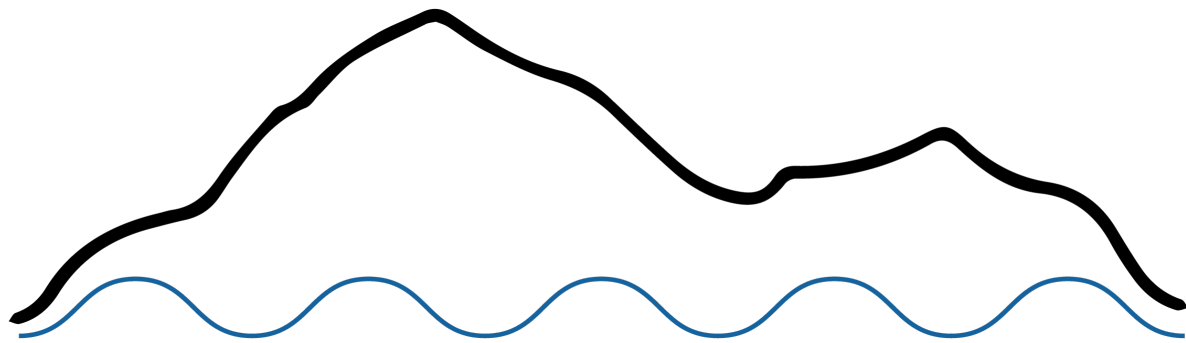
WHAT ARE THE UNKNOWNNS?



→ Target material dependence

→ →Astroparticle Physics European Consortium (APPEC) Recommendation:

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



COSINUS

~25 scientists

Collaboration meeting Nov 2021

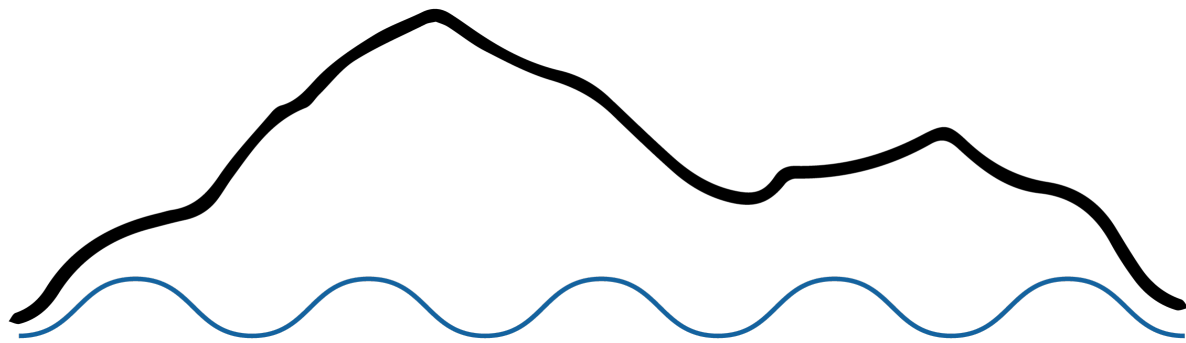


MAX-PLANCK-INSTITUT
FÜR PHYSIK



Istituto Nazionale di Fisica Nucleare





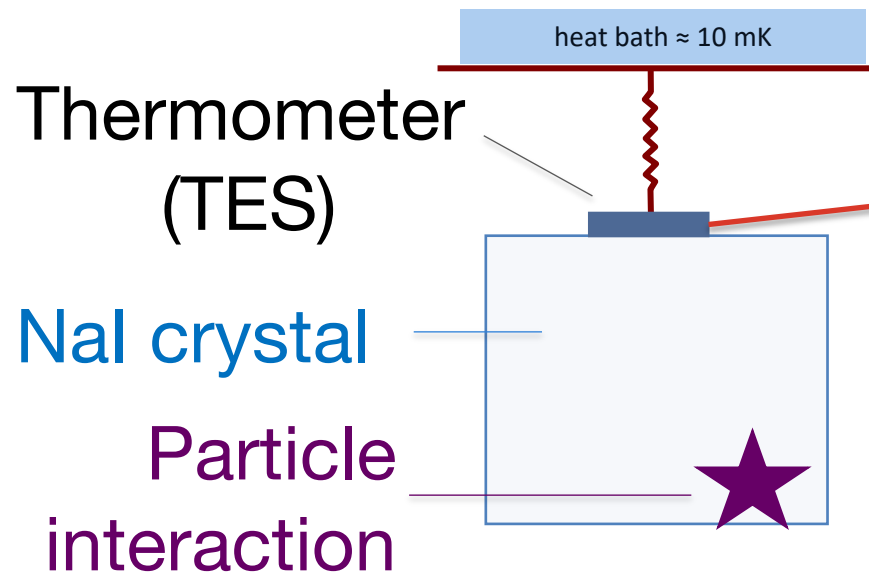
THE COSINUS EXPERIMENT

Aims at a model- and material-independent test of DAMA

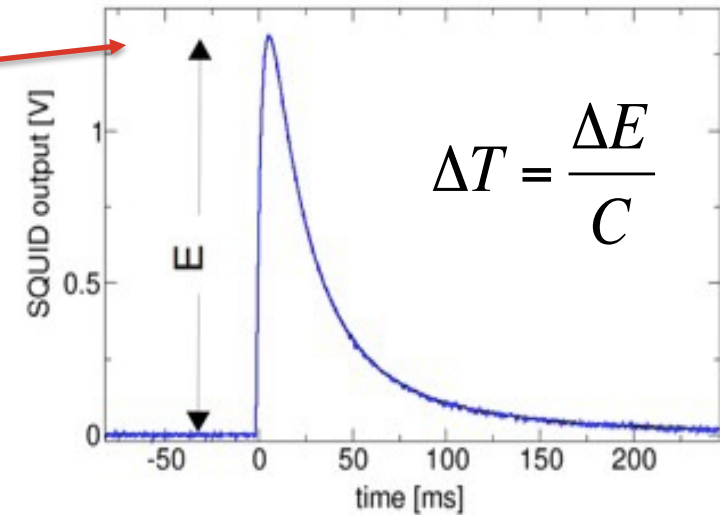
Novel and unique: operation of NaI as cryogenic detector

- Low threshold (in particular for nuclear recoils)
- Precise energy information
- Signal-only measurement of potential DM signal

CRYOGENIC DETECTOR



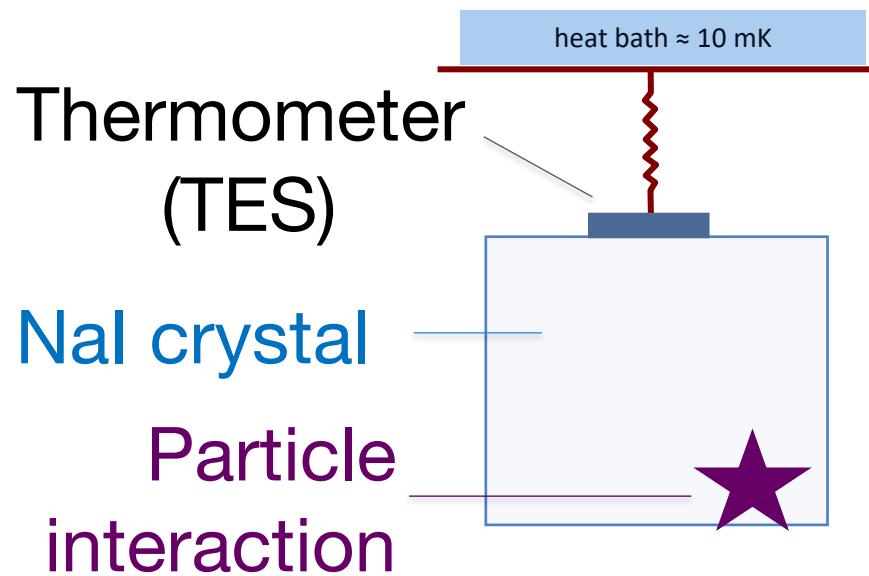
Temperature pulse



Ultimate energy resolution is determined by how well you can measure ΔT against thermodynamic fluctuations

Low temperature
Low heat capacity } High sensitivity

CRYOGENIC DETECTOR

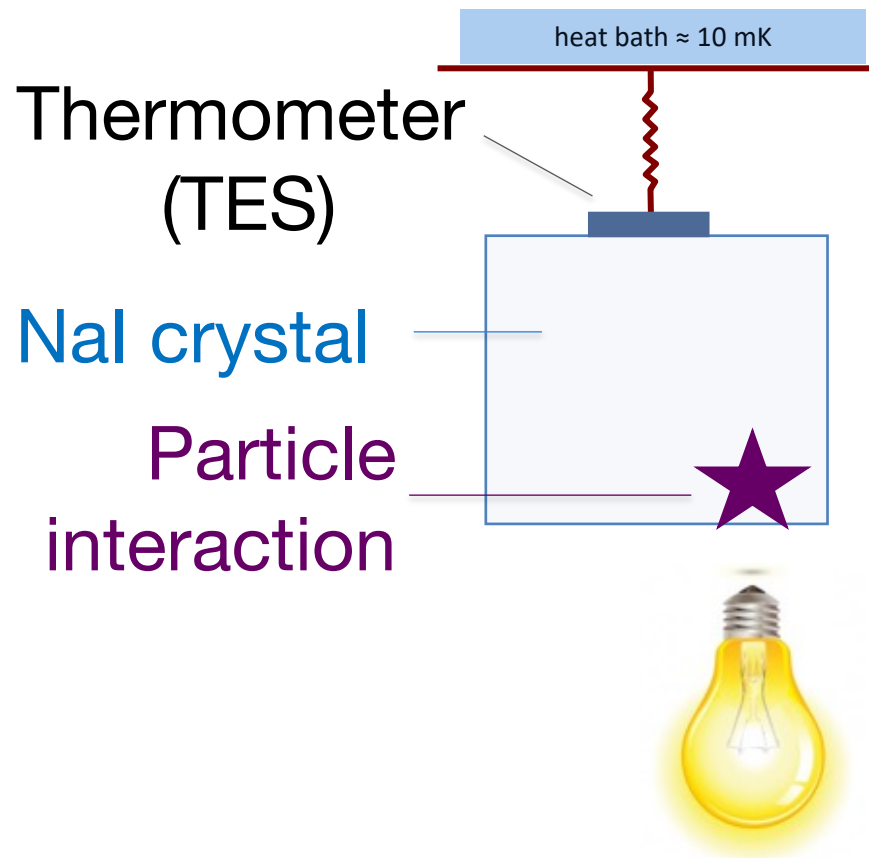


Phonon signal ($\sim 90\%$)

(Almost) independent of particle type

Precise measurement of the deposited energy

SCINTILLATING CALORIMETER



Phonon signal (\sim 90 %)

(Almost) independent of particle type

Precise measurement of the deposited energy

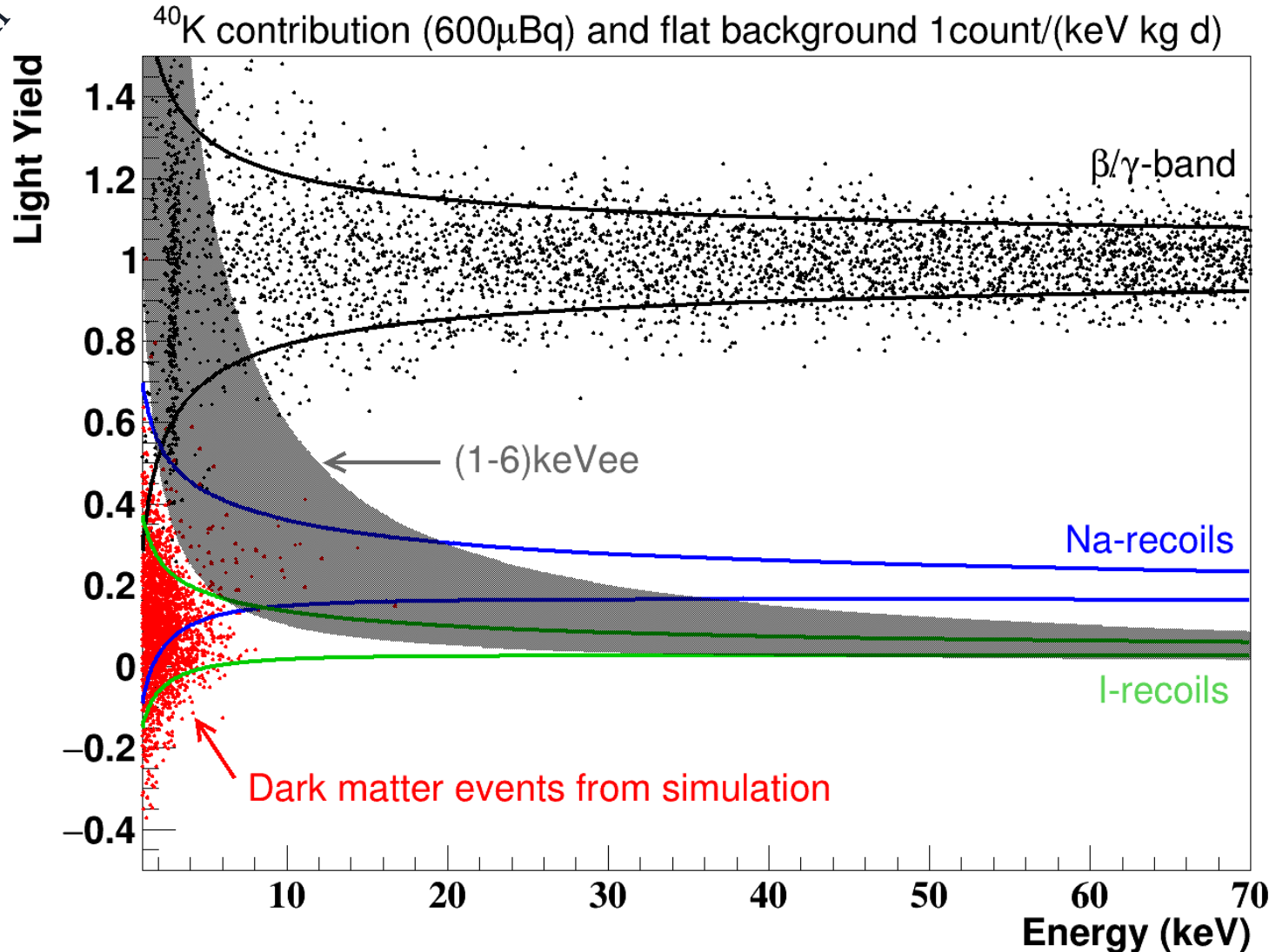
Scintillation light (few %)

Particle-type dependent
→ LIGHT QUENCHING

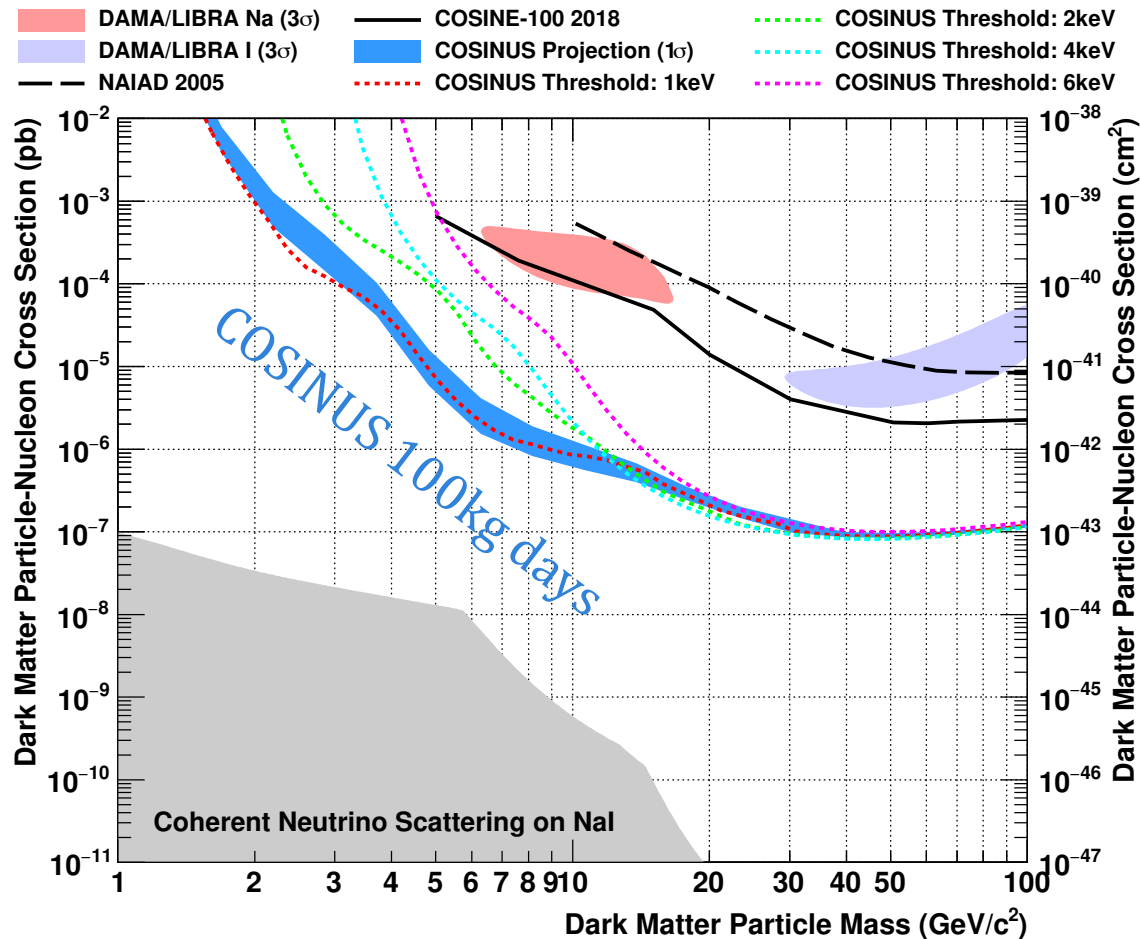
SIMULATION

100 KG-DAYS BEFORE CUTS
1 KEV NUCLEAR RECOIL THRESHOLD

$\frac{\text{light signal}}{\text{phonon signal}}$



(1-6)keVee
=
modulation
signal in
DAMA



COSINUS – 1π (2022-2025)

Exclude or confirm nuclear recoil origin of DAMA with total rate measurement:

- Independent of dark matter halo
- For any interaction of dark matter with nuclei

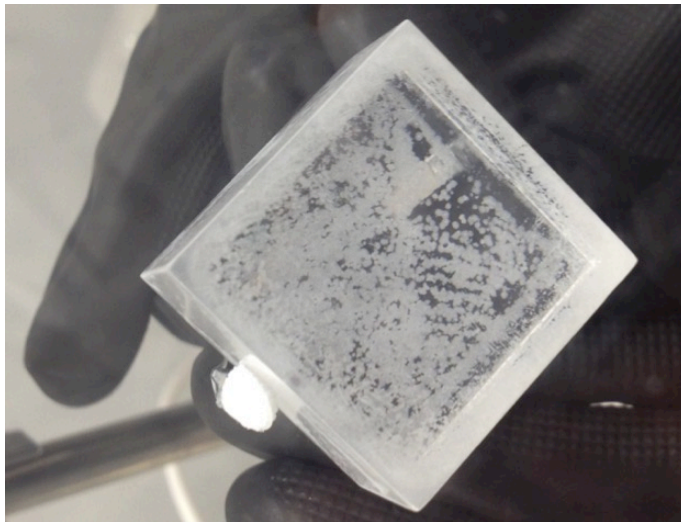
COSINUS – 2π (≥ 2026)

Investigate annual modulation signature with COSINUS

A CRYOGENIC NAI DETECTOR IS AWESOME: WHY DID IT NOT EXIST? → BECAUSE NAI IS NOT NAICE!

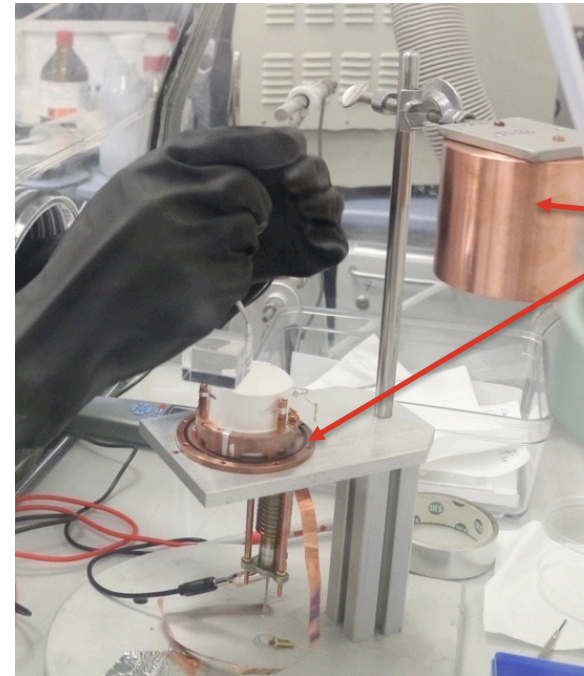
PROBLEM

Hygroscopic nature



SOLUTION

Handling in controlled atmosphere



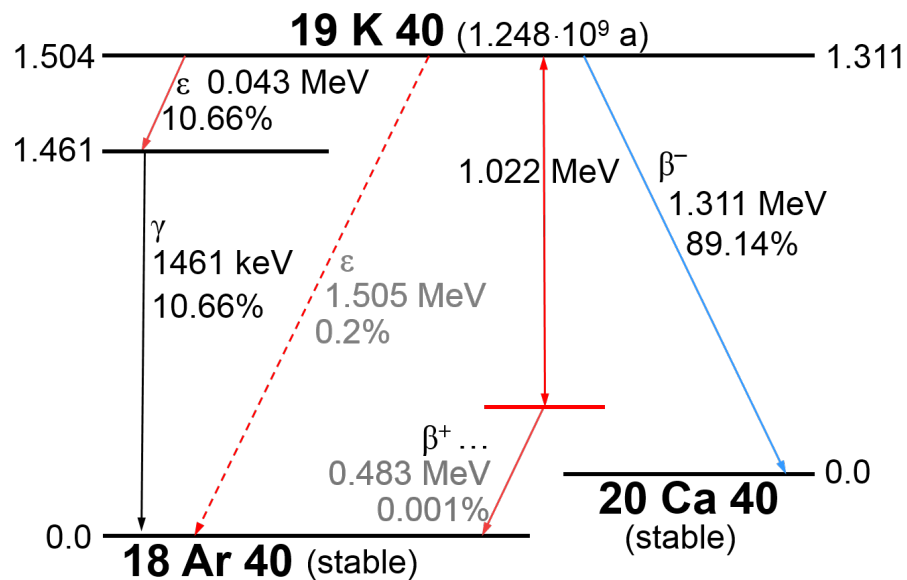
Container with specifically designed cryogenic valve to install container in cryostat

A CRYOGENIC NAI DETECTOR IS AWESOME: WHY DID IT NOT EXIST?

→ BECAUSE NAI IS NOT NAICE!

PROBLEM

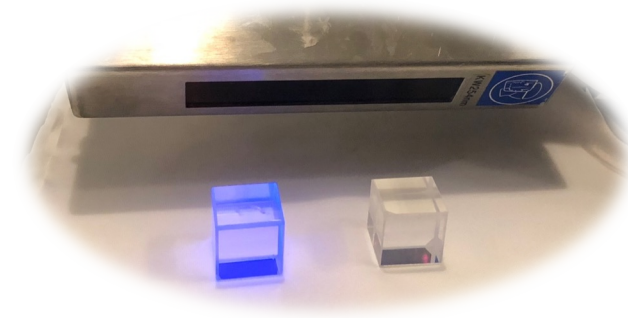
Typically high contamination with ^{40}K



3 keV Auger electron emitted together with the 1.46 MeV gamma quantum

SOLUTION

Cooperation with



DAMA: ~ 13 ppb*

COSINUS (preliminary): 7ppb (crystal nose) to 28ppb (crystal tail)

^{40}K Radiopurity on level with DAMA

A CRYOGENIC NAI DETECTOR IS AWESOME: WHY DID IT NOT EXIST?

→ BECAUSE NAI IS NOT NAICE!

PROBLEM

Low Debye temperature

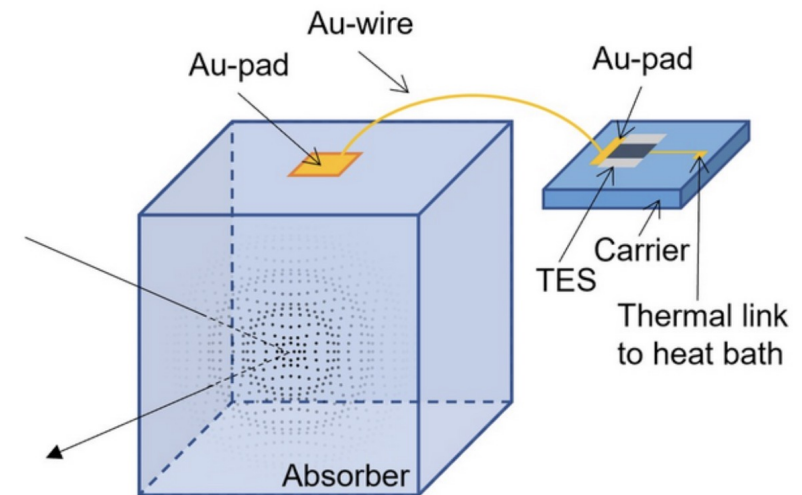
Properties	NaI(pure)	CsI(pure)	CdWO ₄	CaWO ₄
Density [g/cm ³]	3.67	4.51	7.9	6.12
Melting point [°C]	661	894	1598	1650
Structure	CsCl	CsCl	Wolframite	Scheelite
λ_{max} at 300 K [nm]	~300	~315	~475	420-425
Hygroscopic	yes	slightly	no	no
Θ_D [K]	169	125	-	335
Photons per keV at 3.4 K	19.5 ± 1.0	58.9 ± 5.6	-	-
Mean energy of emitted photon [eV]	3.3	3.9	-	3.14

Small signal amplitudes

SOLUTION

[arxiv:2111.00349v1](https://arxiv.org/abs/2111.00349v1)

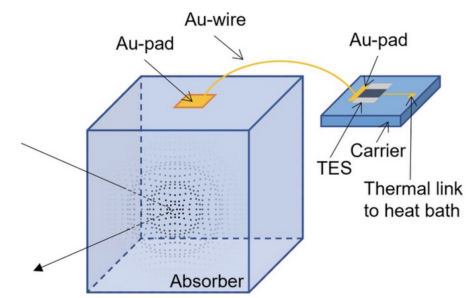
remoTES detector design



NaI → Au-wire/pad → TES

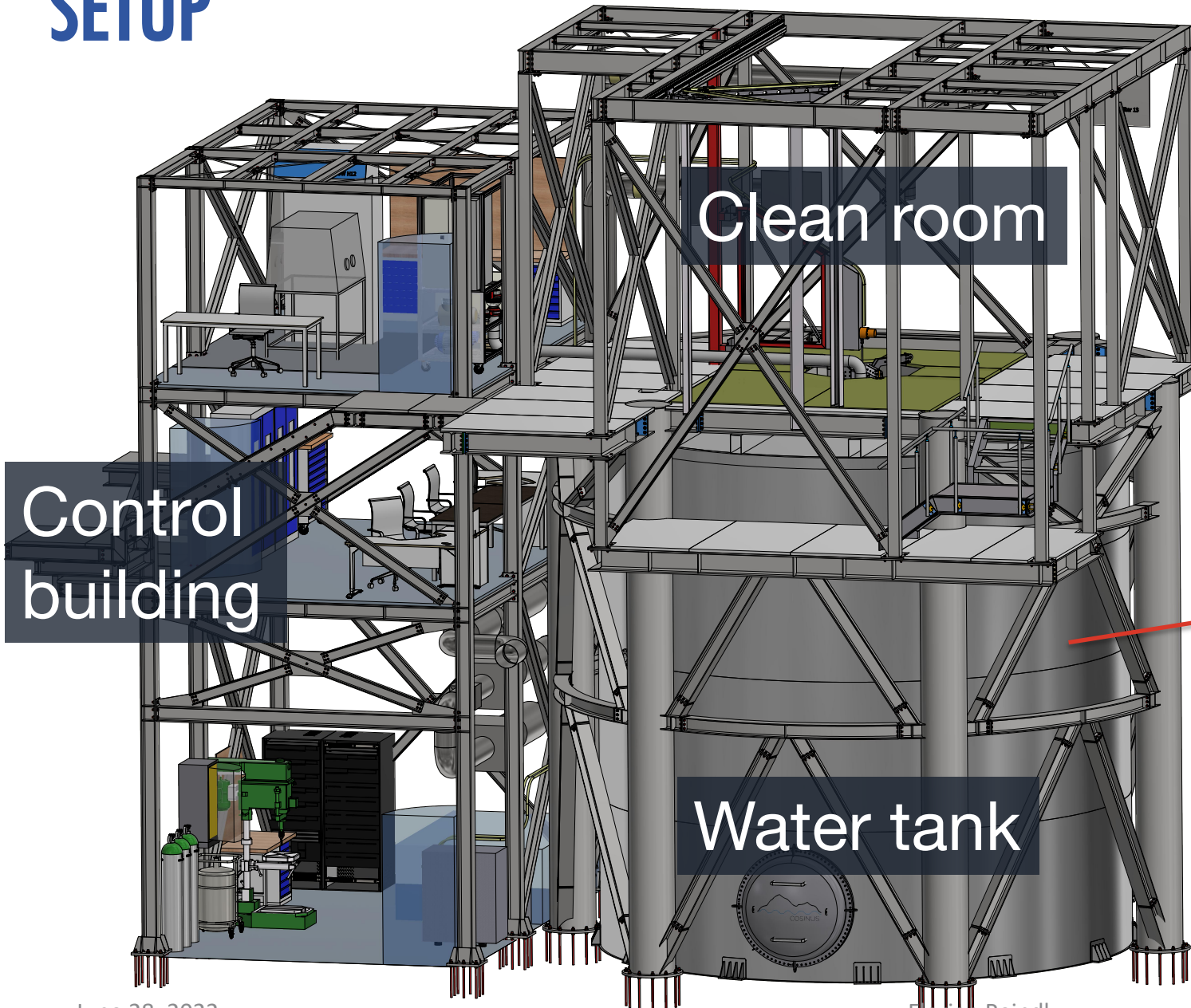
Phonons couple directly to electron system of Au-pad

remoTES MEASUREMENT WITH NAI TARGET

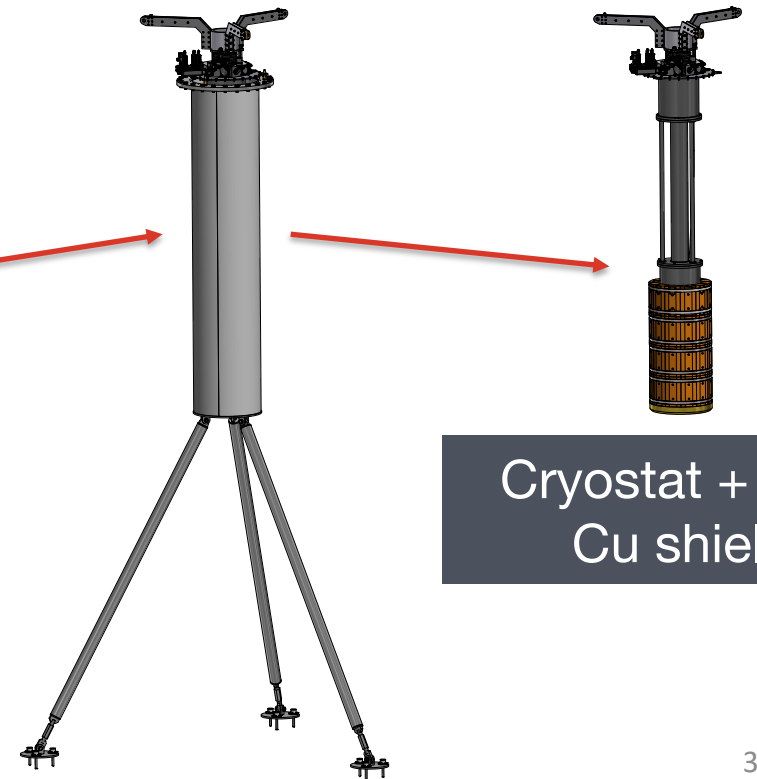


SETUP

Shielding design based on MC:
Simulations: [EPJ C 82, 2022](#)



Dry-well supported by tripod

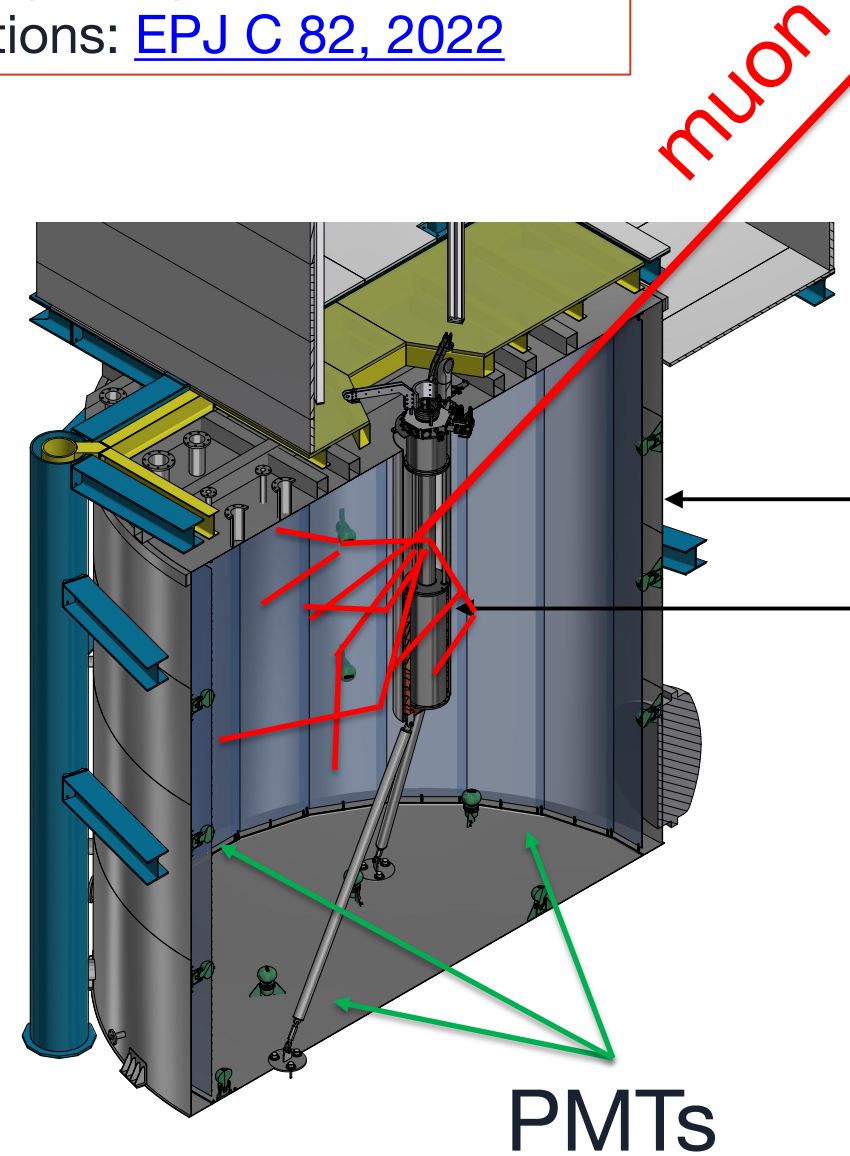


WYY WATER?

Shielding design based on MC:
Simulations: [EPJ C 82, 2022](#)

1. Good moderator for neutrons
2. Veto of (cosmogenic) muons via Cherenkov light emitted in water → Instrumentation of water tank with ~30PMTs

Rate of cosmogenic neutrons:
No veto: (3.5 ± 0.7) cts $\text{kg}^{-1} \text{yr}^{-1}$
With veto: <0.05 cts $\text{kg}^{-1} \text{yr}^{-1}$



Recent updates

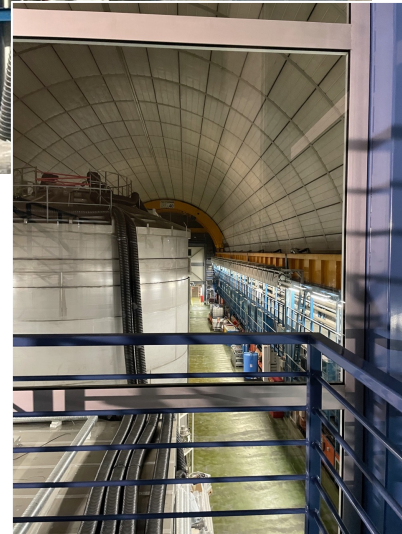


Dec. 2021



April 2022

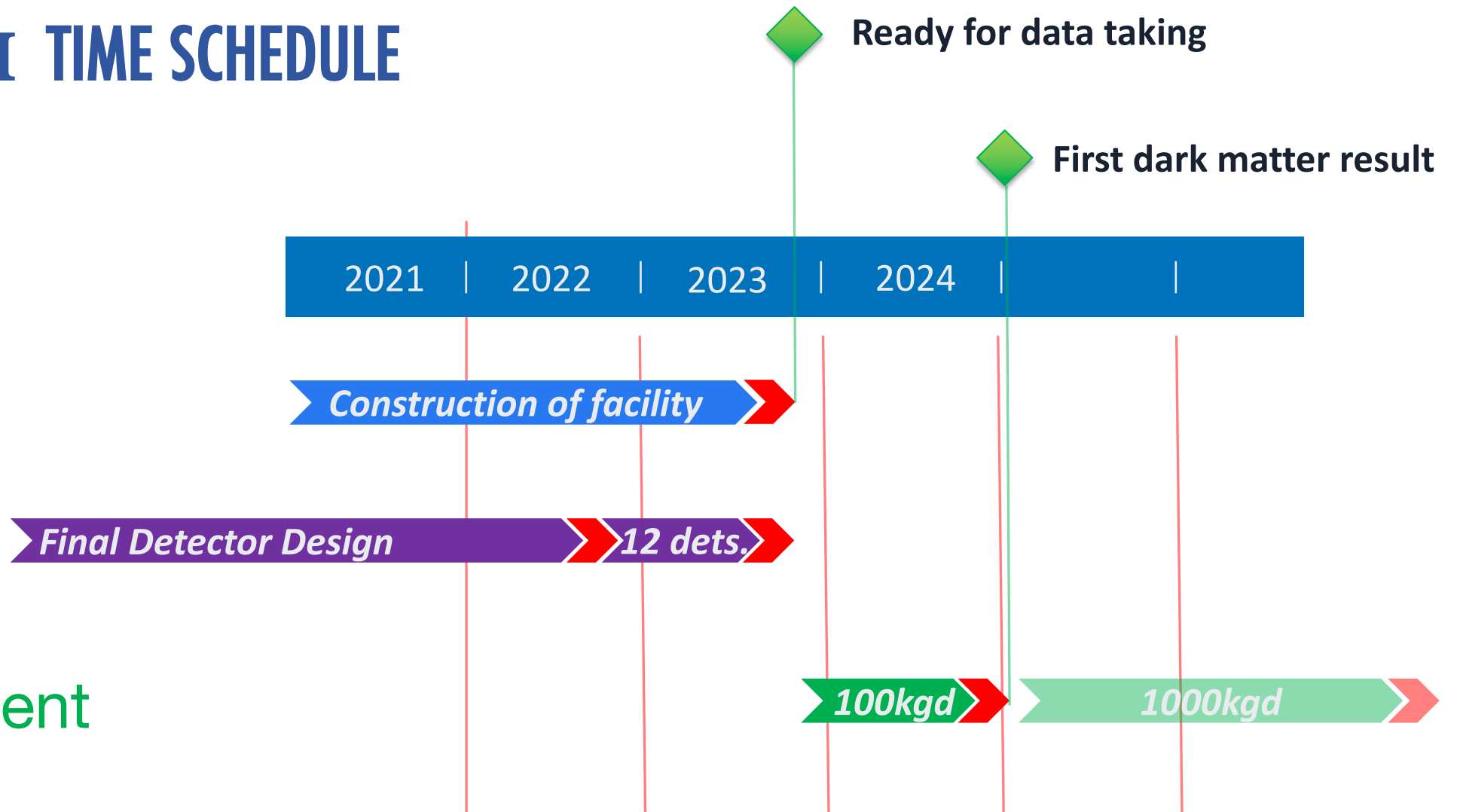
Florian Reindl



June 2022

COSINUS - 100 TIME SCHEDULE

Facility
+
Detector
=
Measurement



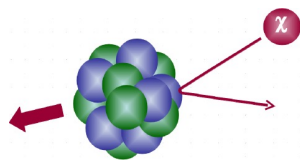
CONCLUSIONS

TAUP 1997: DAMA reports first evidence for an annual modulation signal

COSINUS uses a novel and unique NaI-detector to confirm or reject the DAMA dark matter claim within the next years.

COSINUS is approved and funded; construction is going on full steam

CONCLUSION – DIRECT DARK MATTER SEARCH WITH NUCLEAR RECOILS




Different technologies:

- Liquid noble gases for GeV – TeV-scale
- Cryogenic detectors for GeV-scale and below

Single positive, but highly controversial signal by DAMA/LIBRA

- COSINUS: NaI-based cryogenic detector for cross-check

Community effort to push down to neutrino floor (and below) for a wide mass range



Thank you for your attention

THE COSINUS ADVENTURE

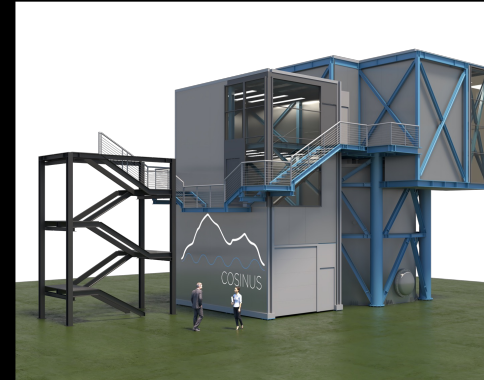
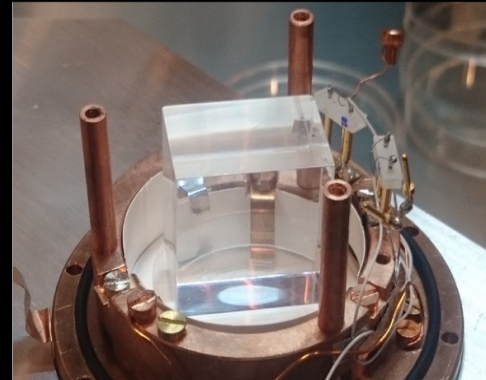
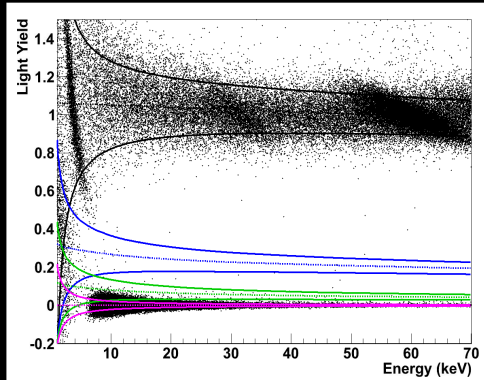
The Idea

2015



Funding and site @LNGS

2020



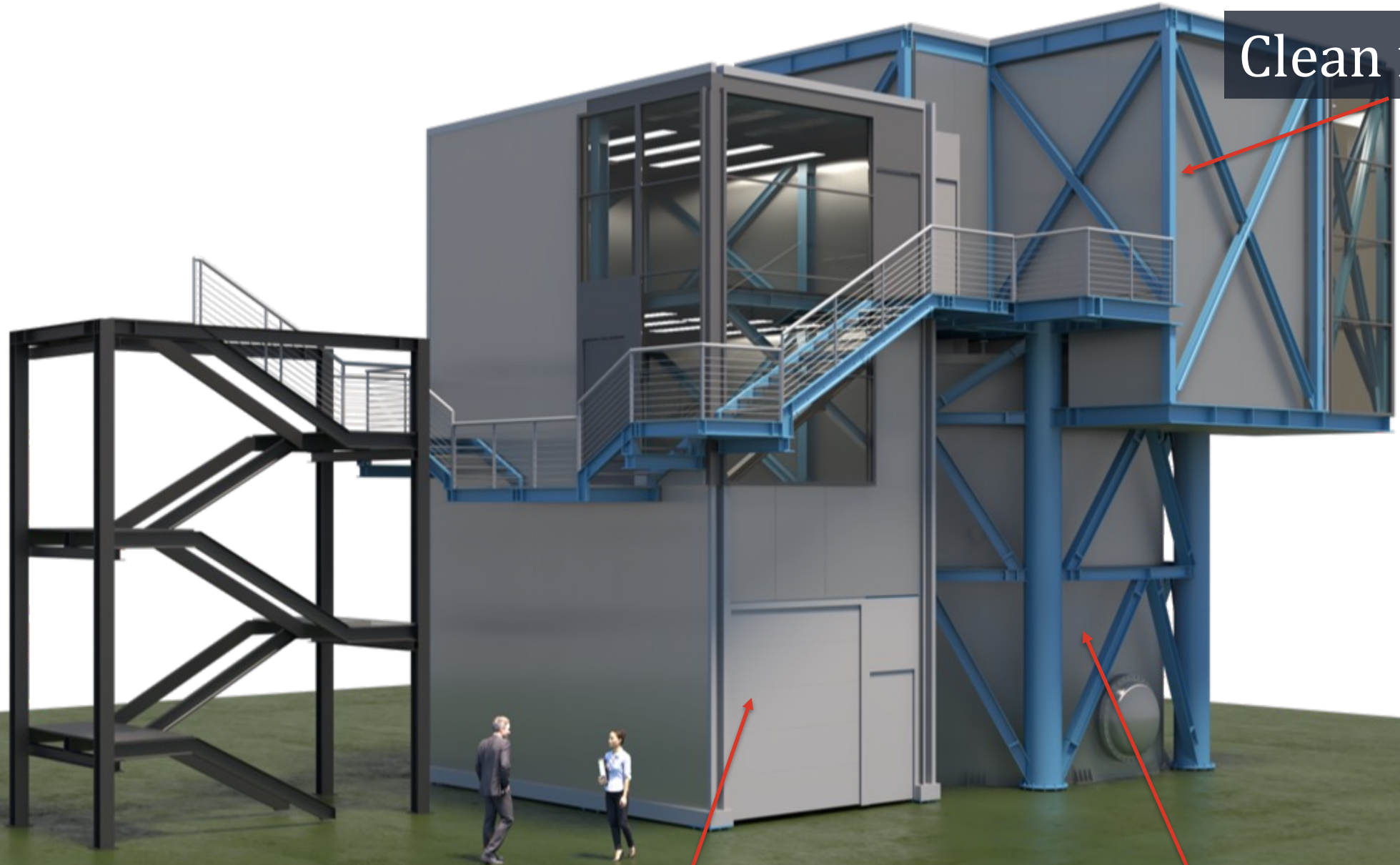
Prototypes work

INFN R&D Grant 2016 -2019

Full approval

- Scientific committee
- Directorate
- Italian authorities

Clean room

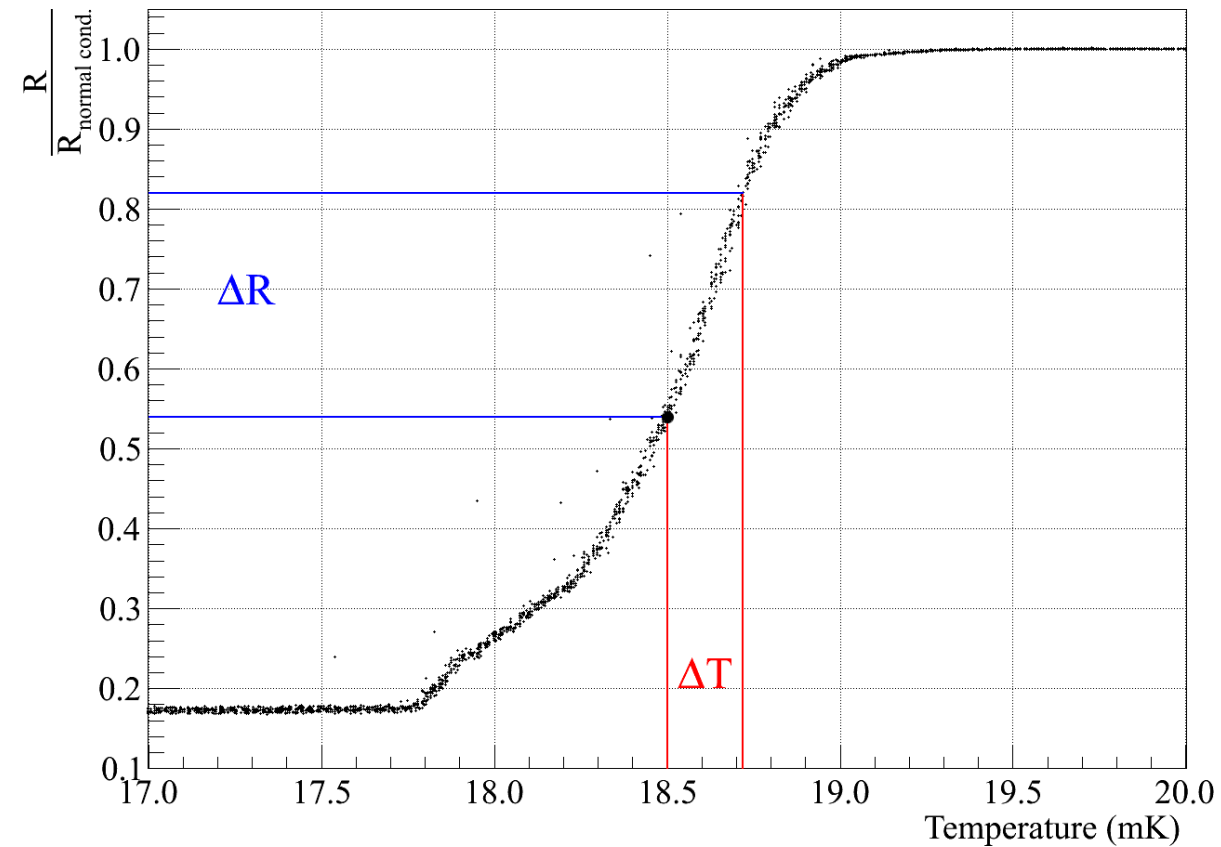
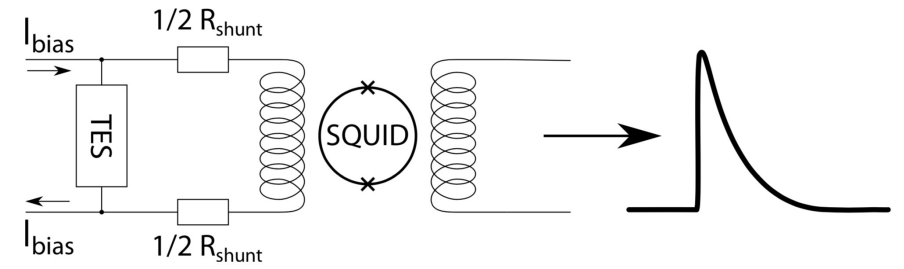


Control building

Water tank

TRANSITION EDGE SENSOR (TES)

WORKING PRINCIPLE



Energy deposition

$\sim keV$



Temperature rise

$\sim \mu K$



Resistance change

$\sim m\Omega$

LABORATORI NAZIONALI DEL GRAN SASSO (LNGS)

