The COSINUS project

searching for dark matter with new NaI-based cryogenic detectors

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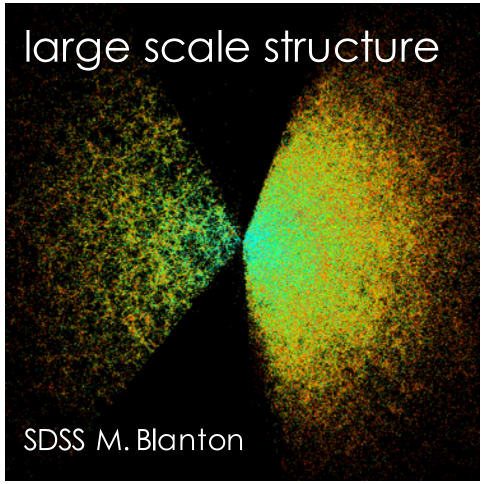
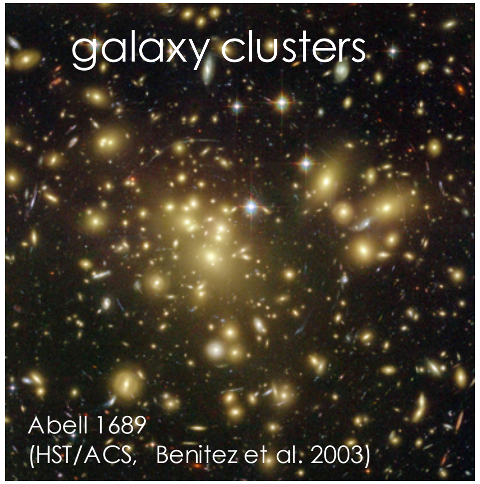
CENTER FOR ADVANCED STUDIES
INFN

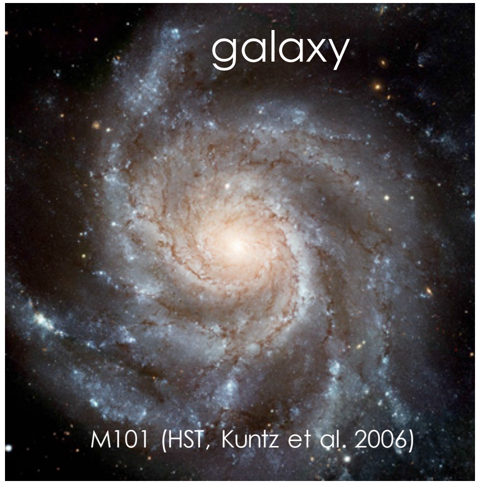
OUTLINE

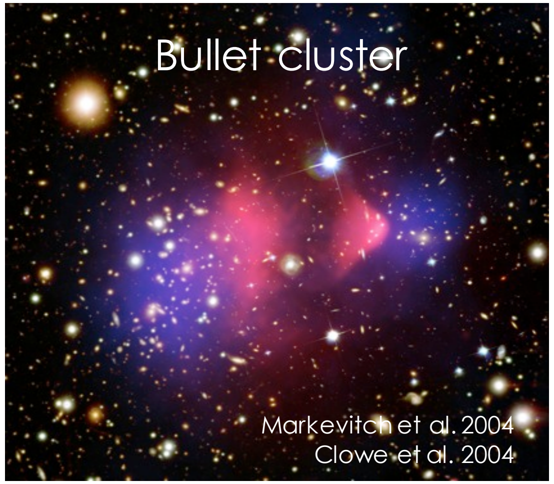
- Introduction to dark matter
- Introduction to low-temperature detectors
- COSINUS

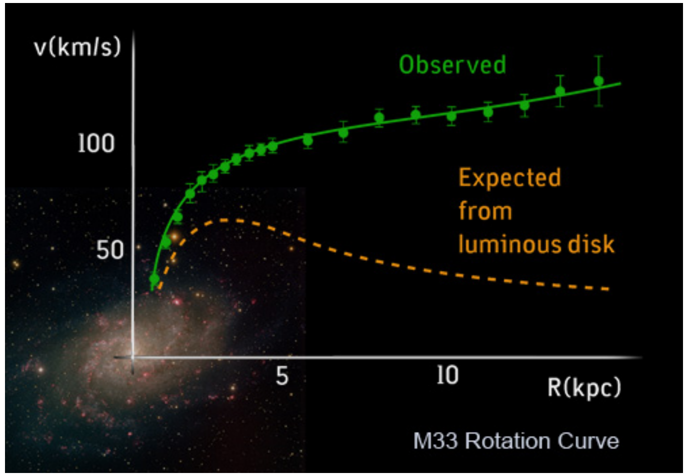
EVIDENCE FOR DARK MATTER





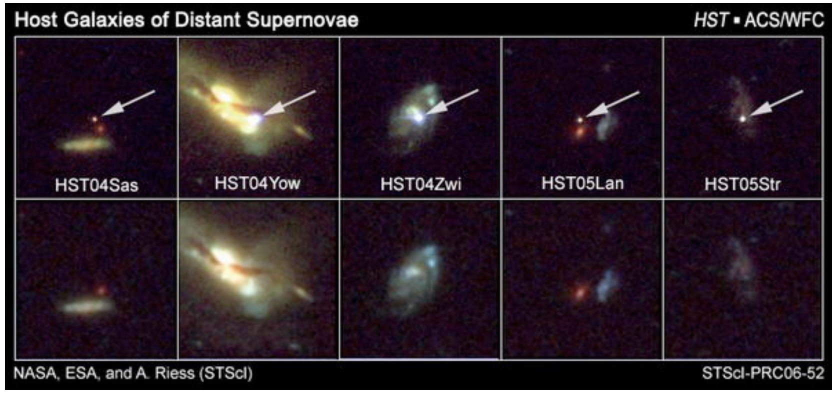






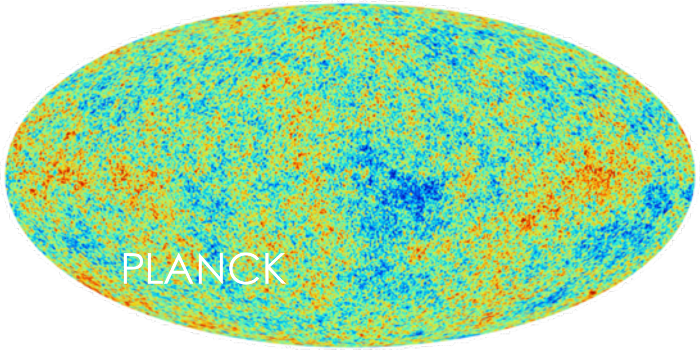
M33 Image: NOAO, AURA, NSF, T.A.Rector.

Supernovae

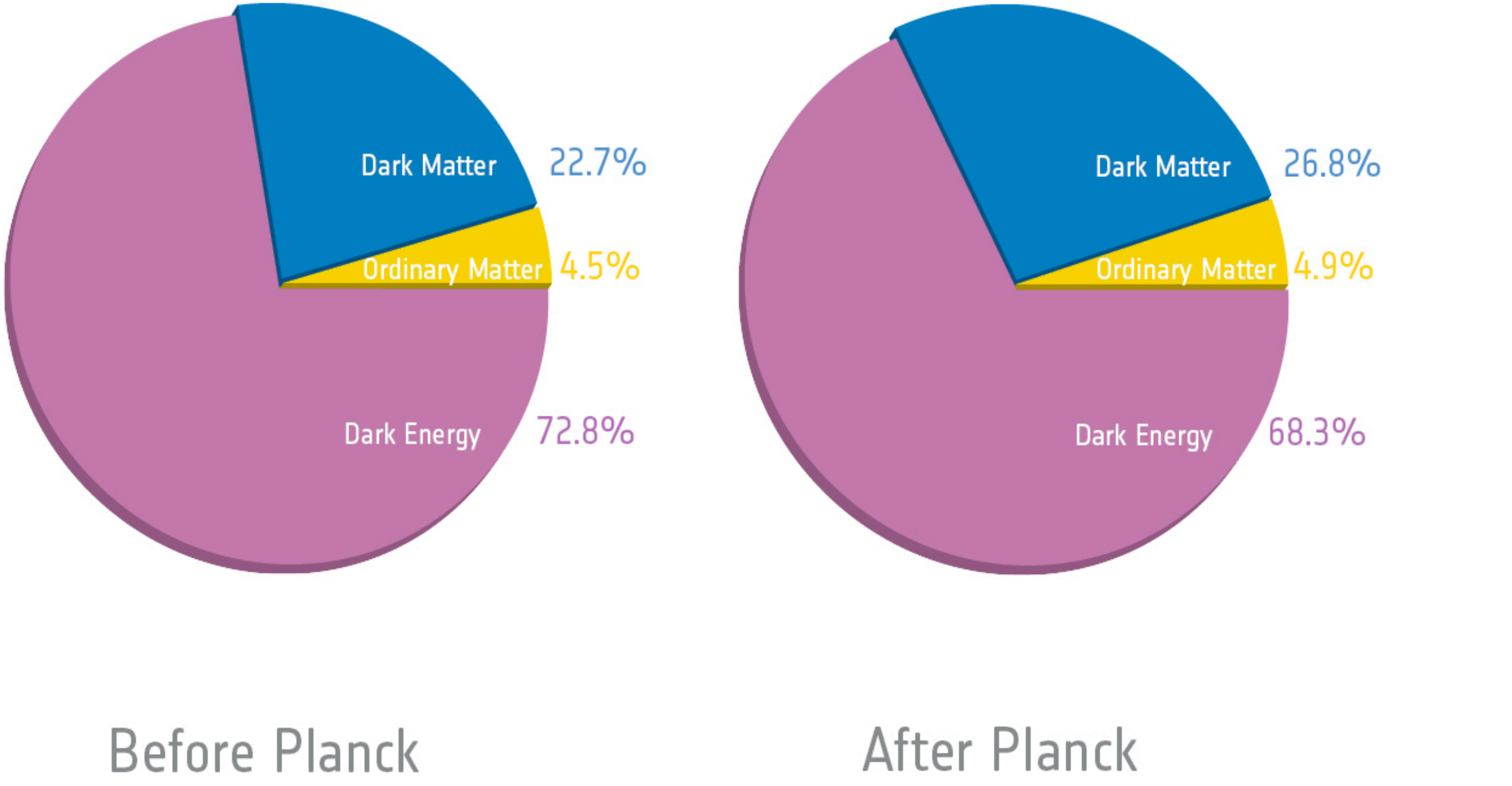


A. Riess

Cosmic Microwave Background



ENERGY CONTENT OF THE UNIVERSE



Picture from: European Space Agency / Planck

WHAT WE KNOW

NON-BARYONIC

- height of acoustic peaks in the CMB
- power spectrum of density fluctuations
- primordial Nucleosynthesis

COLD (non-relativistic)

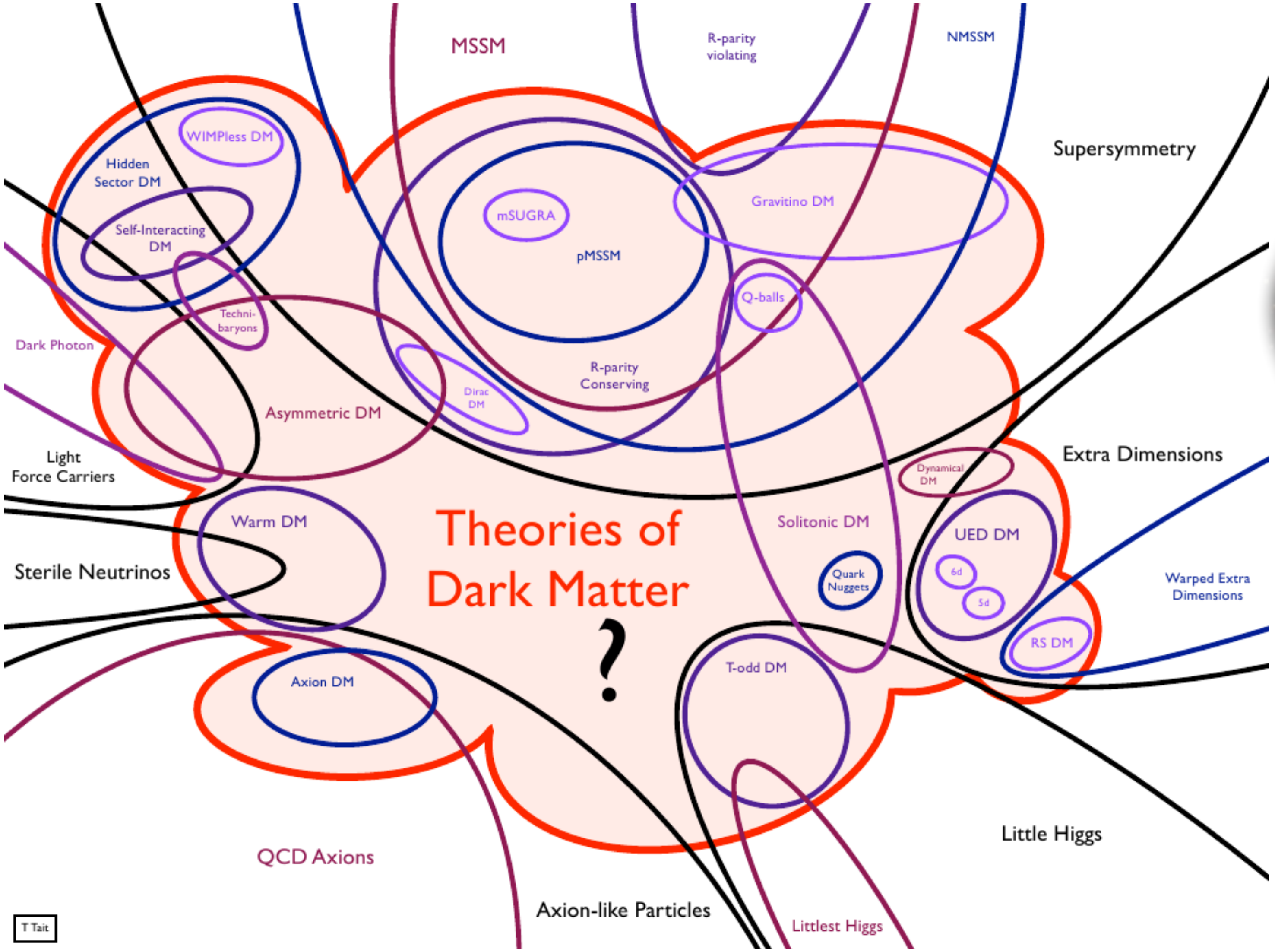
- structure formation of the Universe

STABLE

- still observable today

INTERACTION via GRAVITY and probably on the weak scale

DARK MATTER CANDIDATES

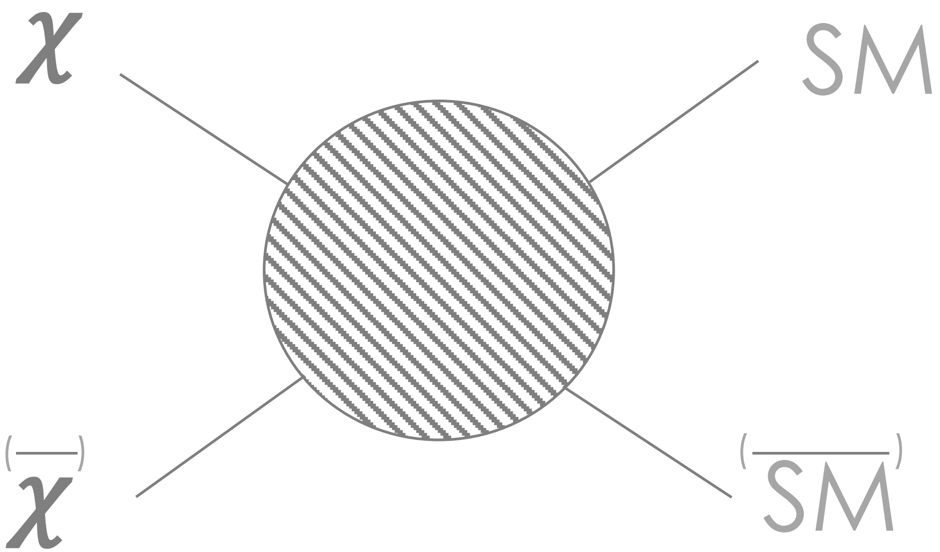


Taken from T. Tait at UCLA DM 2016

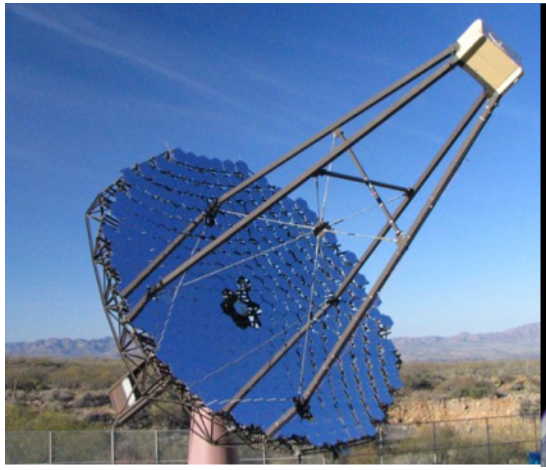
HUNT FOR DARK MATTER

Annihilation

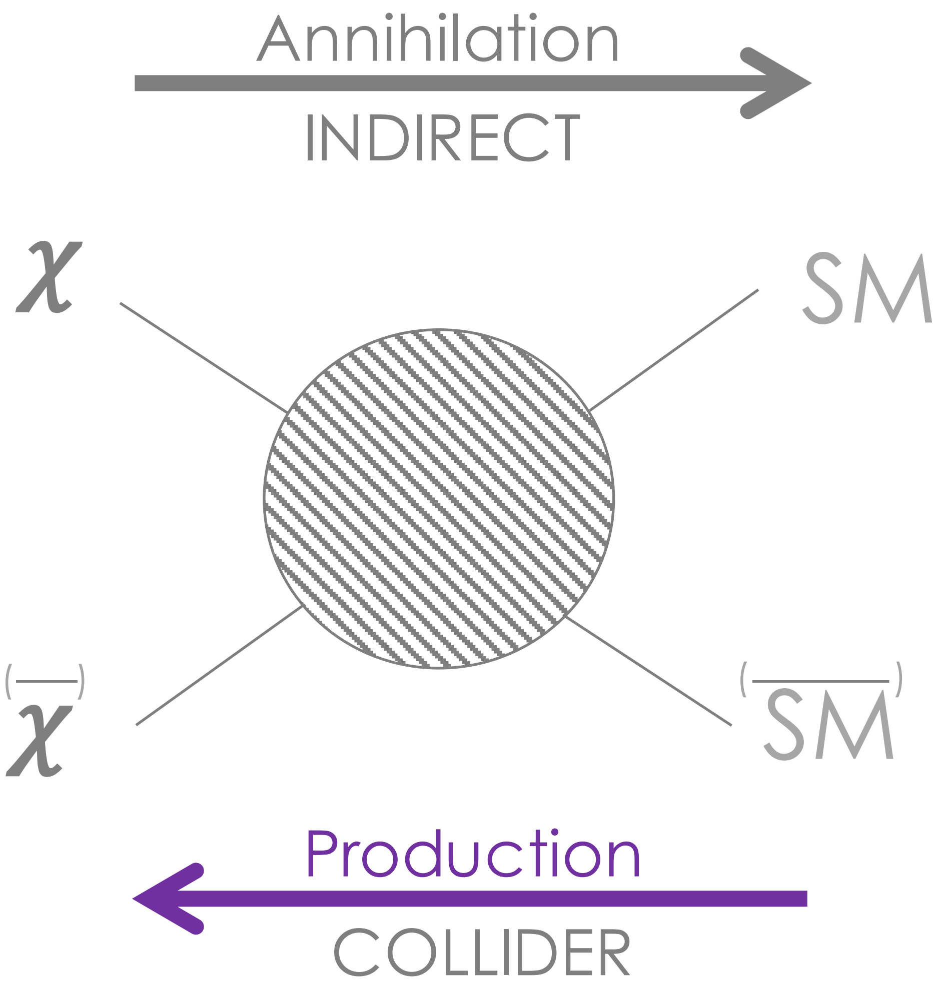
INDIRECT



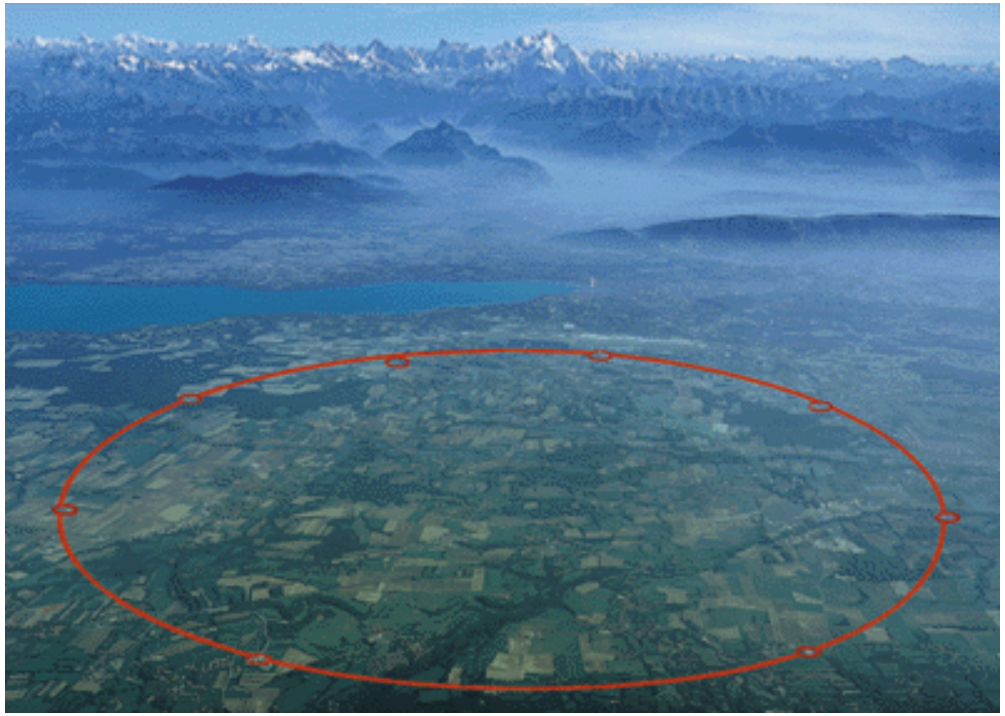
Dark matter particles can transform to ordinary particles, which are then detectable



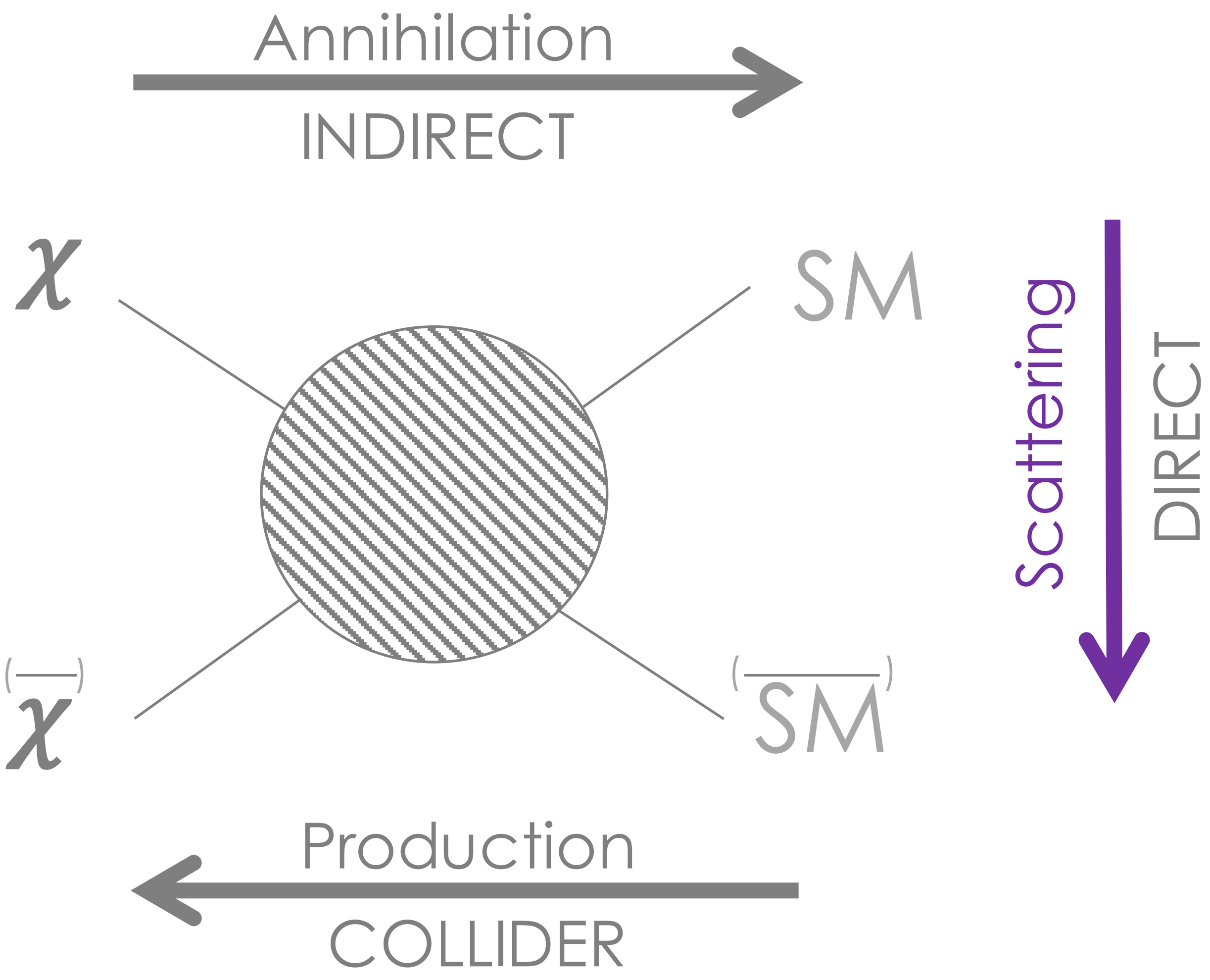
HUNT FOR DARK MATTER



Searching for the conversion
protons → dark matter



HUNT FOR DARK MATTER



Dark matter particles scatter off nuclei or electrons in earth-bound detectors

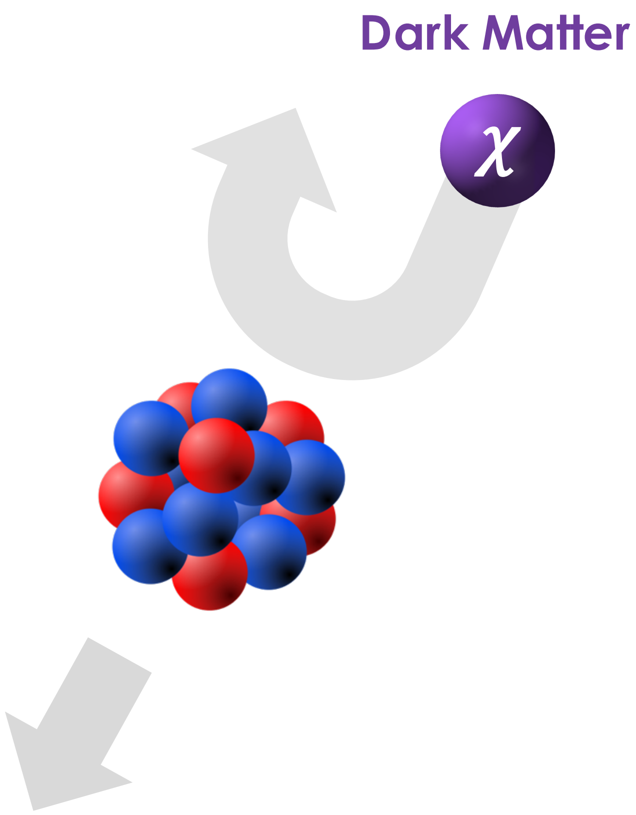
DIRECT DARK MATTER INTERACTION

Assumption

Particle-like dark matter which interacts with Standard Model particles

Most common

Dark matter particles scatters off the nucleus and induce nuclear recoils



DARK MATTER RATE

Total rate

DM velocity

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

number of target nuclei

local DM flux

DM-nucleon cross-section

DARK MATTER RATE

Total rate:

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

Differential rate:

galactic escape velocity

velocity distribution

DM-nucleon cross-section

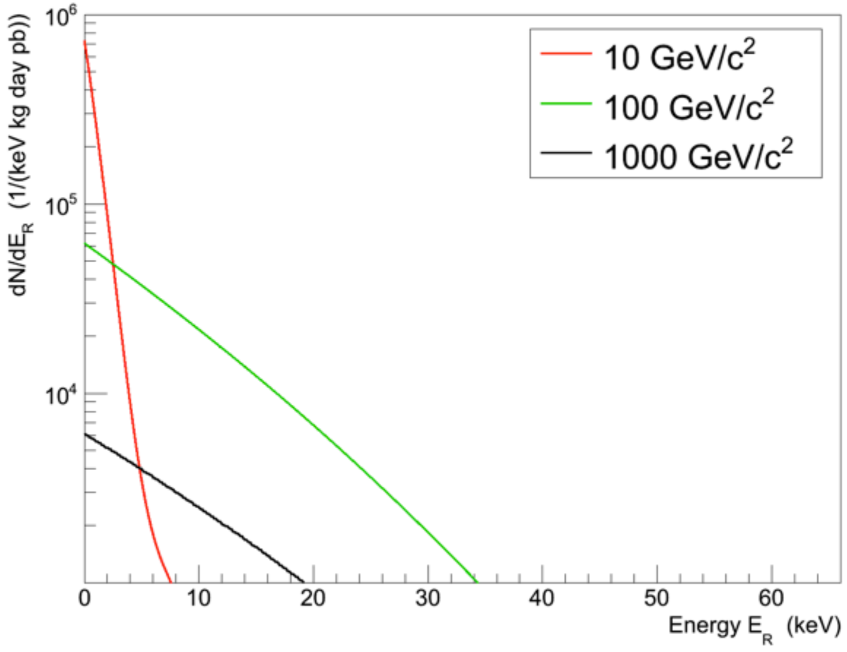
$$\frac{dR}{dE_r} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{min}}^{v_{esc}} d^3 v\, f(\vec{v})\, v \frac{d\sigma(\vec{v}, E_r)}{dE_r}$$

minimal velocity to produce a recoil above threshold

~ A^2
~ form factor

SPECIFIC SIGNATURE

rate and shape of recoil spectrum depend on target material

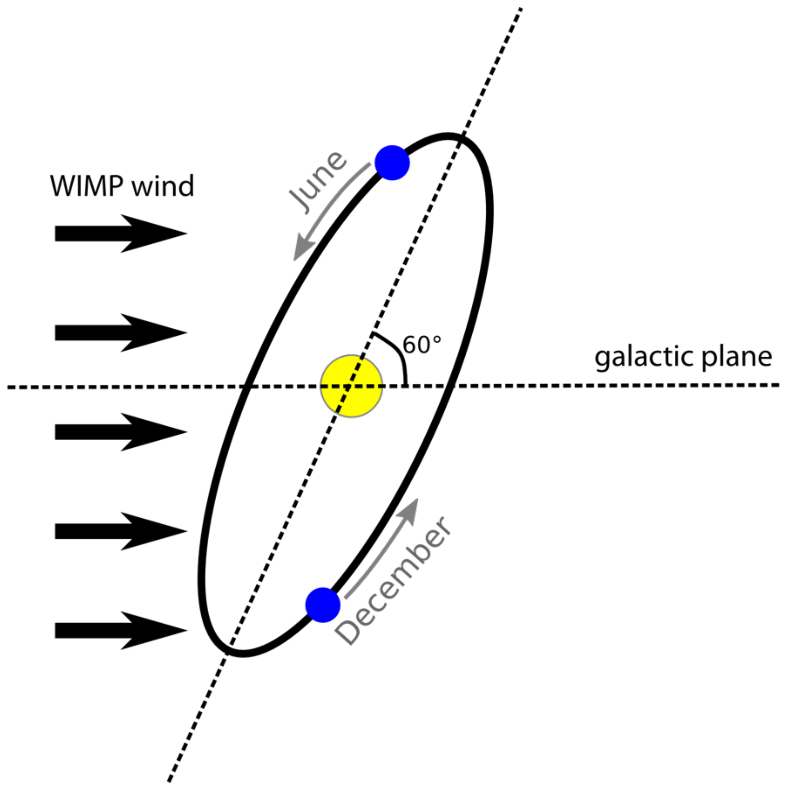


- very small energy deposits
- extremely rare interaction rate

FLAT, FEATURELESS SPECTRUM

MODULATION

rate and shape of recoil spectrum depend on target material



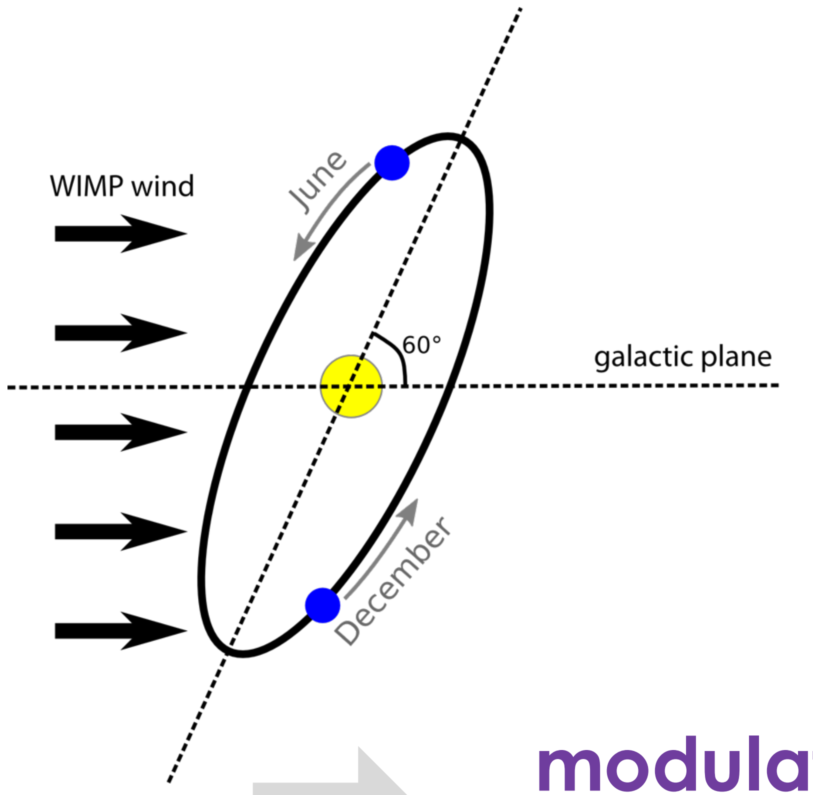
AND

motion of the Earth causes relative modulation of velocity

→ annual variation in the rate

MODULATION

rate and shape of recoil spectrum depend on target material

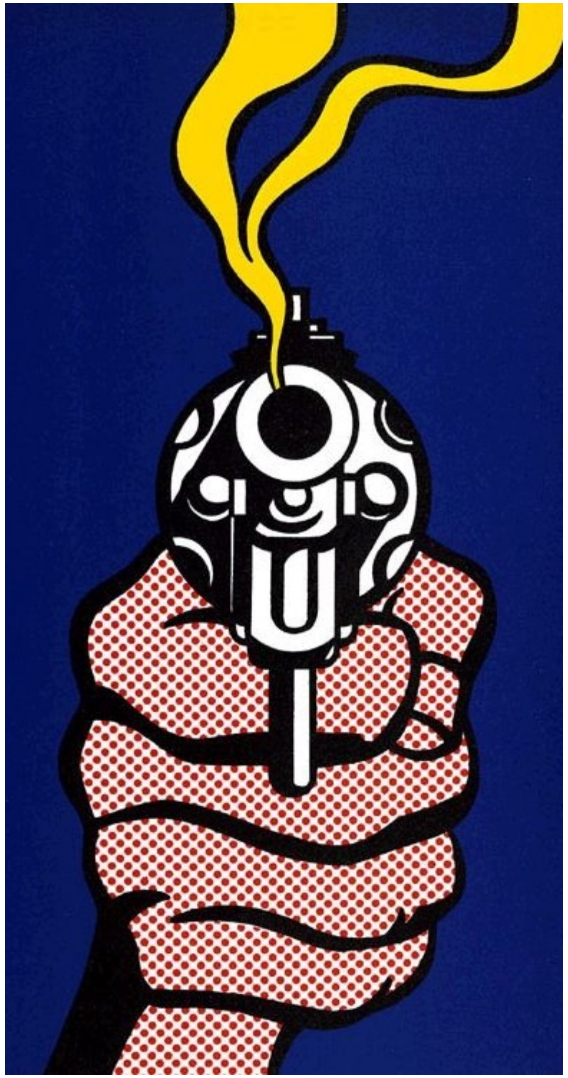


AND

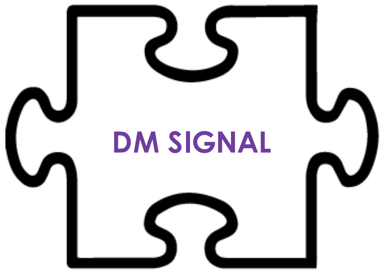
motion of the Earth causes relative modulation of velocity

→ annual variation in the rate

modulation signal detection
a smoking gun evidence ?!?



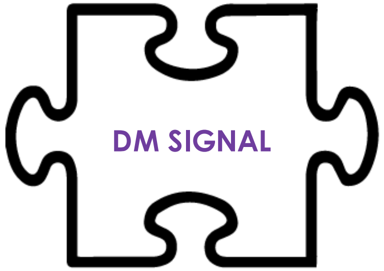
EXPERIMENTAL CHALLENGE



DARK MATTER SIGNAL

- energy deposits few keV - tens of keV
- few events per ton per year
- modulation detection

EXPERIMENTAL CHALLENGE



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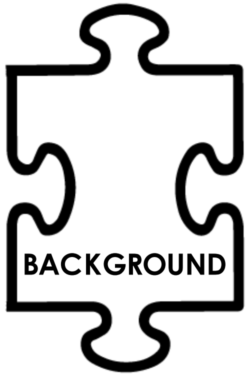
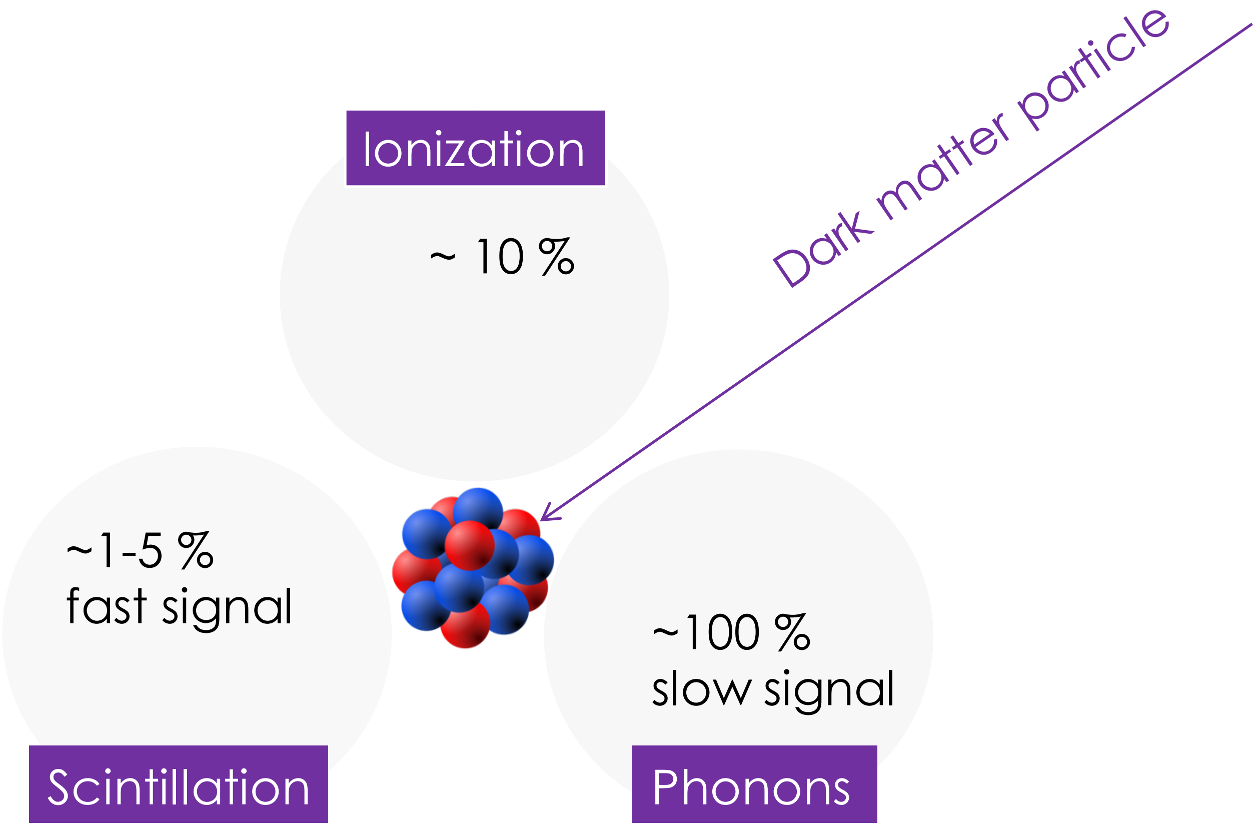


BACKGROUND

- depends on experimental setup
- is typically millions of times higher than signal
- is constant in time (or at least not modulating as DM)

WORLDWIDE EFFORT

DIRECT DETECTION CHANNELS

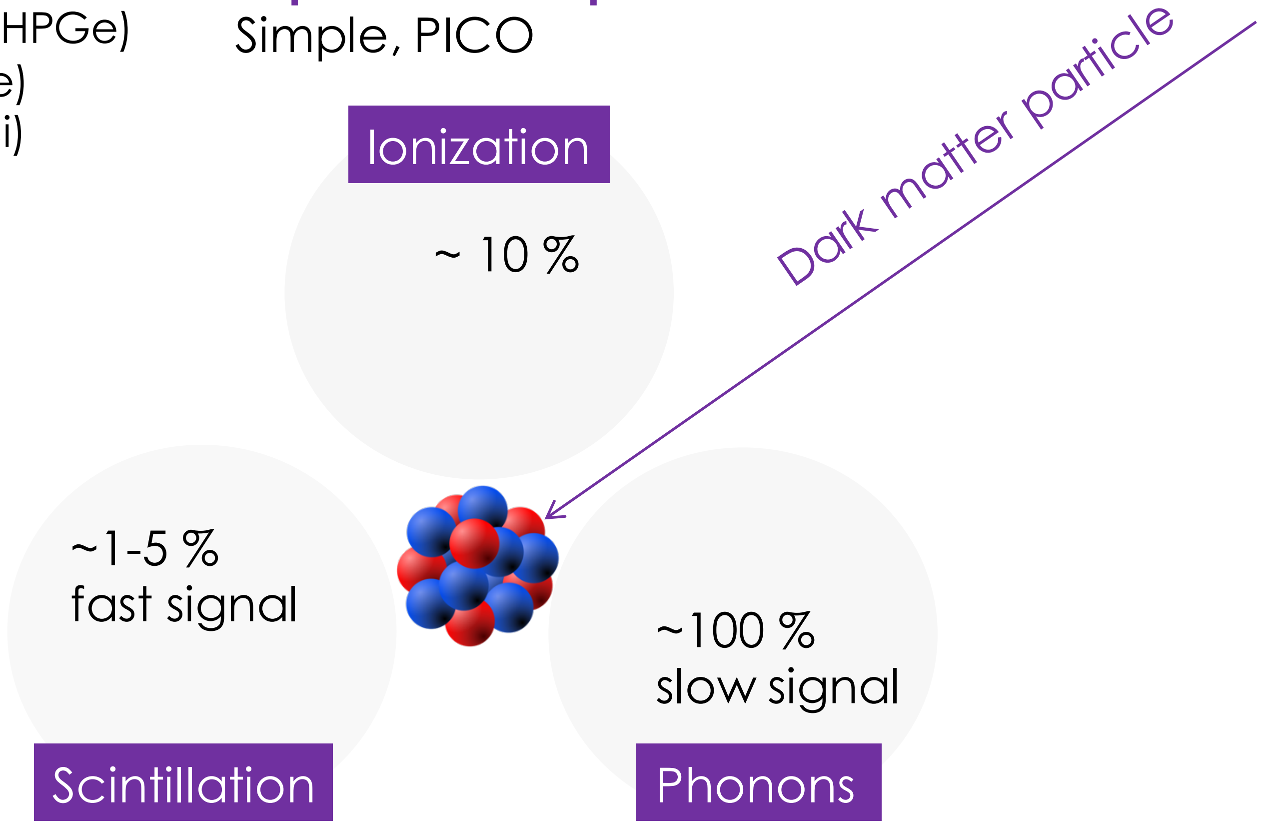


SINGLE CHANNEL DETECTION

not complete list!

Semiconductors:
- CoGent (HPGe)
- CDEX (Ge)
- DAMIC (Si)

Superheated liquids:
Simple, PICO



Inorganic scintillators:
DAMA/LIBRA, COSINE, KIMS

Single-phase liquid nobles:
DEAP, MiniCLEAN, XMASS

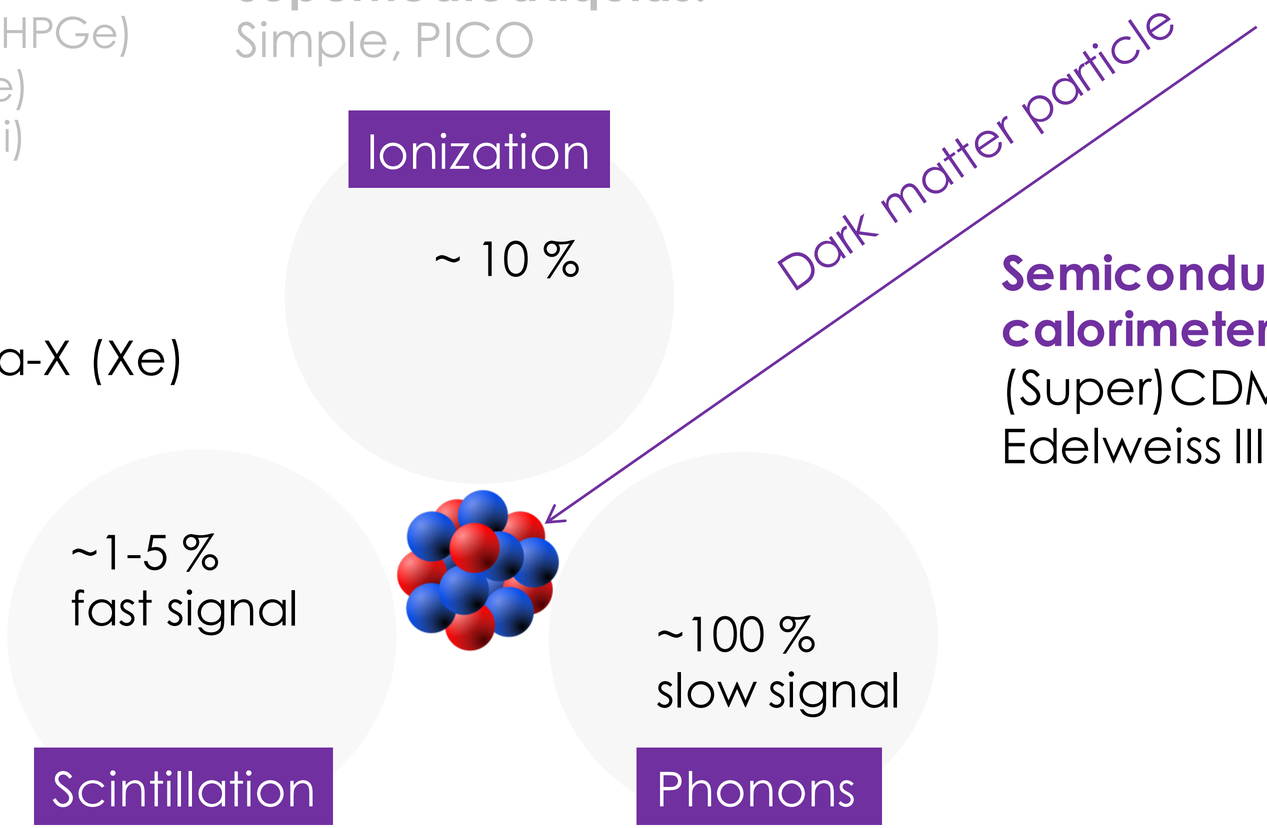
DUAL CHANNEL DETECTION

not complete list!

Semiconductors:
- CoGent (HPGe)
- CDEX (Ge)
- DAMIC (Si)

Superheated liquids:
Simple, PICO

2-phase noble liquids:
XENON 1t, LUX/LZ, Panda-X (Xe)
Darkside-50 (Ar)



Semiconducting calorimeters:
(Super)CDMS (Ge, Si)
Edelweiss III (Ge)

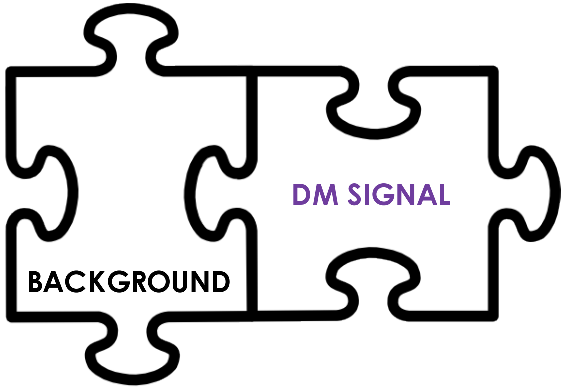
Inorganic scintillators:
DAMA/LIBRA, KIMS

Single-phase liquid nobles:
DEAP, MiniCLEAN, XMASS

Scintillating calorimeters
CRESST-III ($CaWO_4$)

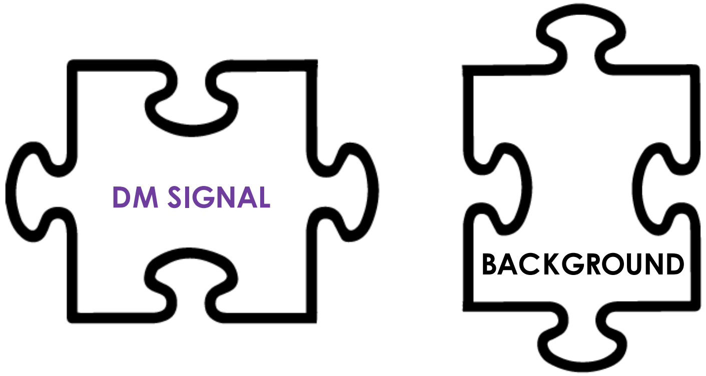
SAME SAME, BUT DIFFERENT

SINGLE CHANNEL



VS.

DUAL CHANNEL



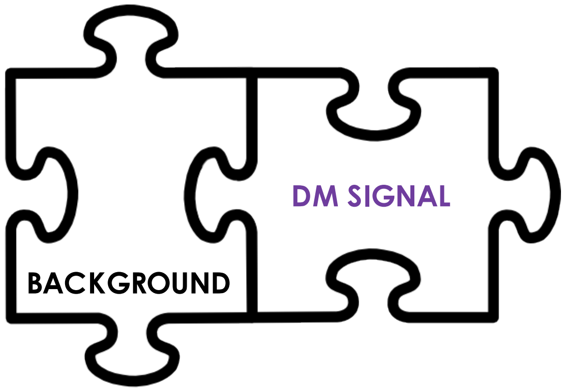
DISCRIMINATION

nuclear recoil events

to β/γ-events

SAME SAME, BUT DIFFERENT

SINGLE CHANNEL



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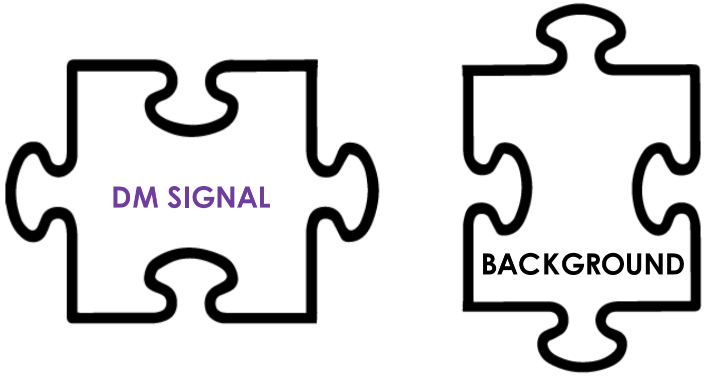
DUAL CHANNEL



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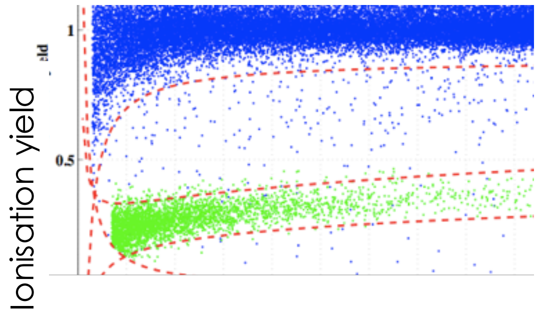
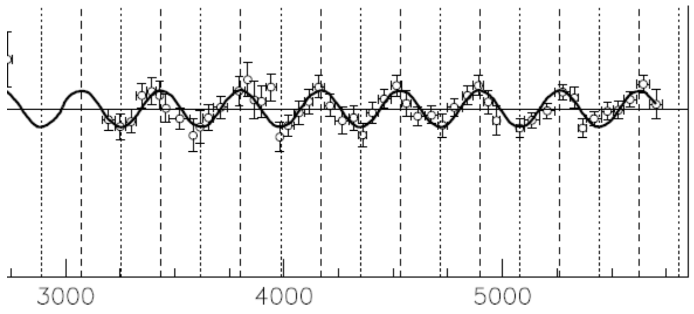
COUNTING EXPERIMENT



XENON

MODULATION EXPERIMENT



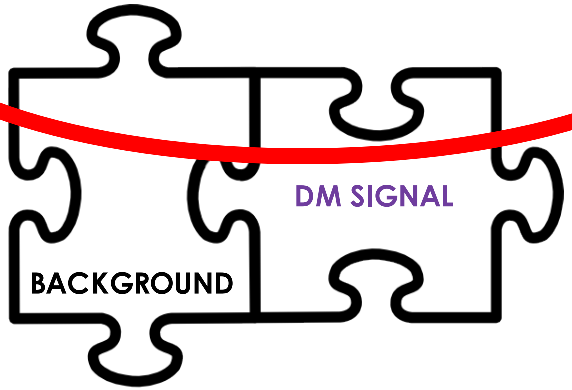
comparison of

result requires

model assumption

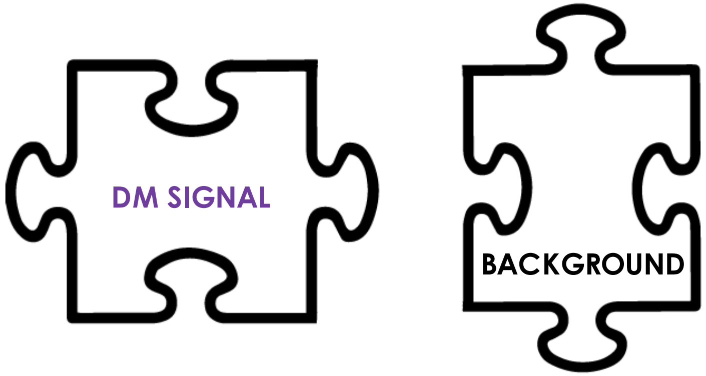
SAME SAME, BUT DIFFERENT

SINGLE CHANNEL



VS.

DUAL CHANNEL



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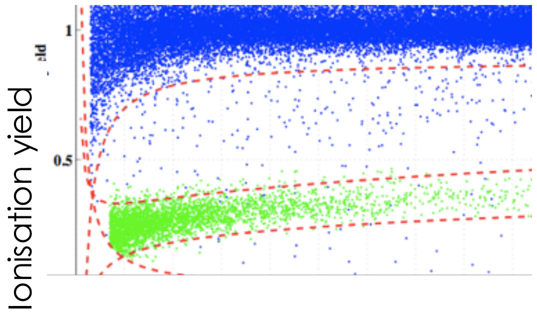
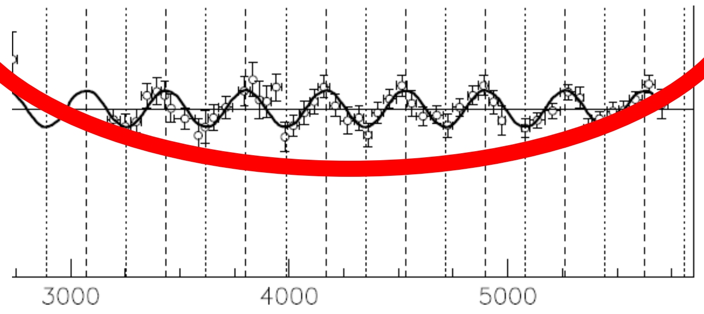


XENON

MODULATION EXPERIMENT



comparison of

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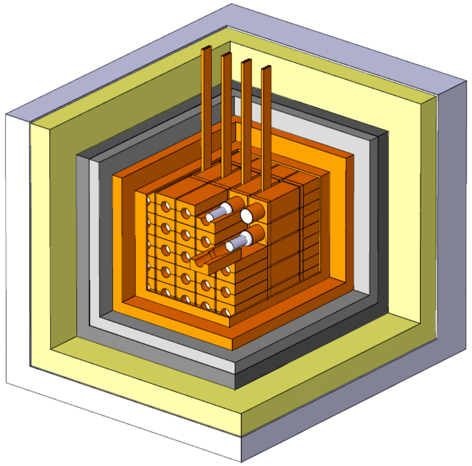
model assumption

DAMA/LIBRA experiment

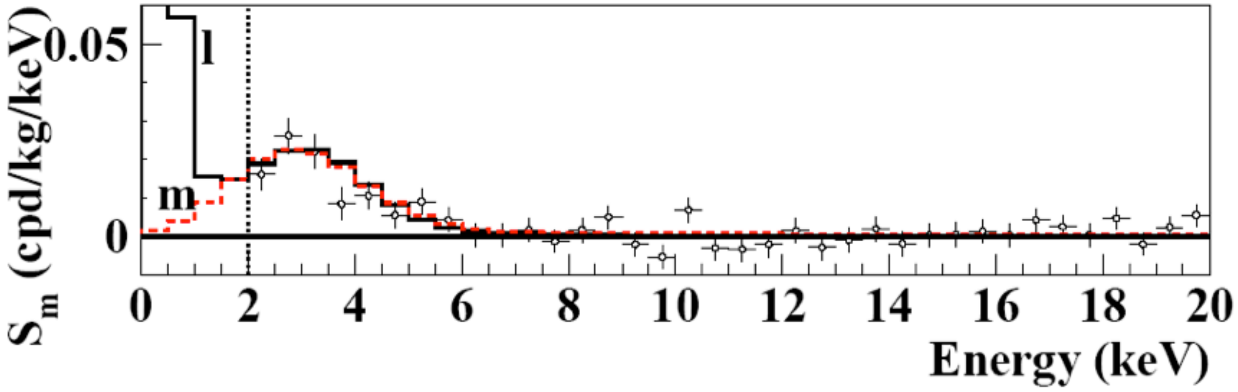


Target:

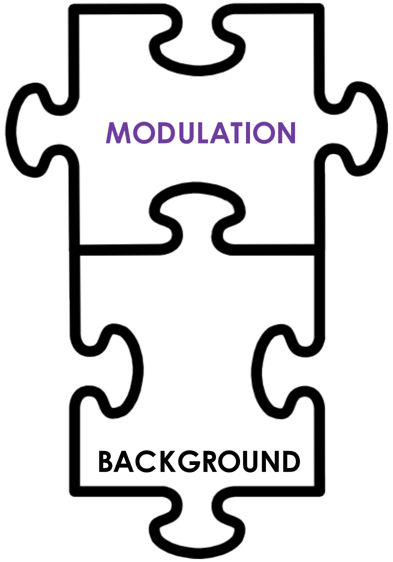
250 kg of high-pure NaI (Tl) crystals

SINGLE channel detection:

- scintillation light using dedicated PMTs
- ~ 5 -7.5 photons/keV
- nuclear recoils show less light (LIGHT QUENCHING)

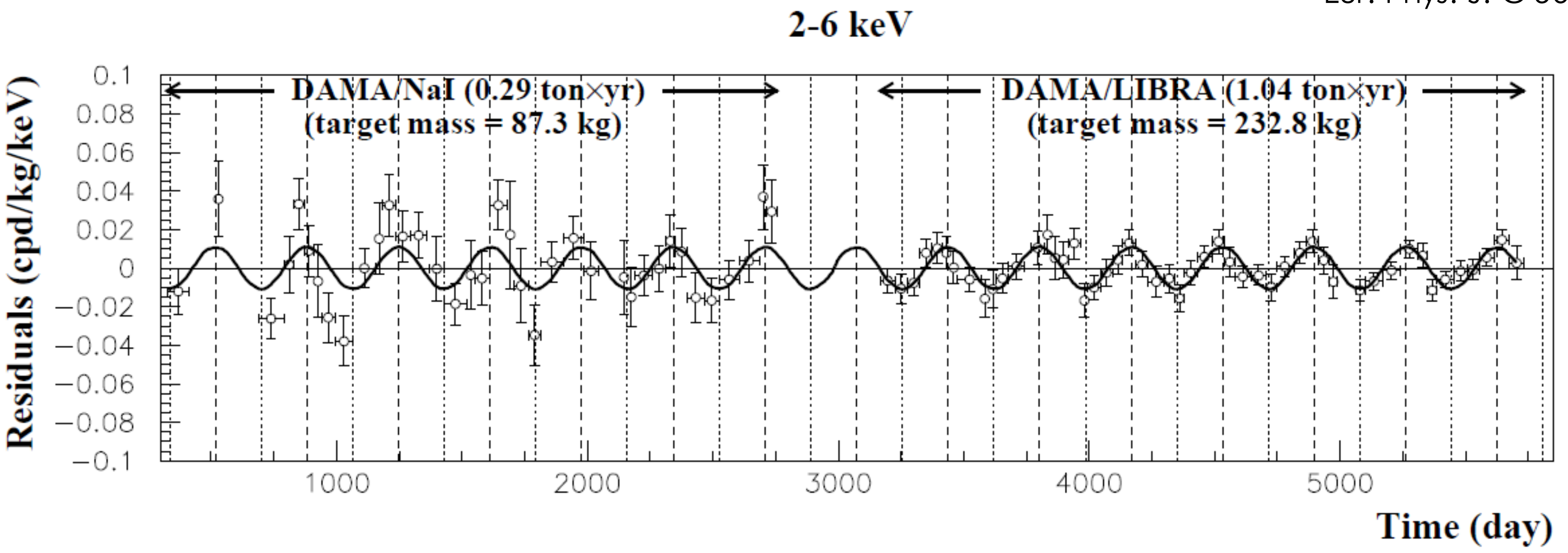


Eur.Phys.J. C 56 333 (2008), arXiv:0804.2741



DAMA/LIBRA results

Eur. Phys. J. C 56 333 (2008), arXiv:0804.2741



- **positive evidence** for the presence of DM particles in the galactic halo
- total: 1.33 ton-y of exposure
- frequency and phase match expectation for dark matter

Modulation signal in energy window: 2-6 keV_{ee}

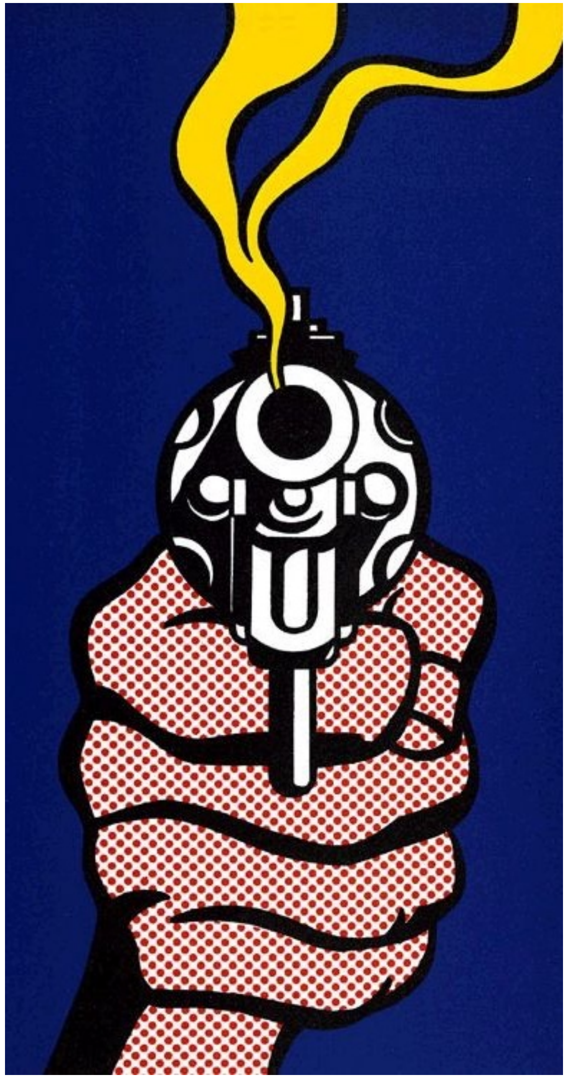
THE SMOKING GUN EVIDENCE?

Statistics: > 9σ ✓

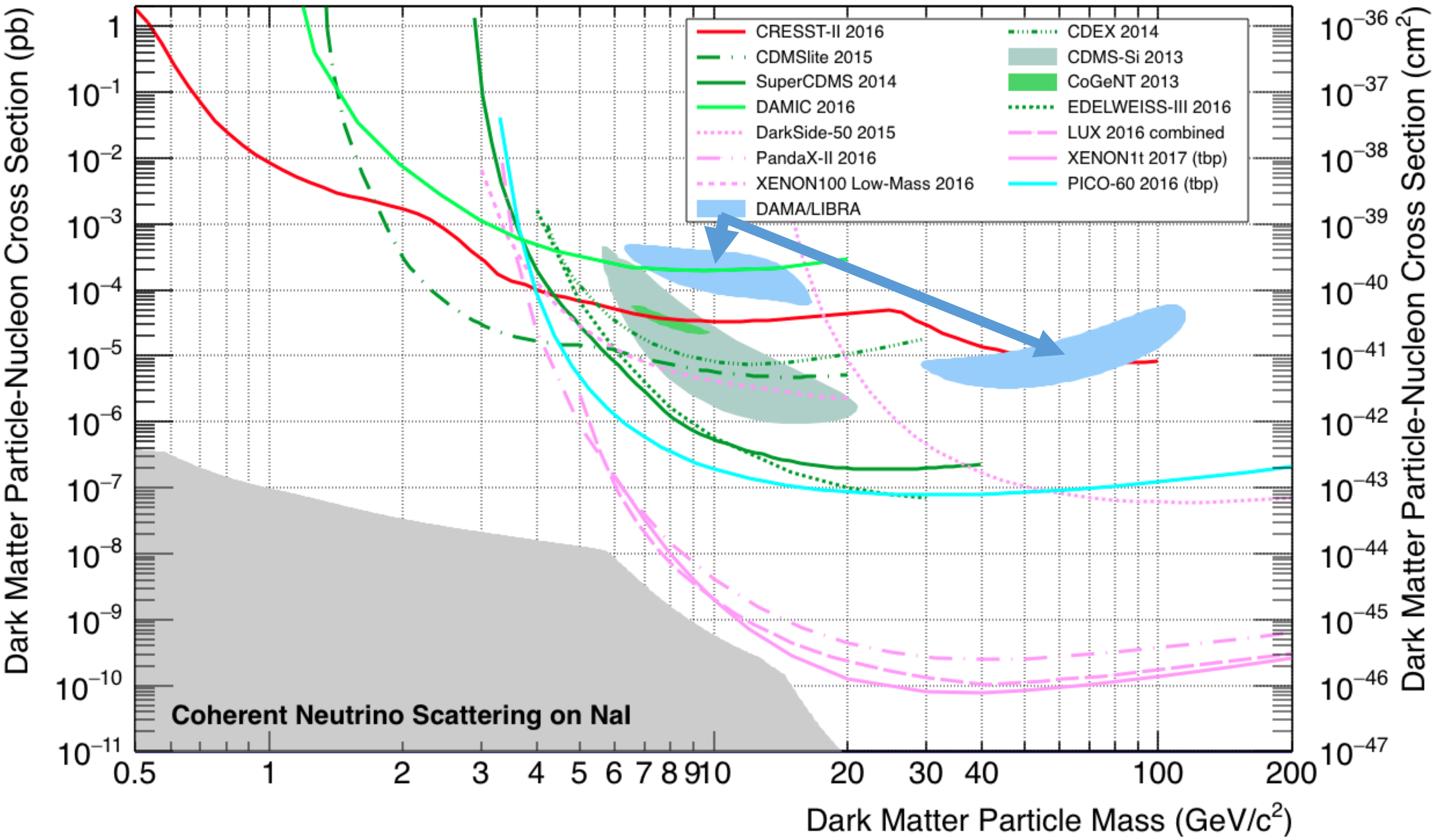
Period: 0.998 ± 0.002 years ✓

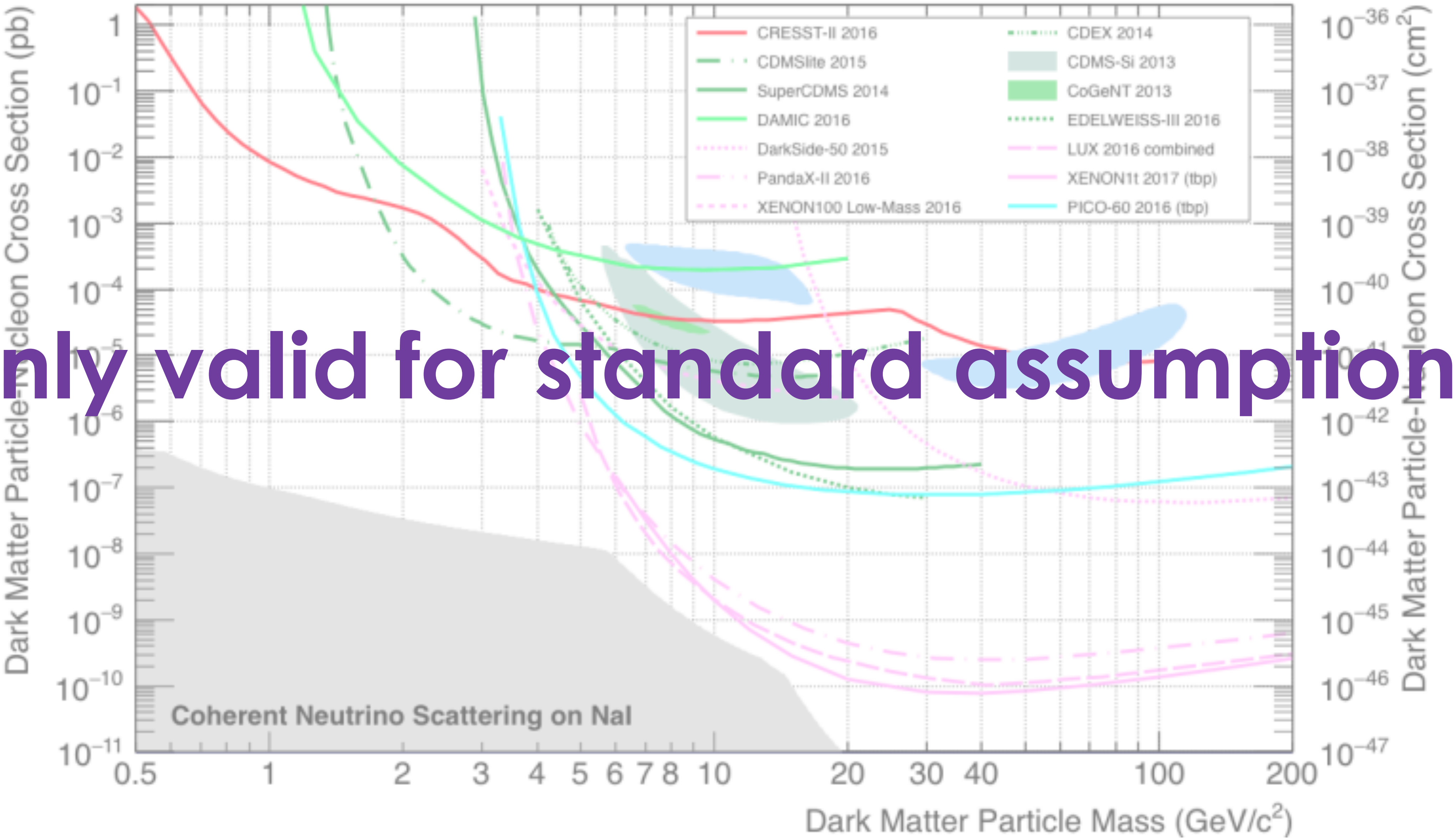
Phase: 24th May +/- 7 days ✓
(cosine peaking June 2nd)

Convincing non-DM explanation ✗



DARK MATTER LANDSCAPE





Only valid for standard assumptions!!!

WHAT ARE THE UNKNOWNS?

galactic escape velocity

velocity distribution

DM-nucleon cross-section

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

minimal velocity to produce a recoil above threshold

Astro physics

dark matter halo

velocity distribution

Particle physics

interaction mechanism

We have a dependence on the target material

→ cross-check DAMA/LIBRA signal with a NaI-based detector

NaI experiments

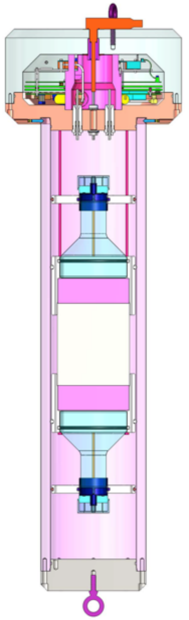
not complete list!

DM-Ice17

South pole
17 kg NaI

energy: 4 keV_{ee}

3.5 y physics run
no hint

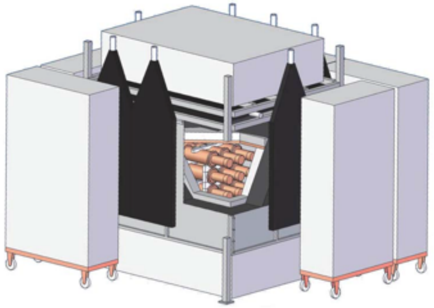


ANAIS-112

LSC - Spain
112.5 kg NaI

energy: < 1 keV_{ee}

spring 2017



COSINE-100

Y2L Korea
KIMS NaI + DM-Ice
106 kg

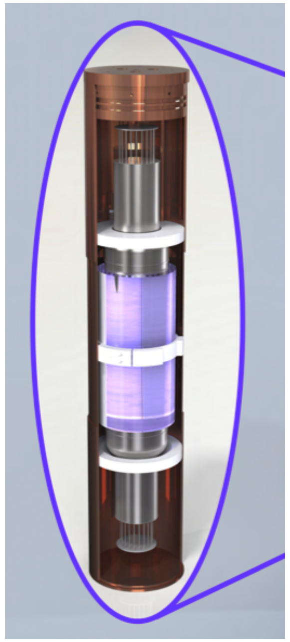
energy: ~ 2 keV_{ee}

since Sept. 2016

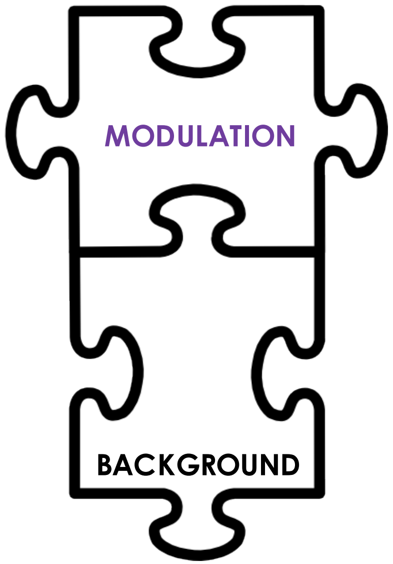
SABRE

Gran Sasso/Australia
40-50 kg NaI

construction phase



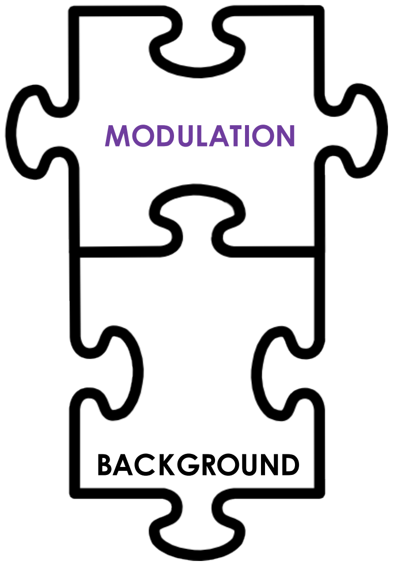
NaI EXPERIMENTS



DAMA/LIBRA
DM-Ice
KIMS-NaI
COSINE
ANAIS-112
SABRE

- large mass
- low background
- **no** β/γ-discrimination

NaI EXPERIMENTS



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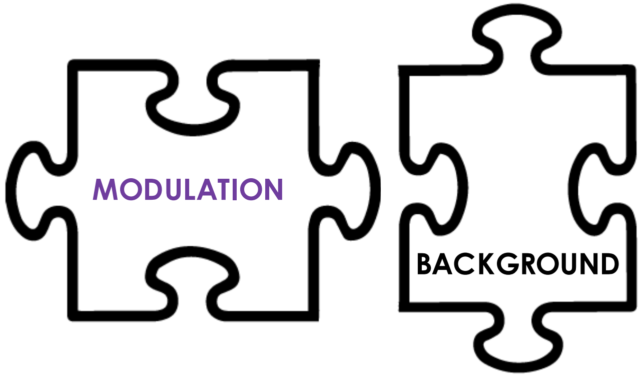

COSINUS

- β/γ-discrimination
- lower threshold, in particular for nuclear recoils

www.cosinus.it

COSINUS

- R&D project
- funded by the "CSN 5" of INFN
- 3 years for prototype development [2016 – 2018]
- Eur. Phys. J. C (2016) 76:441

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INFN

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

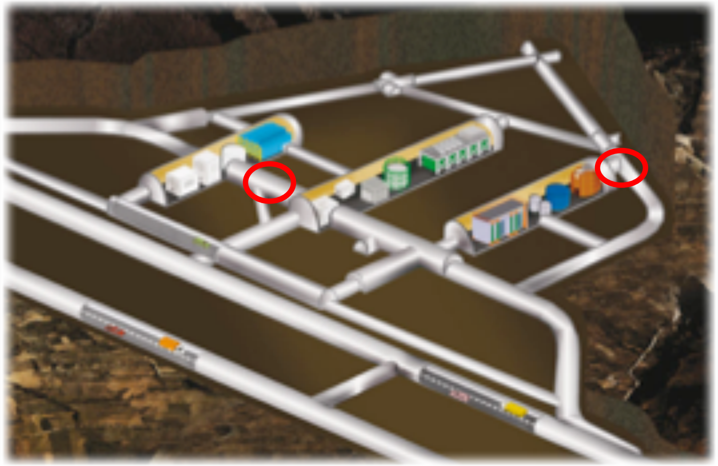
INFN Laboratori Nazionali del Gran Sasso

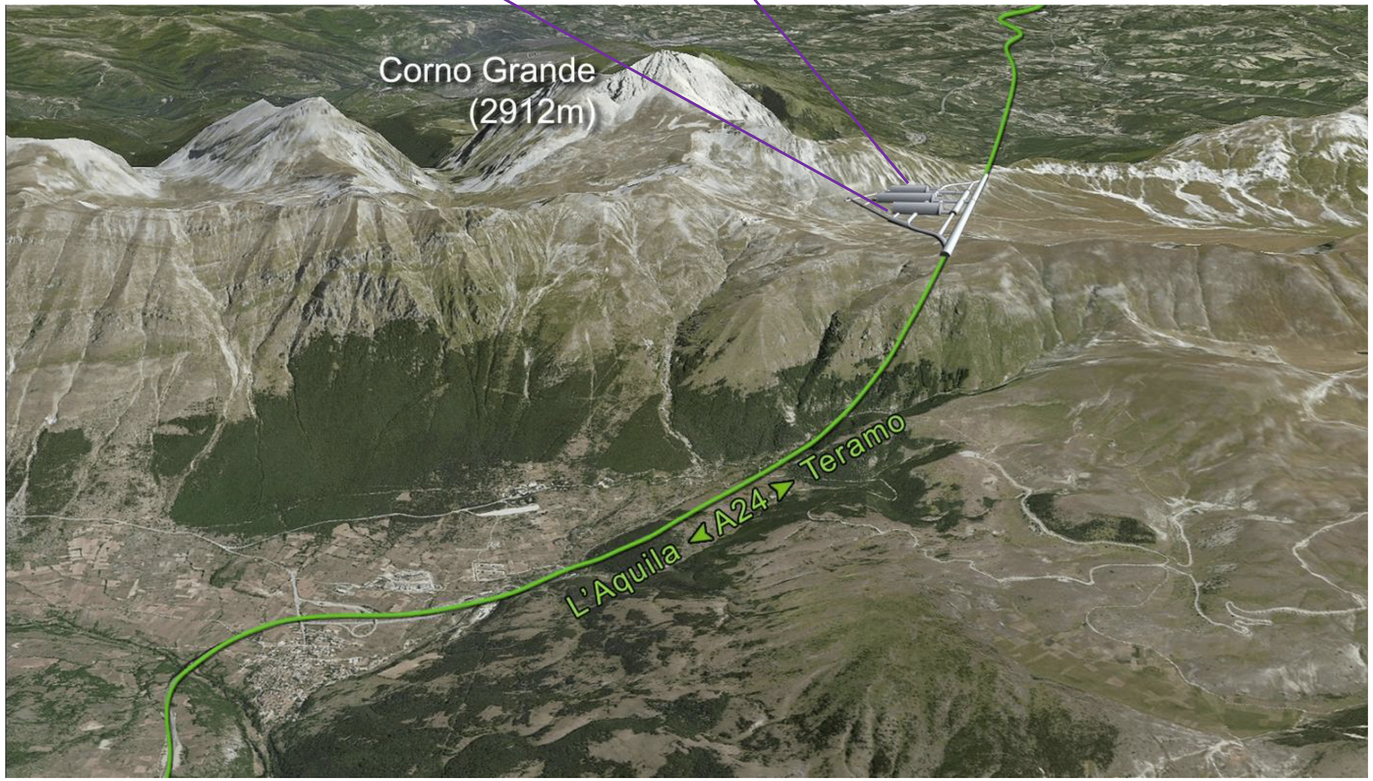
HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

TU WIEN

UNIVERSITÀ DEGLI STUDI DI MILANO BICOCCA

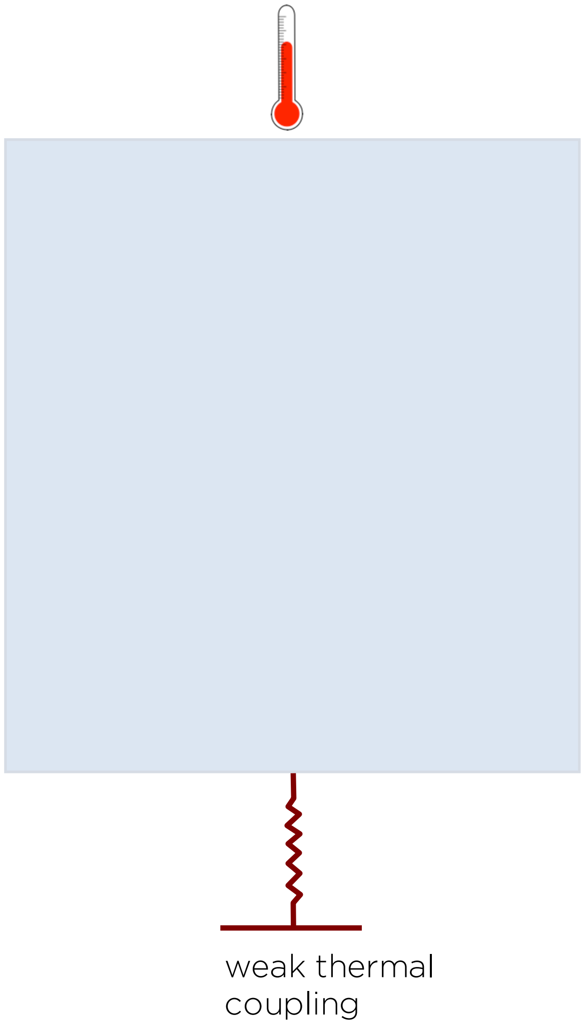
LOCATION





taken from MPI Munich

LOW TEMPERATURE DETECTOR

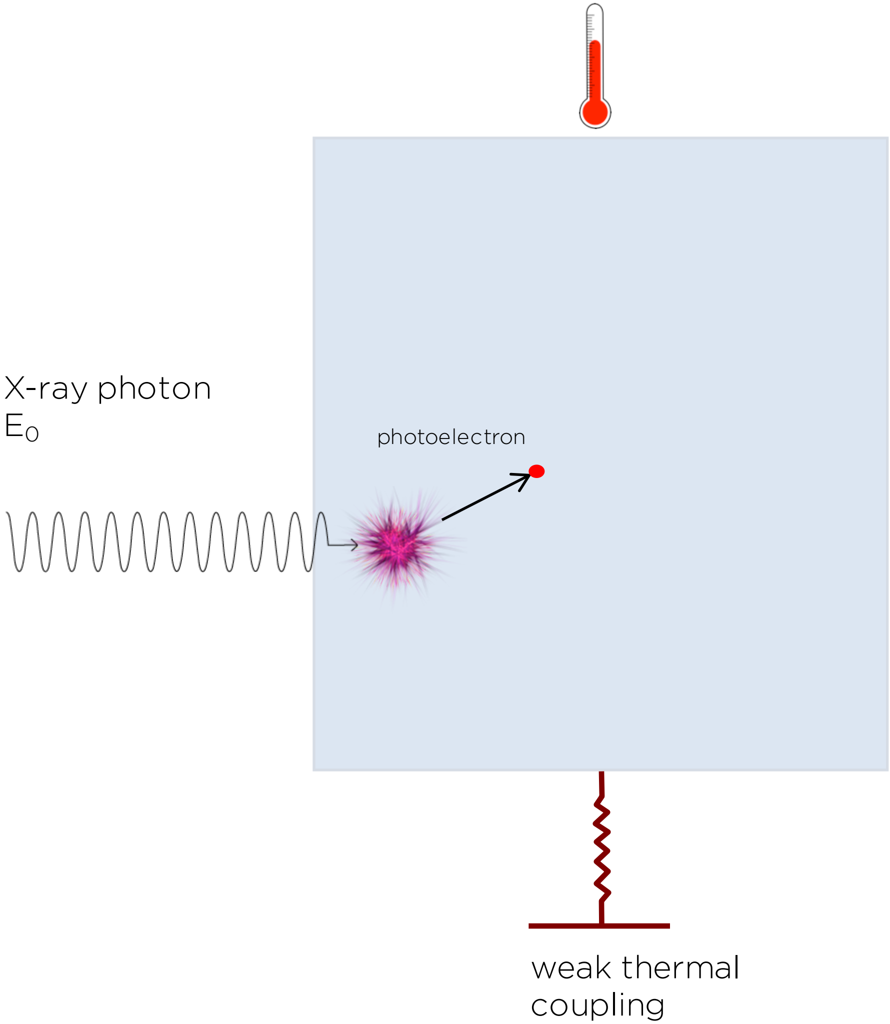


sensitive thermometer

crystal

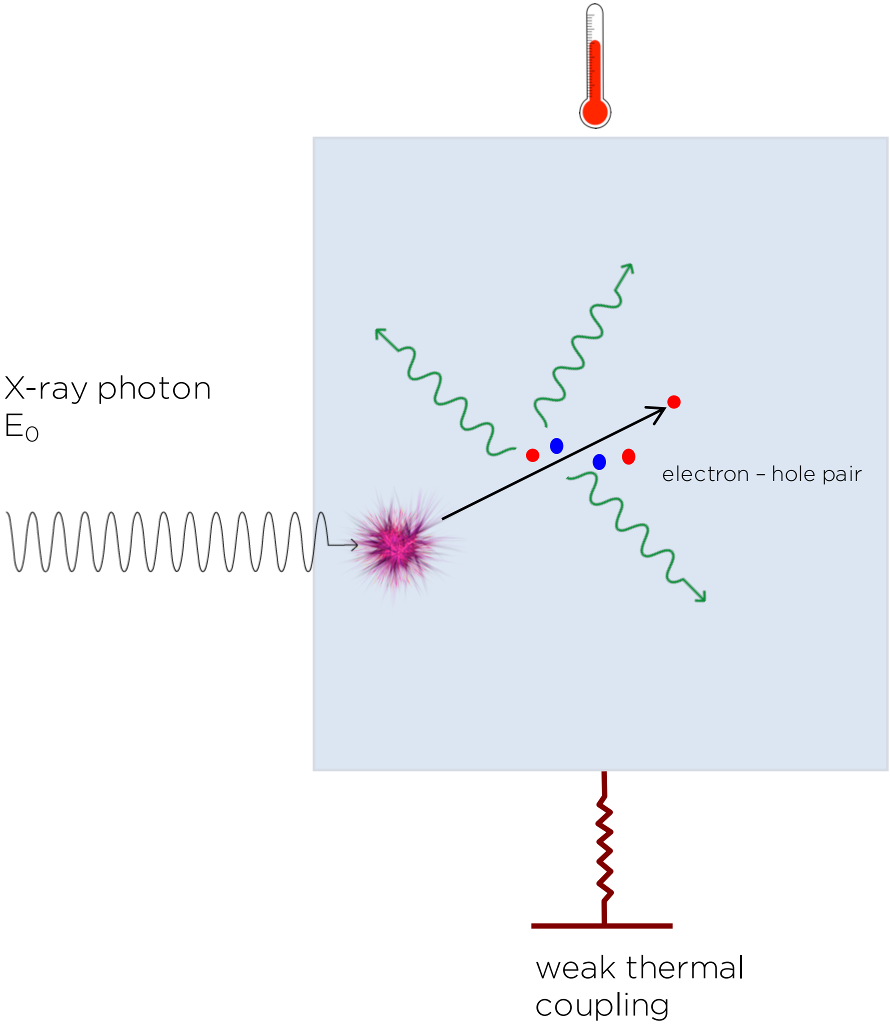
very low temperatures
→ 10 millli-Kelvin

LOW TEMPERATURE DETECTOR



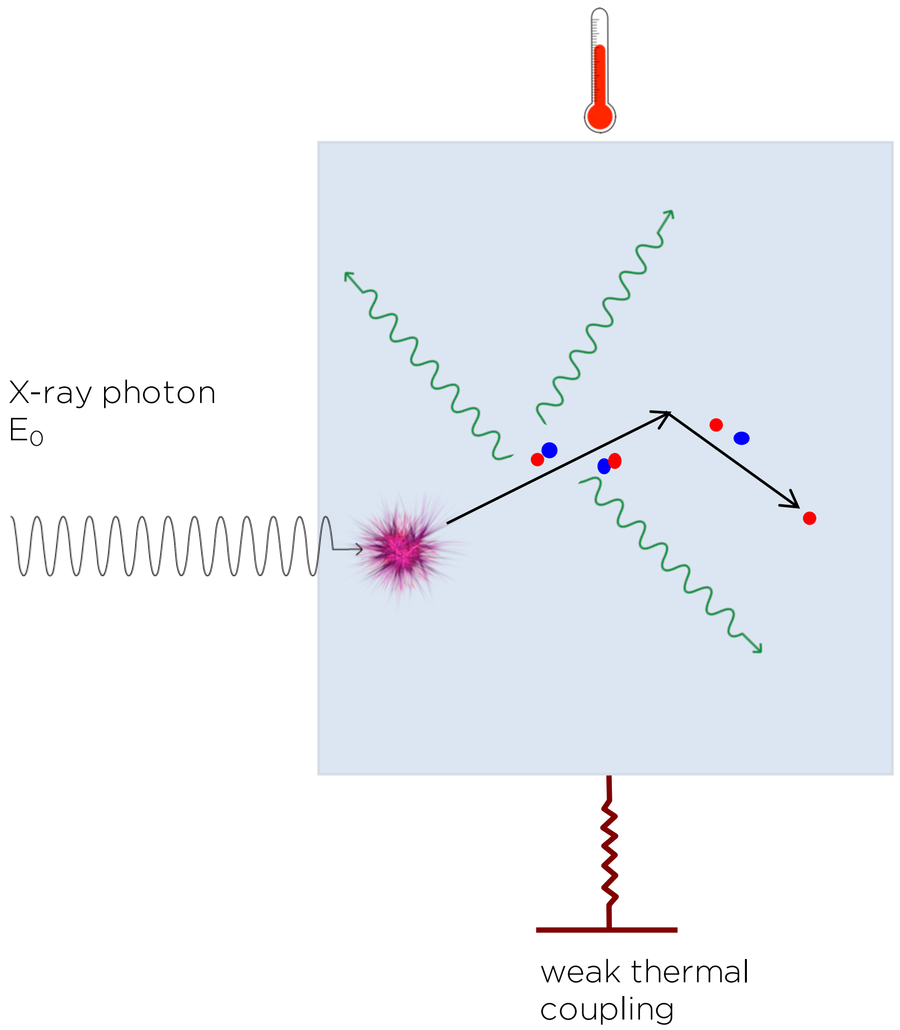
- photon creates photoelectron

LOW TEMPERATURE DETECTOR



- photon creates photoelectron
- photoelectron goes on creating e-h pairs and high energy phonons

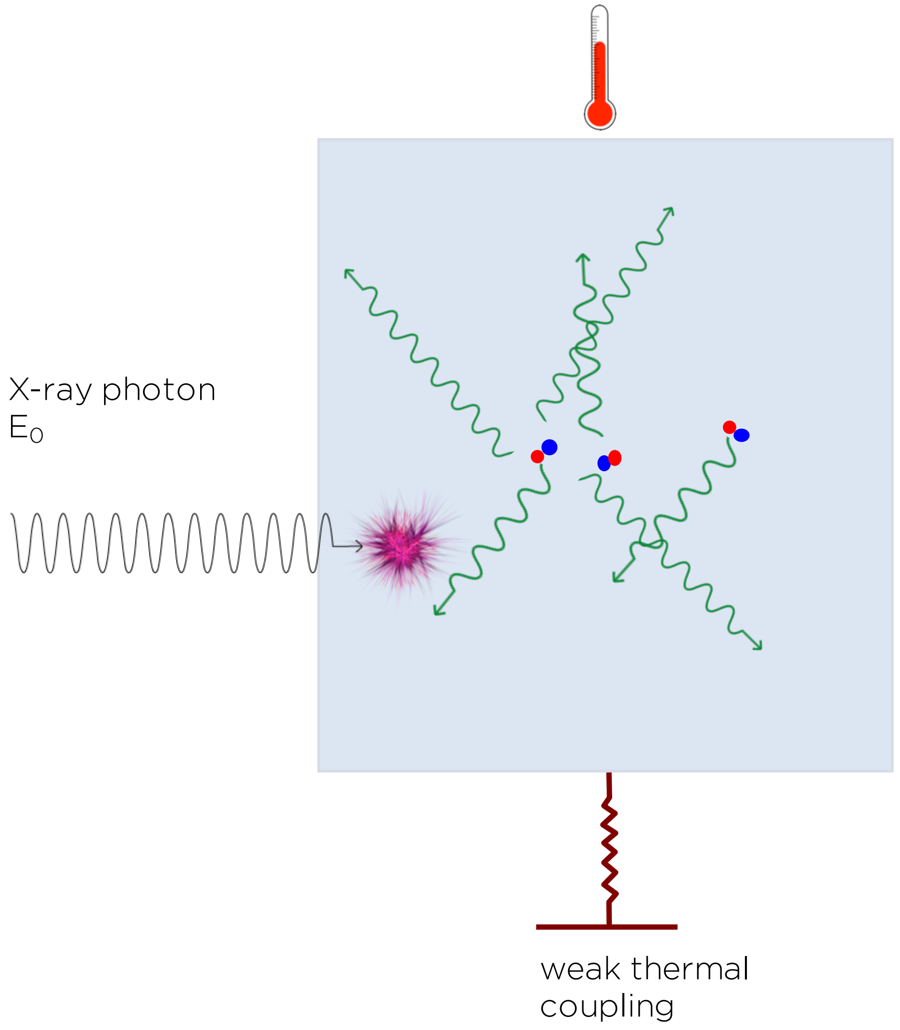
LOW TEMPERATURE DETECTOR



- photon creates photoelectron
- photoelectron goes on creating e-h pairs and high energy phonons
- electron – hole pairs start to recombine while

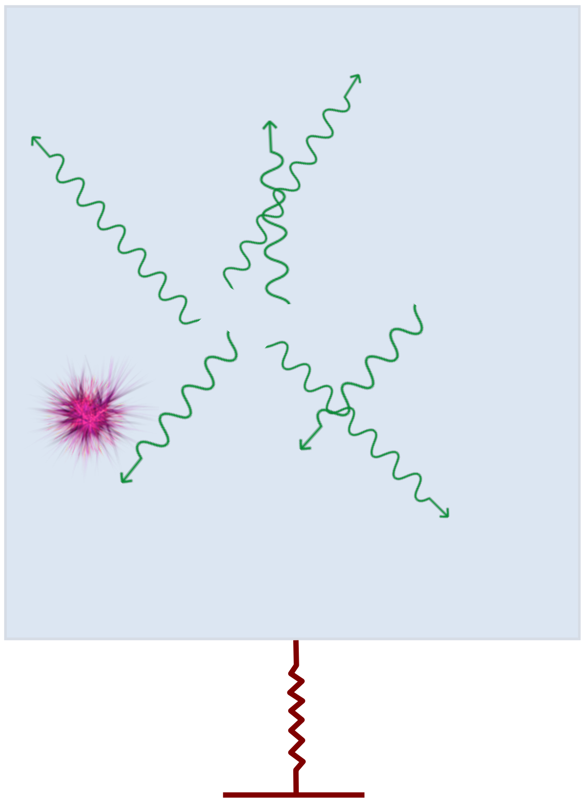
  photoelectrons and phonons continue to down-convert

LOW TEMPERATURE DETECTOR



- photon creates photoelectron
- photoelectron goes on creating e-h pairs and high energy phonons
- electron – hole pairs start to recombine while photoelectrons and phonons continue to down-convert
- electron – hole pairs recombine and emit a phonon

LOW TEMPERATURE DETECTOR

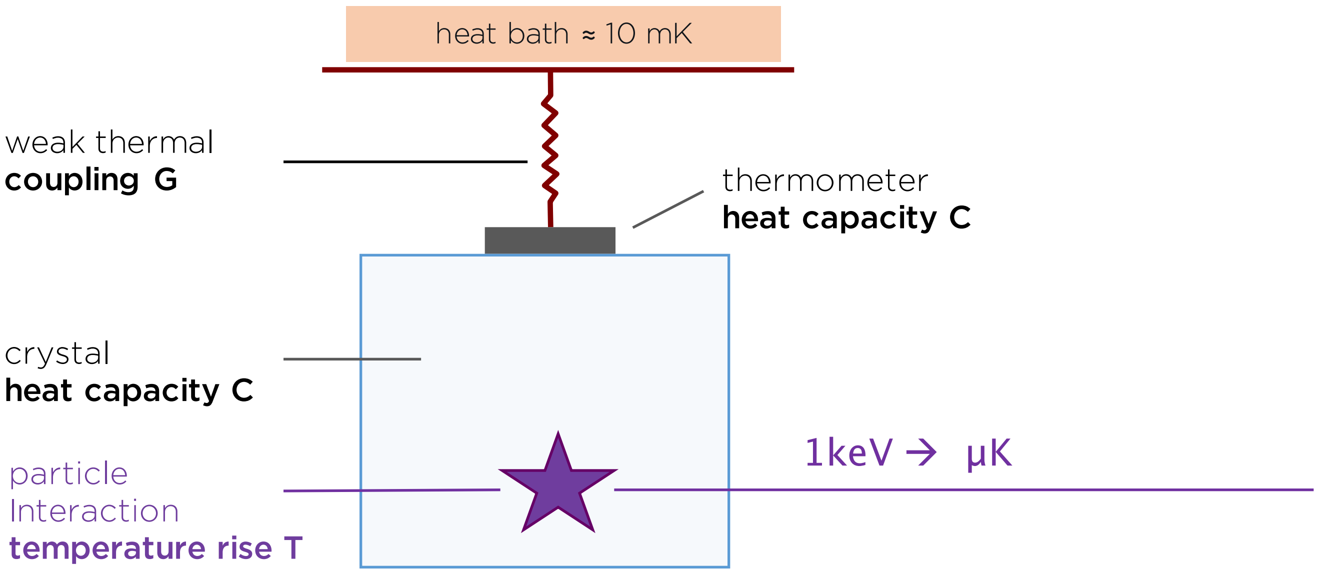


- **IF you have time:**
  (meta-stable states, traps,…)

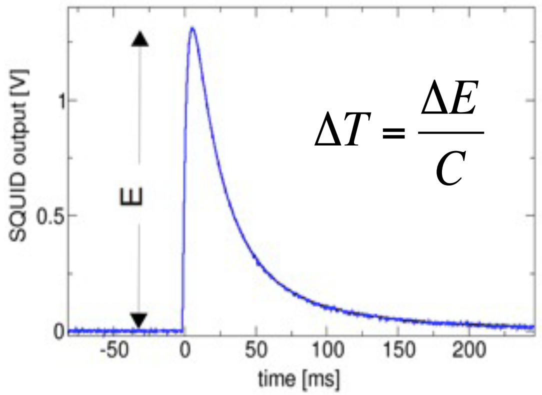
→ **almost all initial energy will be converted in a thermal signal**

such a detector we refer to as
cryogenic bolometer or
cryogenic calorimeter

CRYOGENIC CALORIMETER



Temperature pulse



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

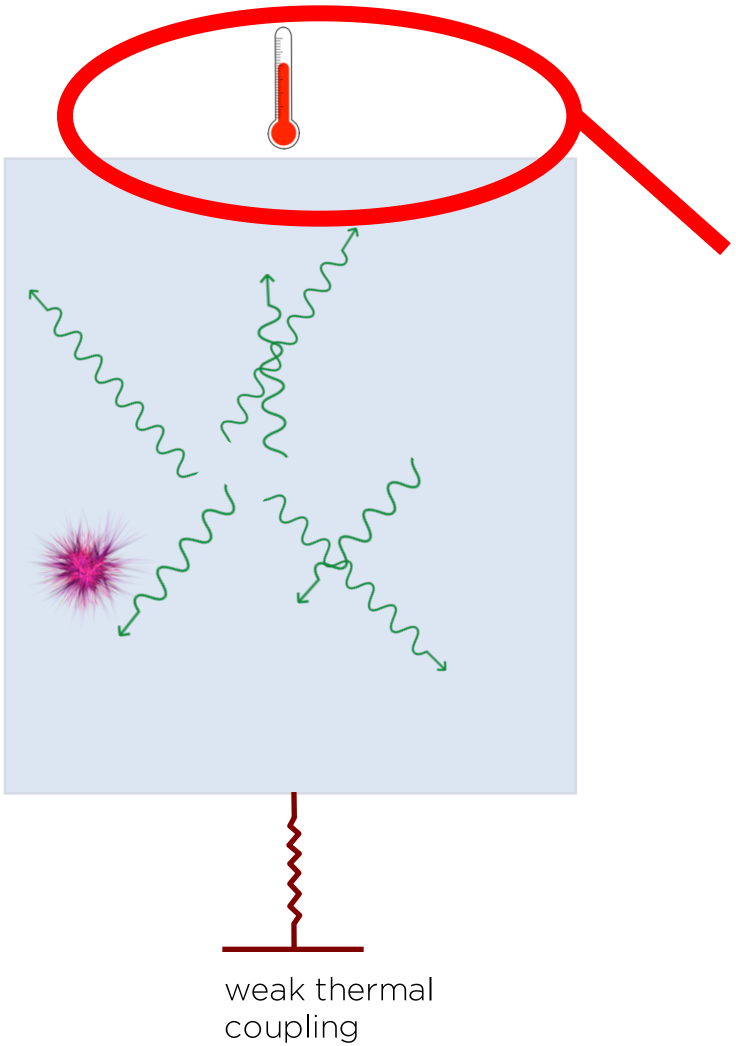
Irreducible thermal fluctuations

$$\langle \Delta E^2 \rangle = k_b T^2 C$$

low temperatures → better energy sensitivity

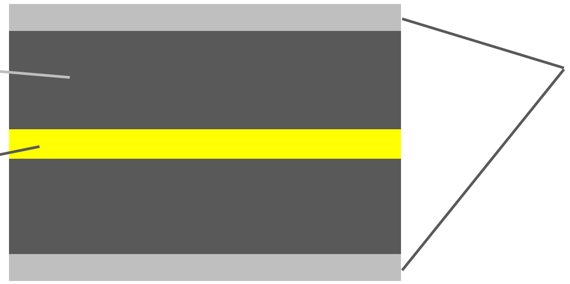
low heat capacity → careful selection of materials

HOW TO MEASURE TEMPERATURE ?

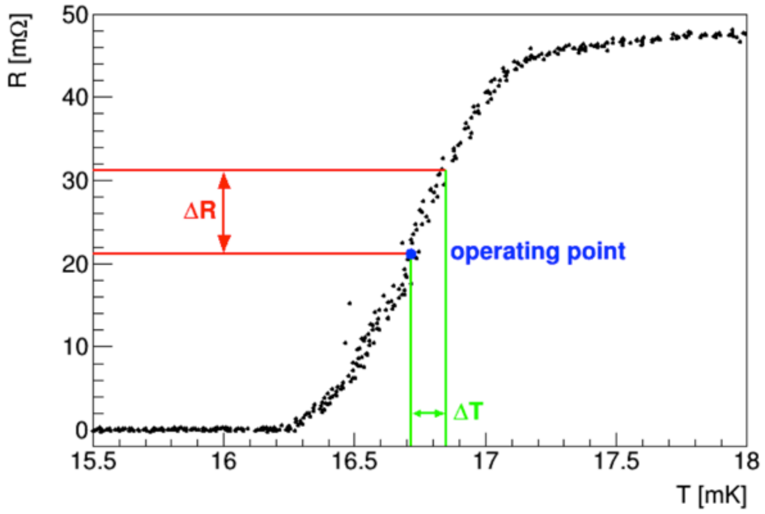


What to use as thermometer?

TRANSITION EDGE SENSOR (TES)



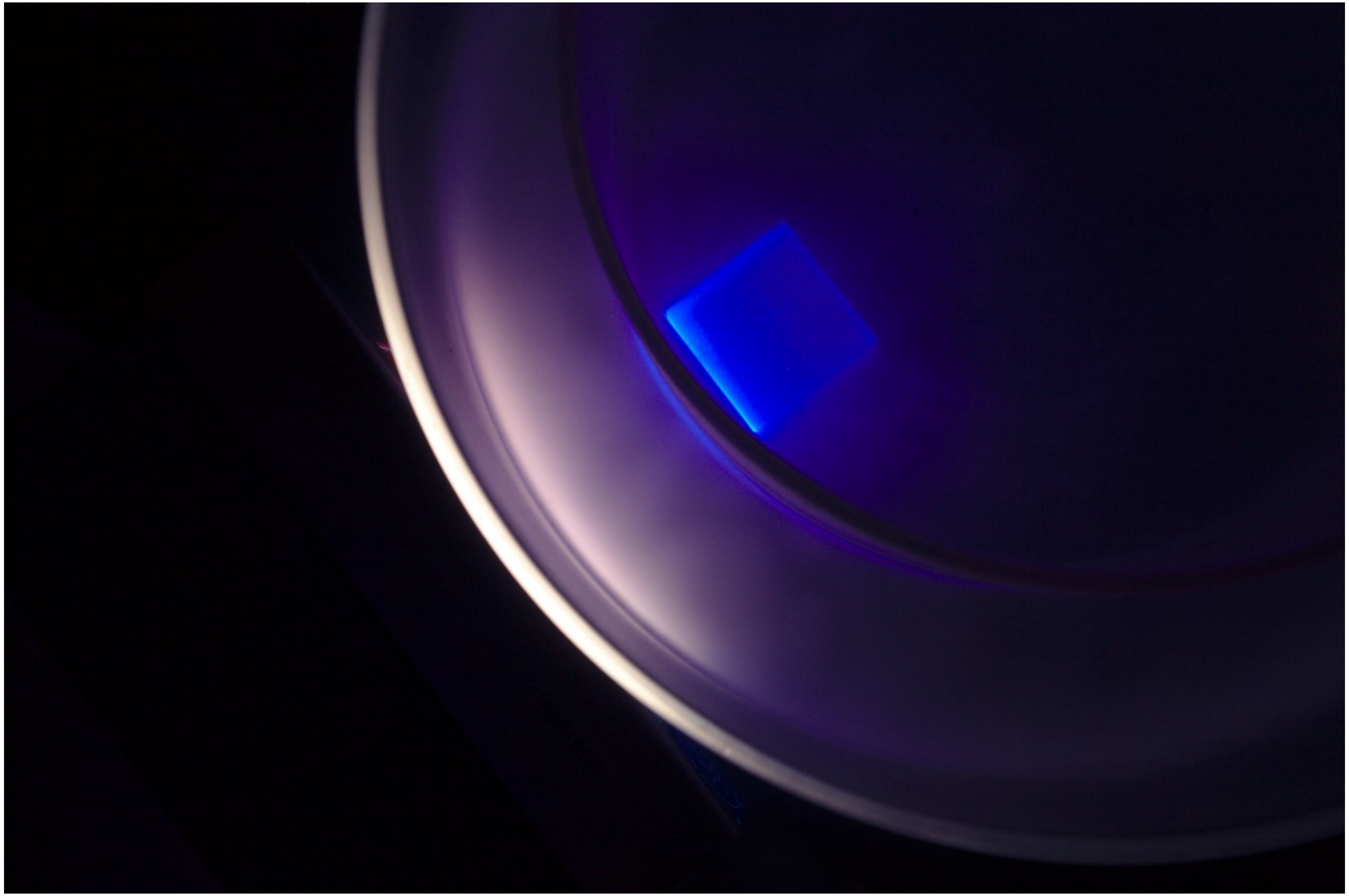
TRANSITION EDGE SENSOR (TES)



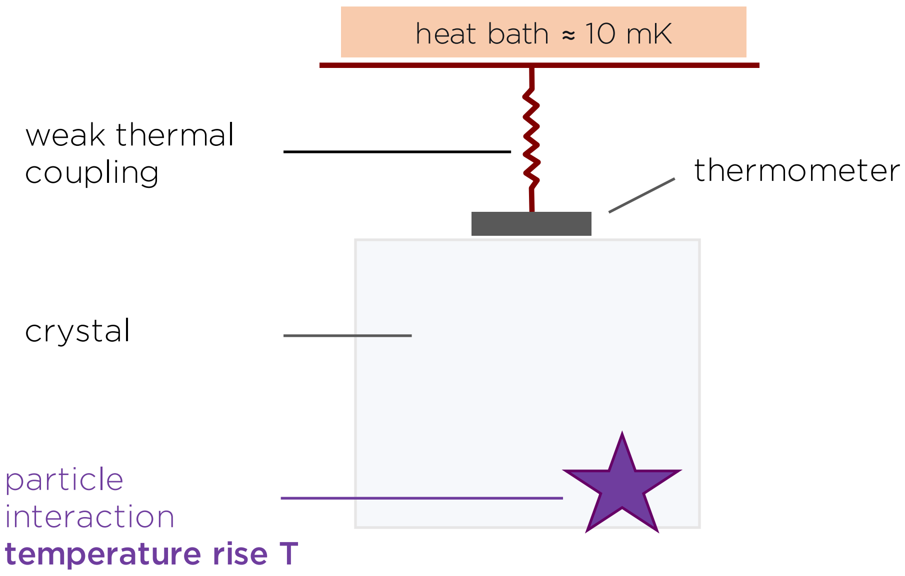
W-film evaporated onto the carrier crystal

- temperature stabilized between normal and superconducting phase
- particle interaction creates phonons
  → rise of film temperature
- resistance change of the film measured with SQUID-based readout

NaI CRYSTAL



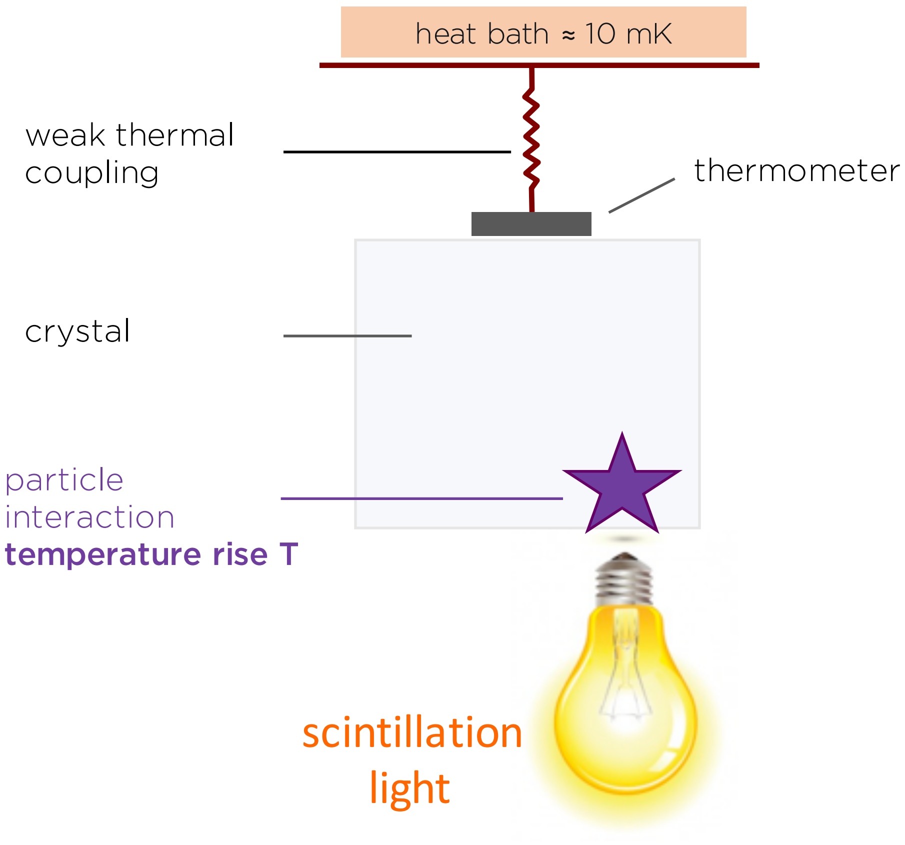
NaI-based SCINTILLATING CALORIMETER



Phonon signal (~ 90 %)

- (almost) independent of particle type
- precise measurement of the deposited energy

NaI-based SCINTILLATING CALORIMETER



Phonon signal (~ 90 %)

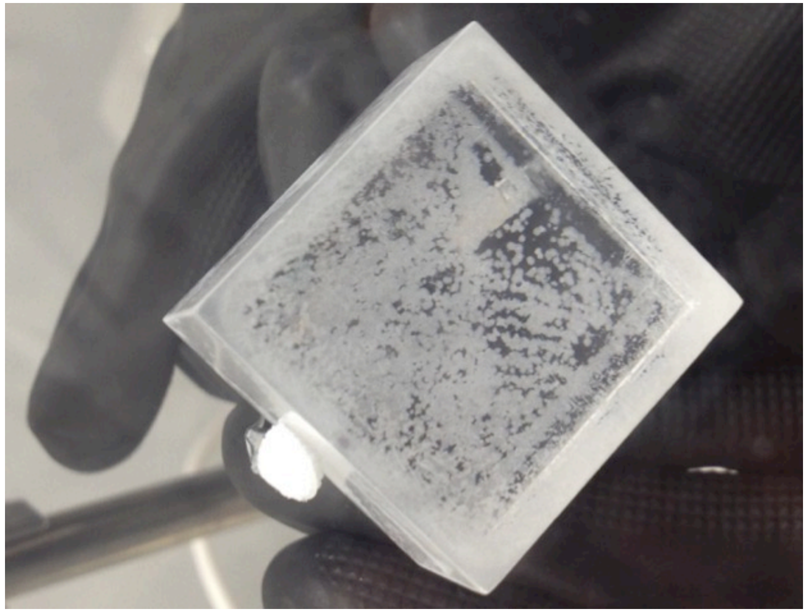
- (almost) independent of particle type
- precise measurement of the deposited energy

Scintillation light (few %)

- amount of emitted light depends on particle type
  → LIGHT QUENCHING
- discrimination of interacting particle via the **ratio light to phonon signal**
  → LIGHT YIELD

… but NaI is not that NaIce!

- hygroscopic nature



handle in controlled atmosphere:

- glove box
- special container for cooldown in dilution refrigerator

… but NaI is not that NaIce!

- 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

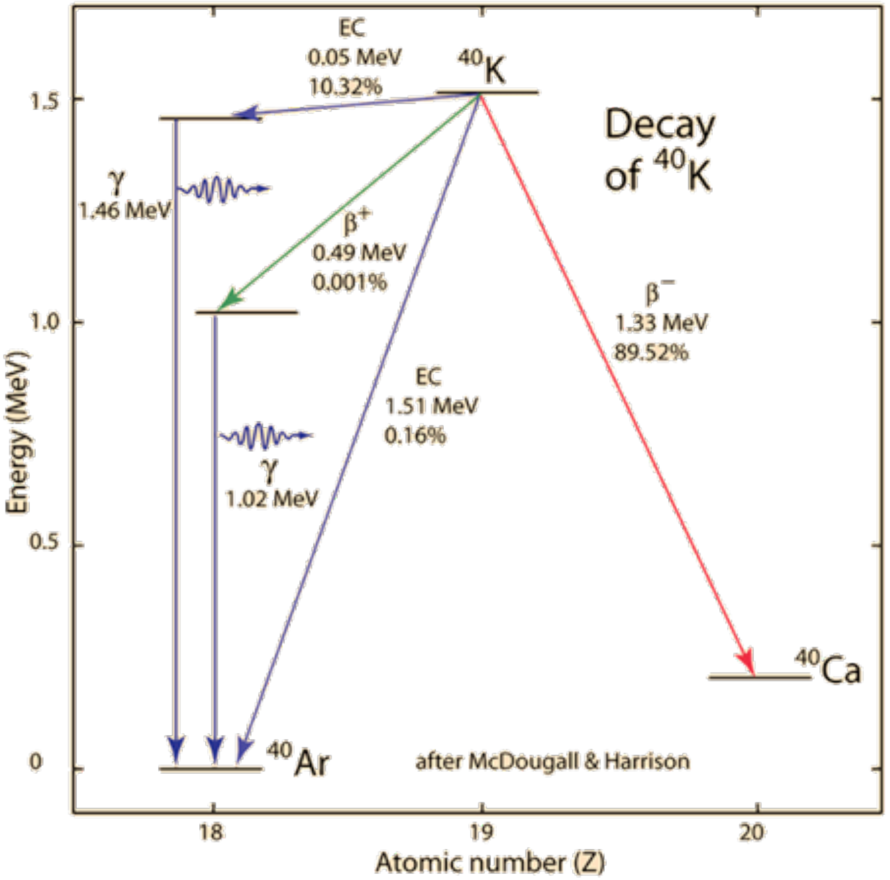
PREPARE FOR:

small signal amplitudes

- develop highly sensitive W-TES
- surface of NaI optically polished

… but NaI is not that NaIce!

- typically high contamination with ^{40}K

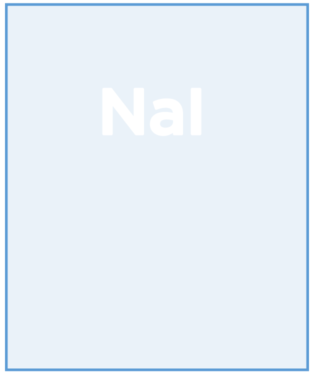


Contamination	DAMA/LIBRA crystal [ppb]
K	~ 13
Rb	< 0.35
U	0.5 – 7.5 x 10^{-3}
Th	0.7 – 10 x 10^{-3}

dangerous background is the 3 keV Auger electrons emitted together with the 1.46 MeV gamma quantum

Bernabei et al., NIM A592 (2008) 297-315

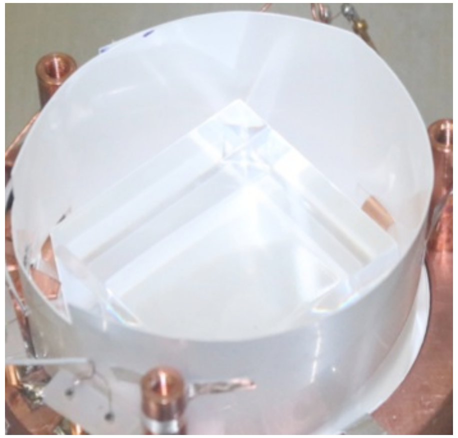
COSINUS DETECTOR CONSTRUCTION



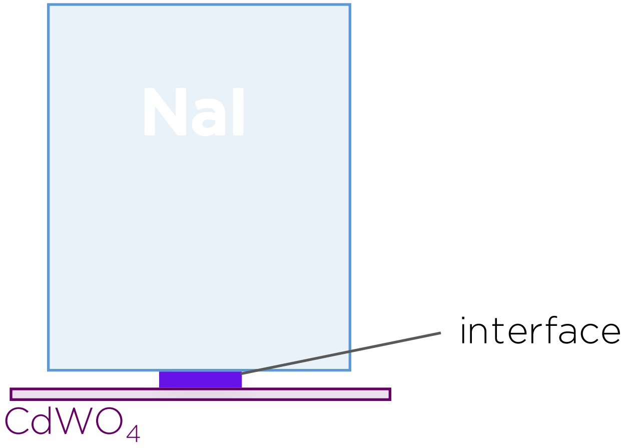
NaI Target Crystal

- scintillator
- multi-element target
- mass: ~ 50 – 200 g

11Na 53I

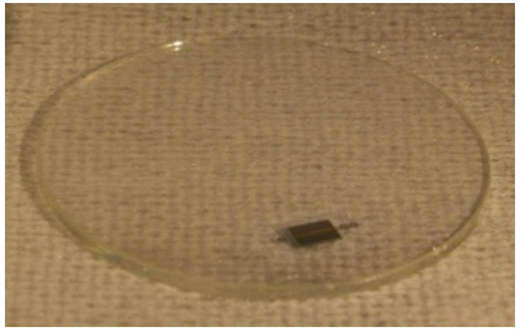


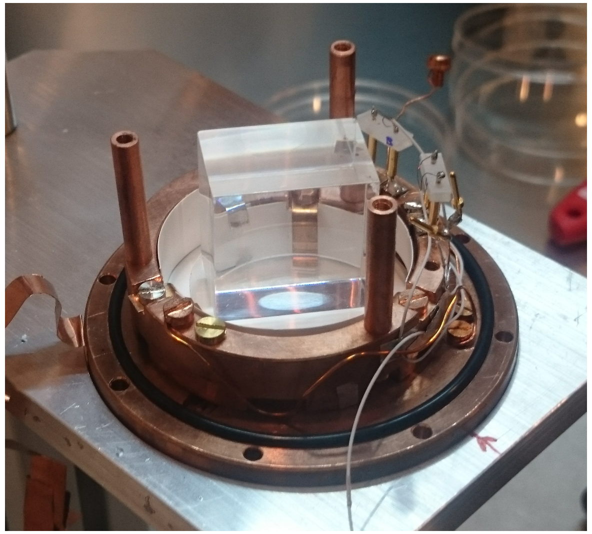
COSINUS DETECTOR DESIGN



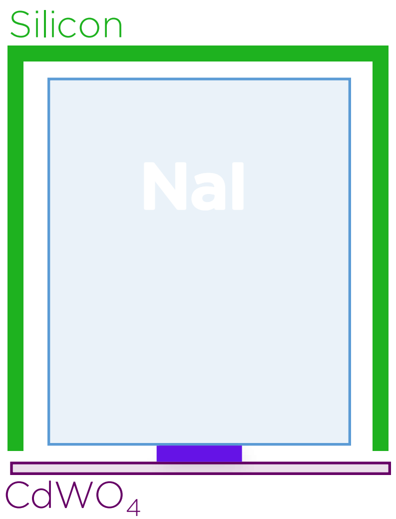
$CdWO_4$ carrier crystal

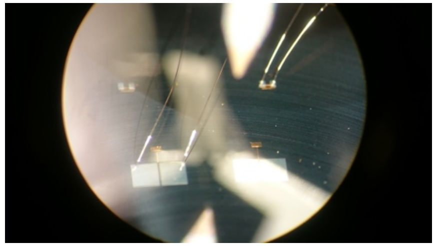
- carries the W-TES
- glue/oil as interface
- mass: ~ 15 g





COSINUS DETECTOR DESIGN

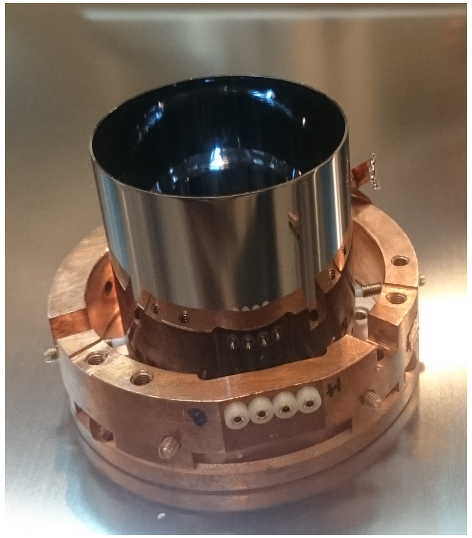


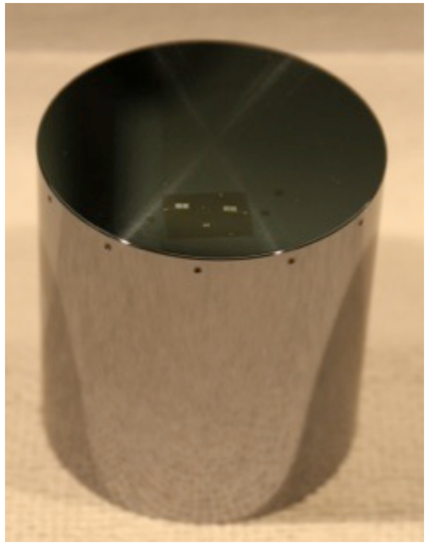


Light absorber

- beaker shape
- 40 mm diameter & height

High Purity silicon





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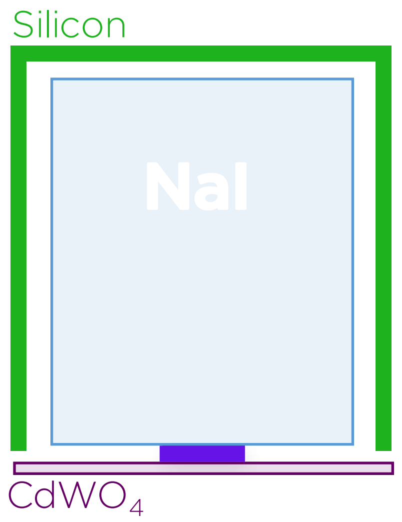
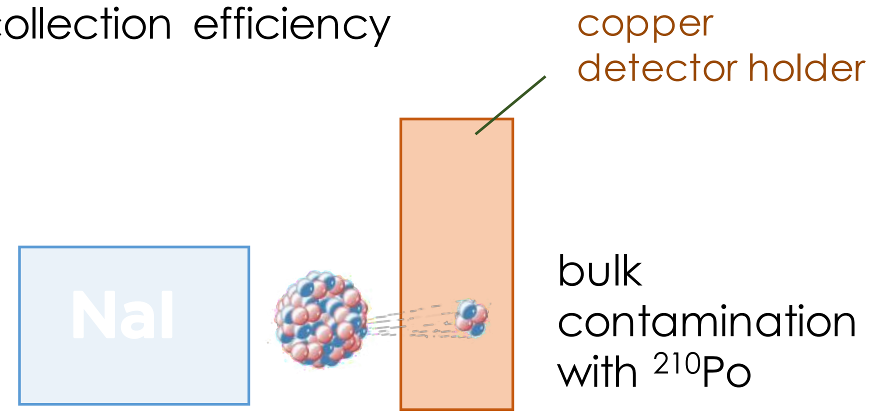


Light absorber

- ~ 40 mm diameter & height
- fully active veto

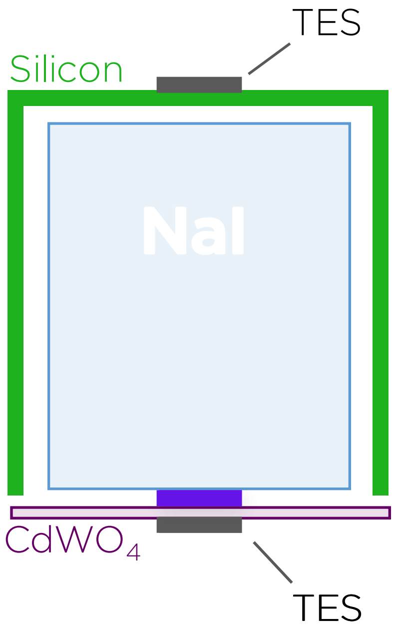
→ reject surface backgrounds

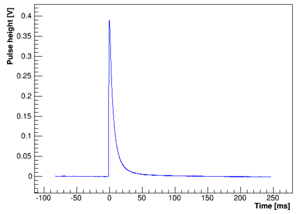
→ high light collection efficiency

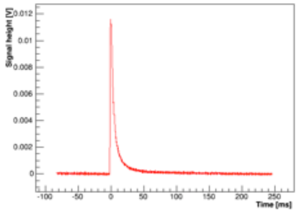


$^{210}\text{Po} \rightarrow {}^{206}\text{Pb}$ (103 keV) + a (5.3 MeV)

COSINUS DETECTOR DESIGN







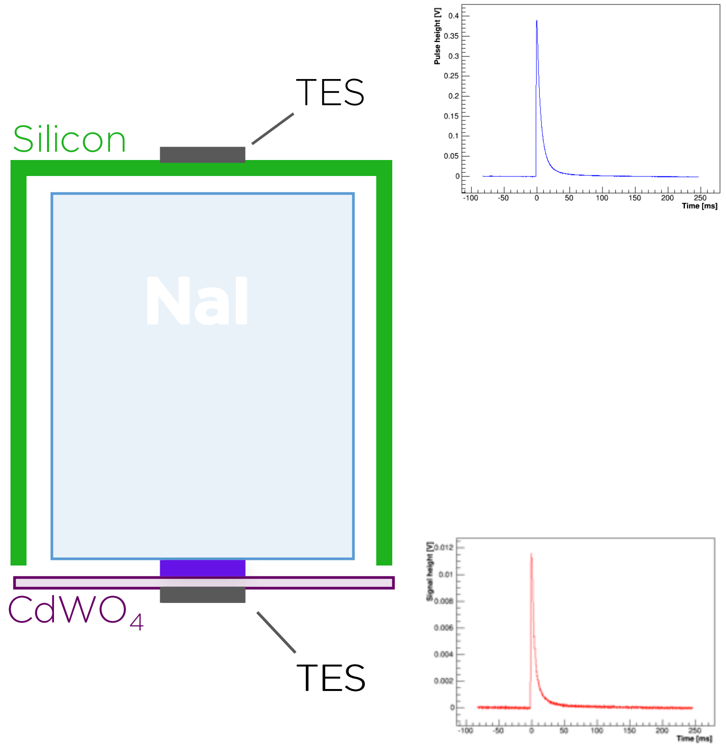
2 independent channels

- W-TESs as thermometers
- simultaneous readout of

  → phonon signal in NaI

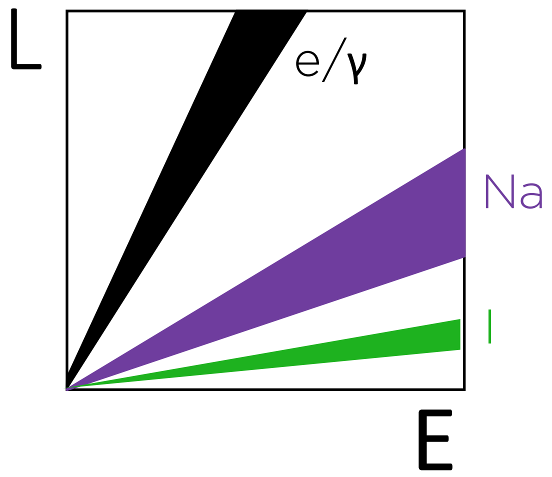
  → scintillation light

COSINUS DETECTOR DESIGN



Particle discrimination

- simultaneous detection of:
  - energy in the crystal E
  - scintillation light L
- discrimination of interacting particle via the ratio L/E



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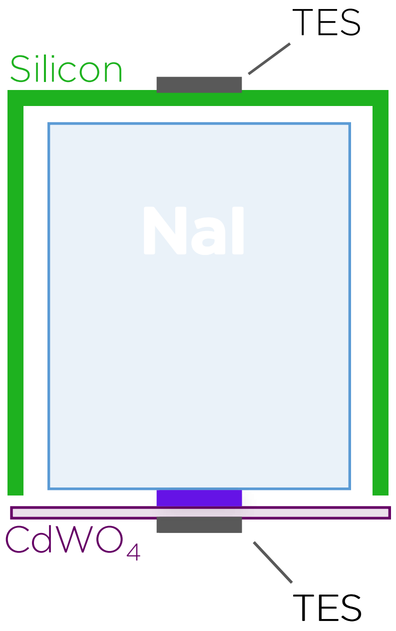


Performance goal

- NaI detector:

  nuclear recoil energy threshold ~ 1 keV

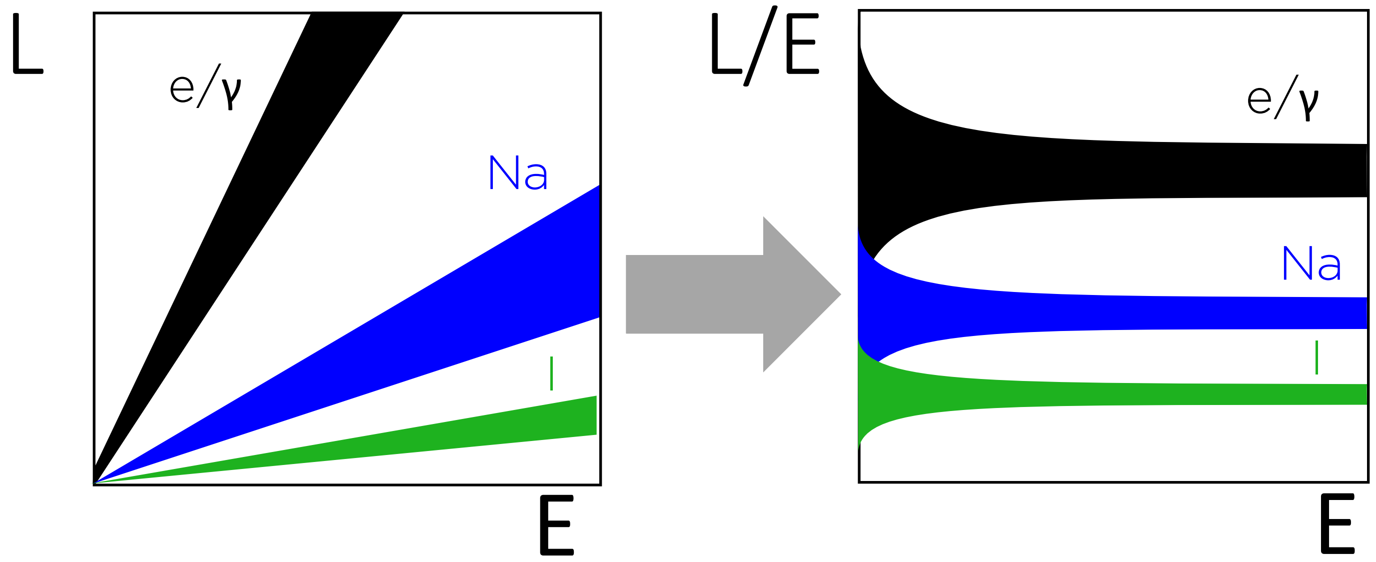
- light detector:

  4% of deposited energy detected in light

bring performance in-line with existing bolometers e.g. produced within **CRESST-II**

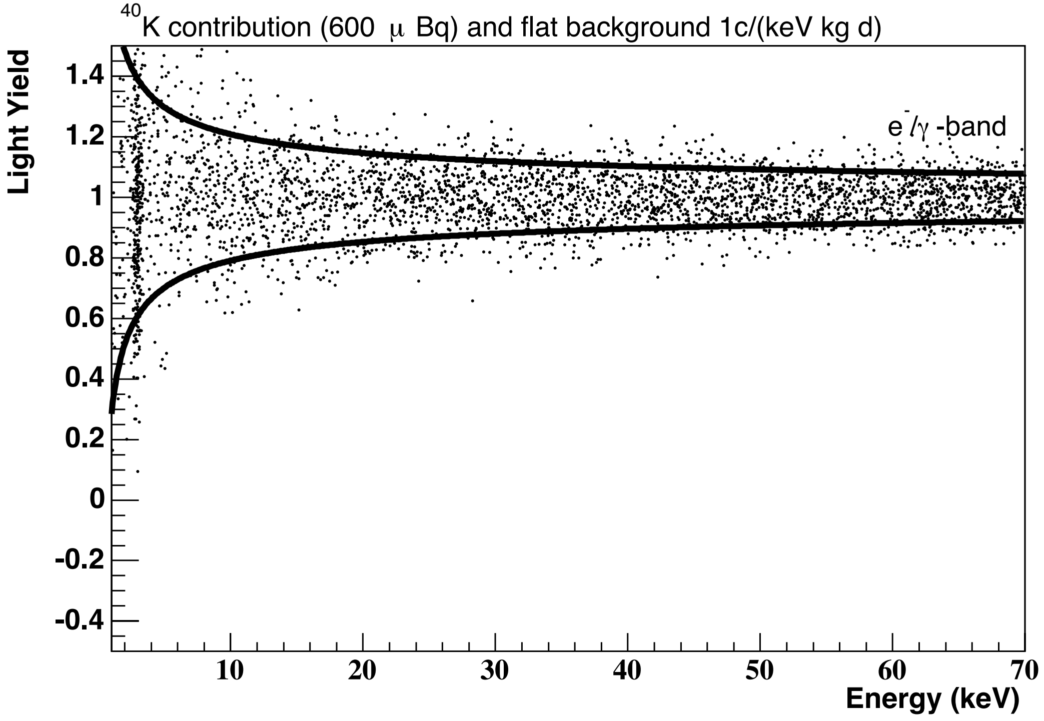
LIGHT YIELD

LIGHT YIELD = $\frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$



SIMULATED DATA FOR 100 kg days

LIGHT YIELD = $\frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$

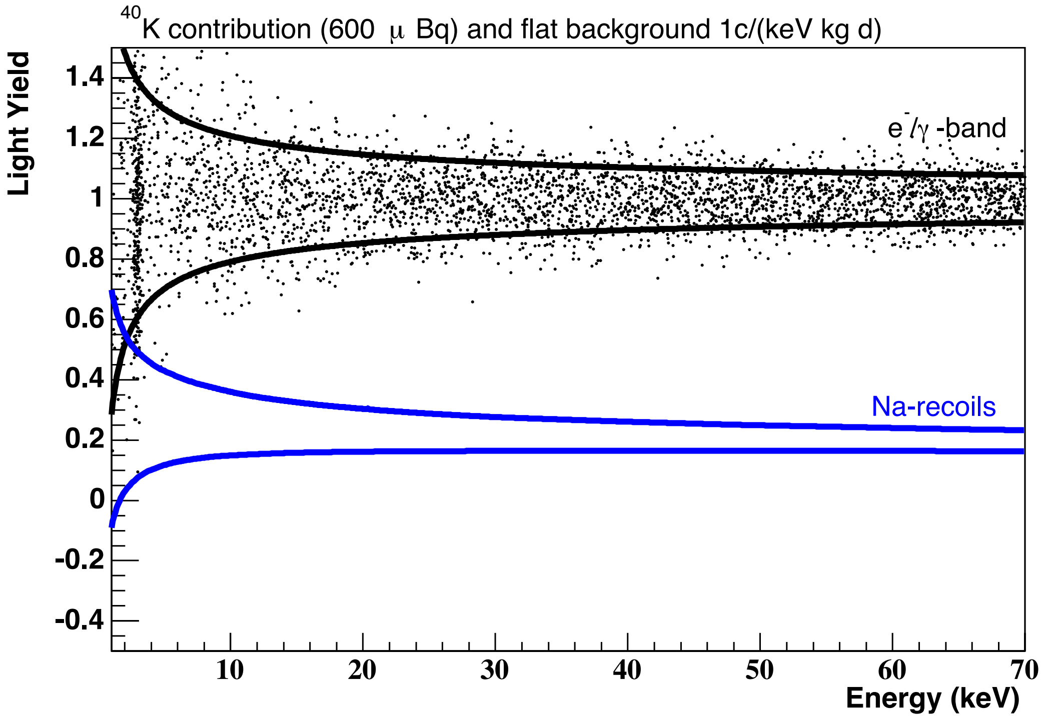


Eur. Phys. J. C (2016) 76:441
DOI 10.1140/epjc/s10052-016-4278-3

- NaI energy resolution σ=200 eV
- NaI energy threshold 1 keV
- 4% of deposited energy detected in form of light
- light detector baseline noise σ=10 eV
- **black events**:
  flat background: 1 /(keV kg day)
  + ^{40}K background: 600uBq/kg = DAMA
- **exposure before cuts: 100 kg-days**
- **solid lines: 80% bands**

SIMULATED DATA FOR 100 kg days

LIGHT YIELD = $\frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$



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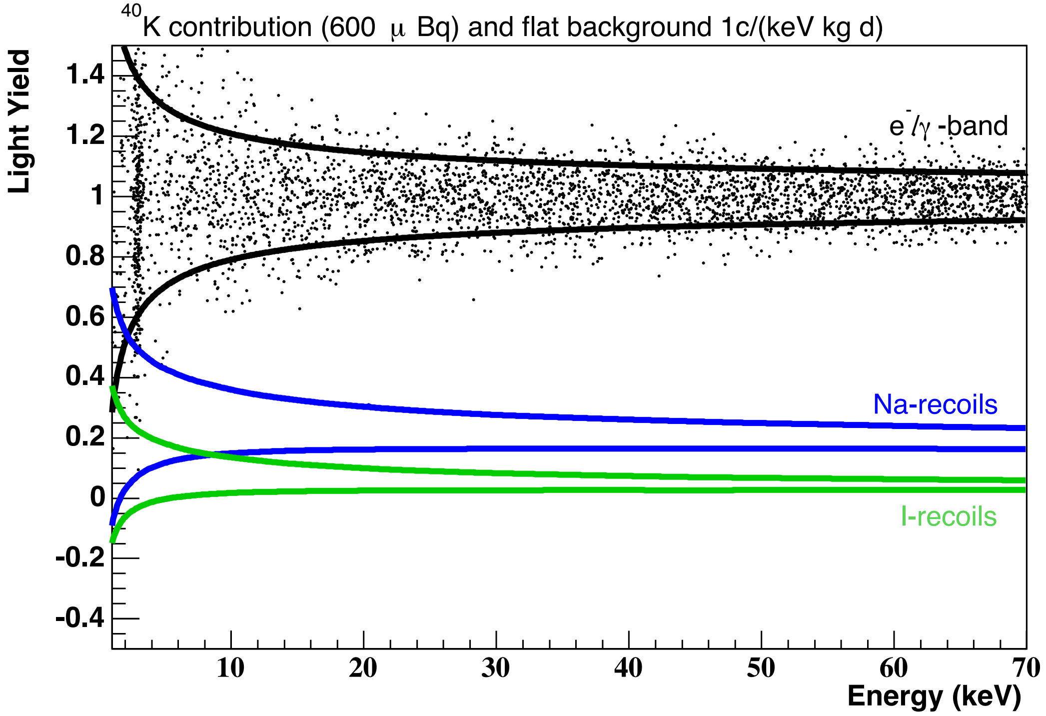
  + ^{40}K background: 600uBq/kg
- exposure before cuts: 100 kg-days
- **recoils off Na**
  QF from Tretyak, Astropart. Phys. 33, 40 (2010)

SIMULATED DATA FOR 100 kg days

LIGHT YIELD = $\frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$



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- **recoils off I**

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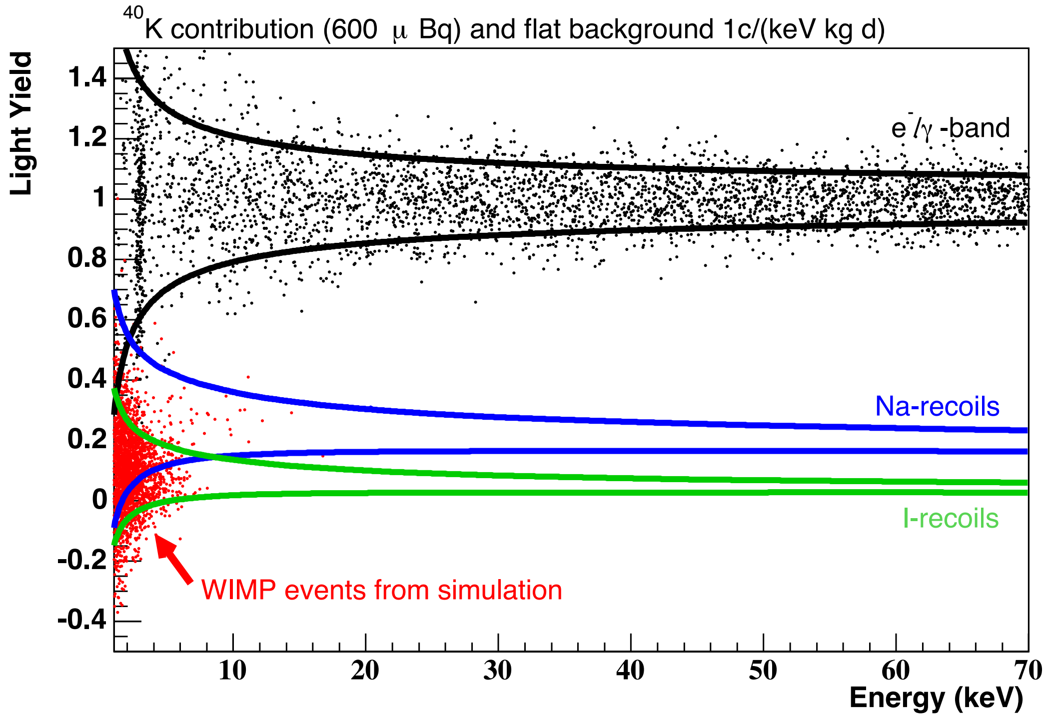
SIMULATED DATA FOR 100 kg days

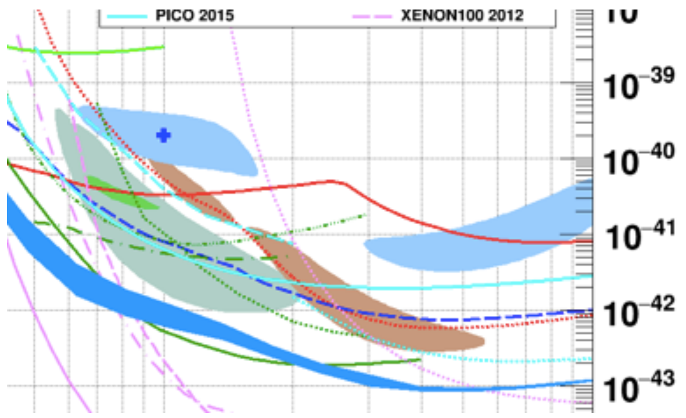
$$\text{LIGHT YIELD} = \frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$$



Eur. Phys. J. C (2016) 76:441

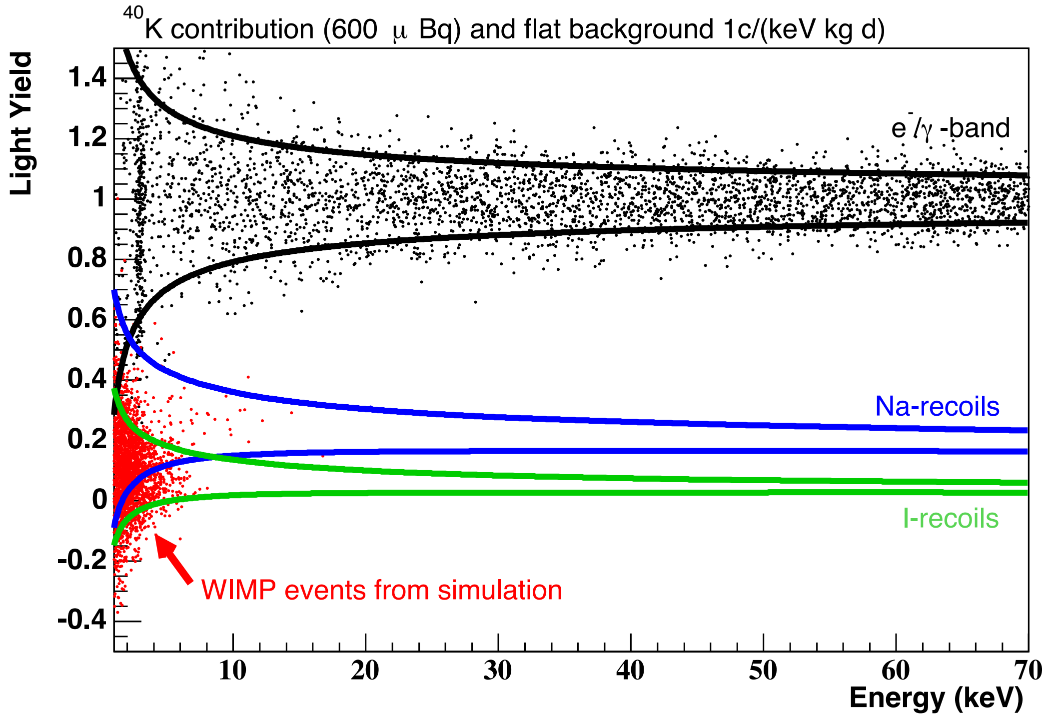
DOI 10.1140/epjc/s10052-016-4278-3

- black events:
  flat background: 1 /(keV kg d)
  + ^{40}K background: 600uBq/kg
- **red events:**
  10 GeV/c² WIMP with 2E-04 pb
  as from Savage et al.



SIMULATED DATA FOR 100 kg days

LIGHT YIELD = $\frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$



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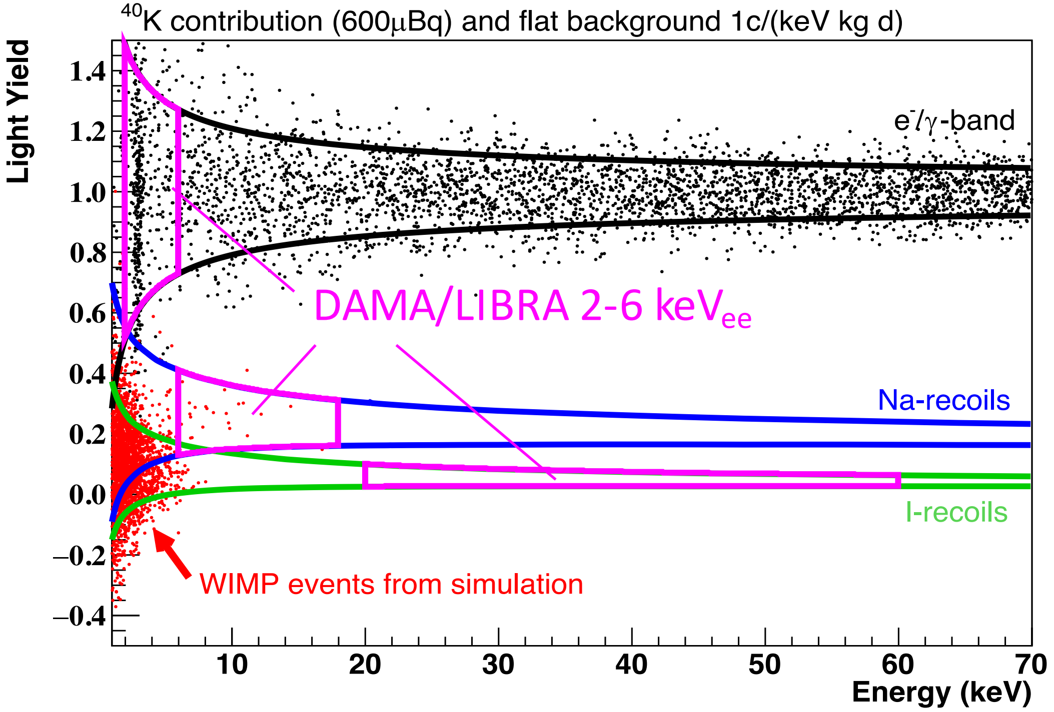
- **red events:**
  10 GeV/c² WIMP with 2E-04 pb
  Savage et al.

Energy	# Events	Fraction
1-2 keV	1078	45 %
2-6 keV	1262	53 %
> 6 keV	46	2 %
TOTAL	**2386**	**100 %**

SIMULATED DATA FOR 100 kg days

LIGHT YIELD = $\frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$



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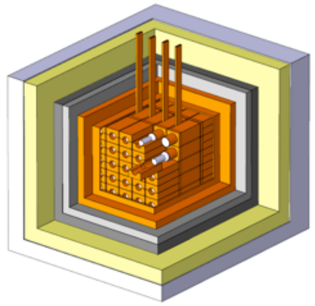
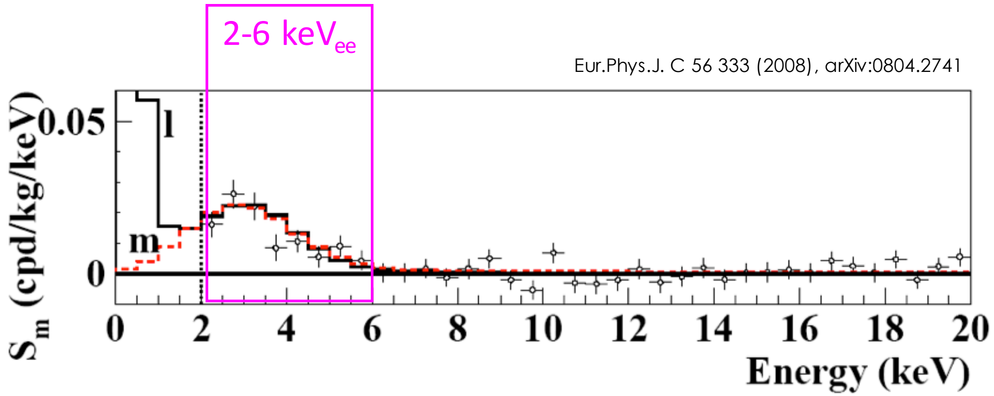
- **pink colored boxes** correspond to DAMA/LIBRA signal regions in the standard elastic scattering scenario

Energy	# Events	Fraction
1-2 keV	1078	45 %
2-6 keV	1262	53 %
> 6 keV	46	2 %
TOTAL	**2386**	**100 %**

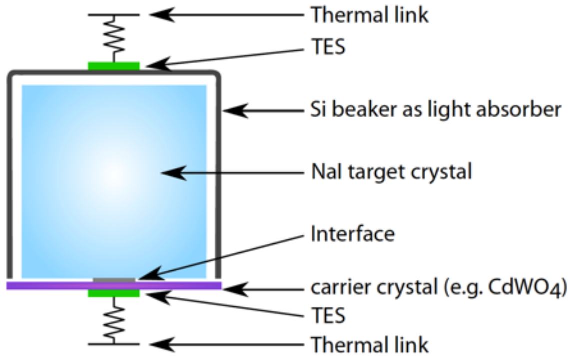
COMPARISON

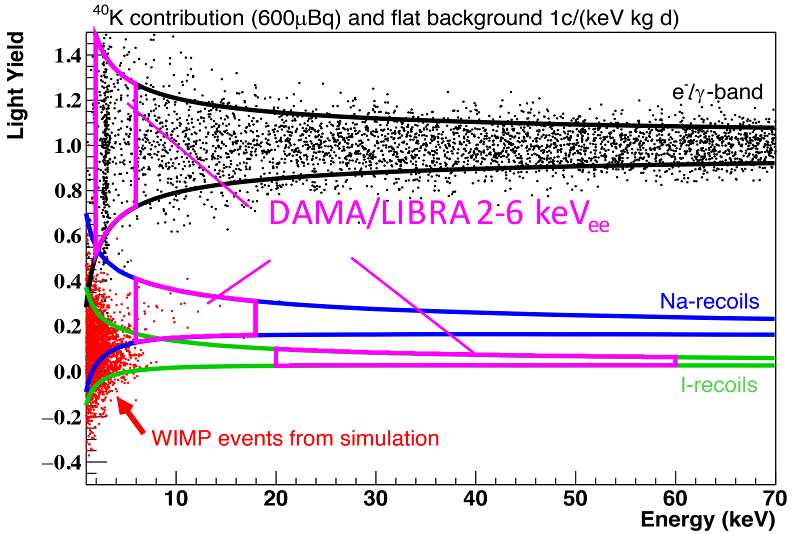
DAMA/LIBRA





COSINUS





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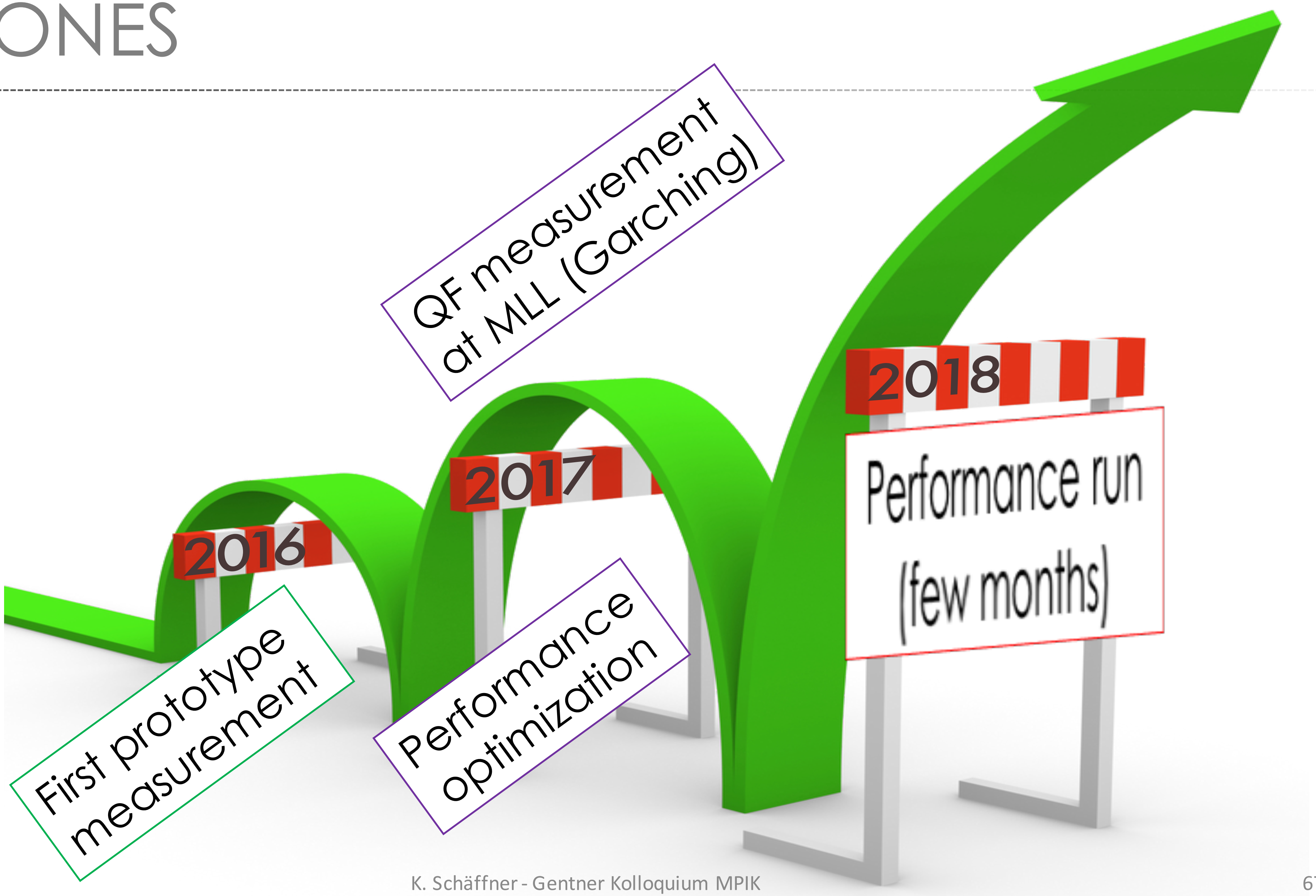
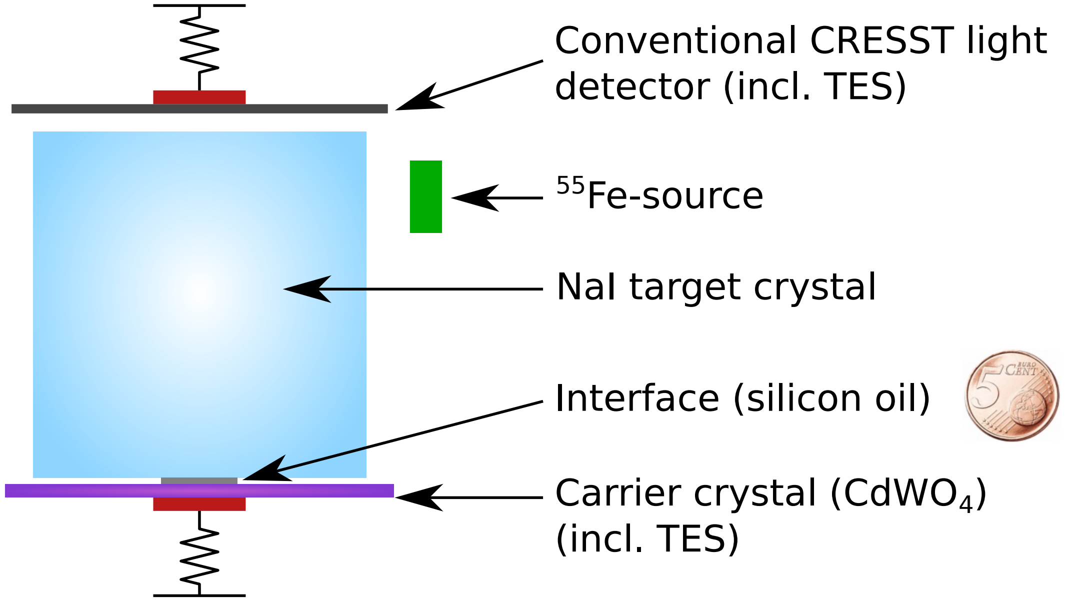
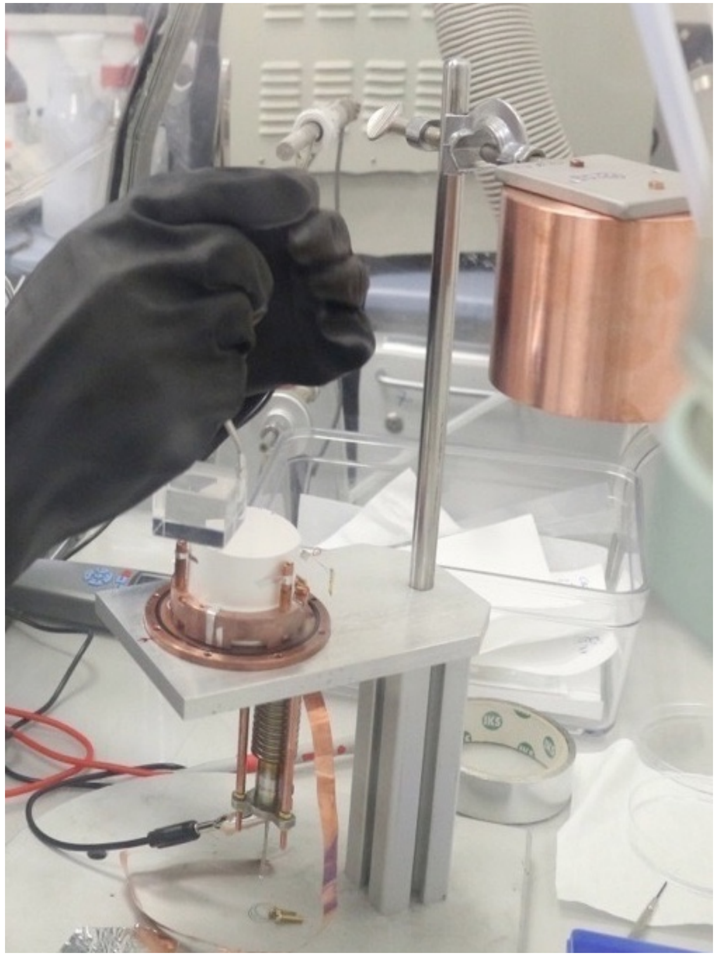
MILESTONES


QF measurement
at MLL (Garching)
2016
2017
2018
Performance run
(few months)
First prototype
measurement
Performance
optimization

1st PROTOTYPE ASSEMBLY





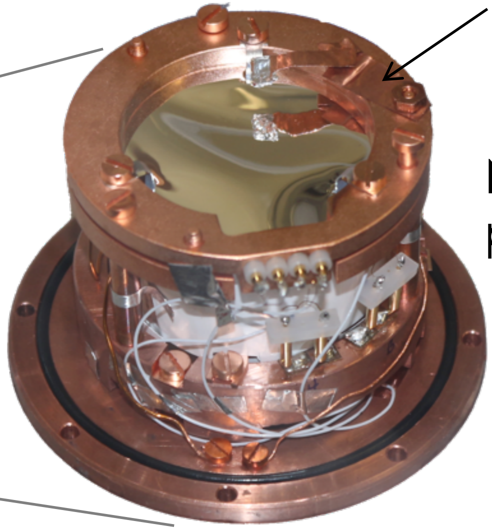
arXiv: 1705.11028
submitted to journal

MOUNTING IN DILUTION CRYOSTAT

5 cm of Pb to shield radioactivity
from the dilution unit of the cryostat

decoupling system
to reduce microphonic noise

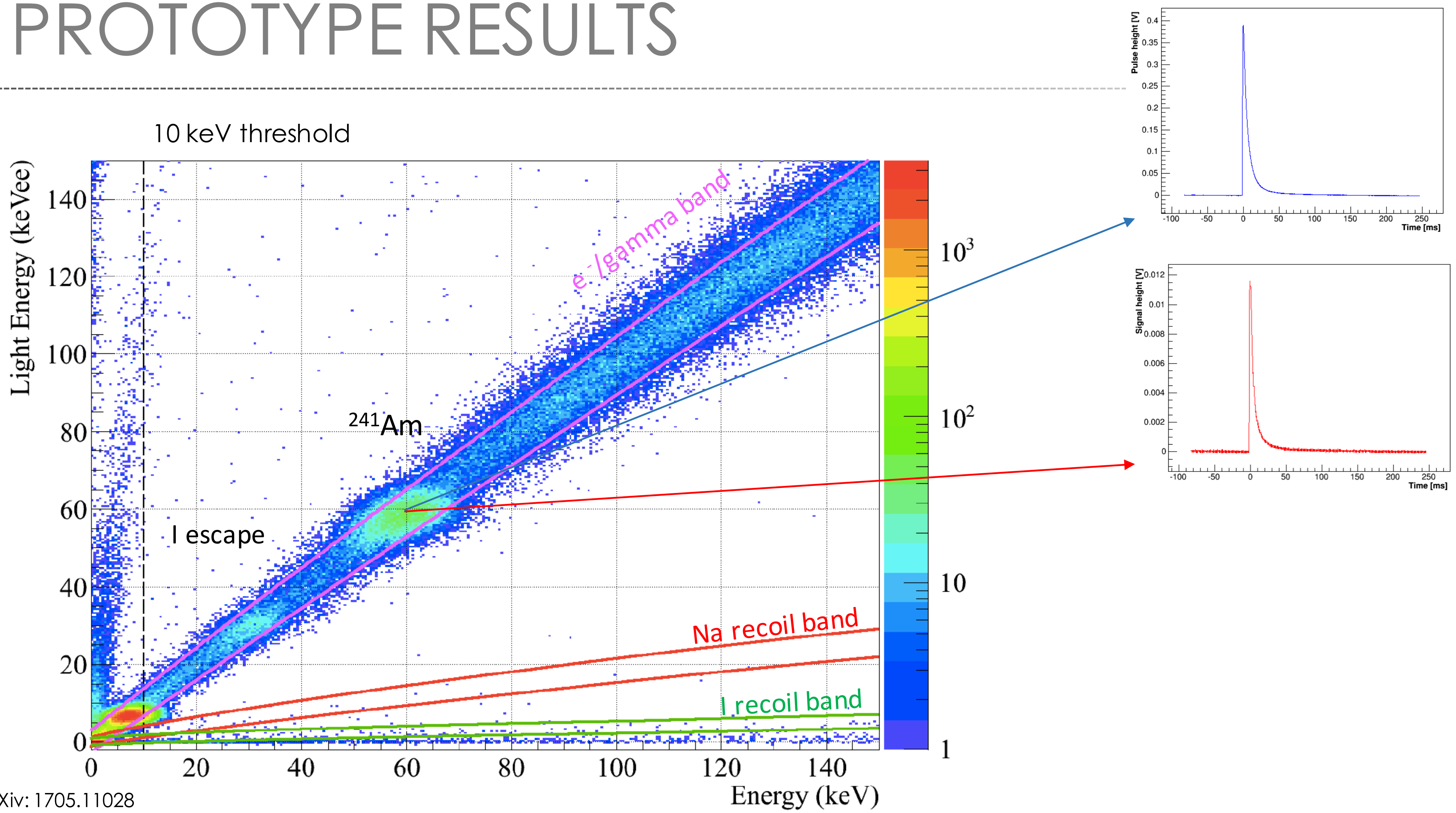
copper
housing



light detector

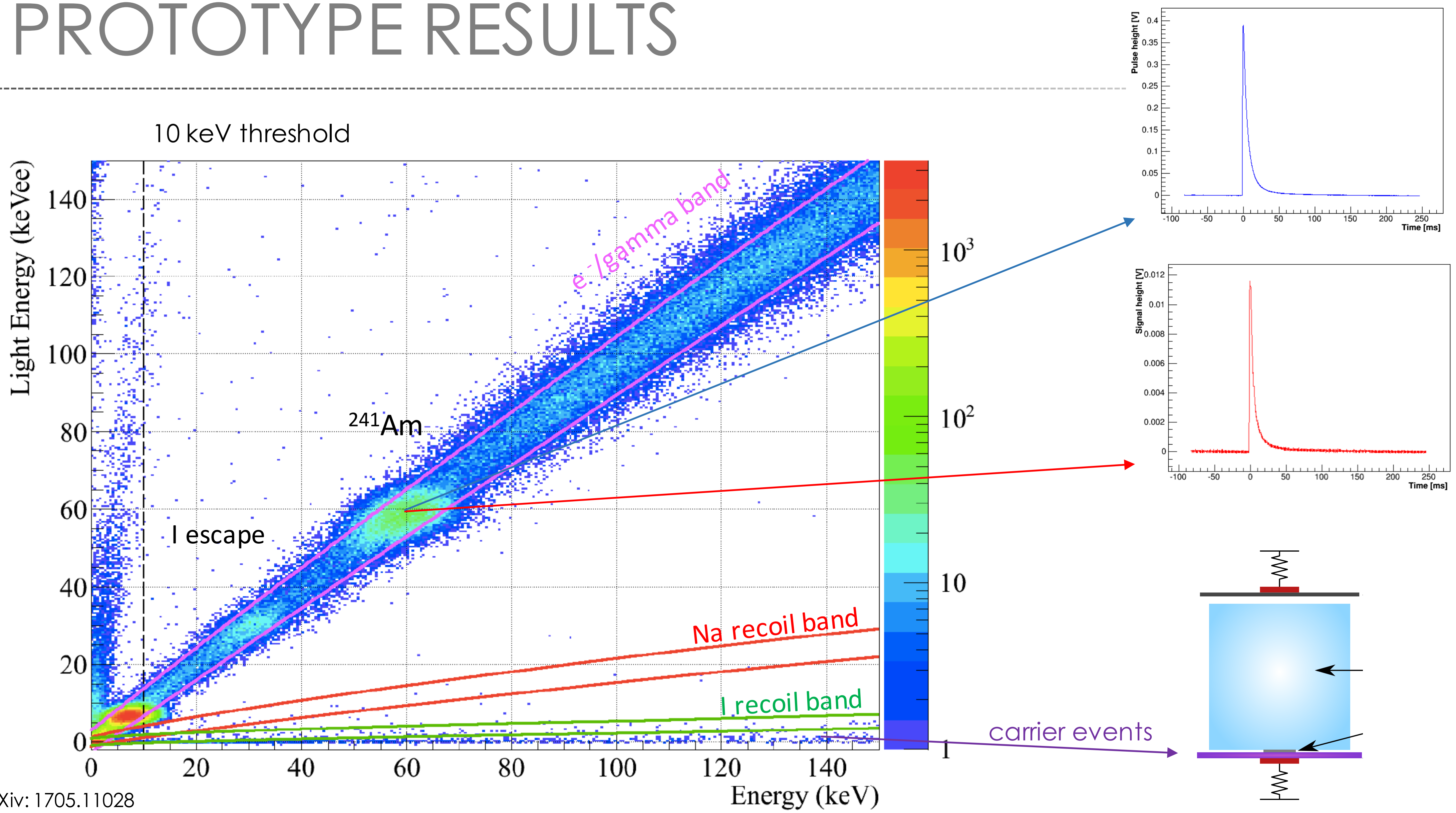
NaI
phonon detector

1st PROTOTYPE RESULTS



plot: arXiv: 1705.11028
QF from Tretyak, Astropart. Phys. 33, 40 (2010)

1st PROTOTYPE RESULTS



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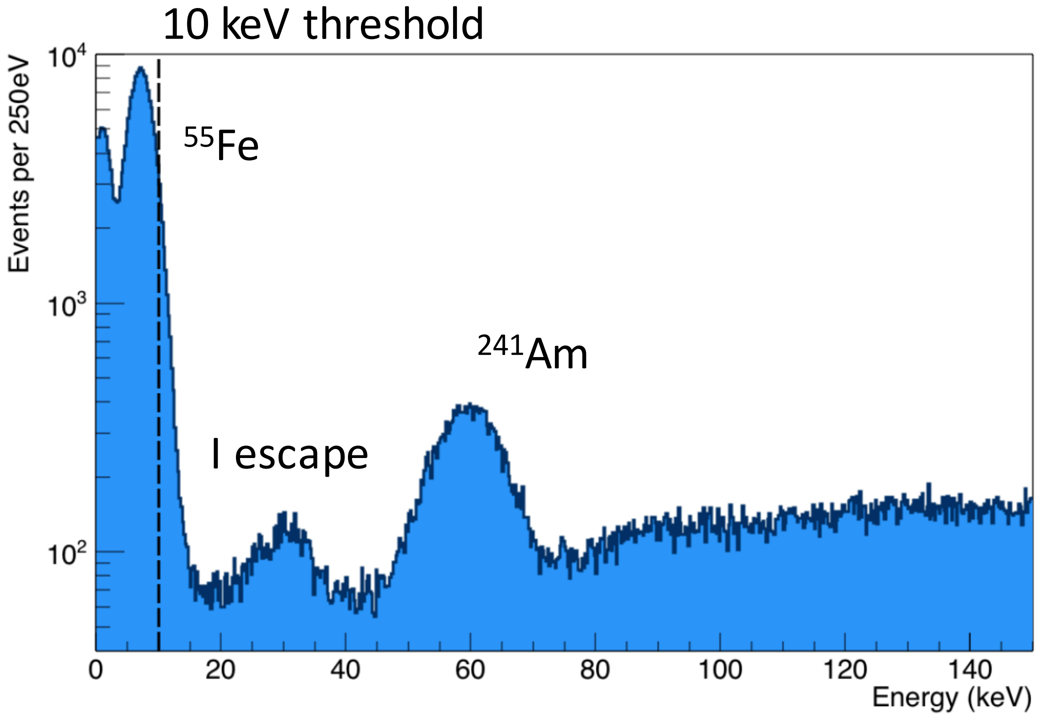
1st PROTOTYPE RESULTS



plot: arXiv: 1705.11028

- energy threshold: 10 keV
- 3.7% of the energy deposited in the NaI crystal is measured by the light detector

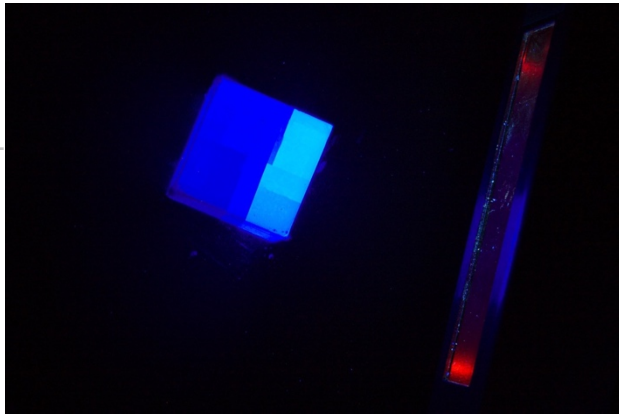
or:

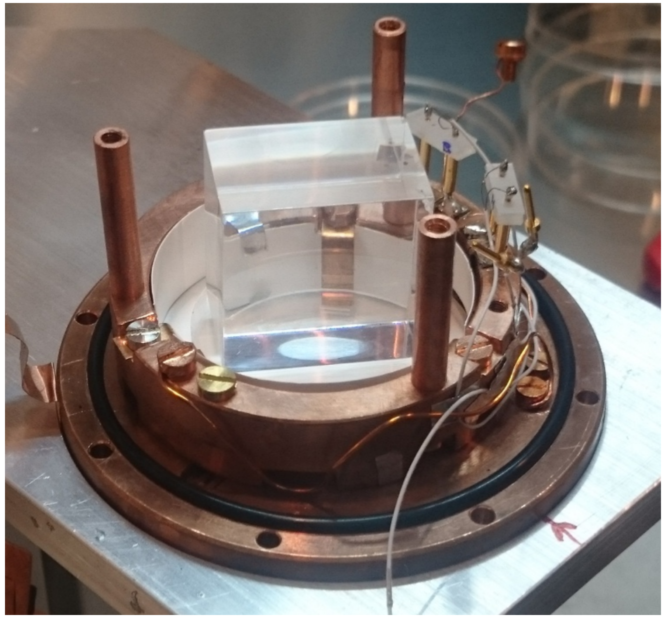
average of 11.2 detected photons per keV of energy deposition for e/gamma events

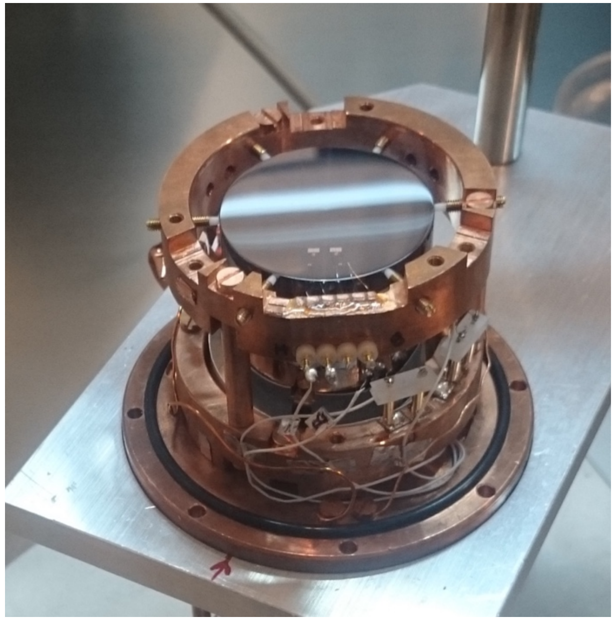
first successful measurement of a NaI crystal as cryogenic detector

improve detector performance

2^{nd} PROTOTYPE DETECTOR





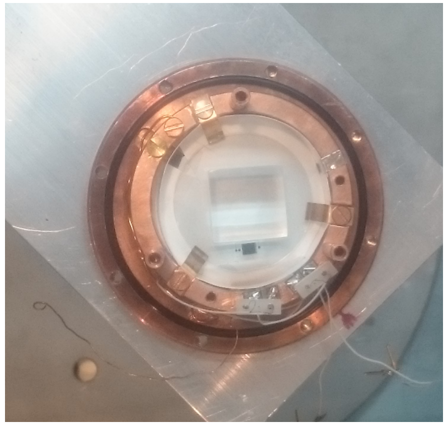


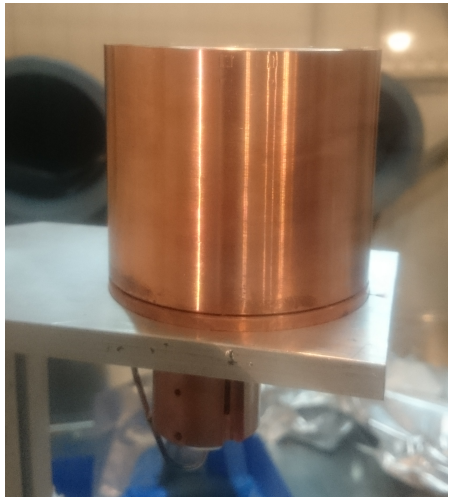
- interface: epoxy resin
- beaker-shaped Si light absorber
- NaI crystal: 66 g

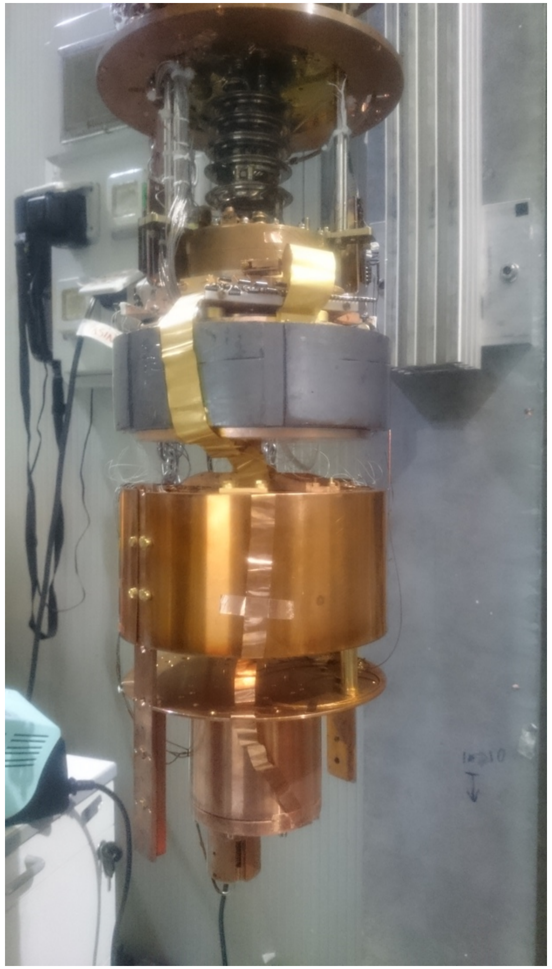
- beaker-shaped light detector exceeds performance goal
- NaI is an excellent scintillator at low temperatures

3^{rd} PROTOTYPE DETECTOR

cryostat cold since yesterday!!!







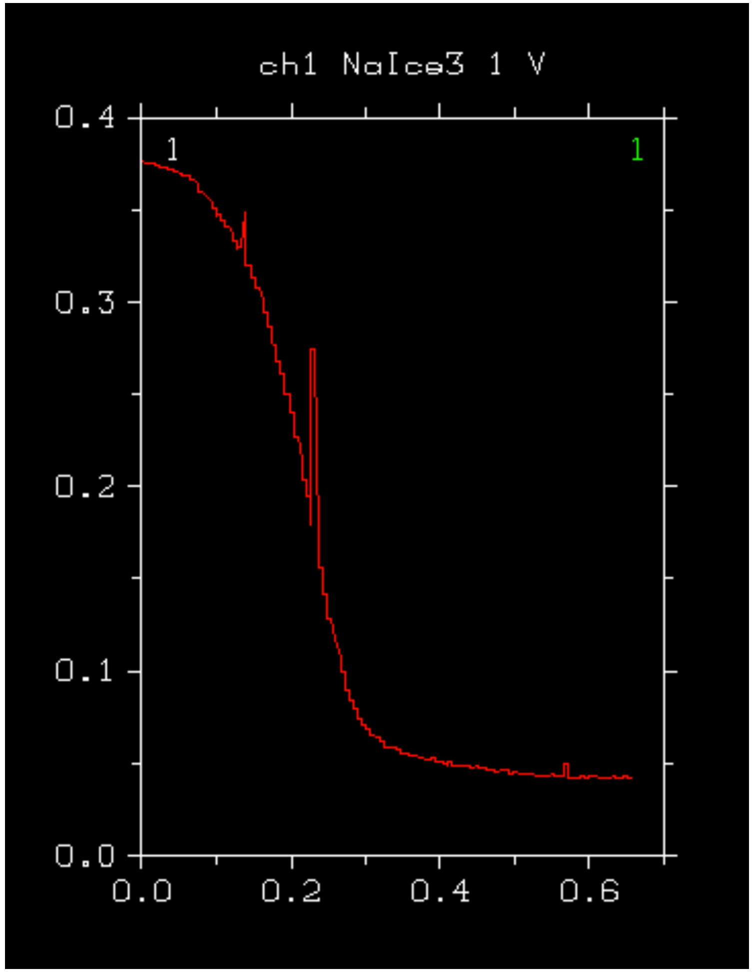
- low background cryostat (Hall C at LNGS)
- interface: silicon oil
- beaker-shaped Si light absorber
- NaI crystal: 30 g

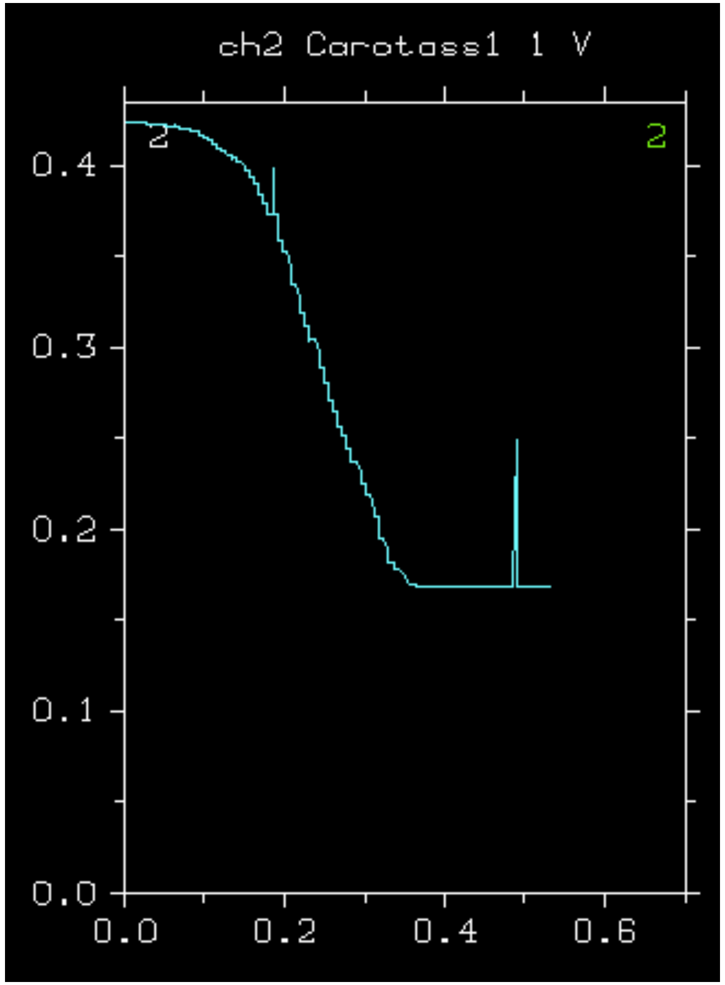
GOAL:

neutron calibration campaign to proof particle discrimination

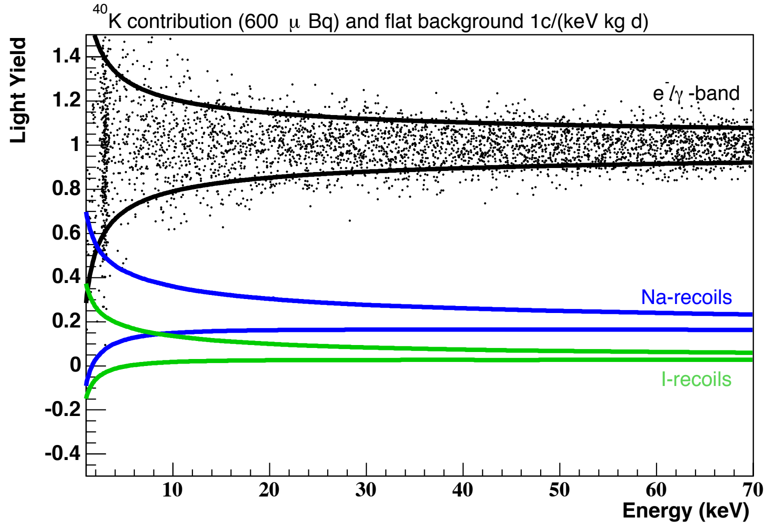
3rd PROTOTYPE DETECTOR

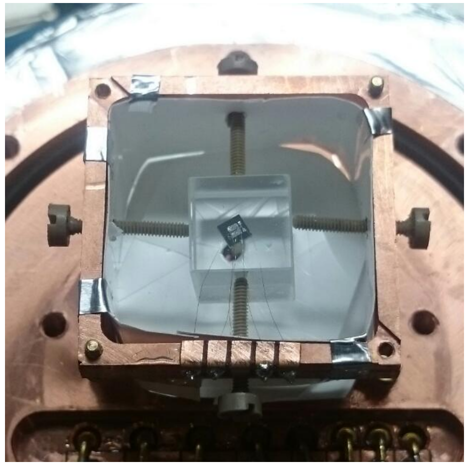
detectors in transition !!!





QUENCHING FACTOR MEASUREMENT





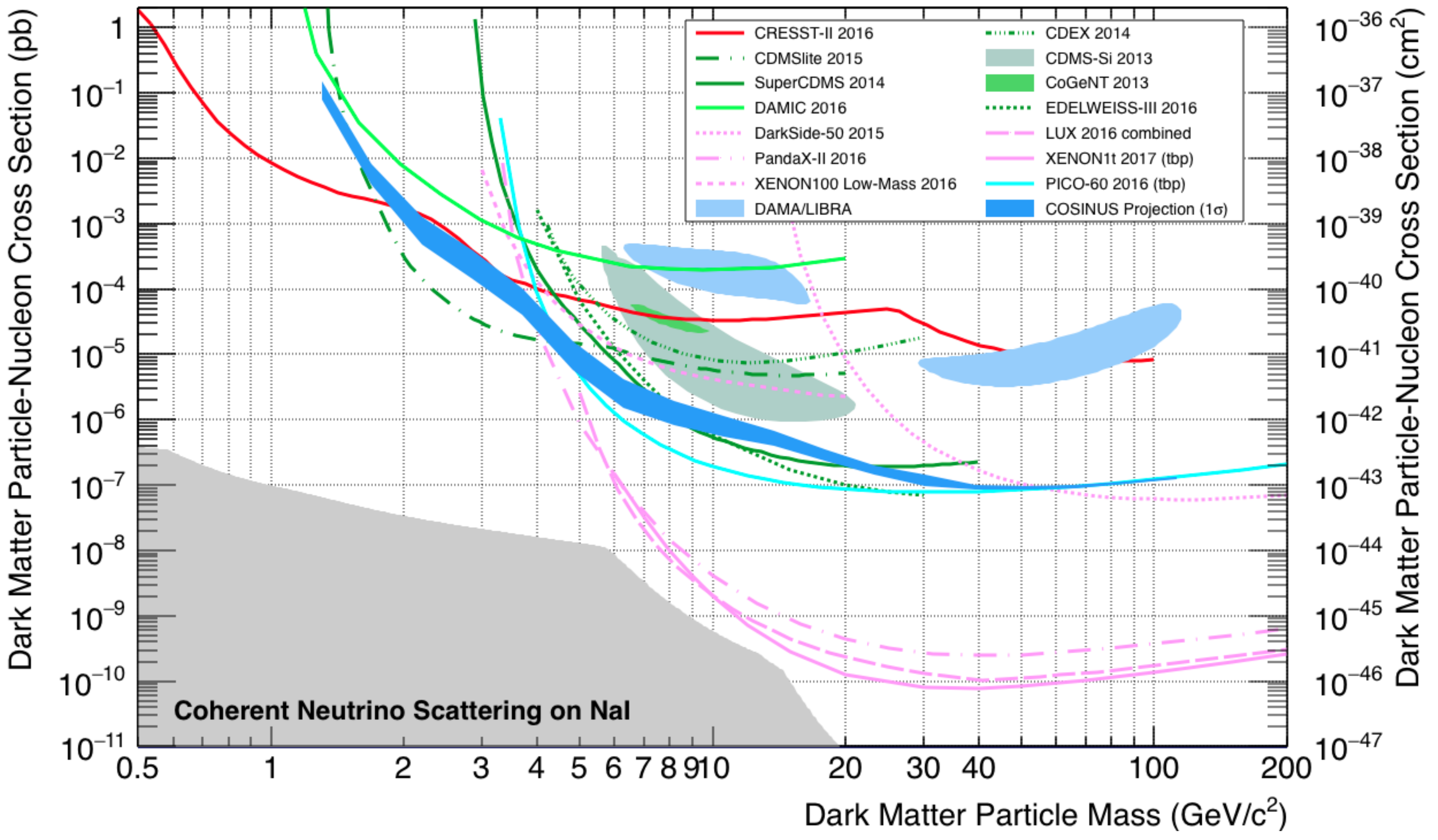
- MLL - Tandem accelerator at TUM in Munich
- 11 MeV neutrons
- dilution cryostat available and ready to be used
- small NaI scintillating calorimeter

GOAL:

Precise determination of light quenching factor for Na and I at mK-tempertures

beam-time accepted for September

PROJECTION FOR 100 kg d



- e/gamma background-only simulation
- projected limit for spin-independent elastic scattering off nuclei
- anticipated sensitivity is about two orders of magnitude better than the interpretation of the DAMA/LIBRA claim under standard assumptions

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

CONCLUSION

- COSINUS aims to develop the first NaI detector with particle discrimination
- first NaI prototype module successfully operated at LNGS in 2016

  --> publication submitted to journal
- **for 2017:**
  - further investigations and R&D to improve threshold and energy resolution of the NaI detector (new TES-design and interface solution)
  - precise measurement of quenching factors at the neutron beam at TUM

- if the performance of NaI calorimeter can be brought in line with already existing scintillating bolometers the COSINUS technique allows us to:
- a moderate exposure of few 10 kg-days will be sufficient to confirm or rule-out a nuclear recoil origin of the DAMA/LIBRA dark matter claim
- by increasing in target mass the COSINUS technique is also able to include the possibility for modulation detection

THANK YOU !

EXTRA MATERIAL

Standard assumptions

- Maxwellian velocity distribution
- asymptotic velocity of 220 km/s
- galactic escape velocity of 544 km/s
- local dark matter density

  $0.3\ GeV/cm^3$

→ 3000 (100 GeV/m_x) WIMPs per m^3

→ FLUX OF WIMPS ON EARTH:

$\sim 10^5\ (100\ GeV/m_x)\ cm^{-2}\ sec^{-1}$

Motivation for low-mass Dark Matter

WIMP "Miracle"

- Thermally produced in early Universe
- Weak scale yields correct relic density
- $10 GeV/c^2 \sim 1 TeV/c^2$

Asymmetric dark matter

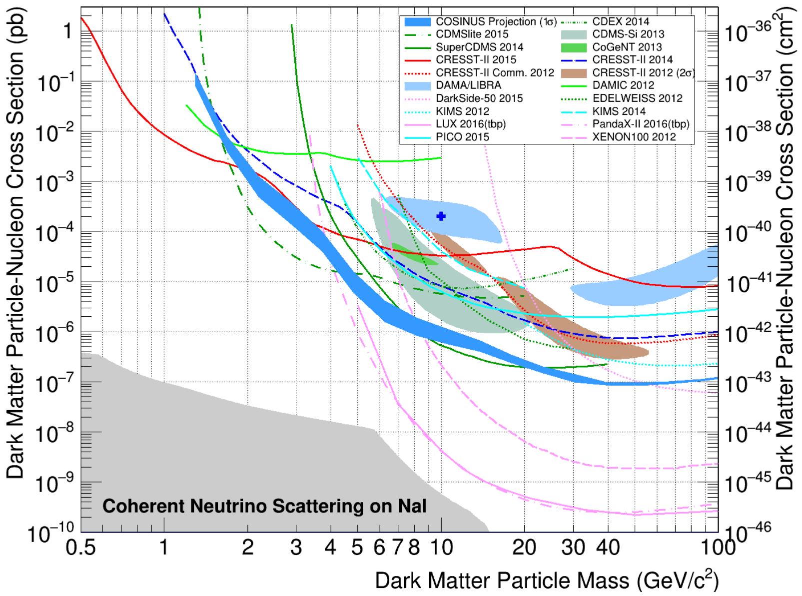
- $\Omega_{DM}/\Omega_B \sim 5$: Why?
- Link asymmetries for baryons and DM in early Universe
- $0.1 GeV/c^2 \sim 10 GeV/c^2$

NEUTRINOS as background

Electronic recoils from pp solar neutrinos: ~ 10^{-48} cm^2

Nuclear recoils from ^{8}B solar neutrinos: below 10^{-44} cm^2 for low-mass WIMPs

Nuclear recoils from atmospheric + DSNB: below 10^{-48} cm^2

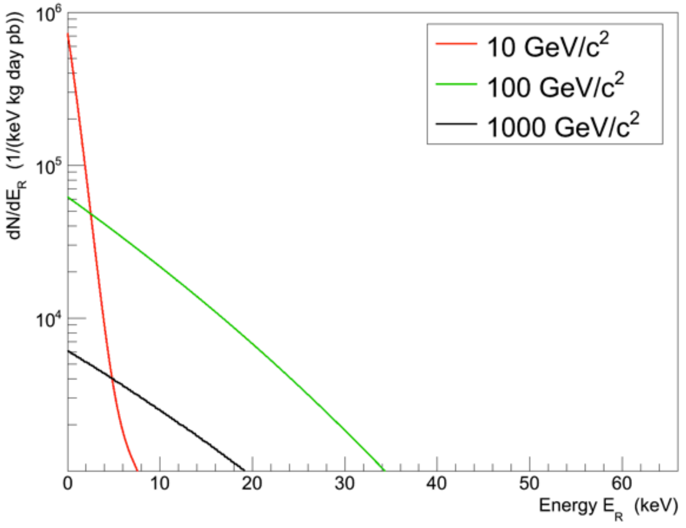


BESIDES,
measurement of CNNS
is also an interesting
physics case itself

DIFFERENTIAL SCATTERING RATE

$$\frac{dR}{dE_r} = \frac{\sigma_0}{m_\chi} \frac{F^2(E_r)}{\mu^2} \frac{\rho_\odot T(E_r)}{v_\odot \sqrt{\pi}}$$

σ_0	interaction cross action at zero momentum transfer
m_x	mass of dark matter particle
$F^2(E_r)$	nuclear form factor
$\mu = \frac{m_x m_N}{m_x + m_N}$	reduced mass
$T(E_r) = \frac{\sqrt{\pi}}{2} v_\odot \int_{v_{min}}^{v_{esc}} \frac{f_1(v)}{v} dv$	Integral over local dark matter velocity distribution
$v_{min} = \sqrt{\frac{E_r m_N}{2\mu^2}}$	minimal velocity to produce a recoil of E_r



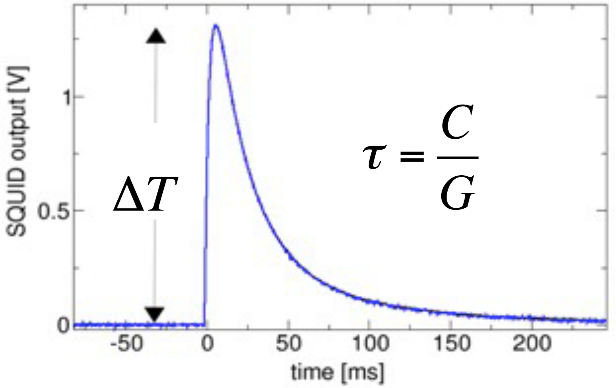
Prepare detector for:

- very small energy deposits (few keV - tens of keV)
- extremely rare detection rate (few events per ton per year)
- signal embedded in a background that is millions of times higher

DIRECT DARK MATTER INTERACTION

Temperature pulse

$$\Delta T = \frac{E}{C}$$



N is the total excitations which have a mean energy **k_BT**

$$N \propto CT / k_B T \quad \text{and} \quad \delta N = \sqrt{N}$$

$$\delta E = \delta N k_B T = \sqrt{k_B T^2 C}$$

Noise comes from irreducible random thermodynamic fluctuations in energy due to transport across the thermal link

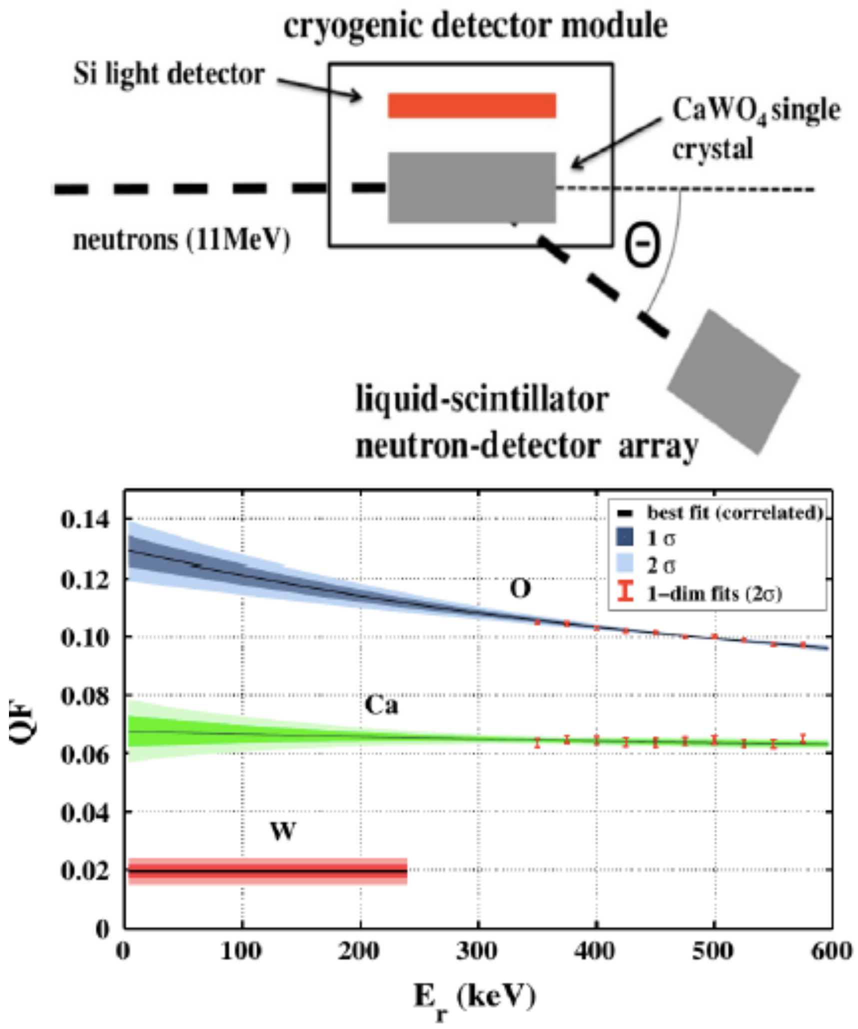
Ultimate energy resolution is determined by how well you can measure **T** against thermodynamic fluctuations

low temperatures → better energy sensitivity

low heat capacity → careful selection of materials

Quenching Factor Measurement of CRESST

@ MLL accelerator



Precise determination of QFs for O, Ca & W @mK temperatures

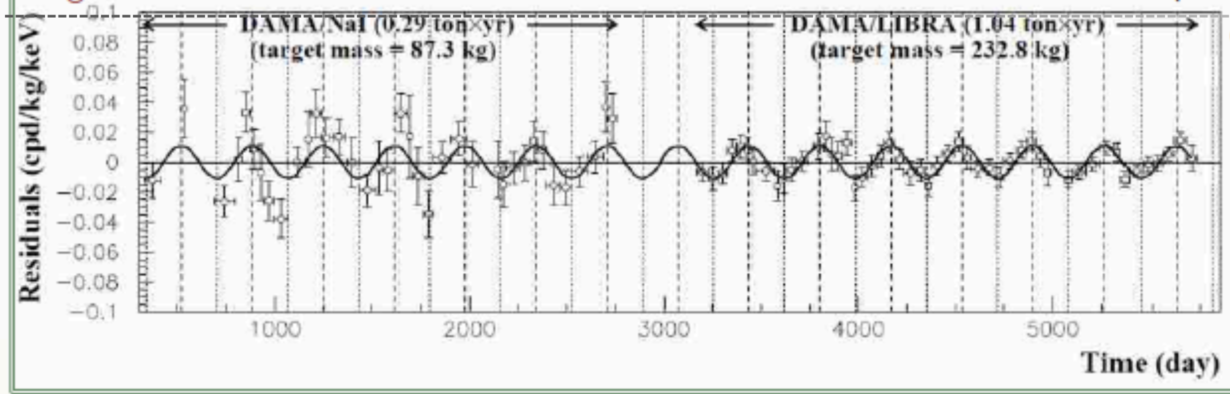
Values (in ROI)
- O: (11.2 ± 0.5)%
- Ca: (5.94 ± 0.49)%
- W: (1.72 ± 0.21)%

Eur. Phys. J. C (2014) 74:2957

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

Single-hit residuals rate of scintillation events vs time in 2-6 keV EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648



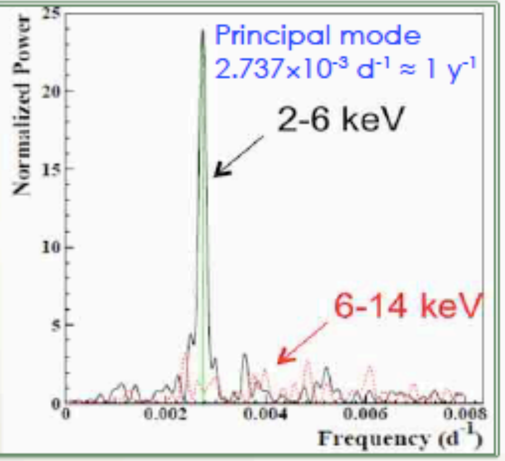
continuous line: t_0 = 152.5 d, T = 1.0 y

A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

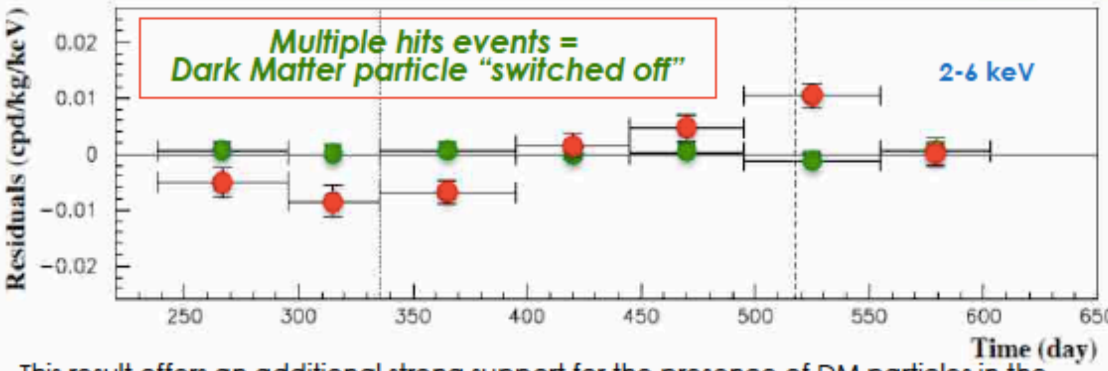
Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y

Power spectrum



Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events
A=-(0.0005±0.0004) cpd/kg/keV



This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.

Taken from: P. Belli UCLA Dark Matter 2016, Los Angeles, USA

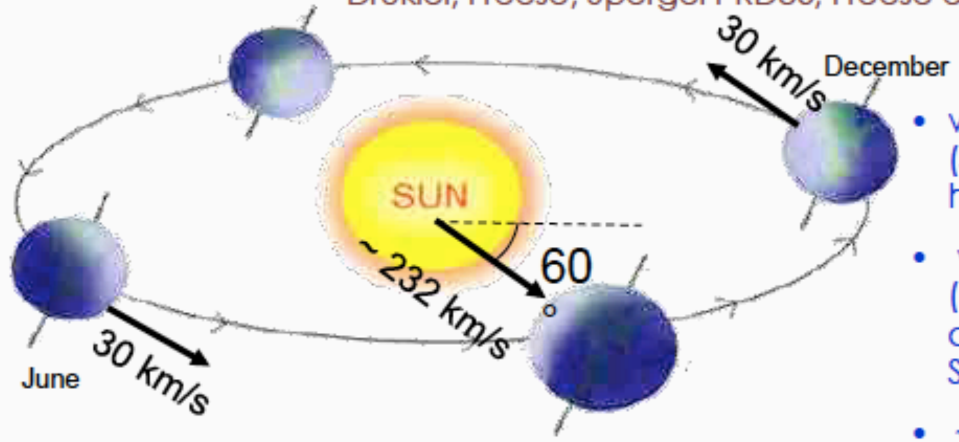
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Drukier, Freese, Spergel PRD86; Freese et al. PRD88

Requirements:

1) Modulated rate according cosine
2) In low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios



- v_{sun} ~ 232 km/s (Sun vel in the halo)
- v_{orb} = 30 km/s (Earth vel around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb}\cos\gamma\cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k}\cos[\omega(t-t_0)]$$

the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Taken from: P. Belli UCLA Dark Matter 2016, Los Angeles, USA