Direct Dark Matter Search Experiments

10th Russbach School on Nuclear Astrophysics

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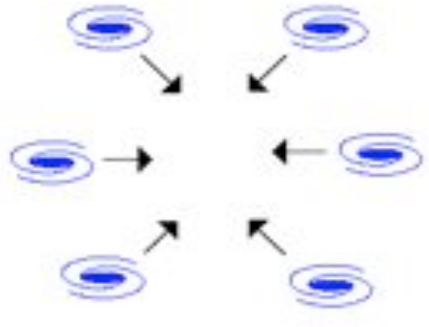
Outline

- Motivation for Dark Matter Search
- Candidates for Dark Matter
- Detection Approaches
- Direct Dark Matter Search
- Conclusions

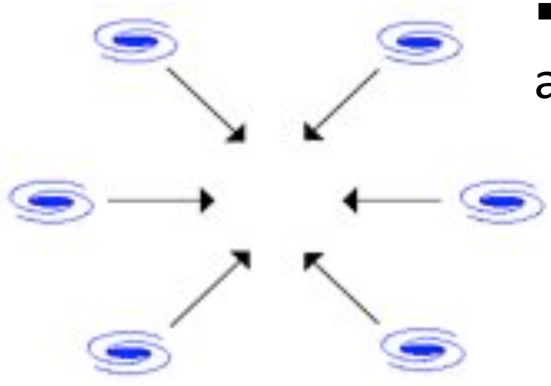
First Hints for Dark Matter

- In the 1930ties Swiss astronomer Fritz Zwicky (1898 – 1974) investigates galaxy clusters in the „Coma Cluster“

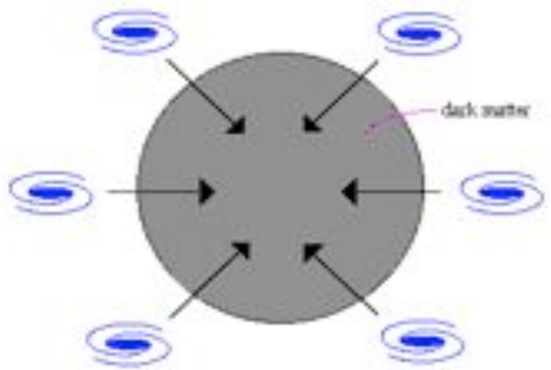
Dynamics of Galaxies



- Observation**: rotation speed of single galaxies too high**



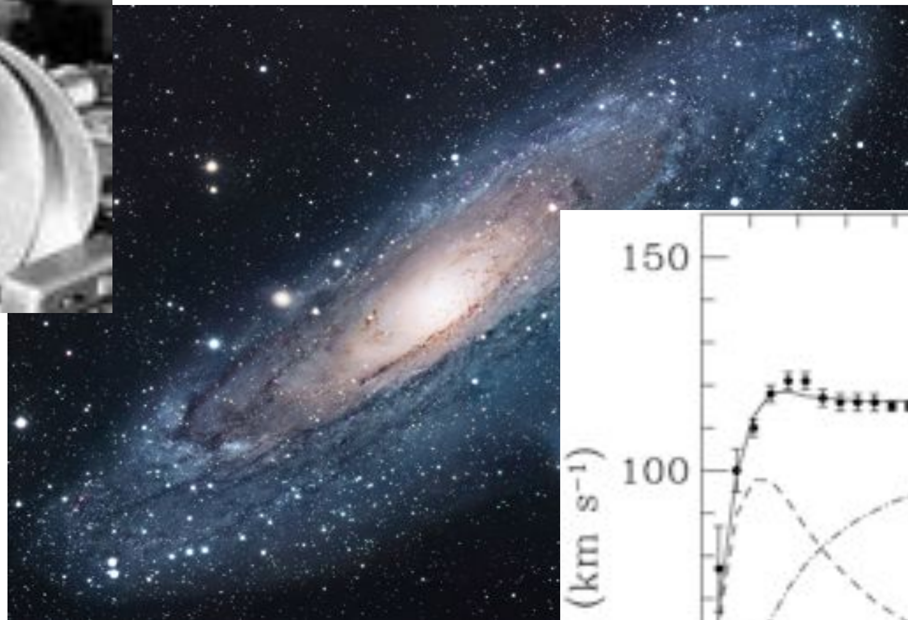
- Luminous matter alone cannot account for the anomaly
- Fritz Zwicky postulates in 1933 the existence of Dark Matter

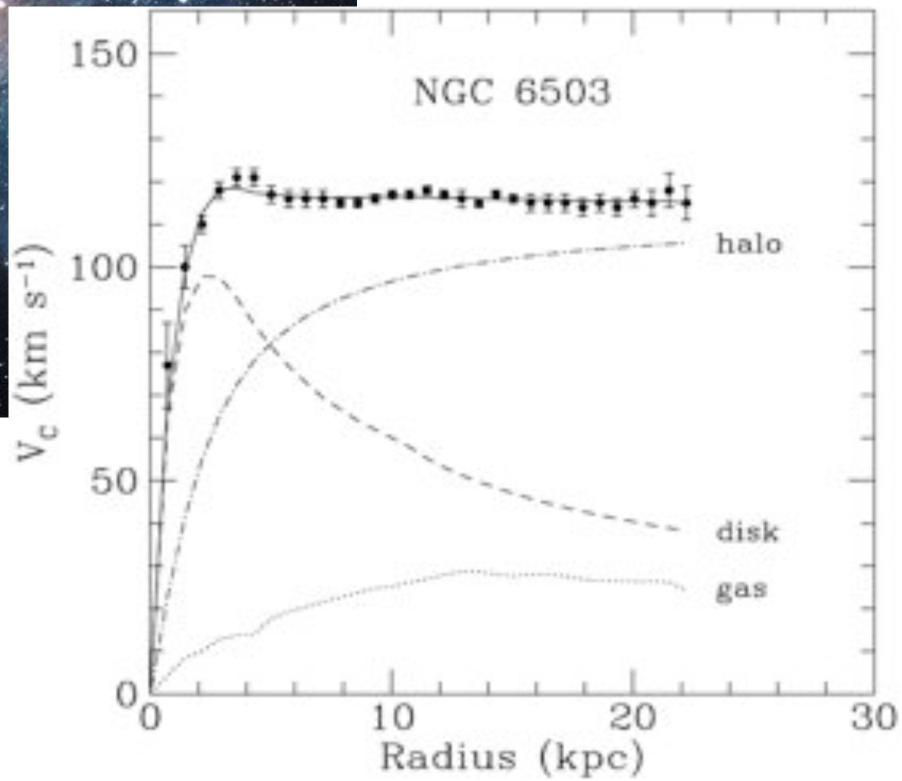


- In 1937 (!) Zwicky predicts that gravitational lensing will be used in the future to investigate DM

Rotation Curves of Single Galaxies

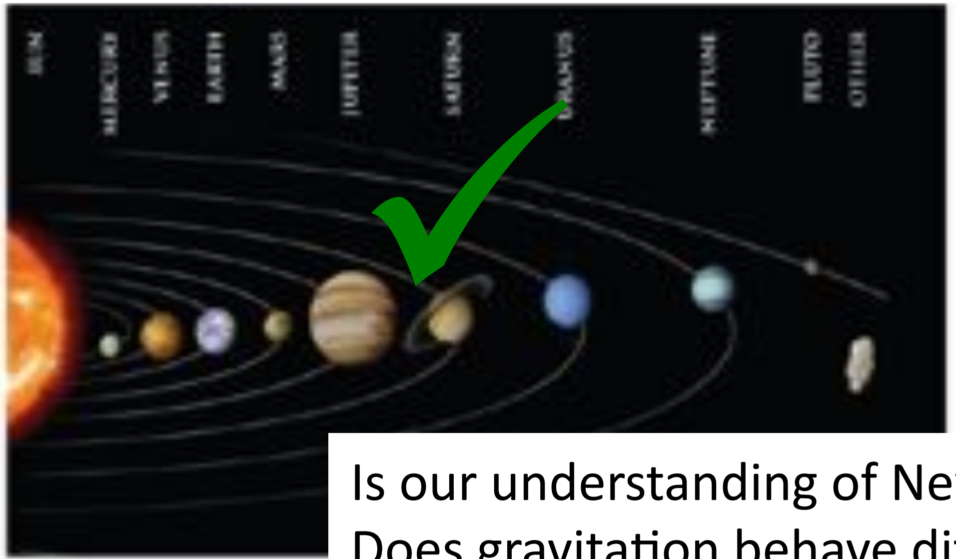
- Analogous finding by Vera Cooper-Rubin as Fritz Zwicky: rotation speed too high in the outer parts of the galaxy
- Gravitational potential of luminous matter alone not sufficient to explain effect



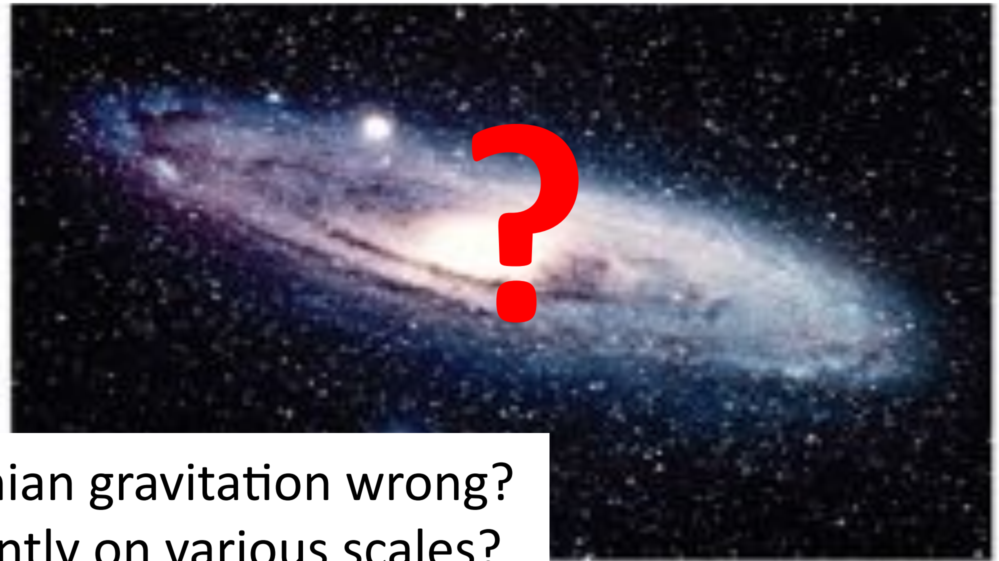


Gravitation on Different Scales

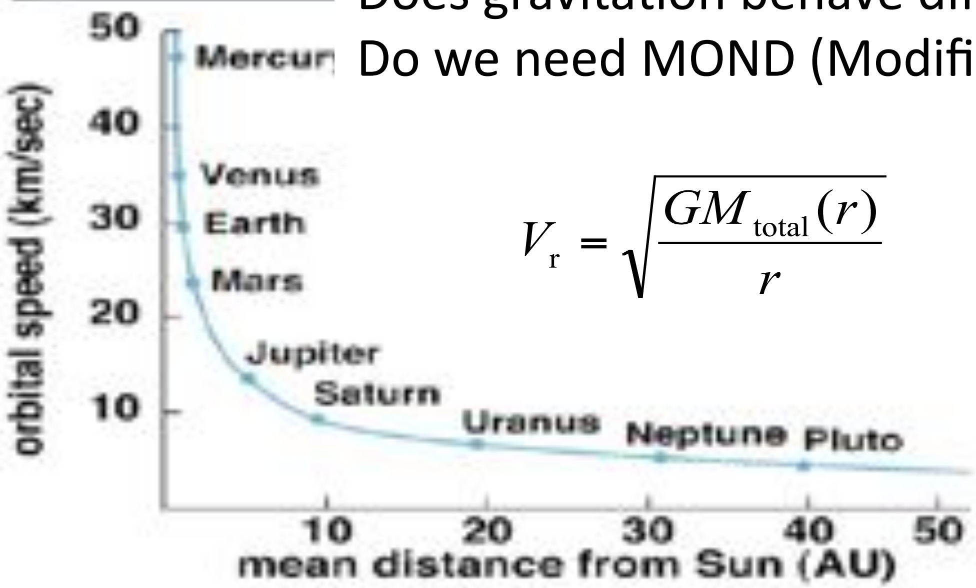
Solar system



Single galaxy

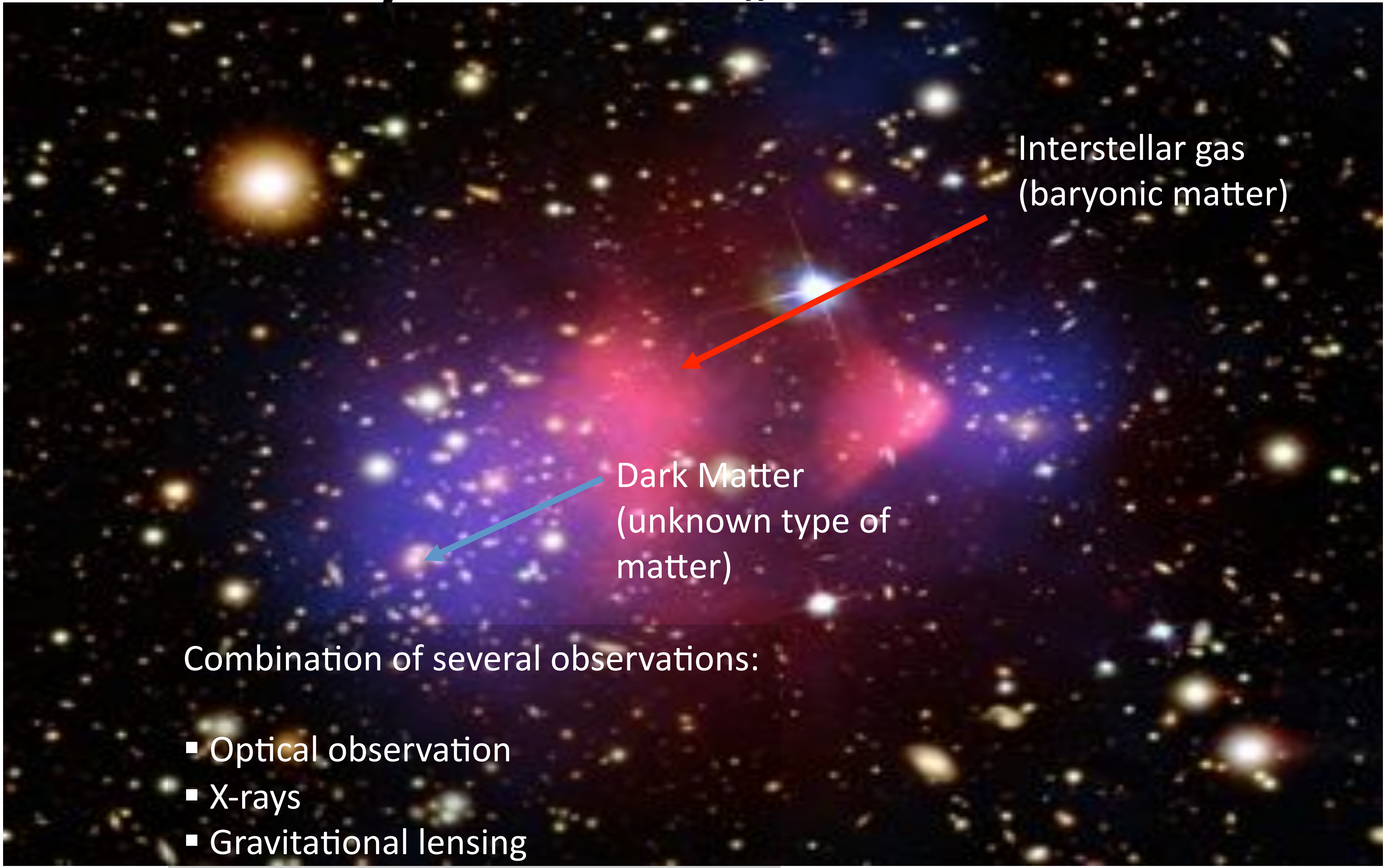


Is our understanding of Newtonian gravitation wrong?
Does gravitation behave differently on various scales?
Do we need MOND (Modified Newtonian Dynamics)?



$$V_r = \sqrt{\frac{GM_{total}(r)}{r}}$$

DM Dynamics: The „Bullet“ Cluster

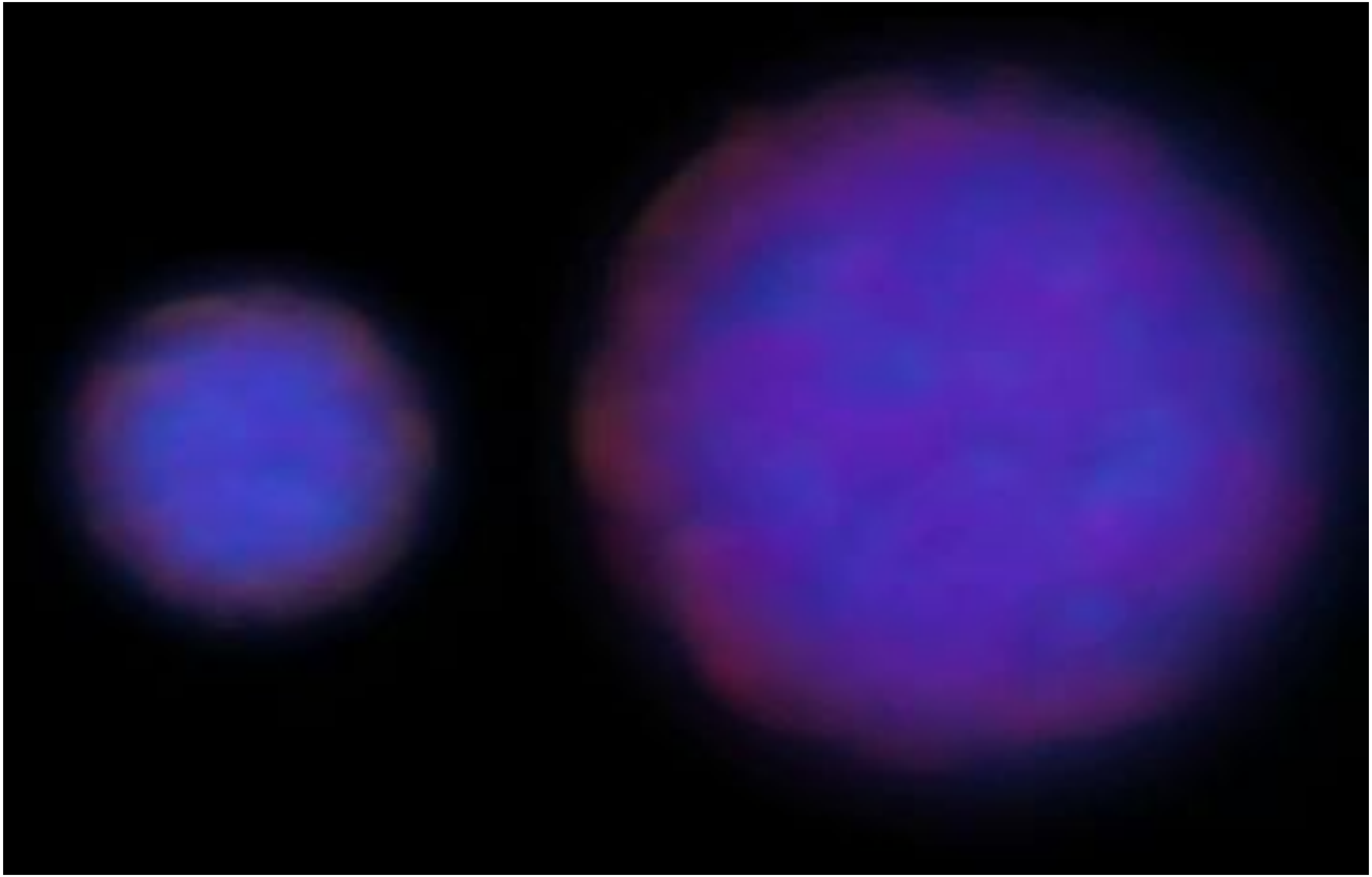


Combination of several observations:

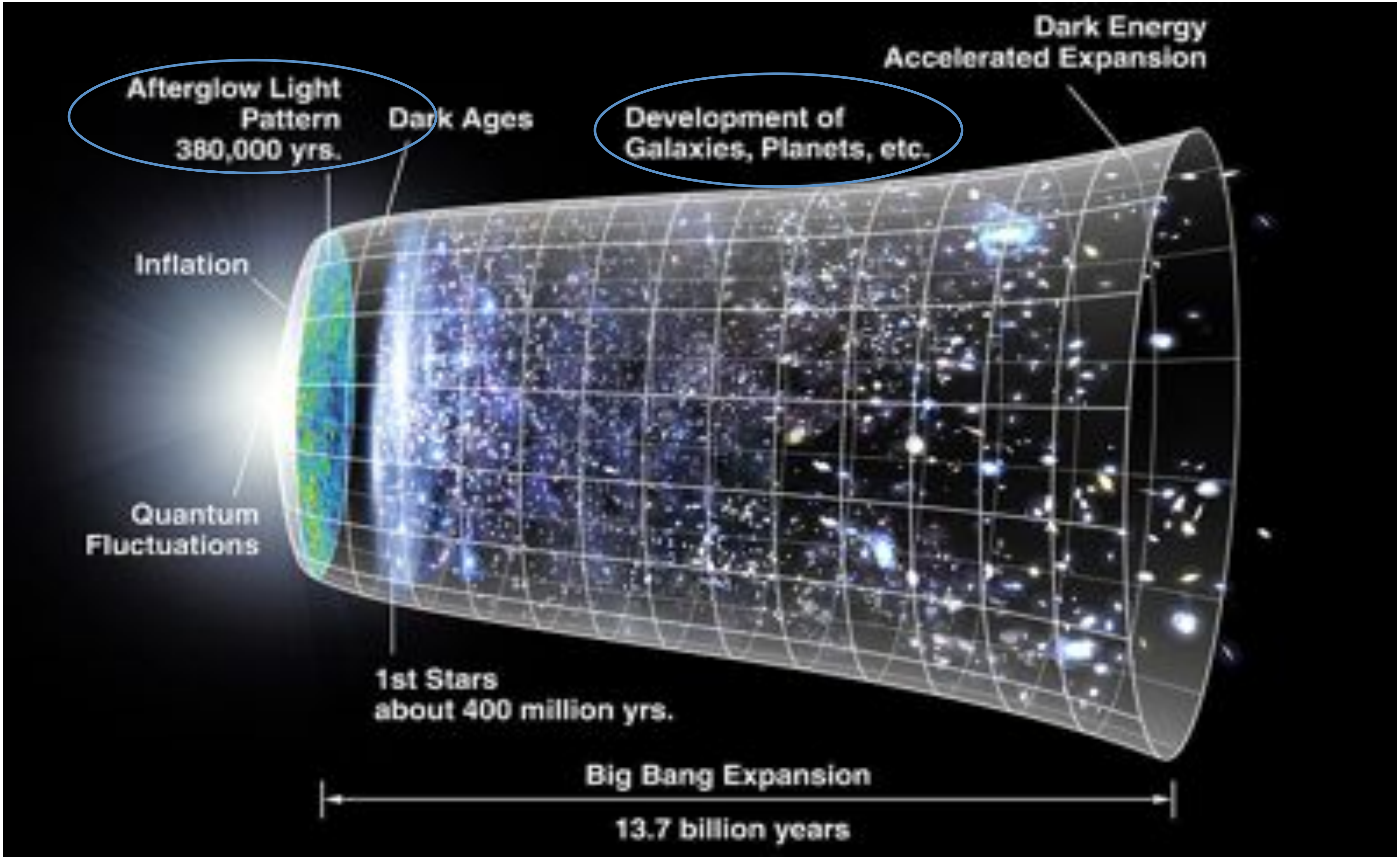
- Optical observation
- X-rays
- Gravitational lensing

-> Up to now strongest indication for the existence of Dark Matter!!

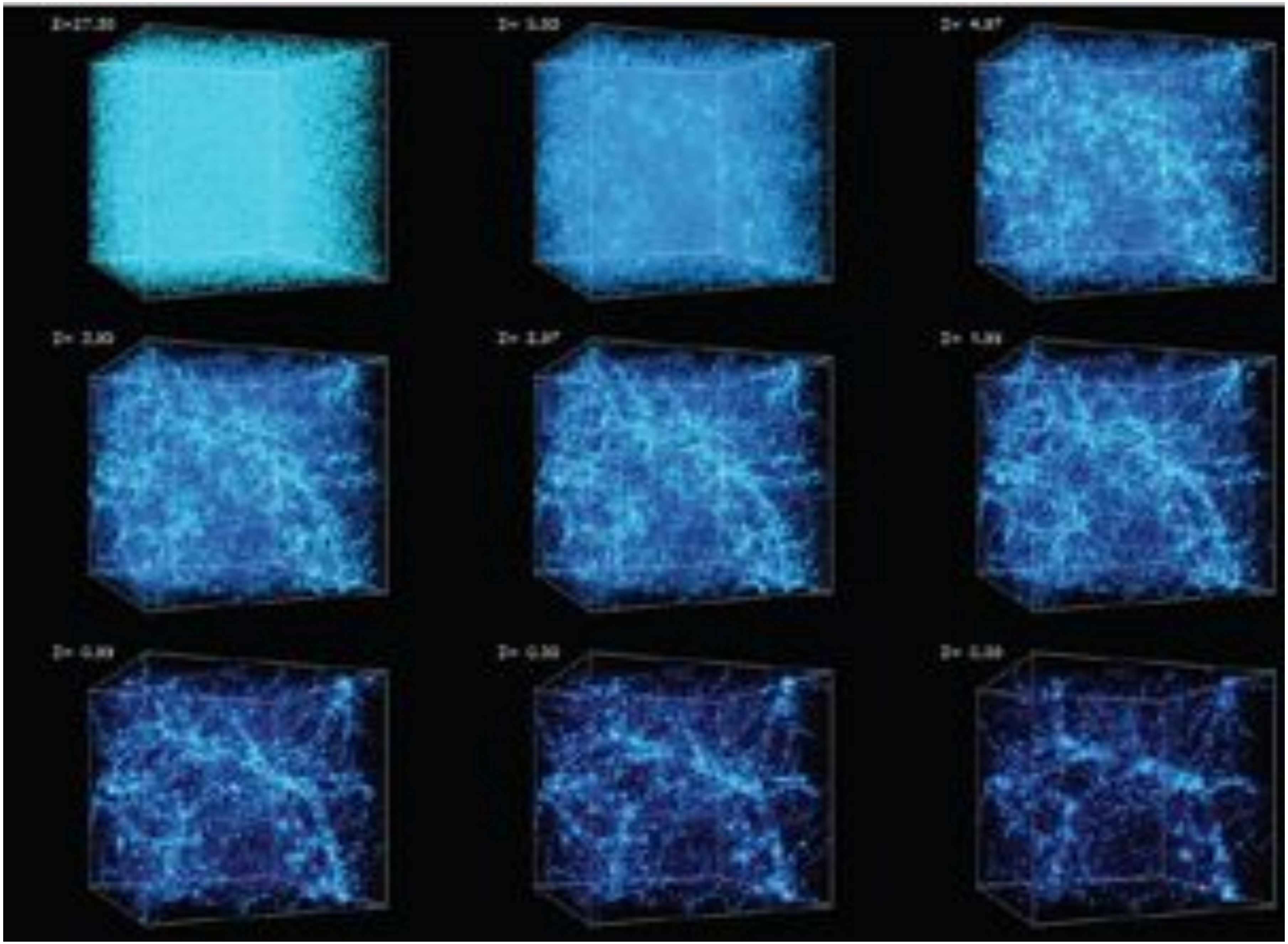
Animation of „Bullet“ Cluster Collision



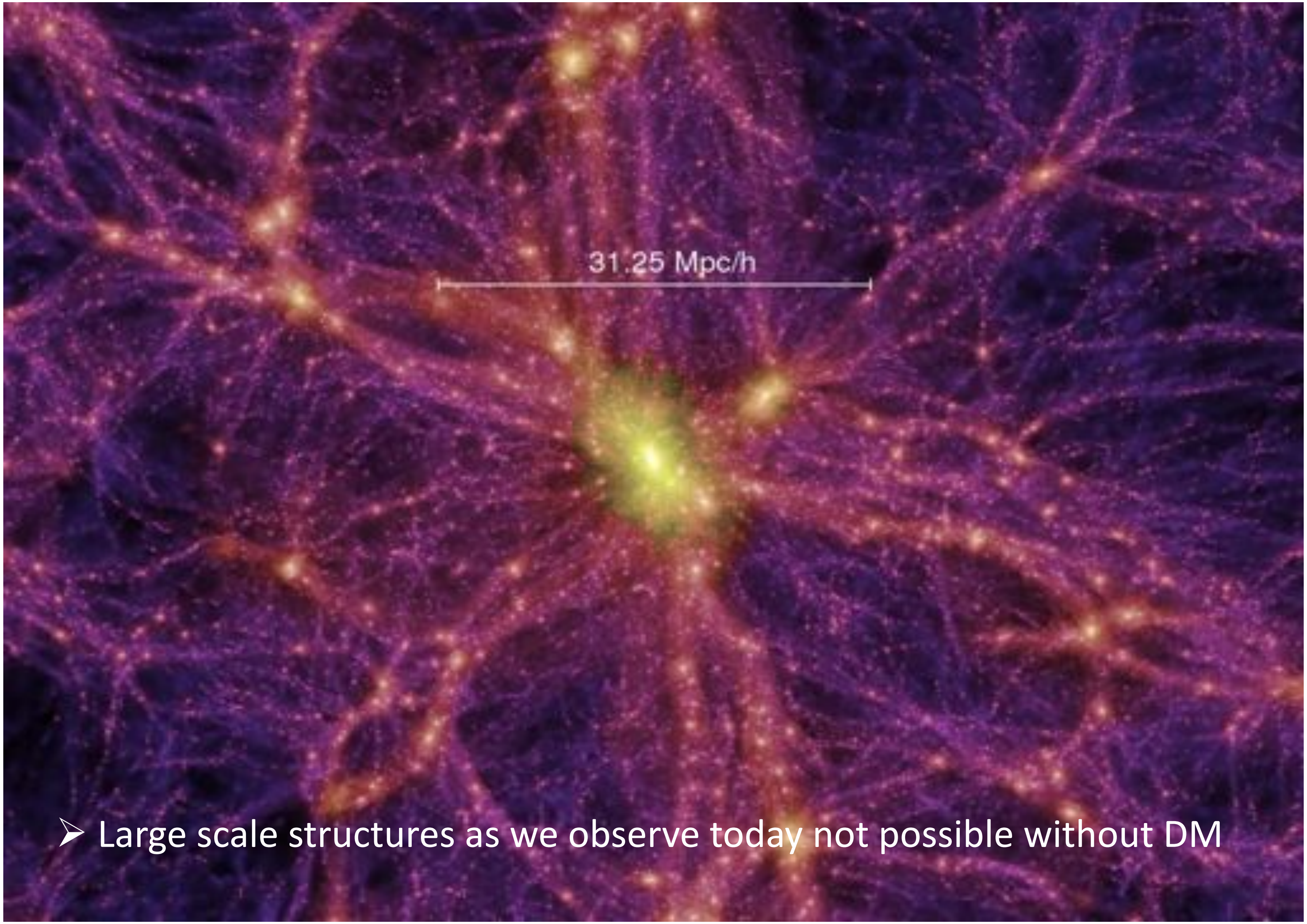
What About Large Scales ?



Large-Scale Structure Formation

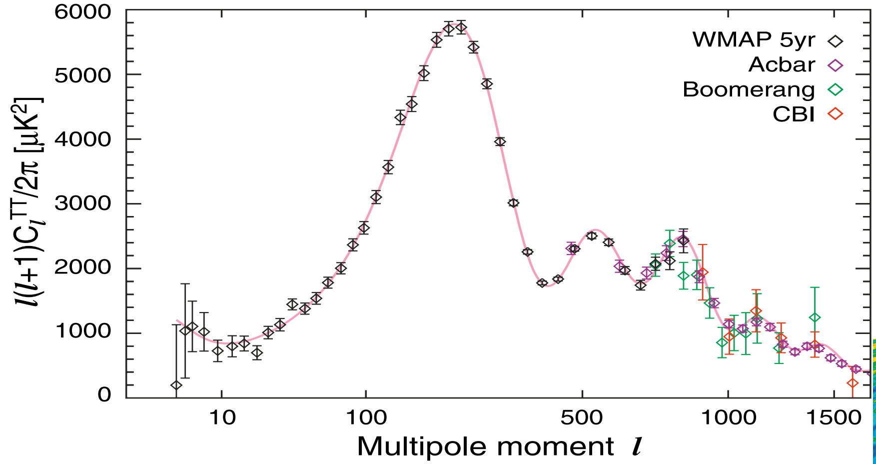


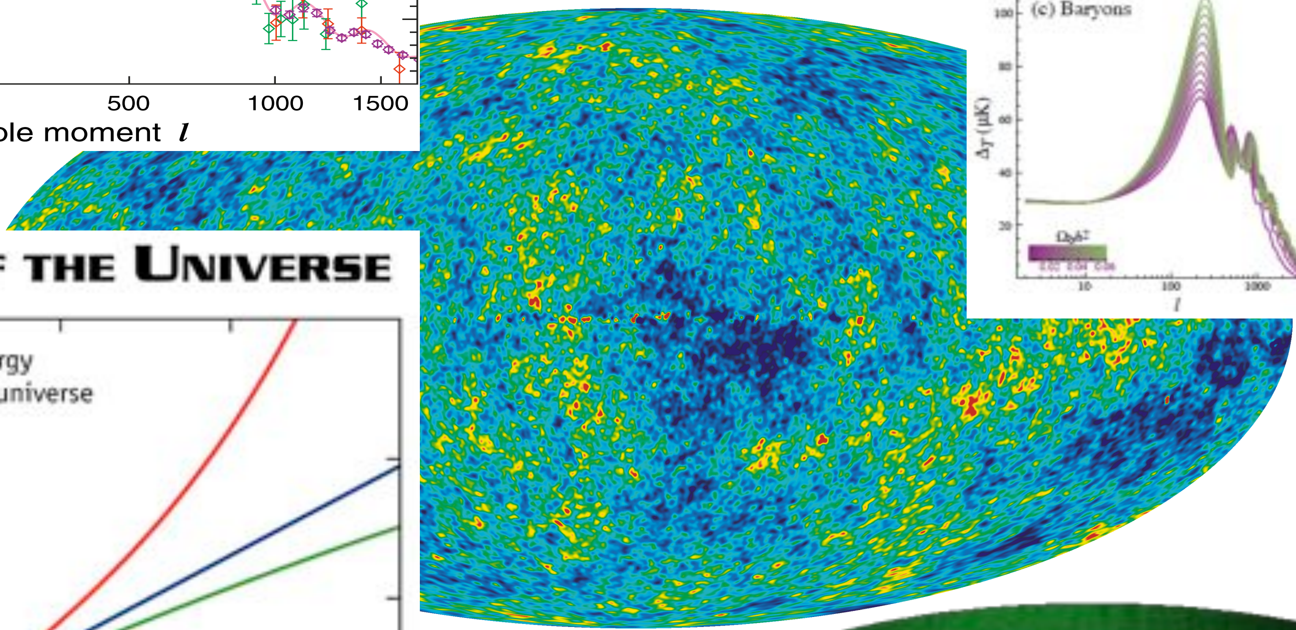
Millenium Simulation

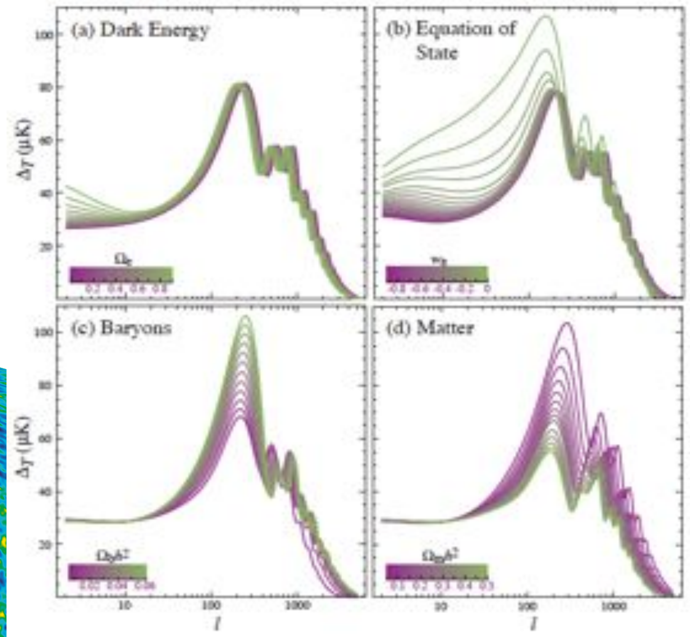


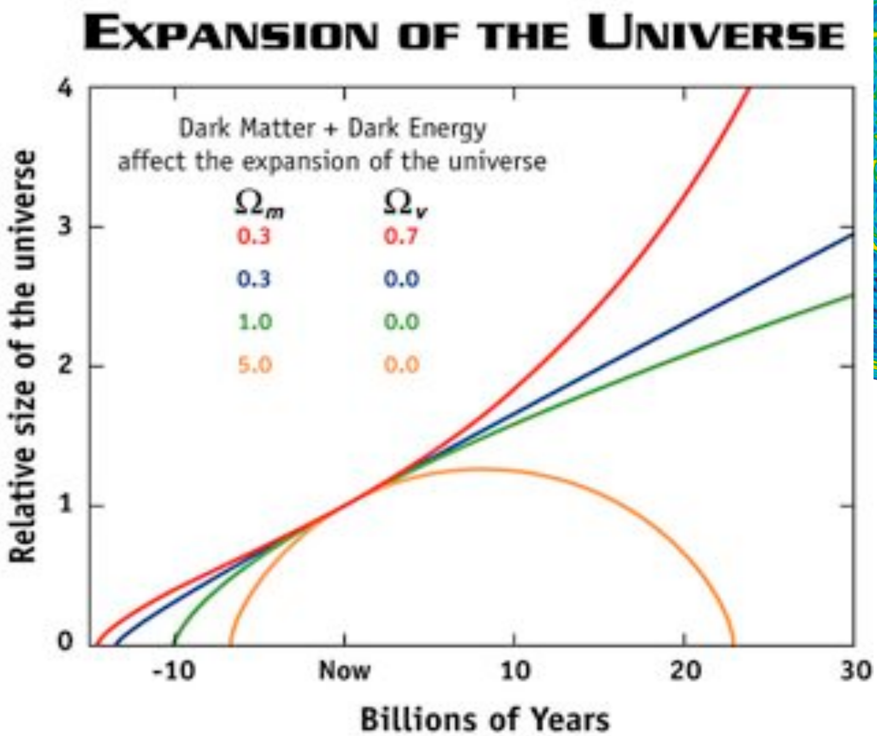
➢ Large scale structures as we observe today not possible without DM

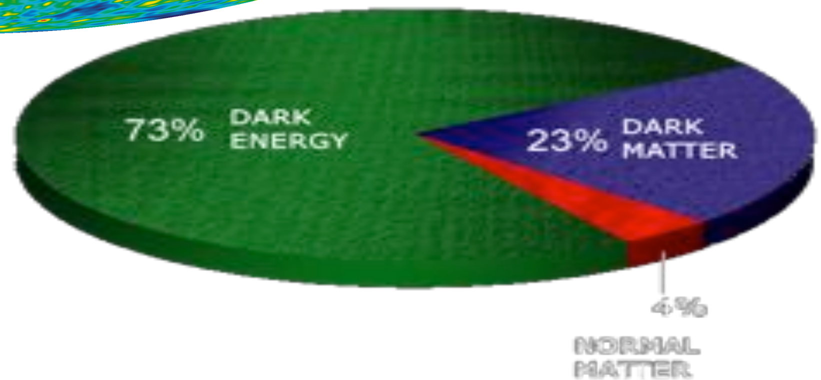
Information from the Cosmic Microwave Background



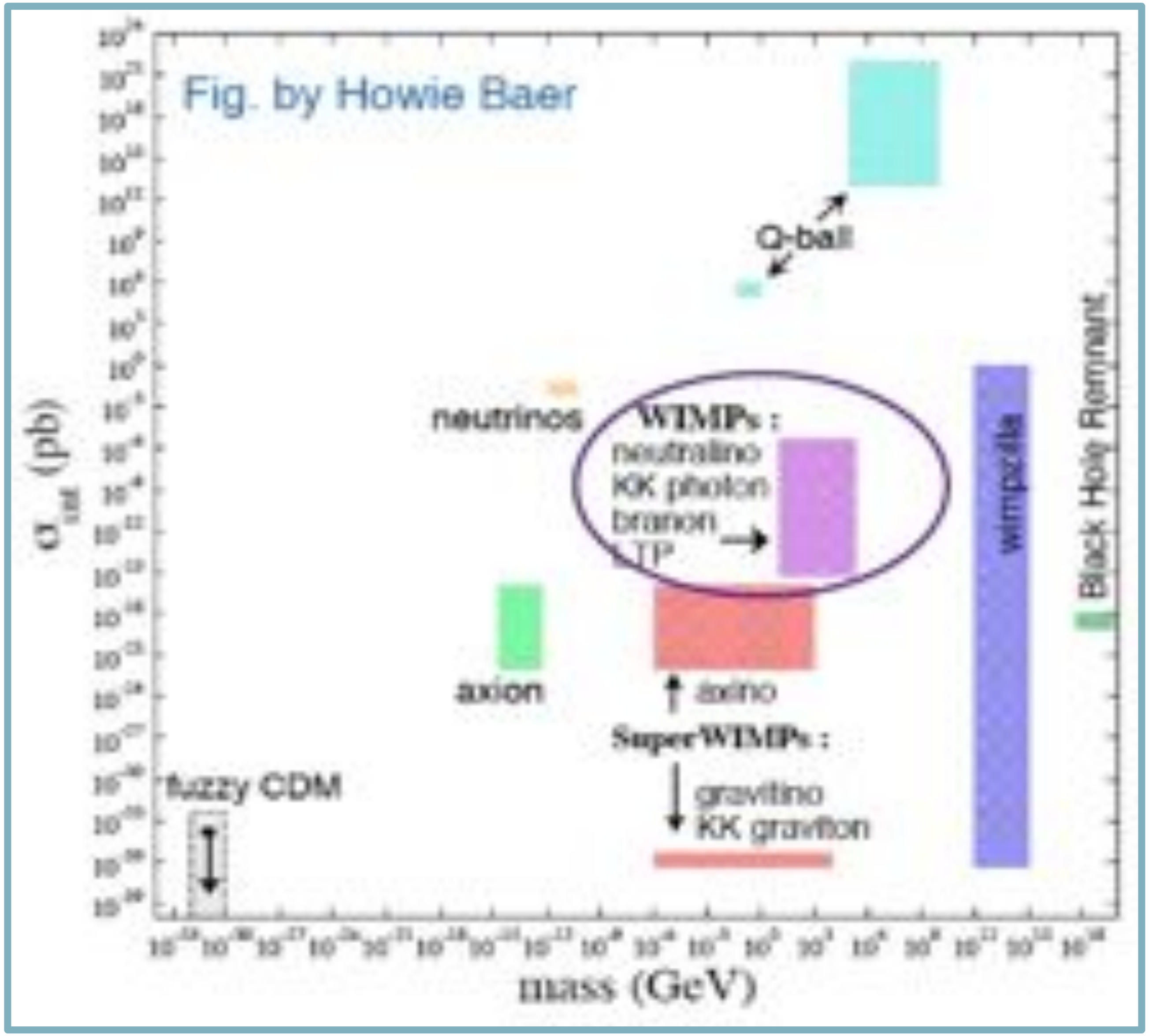








Dark Matter Particle Candidates



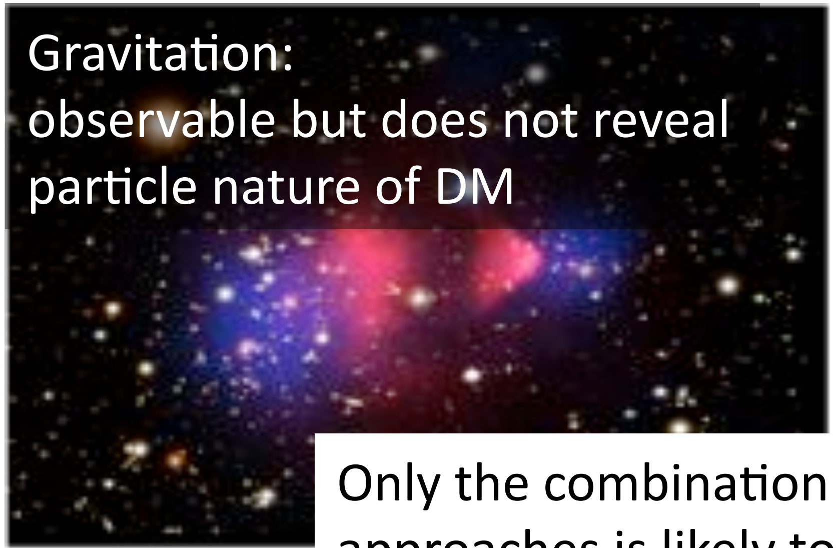
The universe could plausibly consist of particles ranging from 10^{-6} eV axions to 10^{15} GeV WIMPzillas

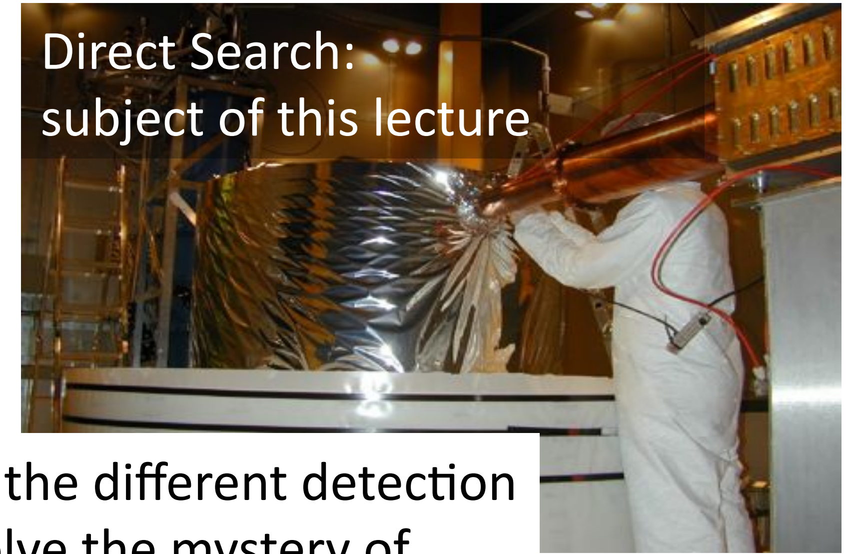
➢ **WIMP (Weakly Interacting Massive Particle)** is focused on by various detection experiments

- WIMP could be the lightest supersymmetric particle (LSP)
-> must be stable on cosmological timescales (R-parity conservation)

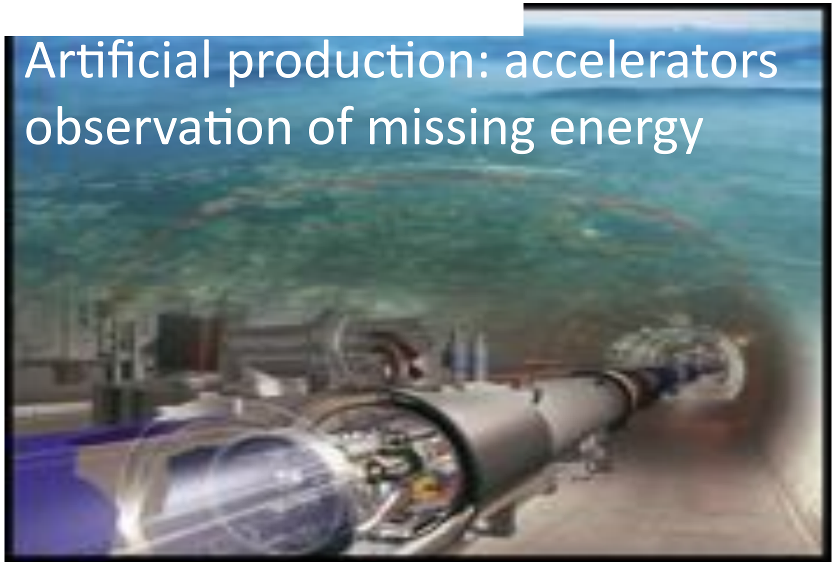
- The lightest neutralino, is a very attractive and thoroughly studied candidate for Dark Matter

Dark Matter Detection Approaches

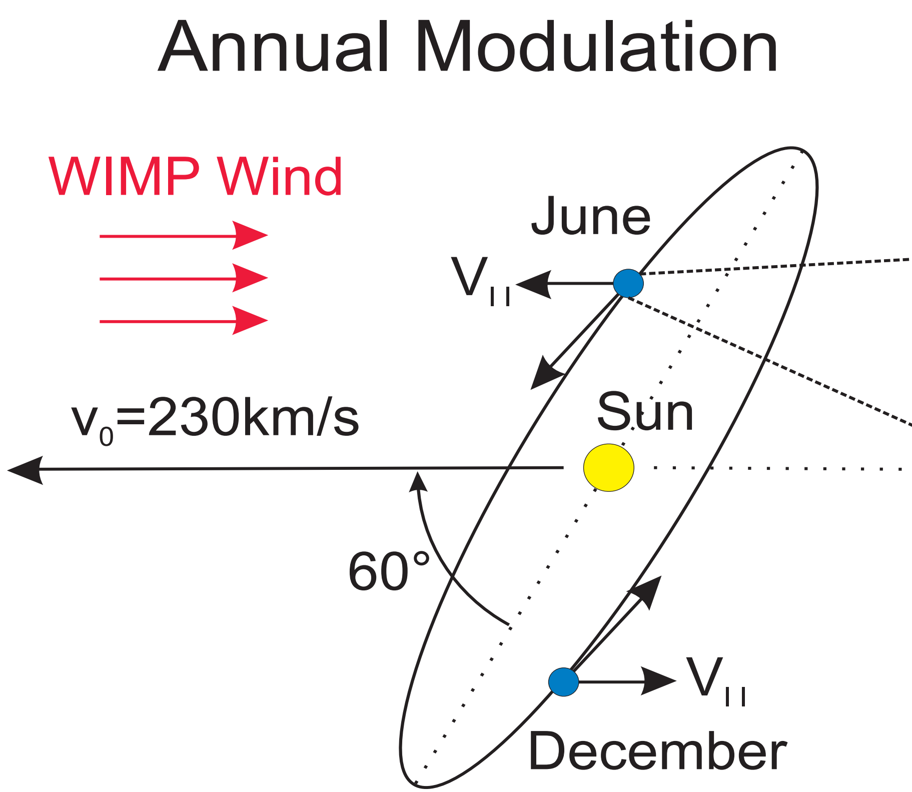


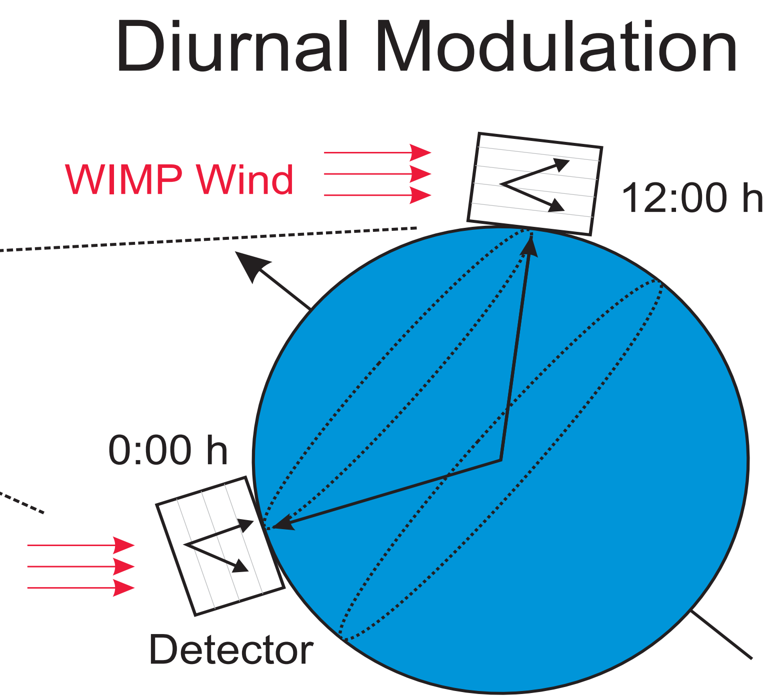


Only the combination of the different detection approaches is likely to solve the mystery of dark matter



Possible „Smoking Gun“ Signatures of Dark Matter

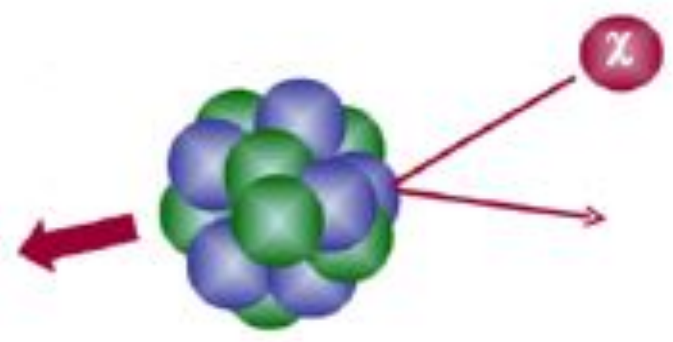




- Coherent interaction with baryonic matter: **~A²** (A = atomic mass number)
- Information provided by high-energy accelerators (e.g., LHC at CERN)

Detection Approach

Goal: Detect **WIMP (Weakly Ineracting Massive Particle)** by measuring nuclear recoil of a few keV in an earth based target material



- WIMP density at the Earth: 0.3 $GeV/c^2/cm^3$
- Wide range of WIMP masses: 10 – 1000 GeV/c^2
- Expected signature: nuclear recoil (of a few keV)
- Expected scattering behaviour: coherent, i.e. ~ A^2
- Single scatters distributed uniformly in target volume
- Extremely rare interaction rate with baryonic matter (< 0.01 evts/kg/d)

$$\frac{\partial R}{\partial E_R} \propto N F^2(\vec{q}) \frac{\rho_D}{M_D} \sigma_\chi e^{-\frac{E_R}{E_0}}$$

R measured rate in detector
M_D mass of WIMP
N number of target nuclei
E_R recoil energy of target nucleus
σ_χ WIMP nucleus cross section
F^2 nuclear Form factor

→ suppress natural radioactivity and cosmic radiation:

- Deep underground facilities
- Additional shielding with selected materials
- Detectors with very low energy threshold and excellent background discrimination capability

Backgrounds

• Intrinsic radioactivity in materials surrounding the detector (U, Th, K, Co, etc.)
-> source of gammas and neutrons
-> careful material screening and selection

• Intrinsic radioactivity in target material itself (U, Th, Rn,...)
-> special handling and purification techniques

• Radioactivity from the surrounding environment
radioactivity of environment materials (γ and neutrons from (α,n)
and μ-reactions)
-> shielding (Pb, Cu, PE, H_2O, ...)

• Cosmic ray muons
-> penetrate deep underground

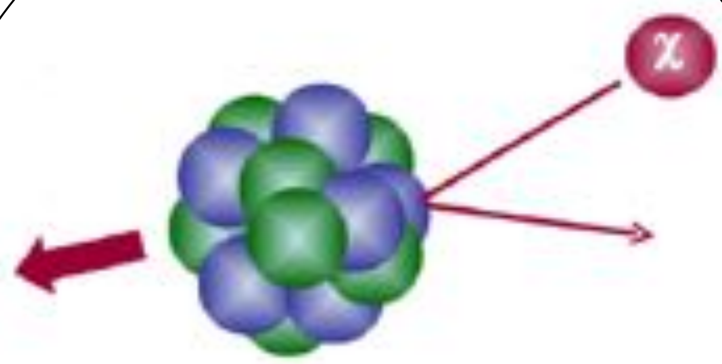
• Fast neutrons induced by unvetoed muon-showers in the surroundings

• Neutrinos (solar, atmospheric, ...)
-> relevant for future ultra-low threshold detectors

Recoil Detection & Background Identification

Phonons

CDMS
EDELWEISS



CRESST

Ionization

Scintillation

XENON100

Phonons

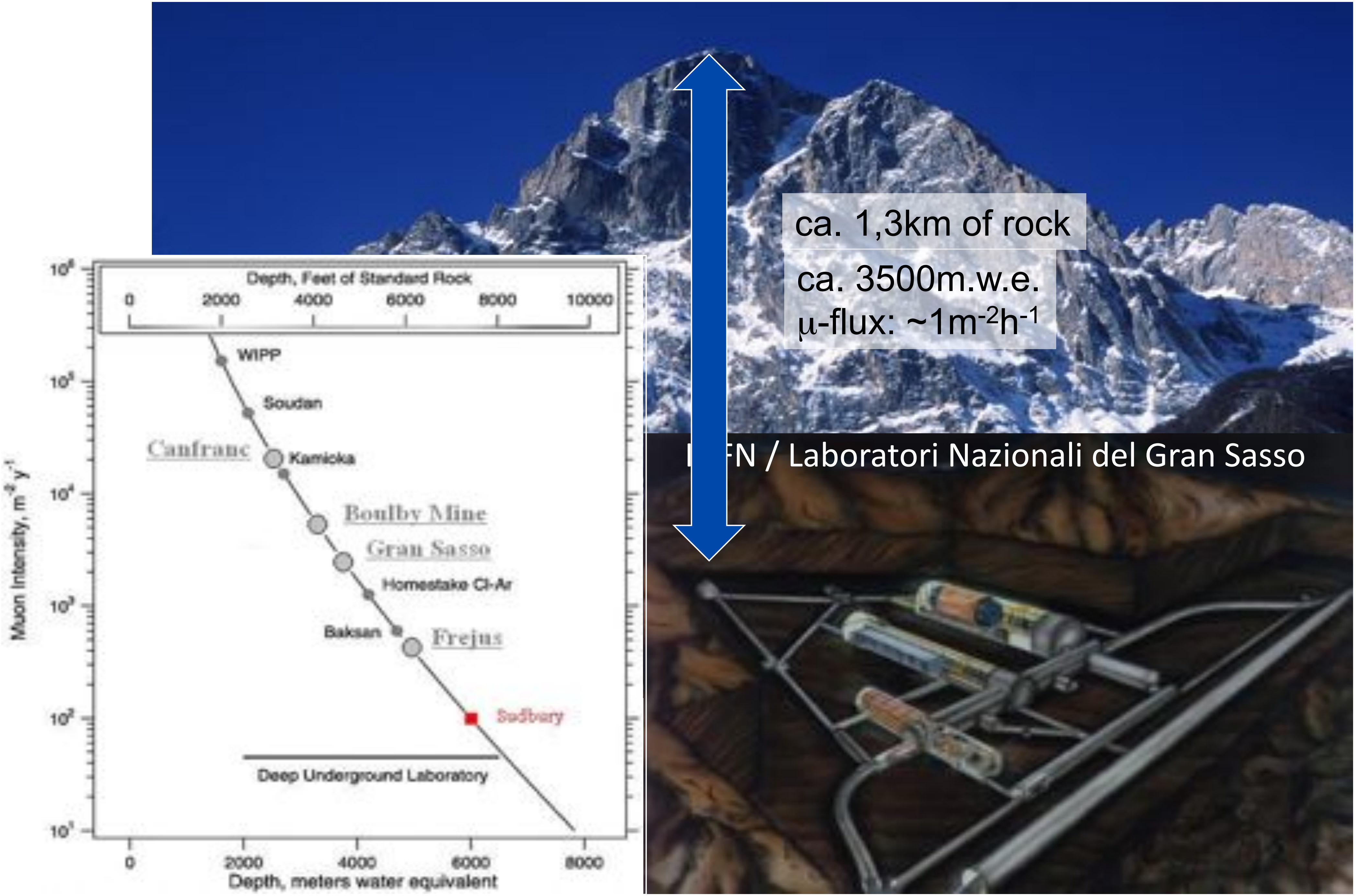
most precise total energy measurement

Scintillation:

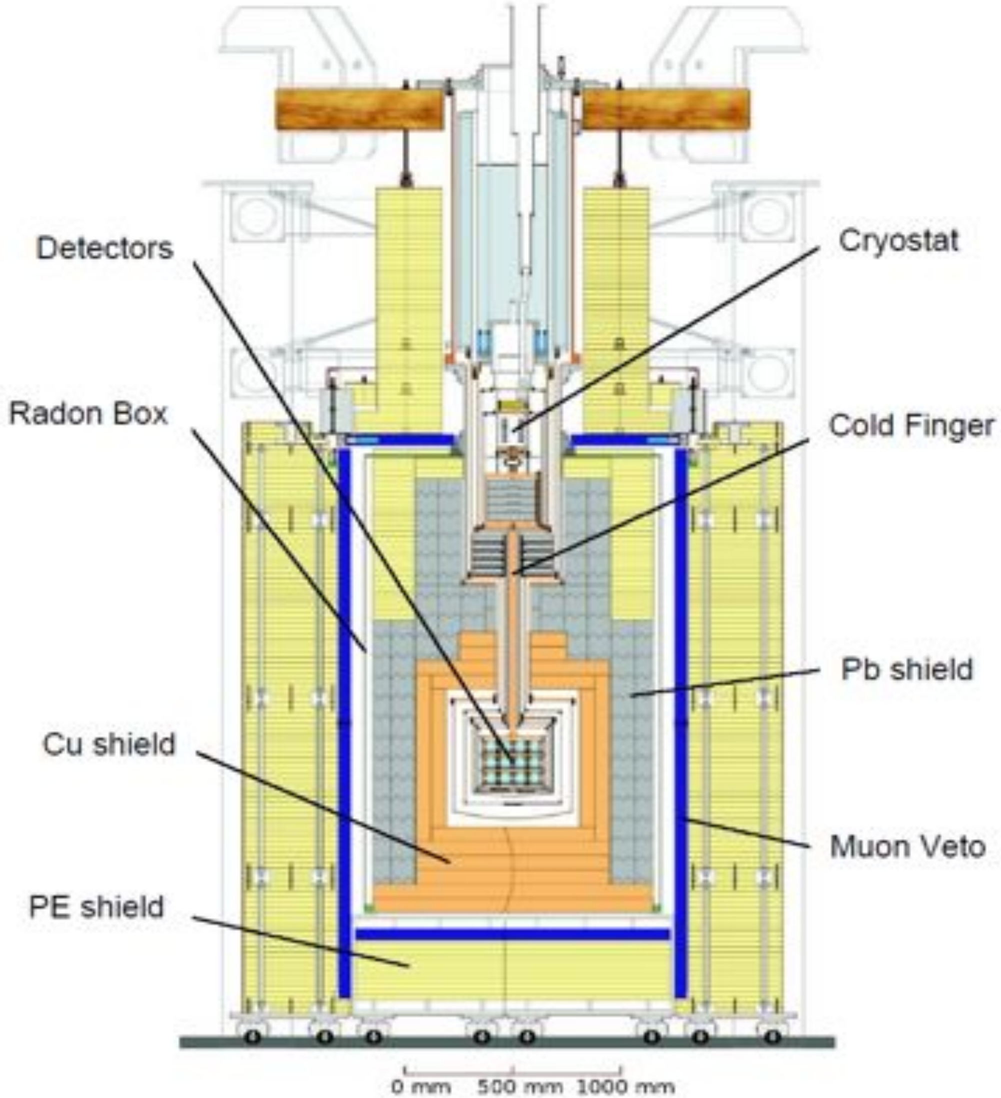
yield depends on recoiling particle

➔ Nuclear / electron recoil discrimination

Underground Laboratories

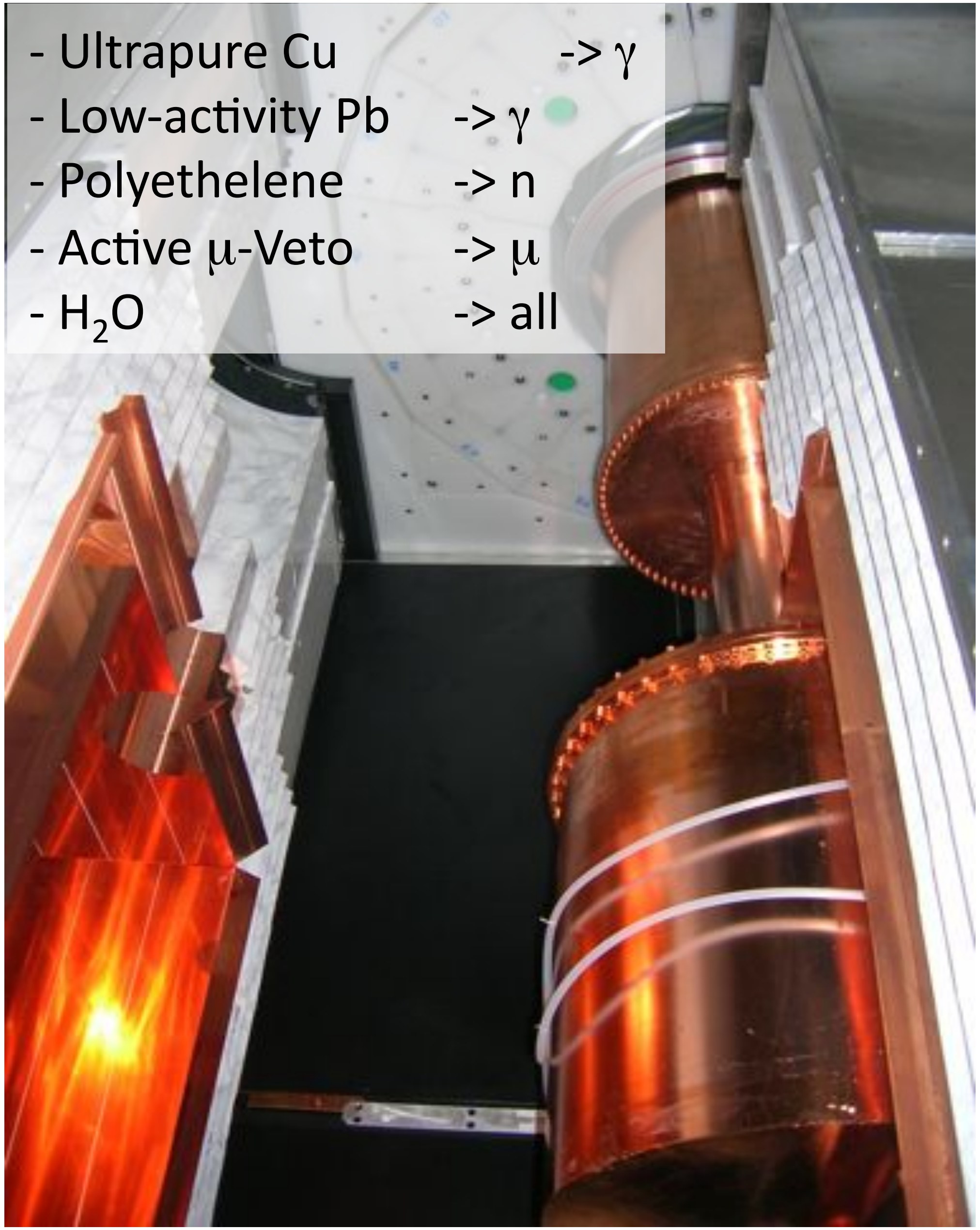


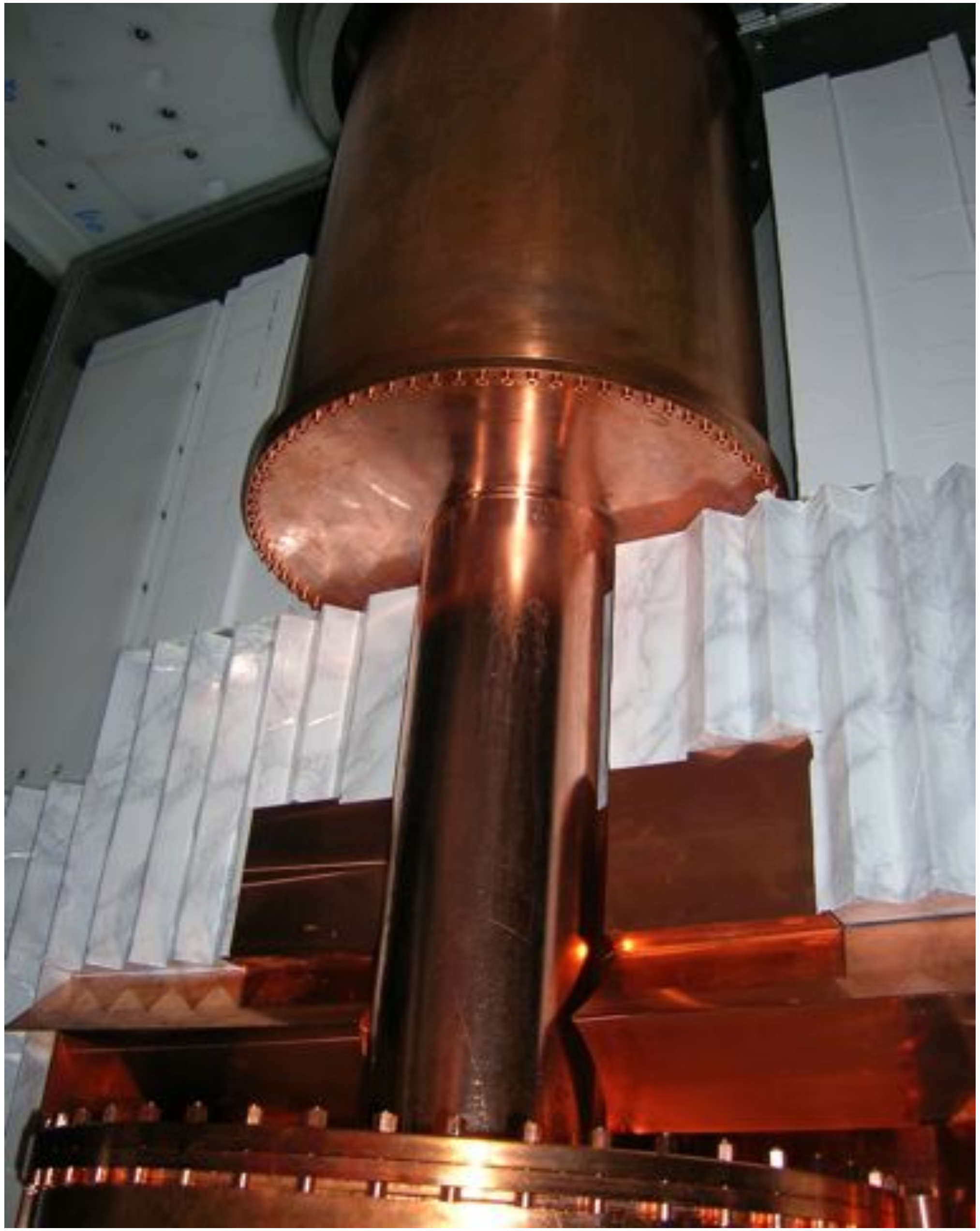
CRESST (Cryogenic Rare Event Search with Superconducting Thermometers)



Typical Shielding Materials

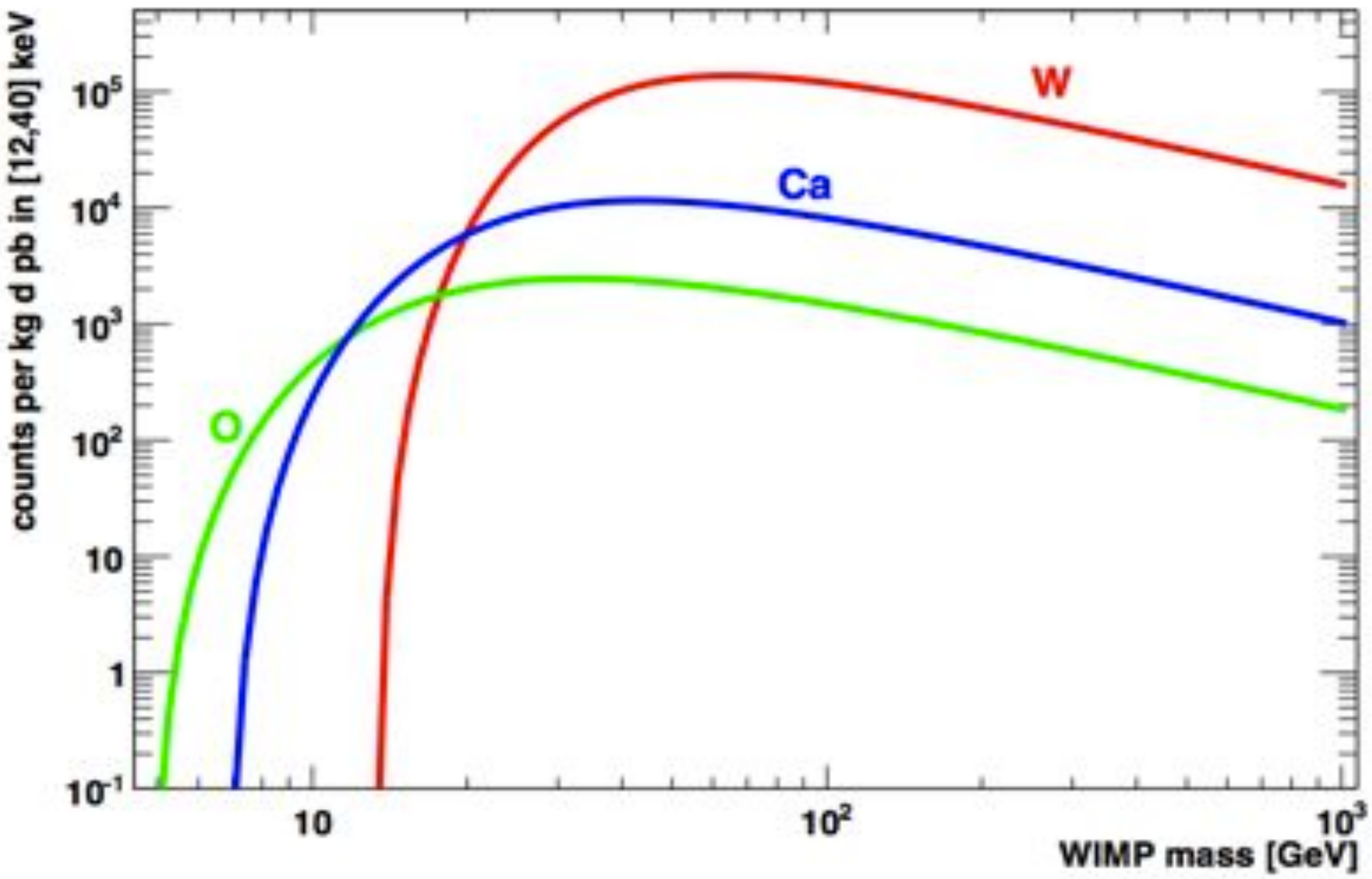
- Ultrapure Cu -> γ
- Low-activity Pb -> γ
- Polyethelene -> n
- Active μ-Veto -> μ
- H_2O -> all





$CaWO_4$ as WIMP-Target

$CaWO_4$ Multi-Material WIMP Target



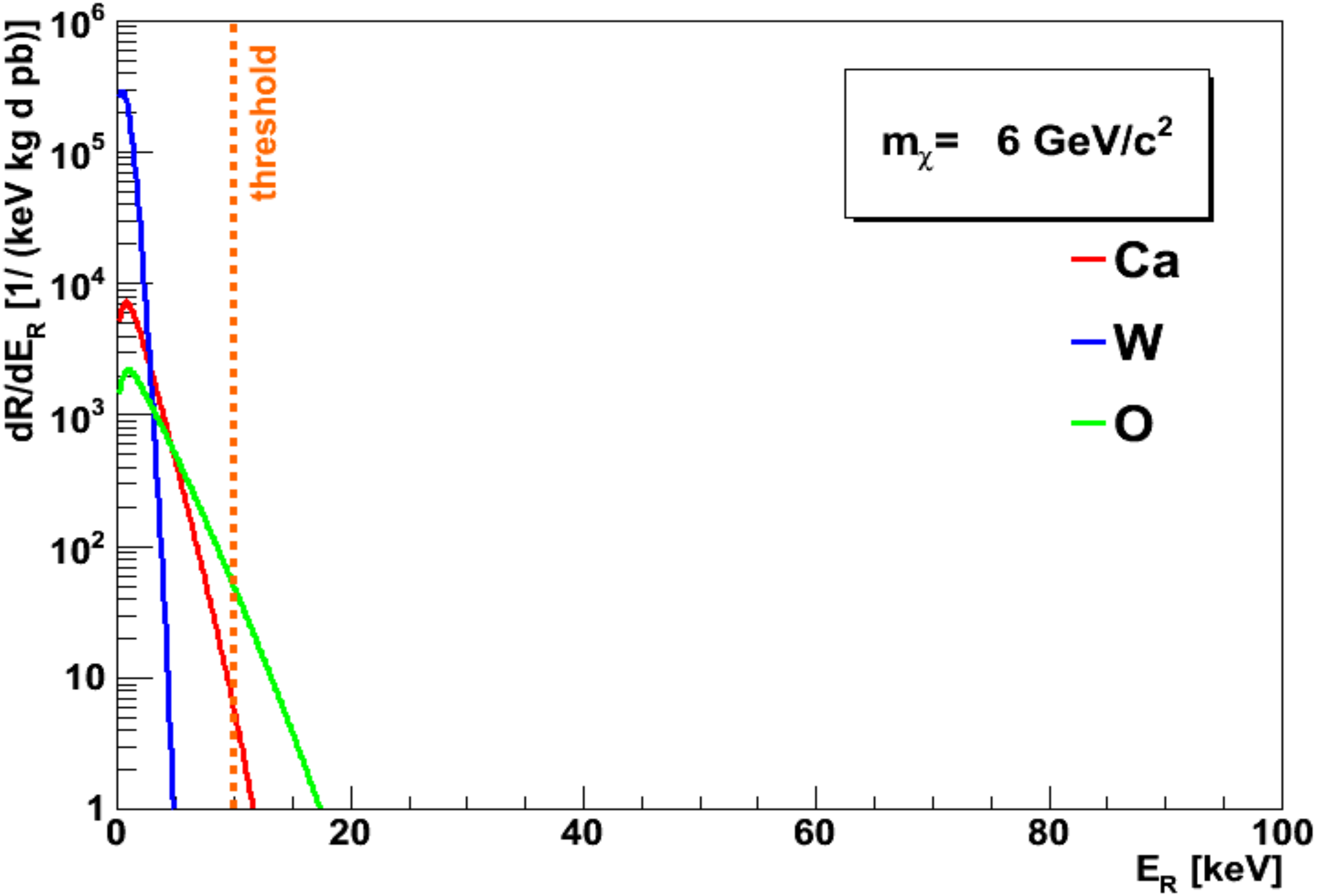
$$\Gamma = \frac{M_{Target}}{m_N} \frac{\varrho_\chi}{m_\chi} < v > \sigma_\chi A^2$$

low WIMP masses ≤20GeV: only O, Ca recoils above detection threshold

high WIMP masses ≥30GeV: dominated by W recoils

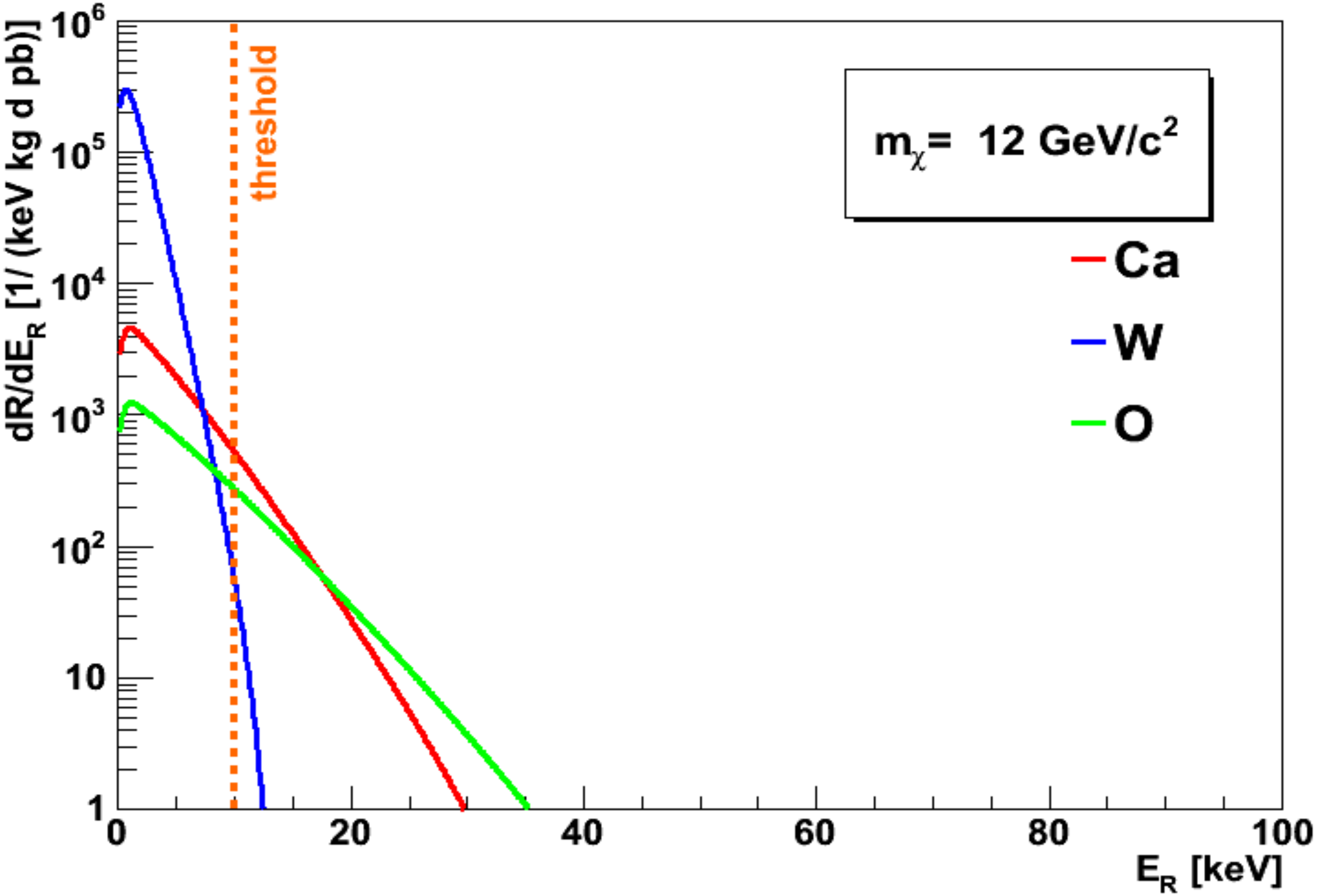
neutron background mainly O recoils above detection threshold

Composition of Recoil Spectrum



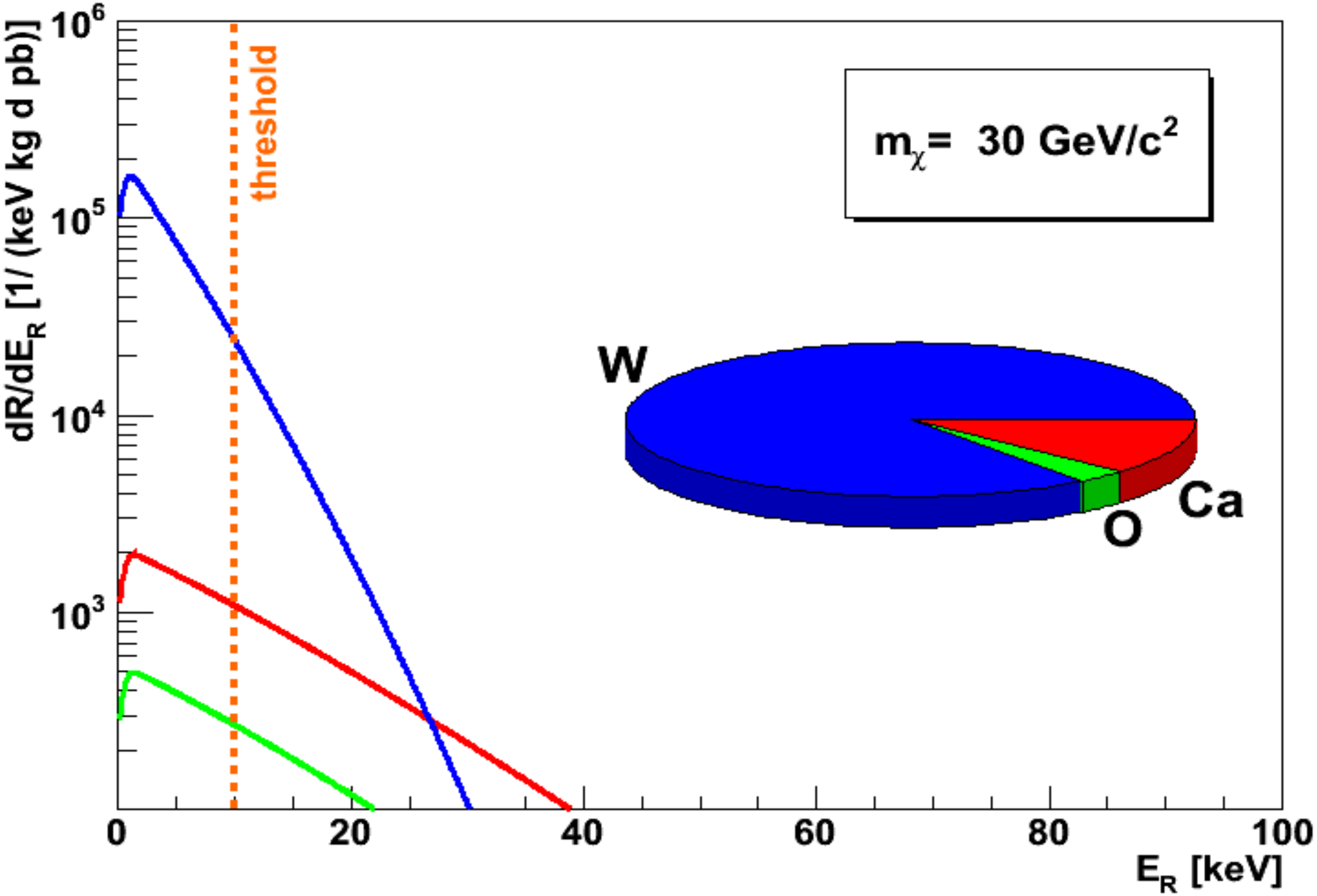
Light-mass WIMP (6GeV): only O recoils above threshold

Composition of Recoil Spectrum



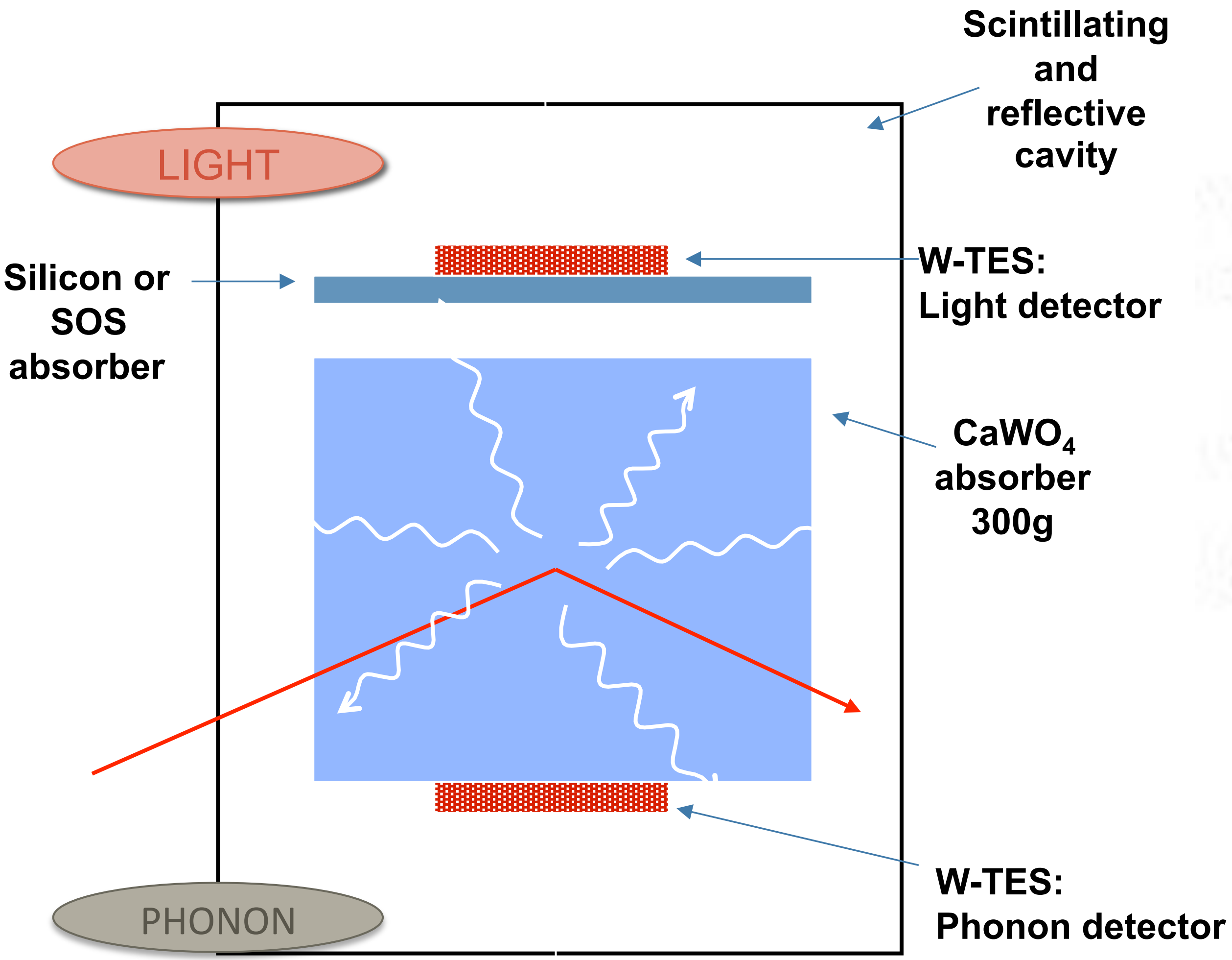
Light-mass WIMP (12 GeV): contribution of O and Ca, W just above threshold

Composition of Recoil Spectrum

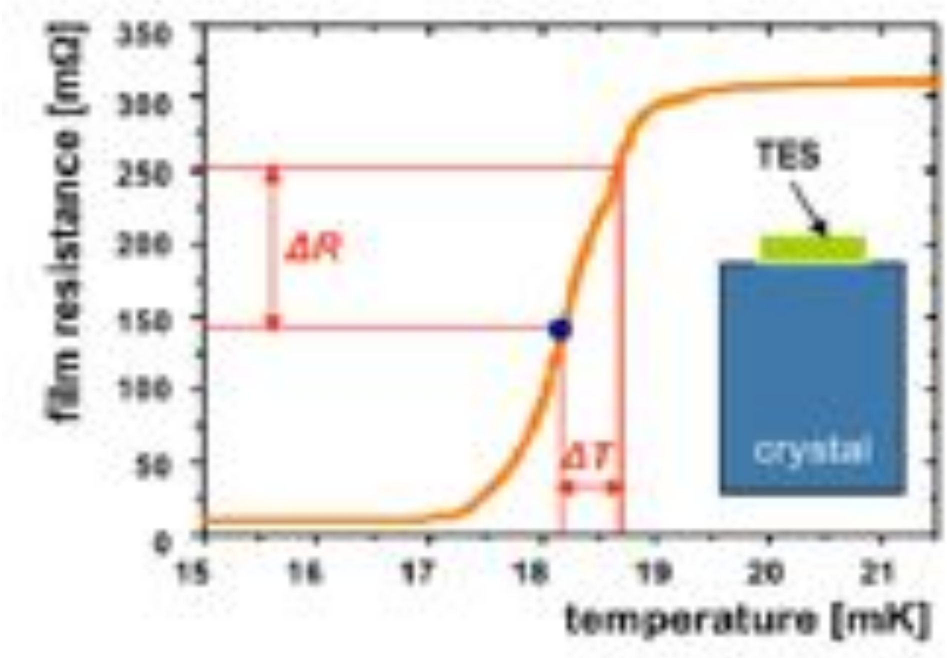


For higher WIMP masses (>30GeV): tungsten dominates recoil spectrum

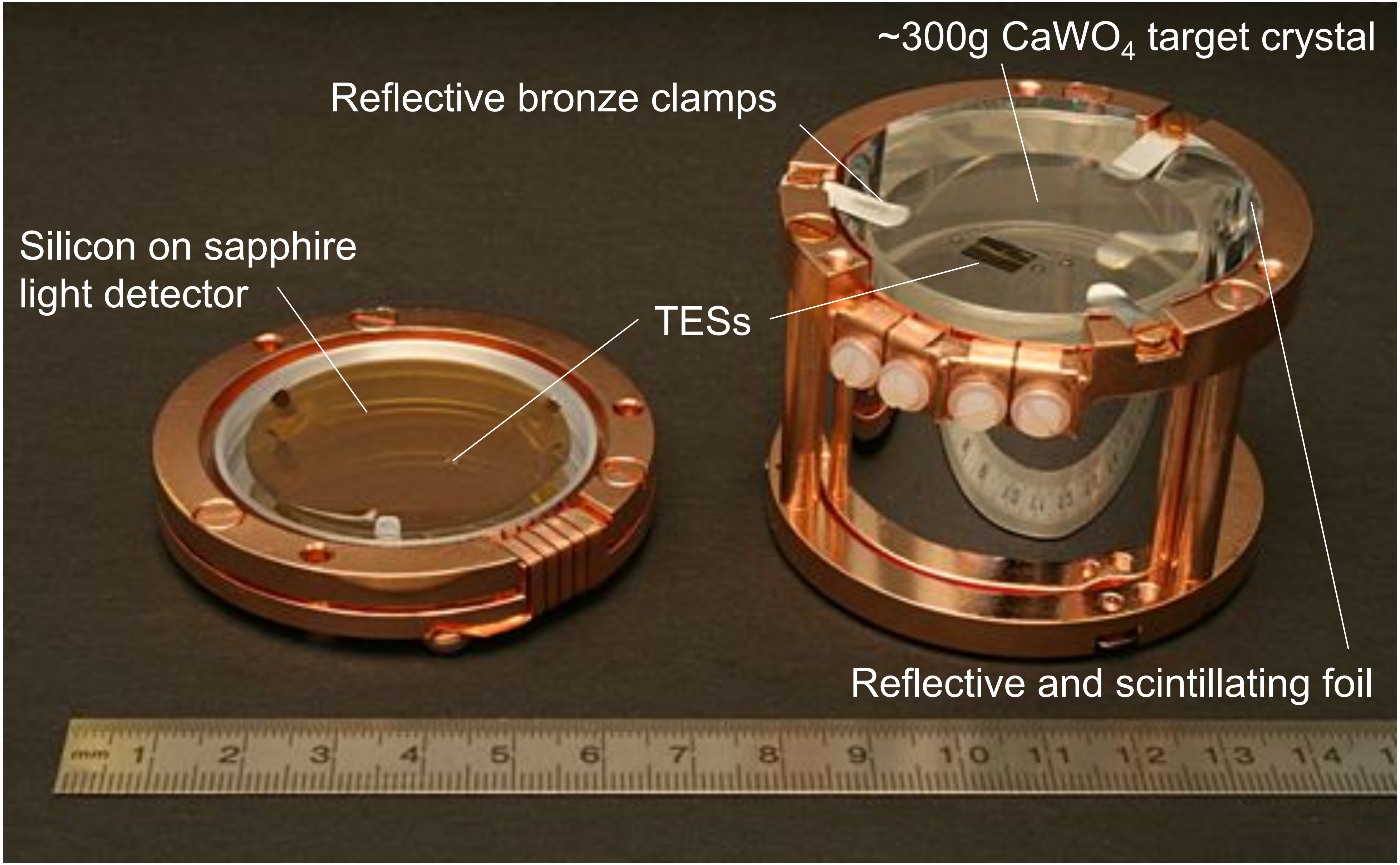
CRESST II Detector Modules



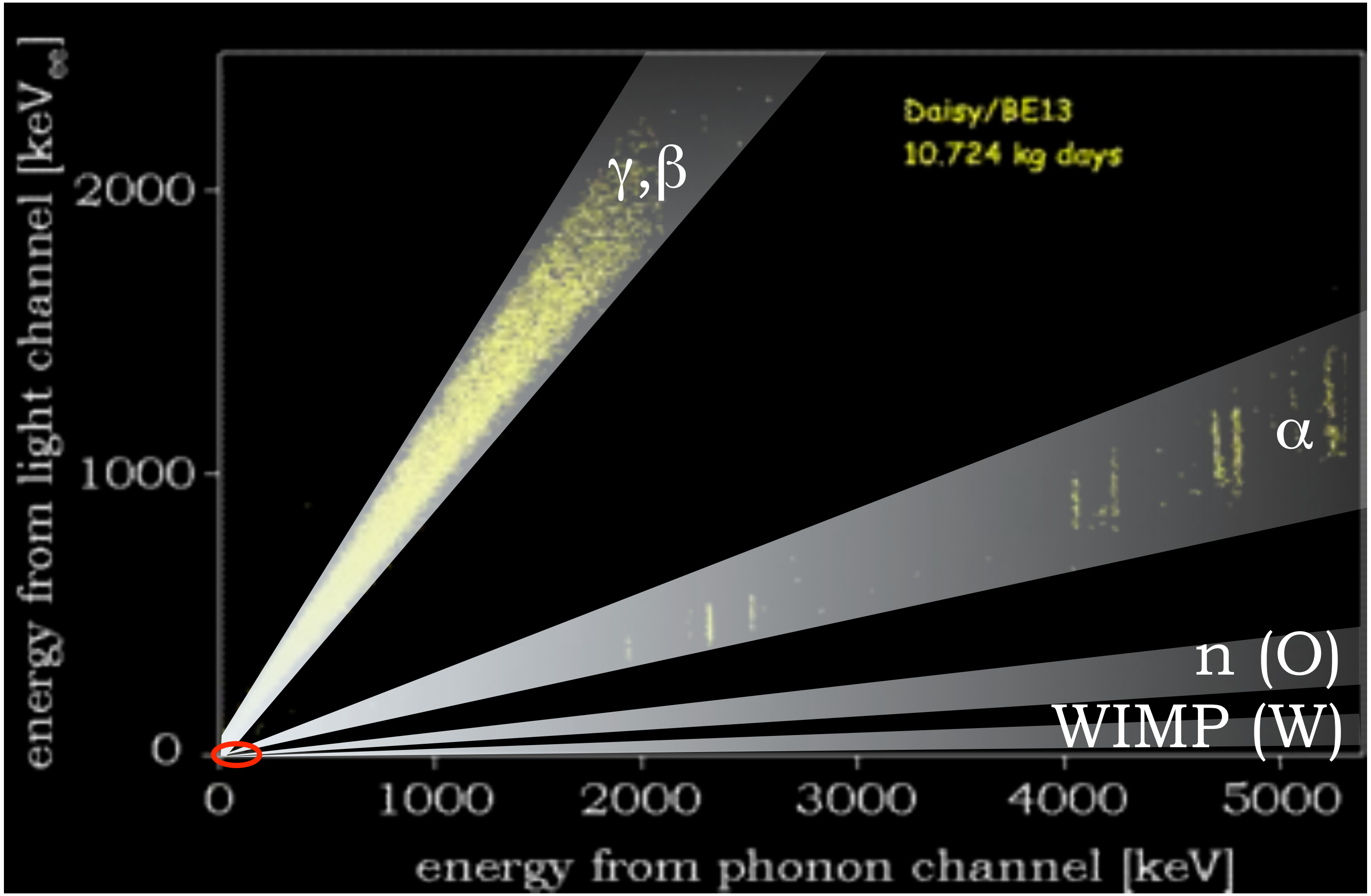
Transition Edge Sensor (TES)



CRESST II Detector Modules



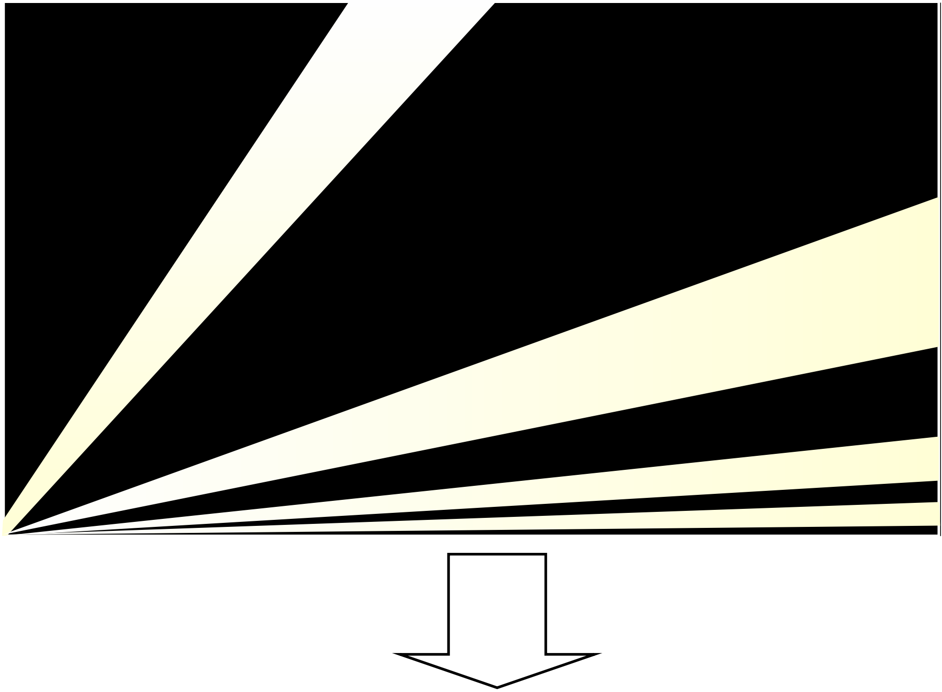
Unique Discrimination Capability



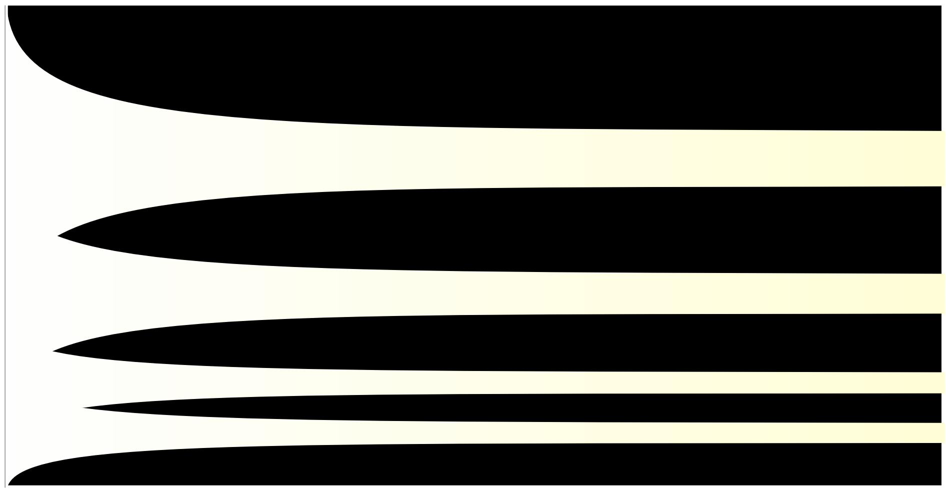
slope
1 (def.)
1/5
1/10
1/40

Event-by-event discrimination !

Data Plots



Light versus phonon-energy



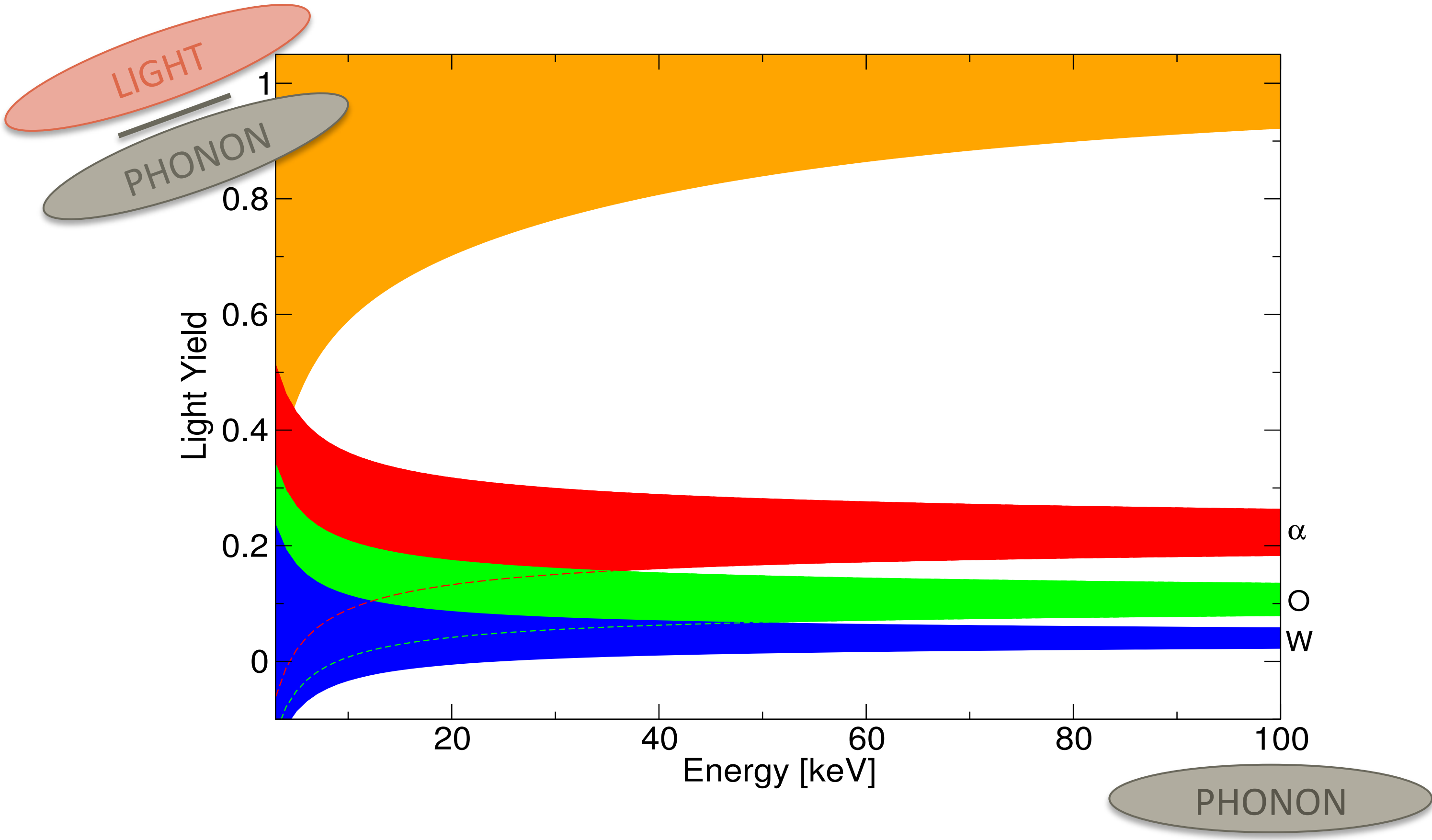
Light yield (light to phonon ratio) versus phonon-energy

Identification of Event Type

- Characteristic light yield (LY) for each type of event:

e-recoil:	1	(by def.)
α:	~ 0.22	
O-recoil:	~0.10	
Ca-recoil:		~0.06
W-recoil:	~0.04	

(„Quenching factors“)

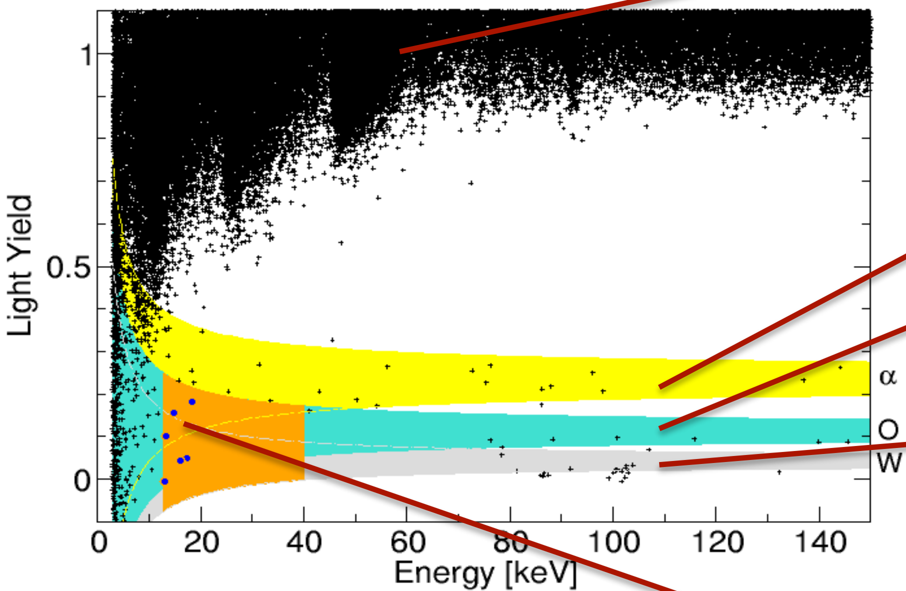


- Excellent discrimination between dominant radioactive background (electron recoils induced by γ and β) and nuclear recoils
- To some extent identification of recoiling nucleus possible (depends on achievable separation of Ca, W and O nuclear recoil bands)
- Possibility to probe different WIMP mass scenarios in same target (unique feature of CRESST)

Results of Run32 (2009-2011)

Eur. Phys. J. C (2012) 72:1971
DOI 10.1140/epjc/s10052-012-1971-8

Data of one single 300g detector module in Run32:



Electron recoils: excellent discrimination of from e/γ–band and nuclear band

α–events: from surfaces

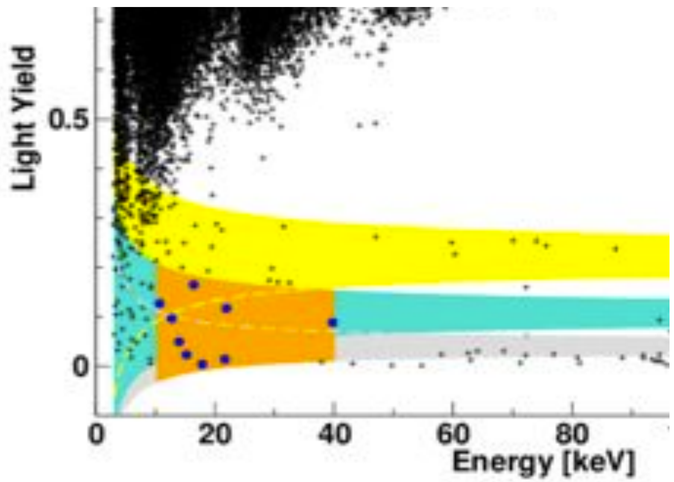
O-band: neutrons or „light"-WIMPs

W-band: expect „heavy"-WIMP interaction
-> band is contaminated by recoiling ^{206}Pb nuclei from ^{210}Po α-decays (clamps), 103keV downwards

67 events at low energy observed in O, Ca and W-bands in all detector modules (~730kg d)

Acceptance region:
includes O, Ca and W recoil bands

Spectral Distribution of Observed Events



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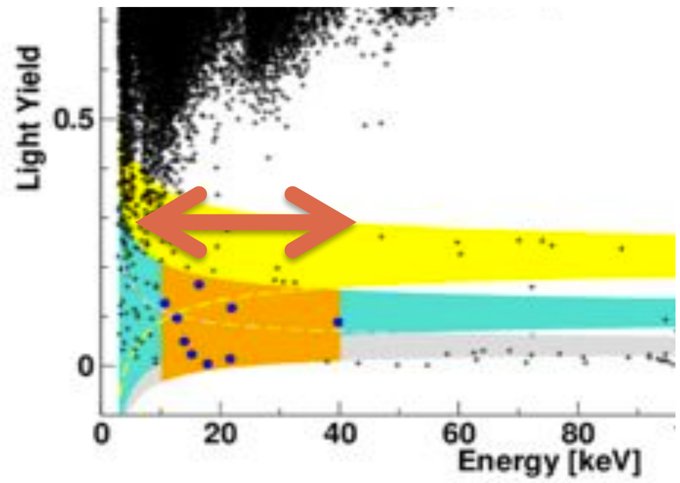
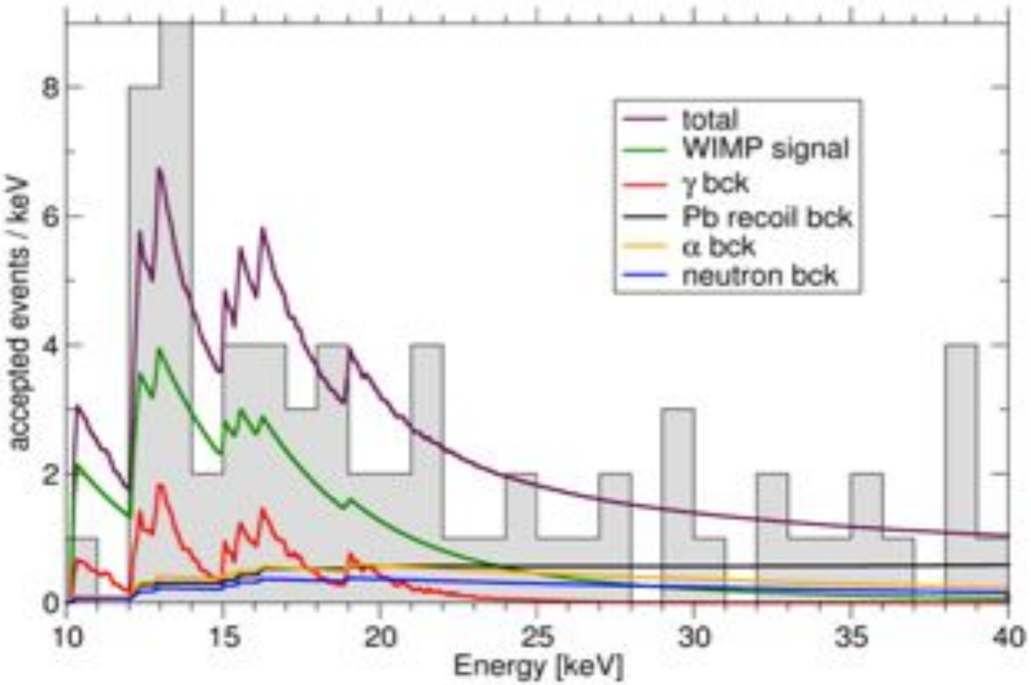


Energy spectrum



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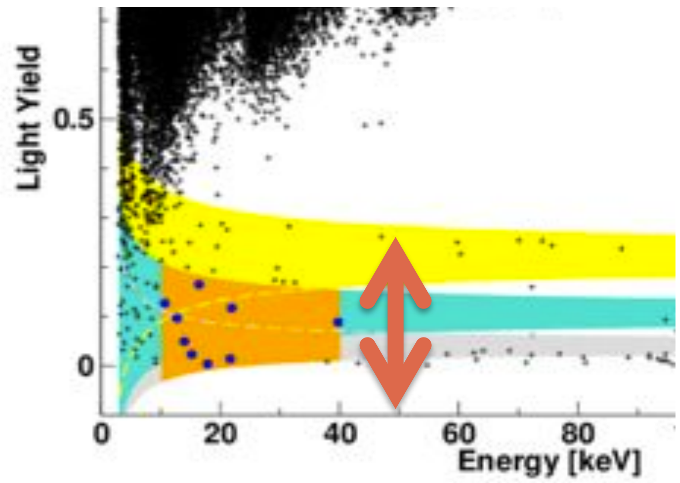

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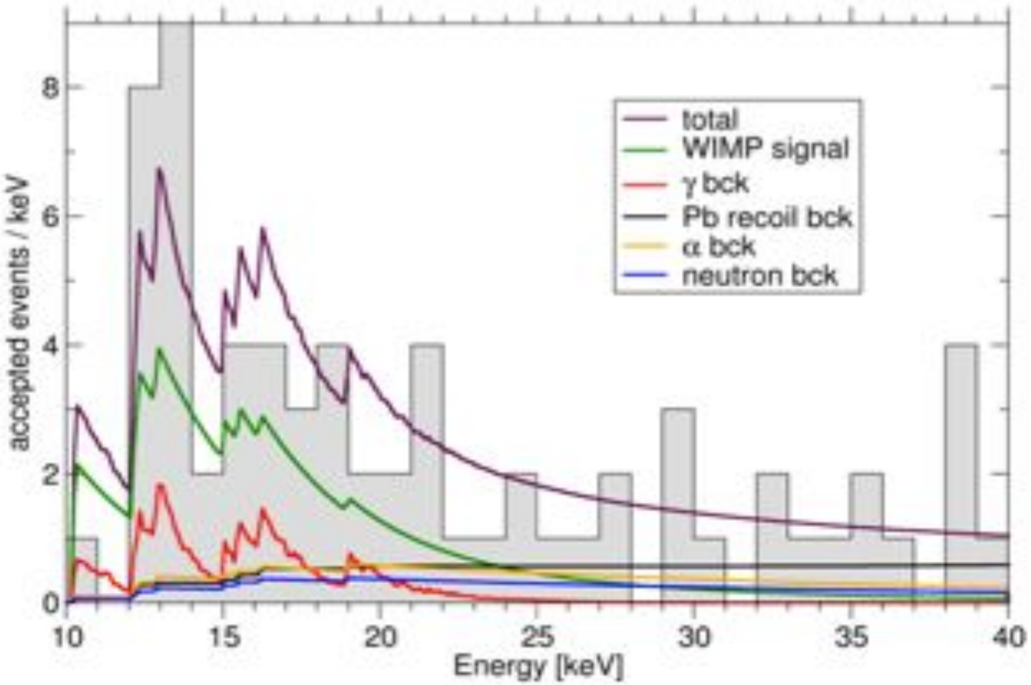
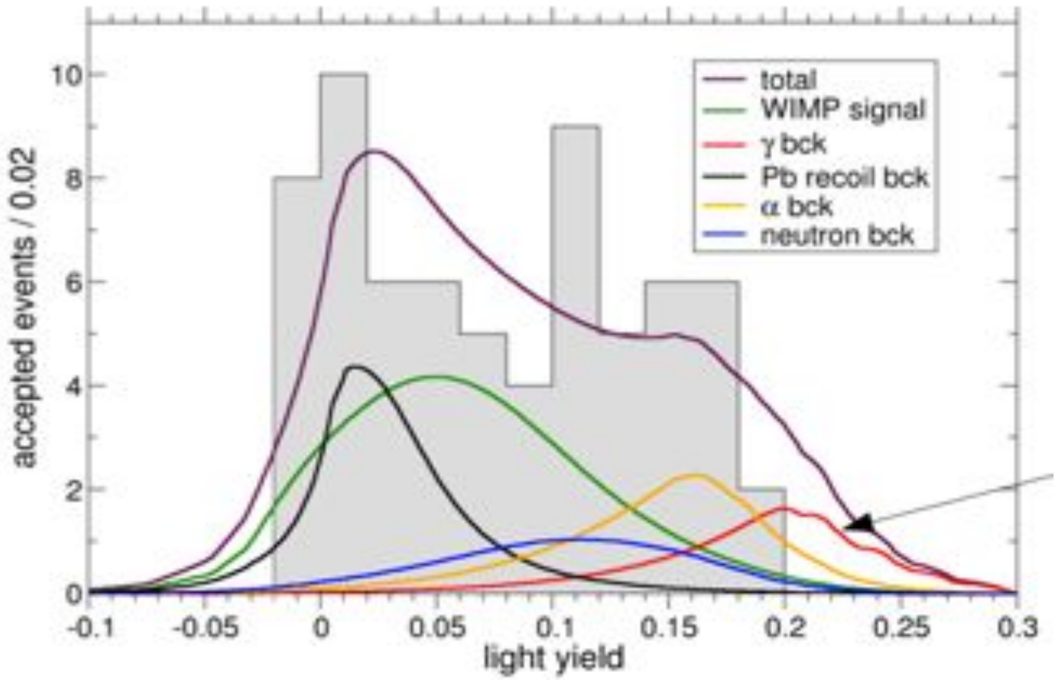


Light yield distribution



Spectral Distribution of Observed Events

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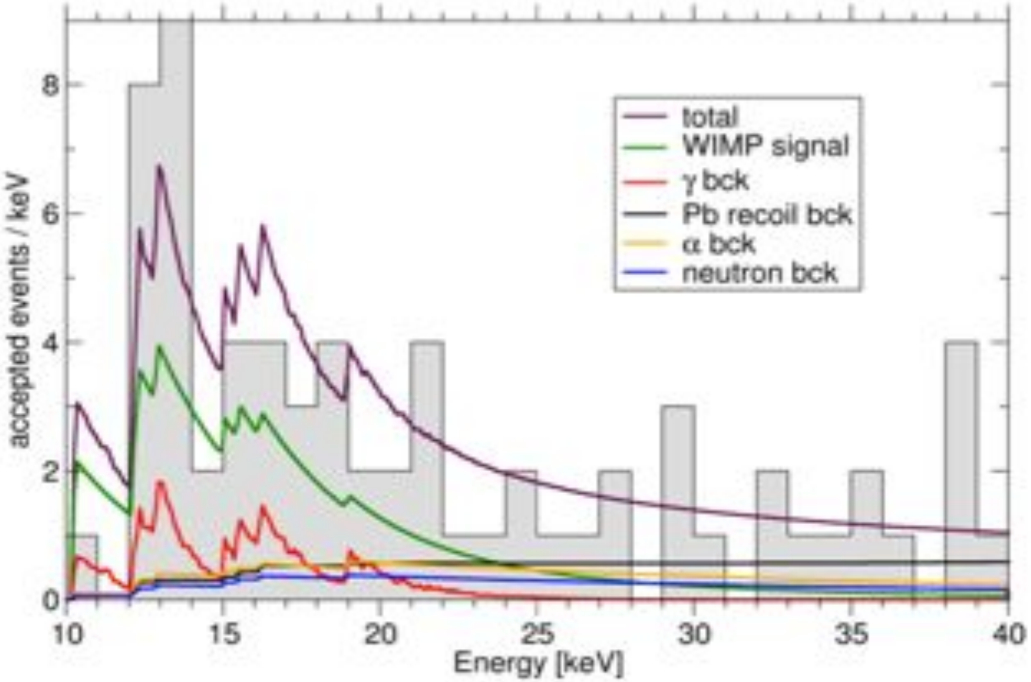

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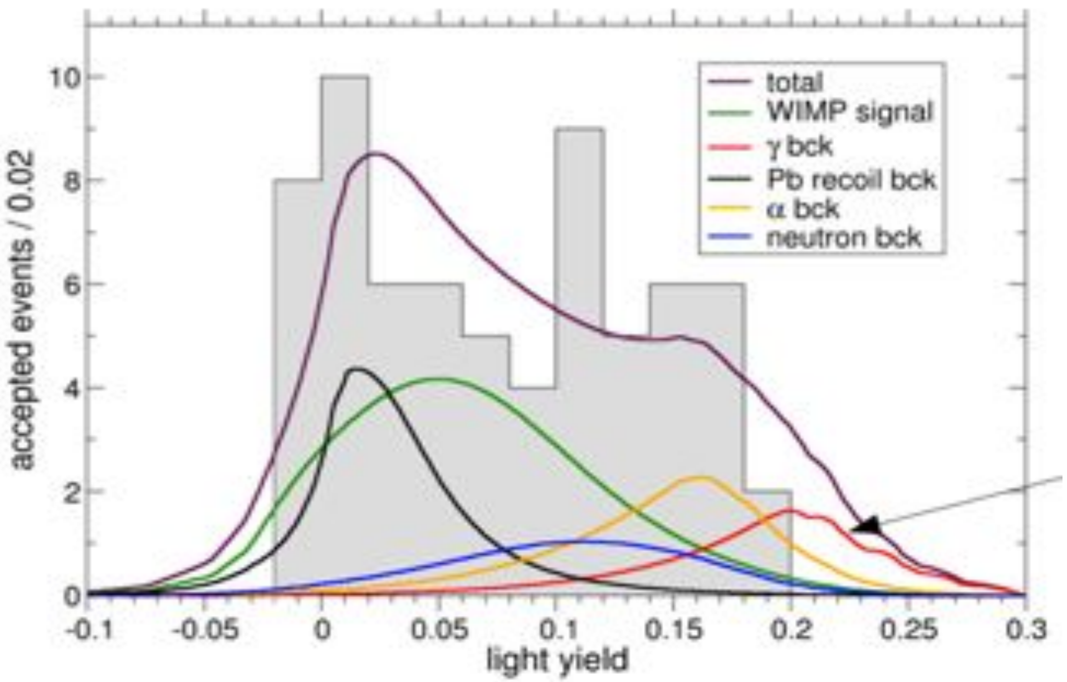
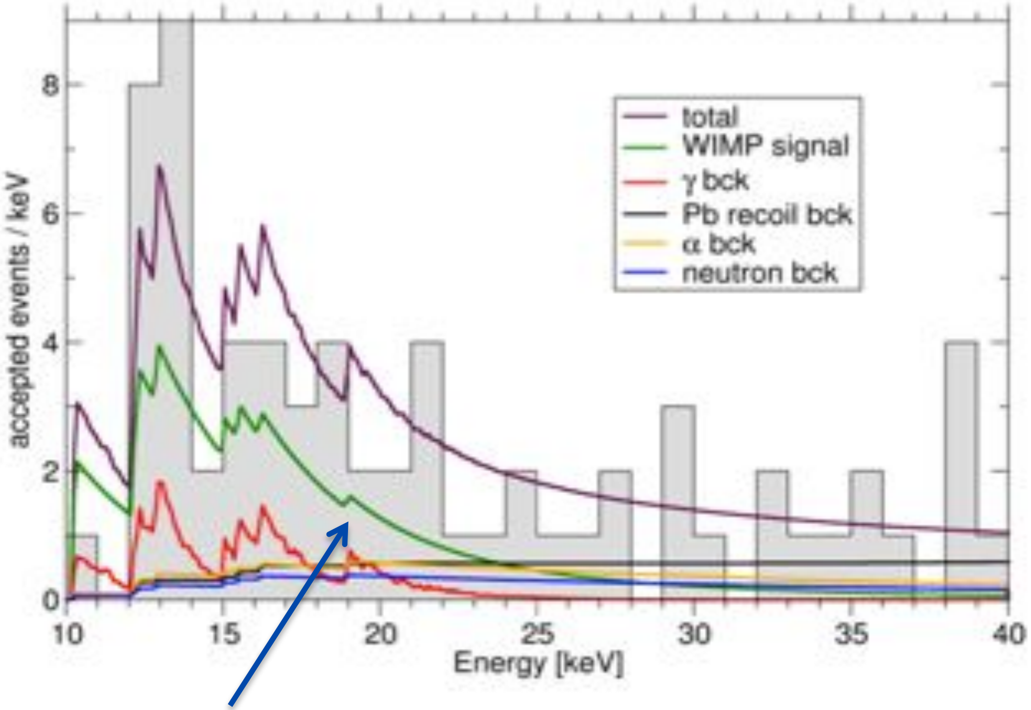
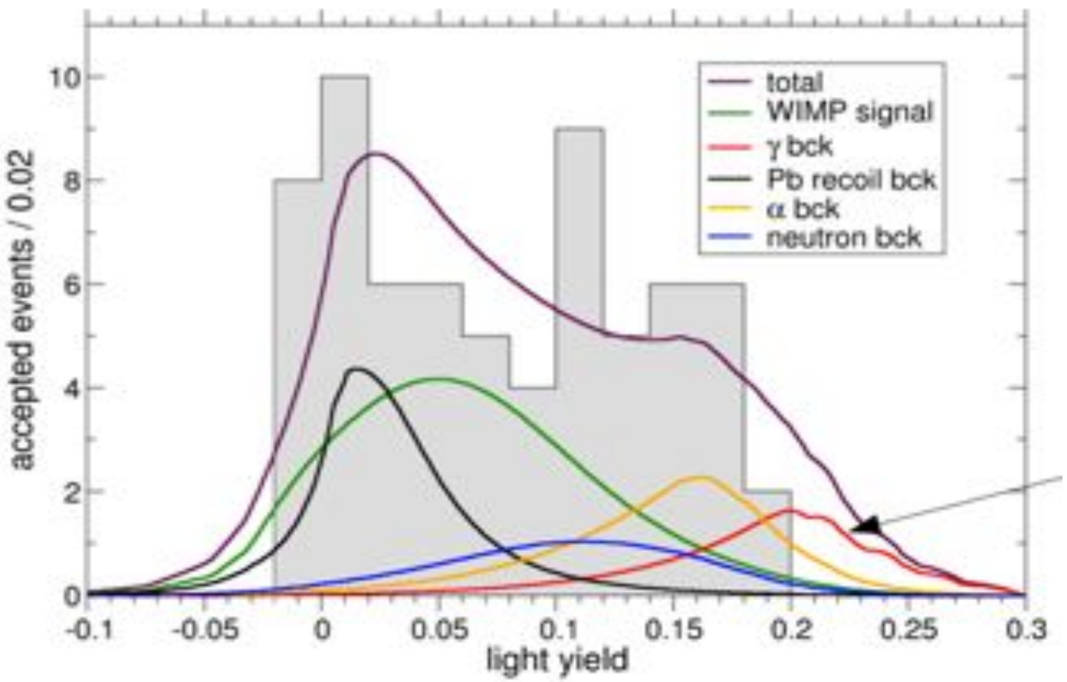


Spectral Distribution of Observed Events

Energy spectrum



Light yield distribution



WIMP-signal spectrum is exponential

like:

gamma background

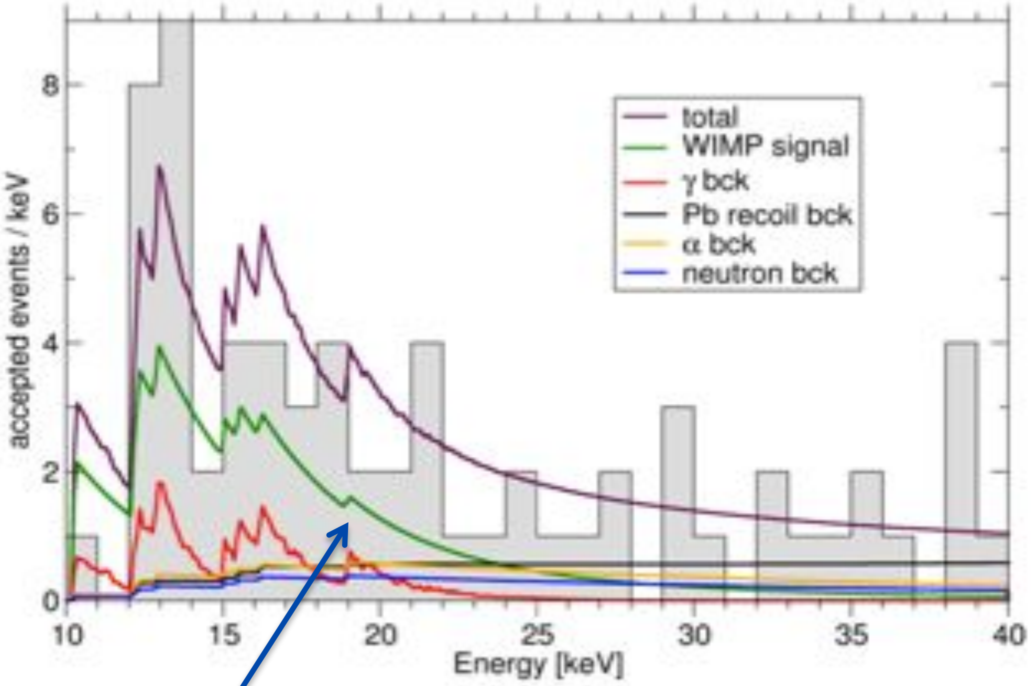
unlike:

^{206}Pb, neutron alpha background

Is the signal due to gamma leakage?

Spectral Distribution of Observed Events

Energy spectrum



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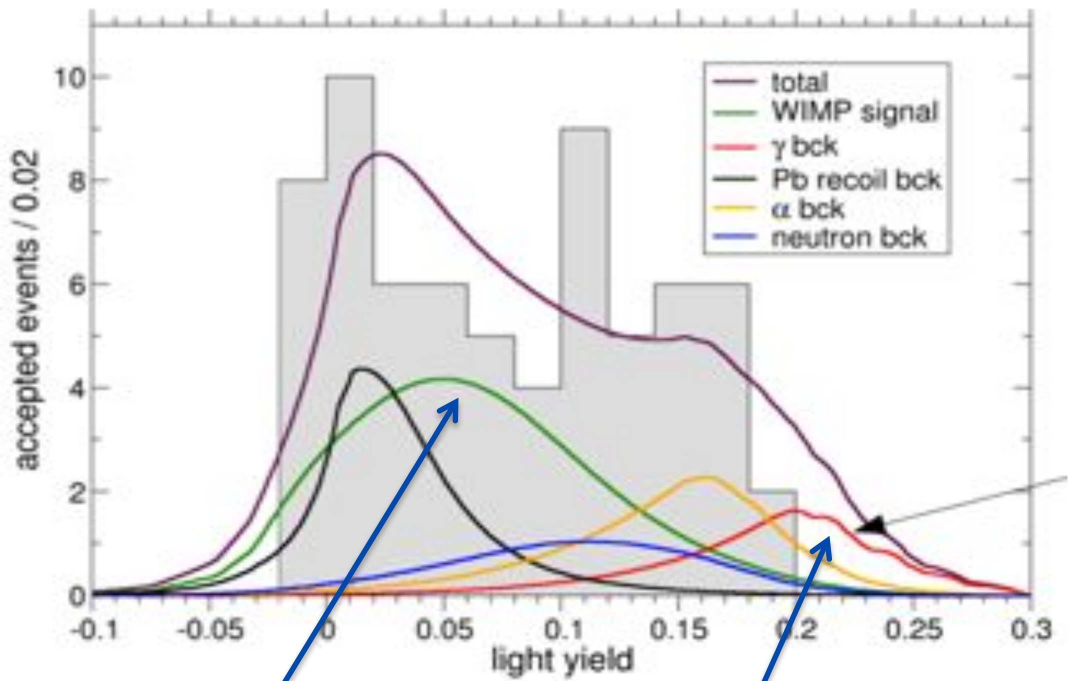
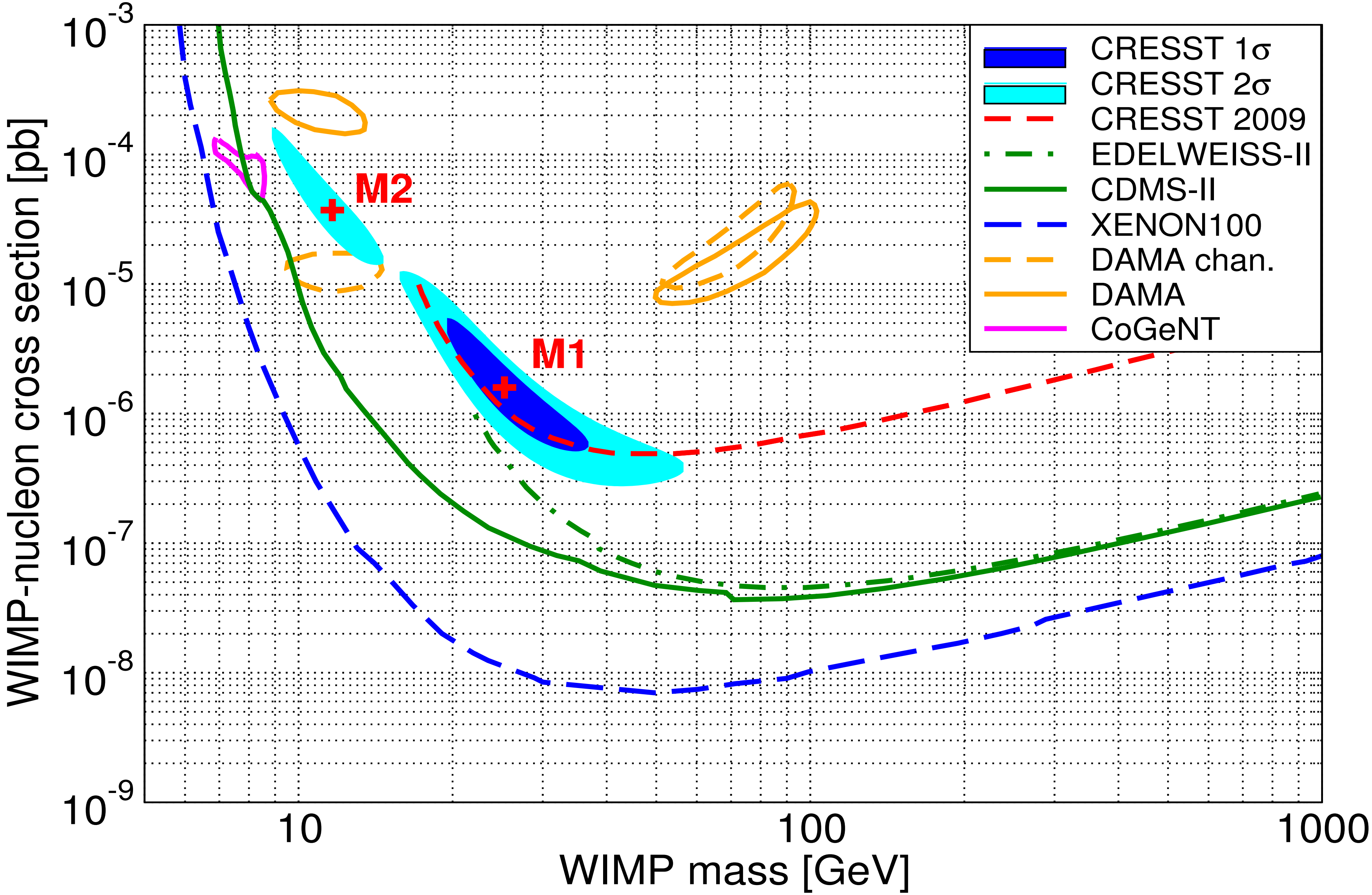
Light yield distribution



Unlikely!

WIMP-signal and gamma leakage differ significantly in the light yield distribution!

WIMP Parameter Space



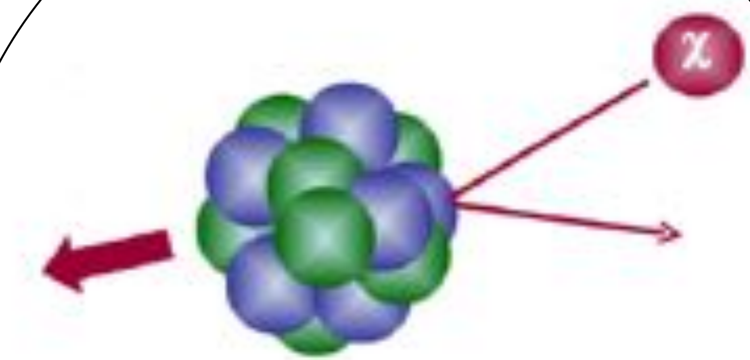
Recoil Detection & Background Identification

Phonons

Germanium Bolometers

CDMS
EDELWEISS

CRESST



Ionization

Scintillation

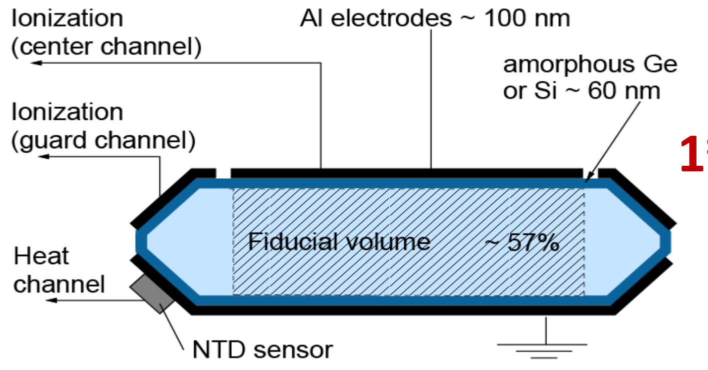
XENON100

EDELWEISS-II Detector Technology

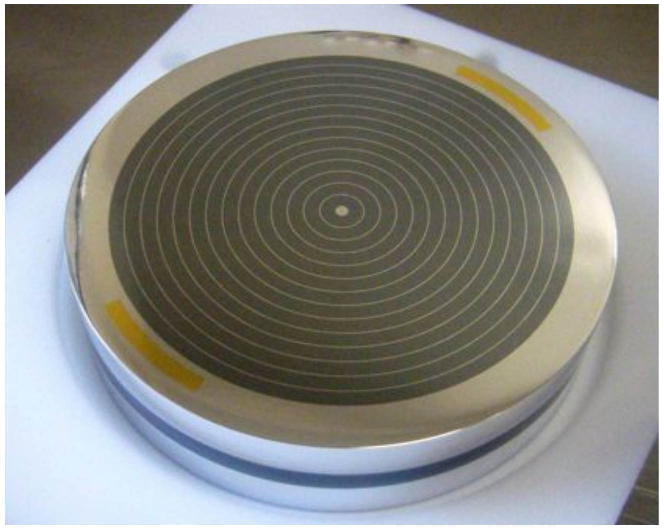
Germanium bolometers

- **Heat measurement (NTD sensor)**
  - **→ $E_{recoil} \approx E_h$ (after NL correct.)**
- **Ionization measurement @ few V/cm**

- discrimination between ER and NR
  Q = ionization/recoil energy
  Q(NR) ~ 1/3 Q(ER)



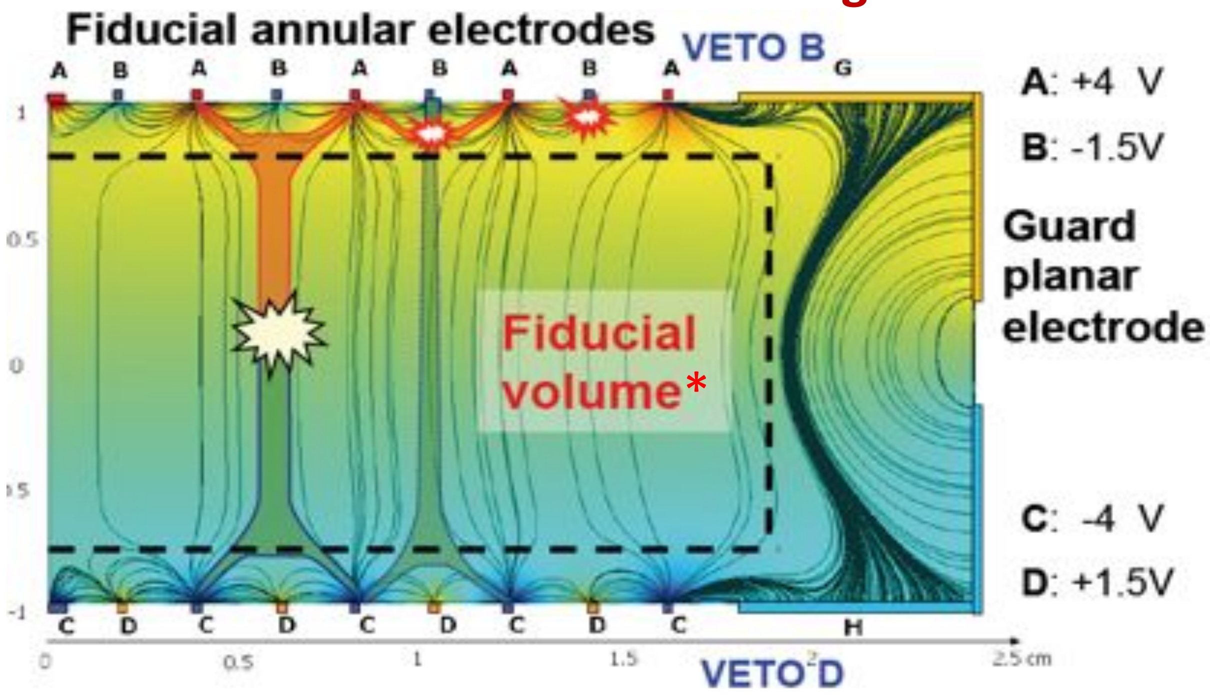
1st generation GeNTD 320g all planar electrodes



ID400g

(Courtesy K. Eitel, KIT)

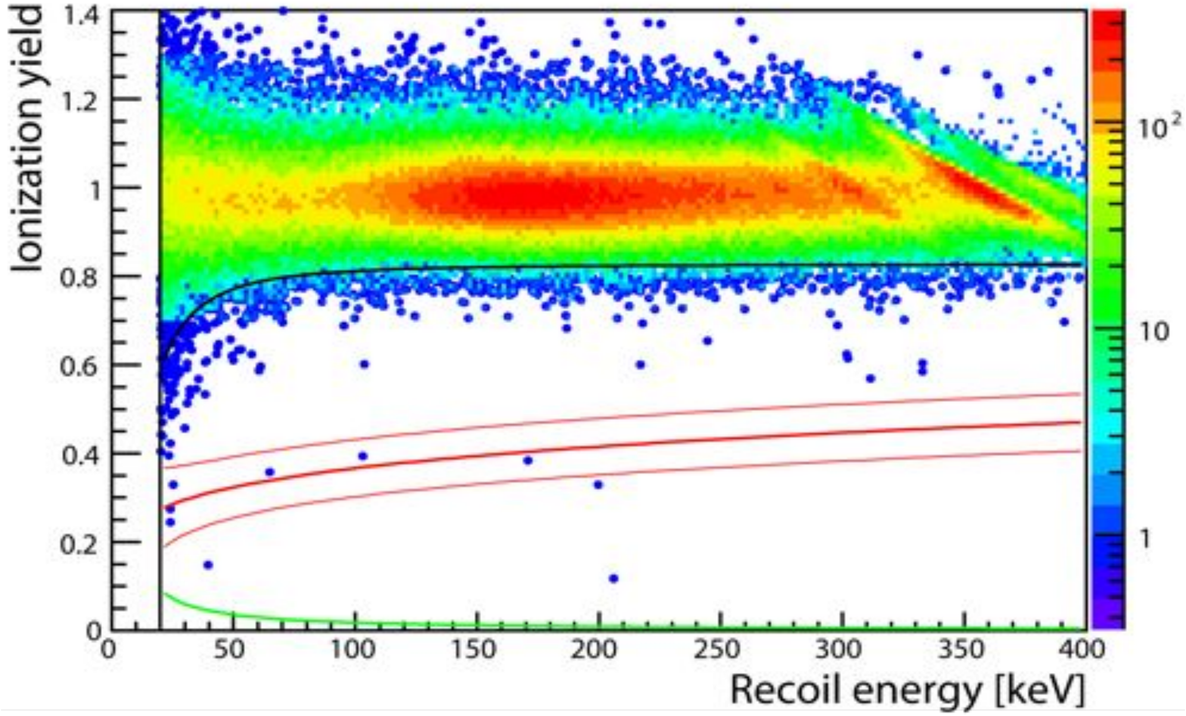
2nd generation ID400



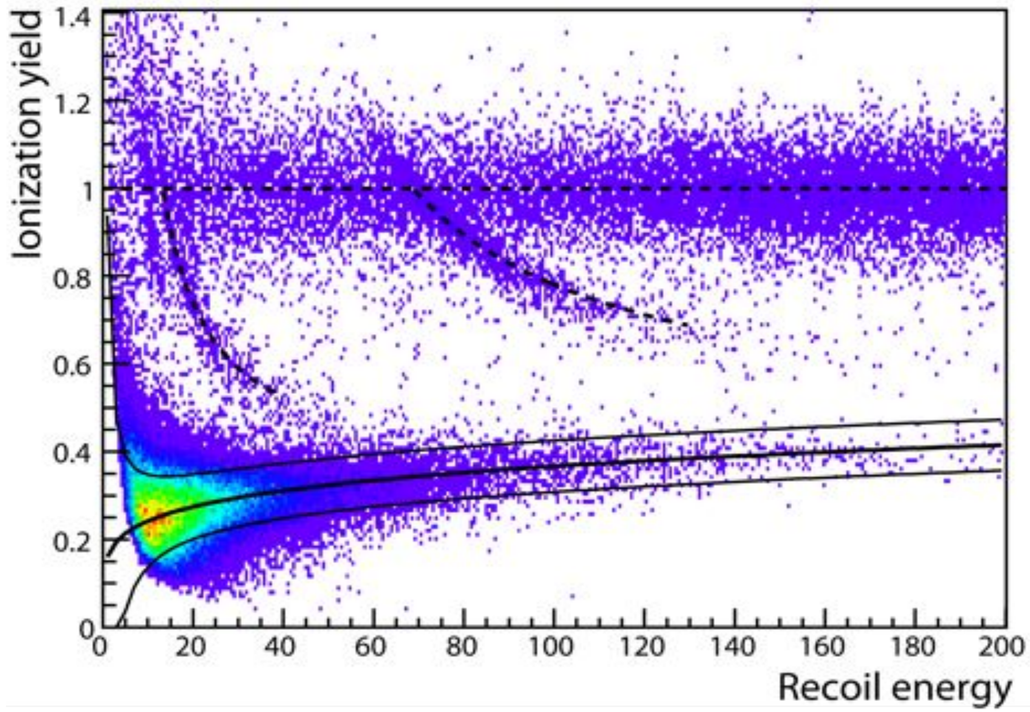
*measured via cosmogenic γ lines

Calibration with γ/n-Sources

γ calibrations with ^{133}Ba



n calibrations with AmBe



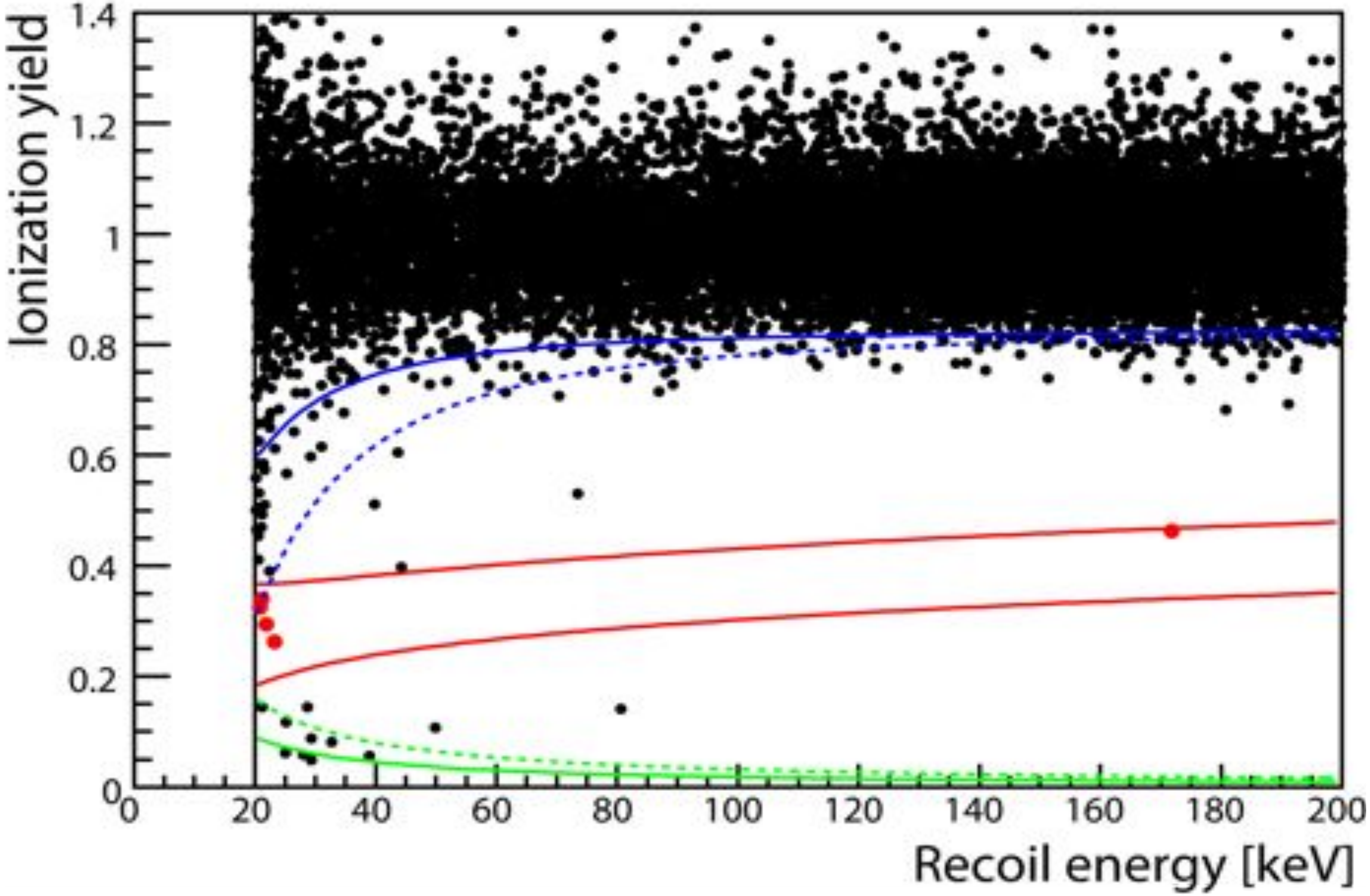
more than 350.000 γ´s
γ suppression factor 3x10^{-5}
1 ”NR” for every 30k γ´s (20-200keV)

90% CL signal region
$Q = 0.16\, E_r^{0.18}$ from <10 to 200keV
(detection efficiency below 20keV)

P. Di Stefano et al., ApP14 (2001) 329
O. Martineau et al., NIMA 530 (2004) 426
A. Broniatowski et al., PLB 681 (2009) 305

(Courtesy K. Eitel, KIT)

EDW-II final result (2008+2009+2010)



(PLB702,5 (2011) 329)

total exposure of 427kg.d → 384kg.d in 90% NR band (WIMP RoI) fiducial mass 1.6kg

5 events observed (4 with E<22.5keV; 1 with E=172keV)

3 evts bg expected 20<E<100 keV

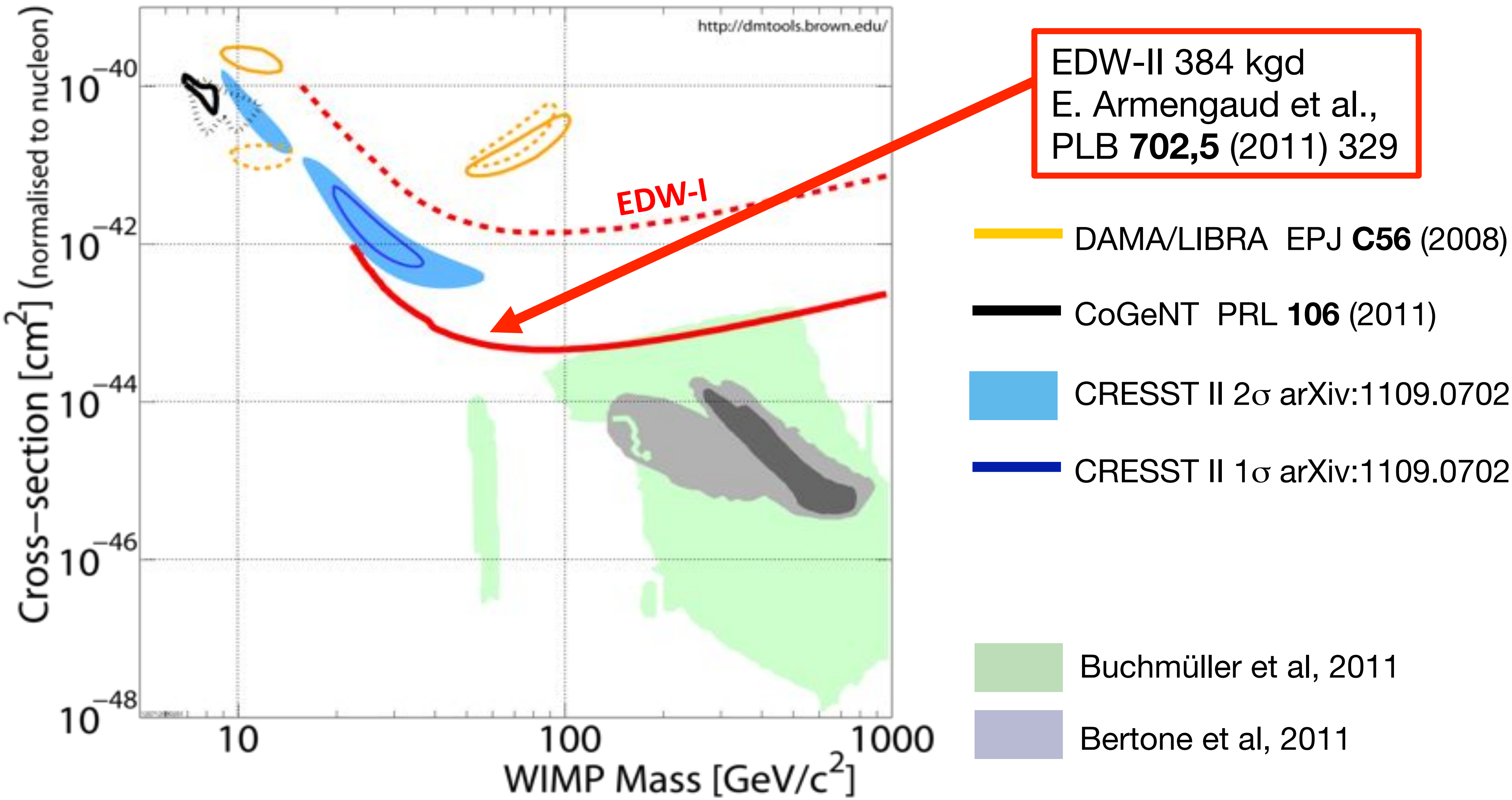
→ no indication for a WIMP signal

standard halo → $\sigma_{SI} < 4.4 \times 10^{-8}$ pb at 90%C.L. for $M_{WIMP} = 85$ GeV/c^2

(Courtesy K. Eitel, KIT)

EDW-II results in σ_χ vs. m_χ

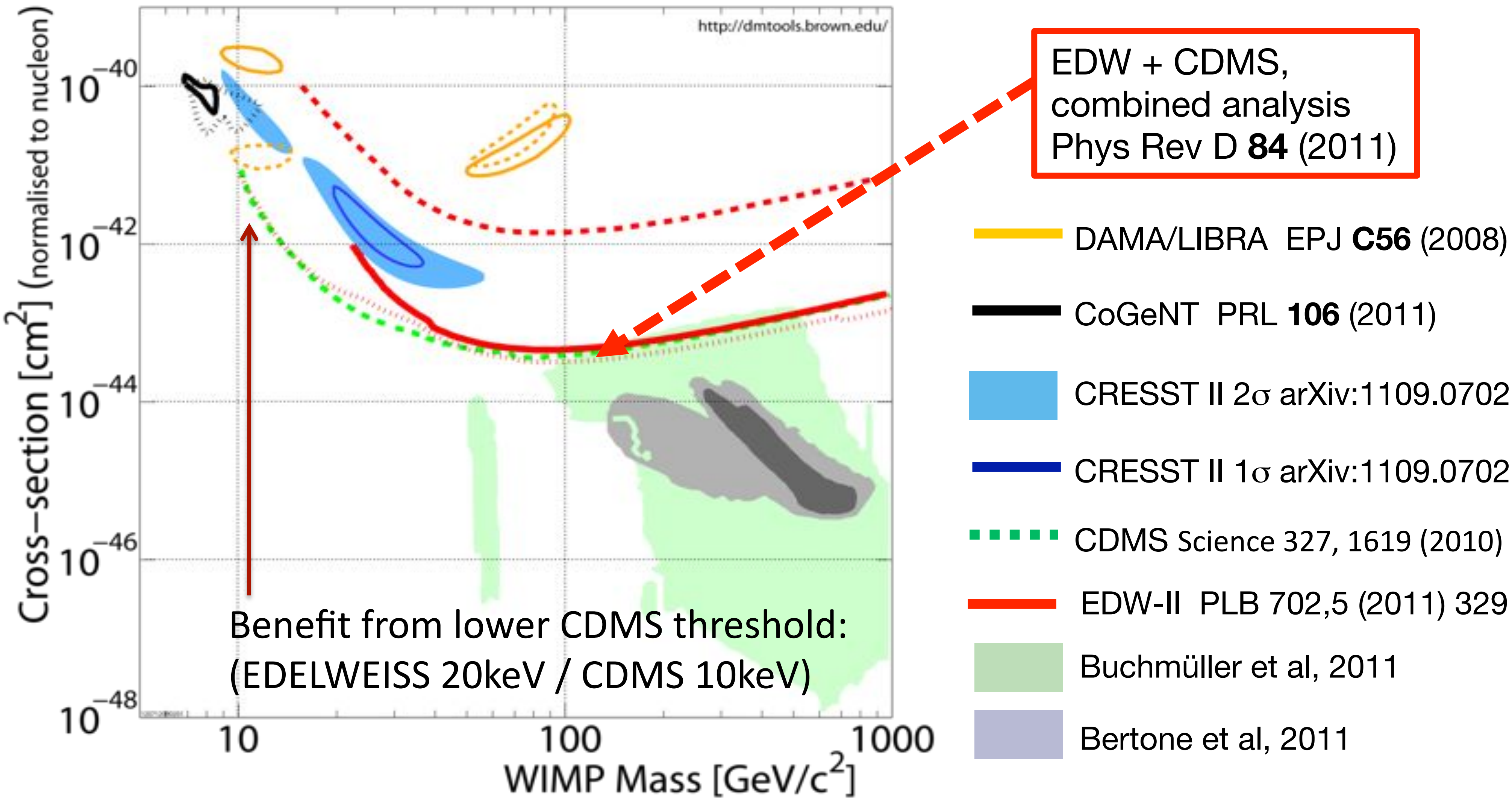
EDW (384kgd; [20-200keV], 5evts → $\sigma_{SI} < 4.4 \times 10^{-8}$ pb; $M_{WIMP} = 85$ GeV/c^2)
EDW-I → EDW-II **x20 improvement**



(Courtesy K. Eitel, KIT)

EDW-II & CDMS comb. in σ_χ vs. m_χ

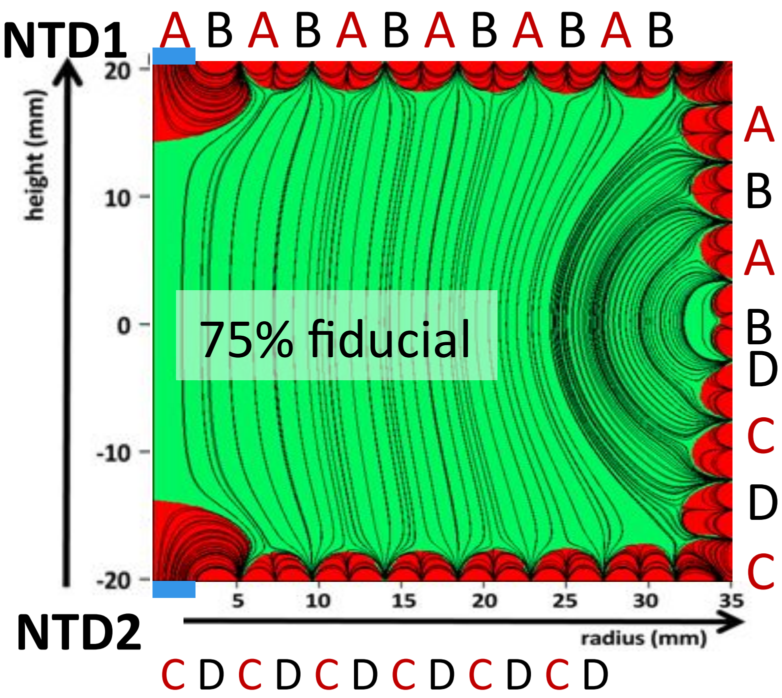
EDW (384kgd; [20-200keV], 5evts → σ_{SI} < 4.4 × 10^{-8} pb; M_{WIMP} = 85 GeV/c^2)
CDMS (~379kgd; [~10-100keV], 4 evts; σ_{SI} <3.8 × 10^{-8} pb; M_{WIMP} = 70 GeV/c^2)

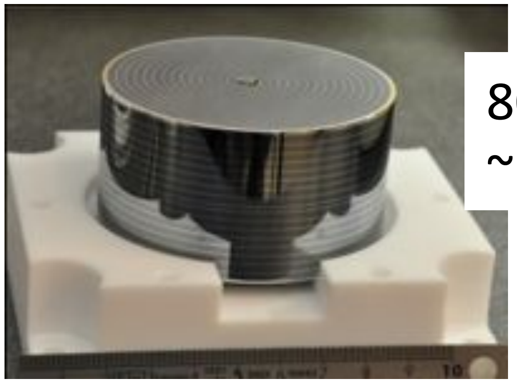


(Courtesy K. Eitel, KIT)

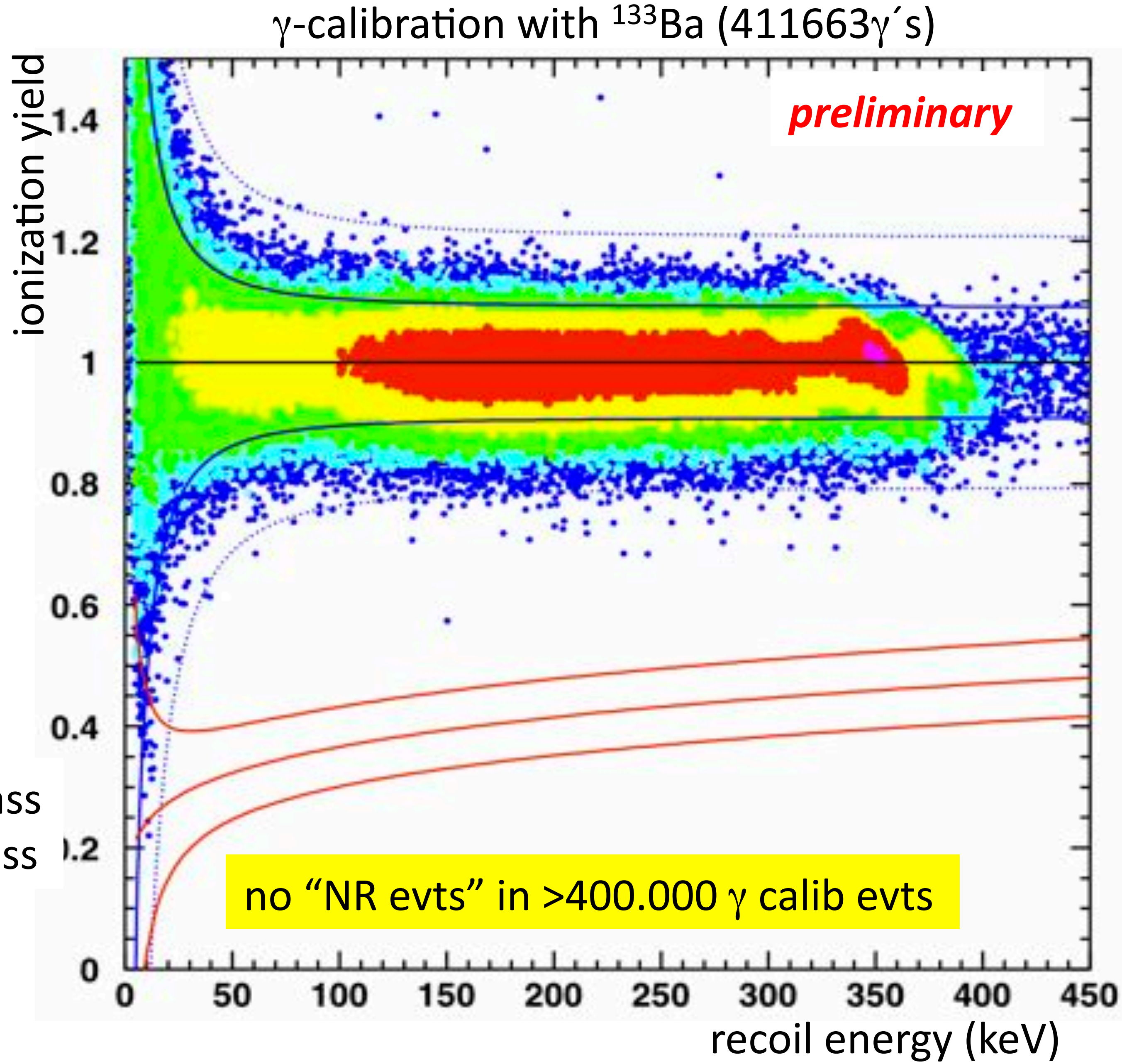
EDW-III: next generation of detectors

3. generation: FID detectors with rings on all surfaces



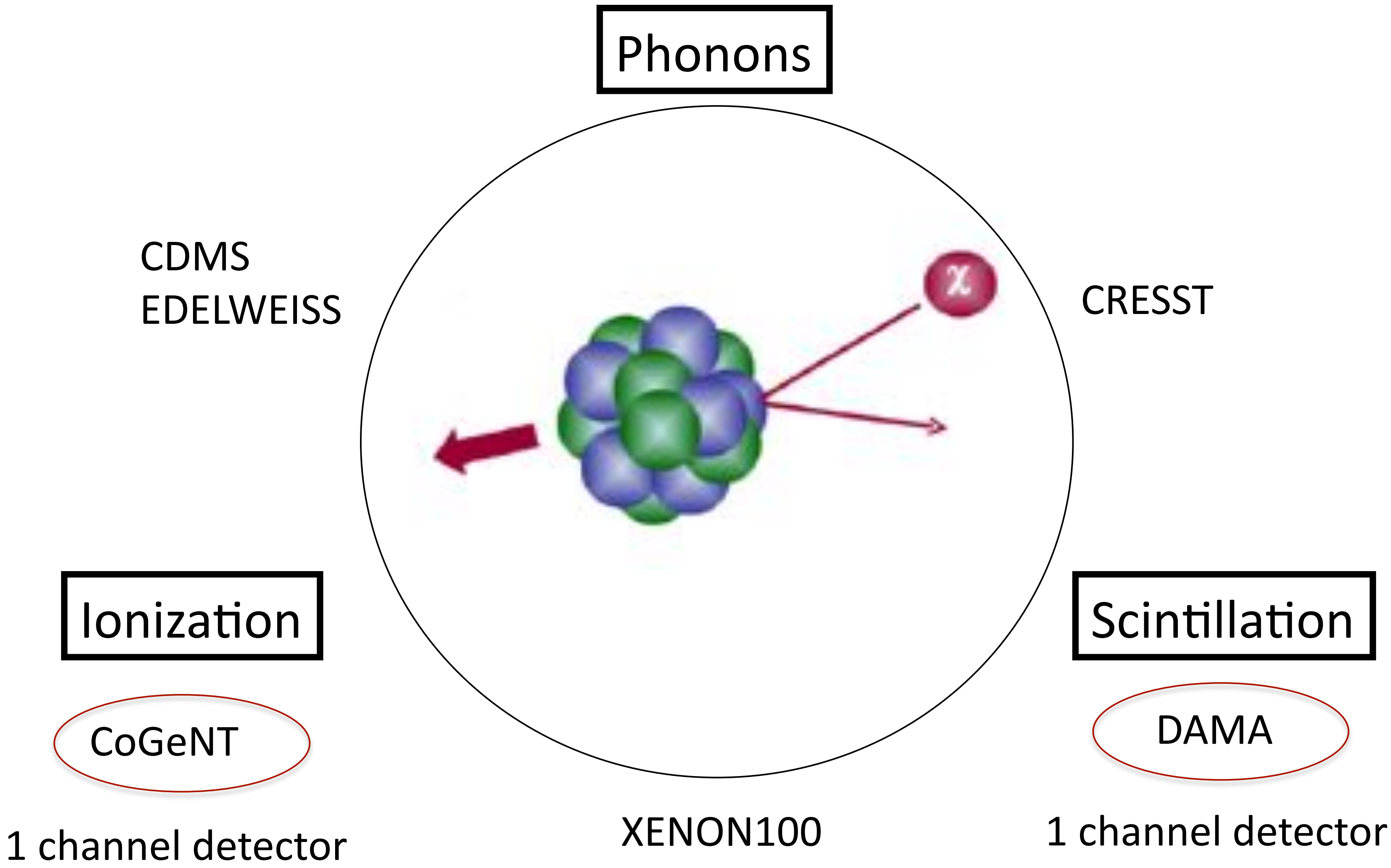


800g total mass
~600g fid. mass

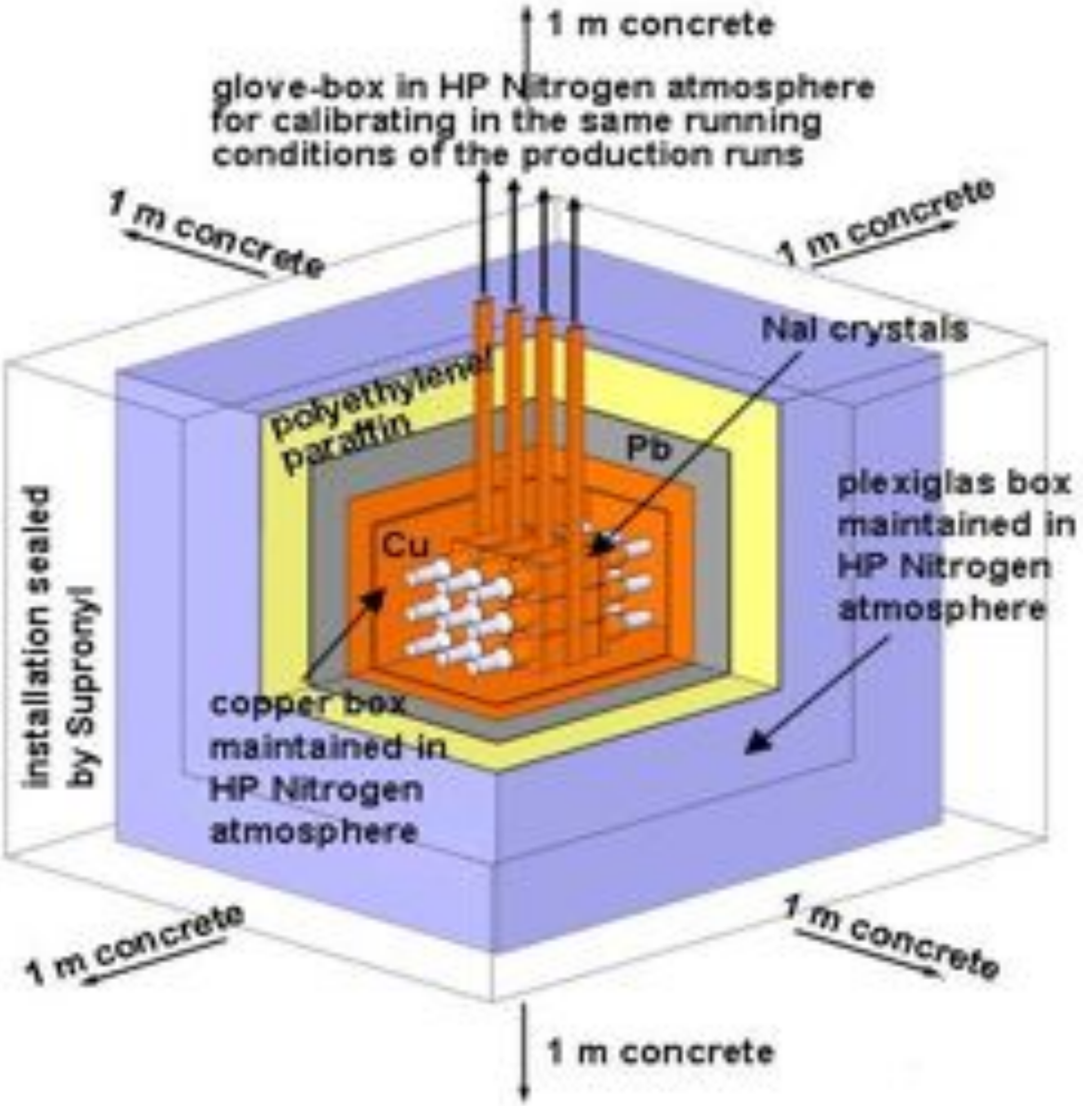


(Courtesy K. Eitel, KIT)

Recoil Detection & Background Identification



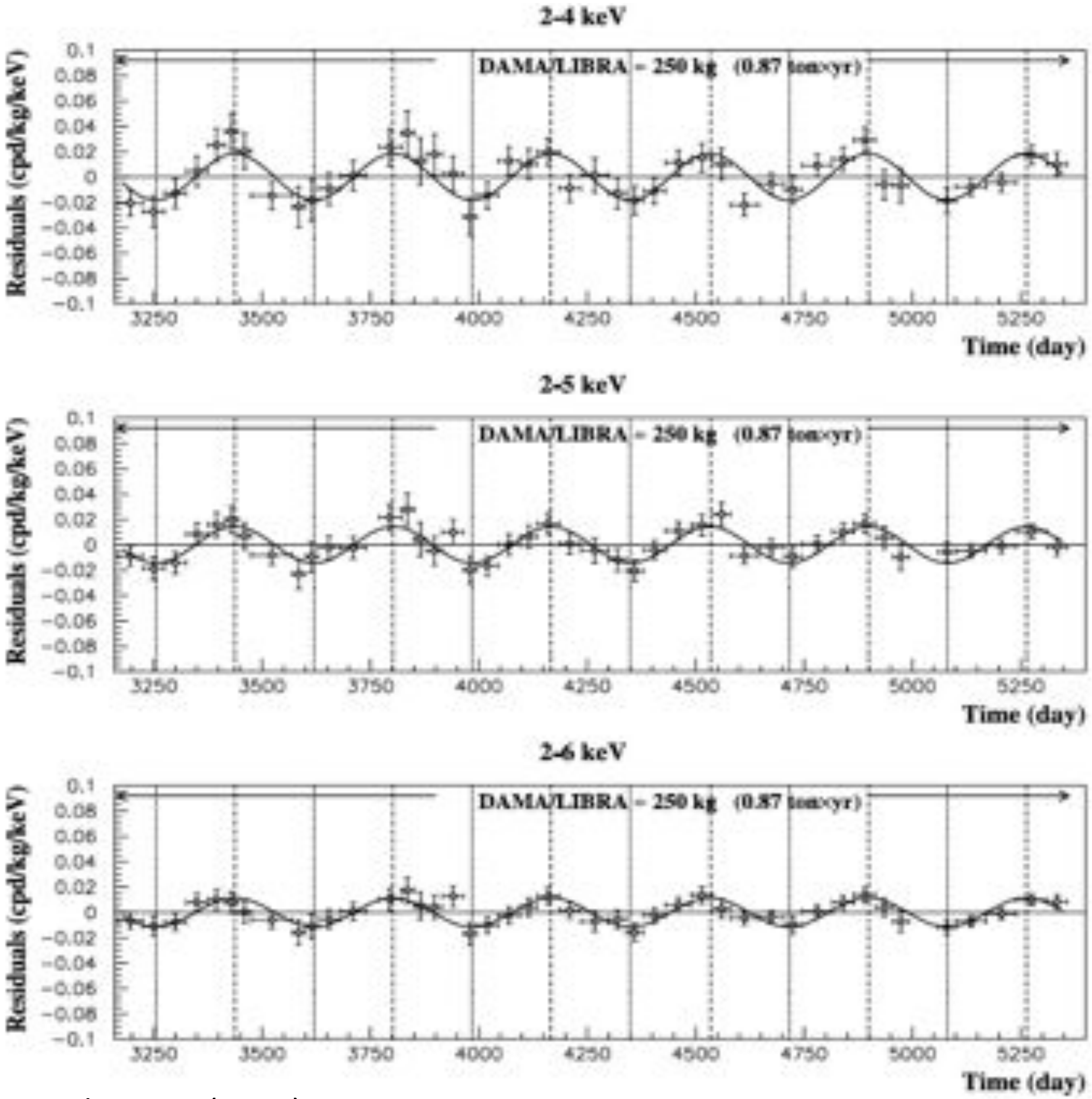
DAMA



Simplified schema of ~ 100 kg NaI(Tl) set-up

Location: Gran Sasso, Italy
Pure scintillation detector using NaJ(Tl)
Large target mass: ~250kg
Goal: measure DM induced modulation of signal over the year: max on June 2nd
Smallest December 2nd
Under standard halo assumptions: <7% effect

DAMA – Annual Modulation



EUR. Phys. J. C (2010) 67: 39-49

Cumulative exposure of DAMA/NaJ and DAMA/LIBRA: **1.17 ton years**

In total: **13 annual cycles**

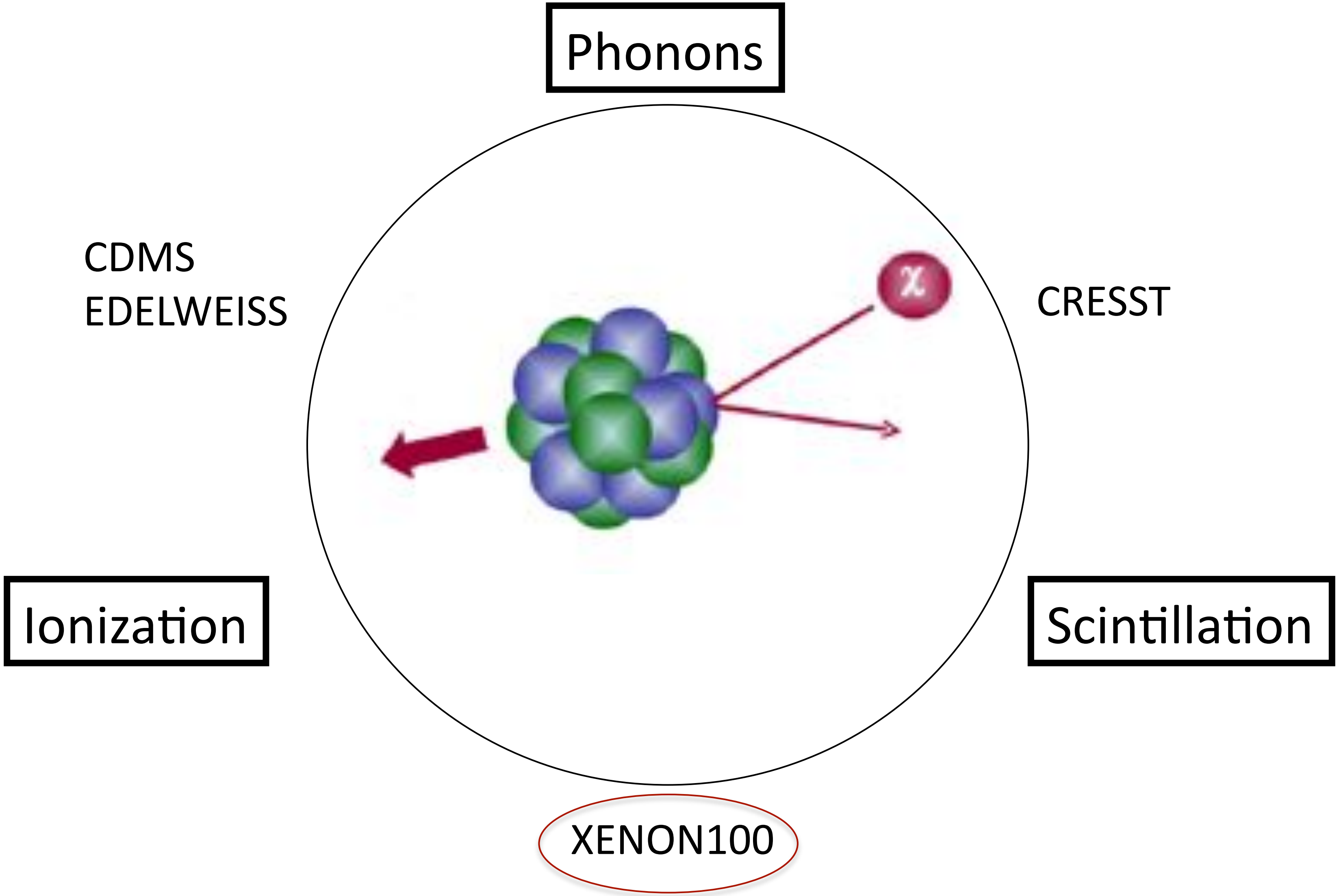
Modulation only present at low energies: **2-6keV**

Only single hits exhibit modulation

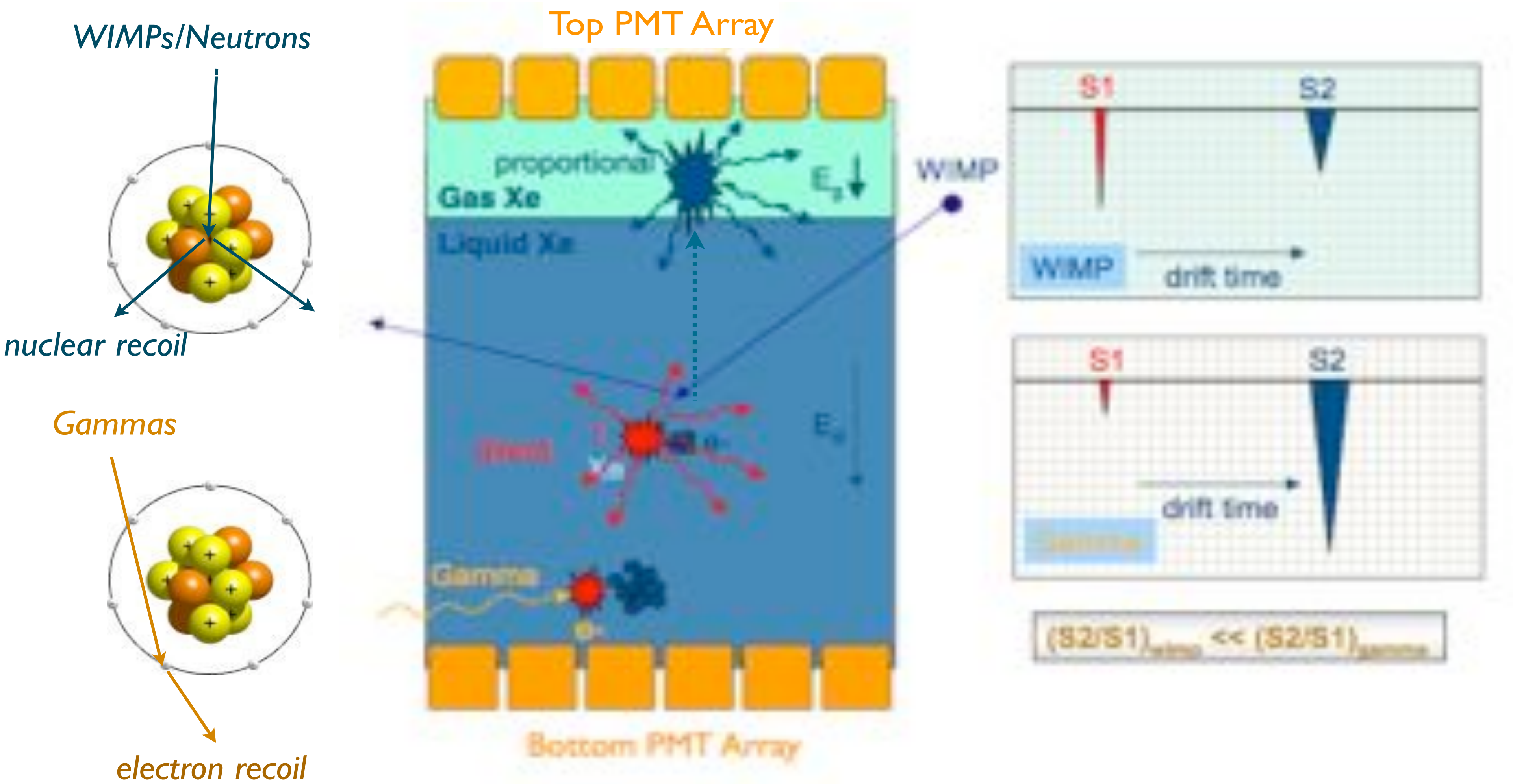
Phase of modulation within error margins agrees well with predictions:
- measured: **147+/-7 days**
- expected: **156.5 days**

DM annual modulation signature: confidence level **8.9σ**

Recoil Detection & Background Identification



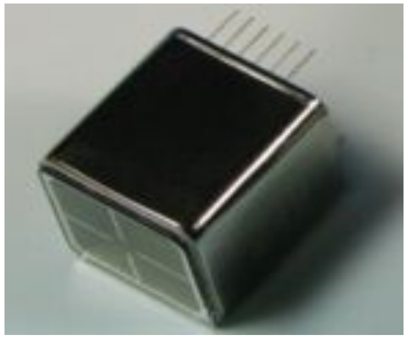
XENON Detector



- **Single electron and single photon measurement sensitivity**
- **> 99.5% ER rejection via Ionization/Scintillation ratio (S2/S1)**
- **3D event-by-event imaging with millimeter spatial resolution**

XENON100 Detector

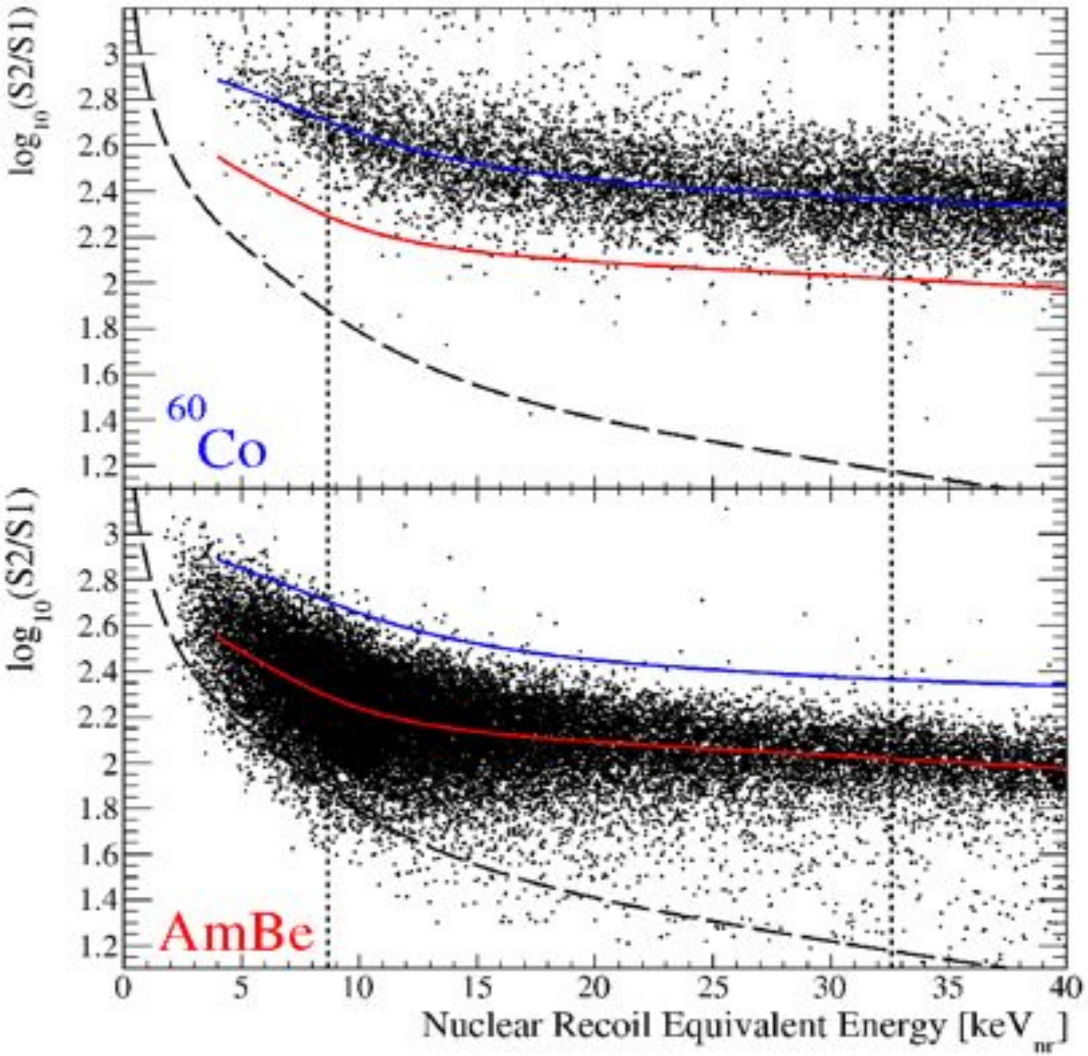
- 30 cm drift length and 30 cm ∅
- 161 kg total (30-50 kg fiducial volume)
- ~ 100x less background than XENON10
- Material screening and selection
- 242 low activity 1” PMTs (R8520)
- Cooling (PTR) outside the shield
- Active liquid xenon veto



1 inch PMTs

30 cm ∅ meshes

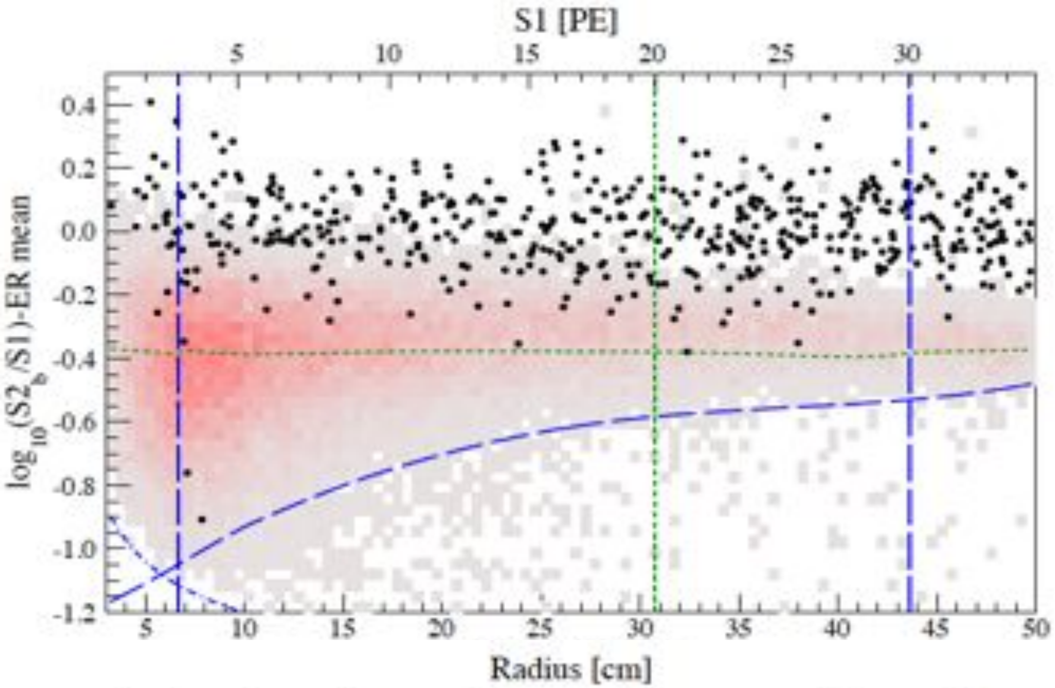
Event Discrimination



- Electronic recoil band: defined with ^{60}Co source
- Nuclear recoil band: defined with AmBe neutron source

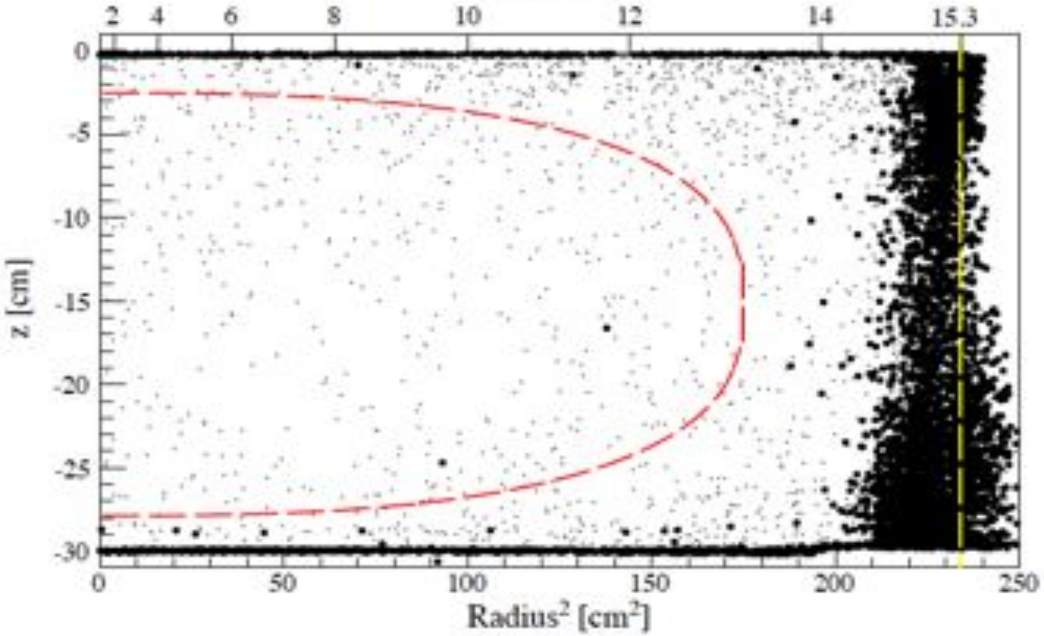
- Discrimination better than 99% @ 50% nuclear recoil acceptance

XENON100



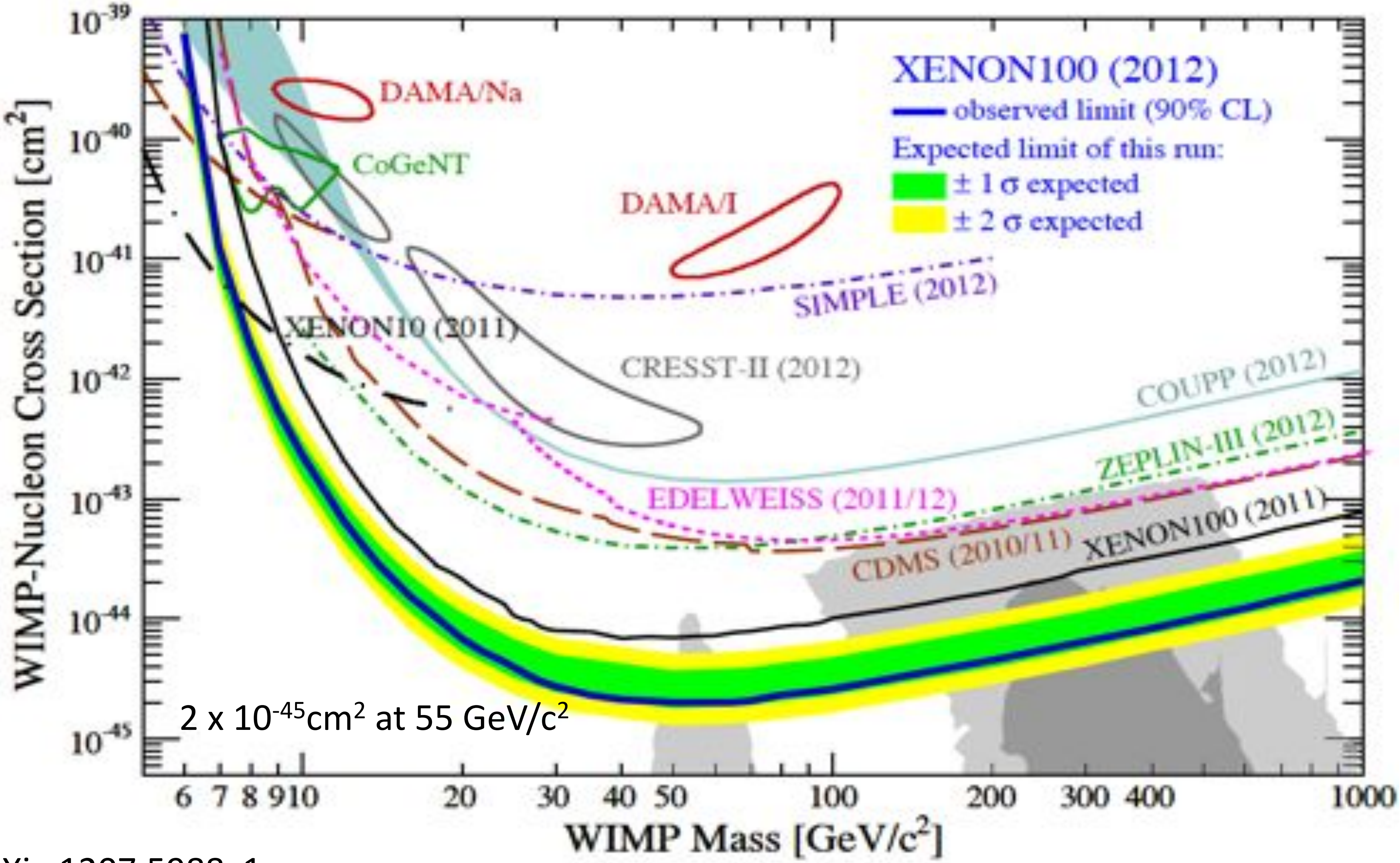
arXiv:1207.5988v1

• Total exposure: 224.6d x 34kg
• 2 events detected (after all cuts) in region of interest for WIMP search
• Expected background: 1.0 +/- 0.2 events
• 2 events still compatible with background



• spatial reconstruction of the 2 events
-> events contained in fiducial volume of the detector

XENON100



arXiv:1207.5988v1

Future Ton-Scale Dark Matter Detectors

~1 event/kg/day

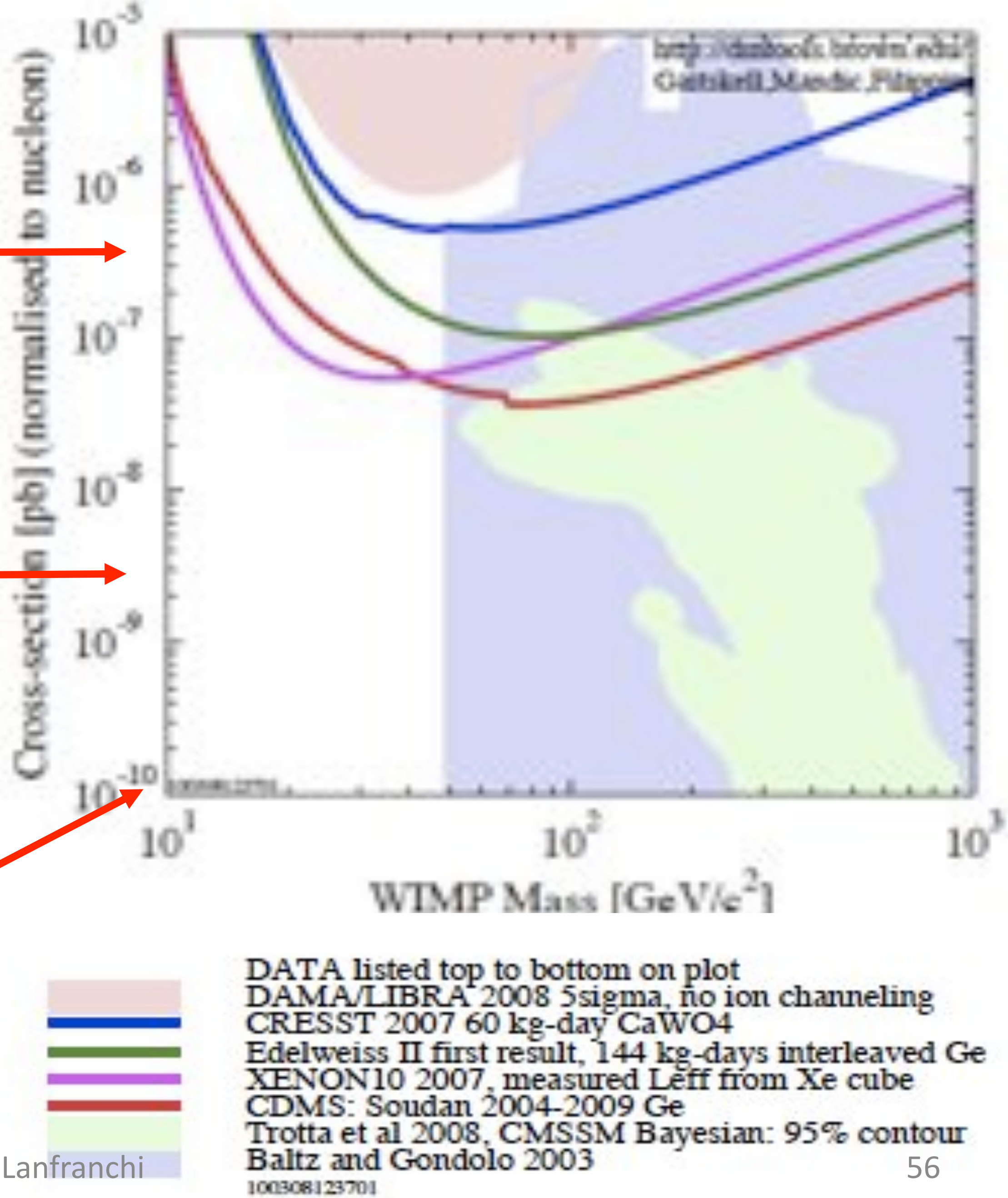
Reached

~3 events/kg/year

Present phase II experiments

~30 events/ton/year

Next generation requires further x100 improvement!



Conclusions

• Great progress has been made in the past few years in the field of direct Dark Matter detection

• Tension between different experiments exists at present

• Theorists and phenomenologists seek solutions for these tensions

• Ongoing searches will produce new results in the near future and new detector concepts on the ton-scale are underway aimed at clarifying the present situation

• Complementary information from indirect searches and accelerator experiments are required to draw a consistent picture in the end

• The understanding of Dark Matter is a great challenge for the next generation of scientists working in this field ...