Materia Oscura

NATALIA DI MARCO
LABORATORI NAZIONALI DEL GRAN SASSO
INFN

natalia.dimarco@lngs.infn.it

OUTLINE

- Dark Matter in Astrophysics and Cosmology
- Dark Matter candidates
- Dark Matter searches

    Present and Future

- Conclusions

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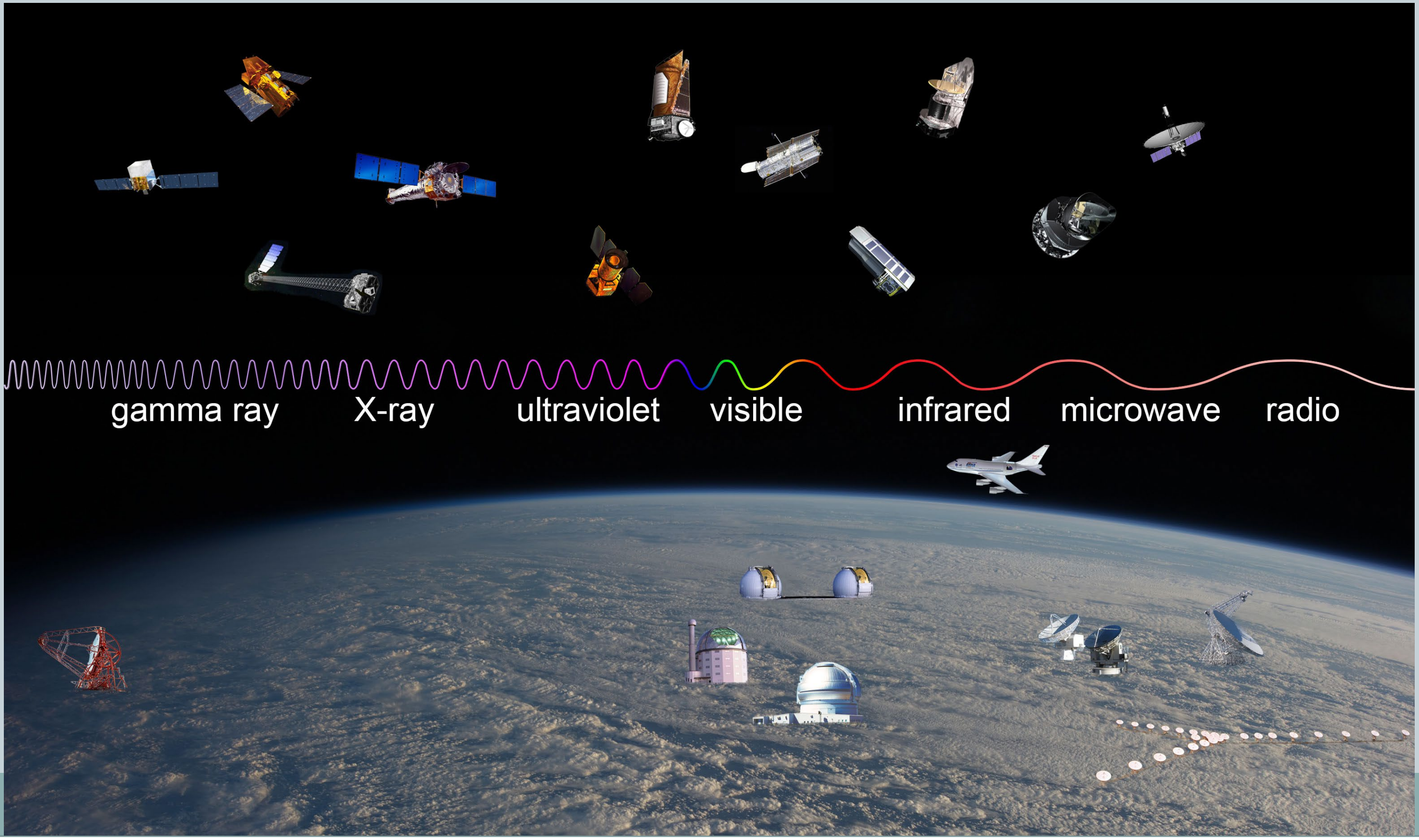
Evidence for Dark Matter

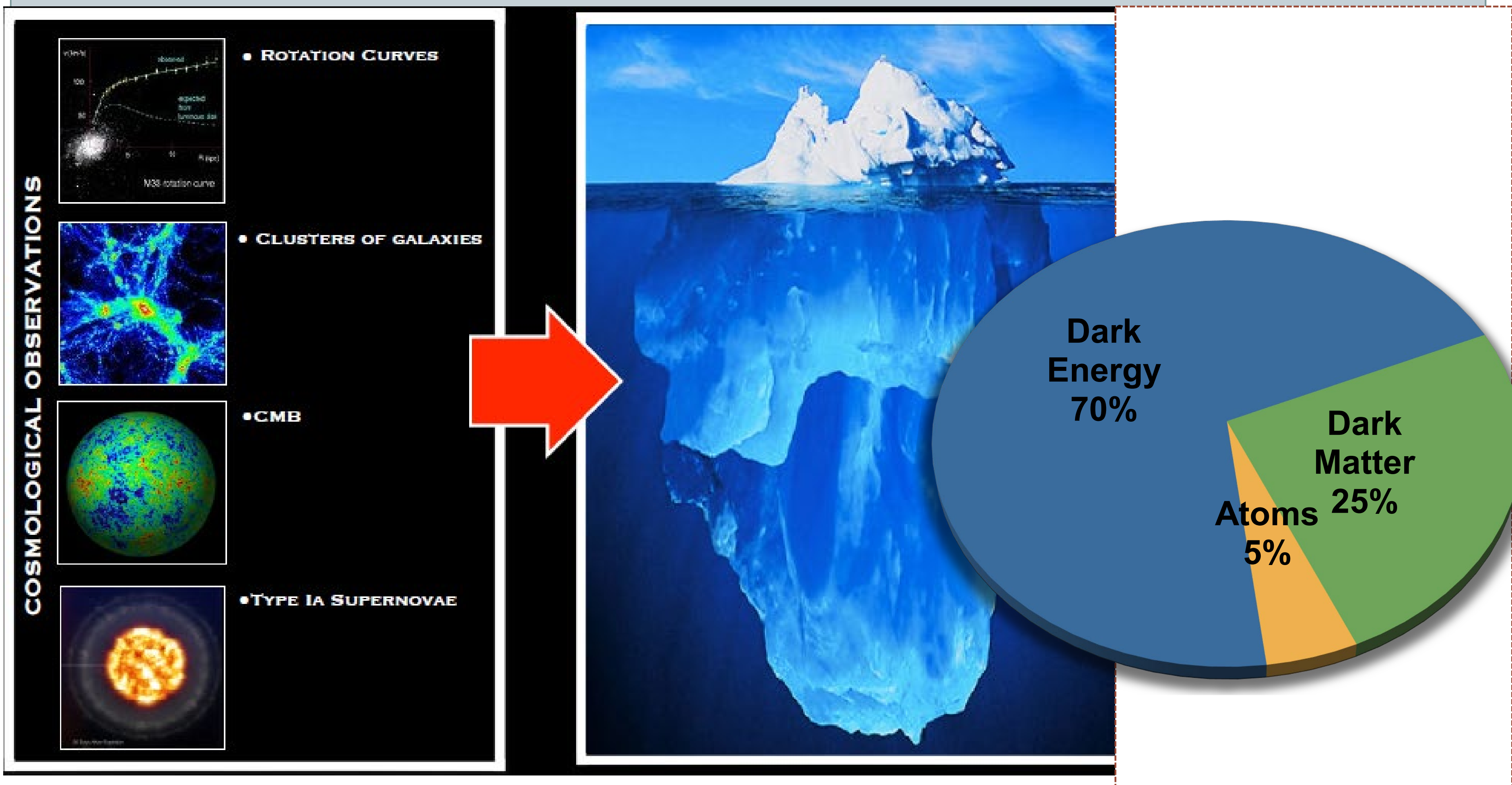
- With today's telescopes, we can observe the Milky Way (*and our Universe*) using light not only on the visible region, but in many different wavelengths

- **However, one of its major components - *the dark matter* - is not directly visible**



Evidence for Dark Matter

Evidence for the existence of an unseen, "*dark*", component in the energy density of the Universe comes from several independent observations at different length scales



History of Dark Matter

Jacobus Kapteyn: *First Attempt at a Theory of the Arrangement and Motion of the Sidereal System*, Astrophysical Journal, vol. 55, p.302 (1922)

Remark. Dark matter. It is important to note that what has here been determined is the total mass within a definite volume, divided by the number of luminous stars. I will call this mass the average effective mass of the stars. It has been possible to include the luminous stars completely owing to the assumption that at present we know the luminosity-curve over so large a part of its course that further extrapolation seems allowable.

Now suppose that in a volume of space containing l luminous stars there be dark matter with an aggregate mass equal to Kl average luminous stars; then, evidently the effective mass equals $(l+K)\times$average mass of a luminous star.

We therefore have the means of estimating the mass of dark matter in the universe. As matters stand at present it appears at once that this mass cannot be excessive. If it were otherwise, the average mass as derived from binary stars would have been very much lower than what has been found for the effective mass.

History of Dark Matter

Fritz Zwicky, On the masses of nebulae and of clusters of nebulae, The Atrophysical Journal 86 (1937):

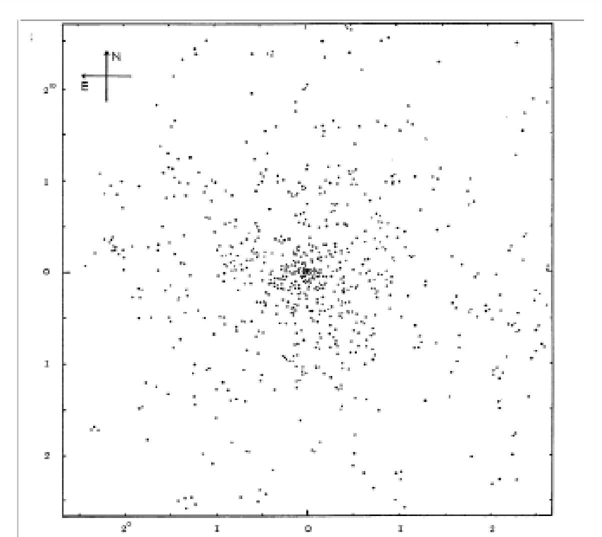
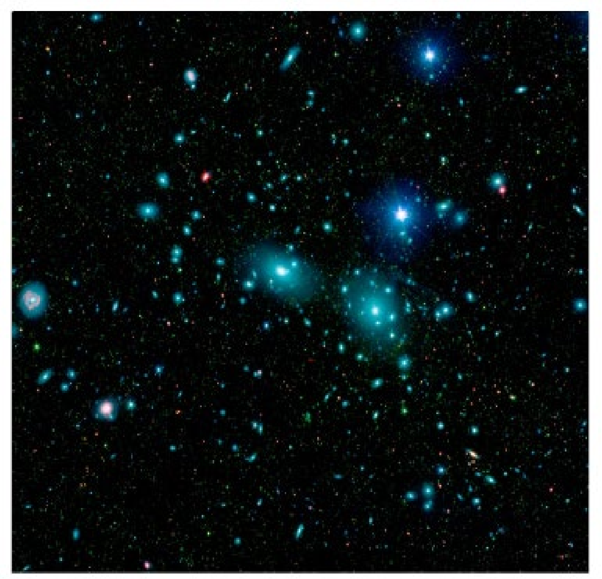
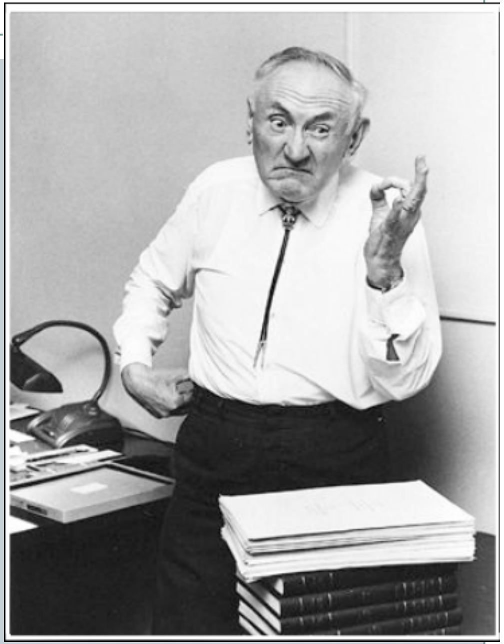


Fig. 3.—The Coma cluster of nebulae





*"If this would be confirmed we would get the surprising result that **dark matter** is present in <u>much greater amount than luminous matter</u>."*

History of Dark Matter

- **Smith 1936,** Mass of Virgo Cluster:

"It is possible that [mass estimates] are correct, and that the difference represents a great mass of intranebular material in the cluster" ApJ, vol. 83, p.23

- **Babcock 1939.** Rotation Curve of M31:

"The obvious interpretation of the nearly constant velocity for 30' outward is that a that a very great portion of the mass of the nebula must lie in the outer regions"

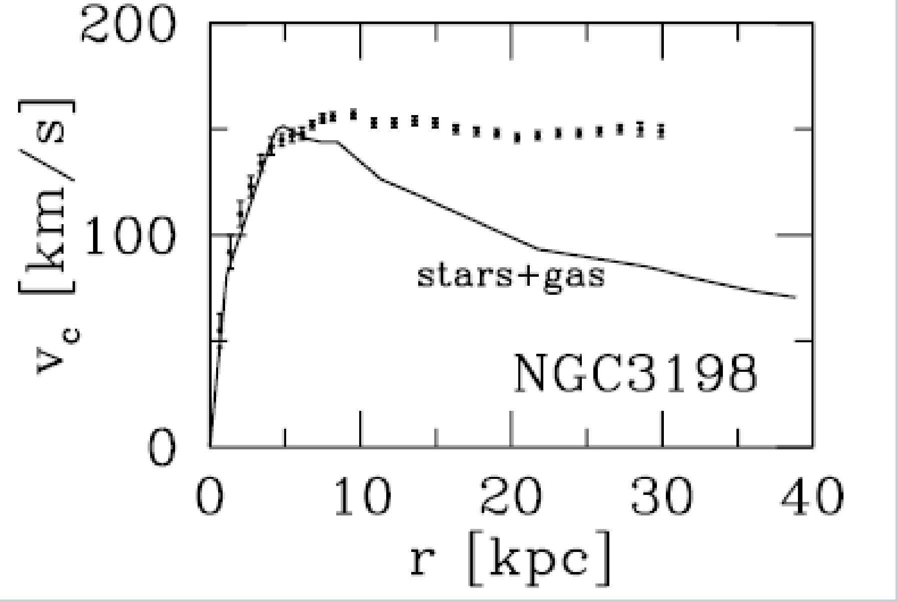
- **Kahn & Woltjer 1959.** Local Group, Mass of the M31-MW system:

"The Discrepancy seems to be well outside the observational errors"

- **Rotation Curves 1970**. Roberts, Bosma, Rubin, et al

Evidence for Dark Matter - 1

1970's: Rotation curves of galaxies



Vera Rubin

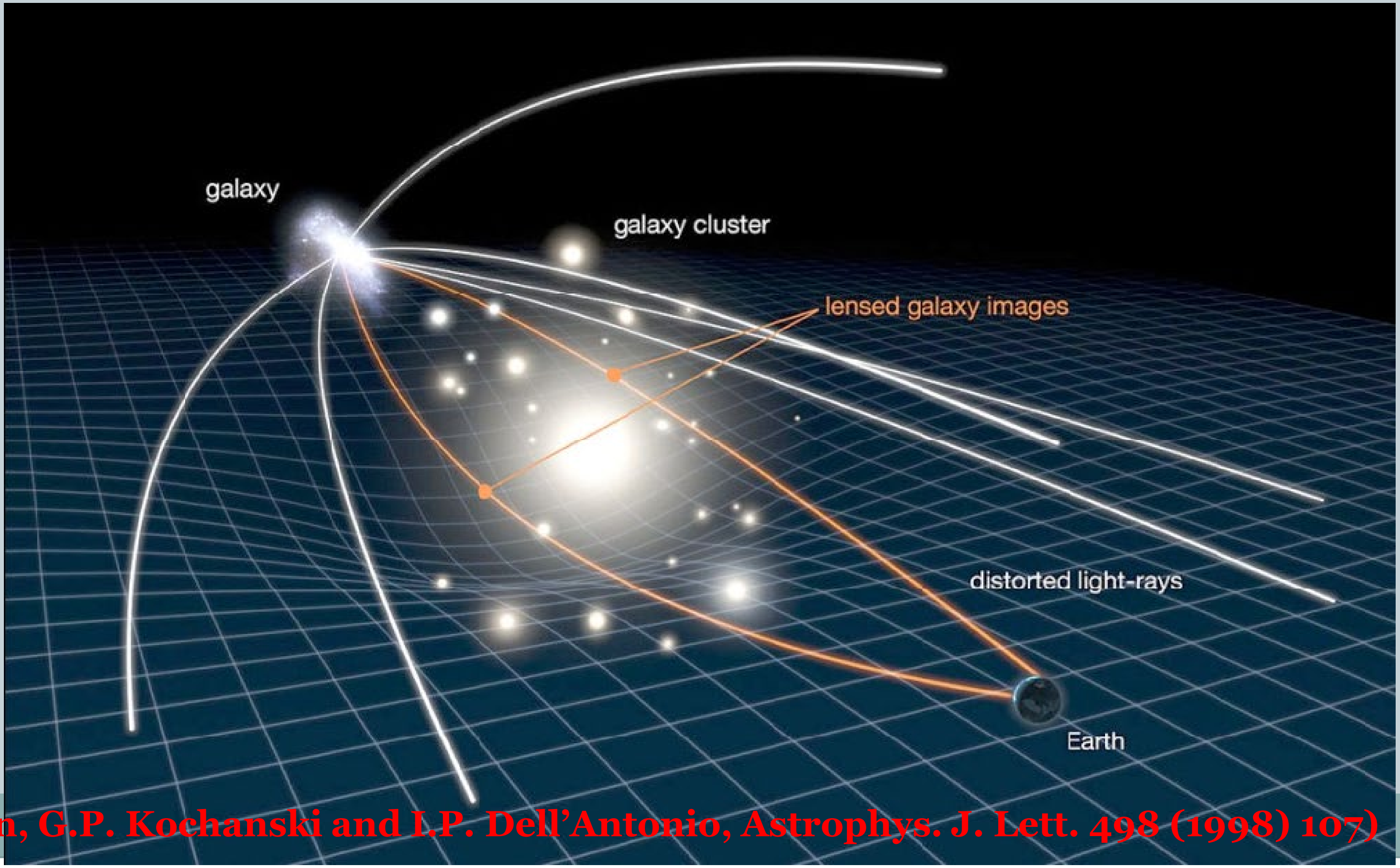
$$\frac{GMm}{r^2} = m\frac{v^2}{r} \Rightarrow v = \sqrt{\frac{GM(r)}{r}}$$

$$v = const. \Rightarrow M(r) \sim r$$

This implies the existence of a **dark halo**, with mass density $\rho(r) \propto 1/r^2$

Evidence for Dark Matter - 2

Gravitational Lensing: Following **Einstein's theory of general relativity**, light propagates along geodesics which deviate from straight lines when passing near intense gravitational fields. The **distortion** of the images of background objects due to the gravitational mass of a cluster can be used to infer the **shape of the potential well** and thus the **mass of the cluster**



(J.A. Tyson, G.P. Kochanski and I.P. Dell'Antonio, Astrophys. J. Lett. 498 (1998) 107)

Evidence for Dark Matter - 2

The mass of a cluster can be determined via several methods, including application of the virial theorem to the observed distribution of **radial velocities**, by **weak gravitational lensing**, and by studying the profile of **X-ray emission** that traces the distribution of hot emitting gas in rich clusters.

Galaxy Cluster Abell 2218 **HST • WFPC2**
NASA, A. Fruchter and the ERO Team (STScI) • STScI-PRC00-08

Total mass: 10^{14} to 10^{15} $M_\odot$

Gas fraction: ~16%
(~ 13% ICM, ~ 3% galaxies)

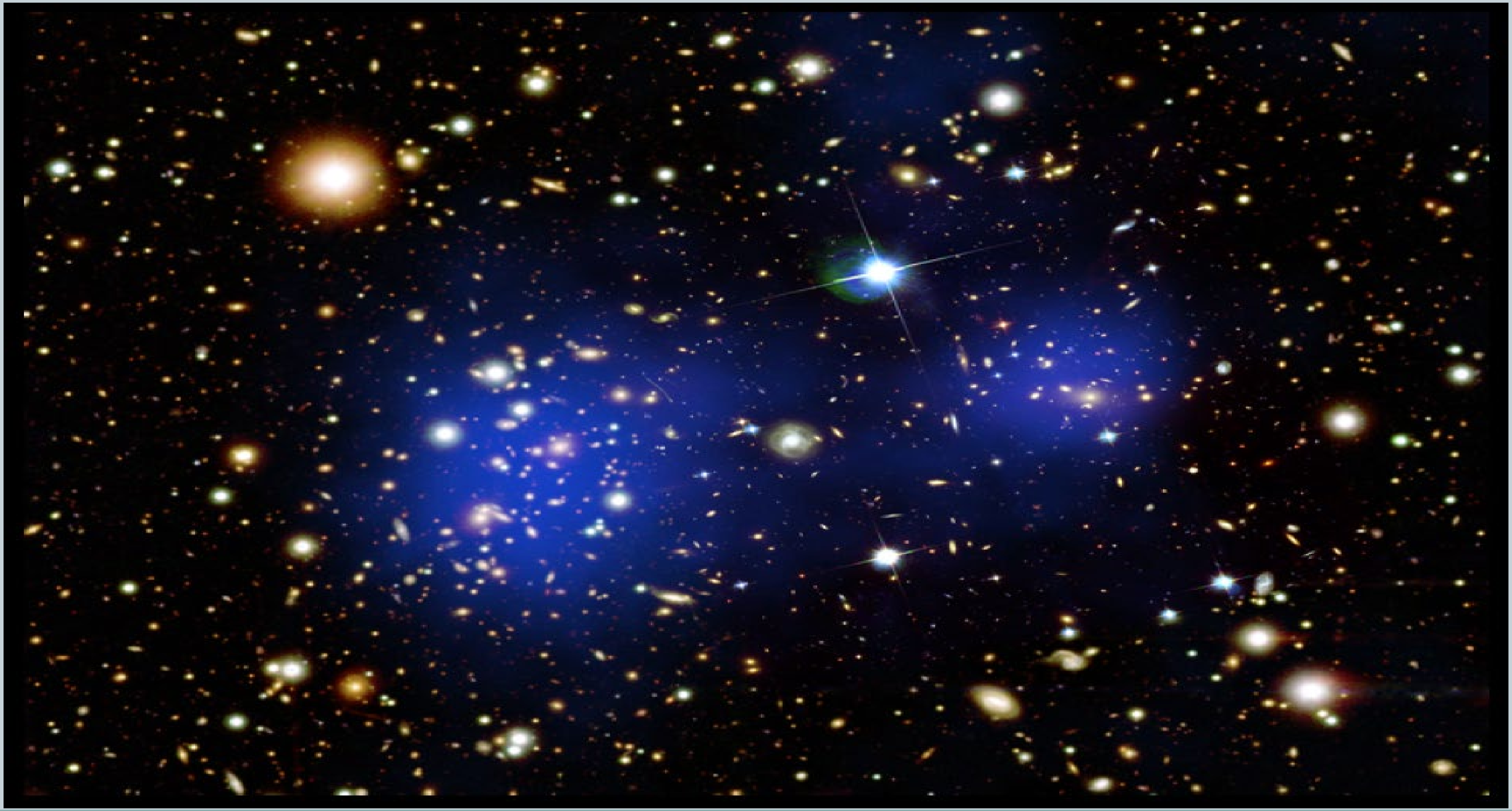
Remaining **84%** of the mass is in dark matter

Evidence for Dark Matter - 3

Bullet Cluster (1E0657-558)

Evidence for Dark Matter - 3

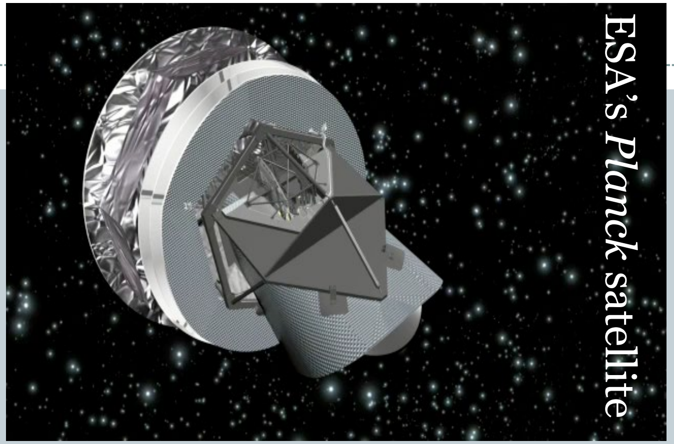
Blue: 2 clusters of galxies



Evidence for Dark Matter - 3

Blue: 2 clusters of galxies Red: X-ray emission from hot gas

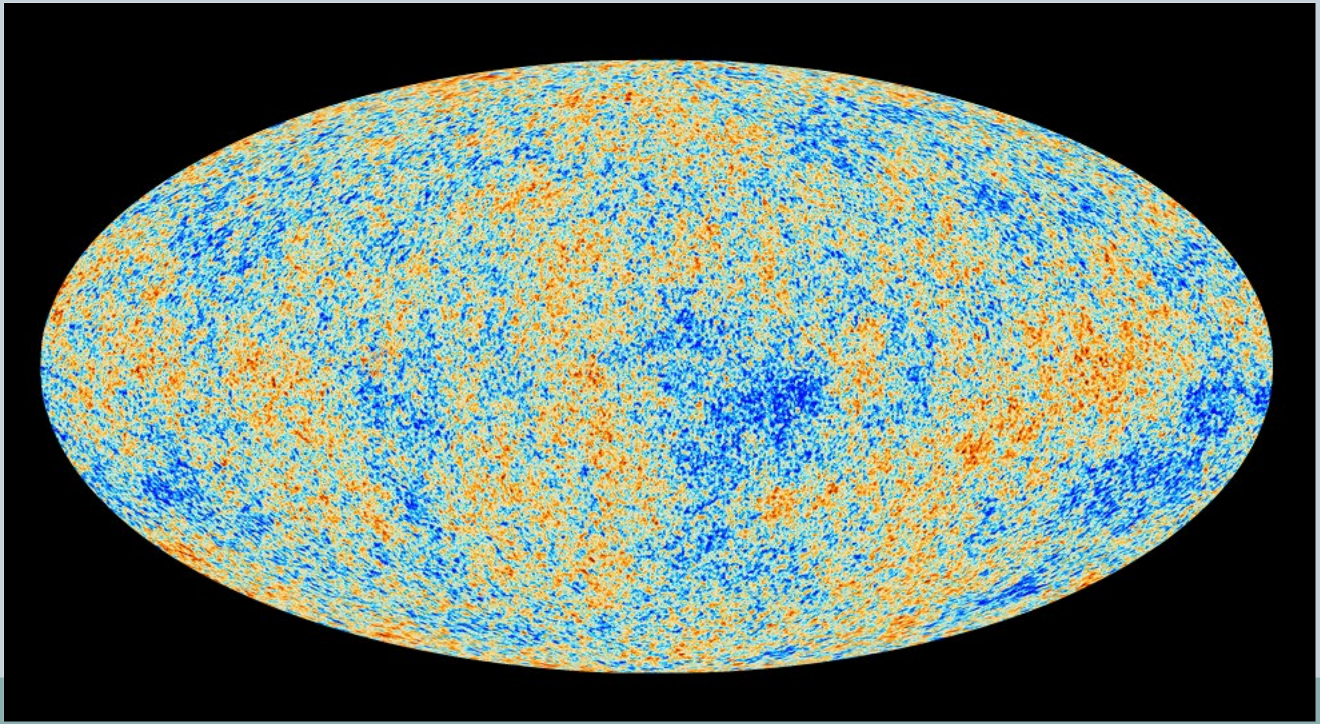
Evidence for Dark Matter - 4



Cosmic Microwawe Background:

$\Omega_{nbm}h^2 = 0.1186 \pm 0.0020$

$\Omega_b h^2 = 0.02226 \pm 0.00023$

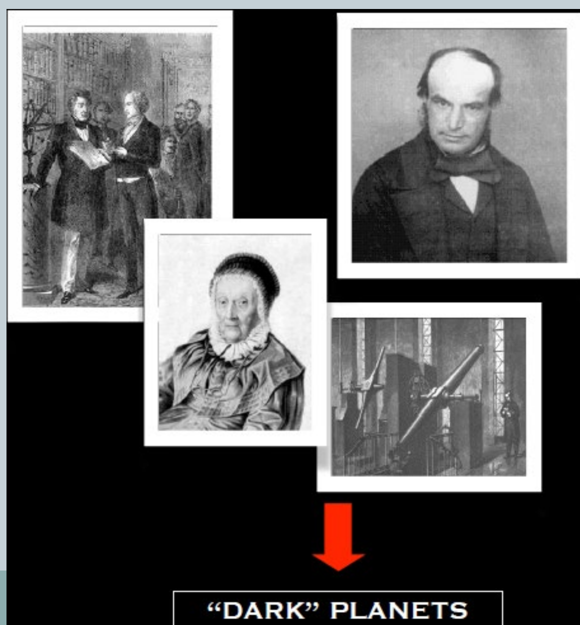


New Matter or New Physics?

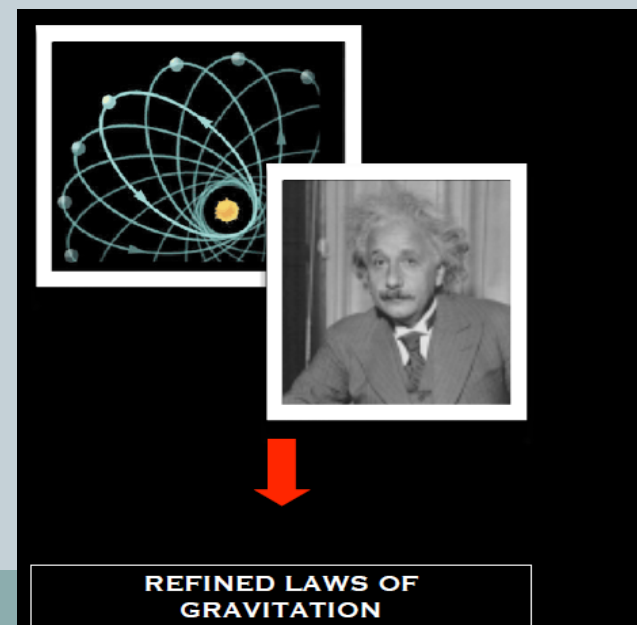
All these arguments rely on Einsteinian, or Newtonian, gravity.

Should such anomalies be regarded as a *refutation of the laws of gravitation* or as an indication of the *existence of unseen dark objects*?

Uranus, Neptune



Mercury



New Matter or New Physics?

Modified Newtonian Dynamics (**MOND**) allows to reproduce many observations on galactic scales, in particular galactic rotation curves, without introducing DM.

However, **MOND is a purely non–relativistic theory**. Attempts to embed it into a relativistic field theory require the existence of additional fields (e.g. a vector field or a second metric), and introduce considerably arbitrariness.

Moreover, the correct description of **large–scale structure formation seems to require some sort of DM** even in these theories.

In contrast, **successful models of particle DM** can be described in the well established language of **quantum field theory**, and do not need any modification of **General Relativity**.

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- Dark Matter candidates
- Dark Matter searches

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Dark Matter candidates

Candidates for non-baryonic DM must satisfy several conditions:

1. they must be **stable** on cosmological time scales (otherwise they would have decayed by now),
2. they must **interact very weakly** with electromagnetic radiation (otherwise they wouldn't qualify as dark matter),
3. they must have the **right relic density**.

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3. they must have the **right relic density**.

Candidates include:

- Primordial black holes
- Axions
- Sterile neutrinos
- Weakly Interacting Massive Particles (WIMPs).

Dark Matter candidates

Supersymmetric dark matter

Neutralinos (the most fashionable/studied WIMP)
Sneutrinos (also WIMPs)
Gravitinos (SuperWIMPs)
Axinos (SuperWIMPs)

WIMP = Weakly Interacting Massive Particle
M~ GeV→TeV
$\sigma = O(\sigma_{weak})$

Dark Matter candidates

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"It doesn't matter how beautiful your theory is,
it doesn't matter how smart you are.
If it doesn't agree with experiment,
it's wrong"

Richard P. Feynman

OUTLINE

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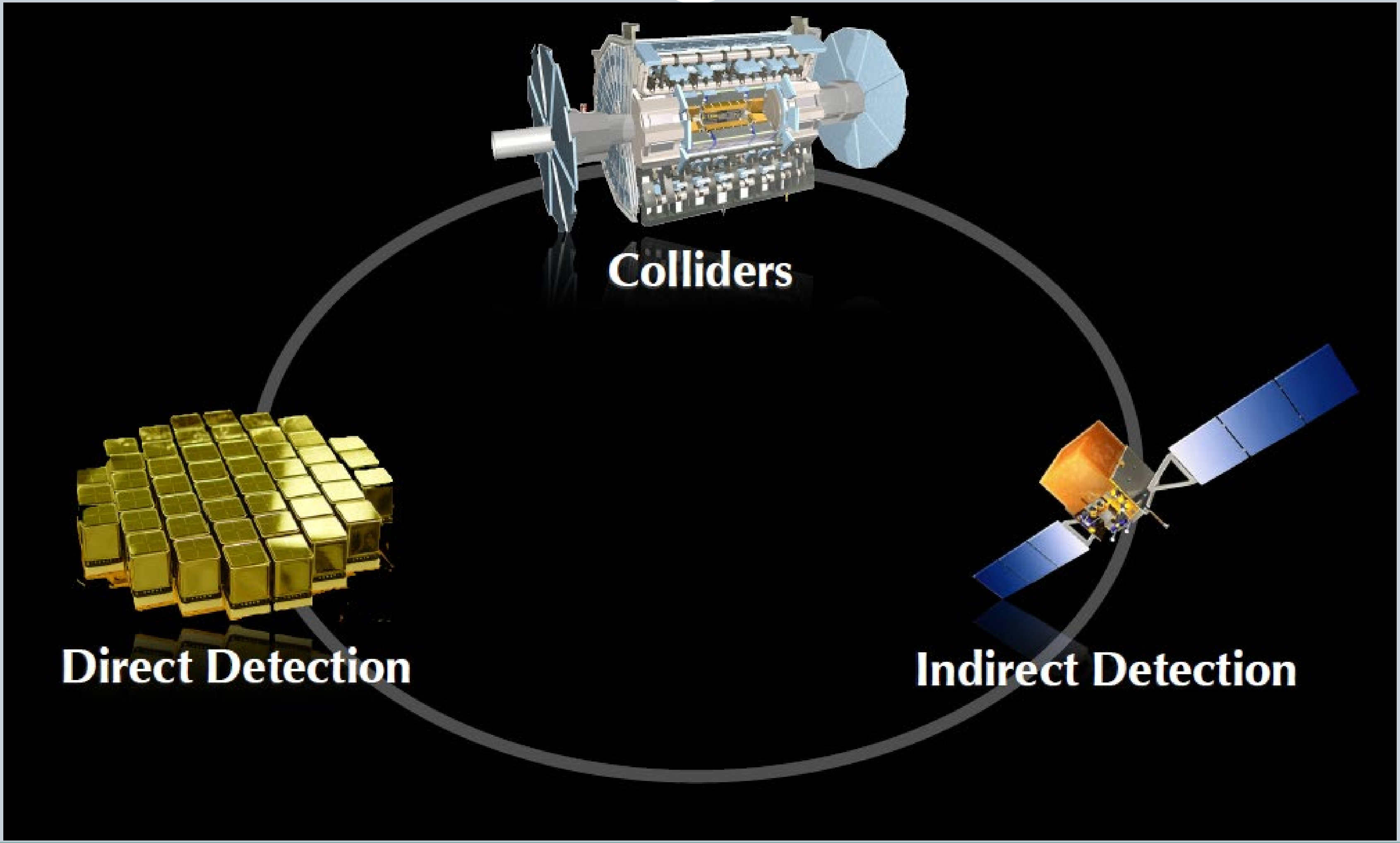
Dark Matter Searches

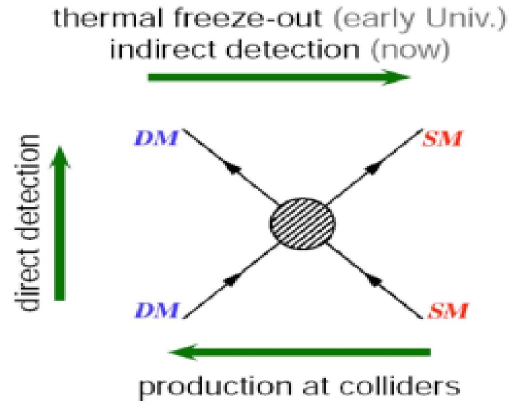


Dark Matter Searches

Graciela Gelmini-UCLA

WIMP DM searches:

- Direct Detection- looks for energy deposited within a detector by the DM particles in the Dark Halo of the Milky Way. Could detect even a very subdominant WIMP component. (Caveat: the DM interaction might be too weak to detect)



- Indirect Detection- looks for WIMP annihilation (or decay) products. (Caveat: the DM may not annihilate)

- At colliders as missing transverse energy, mono-jet or mono-photon events (Caveat: the DM mass may be above 2 TeV or its signature hidden by backgrounds)

All three are independent and complementary to each other!

Even if the Large Hadron Collider finds a DM candidate, in order to prove that it is the DM we will need to find it where the DM is, in the haloes of our and other galaxies.

Dark Matter Searches - Indirect searches

Gamma-ray telescopes

- ACTs: HESS, MAGIC, VERITAS, (CTA)
- Space satellite FERMI LAT
- Future: CTA (Gamma400?, DAMPE?)

Neutrino Telescopes

- Amanda, IceCube
- Antares, Nemo, Nestor
- Km3Net

Anti-matter Satellites

- PAMELA
- AMS-02
- Future: Herd?

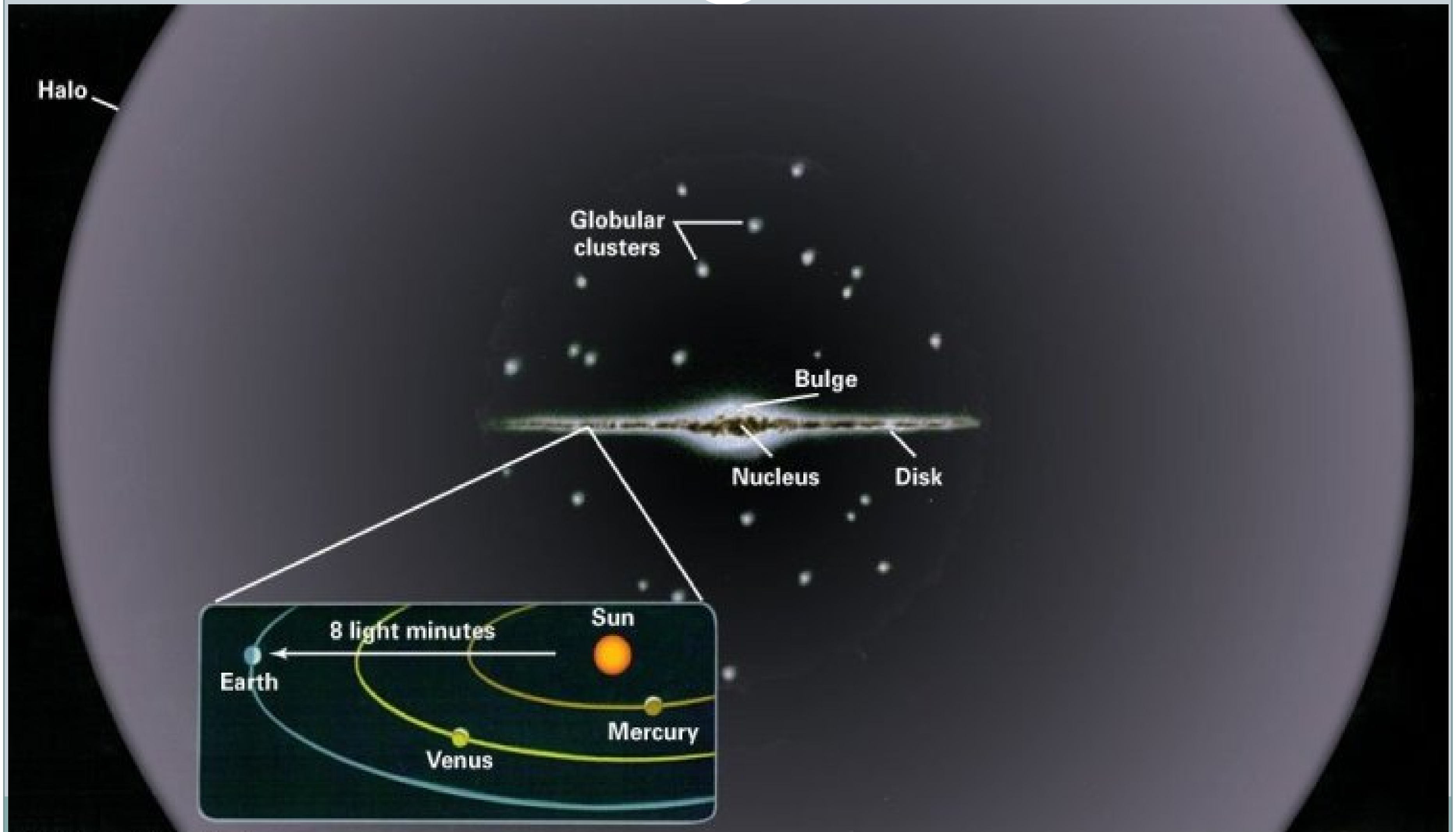
Other

- Synchrotron Emission
- SZ effect
- Effect on Stars
- X-ray telescopes
- Axion searches (recent 'discovery'…)

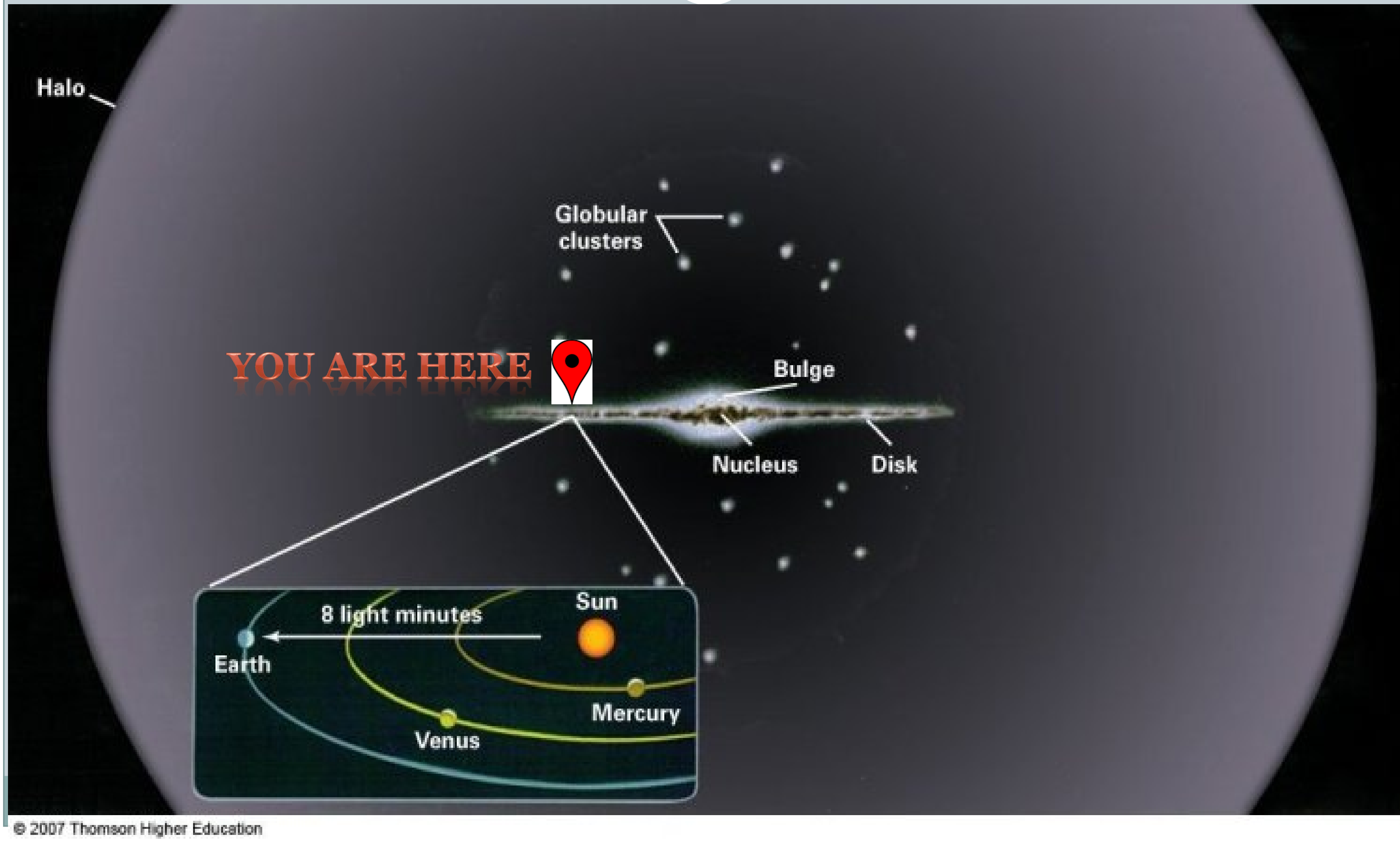
Direct Searches : Ingredients

- Dark Halo Model
- Detection Pricinple
- Recoil Rate
- Signature
- Backgroud
- Methods

Direct Searches – 1: Dark Halo Model



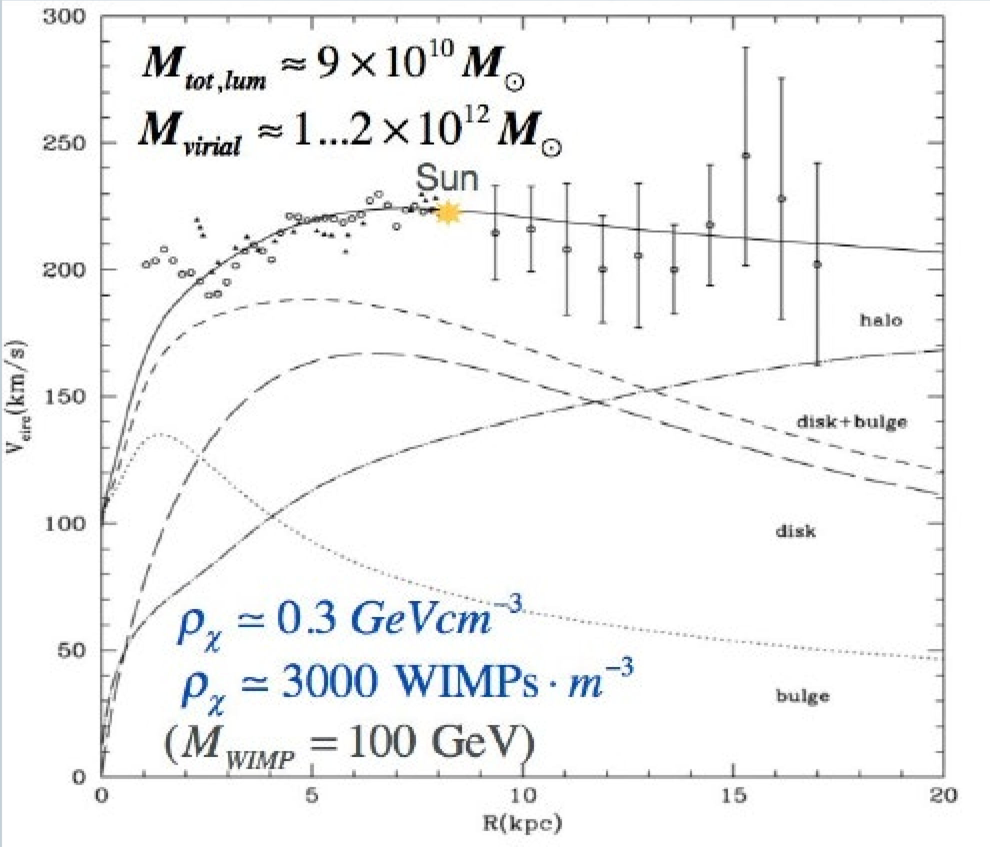
Direct Searches – 1: Dark Halo Model



Direct Searches – 1: Dark Halo Model

Milky Way's Dark Halo

10^{10}(GeV/$m\chi$) WIMP's passing through us per cm^2 per second!

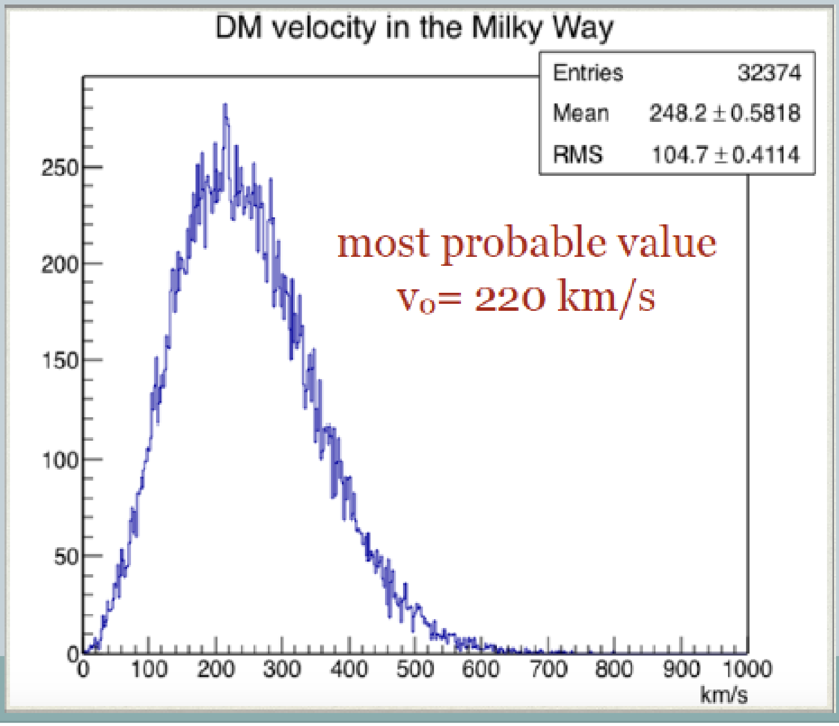


L.Baudis; Klypin, Zhao and Somerville 2002

Direct Searches – 1: Dark Halo Model

Standard Halo Model: isotropic isothermal sphere of collisionless particles with density profile $\rho(r) \sim 1/r^2$ and Maxwellian velocity distribution:

$$f_{\rm gal}(\mathbf{v}) = \begin{cases} \frac{1}{N_{\rm esc}(2\pi\sigma_v^2)^{3/2}} \exp\left[-\frac{\mathbf{v}^2}{2\sigma_v^2}\right] & \text{if } |\mathbf{v}| < v_{\rm esc}\,, \\ 0 & \text{if } |\mathbf{v}| \geq v_{\rm esc}\,, \end{cases}$$

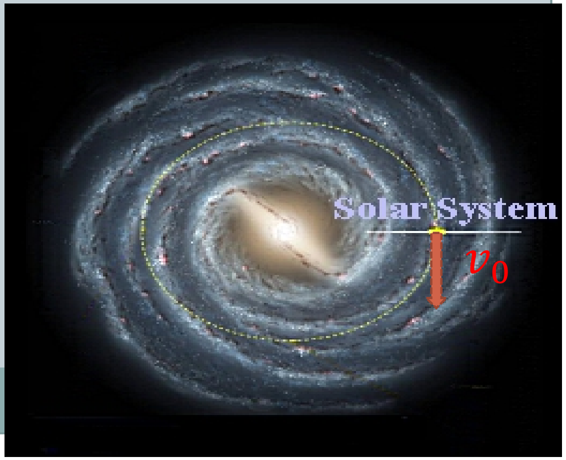


v_{esc}=544 km/s

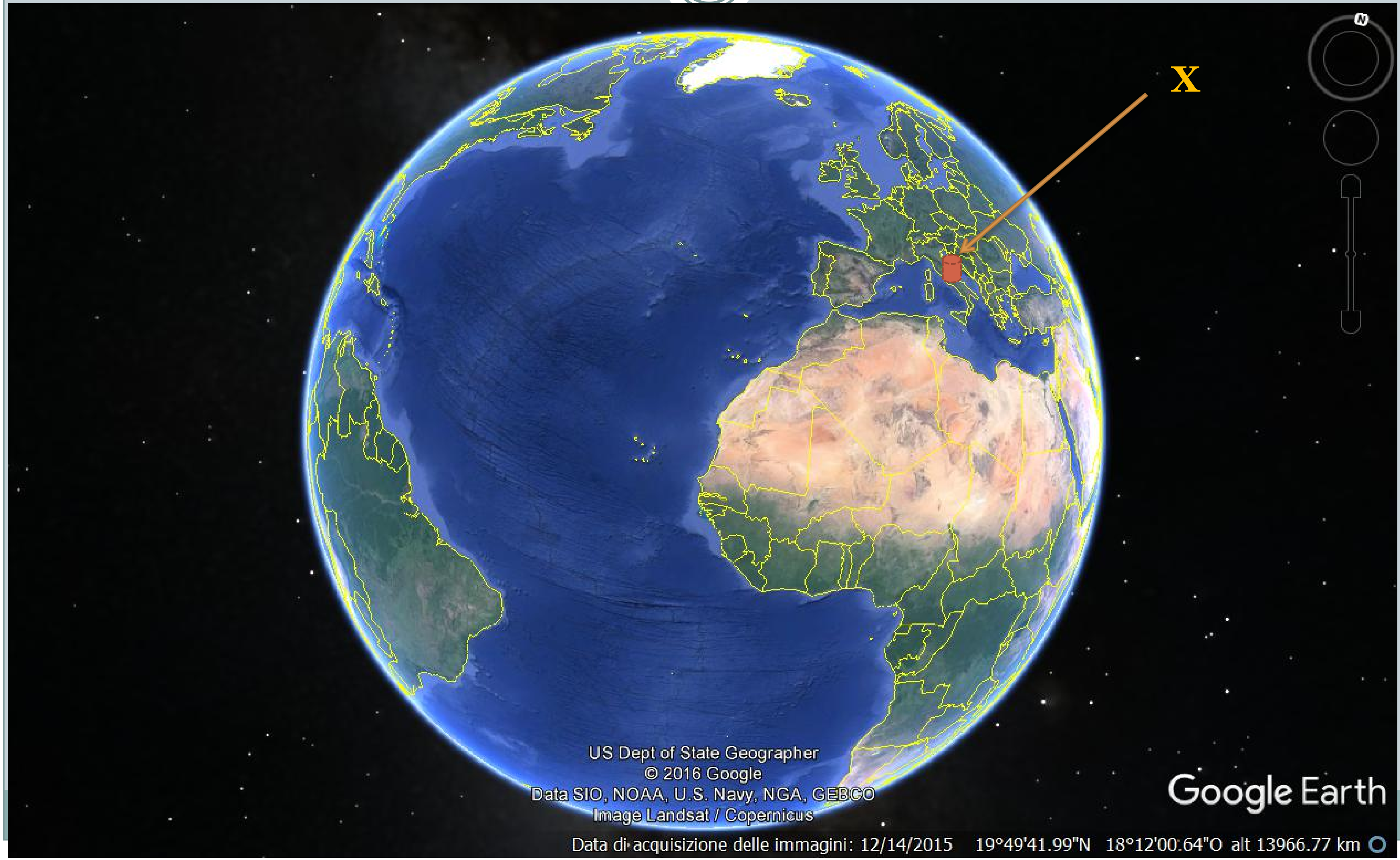
v_0=220 km/s

σ=$\sqrt{3/2}v_0$

Local circular speed

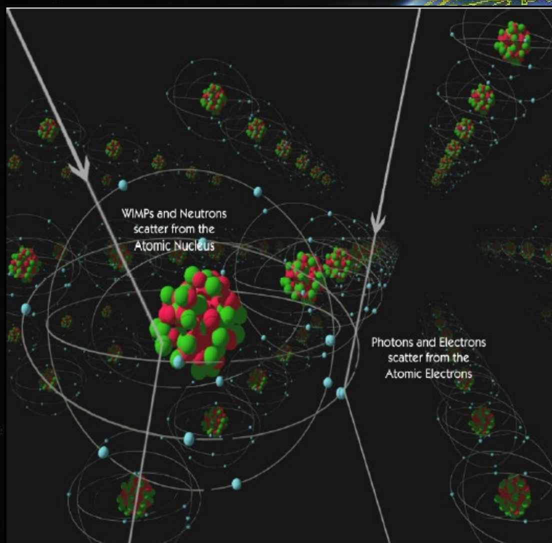


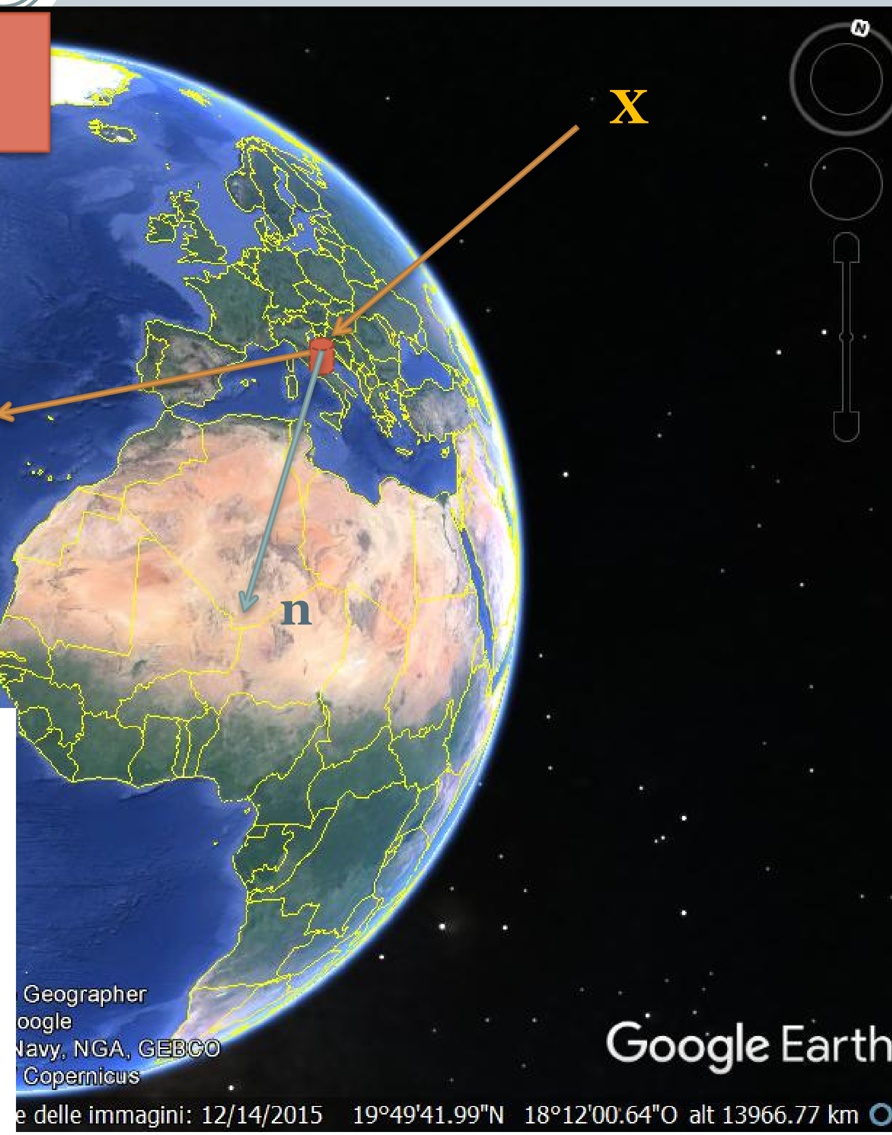
Direct Searches – 2: Detection Method



Direct Searches – 2: Detection Method

Scattering of a WIMP with an atomic nucleus





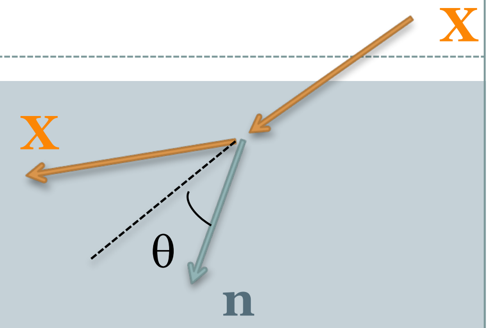
REVIEW D VOLUME 31, NUMBER 12

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

Direct Searches – 3: Recoil Rate

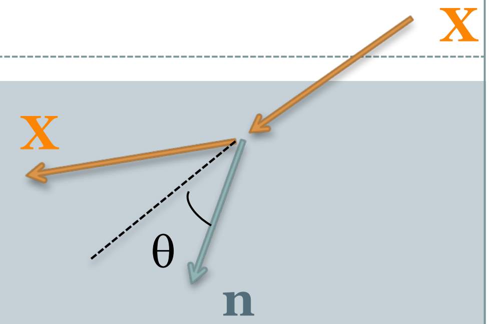


The energy transferred to the recoiling nucleus is:

$$E_r = \frac{m^2{}_r\, v^2}{m_N}\,(1 - \cos\theta),\;\; m_r = \frac{m_\chi \cdot m_N}{m_\chi + m_N}$$

Energy deposited in the detector ~ few keV - tens of keV

Direct Searches – 3: Recoil Rate



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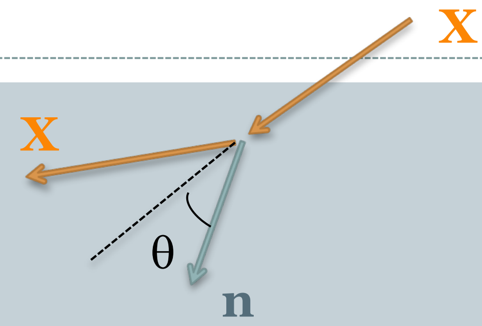
The differential recoil rate is:

$$\frac{dR}{dE_r} = N_N \frac{\rho_0}{m_\chi} \int_{v_{min}}^{v_{max}} d\vec{v}\, f(\vec{v}) v\, \frac{d\sigma}{dE_r}$$

N_N → number of target nuclei
ρ_0 → local WIMP density
$f(\vec{v})$ → WIMP velocity distribution
$v_{min} = \sqrt{\frac{m_N E_{th}}{2m^2{}_r}}$, v_{max} → escape velocity
$\frac{d\sigma}{dE_r}$ → WIMP-nucleus differential cross section

Direct Searches – 3: Recoil Rate



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Astrophysics

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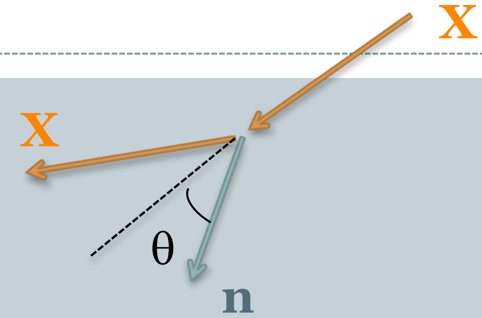

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Astrophysics

Particle/Nuclear Physics

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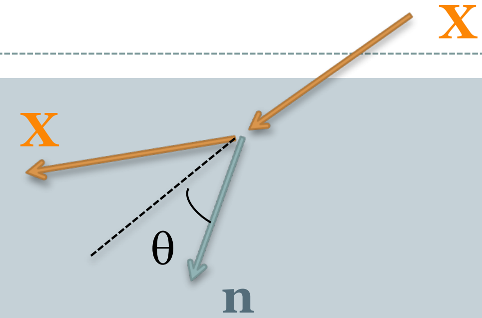
Direct Searches – 3: Recoil Rate



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Astrophysics

Detector Properties

Particle/Nuclear Physics

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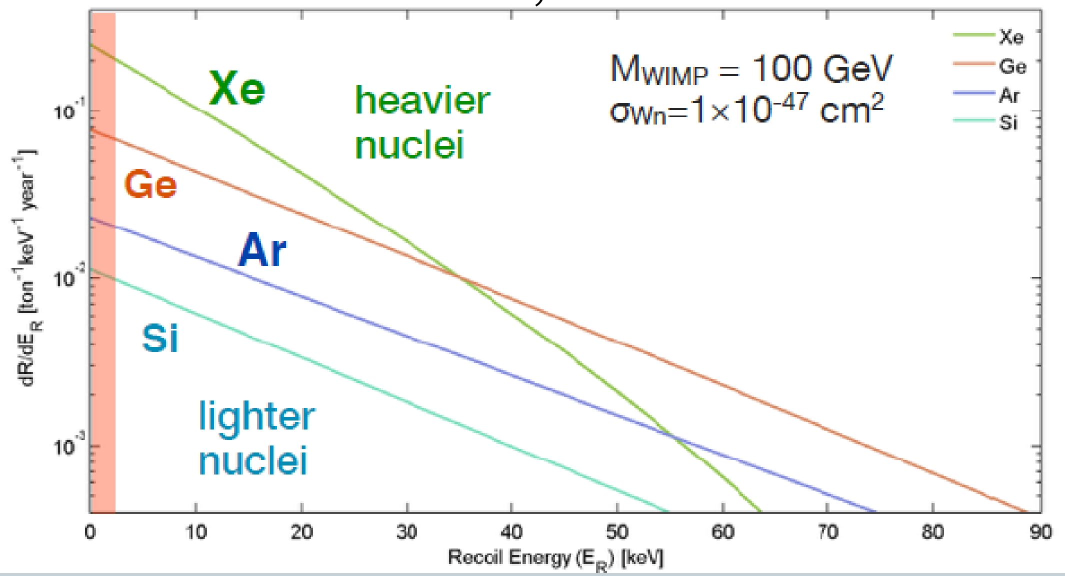
Direct Searches – 3: Recoil Rate

m_χ = 100 GeV/c², $< v > = 220\ km\ s^{-1}$, $\rho_0 = 0.3\ GeV\ cm^{-3}$

$\sigma_{\chi N} \sim 10^{-38}\ cm^2$

$$R \sim \frac{N_A}{A} \times \frac{\rho_0}{m_\chi} \times < v > \times \sigma_{\chi N} \sim 0.13 \text{ events kg}^{-1} \text{ year}^{-1}$$

M. Messina, NOW 2016

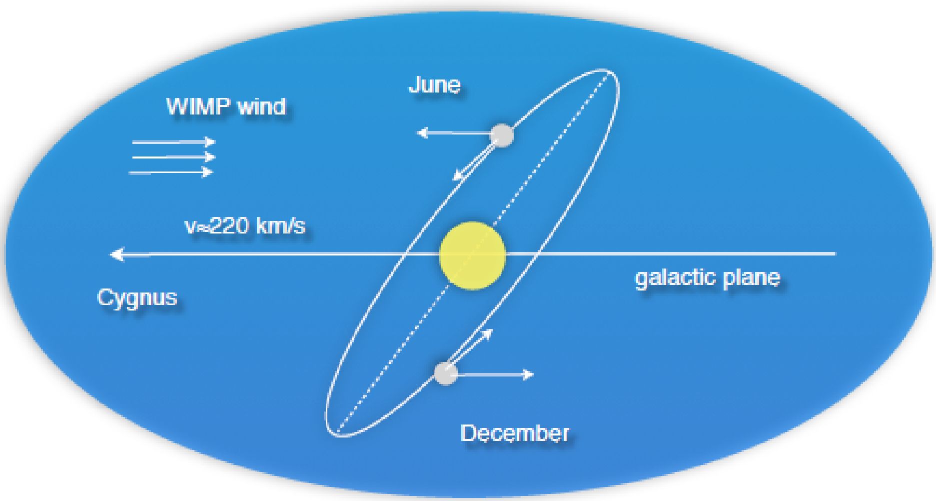


Direct Searches – 4: Signature

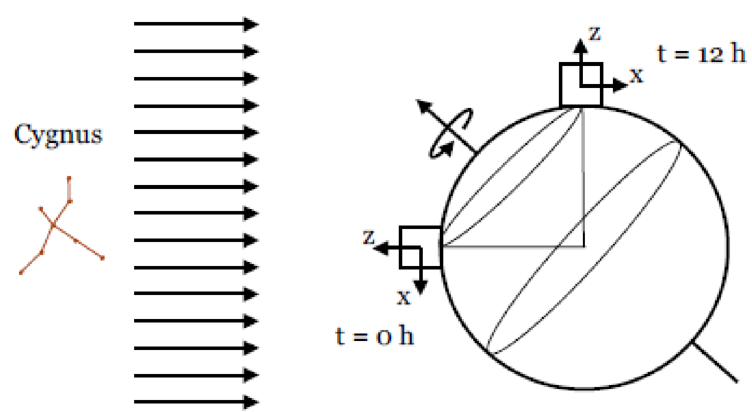
- Earth revolution gives annual modulation:

  June - December asymmetry $O(v_{rev}/v_{sun}) \sim 1\%$

- Due to solar system movement in the galaxy, the WIMP Flux is expected to be **not isotropic @earth** $O(v_{sun}/v_o) \sim 100\%$. A directional measurement would provide a **strong signature** and an unambiguous proof of the galactic origin of DM



Drukier, Freese, Spergel, PRD 33,1986



D. Spergel, PRD 36, 1988

Direct Searches – 5: Background

WIMP events < 1 evts /100 kg/ 100 day
Backgrounds events > $10^{6\text{-}7\text{-}}$evts/kg-d !!!

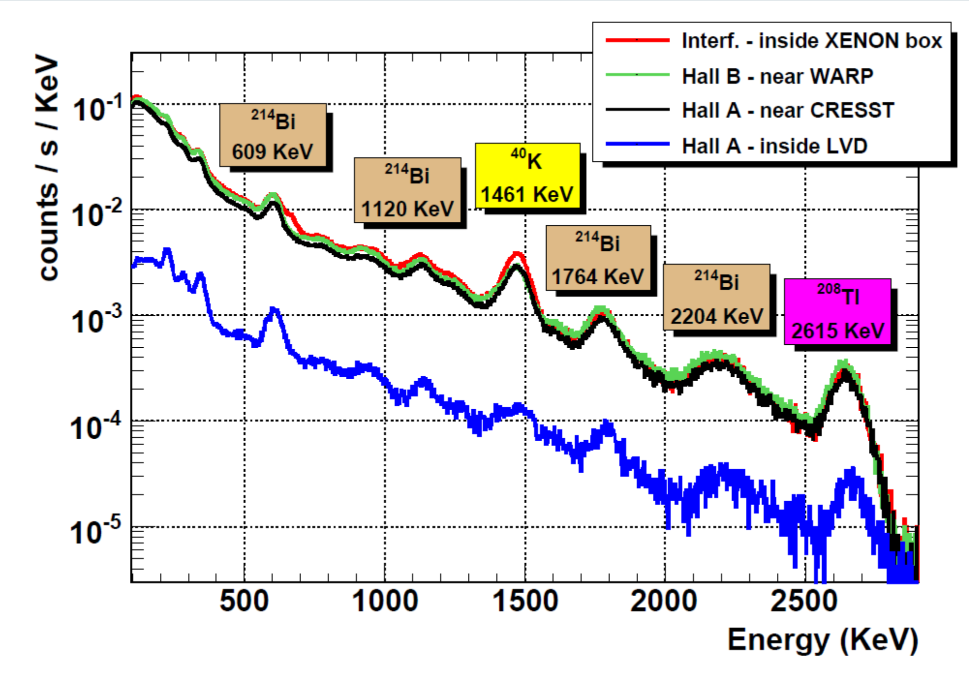
- **Environmental radioactivity**
- **Radon** and its progeny
- **Cosmic rays**
- **Neutrons** from natural fission, (a,n) reactions and from cosmic ray muon spallation and capture
- **Radioimpurities** in detector or shielding components

Direct Searches – 5: Background

Parent	Daughter	Decay Mode	Energy [MeV]	Half Life
^{238}U	^{234}Th	α	**4.27**	4.47×10^9 yr
^{234}Th	^{234}Pa	β	0.273	24.1 d
^{234}Pa	^{234}U	β	2.20	6.70 hr
^{234}U	^{230}Th	α	**4.86**	2.45×10^5 yr
^{230}Th	^{226}Ra	α	**4.77**	7.54×10^4 yr
^{226}Ra	^{222}Rn	α	**4.87**	1.60×10^3 yr
^{222}Rn	^{218}Po	α	**5.59**	3.82 d
^{218}Po	^{214}Pb	α	**6.12**	3.10 min
^{214}Pb	^{214}Bi	β	1.02	26.8 min
^{214}Bi	^{214}Po	β	3.27	19.9 min
^{214}Po	^{210}Pb	α	**7.88**	0.164 ms
^{210}Pb	^{210}Bi	β	0.0635	22.3 yr
^{210}Bi	^{210}Po	β	1.43	5.01 d
^{210}Po	^{206}Pb	α	**5.41**	138 d
^{206}Pb				stable

Parent	Daughter	Decay Mode	Energy [MeV]	Half Life
^{232}Th	^{228}Ra	α	**4.08**	1.41×10^{10} yr
^{228}Ra	^{228}Ac	β	0.0459	5.75 yr
^{228}Ac	^{228}Th	β	2.12	6.25 hr
^{228}Th	^{224}Ra	α	**5.52**	1.91 yr
^{224}Ra	^{220}Rn	α	**5.79**	3.63 d
^{220}Rn	^{216}Po	α	**6.40**	55.6 s
^{216}Po	^{212}Pb	α	**6.91**	0.145 s
^{212}Pb	^{212}Bi	β	0.570	10.6 hr
^{212}Bi	^{212}Po	β 64.06%	2.25	60.6 min
	^{208}Tl	α 35.94%	**6.21**	
^{212}Po	^{208}Pb	α	**8.96**	299 ns
^{208}Tl	^{208}Pb	β	5.00	3.05 min
^{208}Pb				stable

γ background



γ radiation emitted durinng the decay of natural radioativity

(^{238}U, ^{232}Th and its unstable daughters)

Total ambient flux~0.23 cm-2s-1

$$l = \lambda(E_\gamma) \ln f,\ f > 1$$

At 100 keV (2.615 MeV), attenuation by a factor f = 10^5 requires:

- 67(269) cm of H_2O
- 2.8(34) cm of Cu
- 0.18(23) cm of Pb.

α particles

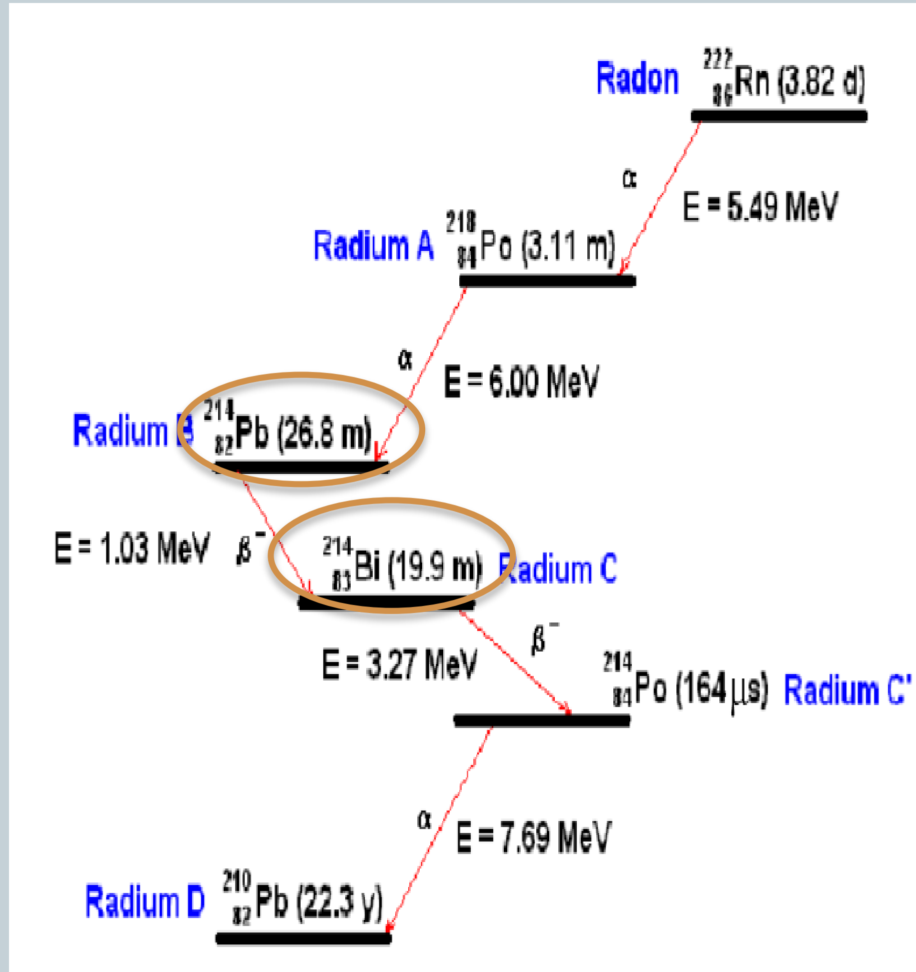
Sources: ^{238}U, ^{232}Th chains and ^{222}Rn

Neutron production throught (α,n) reactions

RADON:

The noble gas **^{222}Rn ($T_{1/2}$=3.8 d)**, a pure α-emitter. It is released by surface soil and is found in the atmosphere everywhere

The detector has to be kept sealed from air and flushed with HP N_2



Neutrons

Neutrons contribute to the background of low-energy experiments in different ways: directly **through nuclear** recoil in the detector medium, and indirectly, through the **production of radio nuclides** inside the detector and its components (inelastic scattering of fast neutrons or radiative capture of slow neutrons can result in the emission of γ radiation).

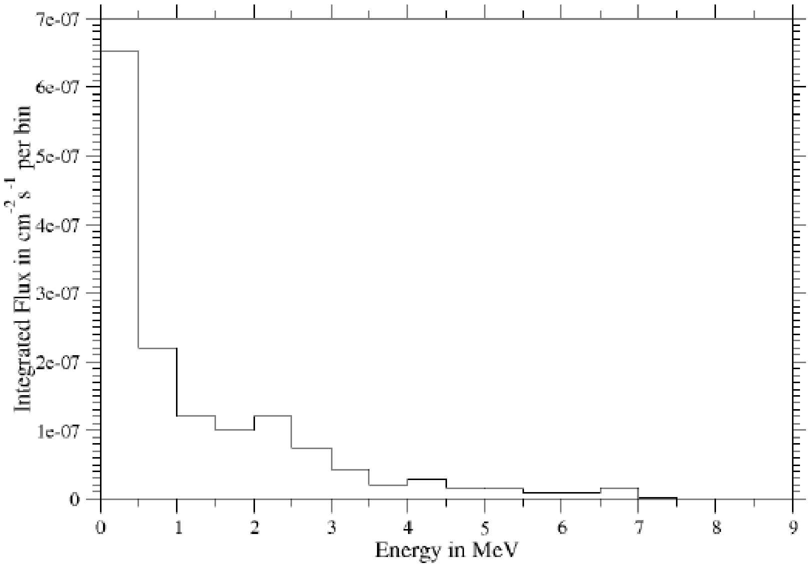
Neutron sources:

- Energetic tertiary neutrons are produced by cosmic-ray muons in nuclear spallation reactions with the detector and laboratory walls;
- In high Z materials, often used in radiation shields, nuclear capture of negative muons results in emission of neutrons;
- Natural radioactivity has a neutron component through spontaneous fission and (α, n)-reactions.

Ambient neutrons

- Spectrum due to H. Wulandari

Wulandari, H. et al. Astropart.Phys. 22 (2004)

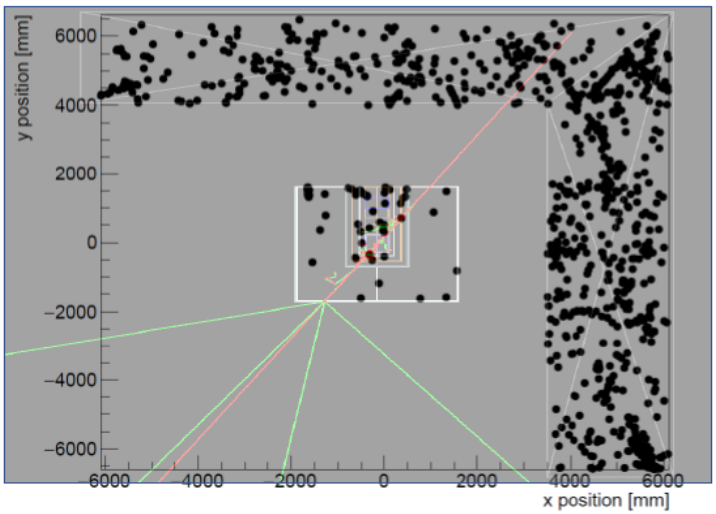


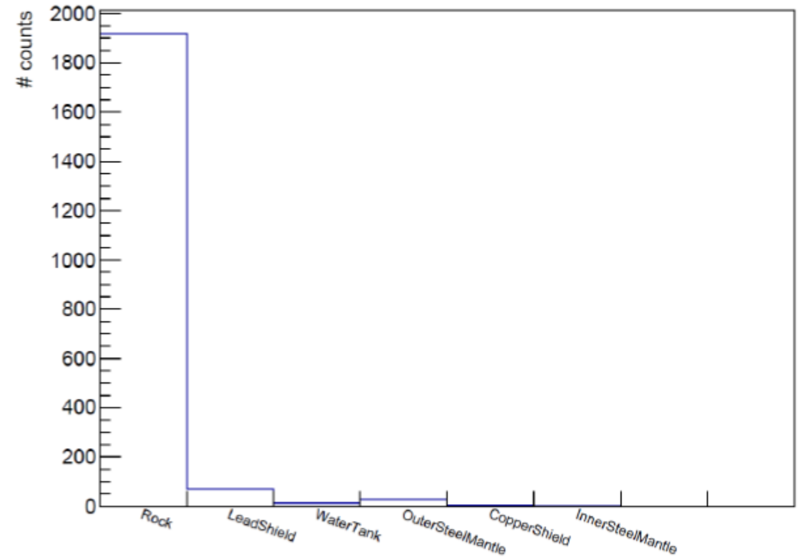
Integrated Flux above 500 keV: ~ $7.9 \cdot 10^{-7}$ n cm^{-2} s^{-1}

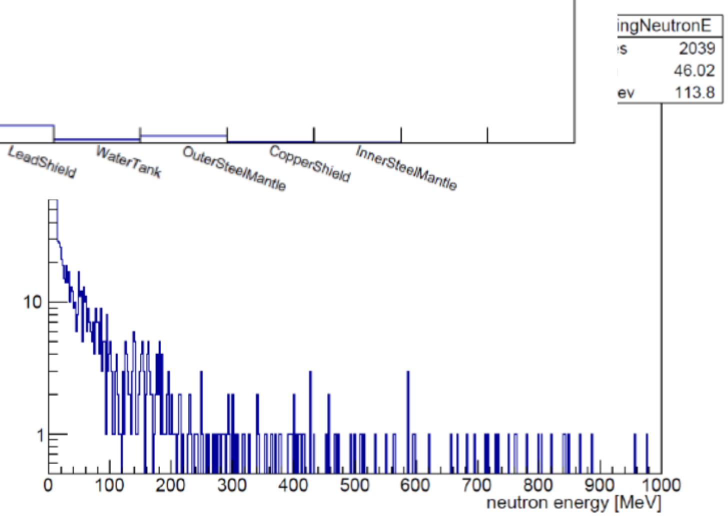
Flux in energy range 1 - 500 keV: ~ $6.5 \cdot 10^{-6}$ n cm^{-2} s^{-1}

Cosmogenic neutrons

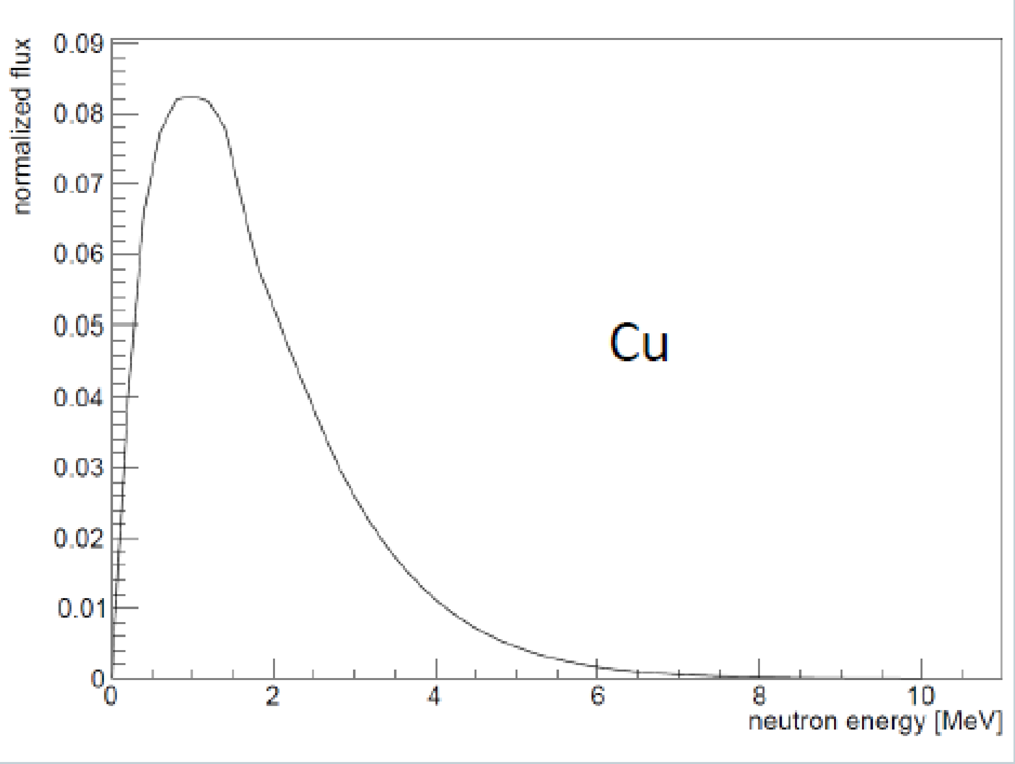
- Secondary neutrons "produced" due to cosmic muons:
  - ~ 0.5 n/μ through a layer of ~ 2.5 m rock with density 2.71 g/cm^3
    i.e. ~ $7.4 \cdot 10^{-5}$ $n/\mu/(g/cm^2)$



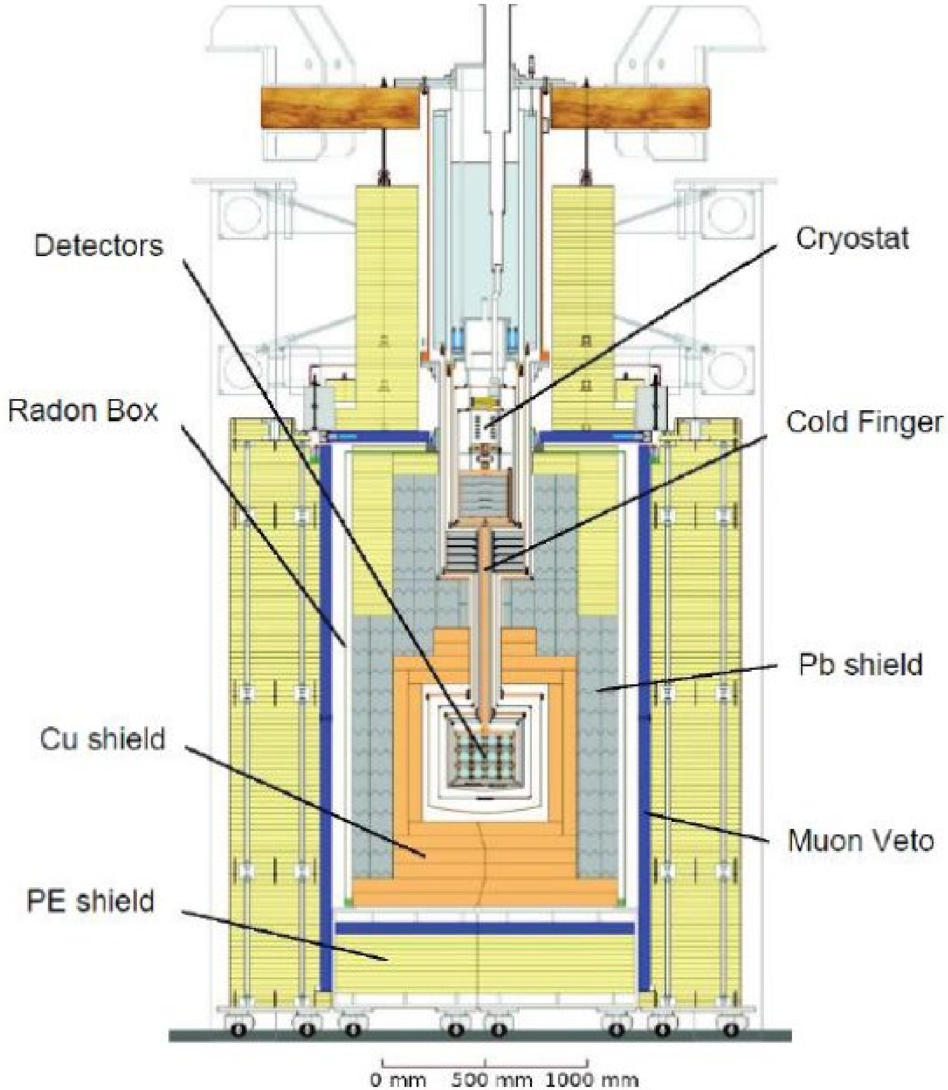




Radiogenic neutrons



Shield!



CRESST:

1400 m rock

+

4cm of radiopure copper

+

20cm of Bolidean lead with a low ^{210}Pb activity of 35Bq/kg.

+

air tight aluminium container (the radon-box)

+

neutron moderator of 50cm polyethylene

With the moderator installed, the remaining neutron flux would be dominated by **neutrons induced by muons in the lead** of the shielding. Such a background is suppressed by the muon **veto system** installed inside the neutron moderator.

Direct Searches – 6: Experiments

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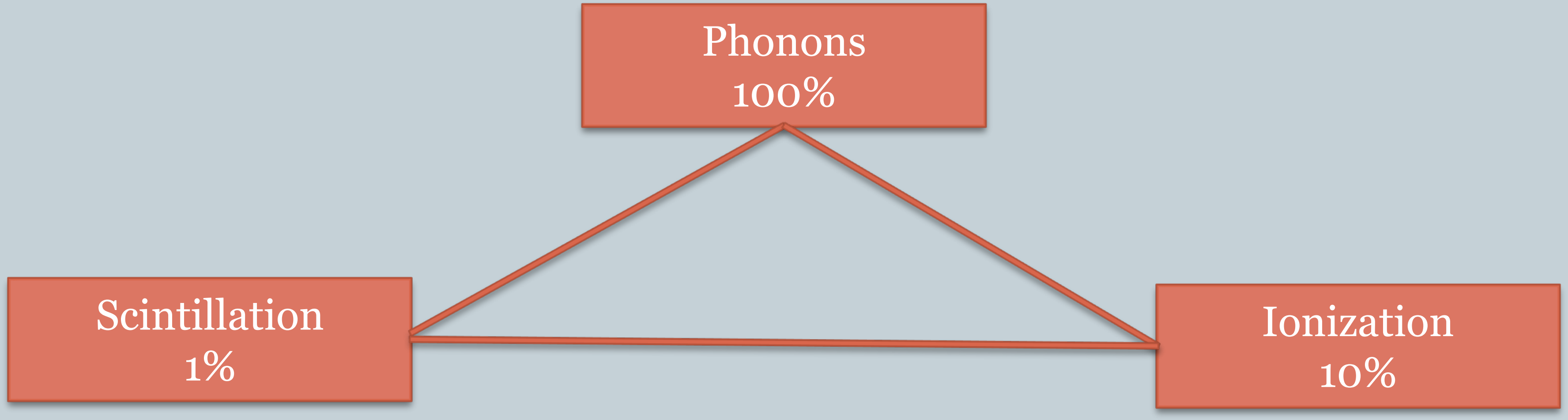

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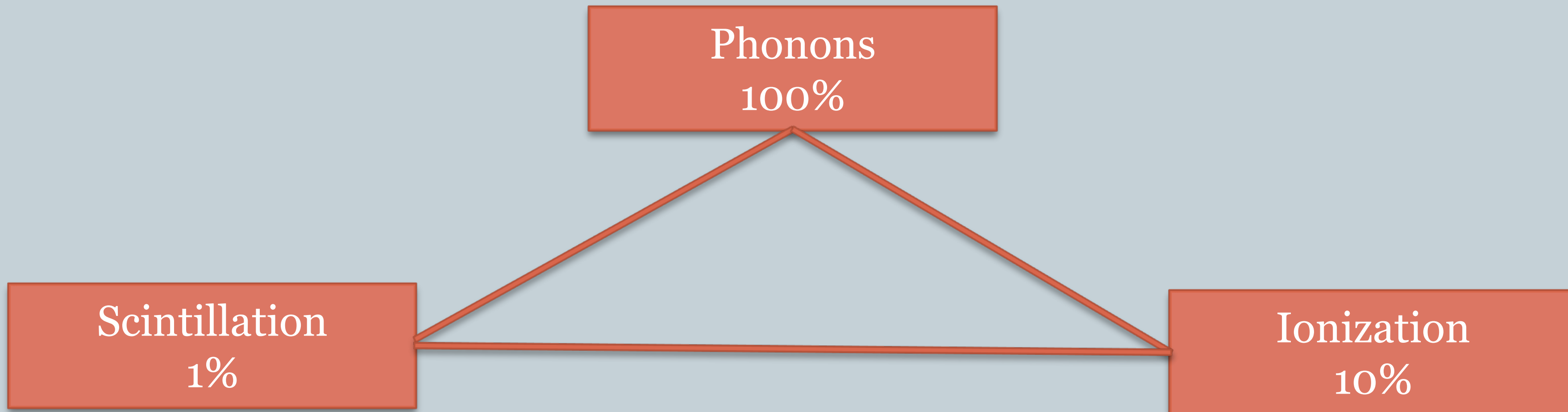
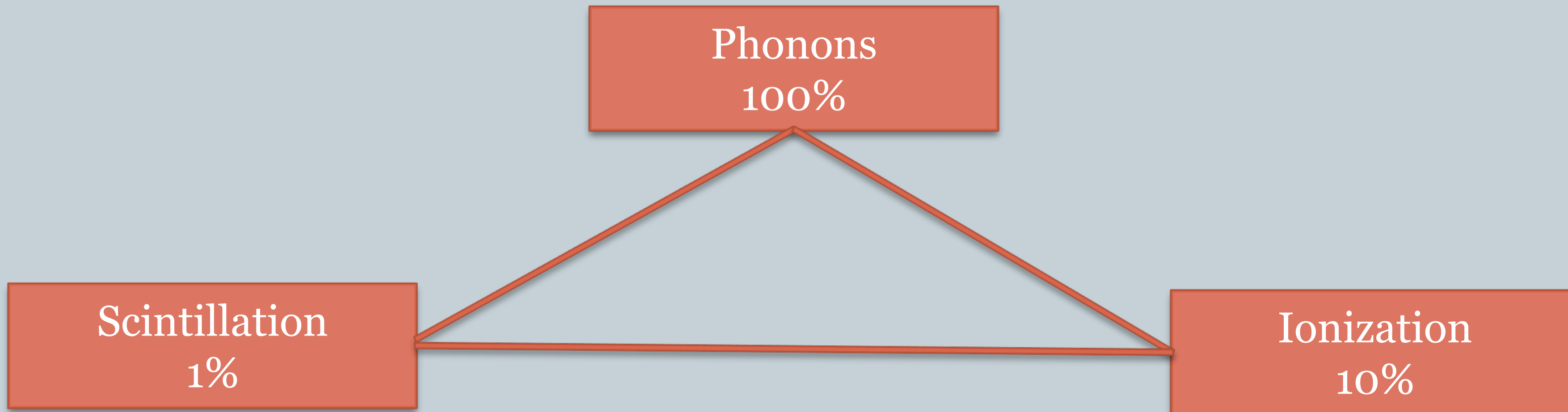


- <u>High purity Ge Detector</u> (*CoGeNT, CDEX, Texono, Malbek, DAMIC*)

Direct Searches – 6: Experiments



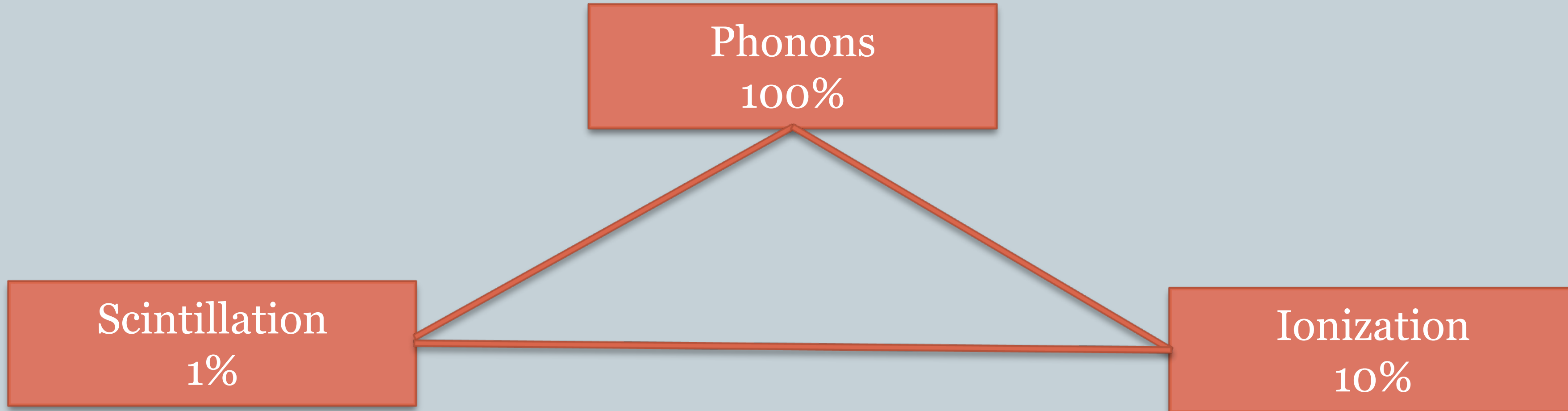
- <u>Inorganic Scintillators</u> (DAMA,KIMS-ANAIS, DM-ICE,SABRE)

- <u>Single Phase Noble Liquids</u> (Xmass, DEAP, MiniCLEAN)

- <u>High purity Ge Detector</u> (*CoGeNT, CDEX, Texono, Malbek, DAMIC*)

Direct Searches – 6: Experiments

- <u>Super-heated Liquids</u>
 (COUP, PICASSO, SIMPLE, PICO)



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Direct Searches – 6: Experiments

- Super-heated Liquids
(COUP, PICASSO, SIMPLE, PICO)

Phonons
100%

- Scintillating calorimeters
(CRESST)

- Super-conducting calorimeters
(CDMS, EDELWEISS)

Scintillation
1%

Ionization
10%

- Inorganic Scintillators
(DAMA,KIMS-ANAIS, DM-ICE,SABRE)

- Dual Phase Noble Liquids
(XENON, DARK-SIDE, LUX/LZ)

- High purity Ge Detector
(*CoGeNT, CDEX, Texono, Malbek, DAMIC*)

- Single Phase Noble Liquids
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Direct Searches – 6: Experiments

1. *Crystals (NaI, Ge, Si)*
2. Cryogenic Detectors
3. Liquid Noble Gases

- <u>Super-heated Liquids</u> (COUP, PICASSO, SIMPLE, PICO)

Phonons
100%

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- <u>Super-conducting calorimeters</u> (CDMS, EDELWEISS)

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Direct Searches – 6: Experiments

1. *Crystals (NaI, Ge, Si)*
2. Cryogenic Detectors
3. Liquid Noble Gases

4. Tracking:
DRIFT, DMTPC MIMAC,NEWAGE, D3, NEWS

- Super-heated Liquids (COUP, PICASSO, SIMPLE, PICO)

Phonons 100%

- Scintillating calorimeters (CRESST)
- Super-conducting calorimeters (CDMS, EDELWEISS)

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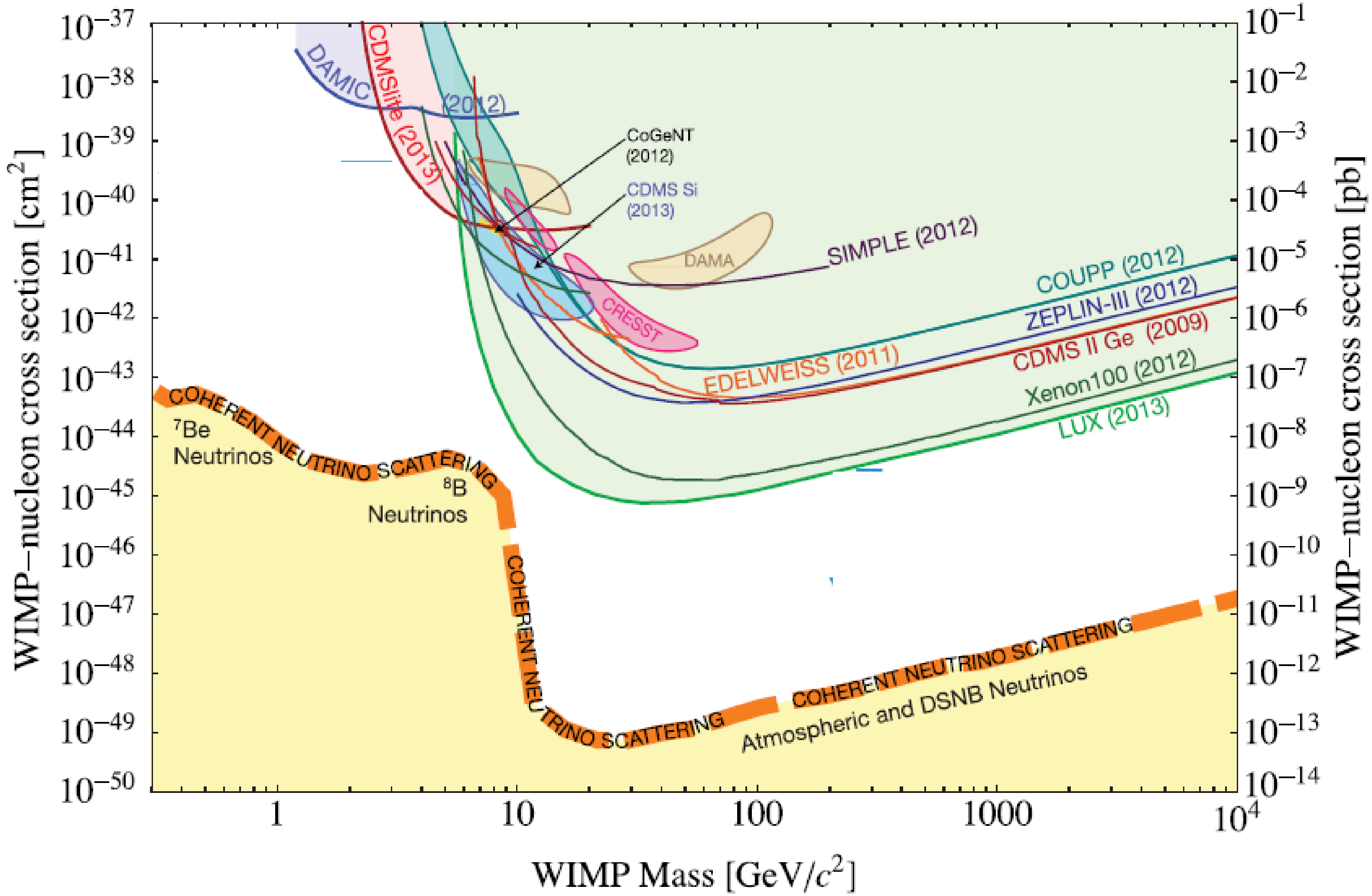


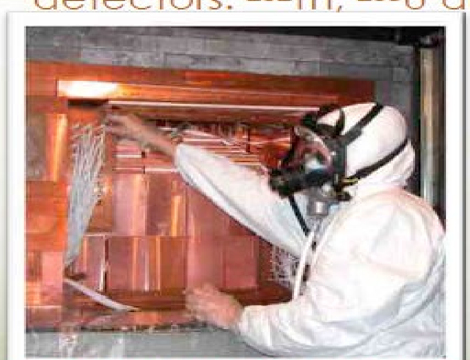
DAMA

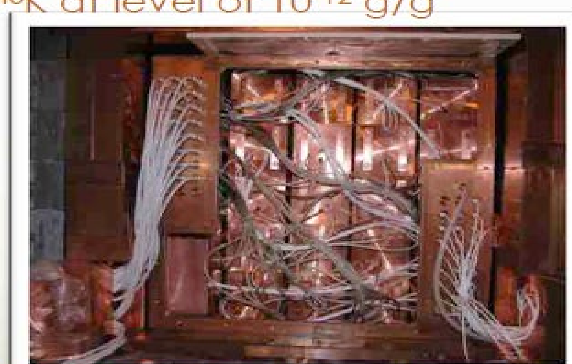
P. Belli@TAUP2015

The DAMA/LIBRA set-up ~250 kg NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

As a result of a 2nd generation R&D for more radiopure NaI(Tl) by exploiting new chemical/physical radiopurification techniques (all operations involving - including photos - in HP Nitrogen atmosphere)

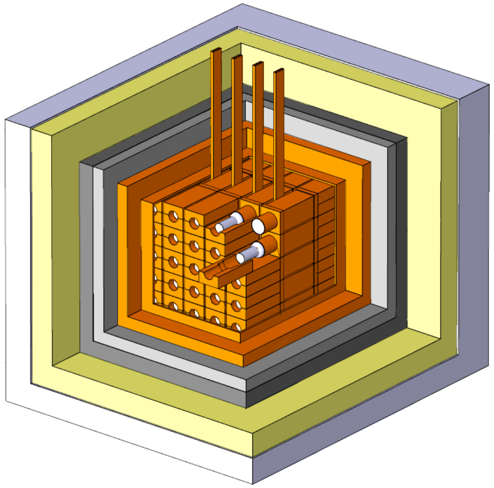
Residual contaminations in the new DAMA/LIBRA NaI(Tl) detectors: ^{232}Th, ^{238}U and ^{40}K at level of 10^{-12} g/g





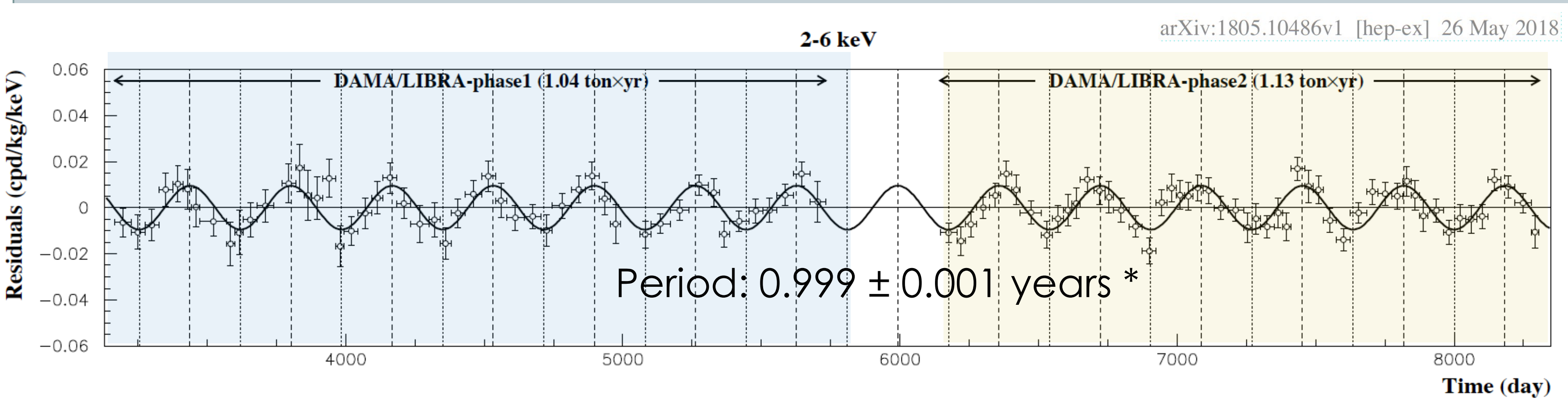
- Radiopurity, performances, procedures, etc.: NIMA592(2008)297, JINST 7 (2012) 03009
- Results on DM particles, Annual Modulation Signature: EPJC56(2008)333, EPJC67(2010)39, EPJC73(2013)2648. Related results: PRD84(2011)055014, EPJC72(2012)2064, IJMPA28(2013)1330022, EPJC74(2014)2827, EPJC74(2014)3196, EPJC75(2015)239, EPJC75(2015)400
- Results on rare processes: PEPv: EPJC62(2009)327; CNC: EPJC72(2012)1920; IPP in ^{241}Am: EPJA49(2013)64

The **DAMA/LIBRA** results

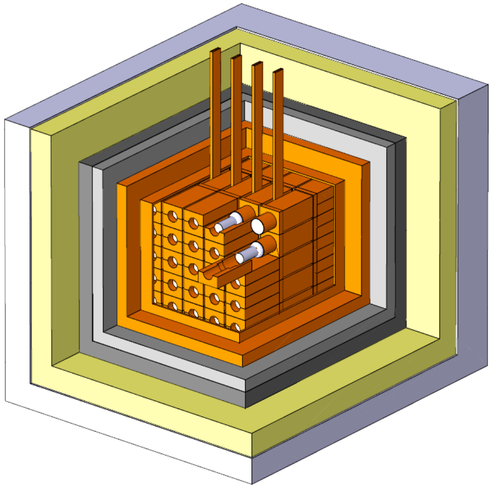


- 250 Kg NaI(Tl)
- Threshold 1 KeVee
- Running since 1996

Total exposure: 2.17 tonne years (phase 1 + 2)
Statistical significance: >11.9 σ
(combined with DAMA/NaI: 2.46 tonne years and 12.9σ !!!!)
Phase: 25th May +/- 5 days (cosine peaking June 2nd)



The **DAMA/LIBRA** results



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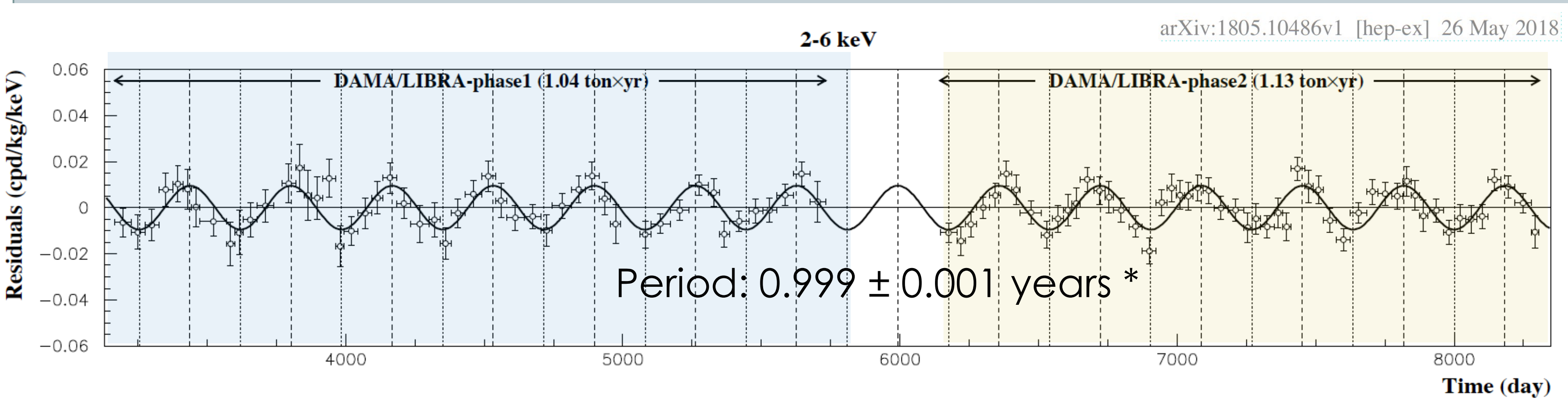


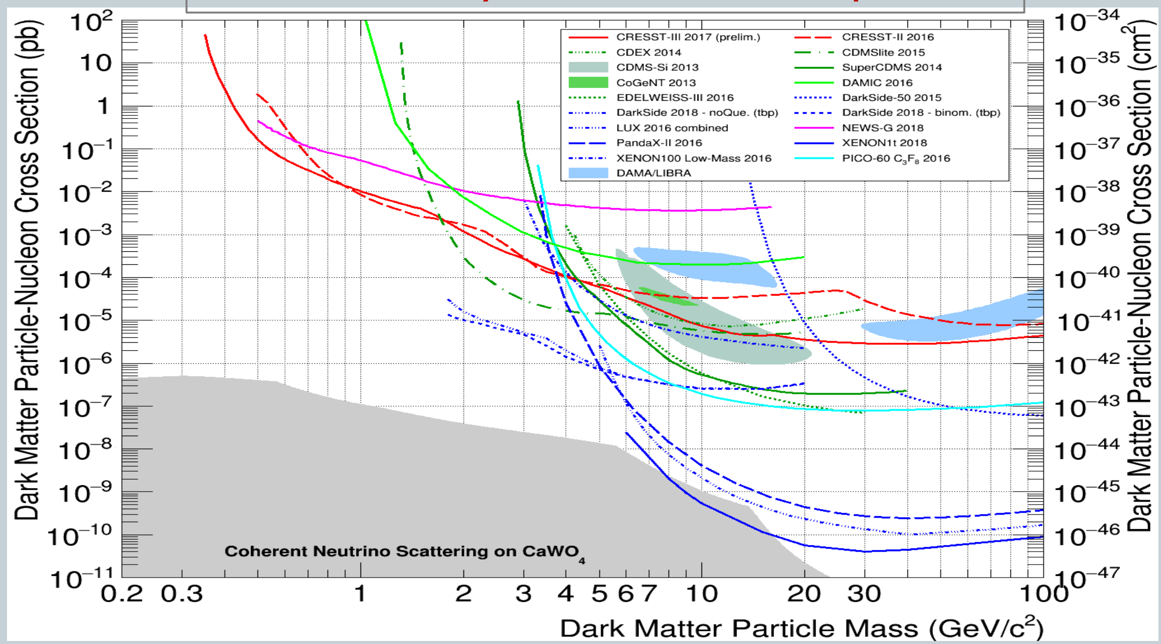
Positive evidence for the presence of DM particles in the galactic halo

GLOBAL LANDSCAPE OF DM Direct Search

Null results shown as 90% C.L. upper limits on the spin-independent DM particle-nucleon cross section

DAMA/LIBRA:
3σ allowed parameter space

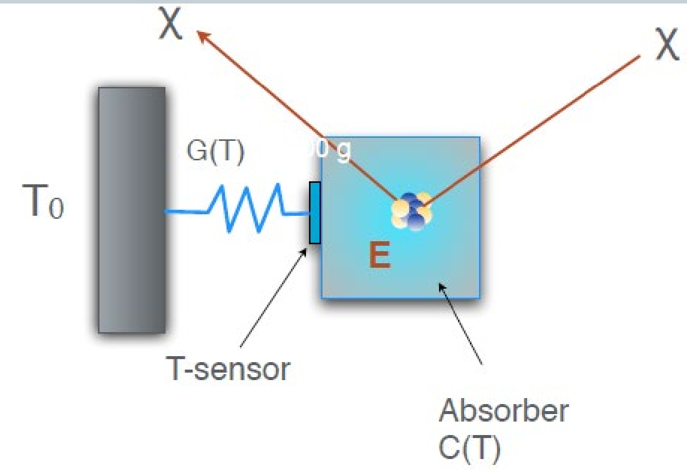
CAVEAT: valid only under standard assumption!



Long-reigning contradicting situation in the dark matter sector: the positive evidence for the detection of a dark matter modulation signal claimed by the DAMA/LIBRA collaboration is (under standard assumptions) **inconsistent with the null-results** reported by most of the other direct dark matter experiments (using different targets Xe, Ge, $CaWO_4$).

Cryogenic detectors

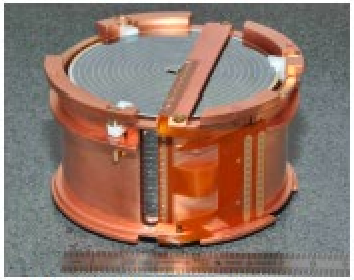
Cryogenic micro-calorimeter at T ~ mK



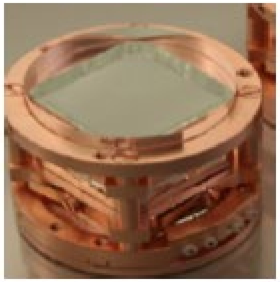
$$\Delta T = \frac{E}{C(T)} e^{-\frac{t}{\tau}}$$

$$\tau = \frac{C(T)}{G(T)}$$

SuperCDMS: Ge, Si

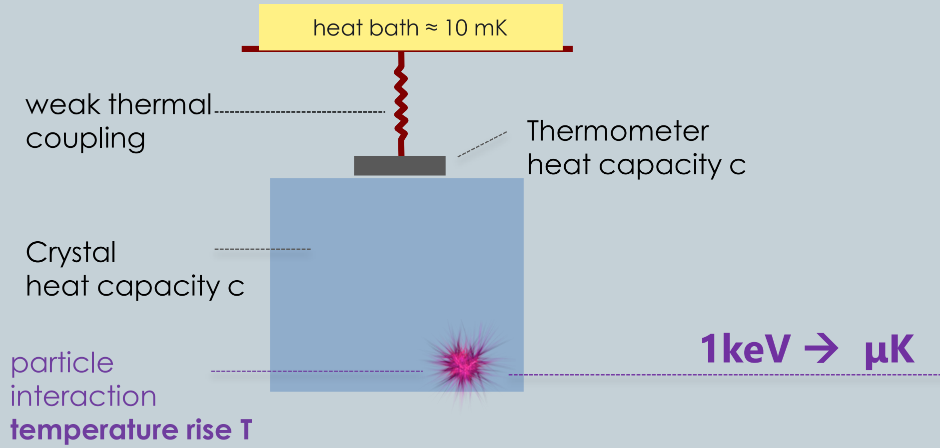


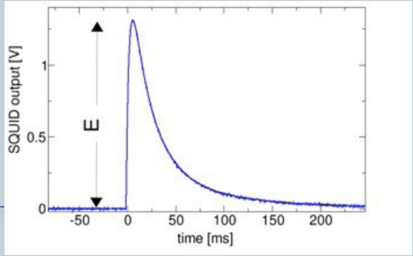
EDELWEISS-III (Ge)



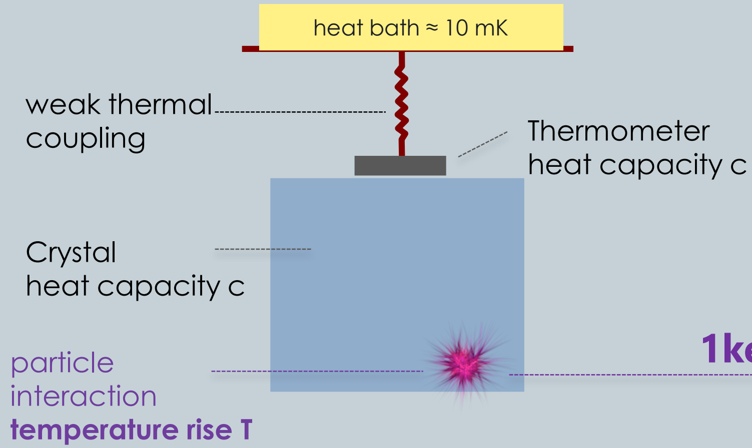
CRESST ($CaWO_4$)

LOW-TEMPERATURE CALORIMETER





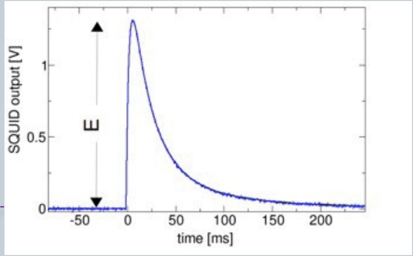
SCINTILLATING CALORIMETER



1keV → µK

Phonon signal (~ 90 %)

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



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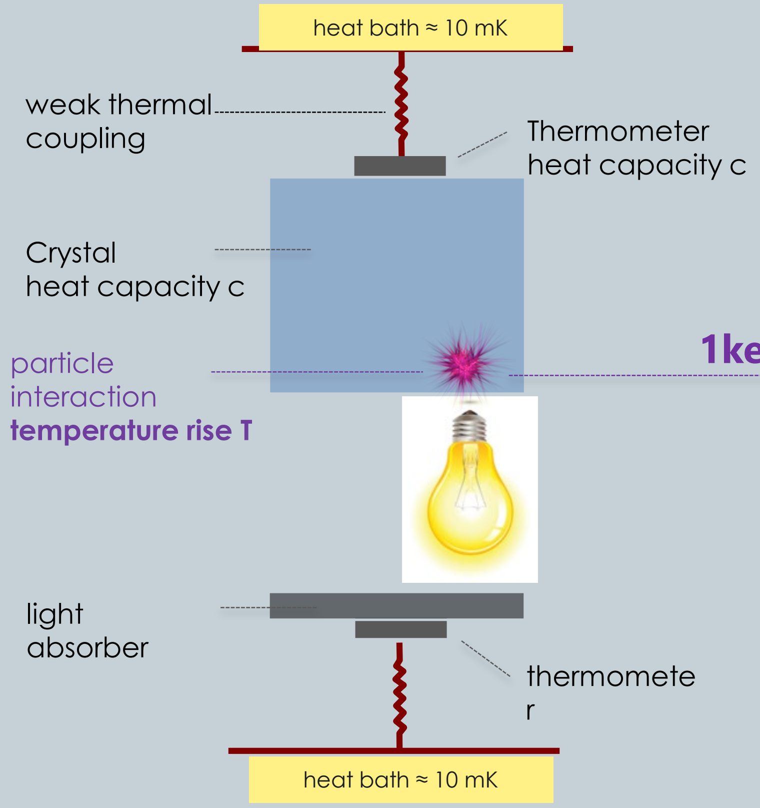

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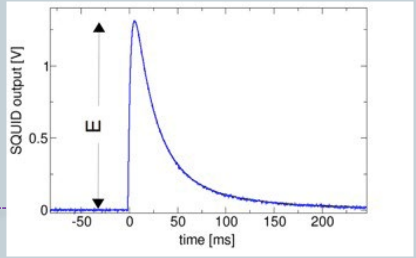
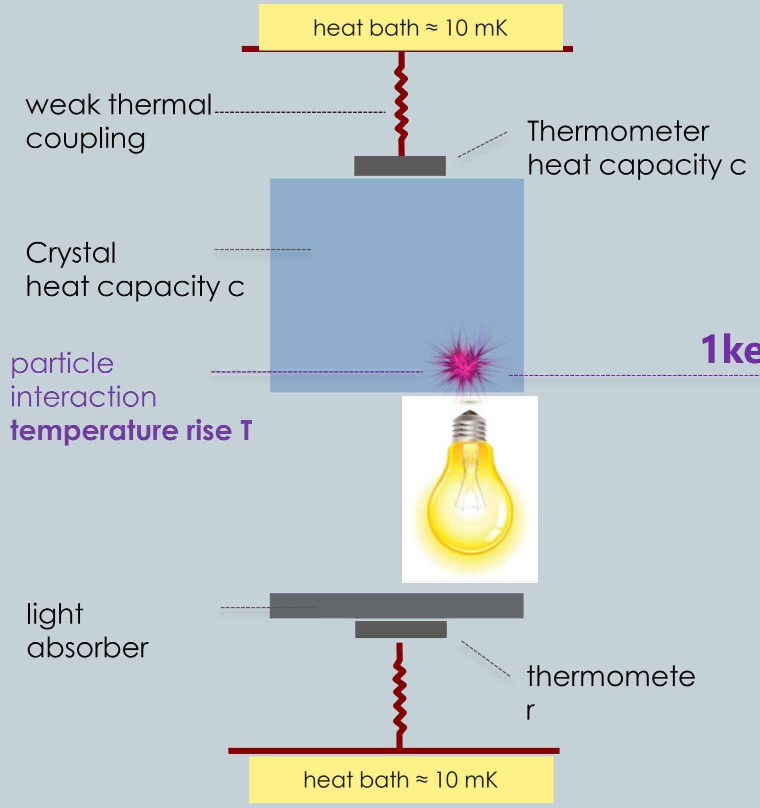


SCINTILLATING CALORIMETER



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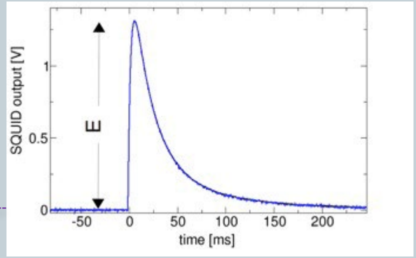


Scintillation light (few %)

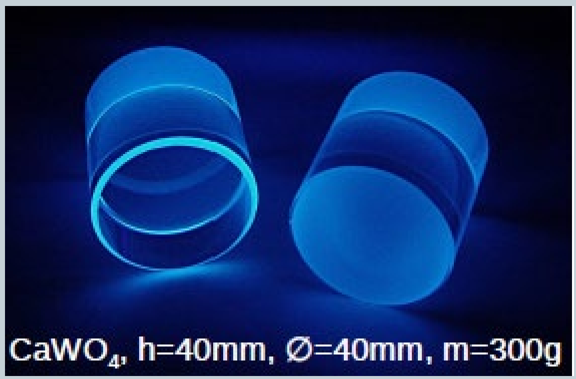
→ **add cryogenic light detector** for scintillation light detection

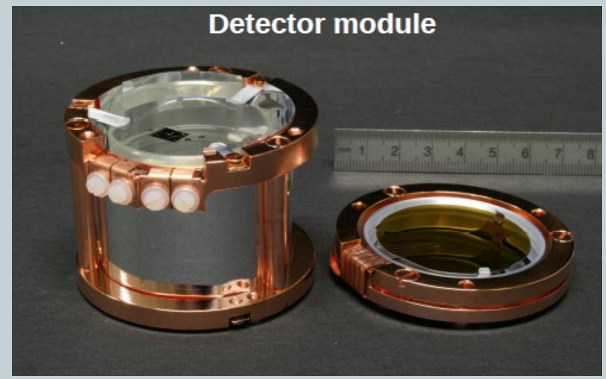
- amount of emitted light depends on particle type → LIGHT QUENCHING
- discrimination of interacting particle via the **ratio light to phonon signal** → ***LIGHT YIELD***

Cryogenic detectors

CRESST: Cryogenic Rare Event Search with Superconducting Thermometers

Scintillating CaWO4 crystals as target operated as **cryogenic calorimeters** (~15mK)





Energy deposition in the crystal:

- mainly phonons

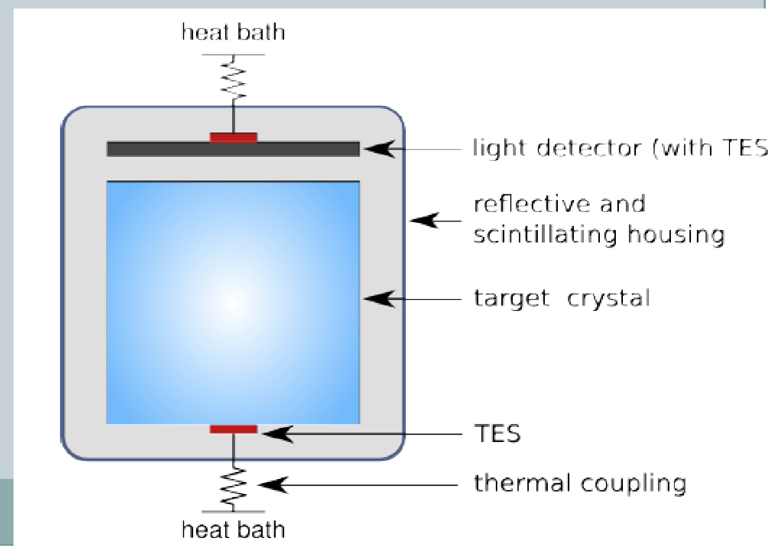
(independent of the type of particle)

Measurement of deposited energy

- small fraction into scintillation light

(characteristic of the type of particle)

Particle discrimination

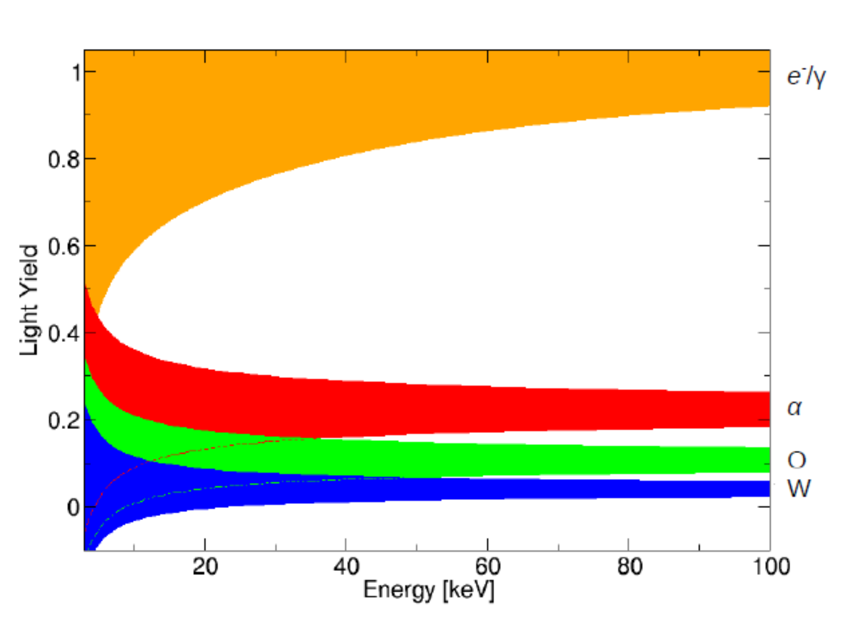


Cryogenic detectors

Event Discrimination

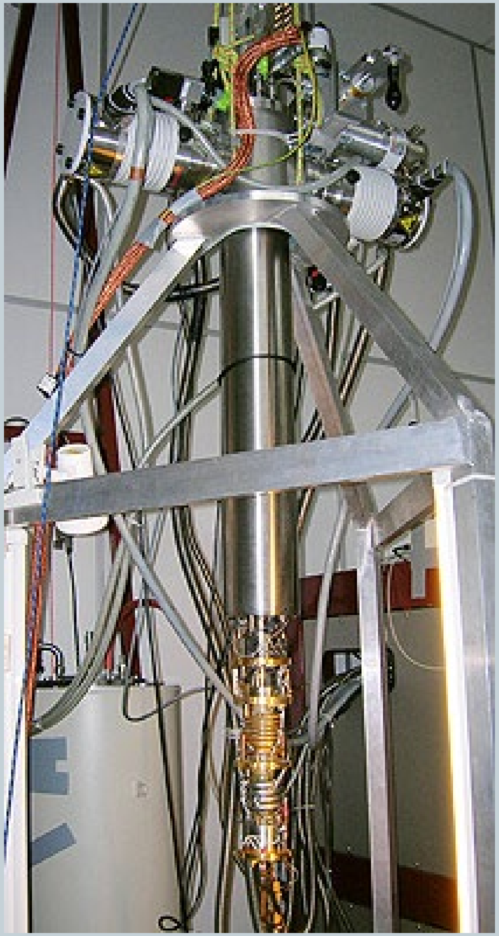
$$\text{Light Yield} = \frac{\text{Light signal}}{\text{Phonon signal}}$$

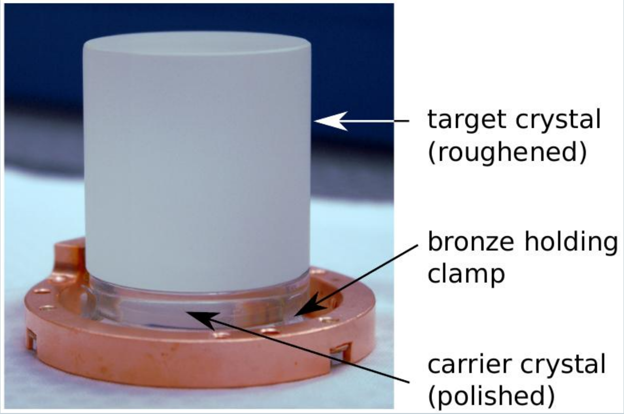
Characteristic of the event type

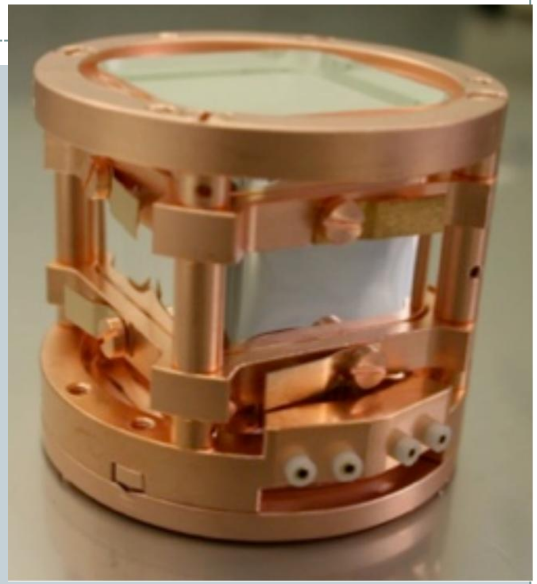


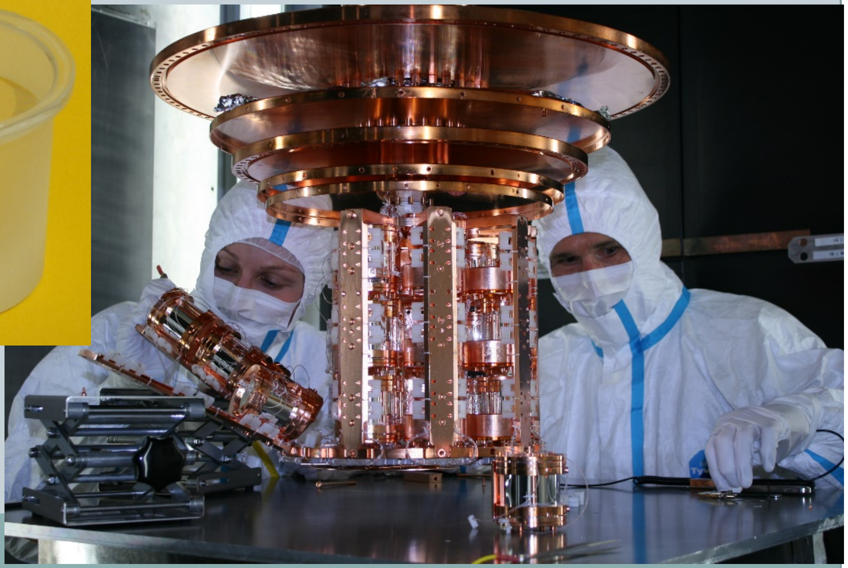
Excellent **discrimination** between potential signal events (**nuclear recoils**) and dominant radioactive background (**electron recoils**)

CRESST experiment

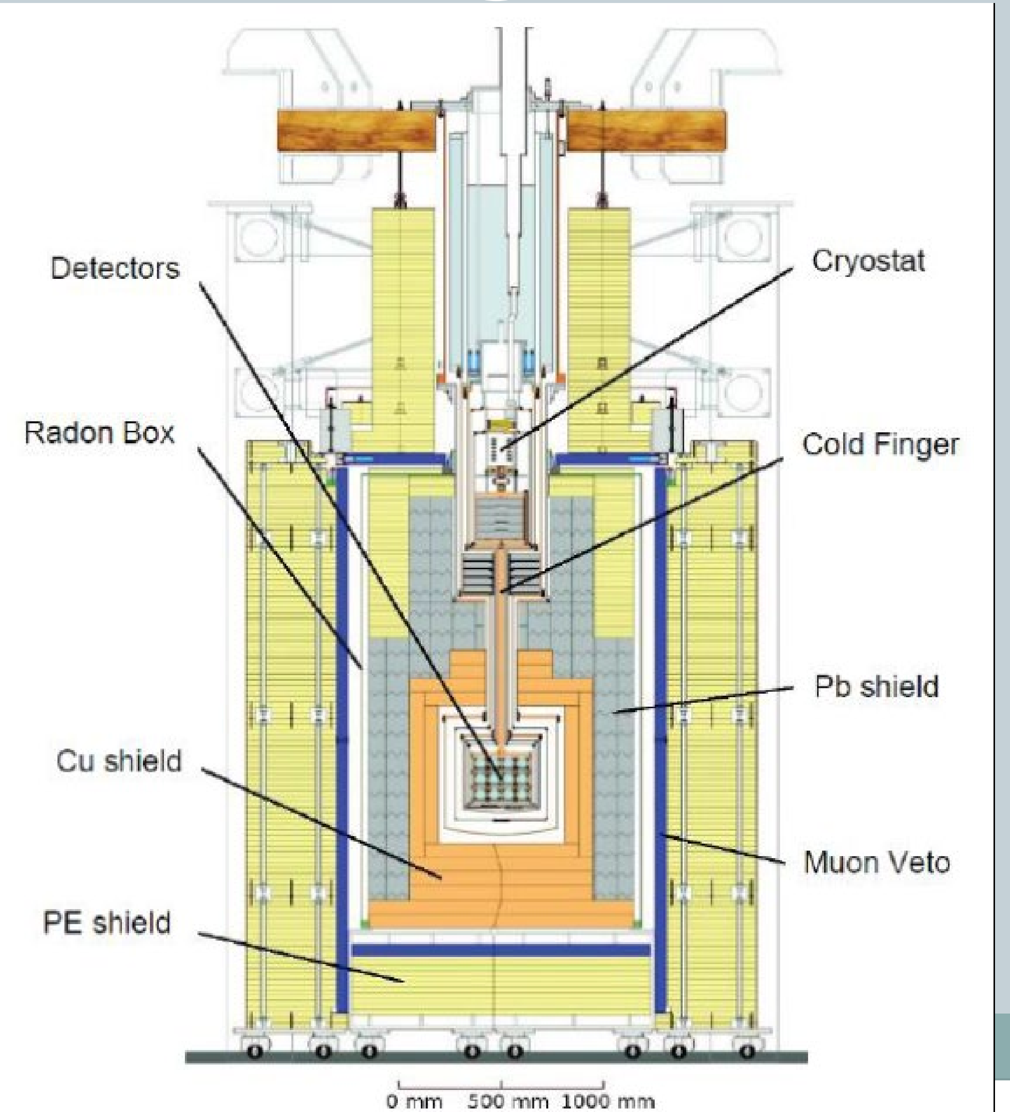




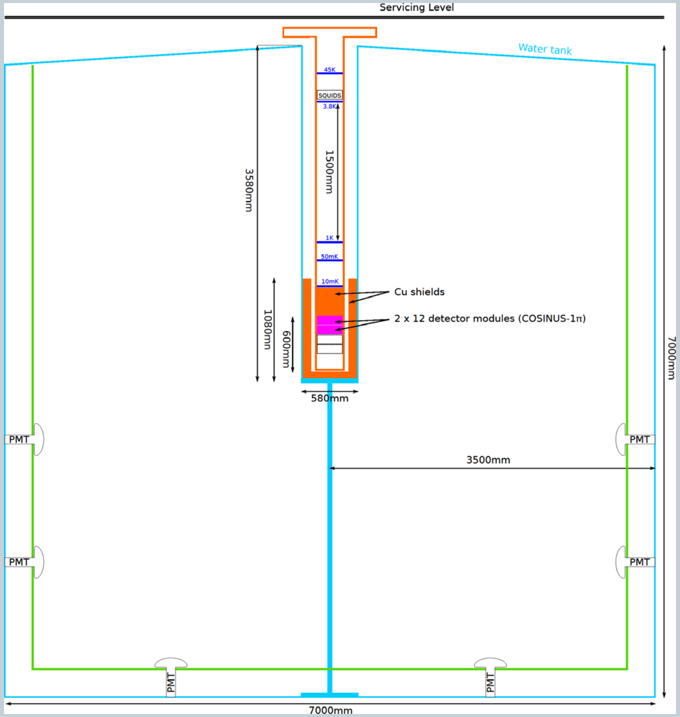


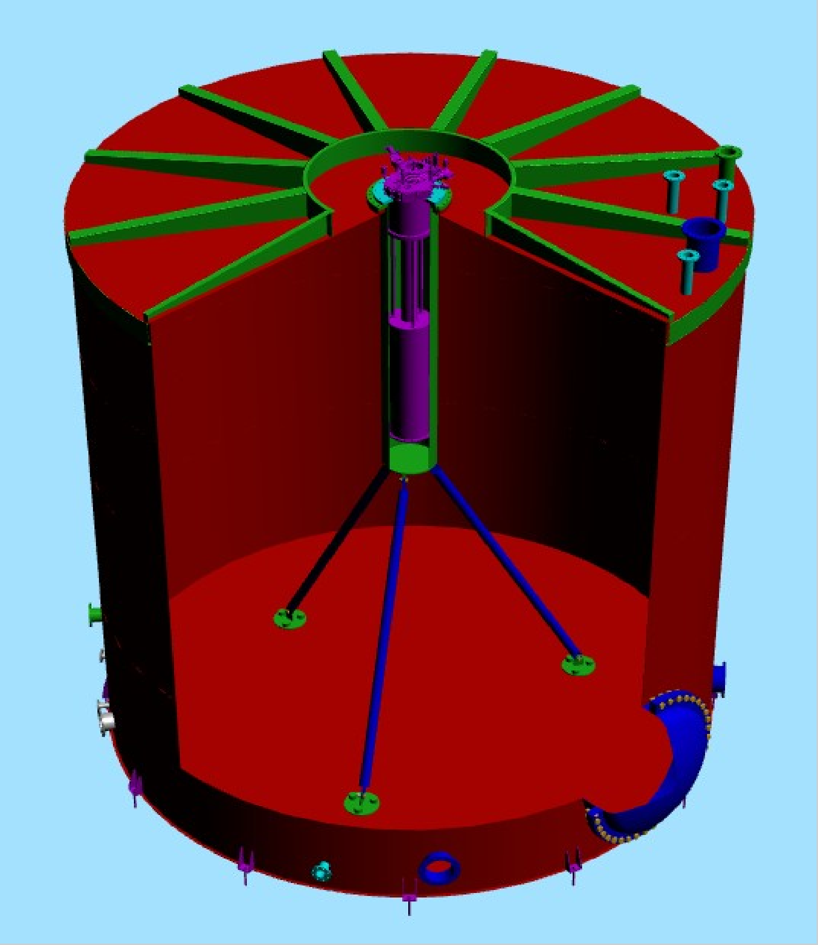


CRESST experiment



COSINUS experiment

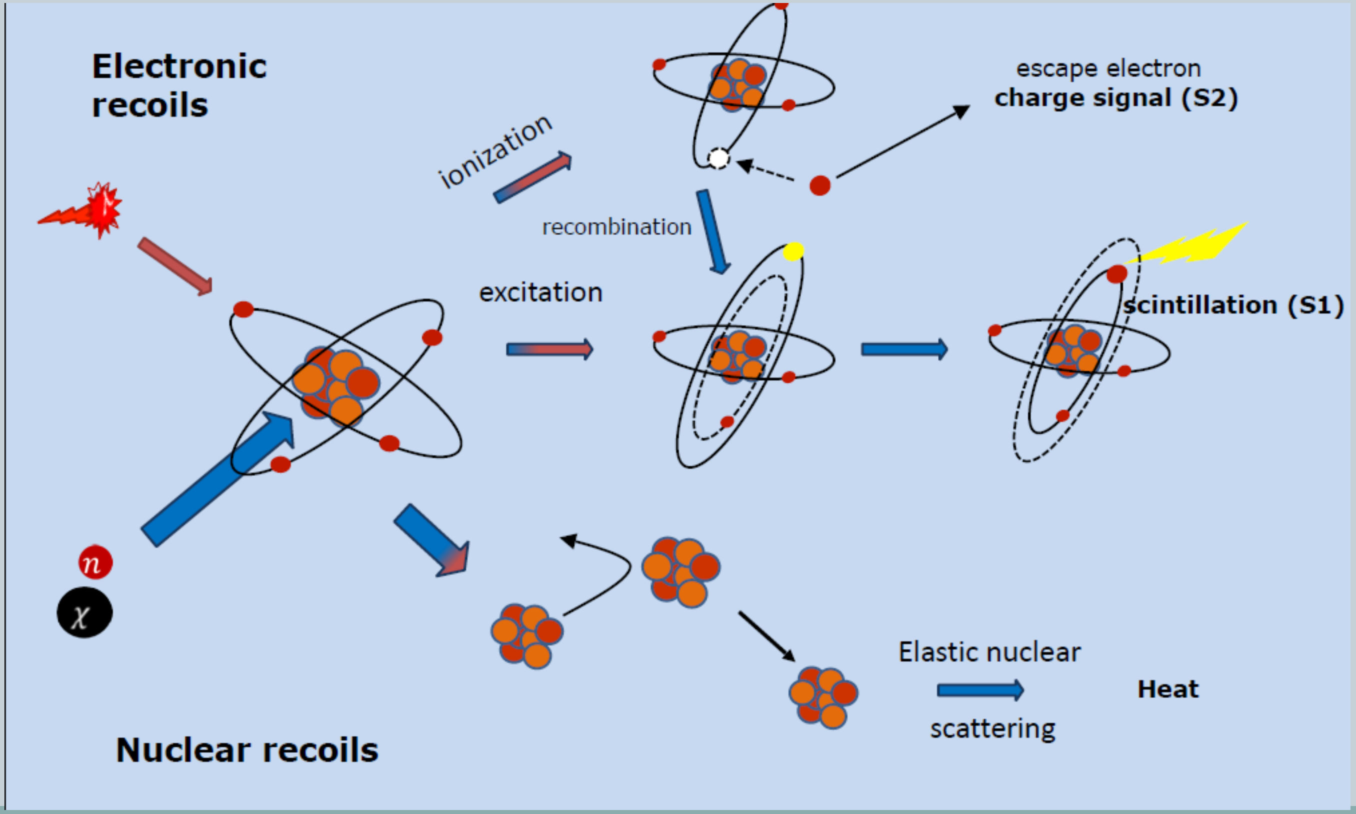




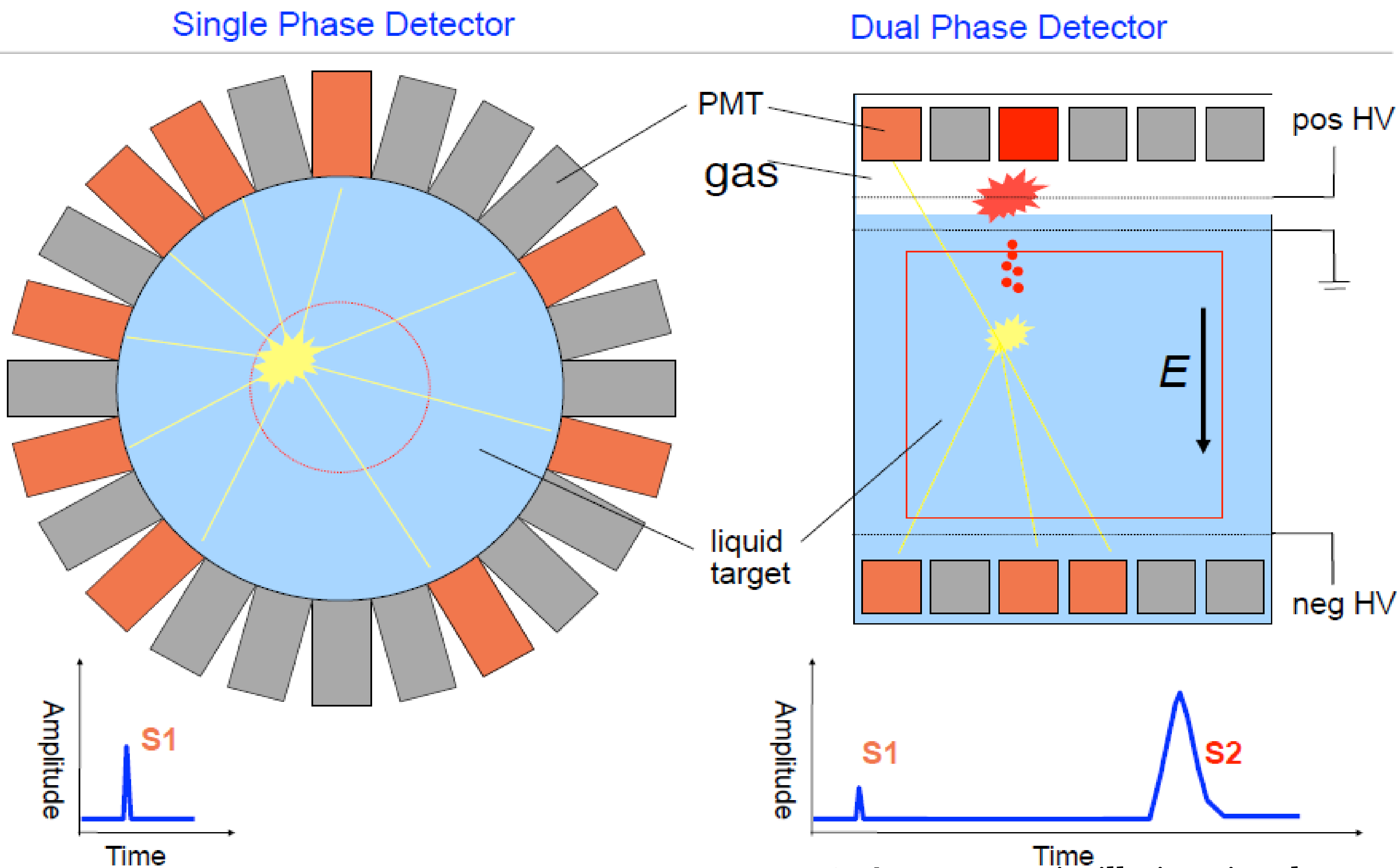
Noble Liquid Detector Concepts

Noble liquids: Xe, Ar, Ne

Detect either **light only** or **simultaneously light and charge signals** produced by a particle interaction in the sensitive liquid target



Noble Liquid Detector Concepts

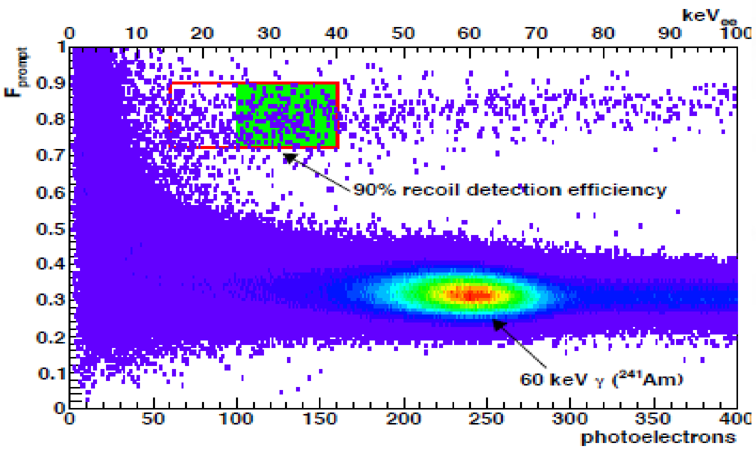


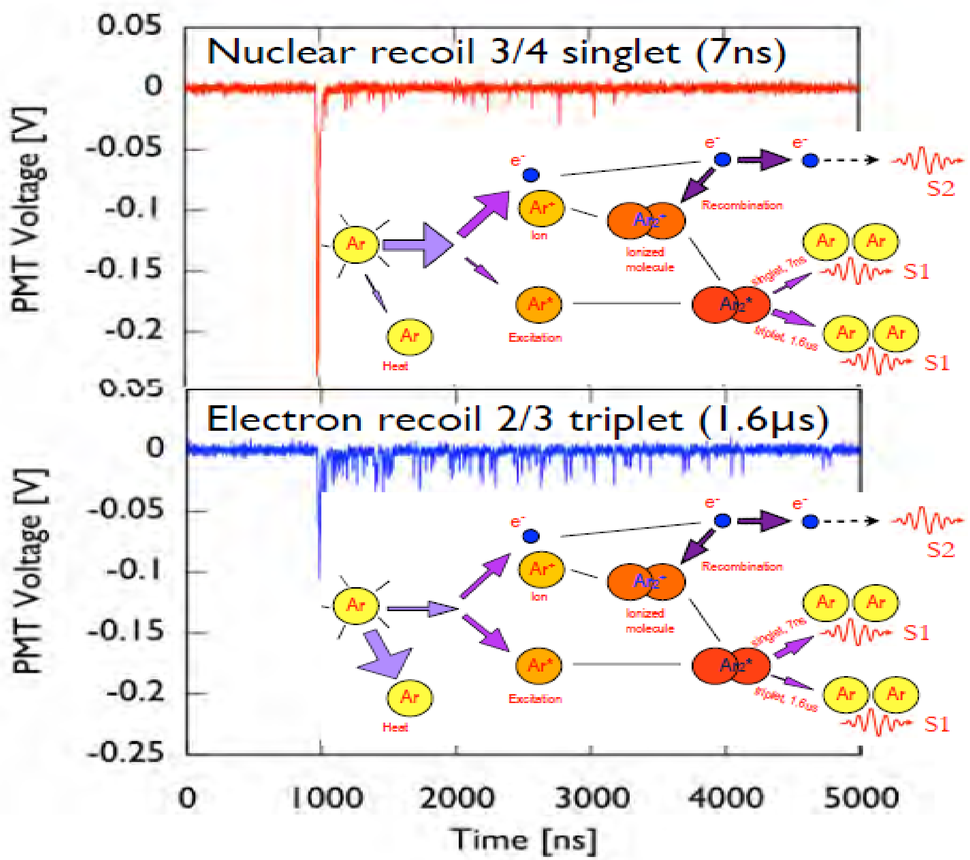
S1→ prompt scintillation signal

S2→ delayed (by the drift time) signal

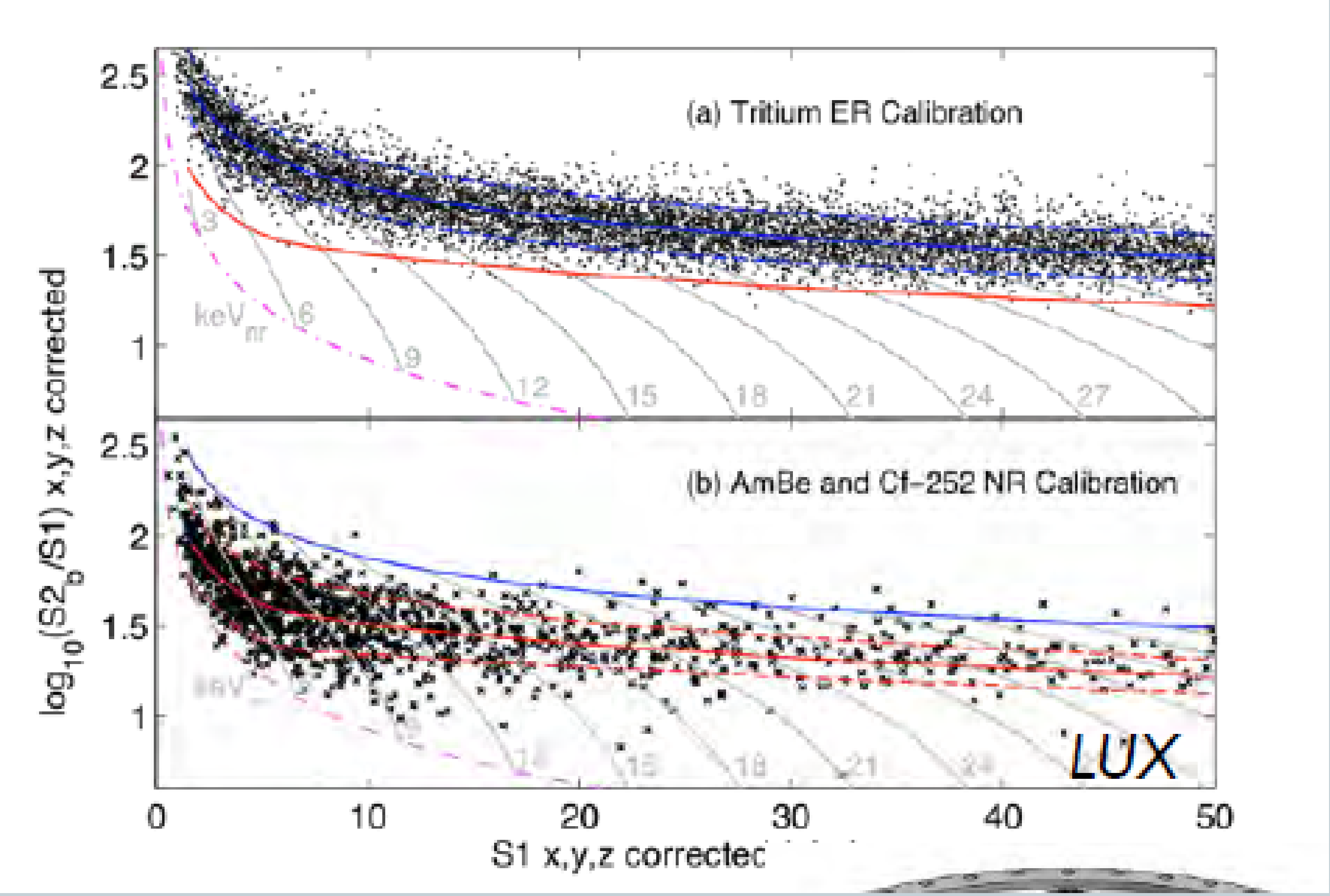
Pulse Shape Discrimination

- ^{39}Ar (β) 1Bq/kg
  - DEAP: 10^9 events in RoI / 3 year
- Recoil discrimination from prompt fraction: 0:200ns / 0:10μs





Signal/Background discrimination: dual phase



Noble Liquid Experiments

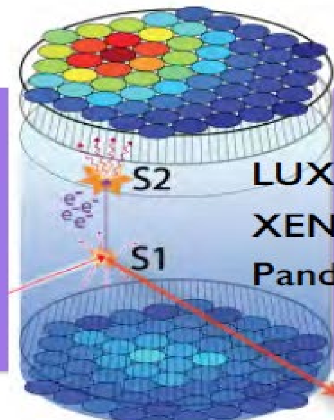
Single Phase

Dual Phase

DEAP
MiniCLEAN

DarkSide
ArDM

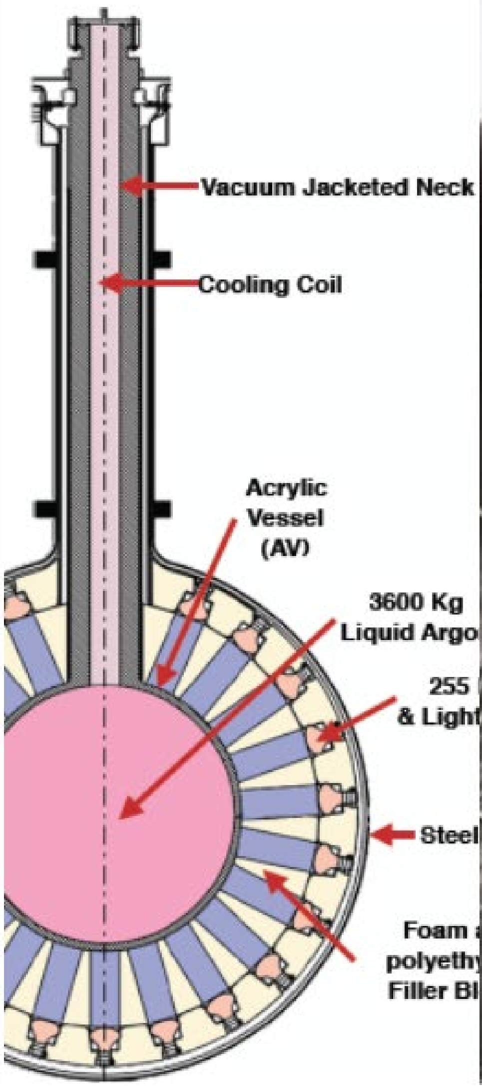
XMASS

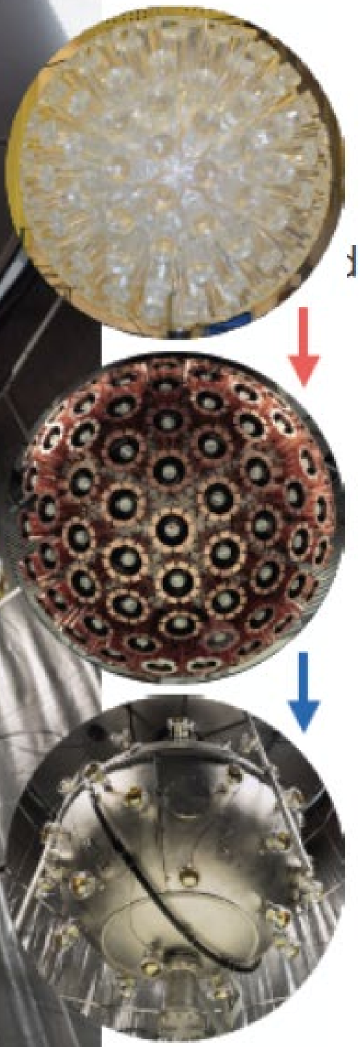


LUX/LZ
XENON-100/1T/nT
Panda-X

discharge tubes from http://periodictable.com

DEAP


Vacuum Jacketed Neck
Cooling Coil
Acrylic Vessel (AV)
3600 Kg Liquid Argo
255
& Light
Steel
Foam
polyethy
Filler Bl



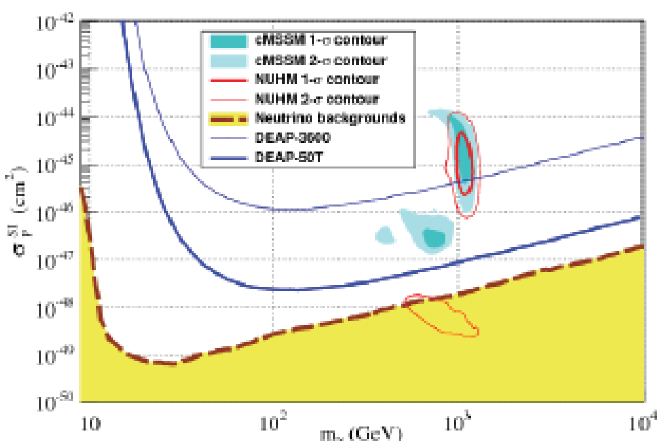
DEAP

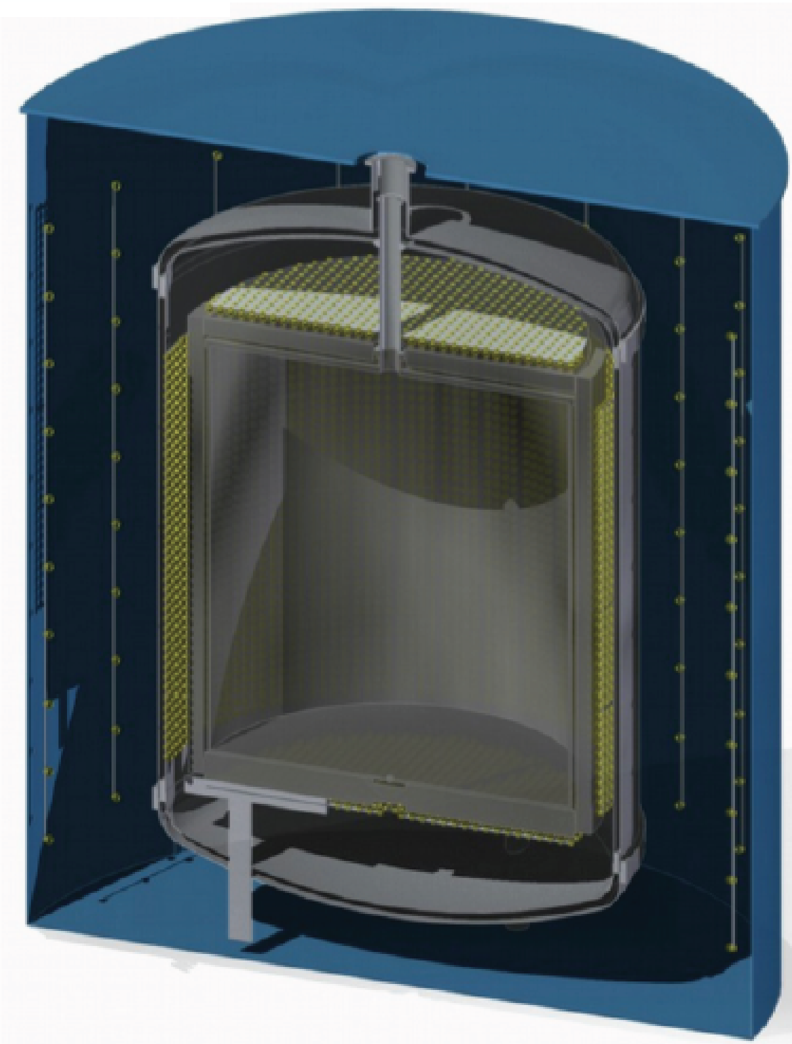
DEAP-3600

- Advanced calibration.
- Ready for first physics run.

DEAP-50T

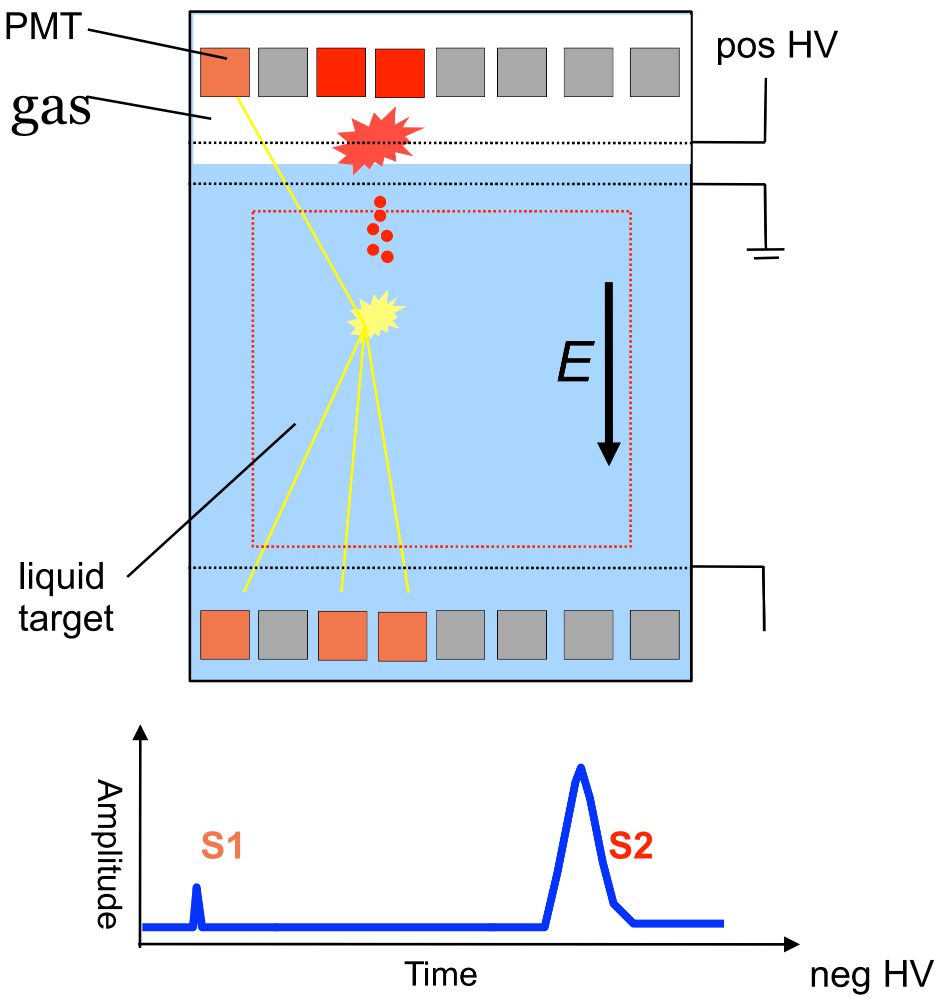
- Plan for a multi tonne DEAP. (150 tonne, 50 tonne fiducial).
- Approaching the neutrino-wall and probing the remaining parameter spaces.
- Possible transition from PMTs to SiPMs.
- Early design and R&D start up at Carleton University.

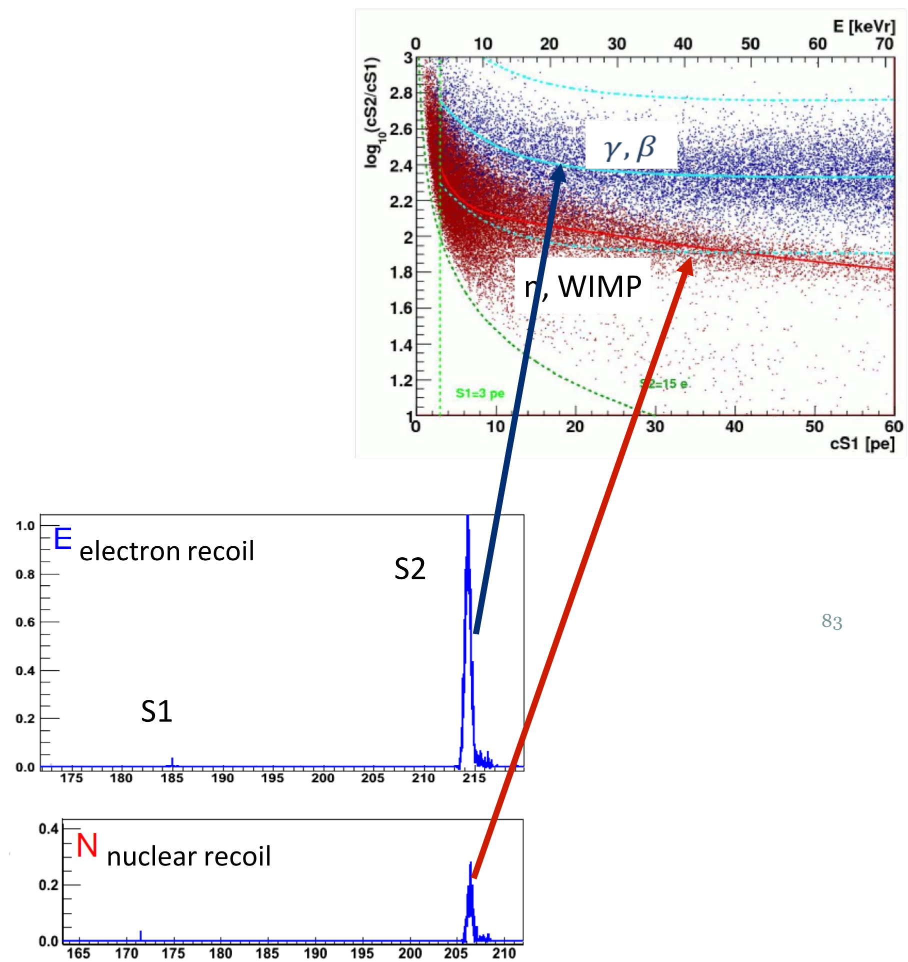




Noble Liquid Detector Concepts

Time Projection Chamber (TPC) a doppia fase





LXeTPCs: 50- 500 kg scale

XENON100 @ LNGS
Astropart. Phys. 35, 573 (2012)

- **62 kg** LXe,

- reached WIMP science goal
- inelastic DM, spin-dependent, modulation, axions, light WIMP, Bosonic Super WIMPs, ..
- still running as test facility for XENON1T/nT

LUX @ SURF
NIM A 704, 111 (2013)

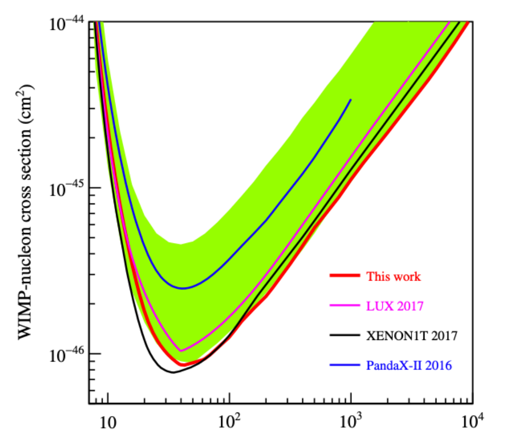
- latest result from 332 days presented at IDM2016
- **250 kg** LXe
- published first limit in 2013
- in 2013 - best world limit
- reanalysis published in 2016
- will be removed by 2017

PandaX-II @ CJPL
arXiv:1602.06563

- at present largest LXe TPC
- still taking data
  - new SS cryostat
    → lower radioactivity
  - TPC: 60cm×60cm, **400 kg** target

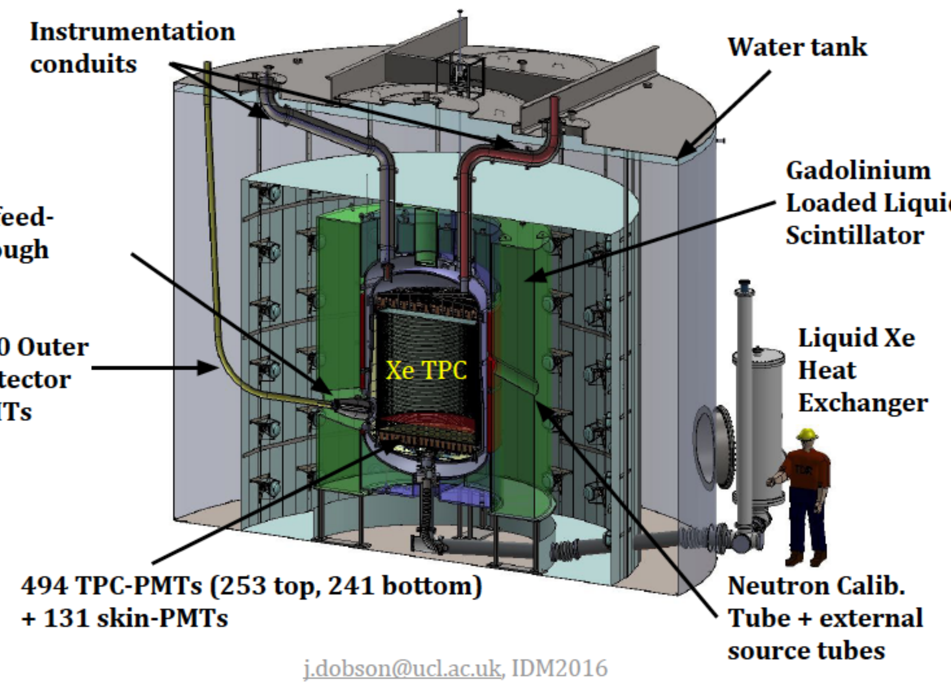
New result from 98.7 days:
- *Best upper limit :*
- *2.5 x 10^{-46} cm^2 at 40 GeV*

arXiv:1607.07400v1



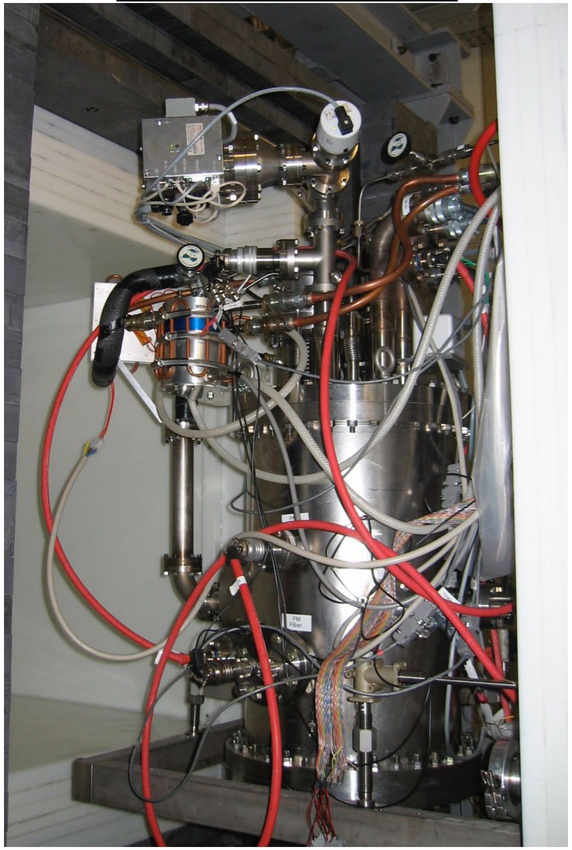
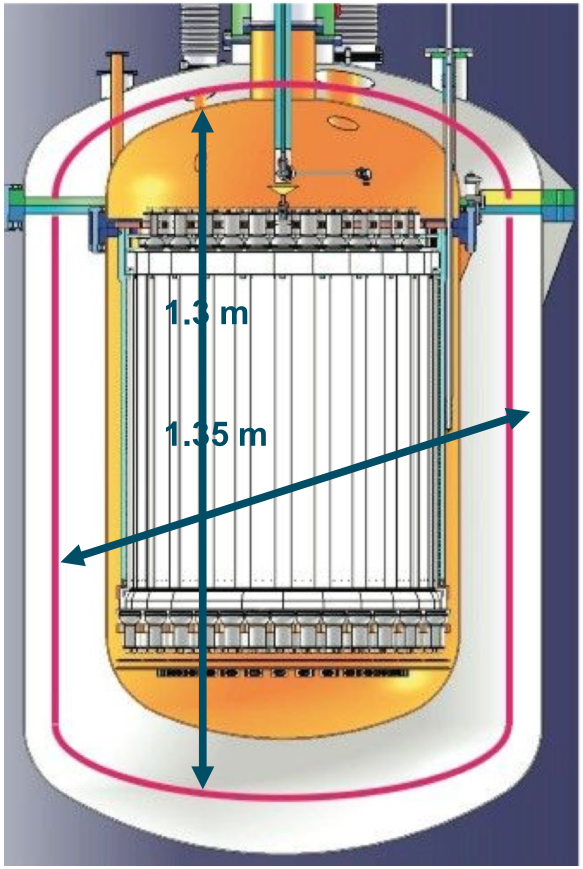
From LUX to LZ @ SURF

- Scale LUX by 40 in Fiducial
- New detector with 7 ton active LXe
- Aimed at 5.6 ton FV with combination of active LXe and LS veto
- Use same water shield of LUX
- Extensive screening campaign and MC simulations
- **Timeline**:
- 2017/18: prepare for surface / UG assembly at SURF
- 2019: start UG installation
- 2020: start operation by end of the year
- 2025+ : plan 5+ years of operation
- **Sensitivity Goal (1000 live days)**: 3x 10^{-48} cm^2 at 40 GeV



XENON @ LNGS - present and future

XENON
Dark Matter Project

2005-2007	2007-2015	2012-2022
		
XENON10	**XENON100**	**XENON1T/XENONnT**
15 cm drift TPC - 25 kg	*30 cm drift TPC - 161 kg*	*100 cm drift TPC - 3500 kg/7000 kg*
~10^{-43} cm^2	*~10^{-45} cm^2*	*~10^{-47} cm^2 / 10^{-48} cm^2*

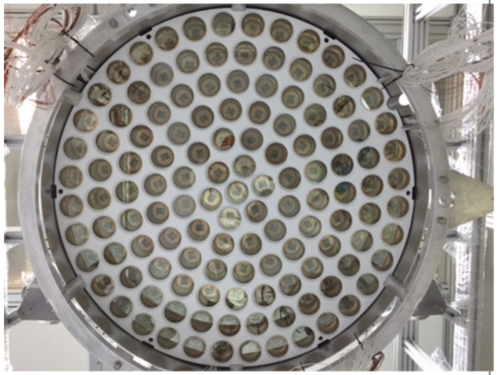
XENON - 1 ton@LNGS

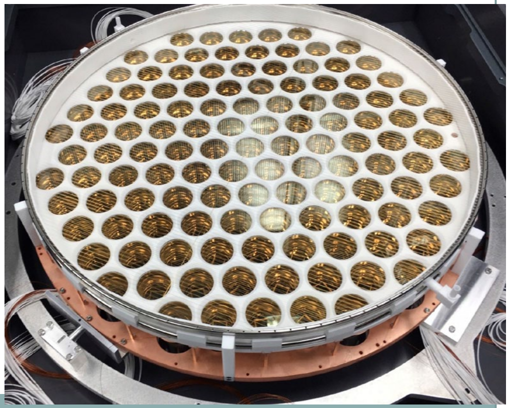
- **Science goal**: 100 x more sensitive than XENON100
- **Target/Detector**: 3.5 ton of Xe/ dual-phase TPC with 250 high QE - low radioactivity PMTs.
- **Shielding:** water Cherenkov muon veto.
- **Cryogenic Plants:** Xe cooling/purification/ distillation/storage systems designed to handle up to 10 ton of Xe. Upgrade to a larger detector ***(XENONnT)*** planned for 2018
- **Status:** All systems successfully tested. Commissioning of detector ongoing. First science run this Fall.
- **Sensitivity Goal: 2 x 10^{-47} cm^2 @ 50 GeV in 2ty**

The XENON1T experiment: inner detector

The TPC

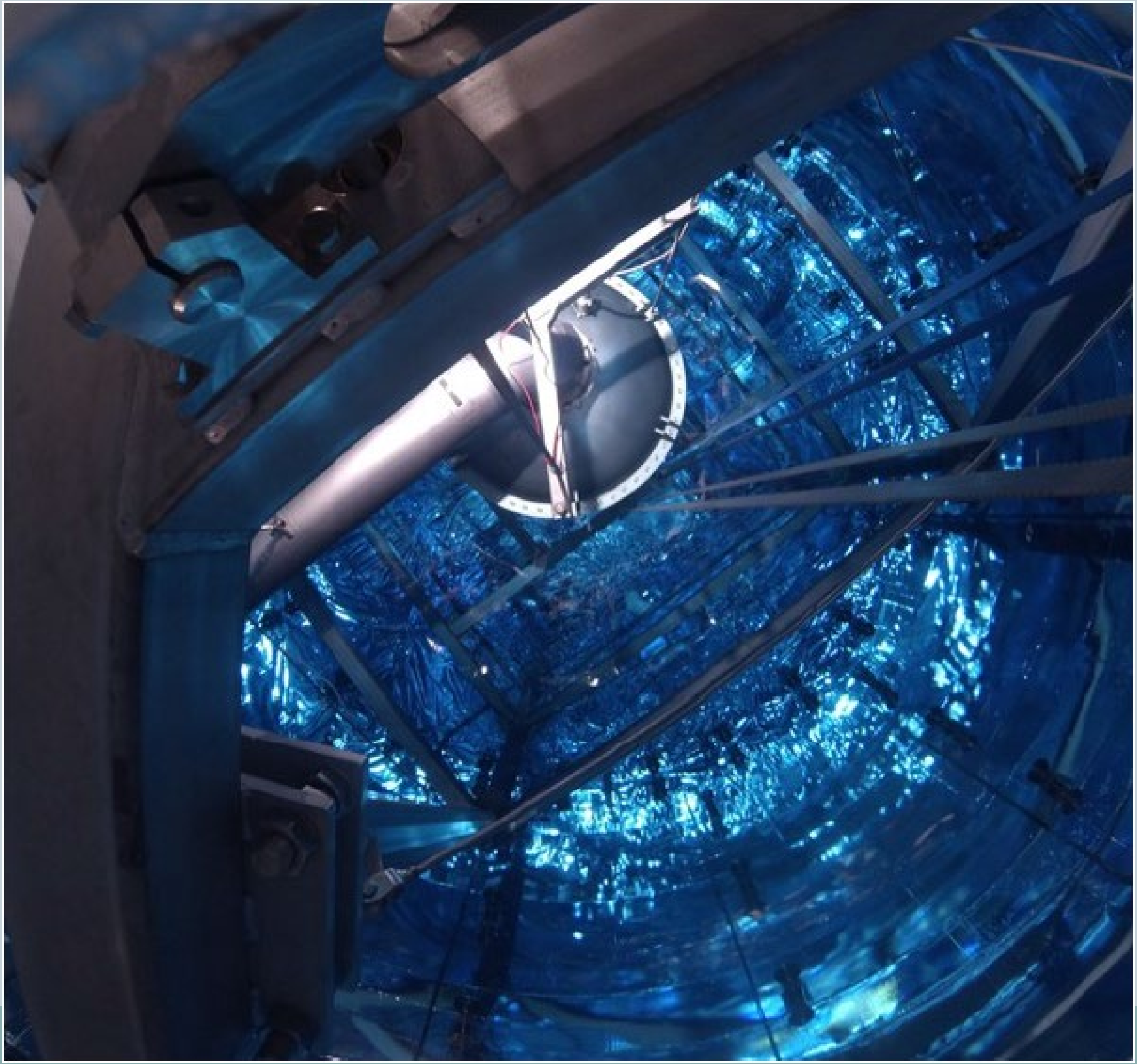
TPC installation underground





PMT arrays

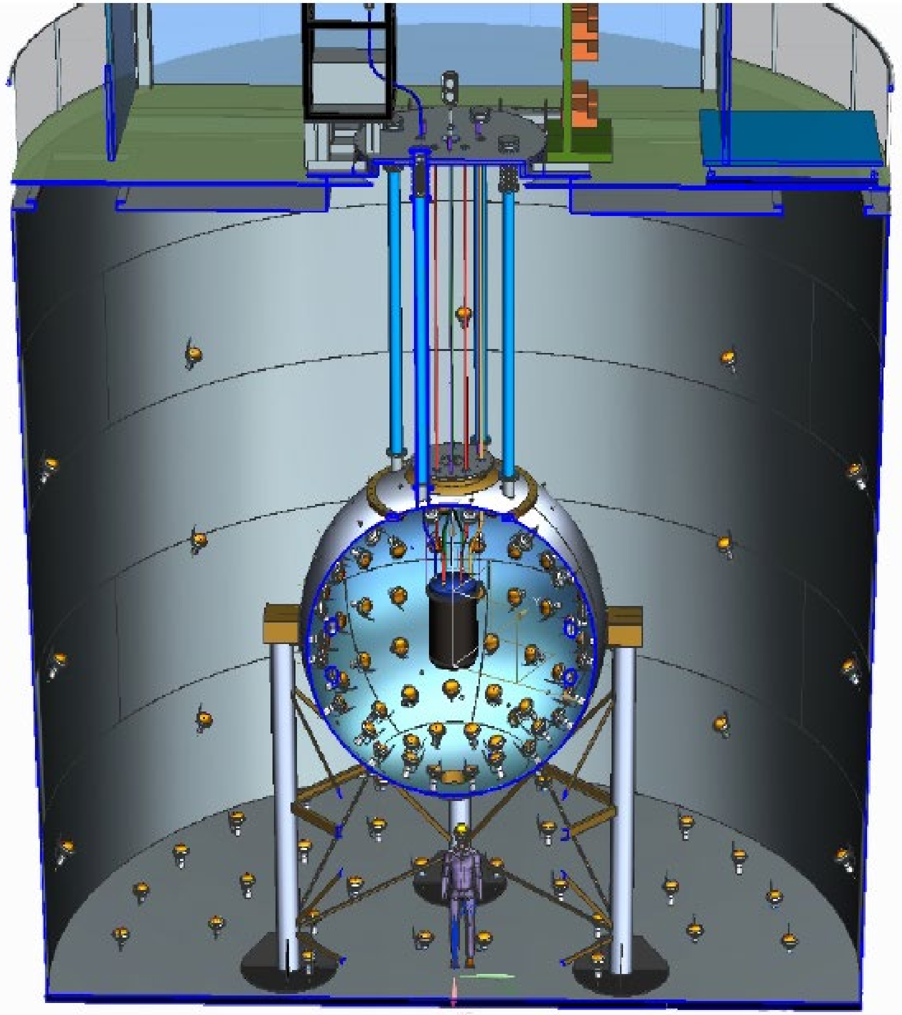
XENON – 1 ton@LNGS



Dark Side@LNGS

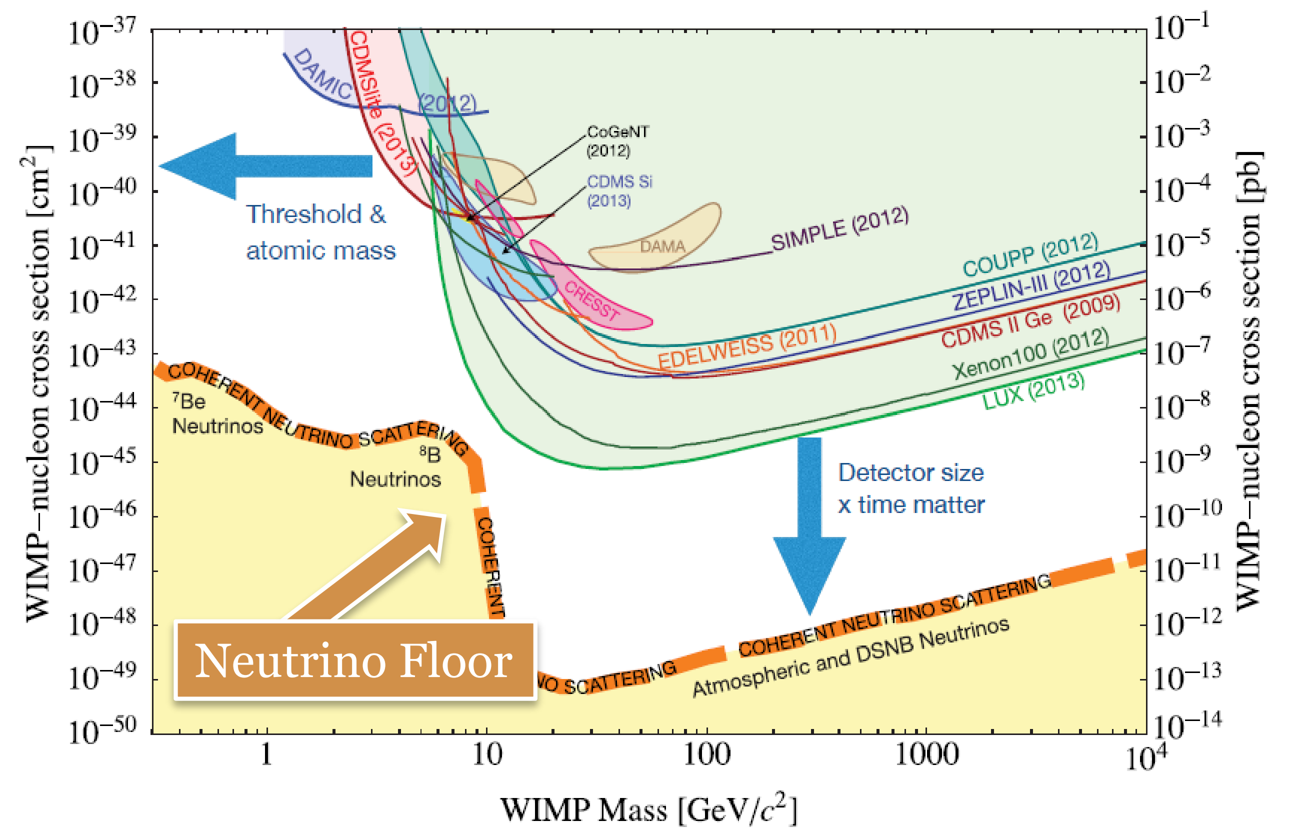
- Dual phase TPC with 46 kg 39Ar-depleted LAr (1400 background reduction factor) inside 30 tons LS neutron veto inside a 1000 tons water Cherenkov muon veto
- 1st result from 2616 kg d with UAr

  -> no event in search region . Still taking data
- Proposed **DS20k.** TDR in preparation. Large R&D effort on SiPMs and other technologies.
- Construction of the very large distillation facility (350 m column) placed inside a coal mine (Seruci, Sardinia) has started.



Future?

1) Solve DAMA tension
2) Explore Low Mass Region
3) Explore Low Cross Section Region
4) … and the Neutrino Floor?



Future: DAMA tension

M. Messina@NOW2016

Upcoming NaI Projects to directly test DAMA

@LNGS

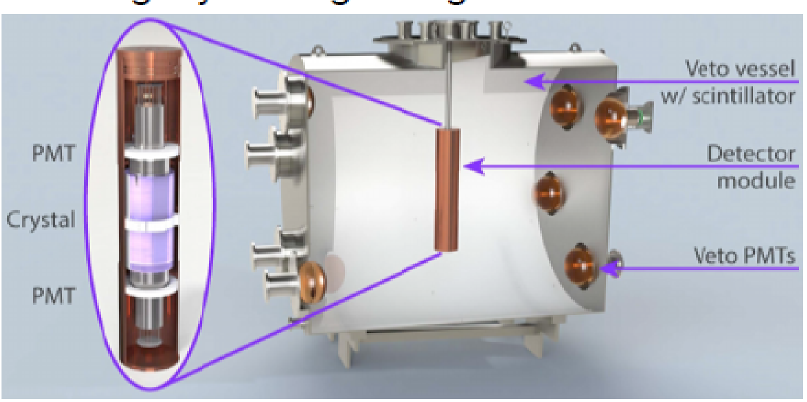
SABRE

*S*odium-iodine with *A*ctive *B*ackground *RE*jection

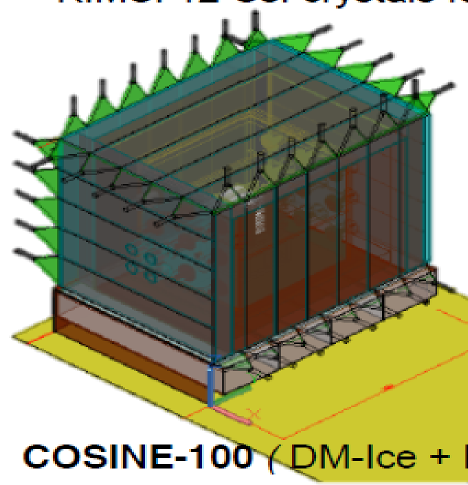
Strategy:

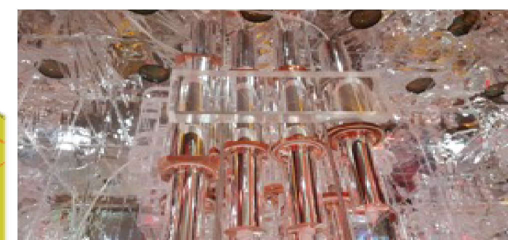
- lower background: better crystals, PMTs
- liquid scintillator veto against ^{40}K (factor 10)
- lower threshold (PMTs directly coupled to NaI)
- Eliminate seasonal effects :North (LNGS) and South Hemisphere(Australia: Stawell Underground Physics Laboratory)

- *Status*: tests with 2.5 kg crystal ongoing and the 5 kg crystal is growing



Predecessors:
DM-Ice: 17 kg 2 Crystals of 8.5 kg NaI@ South Pole
KIMS: 12 CsI crystals for 104.4 kg @ Y2L, Korea





COSINE-100 (DM-Ice + KIMS) **@Yangyang**
arxiv:1602.05939

.107 kg of NaI pure Crystal, LS veto and Pb shield - commissioning

ANAIS @ Canfranc
113 kg in Pb shield

→ start of data taking soon
→ background 2-3x DAMA (no veto)

Future: Low Mass Region

M. Messina@NOW2016

EDELWEISS - SuperCDMS - CRESST: the race for the low WIMP mass region

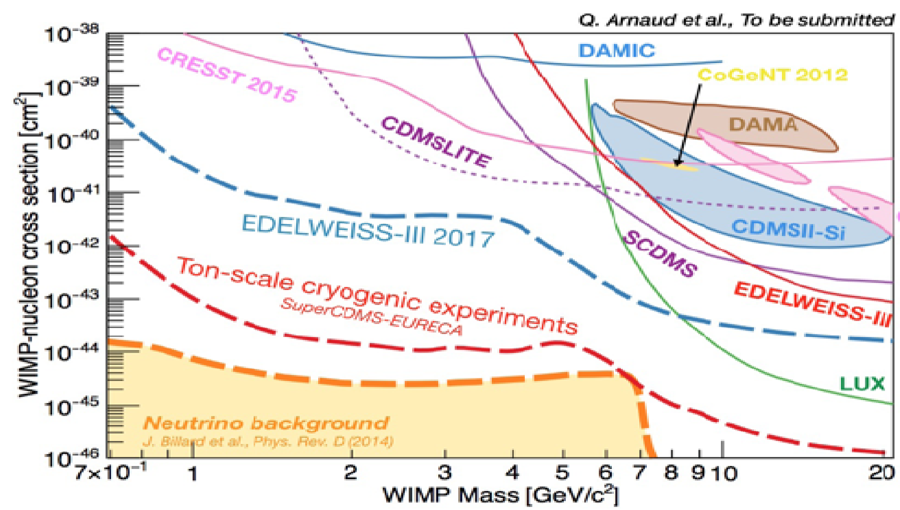
@LNGS

SuperCDMS @SNOLAB
read phonons and charges from Ge and Si crystals
•aim for 50 kg-scale experiment (cryostat can accomodate 400 kg)
low threshold → focus on 1-10 GeV/c² mass range
• Improvements: deeper lab, better materials, better shield, improved resolution, upgraded electronics, active neutron veto?
• 100 x 33.3 mm ZIPs (1.4 kg Ge, 0.6 kg Si) → fabrication protocol established
2018-20: construction
2020: begin data taking

EDELWEISS @ LSM : arXiv:1603.05120
read phonons and charges from Ge crystals
2016: largest (20 kg) Ge array in operation
2017: 350 kg×d in HV mode to optimize 1-10 GeV sensitivity
Future: ton scale together with CDMS (EURECA)

EPJ C, 76, 25 (2016)

CRESST II @ LNGS:
read phonons and scintillation light from $CaWO_4$
successful background reduction;
data taking 2013-2015, 52 kg×d
2016: lowest thresh 300 eVnr
Record sensitivity below 1.7 GeV WIMP mass



Future: Low Cross Section Region

From LUX to LZ@SURF …
From Xenon-1ton to Xenon –nton…
From DS50 to DS20k…

@LNGS

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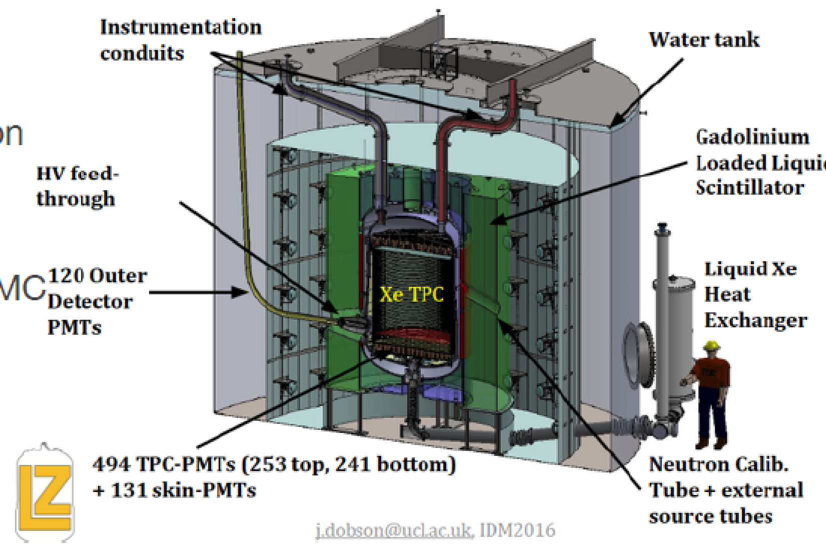
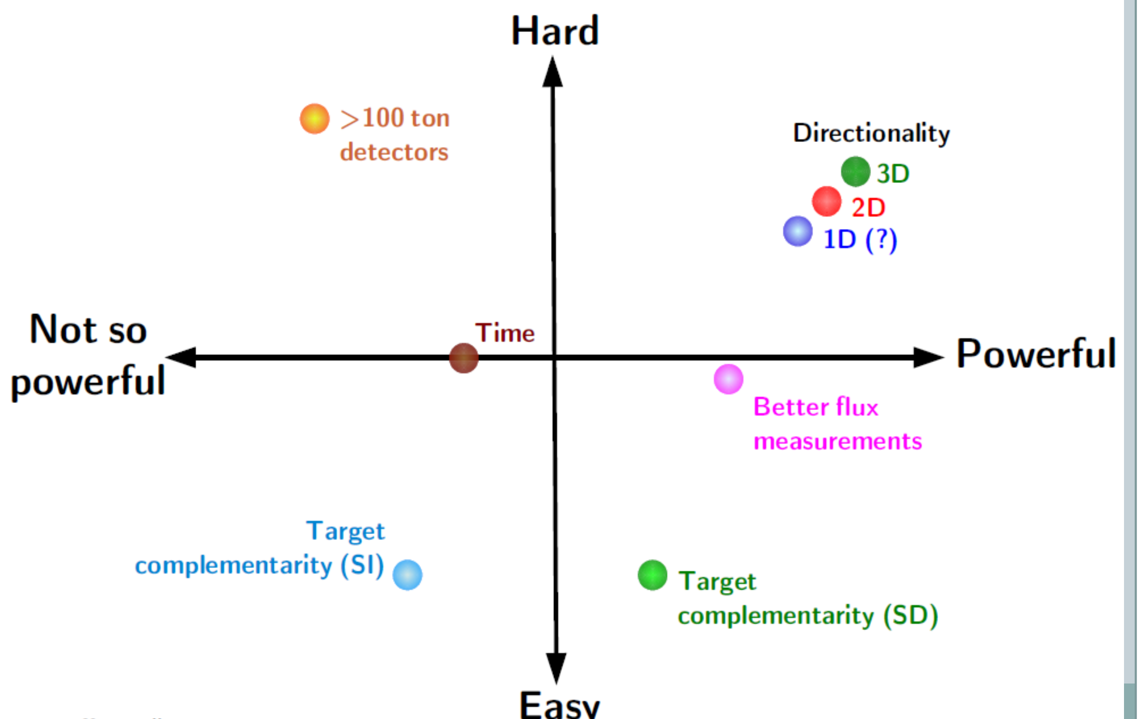


Future: the Neutrino Floor

Neutrino floor not the final limit to direct detection searches

Ciaran A. J. O'Hare @IDM 2016

- There are various strategies for probing below the floor
  - ➔ Better neutrino flux estimates
  - ➔ Larger detectors
  - ➔ Target complementarity
  - ➔ Annual modulation
  - ➔ Direction dependence



NB: "difficulty" axis somewhat subjective

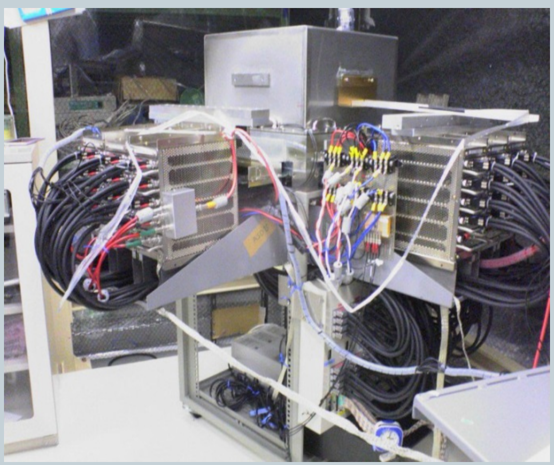
Directional DM searches

Current approach:

low pressure gaseous detector

- Targets: CF_4, CF_4+CS_2, $CF_4 + CHF_3$
- Recoil track length O(mm)
- Small achievable detector mass due to the low gas density

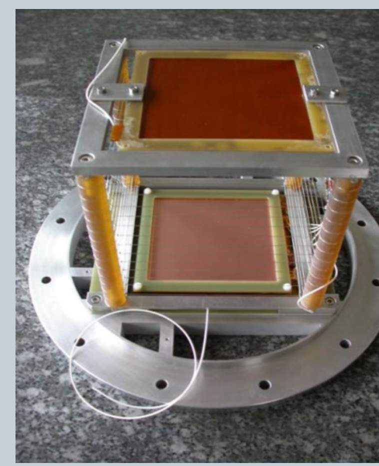
⇒Sensitivity limited to spin-dependent interaction



NEWAGE@ Japan

DM-TPC@ USA

DRIFT @ UK



MIMAC@ France

Directionality@LNGS

The NEWS idea: use solid target:

- Large detector mass
- Smaller recoil track lenght O(100 nm)

Nuclear Emulsion based detector acting both as target and tracking device

NIT: Nano Imaging Tracker , AgBr crystal size ~ 40 nm

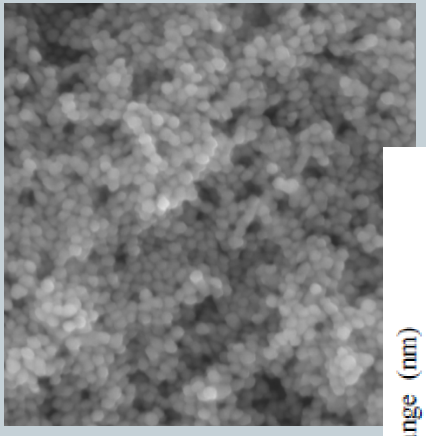
Natsume et al, NIM A575 (2007) 439

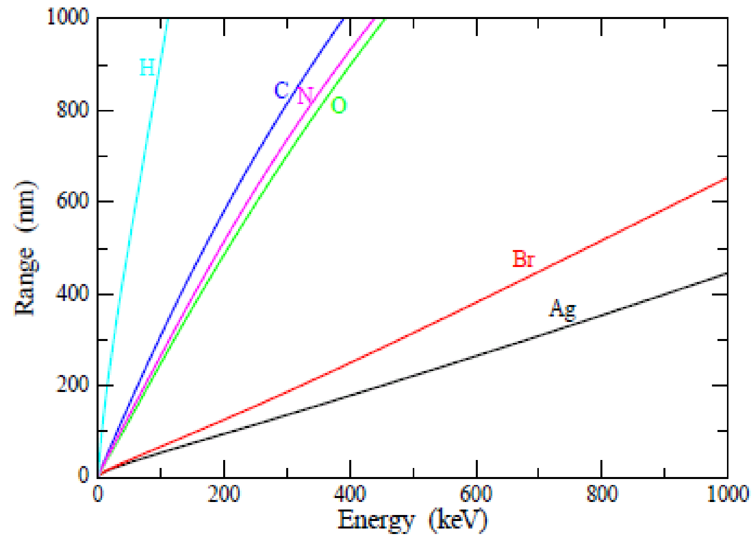
Constituent	Mass Fraction
AgBr-I	0.78
Gelatin	0.17
PVA	0.05

(a) Constituents of nuclear emulsion

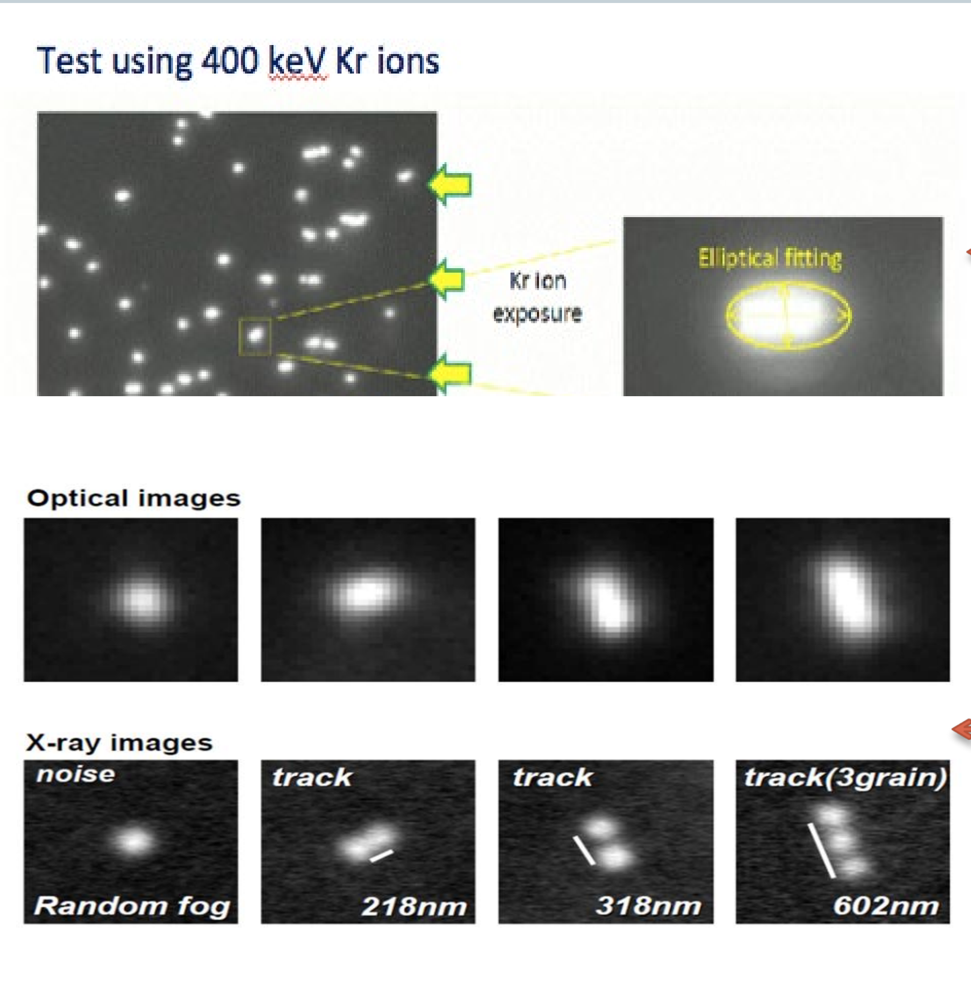
Element	Mass Fraction	Atomic Fraction
Ag	0.44	0.12
Br	0.32	0.12
I	0.019	0.003
C	0.101	0.172
O	0.074	0.129
N	0.027	0.057
H	0.016	0.396
S	0.003	0.003

(b) Elemental composition



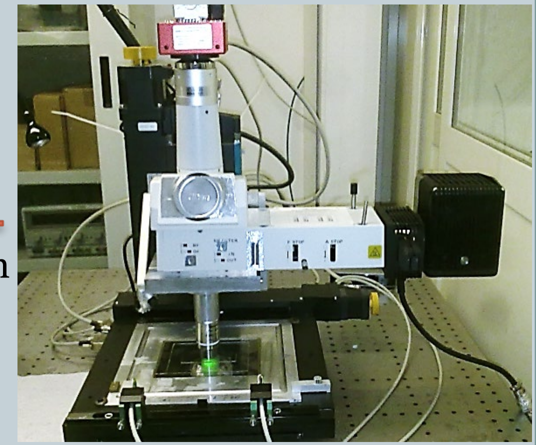


Directionality@LNGS



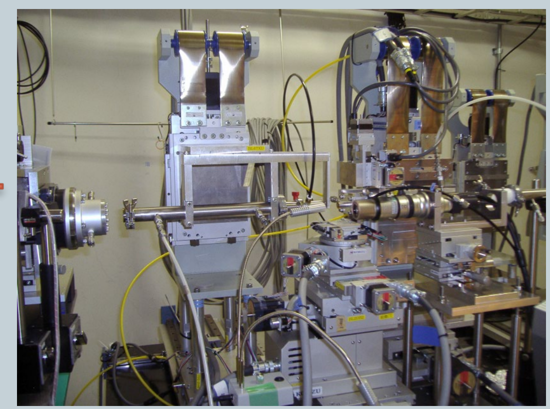
1) Signal preselection

Resolution: 200 nm
Speed: ~20 mm²/h



2) Signal confirmation

Resolution: 30 nm
Speed:
~ (200μm)²/100 s

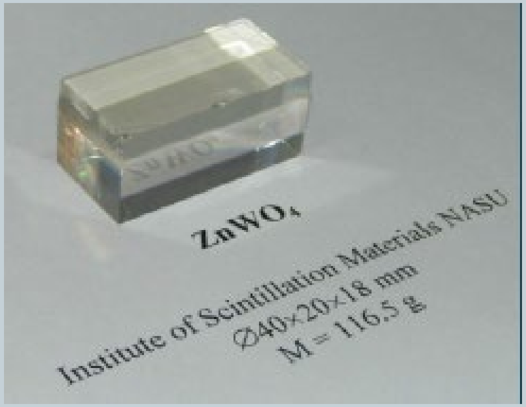


Directionality@LNGS

1) ADAMO: Anisotropic Scintillator

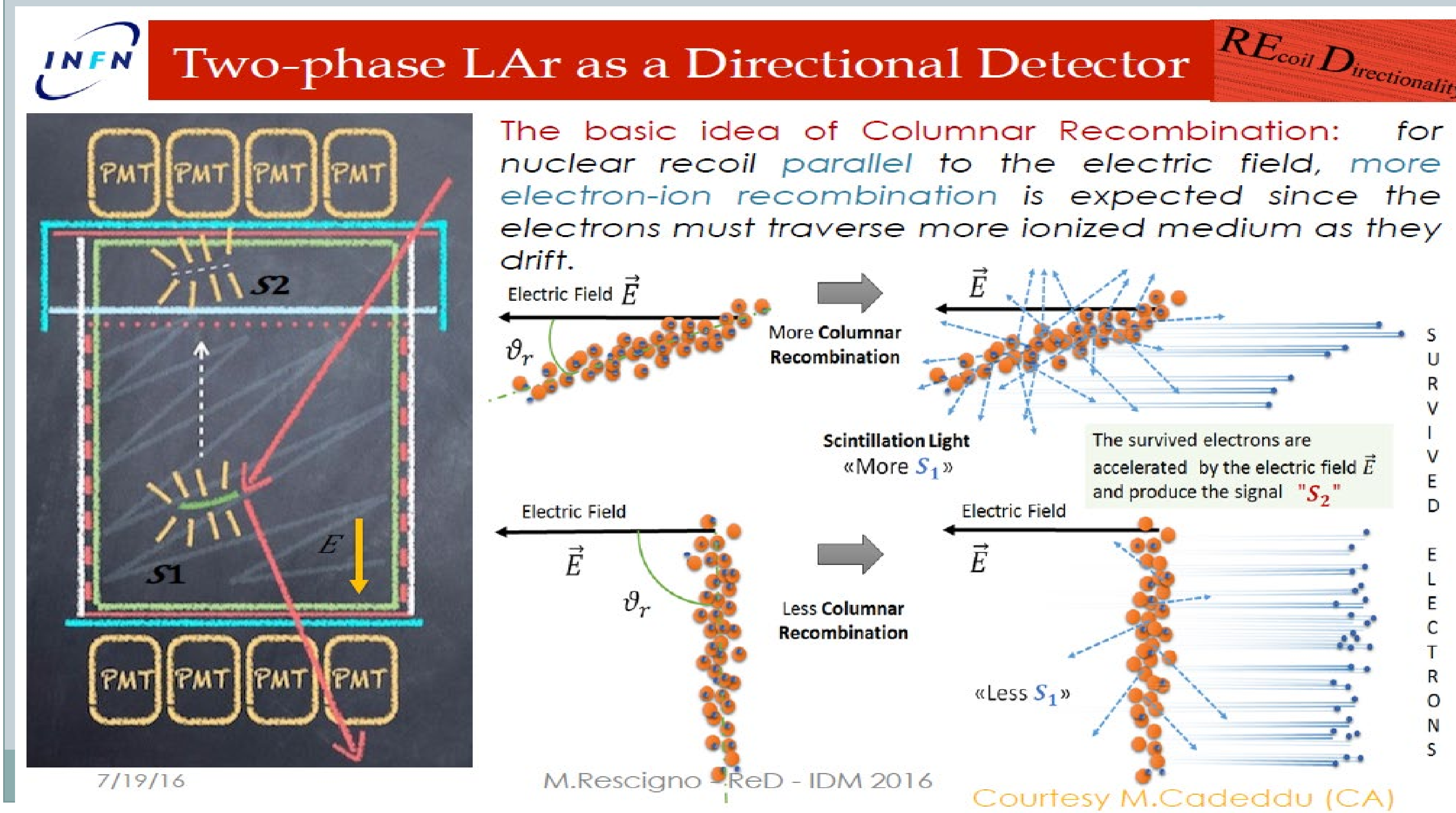
- for heavy particles the light output and the **pulse shape** depends on the particle impinging direction with respect to the crystal axes
- for γ/e the light output and the pulse shape are isotropic
- **ZnWO4 anisotropic scintillator:** a very promising

Detector (**Eur. Phys. J. C 73 (2013) 2276)**



Directionality@LNGS

2) RED



Conclusioni

- Dark Matter is there!
- WIMPs promising candidates
- So far, no convincing evidence of a dark matter particle was found
- However, DAMA/LIBRA experiment is claiming an observation of an annual modulation since long time.

Future

- New experiments, based on NaI technology, are getting ready to run in view of clarifying once and for all the nature of the DAMA/LIBRA longstanding annual modulation.
- New programs on-going to search both for low WIMP mass and low cross section interactions: reach neutrino fllor this/next
- Directionality!

DM discovery is waiting for young brilliant physicist!

THE END