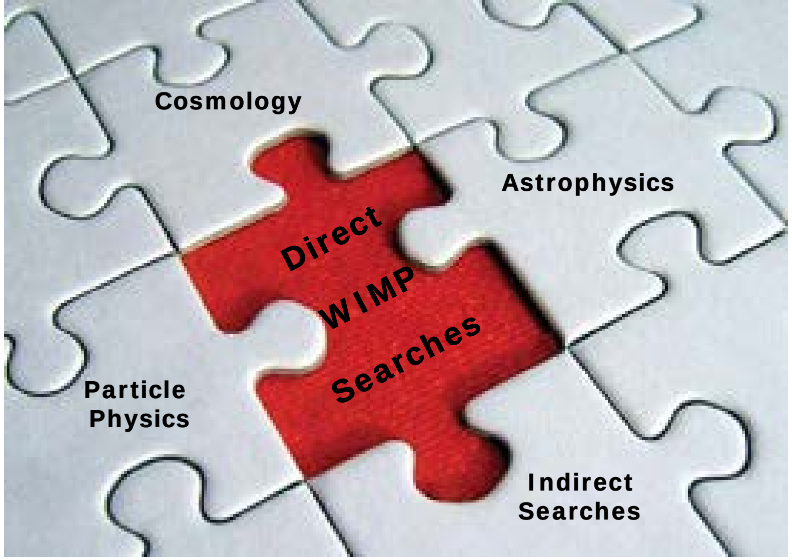
Direct Dark Matter searches: overview

Evgeny Yakushev

JINR, Dubna

- Motivation
- How and what to search
- Experimental status
- Outlook

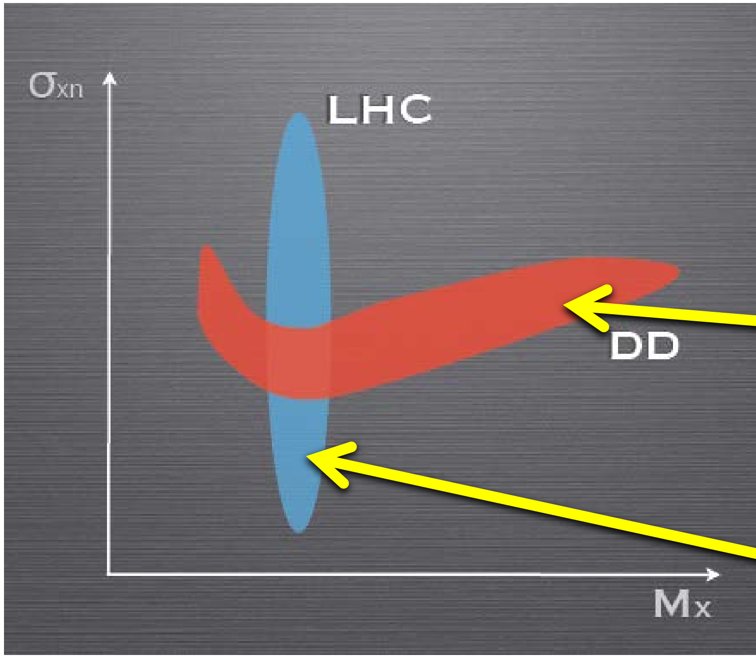
Dark Matter puzzle

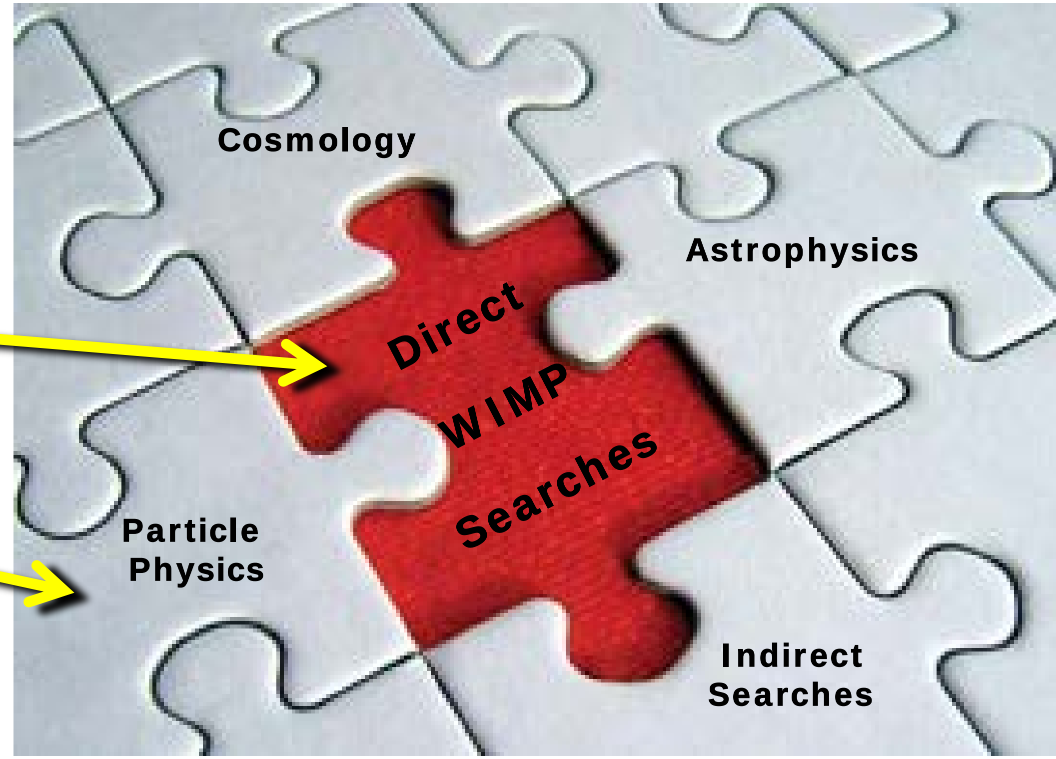


- Cosmology
  - non-baryonic DM in the early Universe *[WMAP, Planck, …]*
- Astrophysics
  - Gravitational probes at galactic/cluster sizes
  - WIMPs present in our Galaxy with density ~0.3 GeV/cm^3
- Particle Physics
  - **Thermal relics WIMPs appear as natural consequence of SUSY *[LHC]***
- Indirect Searches
  - Annihilation decay products:

    too many phenomena too be decisive (?), many experiments with different approaches
- **Direct Searches**:
  - background free measurements
  - winter/summer modulation measurements
  - **Is DM particles of the halo are those can be produced at LHC?**

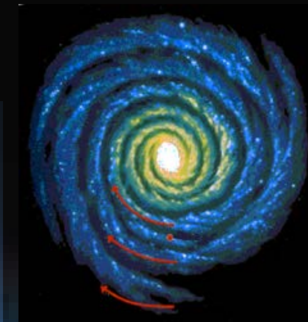
Dark Matter searches

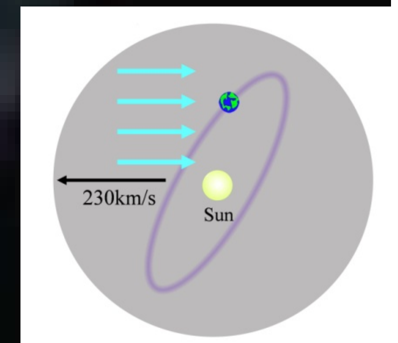


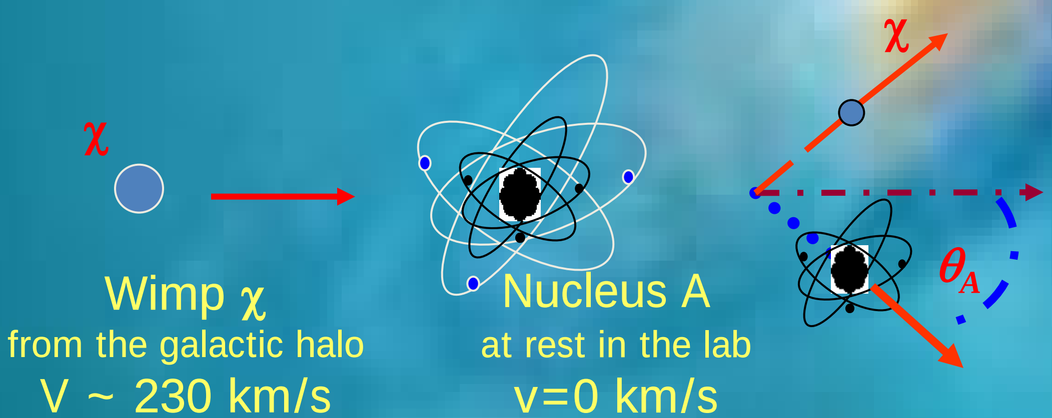


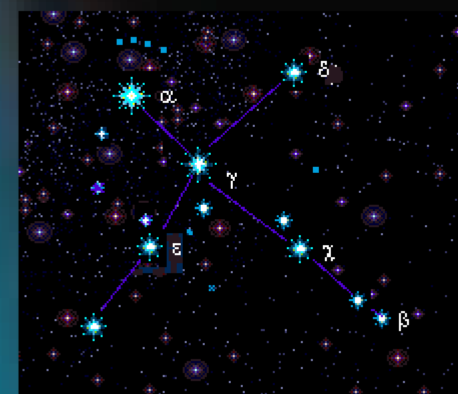
How to detect

According to models of cosmological structure formation, the luminous matter of galaxies is gravitationally bound to a more massive halo of Dark Matter. Its local density is 0.3 GeV/cm^3. If Dark Matter indeed consist from WIMPs, its expect to recoil on the ordinary matter moving through Dark Matter halo (Solar System around Galactic Centre).
A process that can be used for WIMP detection is the elastic scattering of WIMP off nuclei. The energy deposited in the detector during the WIMP elastic scattering can be measured.









$$E_R = E_\chi \frac{4\, M_A\, M_\chi}{(M_A + M_\chi)^2} \cos^2\theta_A$$

E_R < 100 keV !!!

$$\frac{Rate}{Mass} \approx \rho_{wimp} \times f(Velocity) \times \frac{A}{M_{wimp}} \sigma_{wimp-nucleon} \times F(Coherence)$$

Astrophysics:

- *Lewin&Smith [Astrop 6 (1996) 87] agreement for comparison of experiments*
- ρ_{wimp} = 0.3 GeV/c²/cm³

  … even there is the updated value: 0.39±0.02 [Ullio+Catena 0907.0018]
- Spherical isothermal halo : $v_{WIMP} \sim v_{SUN} \sim$ 230 км/сек

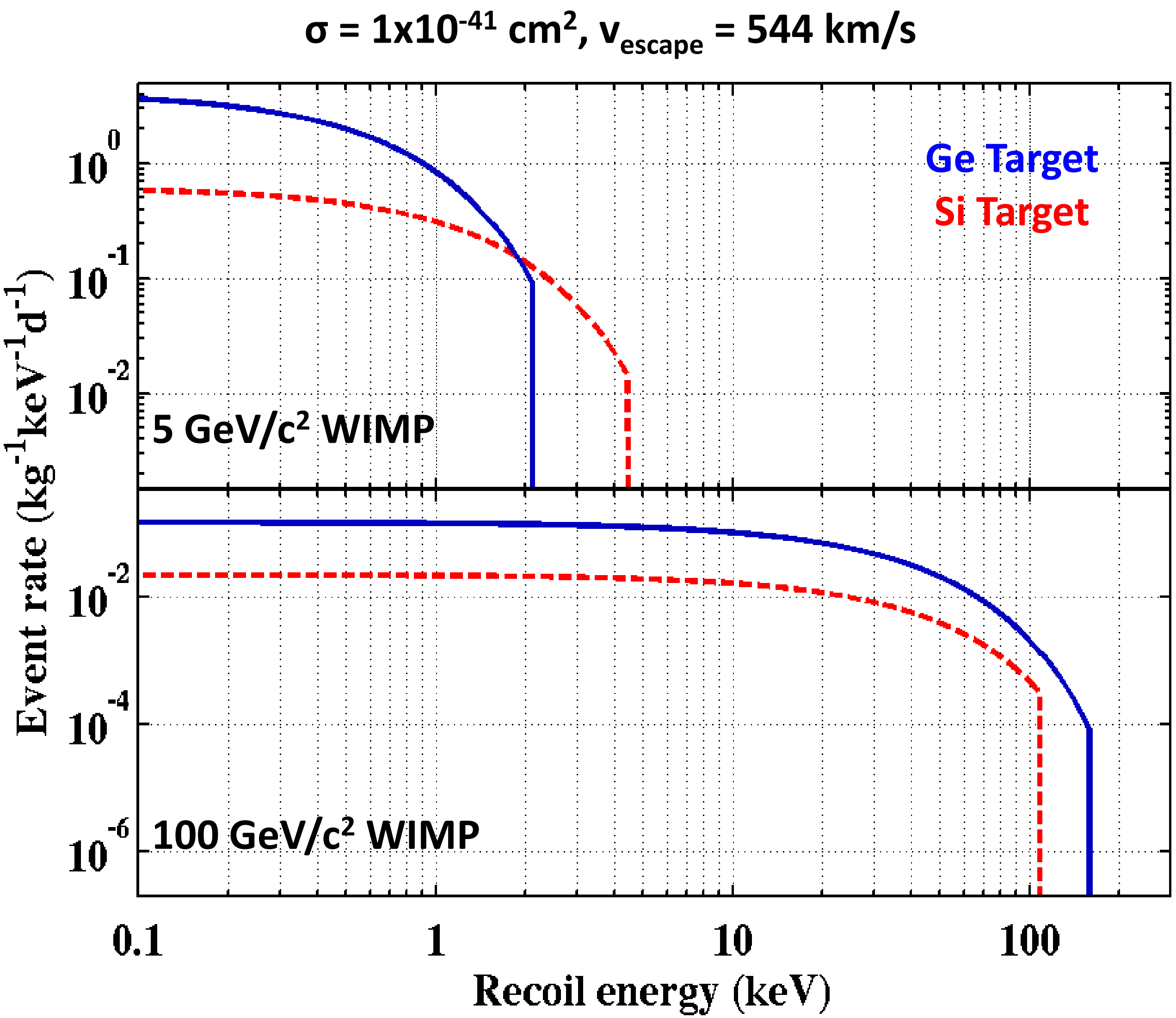
  … despite the fact that more complex halo models exist and can more accurately reflect the reality

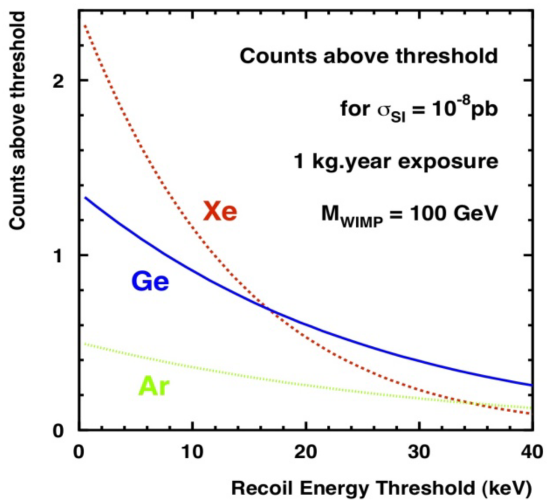
Nuclear and particle physics:

- Free parameters / theoretical predictions : M_{WIMP}, $\sigma_{WIMP\text{-}nucleon}$
  - Extrapolation WIMP-quark -> WIMP-nucleon:
- Other factors (Coherence):
  - ~A² for scalar interaction (SI is dominant for *A>~20*)
  - ~J(J+1) for axial interaction (SD)
  - Nuclear form factor (suppresses A² gain for large A)

Maxwellian (exponential) distribution for WIMPs

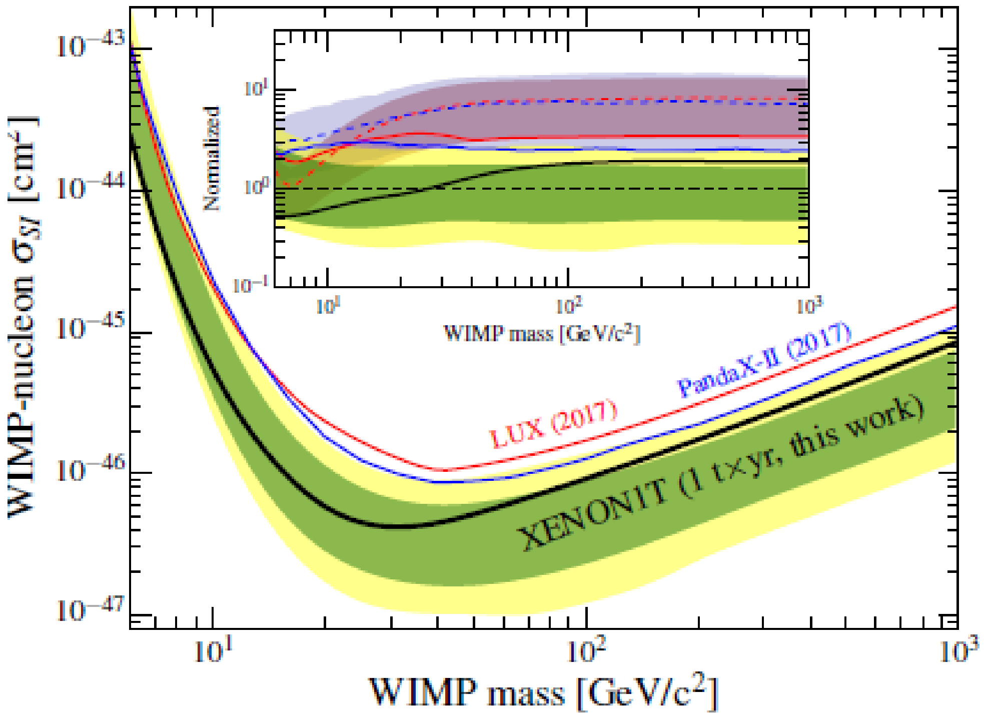
→ Exponential shape for the recoil spectrum, rather similar to background !!





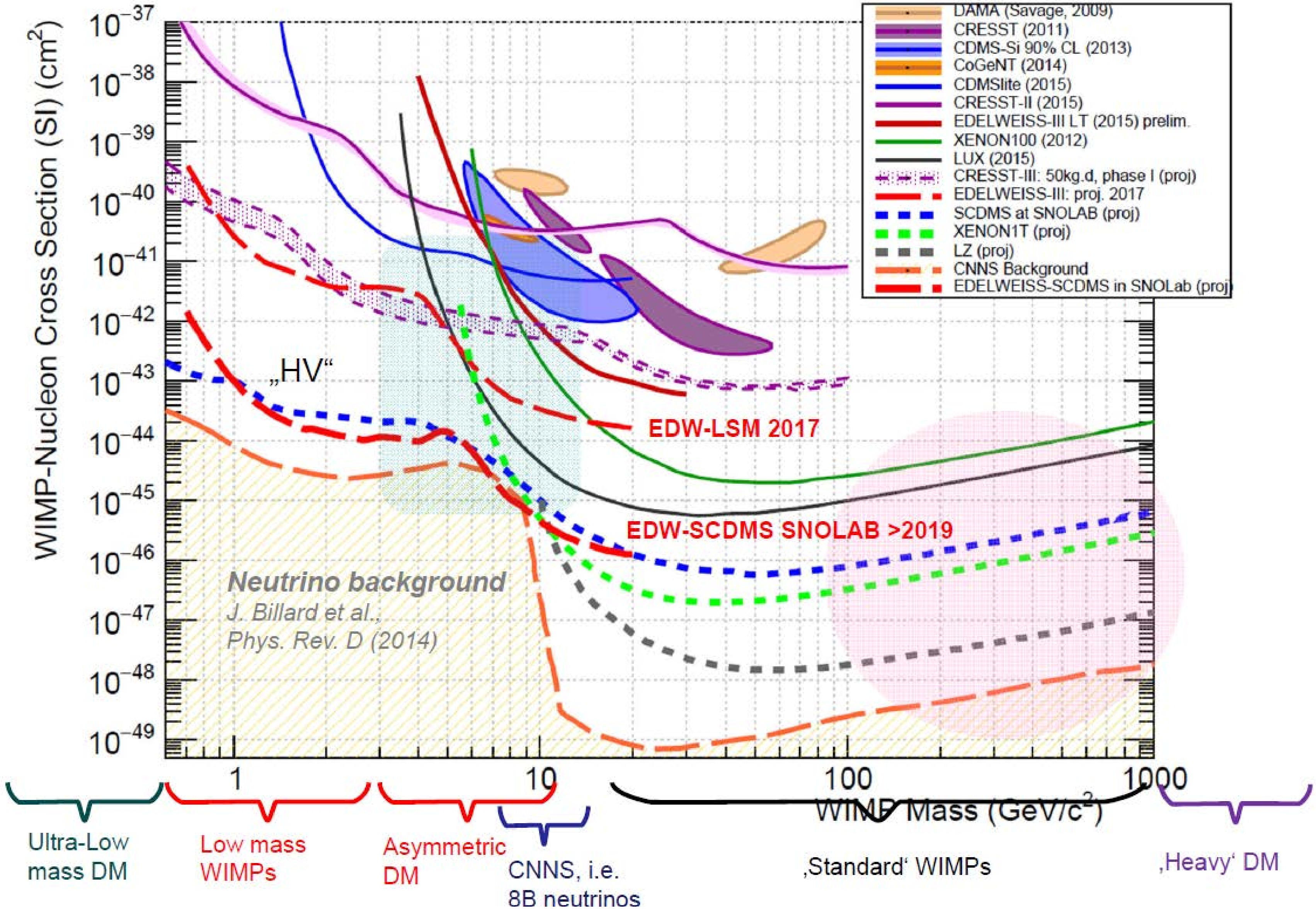
An increasing gain of interest for the search of low-mass, very-heavy WIMPs, other exotics

- Non evidence yet for SUSY at the LHC;
- New theoretical approaches favoring lighter candidates;
- No WIMP signals in the "expected" region;
- Controversial results in the region around and below of 10 GeV/c^2.



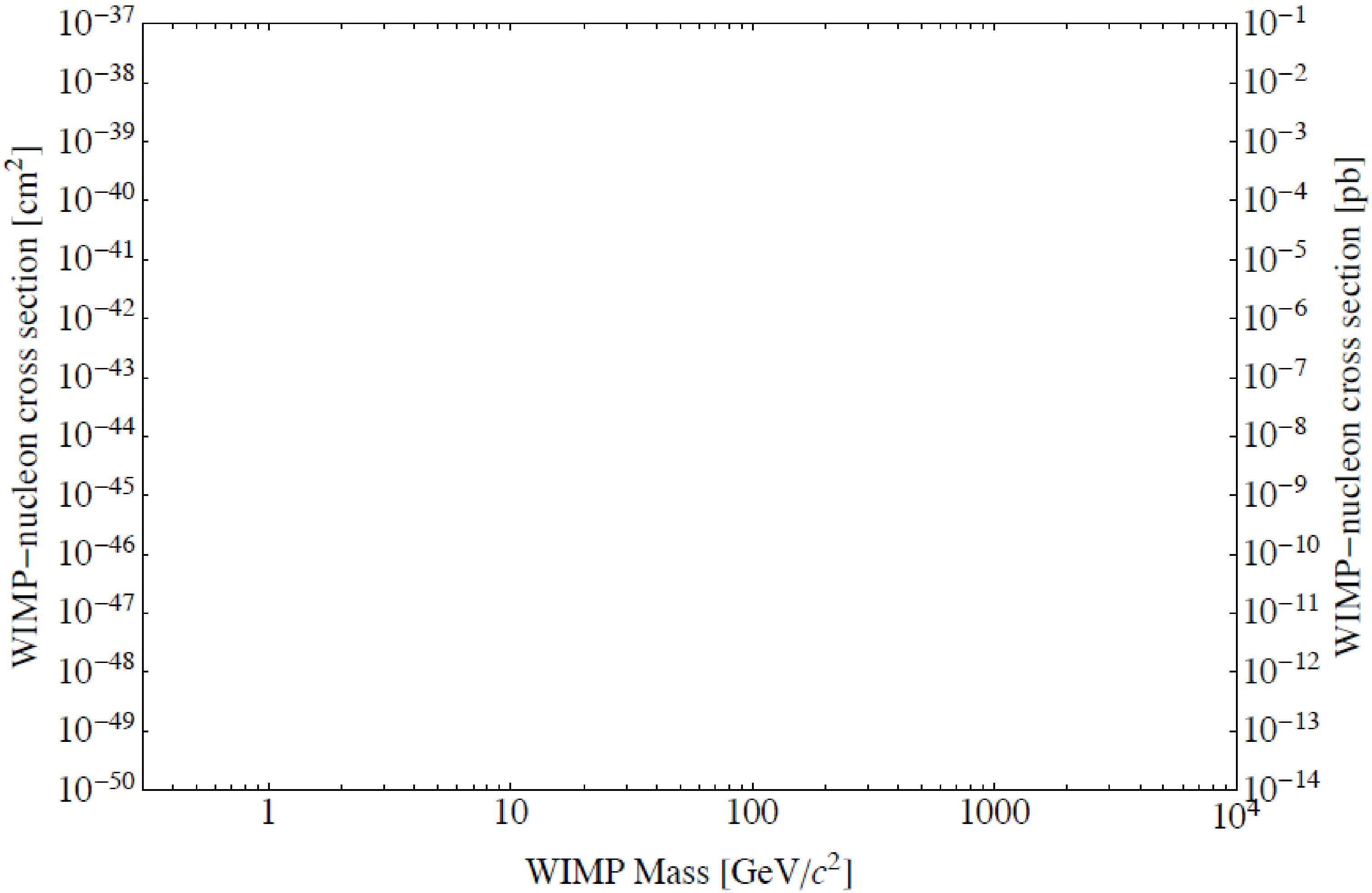
Liquid noble gas: *large mass, heavy elements, very low background*
→ above few 10 GeV/c^2
Cryogenic experiments: *precise energy measurement, multi-target (incl. light elements), low thresholds*
→ below 10 GeV/c^2

What is Dark Matter & where to look for?



In anyway the expected signal rate for direct search is small !!!

A lot of space...



R. Hill 2016 Aspen Winter Conference

• **Main experimental challenges are:**

- ❑ **event rate is ultra small (below of 1 per 100 kg of matter per day);**
- ❑ **energy deposition is tiny (below of 100 keV)**

Thus main tasks for experiments are:

• **Detector mass + long stable data taking + stable predictable detector response**
• **Detectors' performance (low energy thresholds, good resolutions)**
• **Background reduction**

E_R < ~100 keV →	Very performant detector Low threshold, good resolution
R_0 < ~0.01 evt/kg/d →	Large volume 10 kg – 1 ton
Background → 0 →	Efficient shielding, Underground lab, material selection, ...

Background

• **Cosmic Rays and cosmic activation**
• **Natural radioactivity from rock γ and neutrons**
• **Radioactive dust**
• **Radon in air from U-Th radioactive chains**
• **Natural radioactivity in materials**
…

• ***Exotics (neutrino, etc)***

Shield/ underground

Primary cosmic rays composed essentially of all periodic elements:

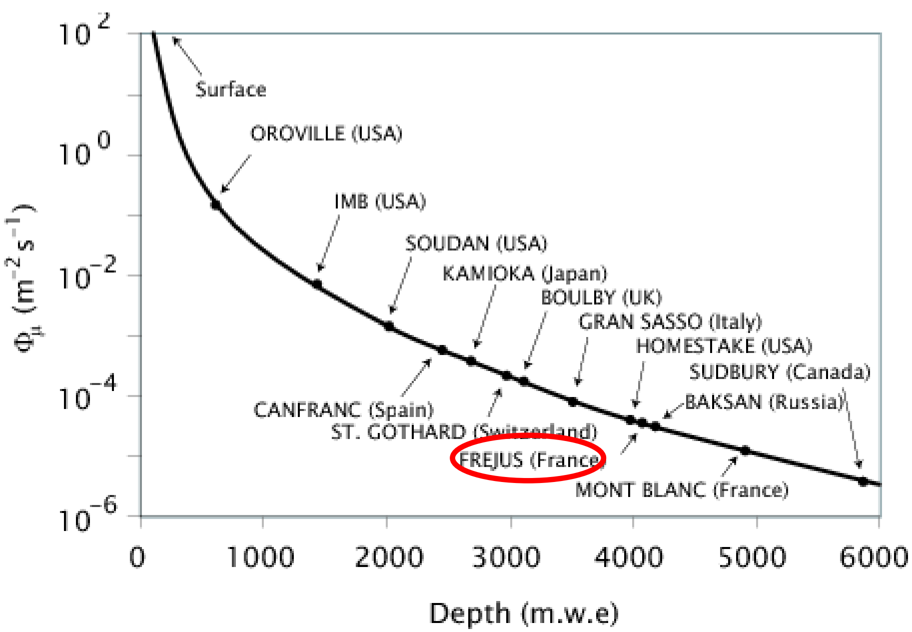
~ 89% protons, ~ 10% helium nuclei

~1% heavy elements (C, O, Si, …)

• At sea level, most are muons with mean energy at 4 GeV, but there are also much higher energies

• Also, about 20% are fast neutrons

• Only deep underground laboratories can provide effective shield from the cosmic



Background / γ (β)

Natural radioactivity is presented everywhere,

This days background requirement: <1 event per kg per year
For example human body has: ~100 Bq/kg
Need to reduce by 10^9 times (minimum)
All construction materials have to be selected by their low radioactivity

High penetration power

Connected problem – radioactive gases in the atmosphere (Rn, Kr, Ar)

Connected problem – radon progenies, ^{14}C, …

- Ultra pure materials (screening facilities, distillation and purification of liquids, radon free clean rooms for storage / assembly/ run).

- Shields (Roman lead, …)
  New bigger detectors provides effective self-shielding

- Special methods (γ/nuclear recoil discrimination, fiducial cut, etc)

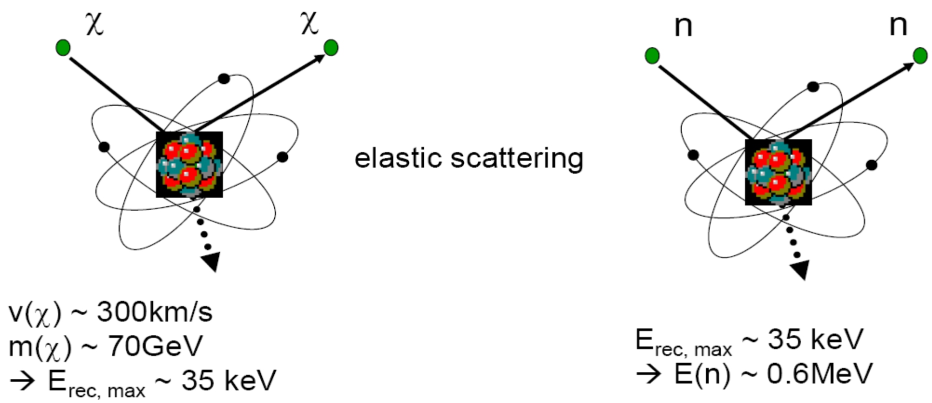
Background / neutrons

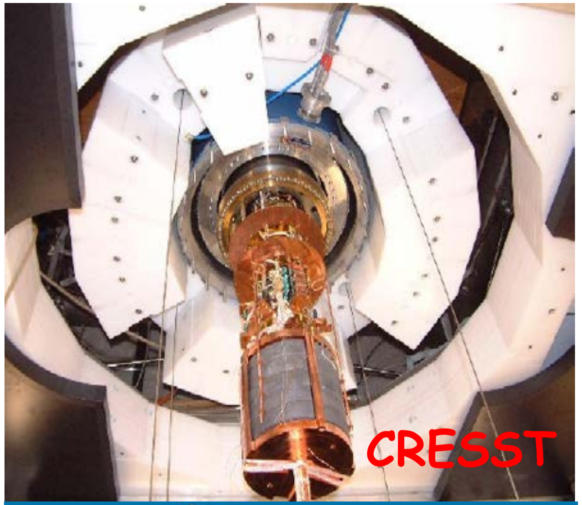
Neutron background sources underground:

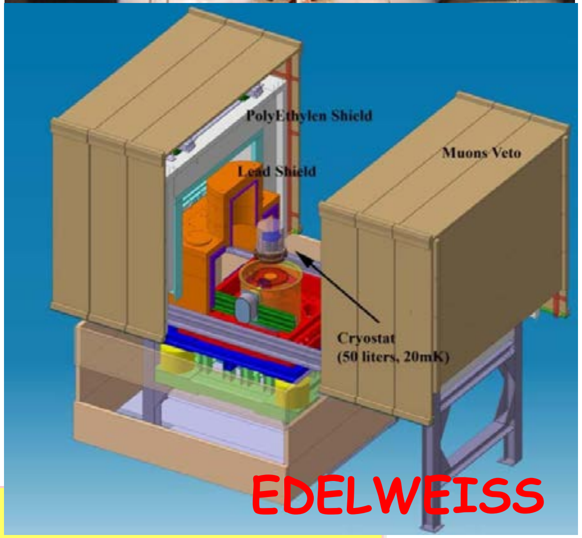
Low energy neutrons induced by U/Th activities

- fission and (α,n) reactions in the surrounding rock/concrete
- fission reactions in detector shield

High energy neutrons induced by muons







Fight with neutron background:

1) **Go underground laboratory / reduce neutron flux by 4+ orders**
2) **Material selection**
3) **Muon veto system**
4) **Passive neutron shield**
5) **Multi-detector assembly / neutron background identification**

Traditional methods of background suppression are not enough for direct DM search experiments.

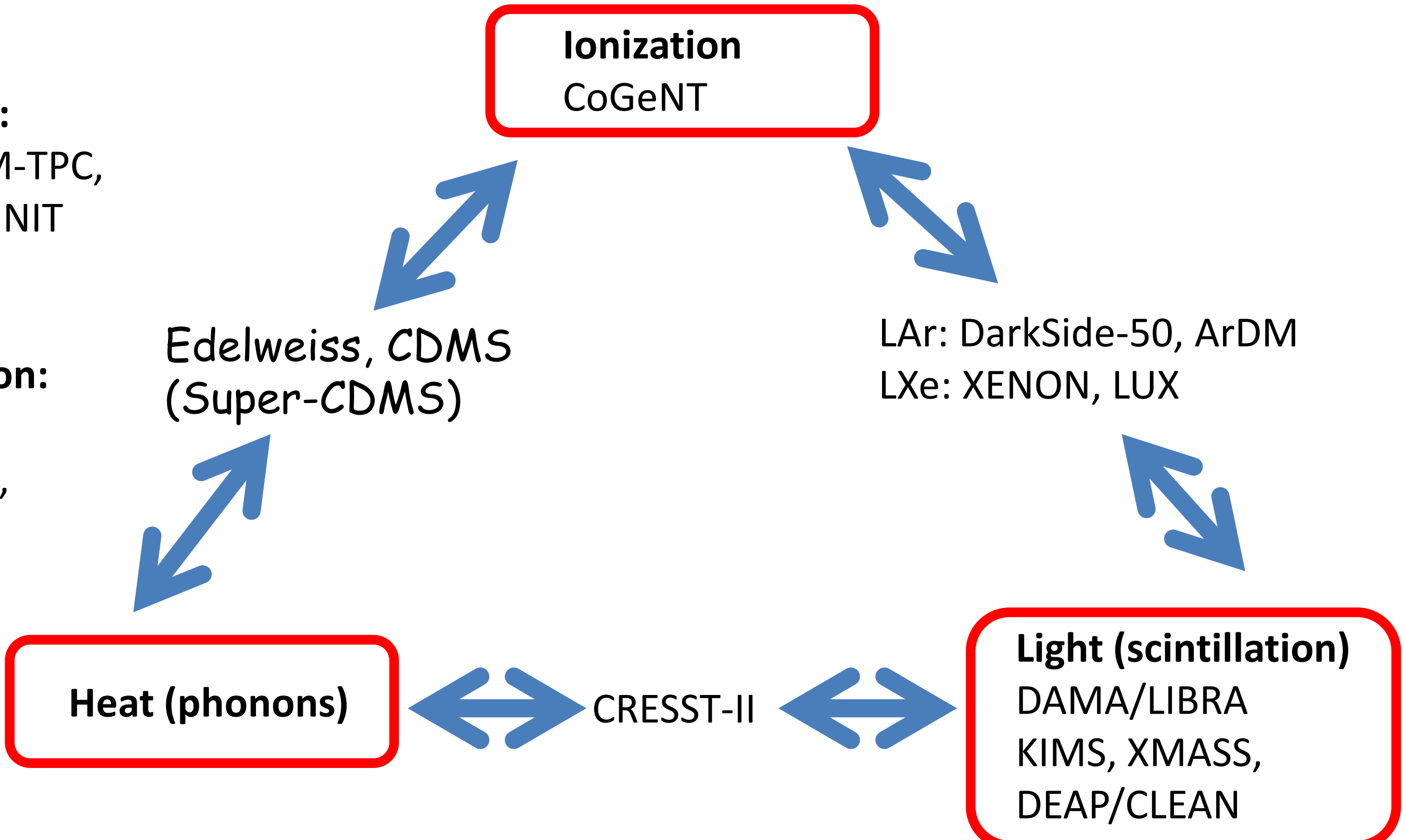
Experiment specific reduction/study of the background (selection of nuclear recoil events, seasonal modulations, …)

<u>Main experimental techniques for direct DM search:</u>

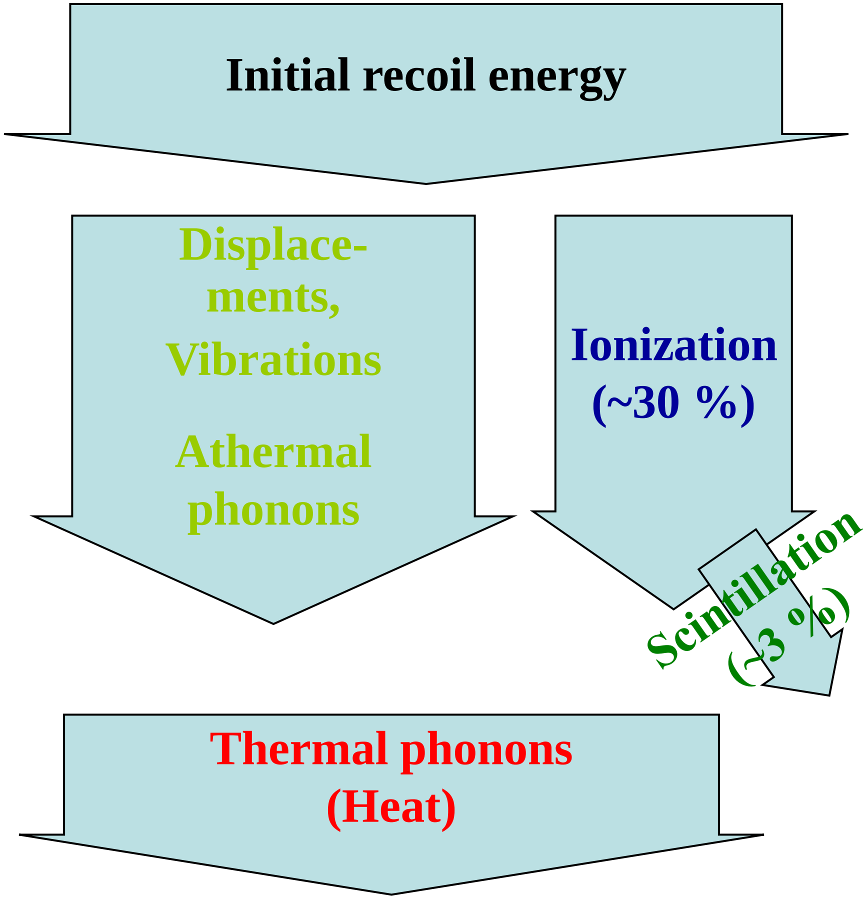
Cryogenic (Ge, Si, …)
Solid Scintillator (NaI, CsI)
Noble Liquids (LXe, LAr)
Others (bubble formation, gas-tracking)

Tracking:
Drift, DM-TPC,
MIMAC, NIT

Bubble Formation:
COUPP,
PICASSO,
PICO



Cryogenic Techniques (Combination of phonon measurement with measurement of ionization or scintillation)

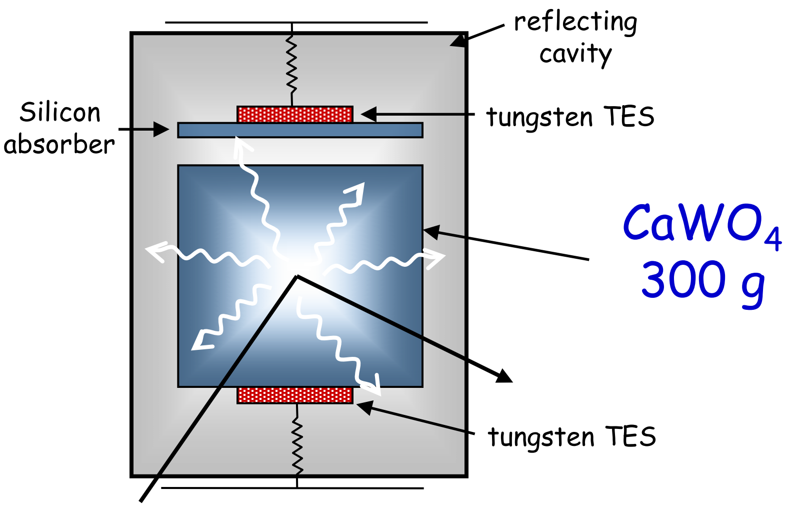


Phonon: most precise total energy measurement

Ionization / Scintillation: yield depends on recoiling particle

Nuclear / electron recoil discrimination.

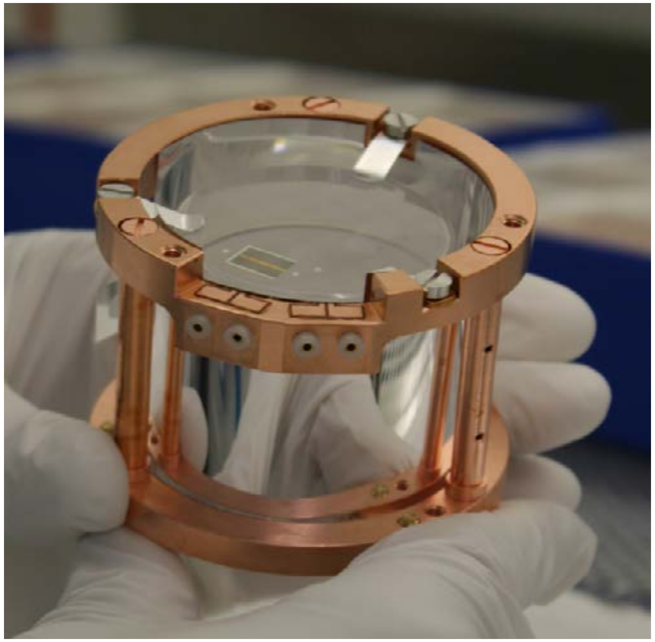
CRESST



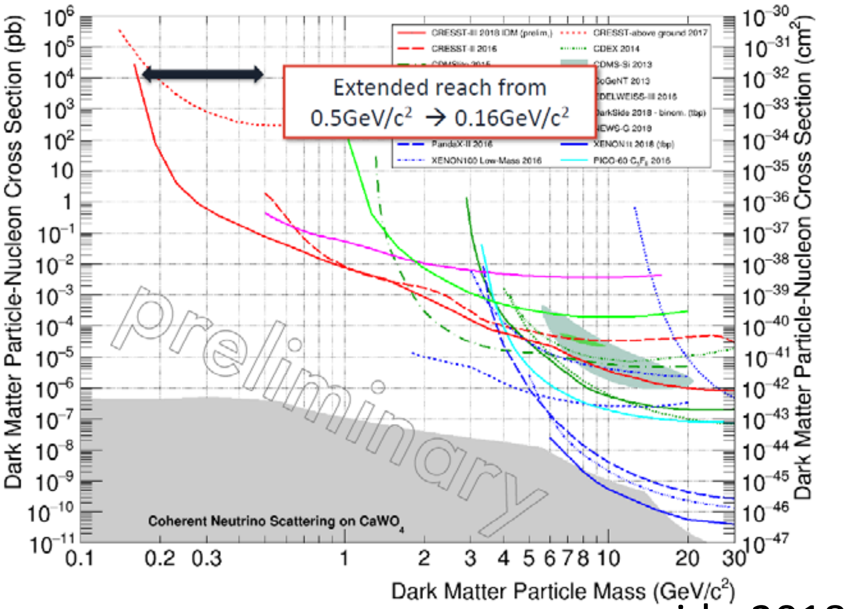
Heat – Light

Energy

Identification



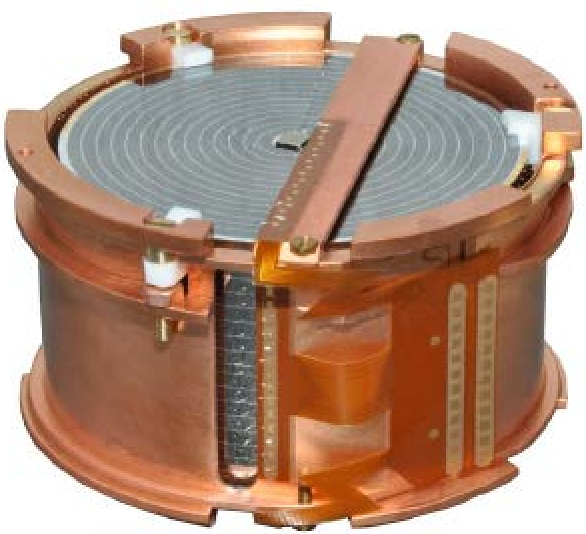
(PRELIMINARY) RESULT



idm2018

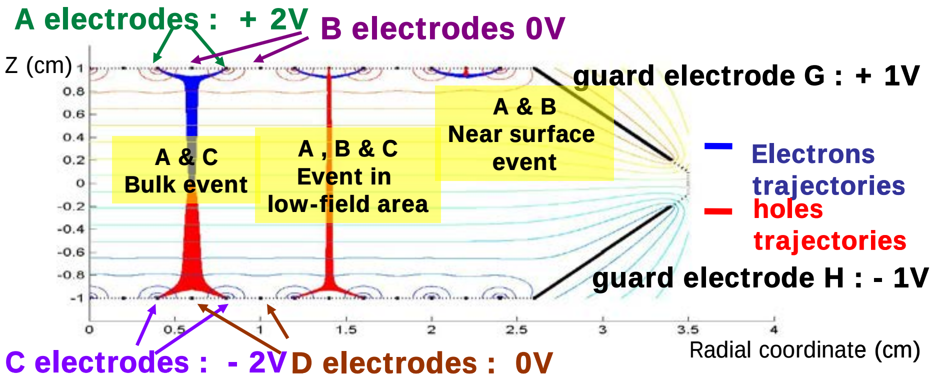
EDELWEISS (Heat and ionization Ge bolometers)

Using of *Heat* and *Ionization* HPGe detectors, running in ^{3}He-^{4}He dilution cryostat (<20 mK)



Ratio $E_{ionization}/E_{recoil}$ is
=1 for electronic recoil
≈0.3 for nuclear recoil
⇒Event by event identification of the recoil
⇒Discrimination g/n > 99.99%

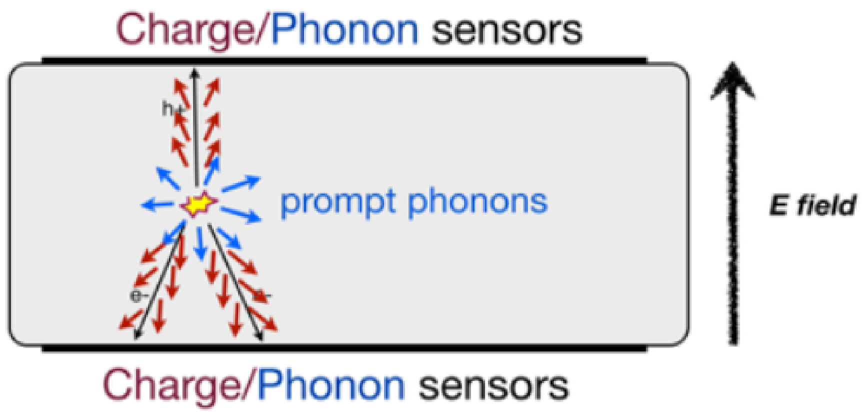
Detectors with special concentric planar electrodes for active rejection of surface events (miss-collected charge)



EDELWEISS/CDMS-LT: Neganov-Luke Amplification

Due to the heat dissipated in the substrate by the drifting electron-hole pairs the phonon signal is amplified.

$$E_t = E_r + \frac{1}{3\ eV} E_Q \Delta V$$



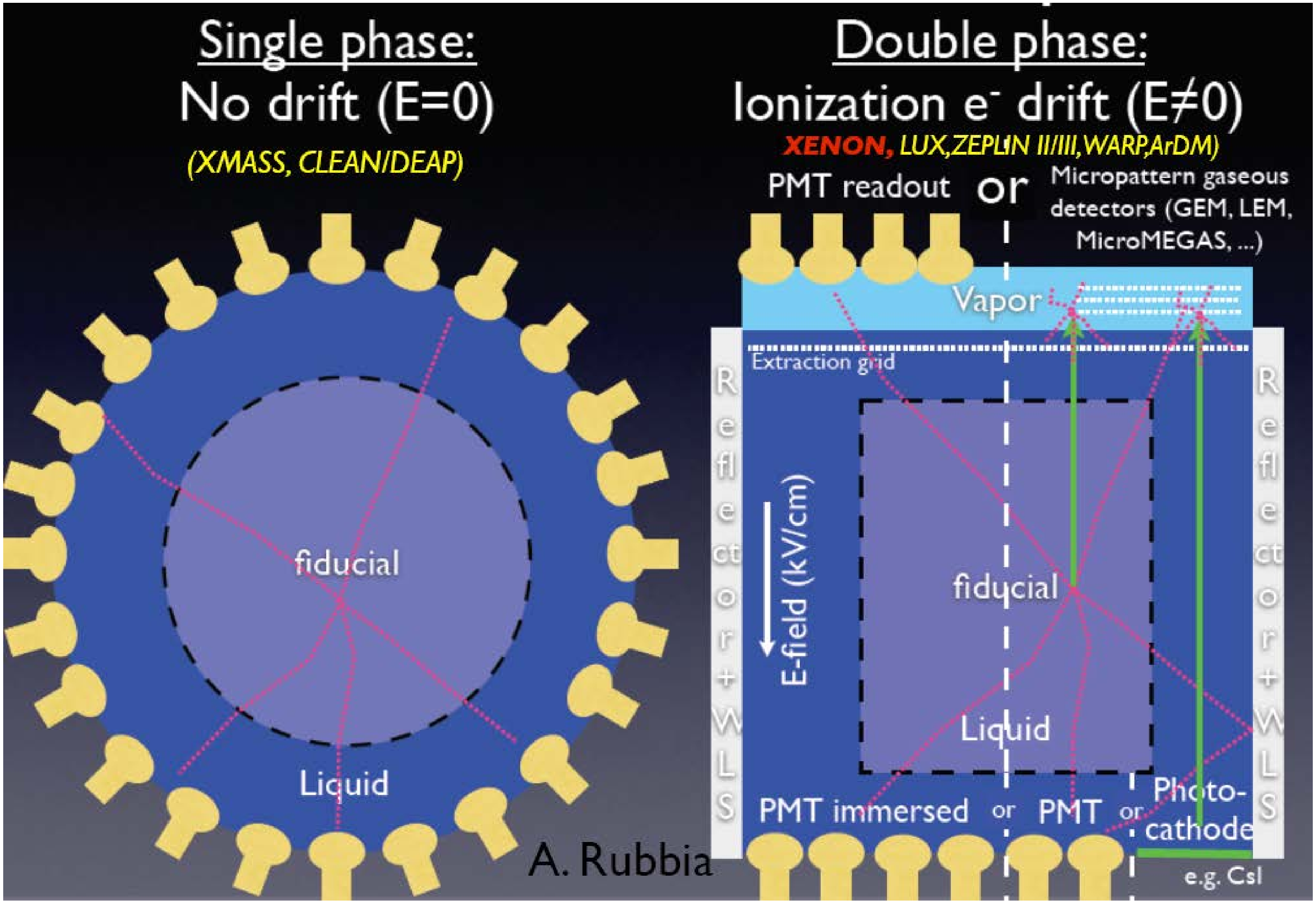
- First Dark Matter run with HV detectors ongoing
- Even in HV mode, we can still **readout both ionization and heat signals**
- Working **up to 100 V** leading to a boost factor of ~35 with Lowest threshold achieved of **60 eVee**

Noble liquid detectors

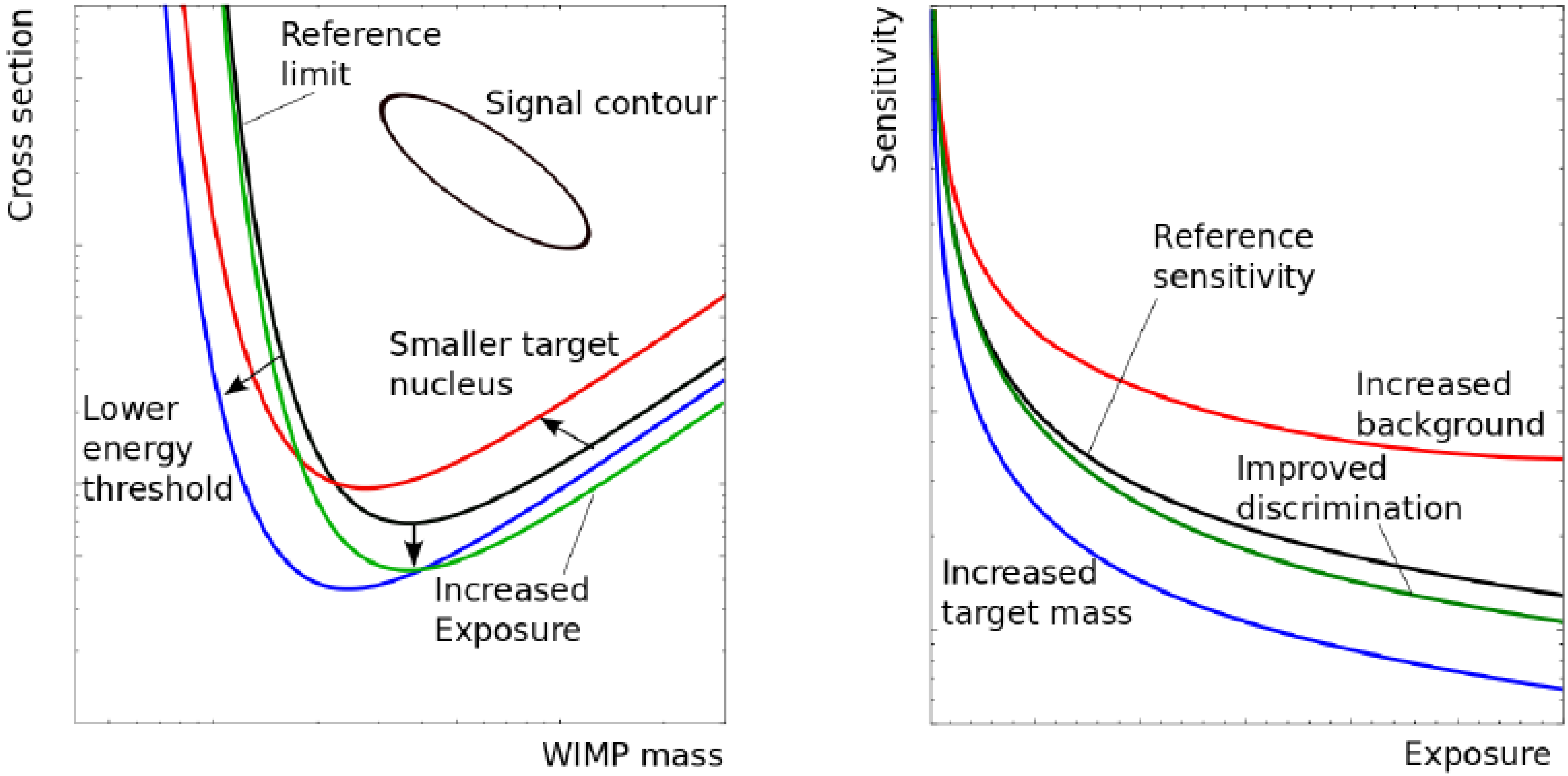
- **Xe:** large A;
- **Ar**: low cost
- High purification (recirculation)
  - ^{39}Ar (1Bq/kg): requires >10^7 rejection for 10^{-8}pb,
  - or depleted Ar (DarkSide)

- Background suppression
  - Self-shielding in large volume
  - Ratio (prompt scintillation)/(ionization)
  - Scintillation pulse shape

Noble liquid detectors



Now we decide what is better like this:



(Teresa Marrodan Undagoitia and Ludwig Rauch)arxiv:1509.08767

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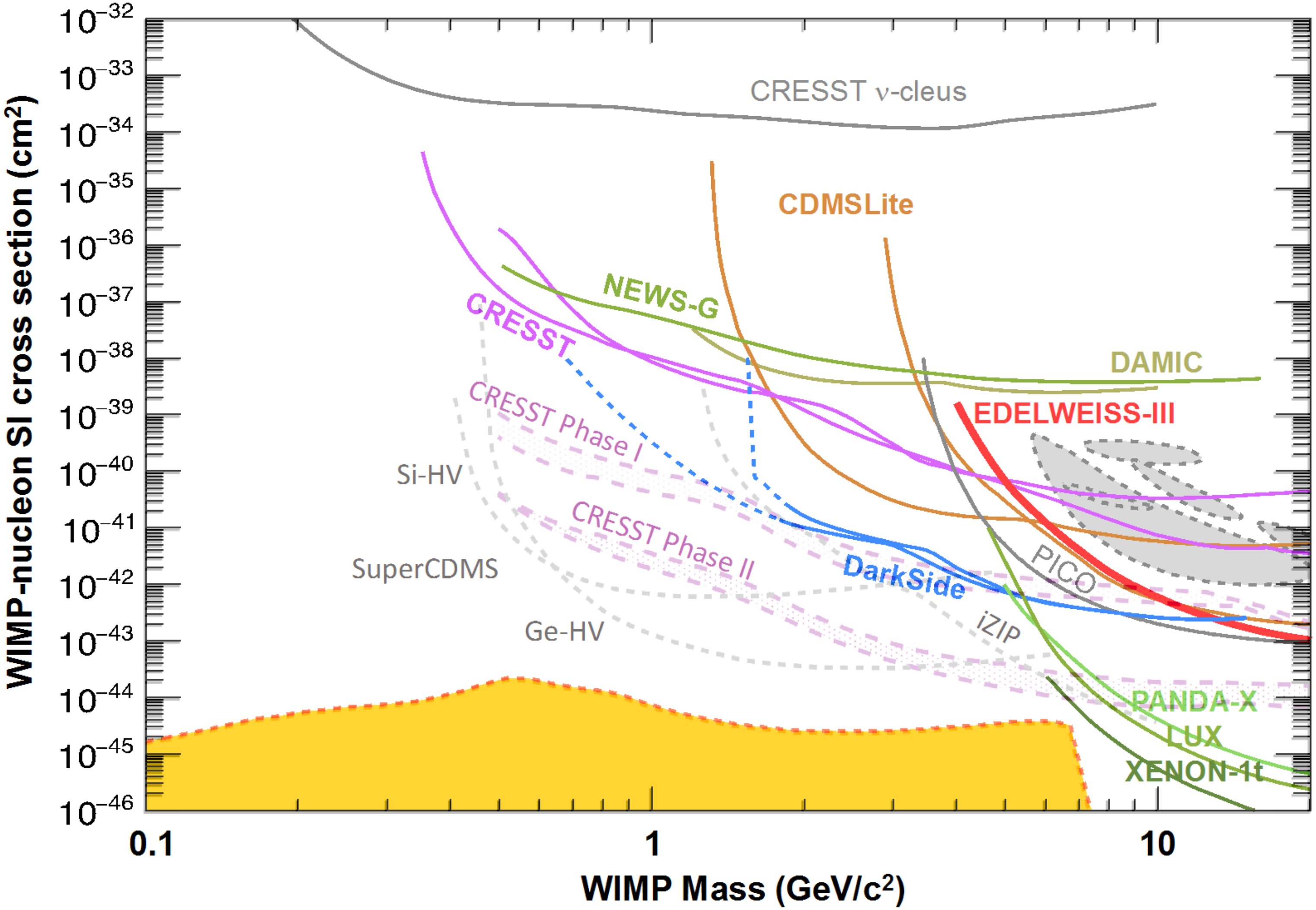
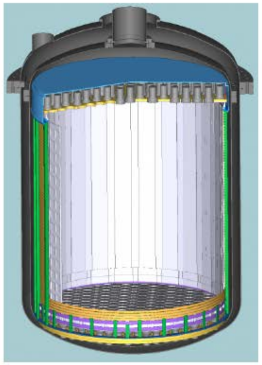
Cryogenic experiments: *precise energy measurement*, *multi-target* (incl. light elements), low thresholds <10 GeV/c^2

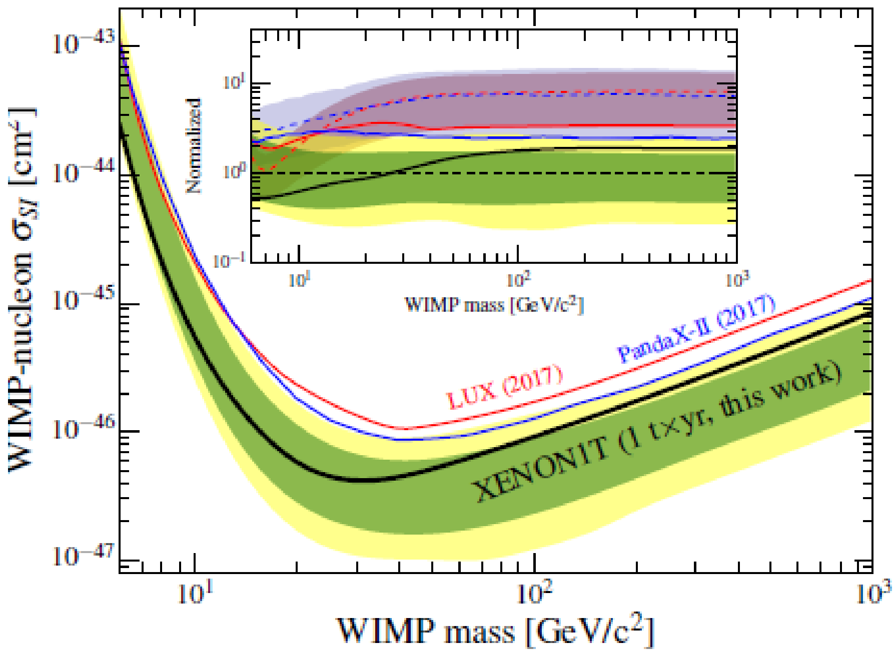


WIMP-nucleon SI cross section (cm^2)
10^{-32}
10^{-33}
10^{-34}
10^{-35}
10^{-36}
10^{-37}
10^{-38}
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
0.1
1
10
WIMP Mass (GeV/c^2)
CRESST ν-cleus
CDMSLite
NEWS-G
CRESST
DAMIC
EDELWEISS-III
CRESST Phase I
Si-HV
CRESST Phase II
SuperCDMS
DarkSide
PICO
iZIP
Ge-HV
PANDA-X
LUX
XENON-1t

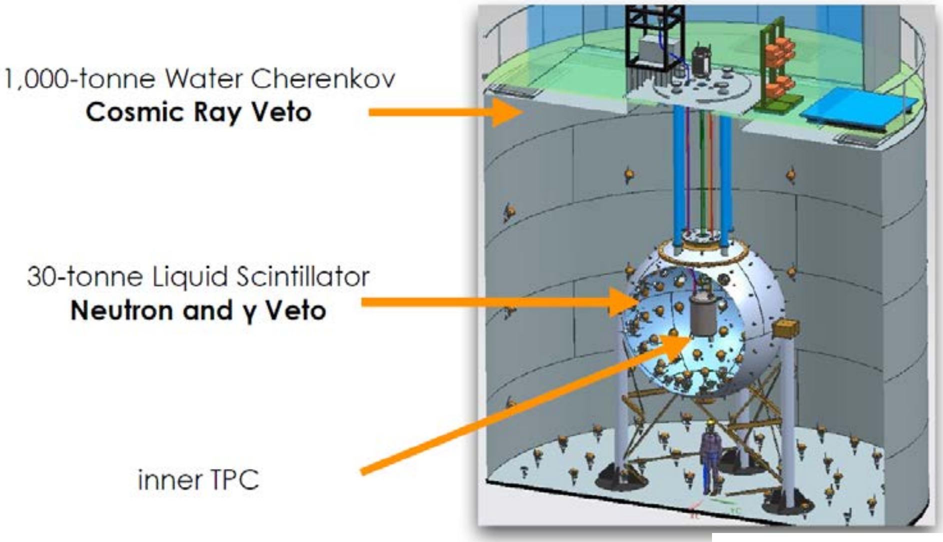
XENON10 XENON100 XENON1T XENONnT

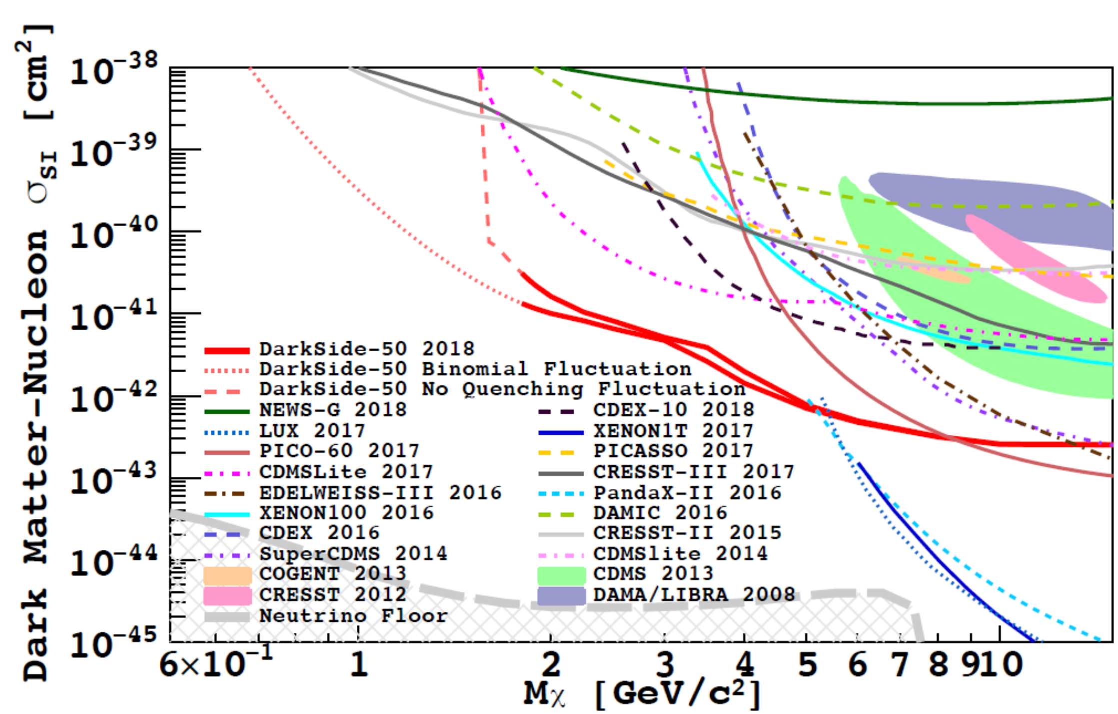


2005-2007	2008-2016	2012-2018	2019-2023
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2



DarkSide-50


1,000-tonne Water Cherenkov
Cosmic Ray Veto
30-tonne Liquid Scintillator
Neutron and γ Veto
inner TPC


Dark Matter-Nucleon σSI [cm2]
10−38
10−39
10−40
10−41
10−42
10−43
10−44
10−45
6×10−1
1
2
3
4
5
6
7
8
910
Mχ [GeV/c2]
DarkSide-50 2018
DarkSide-50 Binomial Fluctuation
DarkSide-50 No Quenching Fluctuation
NEWS-G 2018
LUX 2017
PICO-60 2017
CDMSLite 2017
EDELWEISS-III 2016
XENON100 2016
CDEX 2016
SuperCDMS 2014
COGENT 2013
CRESST 2012
Neutrino Floor
CDEX-10 2018
XENON1T 2017
PICASSO 2017
CRESST-III 2017
PandaX-II 2016
DAMIC 2016
CRESST-II 2015
CDMSlite 2014
CDMS 2013
DAMA/LIBRA 2008

To prove WIMP observation one needs

- A characteristic spectrum that depends on nuclear mass and spin;
- Annual modulation in both the event rate and the recoil;
- Events distributed uniformly throughout the detector;
- Experiment-independent DM parameters;
- Characteristic properties for DM event

Conclusions:

- **Direct Dark Matter Searches: crucial to detect presence of WIMPs in our environment; The main challenge: *extreme low-backgrounds;***

- **To study DM we need variety of targets *(Ar/Xe, Ge+scintillation);***

- **Intense world-wide competition of R&D efforts;**

- **SUSY at LHC potentially can be discovered at any time soon.**

What is omitted:

Spin-dependent, ...

Innelastic, ...

Axions, ...

...