Detectors for astroparticle physics and dark matter searches

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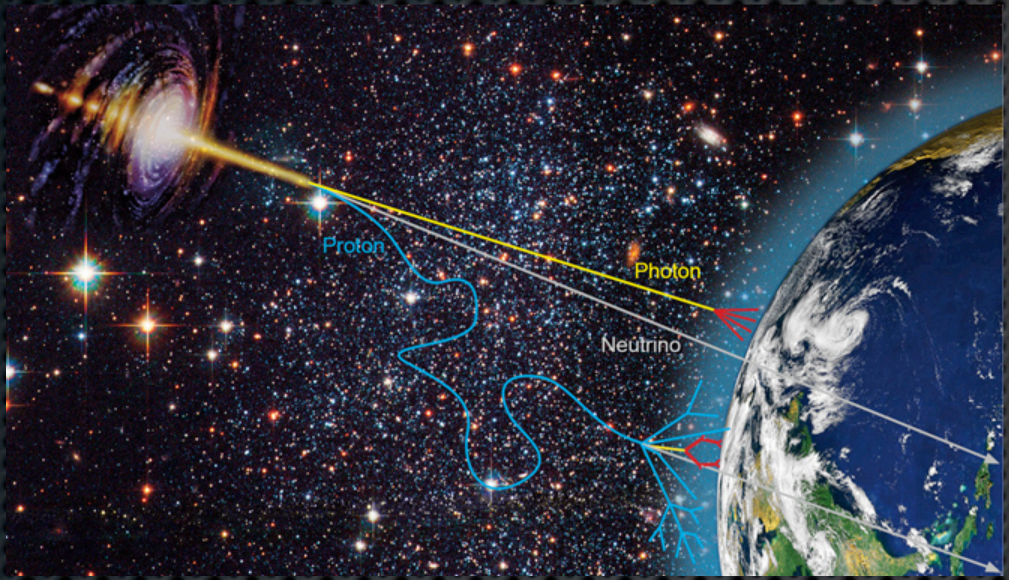
Astroparticle physics: definition

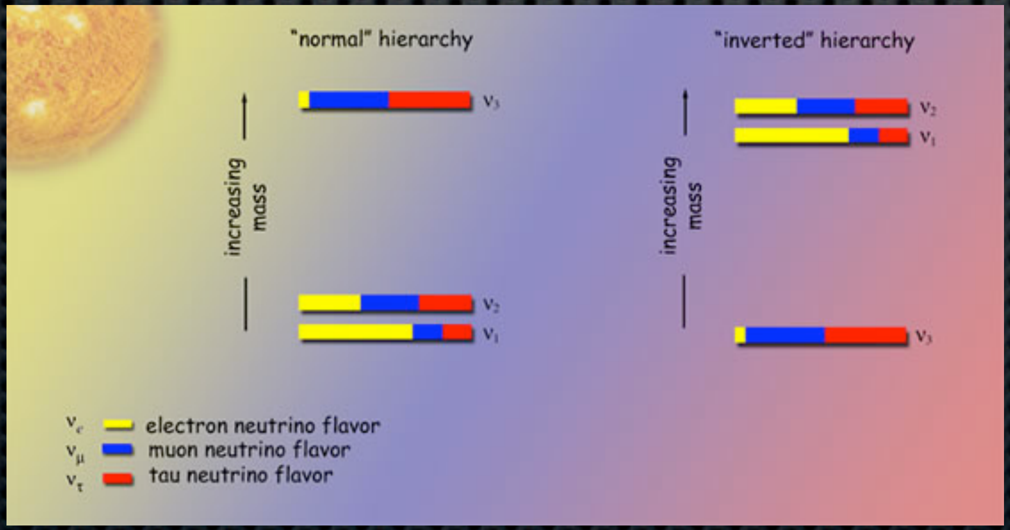
- aspera-eu.org:
  - A new multidisciplinary field of research that deals with the study of particles coming from the Universe
  - *Astroparticles:* high-energy photons, neutrinos, cosmic rays, dark matter particles, gravitational waves
    - on the one hand: we aim to learn more about high-energy cosmic phenomena and the *violent processes* that give rise to them
    - on the other hand: astrophysical sites of *violent phenomena* are used as a laboratory to test the fundamentals laws

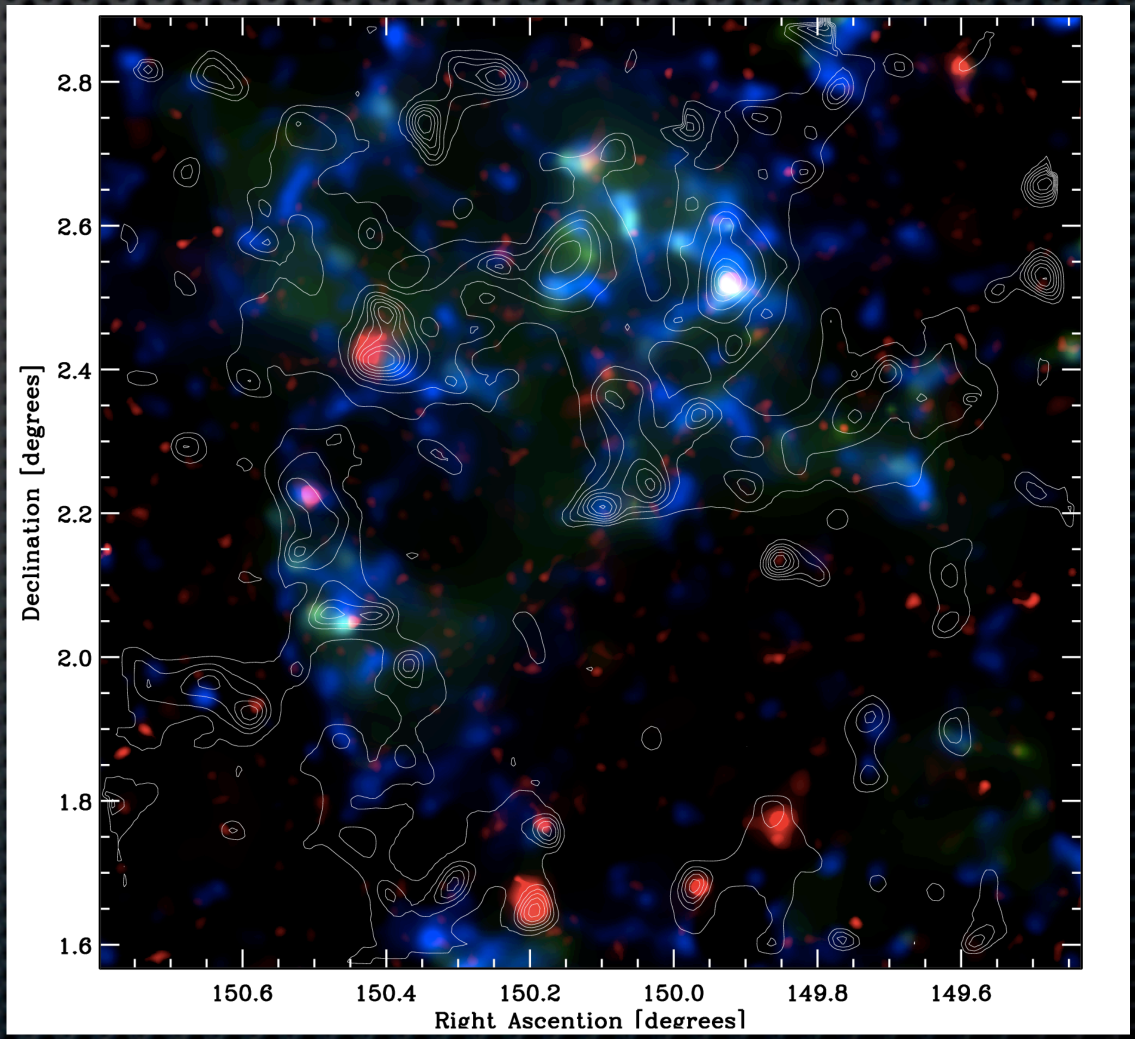
the Universe seems to be a rather violent place

Astroparticle physics: some questions

- High energy cosmic rays: origin, what are the accelerators?
- Neutrinos: mass scale, hierarchy
- Dark matter: composition, distribution







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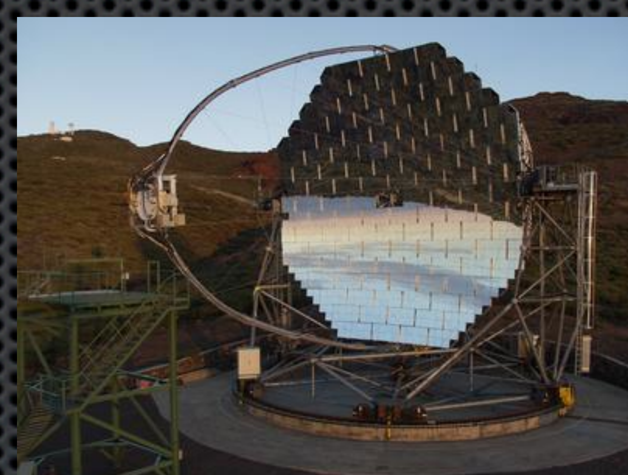
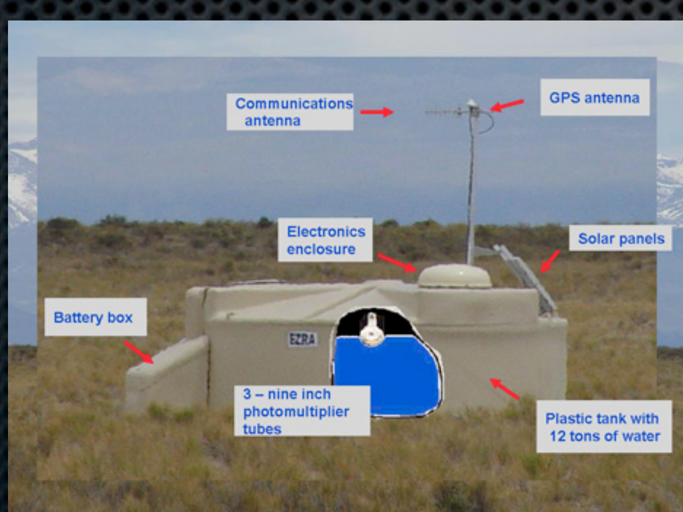
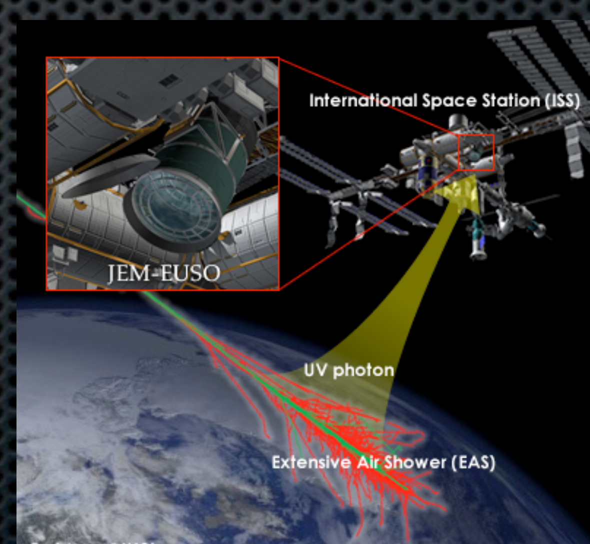
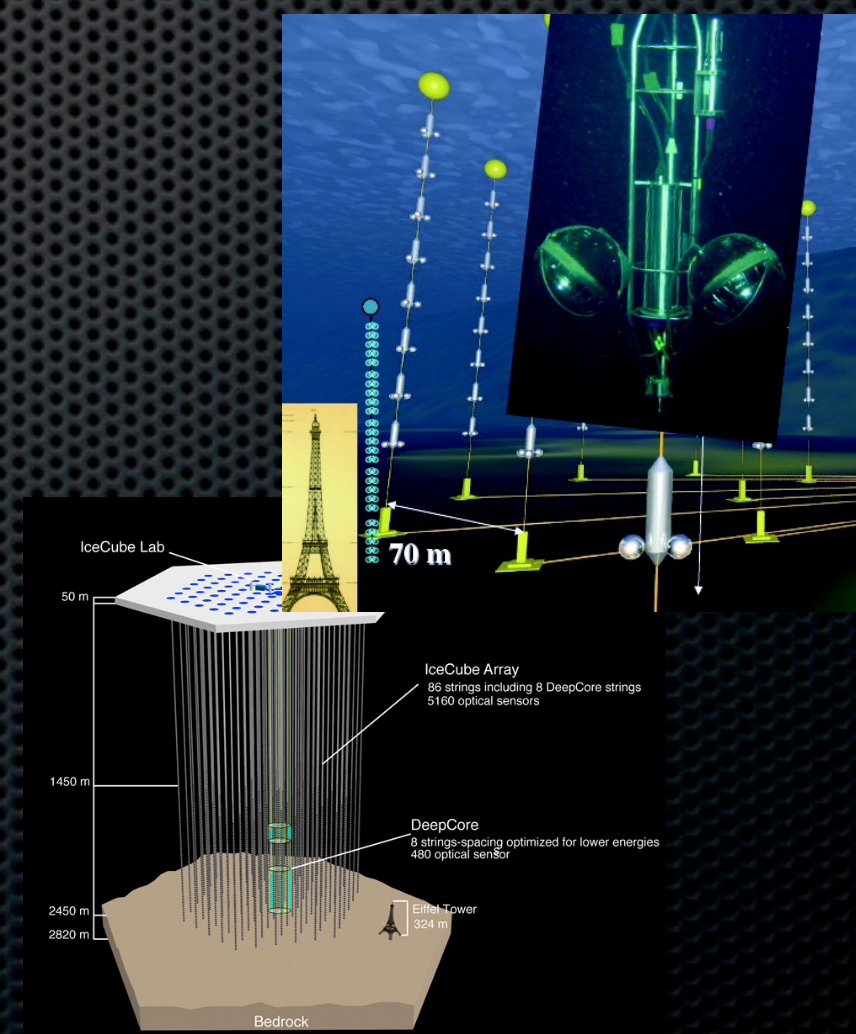
HE cosmic rays: facilities*

- Charged particles: Pierre Auger, Telescope Array; future: JEM-EUSO (on ISS), Square Kilometer array
- Gammas: HESS, MAGIC, VERITAS, ARGO/YBG; future: CTA, HAWC, LHASSO
- Neutrinos: IceCube, ANTARES, NESTOR, NEMO; proposed: KM3Net, PINGU, GVD/Baikal









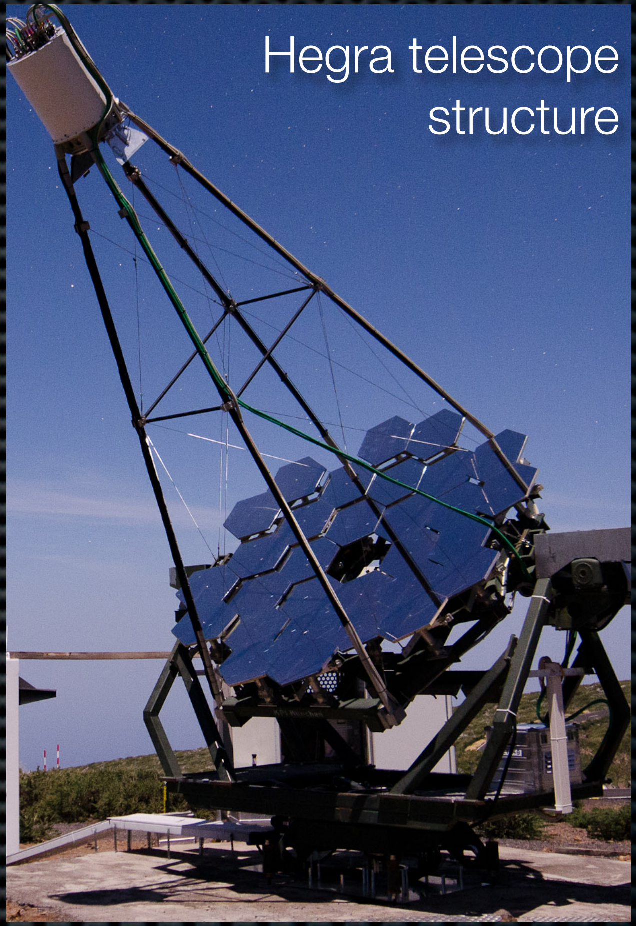
*not an exhaustive list

HE gammas: instrumentation

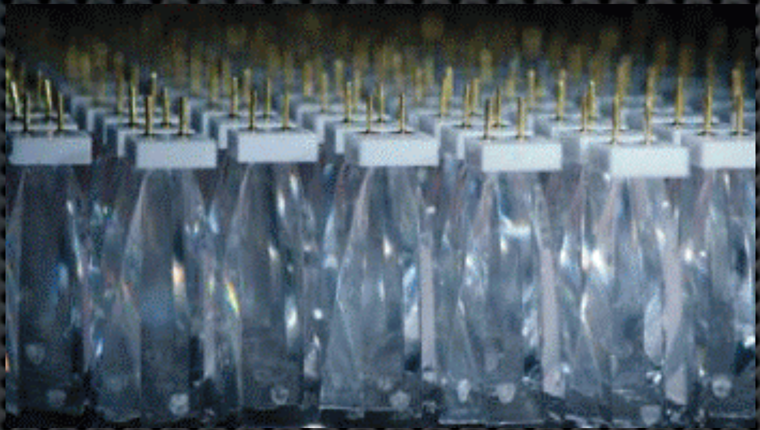
- The hearts of these facilities (air/water Cherenkov detectors) - the cameras - use photodetectors that observe Cherenkov light (lambda ~ 300 - 600 nm)
- In general, photomultipliers (PMTs) are used because of: well established technology, large areas, large gains, single photoelectrons sensitivity
- However, issues with magnetic fields, use of high-voltage, after-pulsing, damage in daylight, bulky, high costs etc
- Other promising detector technologies: APDs operated in Geiger mode (G-APDs) -> some issues: optical cross talk, costs still high but decreasing, T-stability; intrinsic dark rate below night sky background is feasible

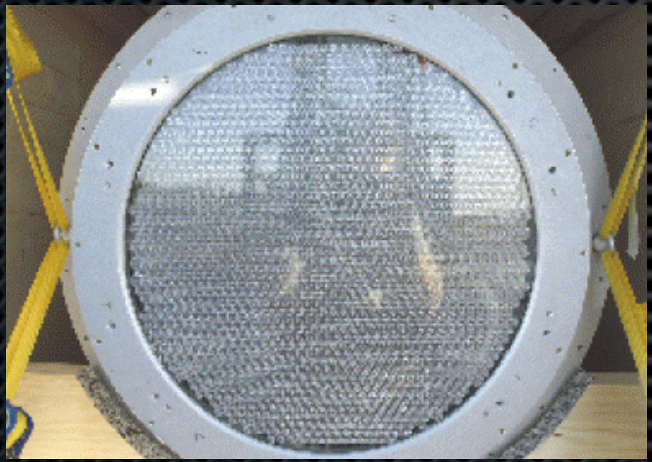
HE gammas: instrumentation

- New ideas: cameras out of SiPMs
- One proof-of-principle: FACT, using G-APDs

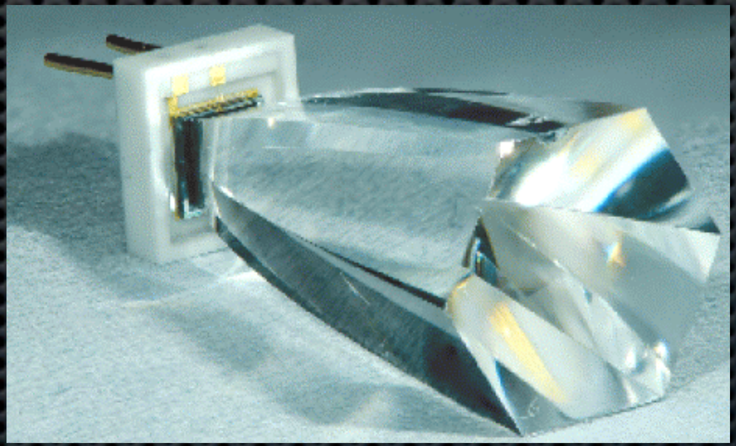


Hegra telescope structure

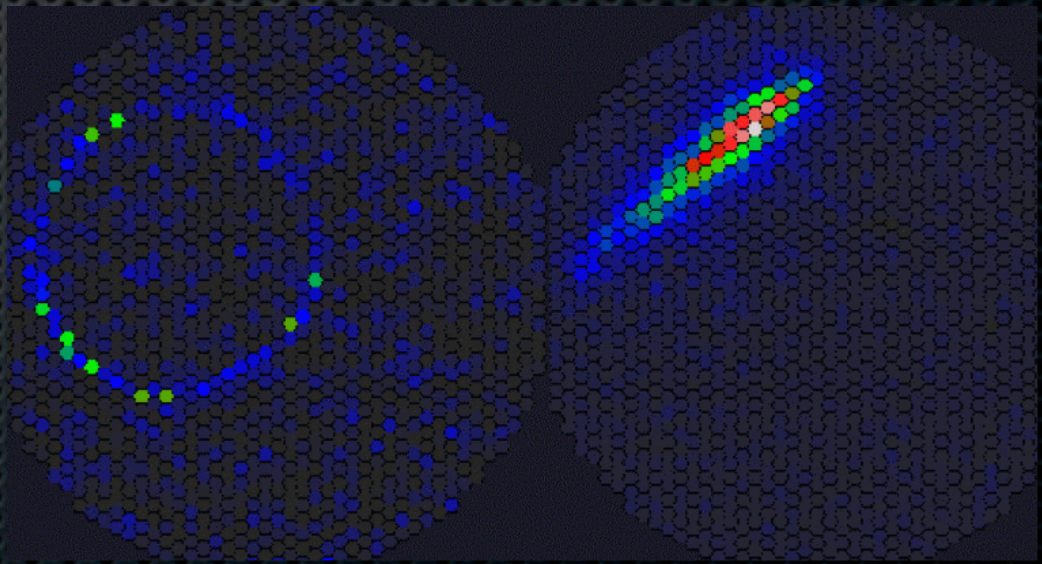




1440 channels



G-APD with solid cone



First events from October 2011

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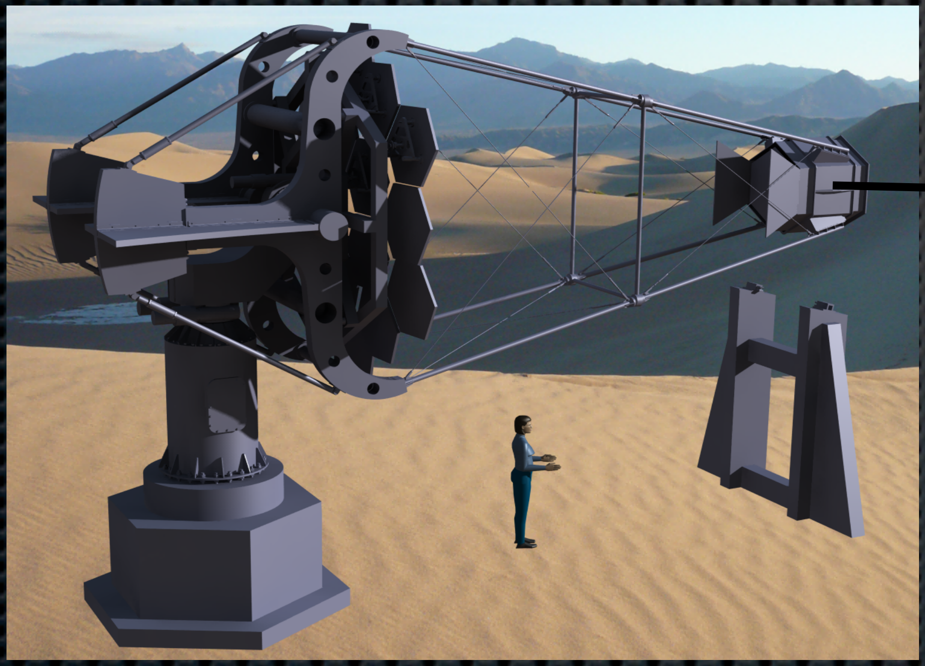
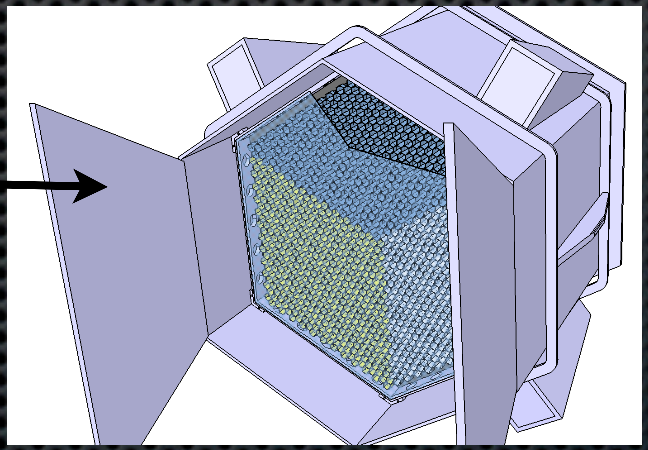
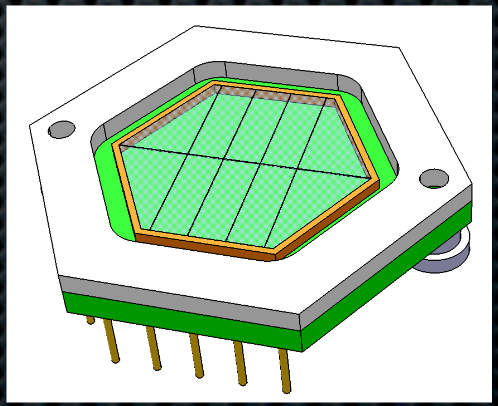
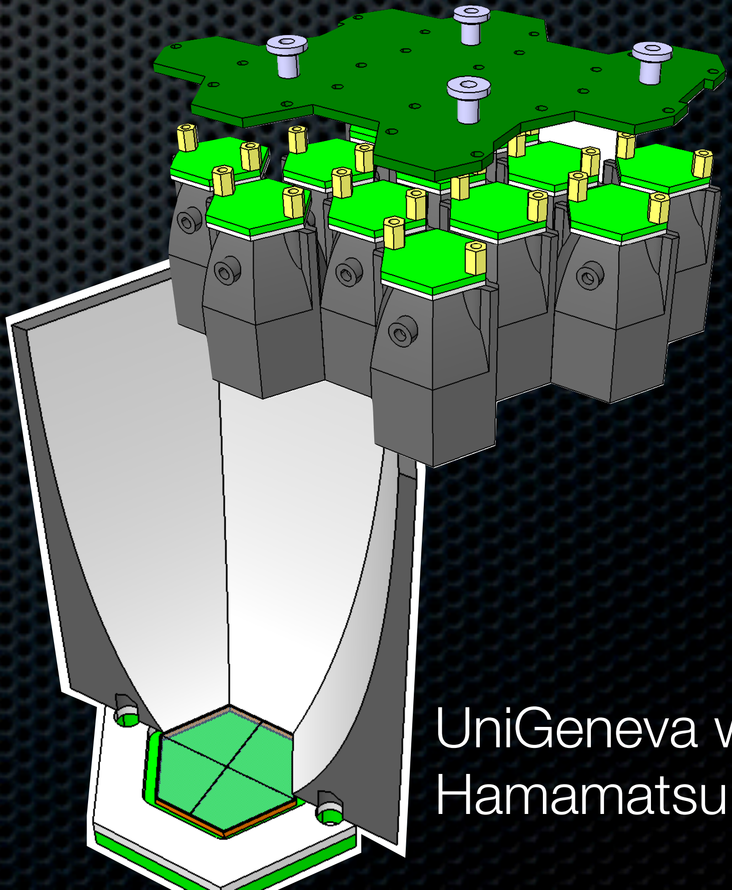
HE gammas: instrumentation

- Example: CTA small size telescope might use G-APDs
- Pixel size naturally matches small dishes; operation during full Moon is possible (30% more lifetime)
- Possible sensor geometry: hexagonal, ~ 100 mm^2 sensitive area, 4 channels









UniGeneva with Hamamatsu

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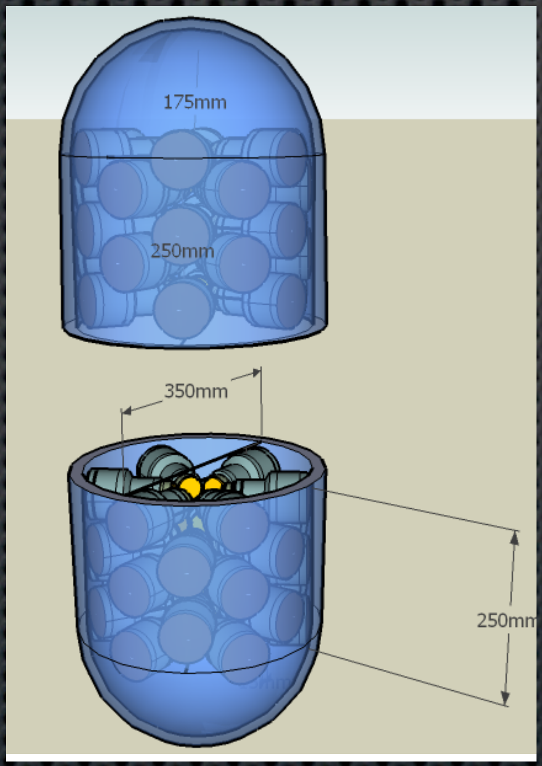
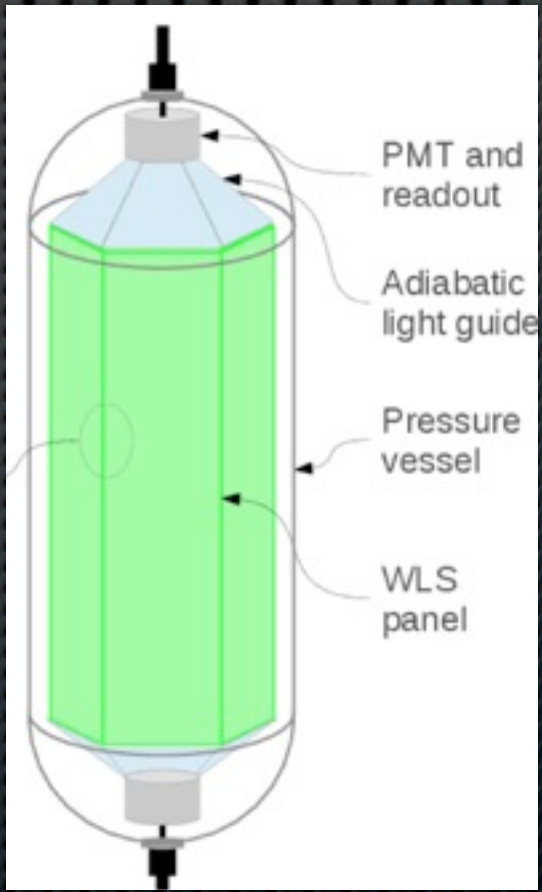
HE neutrinos and CRs: instrumentation

- Projects use photodetectors, mostly photomultipliers (PMTs)
- Issues for future detectors or upgrades: increase sensitivity, energy range, angular and/or temporal resolution, robustness
- New ideas: innovative detection units, such as multiple-small PMTs in an optical module, focal surface with thousands of small PMTs, wavelength shifting optical modules

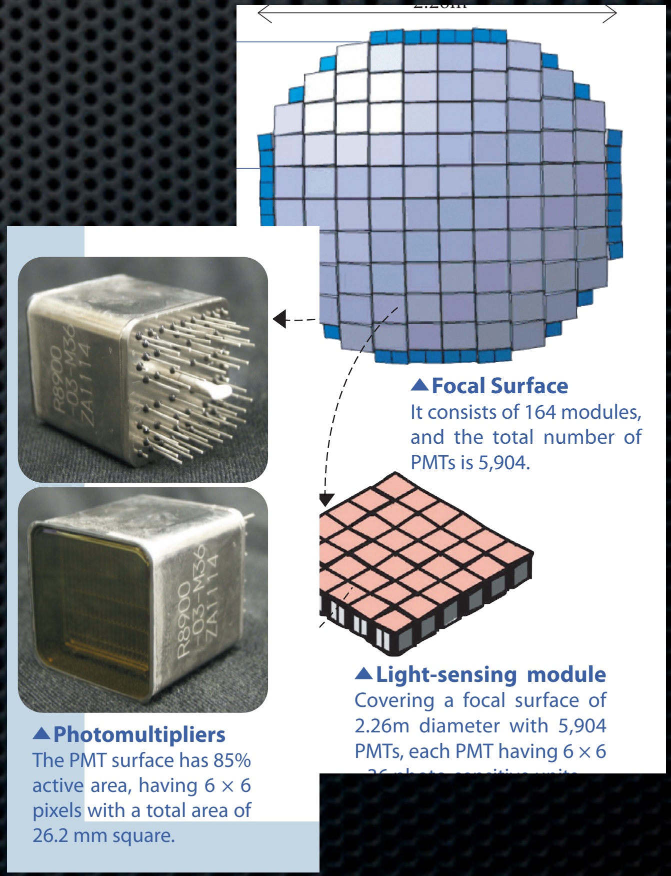
Multi-PMT optical module for KM3Net



Multi-PMT optical module for the SouthPole



Wavelength shifting optical module



5904 1-inch PMTs, JEM-EUSO focal surface

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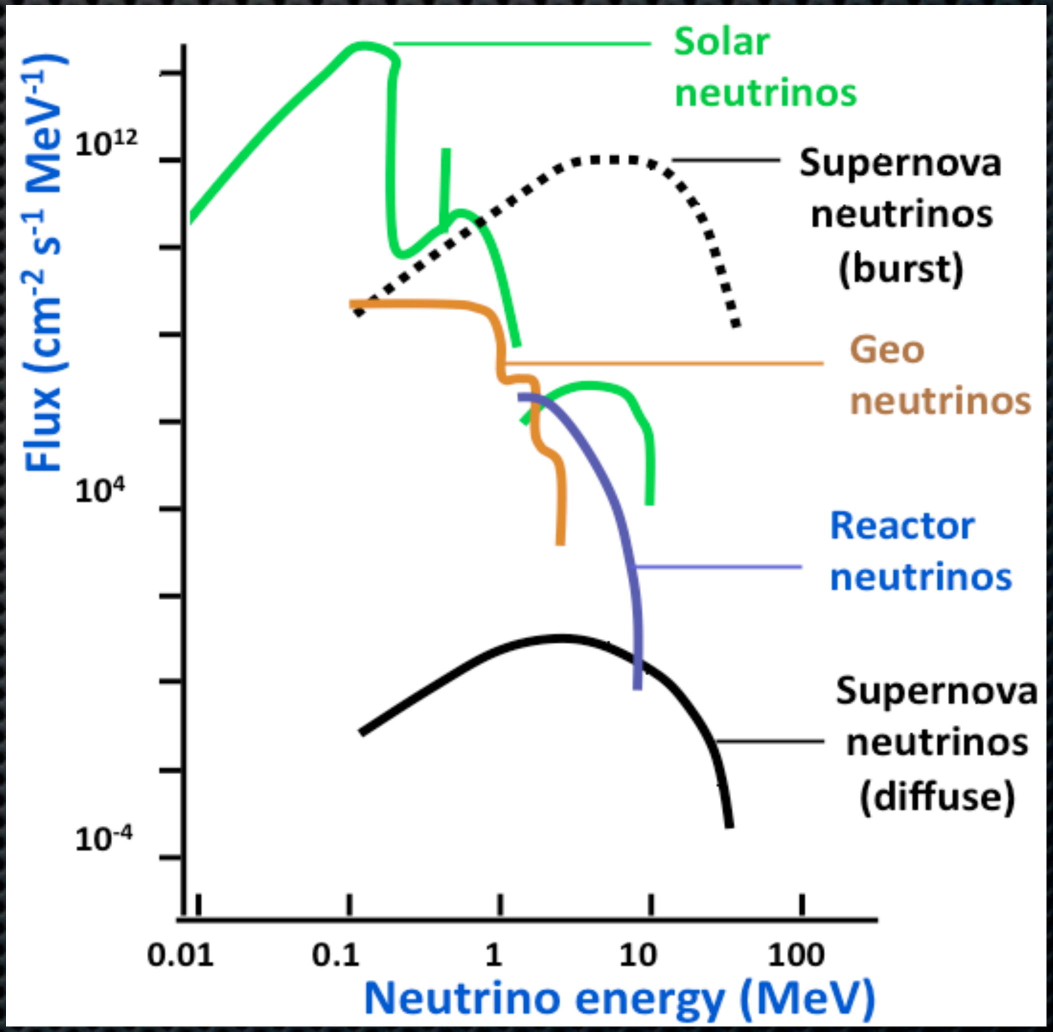
(Low-energy) Neutrinos: facilities*

- Detectors are located in underground facilities to suppress the cosmic ray flux
- Water Cherenkov detectors: SNO, SuperKamiokande; future: HyperKamiokande, proposed MEMPHYS
- Scintillators: LVD, KamLAND, Borexino; proposed LENA
- Liquid Argon: ICARUS; proposed GLACIER



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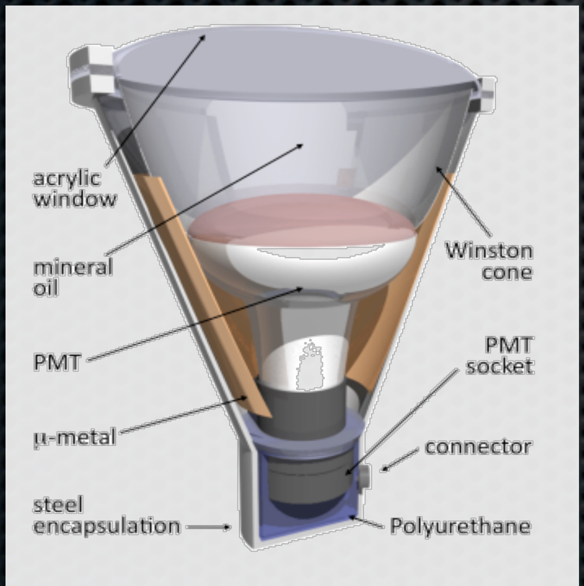
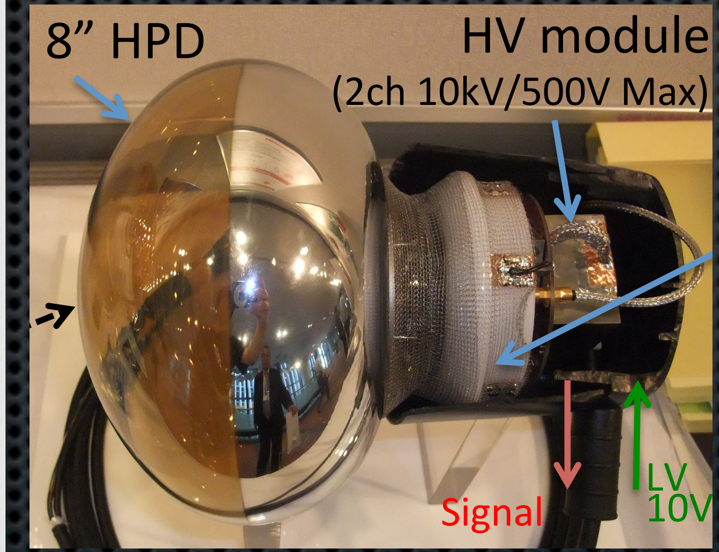
*not an exhaustive list

(Low-energy) Neutrinos: Instrumentation

- Water/scintillator detectors observe Cherenkov/scintillation light, with PMTs
- (New) Ideas: hybrid photo detector with avalanche diode (HPD), large photosensor with scintillator (idea already used in Lake Baikal - QUASAR, and DUMAND - SMART, projects)
- LAr: idea is to detect electrons with LEM readout

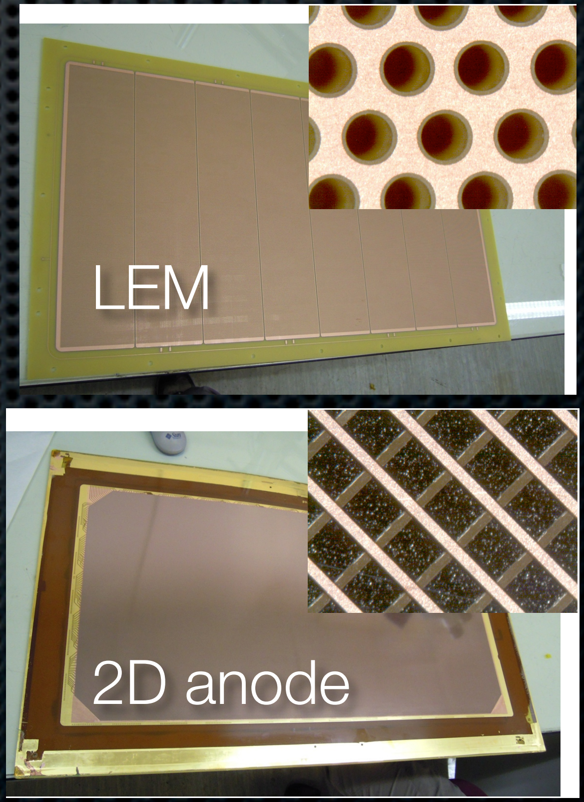


Optical module for LENA



Hybrid photodetector for HyperK

PM with scintillator for HyperK



LEM/THGEM for GLACIER

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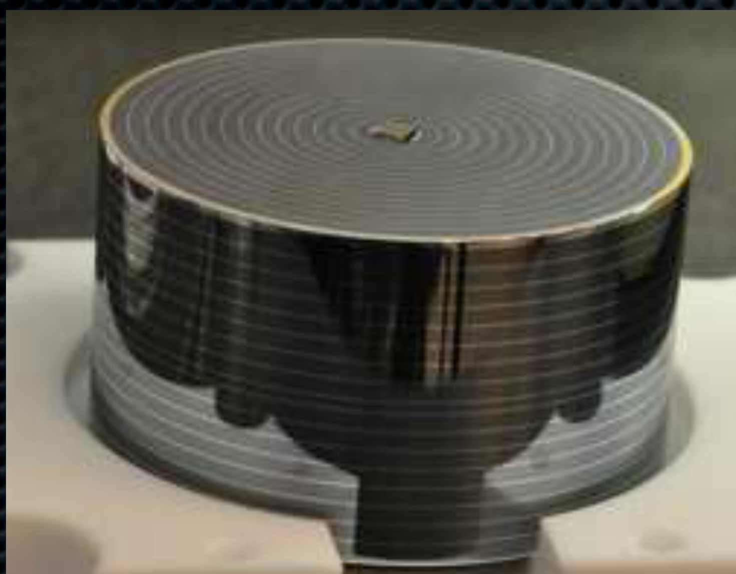
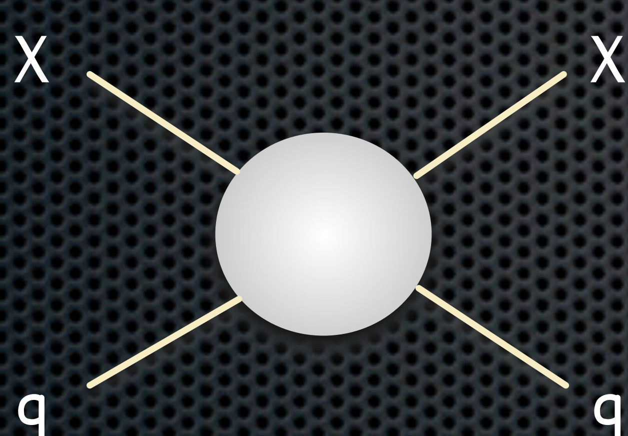
Dark matter: is it made of Weakly Interacting Massive Particles?

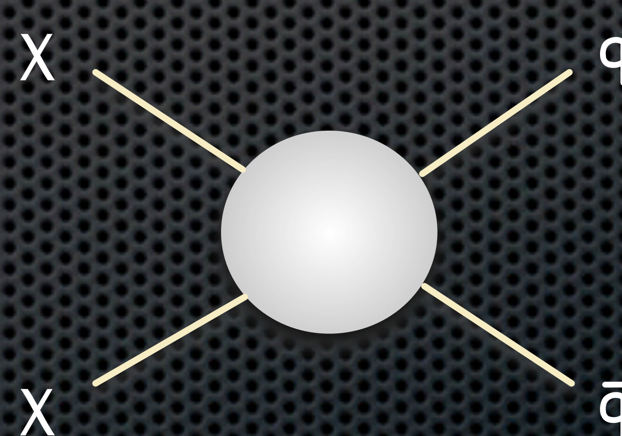


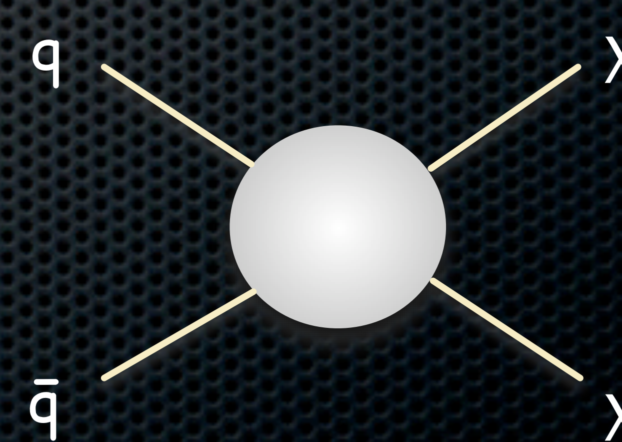
Deep underground

In space

At the LHC







Laura Baudis, University of Zurich, Münster colloquium, 2013

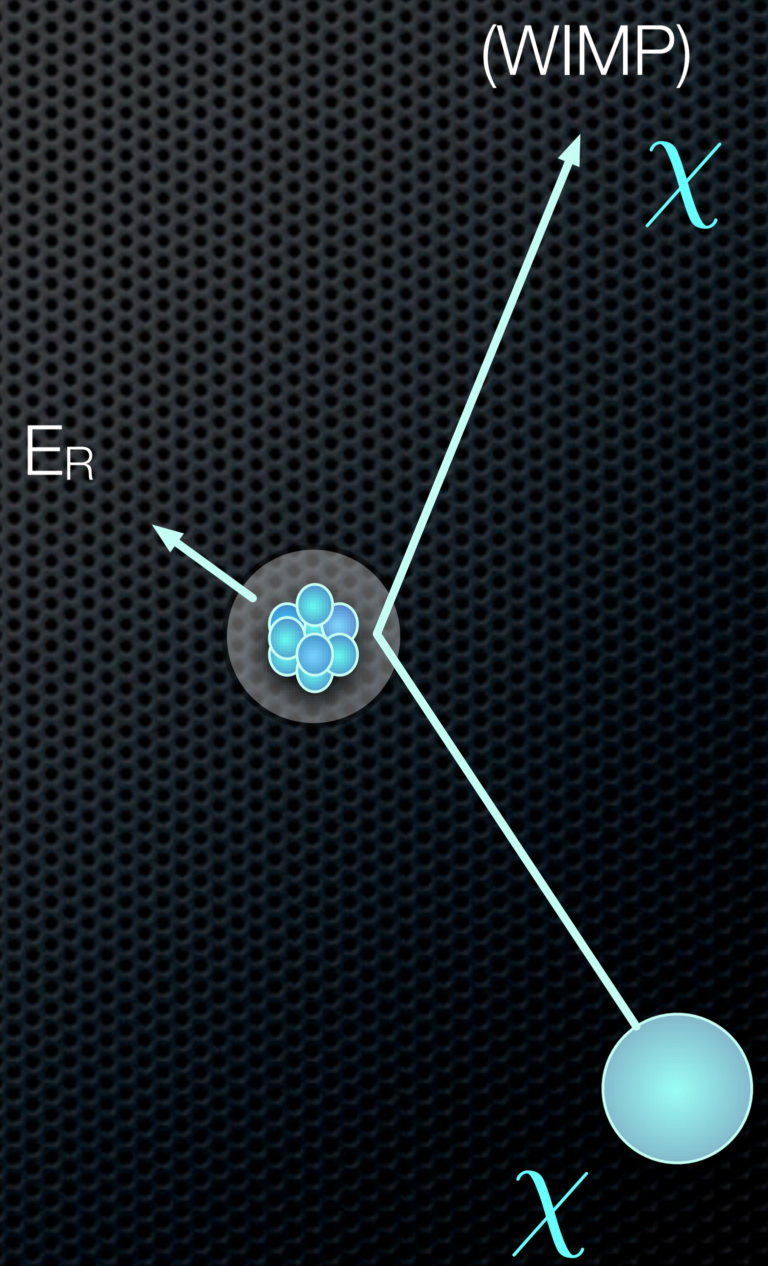
We expect complementary information from direct detectors, from indirect detectors and from the LHC

Direct Detection of WIMPs: Principle

Goodman and Witten, PRD31, 1985

- **Elastic collisions** with nuclei in ultra-low background detectors
- Energy of recoiling nucleus: ***few tens of keV***

$$E_R = \frac{q^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - cos\theta)$$



- q = momentum transfer (~ 10 - 100 MeV)
- μ = reduced WIMP-nucleus mass
- v = mean WIMP-velocity relative to the target
- θ = scattering angle in the center of mass system

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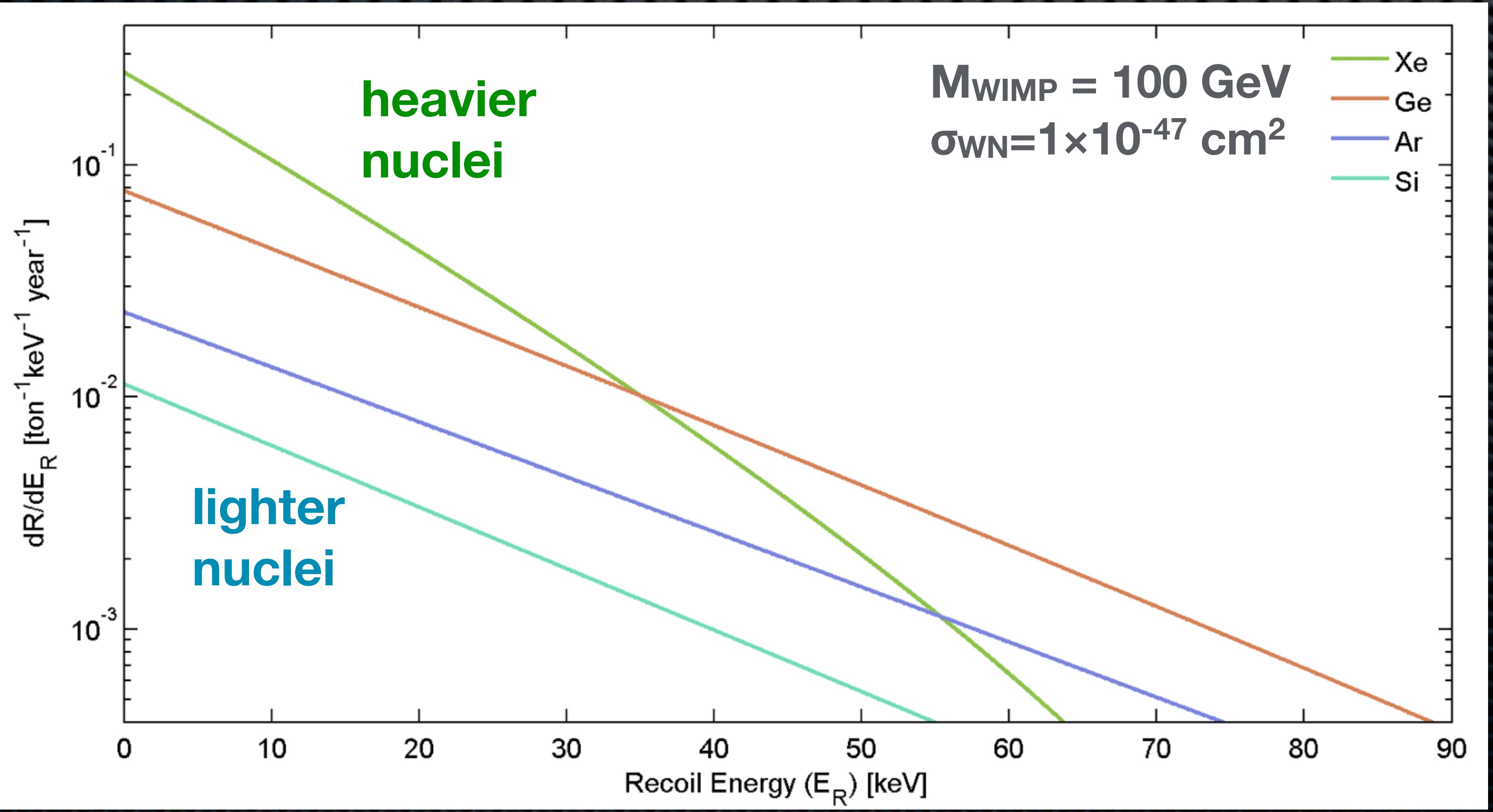
Expected Interaction Rates

- Recoil rate after integration over WIMP velocity distribution

$$R \sim 0.13 \frac{\text{events}}{\text{kg year}} \left[\frac{A}{100} \times \frac{\sigma_{WN}}{10^{-38}\,\text{cm}^2} \times \frac{\langle v \rangle}{220\,\text{km}\,\text{s}^{-1}} \times \frac{\rho_0}{0.3\,\text{GeV}\,\text{cm}^{-3}} \right].$$



Nuclear recoil spectrum for different target nuclei

(Standard halo model with ρ= 0.3 GeV/cm^3)

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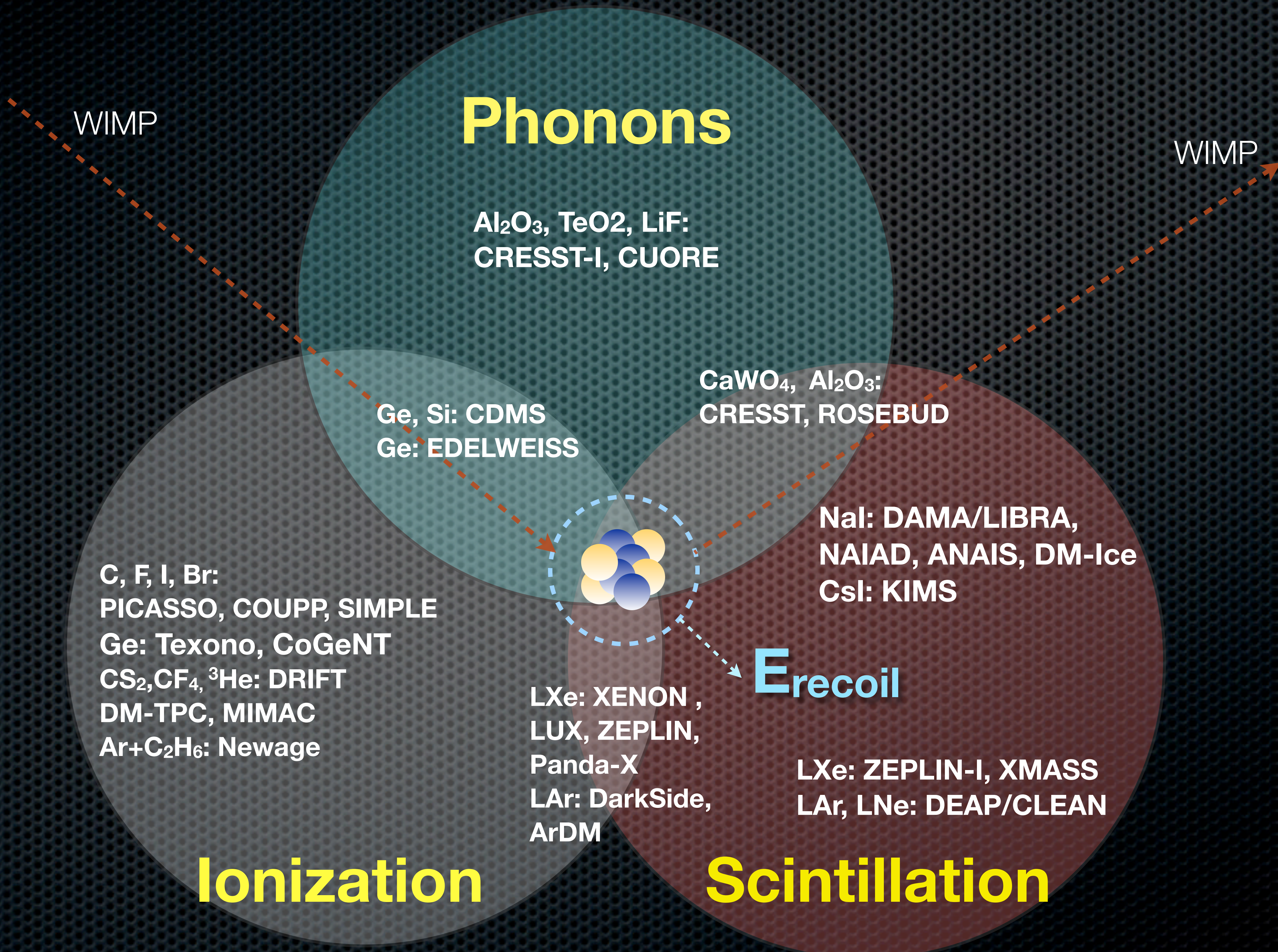
The experimental challenge

- **To observe a signal which is:**
  - very small (few keV)
  - extremely rare (1 per ton per year?)
  - embedded in a background that is millions of times higher

- **Why is it challenging?**
- Detection of low-energy particles - done!
  ➡e.g. micro-calorimetry with phonon readout
- Rare event searches with ultra-low backgrounds - done!
  ➡e.g SuperK, Borexino, SNO, etc
- **But: can we do both?**

Detection Techniques



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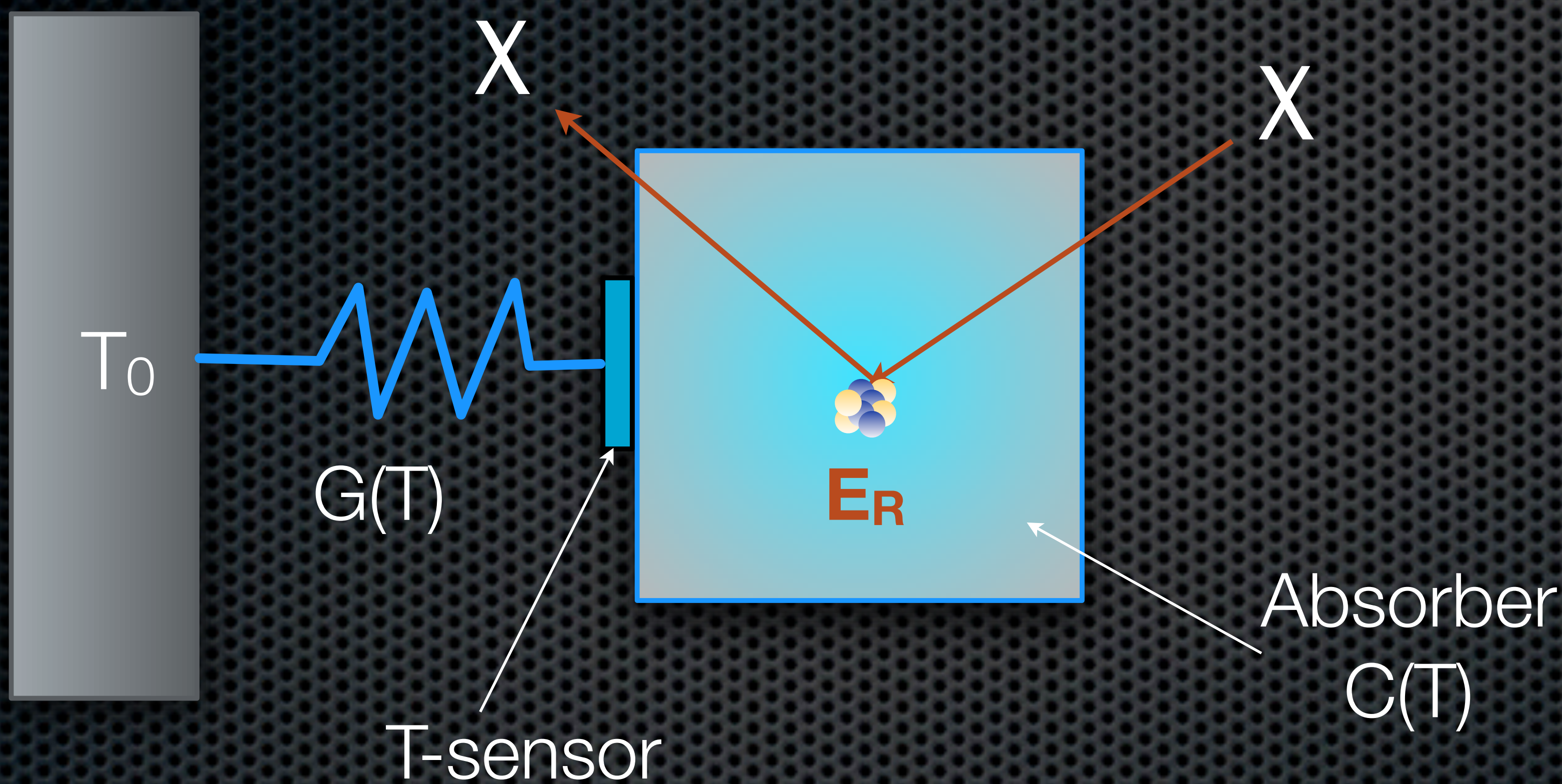
Phonons: Cryogenic Experiments at T~ mK

- Detect a *temperature increase* after a particle interacts in an absorber



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

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

$$C(T) \propto \frac{m}{M}\left(\frac{T}{\Theta_D}\right)^3 JK^{-1}$$

m = absorber mass

M = molecular weight of absorber

Θ_D = Debye temperature (at which the highest frequency gets excited)

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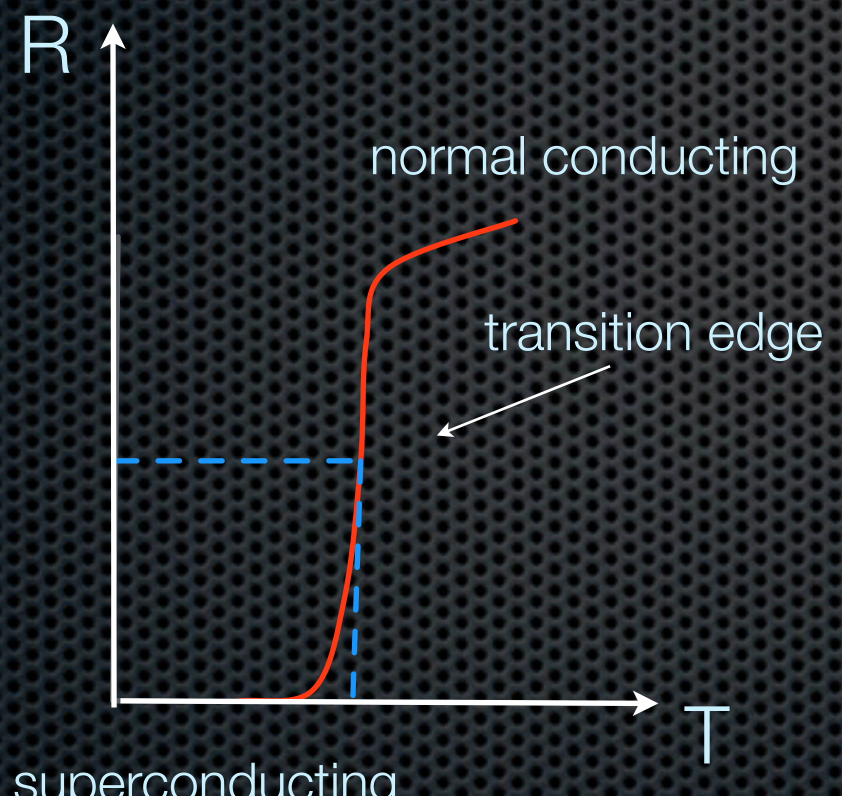
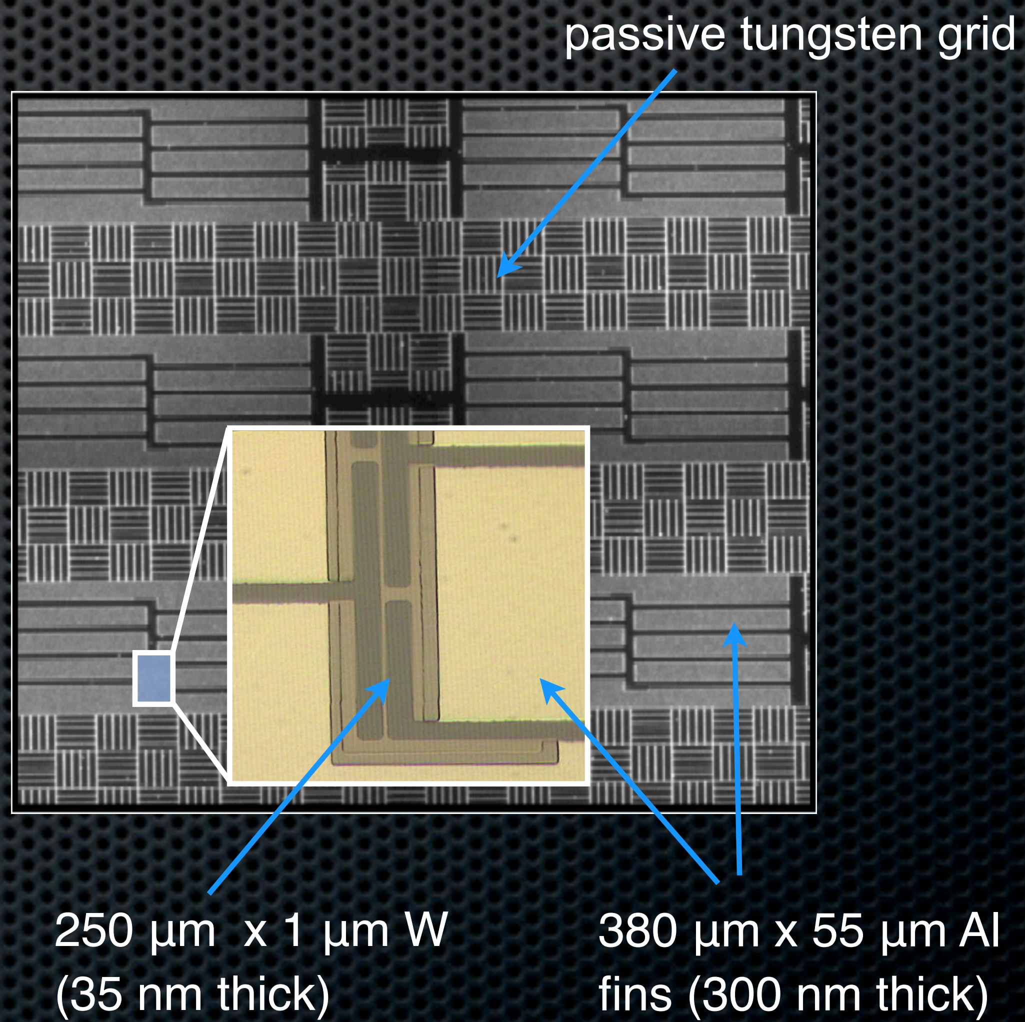
Transition Edge Sensors

- The substrate is cooled well below the SC transition temperature T_C
- The temperature rise (~ μK) is measured with TES





Example: TES for CDMS detectors

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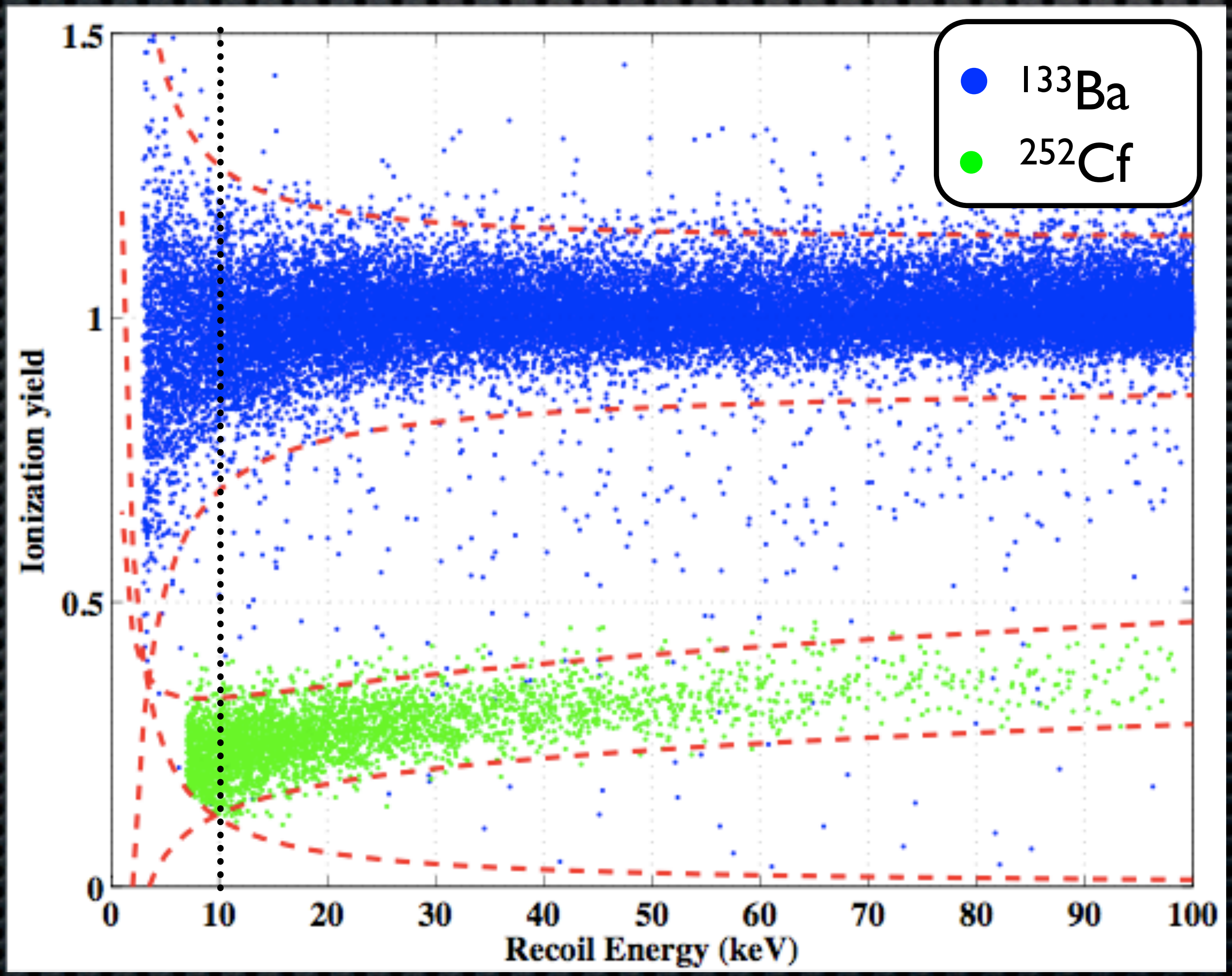
Cryogenic Experiments at T~ mK

- **Advantages**: high sensitivity to nuclear recoils (measure the full energy in the phonon channel); good energy resolution, low energy threshold (keV to sub-keV)
- **Ratio of light/phonon or charge/phonon:**
  - nuclear versus electronic recoils discrimination -> separation of S and B

Ratio of charge (or light) to phonon



Background region

Expected signal region

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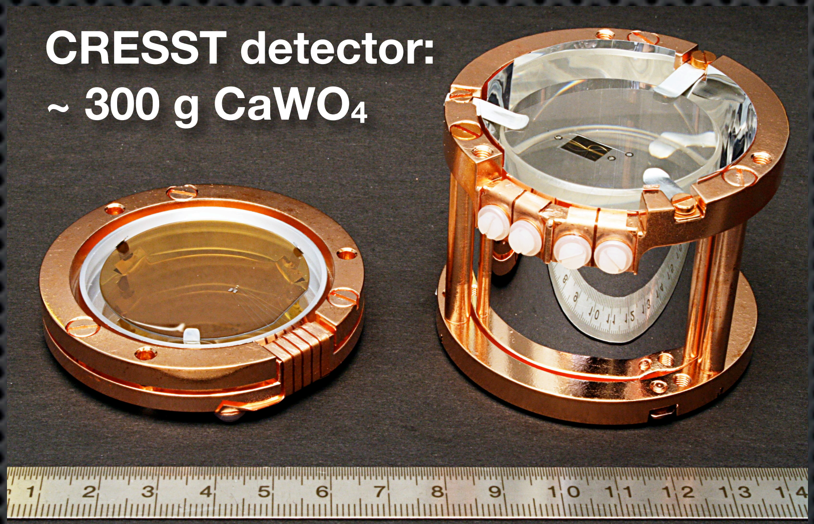
CDMS, CRESST, EDELWEISS

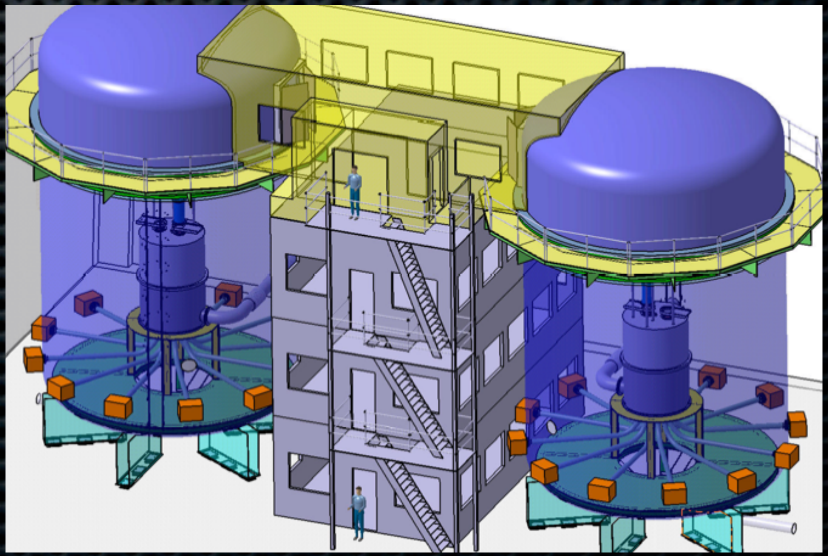
- Absorber masses from ~ 100 g to 1400 g (SuperCDMS at SNOLab)
- Currently running at Soudan, LNGS, Modane
- Future: EURECA (multi-target approach, up to 1 ton mass), SuperCDMS (150 kg) and GEODM (1 ton Ge detectors)

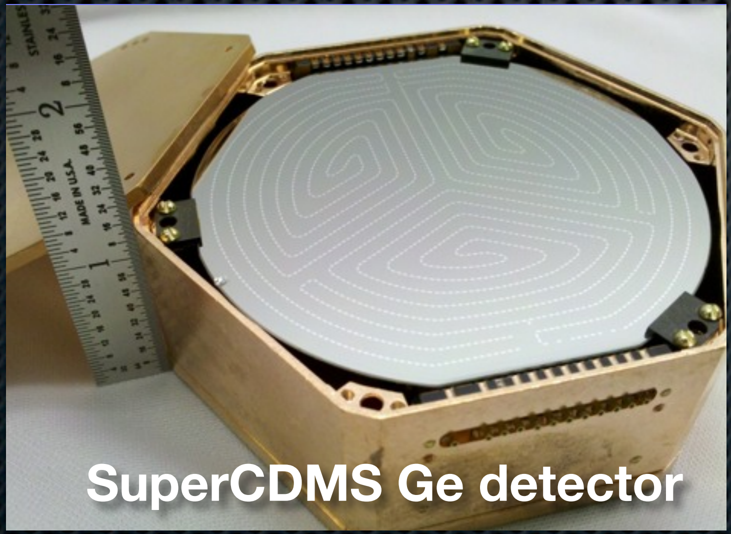
EDELWEISS Ge FID Detector



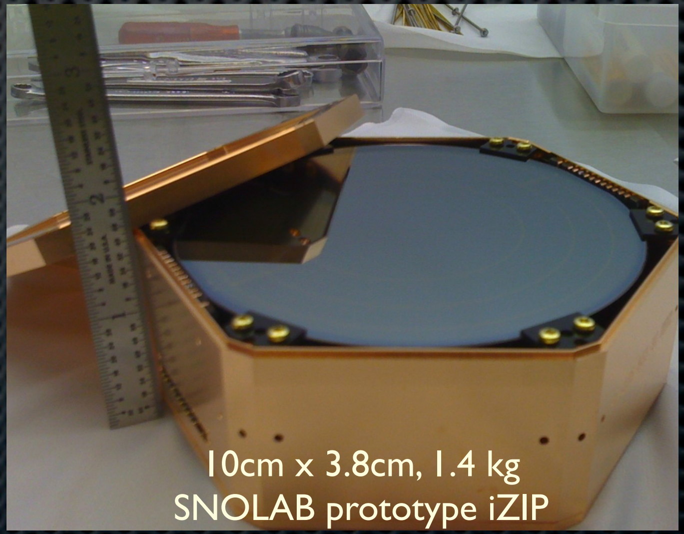
CRESST detector: ~ 300 g $CaWO_4$

EURECA multi-target approach (Ge, $CaWO_4$, ...)





SuperCDMS Ge detector



10cm x 3.8cm, 1.4 kg
SNOLAB prototype iZIP

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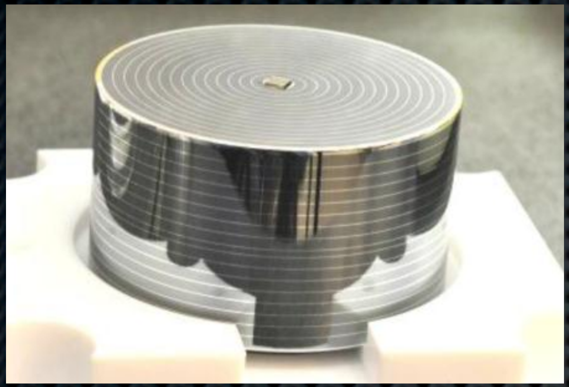
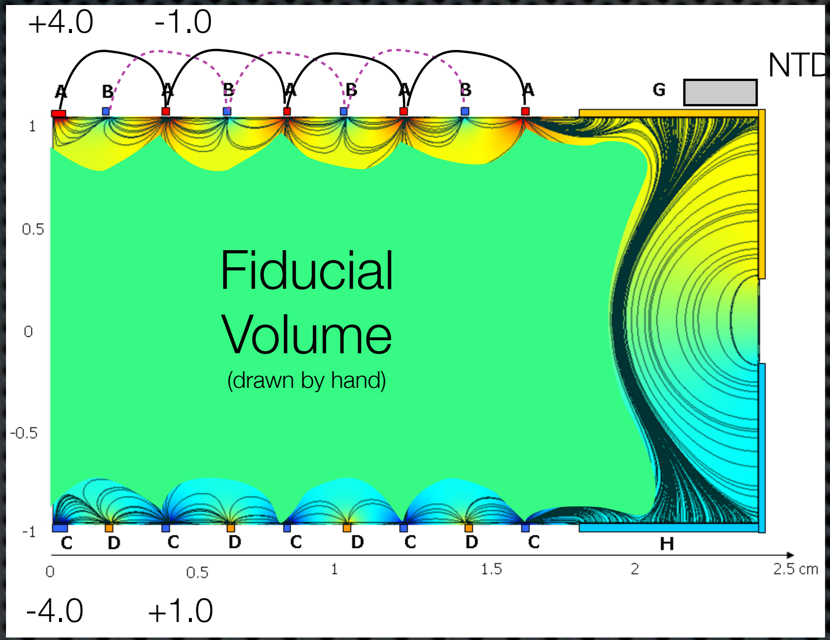
New phonon and charge sensors

- Interleaved z-ionization and phonon detectors (iZIPs,SuperCDMS), interdigitized charge electrodes (EDELWEISS)
- To suppress surface-events with reduced charge collection

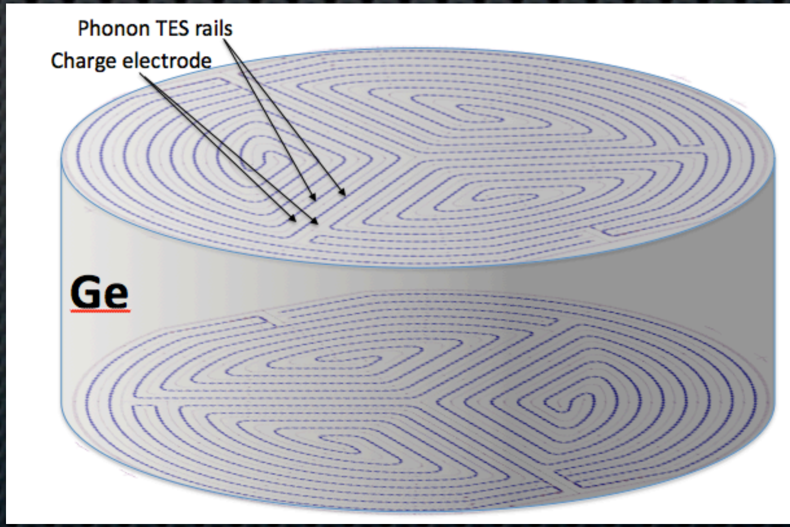


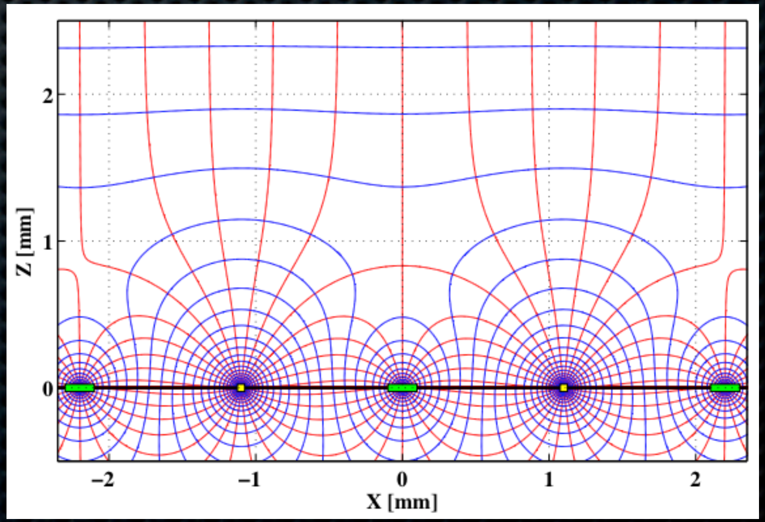
EDELWEISS FID detector design



charge near the surface of the detectors is collected only on one side

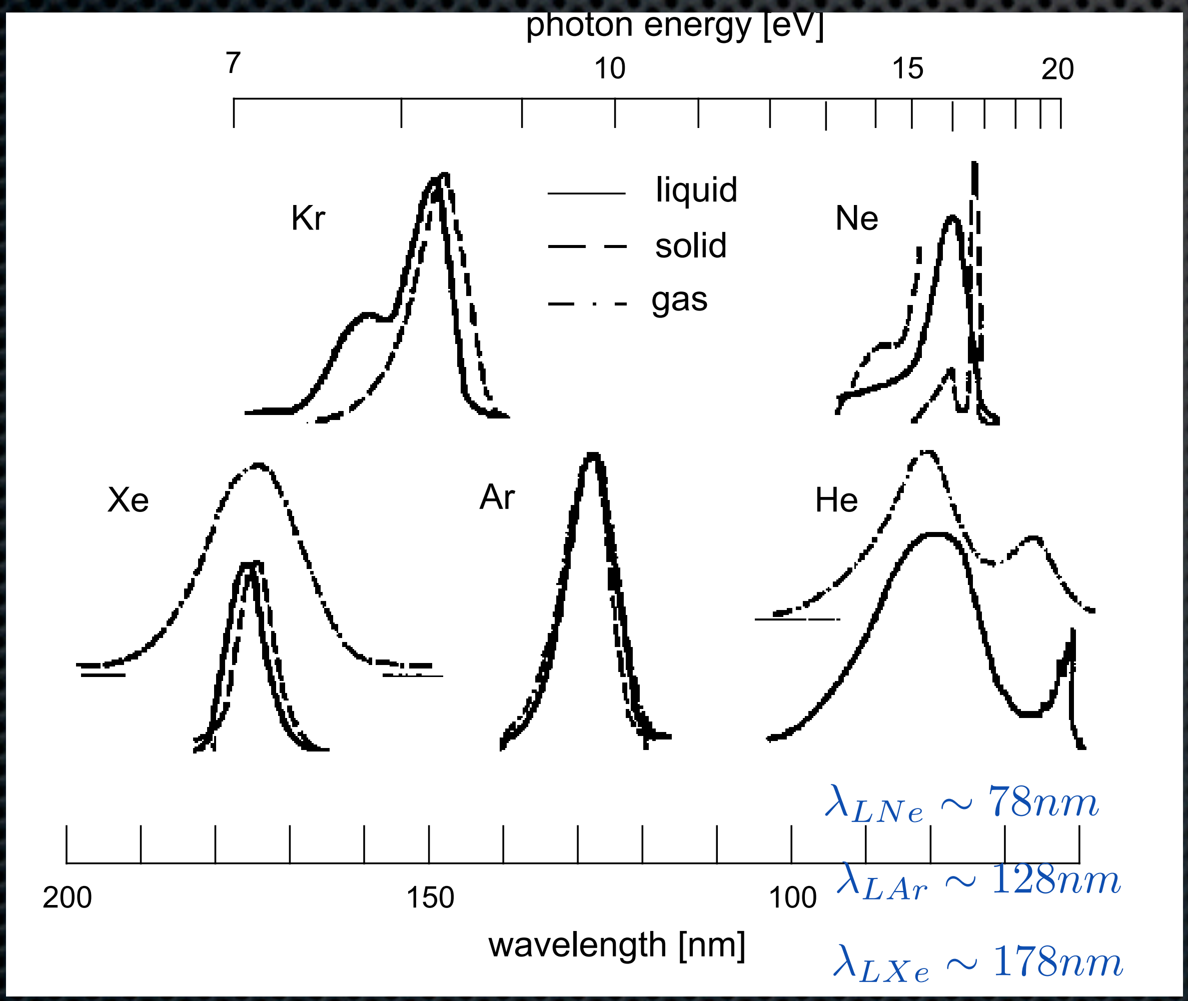
charge in the bulk of the detectors is collected on both sides

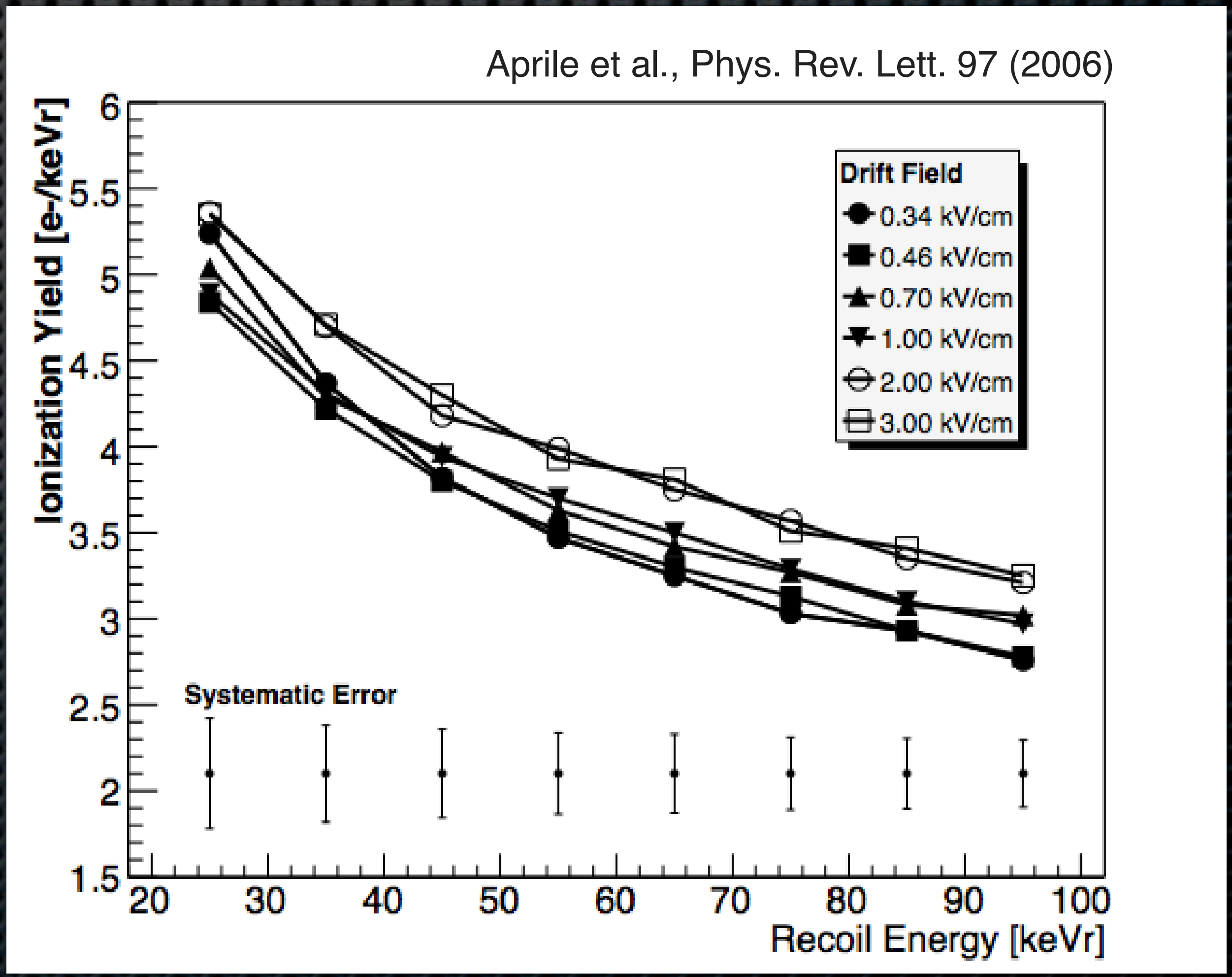




Scintillation/Ionization: Noble Liquids

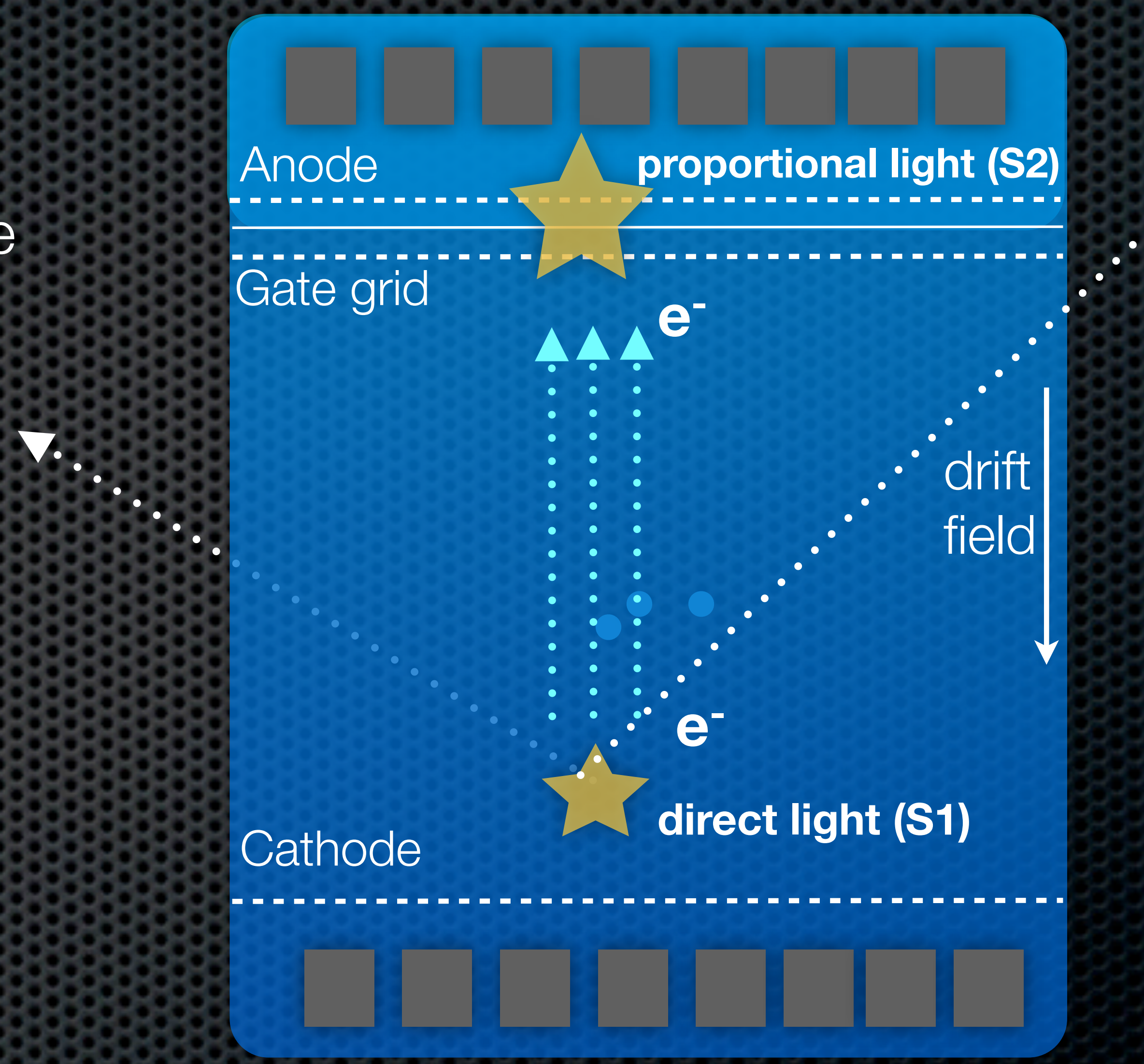
- Noble liquids: high light and charge yield; transparent to their own light
- Large, scalable, homogeneous and self-shielding detectors

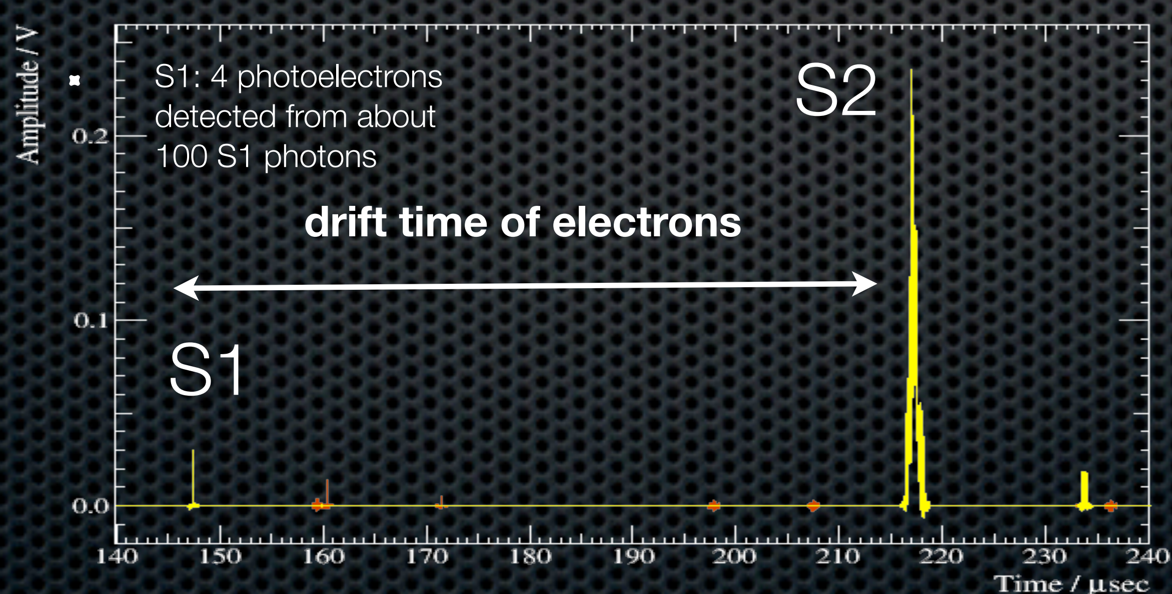




Dual-phase detectors: TPCs

- *Prompt (S1)* light signal after interaction in the active volume
- Charge is drifted, extracted into the gas phase and detected as *proportional light (S2)*
- *Charge/light depends on dE/dx: particle identification*
- *3D-position resolution: fiducial volume cuts*





- S2: 645 photoelectrons detected from 32 ionization electrons which generated about 3000 S2 photons

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Single-phase detectors (light only)

- XMASS at Kamioka (LXe), DEAP/CLEAN at SNOLab (LAr)
- Challenge: ultra-low absolute background

XMASS at Kamioka:
in water Cherenkov shield at Kamioka
835 kg LXe (100 kg fiducial), single-phase, 642 PMTs
soon to take science data

MiniCLEAN at SNOLab:
500 kg LAr (150 kg fiducial)
single-phase open volume
under construction
to run in summer 2013

DEAP-3600 at SNOLab:
3600 kg LAr (1t fiducial)
single-phase detector
under construction
to run in 2014

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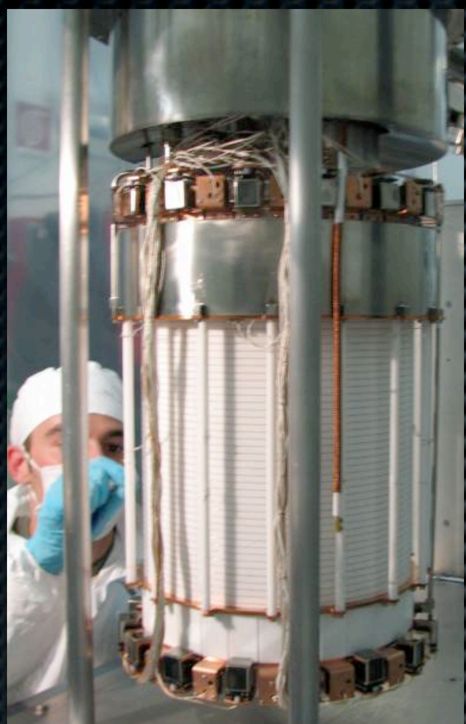
Liquid xenon and liquid argon TPCs



XENON100 at LNGS:

in conventional shield 161 kg LXe (~50 kg fiducial), dual-phase, 242 PMTs
taking science data

LUX at SURF:

in water Cherenkov shield 350 kg LXe (100 kg fiducial), dual-phase, 122 PMTs, physics run to start in early 2013

PandaX in conventional shield at CJPL:

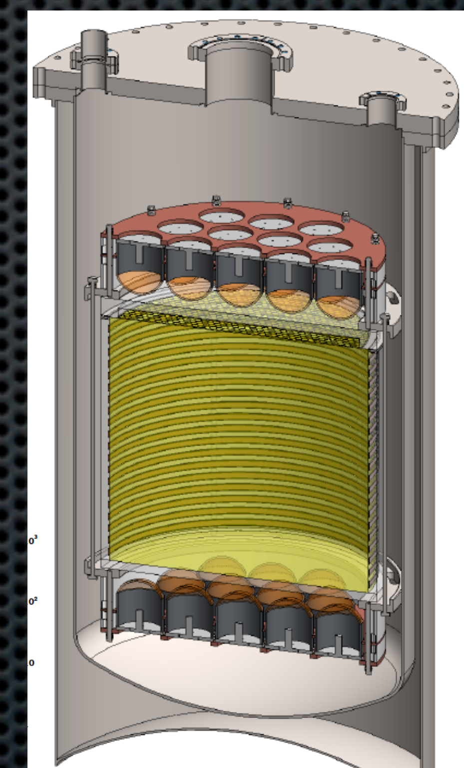
stage I: 123 kg LXe (25 kg fiducial), dual-phase, 180 PMTs starts in early 2013

ArDM at Canfranc:

850 kg LAr TPC

2 arrays of PMTs

in commissioning at Canfranc Laboratory



DarkSide at LNGS

50 kg LAr (depleted in 39Ar) TPC in

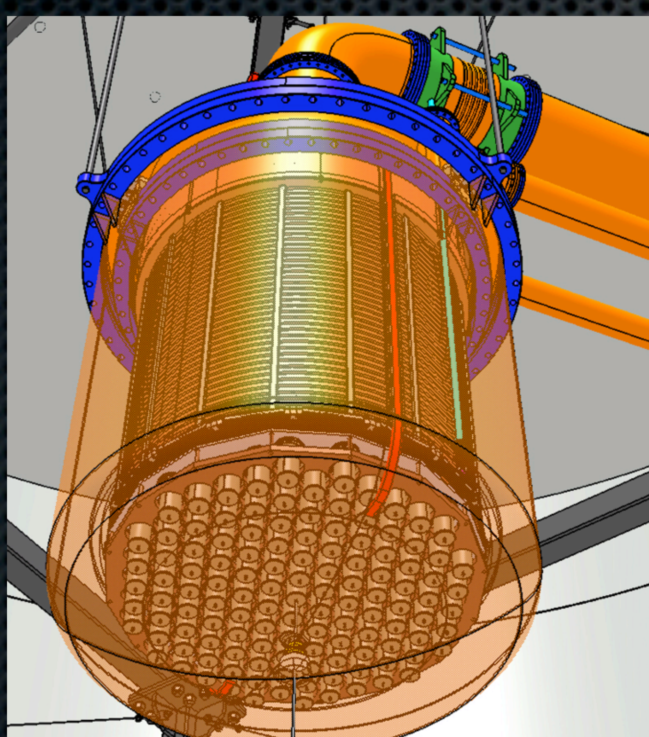
CTF at LNGS

under construction

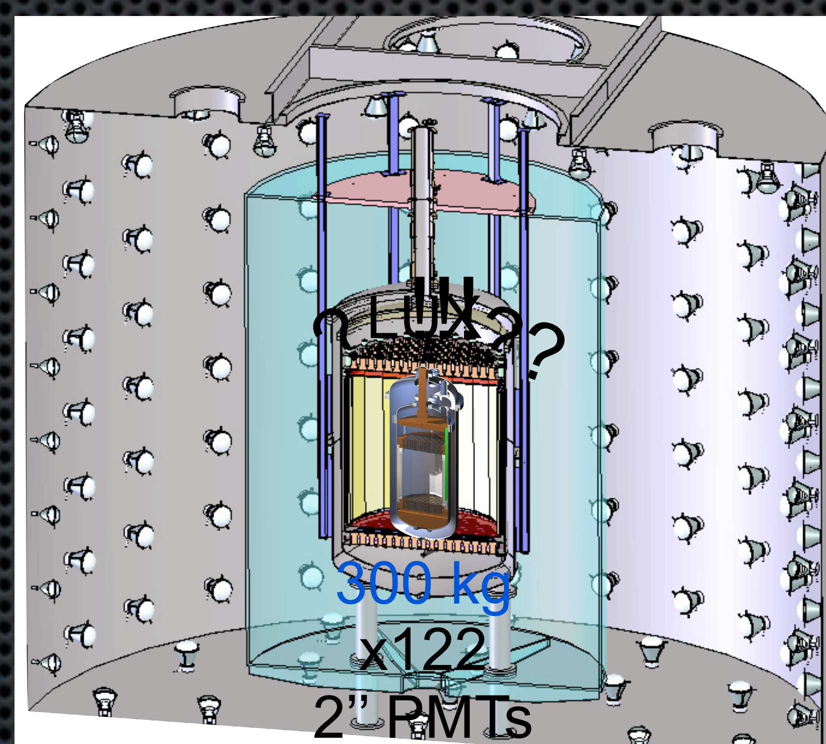
to run 2013 - 2014

Liquid xenon and liquid argon detectors

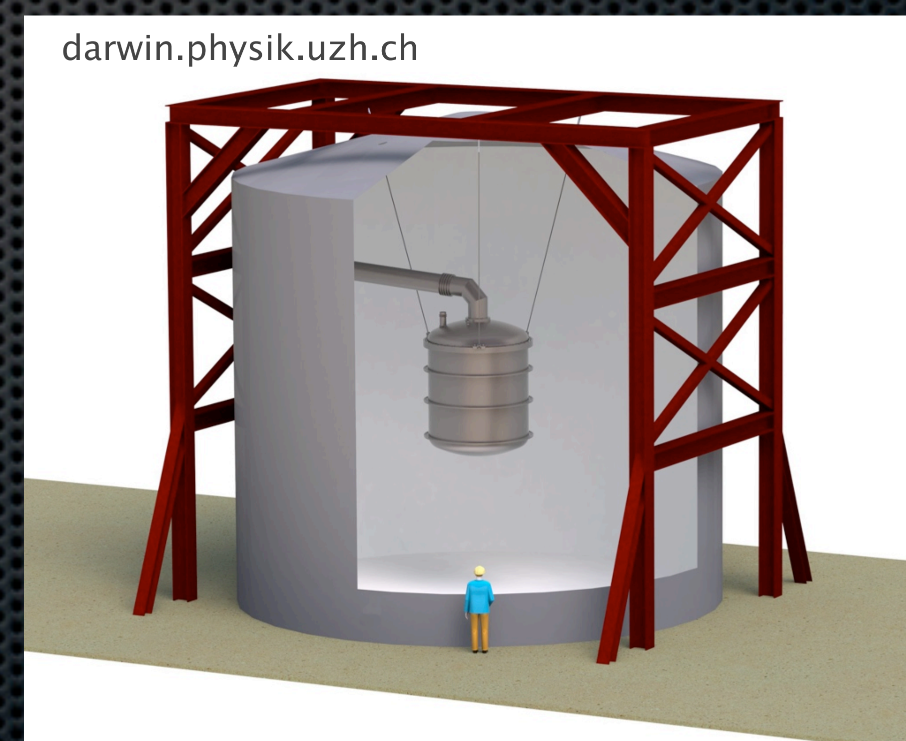
- Under construction: XENON1T at LNGS, 3 t LXe in total
- Future and R&D: XMASS (5 t LXe), LZ (7 t LXe), DARWIN (20 t LXe/LAr)



XENON1T TPC



LZ (LUX + ZEPLIN) 7t LXe

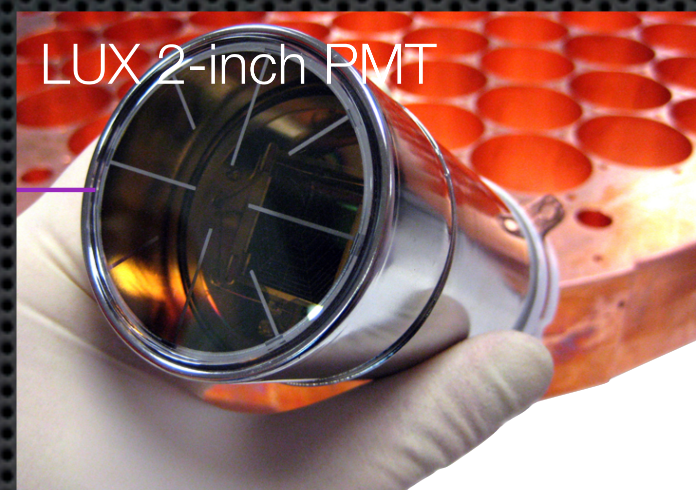


DARWIN 20 t LXe/LAr

Laura Baudis, University of Zurich, VCI2013, Vienna

Photodetectors in noble liquids

- So far mostly PMTs: high QE (~30-35%), work at low-T, high-P
- Ultra-low radioactivity: < 1 mBq/PMT (U/Th/K/Co/Cs)
- Quartz window: transparent to the Xe 178 nm scintillation light



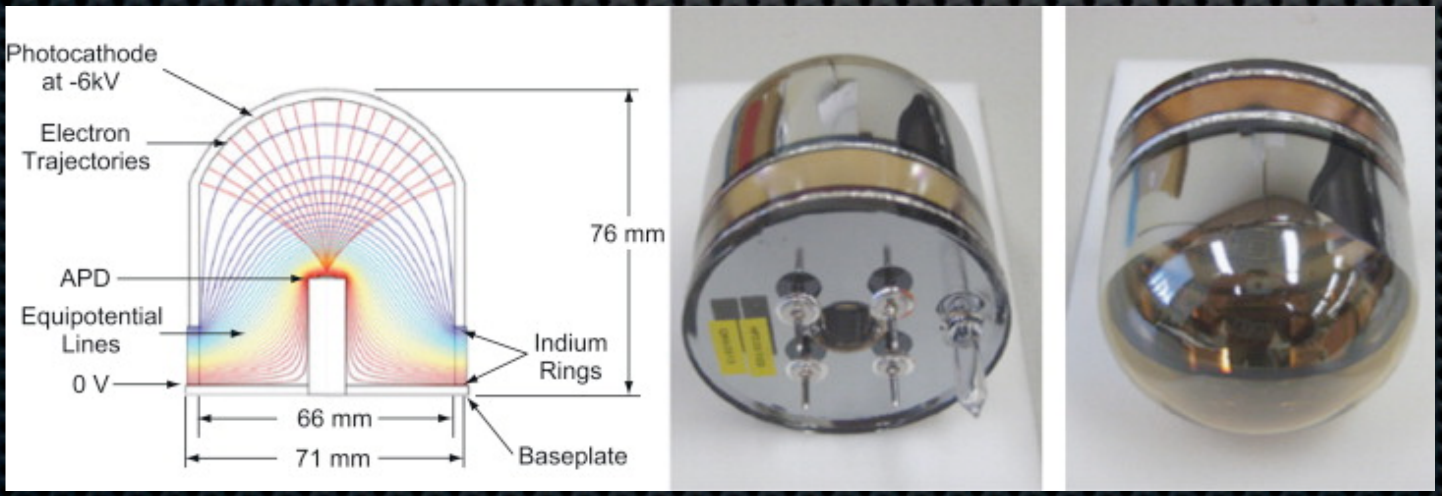

XENON100 array


LUX array

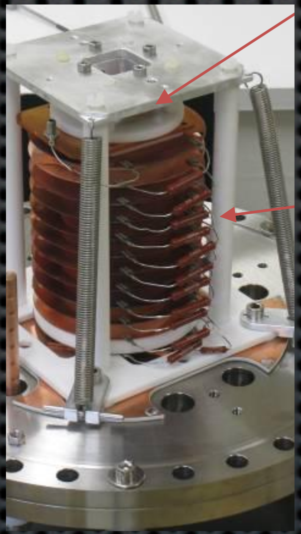

XMASS array

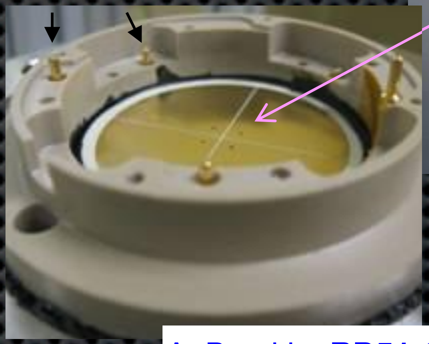
Photodetectors in noble liquids

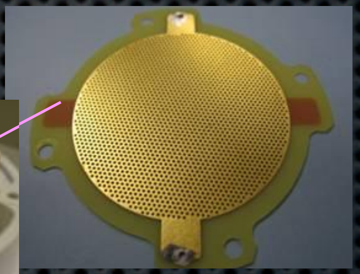
- New ideas: gas photomultipliers (GPMs)
- hybrid photodetectors (QUPID), LAAPDs (so far in EXO - LXe)

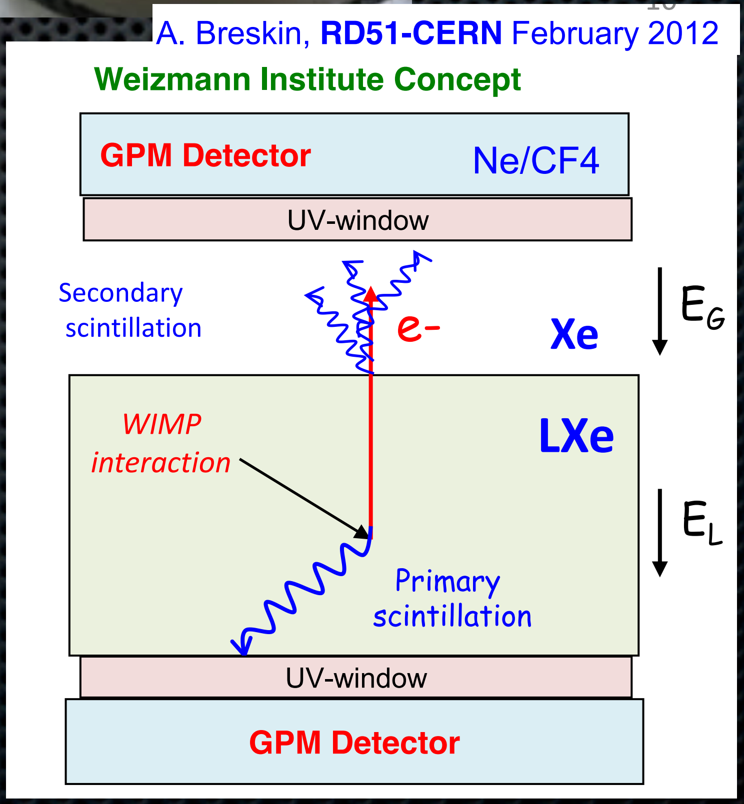


QUPID for LXe/LAr detectors







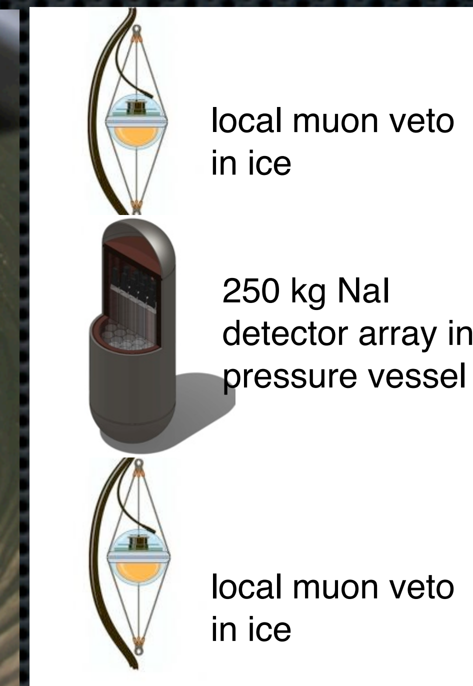


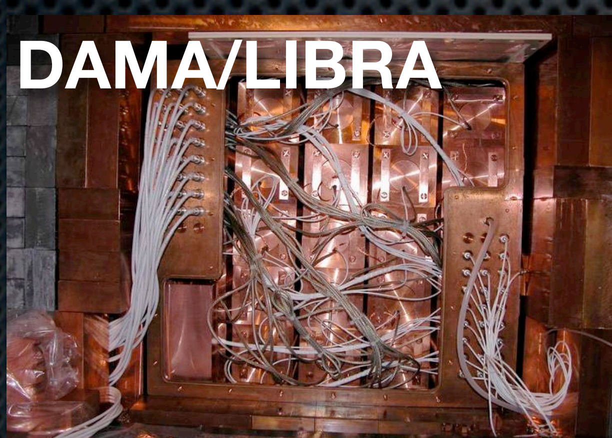
GPM LXe/LAr detectors

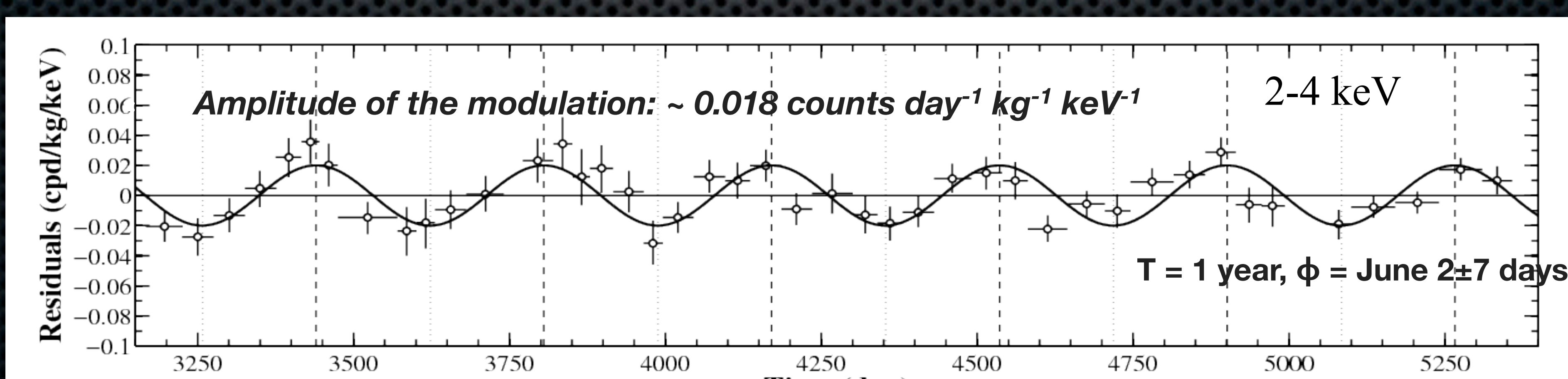
Room temperature scintillators

- NaI: DAMA/LIBRA, ANAIS; CsI: KIMS
- New idea: DM-Ice -> 17 kg NaI deployed as feasibility study at the South Pole (look for annual modulation in the southern hemisphere, 2.4 km deep in ice)
- Goal: build a 250-500 kg NaI detector array, closely packed inside a pressure vessel; use IceCube as a veto

DM-Ice







R.Bernabei et al, Eur.Phys.J. **C67**

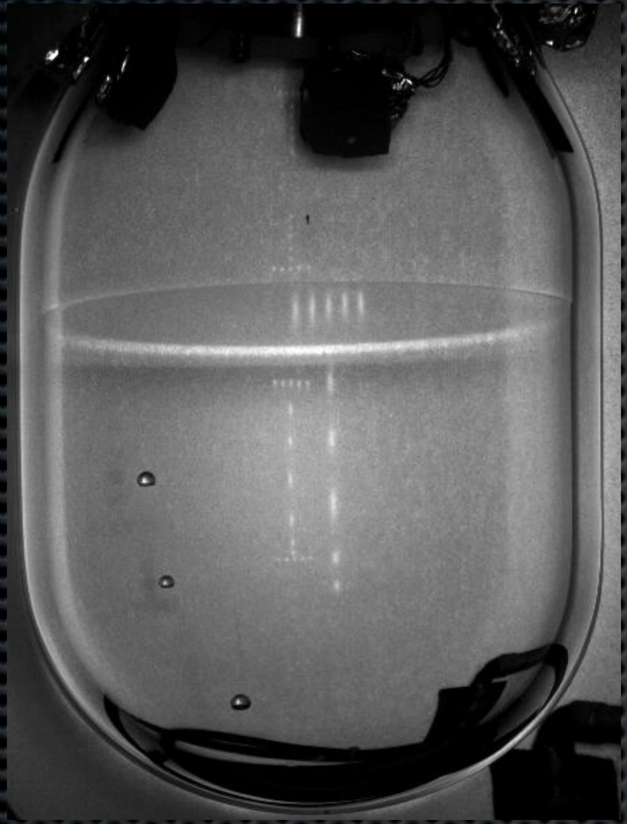
Bubble chambers

- Detect single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chambers (with acoustic, visual or motion detectors)
- Large rejection factor for MIPs (10^{10}), scalable to large masses, high spatial granularity
- Existing detectors: COUPP, PICASSO, SIMPLE
- Future: COUPP-500 -> ton-scale detector

Example:

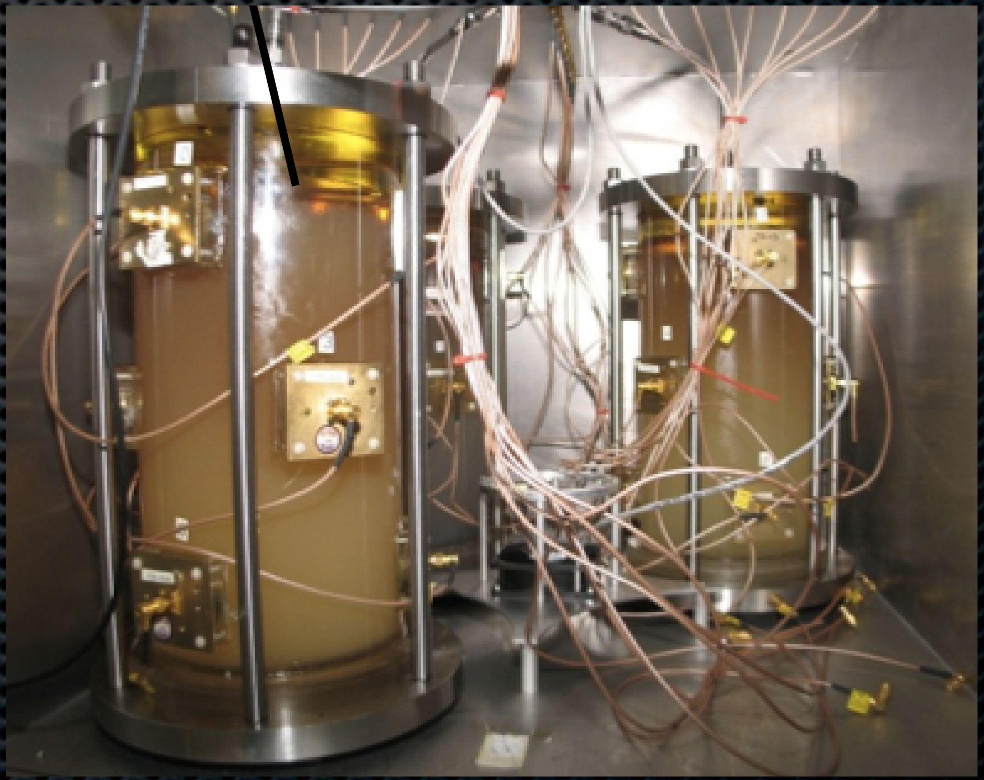
n-induced event (multiple scatter)

WIMP: single scatter



COUPP 4 kg CF_3I detector at SNOLAB

COUPP 60 kg CF_3I detector installed at SNOLAB; physics run in March 2013



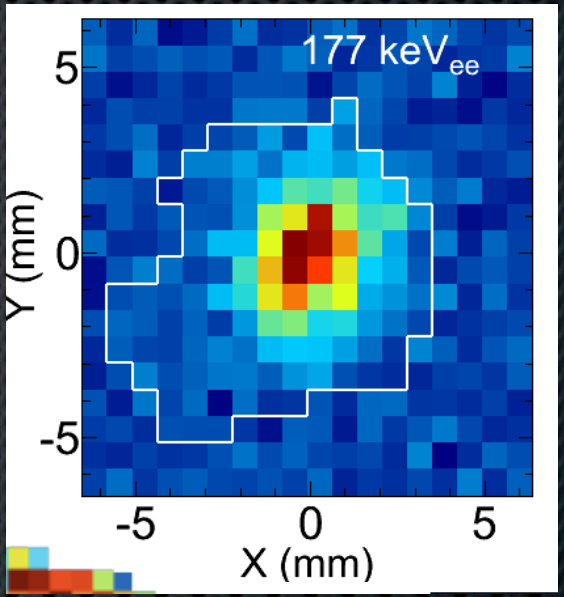
PICASSO at SNOLAB

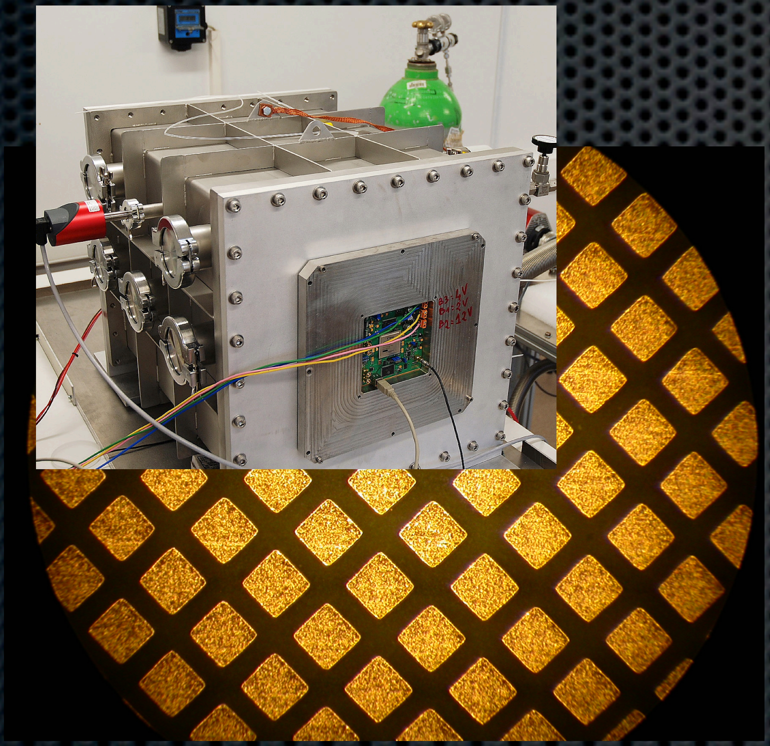
Recoil range << 1 μm in a liquid - very high dE/dx

Directional detectors

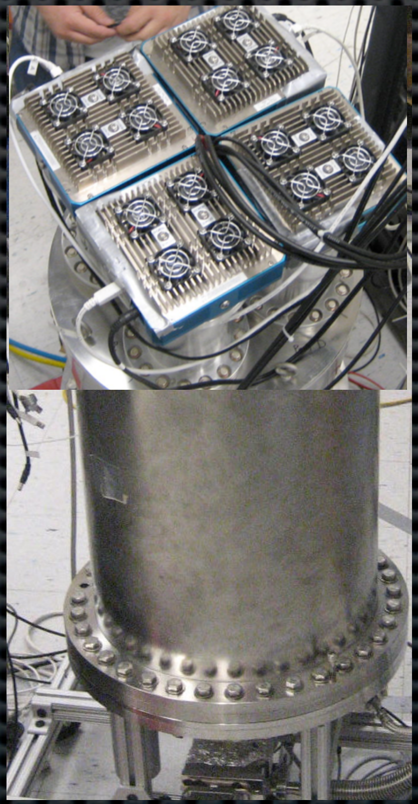
- R&D on low-pressure gas detectors to measure the recoil direction, correlated to the galactic motion towards Cygnus
- MicroTPCs: MIMAC (CF_4, CHF_3, H gas), NEWAGE (CF_4 gas)
- TPC: DRIFT (negative ion, CS_2), DM-TPC (CF_4 gas)
- New ideas: see talk by D. Nygren

DM-TPC
n-calibration



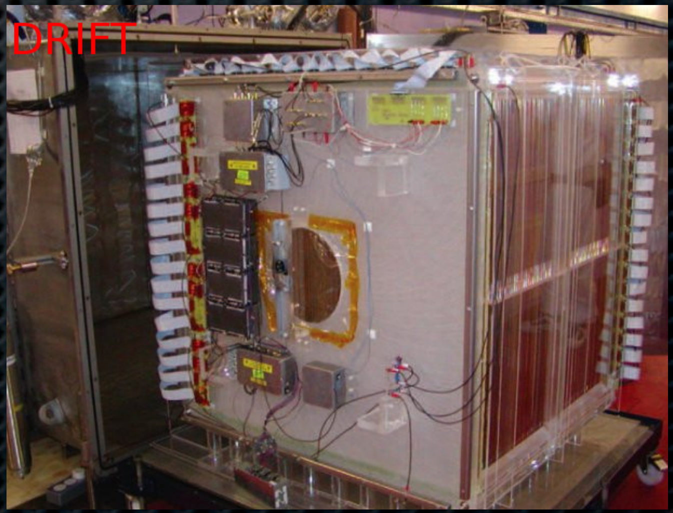


MIMAC 100x100 mm^2
5l chamber at Modane



18l DM-TPC at MIT
CCD readout

NEWAGE, Kamioka

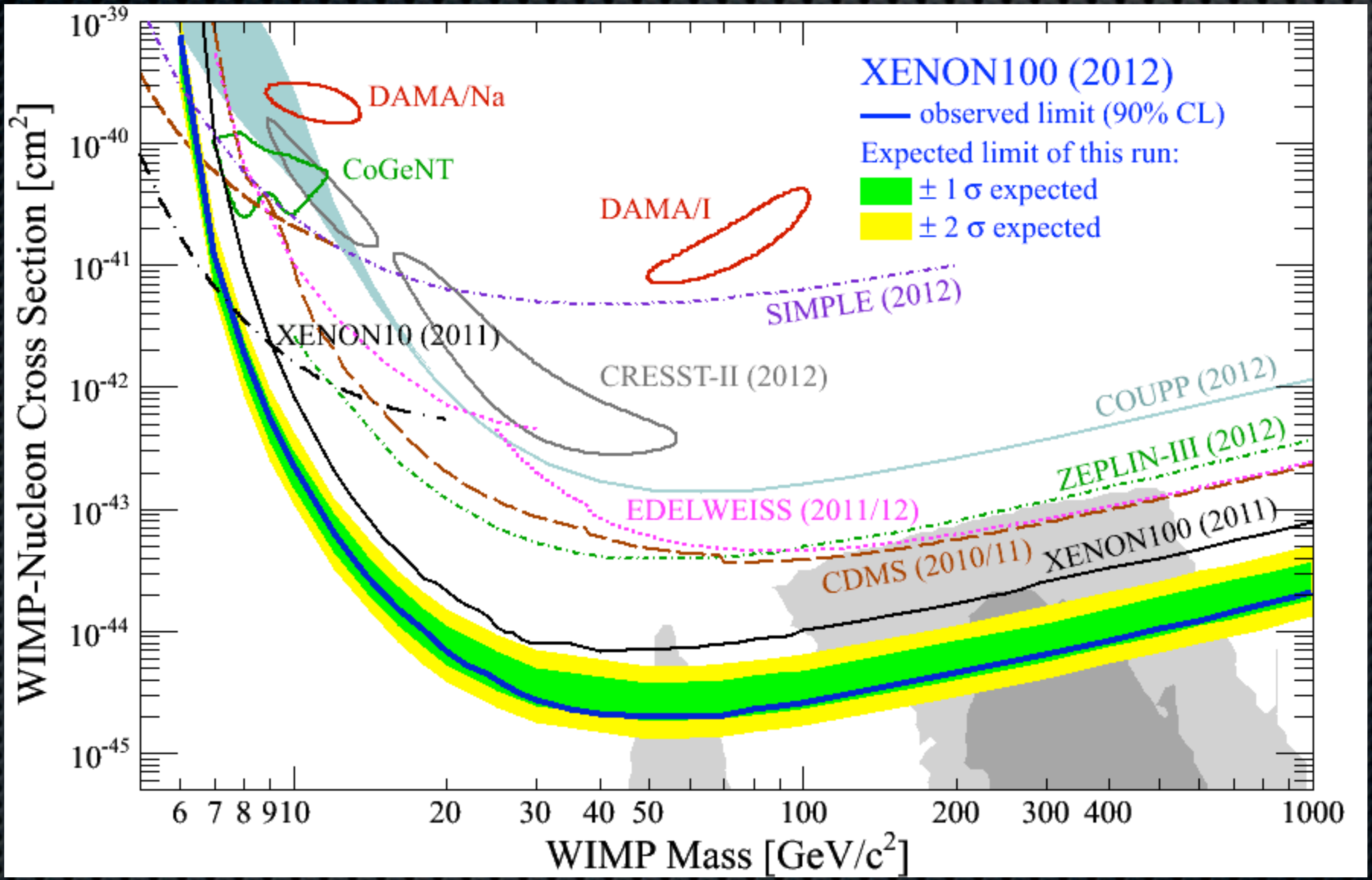


DRIFT, Boulby Mine

The WIMP landscape

- Parameter space above thick blue line excluded

Phys. Rev. Lett. 109 (2012)



Green/yellow bands:

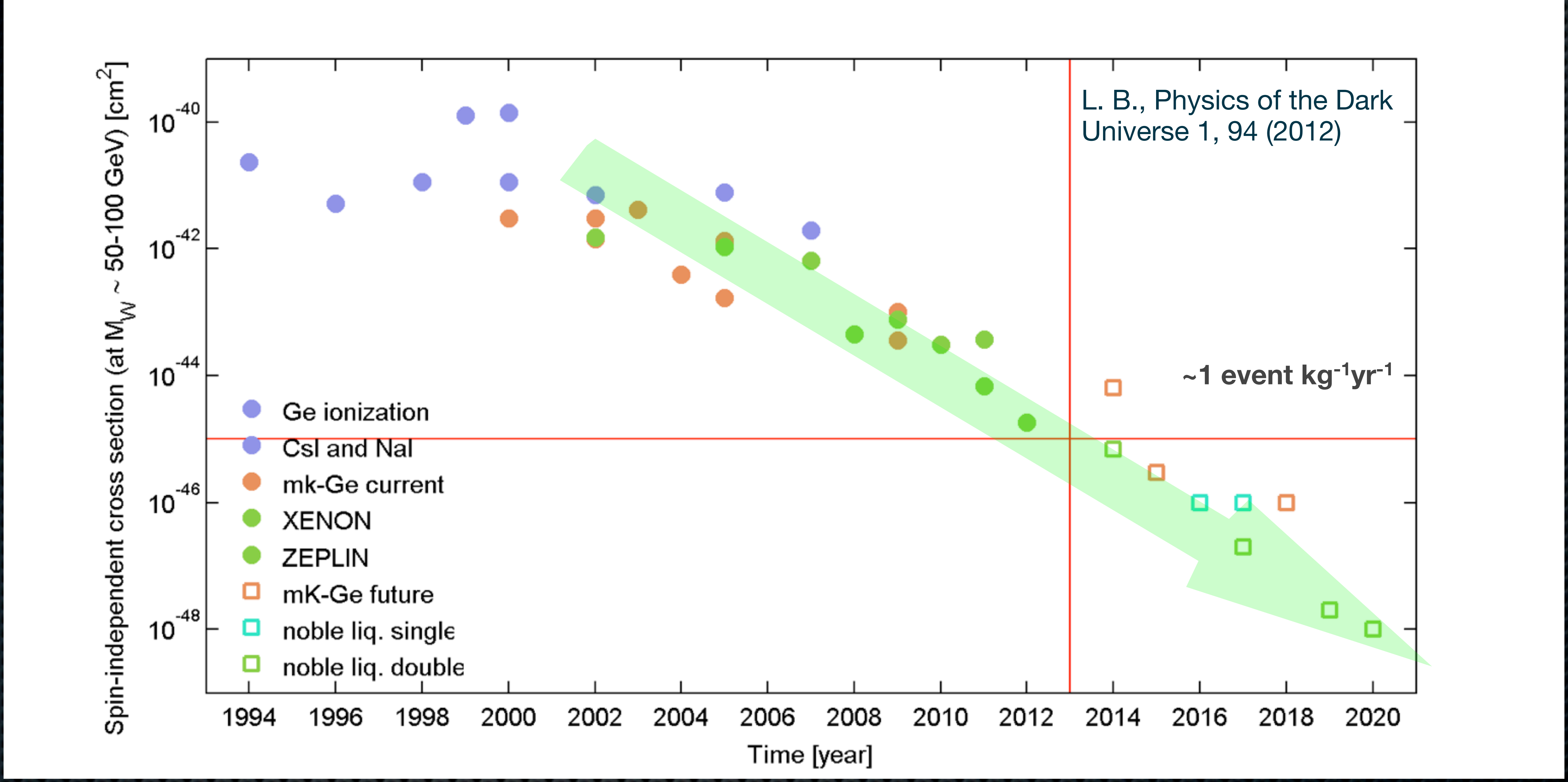
1- and 2-σ expectation, based on zero signal

Limit (dark blue):

Limit at M_W = 50 GeV: 7 x 10^{-45} cm^2 (90% C.L.)

Laura Baudis, University of Zurich, VCI2013, Vienna

WIMP search evolution in time



About a factor of 10 every 2 years!
Can we keep this rate of progress?

Summary

- Astroparticle physics: a growing and exciting field of research
- I have covered only a small part in this talk -> see parallel sessions
- Detectors/facilities: from micro-TPCs (few grams of material) to 1 Gton of water
- Energies: from sub-keV to > 10^{20} eV: very different technological requirements
- Common goal: a deeper understanding of our mysterious Universe

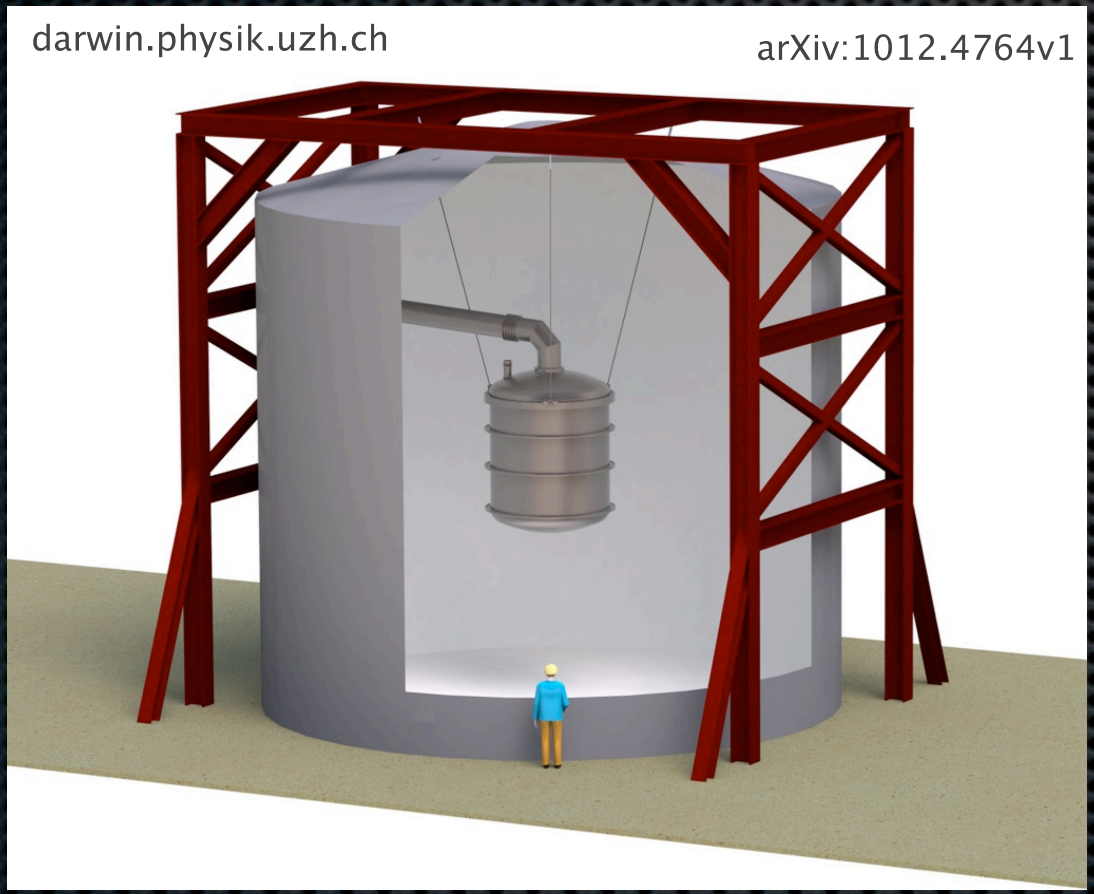
End

DARWIN

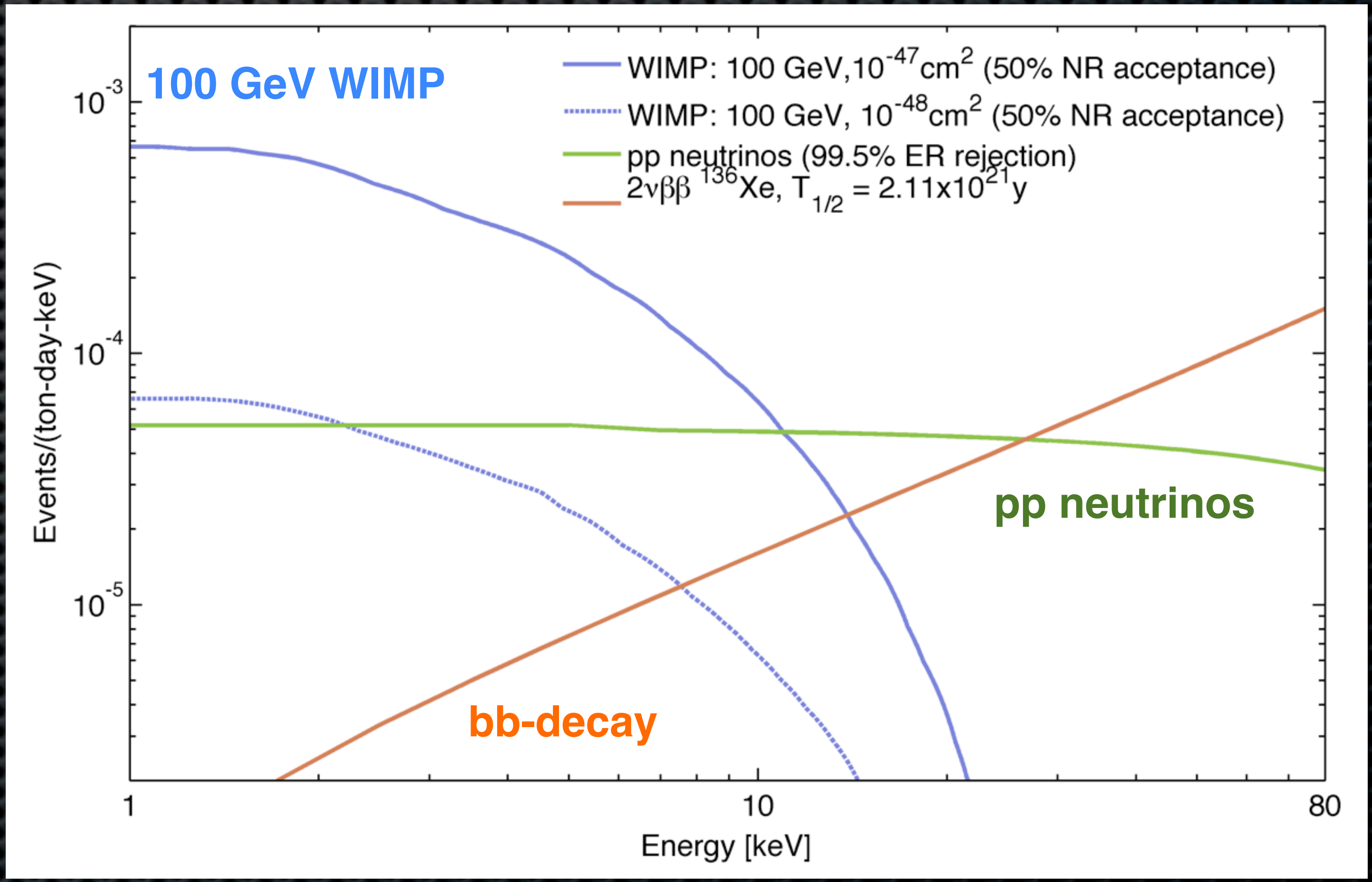
DARk matter WImp search with Noble liquids

- R&D and design study for next-generation noble liquid detector
- Physics goal: build the “ultimate WIMP detector”, before the possibly irreducible neutrino background takes over; probe WIMP cross sections down to ~10^{-48} cm^2

10 m



20 t LXe (and/or LAr) cryostat in large water Cherenkov shield

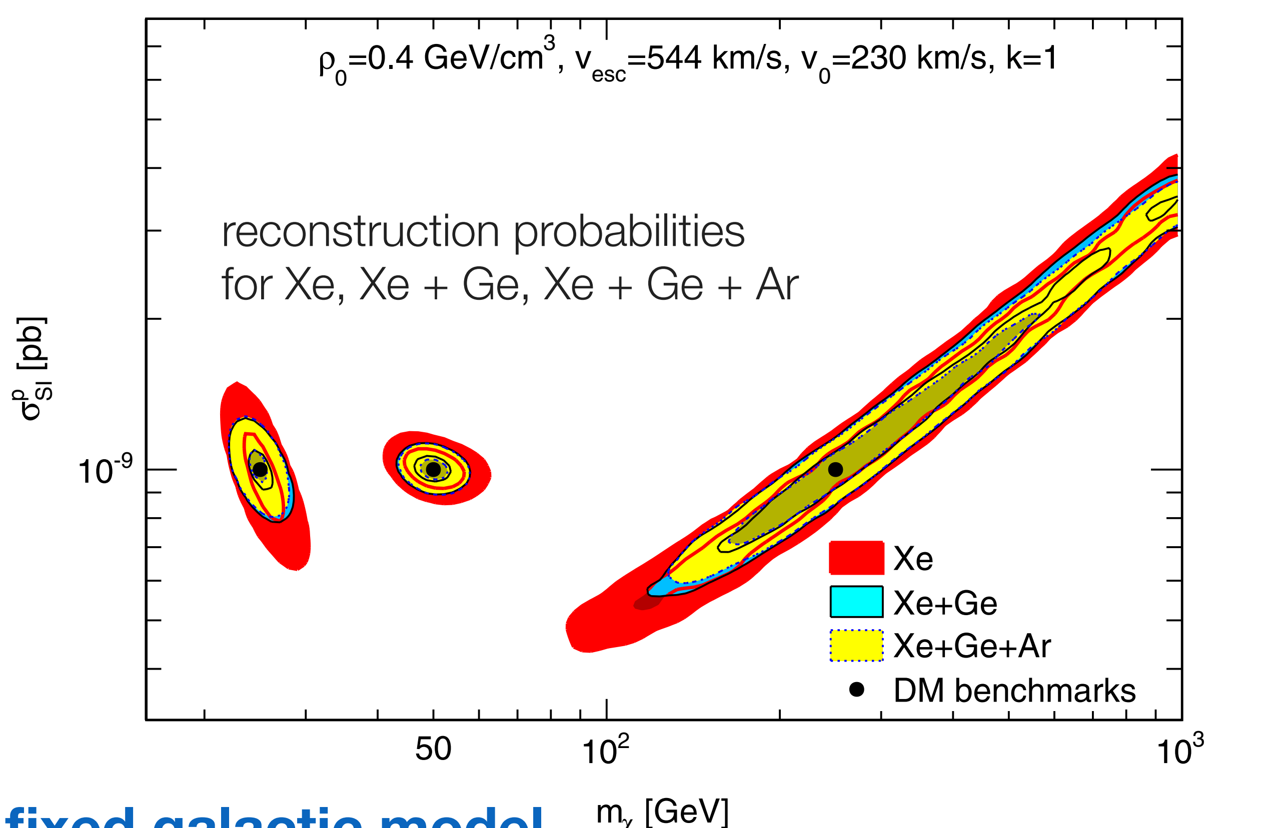


2vbb: EXO measurement of ^{136}Xe $T_{1/2}$
Assumptions: 50% NR acceptance, 99.5% ER discrimination
Contribution of 2vbb background can be reduced by depletion

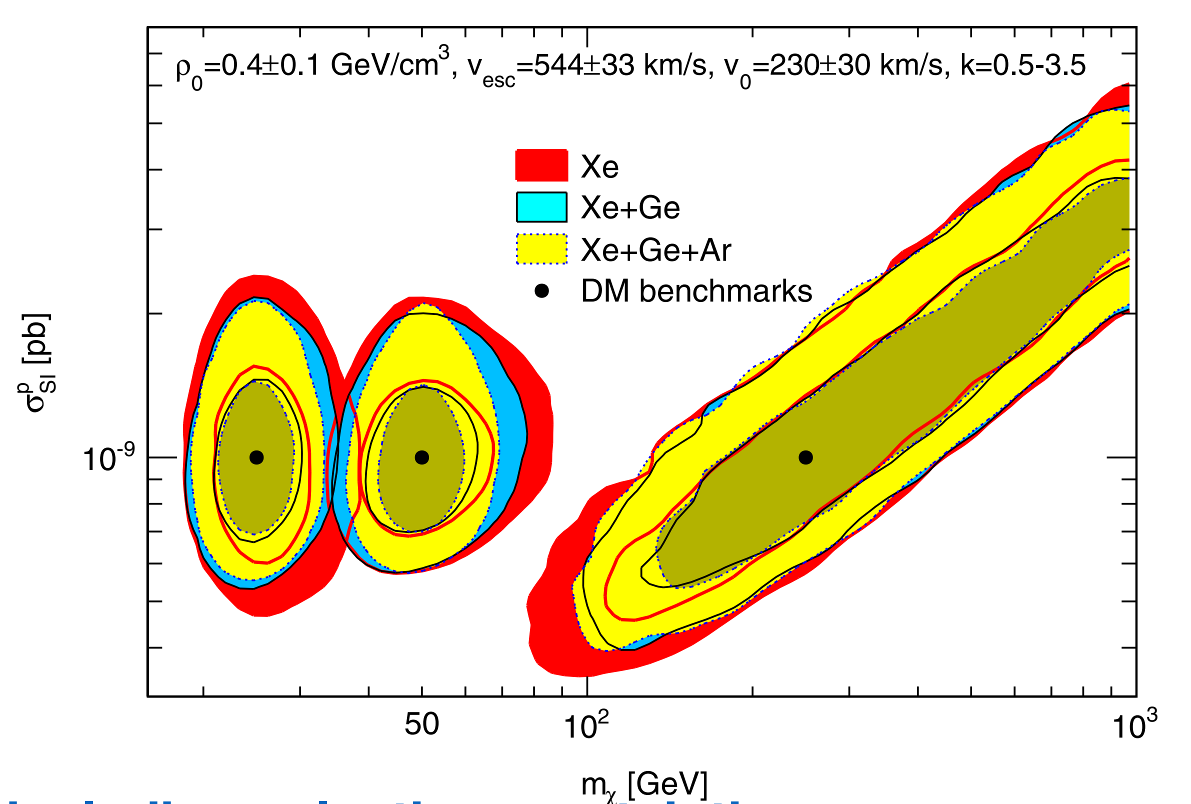
Beyond Current Detectors

- To reconstruct WIMP properties, *larger detectors are needed*
- Different targets are sensitive to different directions in the m_χ- σ_{SI} plane

target	ϵ [ton×yr]	η_{cut}	A_{NR}	ϵ_{eff} [ton×yr]	E_{thr} [keV]	$\sigma(E)$ [keV]	background events/ϵ_{eff}
Xe	5.0	0.8	0.5	2.00	10	Eq. (7)	< 1
Ge	3.0	0.8	0.9	2.16	10	Eq. (6)	< 1
Ar	10.0	0.8	0.8	6.40	30	Eq. (8)	< 1



fixed galactic model



including galactic uncertainties

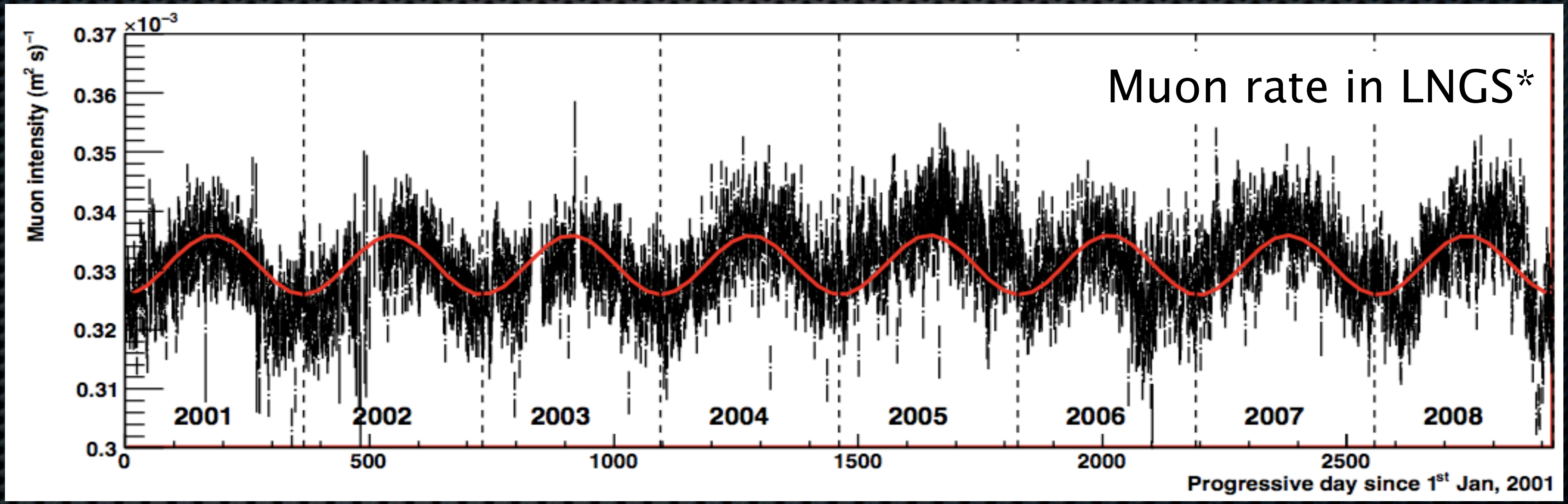
Laura Baudis, University of Zurich, VCI2013, Vienna

Miguel Pato, Laura Baudis, Gianfranco Bertone, Roberto Ruiz de Austri, Louis E. Strigari and Roberto Trotta   Phys. Rev. D 83, 083505 (2011)

Light: DAMA/LIBRA

- Origin of the time variation in the observed rate:
  - motion of the Earth-Sun system through the WIMP halo?
  - environmental effects?
  - unclear!

see also David Nygren, arXiv:1102.0815



Muon rate variation at LNGS: Amplitude: ~ 0.015; T = 1 year, ϕ = July 15±15 days

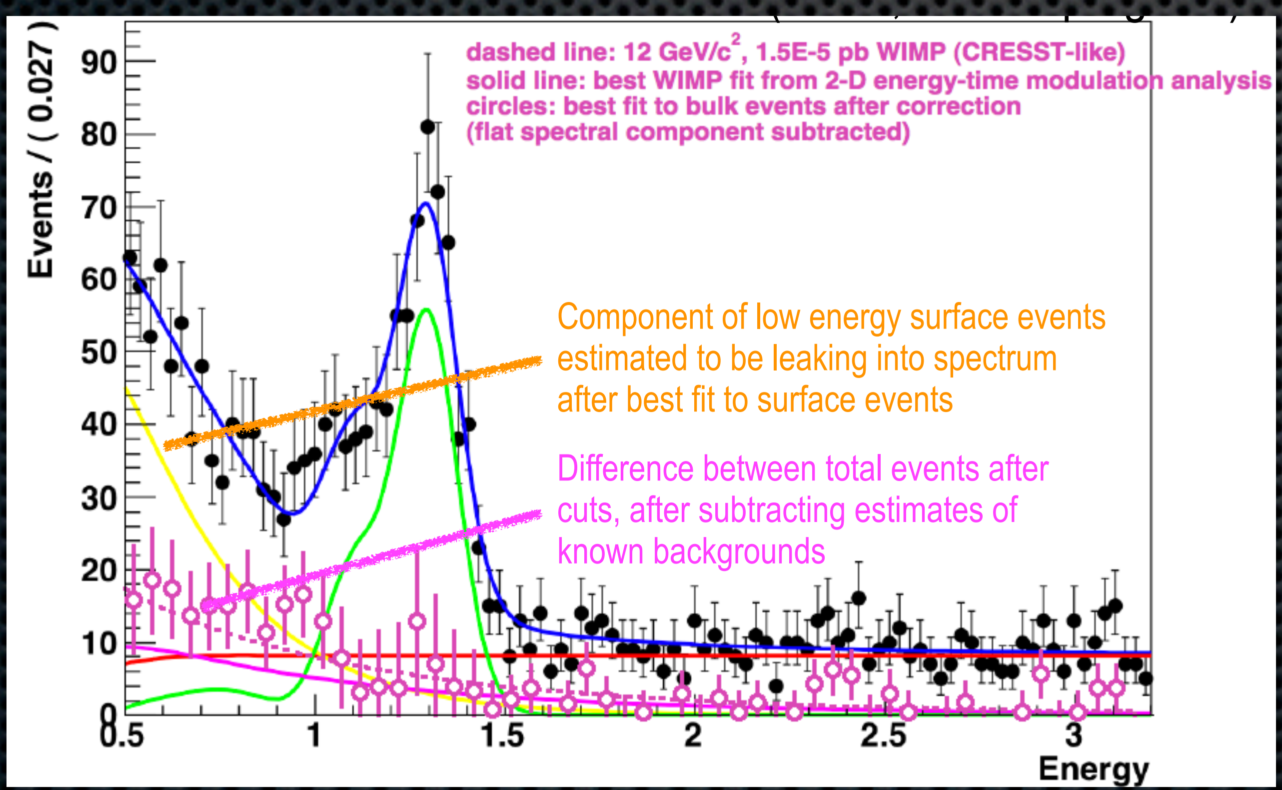
* M.Selvi et al., Proc. 31st ICRC, ŁÓDŹ 2009

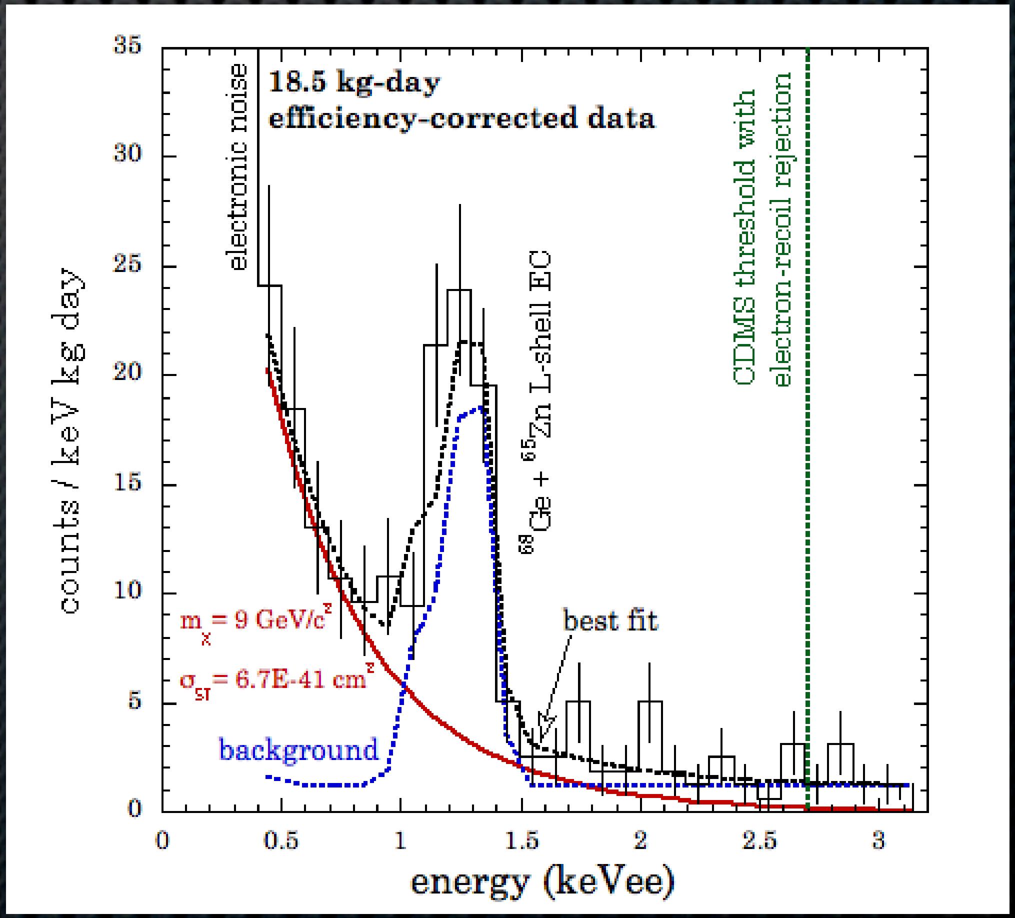
CoGeNT: low-mass WIMPs?

- Point-contact, 330 g Ge detector at Soudan
- Energy threshold: ~ 0.5 keV ionization (~ 2 keV NR energy)
- 2011: claim of an annual modulation at 2.8-σ level (0.5 - 3 keVee), ~ 450 days

arXiv: 1002.4703; C. E. Aalseth et al., PRL106

J. Collar, Feb 2012





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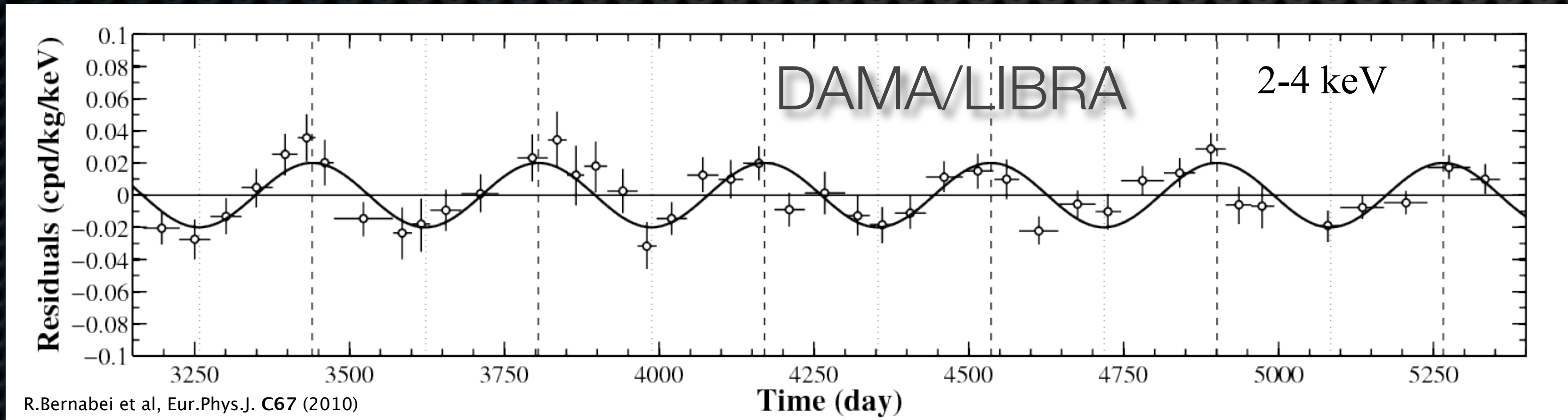
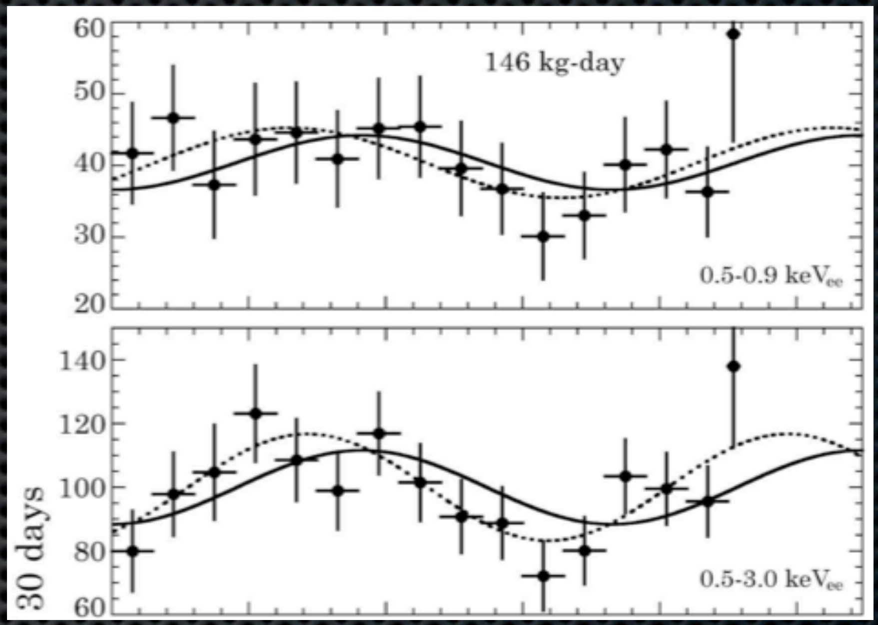
Modulation: DAMA/LIBRA, CoGeNT

- DAMA/LIBRA (250 kg NaI, 0.82 tons-year): 8.9-σ effect
- CoGeNT (330 g HPGe, 450 d): 2.8-σ effect

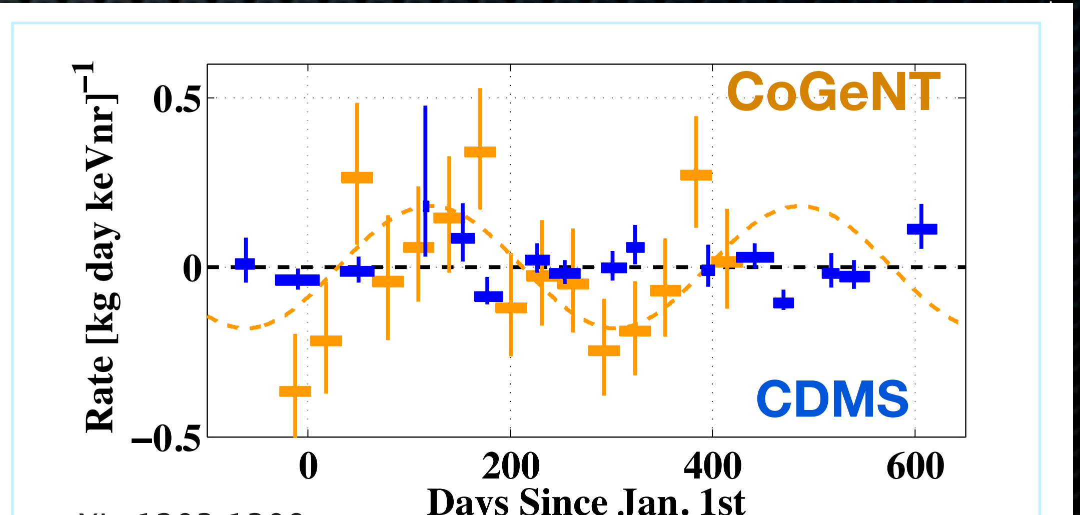


R.Bernabei et al, Eur.Phys.J. **C67** (2010)

CoGeNT



CDMS



arXiv:1203.1309

- Origin of the time variation in the observed rate - unclear!
- Movement of the Earth-Sun system through the dark matter halo?
- Environmental?

ich, VCI2013, Vienna

Expected Rates in a Terrestrial Detector

Astrophysics

$$R \sim N \frac{\rho_\chi}{m_\chi} \sigma_{\chi N} \langle v \rangle$$

Particle physics

N = number of target nuclei in a detector

ρ_χ = local density of the dark matter in the Milky Way

$\langle v \rangle$ = mean WIMP velocity relative to the target

m_χ = WIMP-mass

$\sigma_{\chi N}$ =cross section for WIMP-nucleus elastic scattering

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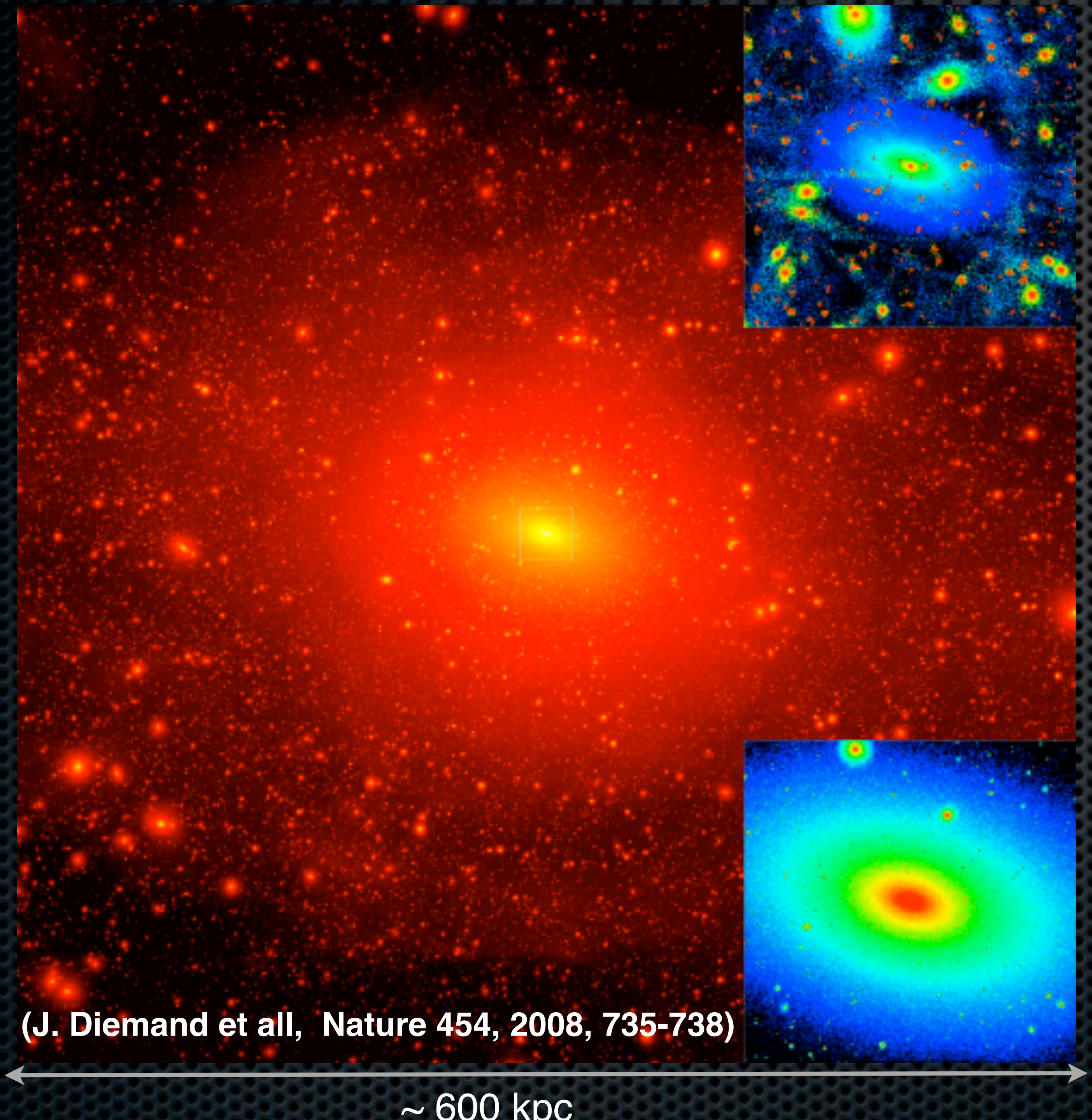
Local Density of WIMPs in the Milky Way

$$\rho_{halo} \sim 0.3\,\mathrm{GeV} \cdot \mathrm{cm}^{-3}$$



$$M_W = 100\,\mathrm{GeV} \Rightarrow$$

$$\sim 3000\,\mathrm{WIMPs} \cdot \mathrm{m}^{-3}$$

WIMP flux on Earth: ~ 10^5 $cm^{-2}s^{-1}$ (100 GeV WIMP)

Even though WIMPs are weakly interacting, this flux is large enough so that a potentially measurable fraction will elastically scatter off nuclei

WIMP Scattering Cross Sections

- A general WIMP candidate: fermion (Dirac or Majorana), boson or scalar particle
- The most general, Lorentz invariant Lagrangian has 5 types of interactions
- In the extreme NR limit relevant for galactic WIMPs (10^{-3} c) the interactions leading to **WIMP-nuclei scattering** are classified as (Goodman and Witten, 1985):
  - **scalar interactions** (WIMPs couple to nuclear mass, from the scalar, vector, tensor part of L)

$$\sigma_{SI} \sim \frac{\mu^2}{m_\chi^2}\left[Z f_p + (A-Z) f_n\right]^2$$

f_p, f_n: effective couplings to protons and neutrons

  - **spin-spin interactions** (WIMPs couple to the nuclear spin, from the axial part of L)

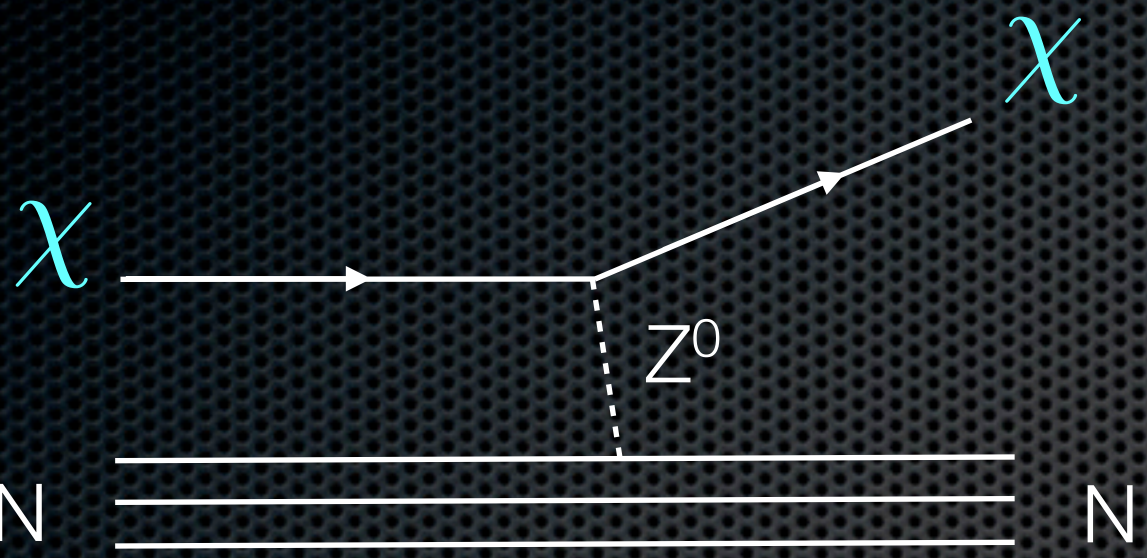
$$\sigma_{SD} \sim \mu^2 \frac{J_N+1}{J_N}\left(a_p\langle S_p\rangle + a_n\langle S_n\rangle\right)^2$$

a_p, a_n: effective couplings to protons and neutrons

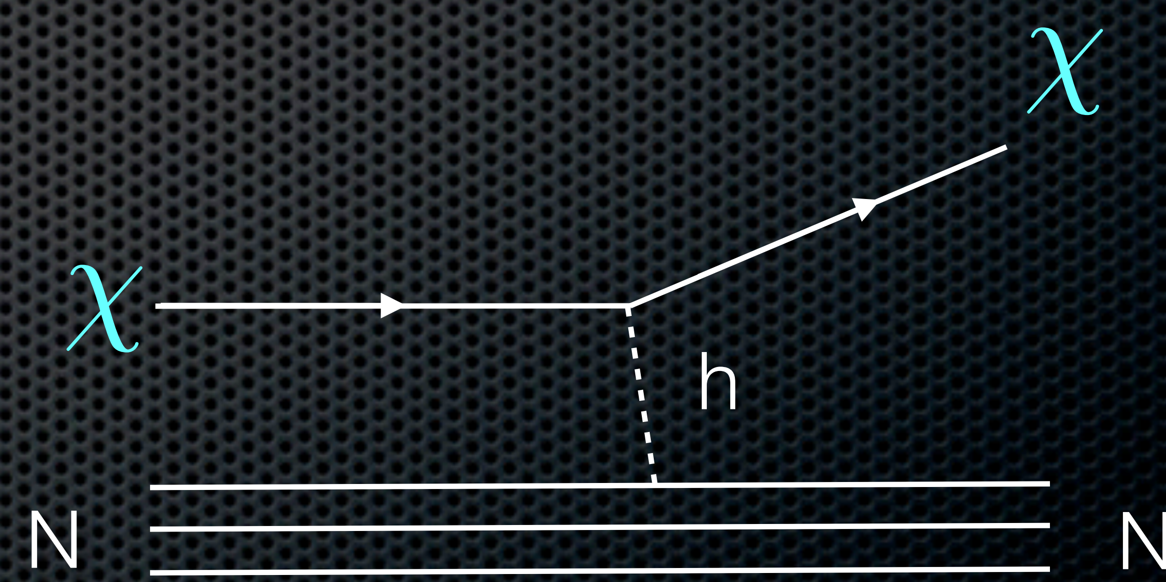
$\langle S_p \rangle$ and $\langle S_n \rangle$

expectation values of the p and n spins within the nucleus

WIMP scattering cross section



$$\sigma_0 \sim 10^{-39}\,\mathrm{cm}^2$$

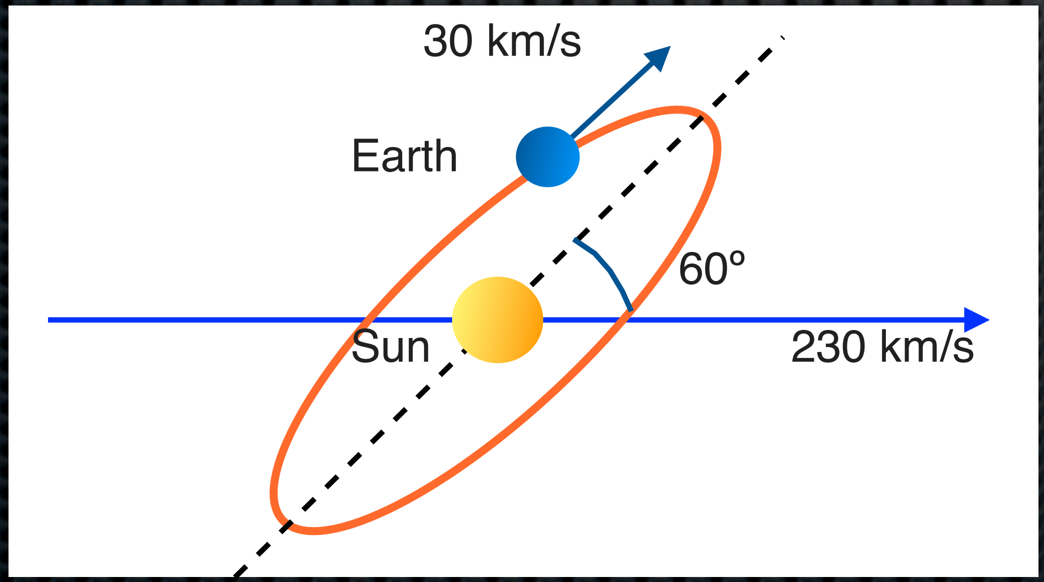


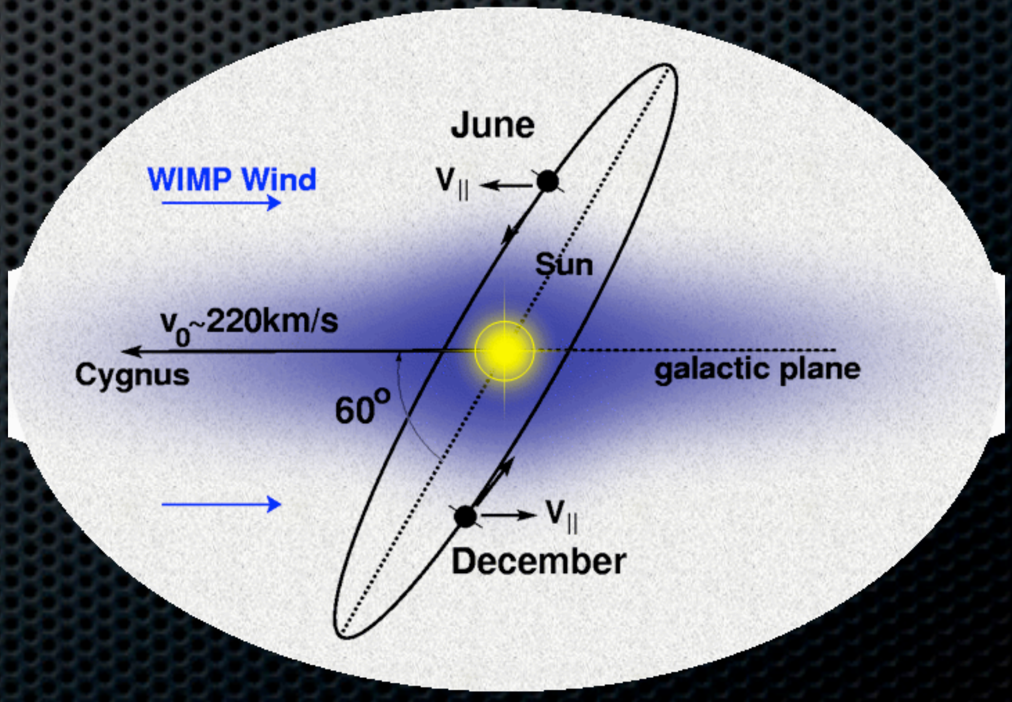
$$\sigma_0 \sim 10^{-45}\,\mathrm{cm}^2$$

Laura Baudis, University of Zurich, Münster colloquium, 2013

How to separate WIMPs from backgrounds

- Signatures:
  - nuclear recoils
  - annual modulation of the recoil spectrum
  - diurnal modulation of the flux direction





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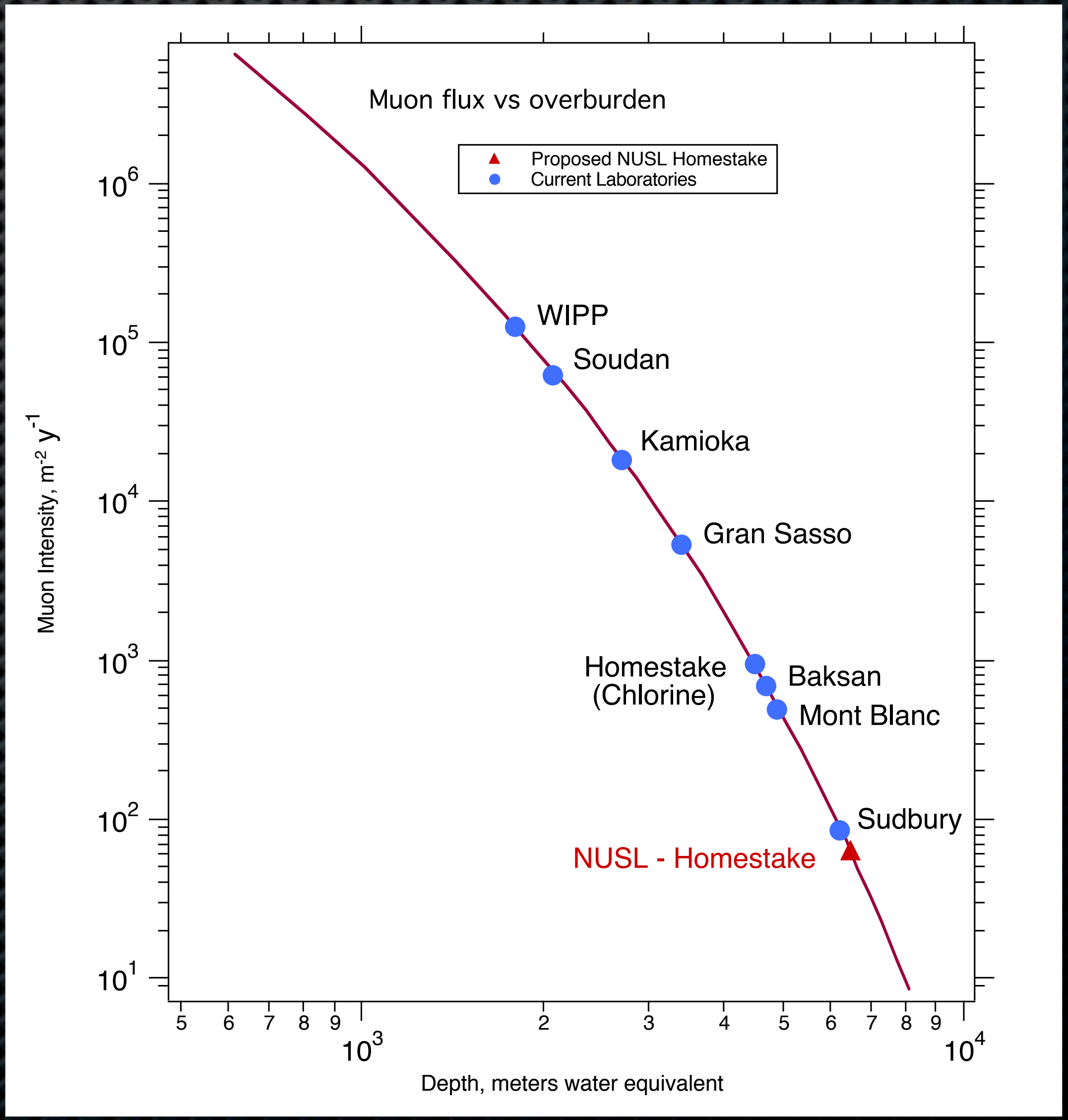
The background noise

- **Electromagnetic radiation**
  - natural radioactivity in detector and shield materials
  - airborne radon (^{222}Rn)
  - cosmic activation of materials during storage/ transportation at the Earth's surface
- **Neutrons**
  - radiogenic from (α,n) and fission reactions
  - cosmogenic from spallation of nuclei in materials by cosmic muons
- **Alpha particles**
  - ^{210}Pb decays at the detector surfaces
  - nuclear recoils from the Rn daughters

Cosmic rays: operate deep underground



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