Direct Detection of Dark Matter: Status and Future

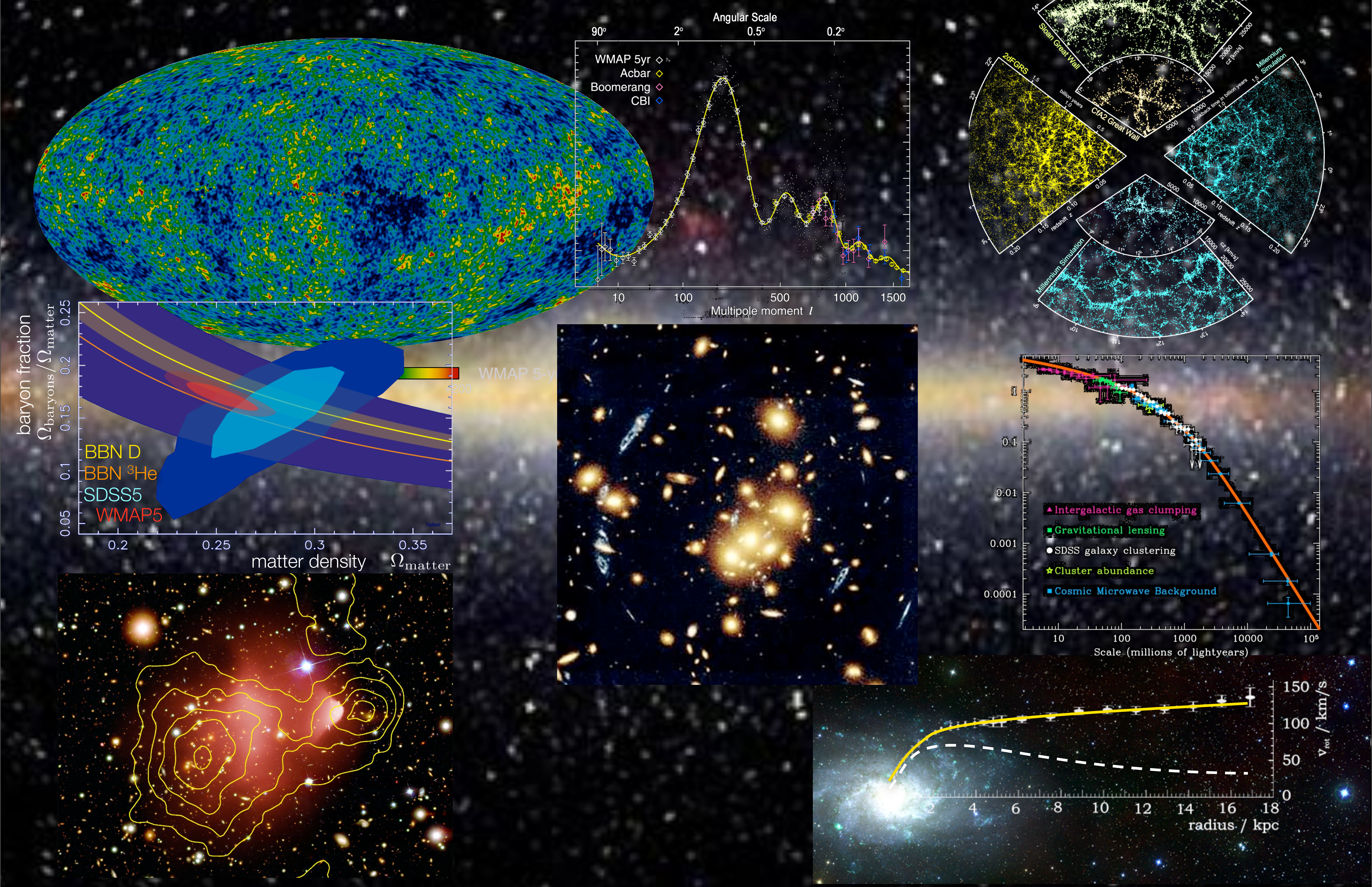
The Latsis Symposium 2013

Zurich, June 5, 2013

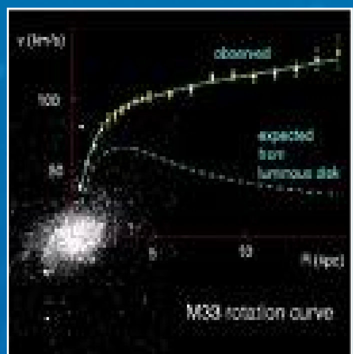
Elena Aprile

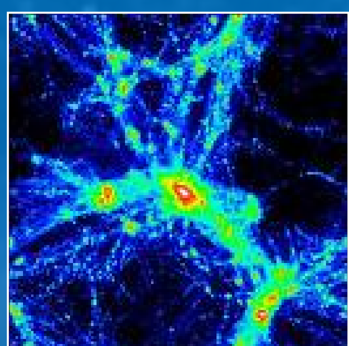
Columbia University

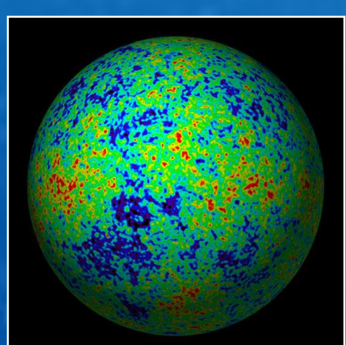
Dark Matter Exists

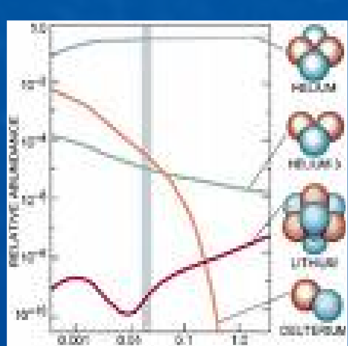


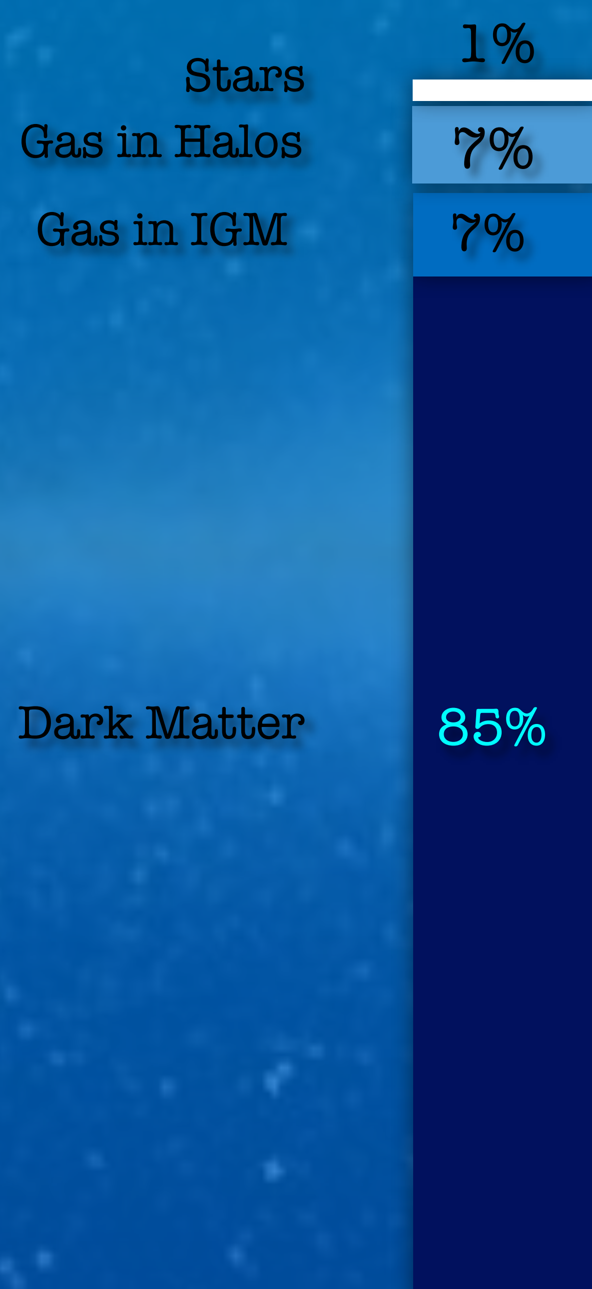
...and it dominates the Universe Matter Budget

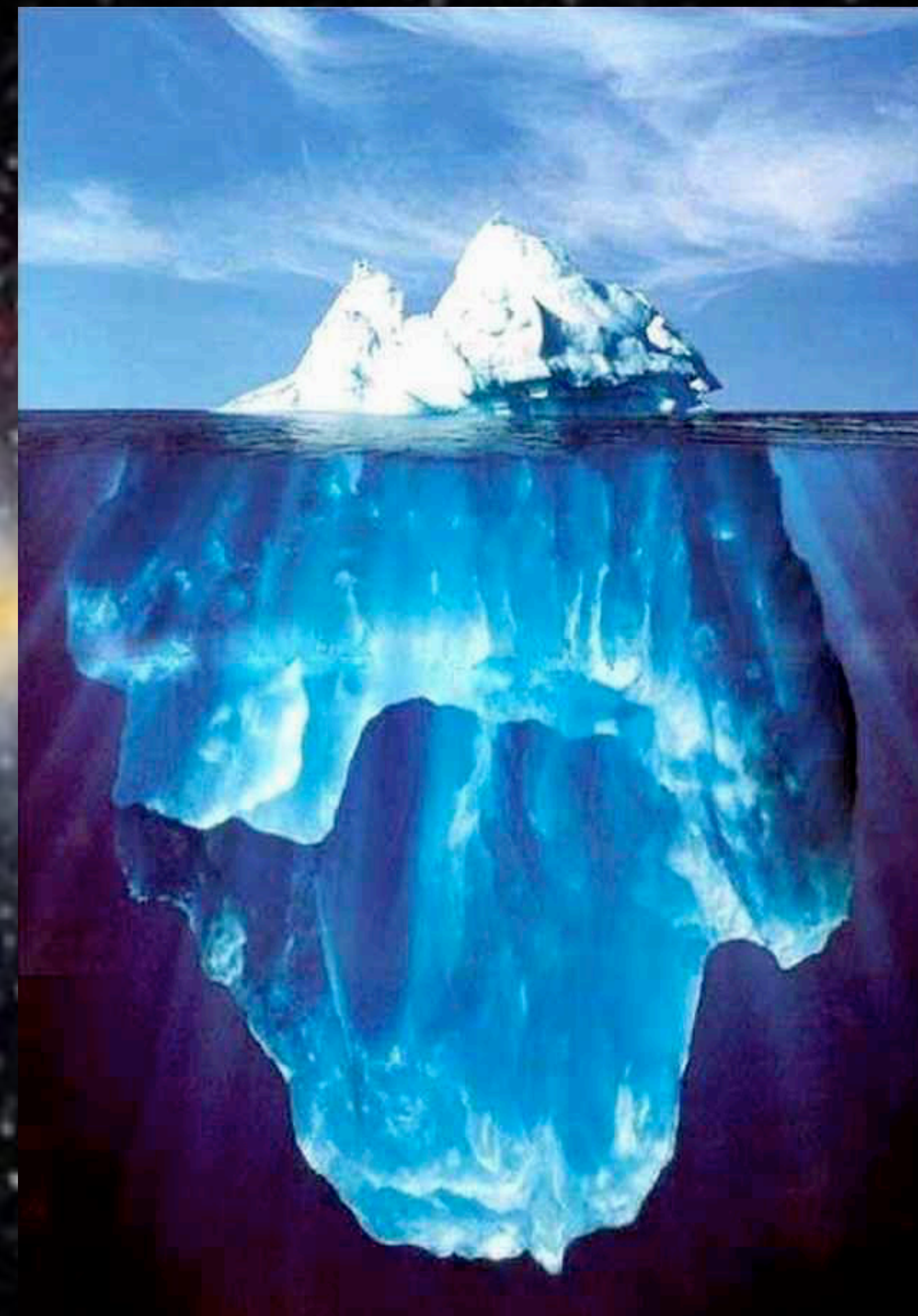












...but what is it made of?

courtesy of G. Bertone

No Standard Model Candidate

Dark Matter has to be

- neutral
- massive (cold)
- stable
- no EM interaction
- non-baryonic
- correct density

→ “physics beyond the standard model”

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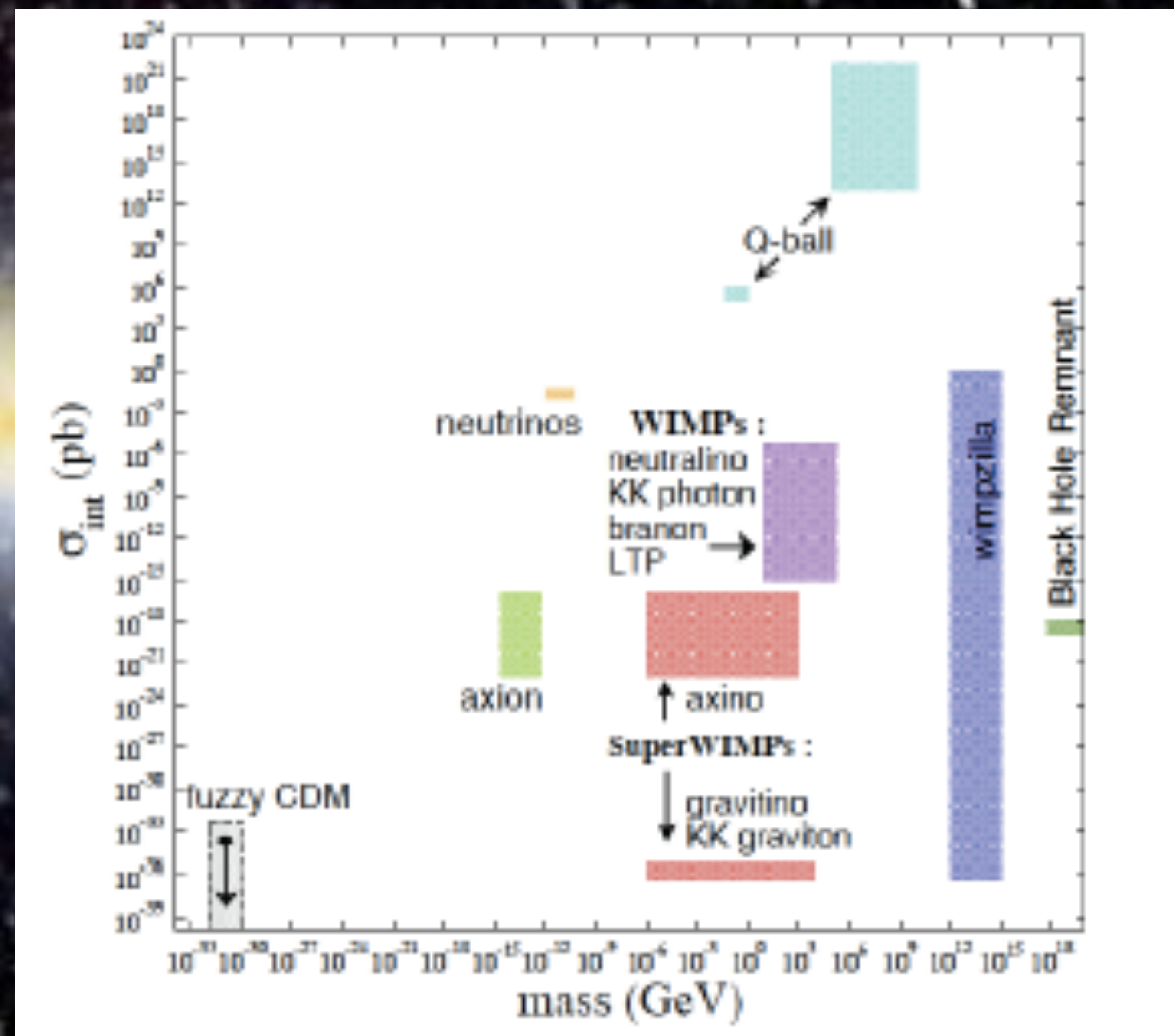
Many models and a zoo of candidates

- the most convincing evidence for a particle candidate to be the dark matter is direct detection in a terrestrial experiment
- Axion and WIMPs well-motivated candidates and well suited for detection with existing technologies

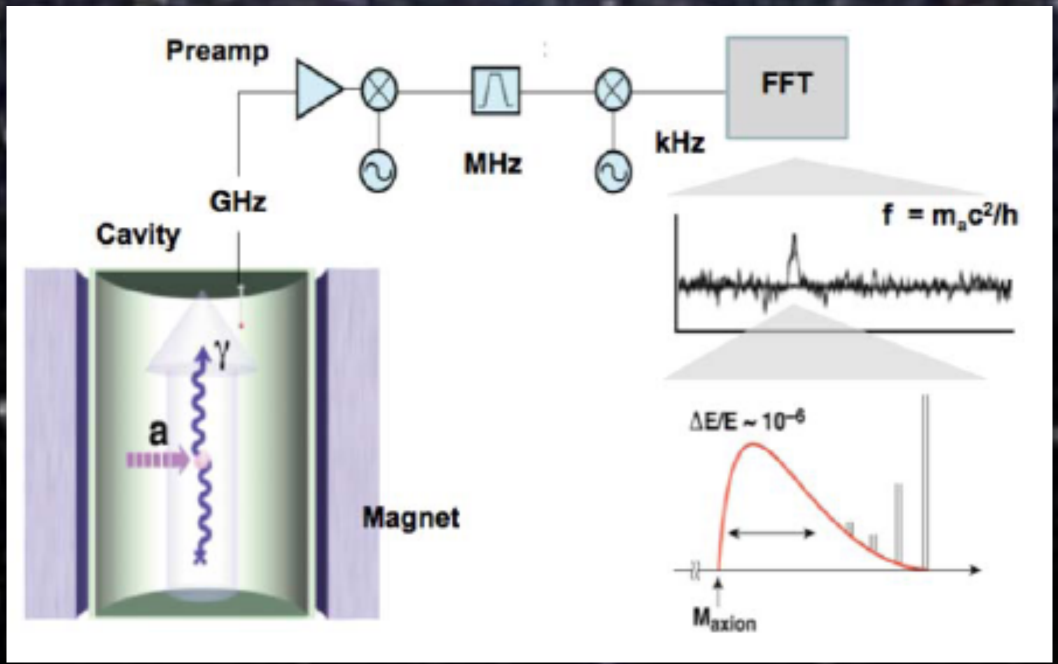


Axion

- Light pseudoscaler as a natural solution to the srong CP problem **(Peccei & Quinn)**
- An excellent DM candidate as its density relative to critical density is given by:

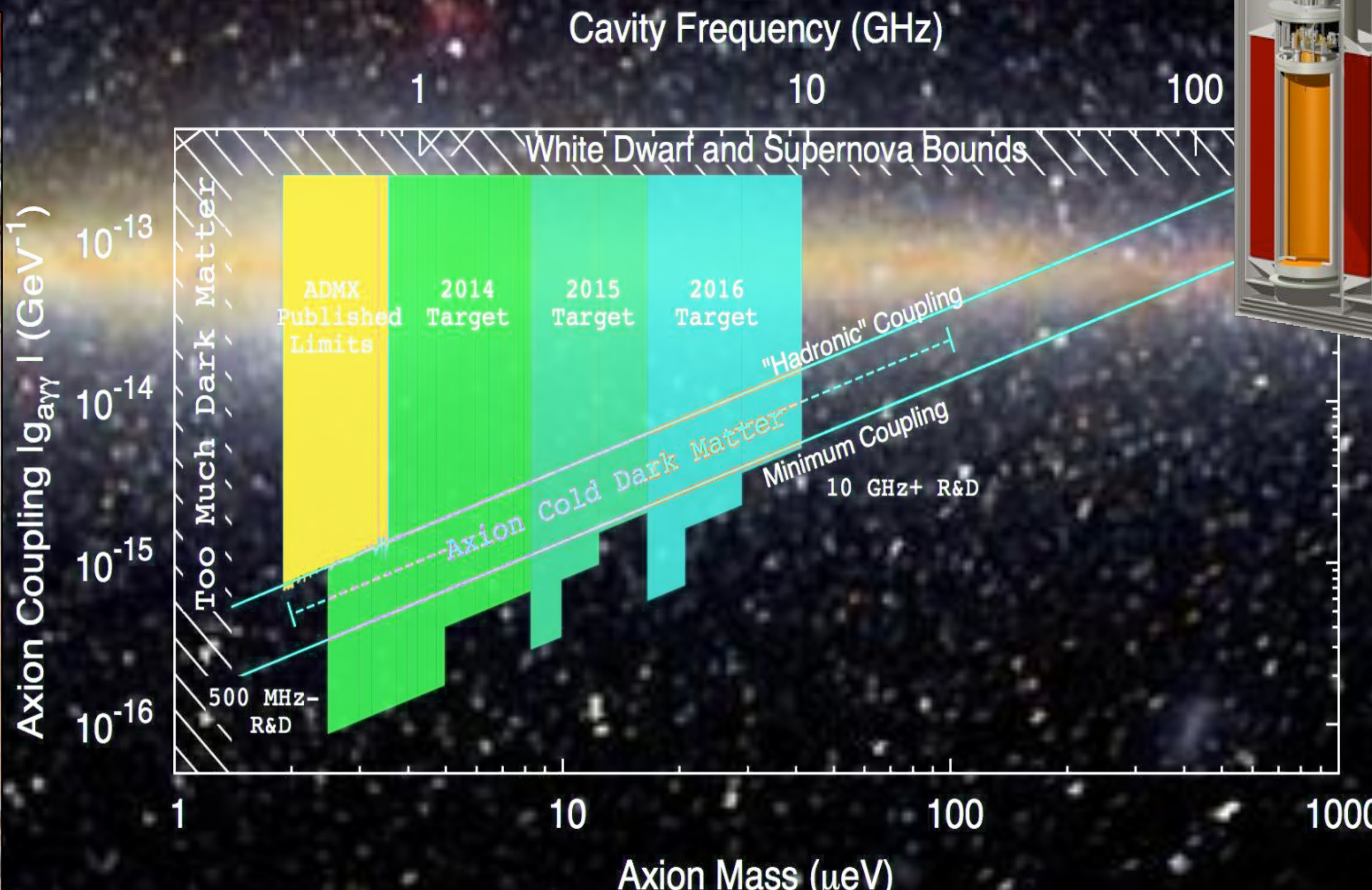
$$\Omega_a \propto m_a^{-7/6} \to m_a > \sim 1\,\mu\text{eV}$$

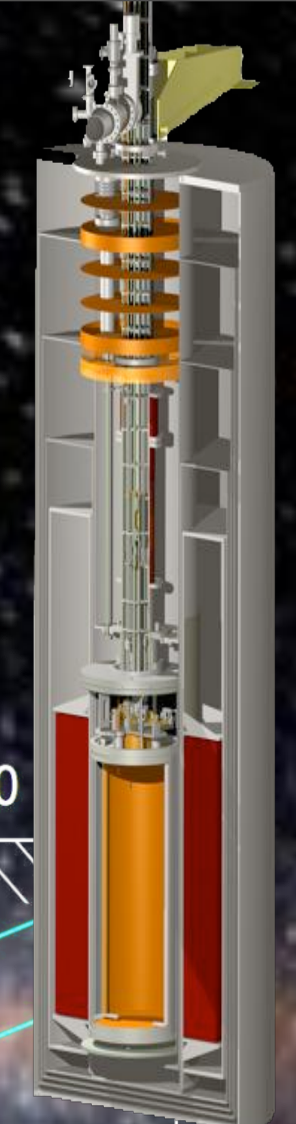
- Axions with $\sim 20\ \mu\text{eV}$ can account for all the DM density of the Universe ($\Omega_m \approx 0.23$). Much lighter axions would overclose Universe thus $1\ \mu\text{eV}$ is lower limit on m_a from cosmology
- **Sikivie** **(PRL51, 1983 & PRD32, 1985)** showed that such light axions could resonantly convert into a quasi-monochromatic microwave signal in a cavity in a strong B-field (Primakov-effect).
- conversion power depends on axion-photon coupling constant, mass and density of axions



ADMX

- Axion Dark Matter eXperiment since 1996 in search of axions in the few **μeV** range
- microwave cavity, up to 8T, down to 100mK (ADMX-phase II)





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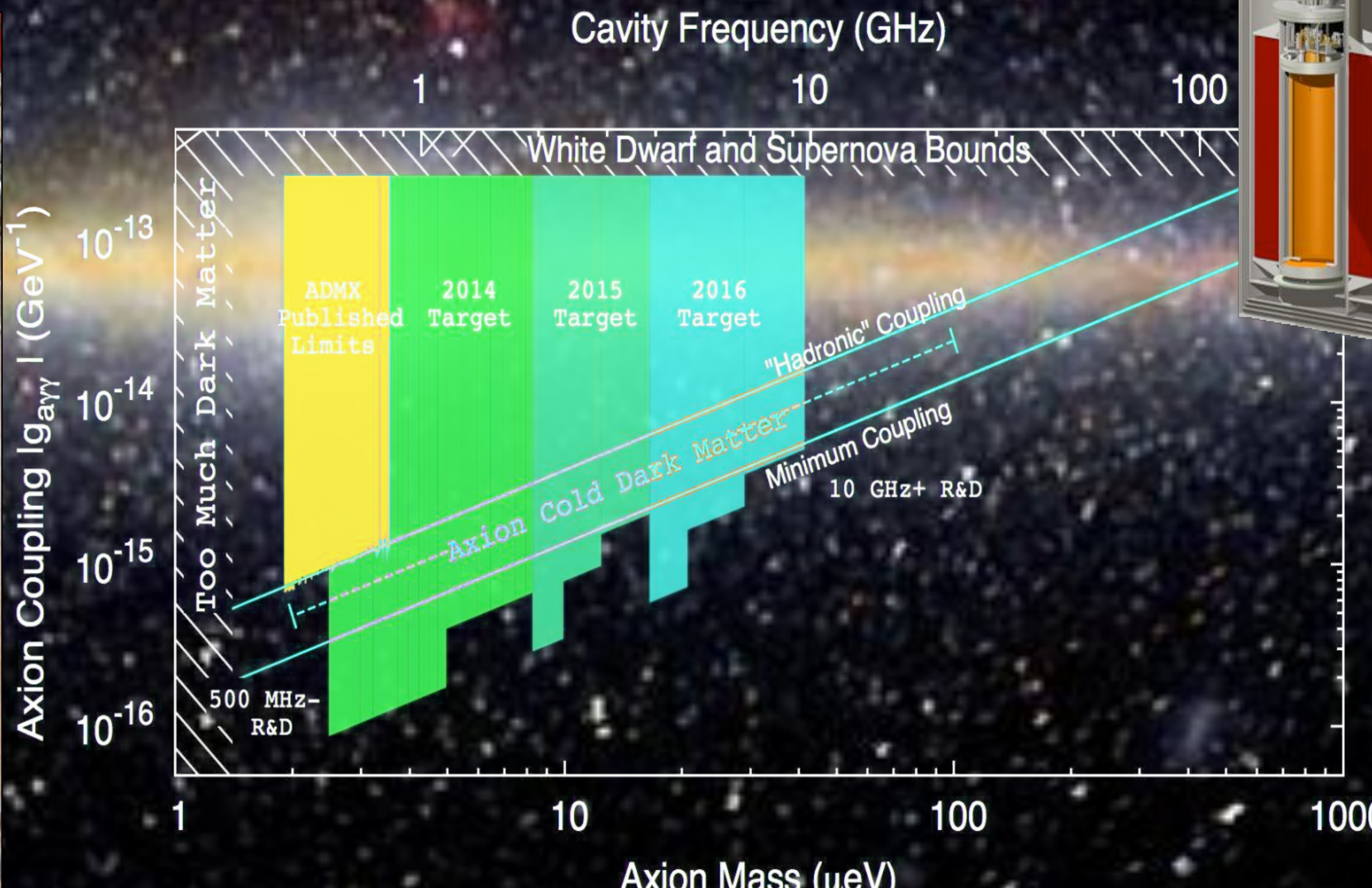
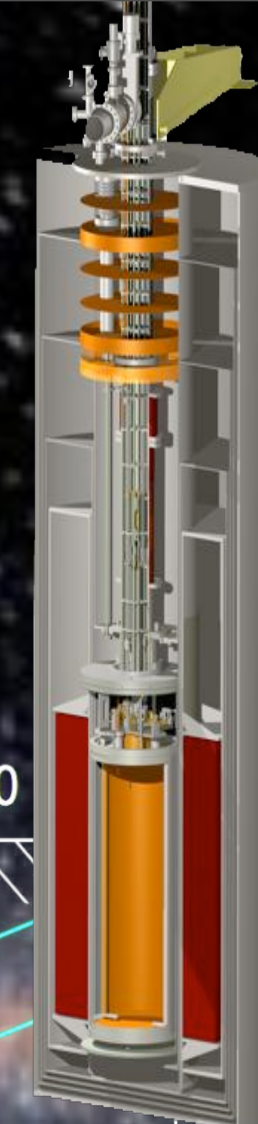




G. Carosi, Aspen 2013

Weakly Interacting Massive Particles

- **relic particles** in thermal equilibrium in the early Universe

$$\chi + \bar{\chi} \leftrightarrow X + \bar{X}$$

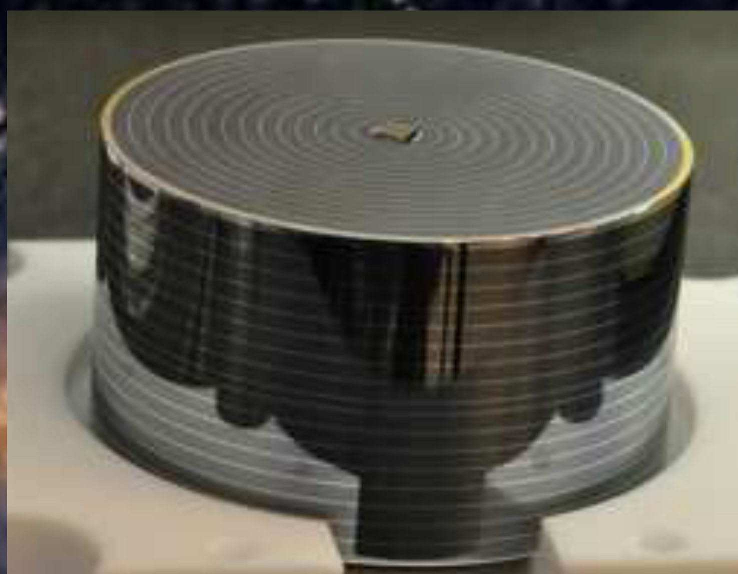
- Decouple from the rest of the particles when **M >> T ("cold")**
- **Their relic density** can account for the dark matter if the annihilation cross section is weak (~ picobarn range)

$$\Omega_\chi h^2 \simeq 3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1} \frac{1}{\langle \sigma_A v \rangle}$$

$$\langle \sigma_A v \rangle \sim \frac{\alpha^2}{(100\,\mathrm{GeV})^2} \sim 10^{-25} \mathrm{cm}^3 \mathrm{s}^{-1}$$

- Such particles are predicted to exist in most **Beyond-Standard-Model** theories (neutralino, lightest Kaluza-Klein particle, etc)

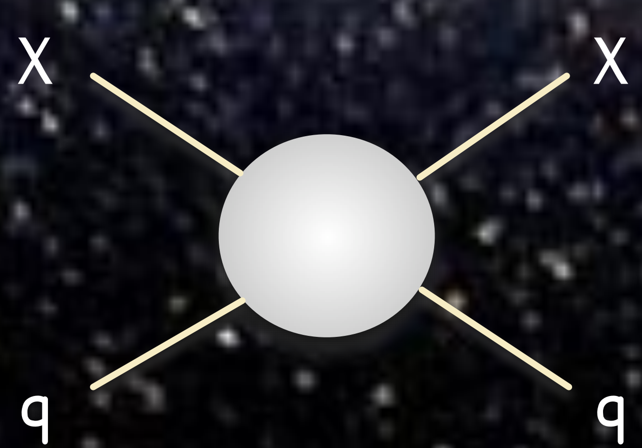
How to search for WIMPs

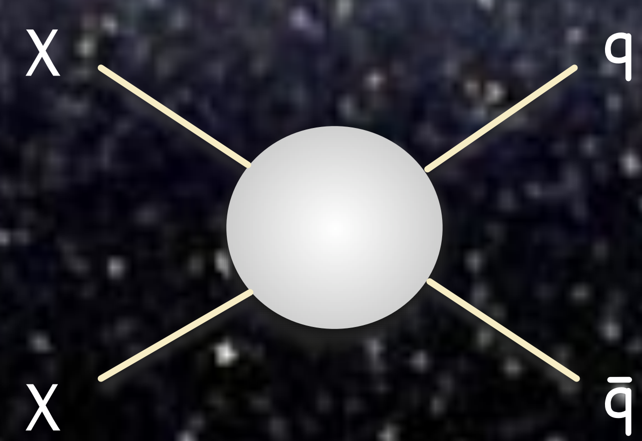


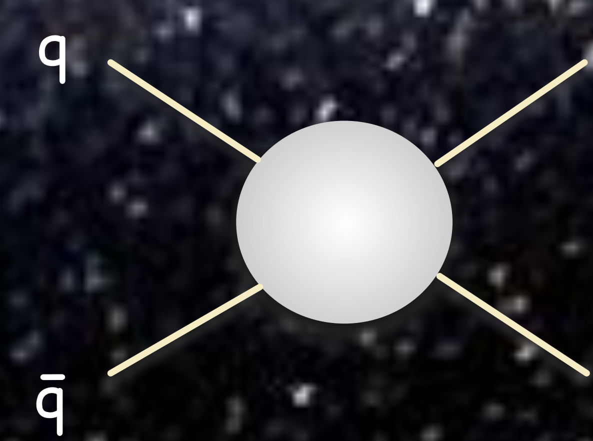
Deep underground

In space

At the LHC





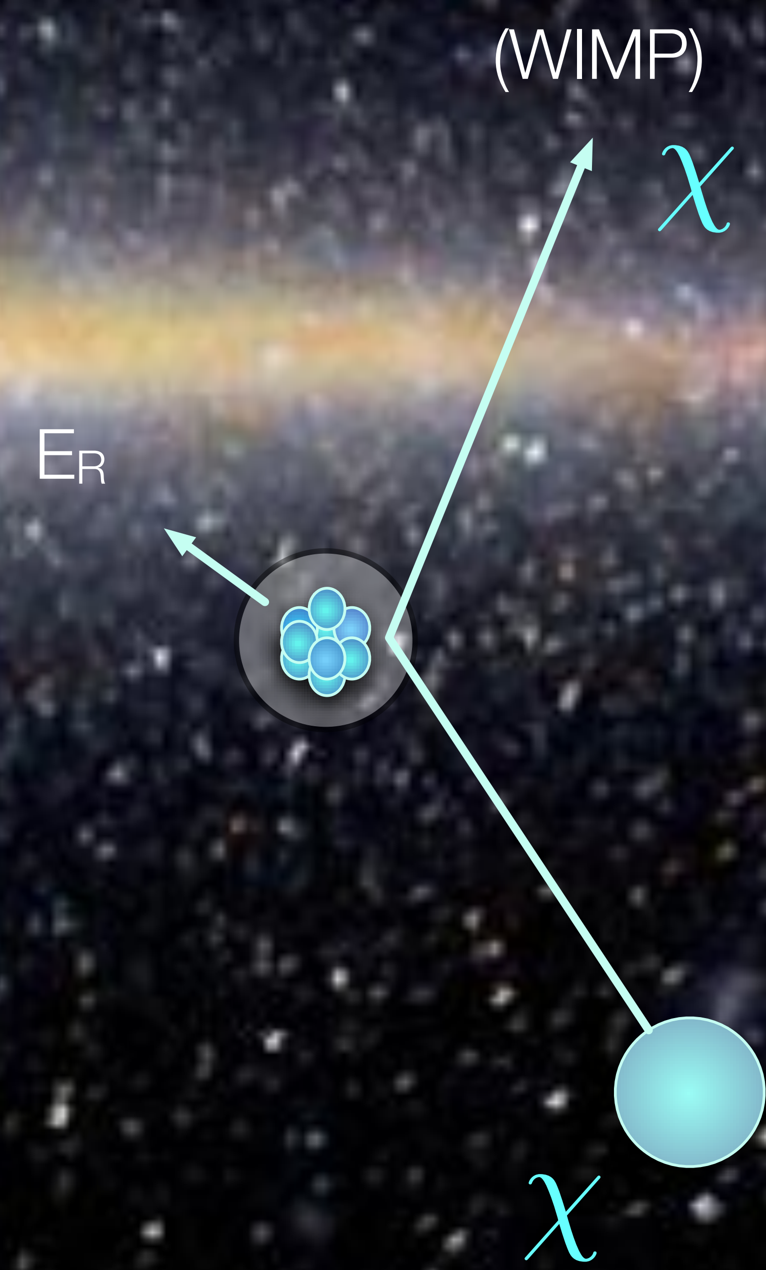


We expect complementary information from direct detectors, from indirect detectors and from the LHC

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

Expected Rate in a Terrestrial Detector

Astrophysics

$$R \propto N_T \frac{\rho_\chi}{m_\chi} \sigma_{\chi N}\, g(v)$$

Particle physics

N_T = number of target nuclei in a detector

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

$g(v)$ = integral over WIMP velocity distribution in lab frame

m_χ = WIMP-mass

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

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

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-nucleon scattering** classified as (Goodman and Witten, 1985):

scalar interaction (WIMP couples 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 interaction (WIMPs couples to the nuclear spin, from the axial part of L)

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

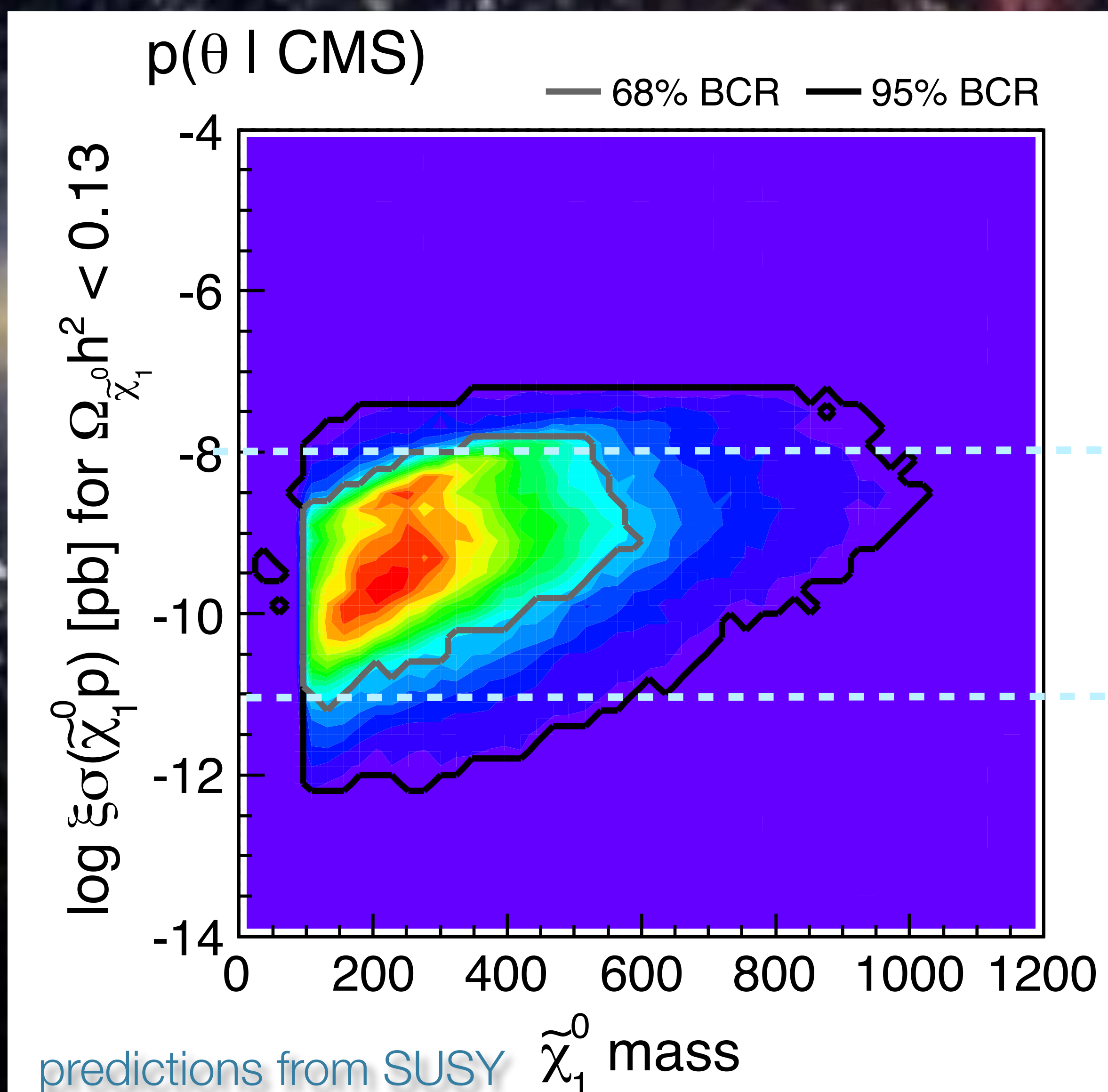
a_p, a_n: effective couplings to protons and neutrons

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

expectation values of protons and neutrons spin within the nucleus

WIMP Mass and Cross Section

- Example for recent predictions from supersymmetry:
    - WIMP-nucleon scattering cross section as low as **~ 10^{-48} cm^2(10^{-12} pb)**



pMSSM (19 parameters at the weak scale)
S. Kraml et al, JHEP 1202 (2012) 075

see also arXiv:1206.4321v2

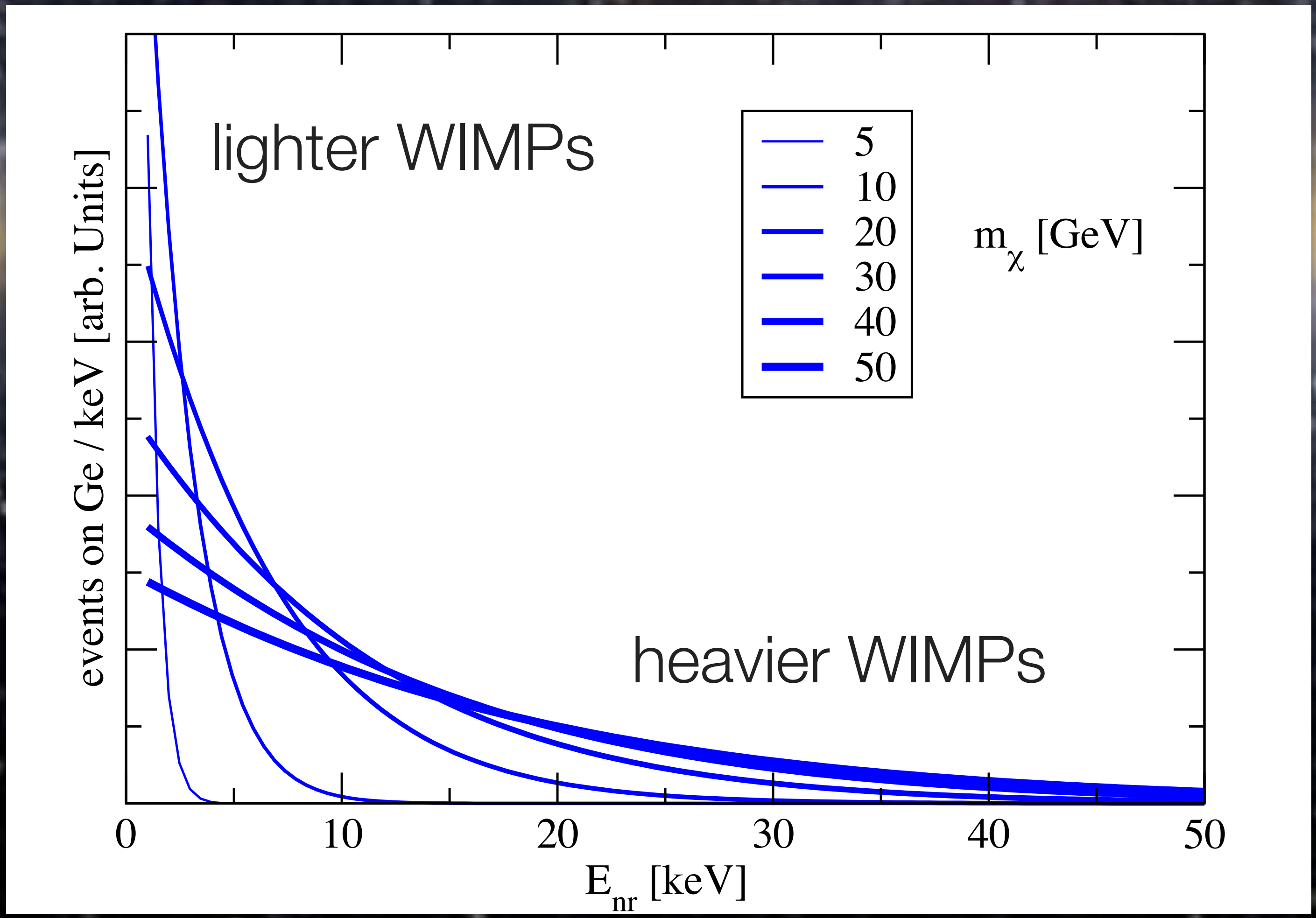
~ 1 event kg^{-1} year^{-1}

~ 1 event ton^{-1} year^{-1}

Expected Interaction Rate

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 WIMP masses

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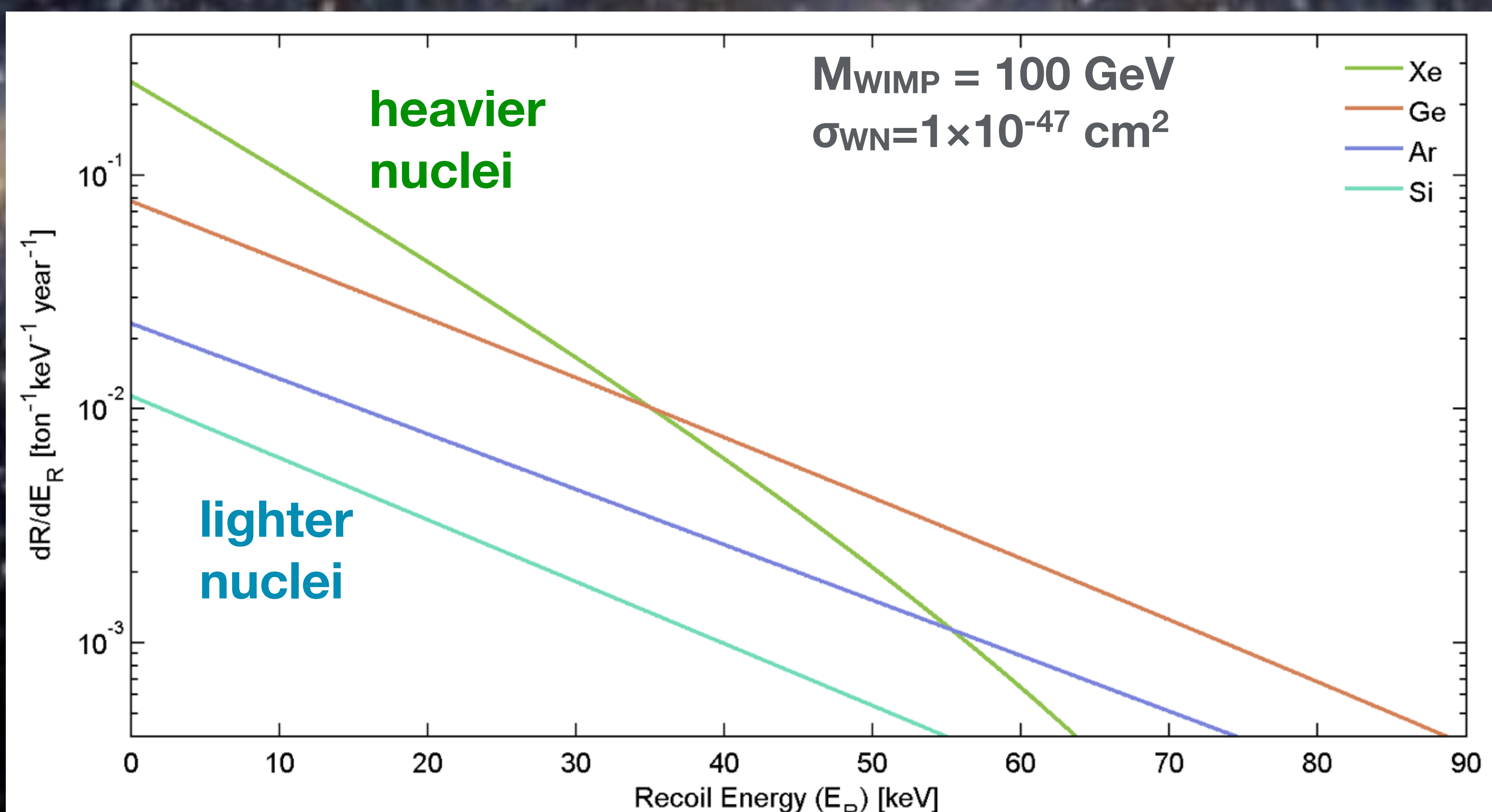


Nuclear recoil spectrum for different target nuclei

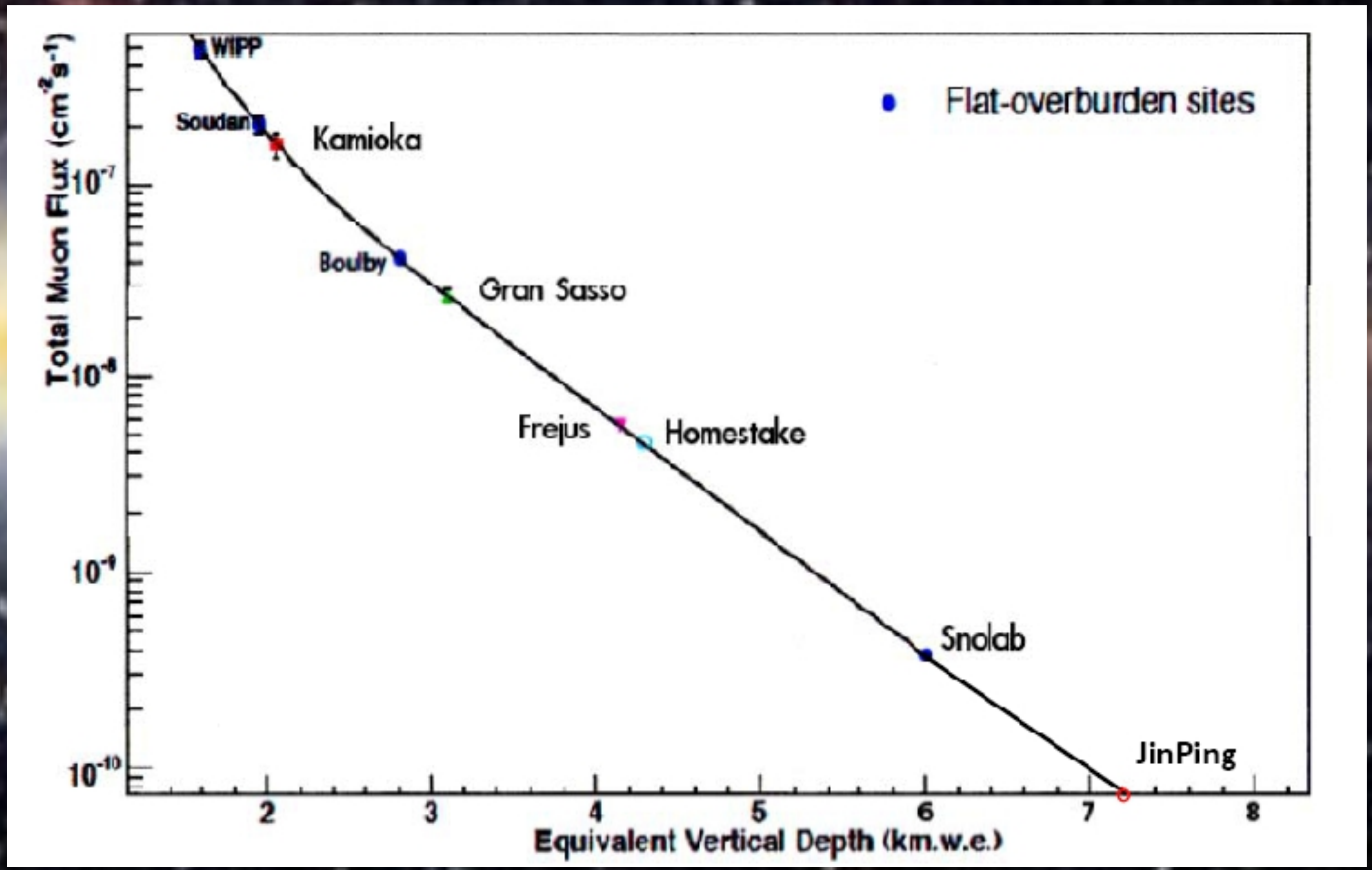
WIMP Detection Challenges

- **Expected signal is:**
  - very small (few keV)
    - detectors with very low energy threshold
  - extremely rare (1 per ton per year?)
    - detectors with very large mass and long term stability
  - embedded in a background that is millions of times higher
    - detectors operated deep underground
    - detectors shielded with effective but clean materials
    - detectors built with lowest radioactivity materials
    - detectors with effective S/N discrimination

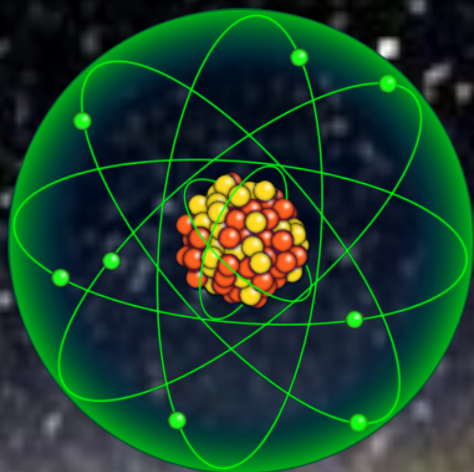
WIMP Detection Background

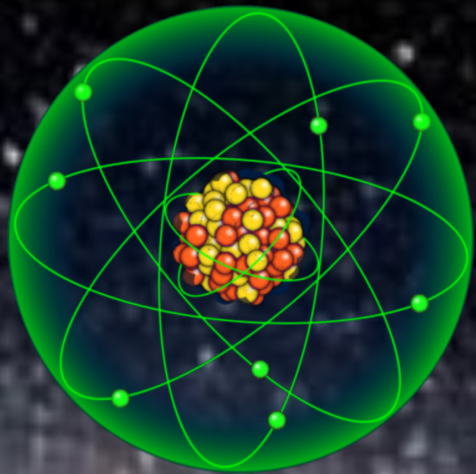
- **Electromagnetic radiation**
  - natural radioactivity in detector and shield materials
  - airborne radon (^{222}Rn)
  - cosmic activation of materials during storage/transport at the Earth's surface
- **Neutrons**
  - radiogenic from (α,n) and fission reactions
  - cosmogenic from spallation of 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



The Power of Discrimination





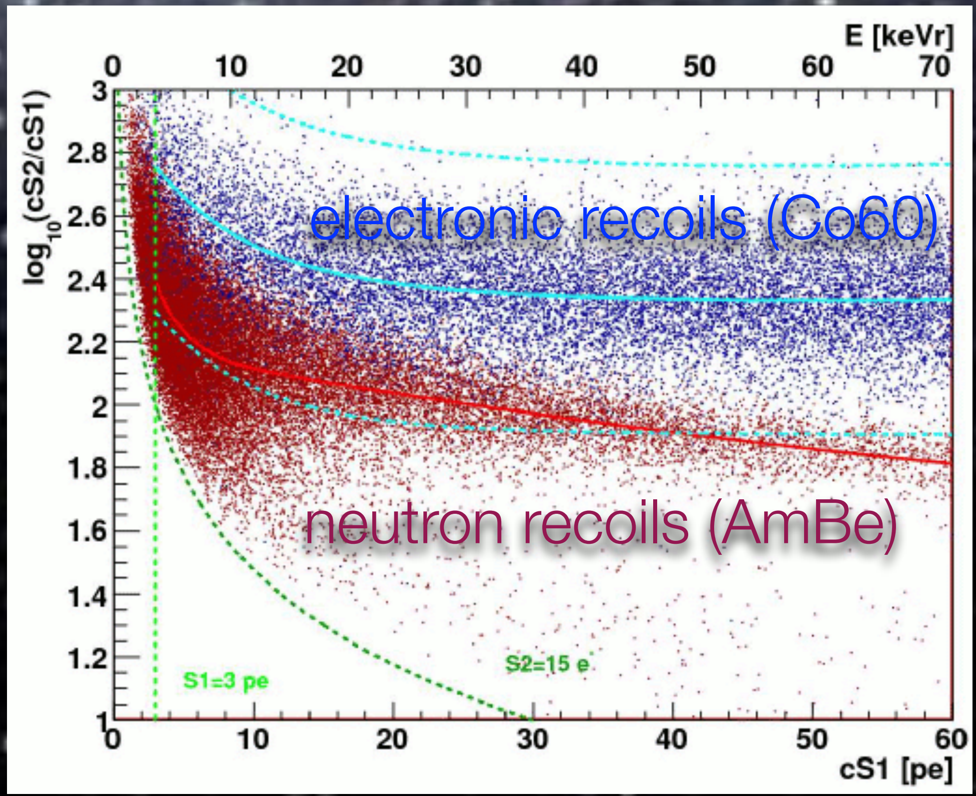
e⁻/γ: electronic recoil

n/WIMPs: nuclear recoil

electronic recoils
- are most common background
- scintillate and ionize more (for given energy)

→ discriminate between the two

e.g. measure both energy and some additional parameter (ionization yield, scintillation yield, ratio ionization/ scintillation, pulse decay time, acoustic signal)



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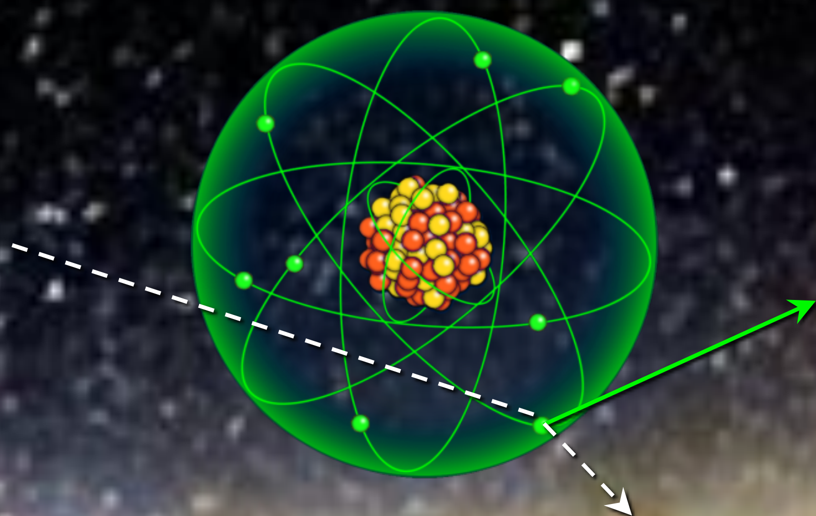

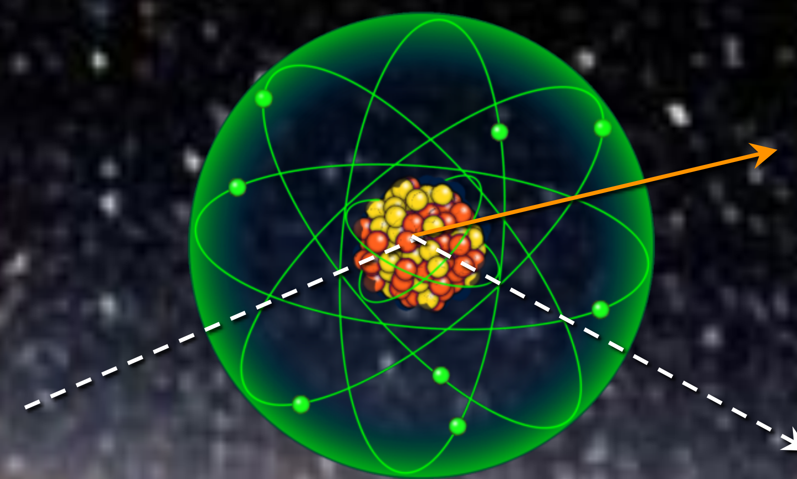

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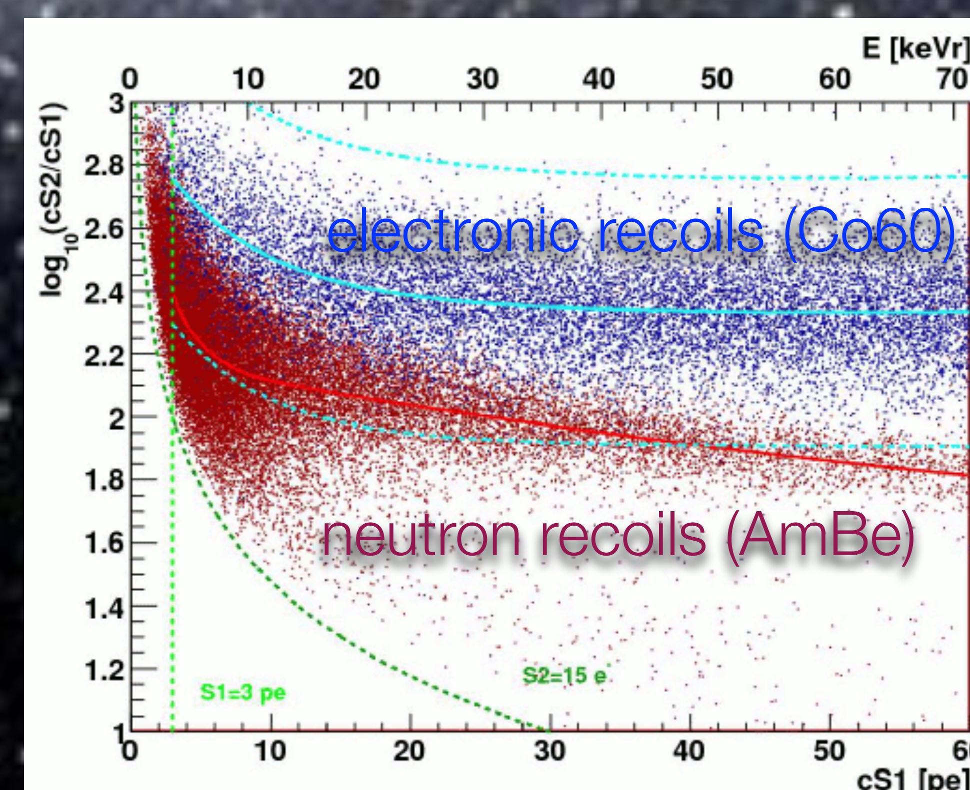
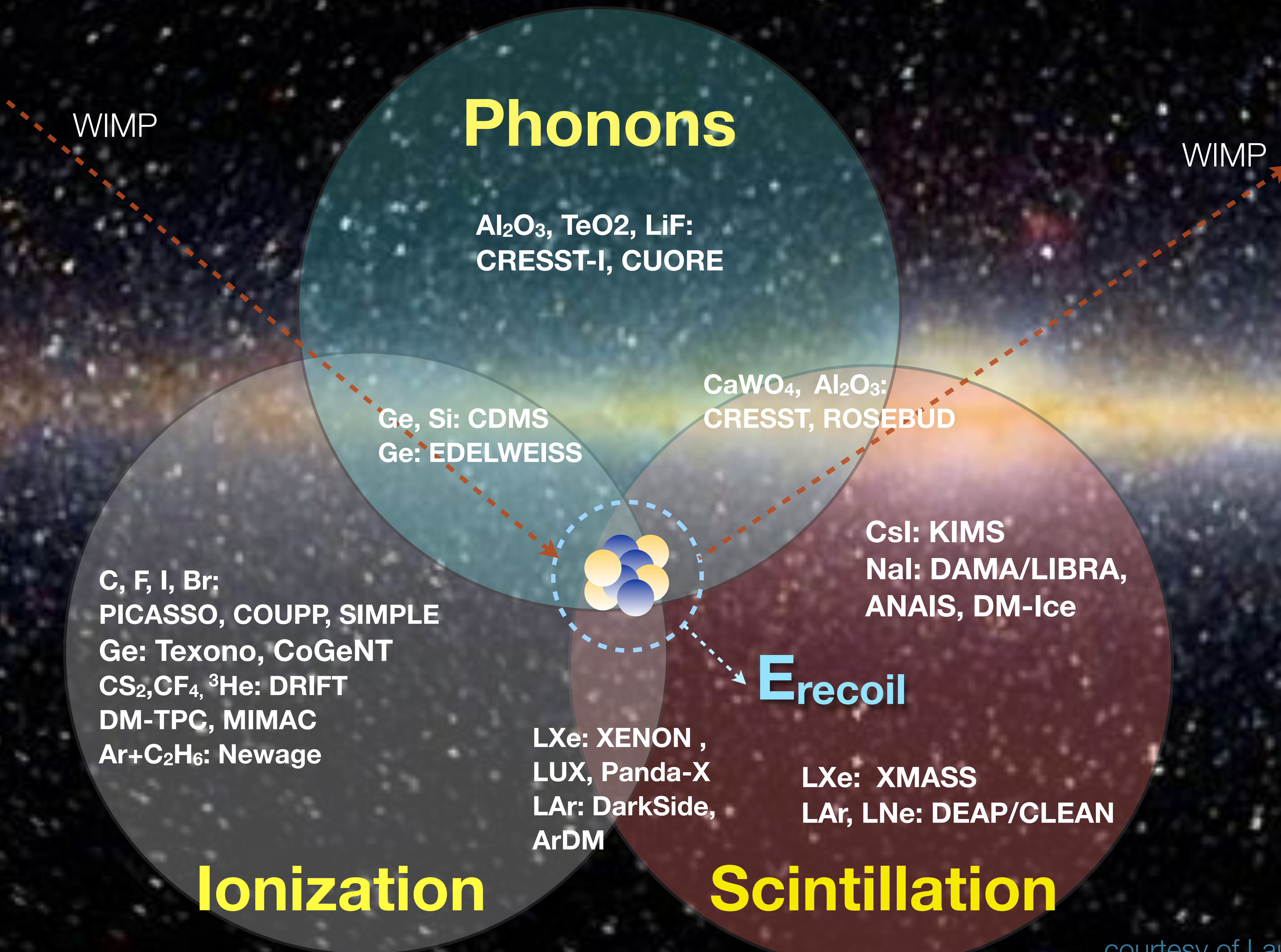


Detection Techniques



courtesy of Laura Baudis

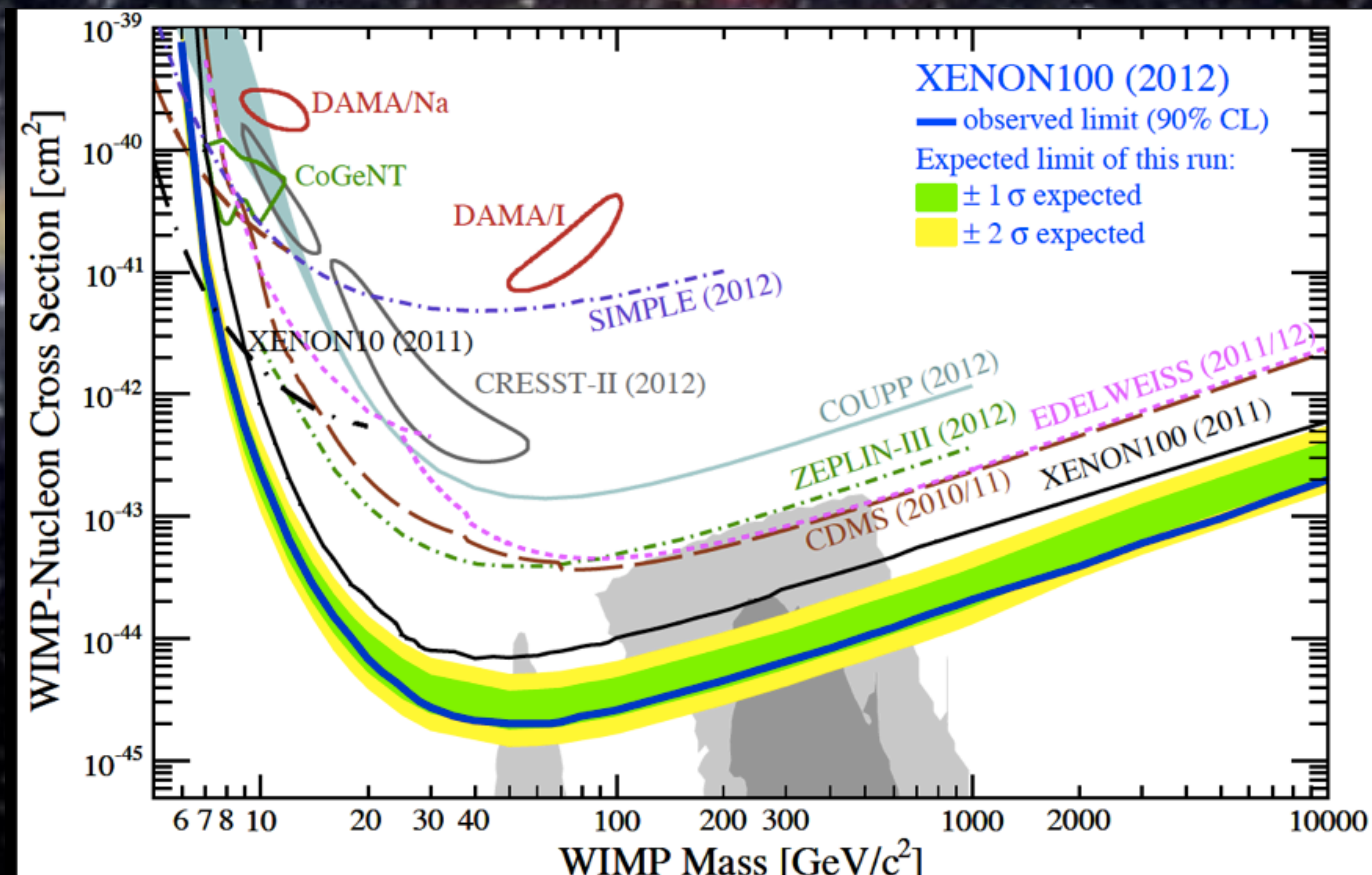
Worldwide WIMP Searches

The WIMP landscape: Spin Independent

The parameter space above thick blue line is excluded

XENON100 yields the strongest limit todate above 10 GeV

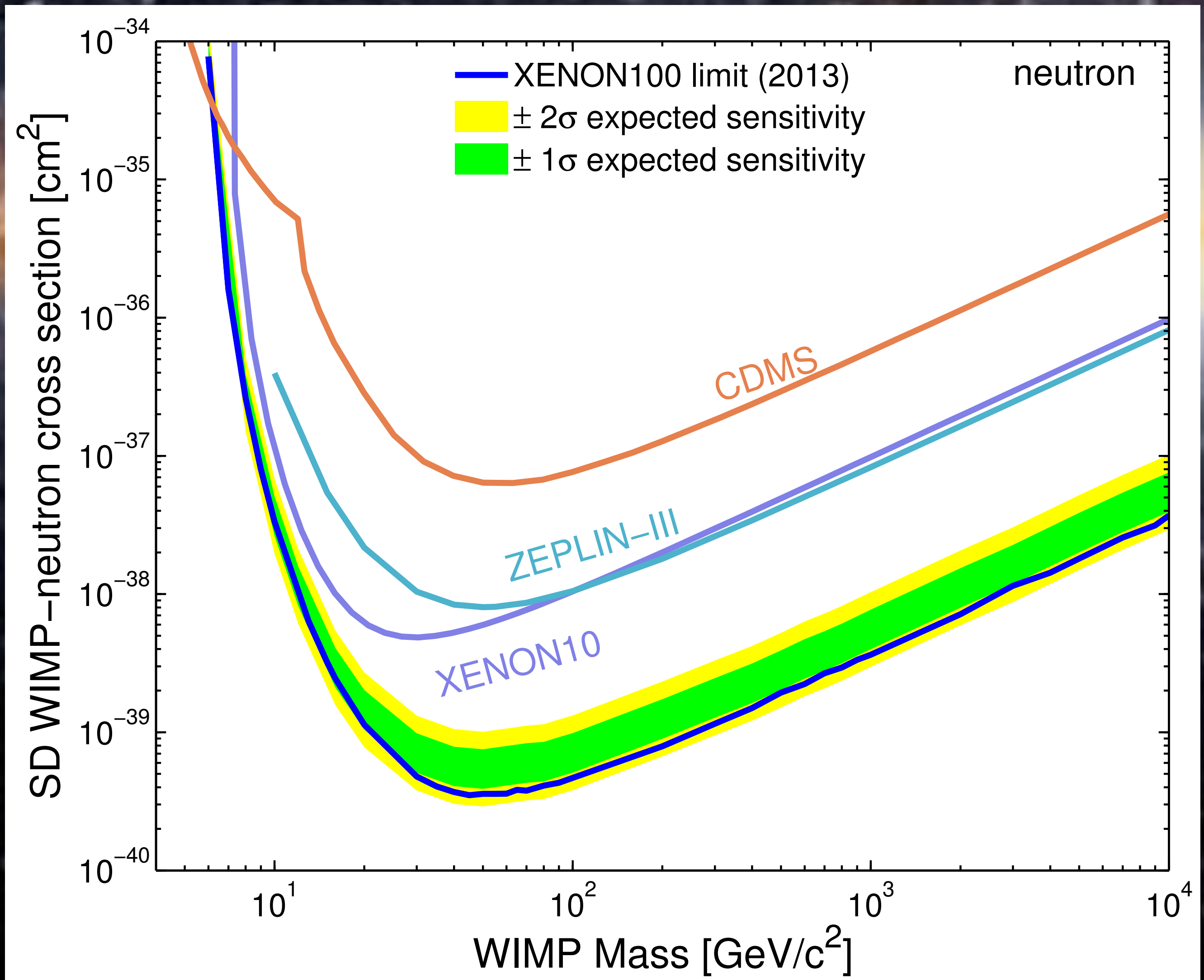
Phys. Rev. Lett. 109 (2012)

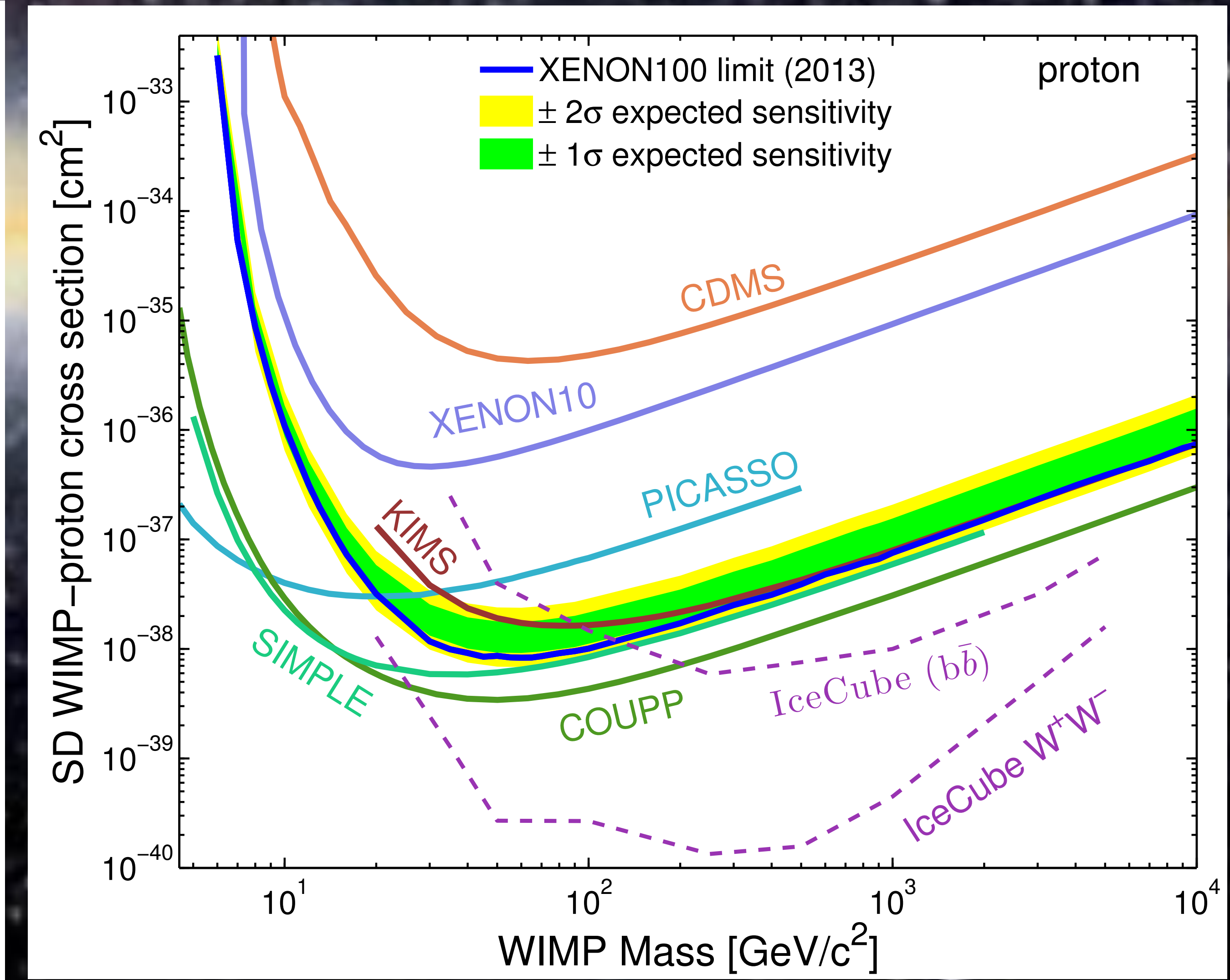


The WIMP landscape: Spin Dependent

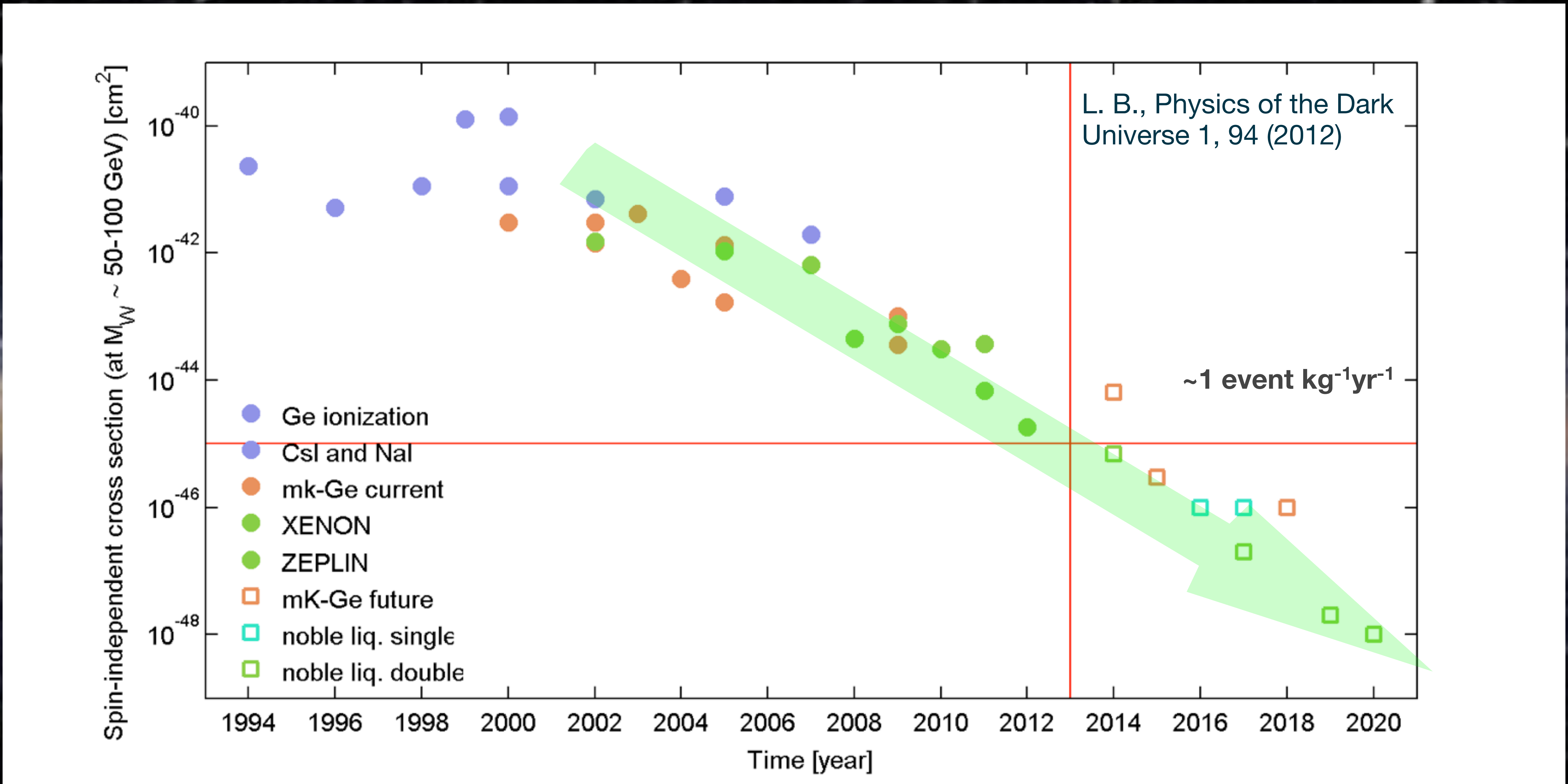
~50% of xenon has spin
XENON100 yields the strongest neutron-only limit
XENON100 yields competitive proton-only limit

WIMP-neutron coupling arXiv:1301.6620 WIMP-proton coupling





WIMP search evolution in time



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

Room temperature scintillators

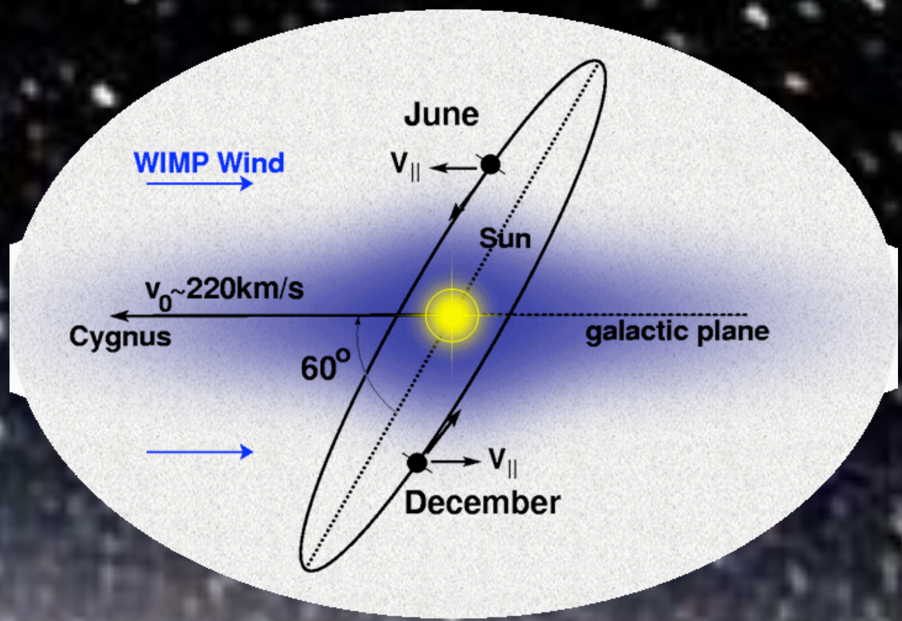
- NaI: DAMA/LIBRA 250 kg of ultra-pure crystals at LNGS. Observed a time variation in the event rate with: T = 1 year, phase = June 2±7 days, amplitude = 0.018 events/(kg keV day)
- CsI: KIMS 103 kg of ultra-pure crystals at Yangyang laboratory. ER / NR discrimination based on time structure of events; does not confirm DAMA/LIBRA modulation
- Future: ANAIS(NaI) at Canfranc and DM-Ice (NaI) at South Pole. A17 kg NaI crystal deployed since 2011 to search for annual modulation in the southern hemisphere, 2.4 km deep in ice. Analysis underway. Final goal is a 250-500 kg NaI detector array, closely packed inside a pressure vessel; use IceCube as a veto

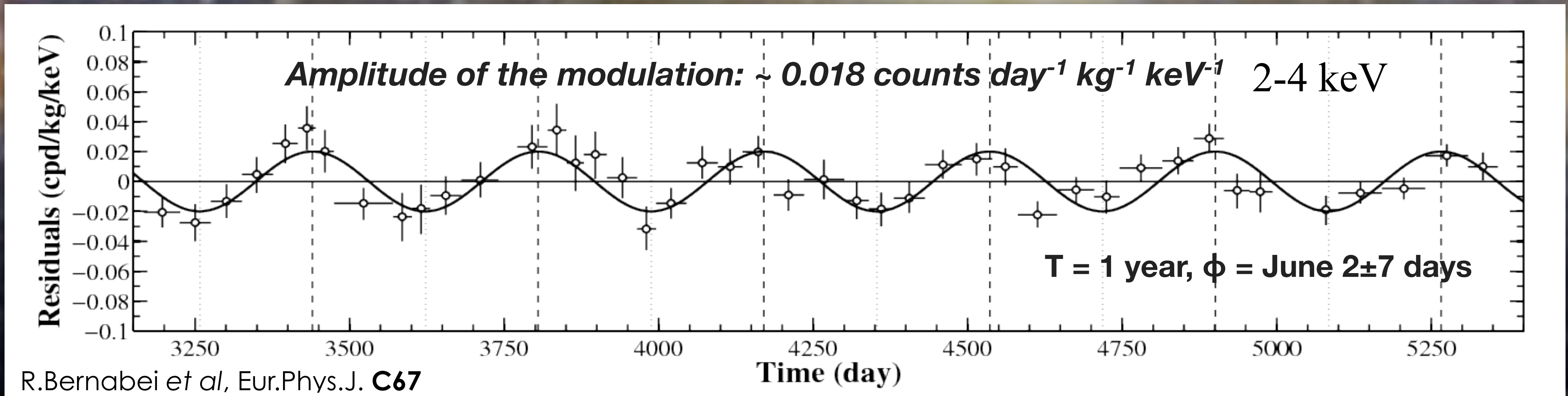
Phys.Rev.Lett. 108 (2012) 181301

CsI(Tl) Crystal 8x8x30 cm^3
(8.7 kg) + 3” PMT (9269QA)

Modulation: DAMA/LIBRA, CoGeNT

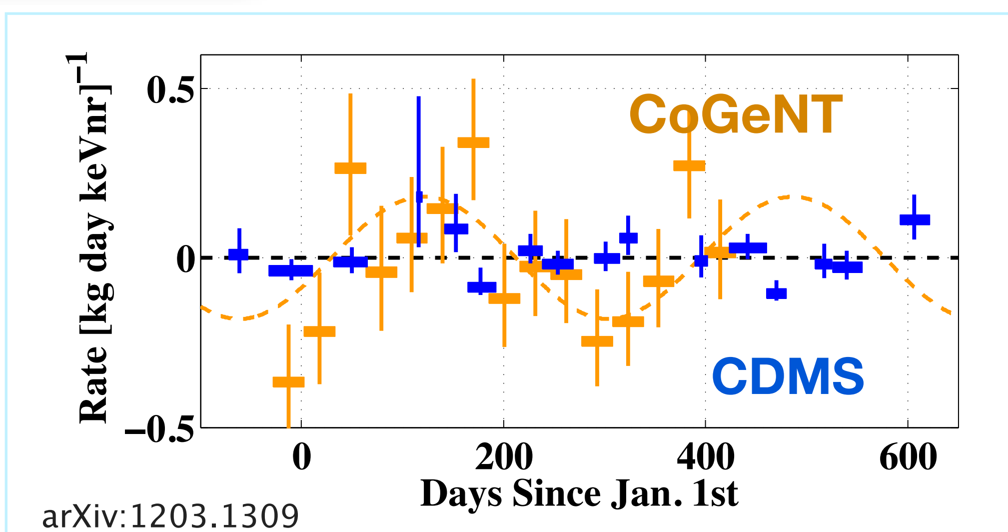
- DAMA/LIBRA (250 kg NaI, 0.82 tons-year): 8.9-σ effect (2-4 keV)
- CoGeNT (330 g HPGe, 450 d): 2.8-σ effect (0.5 - 3 keV)
- Modulation signal compatible with what is expected from a DM particle, due to the movement of the Earth-Sun sytem through the DM halo





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

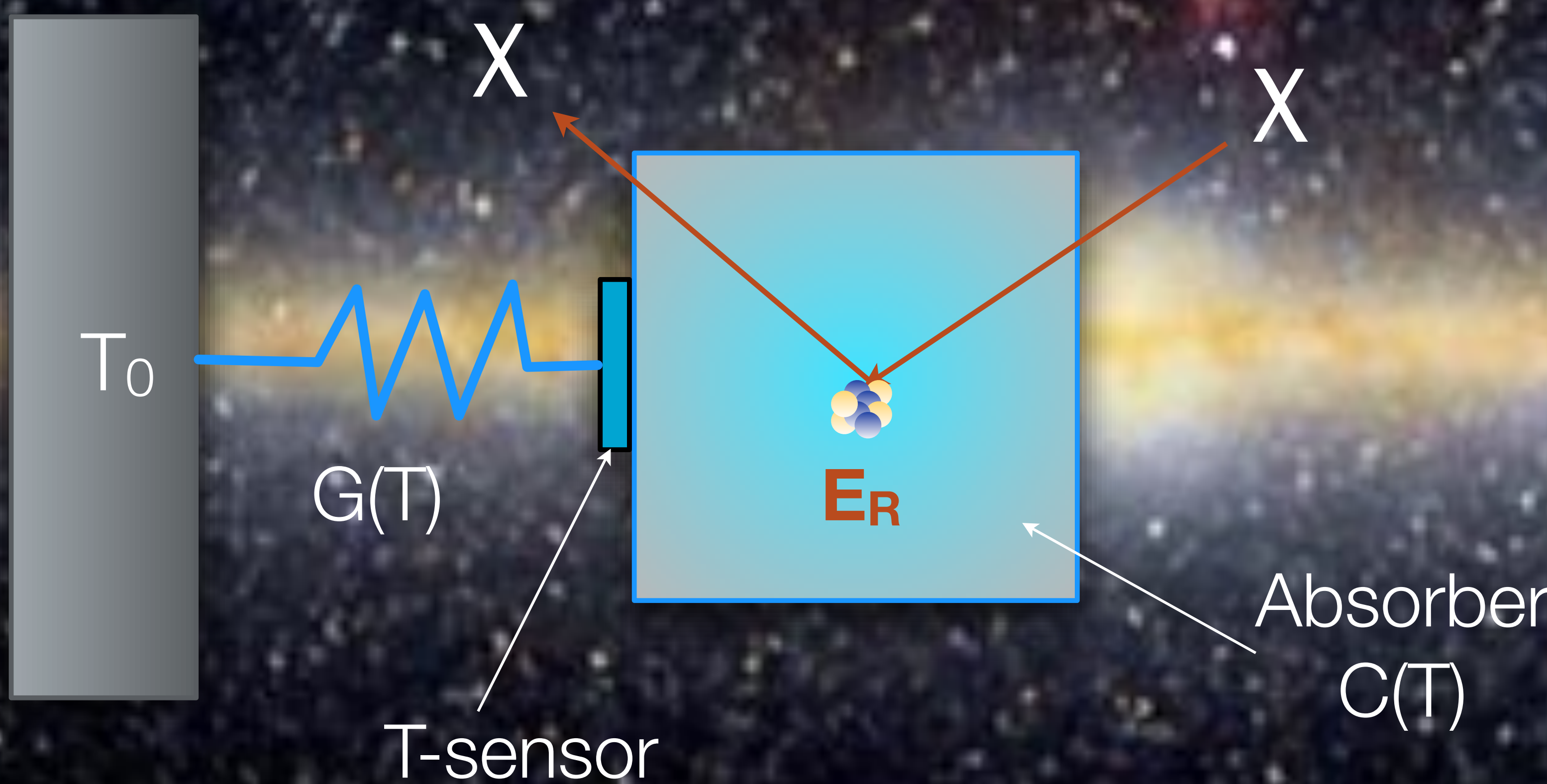
- However when interpreted as due to "vanilla WIMP" other experiments fail to observe such modulation, including KIMS.
- Origin of the time variation in the observed rate remains unclear!
- Environmental effects? Unknown background?



arXiv:1203.1309

Cryogenic Experiments at T~ mK

- Detect a ***temperature increase*** after a particle interacts in an absorber
- The temperature rise (~ μK) is measured with Transition Edge Sensors



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

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

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

m = absorber mass

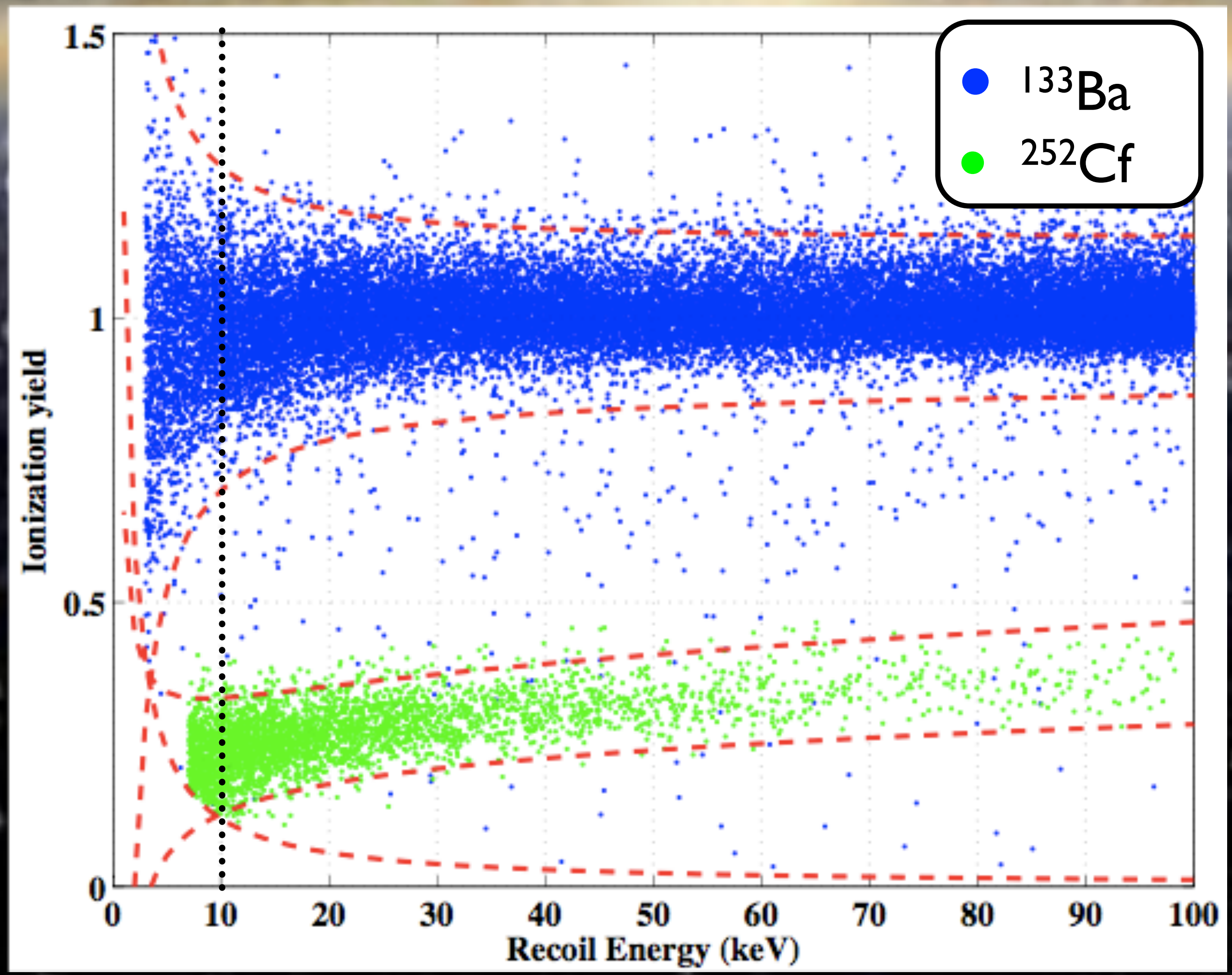
M = molecular weight of absorber

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

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
- **Disadvantages**: small mass, complex and expensive fabrication, surface contamination

Ratio of charge (or light) to phonon

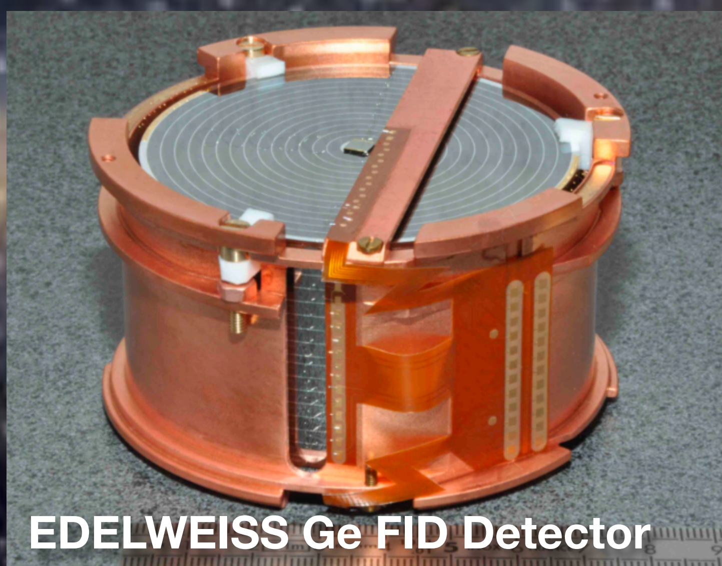


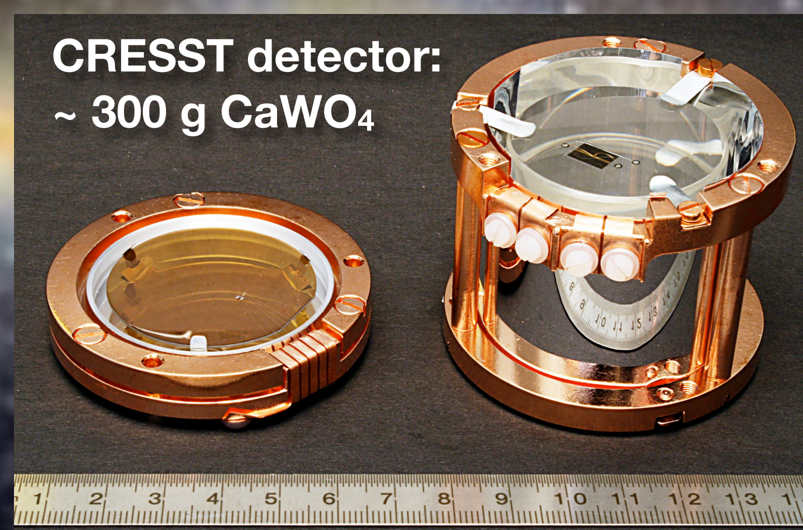
Background region

Expected signal region

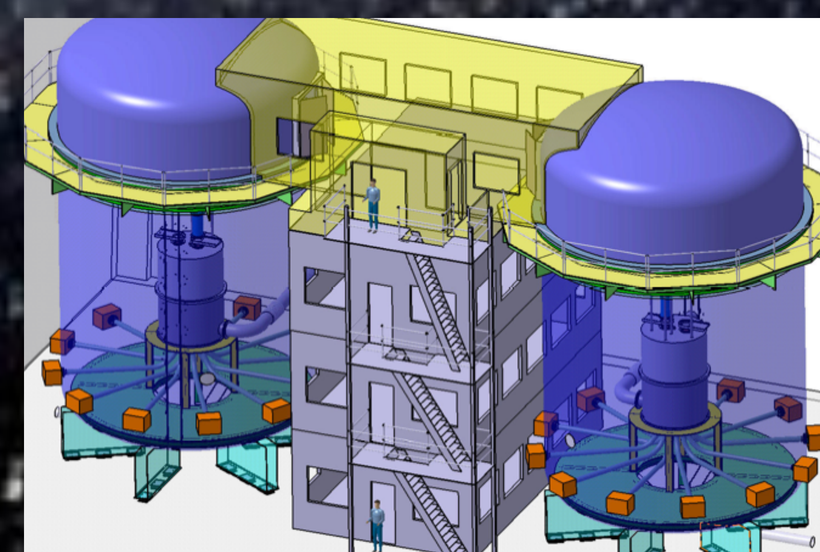
CDMS, CRESST, EDELWEISS

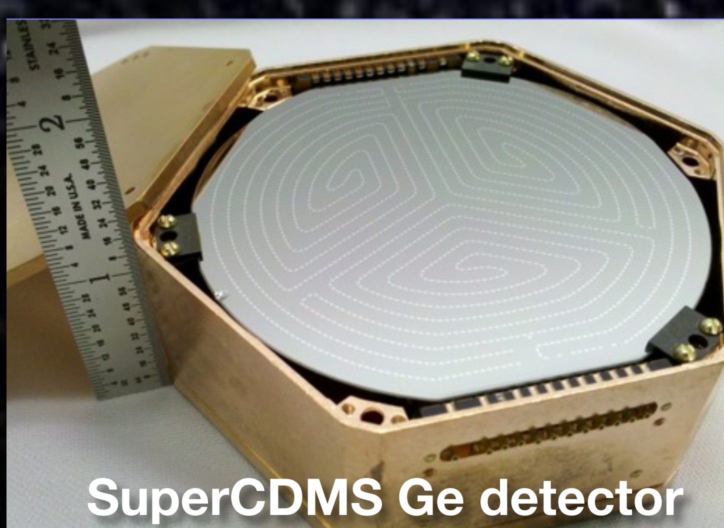
- Absorber masses from ~ 100 g to 1500 g (SuperCDMS at SNOLab)
- Currently running at Soudan, LNGS, Modane
- Future: EURECA (multi-target approach, up to 1 ton mass), SuperCDMS (150 kg) and GEODM (1 ton Ge detectors)


EDELWEISS Ge FID Detector


CRESST detector: ~ 300 g $CaWO_4$

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

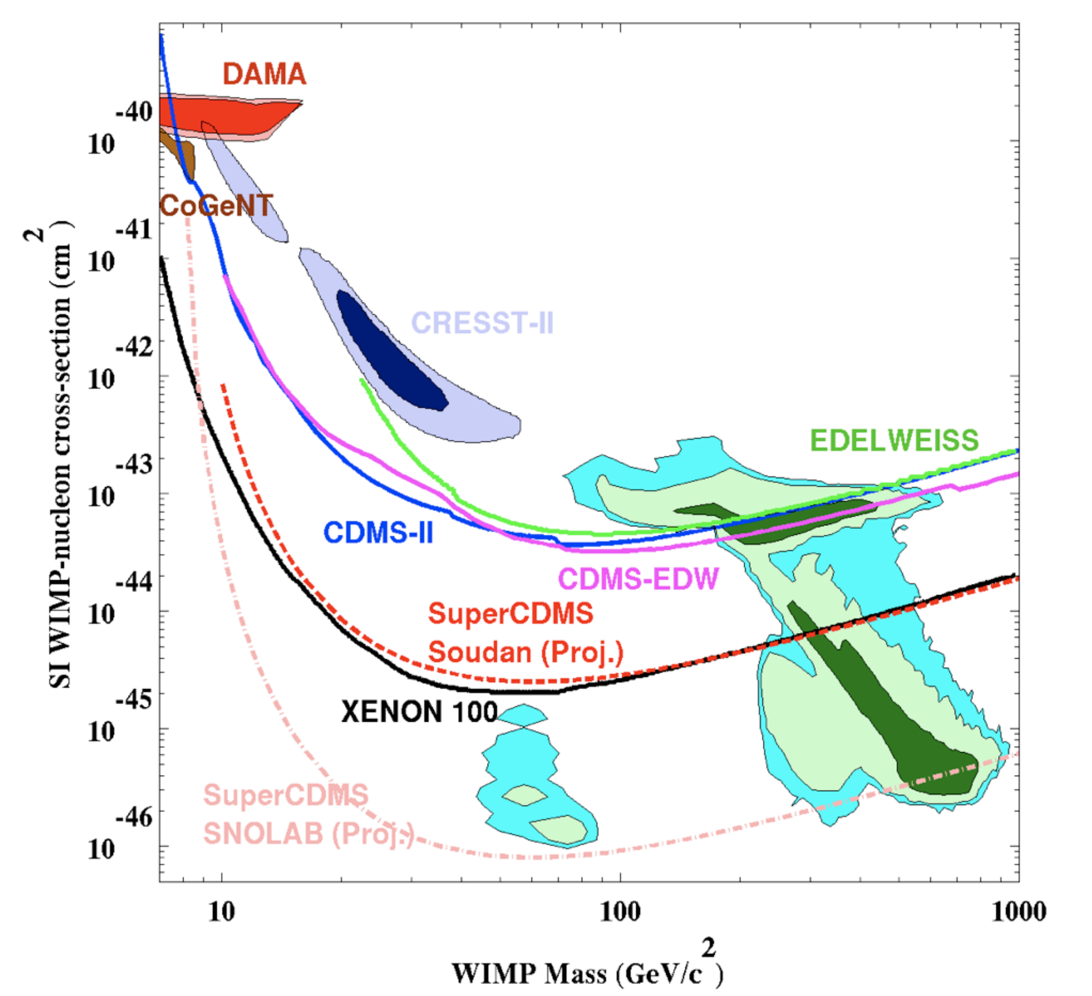


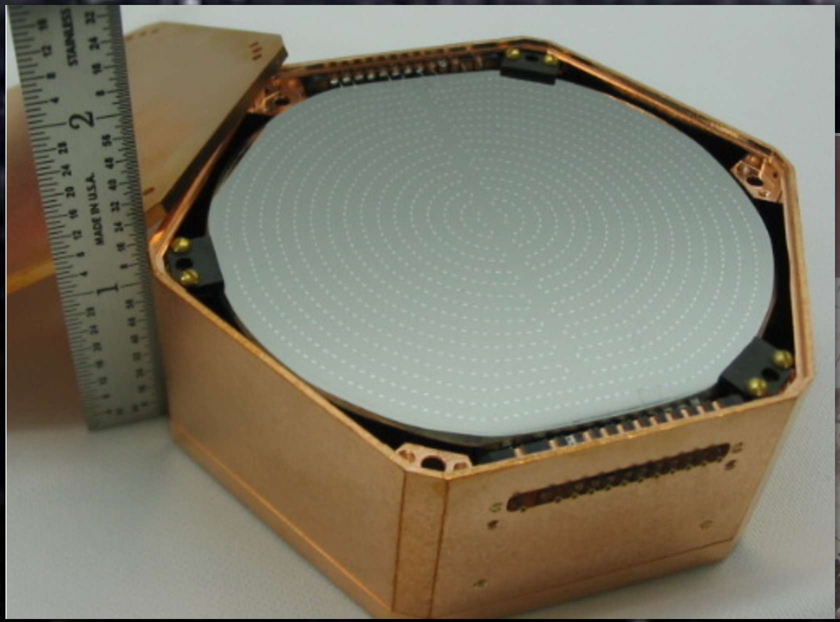

SuperCDMS Ge detector

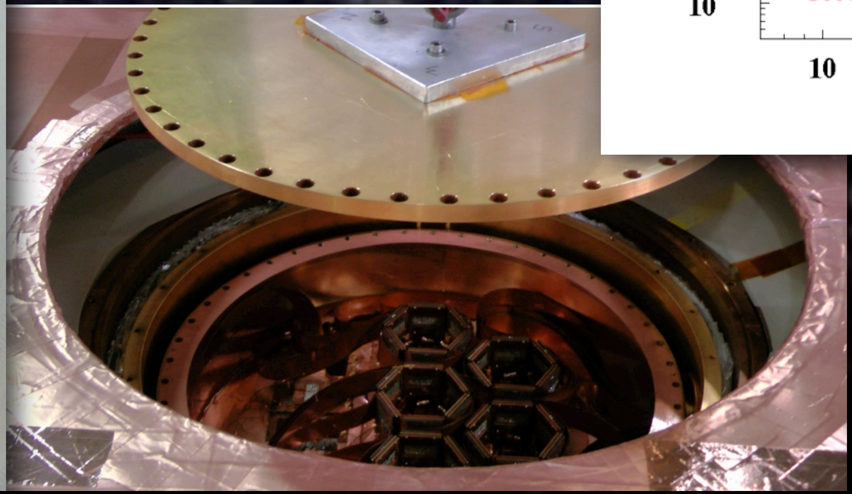

10cm x 3.8cm, 1.4 kg
SNOLAB prototype iZIP

SuperCDMS at Soudan

- Currently operating 5 towers of iZIP detectors (~9 kg Ge) in the existing cryostat at Soudan
- After 3 years of operation, expected to improve sensitivity (SI) by a factor of ~10 over existing CDMS II results, or the same as XENON100 best limit of 2×10^{-45} cm^2







Installation complete Nov. 8, 2011. Operating with final detector settings since Mar. 2012.

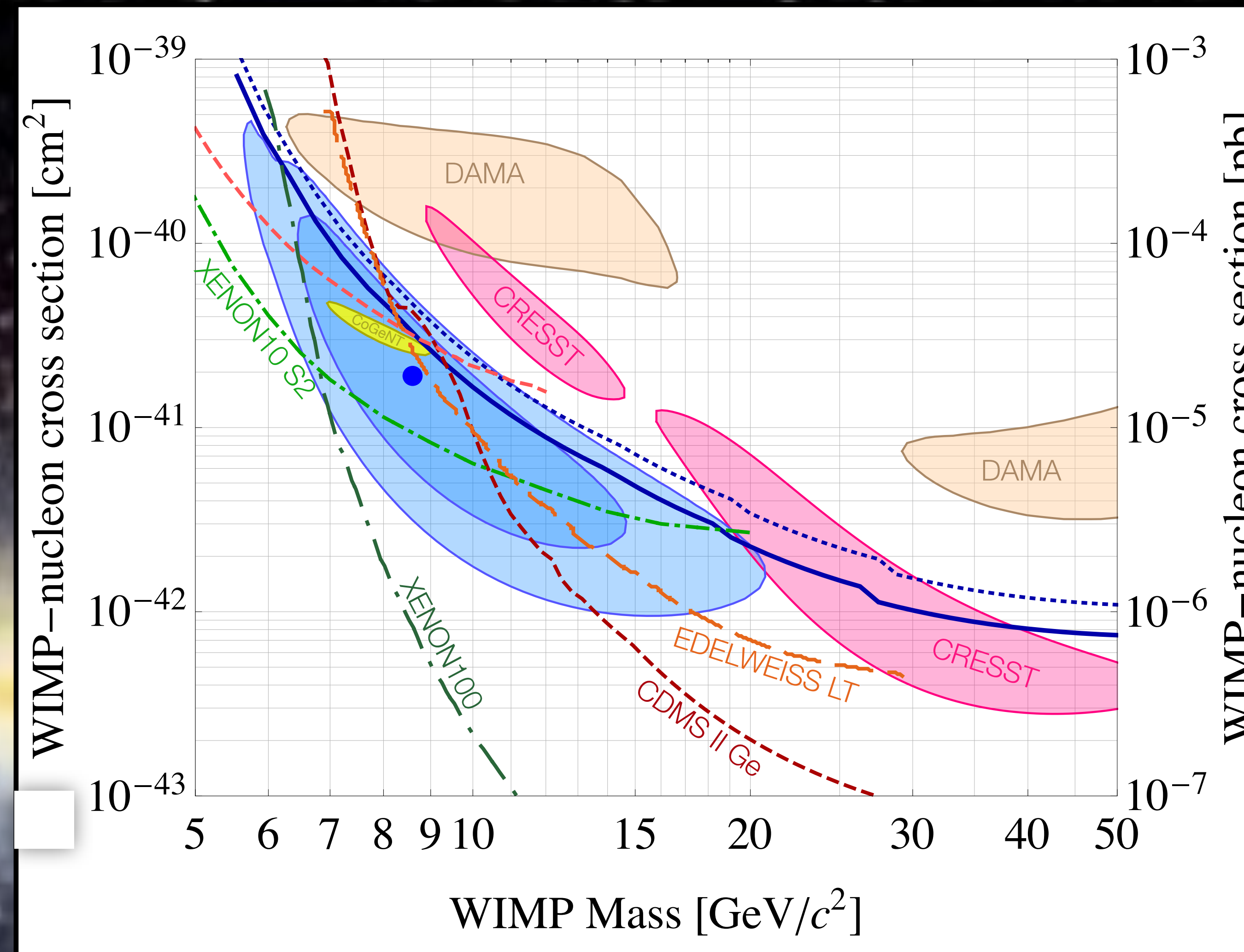
CDMS II: Si Results

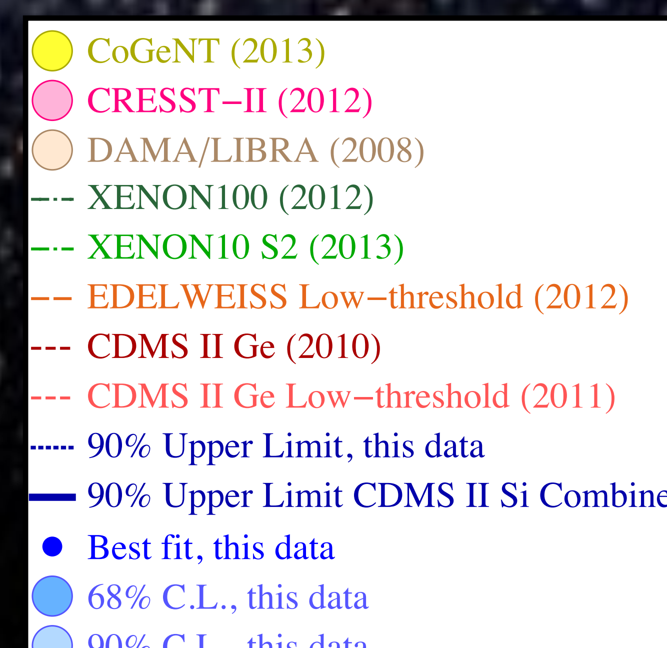
- Si ZIP detectors (106 g)
- Data: July2007 - Sep 2009

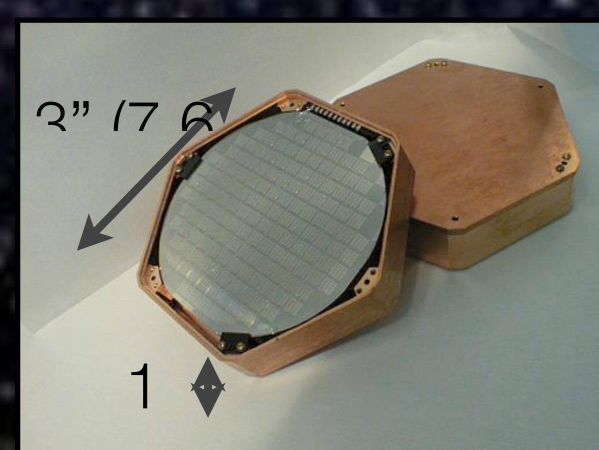
- A profile likelihood analysis favors a WIMP+background hypothesis over the known background estimate as the source of signal (3 events) at the 99.81% C.L. (~3σ, p-value: 0.19%)

- The maximum likelihood occurs at a WIMP mass of 8.6 GeV/c^2 and WIMP-nucleon cross section of 1.9 x 10^{-41}

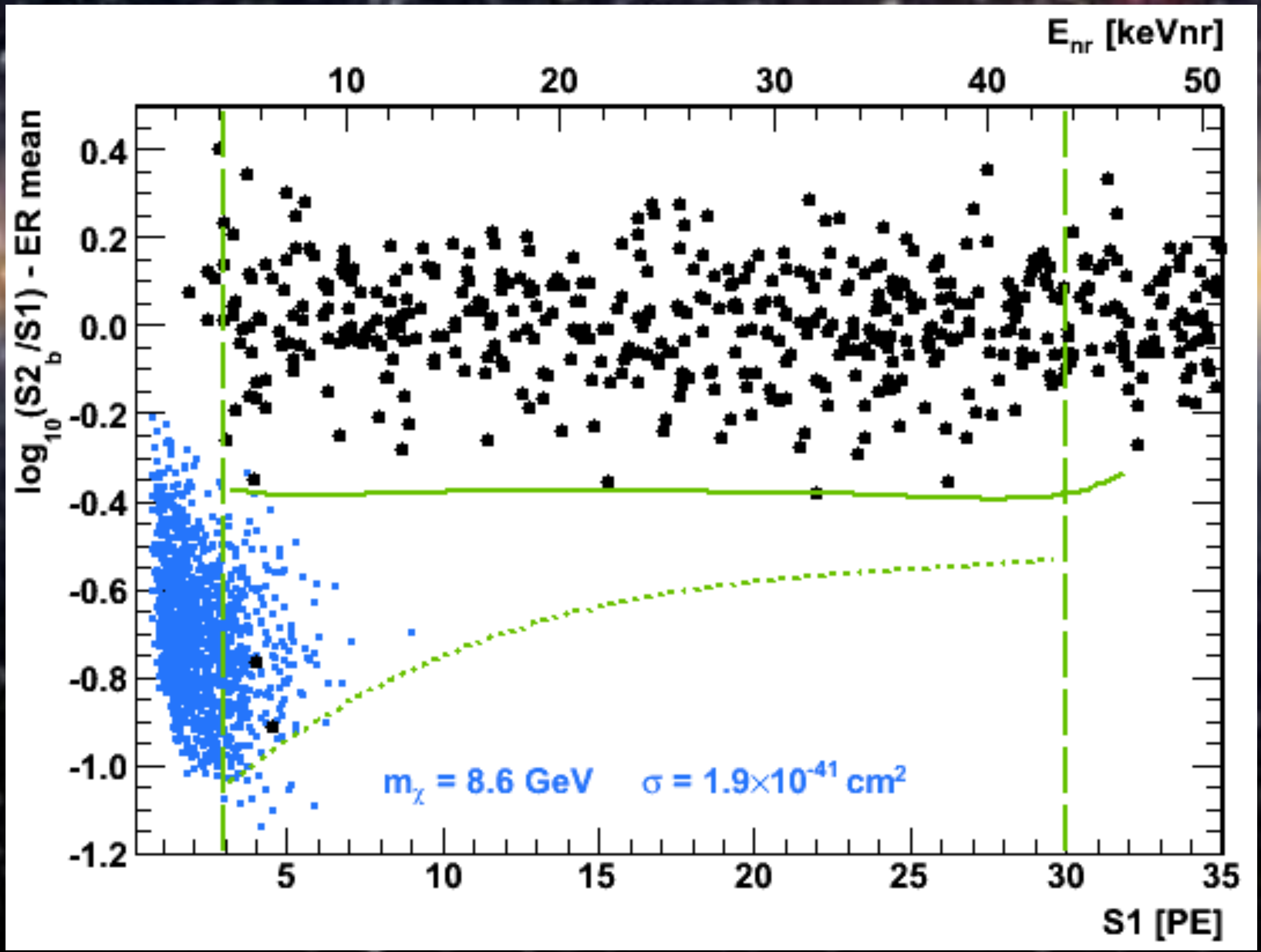
-







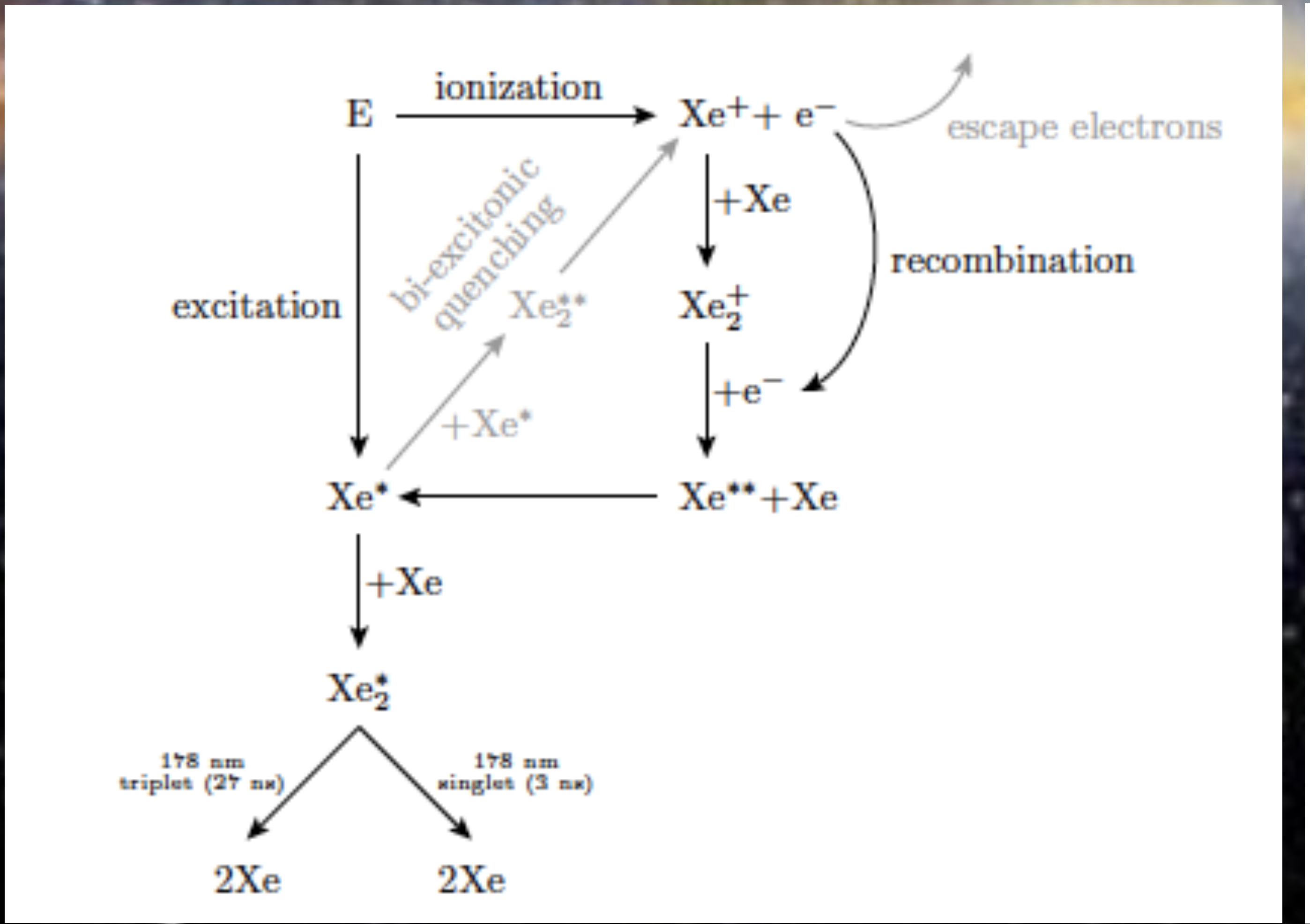
How would these events look like in XENON100?

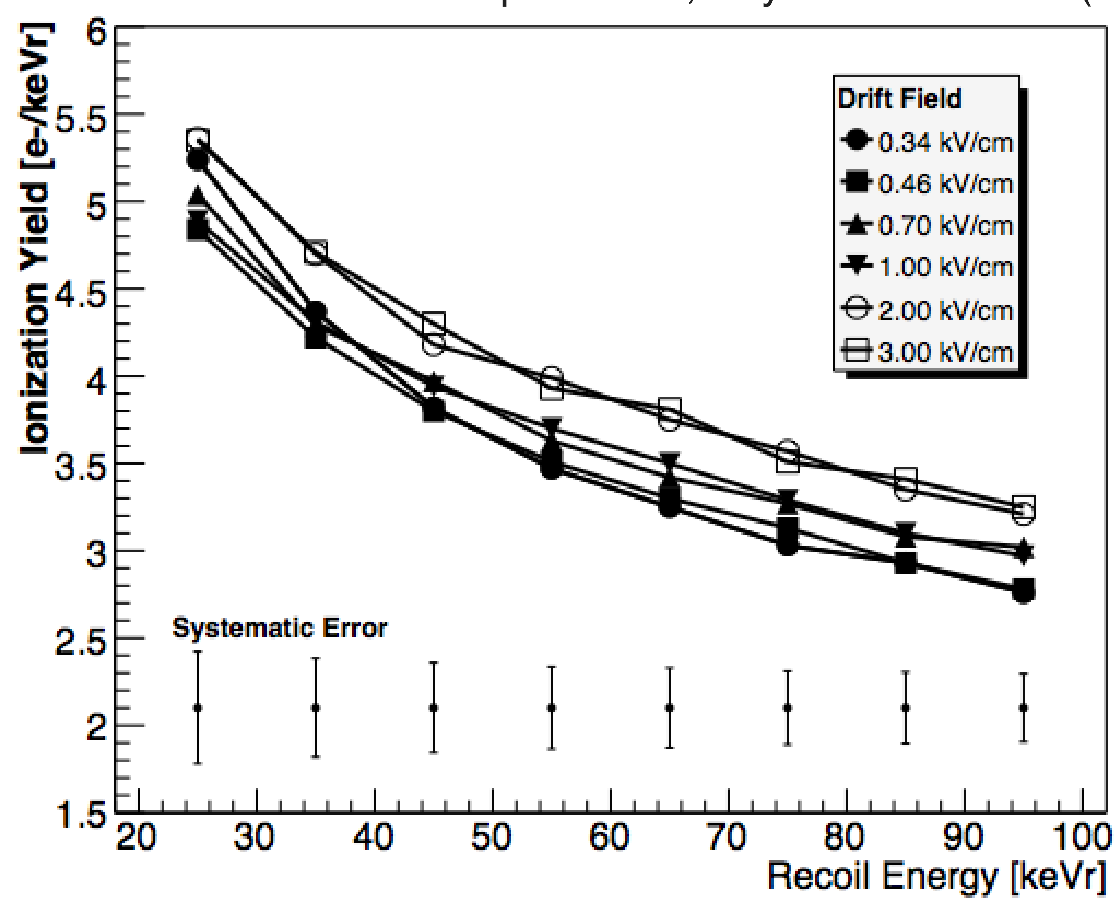


- 1307 events, including events below our analysis threshold, and after all acceptances
- 264 events in the ROI. No way we would have missed them!!!
- New neutron calibration of XENON100 with a YBe source planned to target lower NRs

Scintillation/Ionization: Noble Liquids

- Noble liquids: high light and charge yield; transparent to their own light
- Large, scalable, homogeneous and self-shielding detectors
- In air, by volume - Ar: 0.93%, Ne: 0.0018%, He: 0.00052%, Kr: 0.00011%, Xe: 0.0000087%

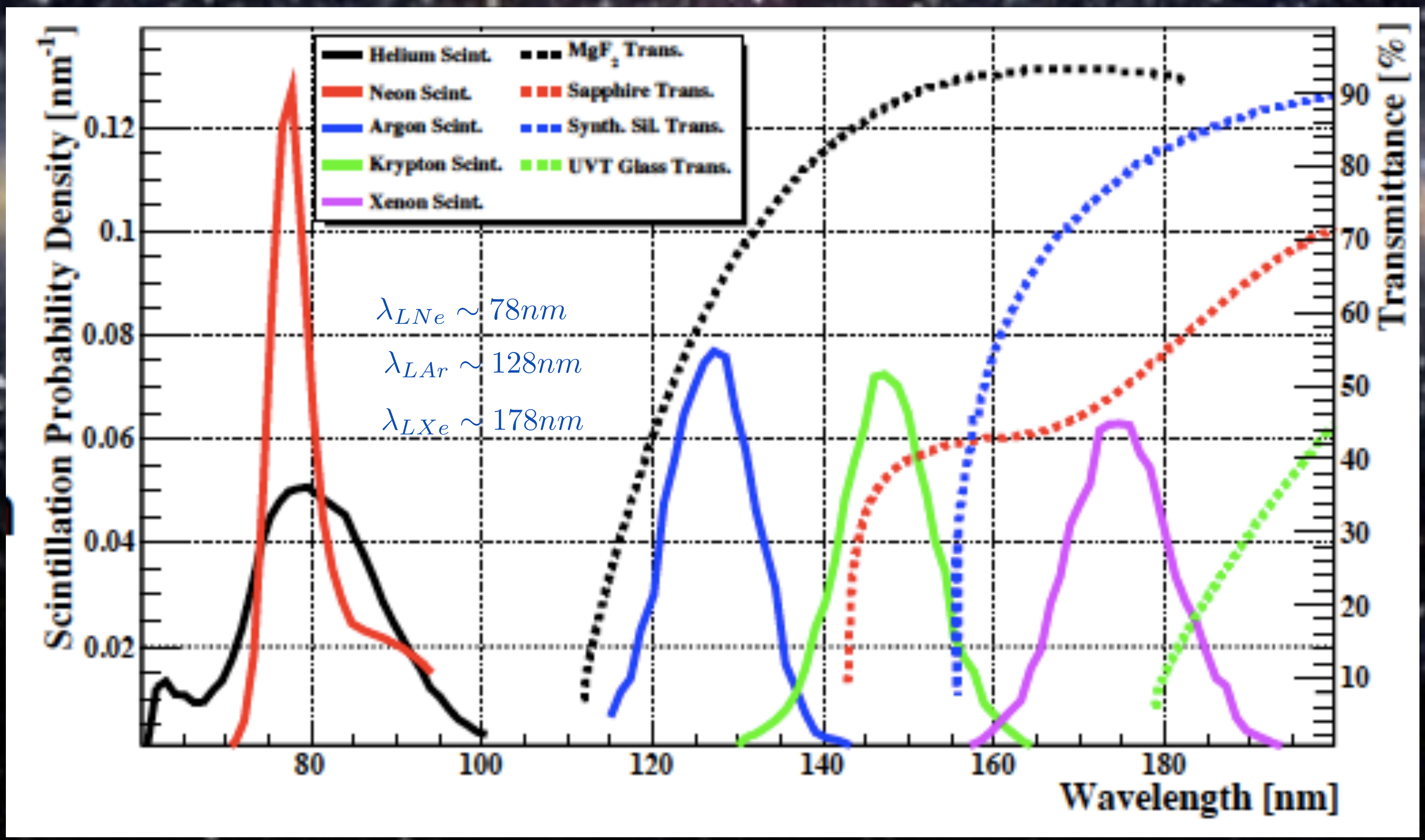




Aprile et al., Phys. Rev. Lett. 97 (2006)

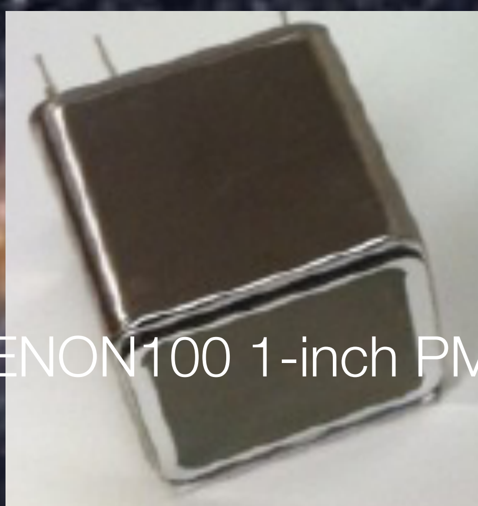
Noble Liquids as Scintillators

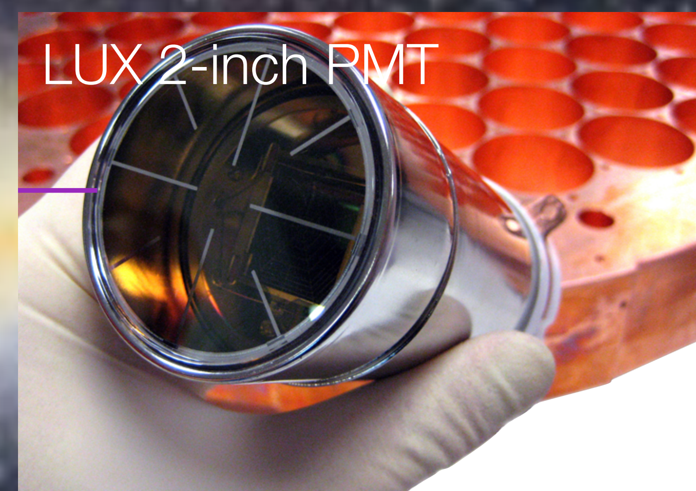
- **Advantage:** scintillation from the breakup of dimers leads to two time constants: **prompt (few ns)** from excited atoms and **delayed (tens of ns)** from ionized atoms -> Pulse Shape Discrimination
- **Disadvantage:** scintillation in the VUV where common windows stop working -> special PMTs with mostly quartz windows and built to withstand several bar pressure and low temperature

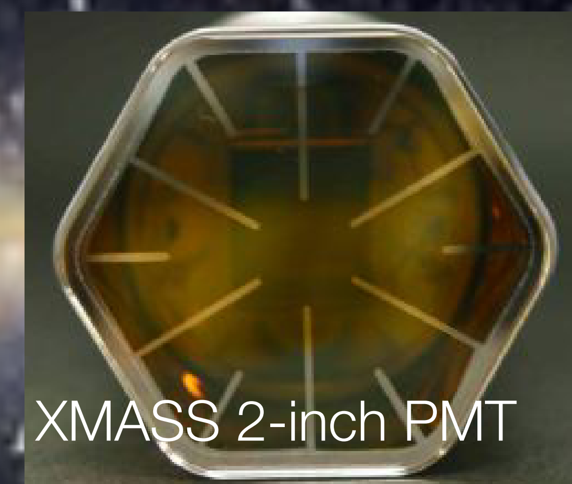


Photomultipliers developed for LXe

- LT bialkali photocathodes: high QE (~30-40%), all metal body, Al seal (up to 5 bar and -100C)
- Ultra-low radioactivity: < 1 mBq/PMT (U/Th/K/Co/Cs)
- Quartz (sapphire under development) window: transparent to the Xe 178 nm scintillation light





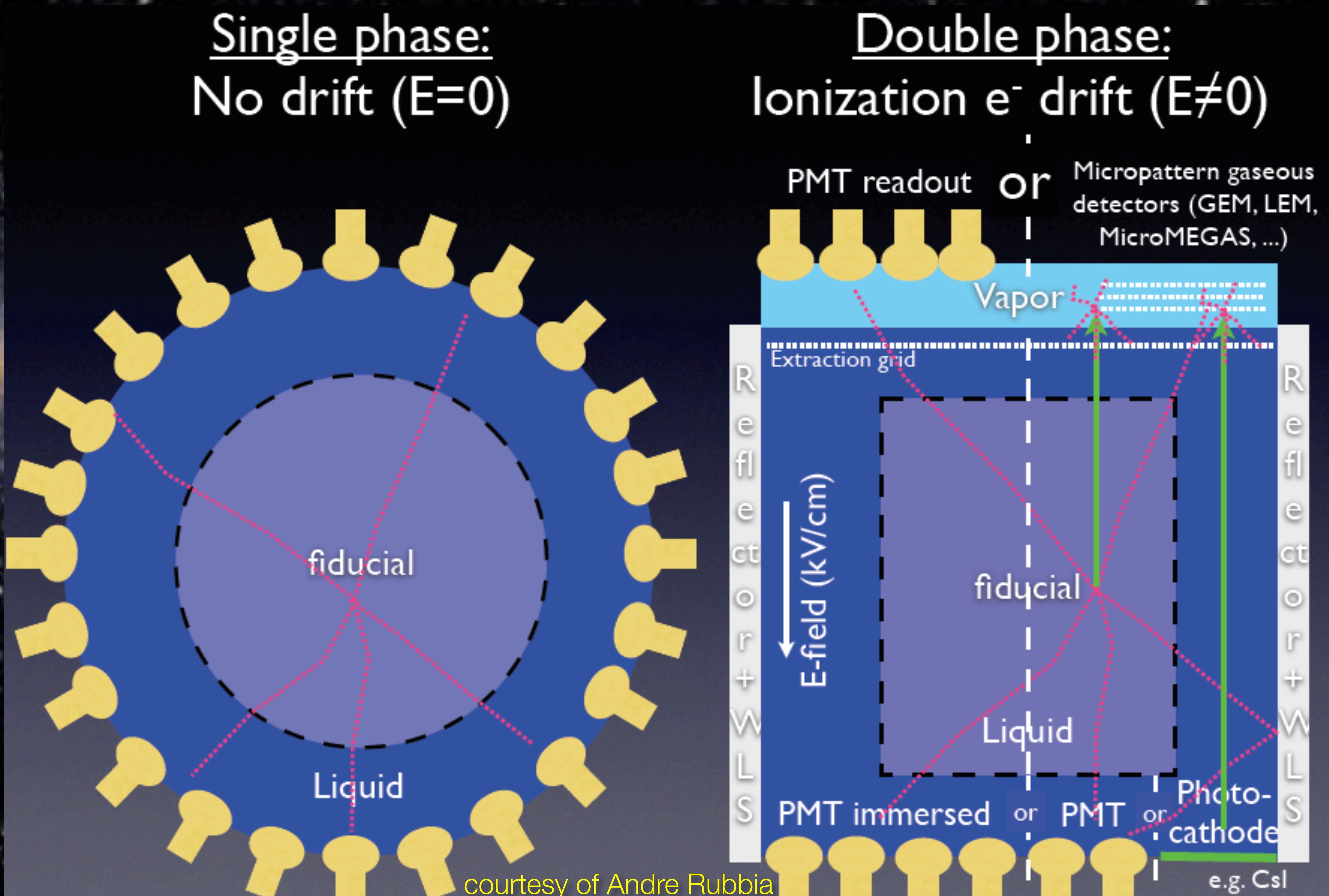


XENON100 array

LUX array

XMASS array

Two Basic Detector Concepts



Single-phase detectors

- **XMASS (current)** at Kamioka (LXe), **DEAP/CLEAN (future)** at SNOLab (LAr)
- Large volume with simple mechanical structure, easily scalable
- Zero field and large PMTs coverage allows high light yield and low energy threshold
- Background reduction by self-shielding and hit pattern reconstruction

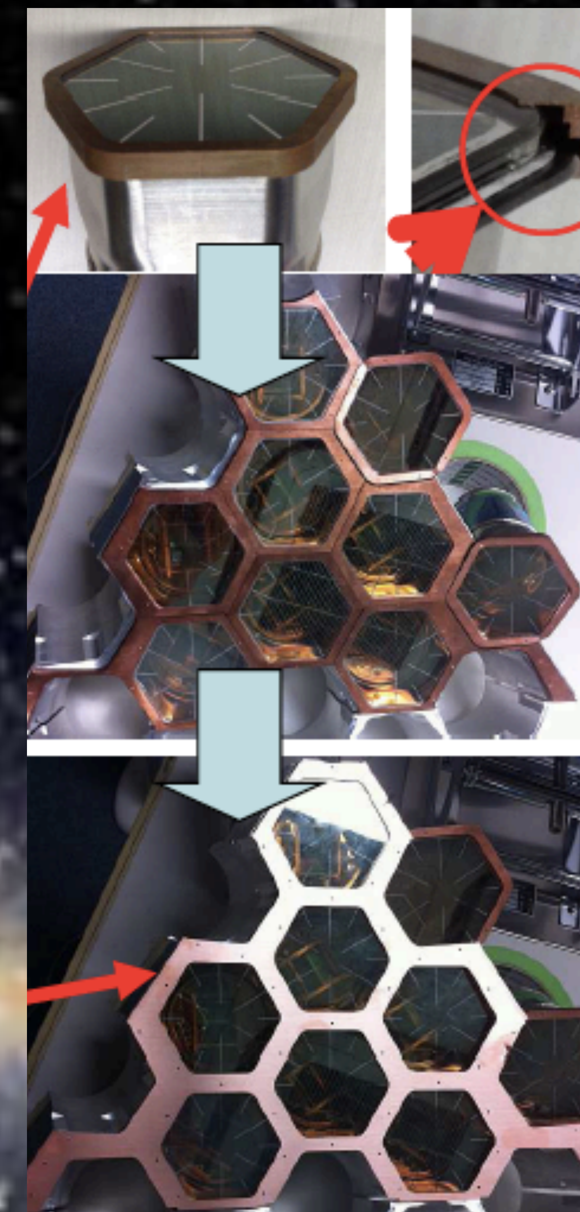
XMASS at Kamioka:
835 kg LXe (100 kg fiducial) in water Cherenkov shield
642 PMTs: **15 pe/keV**
<5keVee ~25keVr in fiducial volume;
Operated in 2011-12
will resume science run in 2014

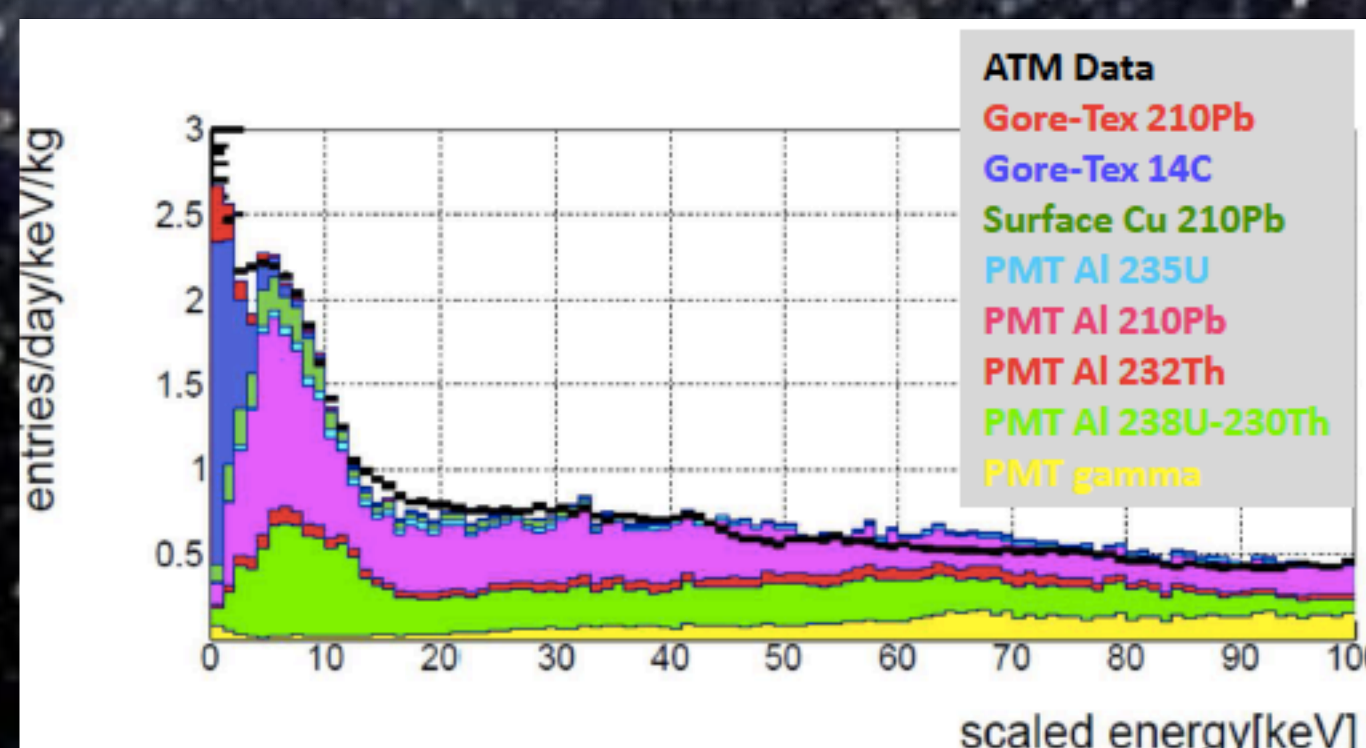
MiniCLEAN at SNOLab:
500 kg LAr (150 kg fiducial)
under construction
to run in summer 2013

DEAP-3600 at SNOLab:
3600 kg LAr (1t fiducial) in water Cherenkov shield
under construction
to run in 2014

XMASS Status

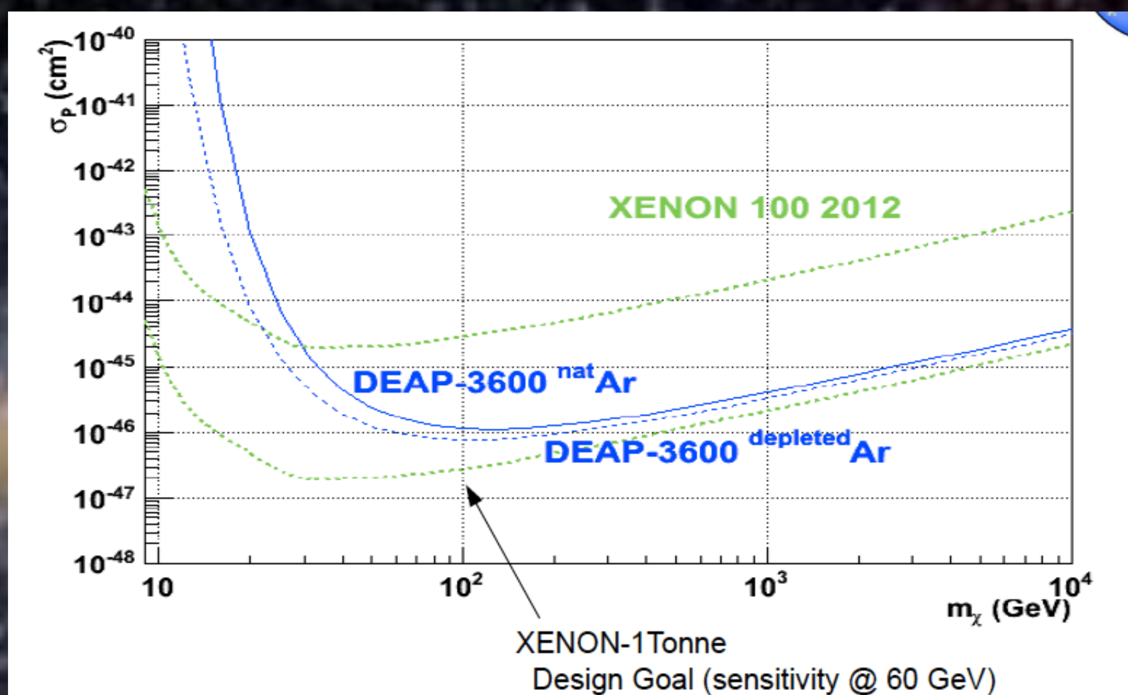
- unexpected BG: 2 order larger than estimated from dominant PMT BG
- most BG from Al seal of PMTs. For <5keV BG most likely culprit is Gore-Tex (14C) used b/w PMTs
- detector disassembled and improvement work in progress
- Al seal covered by Cu ring; Gore-Tex removed and additional Cu structure will cover gaps b/w rings to avoid leakage events produced b/w rings
- Next Detector: 5 ton and 1ton FV. New PMT with selected material under development with feedback from ongoing refurbishment work
- start construction in 2014. Sensitivity (SI) < 10^{-46}cm^2 at 5keVee (~25keVr) for 1ton FV and much lower threshold in full volume

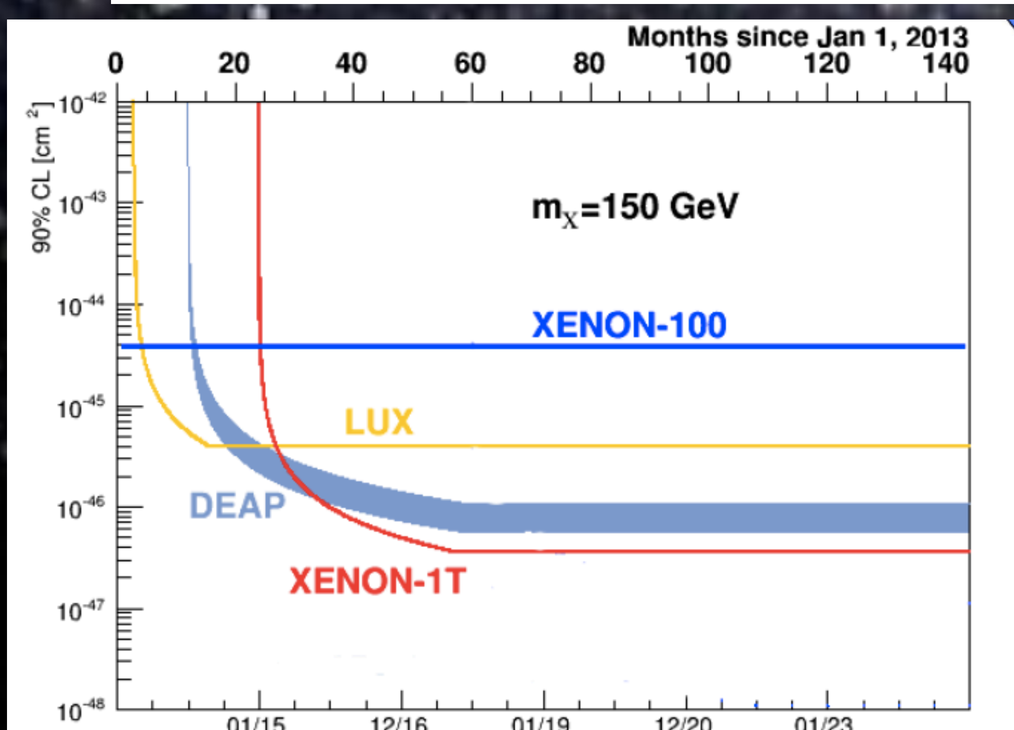


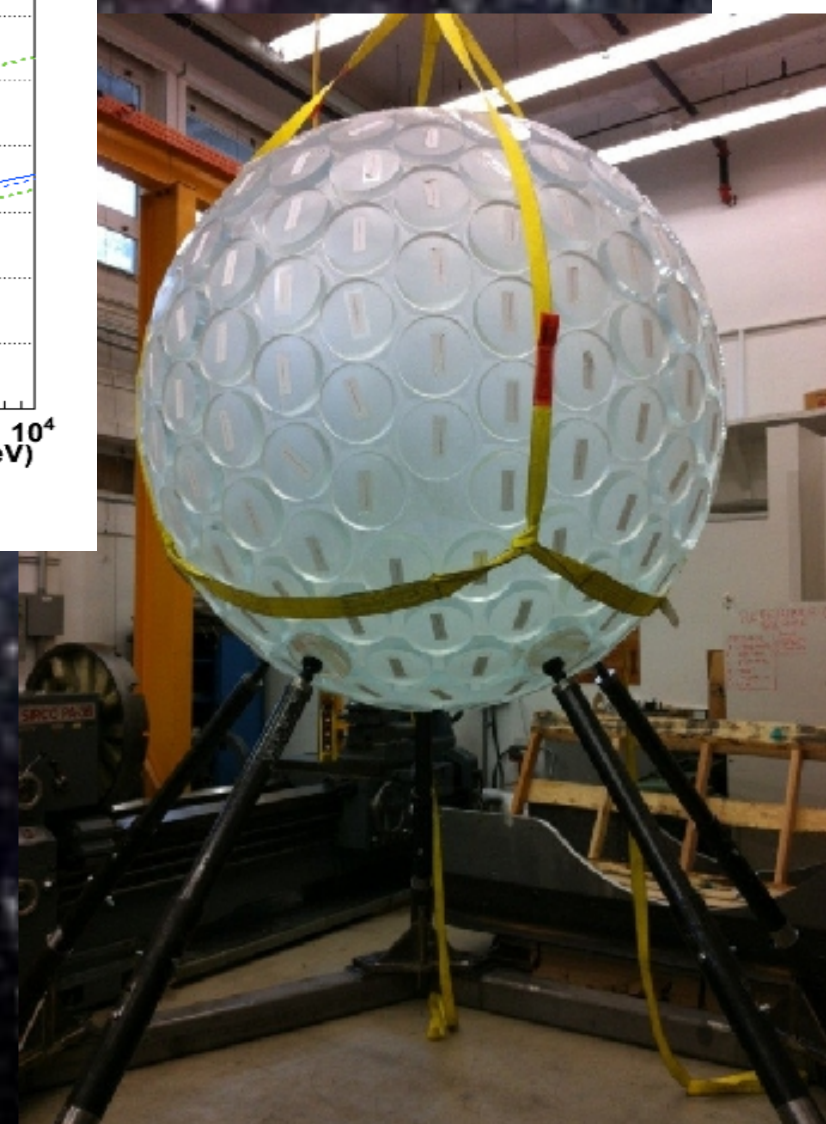


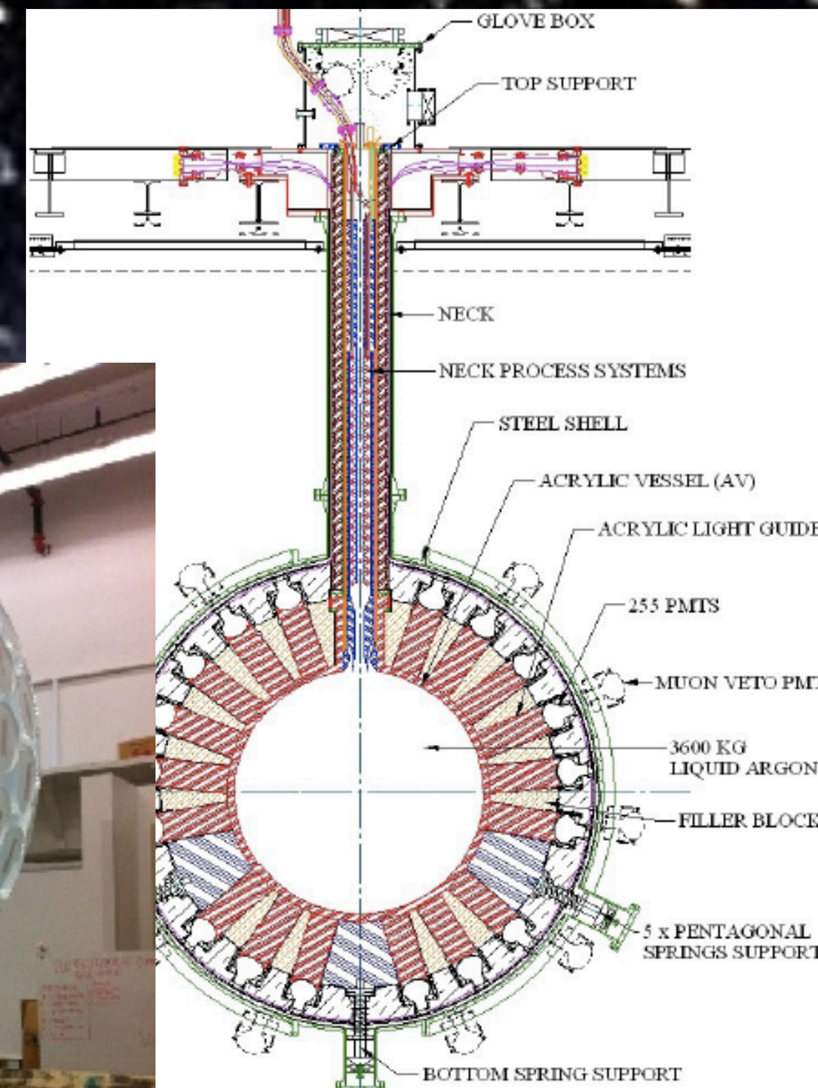
DEAP-3600 Status

- well separated singlet/triplet lifetimes in Ar allow for good PSD: demonstrated to 10^{-8} with DEAP-1; projected to 10^{-10} at 15 keVee
- Sensitivity (SI) ~ 10^{-46}cm^2 at 15keVee (60keVr) for 1ton FV after 3-yr run



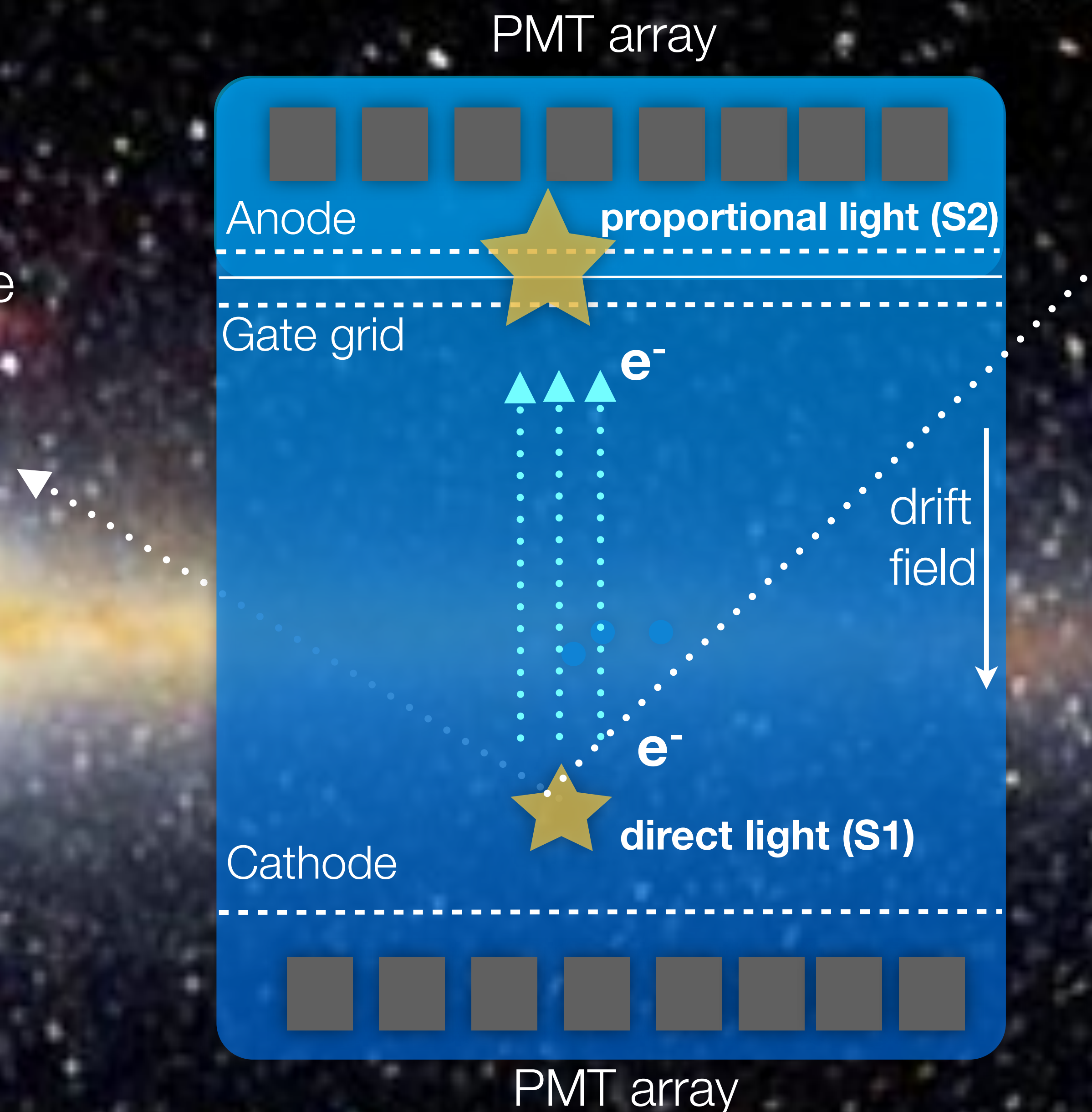




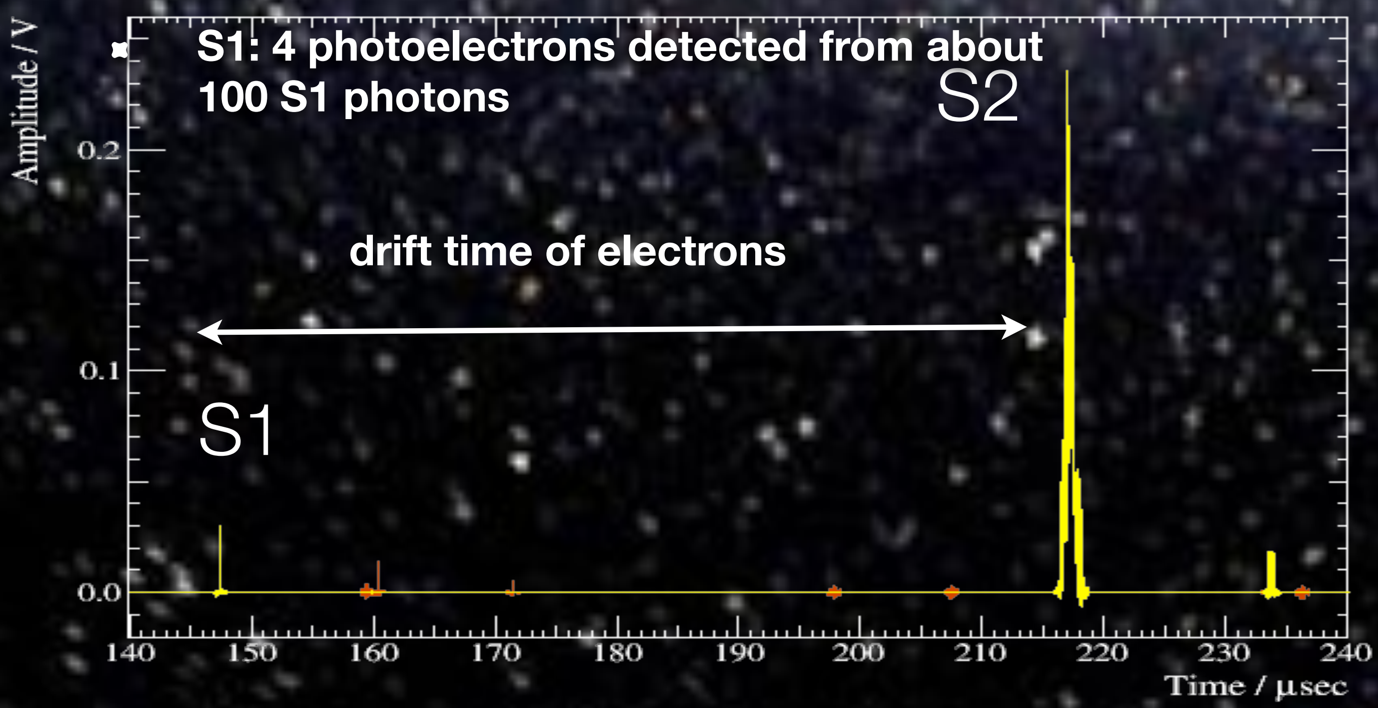


Double-phase detectors: TPCs

- *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*



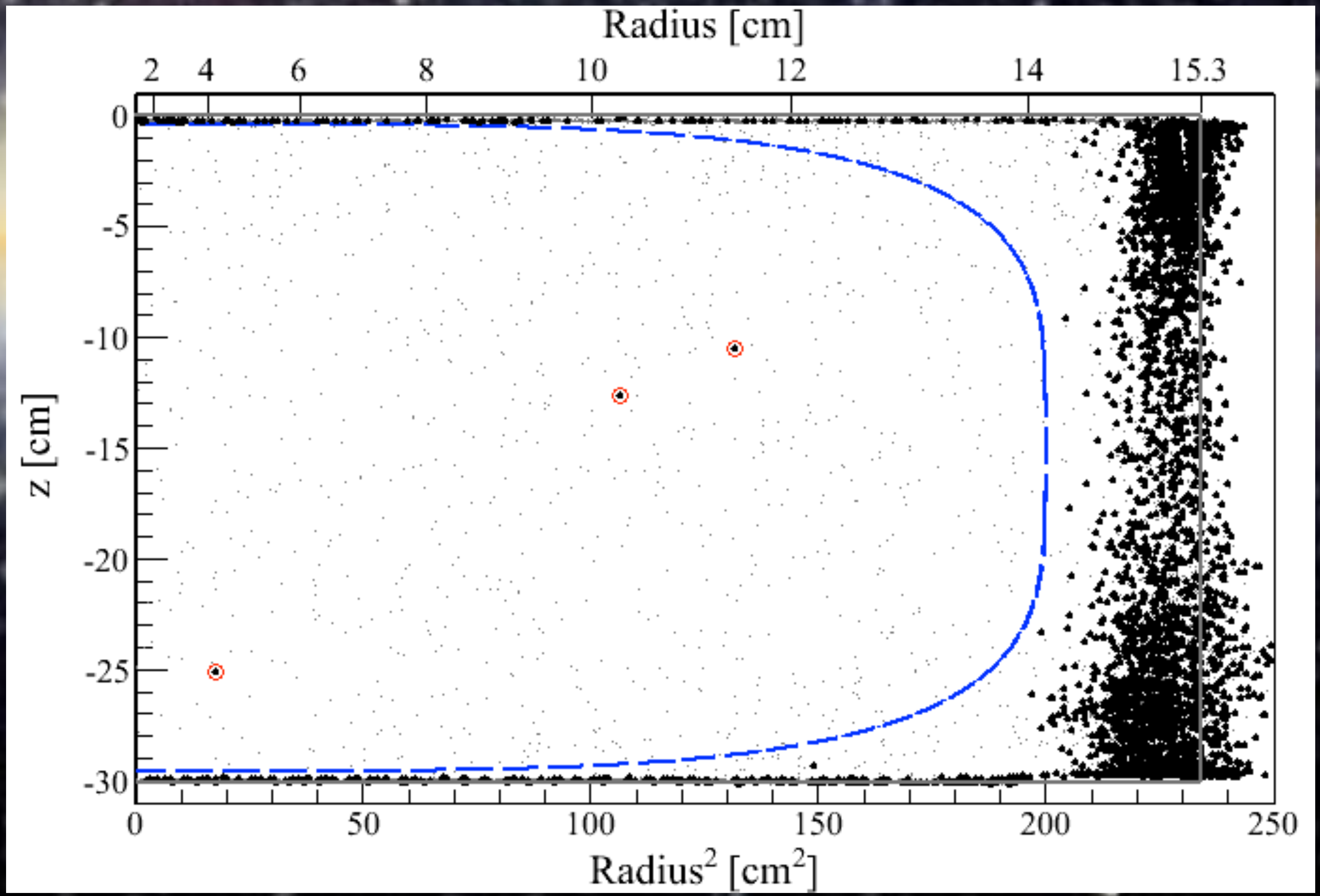
- **S1: 4 photoelectrons detected from about 100 S1 photons**



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

The Power of a TPC for Background Rejection

- 3D event imaging allows to select single scatter events and only in a central volume with lowest background exploiting LXe self-shielding
- Gammas from detector components and external sources stopped at edges
- Remaining background in fiducialized volume dominated by events from ^{85}Kr and ^{222}Rn in LXe



Liquid xenon and liquid argon TPCs

XENON100 at LNGS:

in conventional shield
161 kg LXe (~50 kg fiducial), 242 PMTs

in DM search

LUX at SURF:

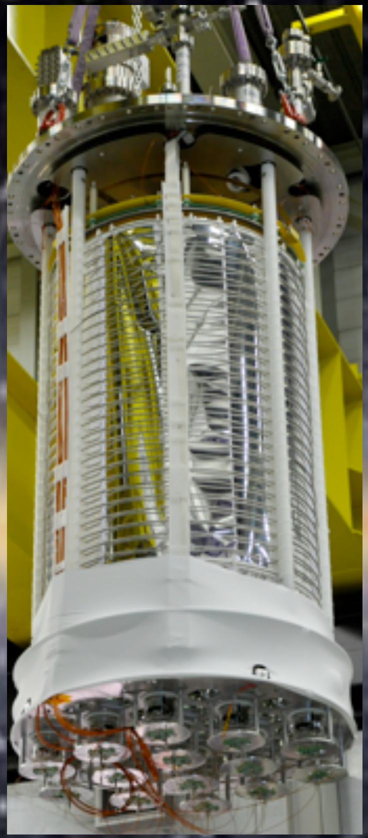
in water Cherenkov shield
300 kg LXe (100 kg fiducial), 122 PMTs

in operation

PandaX at CJPL:

in conventional shield:
123 kg LXe (25 kg fiducial), 180 PMTs

in commissioning



ArDM at Canfranc:

in conventional shield
850 kg LAr
2 arrays of PMTs

in commissioning

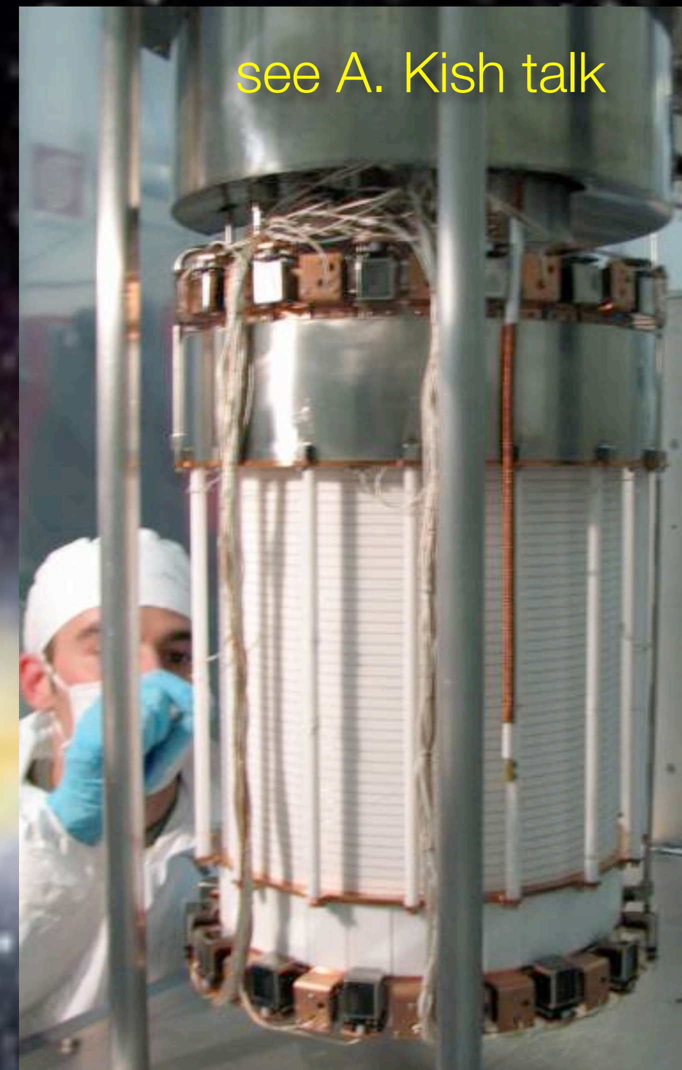
DarkSide at LNGS

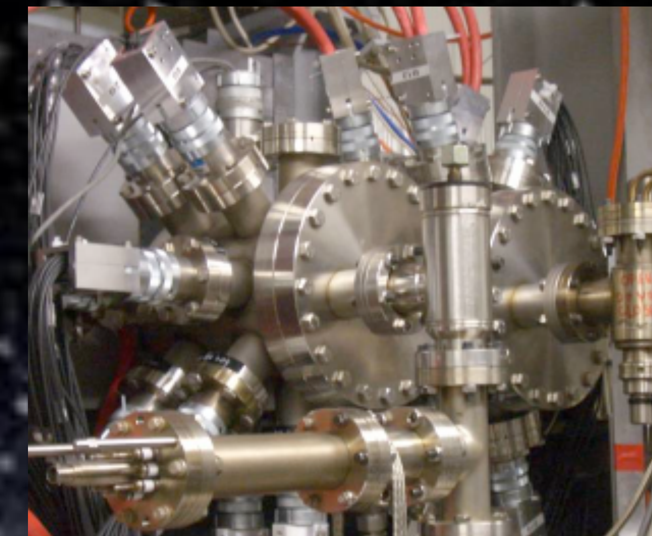
in liquid scintillator and water shield
50 kg LAr (depleted in 39Ar)

in commissioning

XENON100 Status

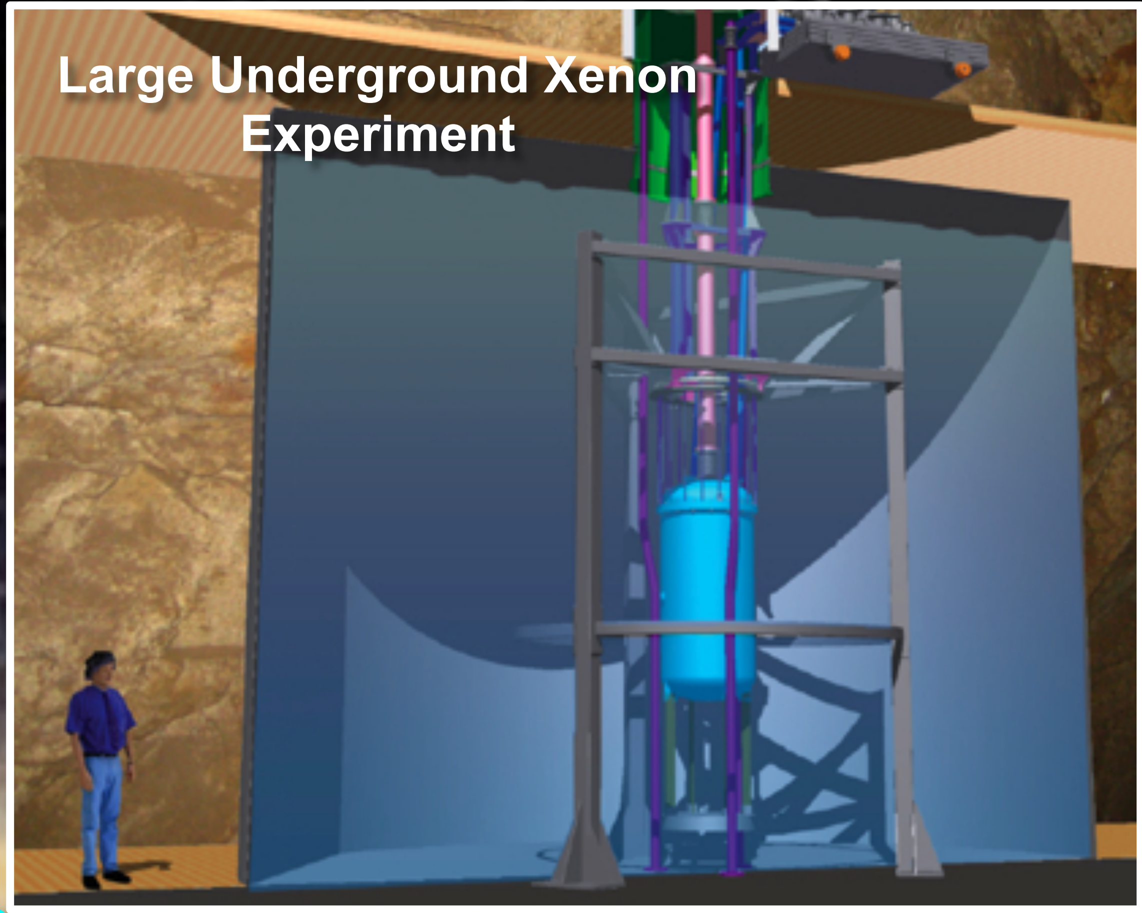
- 161 kg of LXe: 62 kg in the active target and rest as active LXe veto viewed by PMTs
- TPC with 30 cm drift with two PMT arrays (242 PMTs) to detect the prompt and proportional light
- 2012 results for SI and SD DM search plus a study of response to NRs and results from dedicated R&D set-ups.
- Progress on analysis of same data for: annual modulation, MeV and GeV DM, etc.
- In 2013 new distillation of the Xe has lowered Kr/Xe level to < 1.3 ppt (90% CL) reducing background from ^{85}Kr to <0.05 mDRU (in 2012 data this was 0.6 mDRU)
- New AmBe neutron calibration completed
- New Dark Matter search started with excellent detector performance. Plan to take data over 1 year


see A. Kish talk



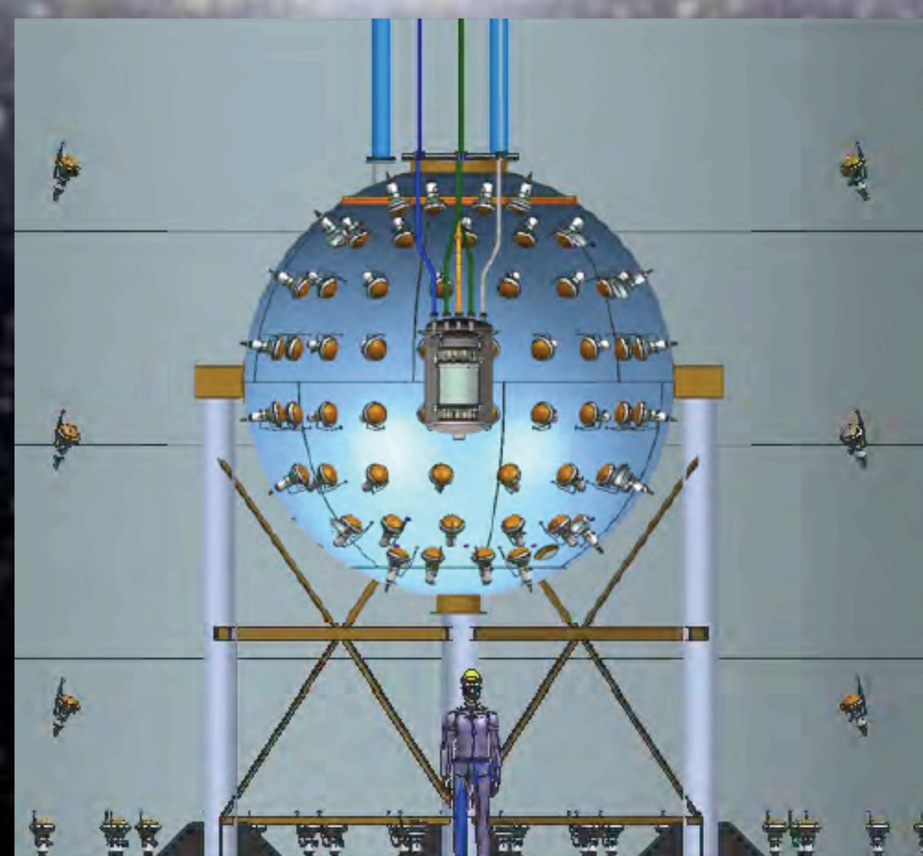
LUX Status

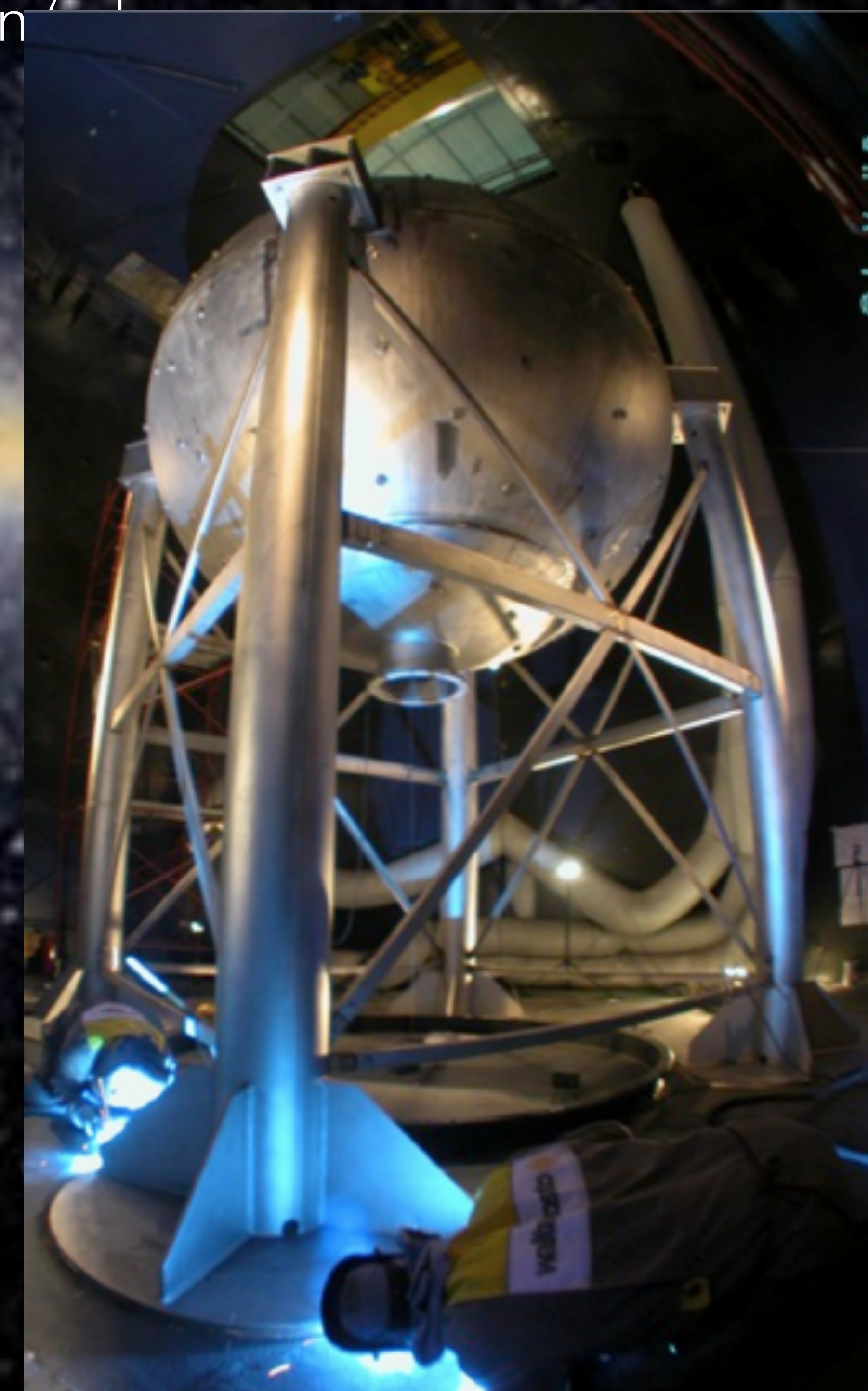
- LXe TPC - 300 kg active / 100 kg fiducial
- Installed in water tank at 4850 level of SURF/Homestake
- Xenon condensed Feb 2013 - circulating > 20 SLPM
- Short (~ 60 day) WIMP search run - result by end 2013
- Full year-long WIMP search run to begin in 2014
- Sensitivity goal (SI): 7x 10^{-46} cm^2 with 300 days x 100kg and zero background



DarkSide Status

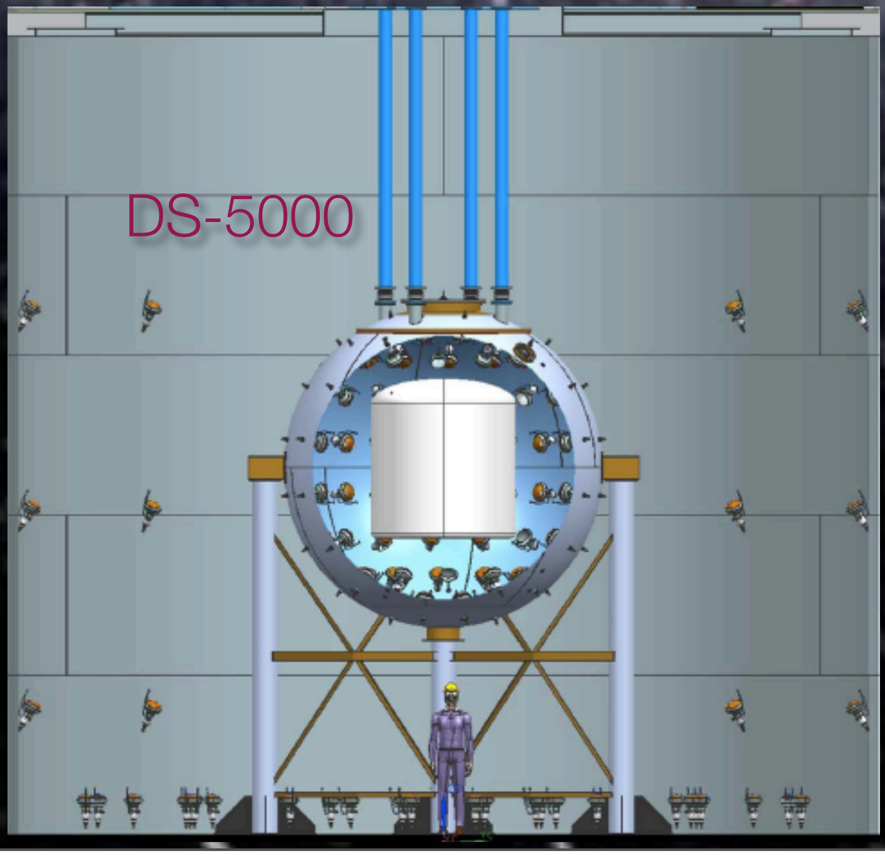
- DS-50 (50kg) LArTPC in commissioning underground
- 38 PMTs (3 in) to detected Ar light shifted by TPB
- PSD (like in DEAP) plus Charge/Light ratio and 3D spatial resolution (sub-cm) for BG rejection
- underground Ar to avoid pile-up from ^{39}Ar
- neutron veto and water shield (Borexino CTF) facilities completed
- Sensitivity (SI) goal ~ 10^{-45}cm^2 at 100 GeV for zero background

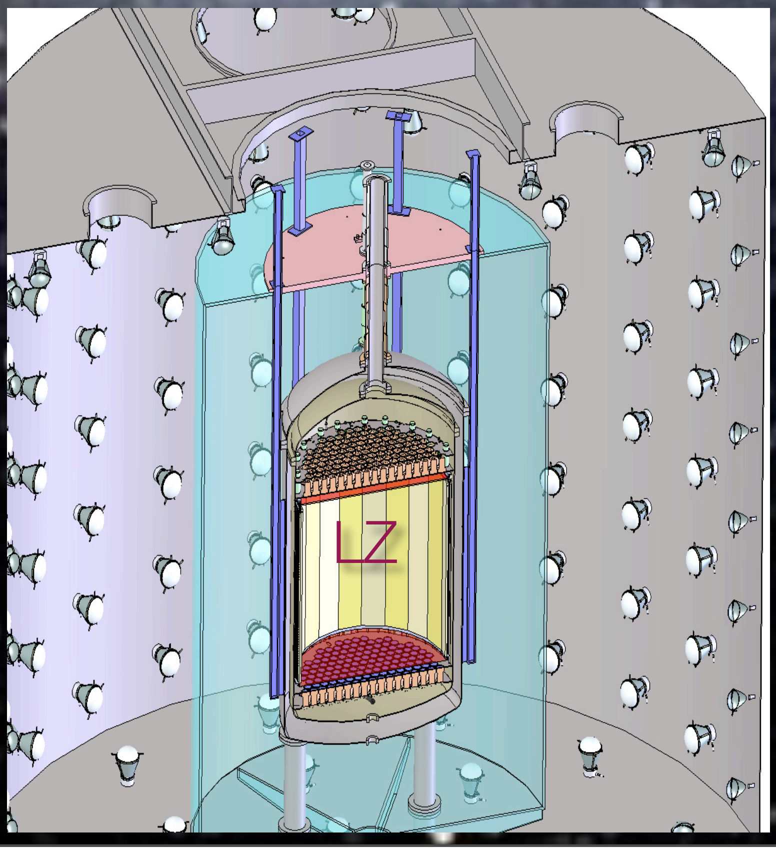


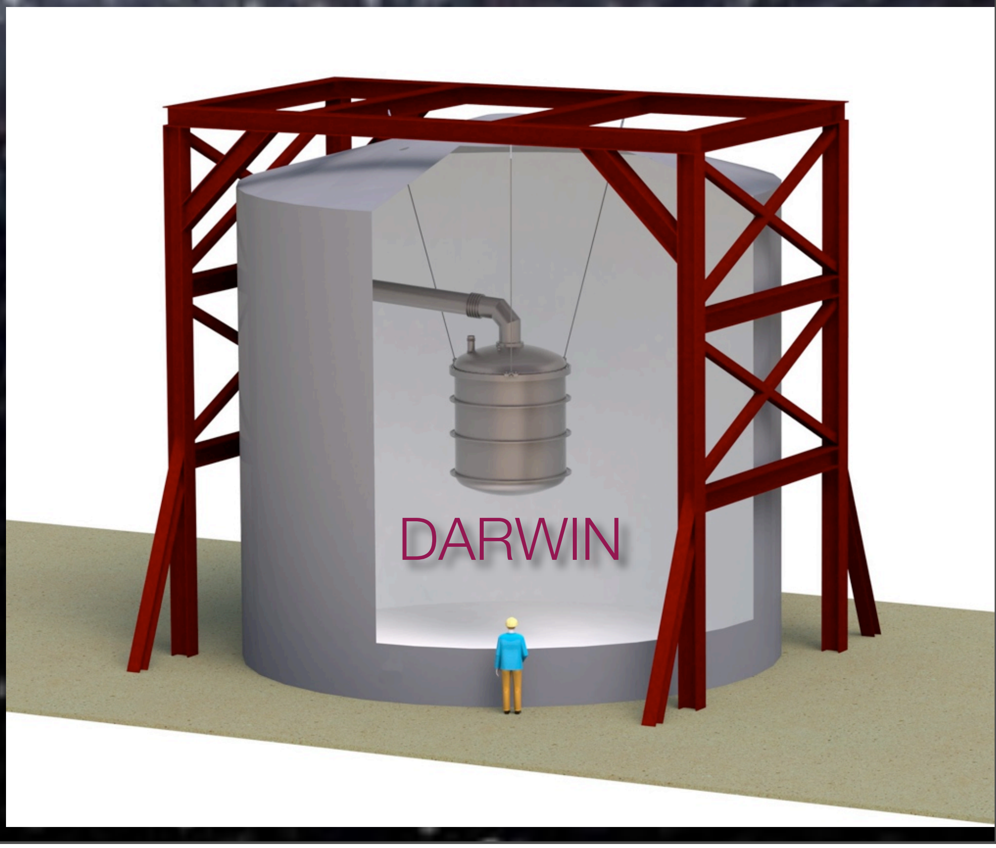


Future ton-scale LXe and LAr Detectors

- Funded and under construction @ LNGS: XENON1T (3.5t LXe)
- Funded for construction start in 2014 @ Kamioka: XMASS (5t LXe)
- Funded for commissioning start in 2014@ SNOLAB: DEAP-3600 (LAr)
- Funded for R&D, proposals in preparation: LZ (7 t LXe) & DS-5000 (5t LAr)
- Under study: DARWIN (20 t LXe/LAr)

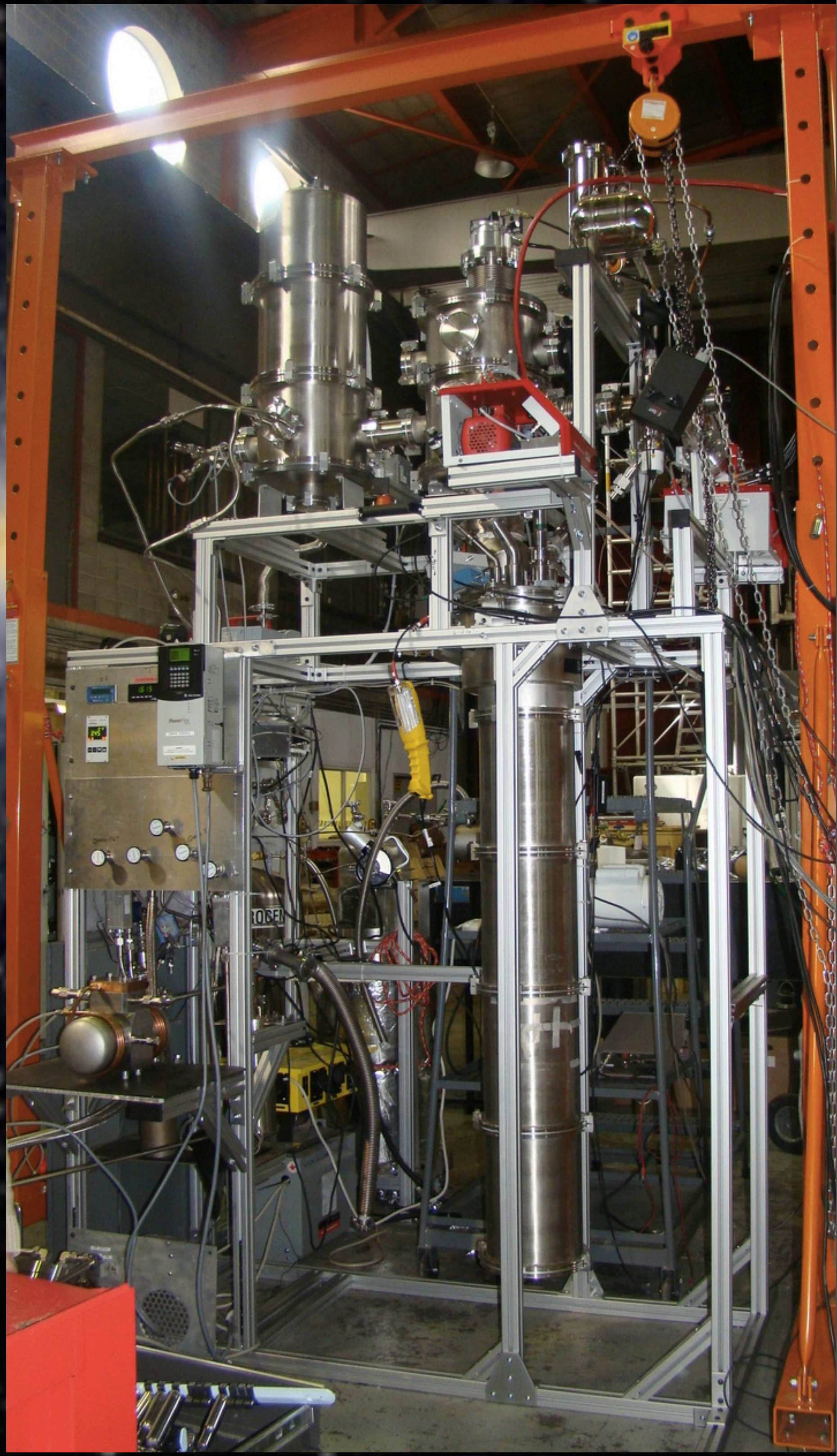






Some of the Technical Challenges for large volume liquid TPCs

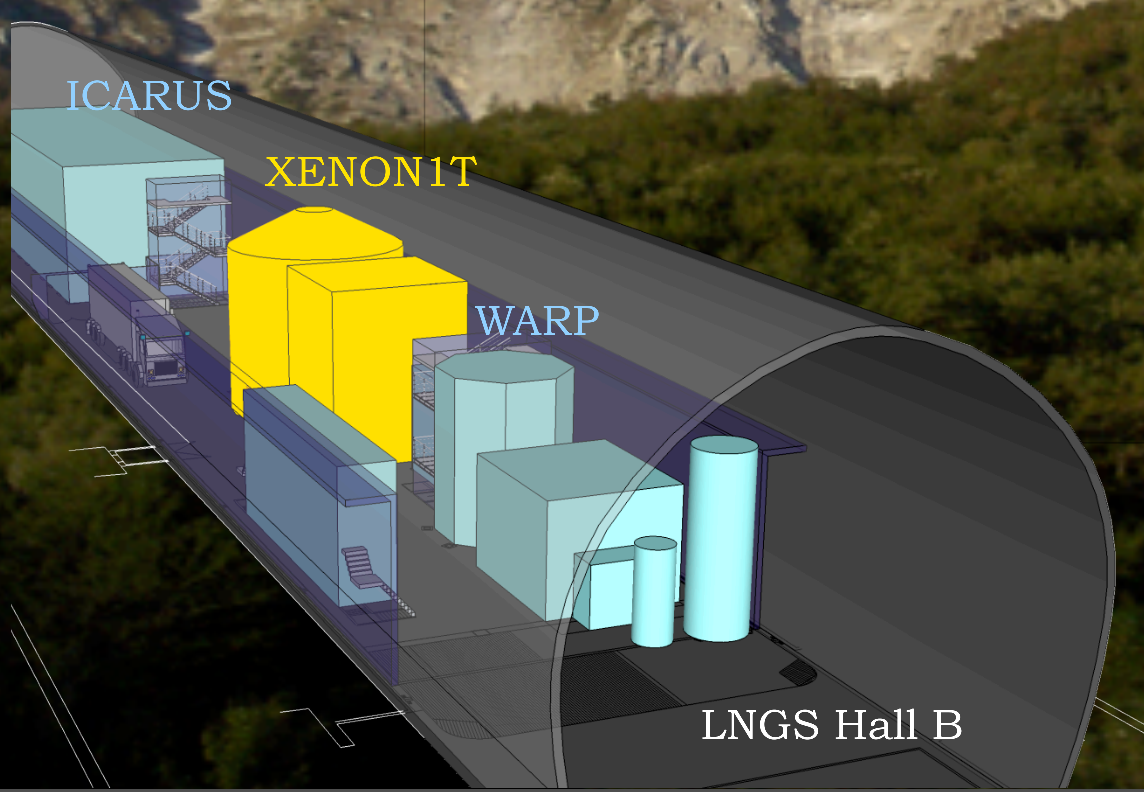
- limited choice of construction materials with the required low radioactivity level -> need large effort on materials screening and selection with multiple techniques
- drift electrons over 1 meter distance with a nominal 1kV/cm field-> need low outgassing materials & ultra pure liquid (<1ppb O_2) & extreme HV
- maximize scintillation light collection -> PMTs with highest QE but also lowest radioactivity & efficient reflectors (LXe) or reliable wavelength shifters (LAr)
- built a dedicated cryogenic facility with a 1 m TPC at Columbia (XENON1T Demonstrator) to test technologies relevant for large volume LXeTPCs:
- achieved high purity on fast time scale with continuous gas circulation through heated getter at~100 SLPM
- tested custom-made low radioactivity HV feedthrough to > 100kV
- tested performance of new R11410 PMTs in a LXeTPC, with E-field
- measured directly the charge (via S2) from events drifting 1 meter

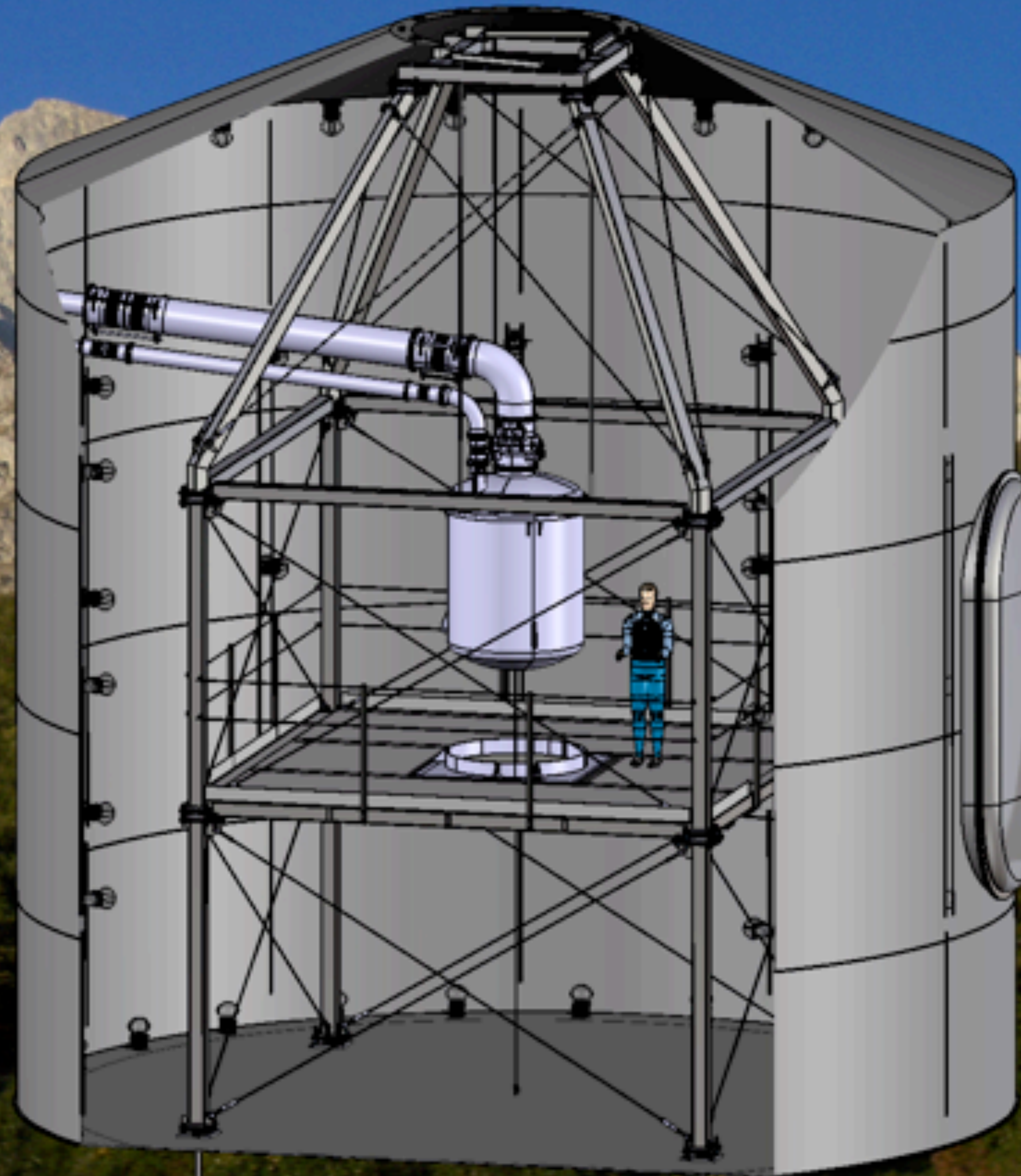


Xe
XENON
Dark Matter Project

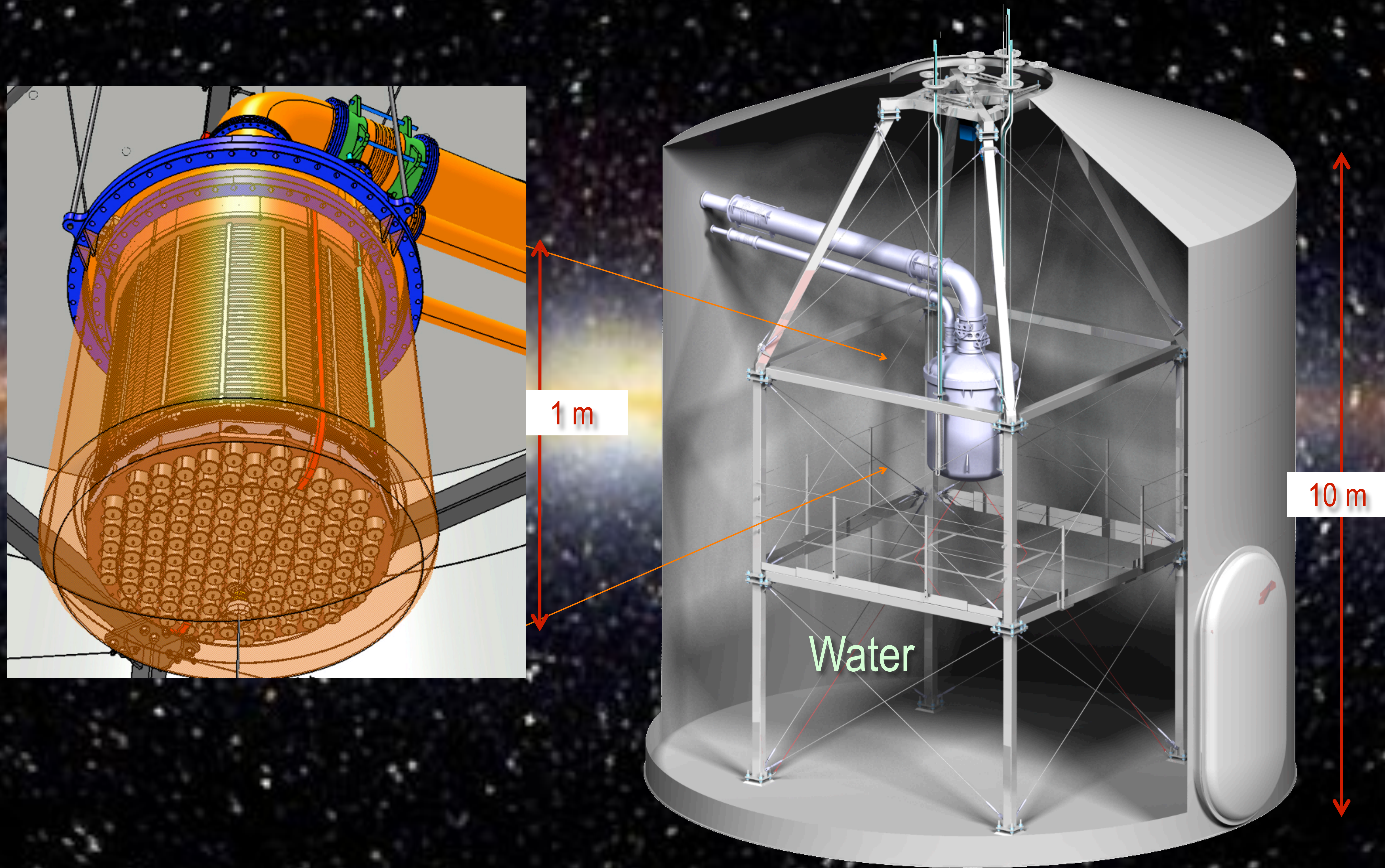
XENON1T

- 3.5 ton LXeTPC
- 1m drift gap and 1 kV/cm field
- 250 PMTs (R11410-21):>35%QE
- in water tank: 10m high, Ø 9.6m
- active Cherenkov μ-veto
- construction in HallB started
- data taking in 2015





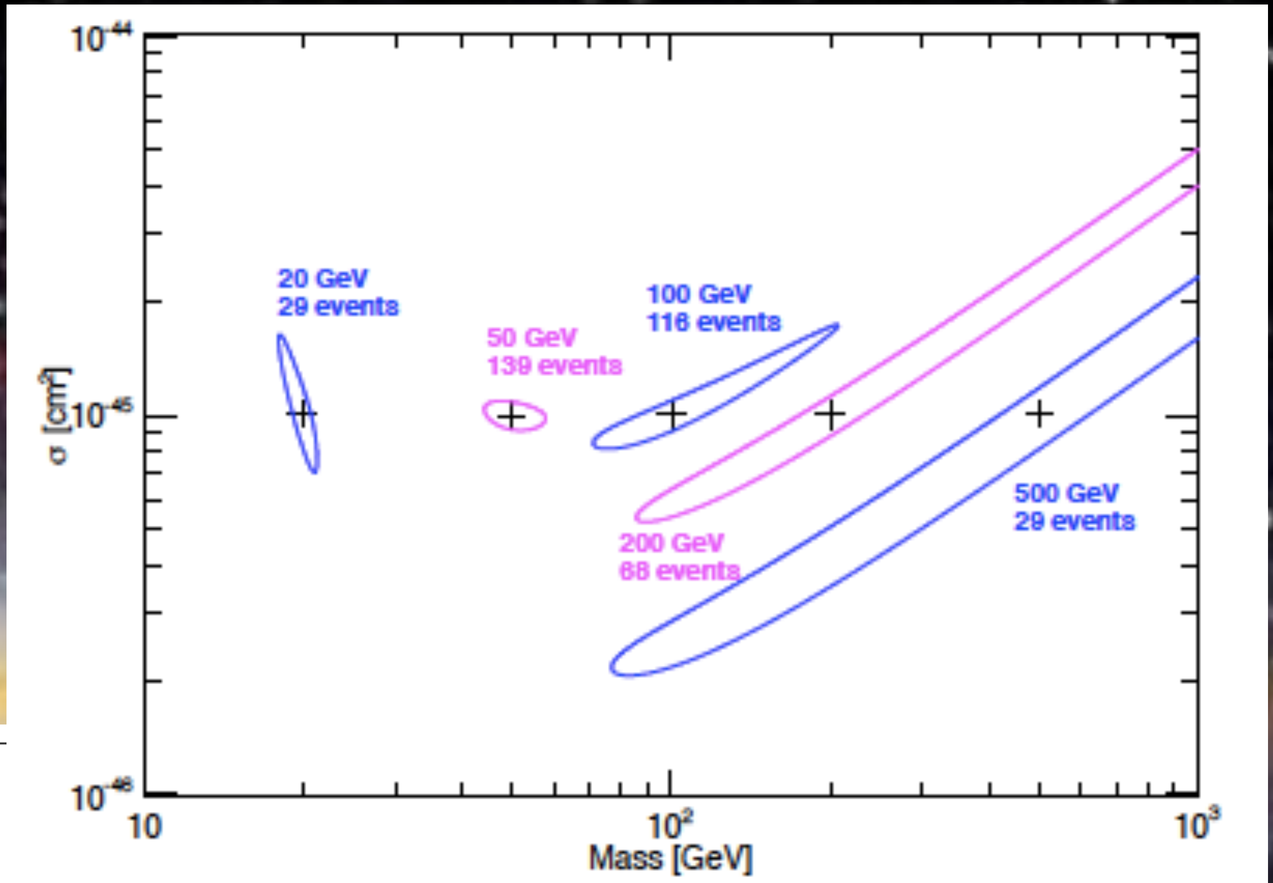
XENON1T

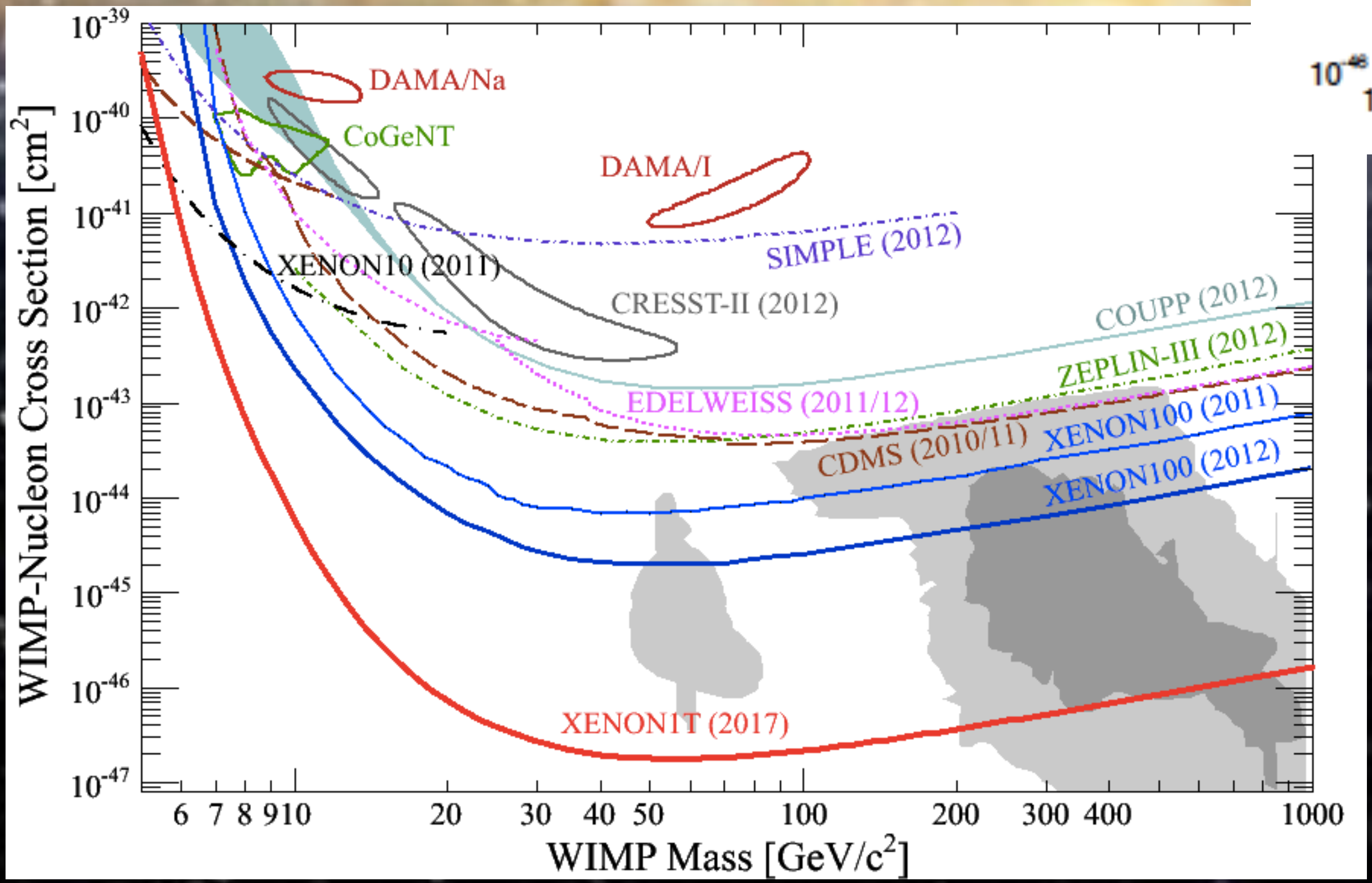


What you can expect from XENON1T

A statistically significant WIMP signal of ~100 events if cross section at 10^{-45} cm^2 after 2 ton-years of data or by 2017

THIS IS MY DREAM

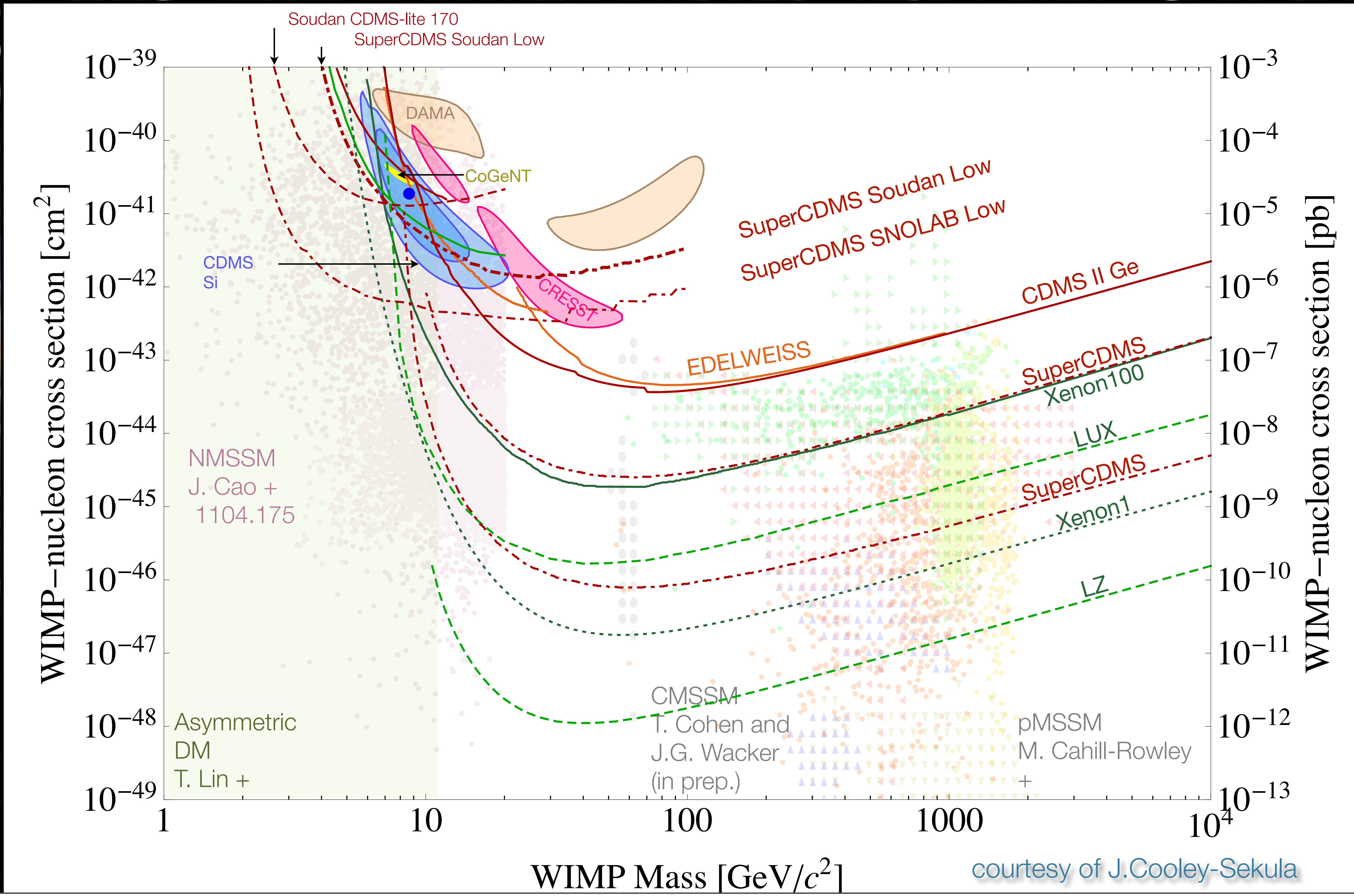




A limit on WIMP-Nucleon SI interactions at the 10^{-47} cm^2 level after 2ton-years of data

THIS IS MY NIGHTMARE

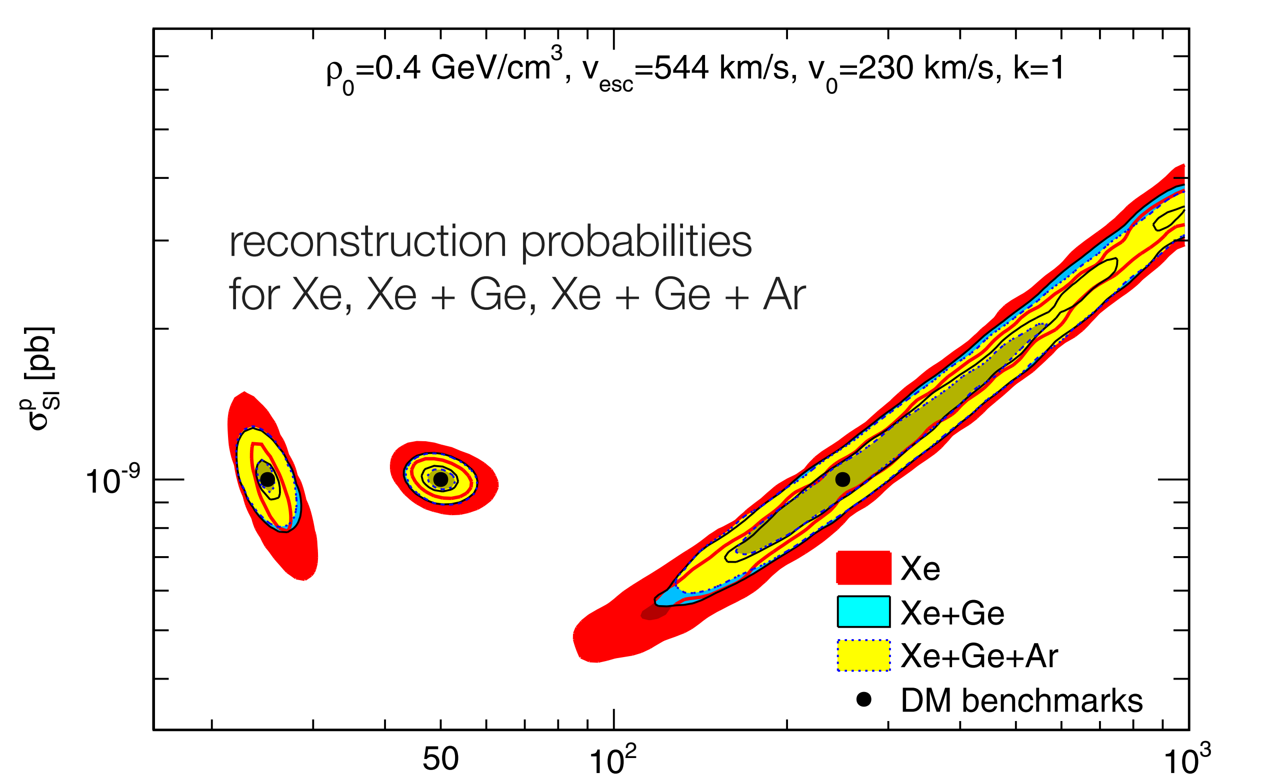
...and this is how the nightmare might unfold by the end of the decade: we reach the irreducible background from solar and atmospheric neutrinos at ~10^{-48} cm^2 ....and still no signal



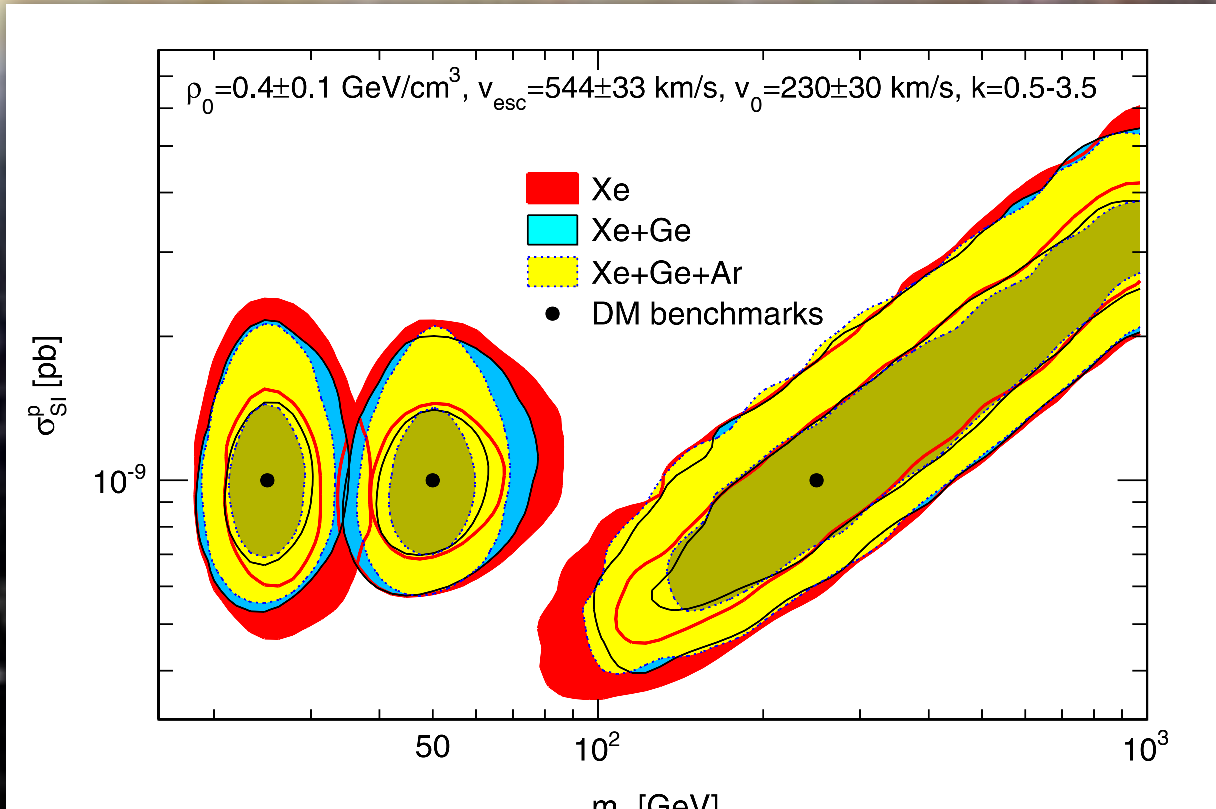
It is however better to dream and wish for multiple experiments with different targets to reconstruct the properties of the DM particle and with the input from a new particle discovery at the LHC in 2015

- 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

Phys. Rev. D 83, 083505 (2011)

Summary and Prospects

- We remain in the dark about 85% of the matter in the Universe. This is both embarassing but also an extraordinary opportunity for discovery.
- The hypothesis that the dark matter could be made of a new, heavy, neutral, stable and weakly interacting particle is well motivated by the expectation of new physics at the weak scale.
- Direct detection experiments have reached unprecedented sensitivity (cross sections down to 10^{-8} pb) and can probe WIMP with masses from a few GeV to a few TeV. A few claim a signal but there is plenty of controversy and confusion which will be resolved with more data and better control of backgrounds.
- WIMP detectors with noble liquid targets of several tons are in construction or advanced design phase, and the first data are expected by 2015. With two orders of magnitude or better sensitivity, they might be able to prove or disprove the WIMP hypothesis and provide complementary information to *indirect searches and the LHC.*
- However, as we keep searching for a WIMP signal, we should remain open for surprises!