Dark Matter and the XENON Experiment

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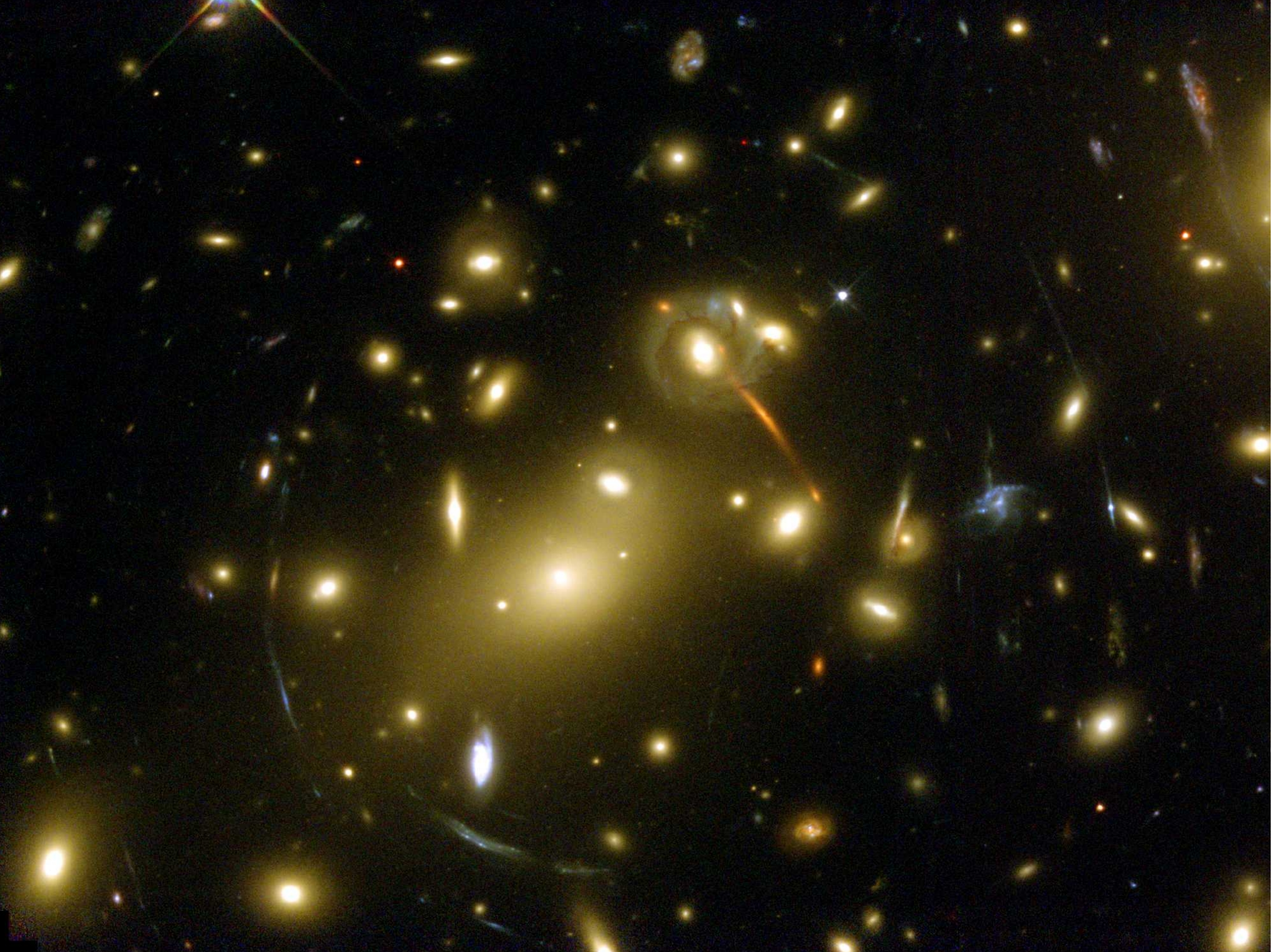
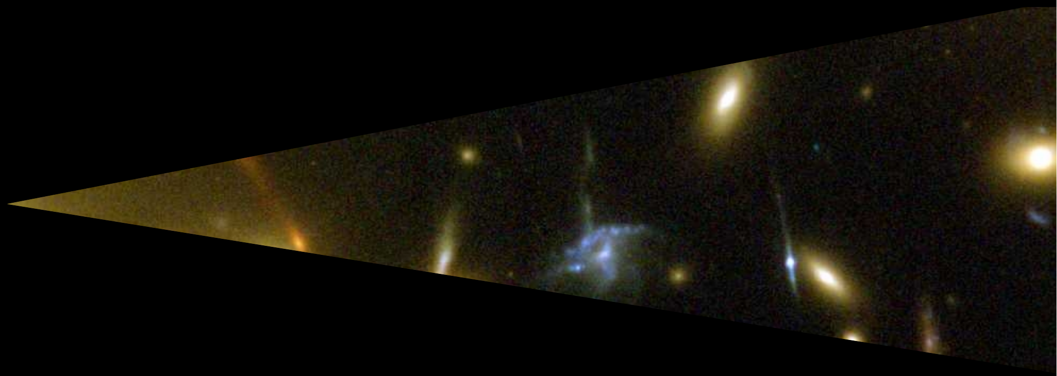
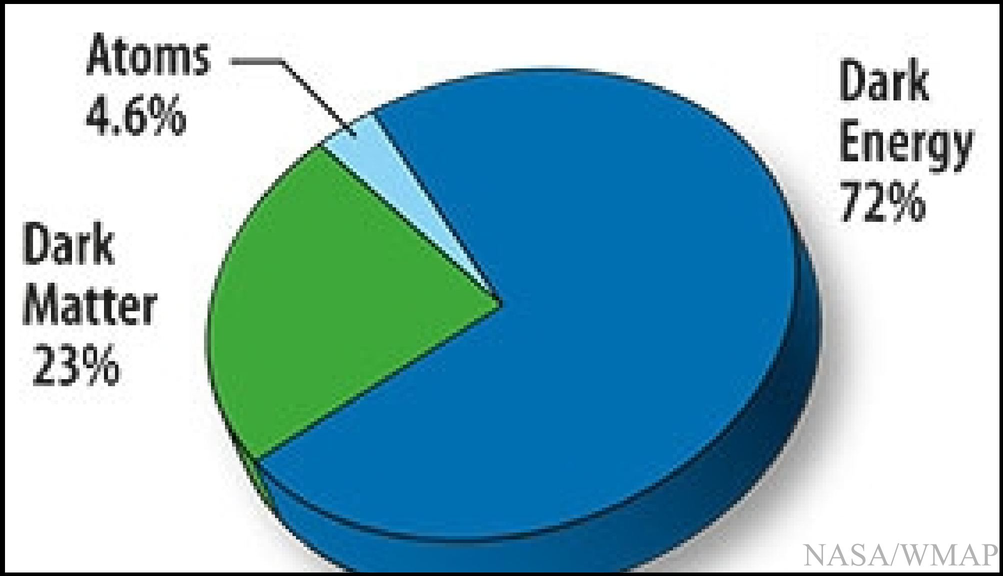
Lunch Seminar, Weizmann Institute of Science, November 4th, 2010

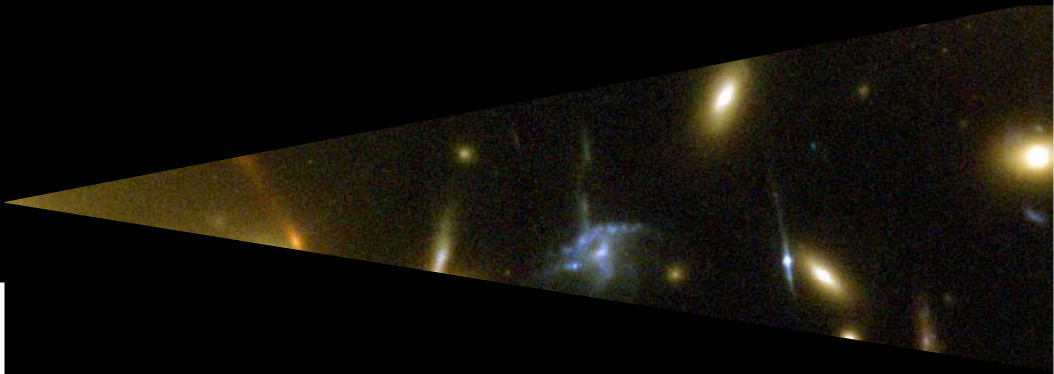
www.physik.uzh.ch/groups/groupbaudis/xenon/

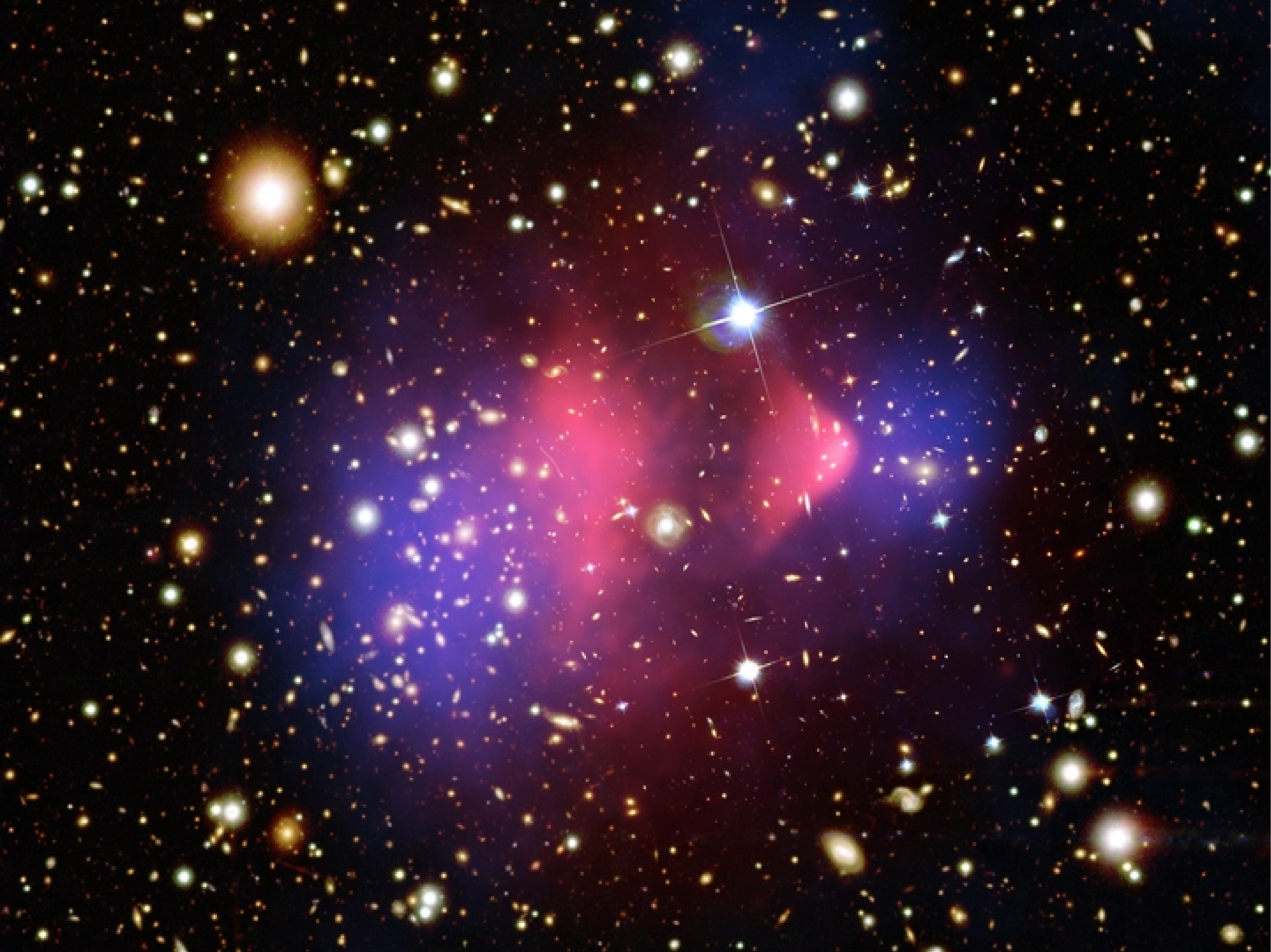




95% of the Universe is DARK



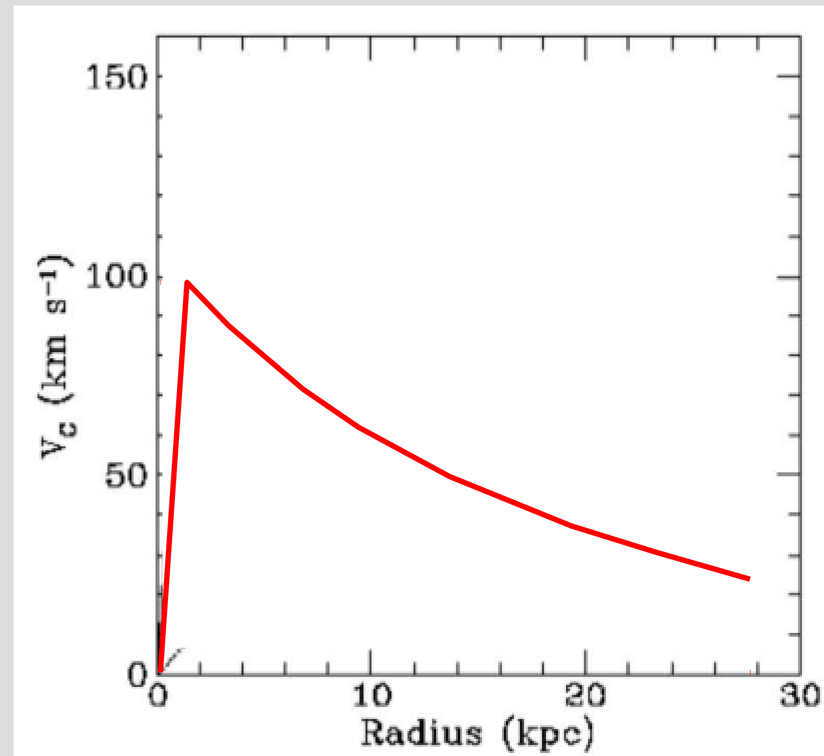




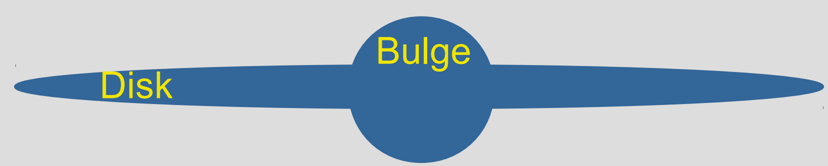

Baryonic Matter
(from X-rays)
Dark Matter
(Gravitational
Lensing)
2 colliding galaxy clusters
separation of Dark and Light (baryonic) matter
→ Dark Matter and not modified gravity

Galactic Rotation Curves

Expect: Kepler Rotation (as in the solar system)

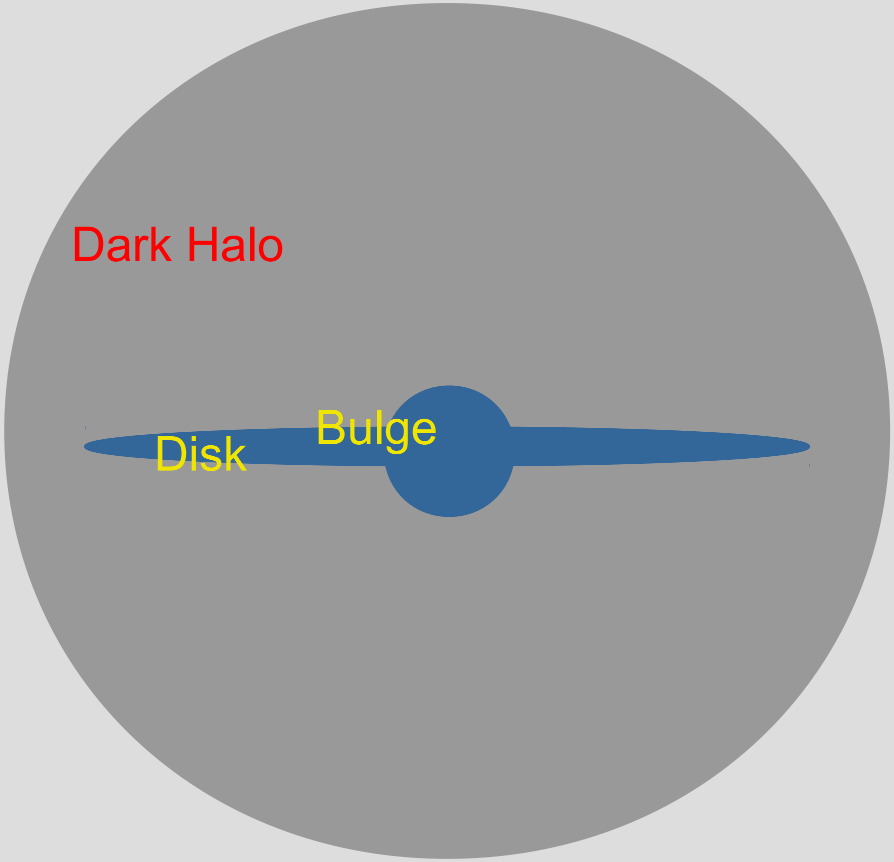


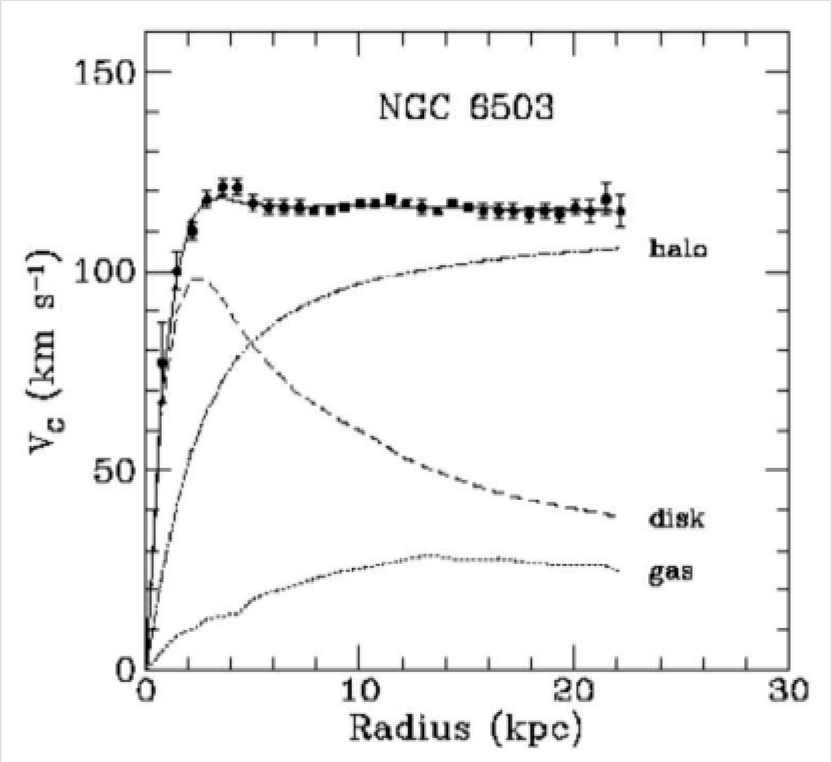
$$v^2 = \frac{G\ M(r)}{r}$$



Galactic Rotation Curves

Measurement: Flat Rotation Profile

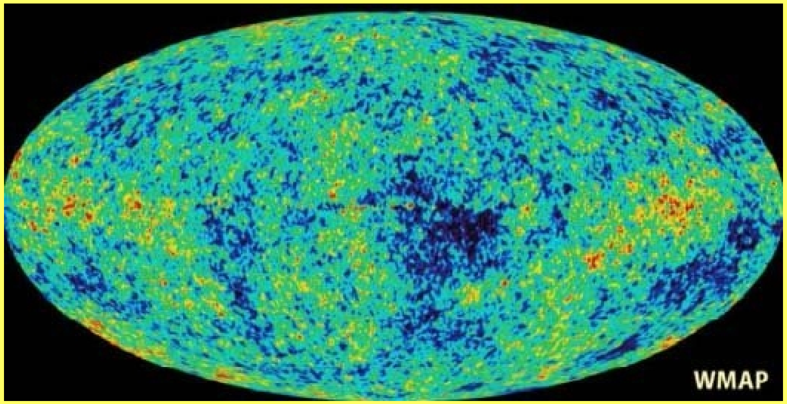




„ball of ideal gas at uniform temperature“

V. Rubin, K. Ford (1970)

Cosmic Microwave Background

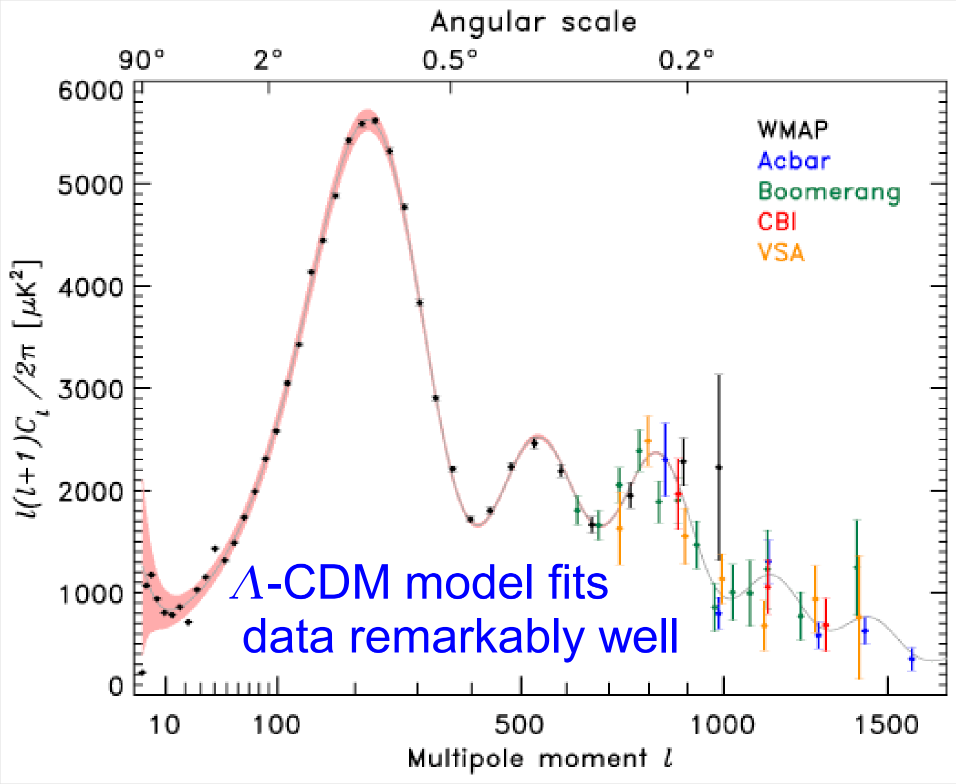


generated when radiation and matter decouple and photons can propagate freely

get information about structures in early universe

→ **Cold Dark Matter:**
Invisible
Cold ($v < 10^{-8}\ c$)
Collisionless
Stable
from „new physics“

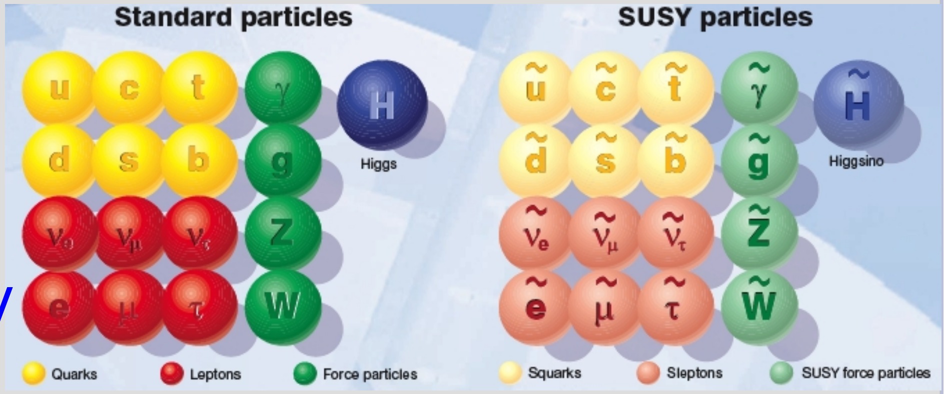
power spectrum of ΔT
„typical variation at typical distance“



$\Omega = \rho/\rho_{crit} = 1.02(2)$
$H = 71(4)$ km/s/Mpc
$t_0 = 13.7(2)$ Gyr
$\Omega_\Lambda = 0.73(4)$
$\Omega_B = 0.044(4)$
$\Omega_m = 0.27(4)$

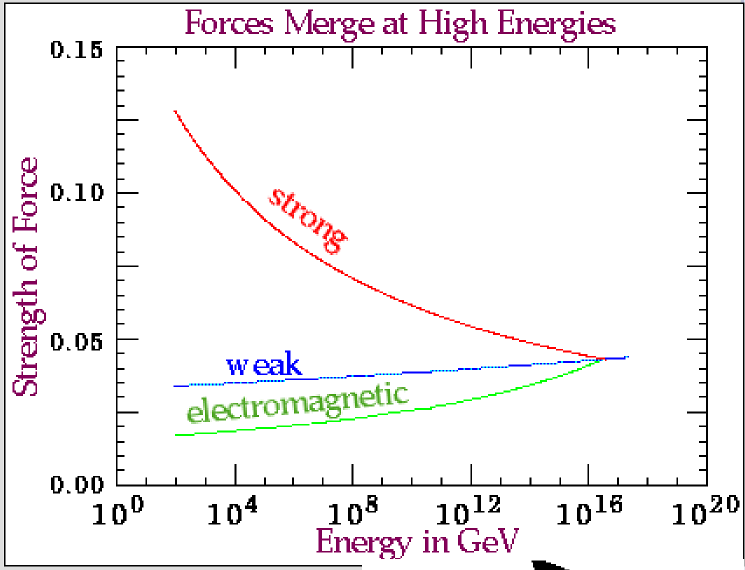
SUSY and the WIMP

SUSY was introduced to solve
Standard Model problems
(i.e. hierarchy problem, Higgs mass)



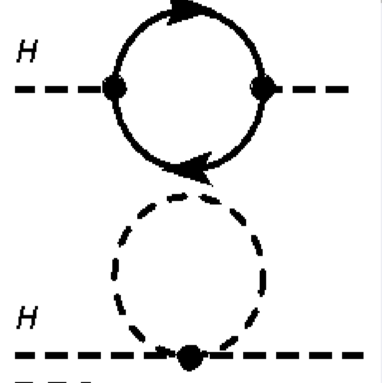
New fundamental space-time symmetry
between fermions and bosons

R-parity avoids B/L number violation:



$$R = (-1)^{(3B+L+2S)}$$

→ lightest supersymmetric particle (LSP)
is stable → cold DM candidate:
WIMP = weakly interacting massive particle



Neutralino: $\tilde{\chi}_1^0 = N_{11}\tilde{B}^0 + N_{12}\tilde{W}_3^0 + N_{13}\tilde{H}_d^0 + N_{14}\tilde{H}_u^0$

SUSY WIMP production

In early Universe:

WIMPs in thermal equilibrium
creation ↔ annihilation

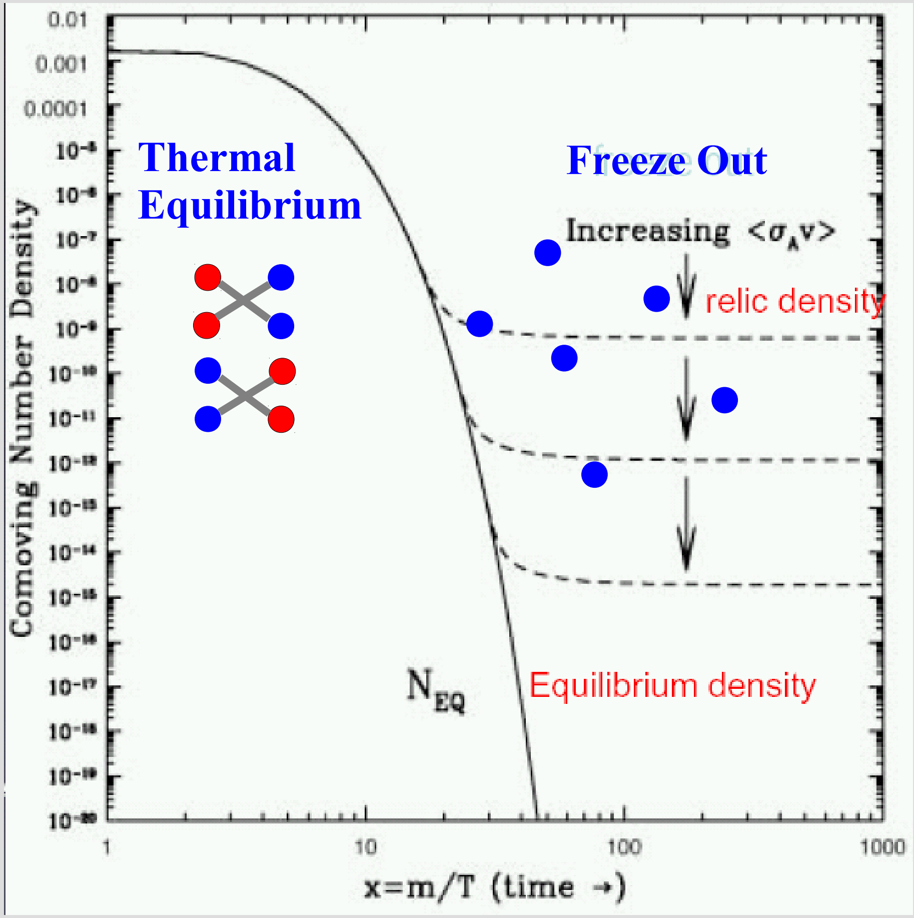
$$p(E) \propto \exp\left(-\frac{E}{k_B T}\right)$$

expanding Universe: „freeze out“

WIMPs fall out of equilibrium, cannot annihilate anymore

$$k_B T \sim \frac{m_\chi c^2}{20}$$

→ non relativistic when decoupling from thermal plasma
→ constant DM relic density
→ relic density depends on σ_A



WIMP relic density:

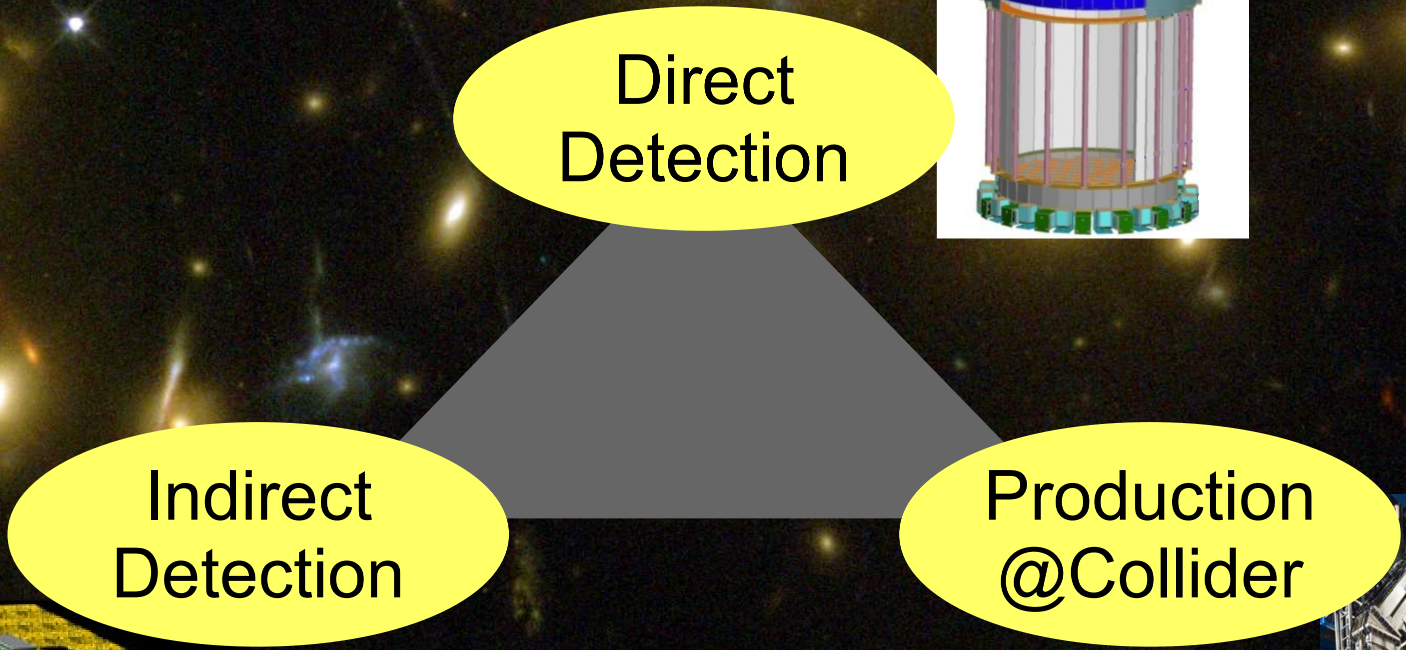
$$\Omega_\chi h^2 \approx \text{const.} \frac{T_0^3}{M_{Pl}^3 \langle\sigma_A v\rangle} \approx \frac{0.1\text{pb}}{\langle\sigma_A \, v/c\rangle}$$

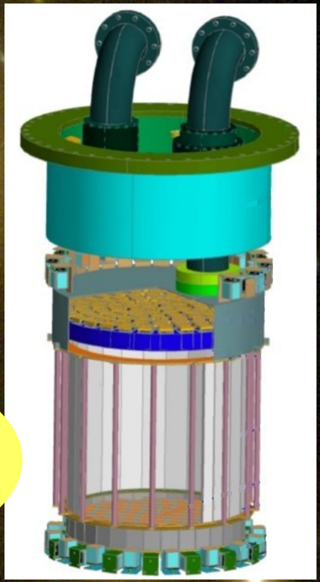
O(1) when $\sigma_A \sim 10^{-9}$ GeV → weak scale

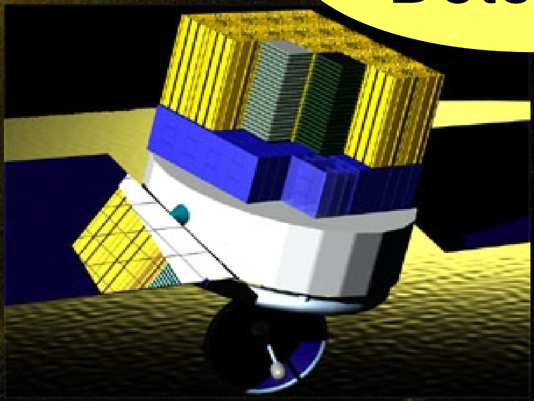
Outline

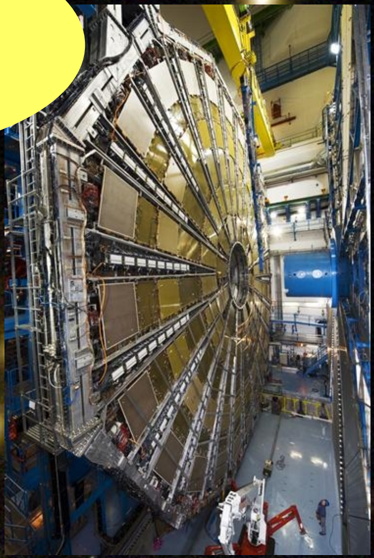
- Motivation: Dark Matter ✓
- Direct Dark Matter Detection
- Xenon as a Detector Medium
- XENON100
- The Future

Dark Matter Search

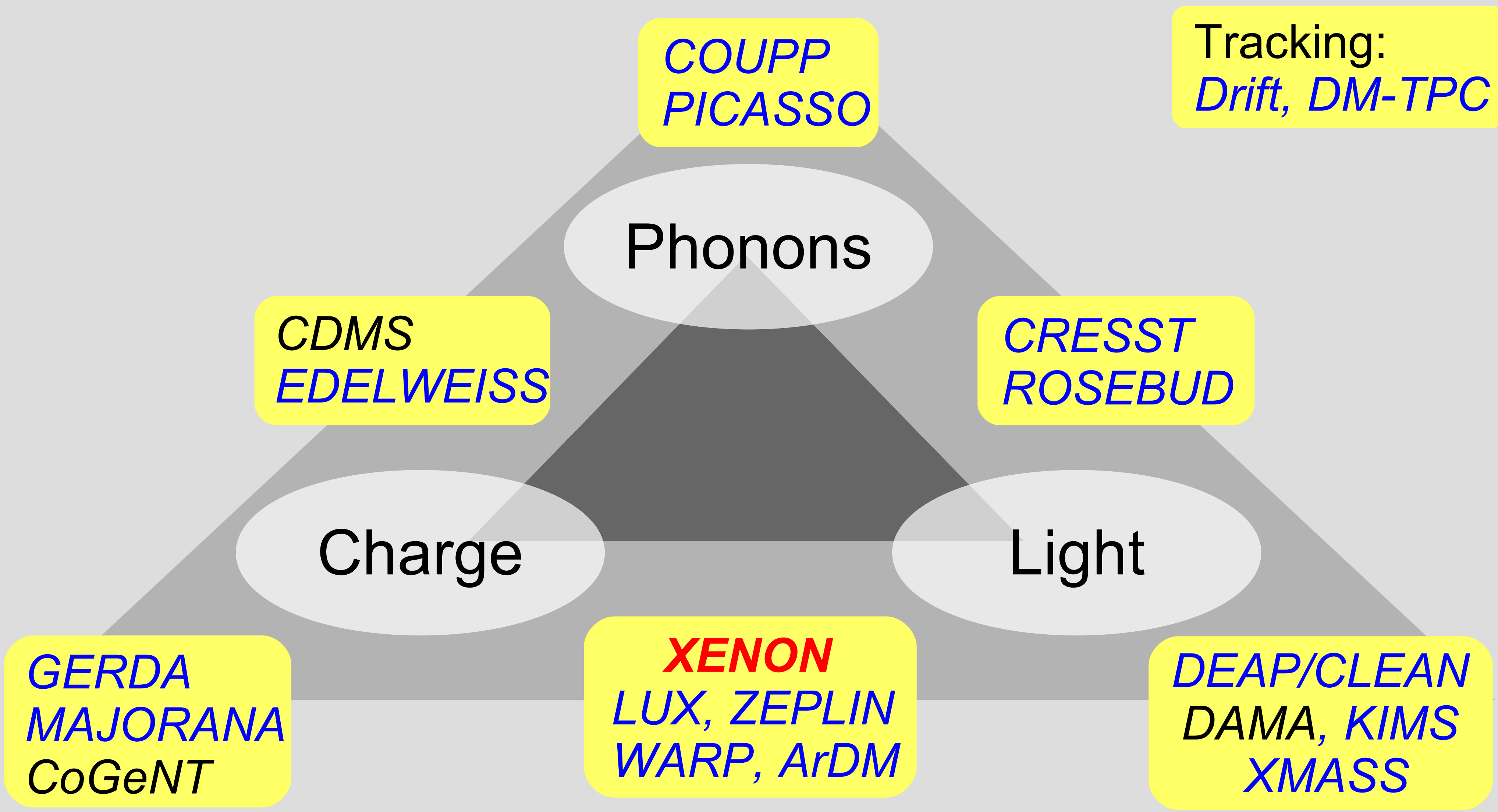






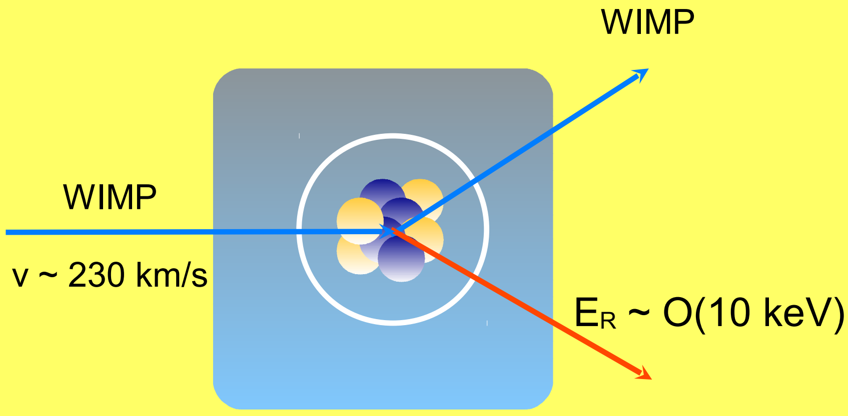


Direct WIMP Detection



Direct WIMP Search

Elastic Scattering of WIMPs off target nuclei
→ nuclear recoil



Recoil Energy: $$E_r = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta) \sim \mathcal{O}(10\ \mathrm{keV})$$

Event Rate: $$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi-N} \rangle$$

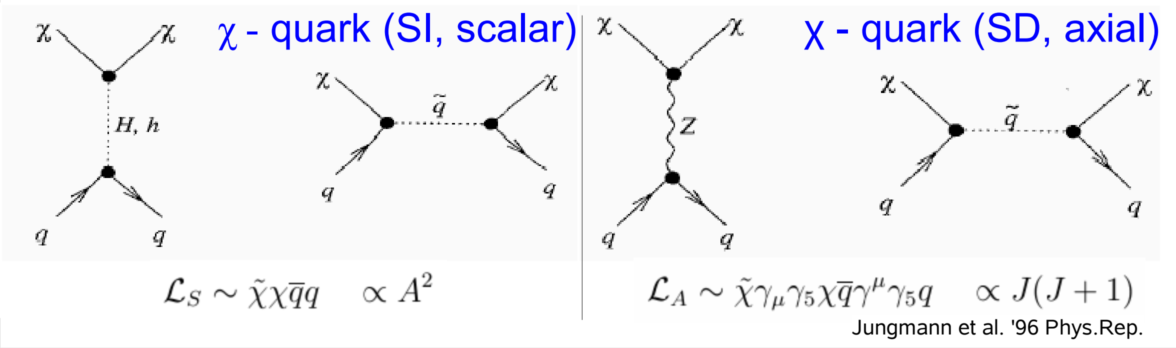
N	number of target nuclei
ρ_χ/m_χ	local WIMP density
$<\sigma>$	velocity-averaged scatt. X-section

→ need information on halo and interaction to get rate

WIMP Interactions
Detector Requirements

Result: Tiny Rates

$R < 0.01$ evt/kg/day
$E_r < 100$ keV

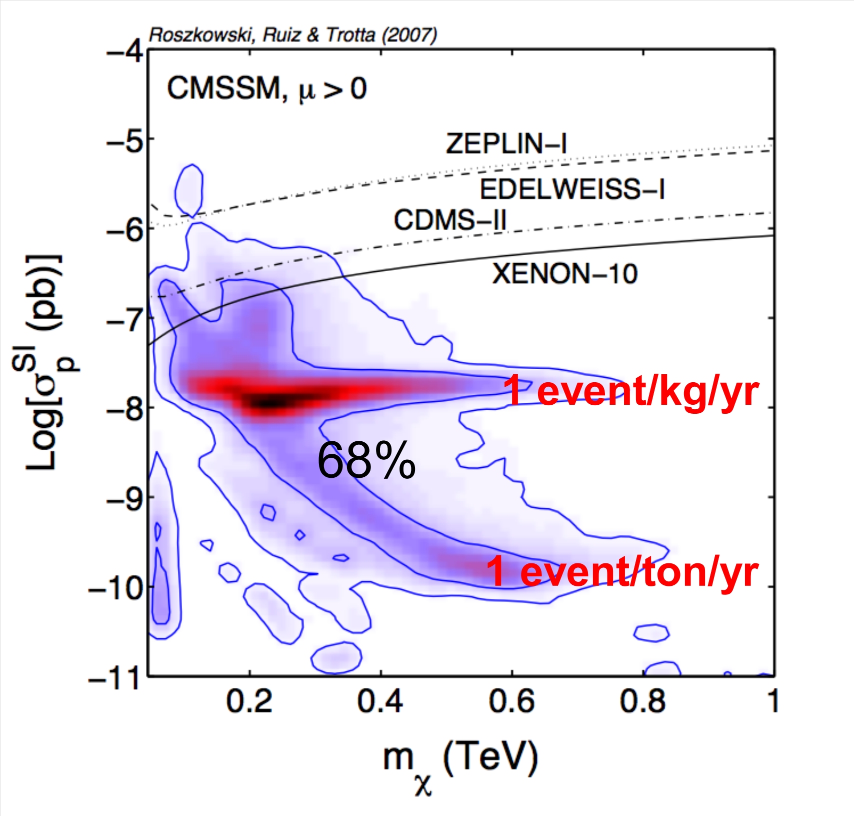


What do we look for?

- nuclear recoils, single scatters
- recoil spectrum falls with *E*
- dependence on *A*, spin?
- annual flux modulation?
- other possibilities? iDM, ...?

How to build a WIMP detector?

- large total mass, high *A*
- low energy threshold
- ultra low background
- good background discrimination



Backgrounds

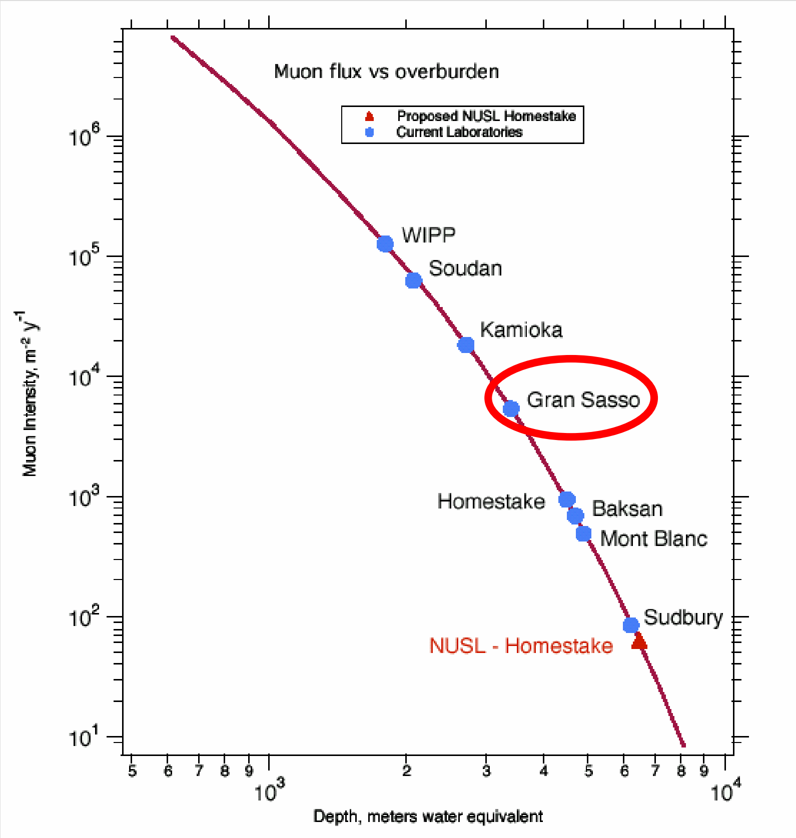
Experimental Sensitivity:
without background: $\propto (mt)^{-1}$
with background: $\propto (mt)^{-1/2}$

Background Sources:
environment: U, Th chains, K

$^{238}U \xrightarrow{\alpha} {}^{234}Th \xrightarrow{\beta} {}^{234m}Pa \xrightarrow{\beta} {}^{234}U \xrightarrow{\alpha} {}^{230}Th \xrightarrow{\alpha} {}^{226}Ra \xrightarrow{\alpha} {}^{222}Rn \xrightarrow{\alpha} {}^{218}Po \ldots$

$^{232}Th \xrightarrow{\alpha} {}^{228}Ra \xrightarrow{\beta} {}^{228m}Ac \xrightarrow{\beta} {}^{228}Th \xrightarrow{\alpha} {}^{224}Ra \xrightarrow{\alpha} {}^{220}Rn \xrightarrow{\alpha} {}^{216}Po \ldots$

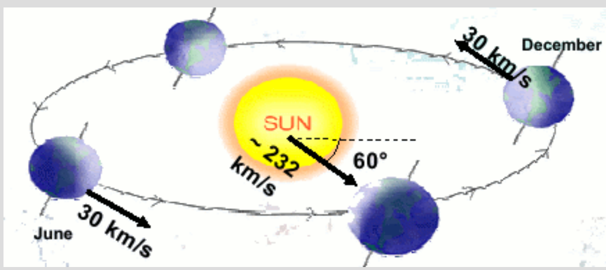
- γ and β Decays (electron recoil)
  careful material selection, discrimination, shielding (Pb, Cu, Xe, Ar, water)
- Neutrons from (α,n) in rocks
  neutron moderators (paraffin, poly, water)
- Neutrons from cosmic ray muons
  → go deep underground



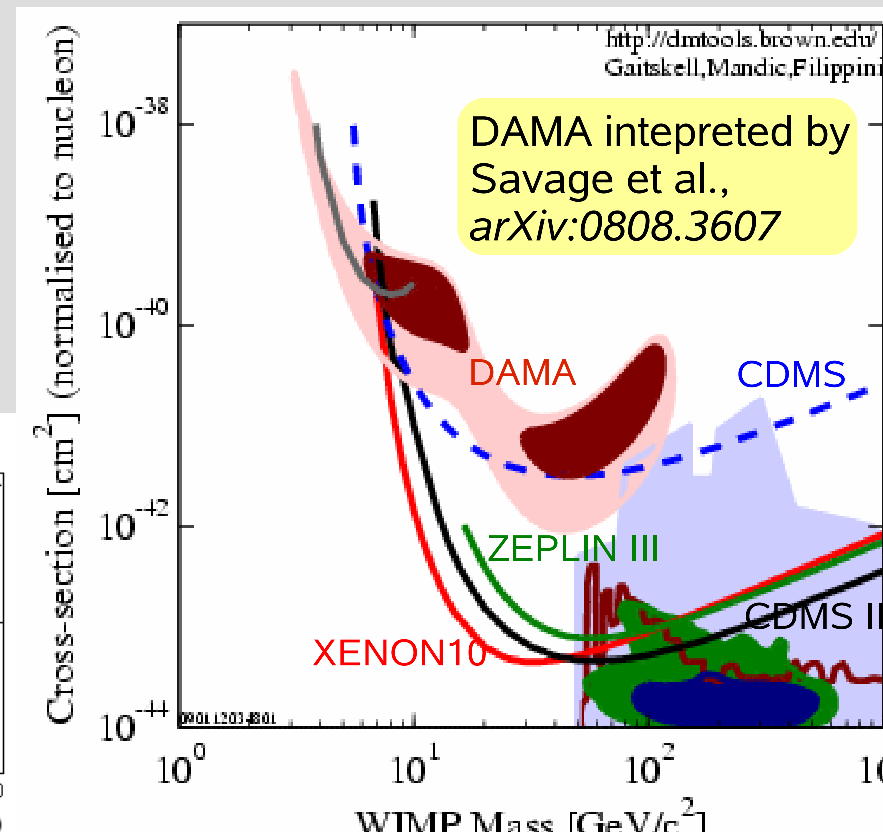
Neutrons are most dangerous background since they interact like WIMPS! (nuclear recoil)

The DAMA Observation

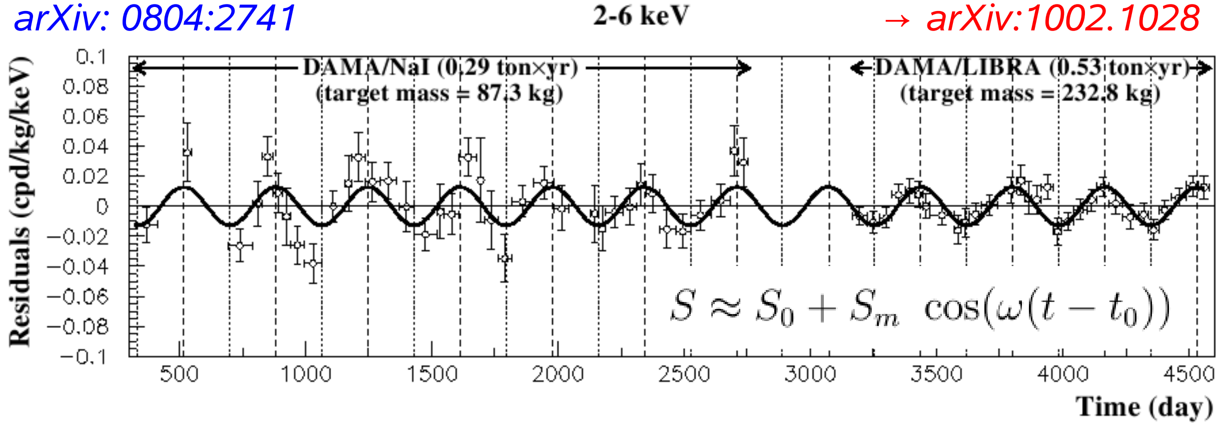
- DAMA: PMTs coupled to NaI Scintillators
  → extremely clean background necessary
- looks for annual modulation @ LNGS
- large mass and exposure: 0.82 ton years



- DAMA finds annual modulation @ 8.9σ C.L.
- BUT: result cannot be explained with standard neutralinos or KK Dark Matter, result in conflict with other experiments



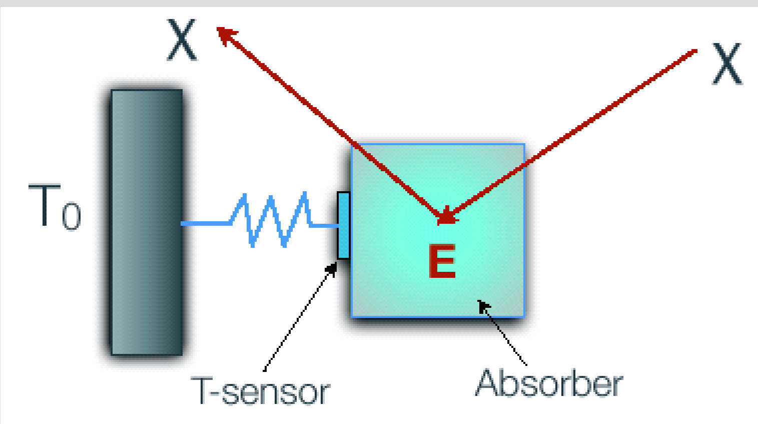
arXiv: 0804:2741 → *arXiv:1002.1028*

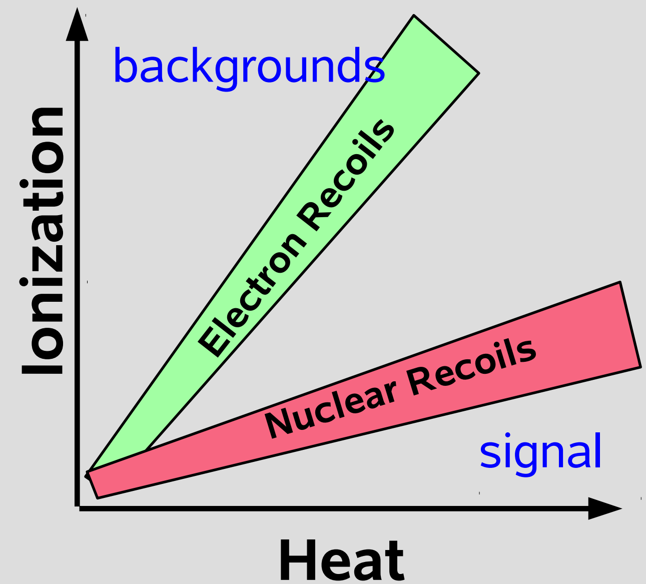


CDMS: Cryogenic Detectors

Located underground in Soudan Lab, Minnesota (USA)

Principle: measure charge and heat (phonons)
a deposited energy *E* produces temperature rise *ΔT*





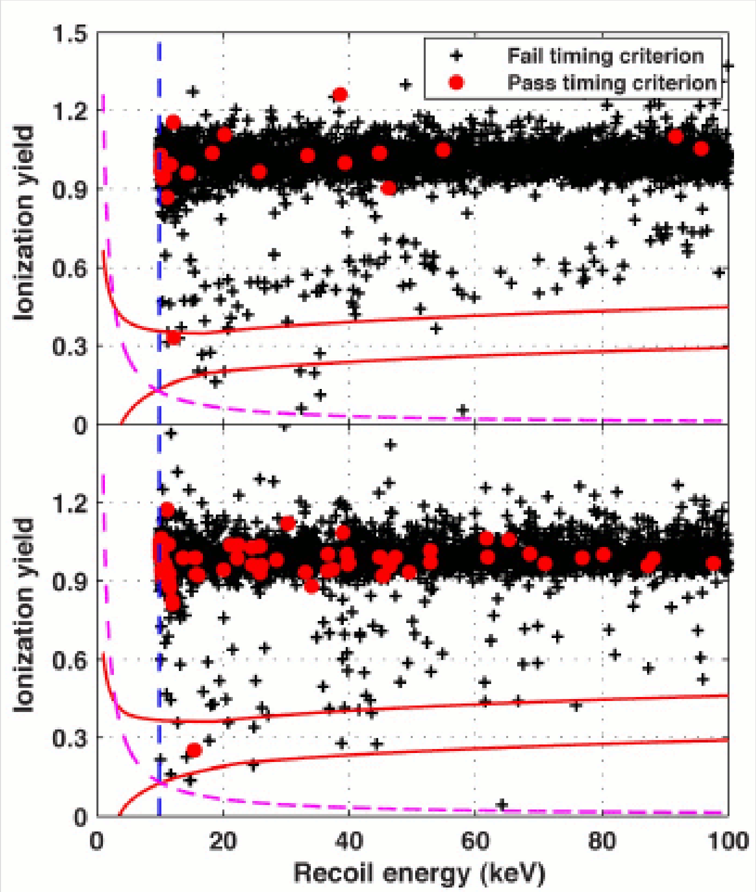
Crystals: Ge, Si cooled to few mK
➡ low heat capacity
➡ measurable µK temperature!

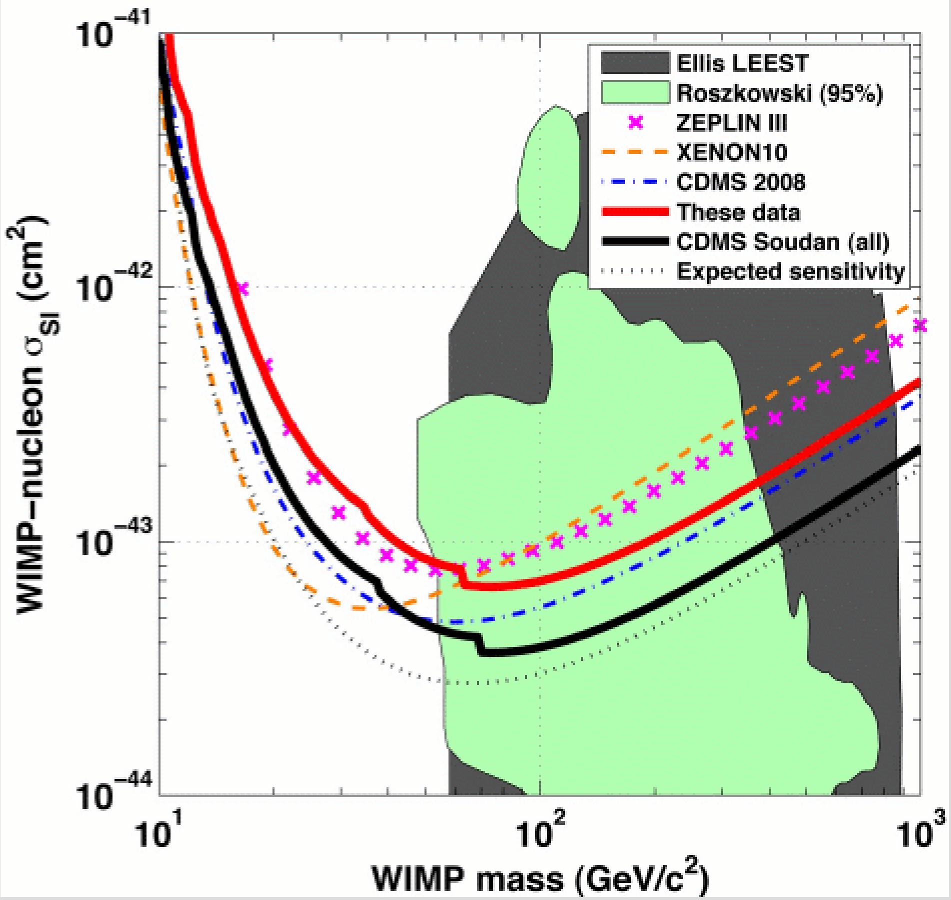
good discrimination
→ „backgound-free experiment“
→ BUT: reject surface events via PSA

similar: CRESST, EDELWEISS, Rosebud

The latest CDMS Result

Science 327, 1619 (2010)



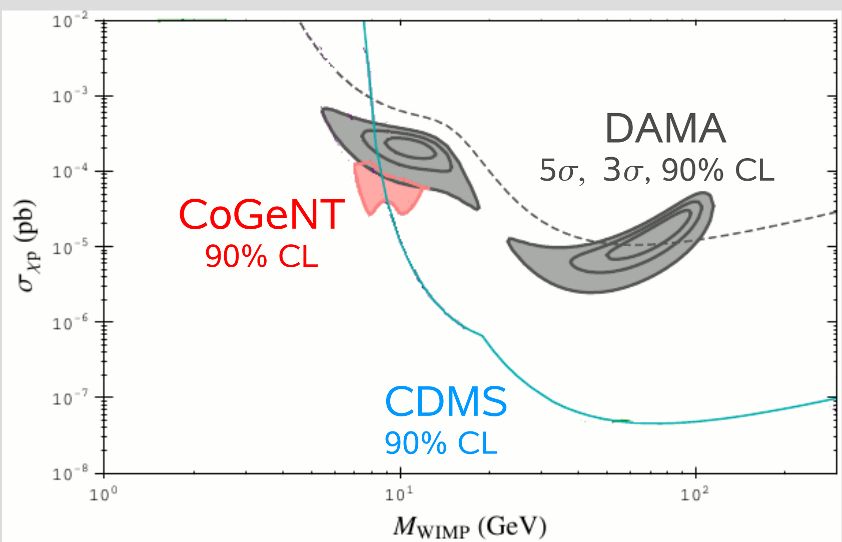


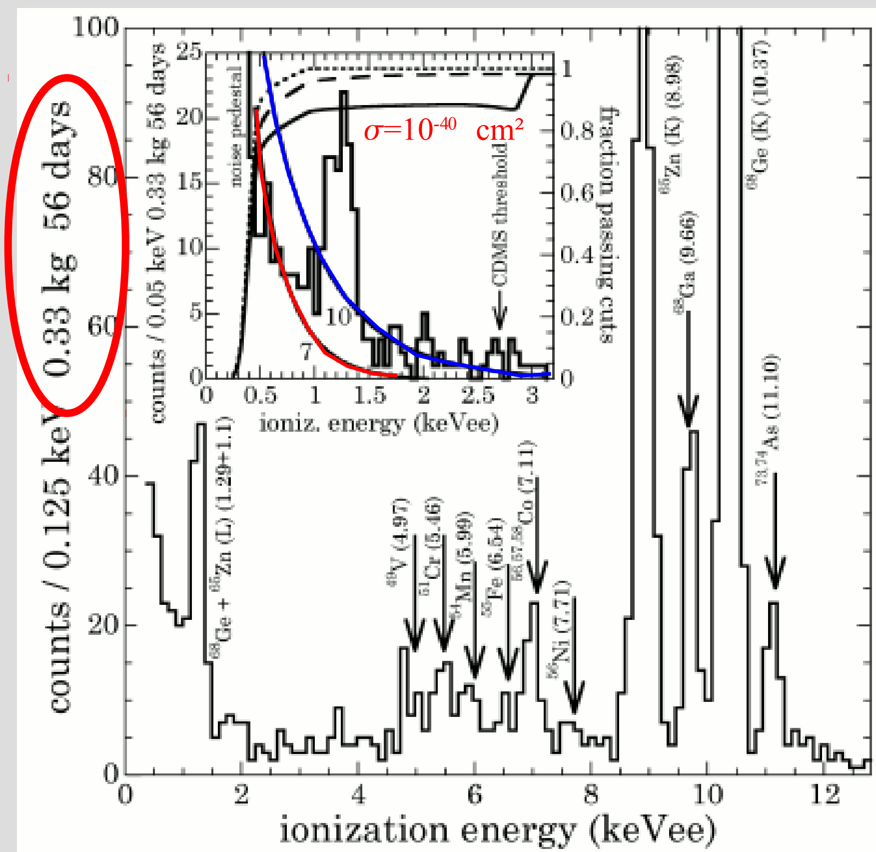
- 2 events remain after all cuts after un-blinding
- Background expection: 0.9 $\pm$ 0.2 events
- probability for 2 or more events: 23%

CoGeNT

arXiv:1002.4703

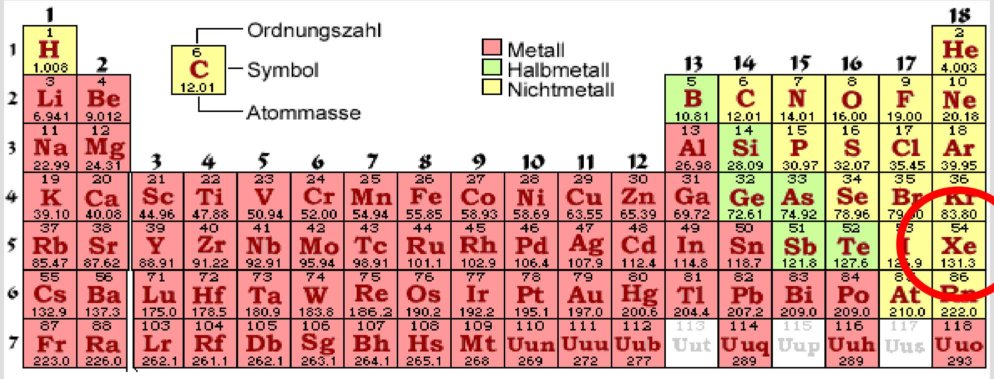
- CoGeNT: p-type point contact Ge-detector, ultra low noise
- prototype for MAJORANA, operated underground at Soudan
- very low threshold: 0.4 keVee (electronic noise)
- only one observable (charge), some pulse shape discrimination
- Excess at lowest energies
  → light mass WIMP claim
  (BUT: null hypothesis has similar χ^2)

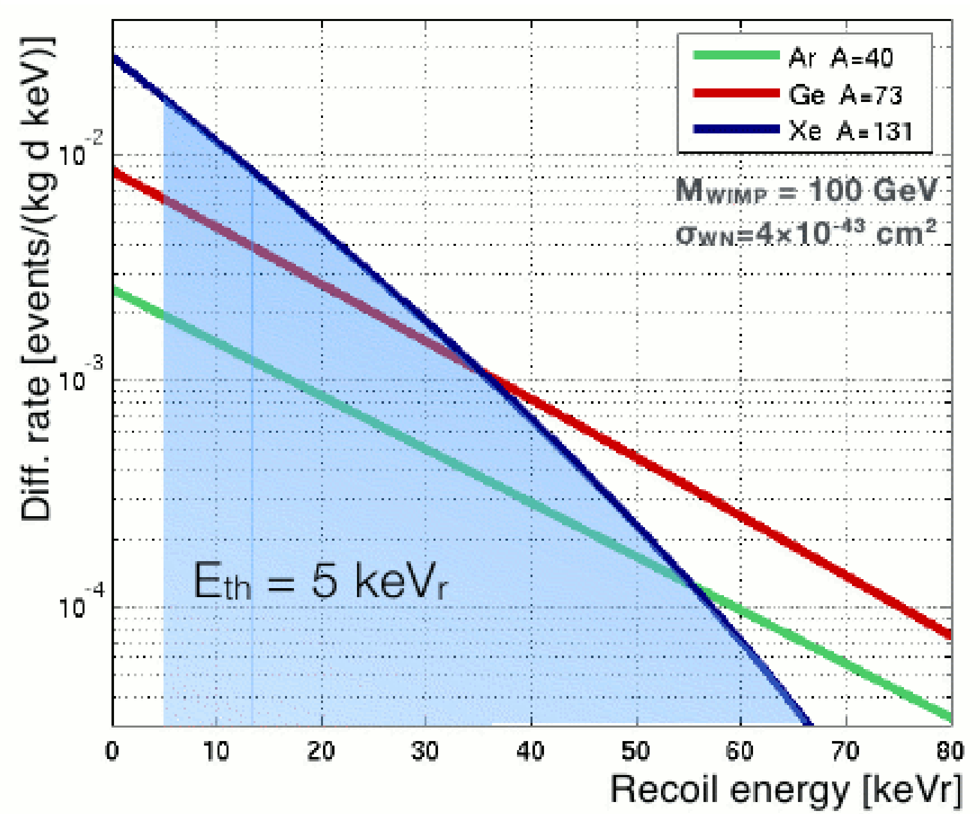




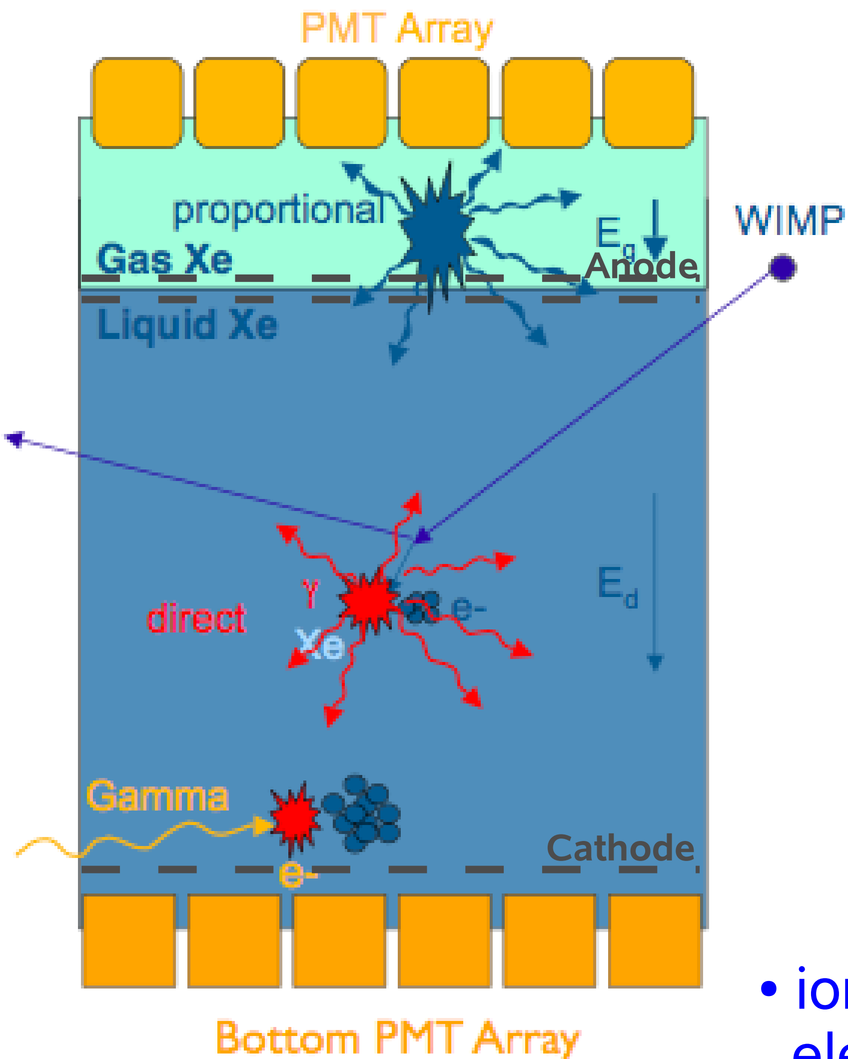
Why Xenon?

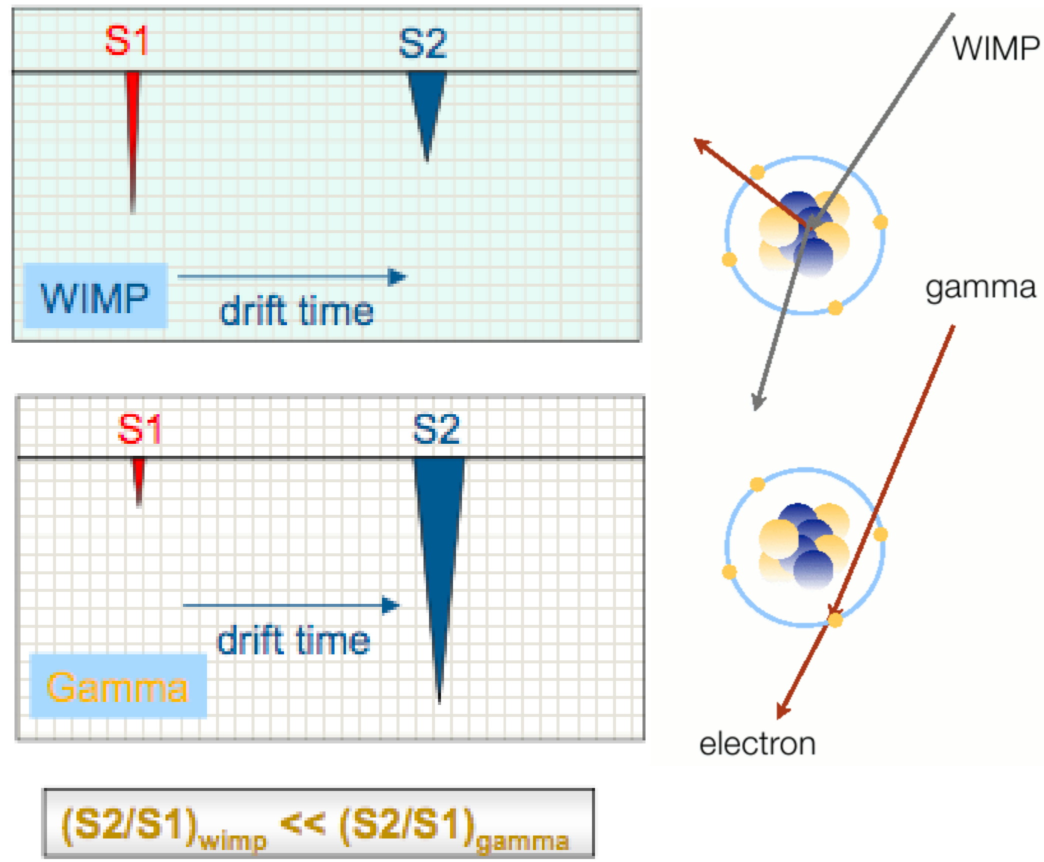
- efficient, fast scintillator (178nm)
- high mass number *A*~131:
  SI: high WIMP rate @ low theshold
- high atomic number *Z*=54,
  high density (~3kg/l):
  self shielding, compact detector
- SD: 50% odd isotopes
  allows further characterization after detection by testing only SI or SD
- no long lived Xe isotopes,
  Kr-85 can be removed to ppt
- "easy" cryogenics @ -100°C
- scalability to larger detectors
- in 2-phase TPC:
  good background discrimination





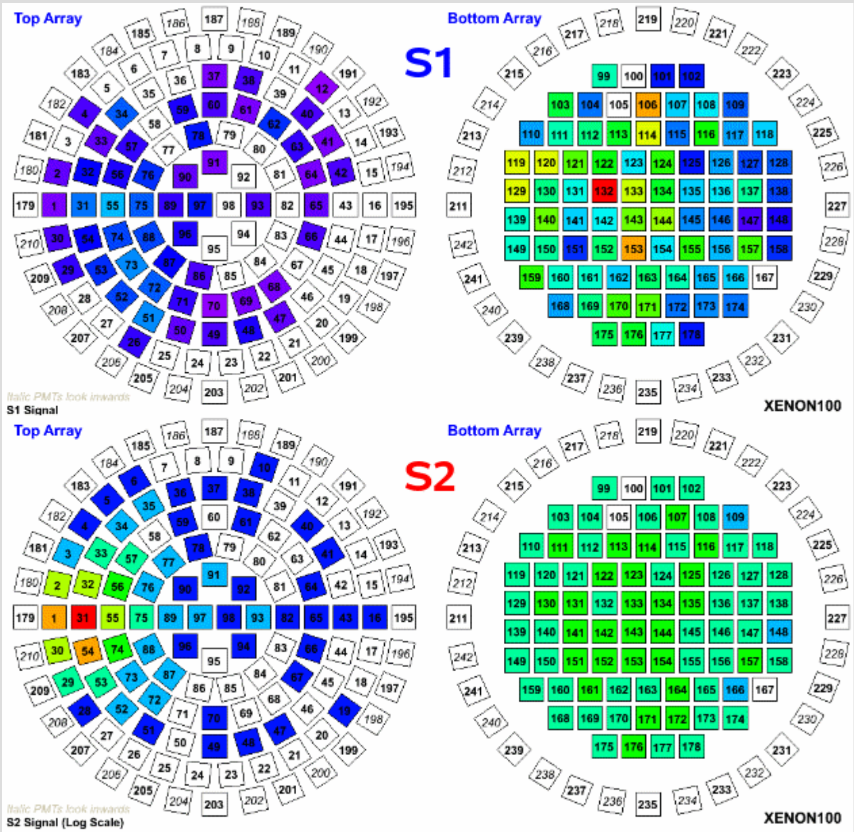
Dual Phase TPC

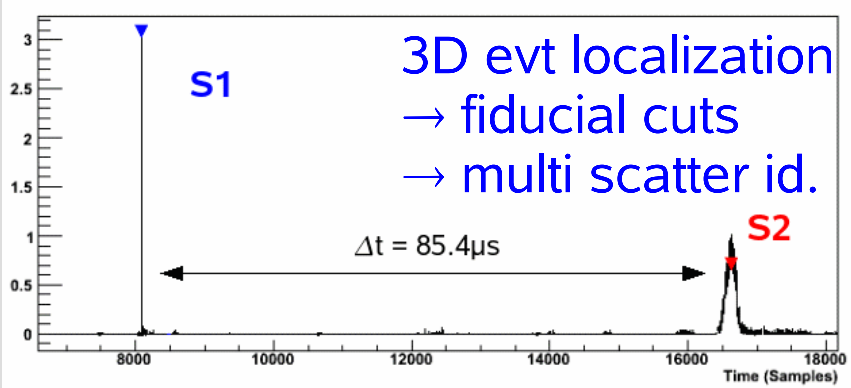




- ionization/scintillation ratio (S2/S1) allows electron recoil rejection to >99.5%
- 3d position reconstruction in TPC

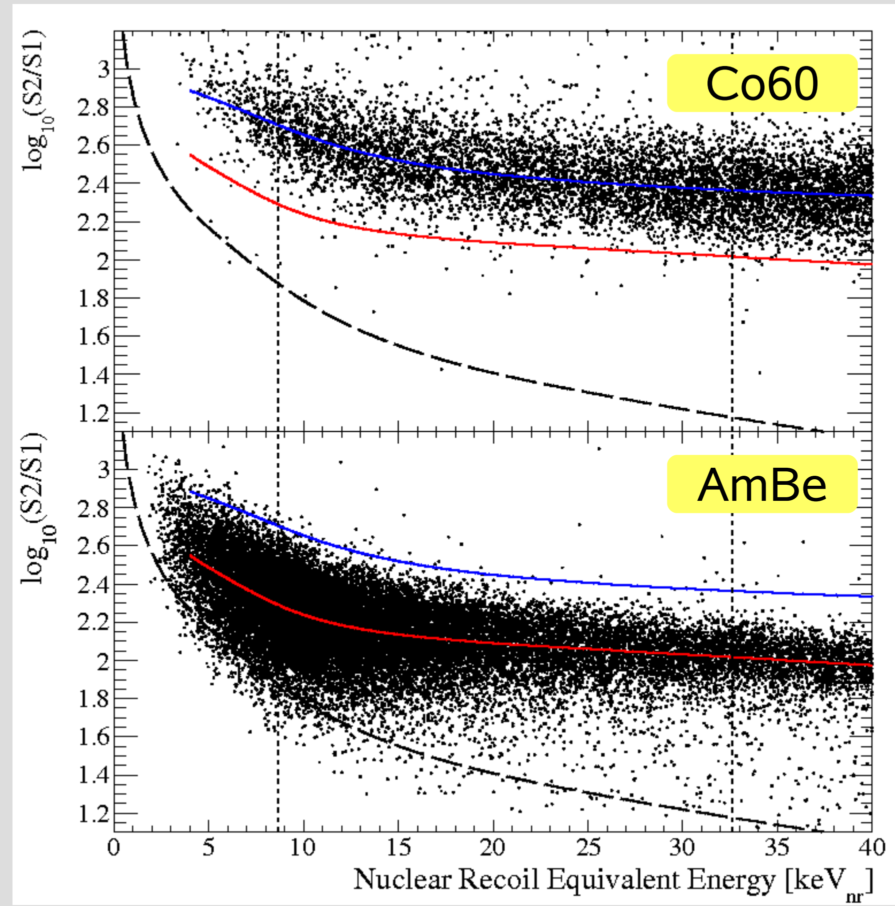
Localization / Discrimination





3D evt localization
→ fiducial cuts
→ multi scatter id.

Discrimination:



~99.5% bg rejection
@ 50% acceptance *(Xe10 performance)*
definition of *WIMP search region*

Outline

Motivation: Dark Matter ✓

Direct Dark Matter Detection ✓

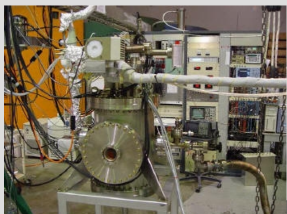
Xenon as a Detector Medium ✓

XENON100

The Future

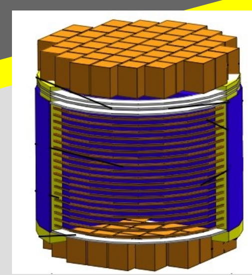
The XENON program

XENON: A phased WIMP search program

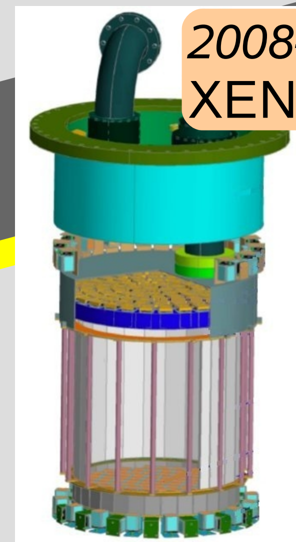


XENON R&D

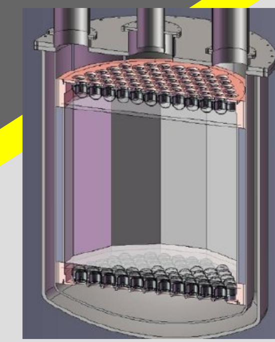
2005-2007: XENON10



2008-2011: XENON100



2010-2015: XENON1T



Columbia *Rice* *UCLA* *U Zürich* *Coimbra* *LNGS* *SJTU*

Bologna *MPIK* *NIKHEF* *Mainz* *Subatech* *Münster* *WIS*

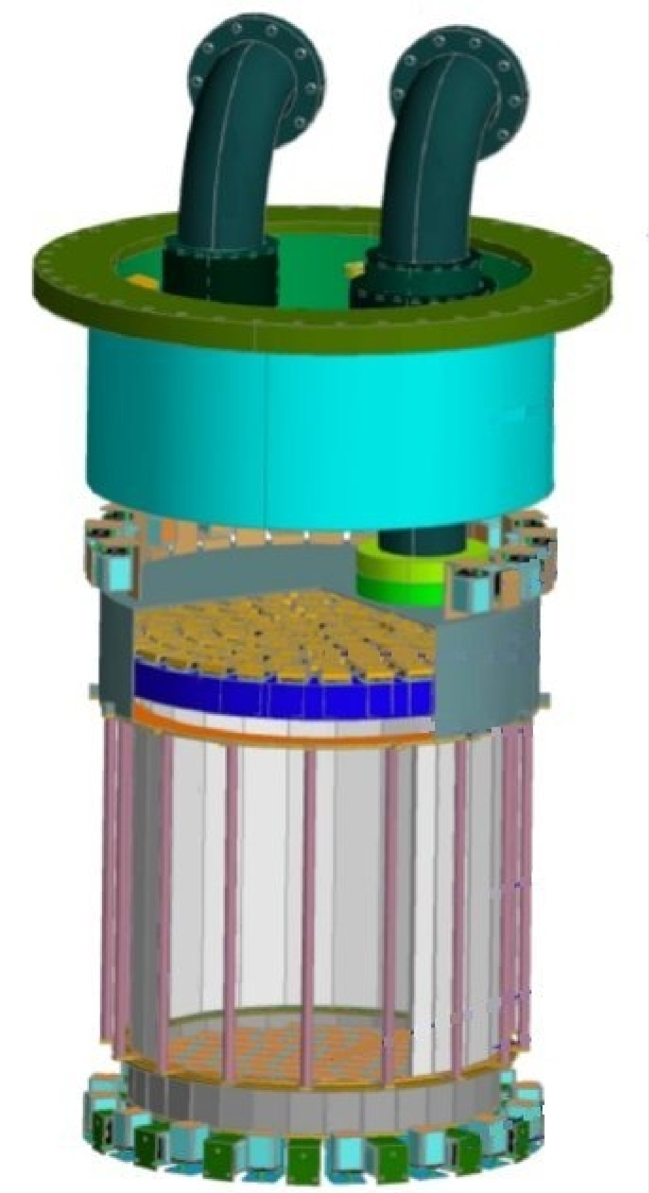
XENON100 Collaboration

XENON100

Goal (compared to XENON10)**:**
- increase target ×10
- reduce gamma background ×100

→ material selection & screening
→ detector design

Quick Facts:
- 161 kg LXe TPC (mass: 10 × Xe10)
- 62 kg in target volume
- active LXe veto (≥4 cm)
- 242 PMTs
- improved Xe10 shield
  (Pb, Poly, Cu, H_2O, N_2 purge)



XENON100

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→ detector design

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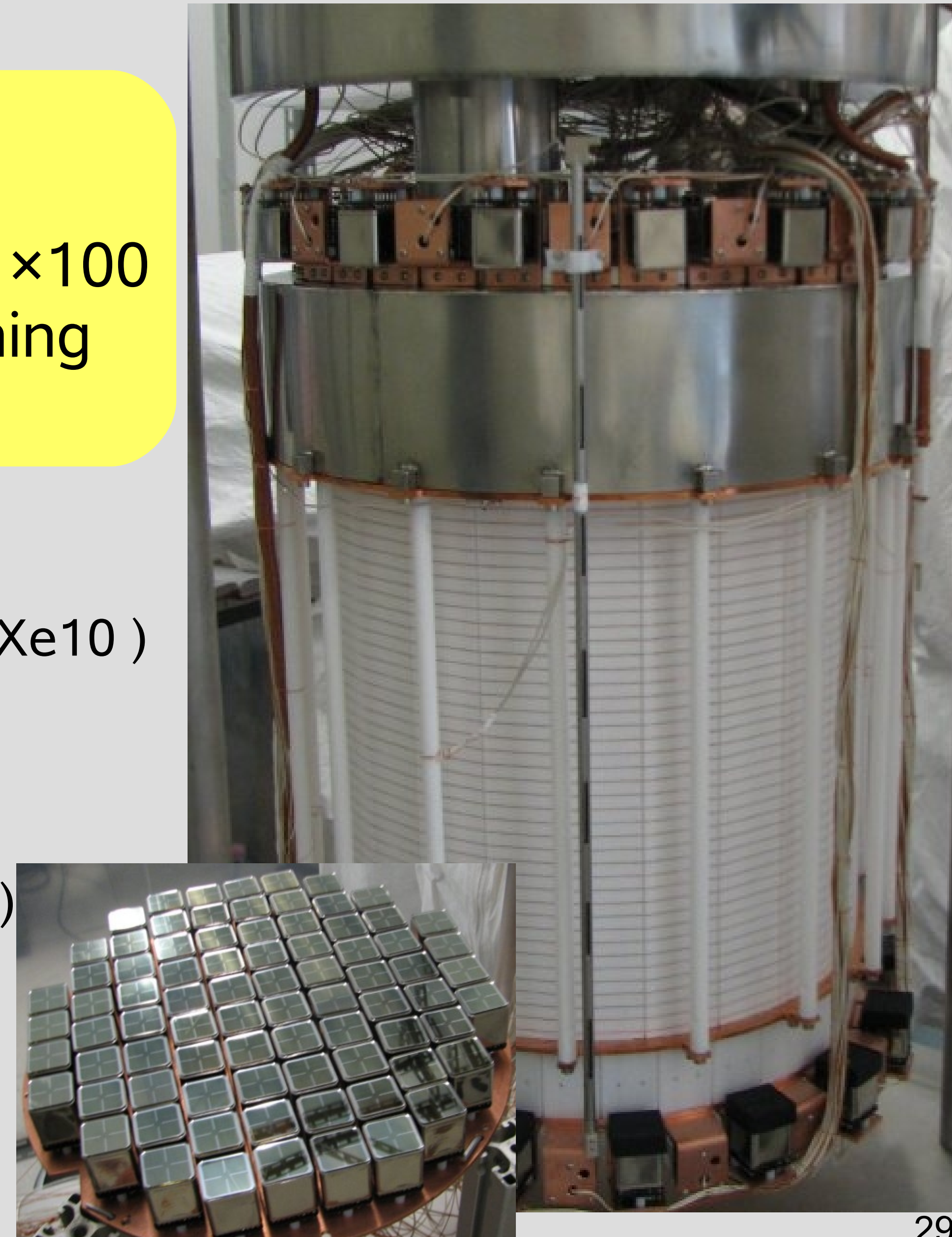
- 242 PMTs (Hamamatsu R8520)
- improved Xe10 shield (Pb, Poly, Cu, H_2O, N_2 purge)



XENON100

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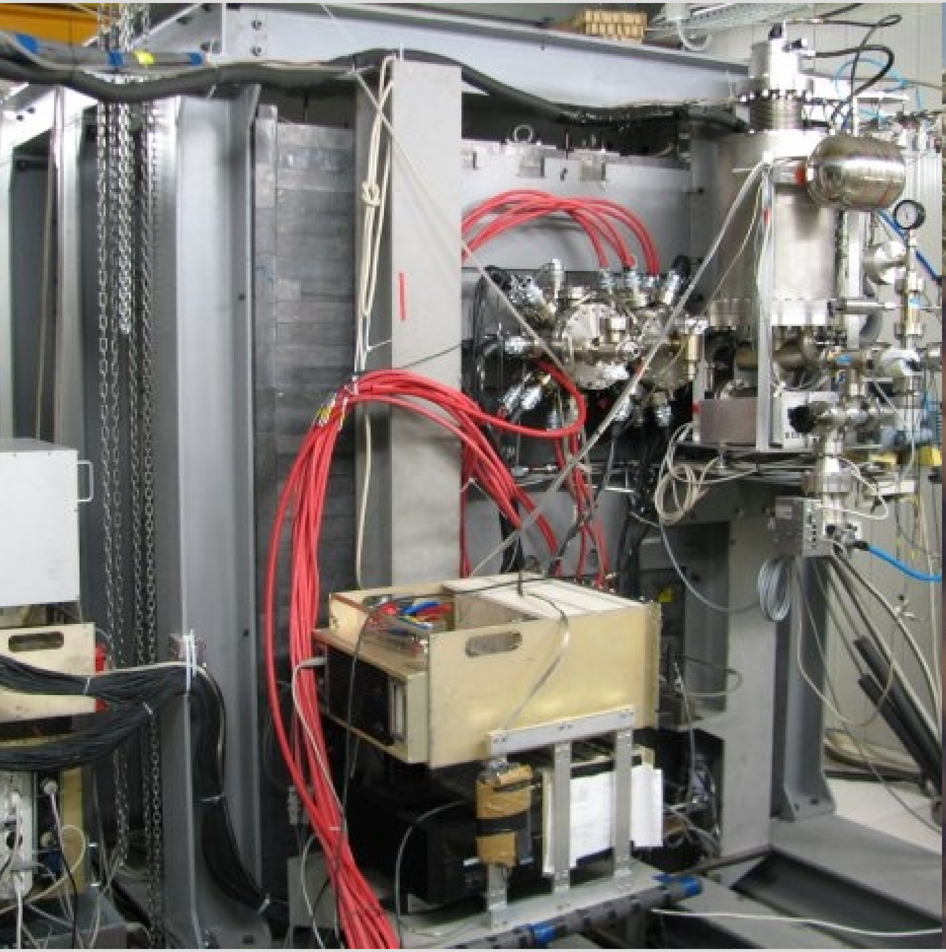
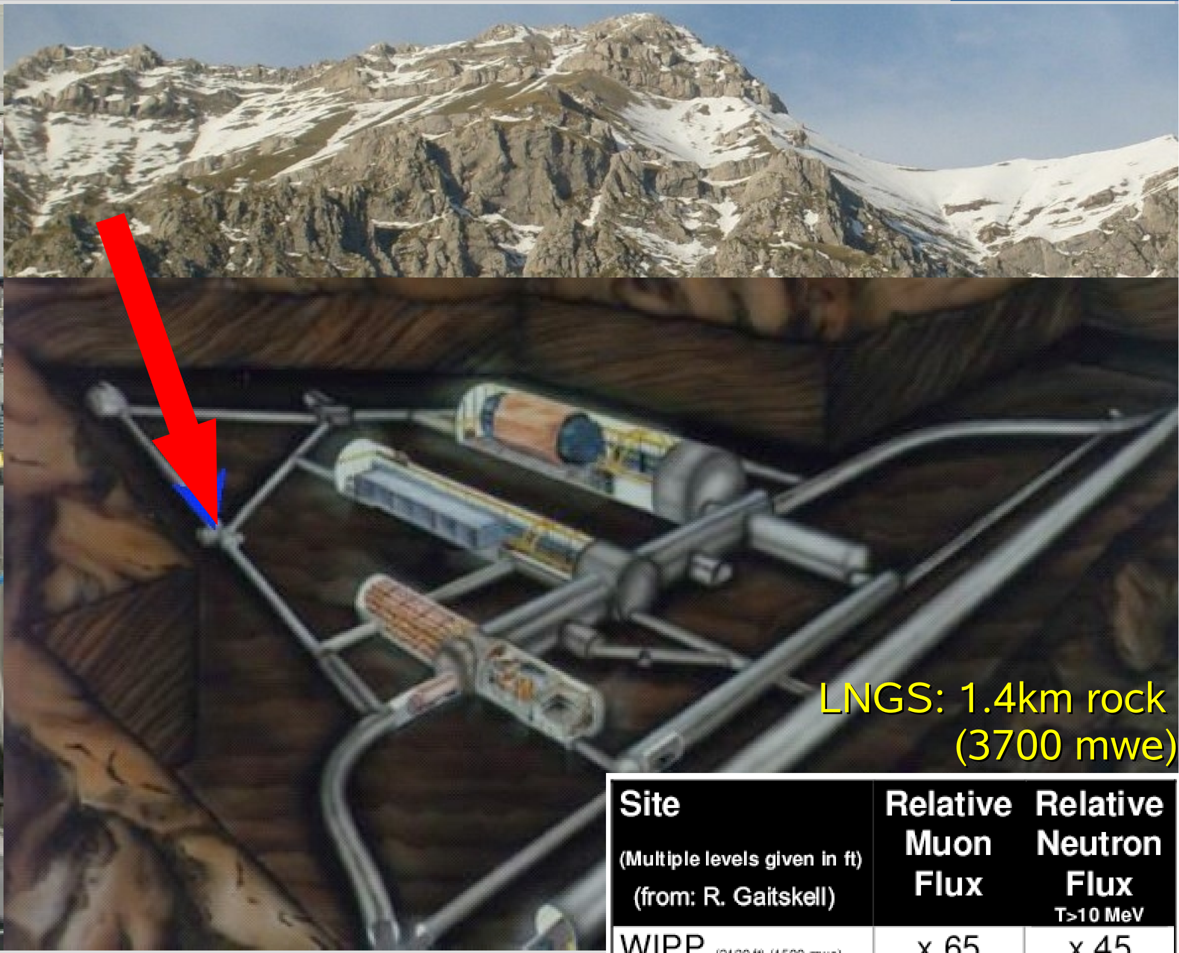
XENON100 @ LNGS





Site (Multiple levels given in ft) (from: R. Gaitskell)	Relative Muon Flux	Relative Neutron Flux T>10 MeV
WIPP (2130 ft) (1500 mwe)	x 65	x 45
Soudan (2070 mwe)	x 30	x 25
Kamioke	x 12	x 11
Boulby	x 4	x 4
Gran Sasso (3700 mwe) Frejus (4000 mwe), Homestake (4860 ft)	x 1	x 1
Mont Blanc	x 6^{-1}	x 6^{-1}
Sudbury	x 25^{-1}	x 25^{-1}
Homestake (8200 ft)	x 50^{-1}	x 50^{-1}

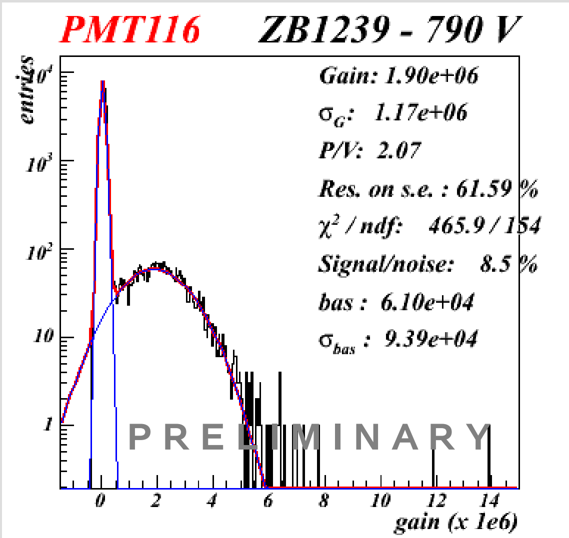
underground since end of February 08

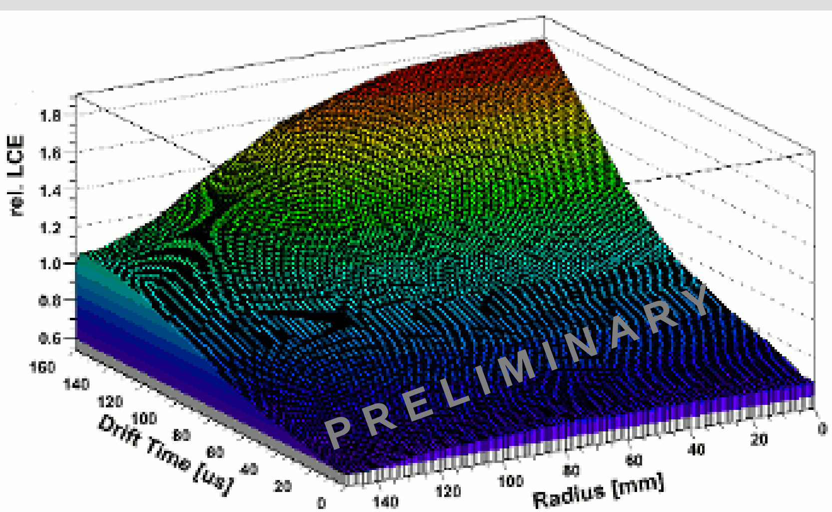
first filled with Xe in mid May 08

detector fully operational, taking science data

Calibration I

Xe
XENON
Dark Matter Project





Gain calibration, Gain Stability:
blue LED (+optical fibers)

➡ gains stable within $\pm$2% (σ/μ)

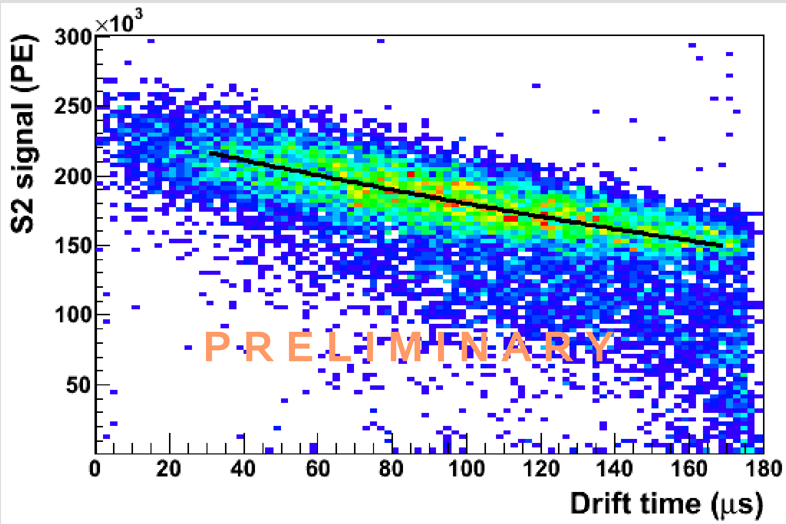
Average Light Yield, combined *E*-Scale:
Cs-137, AmBe inelastic (40 keV, 80 keV),
Xe* (164 keV, 236 keV), Co-60, ...

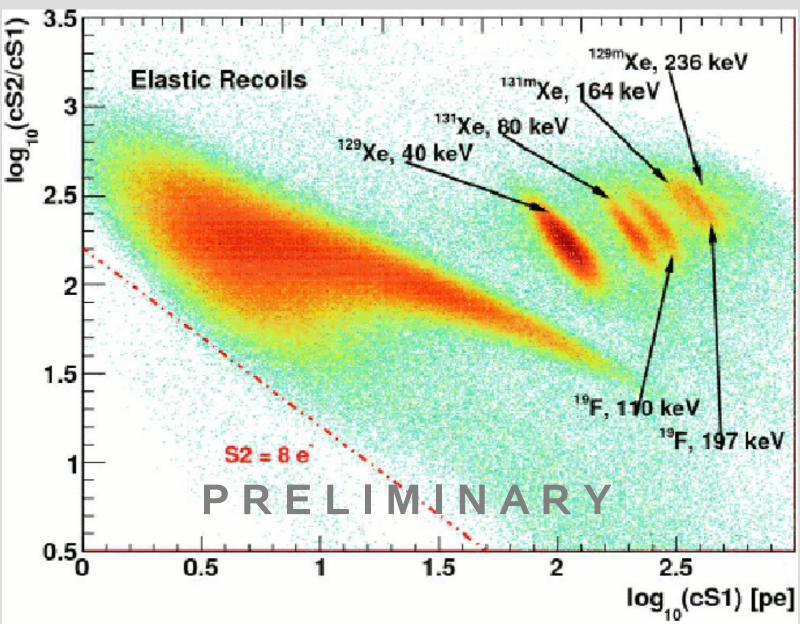
➡ *LY*(122 keVee) = 2.20(9) PE/keVee

Position dependent Corrections:
Cs-137, AmBe inelastic (40 keV),
Xe* (164 keV)
Kr-83m (planned)

➡ Agreement better than 3%

Calibration II





Electron Lifetime:
Cs-137

➡ ~200 µs (11.2d), up to 400 µs (run_08)

Position Reconstruction Tests:
Co-57 (collimated), Cs-137, + MC

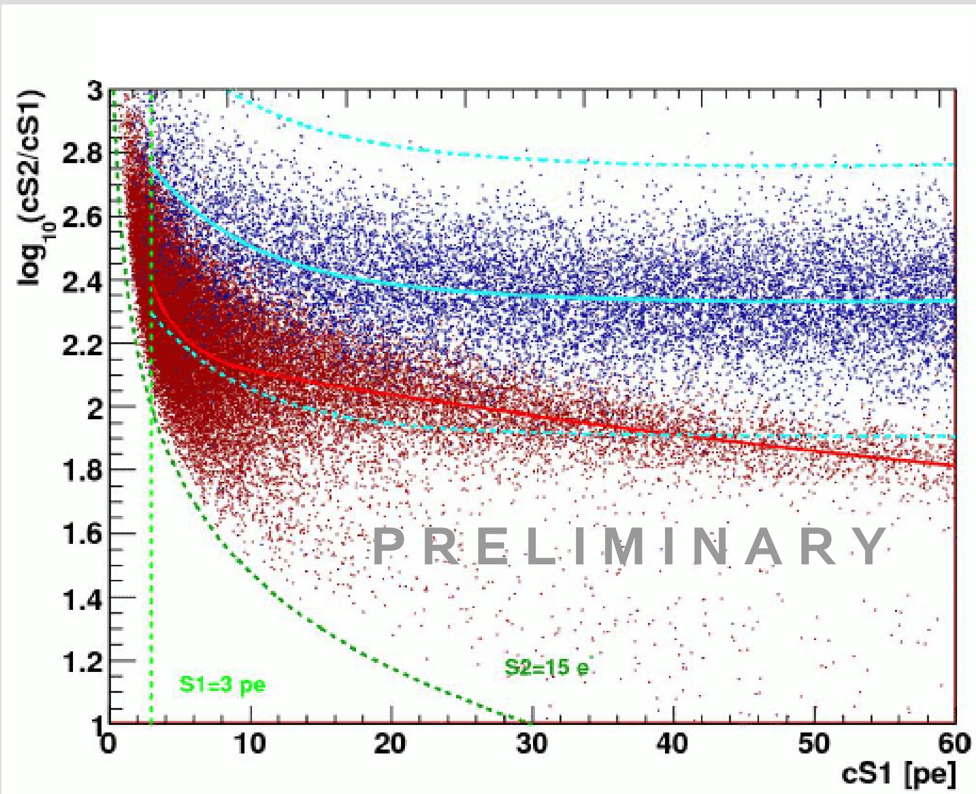
➡ 3 algorithms (NN, SVM, χ^2) available:
$\Delta r < 3$ mm, $\Delta z < 2$ mm

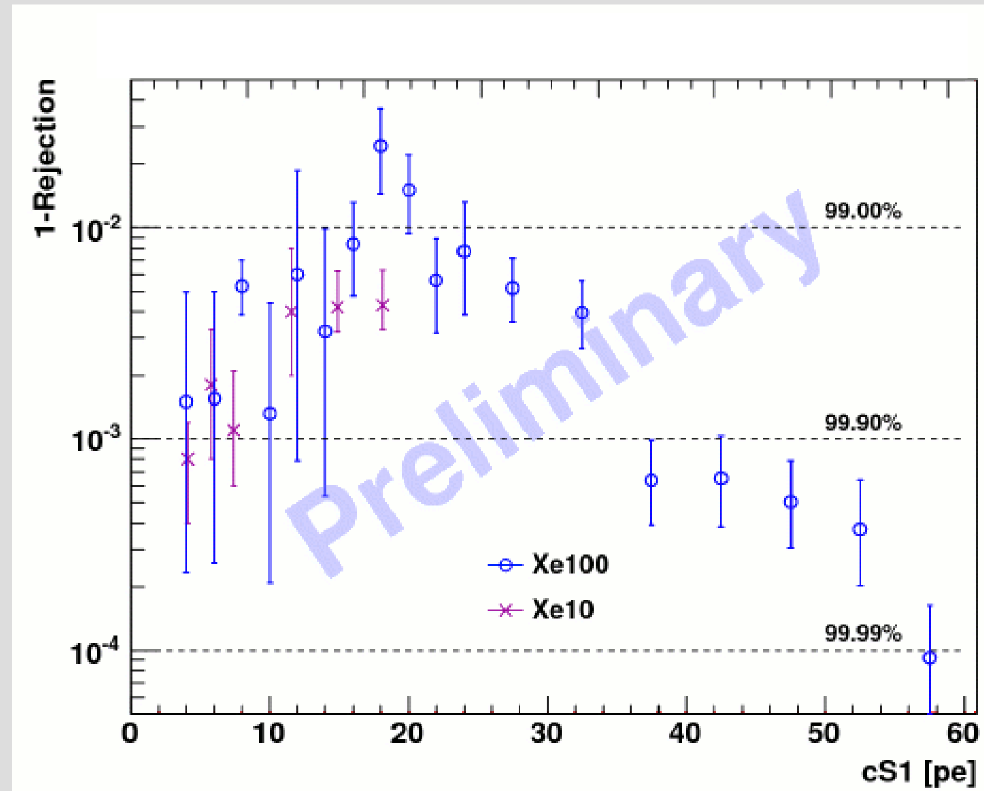
Electron Recoil Band (Background):
Co-60, Cs-137, Th-228

Nuclear Recoil Band (Signal):
Neutrons: AmBe

➡ definition of WIMP search region, discrimination

ER / NR Discrimination

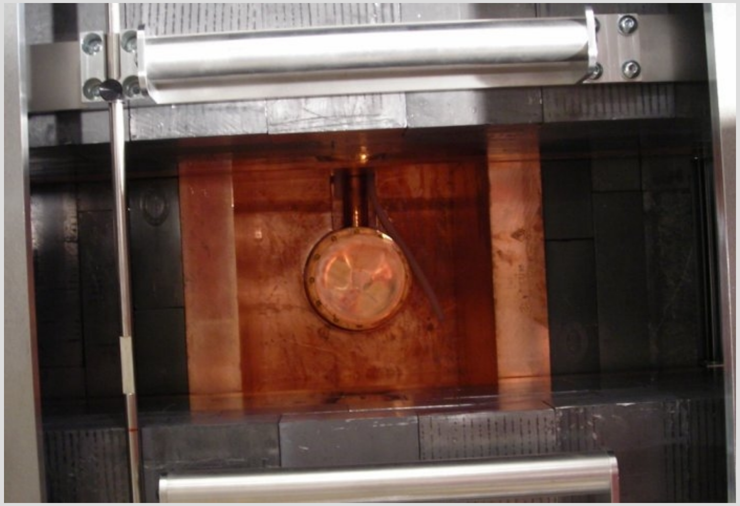


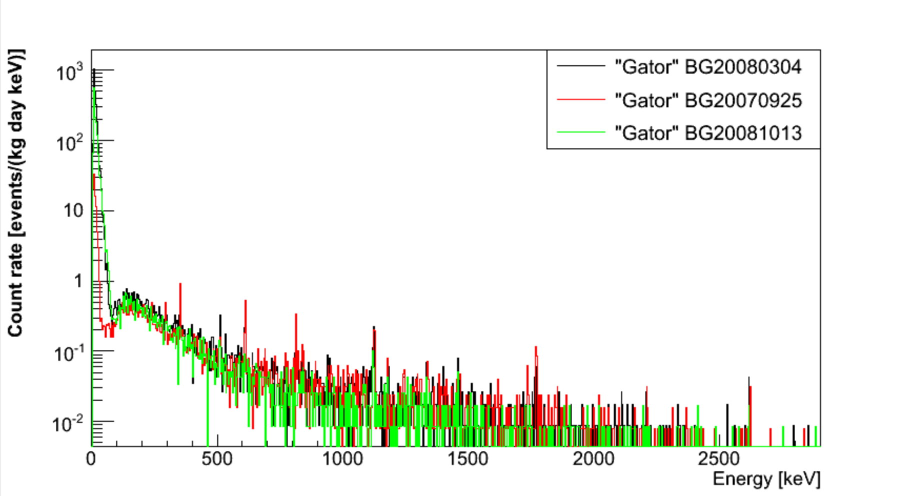


- ER/NR discrimination via S2/S1 ratio
- Discrimination efficiency similar to XENON10 (>99%)

Material Screening

GATOR: 2.2kg high purity Ge detector
operated by UZH in low bg environment @ LNGS





TPC Material	Unit	Quantity used	^{238}U [mBq/unit]	^{232}Th [mBq/unit]	^{40}K [mBq/unit]	^{60}Co [mBq/unit]	^{210}Pb [Bq/unit]
R8520 PMTs	PMT	242	0.15±0.02	0.17±0.04	9.15±1.18	1.00±0.08	
PMT bases	base	242	0.16±0.02	0.07±0.02	< 0.16	< 0.01	
Stainless steel	kg	70	< 1.7	< 1.9	< 9.0	5.5±0.6	
PTFE	kg	10	< 0.31	< 0.16	< 2.2	< 0.11	
QUPID	QUPID	-	<0.49	<0.40	<2.4	<0.21	
Shield Material							
Copper	kg	1600	< 0.07	< 0.03	<0.06	<0.0045	
Polyethylene	kg	1600	< 3.54	< 2.69	< 5.9	< 0.9	
Inner Pb (5 cm)	kg	6300	< 6.8	< 3.9	< 28	< 0.19	17±5
Outer Pb (15 cm)	kg	27200	< 5.7	< 1.6	14±6	< 1.1	516±90

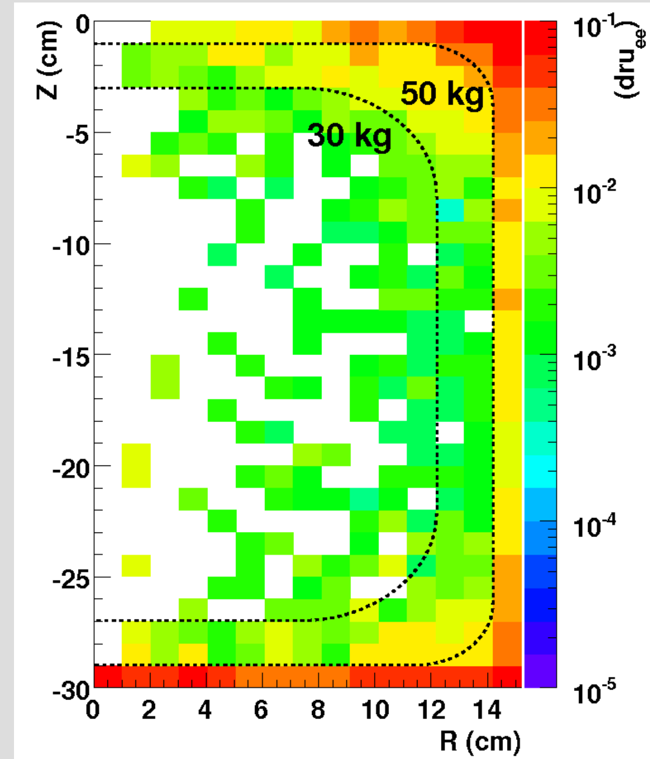
use results for Monte Carlo Simulations

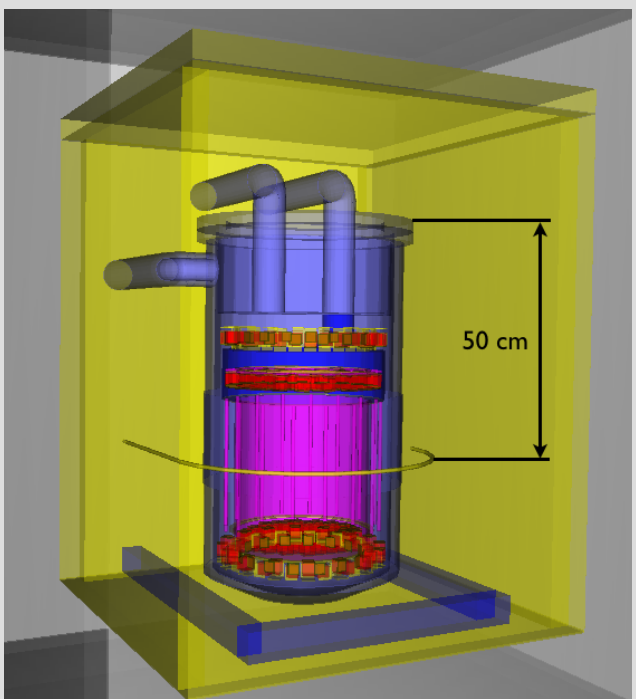
Monte Carlo Simulations

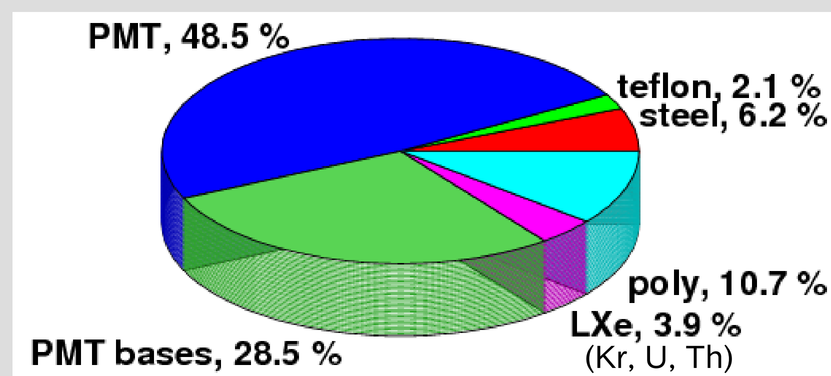
GEANT4 simulations of full experiment
(detector+shield+surrounding)

Gamma Background:

in DM search region, after cuts
50 kg: < 9.8×10^{3} events/kg/keV/day
30 kg: < 3.2×10^{3} events/kg/keV/day
before S1/S2 discrimination cut!





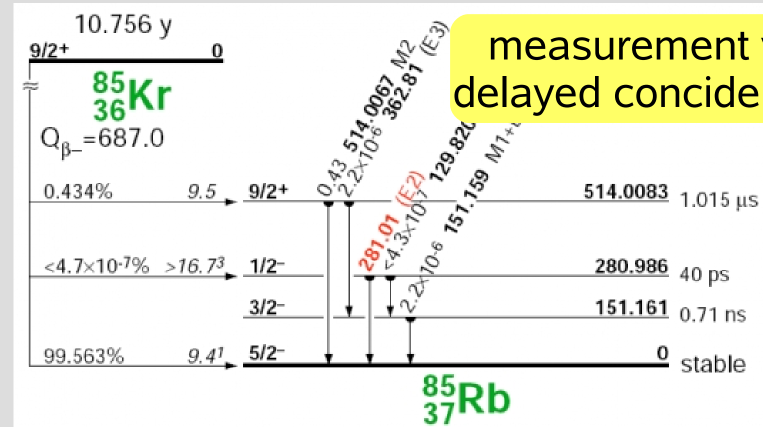


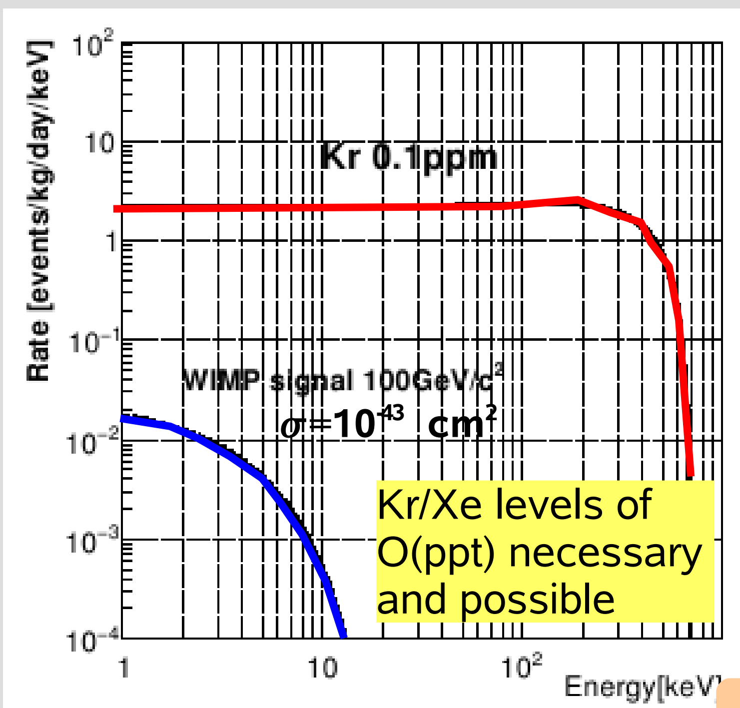
Kr-85-Removal

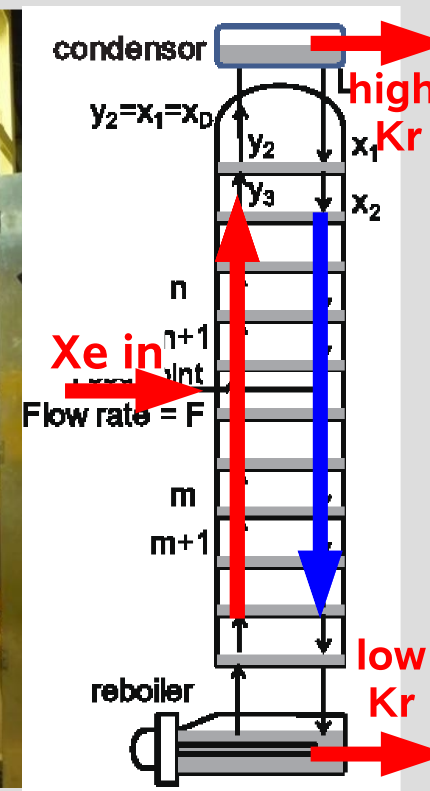
- Xe has no long lived radioactive isotope
- BUT: Xe contains Kr-85

in air:	Kr/Xe ~ 10
in Xe gas (commercial)	Kr/Xe ~ ppm-ppb
necessary (Xe100)	Kr/Xe ~ 100 ppt (<1 evt in 0.5 yr)

⇒ dedicated Kr-85 removal to ppt level



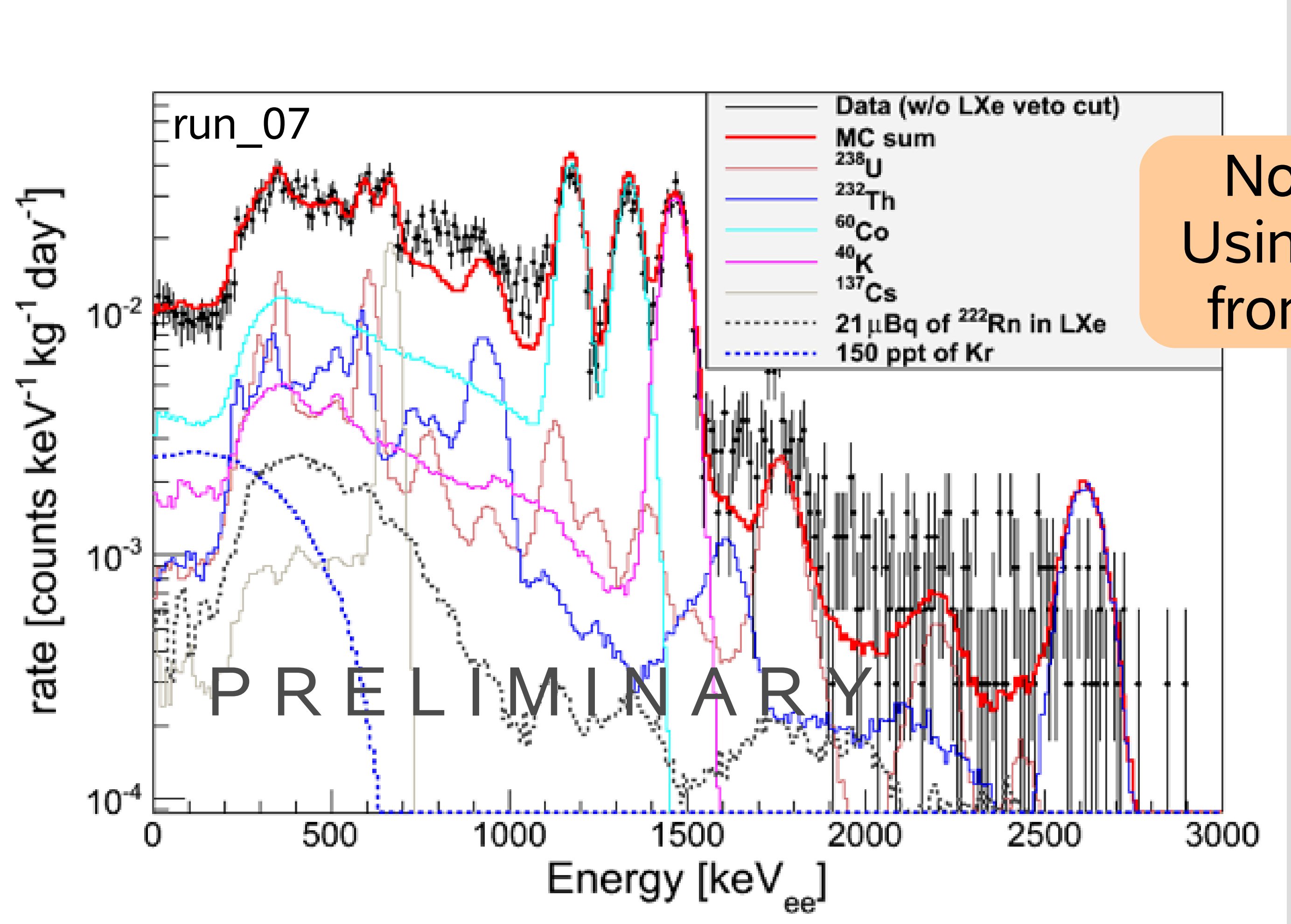




used successfully

XMASS, arXiv:0809.4413 (2008)

XENON100 Background

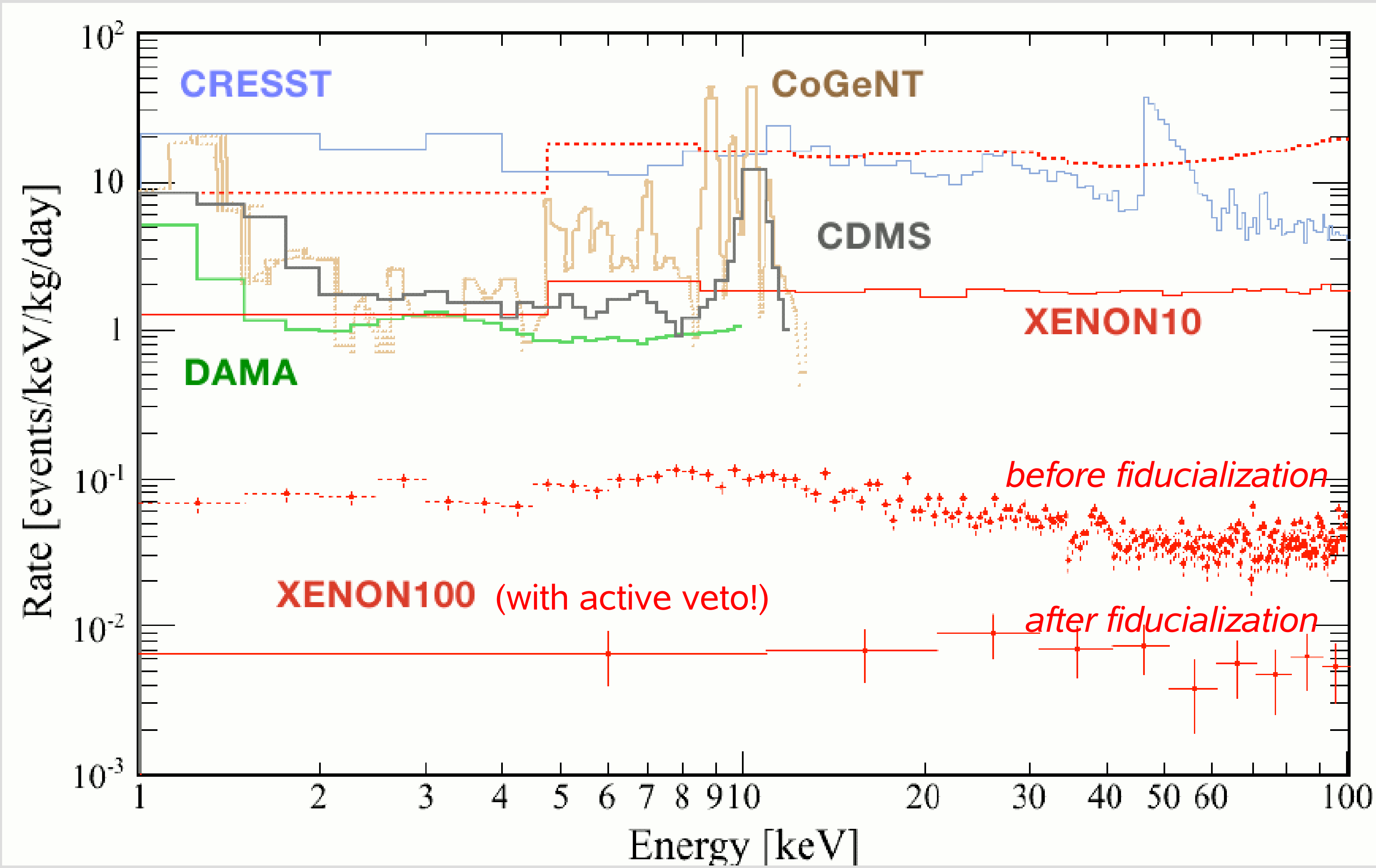


No MC tuning!
Using only values from screening.

- 30 kg fiducial mass
- active LXe veto not used for this plot
- exploit anti-correlation between light and charge for better ER-energy scale

Measured Background in good agreement with Monte Carlo prediction.

Background Comparison



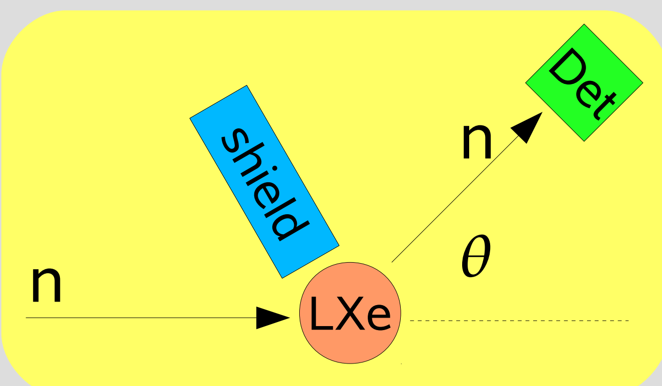
This is the lowest Background ever achieved in a Dark Matter Experiment!

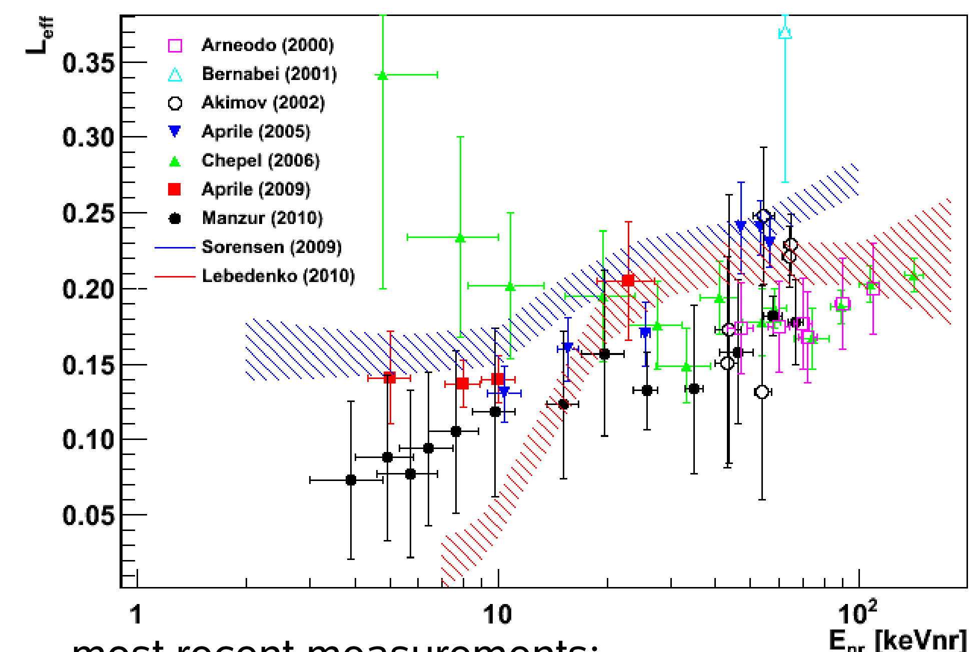
Nuclear Recoil Scale

- WIMPs interact with Xe nucleus
  ➞ nuclear recoil (*nr*) scintillation (β and γ's produce electron recoils)
- absolute measurement of *nr* scintillation yield is difficult
  ➞ measure relative to Co57 (122keV)
- relative scintillation efficiency $\mathcal{L}_{eff}$:

$$\mathcal{L}_{\mathrm{eff}}(E_{\mathrm{nr}}) = \frac{\mathrm{LY}(E_{\mathrm{nr}})}{\mathrm{LY}(E_{\mathrm{ee}} = 122\ \mathrm{keV})}$$

measurement principle:





most recent measurements:
■ *Aprile et al., PRC 79, 045807 (2009)*
● *Manzur et al., PRC 81, 025808 (2010)*

for discussion of possible systematic errors see *A. Manalaysay, arXiv:1007.3746*

Nuclear Recoil Scale II

- difficult measurements
- measurements differ systematically
- large uncertainties
- direct measurements vs. indirect determinations
- no proper theoretical model available

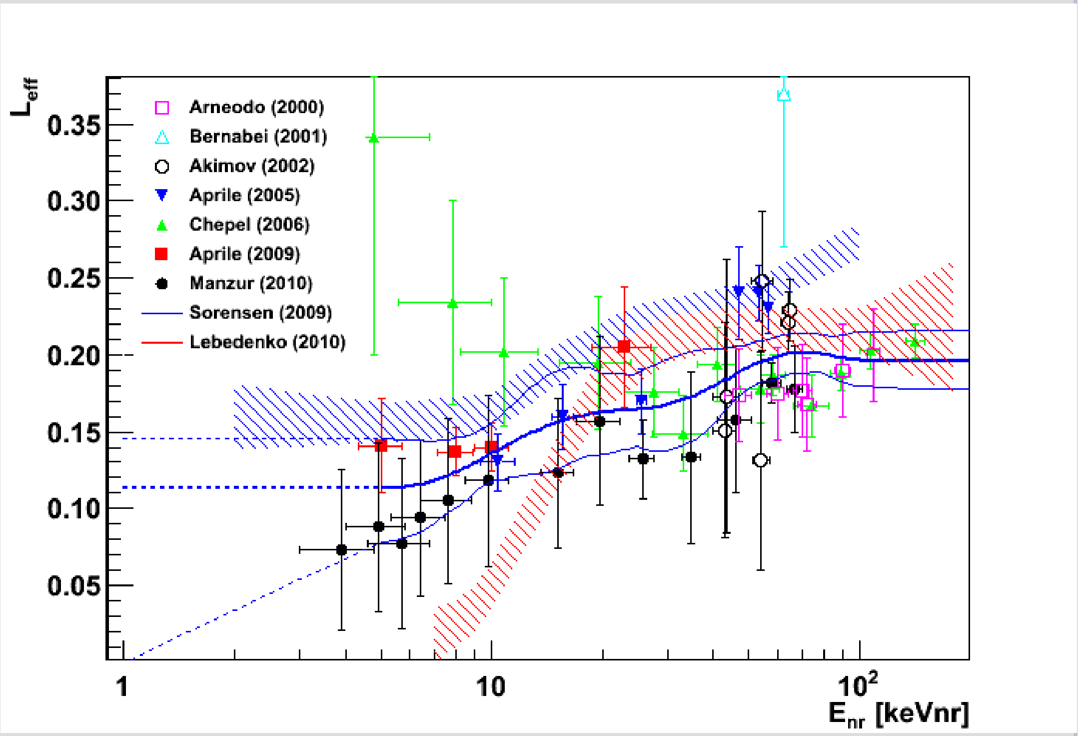
New measurements ongoing at Columbia; In preparation in Zürich

➡ do not prefer single measurement
(not even our own ones)

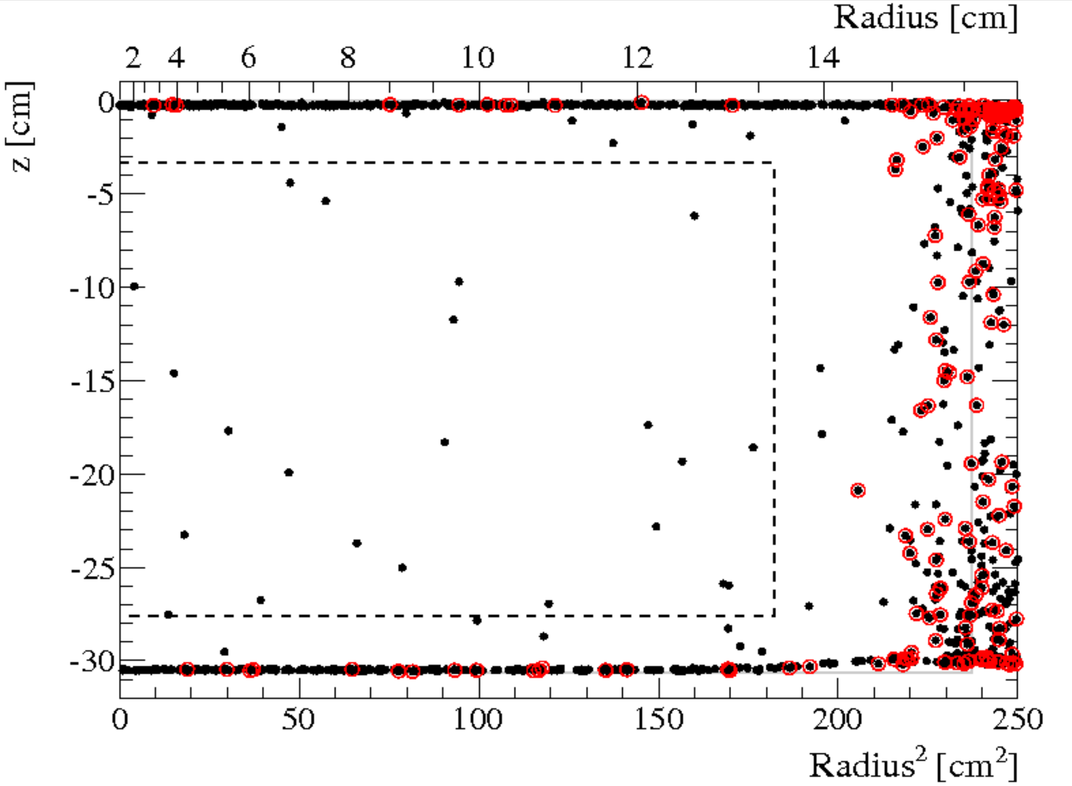
➡ global fit to all direct measurements

➡ get 90% CL from statistics

➡ extrapolation to low energies motivated by available data



First XENON100 Data

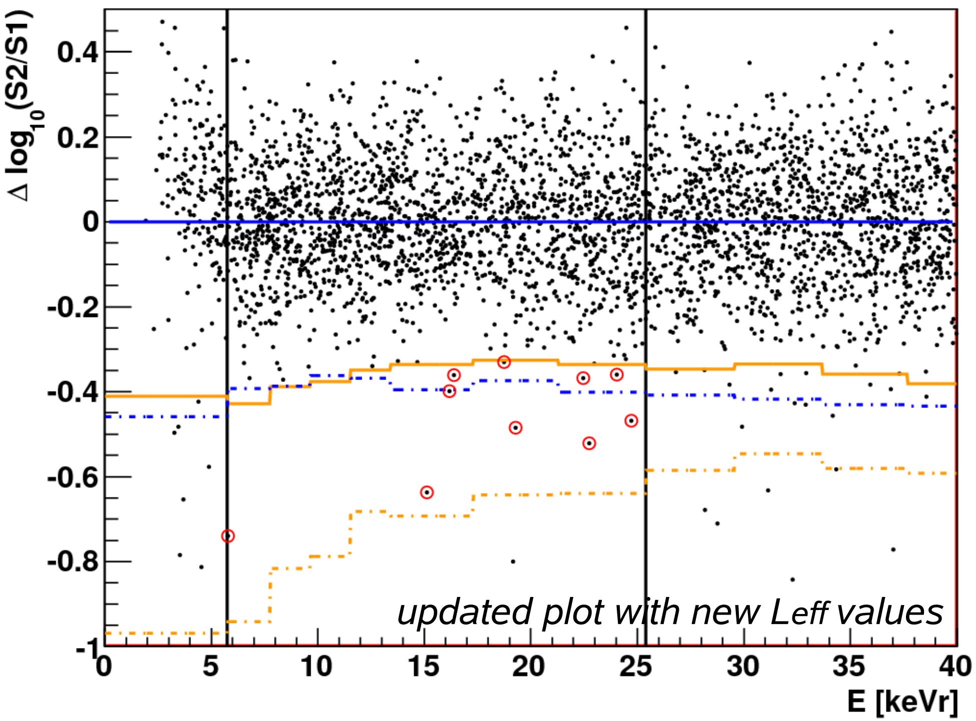


- Energy cut: <30 keV$_{nr}$
- make use of excellent self-shielding capability of LXe
- 40 kg fiducial mass

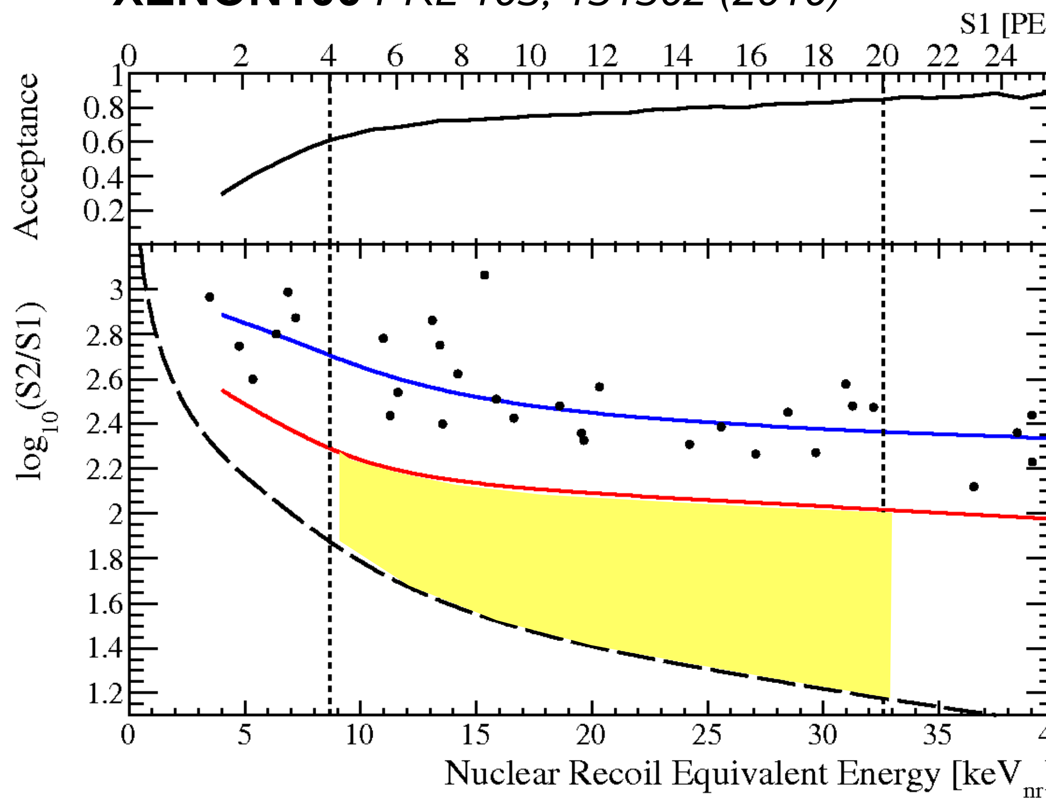
- Background data taken in stable conditions Oct-Nov 2009
- 11.2 life days
- Data was not blinded
- But: Cuts developed and optimized on calibration data only
- PRL 105, 131302 (2010) *arXiv:1005.0380*

A Look at the Bands

XENON10 *PRL 100, 021303 (2008)*



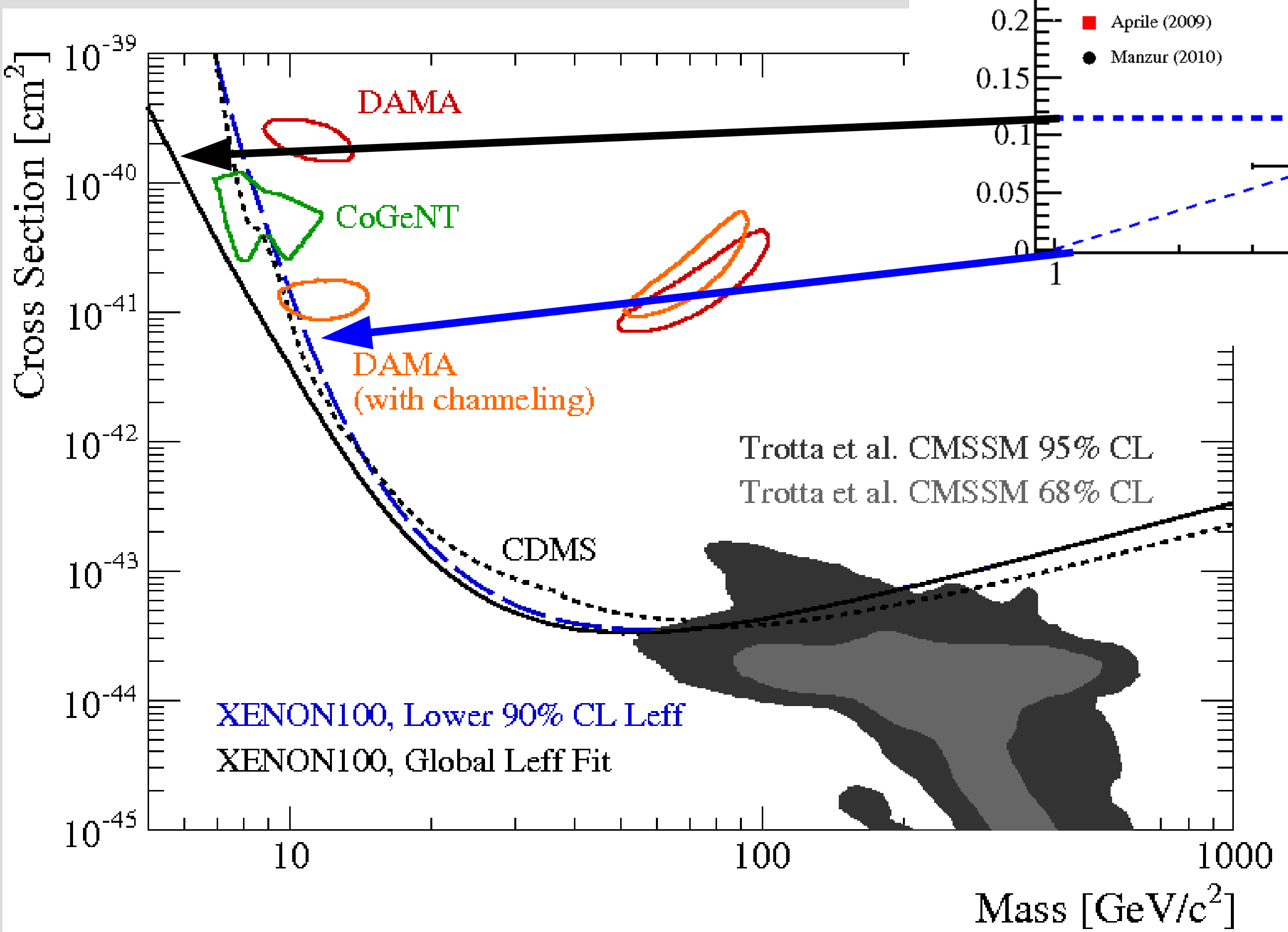
XENON100 *PRL 105, 131302 (2010)*

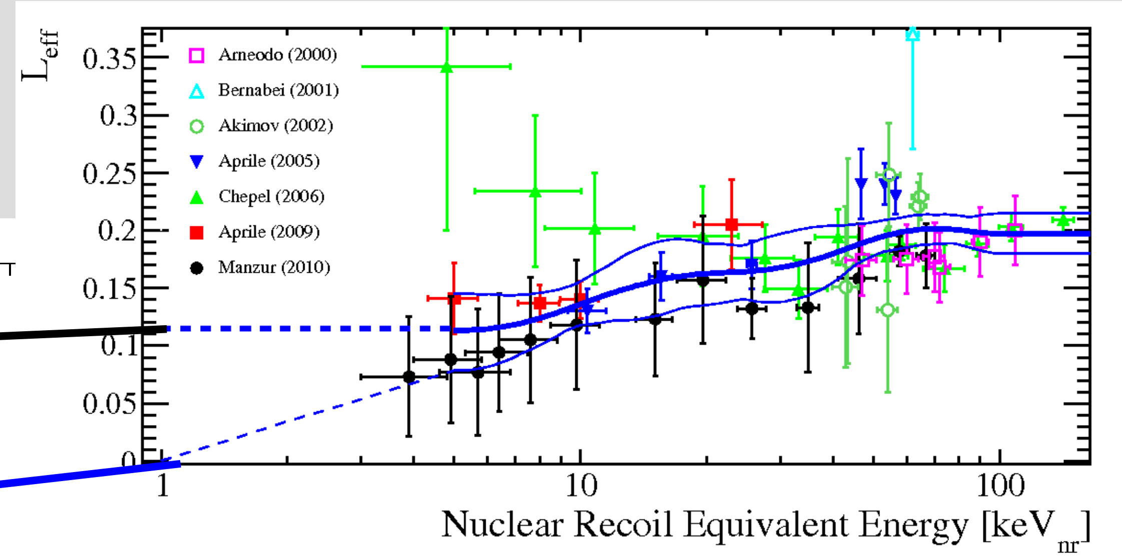


- Background free in 11.2 days after S2/S1 discimination
- Both plots show similar exposure

NR acceptance = 50%
cut efficiency ~ 60-85 % (conservative)
Background expectation $\ll 1$

A first Limit from XENON100





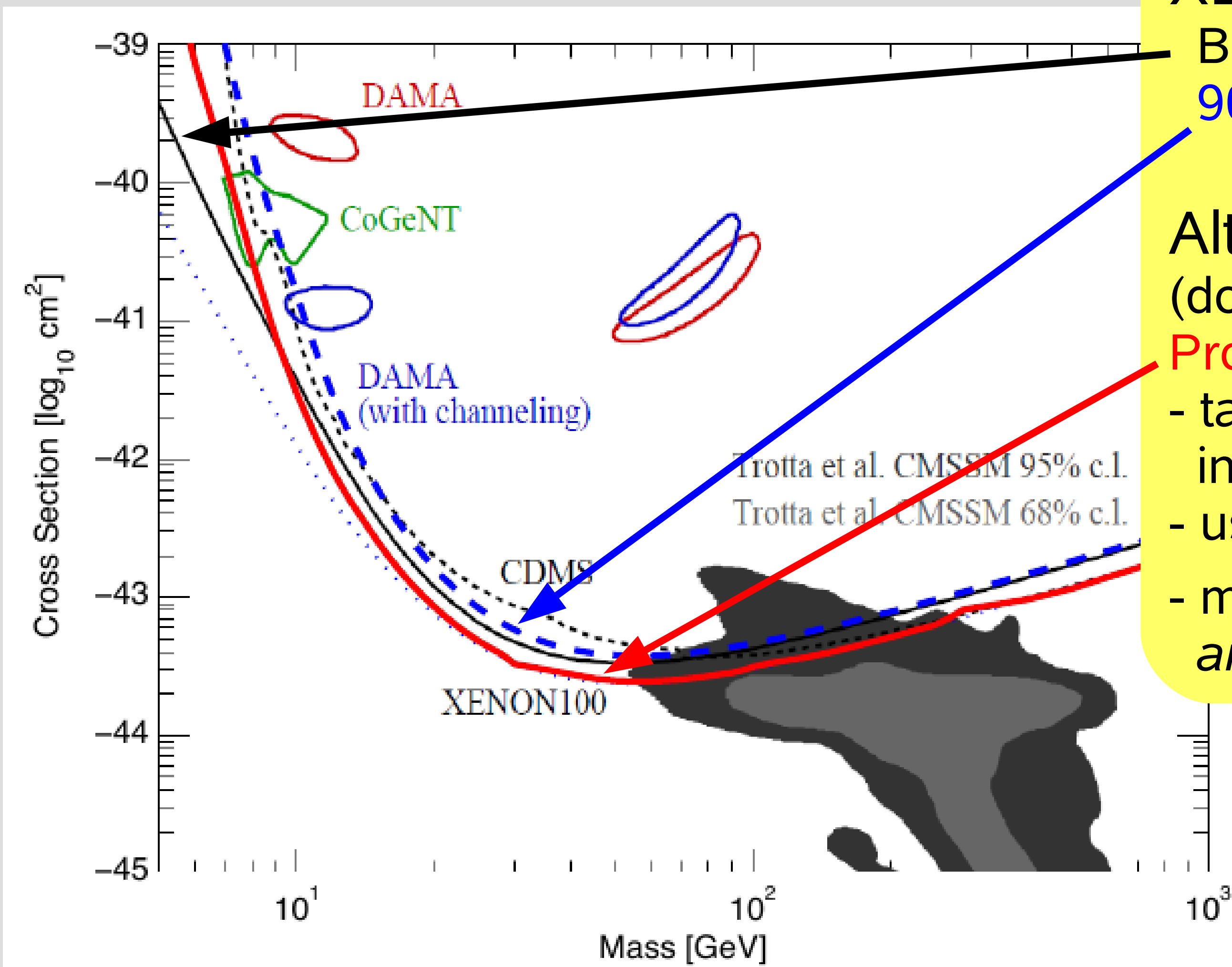
spectrum averaged exposure: 170 kg days

XENON100 is working extremely well and is back at the sensitivity frontier.

This is just a first glimpse! We have much more (blinded) data waiting to be analyzed.

PRL 105, 131302 (2010)
arXiv: 1005.0380

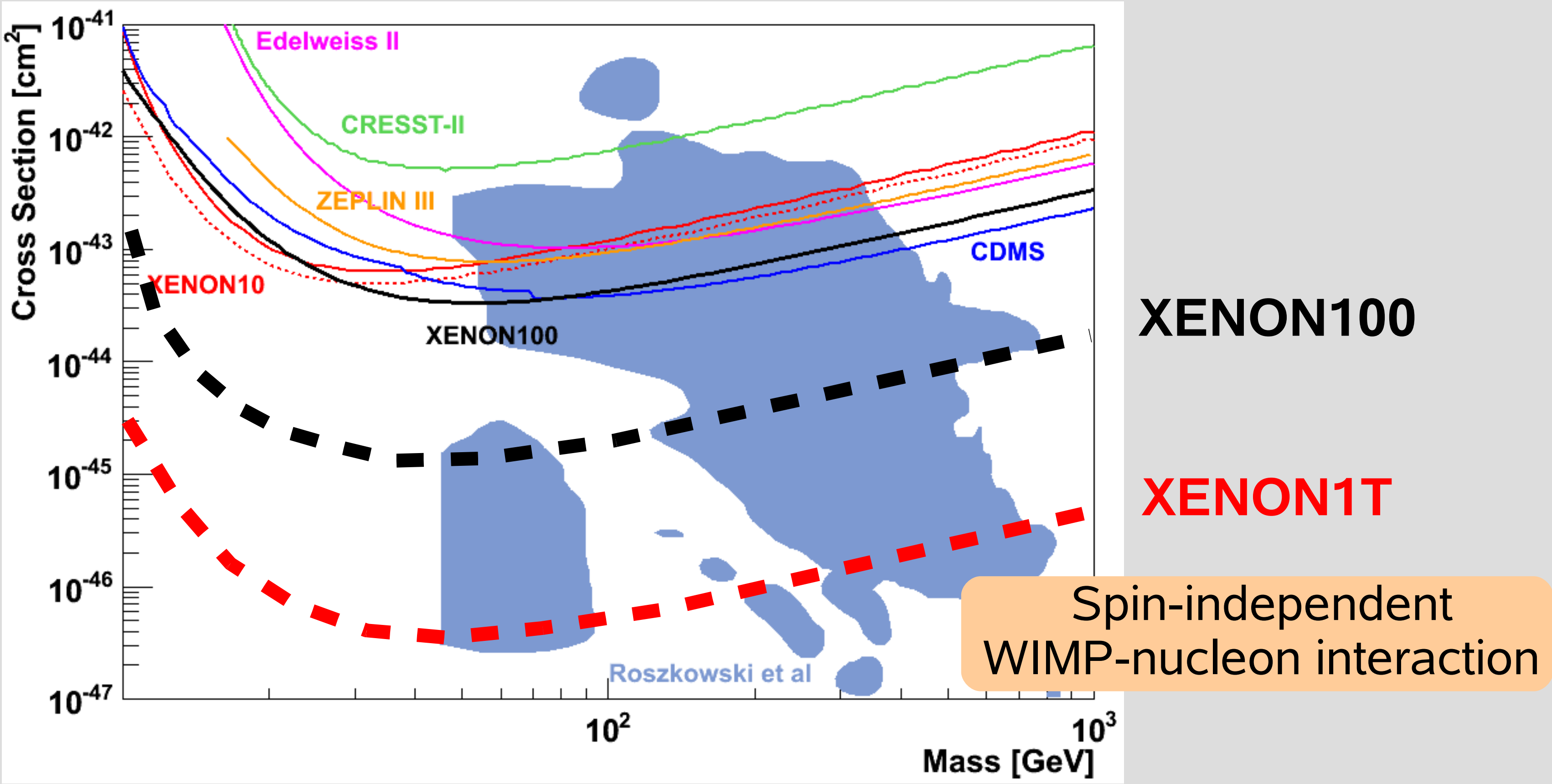
New: Alternative Interpretation



XENON100 PRL:
Best fit limit
90% lower CL *L*eff limit

Alternative Interpretation:
(done at Weizmann Institute)
Profile Likelihood Method
- takes *L*eff uncertainties into account
- uses full log(S2/S1) space
- method described in *arXiv:1007.1727*

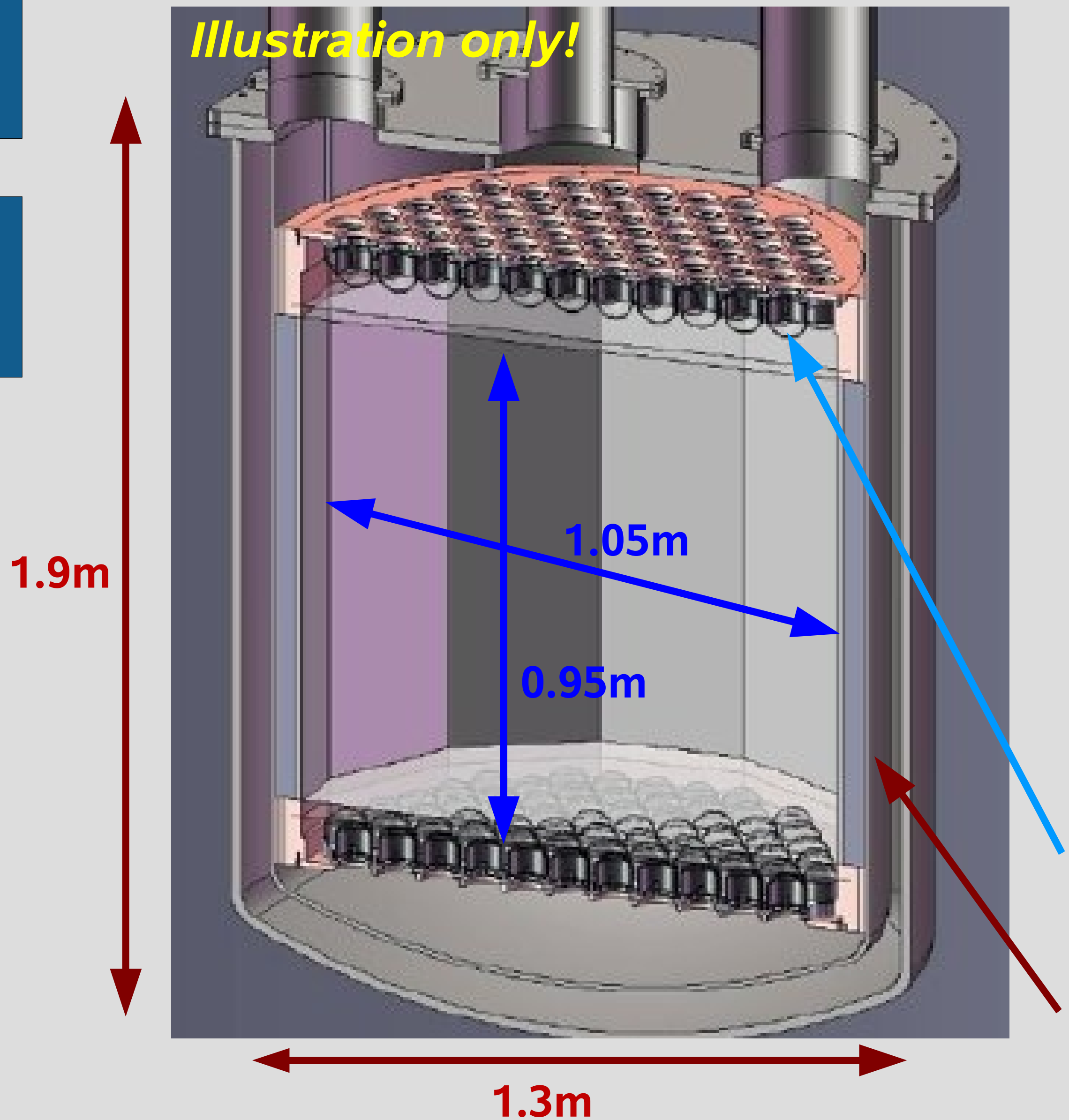
XENON100: Sensitivity



50 kg Target: 40 days $\sigma = 6\times10^{-45}$ cm² (@ 100 GeV)

30 kg Target: 200 days $\sigma = 2\times10^{-45}$ cm² (@ 100 GeV)

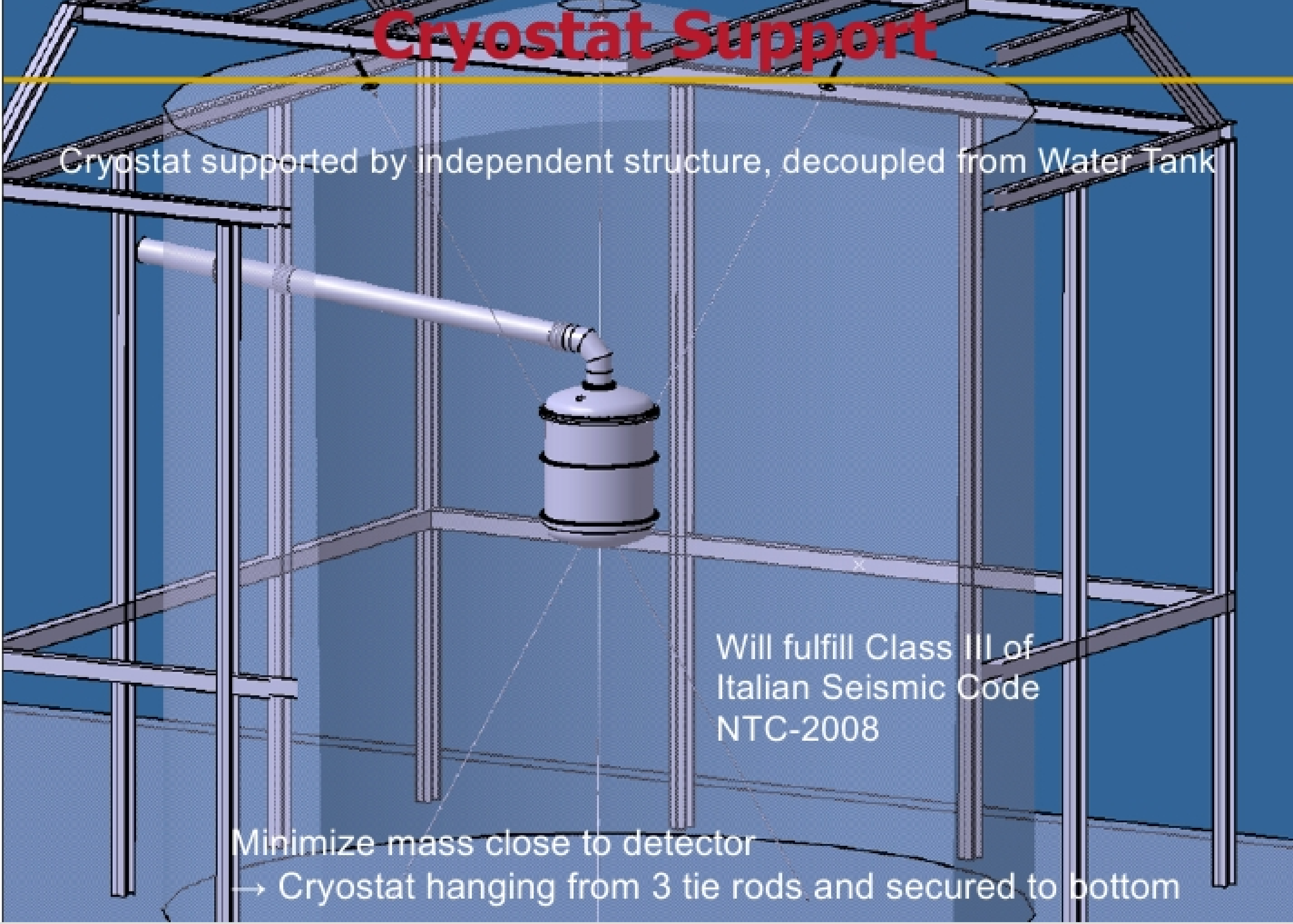
The next step: XENON1T



- 2.4t LXe ("1m³ detector")
  1t fiducial mass
- 100x lower background
  (10 cm self shielding, QUPID)
- MC studies, design studies already started 2009
- proposal and TDR submitted; currently: working on the details; secure funding
- Timeline: 2010 – 2015 ???

Cryostat Support

Cryostat supported by independent structure, decoupled from Water Tank



Will fulfill Class III of Italian Seismic Code NTC-2008

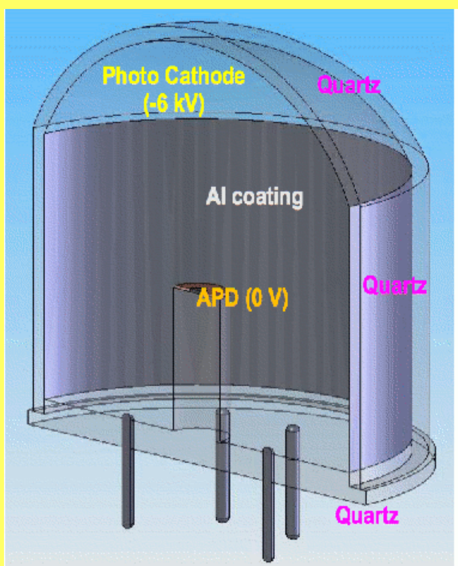
Minimize mass close to detector
→ Cryostat hanging from 3 tie rods and secured to bottom

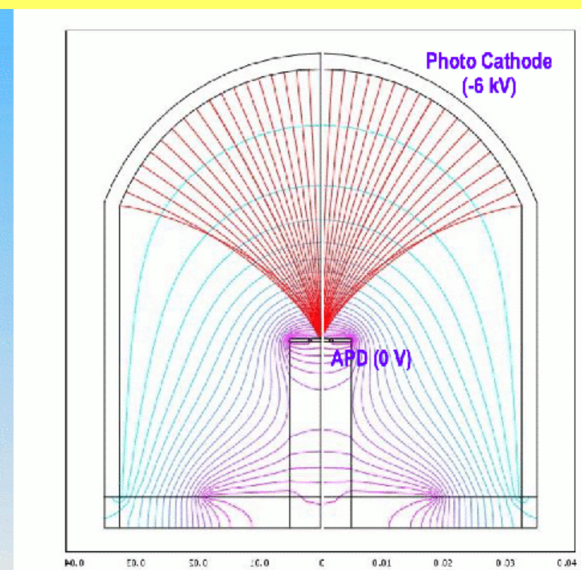
The QUPID

- invented and developed by UCLA group (Arisaka/Wang)
- very low radioactive photosensor to replace PMTs
  APD, quartz, only a few pins, no voltage divider
- QUPIDs are „invisible“ in GATOR screening facility
- first units were build by HAMAMATSU,
  ongoing tests and R&D at UCLA (later also UZH)

QUPID
Quartz
Photon
Intensifying
Detector

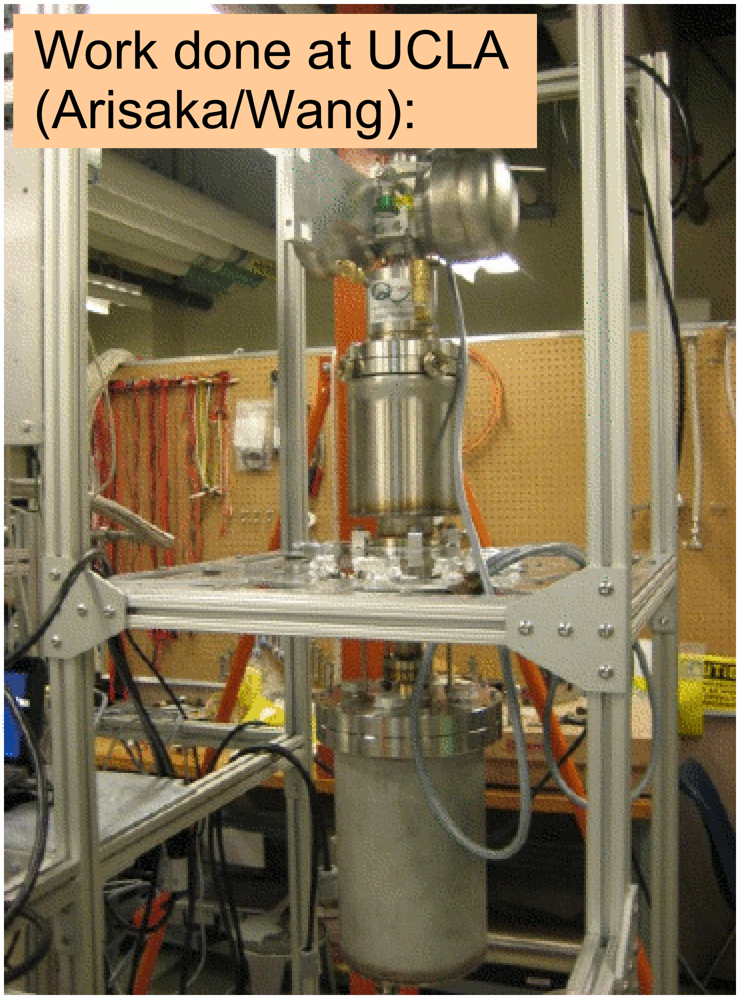
arXiv:0808.3968



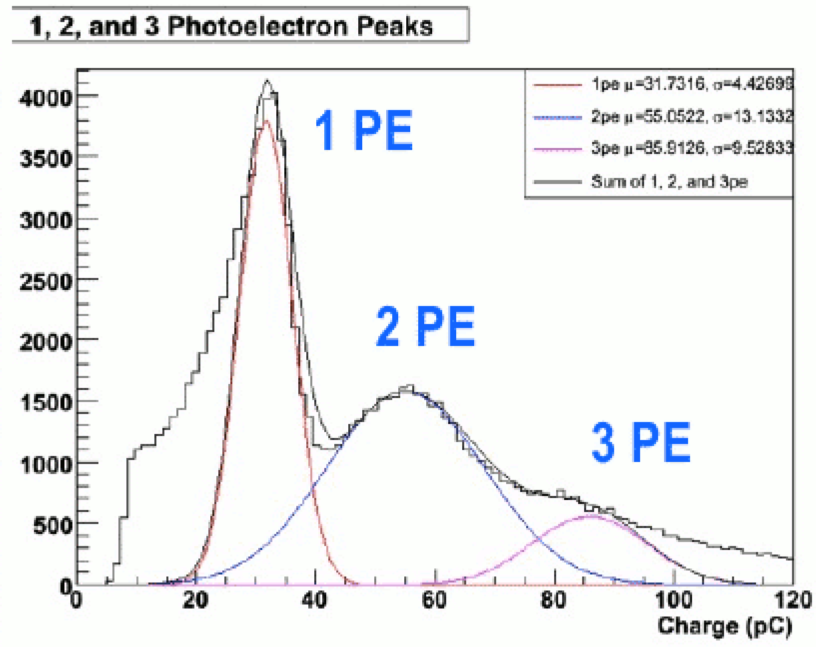


It is actually working...

Work done at UCLA (Arisaka/Wang):

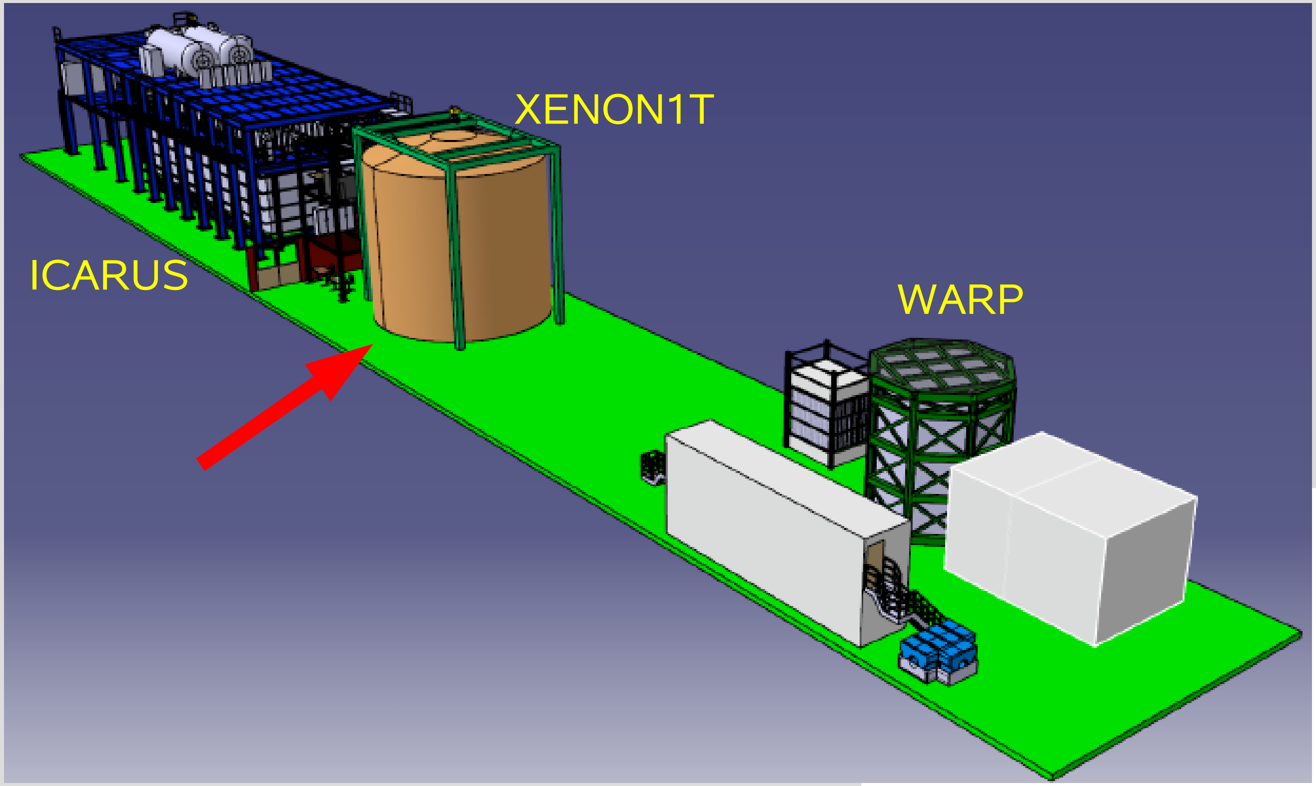


QUPID Test in Liquid Xenon



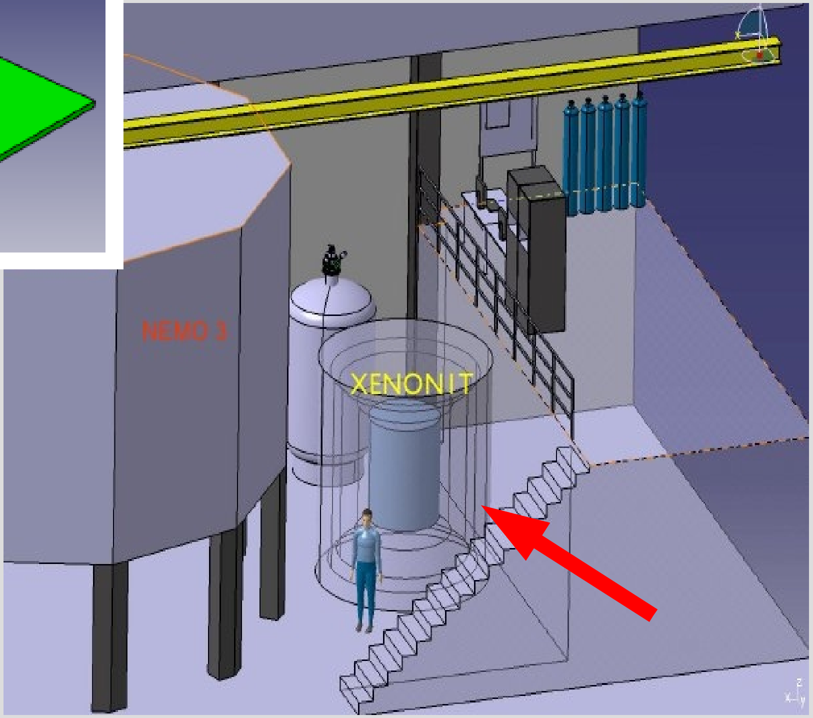
Alternative:
Hamamatsu R11410
- 3“ PMT
- high gain
- LXe operation
- Low radioactivity

XENON1T: Location?

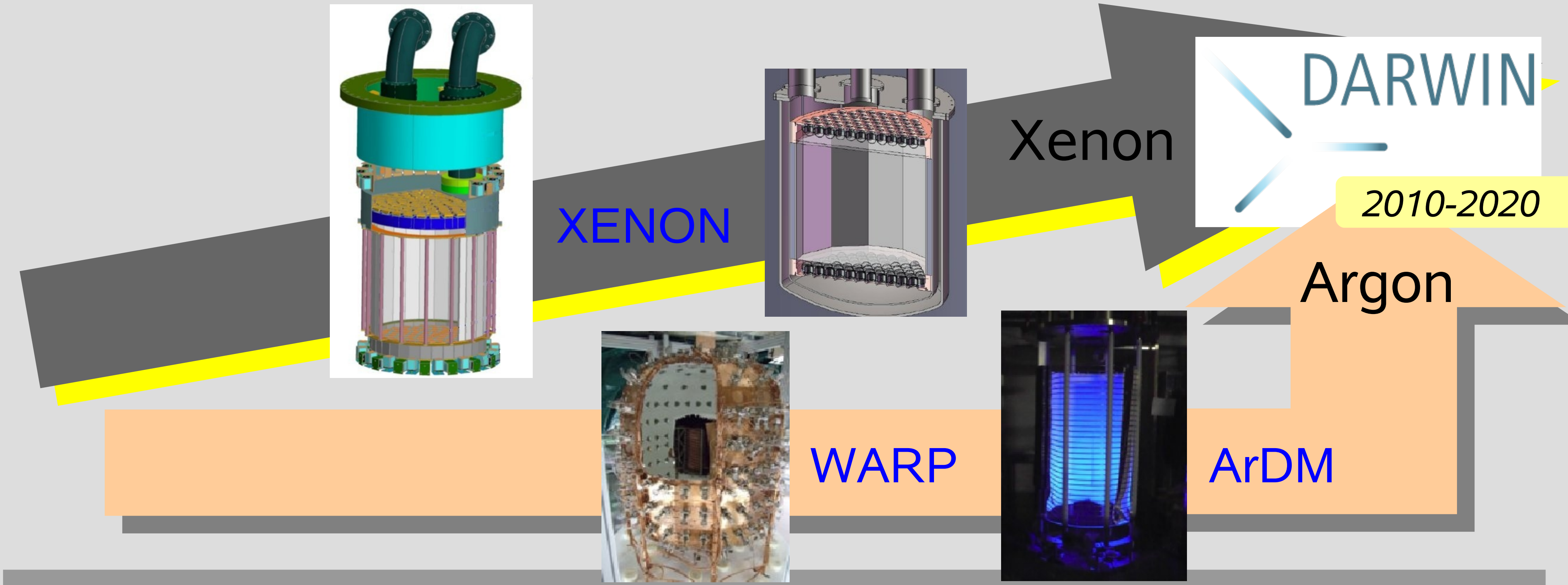


XENON1T
@ LNGS (Hall B)
➞ 5 m water shield acting as active muon veto

XENON1T @ LSM
➞ solid shield (55cm poly, 20cm Pb, 15cm poly, 2cm ancient Pb, >99% muon veto)



The Future: DARWIN



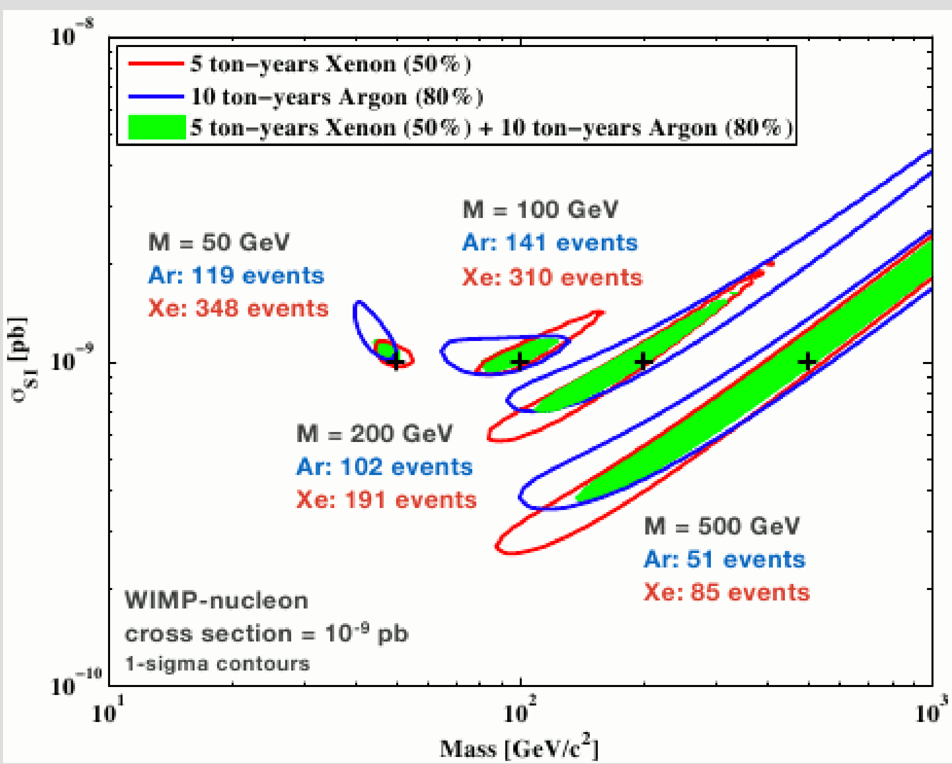
DARWIN – Dark Matter WIMP Search with Noble Liquids

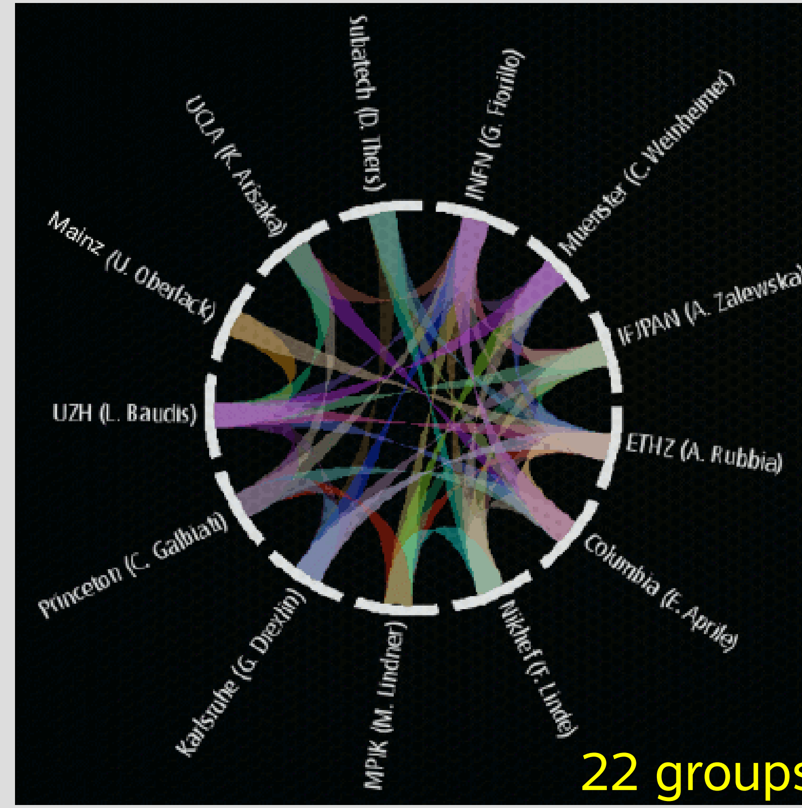
- *R&D and Design Study* for a next generation noble liquid facility in Europe. Approved by ASPERA in late 2009
- Coordinate existing European activities in LXe and LAr towards a multi-ton Dark Matter facility
- Physics goal: probe WIMP cross sections well below 10^{-47} cm²

Goals and Structure

R&D and Design Study for
Light/Charge Readout, Electronics/DAQ,
Detector/Underground/Shield Infrastructure,
Material Screening/Backgrounds, Science Impact

Multiton LXe and/or LAr WIMP detector
find best choice/design, exploit complementarity?

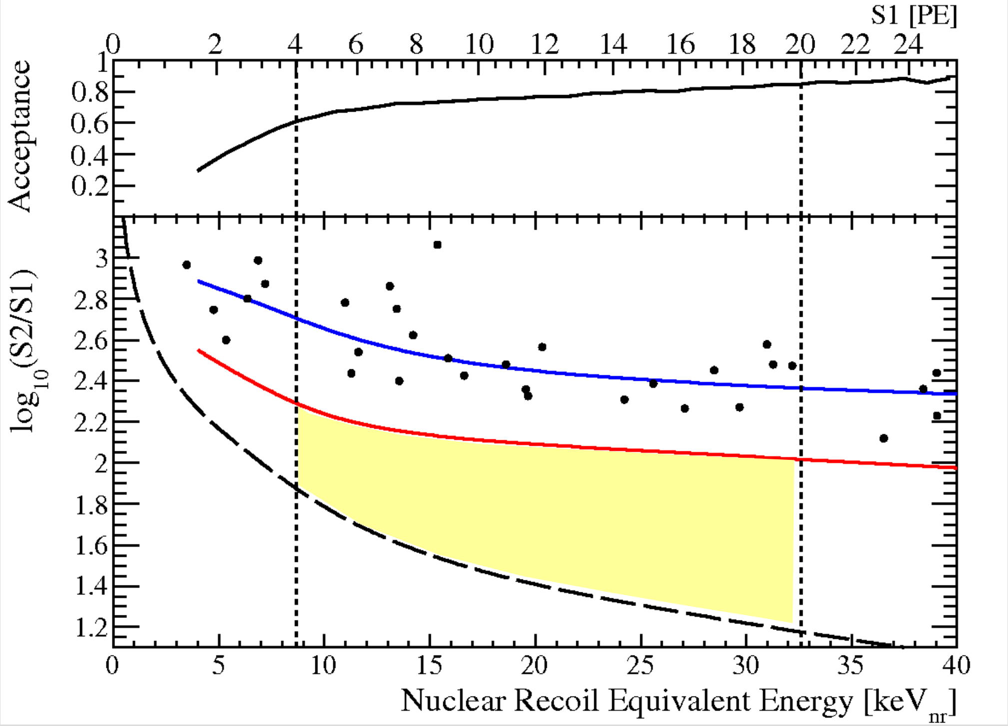




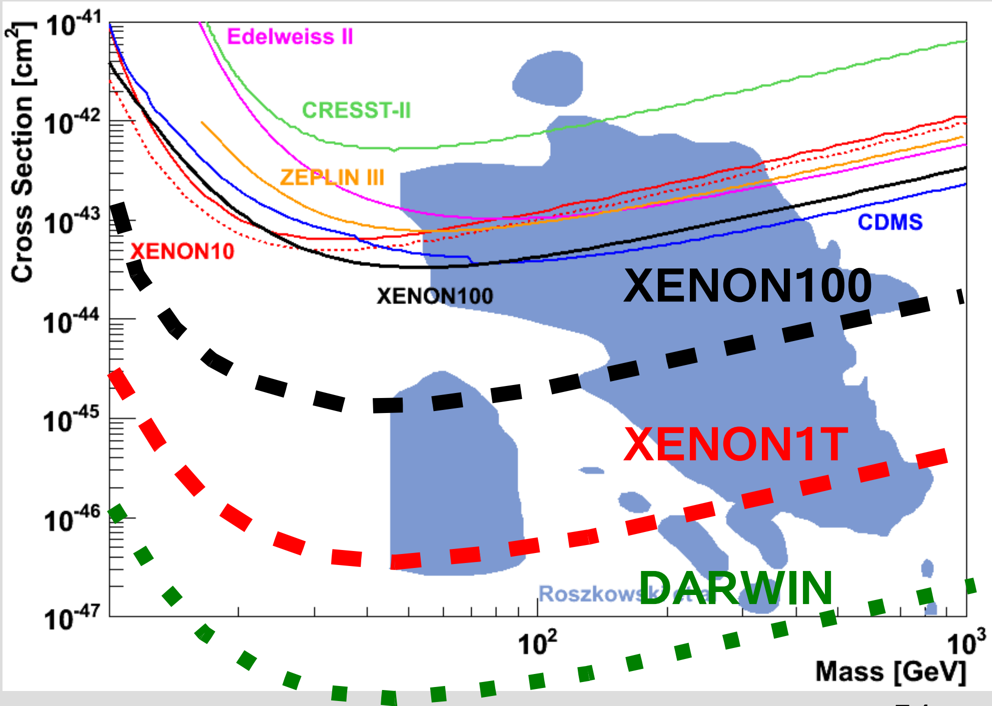
ArDM, WARP, XENON Groups:
UZH (CH), INFN (I), ETHZ (CH),
Subatech (F), Mainz (D), MPIK (D),
Münster (D), Nikhef (NL), KIT (D),
IFJPAN (PL)
+ Columbia, Princeton, UCLA (USA)

`http://darwin.physik.uzh.ch`

Summary



- Dark Matter: One of the big unsolved puzzles
- **XENON100**
  62 kg dual-phase LXe TPC
- extremely low background
- first results from 11.2d data:
  PRL 105, 131302 (2010)



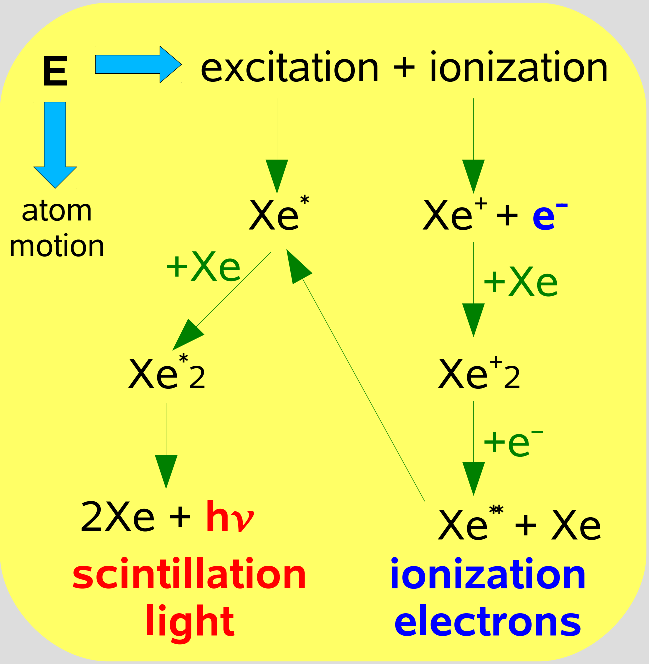
Two new projects upcoming:

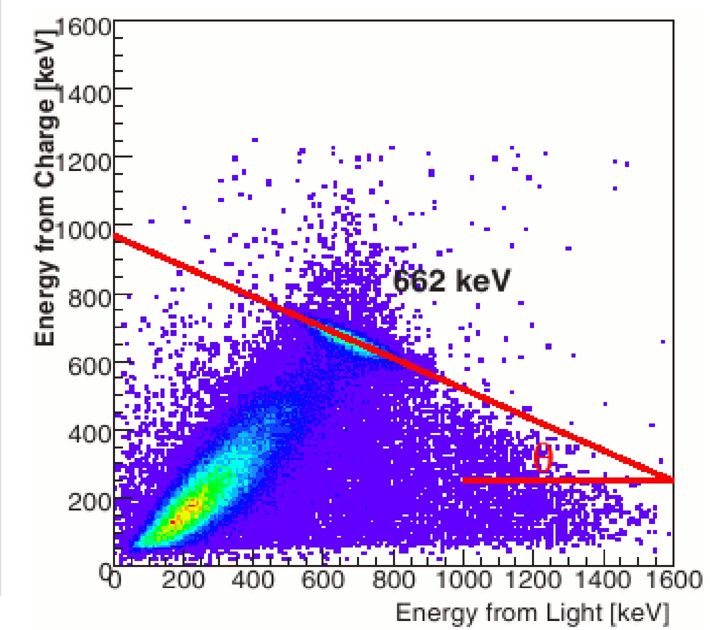
- **XENON1T**
  1 ton LXe target mass
- **DARWIN**
  multiton LXe/LAr detector

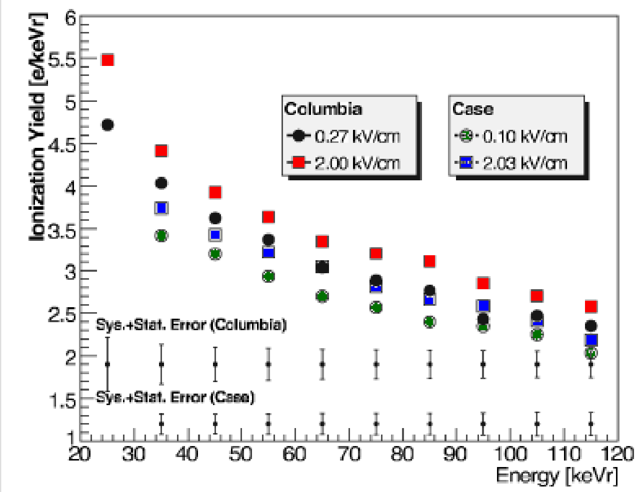
Backup

Xenon: Light and Charge

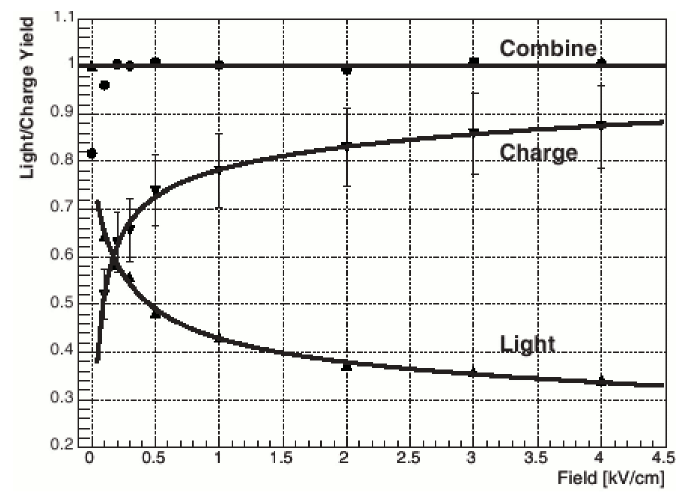
- energy deposited in LXe produces *electron-ion pairs* and *excited atom states*; both processes can lead to scintillation
- anti-correlation between charge and light
  ➡ improvement of energy resolution possible
- E-field dependence (field quenching)
- response also depends on particle energy





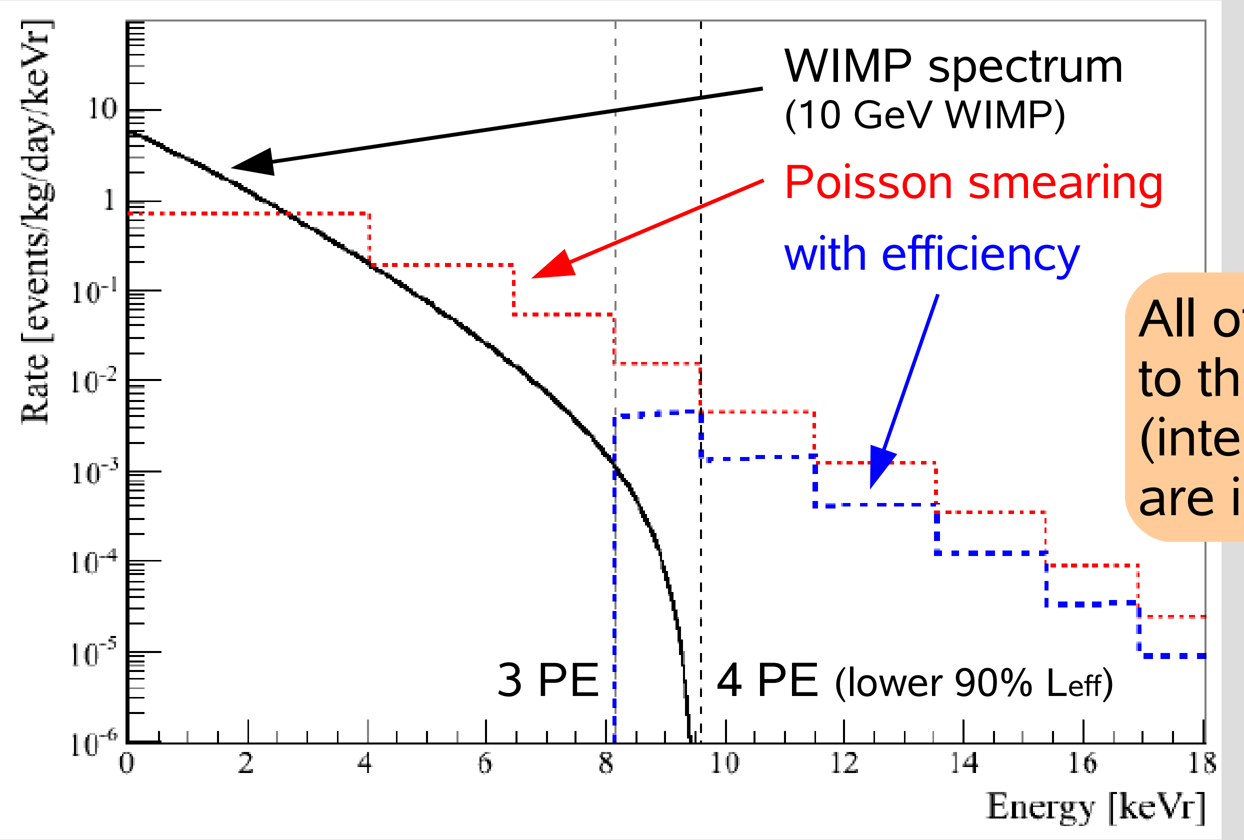


from: *Aprile et al., PRL 97, 081302 (2006)*



from: *Aprile et al., PRB 76, 014115 (2007)*

Poisson Smearing



All other contributions to the energy resolution (interaction in LXe etc.) are ignored here.

- Resolution at low *E* is dominated by Poisson counting statistics ➡ a few photoelectrons seen by PMTs
- WIMP spectrum is expeced to drop exponentially with *E* ➡ more events make it above threshold than vice versa