New Limits on SUSY WIMP Dark Matter from the XENON10 Experiment

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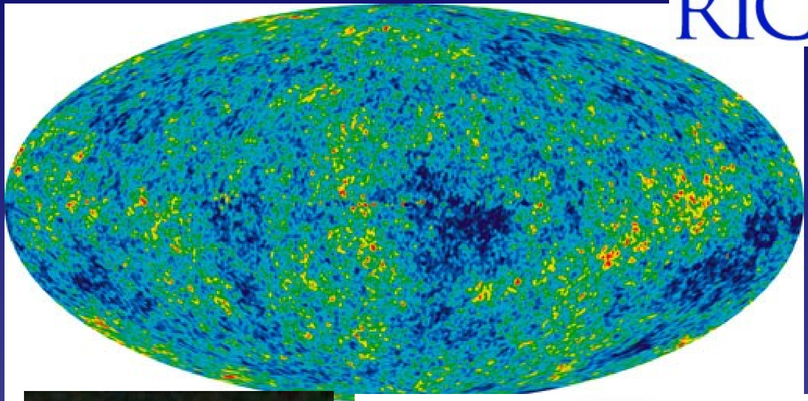
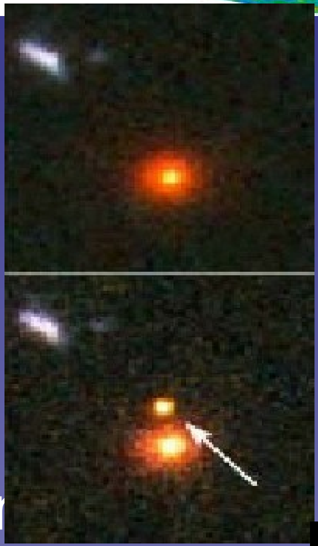
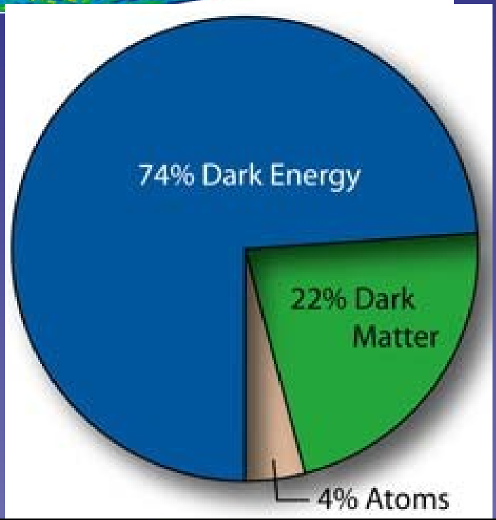
The ~~Dark~~ Transparent Universe

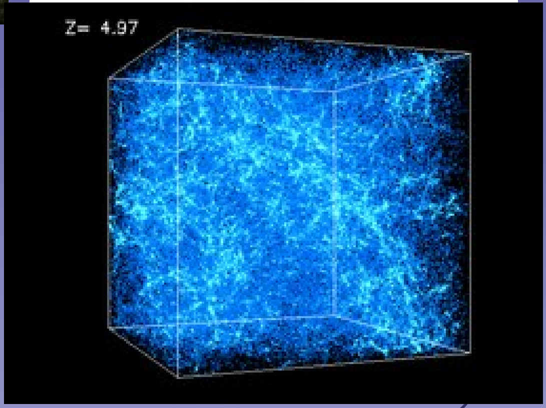
How do we know the cosmic recipe?

- Cosmic Microwave Background.
  - → Uniformity at age 380,000 yr.
  - → Geometry of the universe (with H_0).
- Supernovae as standard light beacons.
  - → Expansion history of the universe.
- Galaxy surveys (wide or deep) and Simulations of structure formation.
  - → Large scale structure.
  - → Early structure formation.
    First stars. Quasars and galaxies.
- Big Bang Nucleosynthesis and light ele abundances observed in the early universe.
  - → Limit on baryon density.
- Galaxy clusters, etc.









Evidence for Non-Baryonic Cold DM

$\Omega_i = \rho_i / \rho_c$

ρ_i: mass density of component i

$\rho_c = (1.9 \times 10^{-29})\ h^2\ \mathrm{cm}^{-3}$
critical density

$h = H_0 / 100\ (\mathrm{km/s})\ \mathrm{Mpc}^{-1}$:
Hubble parameter.

WMAP + galaxy surveys + SNe + BBN:

Total density: $\Omega_{Total} = 1.02 \pm 0.02$

Dark energy: $\Omega_\Lambda = 0.73 \pm 0.04$

Matter density: $\Omega_m = 0.27 \pm 0.04$

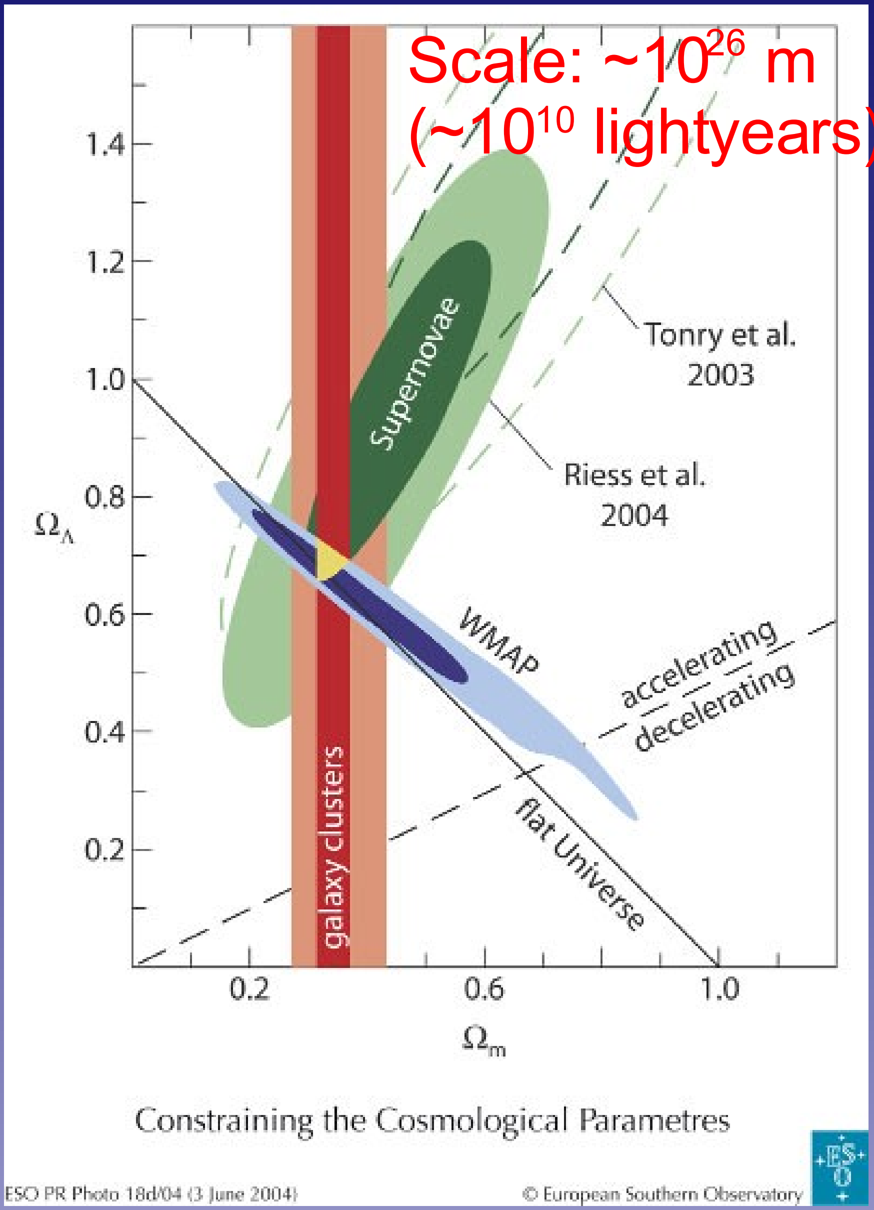
Baryon density: $\Omega_b = 0.044 \pm 0.004$

Neutrinos (HDM): $\Omega_\nu < \sim 0.015$

Non-baryonic Cold Dark Matter:

$\Omega_d = \Omega_m - \Omega_b = 0.22$

Scale: $\sim 10^{26}$ m
($\sim 10^{10}$ lightyears)

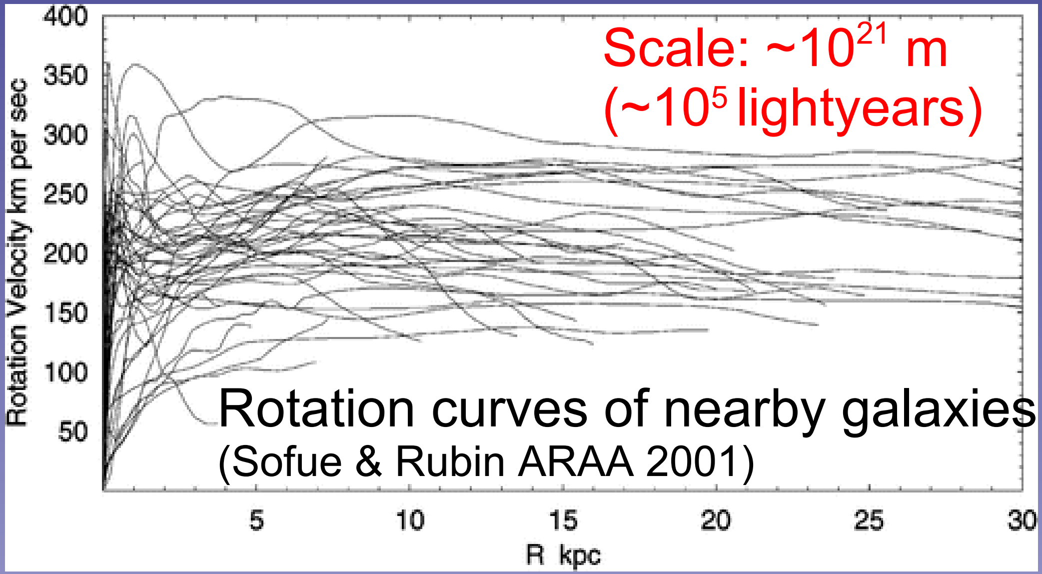


Evidence for Dark Matter in Galaxies and Galaxy Clusters

Spiral Galaxies

Rotation curves remain flat far beyond the edge of the visible disk.

$$\left.\begin{array}{lcl} v(R) & = & \sqrt{GM(R)/R} \\ v(R) & \approx & const \end{array}\right\} \Rightarrow \left\{\begin{array}{lcl} M(R) & \propto & R \\ \rho(R) & \propto & R^{-2} \end{array}\right.$$



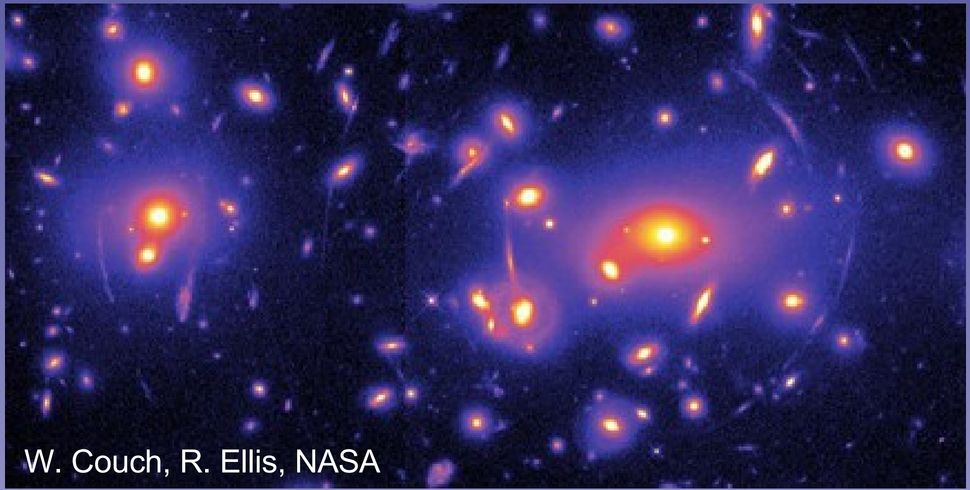
Scale: ~10^{21} m (~10^{5} lightyears)

Rotation curves of nearby galaxies (Sofue & Rubin ARAA 2001)

Galaxy Clusters

Scale: ~10^{22} m (~10^{6} lightyrs)

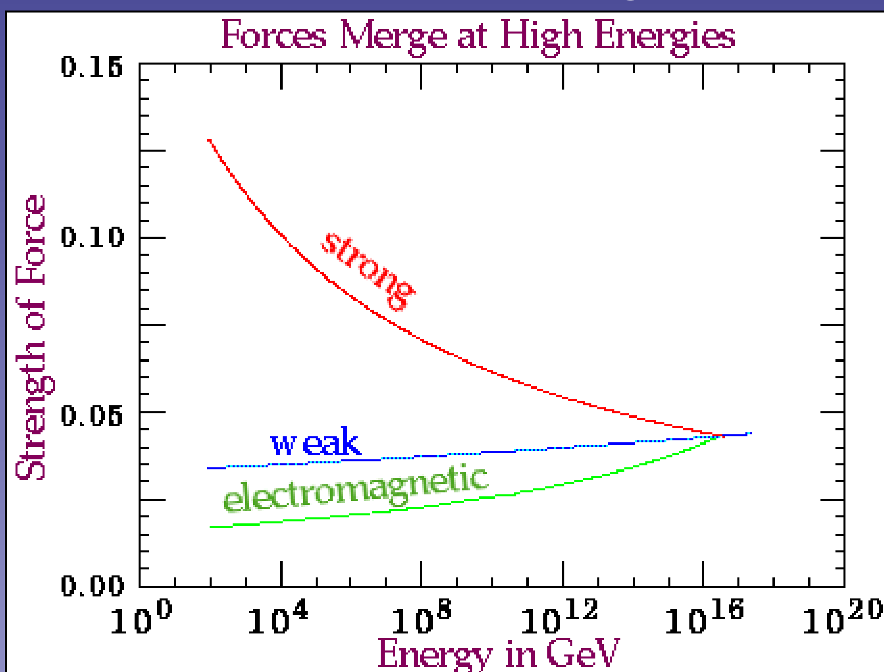
- Orbital velocities of galaxies > escape velocity
- X-ray gas: pressure too great for visible mass.
- Gravitational lensing: measures total mass distribution in clusters.

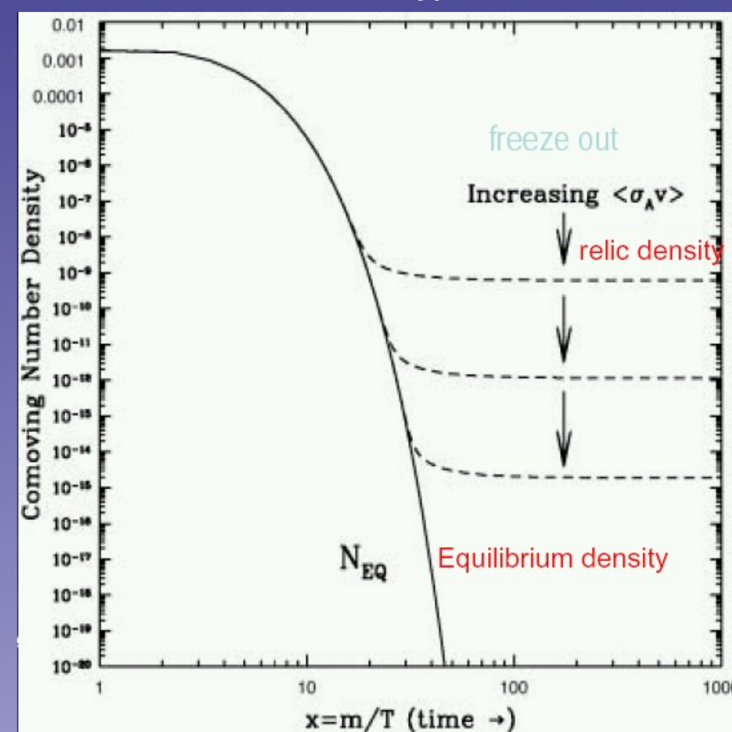


W. Couch, R. Ellis, NASA

Dark Matter: A Relic of SUSY WIMPs?

- The Standard Model (SM) is incomplete.
- Dark Matter and Dark Energy: striking evidence for physics beyond the SM.
- Postulate of “Supersymmetry” (SUSY) between fermions and bosons: each fermion (boson) in the SM has a bosonic (fermionic) SUSY counterpart.
  - SUSY partners of particles: “sparticle” (squarks, selectrons, etc.).
  - SUSY partners of gauge bosons: “gauginos”. (wino, zino, etc.)
- SUSY was invented to solve problems in particle physics (e.g., GUT), ***not*** to explain DM. It provides a natural DM candidate if the lightest SUSY particle is ~stable. The mass eigenstate of the LSP is called **neutralino** χ



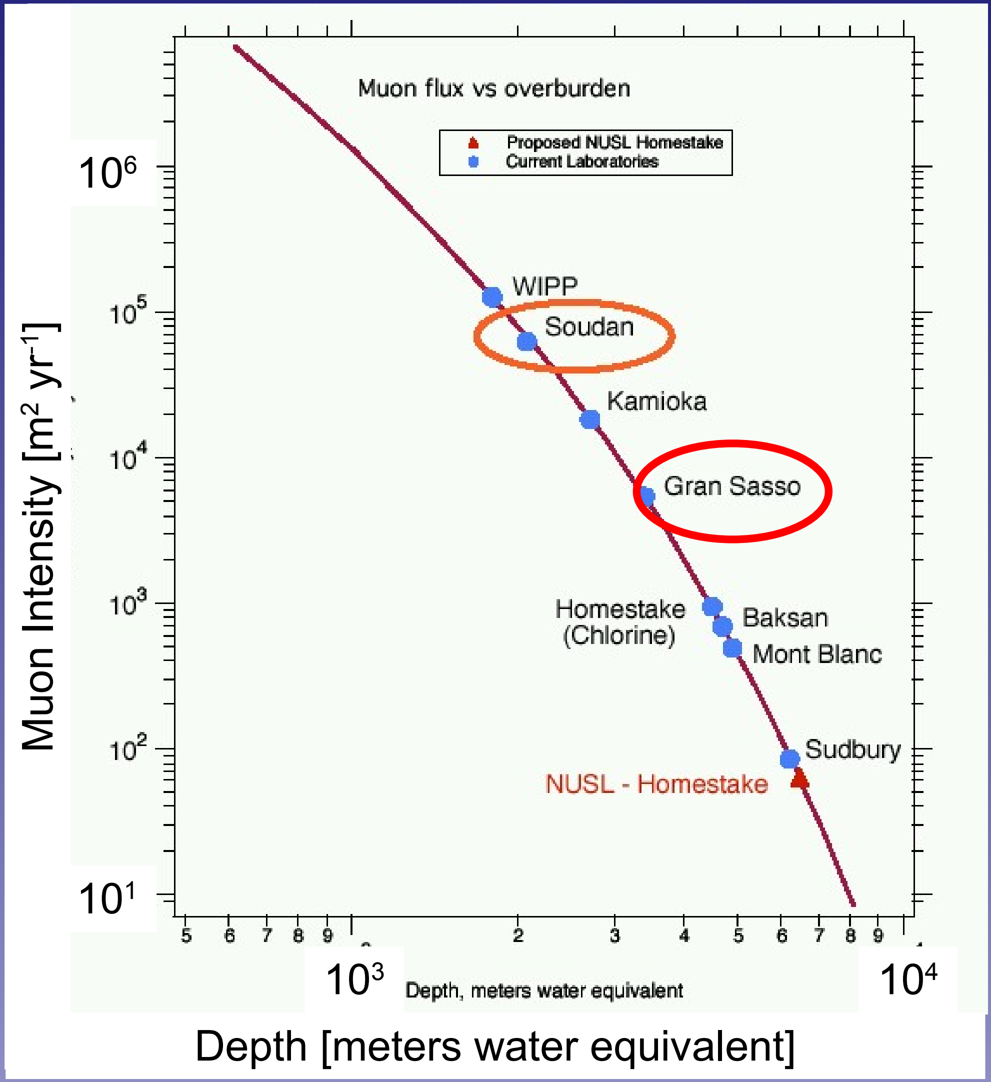


WIMP DM Direct Detection

- Elastic scattering of WIMP's χ off of nuclei A.
- Energy spectrum and rate depend on WIMP distribution in DM halo.
- Standard spherical halo: featureless continuum with <E> ~ 50 keV.
- **Scattering rate ~ N (ρ_χ/m_χ) $\langle\sigma_{scat}\rangle$**
  - → N: number of target nuclei in the detector
  - → ρ_χ/m_χ: local number density of WIMPs
  - → $\langle\sigma_{scat}\rangle$: velocity-averaged scattering cross section.
- ρ_χ, v_χ : given by DM halo model.
  - → Typical ρ_χ ~ 0.3 GeV/cm^3, (ρ_χ/m_χ) ~ 1-10 / liter
  - → v_χ ~ 230 km/s
- Cross-sections:
  - → spin-dependent: coupling of spins of nucleus and neutralino ~J (J+1)
  - → spin-independent: coupling to mass of nucleus ~A^2 (* nuclear form factor)
- Rate: 10^{-1} – 10^{-5} events / kg / day

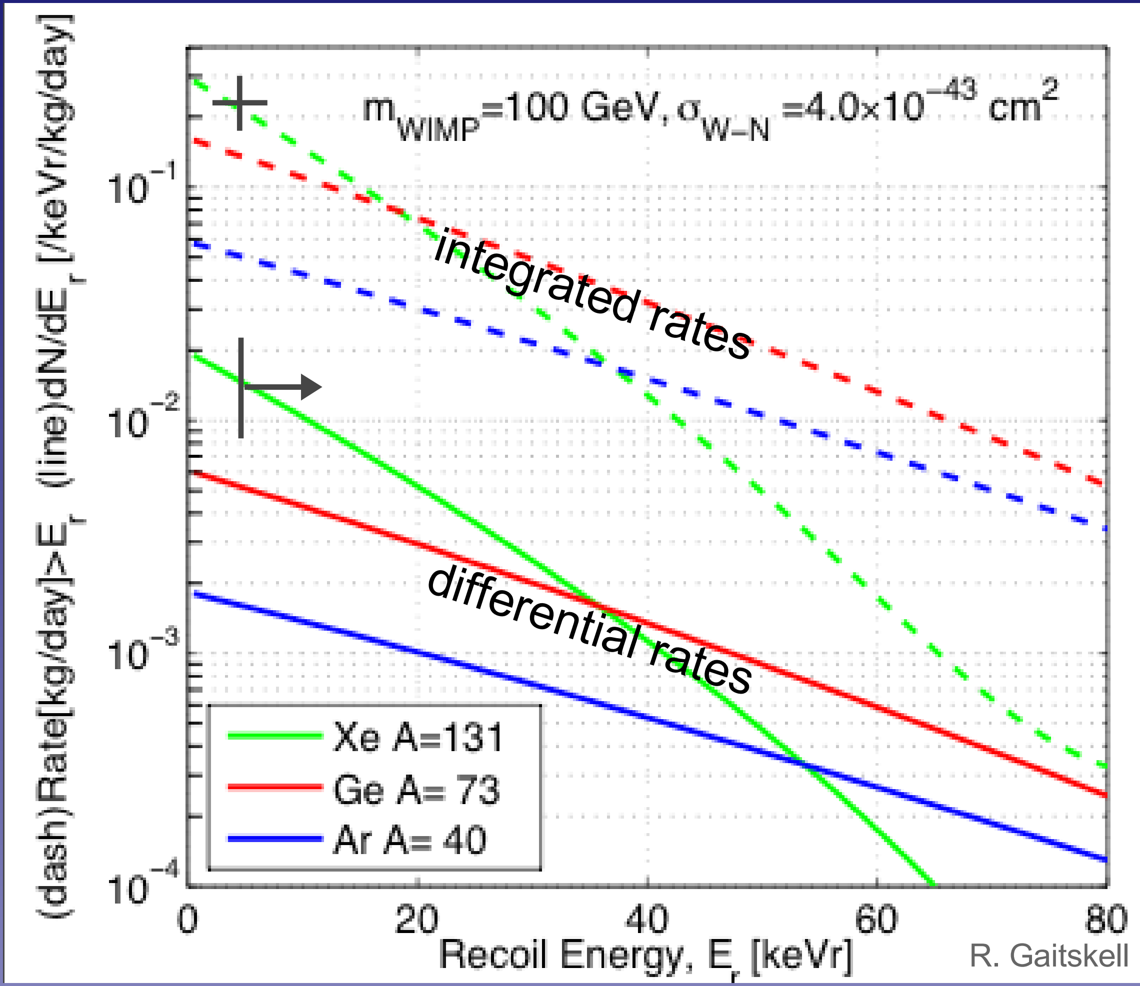
Backgrounds in Direct DM Search

- Cross-sections are *very* small: <10^{-43} cm^2 or 10^{-7} pb (spin-independent)
- Without background, sensitivity $\propto$ (mass × exposure time)$^{-1}$
- With background subtraction $\propto$ (M t)$^{-1/2}$
- Backgrounds:
  - → Gamma-rays & beta decays: ~100 events/kg/day
    - Need efficient β and γ background discrimination.
    - Shielding: low-activity lead, water, noble liquids (active), liquid N_2, ...
  - → Neutrons from (α, n) reactions in rock: ~ 1 event/kg/day (LNGS)
    - Neutron moderator (polyethylene, paraffin, ...)
  - → Neutrons from CR muons: depends on depth.



Liquid Xenon for Dark Matter Search

- Large atomic number A~131 best for SI interactions (σ~A^2) if low threshold
- ~50% odd isotopes: very good for SD interactions
- No long-lived isotopes. Kr-85 reduction to ppt proven.
- High Z (54) and density:
  - → compact & self-shielding
- Scalability to large mass for σ~10^{-46} cm^2 ~ 1evt/100kg/yr
  - → cost
  - → "easy" cryogenics (-100°C)
- Efficient scintillator
- Background discrimination
  - → Ionization/Scintillation
  - → 3D imaging of TPC



XENON Collaboration

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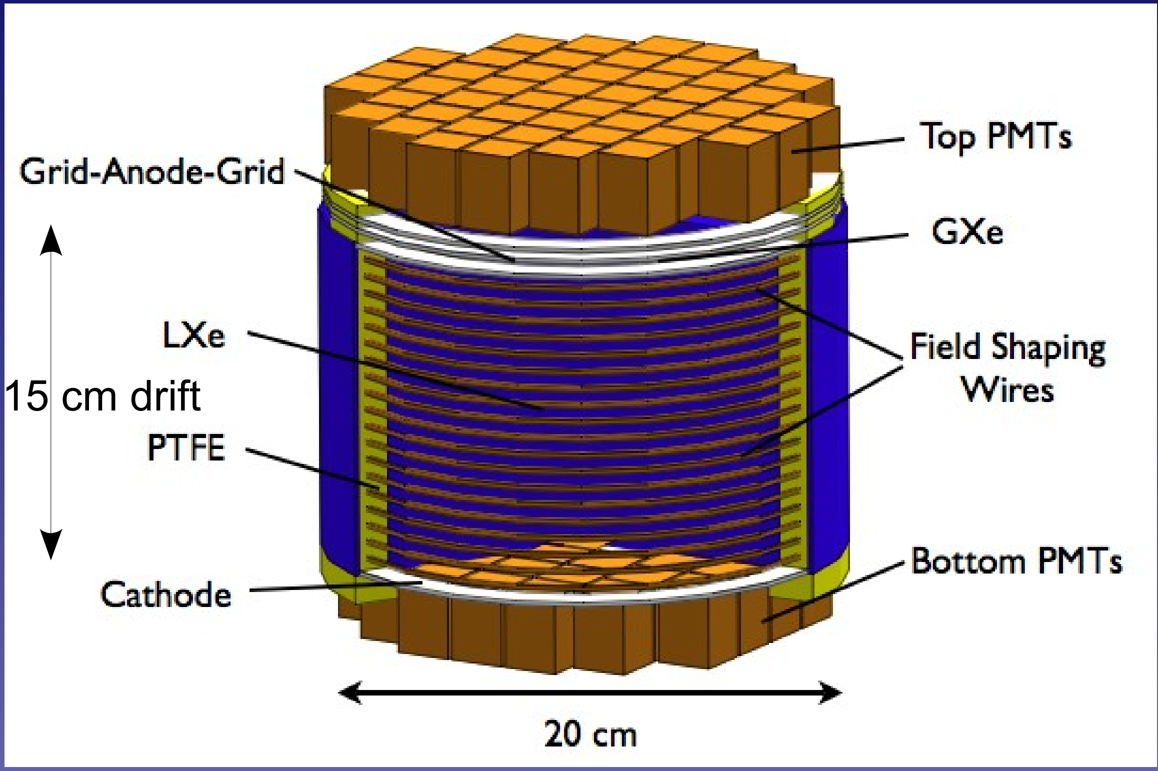
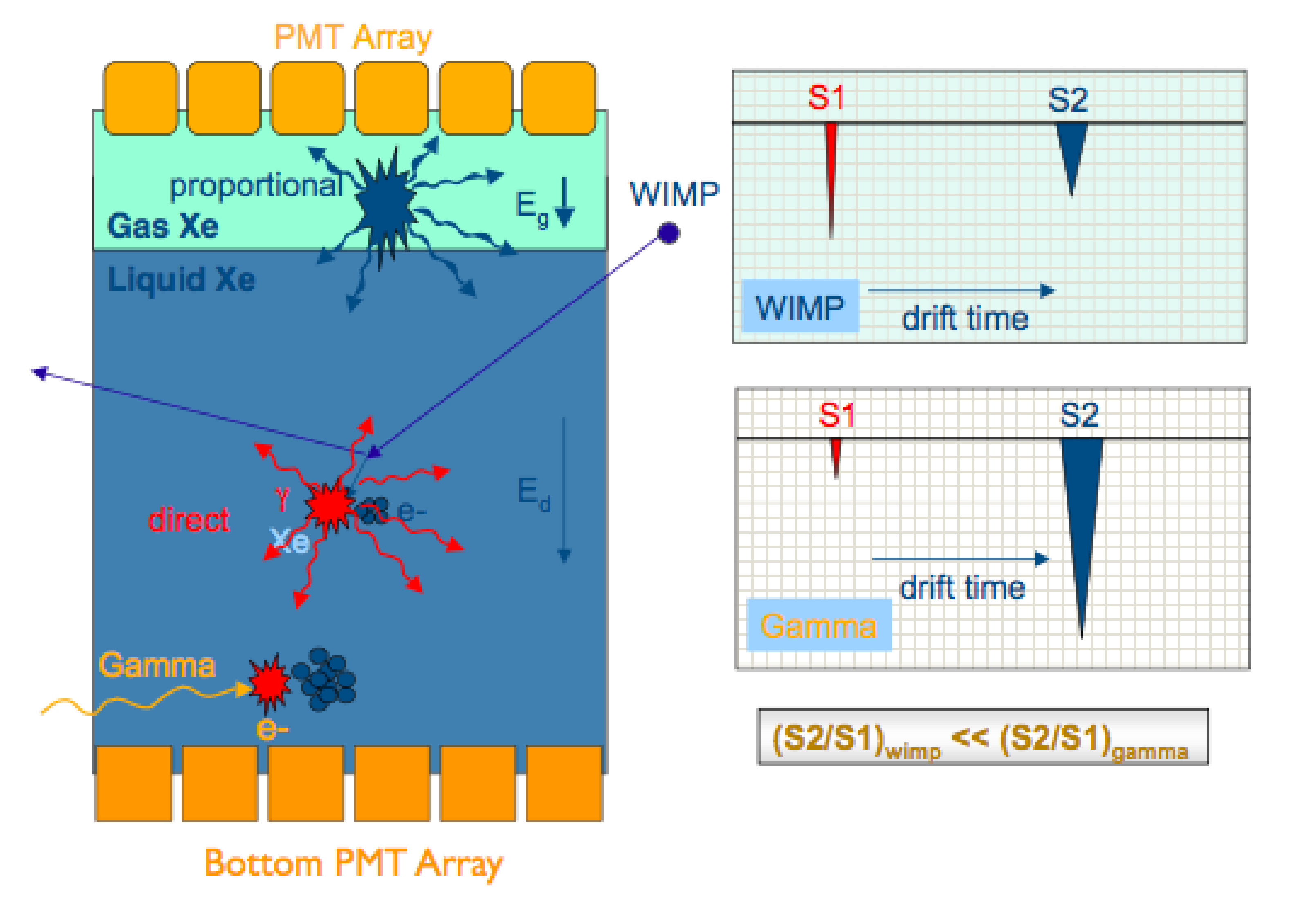
XENON – Principle of Operation

- Dual phase liquid-gas xenon TPC at ~ -94°C / 2 bar.
- Wimp recoil at Xe nucleus in dense liquid (2.85 g/cm^3) → Ionization + UV Scintillation.
- Detection of primary scintillation light (S1) with PMTs on top (48) and bottom (41).
- PTFE cylinder for reflectivity.
- Charge drift towards liquid/gas interface at field of ~ 0.7 kV/cm.
- Charge extraction liquid/gas at high field (5 kV/cm) between 1st mesh (liq) and anode mesh (gas).
- Proportional scintillation in gas phase converts charge signal in amplified light signal (S2).

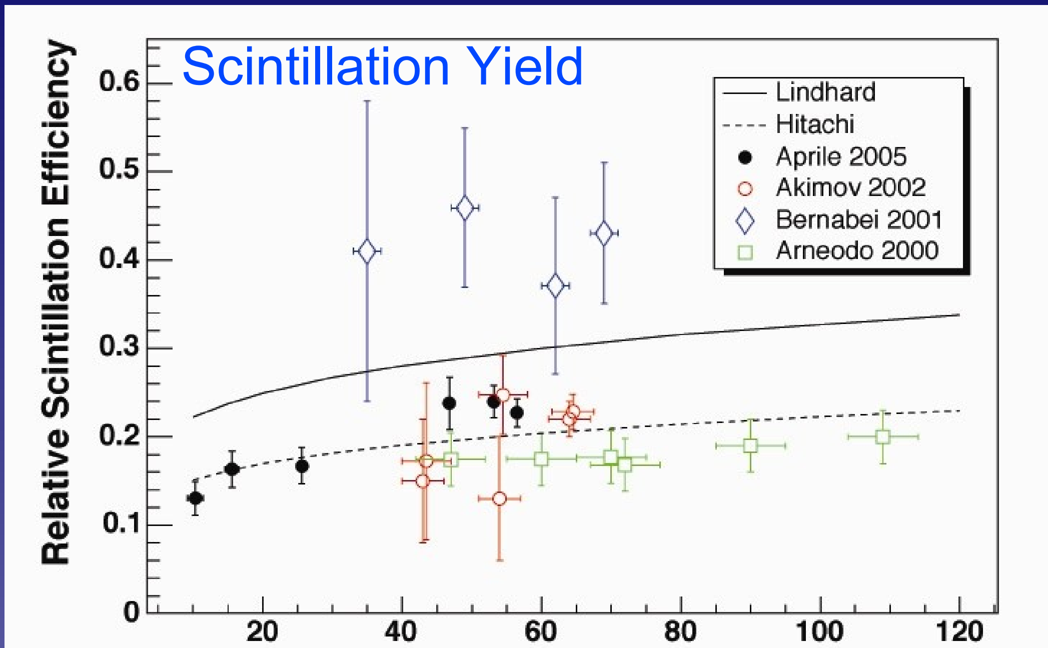


- 3D position measurement:
  - → X/Y: from S2 signal, resolution few mm due to small PMT size (1”).
  - → Z: from electron drift time (~1 mm).
- 20 cm diameter, 15 cm drift length.
- 14 kg LXe, ~ 6 kg fiducial mass.

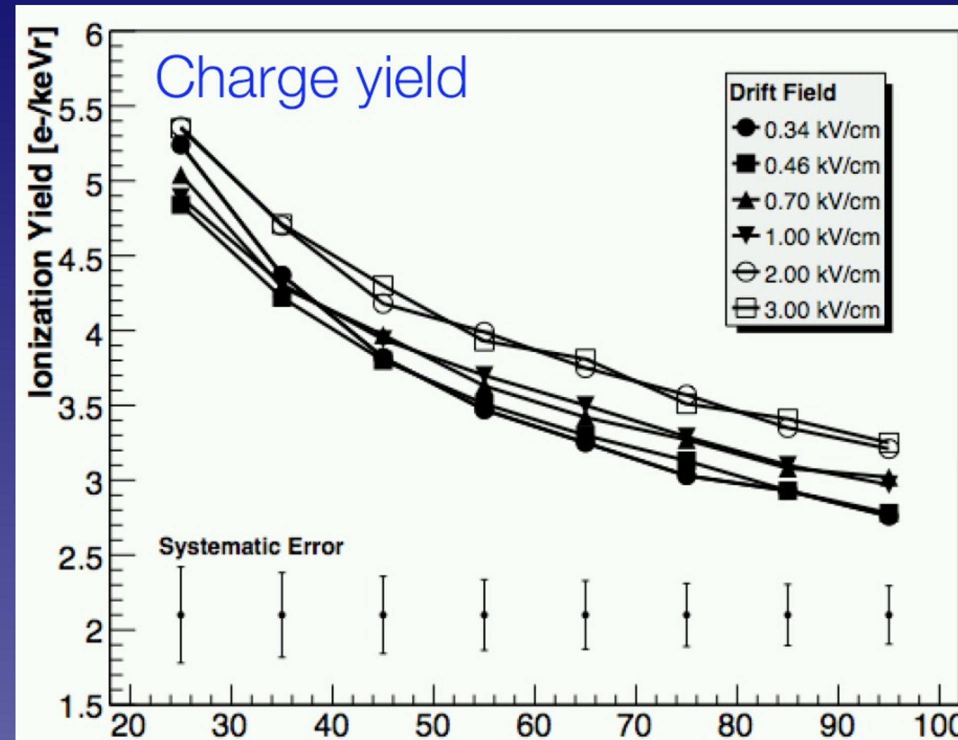
XENON – Background Discrimination



Nuclear Recoil Scintillation and Ionization Yields in LXe



Aprile et al., Phys. Rev. D 72 (2005)



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

Nuclear Recoil vs. Electronic Interaction Energy Scale: $E_r\, S_r\, L_{\mathrm{eff}} = E_e\, S_e$

E_e: linear electron interaction scale

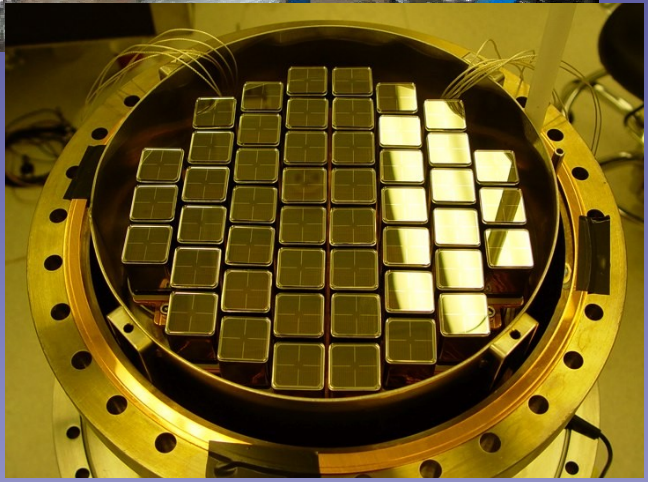
L_{eff}: effective Lindhard factor $(\vec{E}=0)$

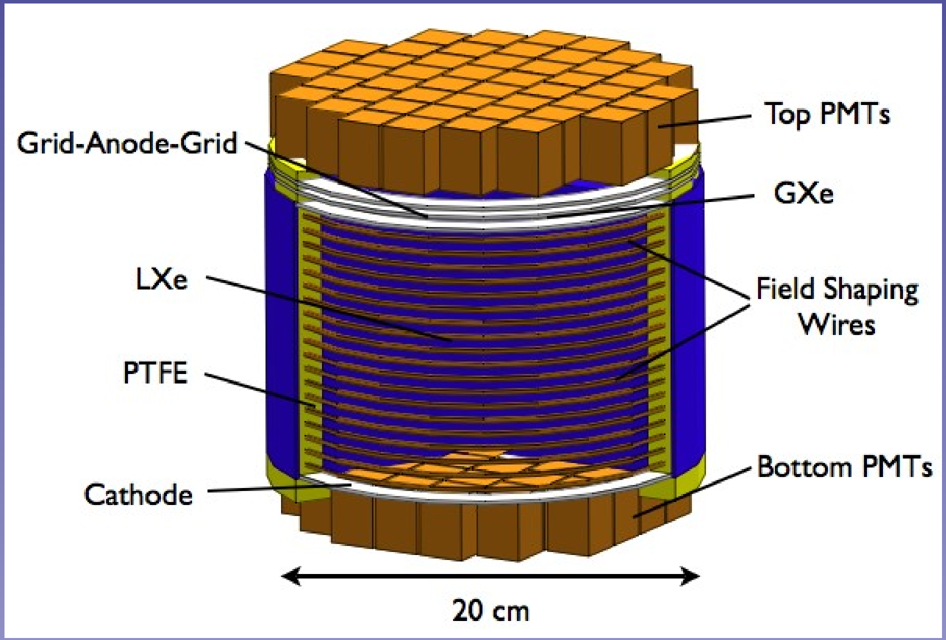
$S_x(|\vec{E}|)$: scintillation loss due to recombination suppression

Charge yield measurement of low energy nuclear recoils in LXe.

- Yield increases at low recoil energies.
- Weak field dependence.

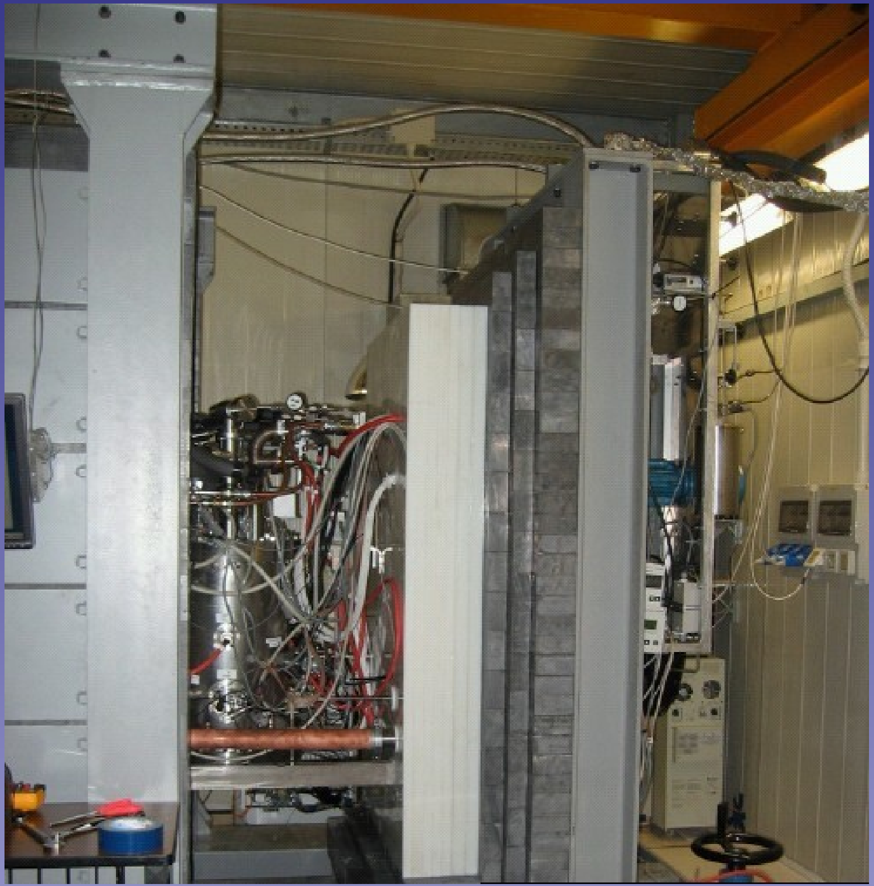
XENON-10 Assembly at LNGS

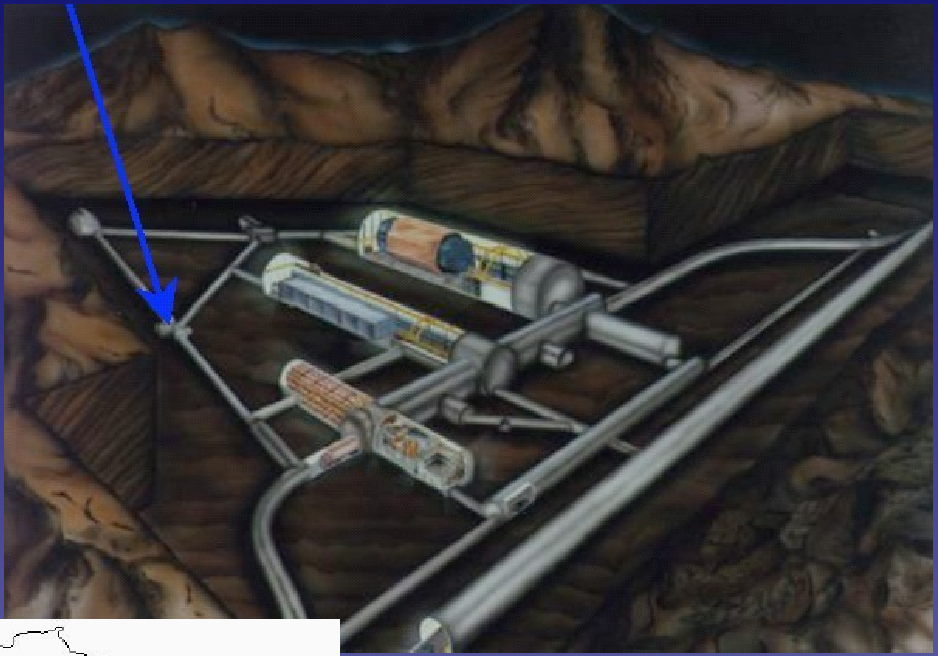


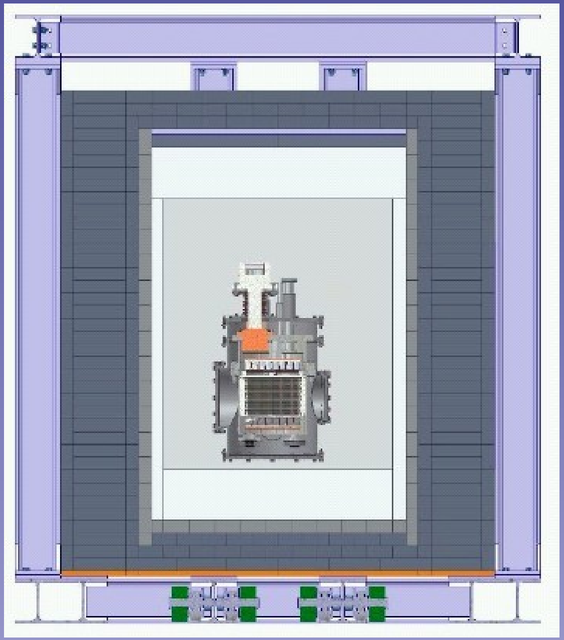


XENON-10 Dark Matter Search at LNGS

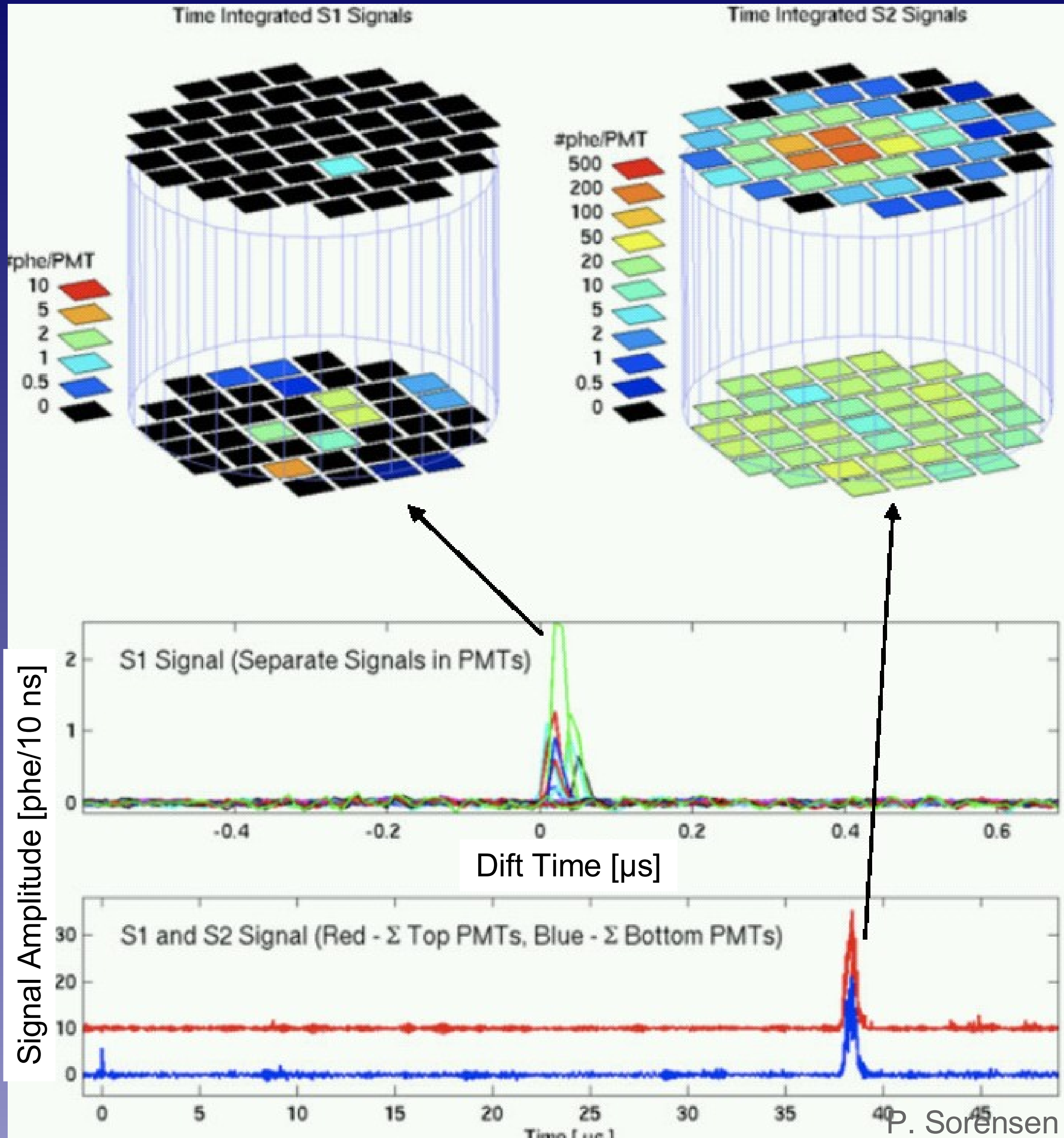
- XENON10 operating at LNGS (Gran Sasso, Italy)
- Since August 2006: Operation inside shield, DM search & calibrations.
- Oct'06 – Feb'07: First DM run (+cal.)



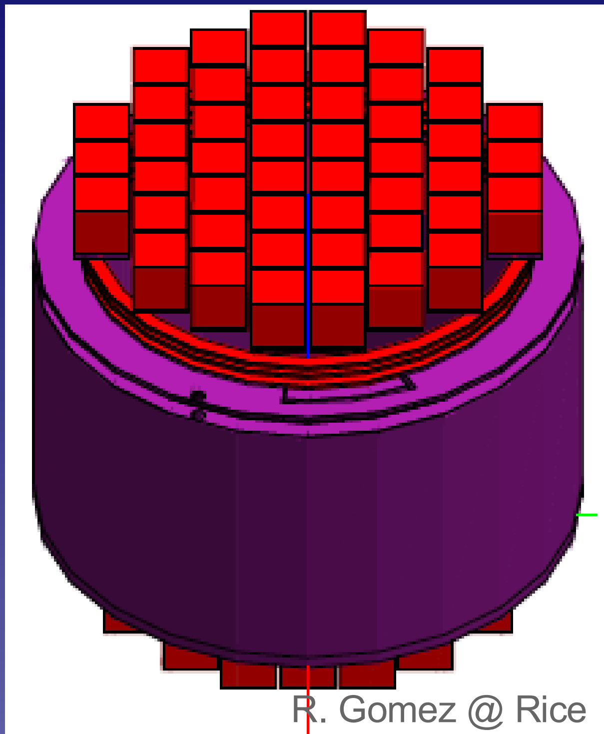


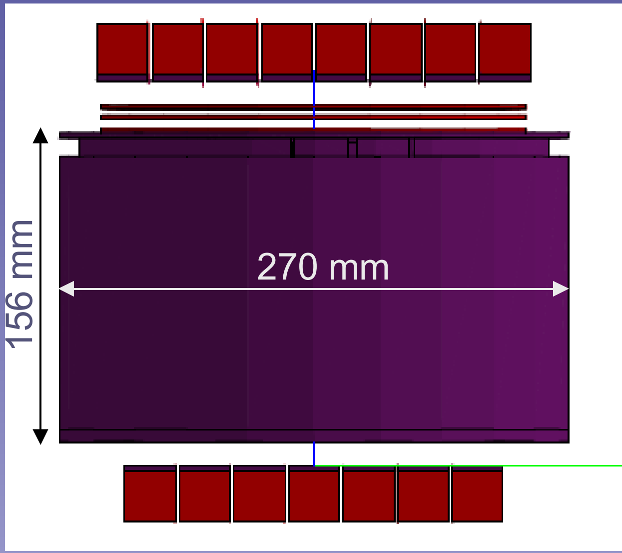


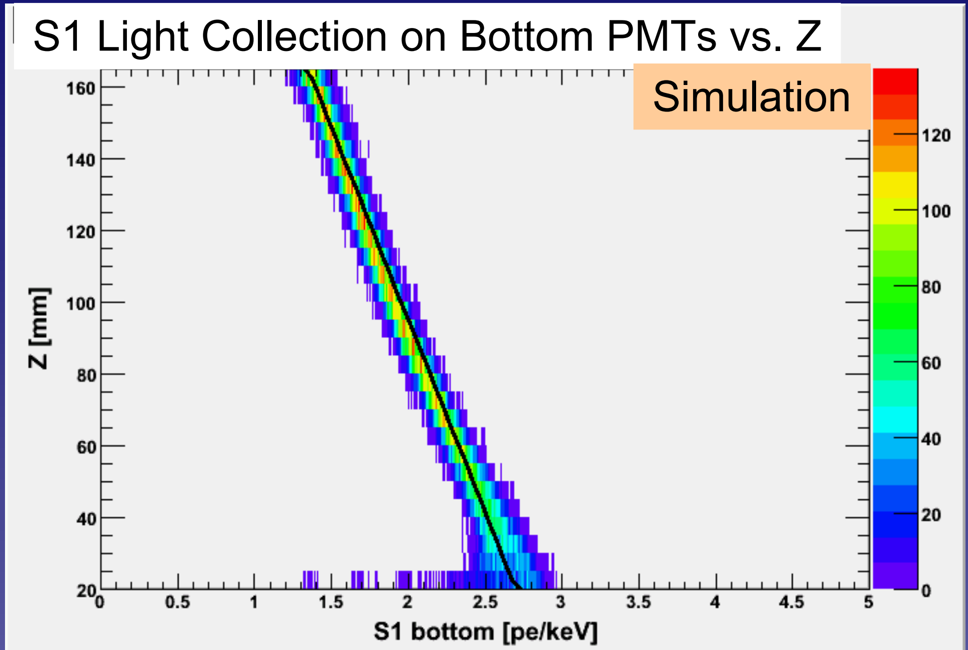
XENON-10 Events

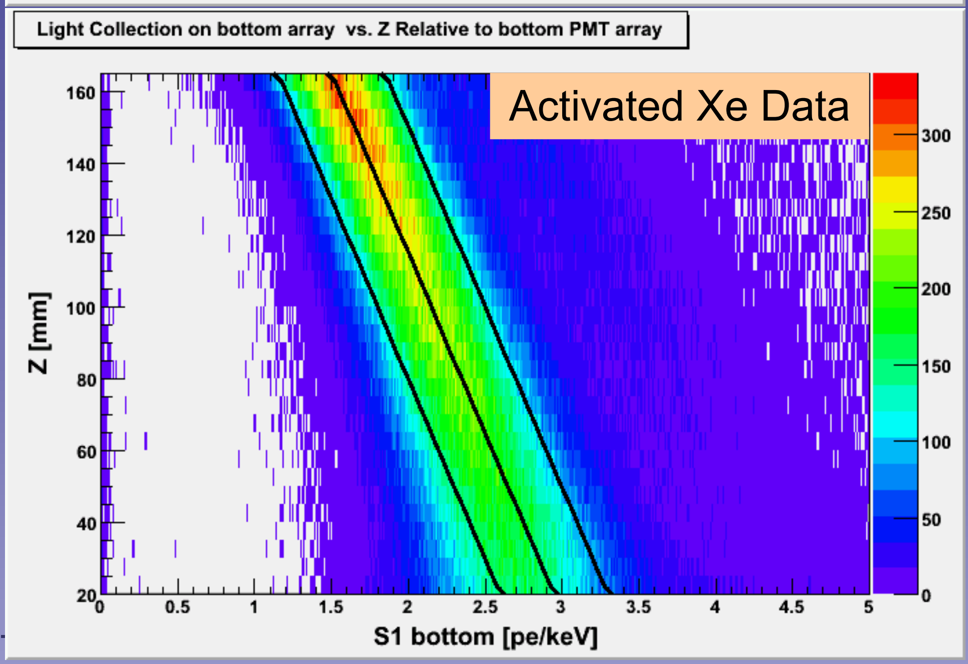


Simulation of XENON10 Light Response

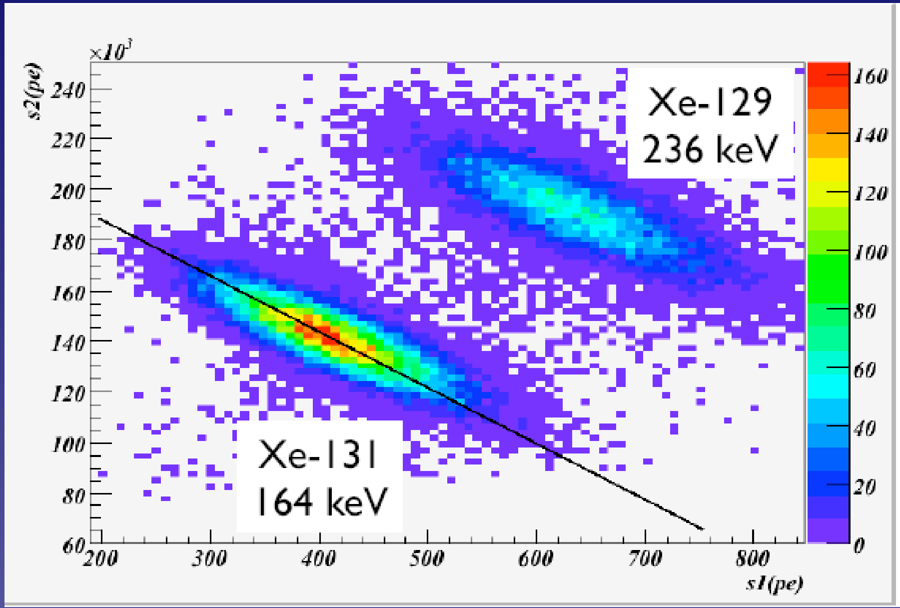


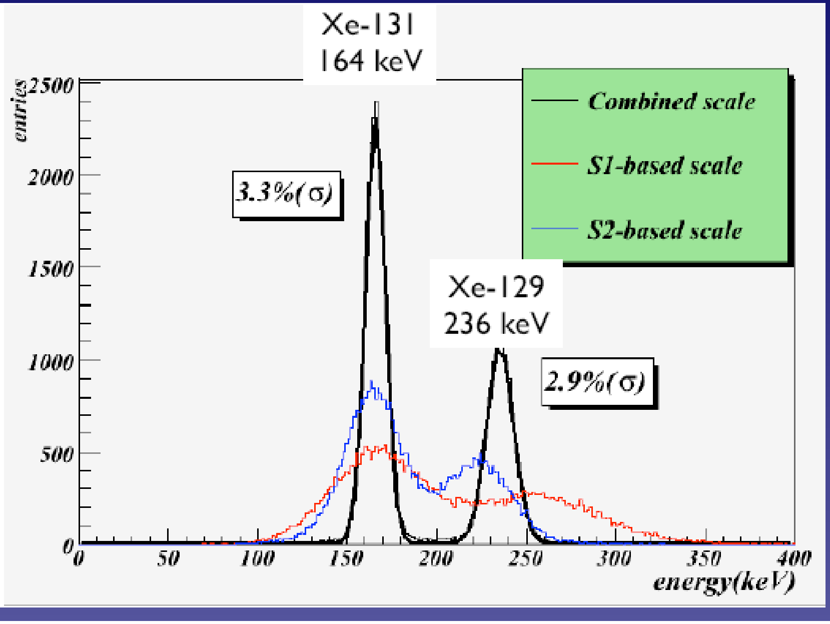




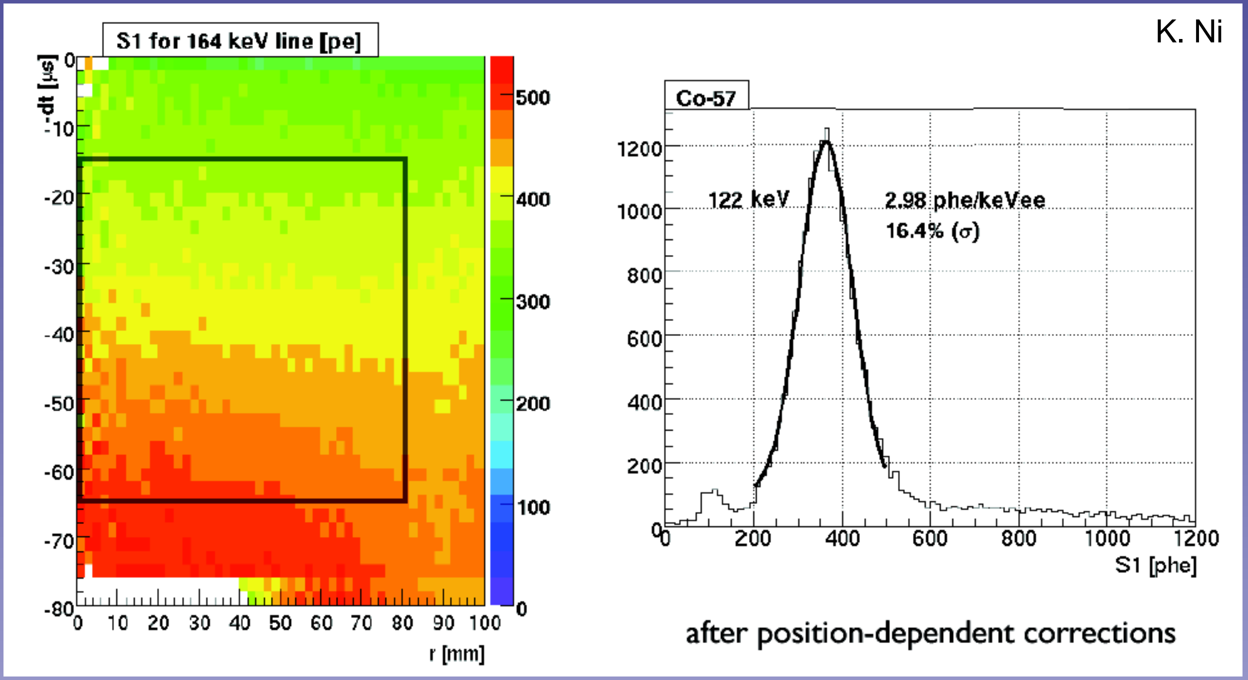


Xe Neutron Activation: 3D Gamma Calibration

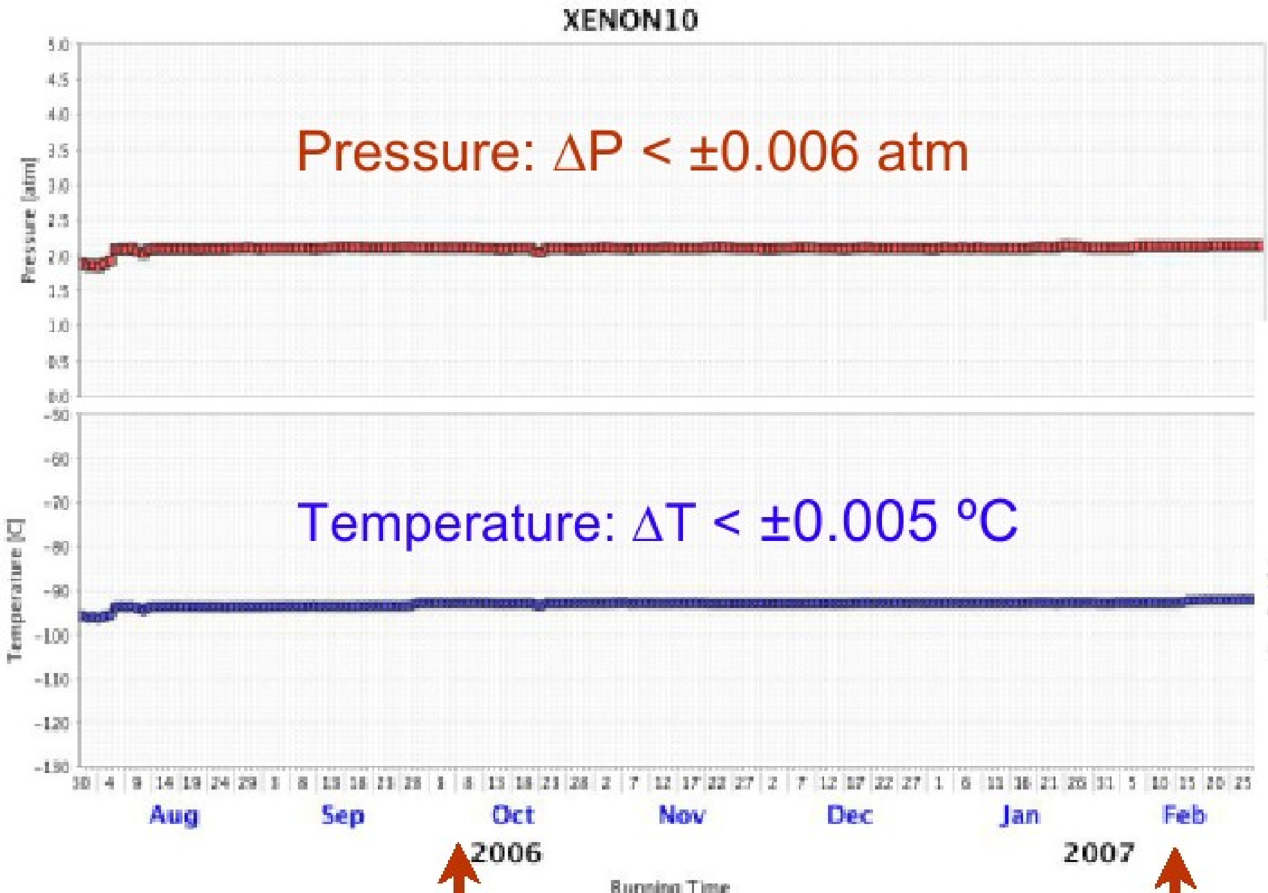


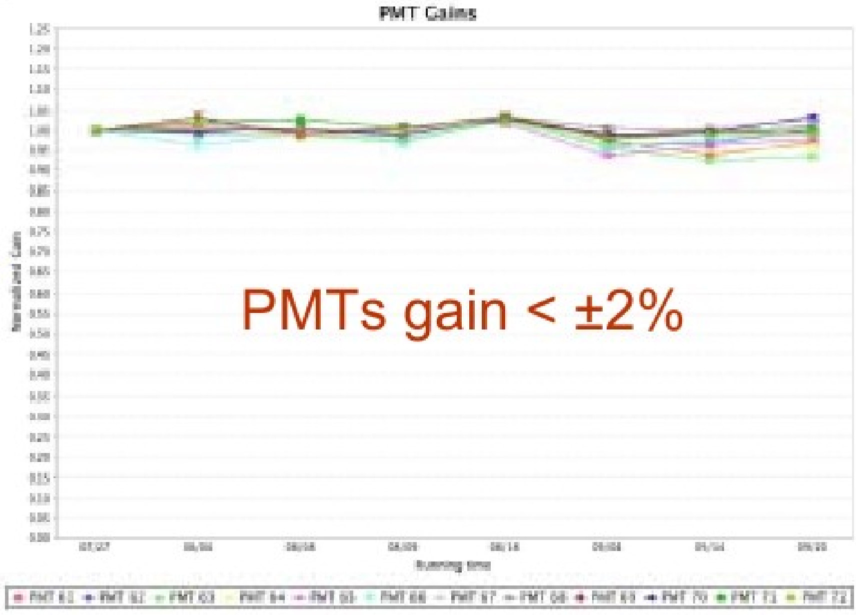


- Uniform distribution of line source.
- Accurate position dependent corrections:
  →in 3D for S1
  →in x/y for S2



Xenon10 Stability of Operation

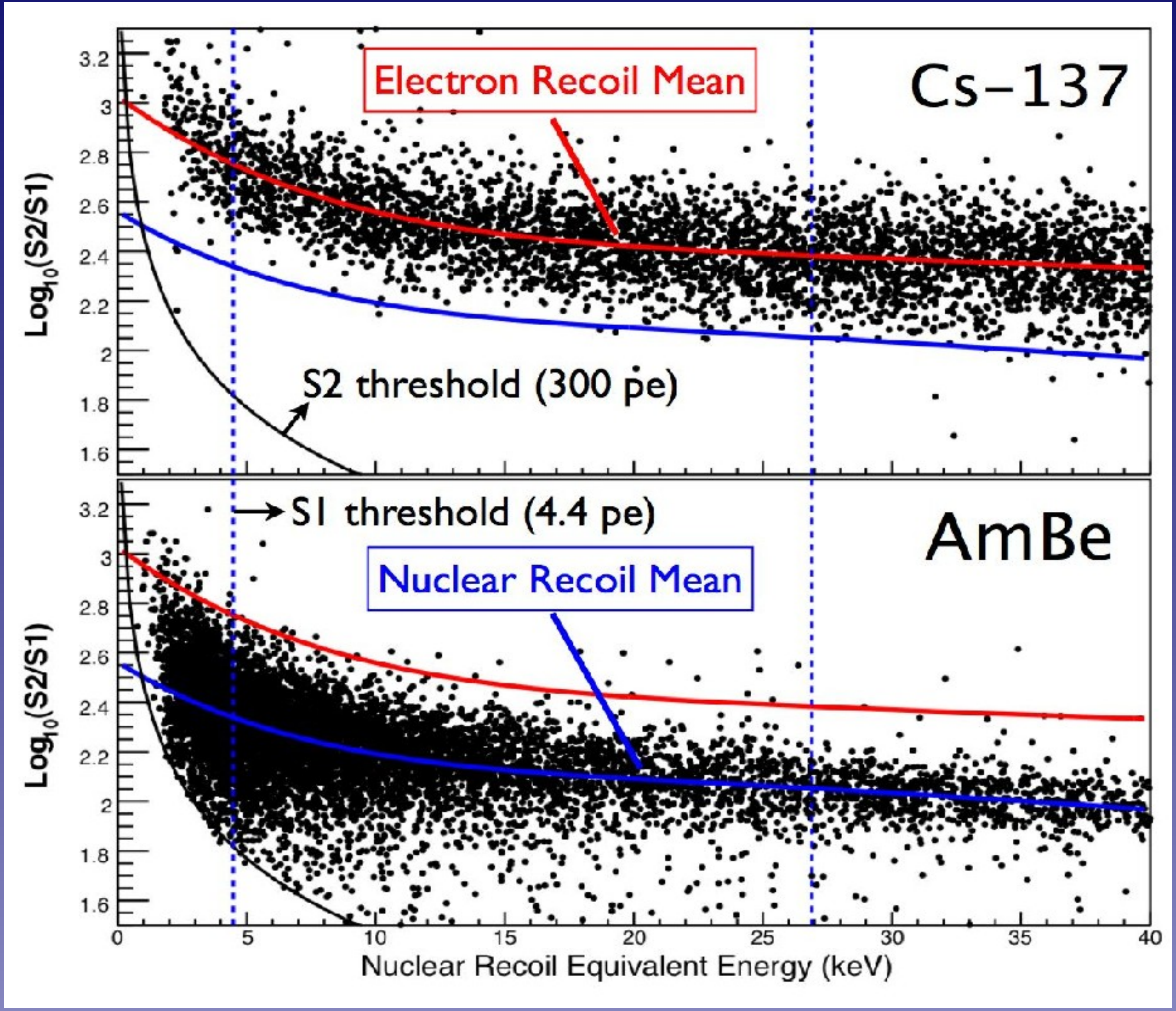




Start of Blind WIMP Search

End of Blind WIMP Search

XENON10 Background Rejection: S2/S1



Gamma Calibration (ER band)

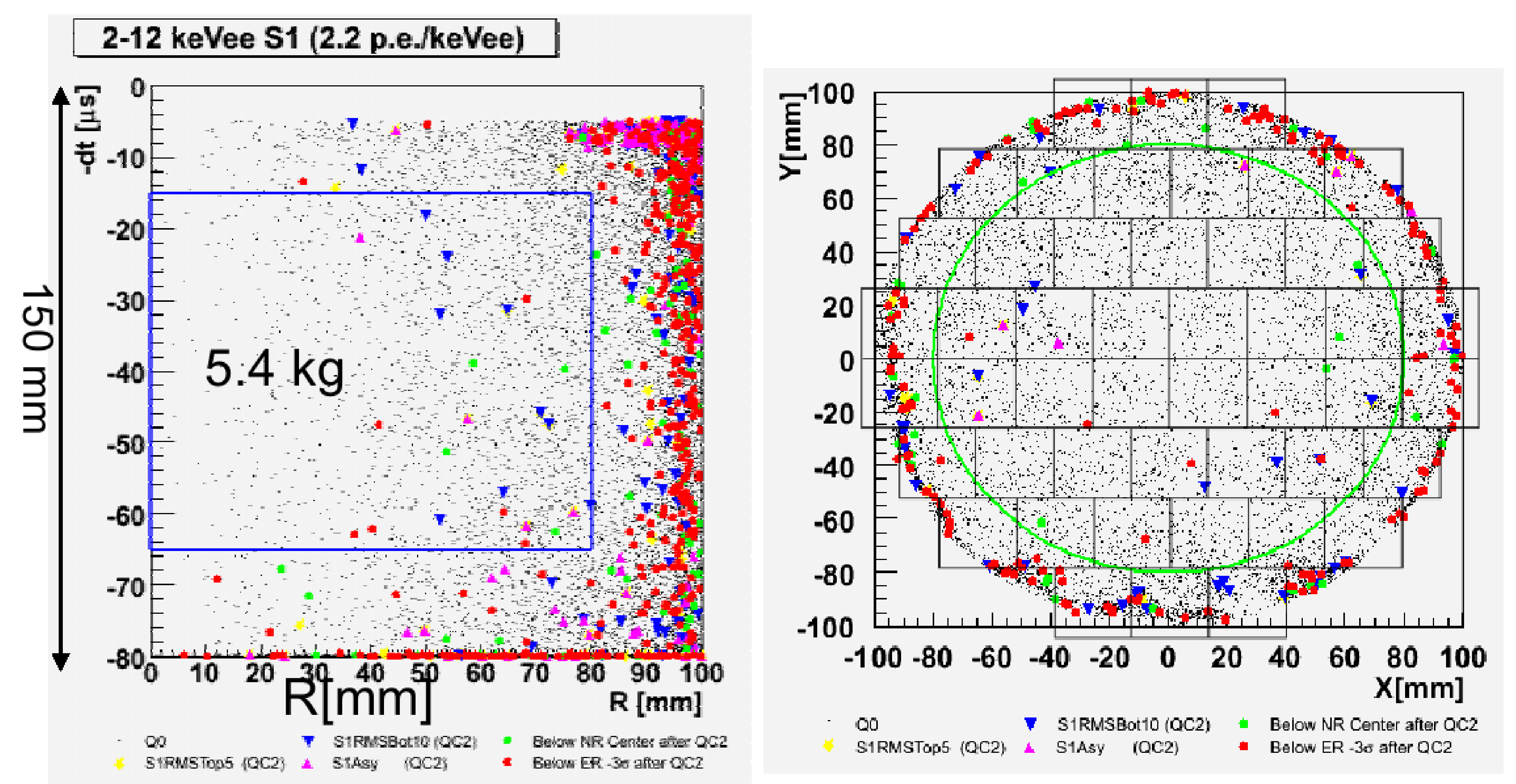
- Weekly
- Cs-137 source (1 kBq) in shield

Neuton Calibation (NR Band)

- Dec 1, 2006 (12 h)
- AmBe source (3.7 MBq) in shield

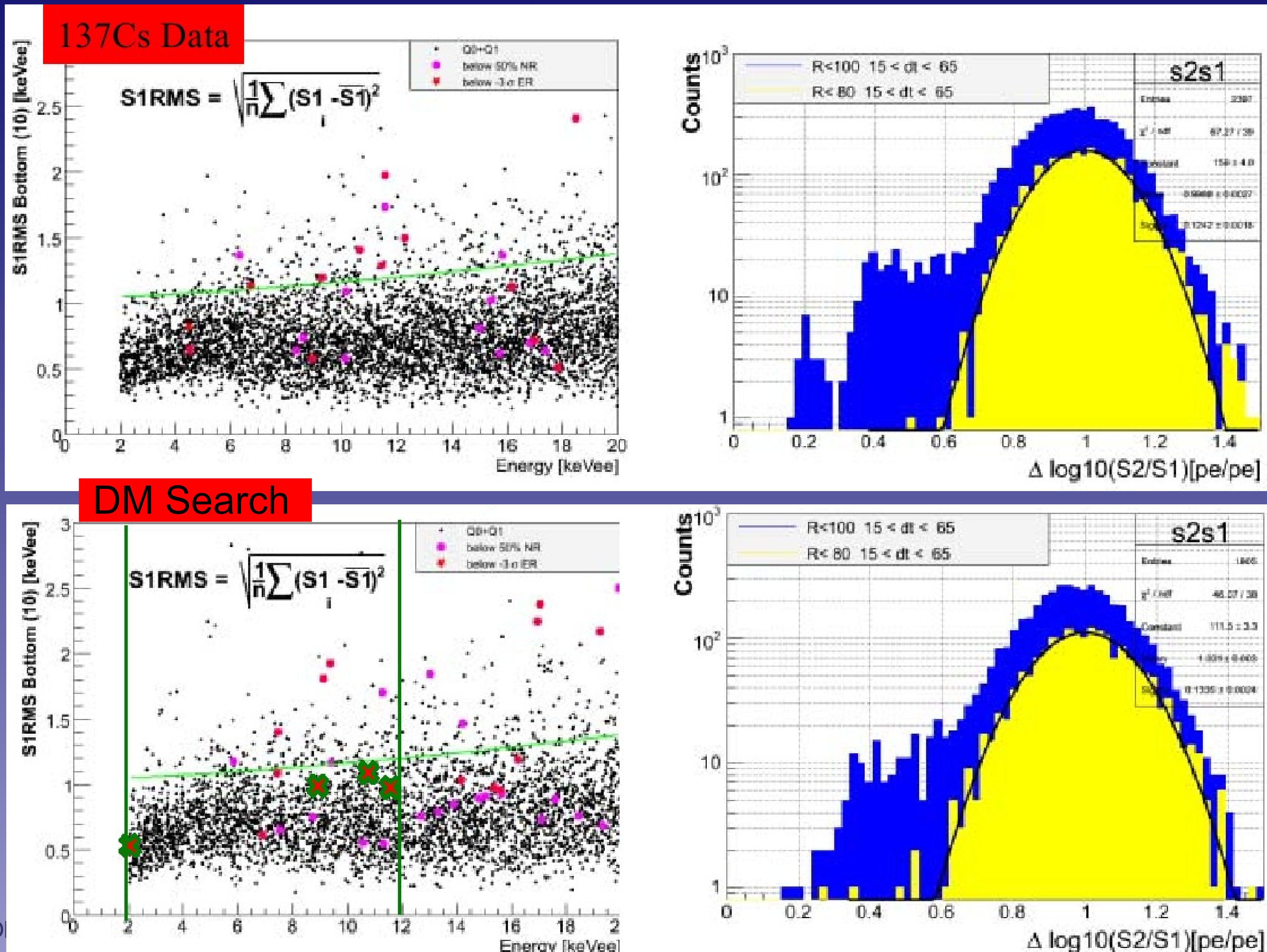
99.5% background rejection (99.9% at low E) at 50% acceptance.

XENON10 Background Rejection: Spatial



13 events inside fiducial volume removed by final quality cut.

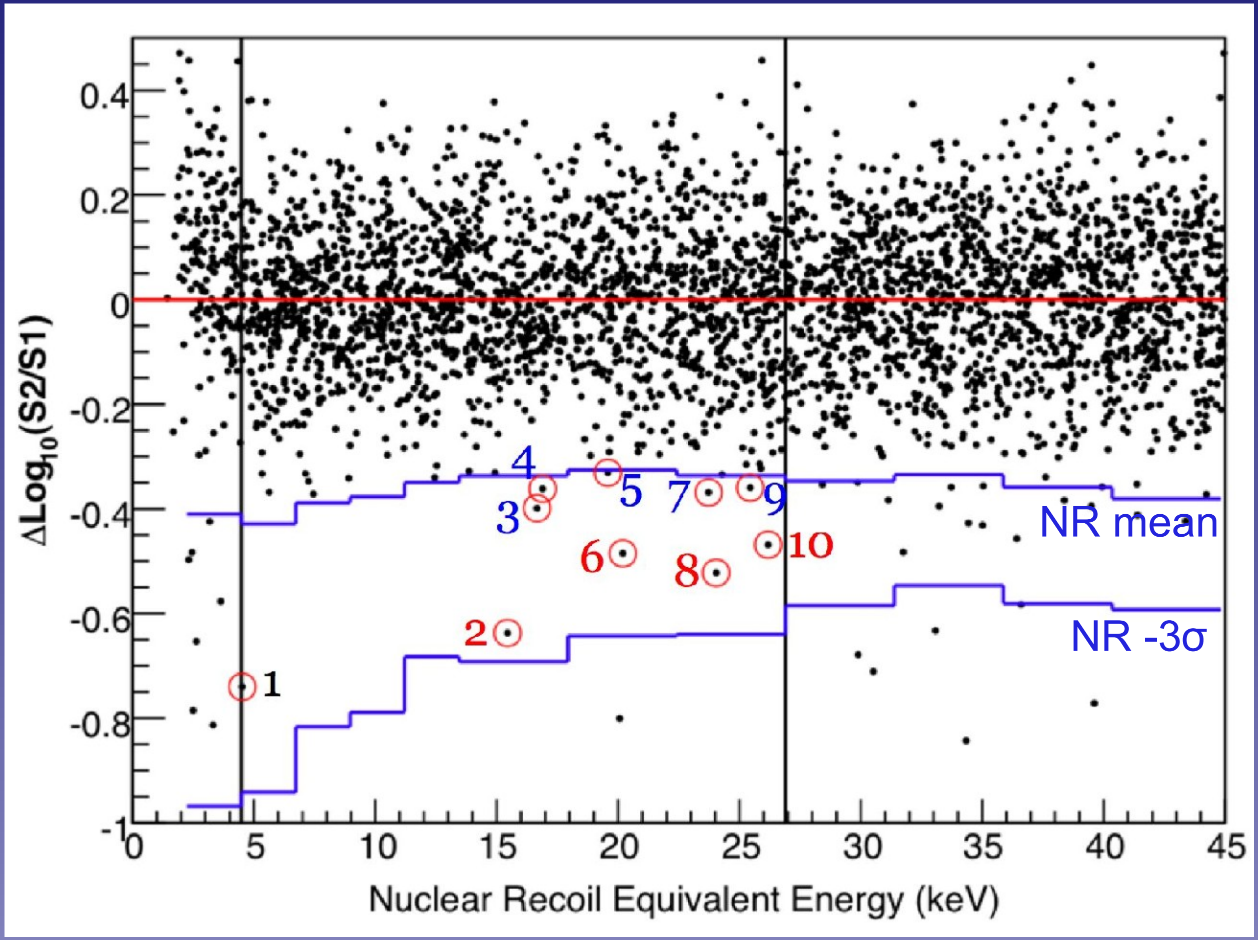
Elimination of Non-Gaussian Leakage Example: “S1rms” Data Cut



XENON10 WIMP Search with Blind Cuts

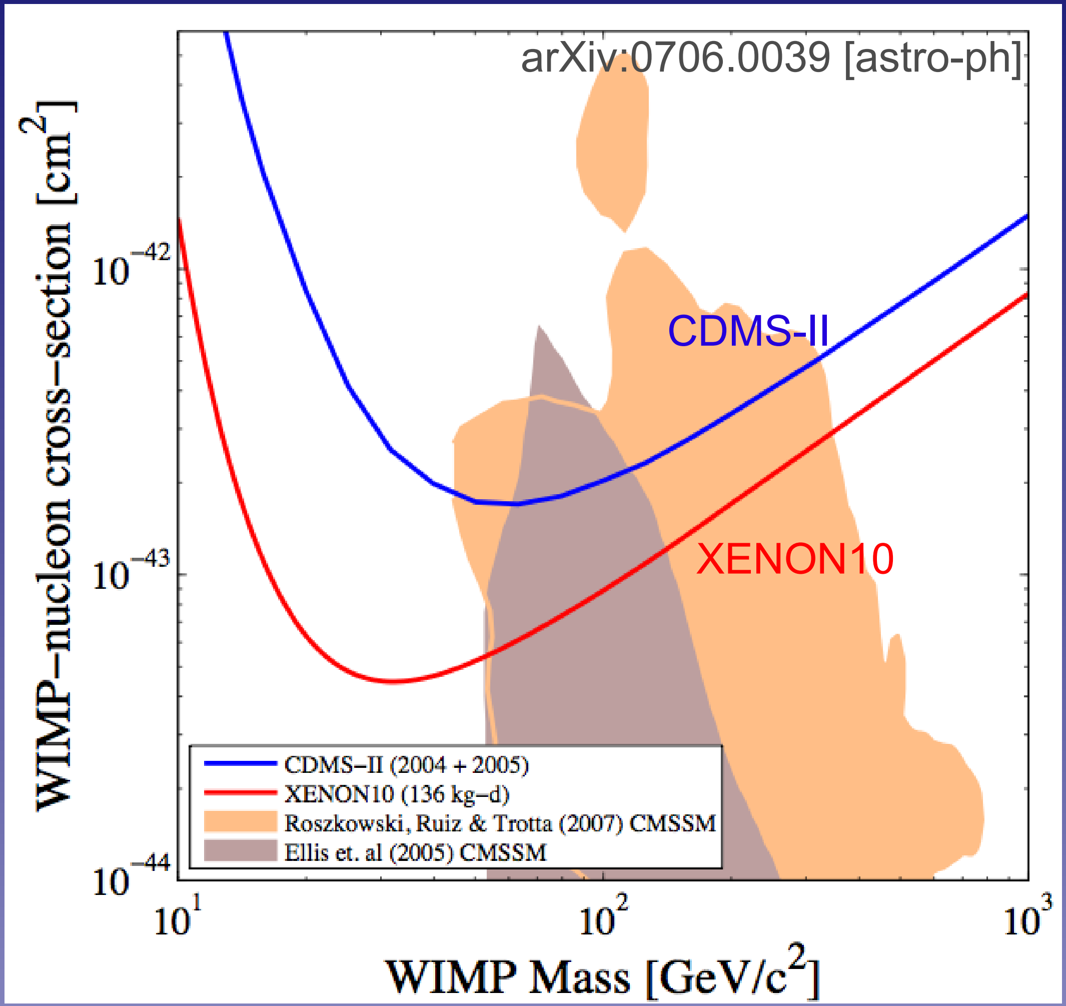
Oct 6, 2006 – Feb 14, 2007: 136 kg days exposure

(58.6 live days × 5.4 kg × 0.86 cut efficiencies × 0.50 NR acceptance)



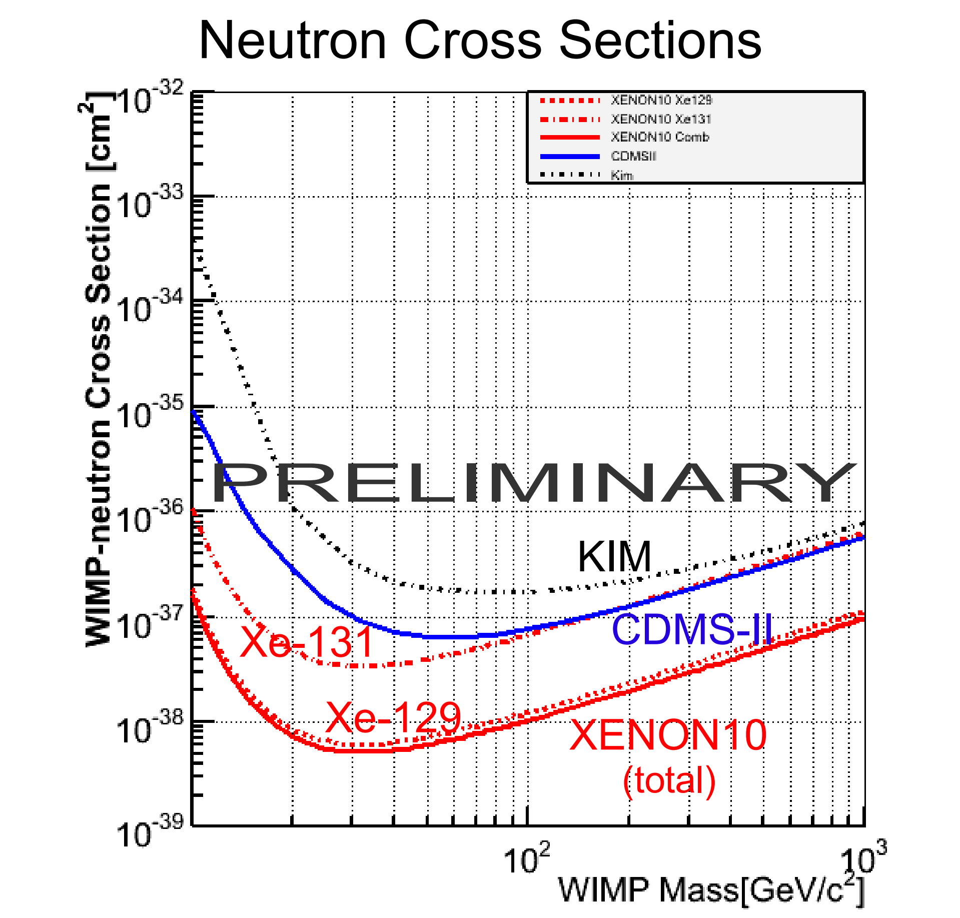
- WIMP search box defined by 50% NR acceptance region (blue lines) and E_r in 4.5-27 keV (black lines).
- Search box optimized with calibration data and additional 40 live days of unmasked data.
- 10 events in the box from "blind" data after cuts.
- Energy spectrum not as expected from WIMPs.
- ~7 events expected from gamma-ray leakage.
- NR energy scale based on 19% constant "quenching factor" at low energies.

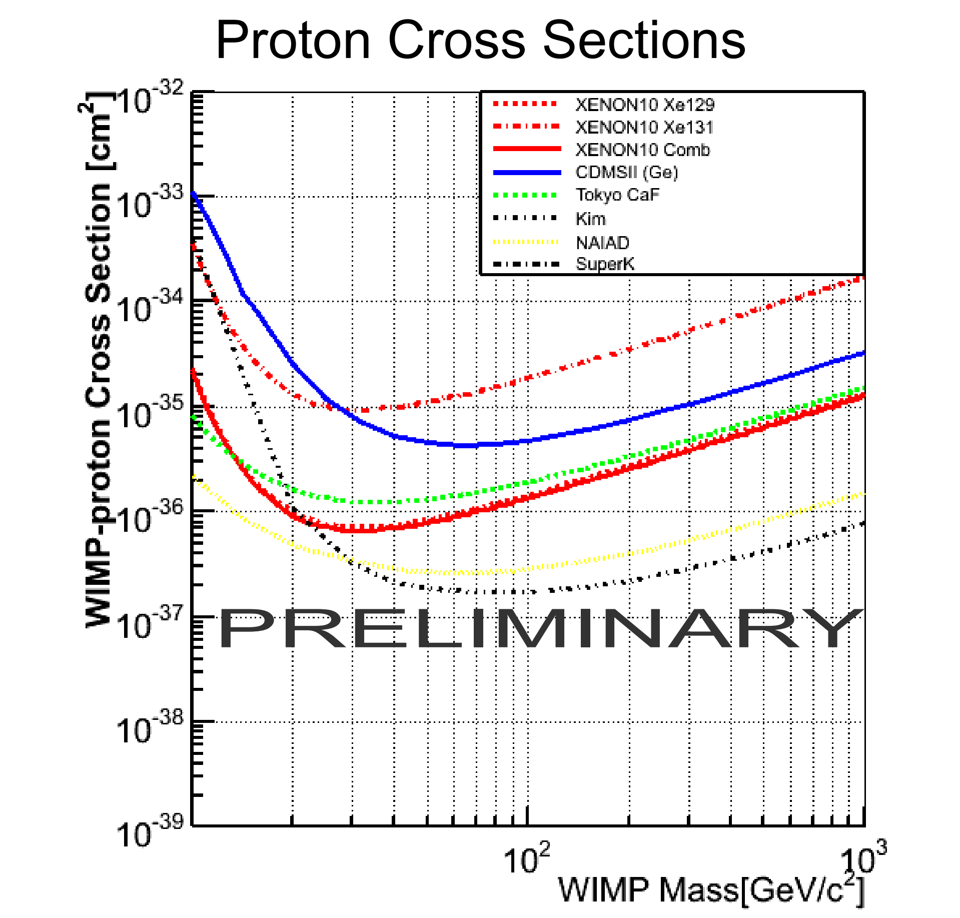
XENON10 WIMP Search Result for Spin-Independent Interactions



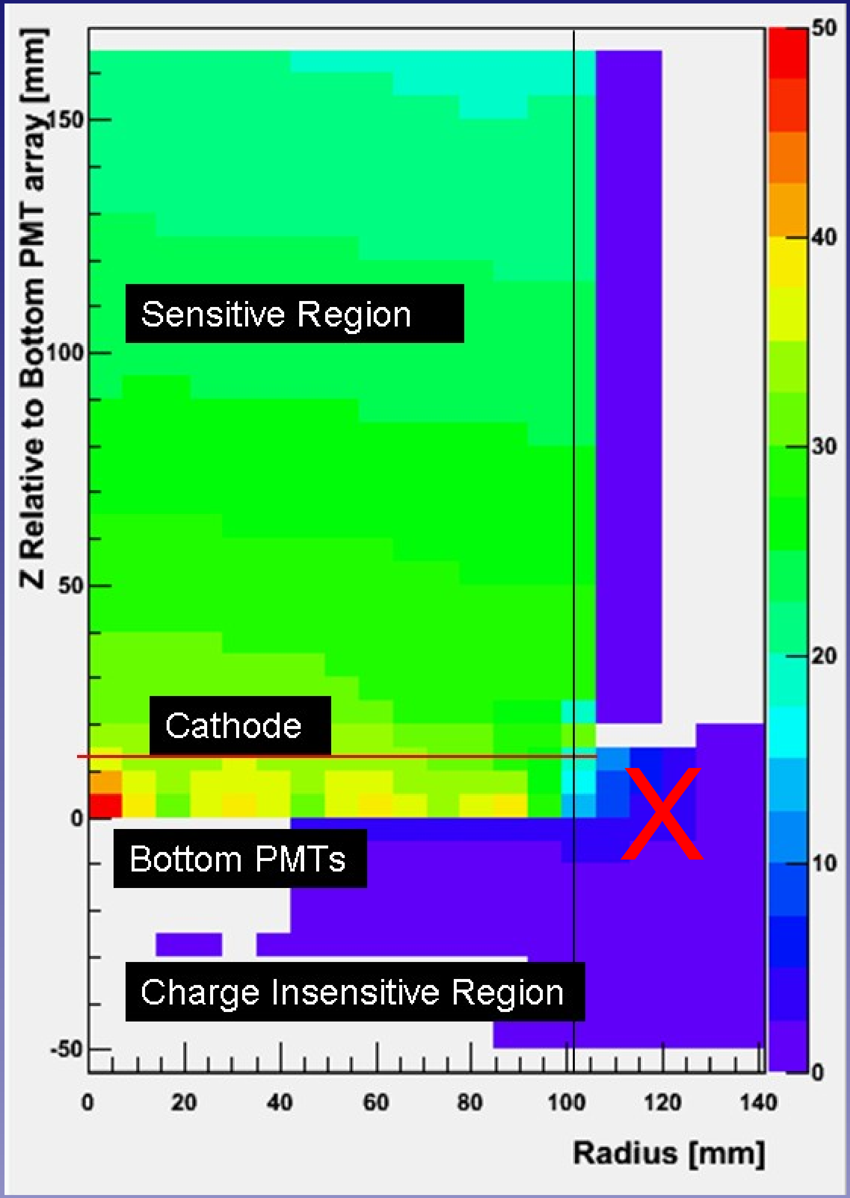
- 90% CL upper limit on WIMP-nucleon cross section derived with Maximal Gap Method [Yellin, PRD 66 (2002)]
- At 100 GeV/c^2 WIMP mass 8.8×10^{-44} cm^2 (no background subtraction)
- 5.5×10^{-44} cm^2 (known background subtracted, not shown) factor 6 lower than previous limit

XENON10 Spin-Dependent Limits

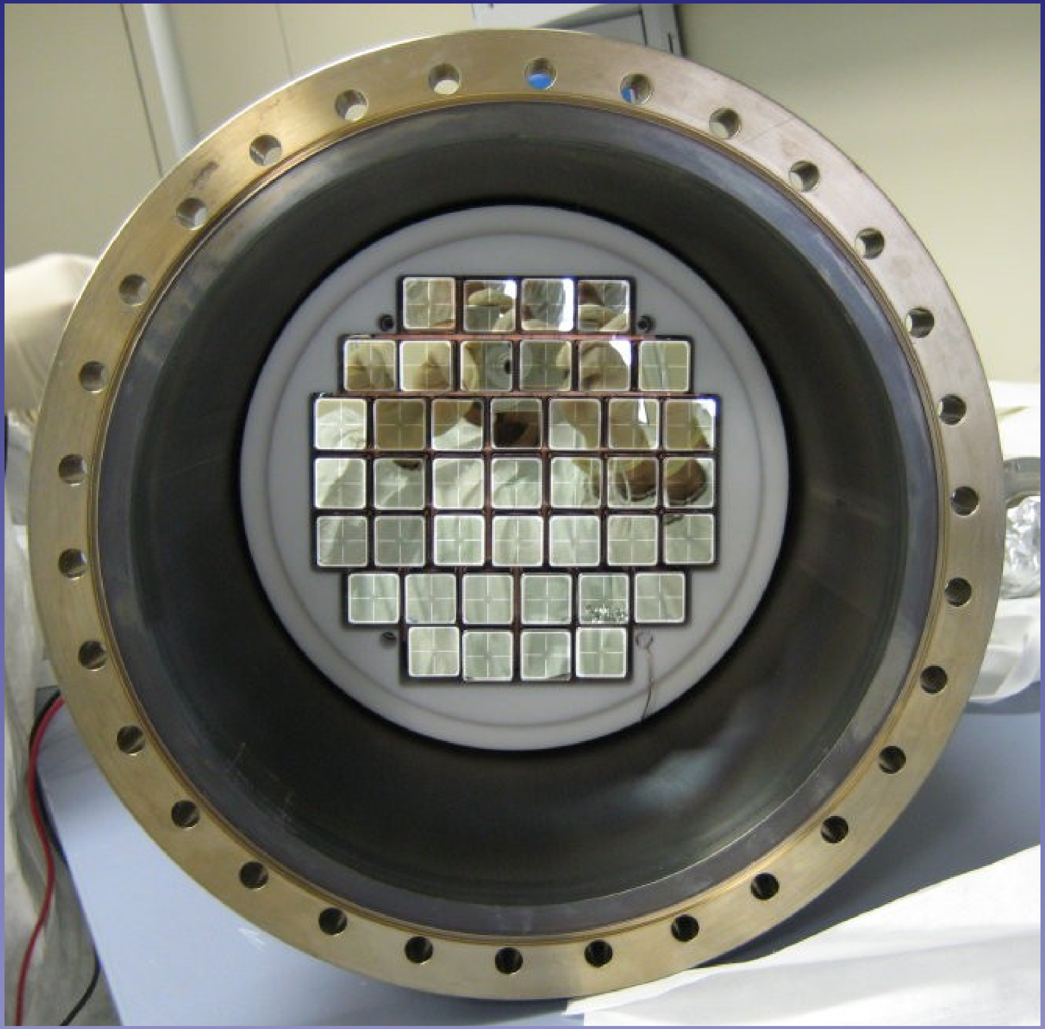




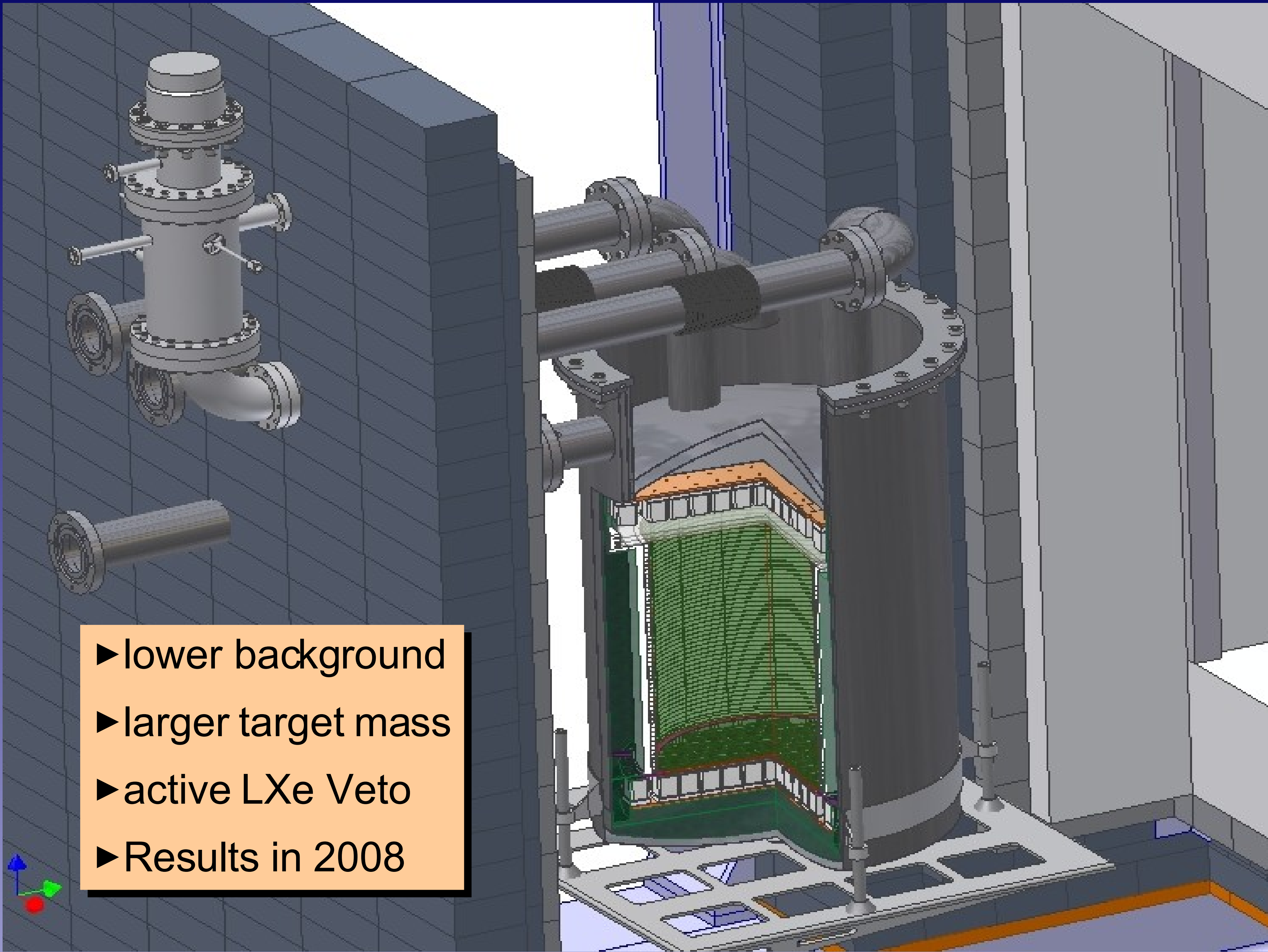
XENON10 Recent Upgrades



- Study whether anomalous events are due to light leakage from LXe around bottom PMT's.

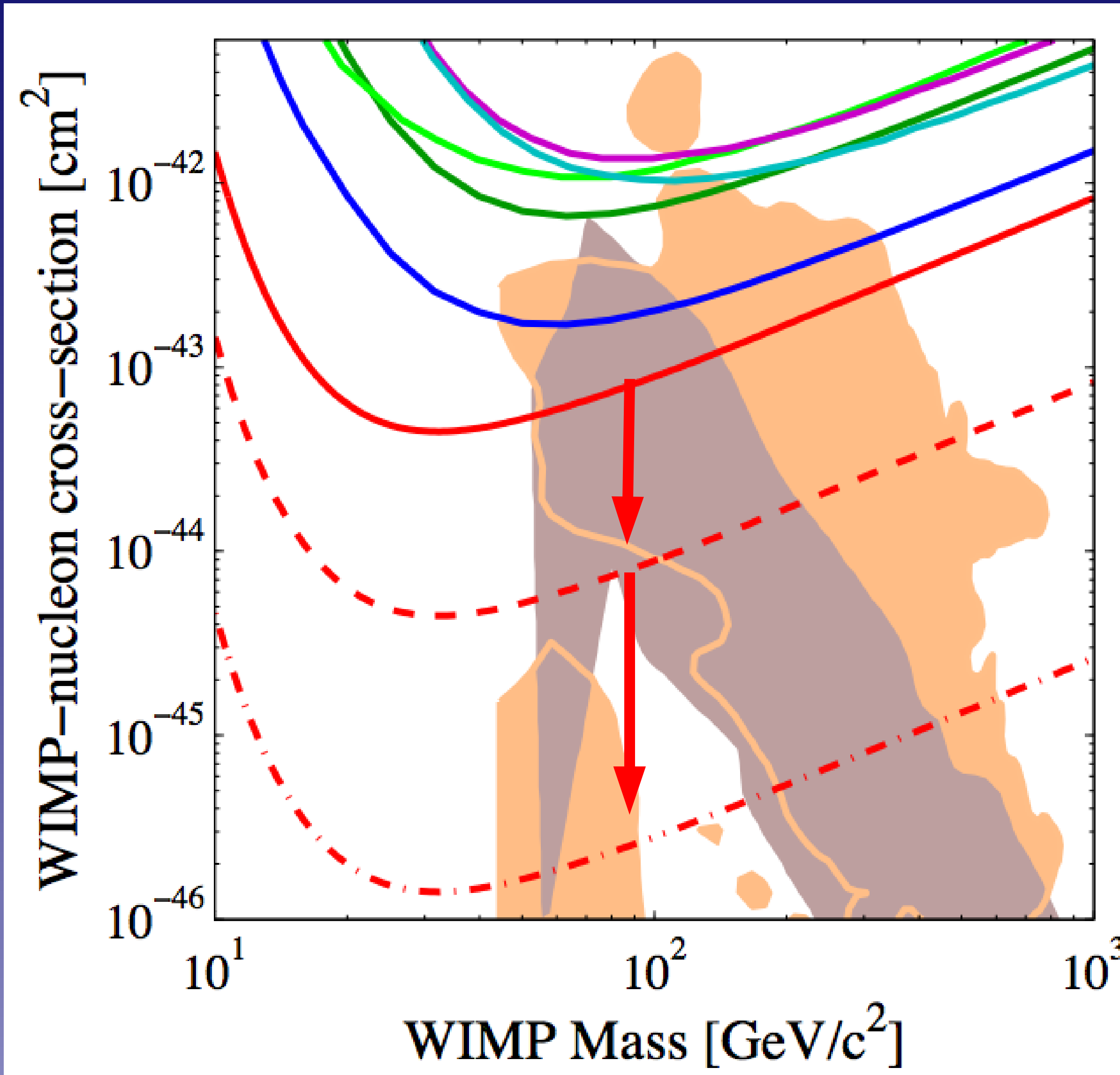


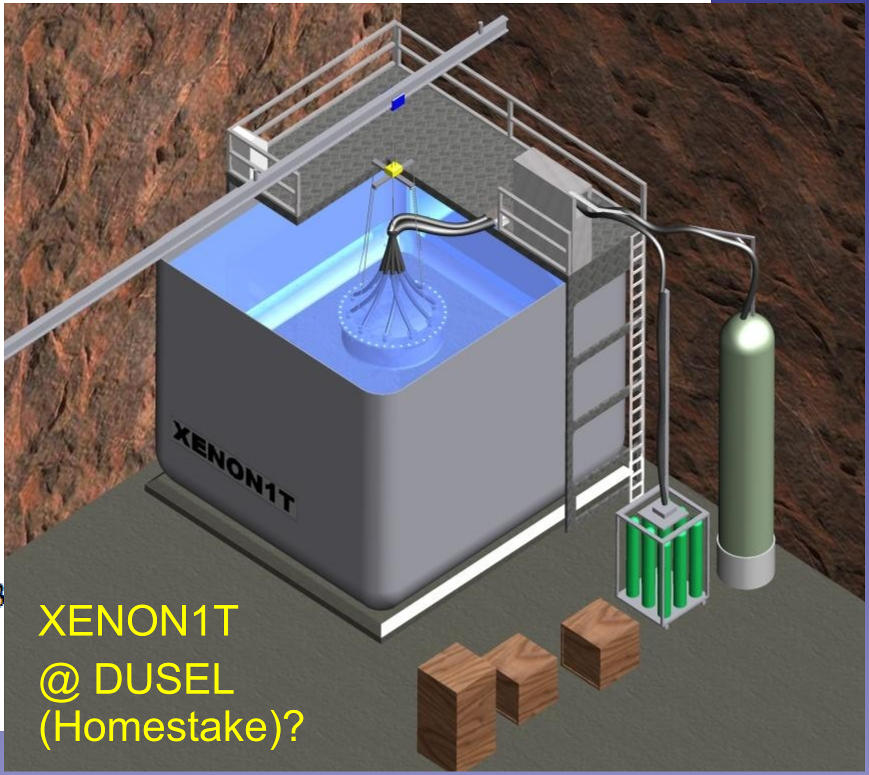
New XENON10+ Experiment at Gran Sasso



- lower background
- larger target mass
- active LXe Veto
- Results in 2008

XENON Projected Sensitivity





Summary & Outlook

- The XENON approach to WIMP DM search has made rapid progress.
- XENON10 has now the best spin-independent DM limits. New spin-dependent limits (neutron cross sections!) coming up.
- Intermediate step XENON10+ planned for 2008 – aiming at factor 10 improvement in sensitivity.
- Scalability of liquid noble detectors promises ton-scale detectors by the end of the decade.
- Timeline for new DM direct search detectors is compatible with LHC (2008) and indirect searches by GLAST (Nov/'07).
- Other detectors? Need to search DM with more than 1 concept.
  See DM review by B. Sadoulet in the plenary session on Tuesday.
- *This is an exciting period in WIMP DM search – stay tuned!*