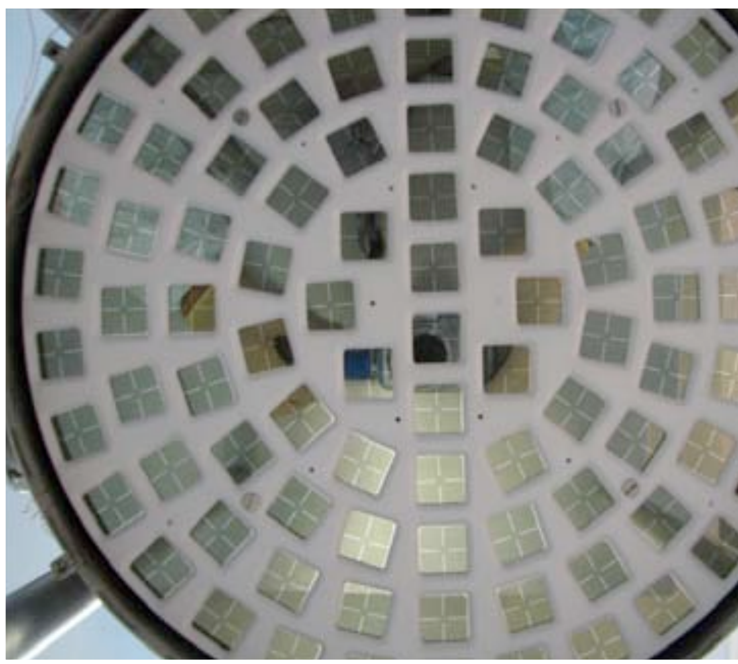
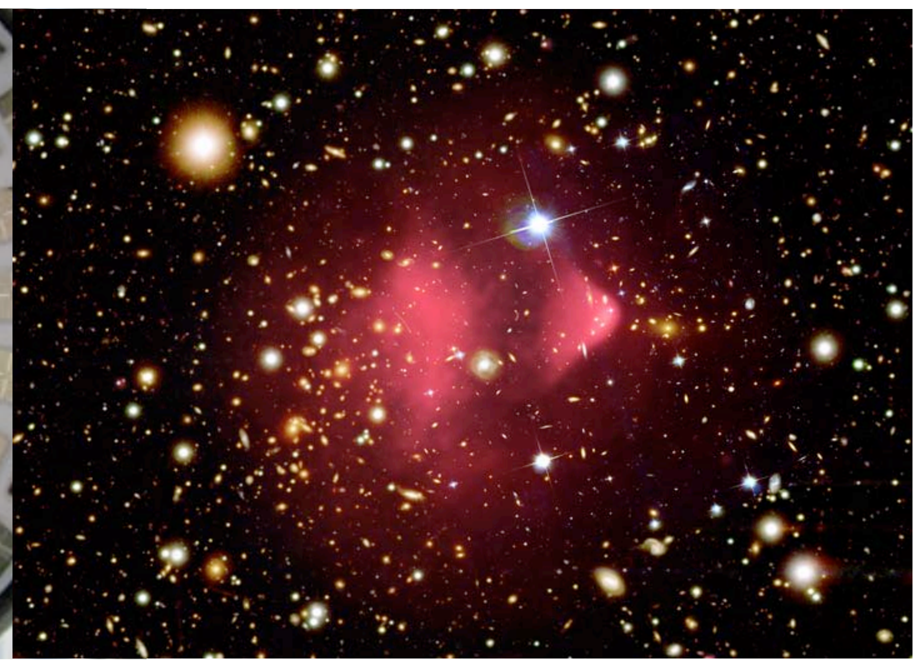
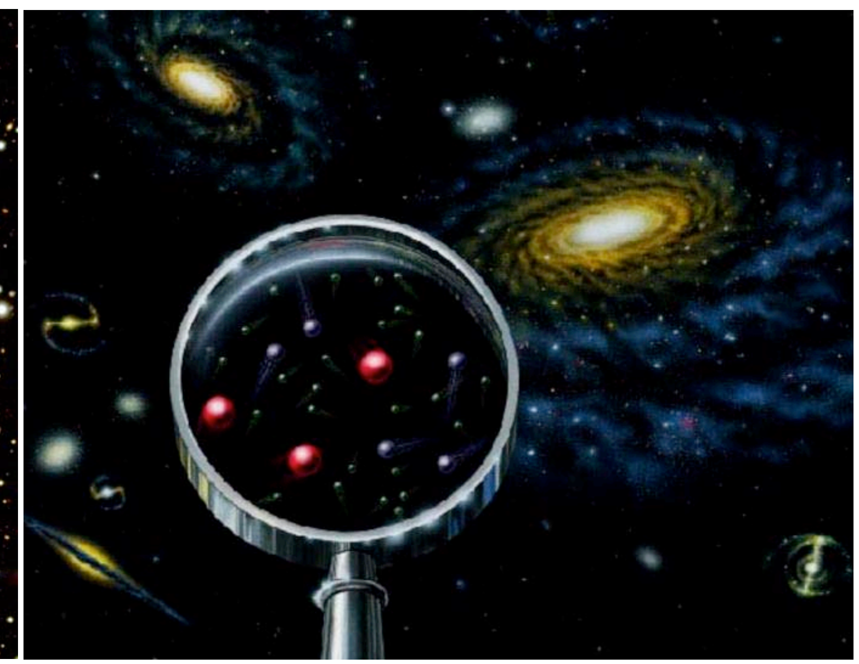
Dark Matter Detection: An Overview

ra



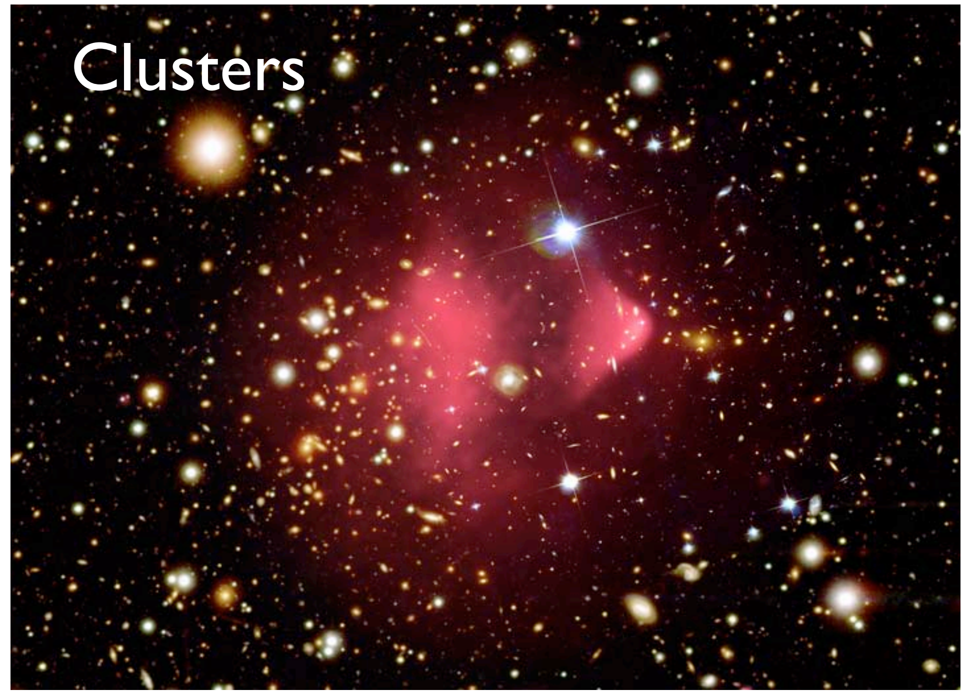


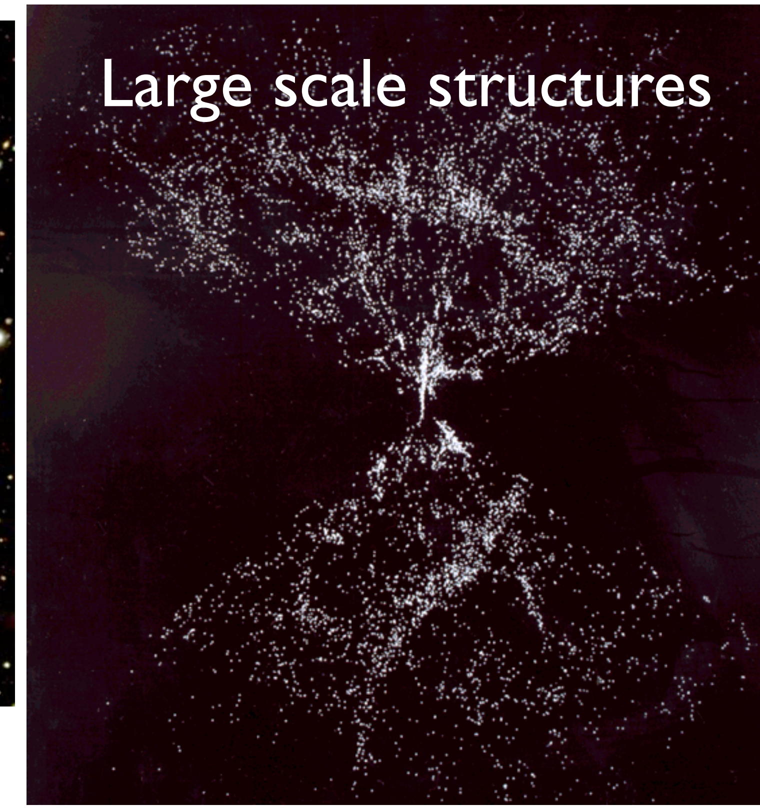


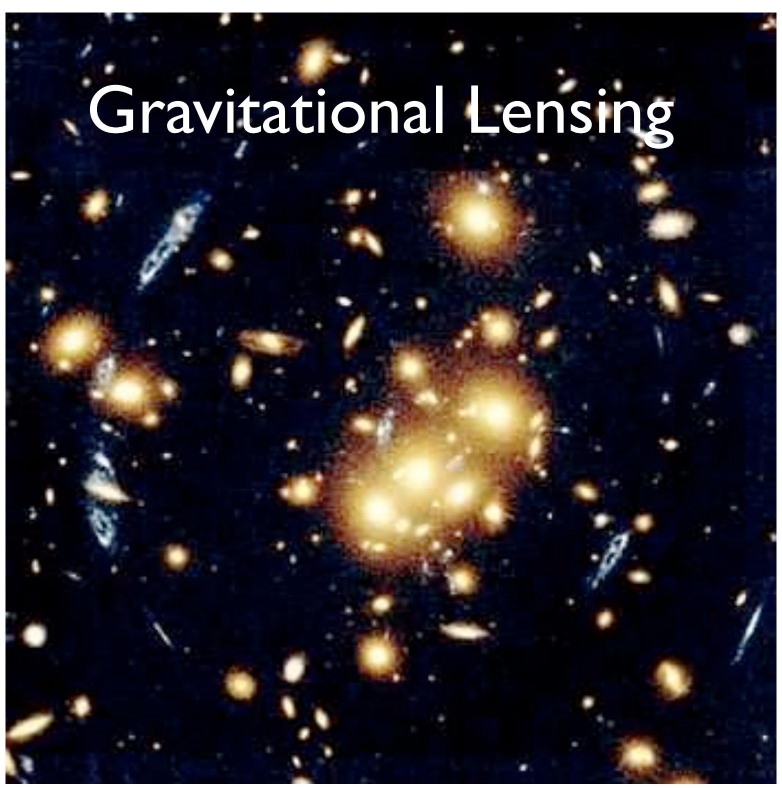
Elena Aprile
Columbia University

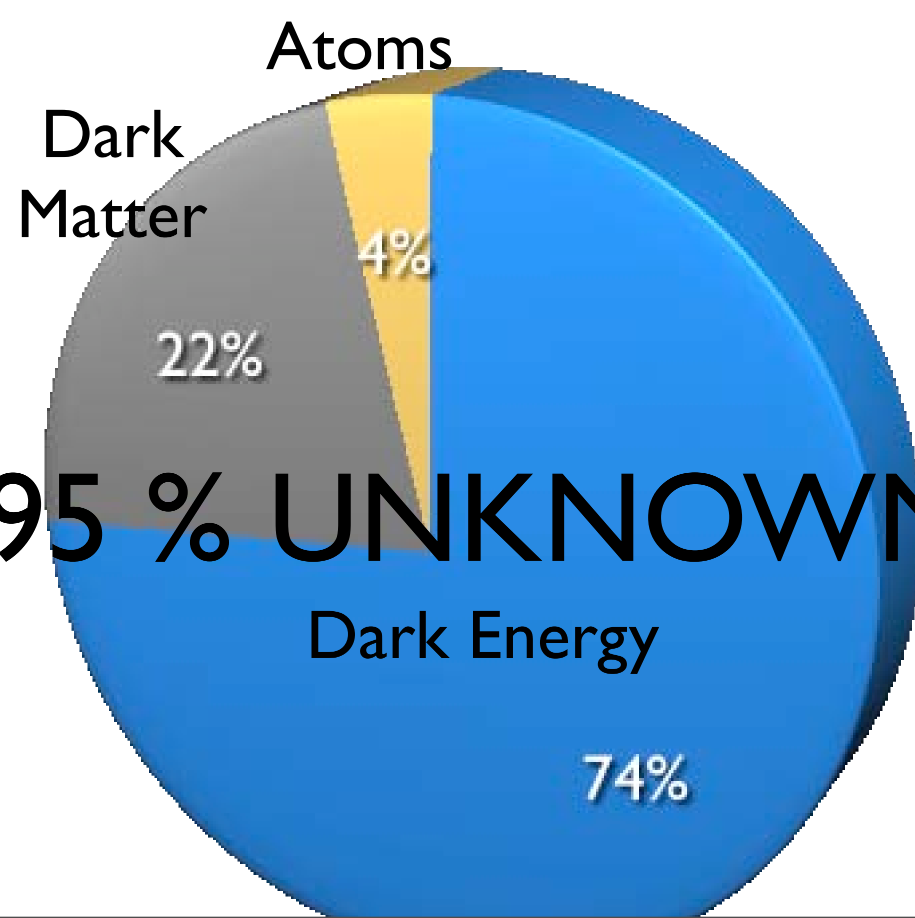
XXVIII Physics in Collision
Perugia, June 27, 2008

Concordance Cosmology

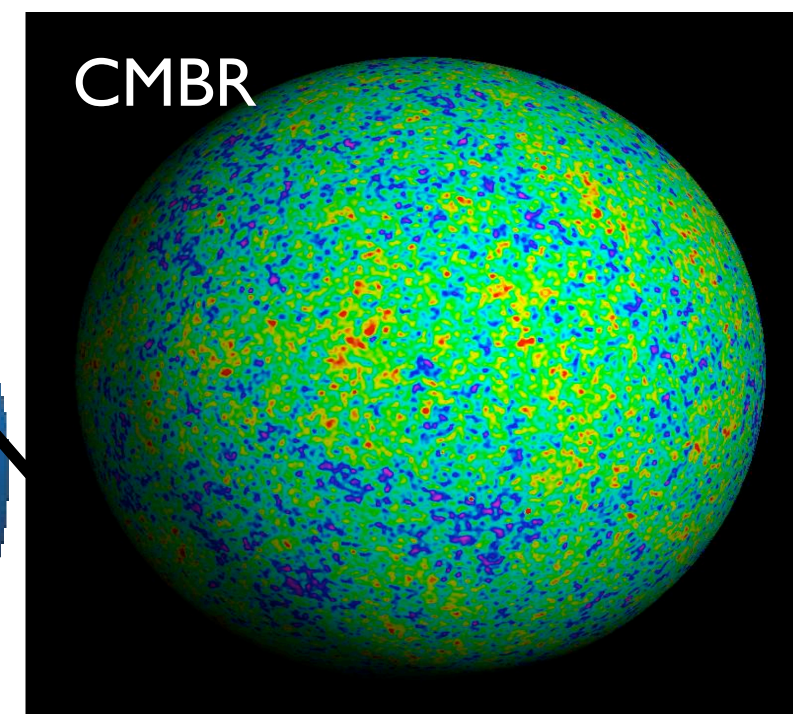






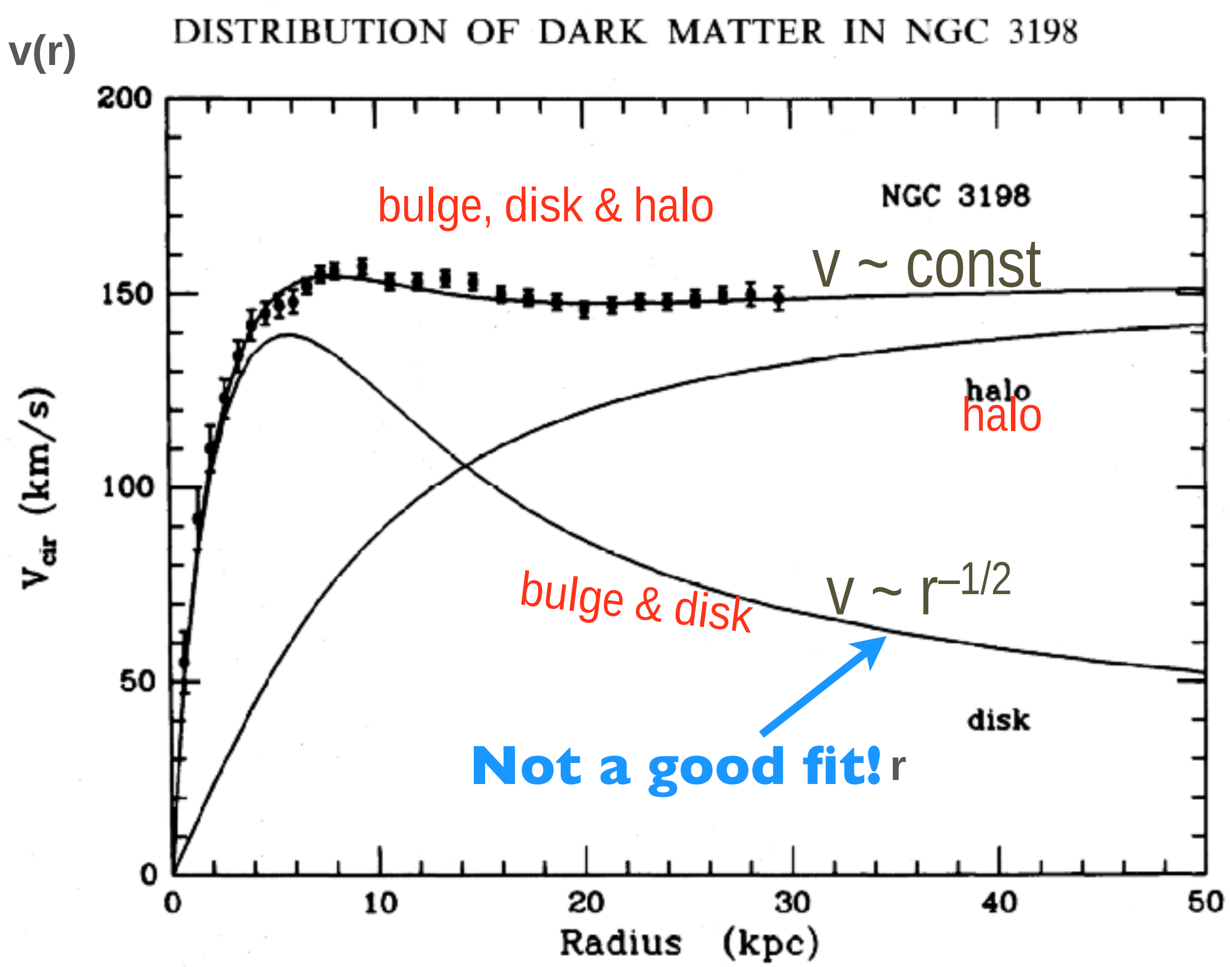


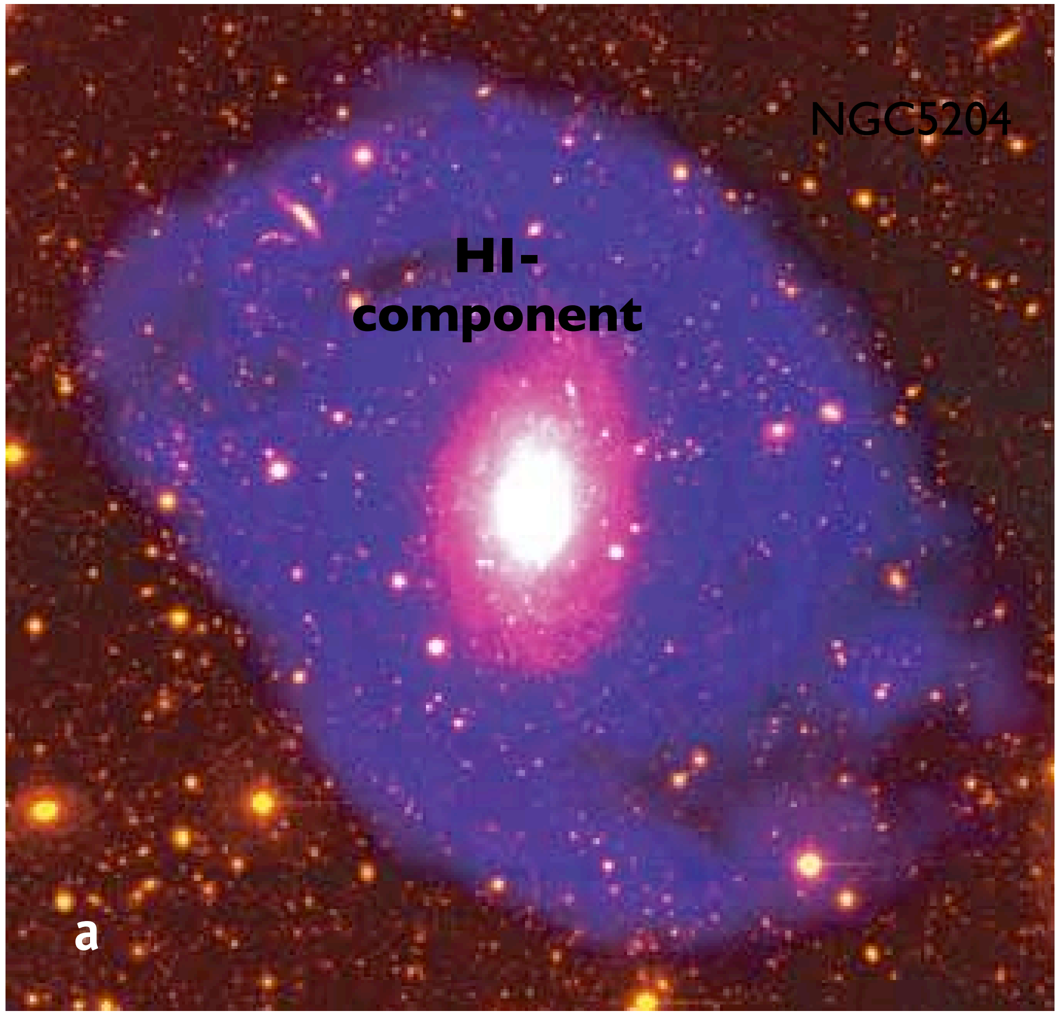
>95 % UNKNOWN



Dark Matter in Galaxies

- Observations of interstellar gas (21 cm HI-Emission Line) at large radii
  => the rotation curves are constant as far as one can measure!
- => ~ **10 x more Matter, as one can directly see** => $M_{\text{dark}} \geq 10 M_{\text{stars}}$

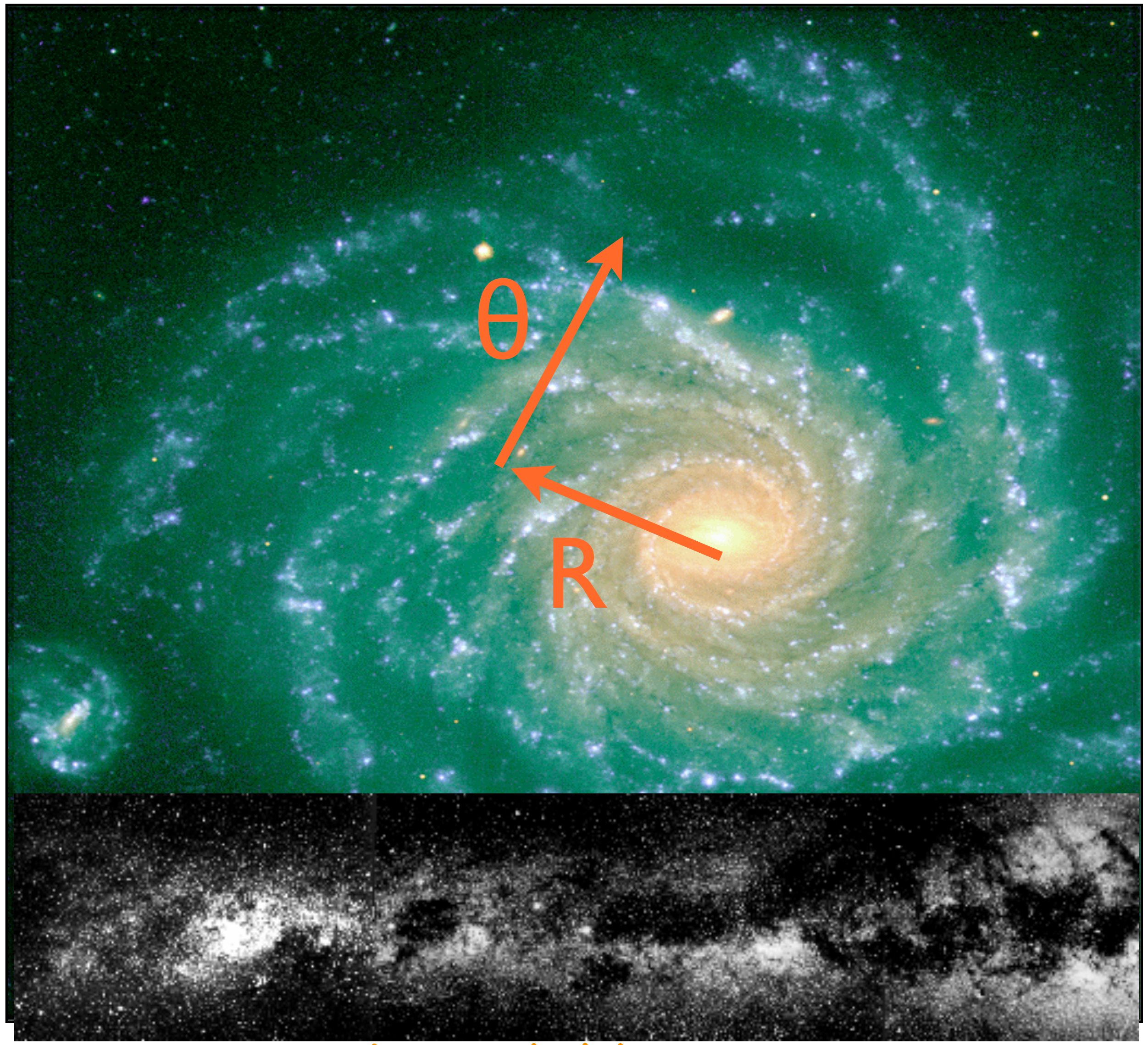




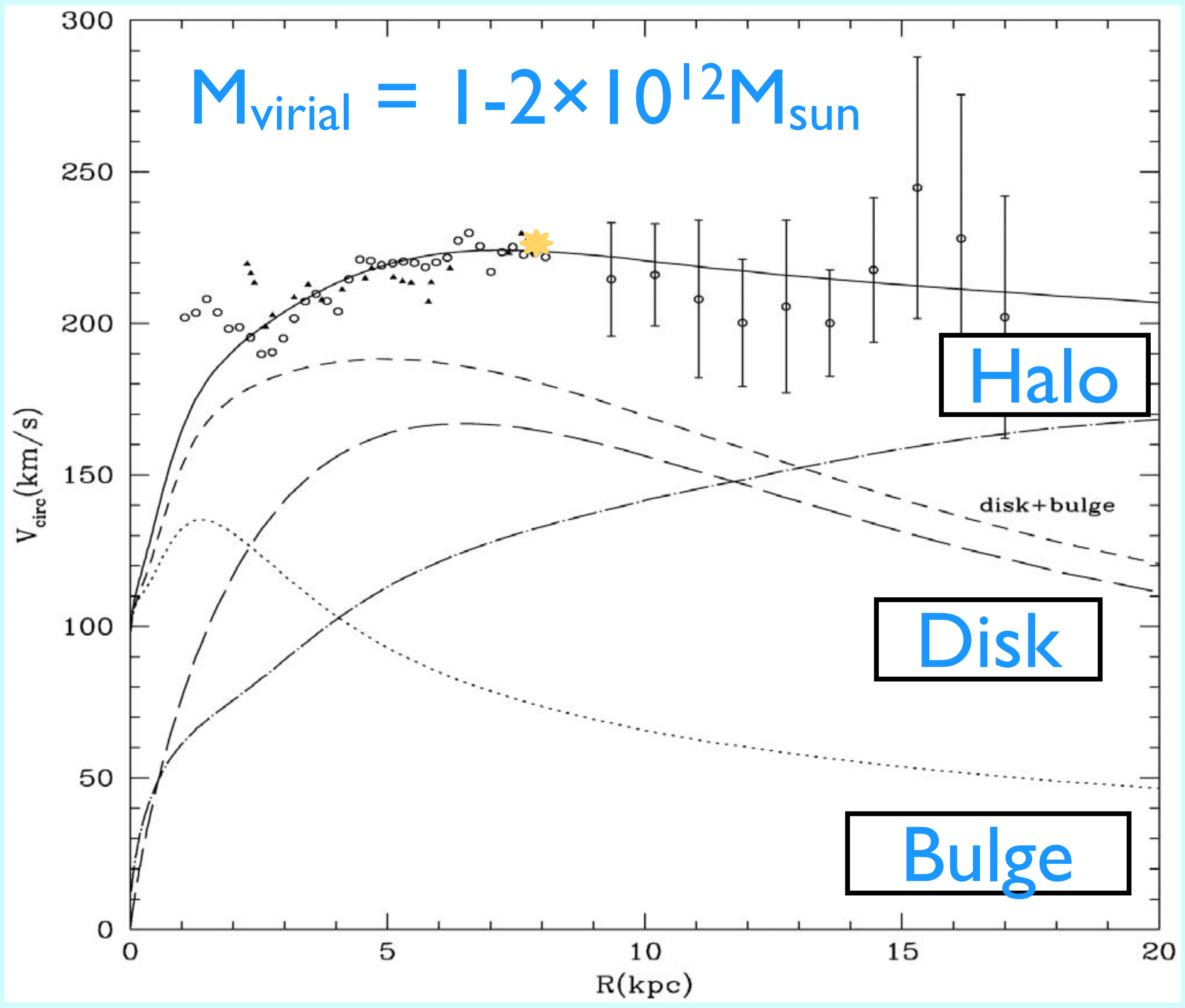
U. Klein et al., SuW Sept. 2005

Dark Matter in our Galaxy

- Measured Rotation Curve of the Milky Way: flat up to ≈ 50 kpc



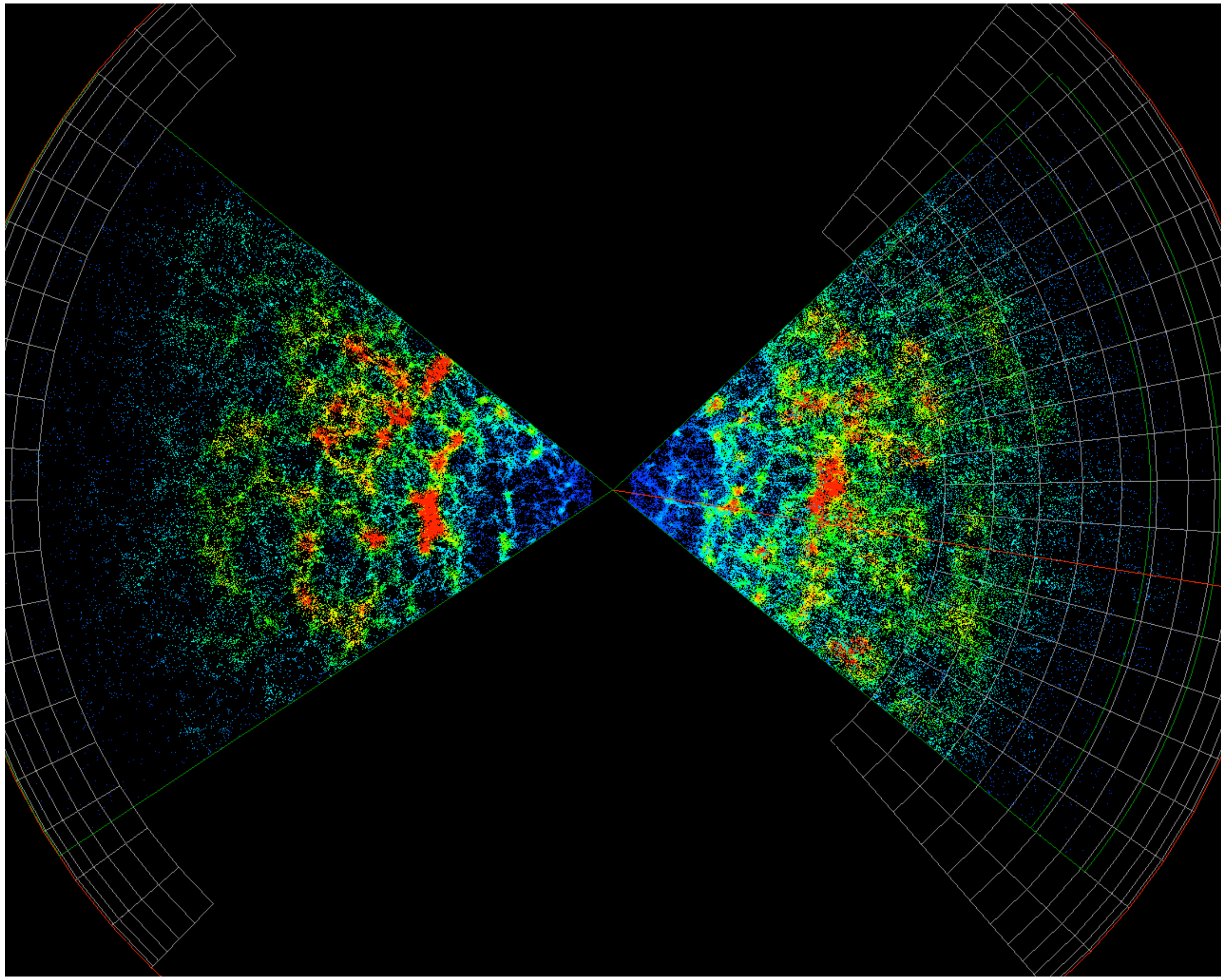
Acceptable range:
$\rho_0 = 0.3 - 0.6\ \mathrm{GeV/cm^3}$
~ 10^5 larger than in the universe at large



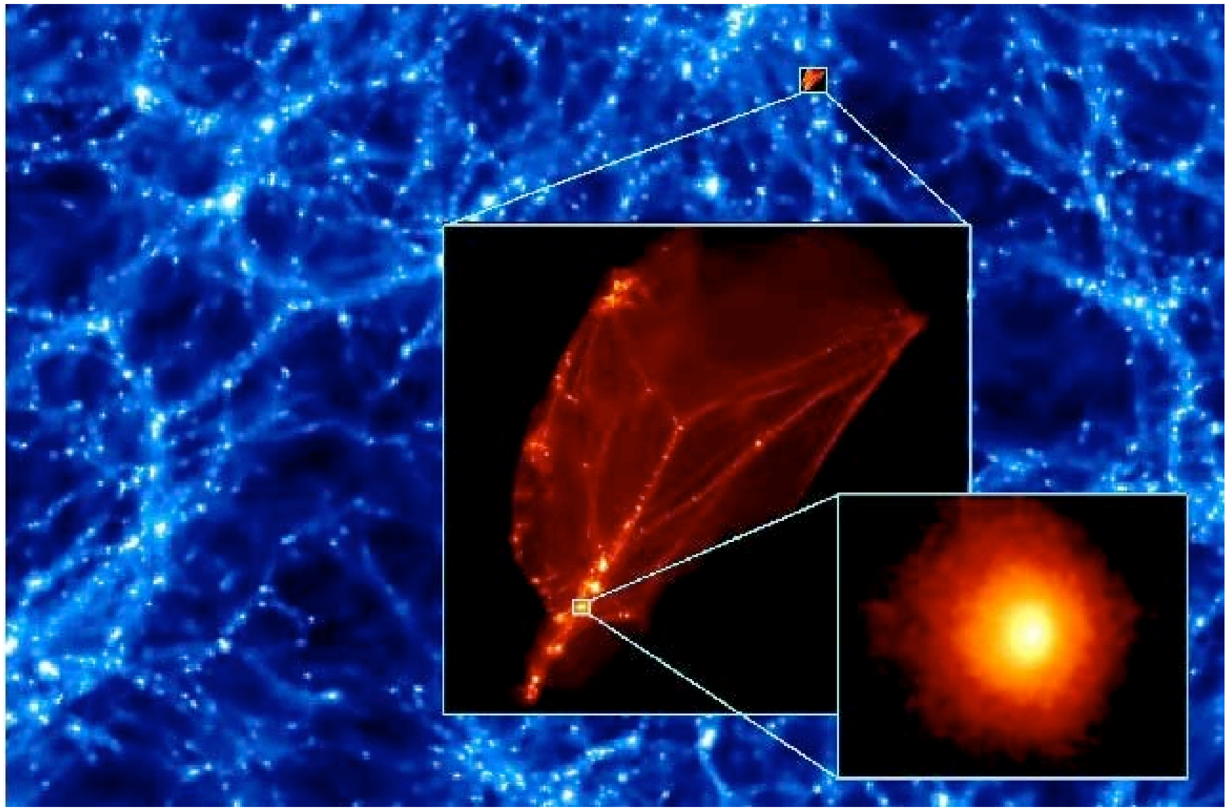
(Klypin, Zhao & Somerville 2002)

Large Scale Structure

Measurement: 2dF Survey



Simulation: http://krone.physik.unizh.ch/~moore/

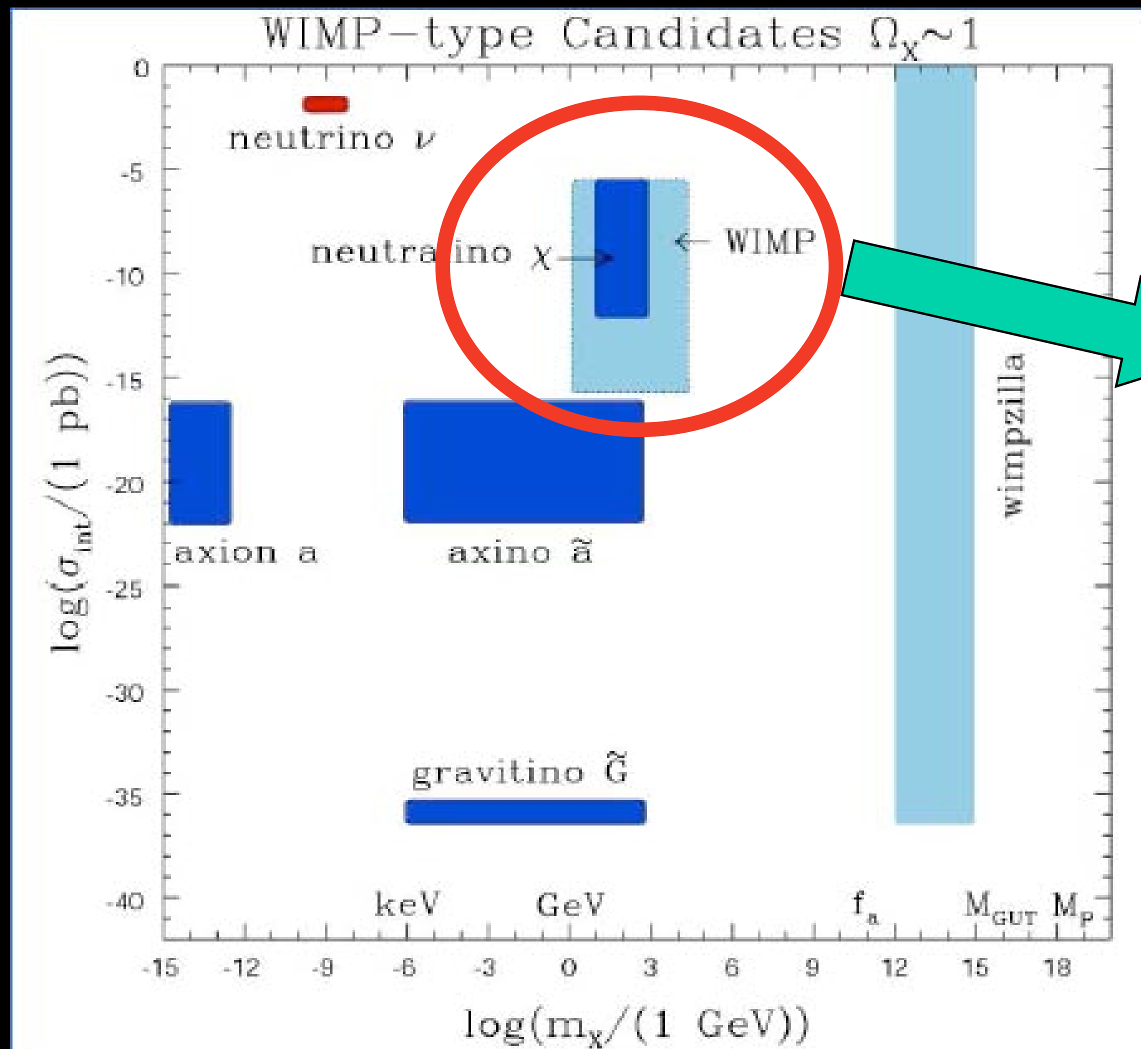


Simulation results depend primarily on whether the dark matter is hot (relativistic) or cold (non-relativistic) when structures were formed

Most of the Universe's matter must be Cold Dark Matter

Particle Candidates for Cold Dark Matter

Different models and theories of elementary CDM particles



NB: Mirror matter is not considered here

Supersymmetry inspired:

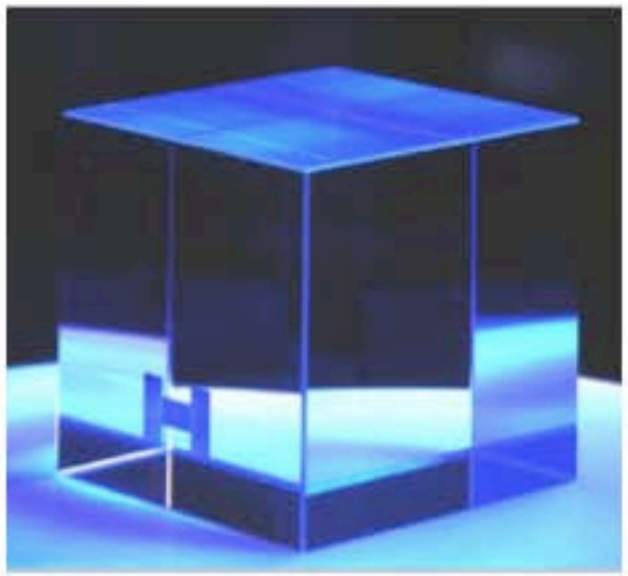
Mass: 1÷1000 GeV

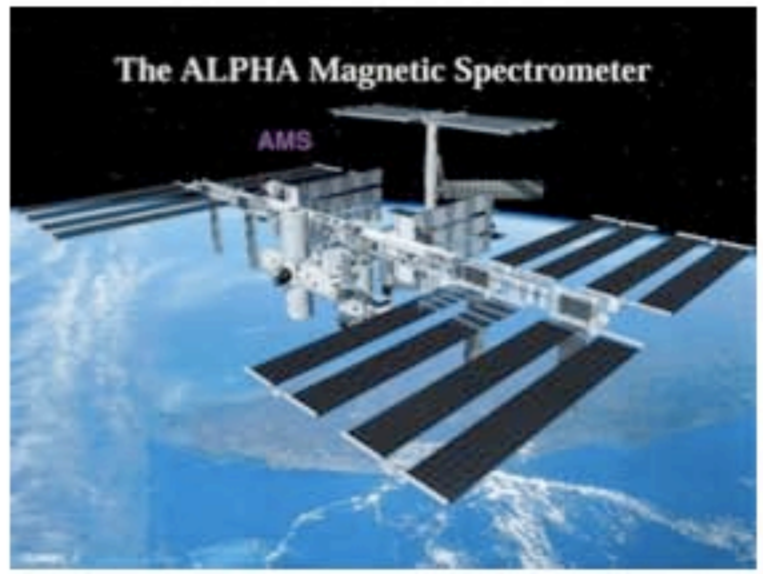
Weak interaction with ordinary matter:
$\sigma = 10^{-5} \div 10^{-12}$ pb
$= 10^{-41} \div 10^{-48}$ cm^2

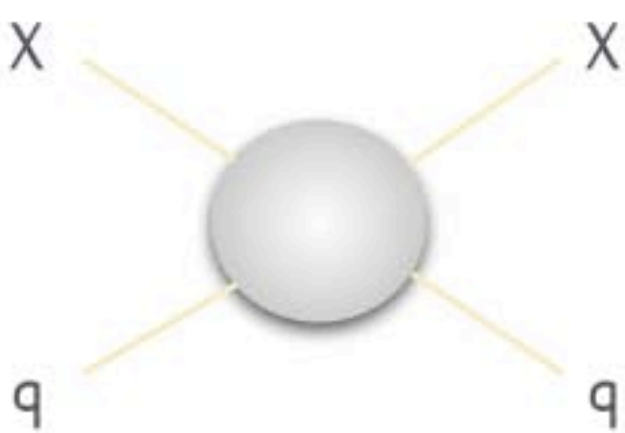
WIMP

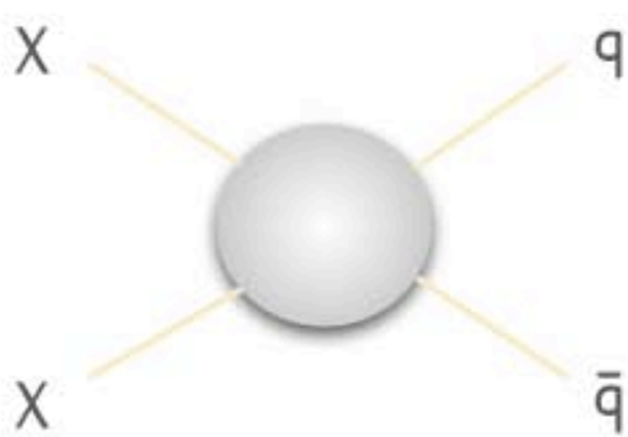
- WIMPs (GeV-TeV)
  - SUSY neutralinos
  - Kaluza-Klein excitations
- Axions (10^{-3} -> 10^{-6} eV masses)
- Pseudoscalar, Light DM

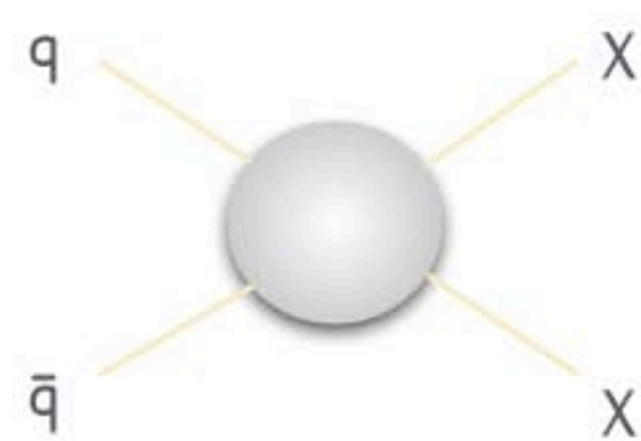
Approaches to (WIMP) Dark Matter Detection









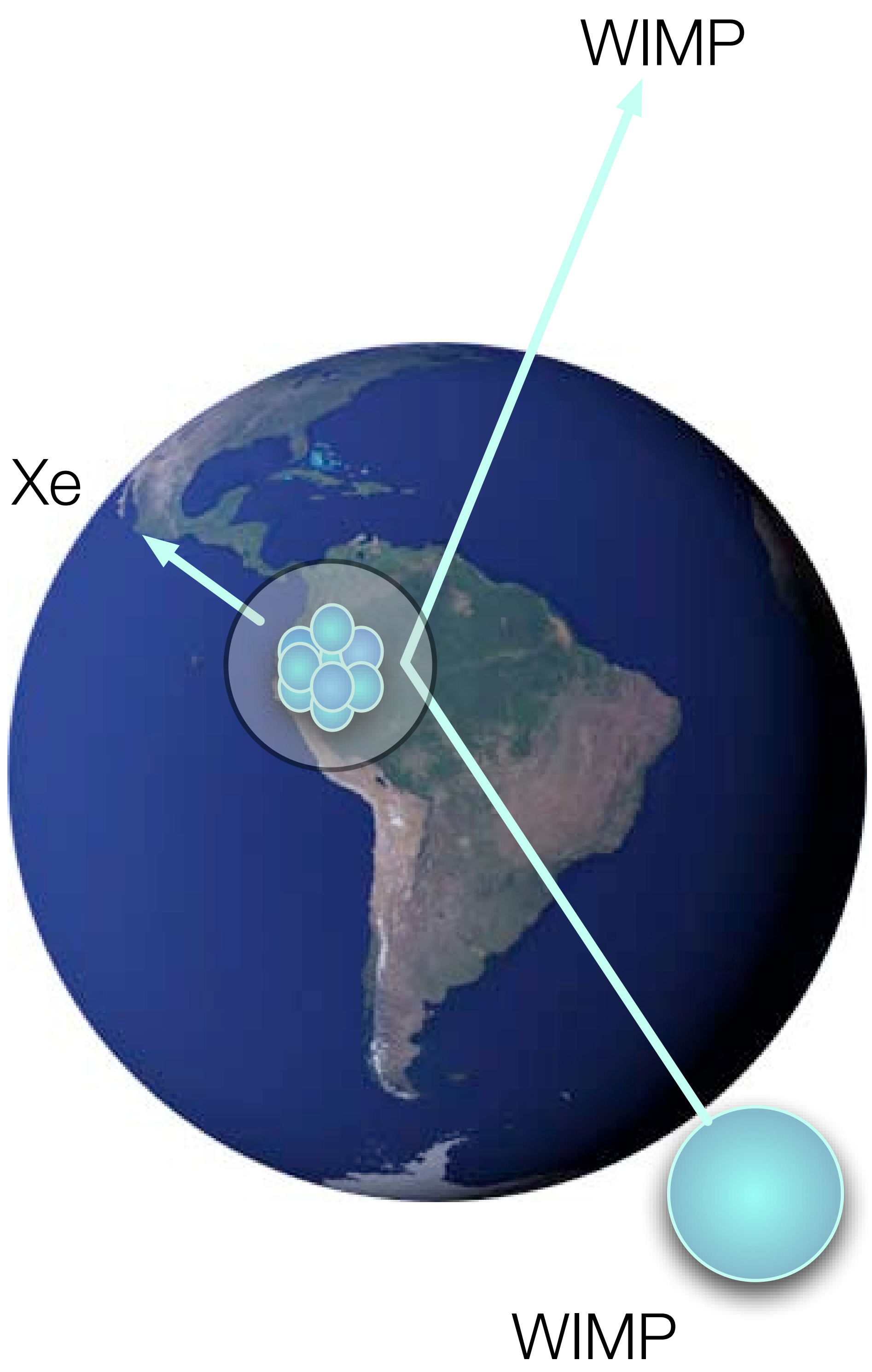


Direct

Indirect

Colliders

WIMP Direct Detection



- 10-100 WIMPs/liter, v ≈ 10^{-3}c
- Elastic collisions with nuclei

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq 50\ keV$$

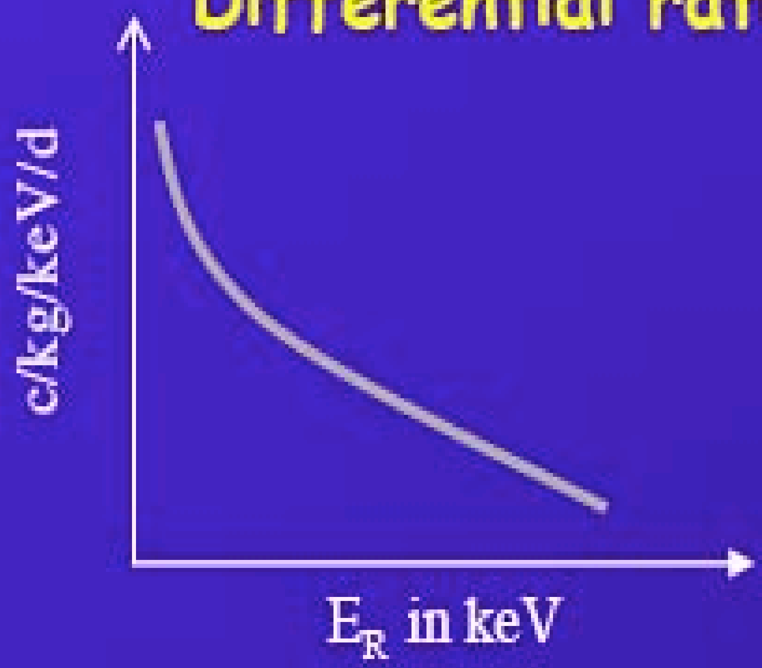
- Rate << 1 Event/kg/Day

$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi N} \rangle \qquad \mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

N = number of target nuclei in detector
ρ_χ = local WIMP density, m_χ = WIMP mass
$\langle\sigma_{\chi N}\rangle$ = scattering cross section

Rates and Energy Spectrum

Differential rate :



Exponentially shaped recoil spectrum

Particle physics

$$\frac{dR}{dE_R} = N_T \frac{\sigma\ \rho}{2\ m_N\ m_W} F^2(E_R) \int \frac{f(v)}{v}\ dv$$

Detector properties

Astrophysics

Nuclear physics

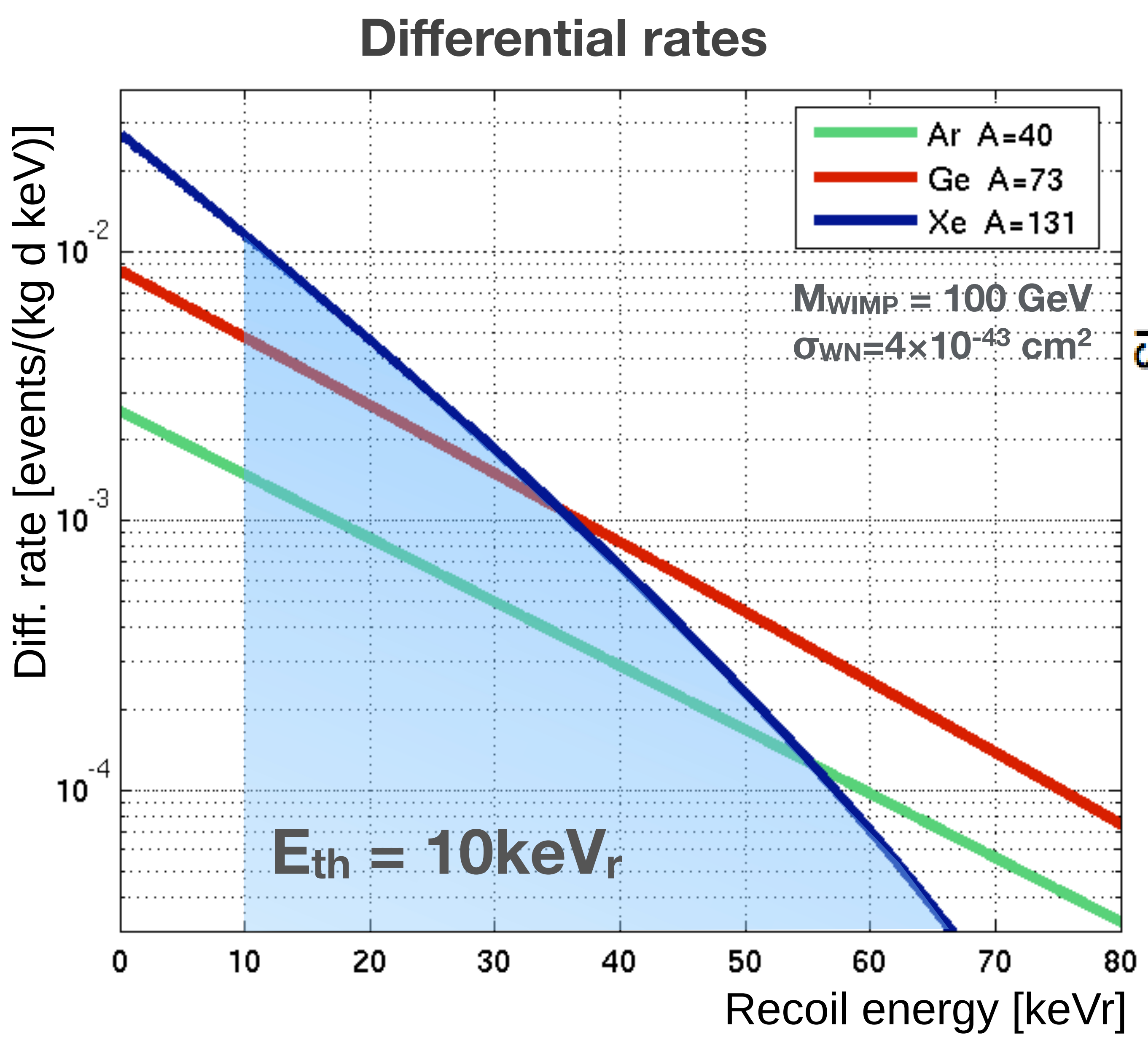
Depending on its composition, neutralinos can have
spin dependent and/or spin independent interactions

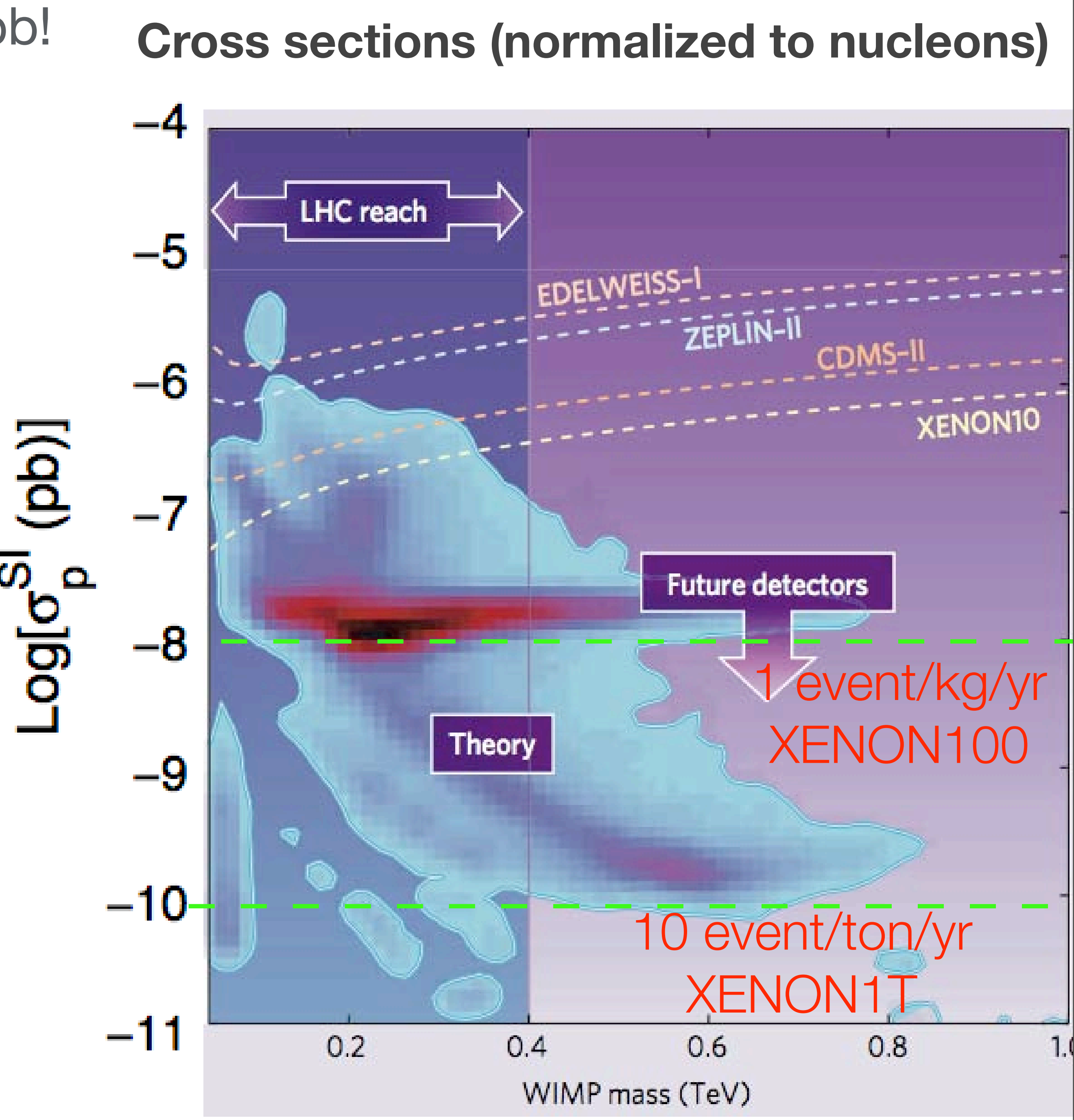
$\sigma_{sd} \propto \lambda^2\ J(J+1)$ spin dependent (favoures nuclei with spin) F, Al

$\sigma_{sid} \propto A^2$ spin independent (favoures heavy nuclei) Ge, I, W

Predicted Rates in Different Targets

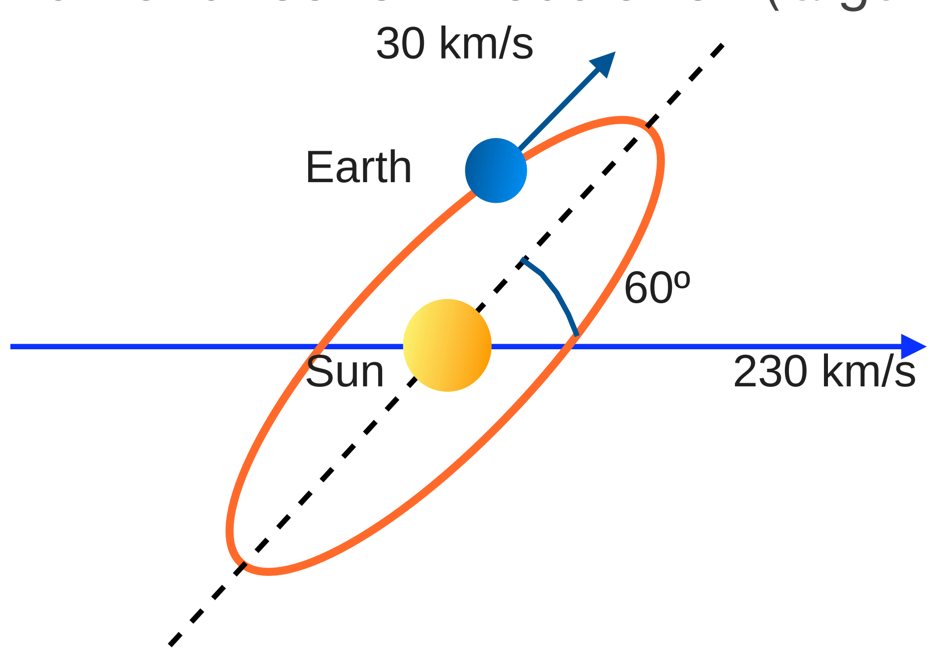
- Cross sections on nucleons: below 10^{-7} pb!
- **Rates: << 1 event/kg/month**

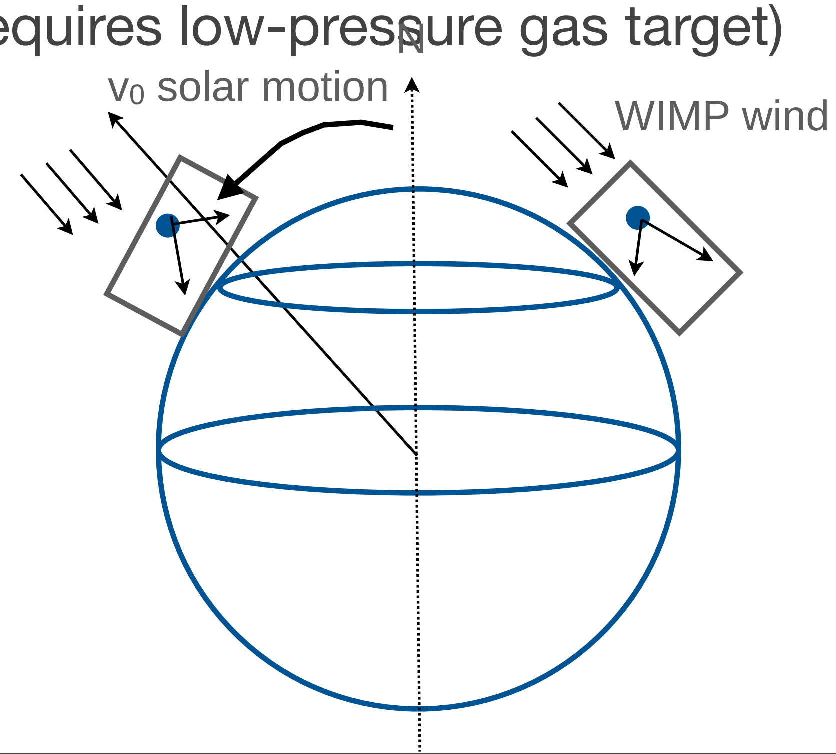




WIMP Signatures

- **WIMP interactions in detector should be:**
  - nuclear recoils
  - single scatters, uniform throughout detector volume
  - as we sweep the WIMP halo, interaction rate is low and modulated
- **Spectral shape** (exponential, however similar to background)
- **Dependance on material** (A^2, $F^2(Q)$, test consistency between different targets)
- **Annual flux modulation** (~ 3% effect, most events close to threshold)
- **Diurnal direction modulation** (larger effect, requires low-pressure gas target)



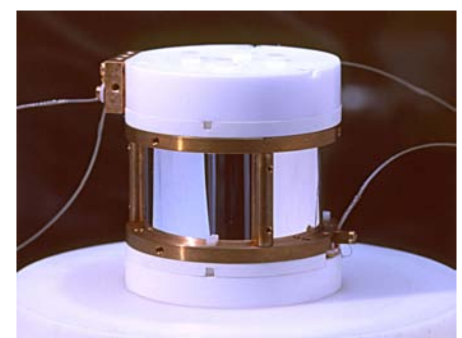


Direct Detection Experiments

COUPP,
PICASSO

Phonons

CDMS
EDELWEISS



CRESST
ROSEBUD

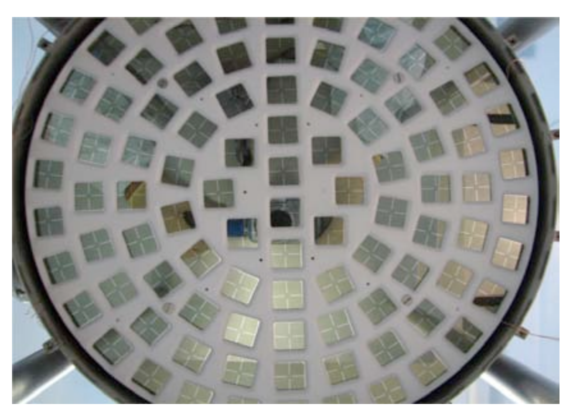
E_R

Charge

Light

DAMA, LIBRA,
XMASS, CLEAN,
ANAIS, KIMS

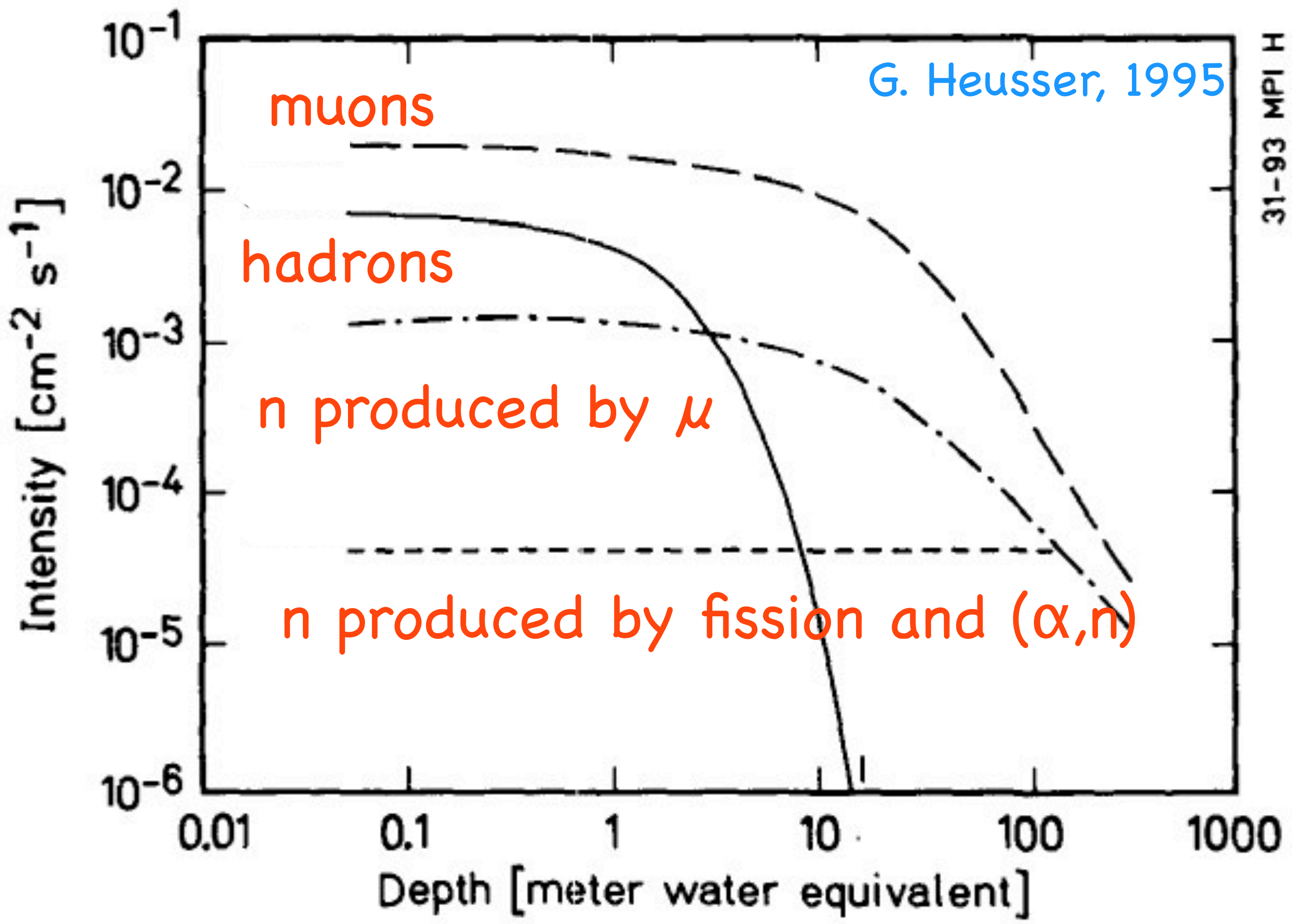
GERDA, MAJORANA



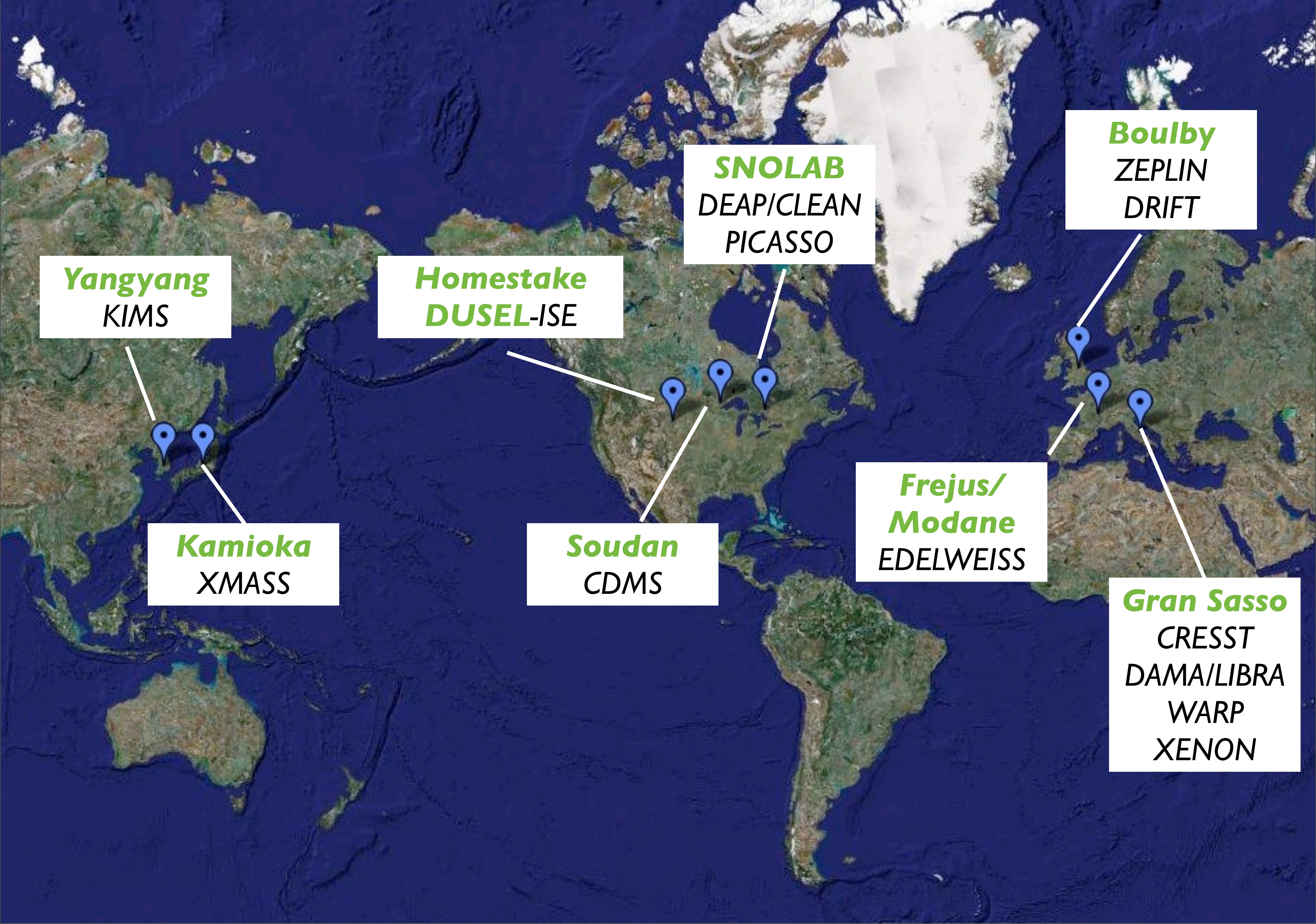
ZEPLIN, XENON,
WARP, ArDM

Challenges for Direct Detection Experiments

- **Low event rates** ⇒ ton-scale detectors
- **Small deposited energies** ⇒ low (~ few keV) energy thresholds
- **Low backgrounds**
  - shield against cosmic rays (deep underground laboratories → μ-spallation reactions)
  - low intrinsic radio-activity (ultra-pure materials → (α,n)-reactions)
  - shield radio-activity from surroundings (Pb, PE, H_2O, etc)
- **Good background rejection**
  - Particle identification
    - nuclear vs. electron recoils
  - Identification of surface events
  - Position sensitivity/fiducialisation
  - Self-shielding



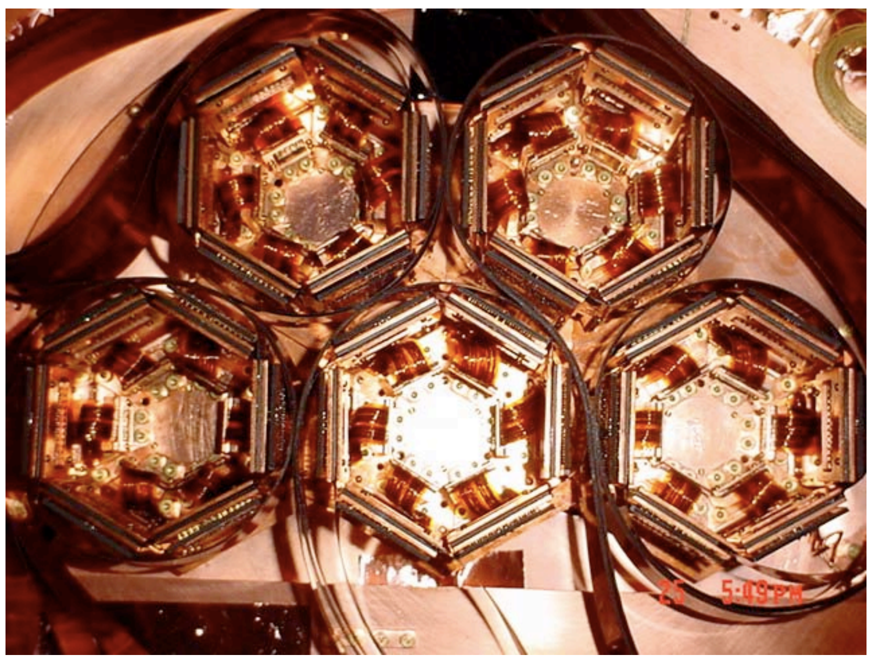
World Wide WIMP Searches

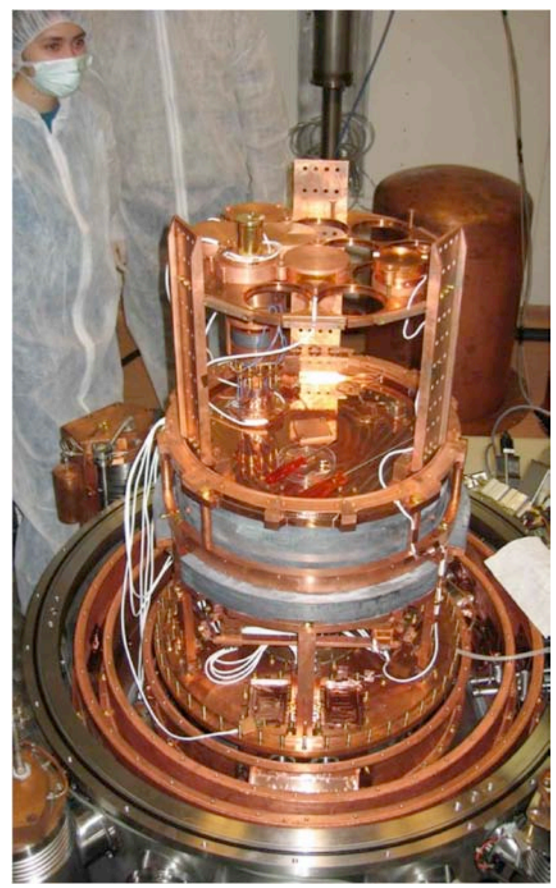


mK Cryogenic Experiments

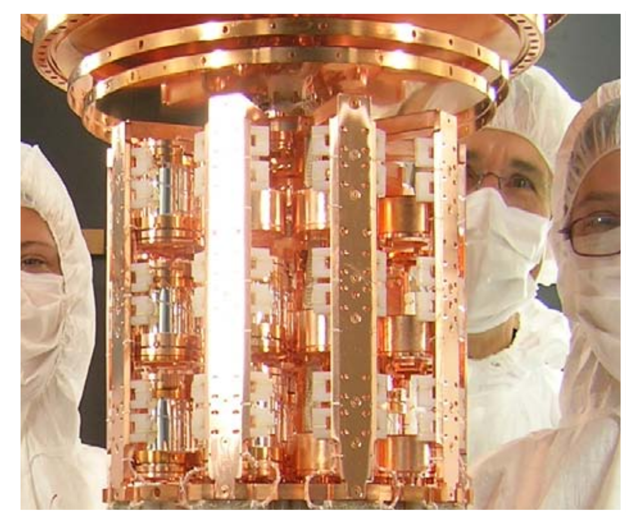
- Detectors with excellent background discrimination (> 99.99 % for Er >10 keV). Simultaneous
- measurement of Heat @ 50 mK with Ge/NTD thermometers and Ionization @ fewV/cm
- with Al electrodes. Mass in the range of a few kg. Next generation (>2009) expts aim at
- 25 -1000 kg

CDMS II (Soudan Mine): 19 Ge (4.75 kg) and 11 Si (1.1 kg)





EDELWEISS II (Frejus Tunnel)
21 Ge (NTD) and 2 NbSi for up to 40 kg

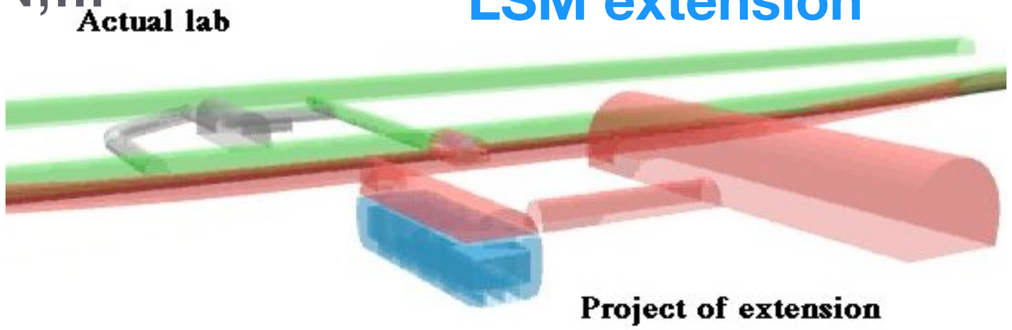


CRESST II (Gran Sasso): 16 $CaWO_4$ crystals (5 kg) and 10 kg in future with multiple targets

Future mK Cryogenic Experiments

- **EURECA (European Underground Rare Event Calorimeter Array)**
- Joint effort: CRESST, EDELWEISS, ROSEBUD, CERN,...
- Mass: 100 kg - 1 ton, multi-target approach
- FP7 proposal for design study submitted

LSM extension



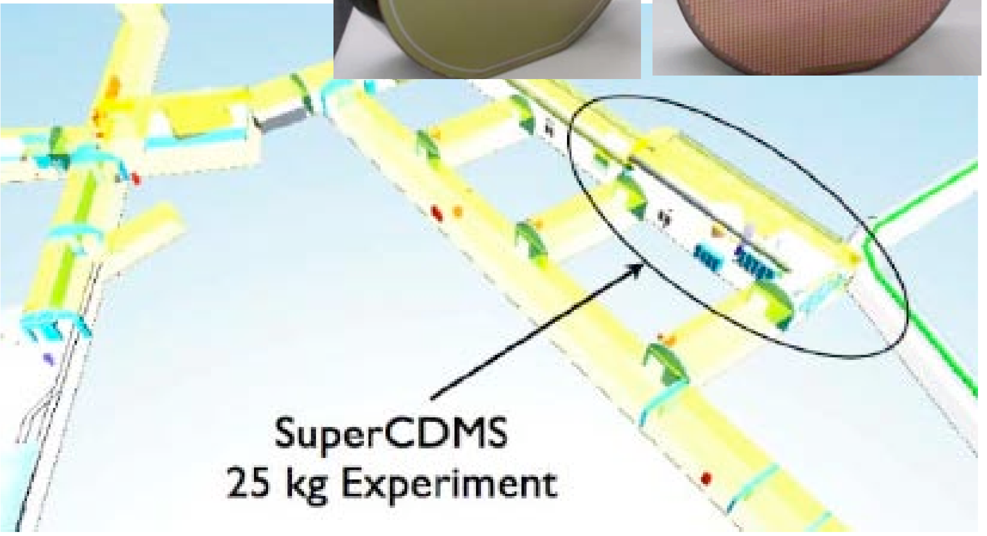
- **SuperCDMS (US/Canada):** 3 phases 25 kg - 150 kg - 1 ton
- 640 g Ge detectors with improved phonon sensors
- 4 prototype detectors built and tested

R&D for SuperCDMS:

1” thick **SuperZIPs** (0.64 kg)

2 SuperTowers at Soudan

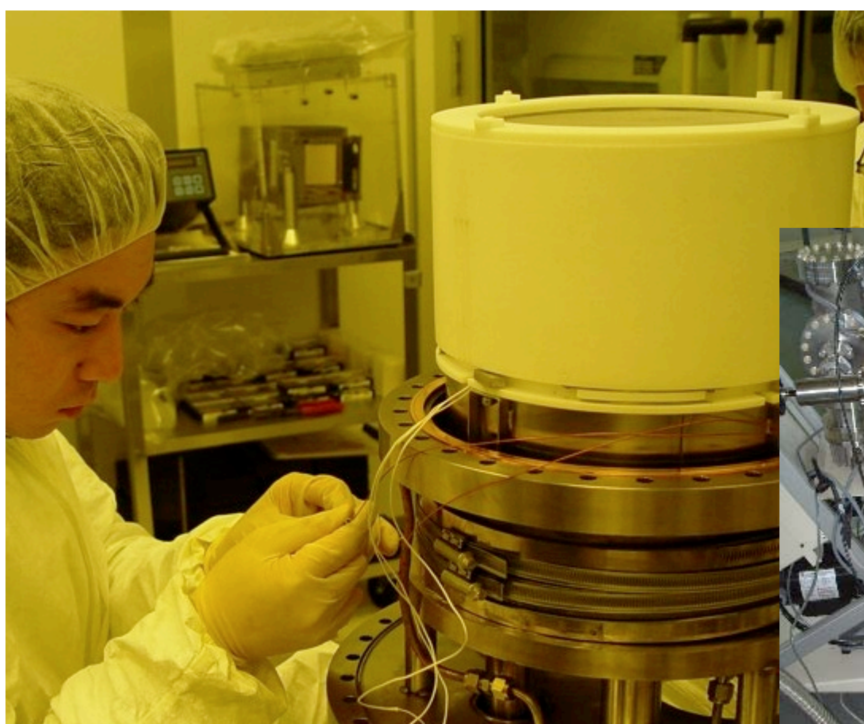
7 SuperTowers at SNOLAB



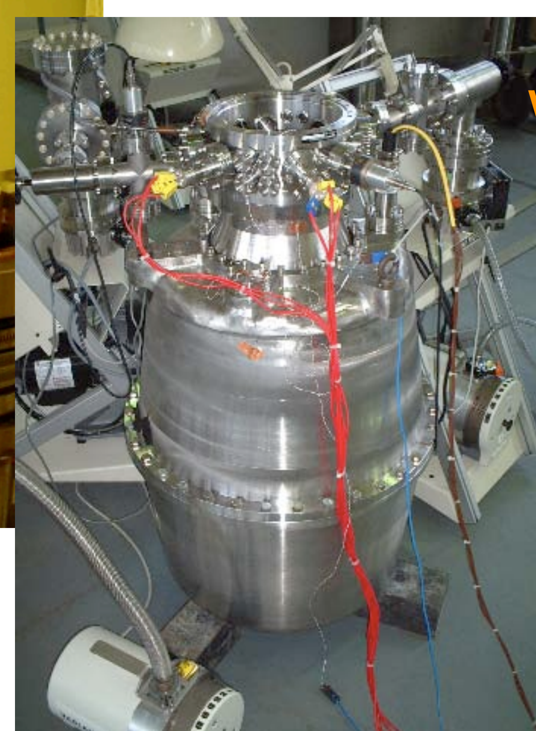
Noble Liquid Experiments

- Detectors with fine position sensitivity in one homogeneous large volume filled with
- either liquid Xe or liquid Ar. Scalable to multi-ton mass at modest cost compared to
- cryogenic detectors. Background discrimination (> 99.95 % for Er ~ 5 keV demonstrated by
- the XENON experient). Simultaneous measurement of Scintillation @ 178 (128) nm with
- PMTs and Ionization @ 1 kV/cm with 2-phase TPCs. Mass in the range of a 10 kg.
- Next generation (2009- 2012) expts aim at 100 - 1000 kg in fiducial volume.

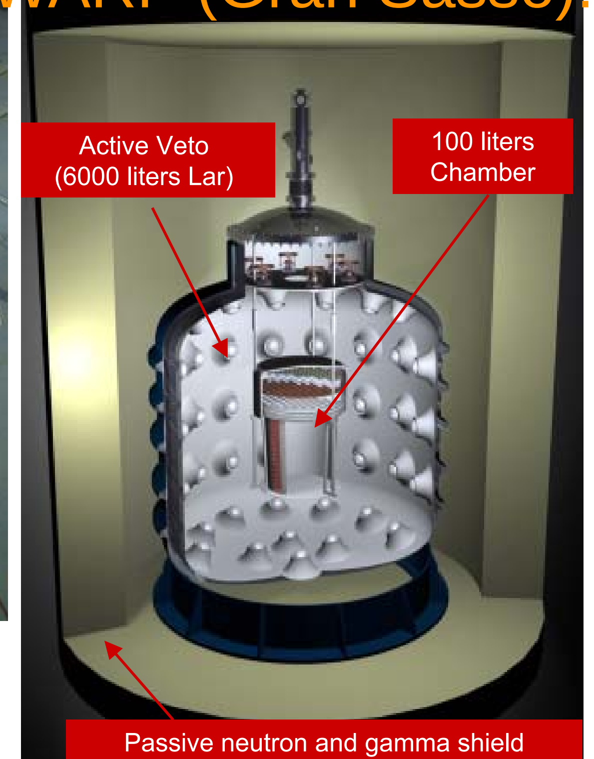
XENON10 (Gran Sasso Lab): 22 kg LXe 2-phase TPC



ZEPLIN II & III (Boulby Mine): 30 kg LXe 2-phase TPC



WARP (Gran Sasso): 140 kg LAr 2-phase TPC



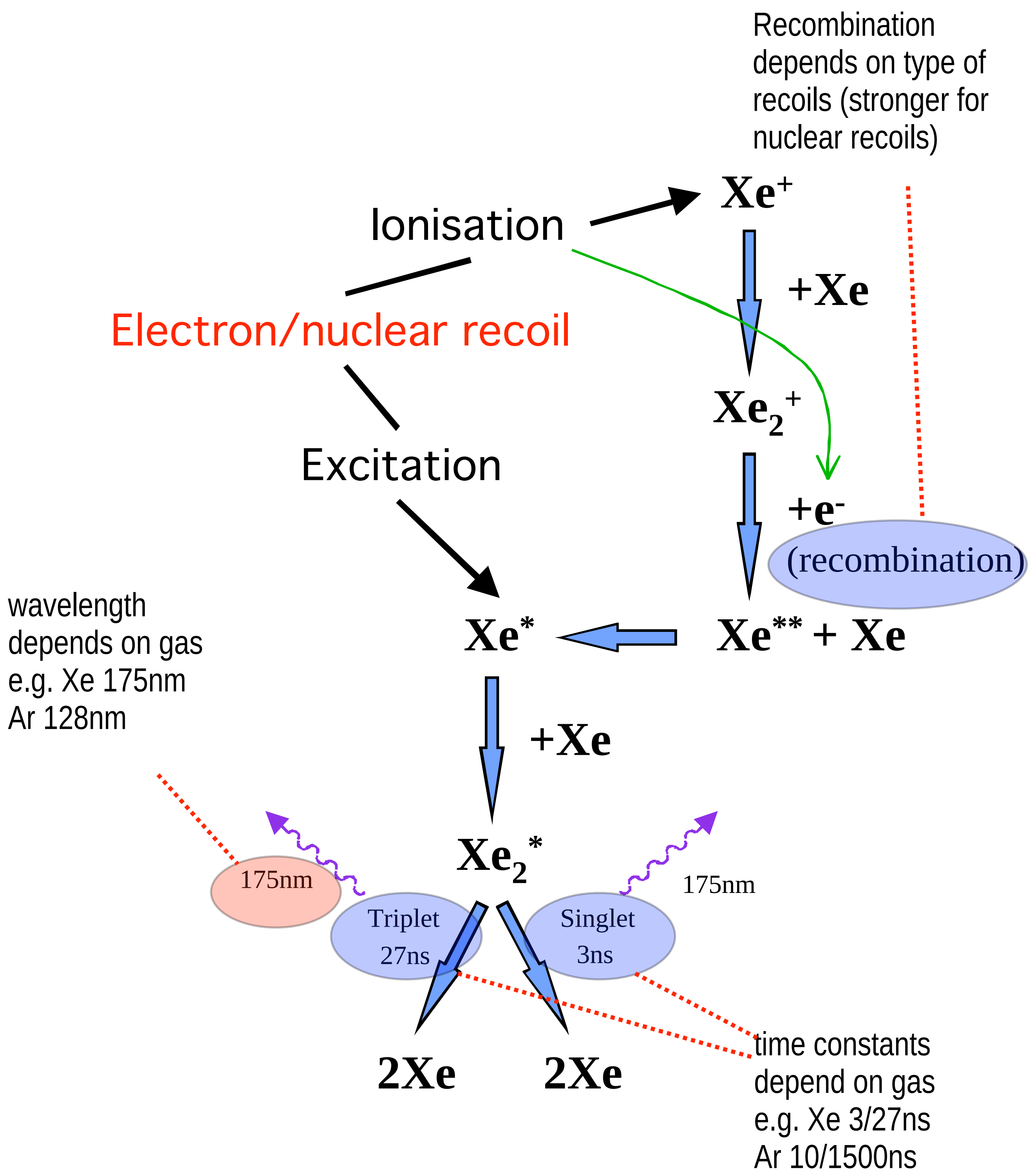
Liquified Noble Gases: Basic Properties

Dense and homogeneous
Do not attach electrons, heavier noble gases give high electron mobility
Easy to purify (especially lighter noble gases)
Inert, not flammable, very good dielectrics
Bright scintillators

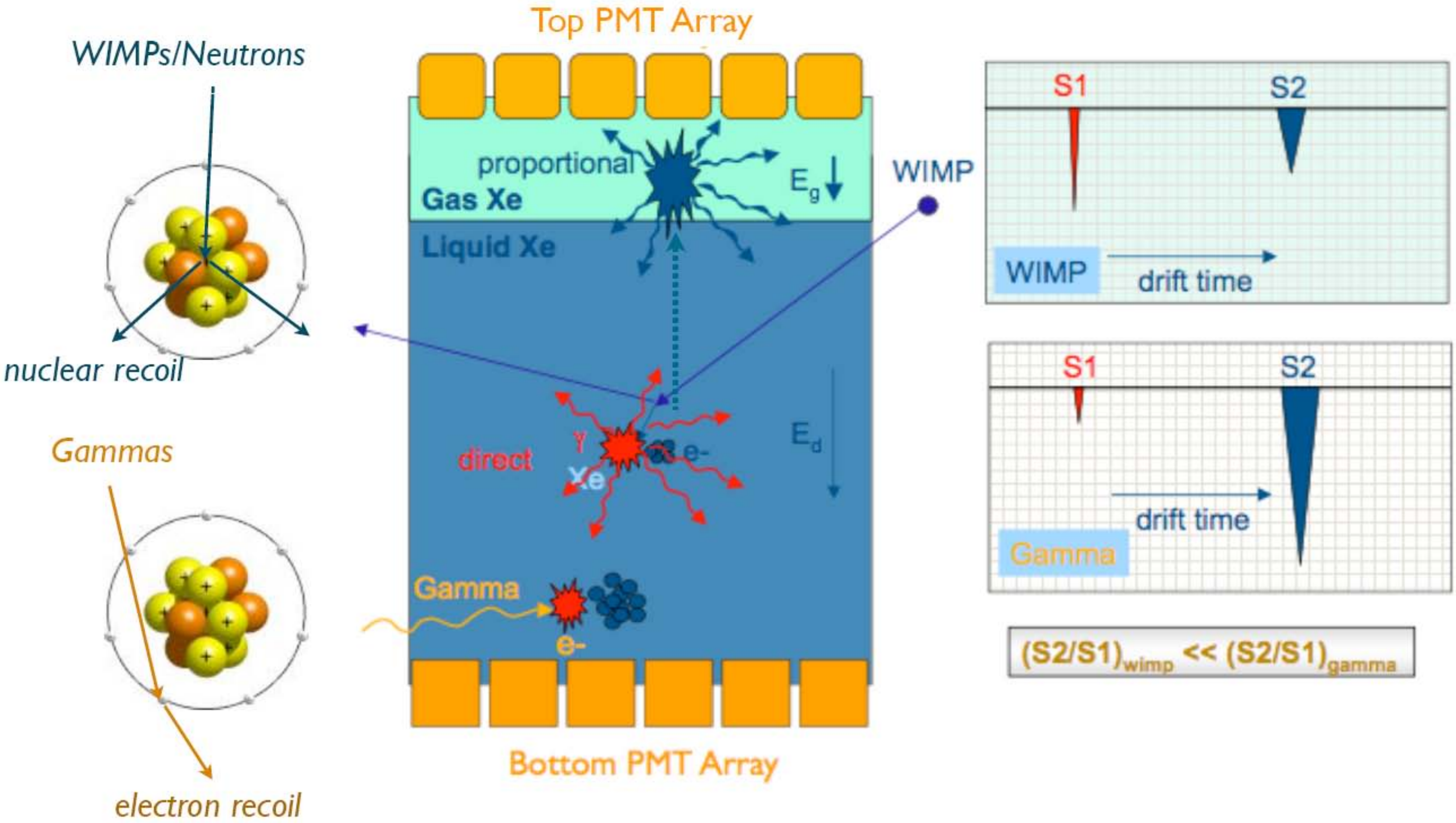
	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

Liquid Xenon for Dark Matter Detection

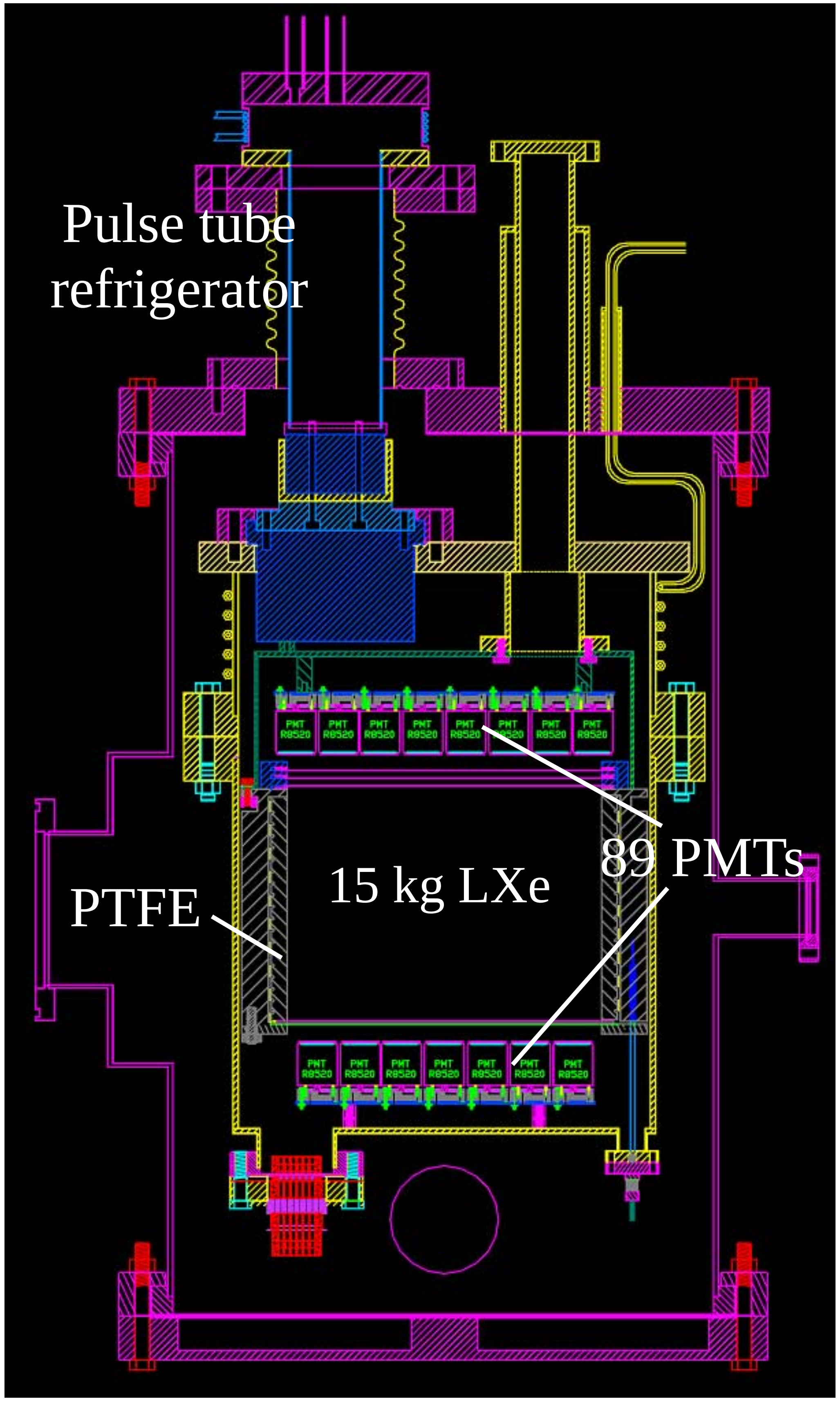
- *Large nucleus (A~131) : good for SI plus SD sensitivity (~50% odd isotopes)*
- *scalability : relatively cheap ($1500/kg) and "easy" cryogenics at 160 K*
- *background reduction: via self-shielding* (Z=54, ρ=3 g/cc)
- *intrinsically background free: Kr in Xe can be purified to ppt level*
- *low threshold : high scintillation yield* (~80% of NaI but much faster)
- *gamma rejection: electron and nuclear recoil discrimination*



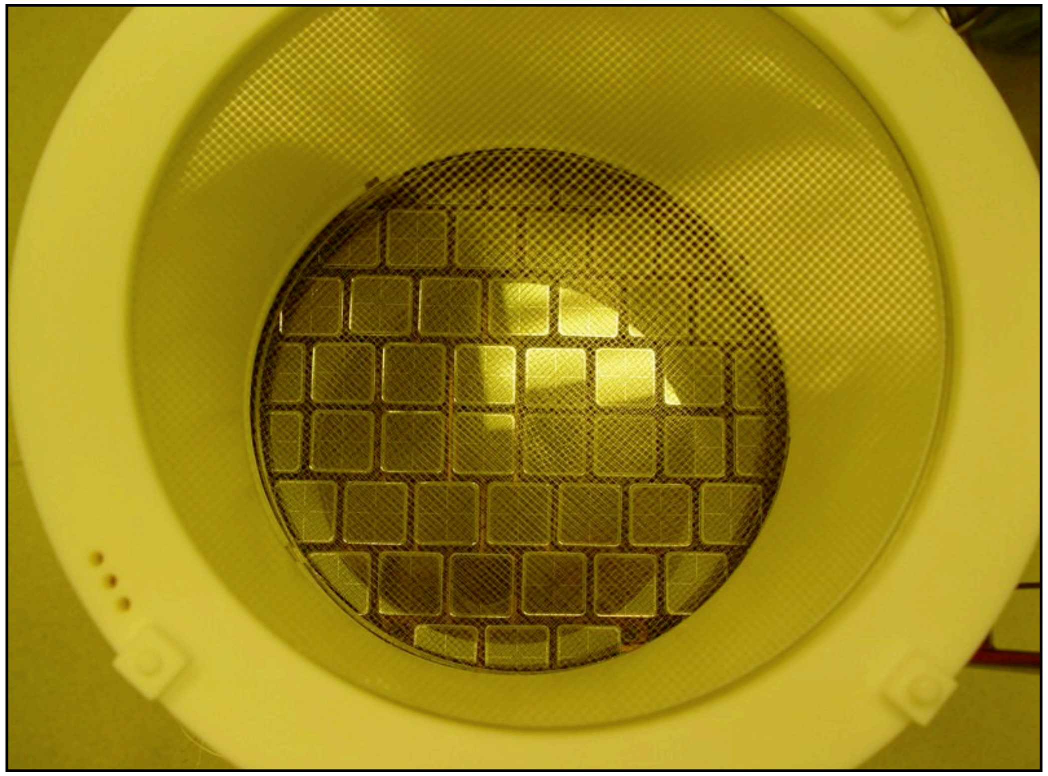
Two Phase Xe Time Projection Chamber



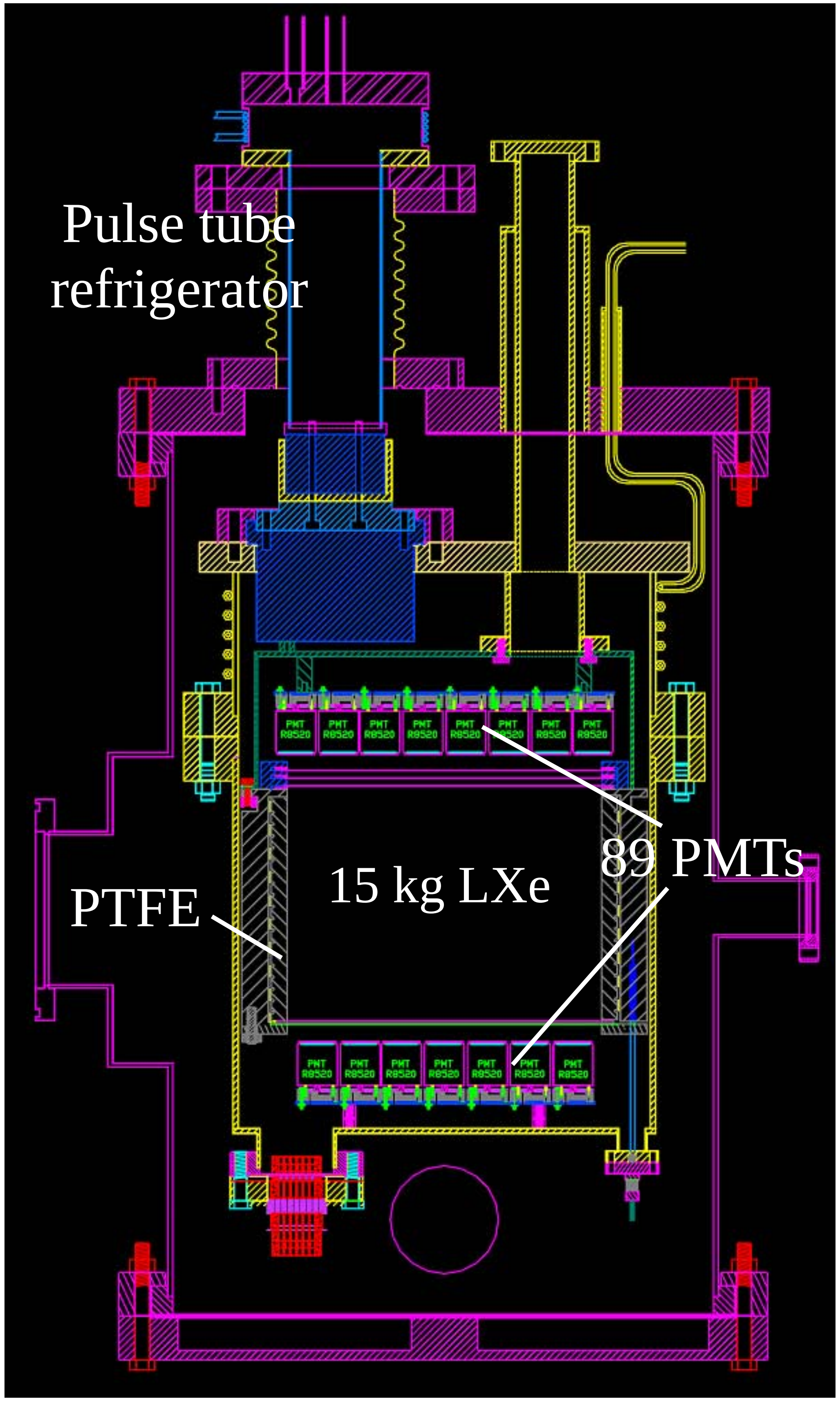
XENON10: 1st Phase of XENON DM Program



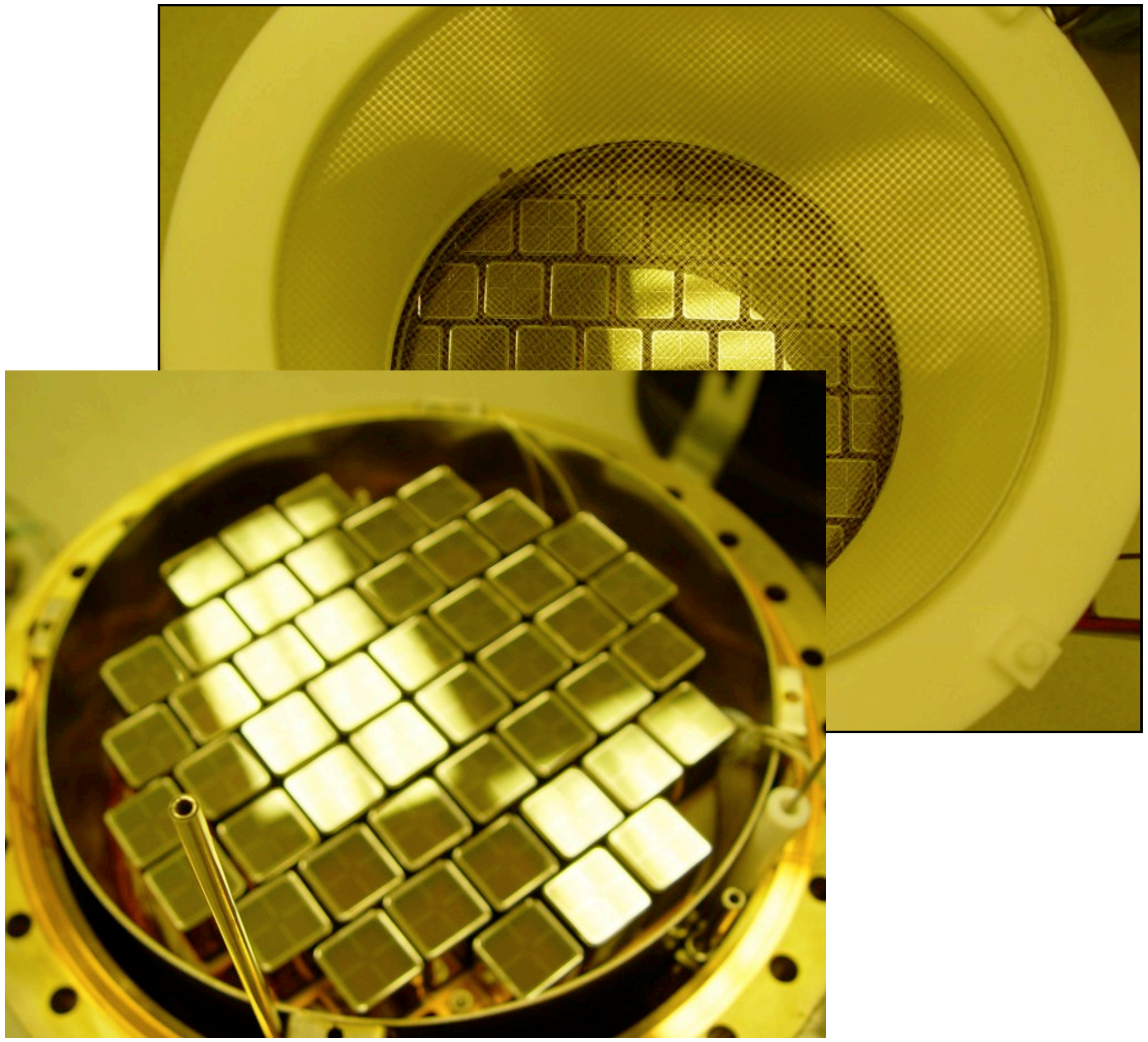
- *Pulse Tube refrigerator:* stable operation at 170 K
- *TPC active volume:* 20 cm (Φ) x 15 cm (H) - 15 kg
- *PTFE Teflon:* ~95% UV reflectivity at 175 nm
- *89 PMTs (R8520)*: 20% QE, low radioactivity



XENON10: 1st Phase of XENON DM Program



- *Pulse Tube refrigerator:* *stable operation at 170 K*
- *TPC active volume:* *20 cm (Φ) x 15 cm (H) - 15 kg*
- *PTFE Teflon:* *~95% UV reflectivity at 175 nm*
- *89 PMTs (R8520):* *20% QE, low radioactivity*



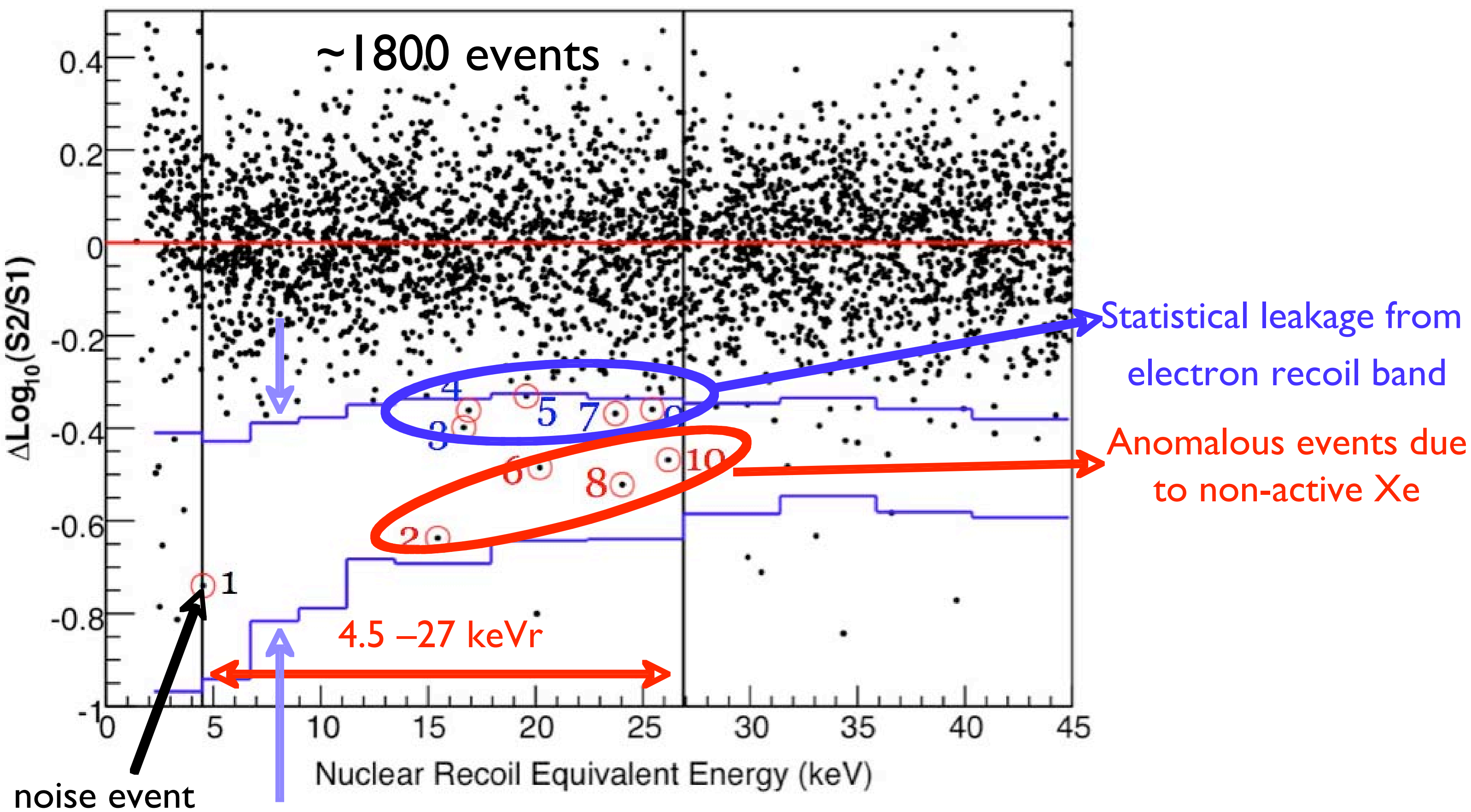
XENON10: SI WIMP-Nucleon Cross-Section Upper Limits (90% CL)

Phys. Rev. Lett. ***100***, *021303 (2008)*

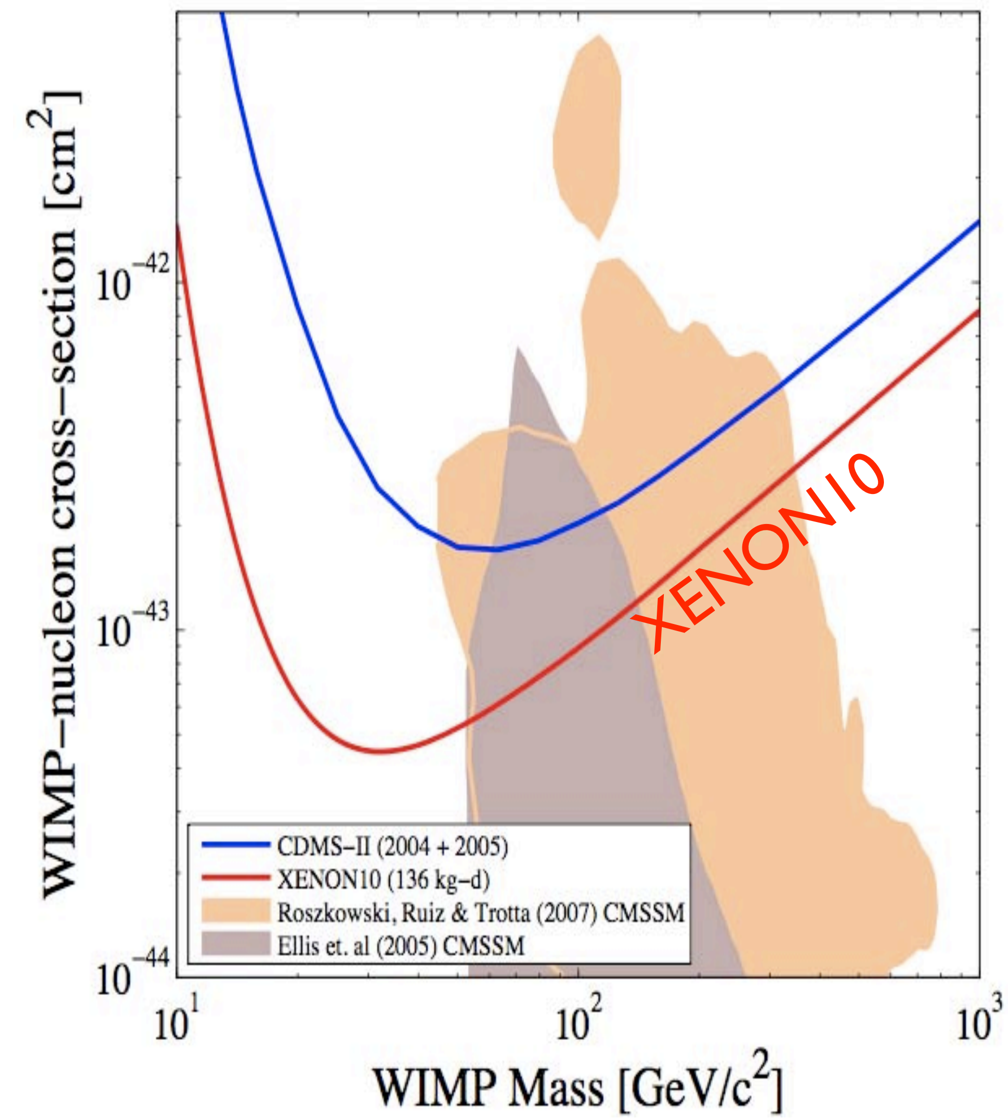
XENON10 WIMP Search Data

Blind Analysis

136 kg-days Exposure= 58.6 live days x 5.4 kg x 0.86 (ε) x 0.50 (50% NR)



WIMP Search Window defined at ~50% acceptance of Nuclear Recoils (blue lines): [Mean, -3■]



XENON10: SD WIMP-Nucleon Cross-Section Upper Limits (90% CL)

Angle et al. :arXiv 0805.2939, submitted to Phys. Rev. Lett.

Natural Xe has non-zero nuclear spin isotopes: 129Xe (spin-1/2) @ 26.4% and 131Xe (spin-3/2)@ 21.2%. Both contain unpaired neutrons thus XENON10 is mostly sensitive to WIMP-neutron spin-dependent couplings, yielding the best sensitivity to-date.

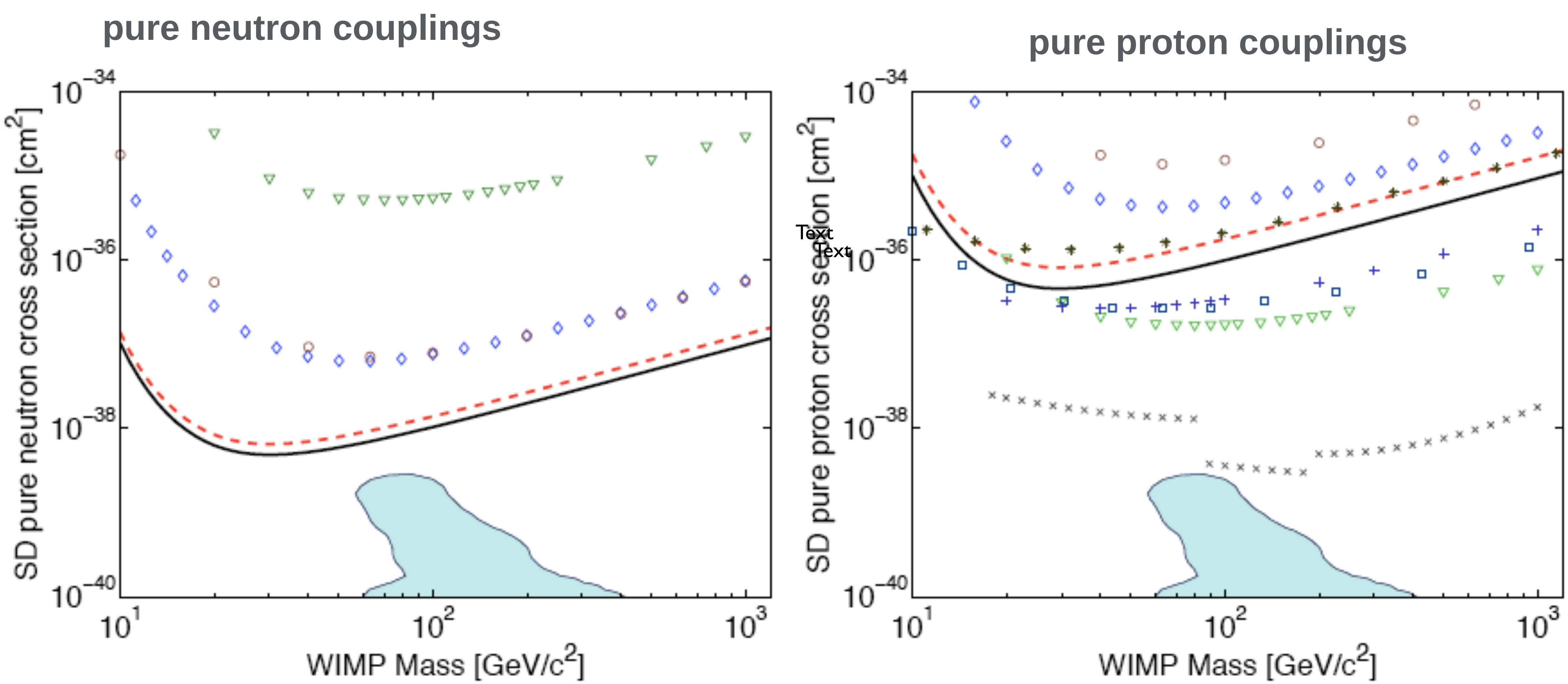


FIG. 1: XENON10 combined 90% CL exclusion limits for ^{129}Xe and ^{131}Xe for pure neutron (left) and pure proton (right) couplings (solid curves). The dashed curves show the combined Xe limits using the alternate form factor. Also shown are the results from the CDMS experiment [20] (diamonds), ZEPLIN-II [21] (circles), KIMS [22] (triangles), NAIAD [23] (squares), PICASSO [24] (stars), COUPP [25] (pluses) and SuperK [31] (crosses). The theoretical regions for the neutralino (in the constrained minimal supersymmetric model) are taken from [32].

XENON10: Heavy Majorana Neutrino Upper Limit (90% CL)

Exclude Majorana Neutrino with ~10 GeV - 2 TeV as DM candidate

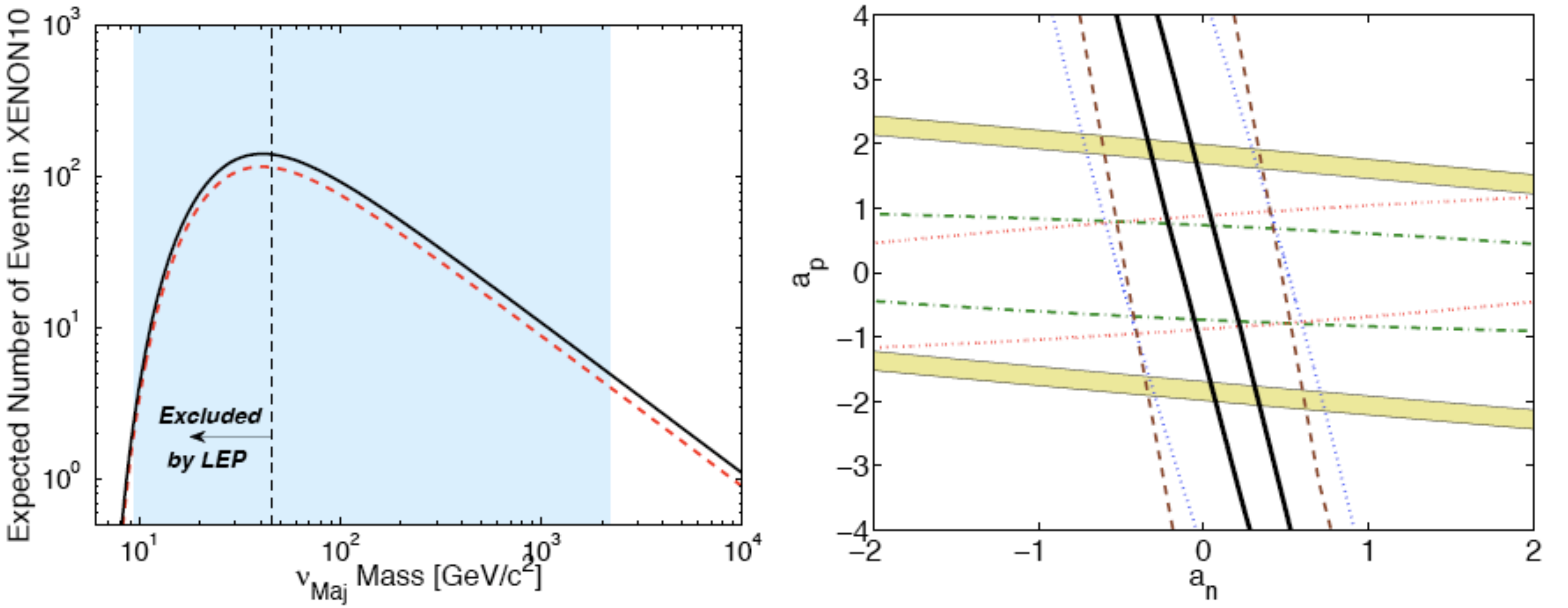
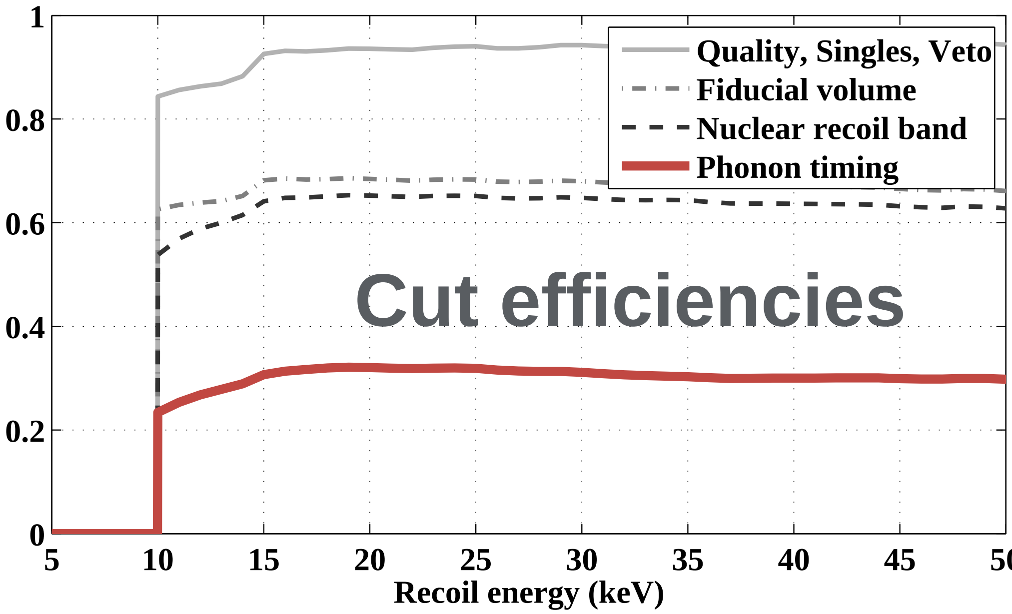


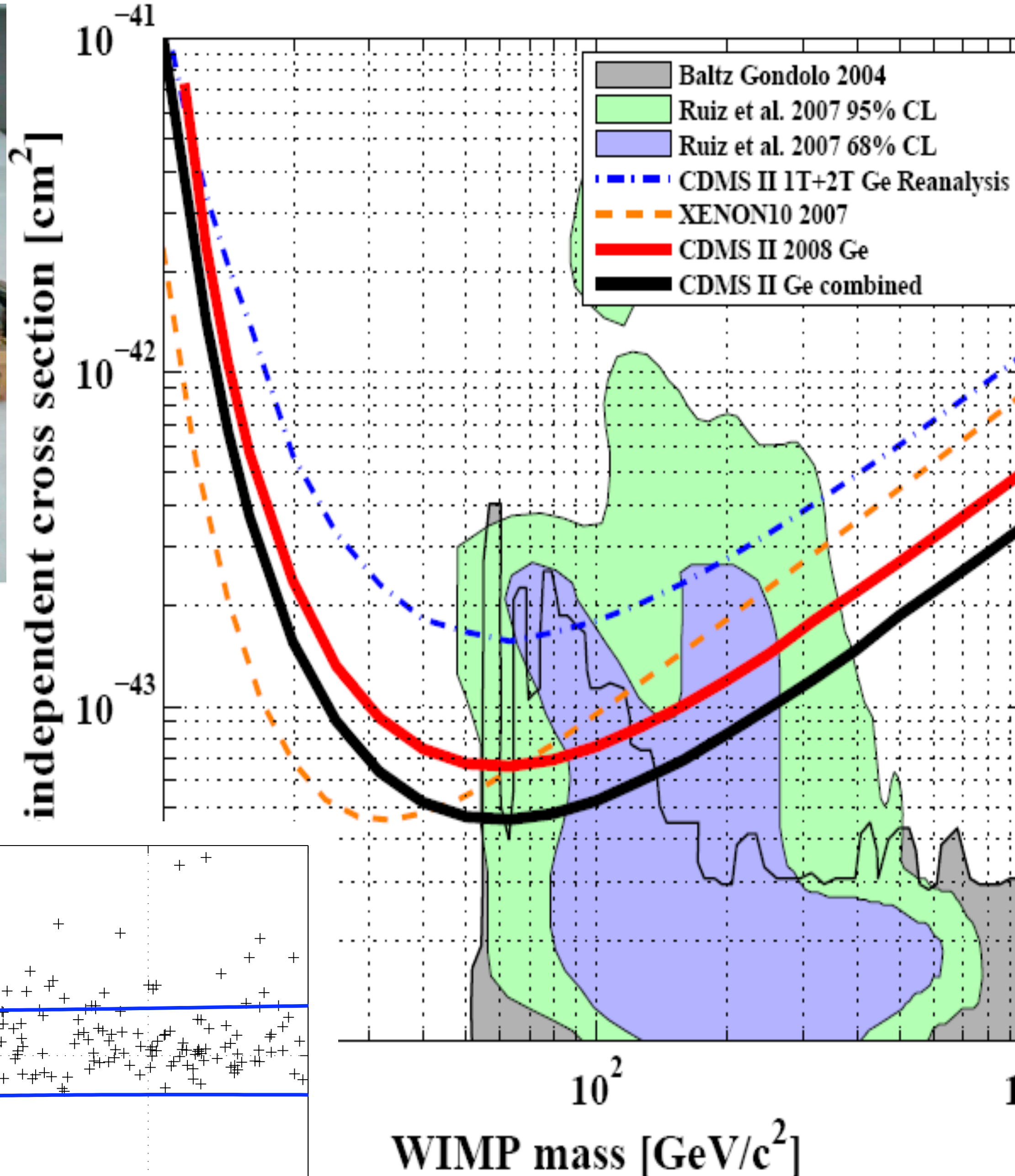
FIG. 2: Left: Predicted number of events in XENON10 for a heavy Majorana neutrino with standard weak interaction as a function of the neutrino mass, using the main (solid curve) and alternate (dashed curve) form factors. The light shaded area shows the excluded mass region at 90% CL, calculated with Yellin's Maximal Gap method [19] for the main form factors. Right: Regions allowed at the 90% CL in $a_n - a_p$ parameter space for a WIMP mass of 50 GeV/c^2. The combined limit from ^{129}Xe and ^{131}Xe is shown as a dark solid curve (using the main form factor, see text), The exteriors of the corresponding ellipses are excluded, the common space inside the ellipses being allowed by the data. We also show the results obtained by KIMS [22] (dot-dashed), COUPP [25] (dotted) ('horizontal' ellipses) and CDMS [20] (dotted), ZEPLIN-II [21] (dashed) and the DAMA evidence region [18] (light filled region) ('vertical' ellipses).

Feb 08: New CDMS Limit

First CDMS 5-Tower Results

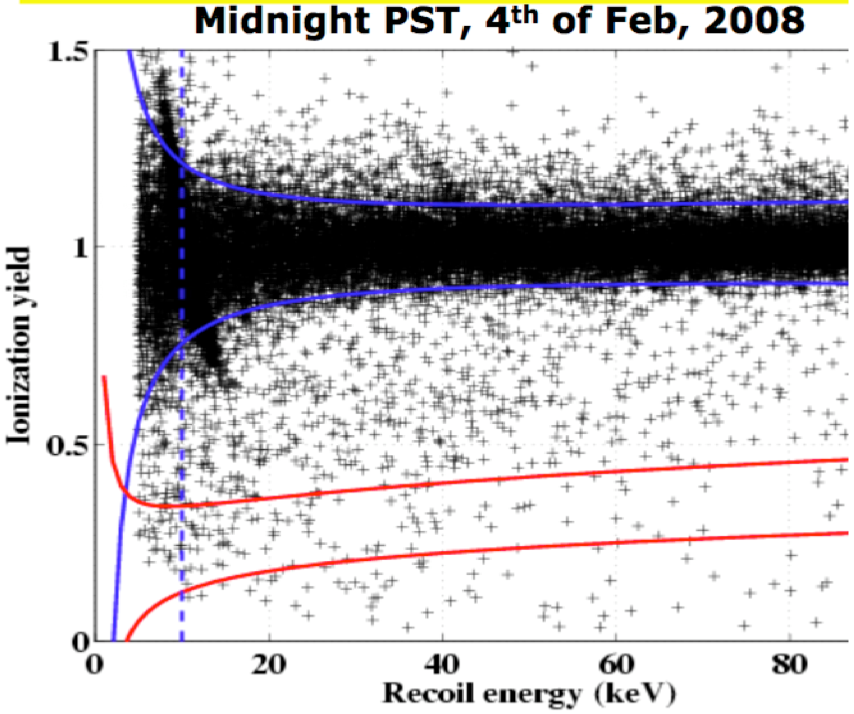
Rupak Mahapatra



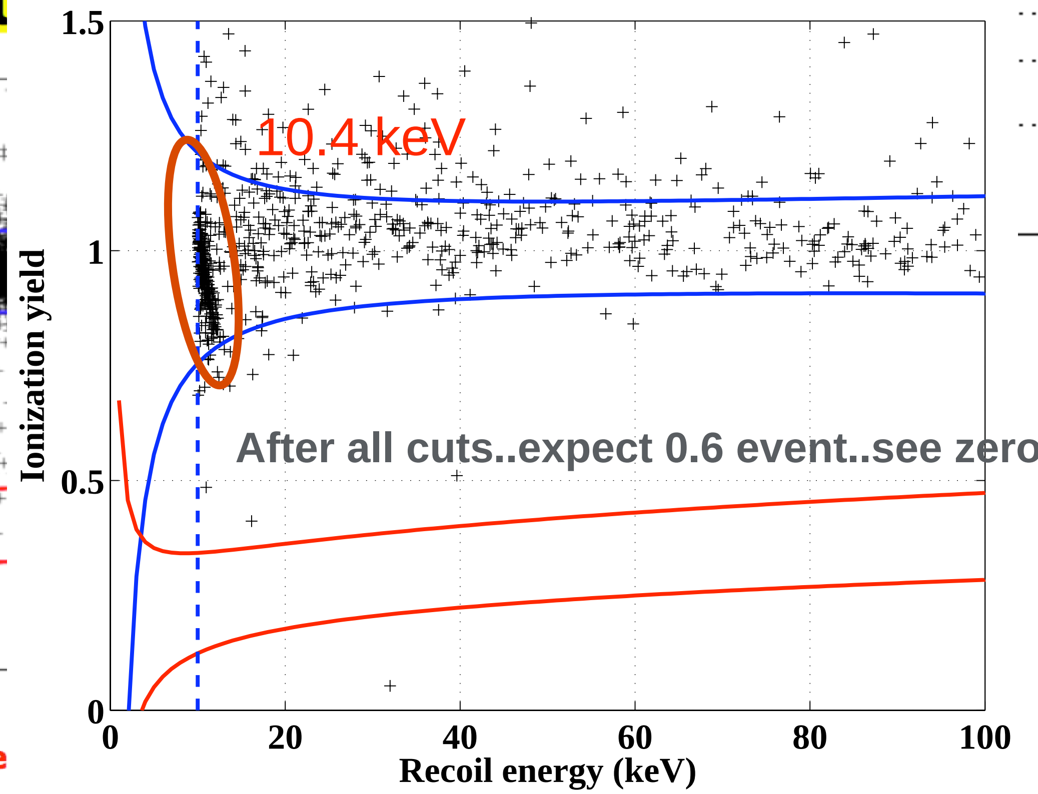


The WIMP Search Data

Midnight PST, 4th of Feb, 2008



97 Singles in Signal region rejected by Surface Eve



After all cuts..expect 0.6 event..see zero

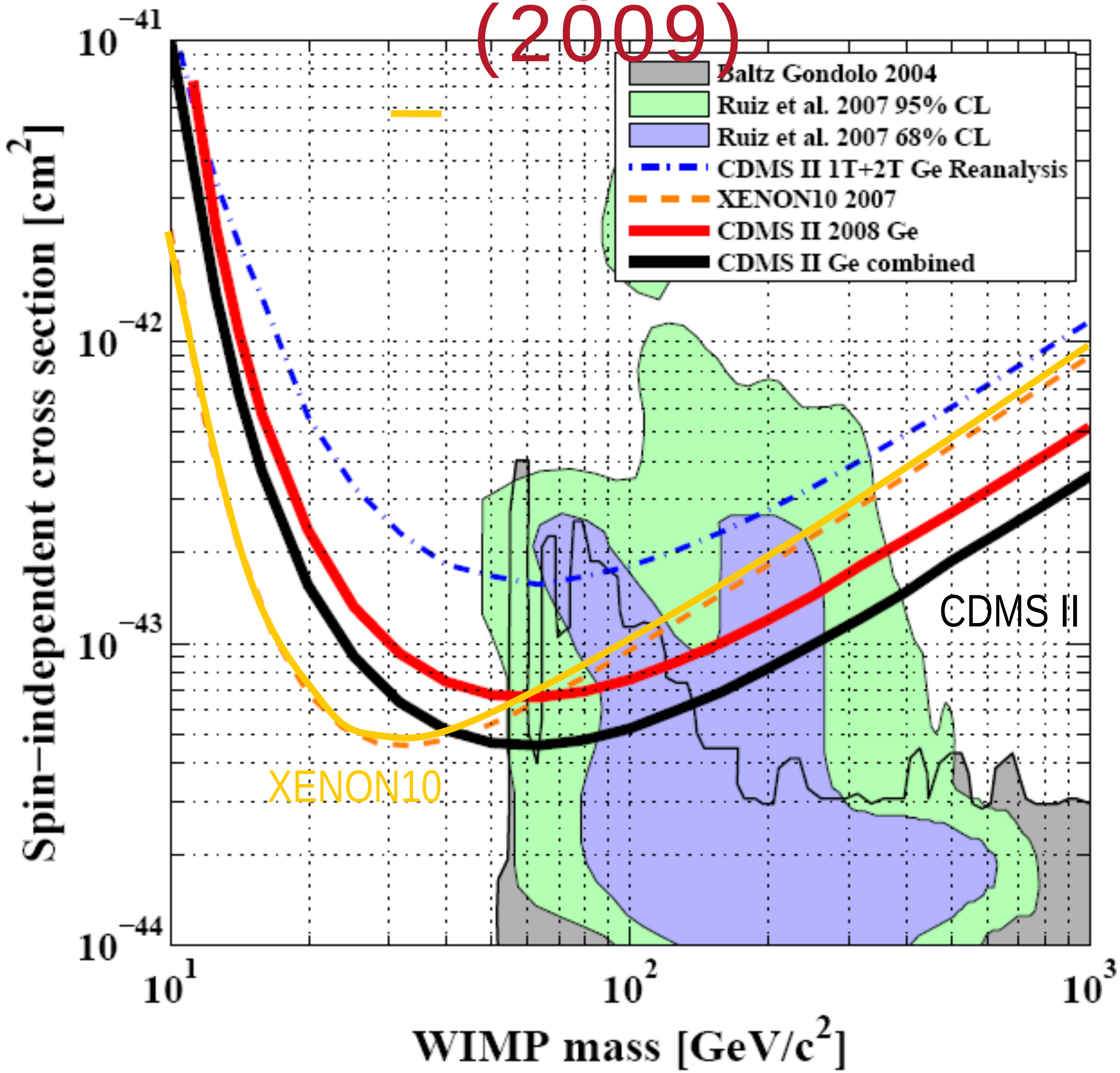
Would expect roughly 650 kg.d * 30% effective/fiducial exposure= 200 kg.d

Actually used exposure is **125 kg.d**
7/19 detectors used because of "variations of performances"
on run 124

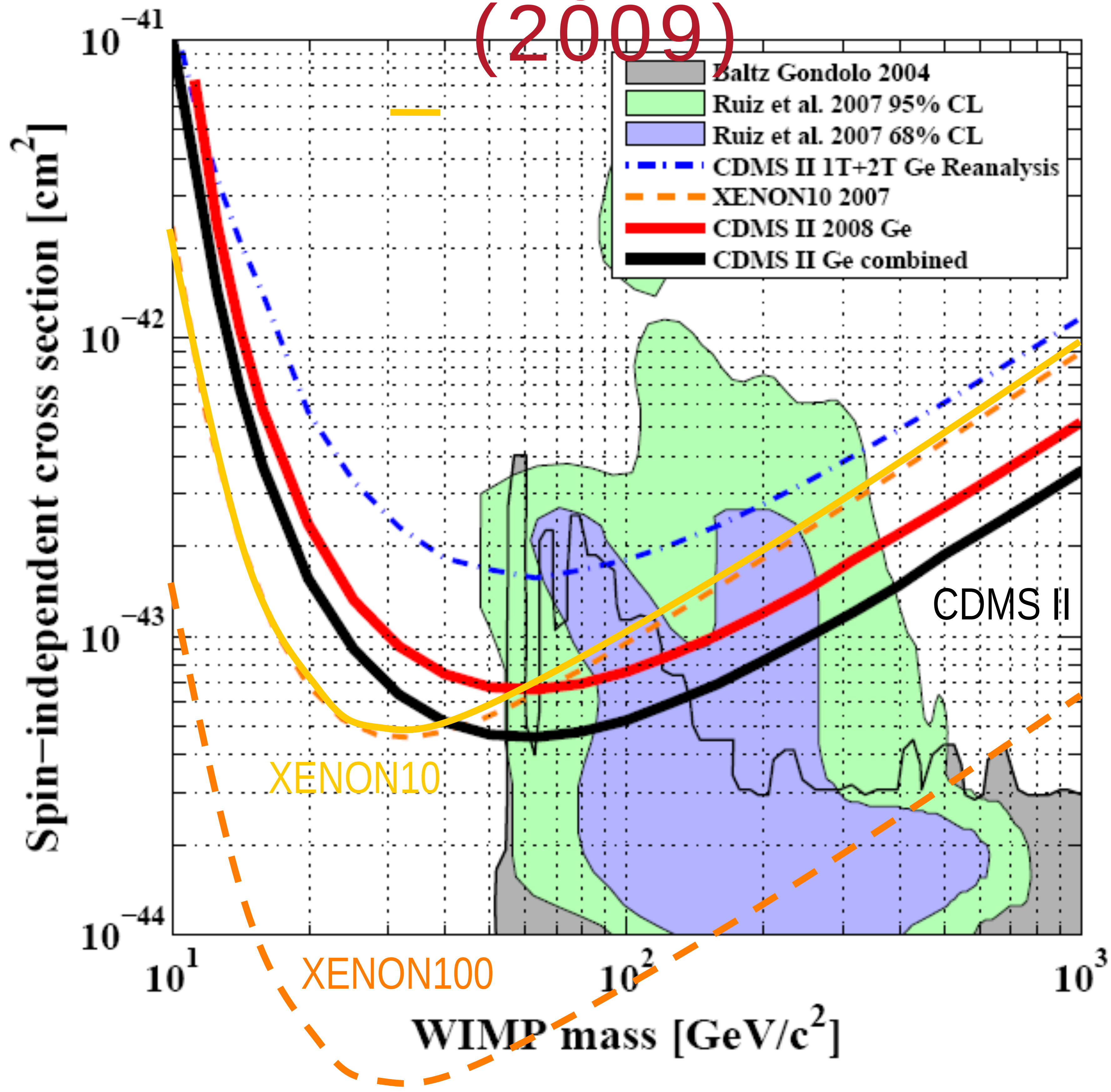
Feb 08: New XENON TPC @ LNGS

- 170 kg Xe-TPC (30 cm drift)
  - 100 kg LXe active shield
  - 70 kg LXe target
  - x10 fiducial mass of XE10
- Improved PMTs (242 for Target & Veto)
  - Low activity (U/Th ~1 mBq/PMT)
  - QE >30% @ 175 nm (bottom array)
- New Cryostat and Cryogenics System
  - Low activity SS (U/Th<1 mBq/kg)
  - Cryocooler and Feedthroughs outside shield
  - Kr-removal by distillation tower
  - Improved Shielding (Pb,Poly,Cu)
- Calibration: Summer 08
- 1st Science Data: Fall 08

XENON100: Projected Sensitivity (2009)



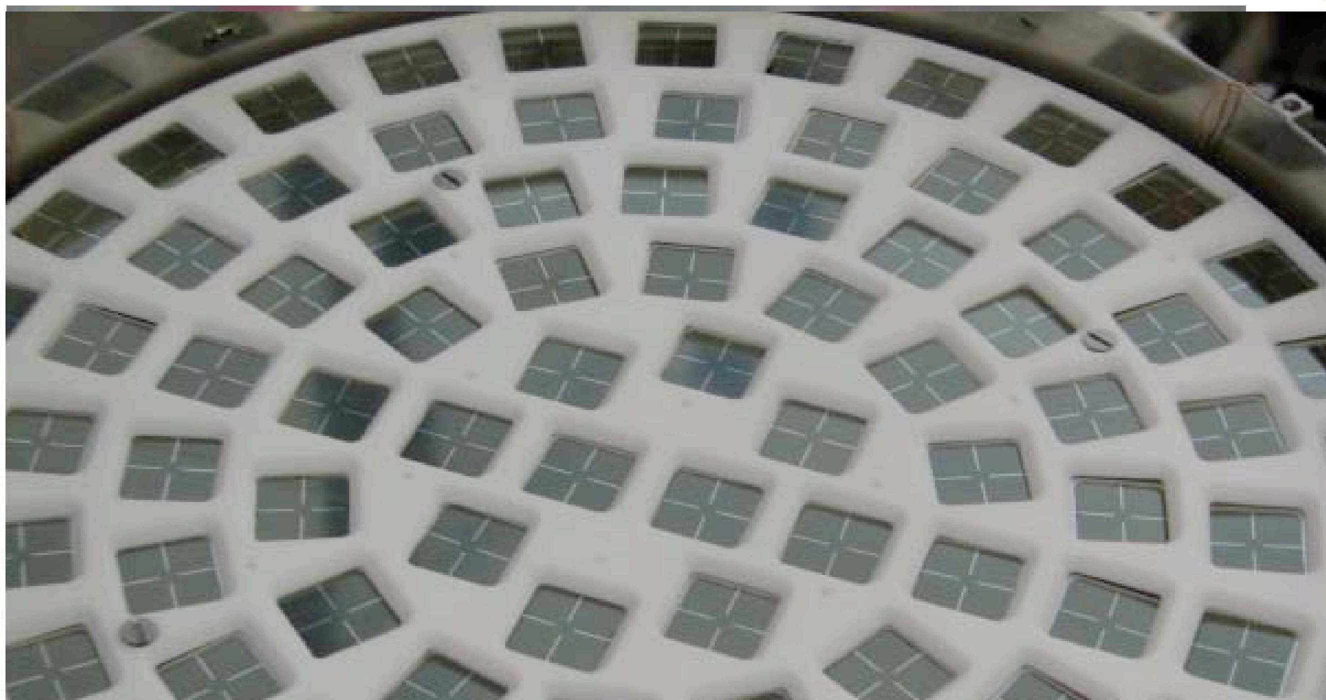
XENON100: Projected Sensitivity (2009)

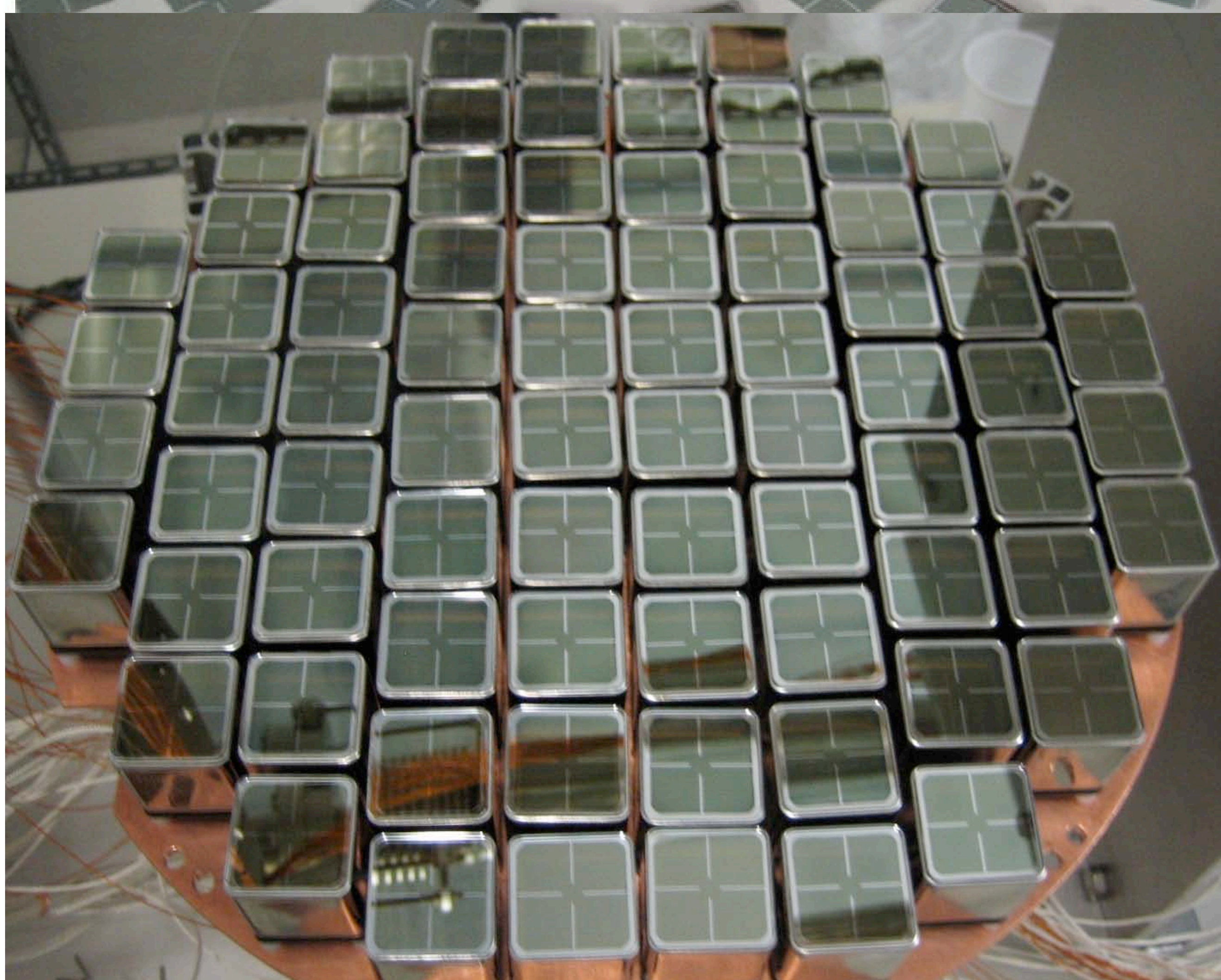


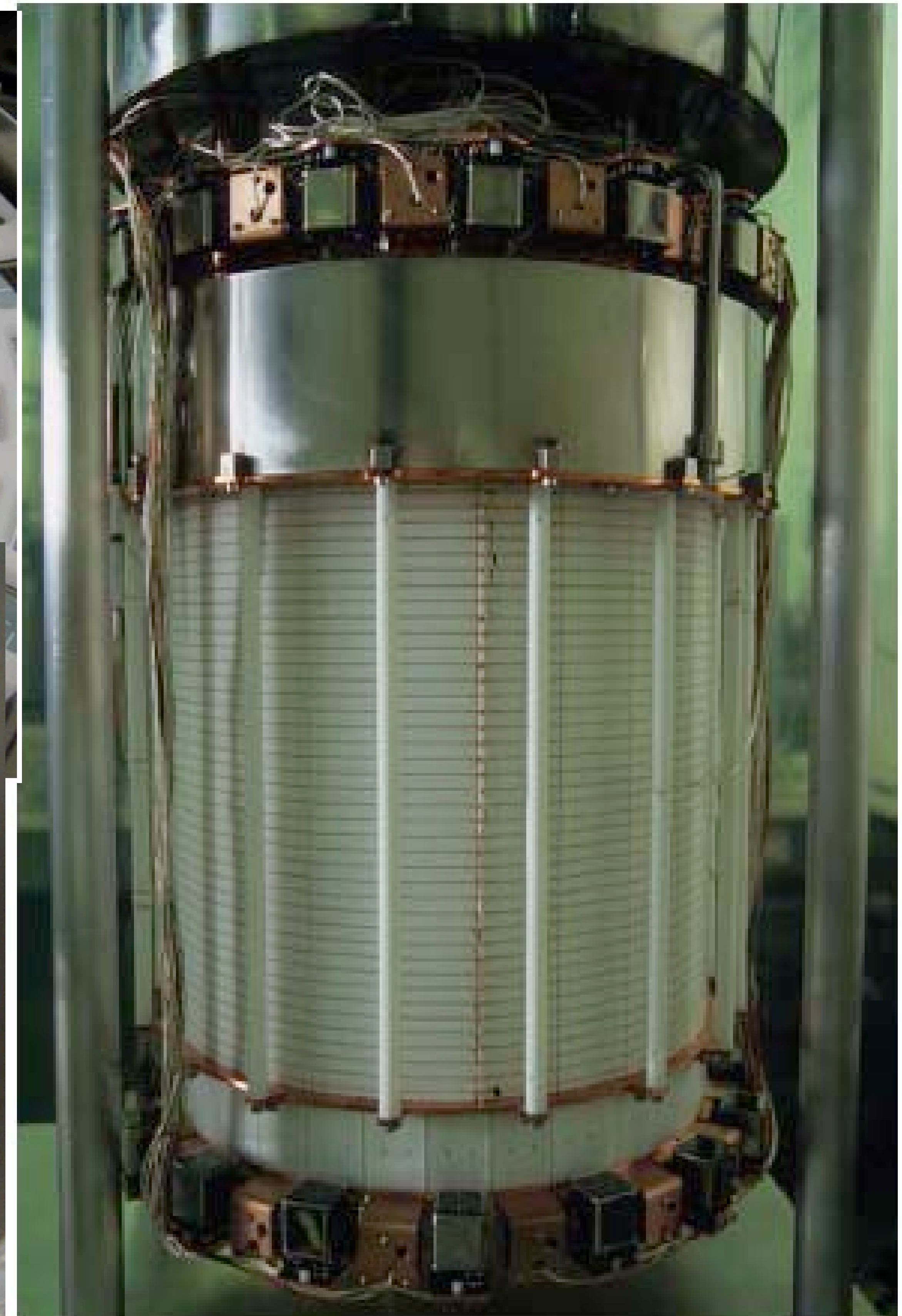
The XENON100 Collaboration

US	US	US	Switzerland	Portugal	Italy
Katsushi Arisaka Hanguo Wang UCLA	Elena Aprile Columbia University	Uwe Oberlack Rice University	Laura Baudis University of Zurich	Jose Matias Lopes University of Coimbra	Francesco Arneodo LNGS

XENON100: the TPC Assembly







XENON100 @ LNGS

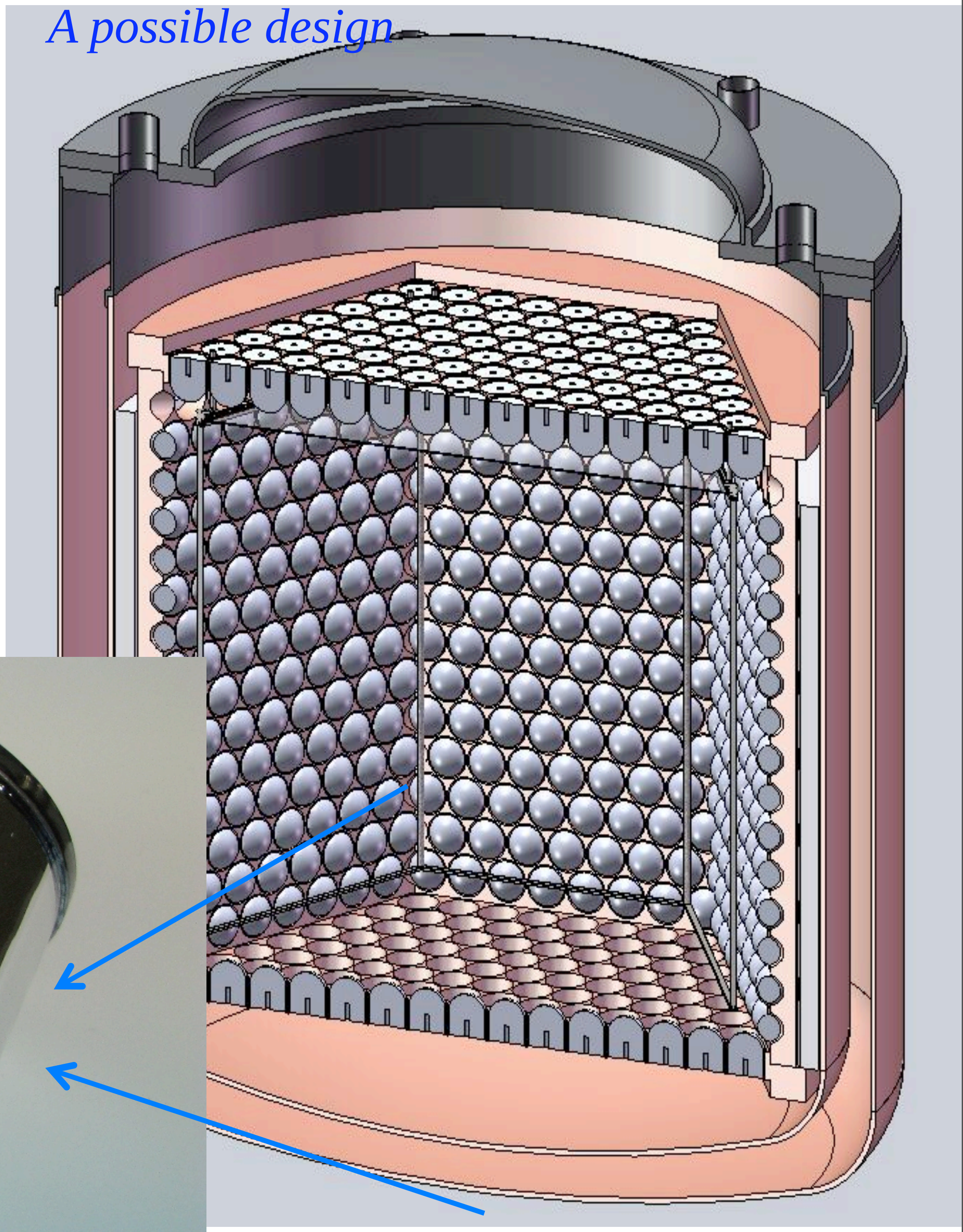
- installed underground since end of February
- filled with 140 kg xenon since mid May

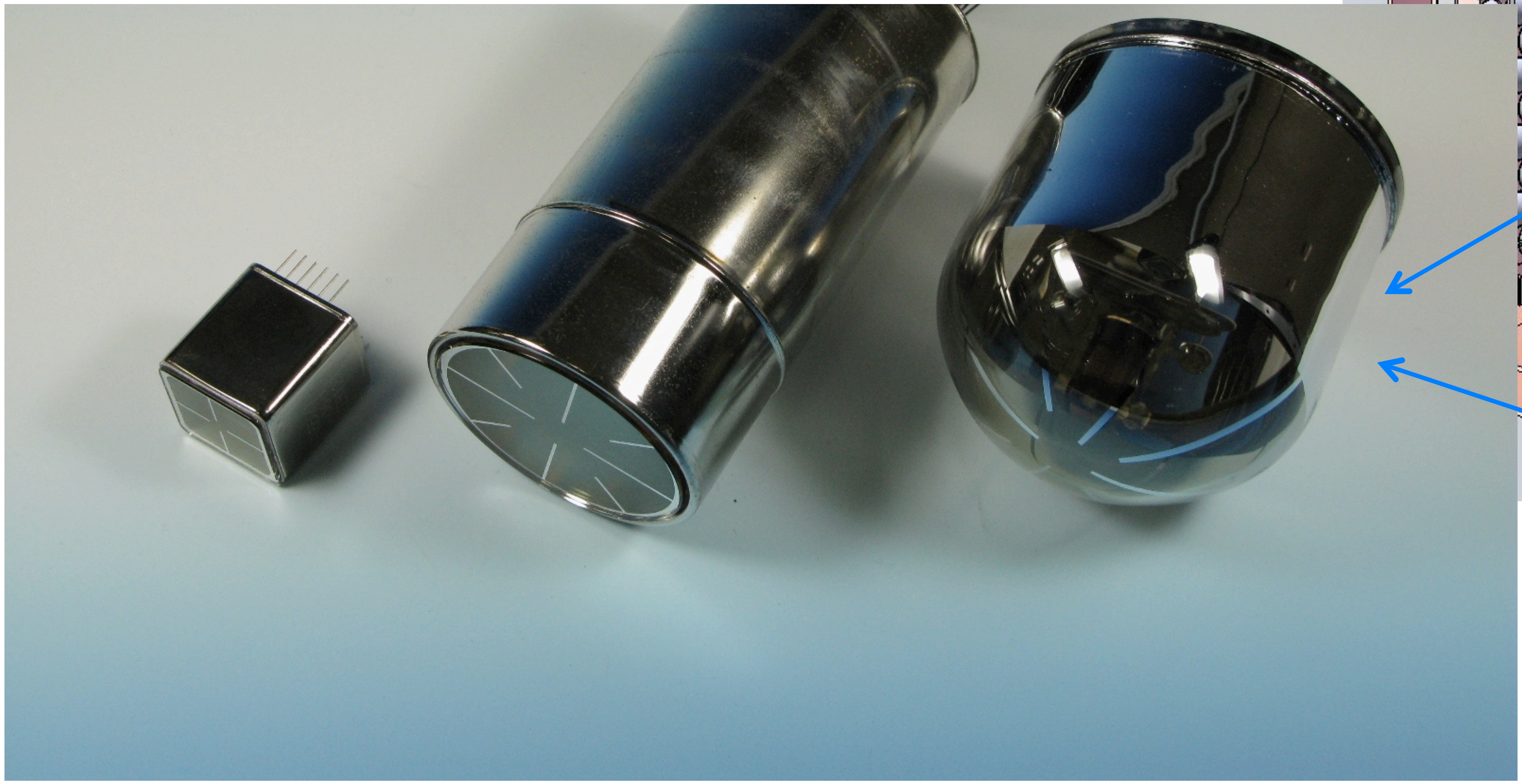
LNGS: 1.4km rock (3100 mwe)

The Next Step: XENON1T

3t LXe ("1m³ detector")
1t fiducial mass
Design study ongoing

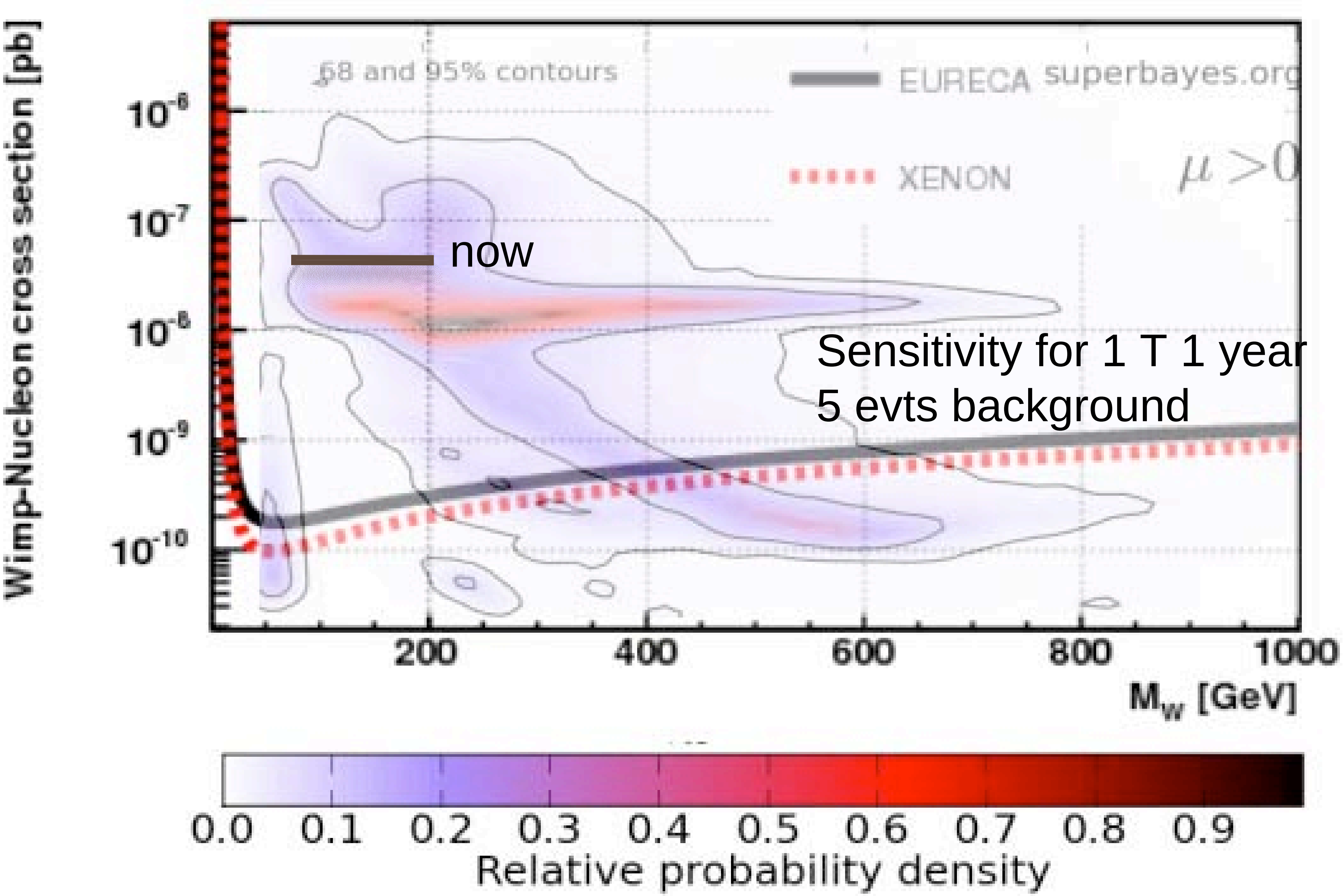
Proposal to NSF/DoE in 2008
Timeline: 2009-2013
Larger US & European Collaboration





Radiation- free
Photon Detector
(3” QUPID, Total 968)

Summary



68 and 95% contours
EURECA
superbayes.org
XENON
$\mu > 0$
now
Sensitivity for 1 T 1 year
5 evts background
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
Wimp-Nucleon cross section [pb]
200
400
600
800
1000
M_W [GeV]
0.0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9
Relative probability density