Towards precision measurements of

coherent scatter cross-sections

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WHAT DO WE MEAN BY "PRECISION"

ca. 2002

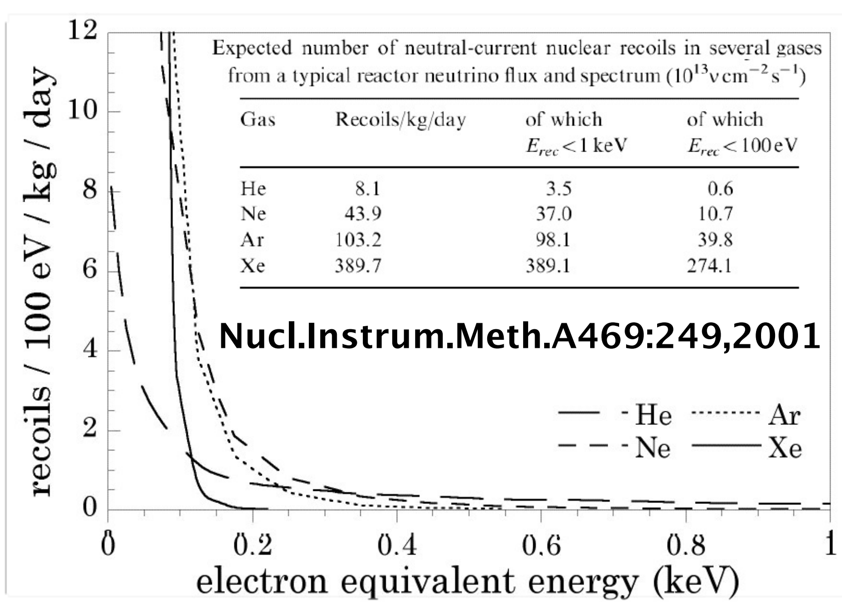
A one-page tutorial on coherent ν-N scattering

- Uncontroversial Standard Model process
- Large enhancement in cross-section for E_ν < few tens of MeV ($\sigma \propto N^2$, possible only for neutral current)
- However, not yet measured... detector technology has been missing.

Detector mass must be at least ~1 kg (reactor experiment) + recoil energy threshold << 1keV

(low-E recoils lose only 10-20% to ionization or scintillation)

- Cryogenic bolometers and other methods proposed, no successful implementation yet



Gas	Recoils/kg/day	of which E_{rec} < 1 keV	of which E_{rec} < 100 eV
He	8.1	3.5	0.6
Ne	43.9	37.0	10.7
Ar	103.2	98.1	39.8
Xe	389.7	389.1	274.1

Nucl.Instrum.Meth.A469:249,2001

Fundamental physics:

- Largest σ_ν in SN dynamics: should be measured to validate models (J.R. Wilson, PRL 32 (74) 849)
- A large detector can measure total E and T of SN ν_μ, ν_τ ⇒ determination of ν oscillation pattern and mass of ν star (J.F.Beacom, W.M.Farr & P.Vogel, PRD 66(02)033001)
- Coherent σ same for all known ν... oscillations observed in a coherent detector ⇒ evidence for $\nu_{sterile}$ (A.Drukier & L.Stodolsky, PRD 30 (84) 2295)
- Sensitive probe of weak nuclear charge ⇒ test of radiative corrections due to new physics above weak scale (L.M.Krauss, PLB 269, 407)
- More sensitive to NSI and new neutral bosons than ν factories. Also effective ν charge ratio (J. Barranco et al, hep-ph/0508299,hep-ph-0512029
- σ critically depends on μ_ν: observation of SM prediction would increase sensitivity to μ_ν by an order of magnitude (A.C.Dodd et al, PLB 266 (91) 434)

Smallish detectors... "ν technology"?

- Monitoring of nuclear reactors against illicit operation or fuel diversion: present proposals using conventional 1-ton detectors reach only > ~3 GWt reactor power
- Geological prospection, planetary tomography... the list gets much wilder

Low Hanging Fruit?

- ~~NC sterile □ search~~
- ~~Coherent scattering μ□ search~~
- Test Q_W radiative corrections
- NSI □ cross-sections
- Light Wimps

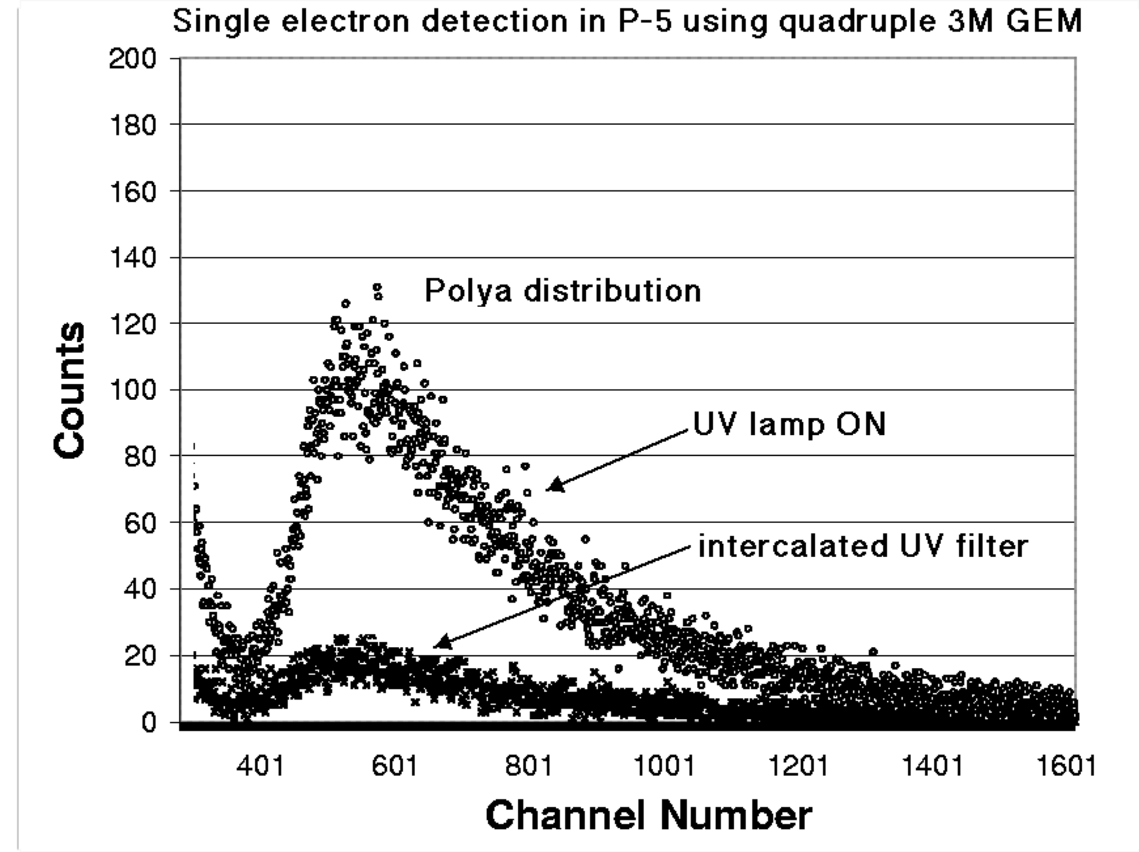
Not with scheme proposed here

AN OLD EFFORT: LOW THRESHOLD GAS DETECTORS

- Identical detector construction for all targets (controls systematics)
- Continuously re-purify
- Low thresholds: single electron sensitivity for ~1-10 Bar
- High Precision quenching factor measurement
- Target Masses (~kg/m^3)
- Standard drift gas targets: H_2, $^{3,4}He$, $^{10,11}BF_3$, $^{12,13,14}CH_4$, C_2H_6, C_4H_{10} ... CF_4, $^{32,34}SF_6$, CO_2, $^{20,22}Ne$, N_2, $^{82,83,84,85,86}Kr$, $^{39,40}Ar$, $^{129\text{-}132,134,136}Xe$
- Low backgrounds: ^{222}Rn @EXO, n & γ @CoGeNT.

3M GEM

P.S. Barbeau, J.I. Collar et al., NIM A515:439– 445, 2003.



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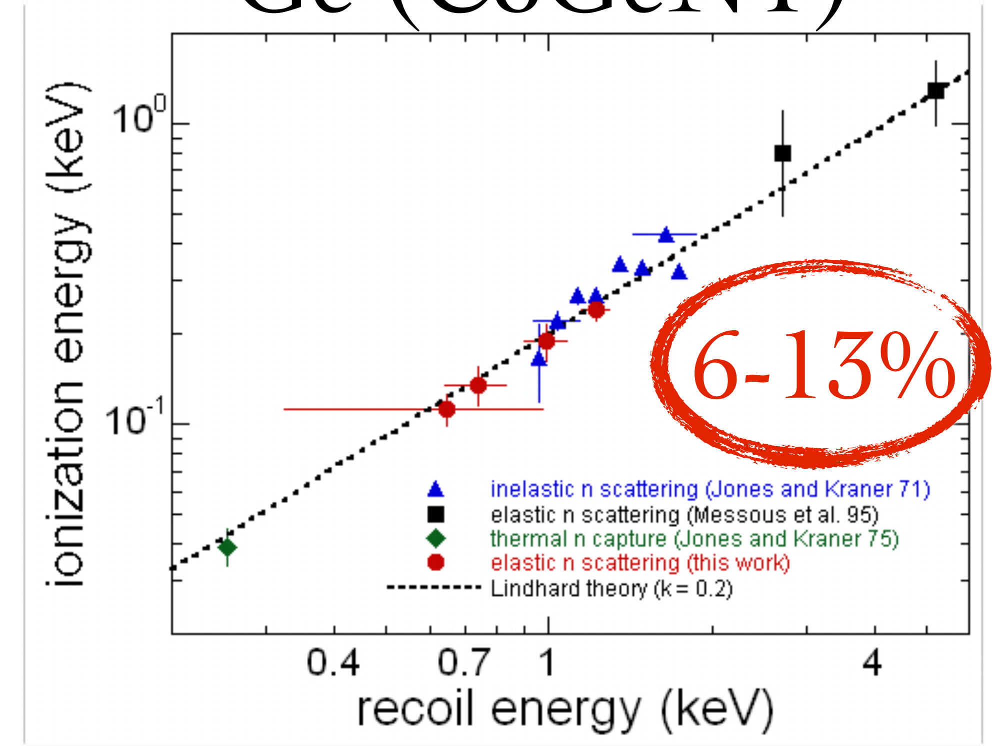
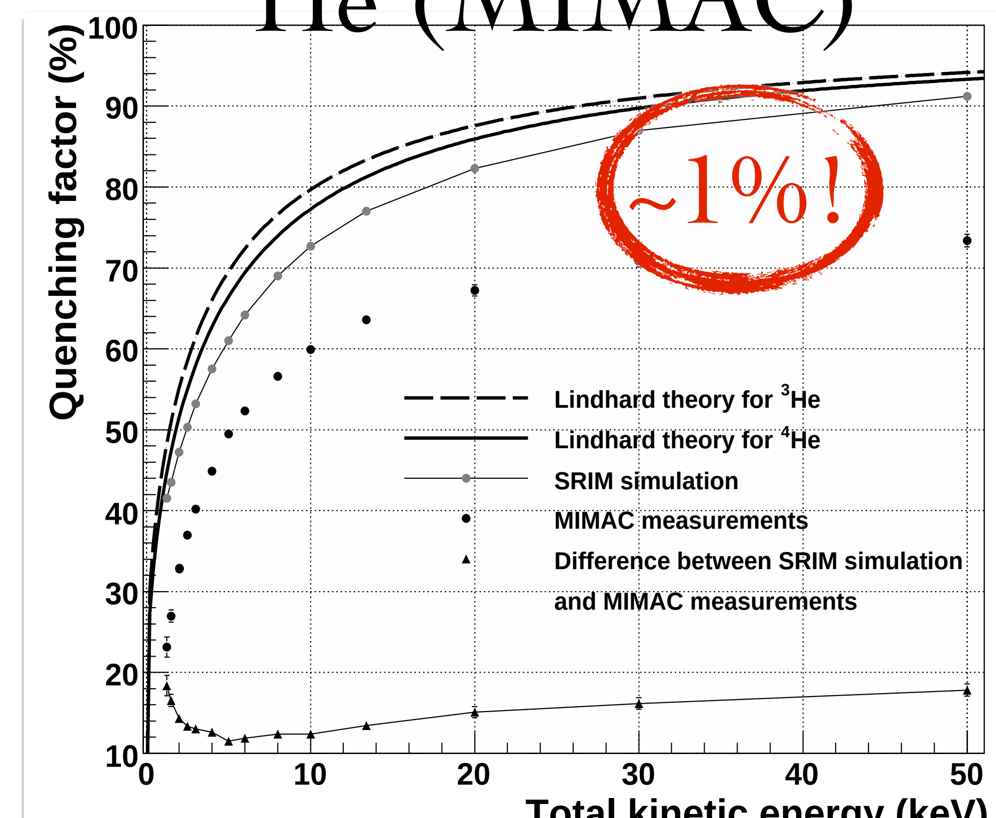
Ge (CoGeNT)



Barbeau, P. S., Collar, J. I., & Tench, O. 2007b, JCAP, 2007, 009

He (MIMAC)



arXiv:0810.1137v1 [astro-ph]

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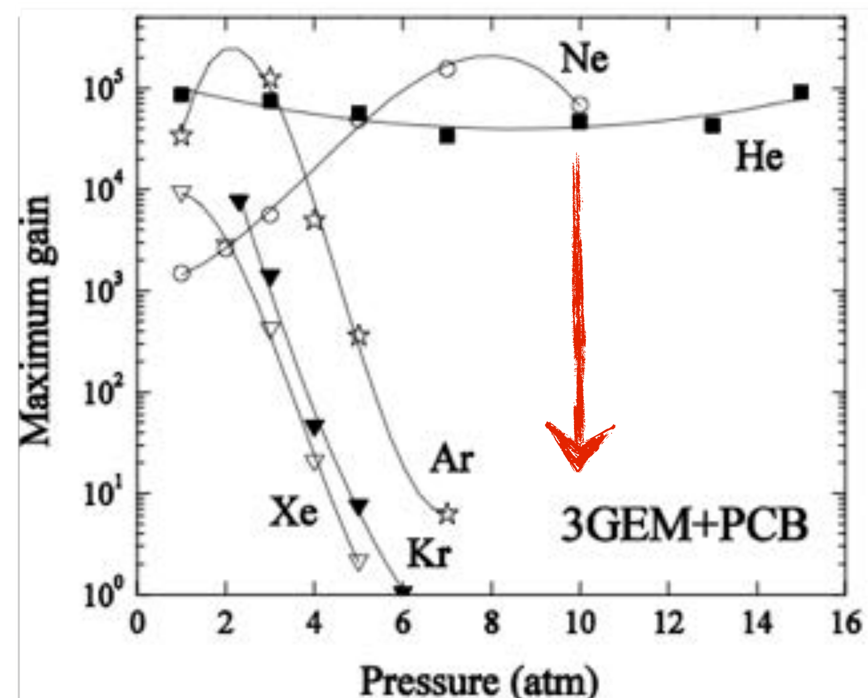
UofC cleanroom



Nucl.Instrum.Meth. A493 (2002) 8-15

Fig.8 Maximum gain of a triple GEM detector as a function of pressure in He, Ne, Ar, Kr and Xe.

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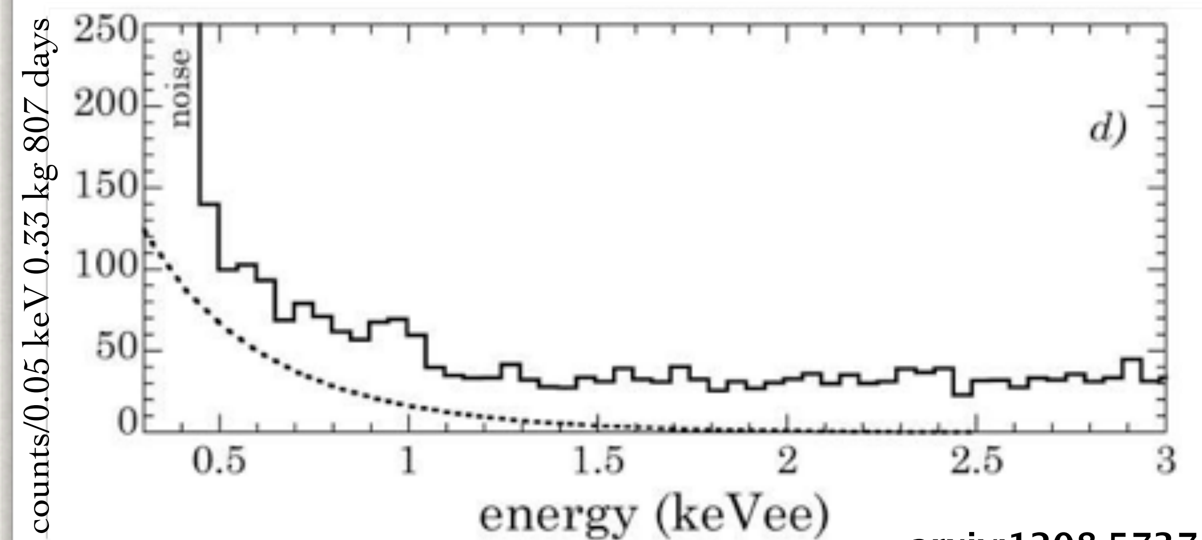


arxiv:1208.5737

^{222}Rn in EXO-200 (continuously circulating):
4.6 μBq kg^{-1} → ~0.01-0.1 c keV^{-1} kg^{-1} d^{-1}

^{85}Kr in Xe: < ~10^{-3} - 0.5 c keV^{-1} kg^{-1} d^{-1}

^{222}Rn daughters on SNO NCD surfaces:
~2 m^{-2} d^{-1} → ~0.5 c keV^{-1} kg^{-1} d^{-1}

^{14}C @ Borexino levels (measured in CH_4):
$^{14}C/^{12}C < 10^{-18}$ → < ~0.15 c keV^{-1} kg^{-1} d^{-1}

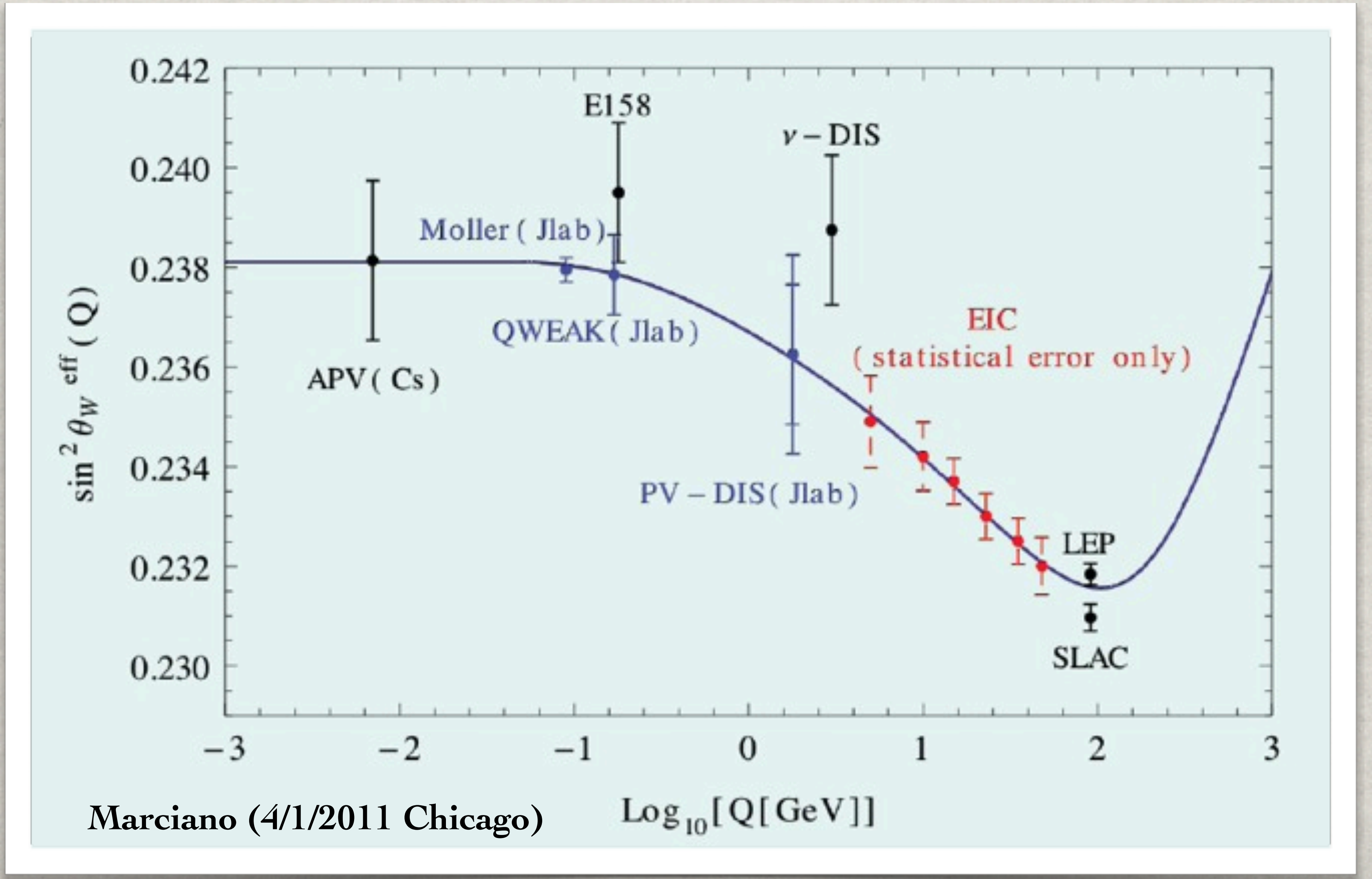
^{39}Ar in Ar @ ~ 15 - 300 c keV^{-1} kg^{-1} d^{-1}

CoGeNT backgrounds (0.5-3 keV)
2.6 - 7.4 c keV^{-1} kg d^{-1}

Weak Nuclear Charge

- We now know M_{top} and M_{Higgs} → uncertainties on radiative corrections are small
- Remaining hadronic uncertainties similar to those from APV experiments (~0.2%)
  (L. M. Krauss, PLB 269, 407)

$$Q_w = N - (1 - 4sin^2\theta_w)Z$$



Weak Nuclear Charge

Measure Qw with coherent scattering at nuclear reactor
(SONGS ~10^{13} cm^{-2} s^{-1} & 30 m.w.e)
Deviations → new Physics

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi}((G_V + G_A)^2 + (G_V - G_A)^2(1 - \frac{T}{E_\nu})^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2})$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

$$G_A = ((g_a^p + 2\epsilon_{ee}^{uA} + \epsilon_{ee}^{dA})(Z_+ - Z_-) + (g_a^n + \epsilon_{ee}^{uA} + 2\epsilon_{ee}^{dA})(N_+ - N_-))F_{nucl}^A(Q^2)$$

$$g_V^p = \rho_{\nu N}^{NC}(\frac{1}{2} - 2\hat{\kappa}_{\nu N} sin^2\theta_w) + 2\lambda^{uL} + 2\lambda^{uR} + \lambda^{dL} + \lambda^{dR}$$

$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}$$

+ axial vector factors which have more theoretical uncertainty (strong quark contributions, weak magnetism term, effective neutrino charge radii)

Weak Nuclear Charge

0) Use gas targets (swappable) to control fiducial volume systematics

1) Low q^2 @ Rx to avoid $F(Q^2)$ theoretical systematics

2) eliminate axial couplings along with their (larger) uncertainties

→ Choose even-even nuclei

H_2	$^{32,34}SF_6$
$^{3,4}He$	CO_2
$^{10,11}BF_3$	$^{20,22}Ne$
$^{12,13,14}CH_4$	N_2
C_2H_6	$^{82,83,84,85,86}Kr$
C_4H_{10} ...	$^{39,40}Ar$
CF_4	$^{129-132,134,136}Xe$

Weak Nuclear Charge

3) Factorize out □ flux (~6%) & absolute rate uncertainties

→ group according Z=N & Z≠N & measure ratio: $\frac{R_{Z=N}}{R_{Z\neq N}}$

$$Q_{w,{}^{4}He} = 2 \times 4sin^2\theta_w$$
$$Q_{w,{}^{12}C} = 6 \times 4sin^2\theta_w$$
$$Q_{w,{}^{16}O} = 8 \times 4sin^2\theta_w$$
$$Q_{w,{}^{20}Ne} = 10 \times 4sin^2\theta_w$$

$$Q_{w,{}^{22}Ne} = 2 + 10 \times 4sin^2\theta_w$$
$$Q_{w,{}^{40}Ar} = 4 + 18 \times 4sin^2\theta_w$$
$$Q_{w,{}^{136}Xe} = 28 + 54 \times 4sin^2\theta_w$$

$$Q_w = N - (1 - 4sin^2\theta_w)Z$$

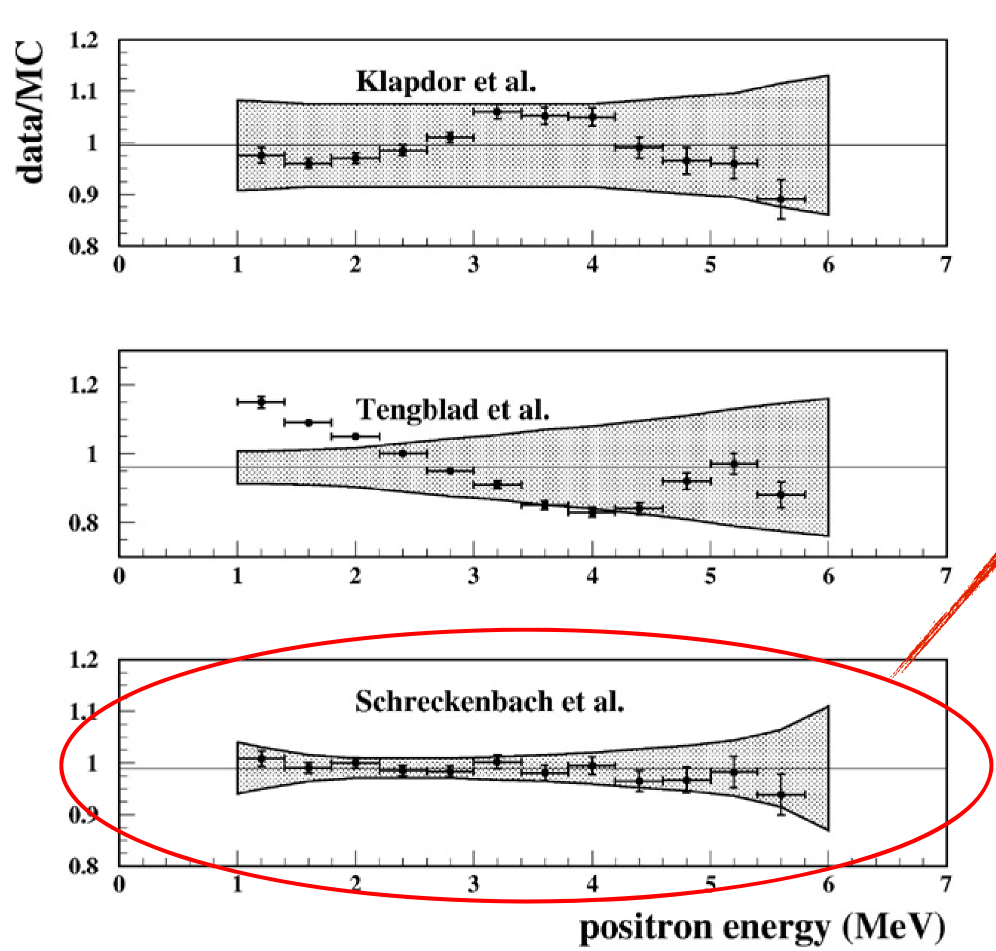
Weak Nuclear Charge

4) Use $A_1 \sim A_2$ nuclei to minimize impact of neutrino spectrum uncertainties → $^{20, 22}$Ne

Recoil energy: $T_{max} = 2E_{\square}/M$

Choose recoil thresholds (10% change between ^{20,22}Ne) to select same population of □ energies (spectral uncertainties factorize out)

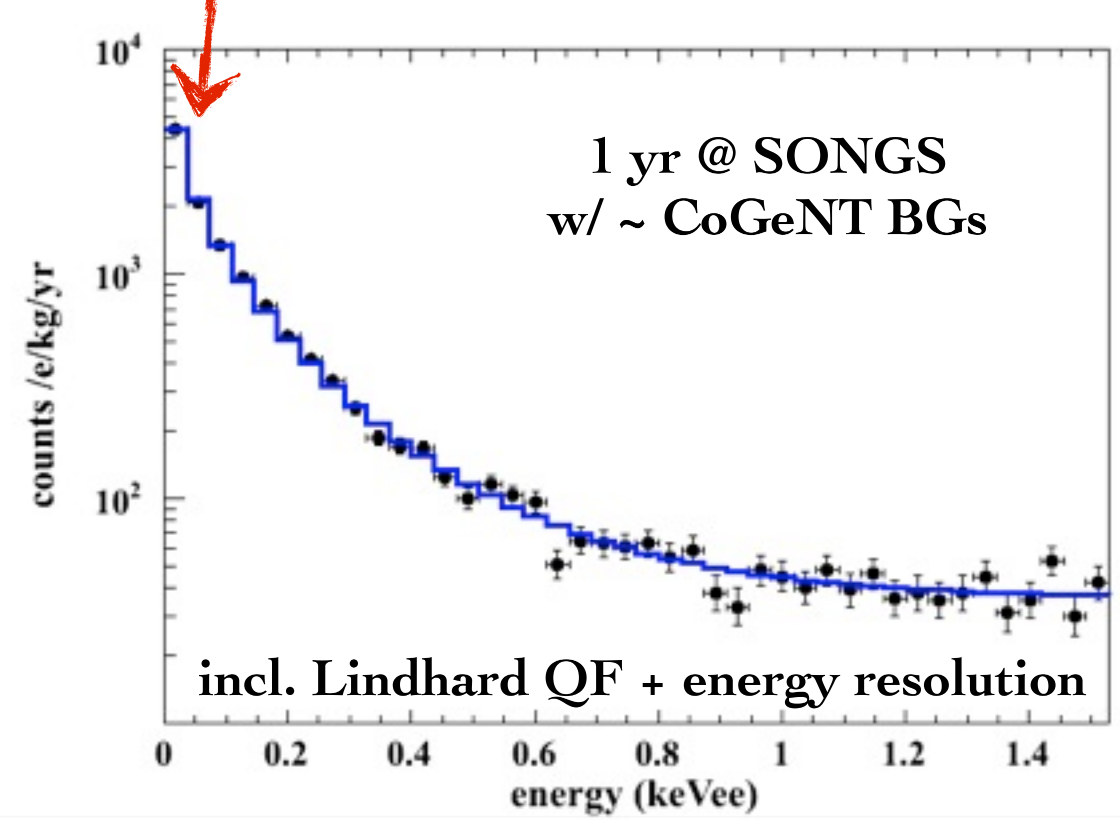
Introduces <0.1% uncertainty due to discrete nature of the recorded signal (single e⁻'s) @ threshold.



Shape verified by Bugey-3 data

Normalization improved to 1.6%

Liang Zhan SNAC, September 26-28, 2011



Weak Nuclear Charge

4.5) Using same element (Ne) eliminates atomic effects on the quenching factor

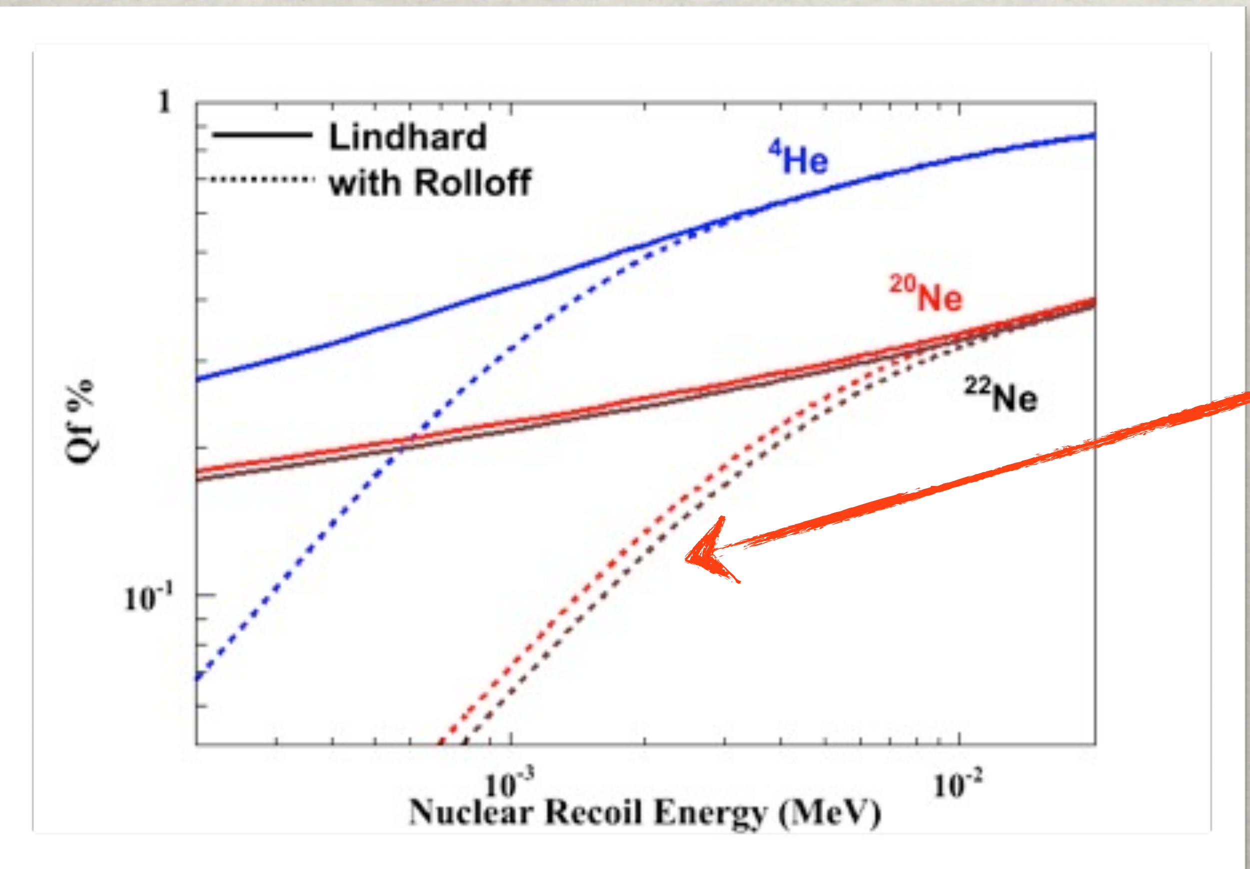
impact of 1% $Q(E_{rec})$ uncertainty & threshold

Threshold (e⁻'s)	Systematic impact (%)
0	0.1%
1	0.4%
2	0.6%
3	0.8%

If we measure the Ratio of the Quenching Factor in ^{20,22}Ne to ~ 1%, then the systematics are manageable

From Lindhard, this kinematic change comes in as:

$$f_n \sim \frac{1}{A^{\frac{1}{2}}+1} \times (1 - e^{\frac{-E_r}{E_t}}); \quad E_t \sim A$$



Should be able to predict the difference; but should still measure that it is non-zero. Can test ratio with other targets ^{3,4}He.

Weak Nuclear Charge

Statistical uncertainty from backgrounds dominate.

→ Need Rx-off time

Run for 4.5 cycles at SONGS. 1 cycle = 18 mo. On, 1 mo. Off *(When they are operating normally)*

Operate in both Tendon Galleries to maximize Rx off time.

→ 2 x 20 kg detectors at ~ 1-10 Bar

Result → uncertainties on sin^2 □$_w$:

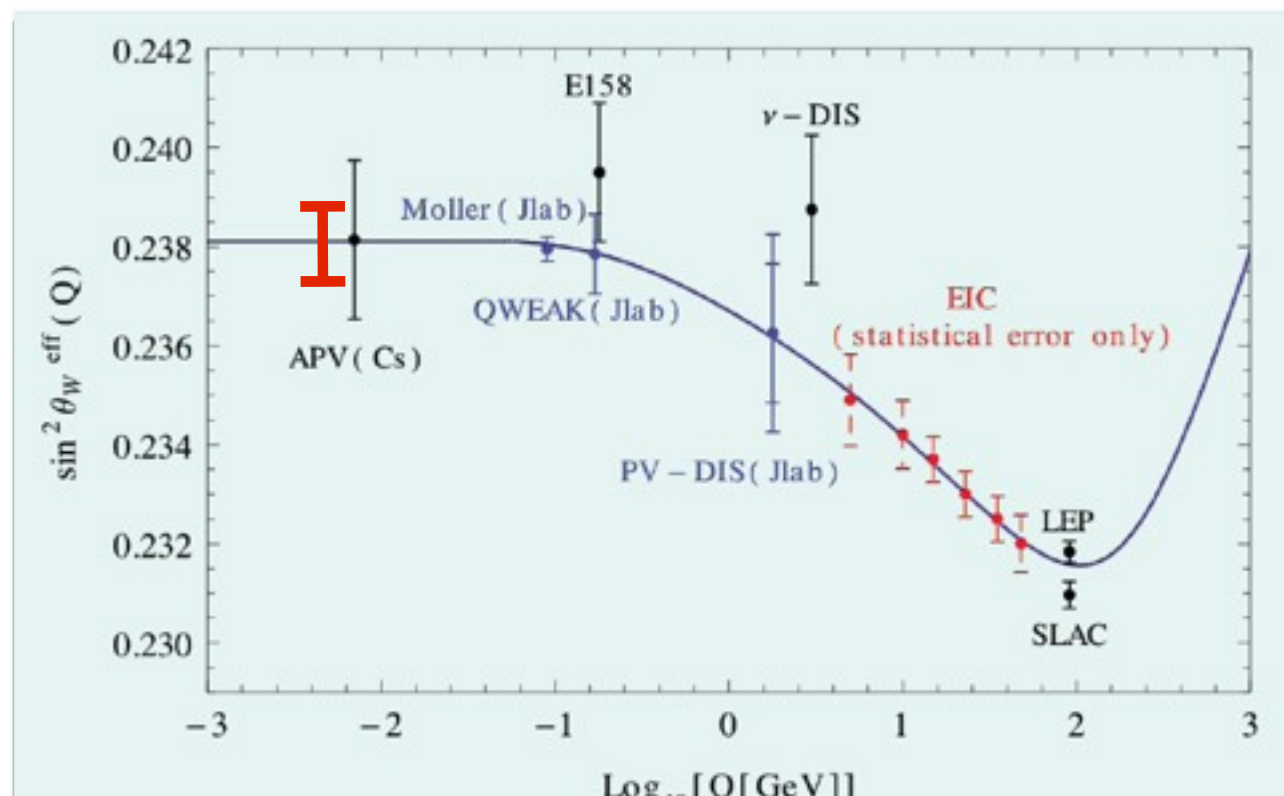
±0.22% (stat.) ±[0.1-0.4]% (sys.) ± <0.2 (th.)

Gives us another neutrino test, at lower Q.

Ignoring radiative corrections

$$R\left(\frac{^{22}Ne}{^{20}Ne}\right) = \frac{(2 + 10 \times sin^2\theta_w)^2}{(10 \times sin^2\theta_w)^2}$$

$$\sigma(sin^2\theta_w) = 0.57 \times \sigma R$$



Marciano (4/1/2011 Chicago)

(non-universal) NSI search

- Essentially, the same game as the before

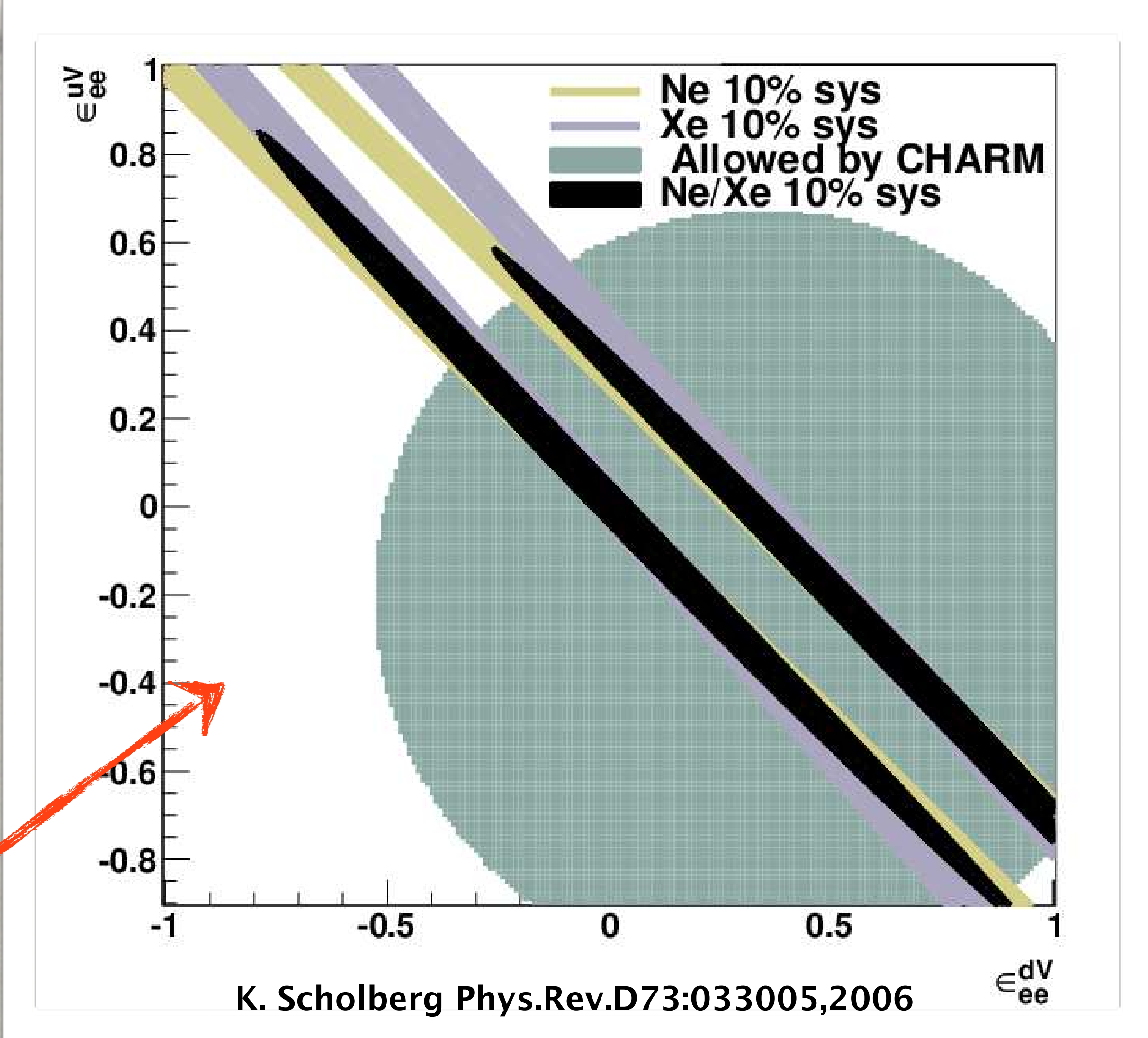
$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi} = G_V^2(1 + (1 - \frac{T}{E_\nu})^2 - \frac{MT}{E_\nu})$$

$$G_V = ((g_v^p + 2\epsilon_{ee}^{uV} + \epsilon_{ee}^{dV})Z + (g_v^n + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV})N)F_{nucl}^V(Q^2)$$

Including radiative corrections, and earlier stat. & sys. uncertainties, the ratio for ^{20}Ne/^{22}Ne gives:

$$1.0345 \pm 0.0202 = \frac{-0.512 + \epsilon_{ee}^{uV} + 2\epsilon_{ee}^{dV}}{-0.495 + 3\epsilon_{ee}^{uV} + 3\epsilon_{ee}^{dV}}$$

Makes for interesting constraints here (not yet drawn)



NSI SEARCH

While we are at it, lets not forget that this scheme is information rich

→ H_2, CH_4 (very distinctive spectrum) and CF_4 (unpaired protons)

→ ^3He (unpaired neutron), D_2 (unpaired neutron and proton) Can't decide which is crazier

→ BF_3 (unpaired neutron and proton).

→ Varying weak magnetism effect.

$$\frac{d\sigma}{dT}_{coh} = \frac{G_f^2 M}{2\pi}((G_V + G_A)^2 + (G_V - G_A)^2(1 - \frac{T}{E_\nu})^2 - (G_V^2 - G_A^2)\frac{MT}{E_\nu^2})$$

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$$g_V^n = -\frac{1}{2}\rho_{\nu N}^{NC} + \lambda^{uL} + \lambda^{uR} + 2\lambda^{dL} + 2\lambda^{dR}$$

+ pesky axial couplings

Light WIMPS

Or, what else can you use these detectors for...?

Deploy a number of similarly built detectors, with much larger variance in A.

Use the kinematics of WIMP-nucleus scattering to test putative signals.

H_2	$^{32,34}SF_6$
$^{3,4}He$	CO_2
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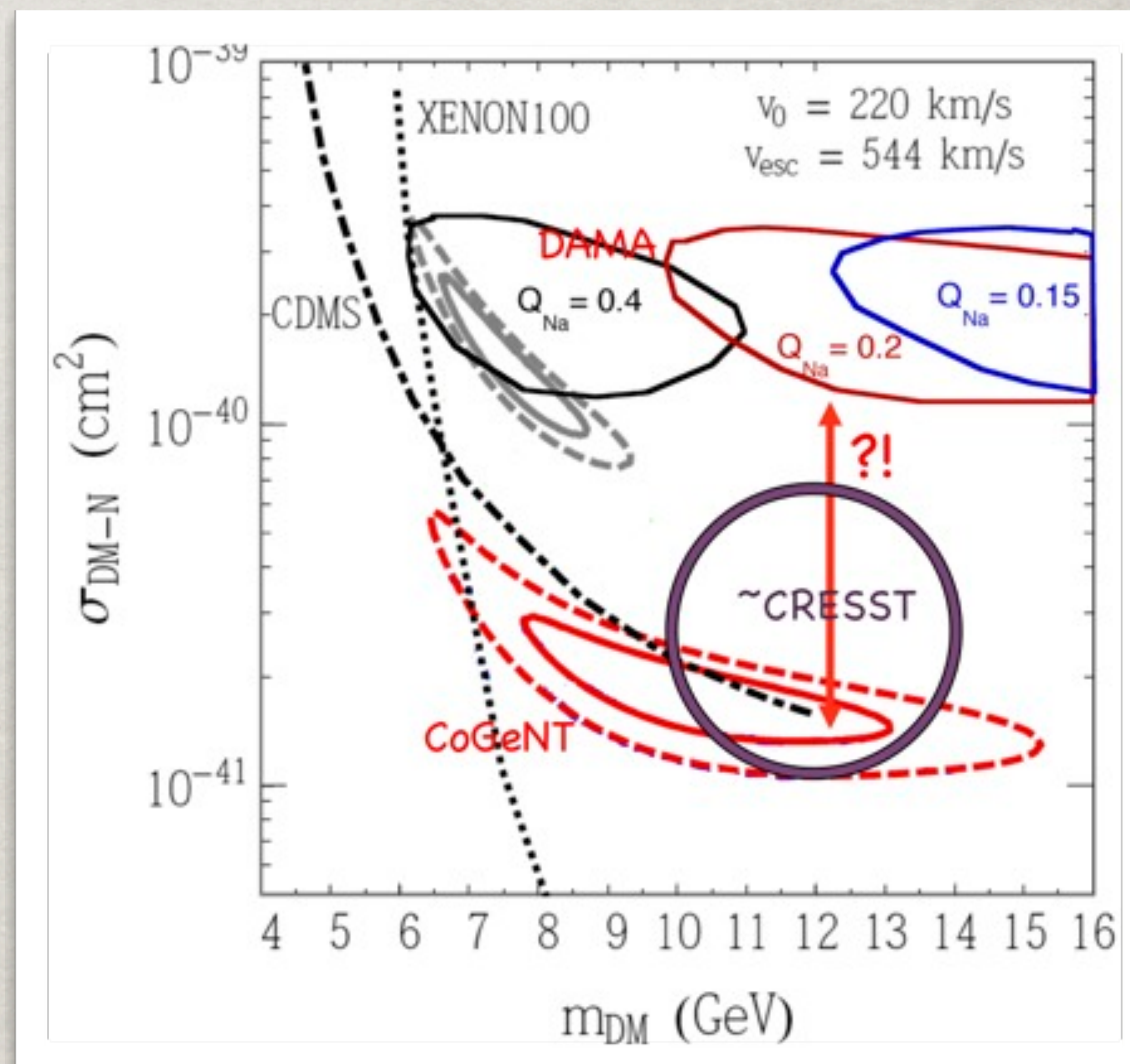
Tension?



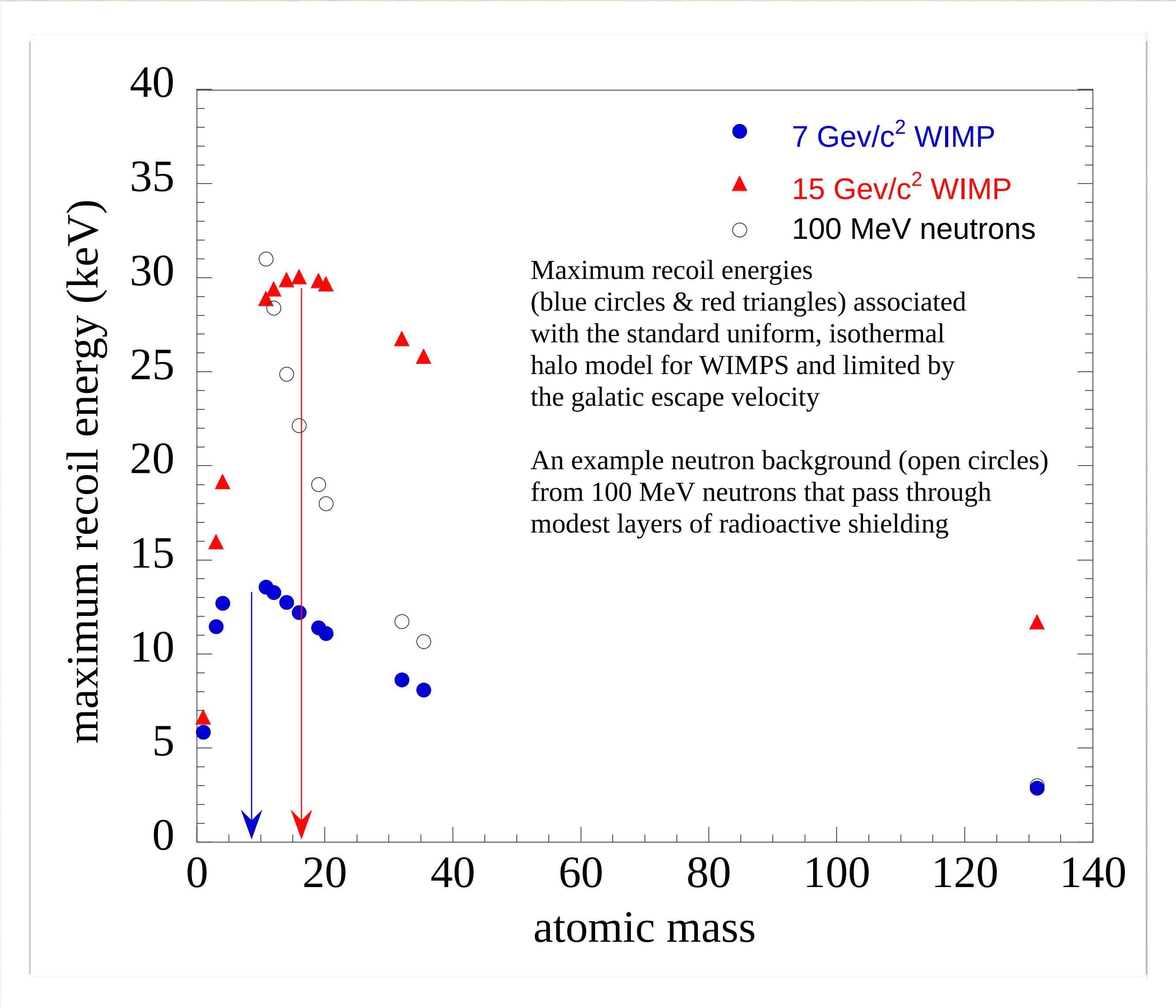
Light WIMPS

Fit characteristic energy scale of any observation versus target mass, increases the precision on putative WIMP mass

→ kinematic check against certain (neutron) background hypotheses

Amplitude of spectra indicates WIMP escape velocity

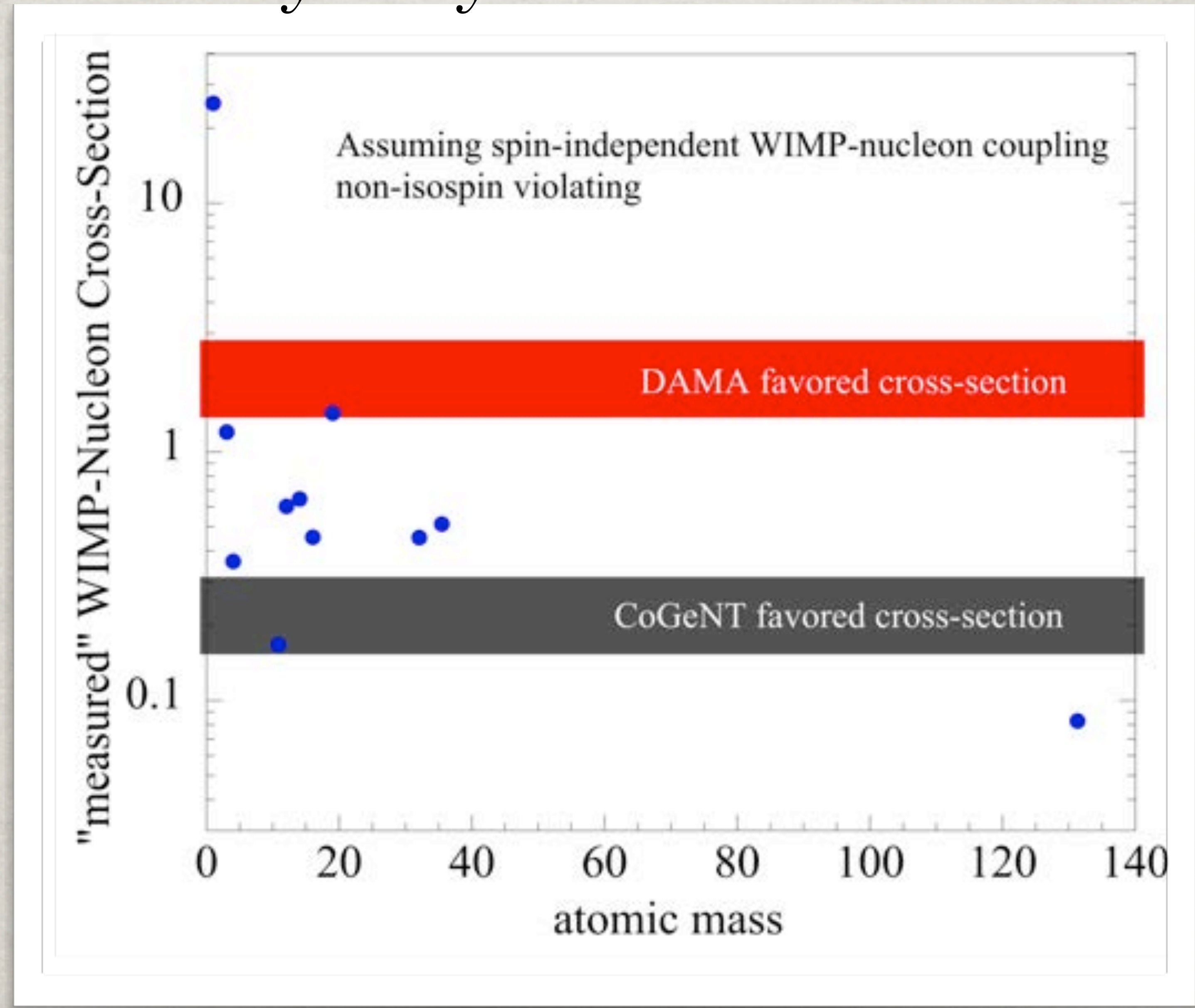
→ ascertain/factorize astrophysical systematic (Streams, etc.)



Light WIMPS

Study cross-section versus target mass.
→ Search for (neutron) background systematic
→ Characteristic coherence signal

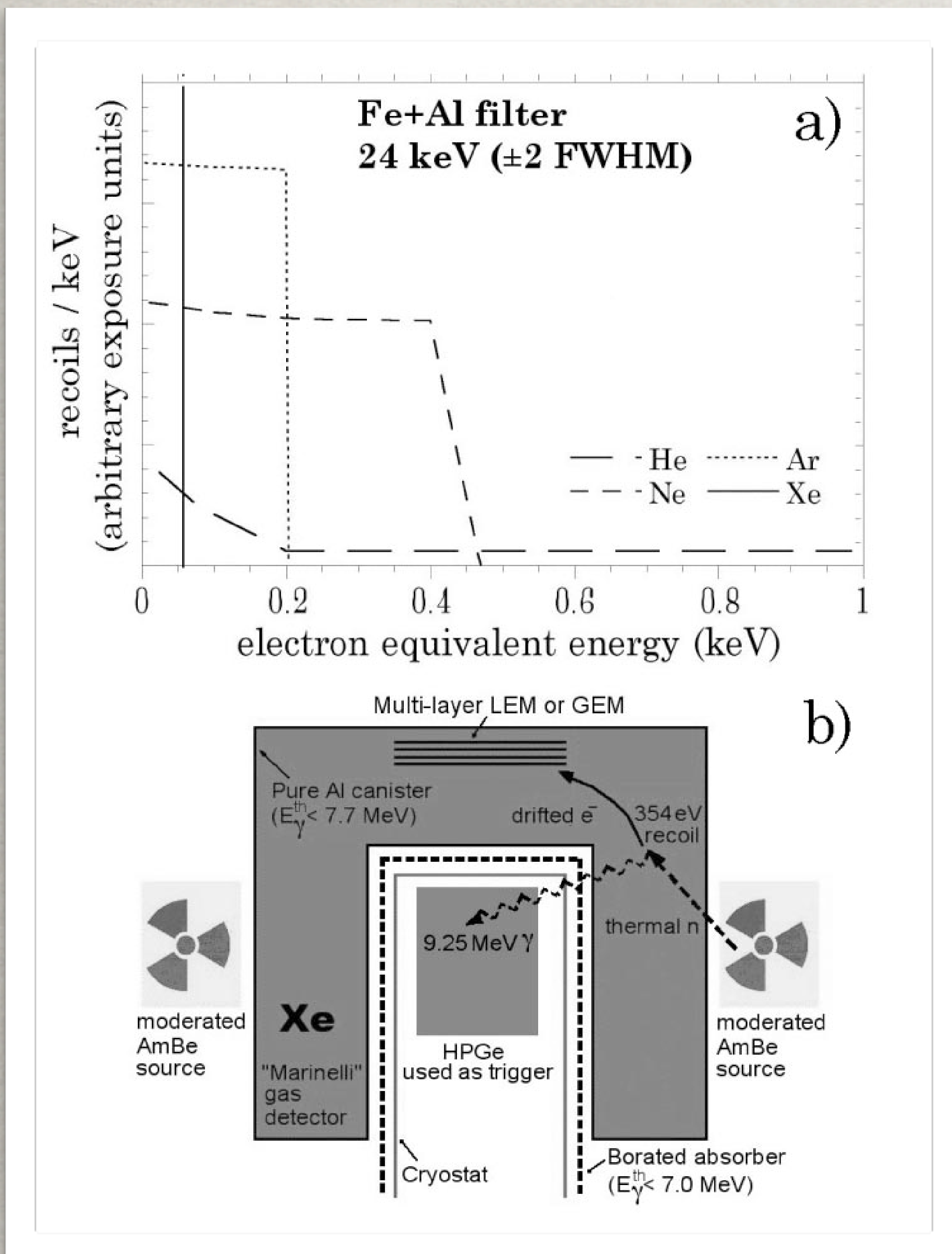
Cross-section cancelations can occur if we have isospin-violating WIMP interactions.
→ Factorize out Particle Physics Systematic.

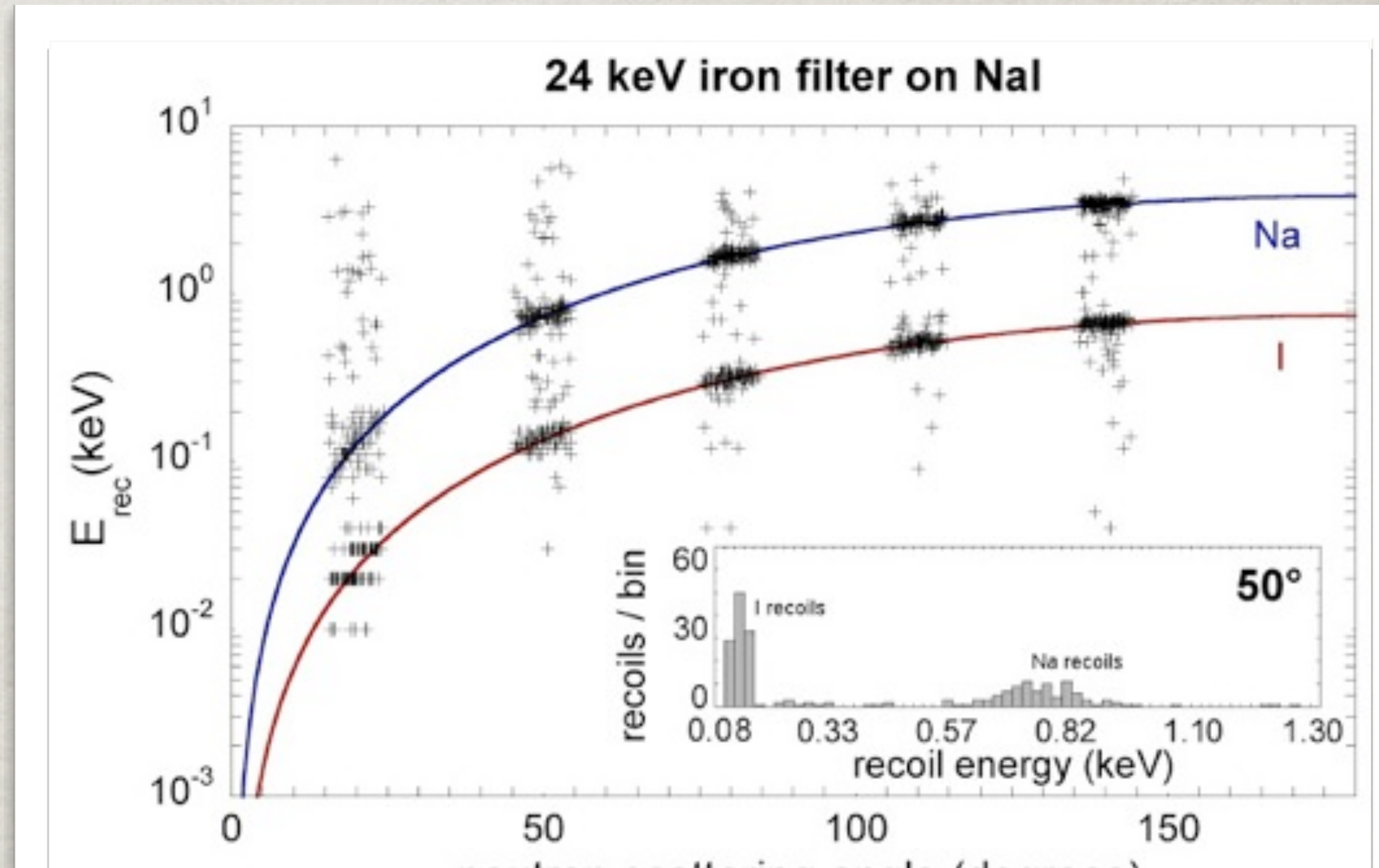


Summary & Open Issues

- A detector concept has been presented which focuses on eliminating systematics with a simple/robust technology for precision CNNS & WIMP experiments
- Can we really predict the relative QF between ^{20}Ne and ^{22}Ne based on kinematics?
- Is there any ionization signal at all at low Q?
- How difficult to enrich to ^{22}Ne?
- High precision calibration of energy scale/electron gain...laser calibration?

QF Measurement: 24 keV monochromatic neutron beam (KSU)

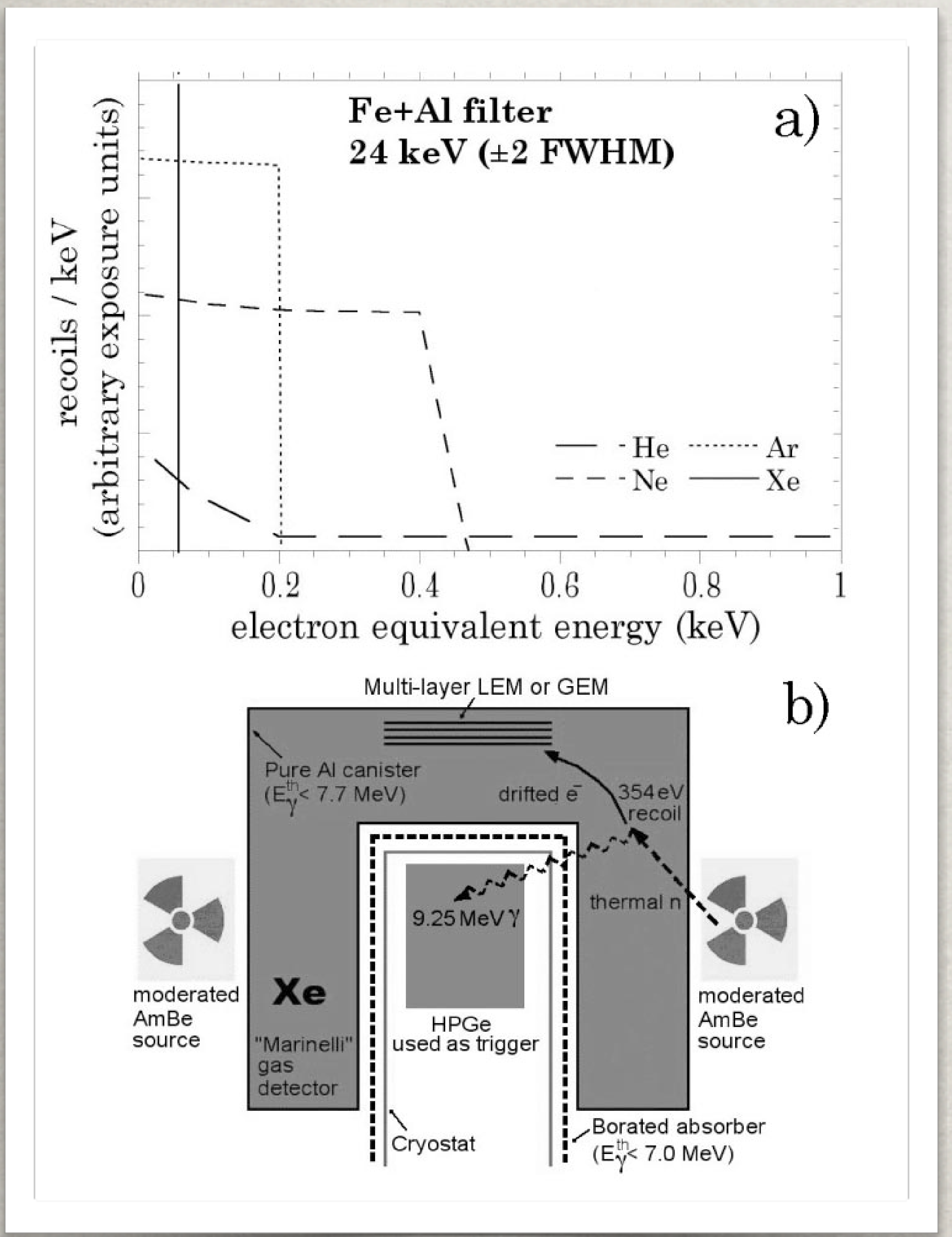


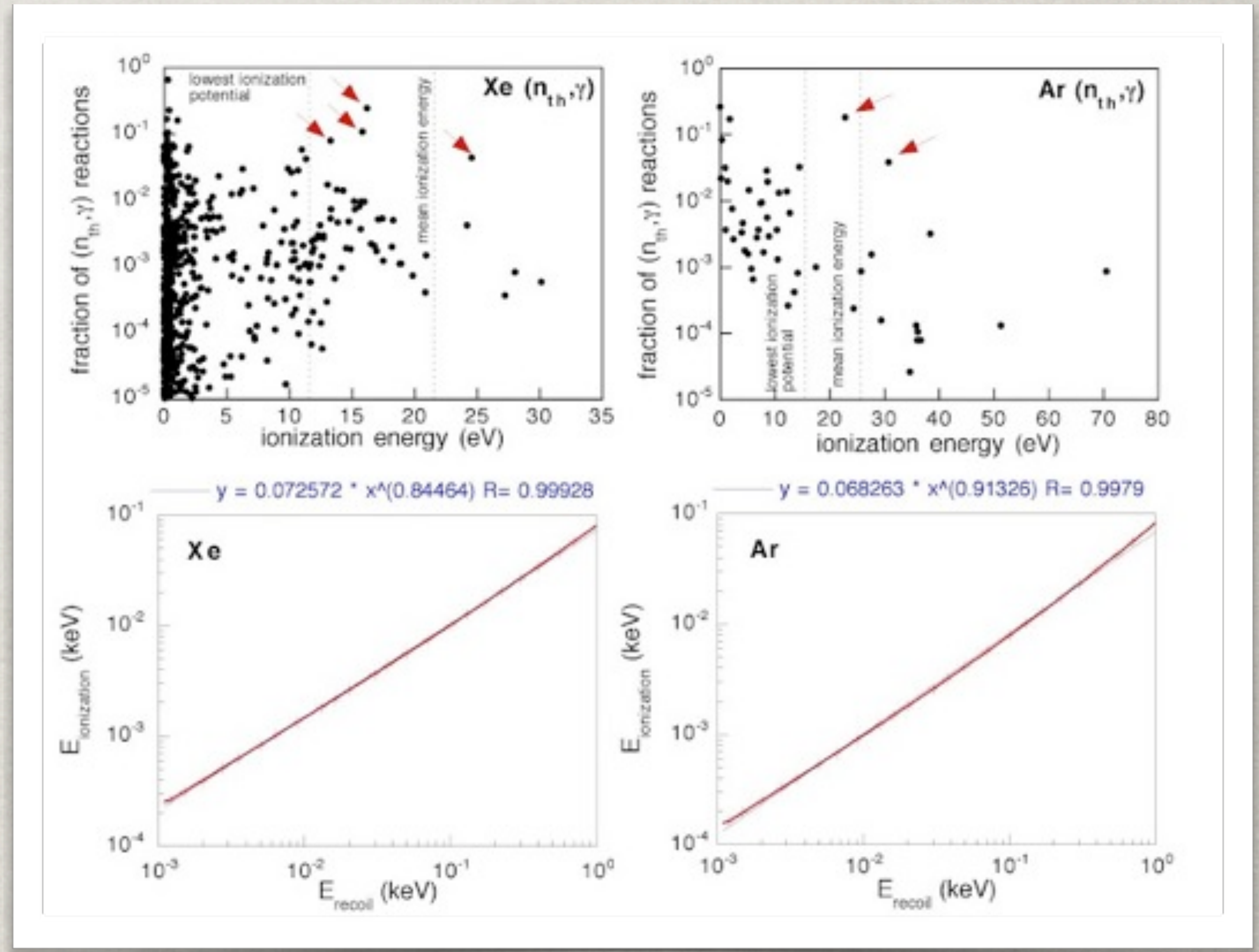


P. Barbeau, J. Collar, and P. Whaley. NIM A, 574(2):385 – 391, 2007

P. Barbeau, J. I. Collar, J. Miyamoto, and I. Shipsey. IEEE Trans. Nucl. Sci., 50:1285–1289, 2003.

QF Measurement: thermal neutrons





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