TAUP 2015 Torino

Using XENON100 Data to Probe Electronic Recoils as an Explanation of the DAMA/LIBRA Anomaly

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On behalf of the
XENON Collaboration

September 8, 2015

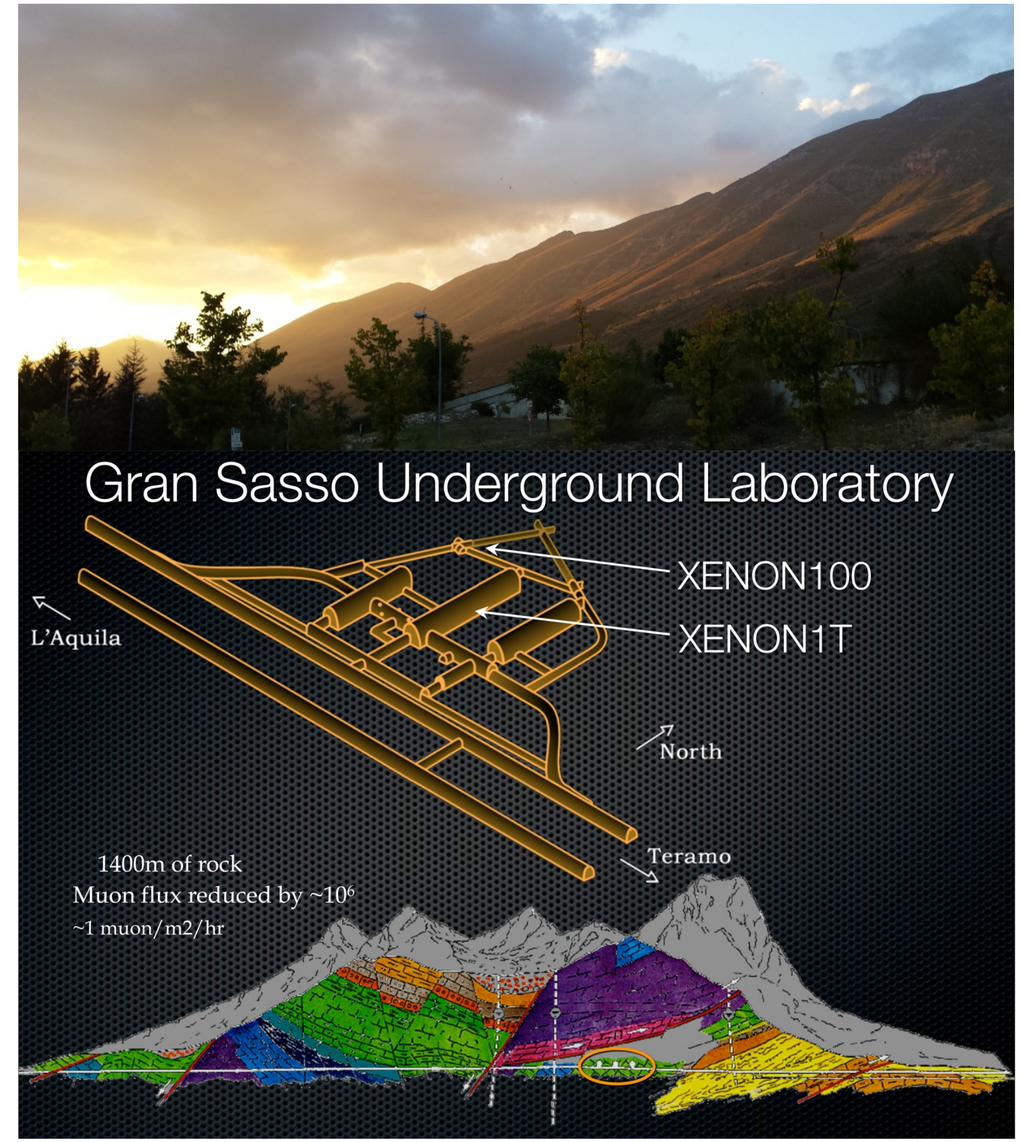
Xe XENON Dark Matter Project

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

XENON Collaboration

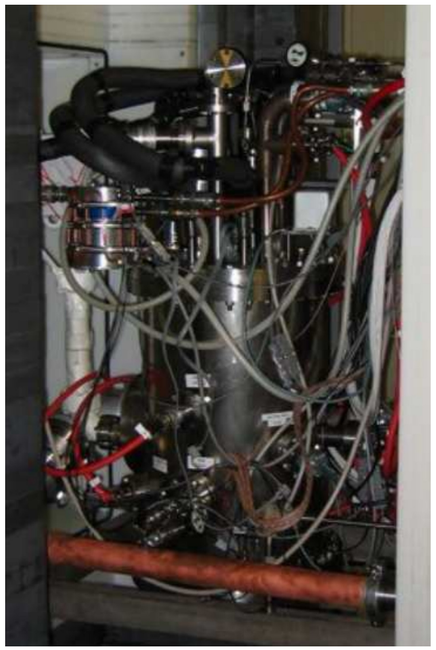
21 institutions, ~130 scientists

Columbia, RPI, Nikhef, Mainz, Stockholm, Muenster, Chicago, MPIK, UCLA, Bern, UCSD, Zurich, Rice, NYUAD, Purdue, Coimbra, Subatech, Bologna, LNGS, Torino, Weizmann



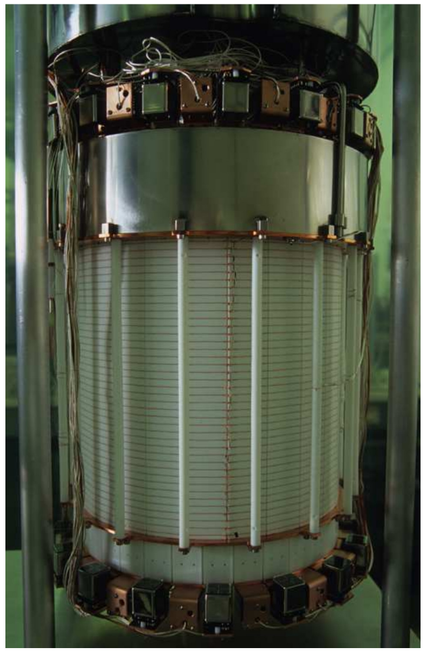
XENON Program

XENON10



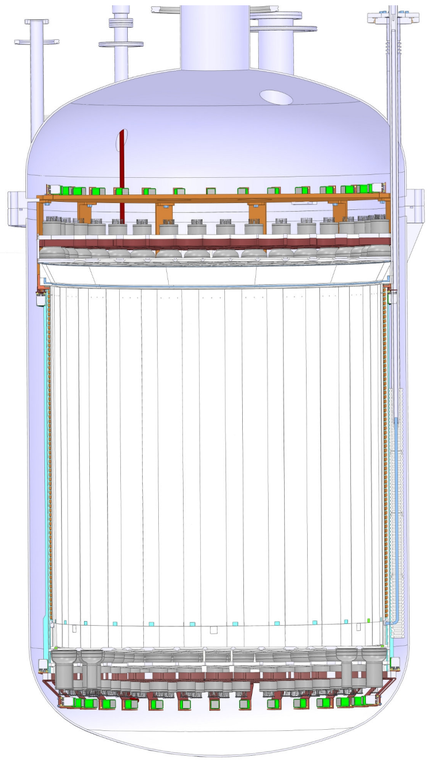
2005-2007
25 kg
15 cm drift
$\sigma_{SI} = 8.8 \times 10^{-44}\,cm^2$

XENON100



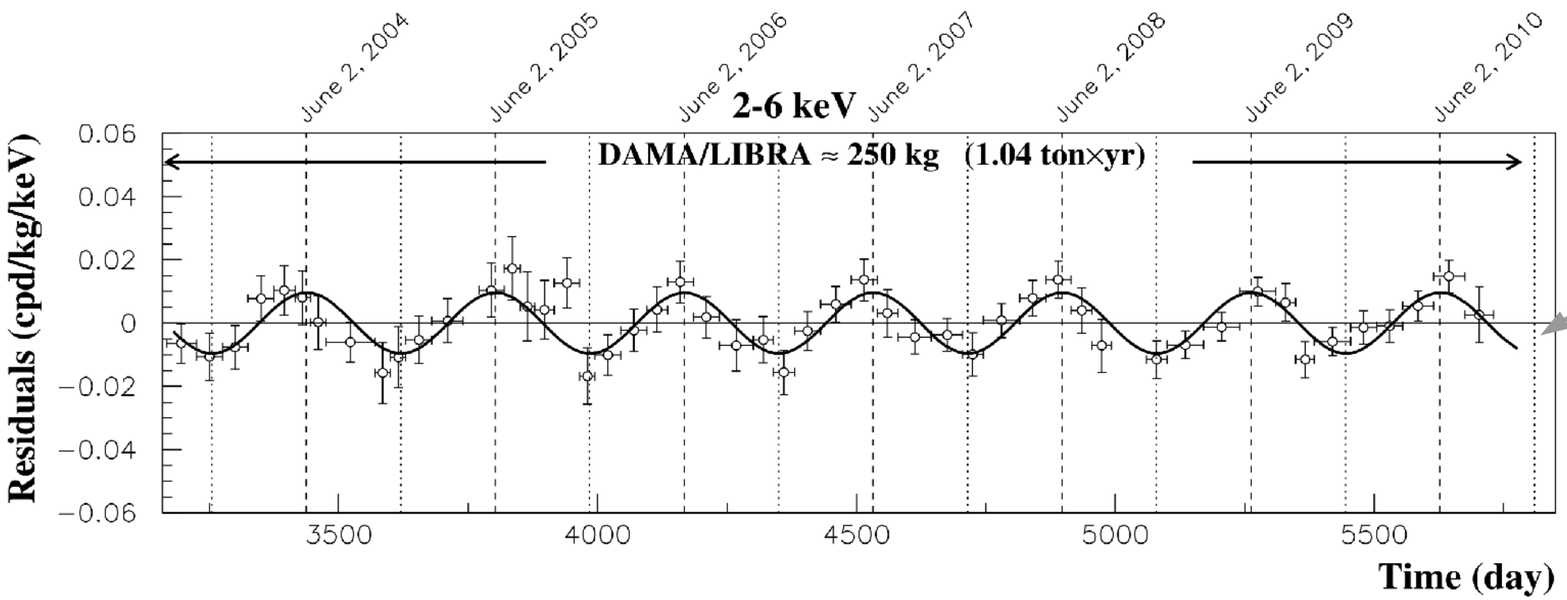
2008-2015
161 kg
30 cm drift
$\sigma_{SI} = 2.0 \times 10^{-45}\,cm^2$

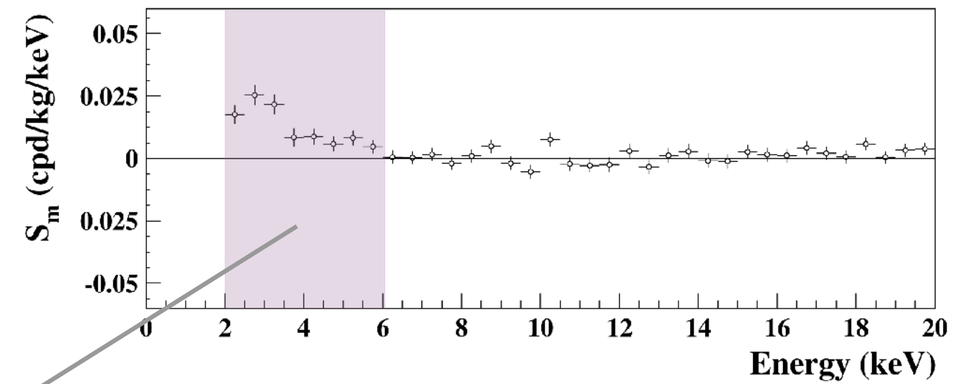
XENON1T/XENONnT



2012-2018 / 2016-2022
3300 kg / 7000 kg
96 cm drift
$\sigma_{SI} \cong 2 \times 10^{-47}\,cm^2 / \sigma_{SI} \cong 3 \times 10^{-48}\,cm^2$

DAMA/LIBRA Annual Modulation



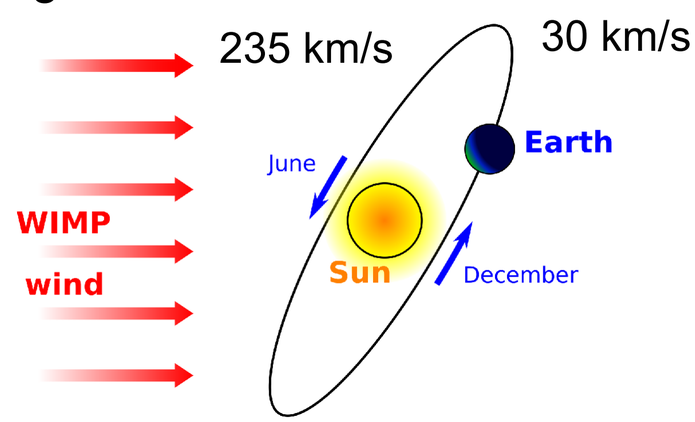


Bernabei *et al.*, Eur. Phys. J. C 73, 12 (2013)

- 2-6 keV, single-hit
- Peak phase 144 ± 7 days (May 24)
- 9.3σ confidence level
- Could be from DM halo

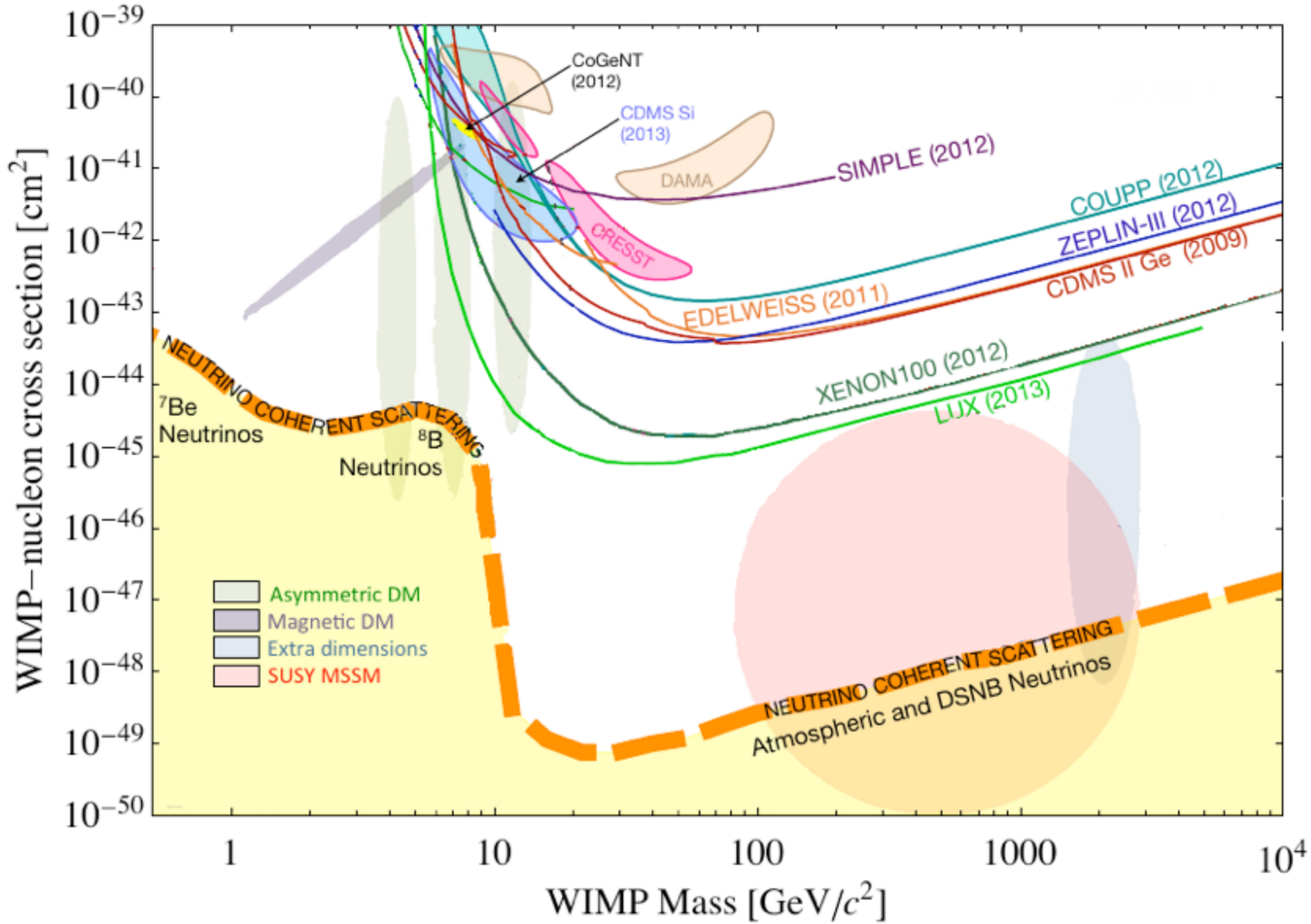
Expected annual modulation signal

- peak phase ~152 days (~June 1)
- ~6% change in flux



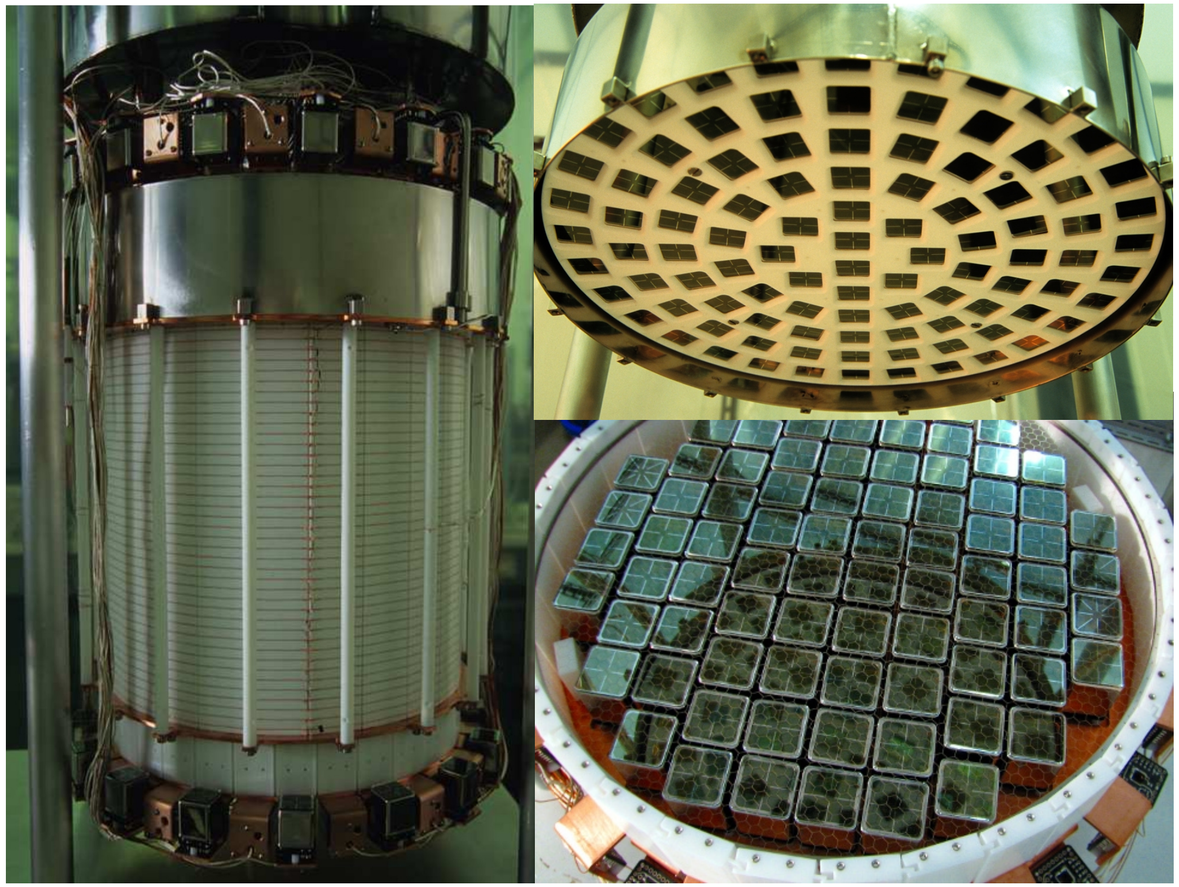
Freese *et al.*, Rev. Mod. Phys. 85, 1561 (2013)

Nuclear Recoils



Null results from many experiments *more sensitive* than DAMA/LIBRA

XENON100 Detector



Aprile *et al*., Astropart. Phys., 35, 573-590 (2012)

Annual Modulation in XENON100

- First LXe DM detector with single run > 1 year
- Can discriminate ER from NR
- Average ER rate ~155x *lower* than DAMA/LIBRA average, and ~2x *lower* than modulation amplitude
- First detector at LNGS to study annual modulation after DAMA/LIBRA

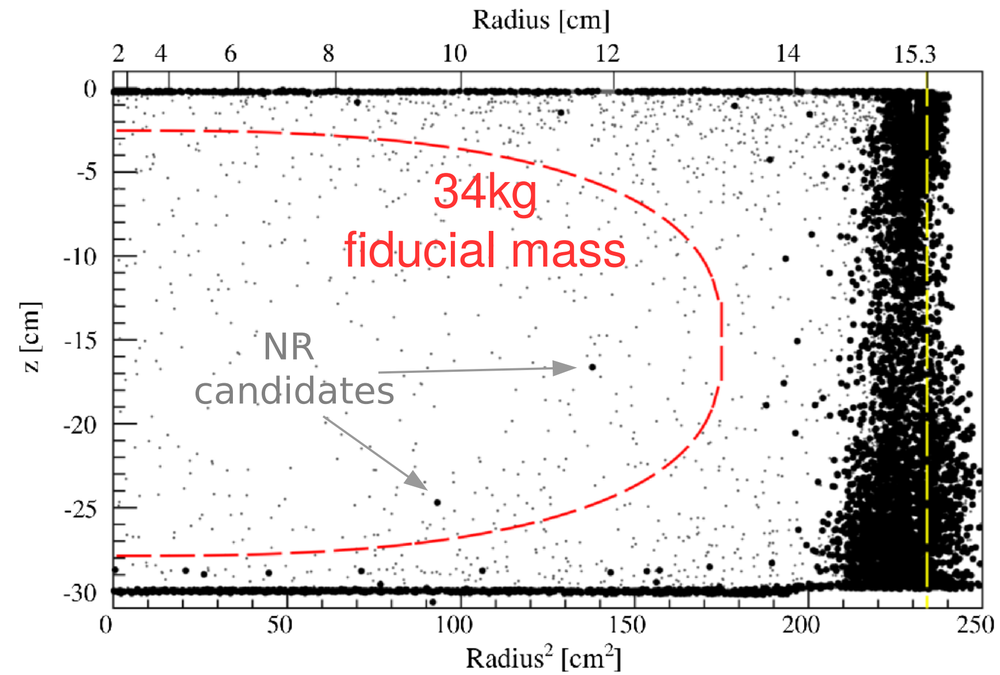
Annual Modulation in DAMA/LIBRA from ERs?

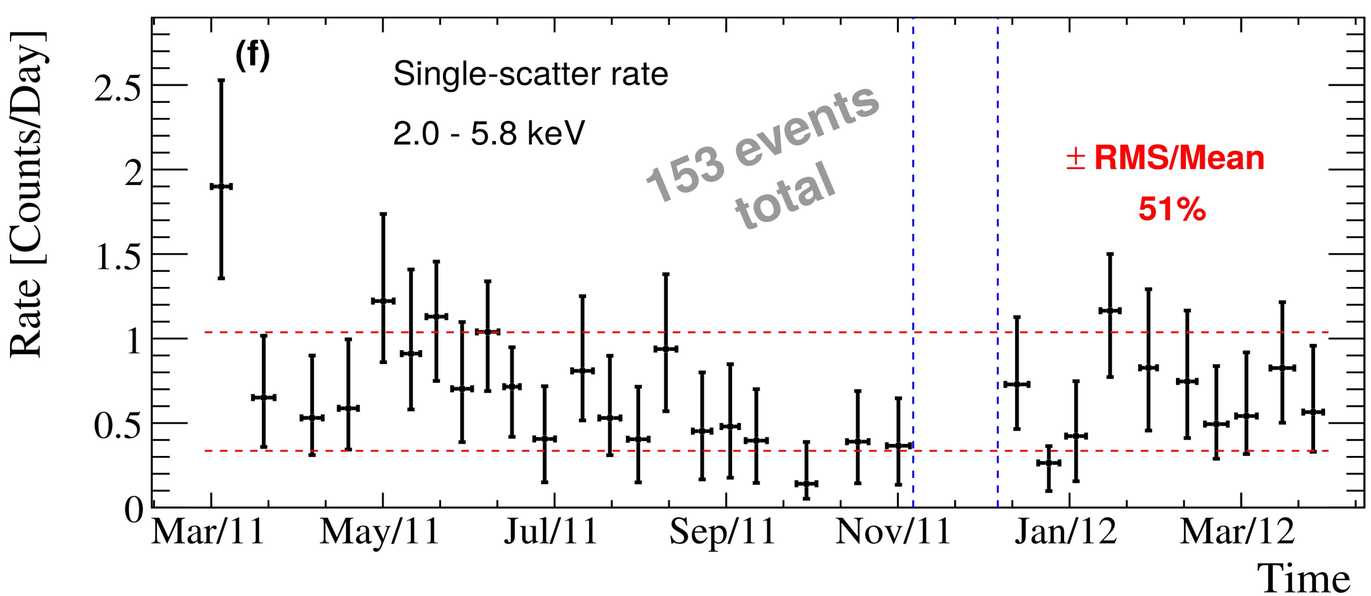
Study Overview

Data: 225 live-days used for DM Search

- 397 days total (Feb 28, 2011 – March 31, 2012)
- ERs: ~ 6.6 events/(keV · tonne · day)
- NRs: expected 1±0.2; detected 2
- $\sigma_{SI} = 2\times10^{-45}\,cm^2$ for $m_\chi = 55\ GeV/c^2$

NR (spin-dependent): Aprile *et al.*, Phys. Rev. Lett., 109, 181301 (2012)
NR (spin-independent): Aprile *et al.*, Phys. Rev. Lett., 111, 021301 (2013)
ER (axions): Aprile *et al.*, Phys. Rev. D, 90, 062009 (2014)





Electronic recoil study

- Time evolution of single-scatter events
- S1-based energy scale:

  3-14 pe = 2.0-5.8 keV (DAMA/LIBRA range)

Aprile *et al.*, Phys. Rev. Lett. 115, 091302 (2015)

Aprile *et al.*, Science vol. 349 no. 6250 pp. 851-854 (2015)

Energy Scale

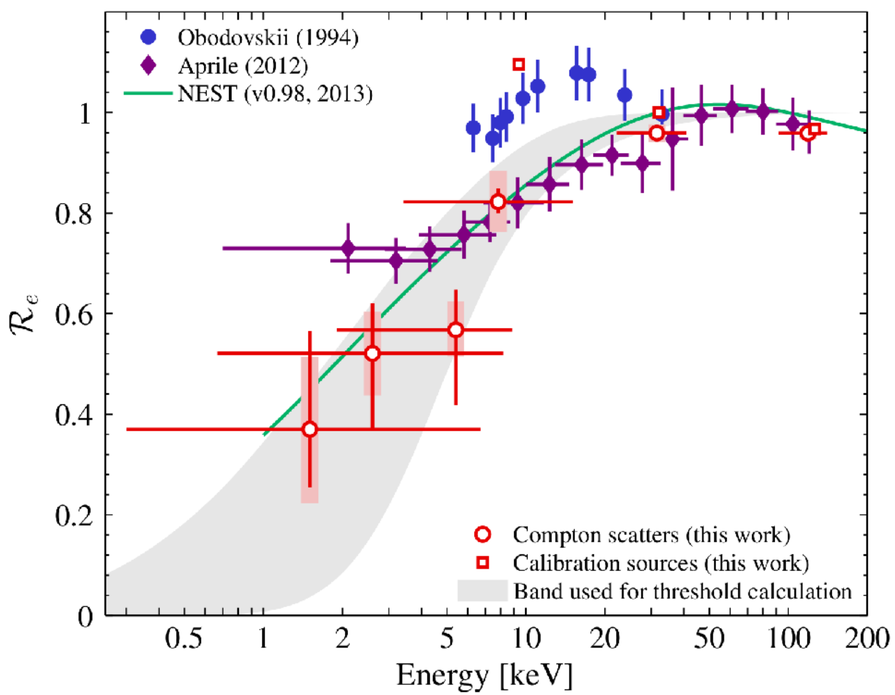
Current Status

- Mean from NEST v0.98, assume 500V/cm, weighted fit of uncertainties (4% NEST + spread in)

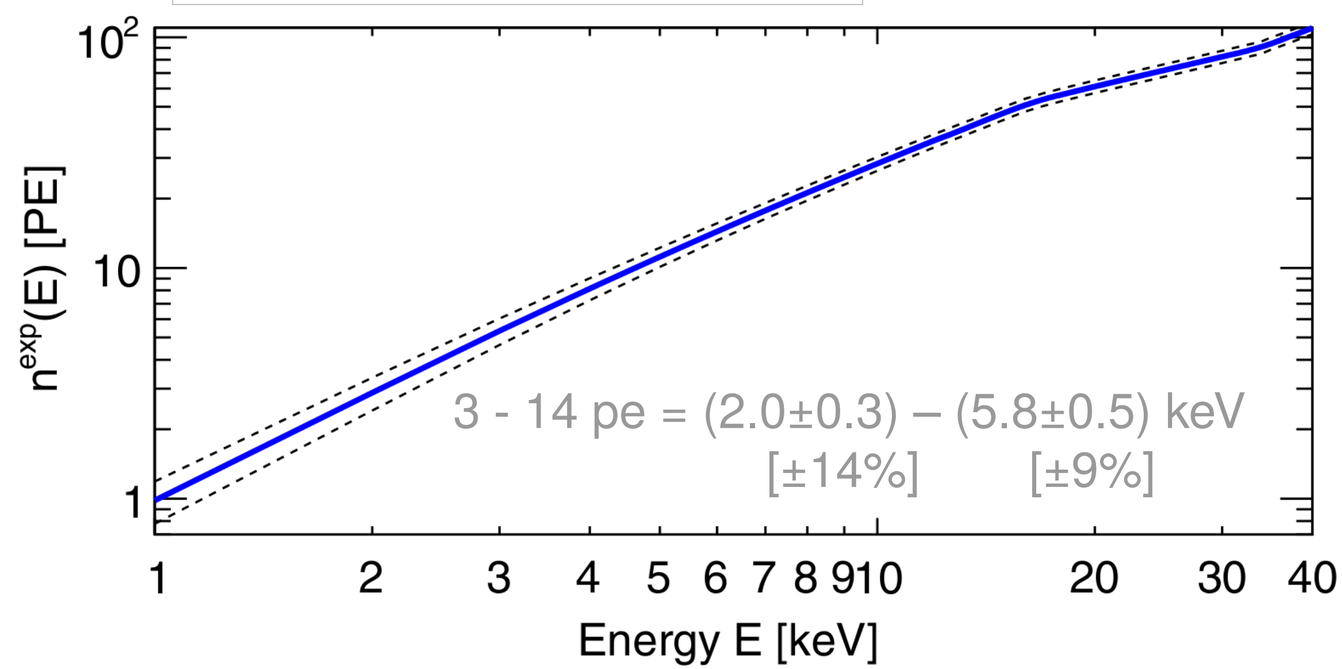
Szydagis *et al.*, J. Instrum. 6, P10002 (2011)

- Based on dedicated calibration measurements of light yield (S1 [pe/keV])

Aprile *et al.*, Phys. Rev. D 86, 112004 (2012)
Baudis *et al.*, Phys. Rev. D 87, 115015 (2013)



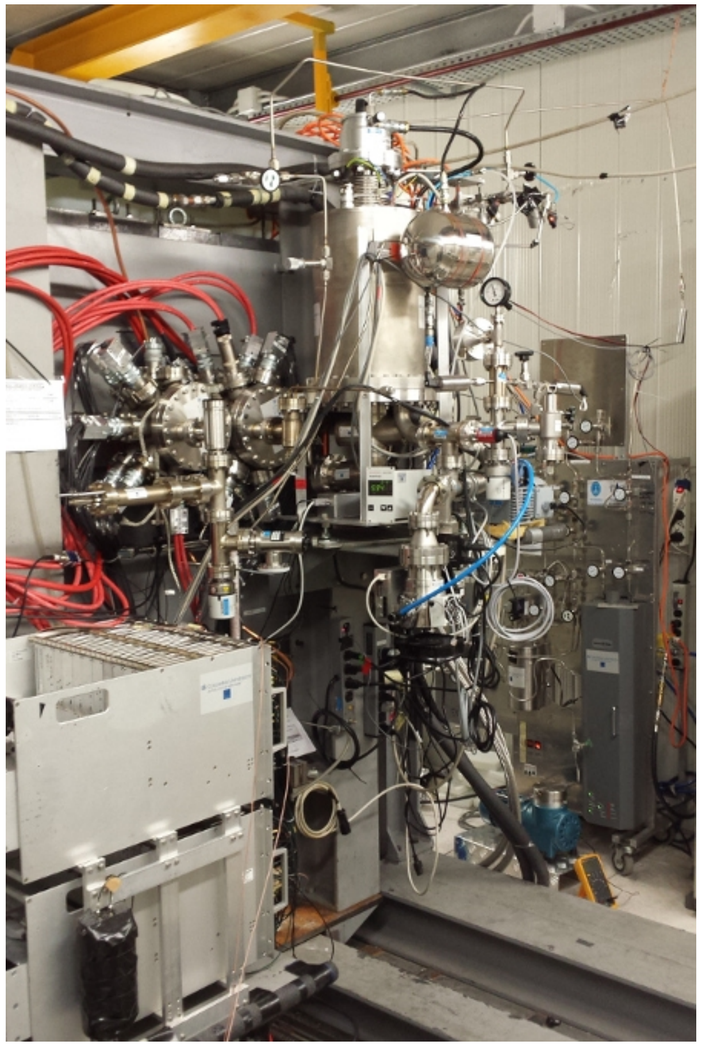
Aprile *et al.*, Phys. Rev. D 90, 062009 (2014)



New measurements of light and charge yield and field dependence to improve uncertainty
Results forthcoming!

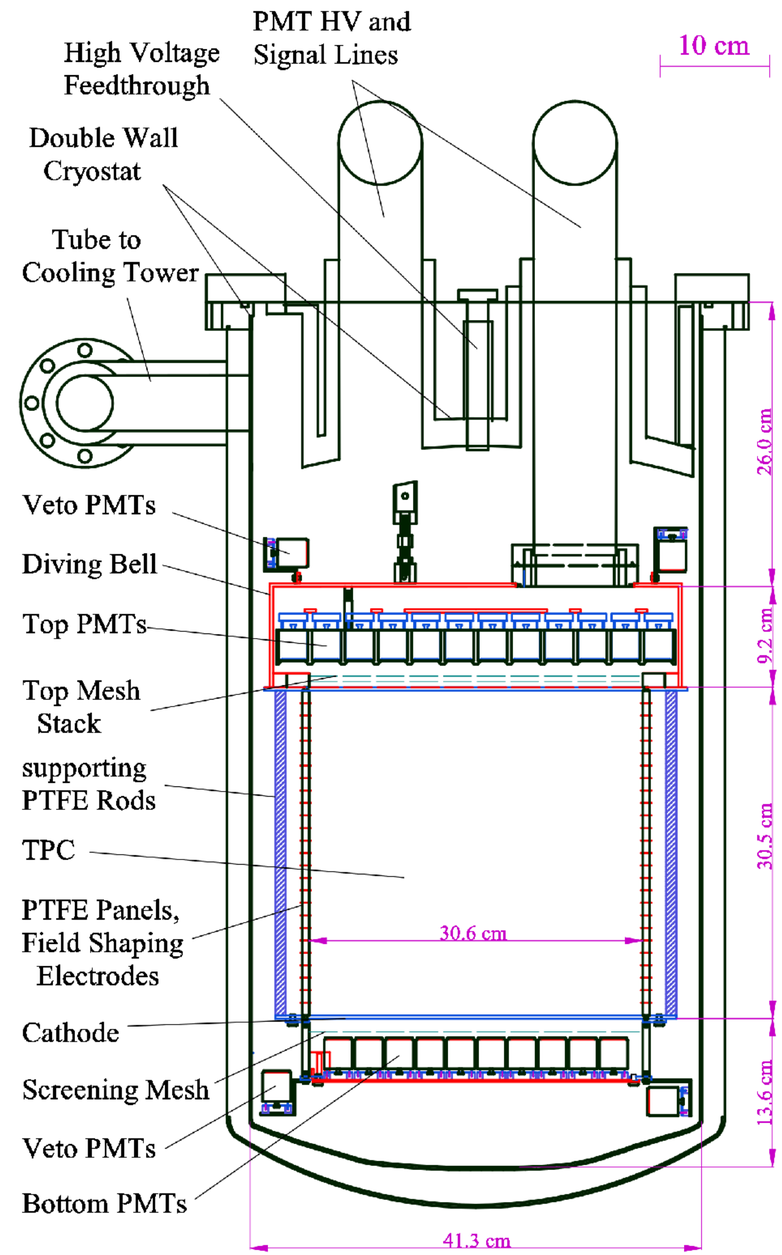
Detector Stability

- Detailed stability and correlation analysis of **detector parameters**
- Variations small, no significant impact on ER rate



- Absolute detector pressure
- Relative detector pressure
- Room pressure
- LXe temperatures (4)
- PTR temperature
- Room temperature
- Purification flow
- N_2 purge flow
- LXe levels (2)
- PMT gain
- Rn level (2)

Aprile *et al.*, Astropart. Phys., 35, 573-590 (2012)



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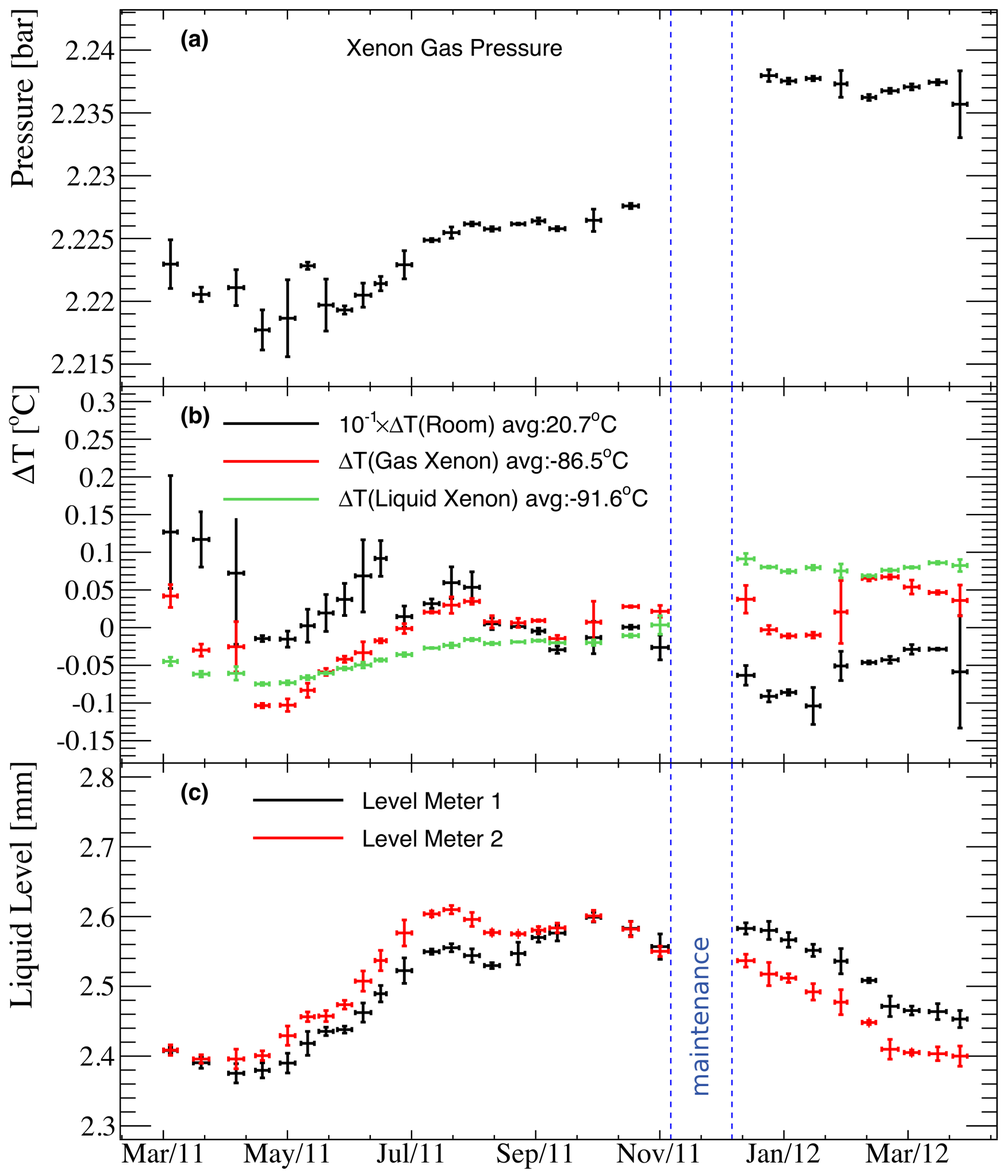
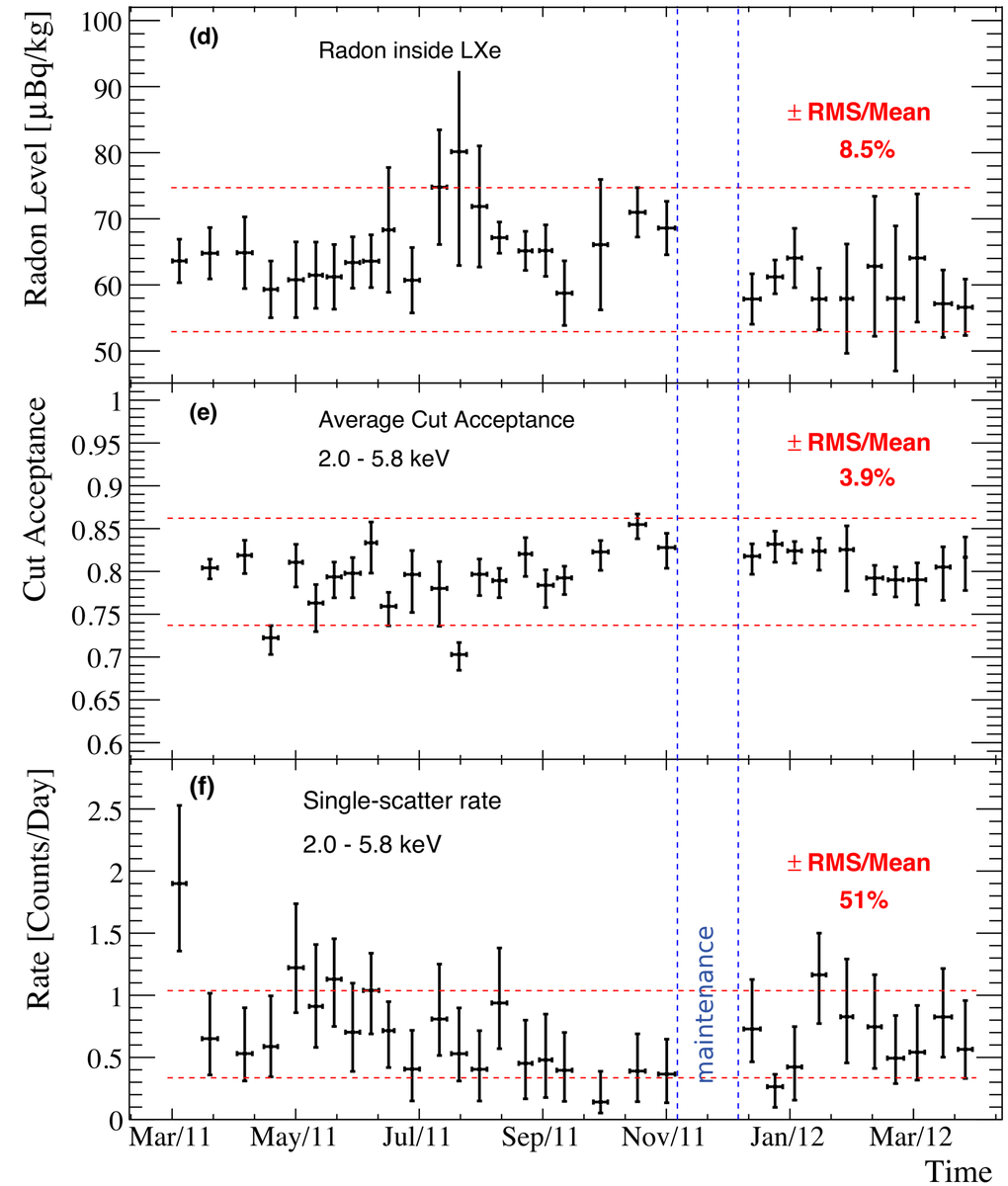


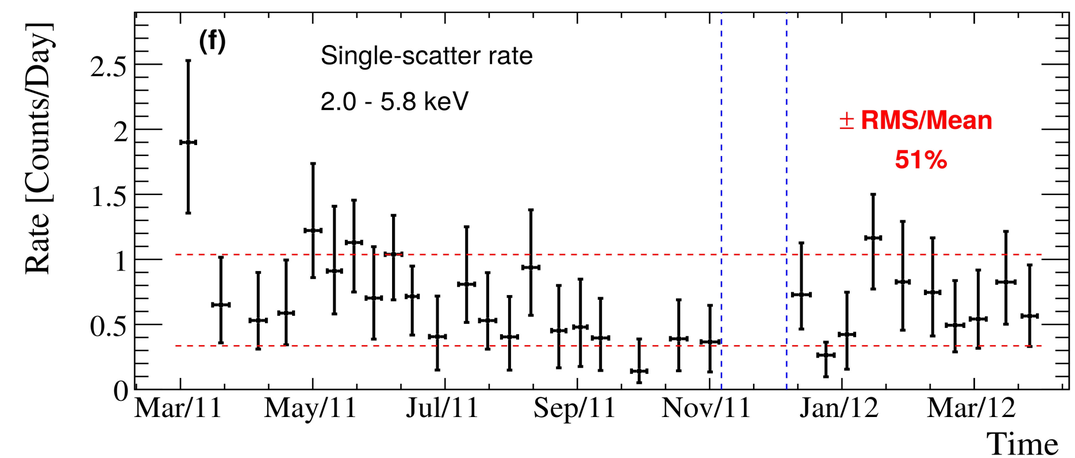


ER Rate Periodicity

ER Rate Model

- ~~Detector parameters~~
- Radioactive backgrounds from measurement or MC: ^{85}Kr, ^{222}Rn, ^{60}Co
- Test for periodic component

Aprile *et al.*, Phys. Rev. Lett. 115, 091302 (2015)



Cut acceptance

^{222}Rn, ^{60}Co, ...

$$f(t) = \epsilon(t)\left[C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right]$$

^{85}Kr background from air leak:
K = 2.54±0.53×10^{-3}
(events/(keV · tonne · day))/day

Null hypothesis (L_0):
A=0

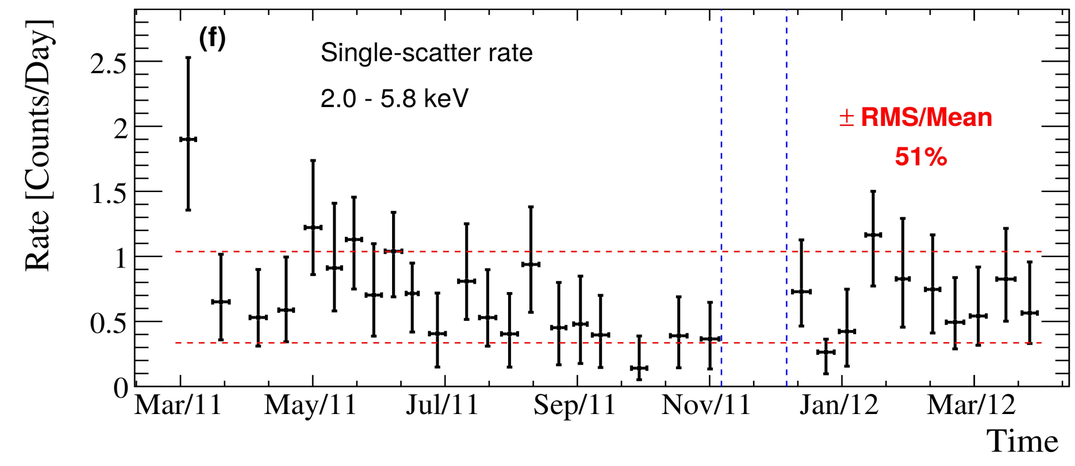
Signal hypothesis (L_1):
any P, P = 1 year

ER Rate Periodicity

Periodicity Test

- *Unbinned* profile likelihood analysis
- Most significant uncertainties *constrained by data*: cut acceptance, Kr level, energy scale
- Binned cross checks: χ^2, Lomb-Scargle

Aprile *et al.*, Phys. Rev. Lett. 115, 091302 (2015)



$$f(t) = \epsilon(t)\left[C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right]$$

Normalized

$$\mathcal{L} = \left(\prod_{i=1}^{n}\tilde{f}(t_i)\right)\mathrm{Poiss}[n|N_{\mathrm{exp}}(E)]\mathcal{L}_\epsilon\mathcal{L}_K\mathcal{L}_E$$

Total observed events

Constraints

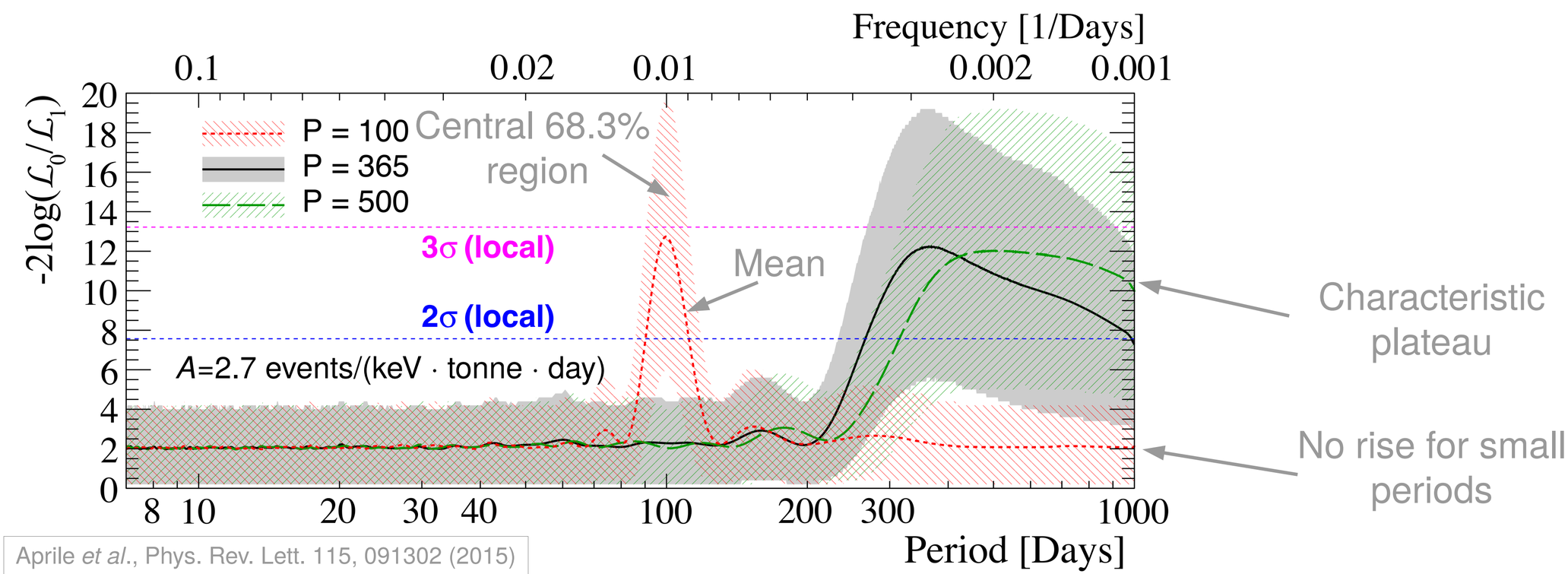
ER Rate Periodicity

Discovery Potential

- Simulate synthetic signals, n = 153 events
- Follow time distribution of actual data
- Fix C, A at best-fit values for P = 365 days
- Local significance from null hypothesis test

$$f(t) = \epsilon(t)\left[C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right]$$

$$\mathcal{L} = \left(\prod_{i=1}^{n}\tilde{f}(t_i)\right)\mathrm{Poiss}[n|N_{\mathrm{exp}}(E)]\mathcal{L}_\epsilon\mathcal{L}_K\mathcal{L}_E$$



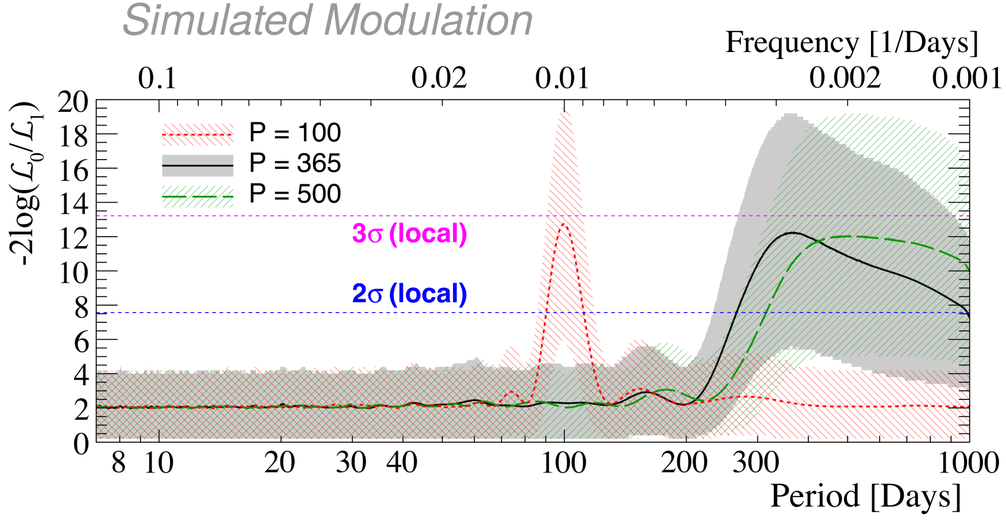
Aprile *et al.*, Phys. Rev. Lett. 115, 091302 (2015)

ER Rate Periodicity

PL Results

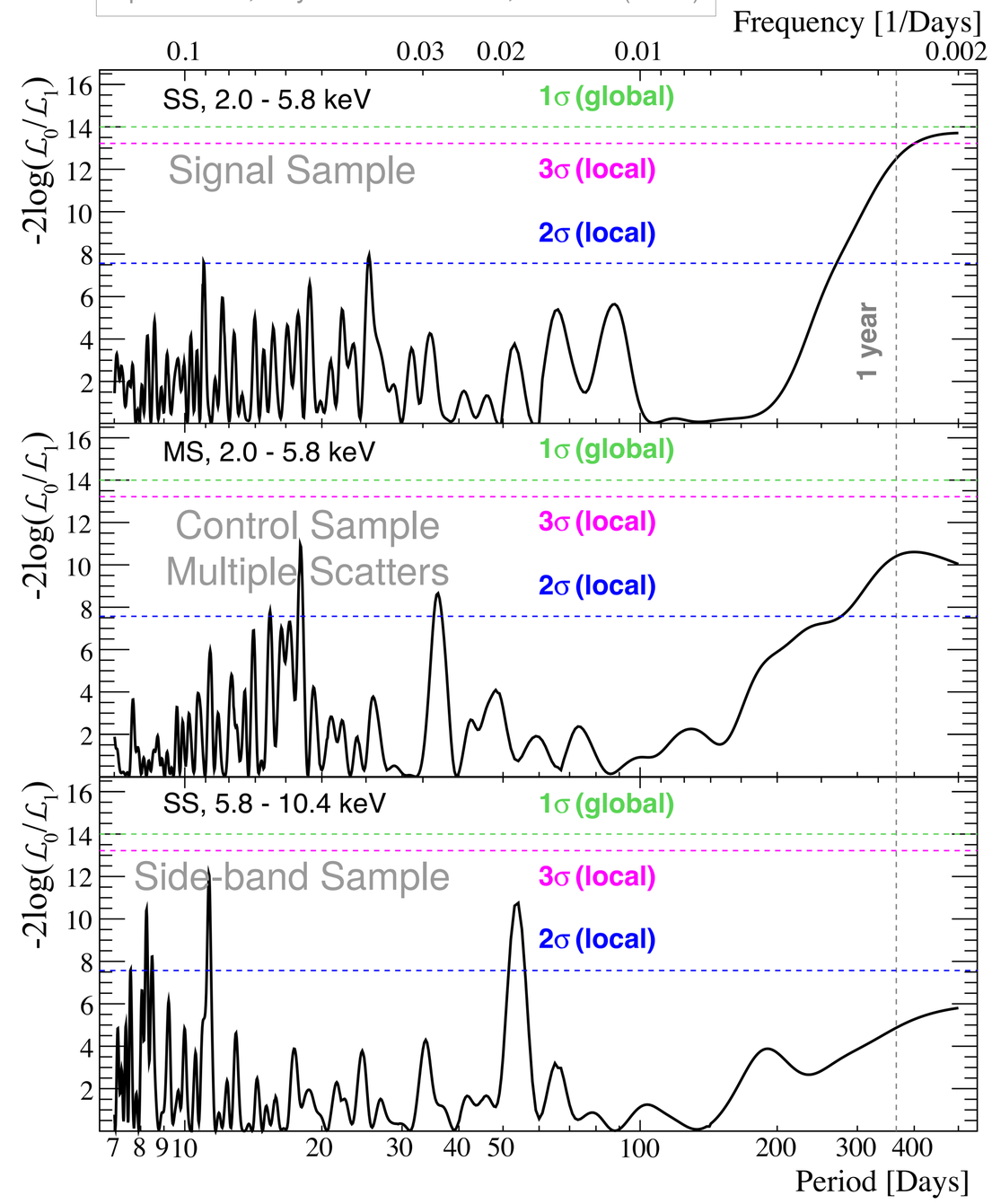
- Global sig < 1σ for all periods
- Local sig rise at long periods for signal *and* control
- Binned cross checks in agreement

Simulated Modulation



SS = single scatters
MS = multiple scatters (coincident signal in veto)

Aprile *et al.*, Phys. Rev. Lett. 115, 091302 (2015)



ER Rate Periodicity

PL Results: P = 365.25 days

- Local sig rise at long periods for signal *and* control
- Best-fit SS and MS phases *in agreement*
- Standard DM halo phase **disfavored at 2.5σ**

Hint of annual modulation...

...but in strong tension with DM interpretation

Uncertainty on best-fit values from scan of $\mathcal{L}_1/\mathcal{L}_{\max}$

Annual modulation best-fit:

C = (5.5 ± 0.6) events/(keV · tonne · day)

A = (2.7 ± 0.8) events/(keV · tonne · day)

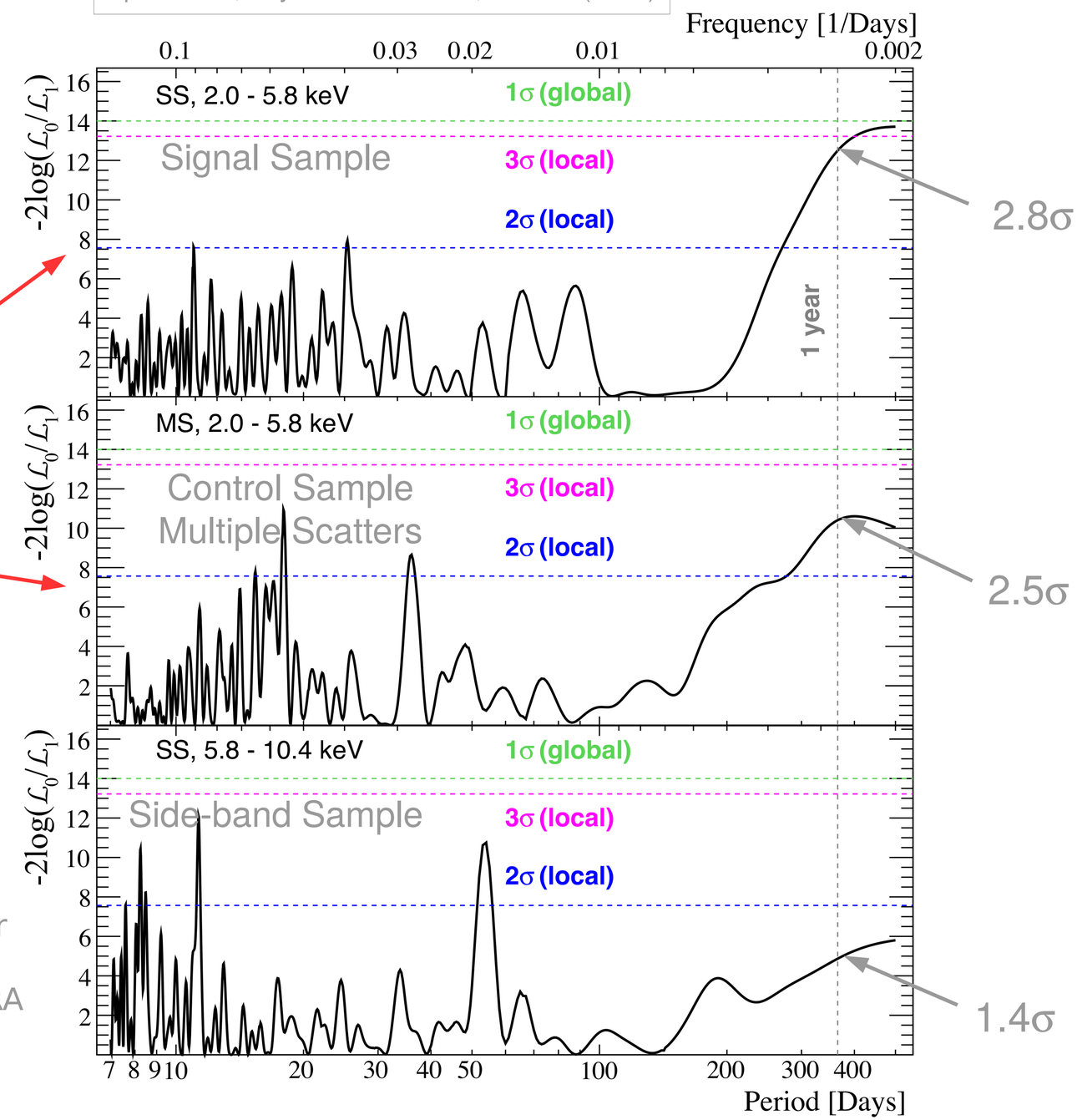
ϕ = (112 ± 15) days (April 22)

~4x lower than DAMA/LIBRA

Shifted ~1 month from DAMA/LIBRA

$$f(t) = \epsilon(t)\left[C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right]$$

Aprile *et al.*, Phys. Rev. Lett. 115, 091302 (2015)



DAMA/LIBRA Comparison

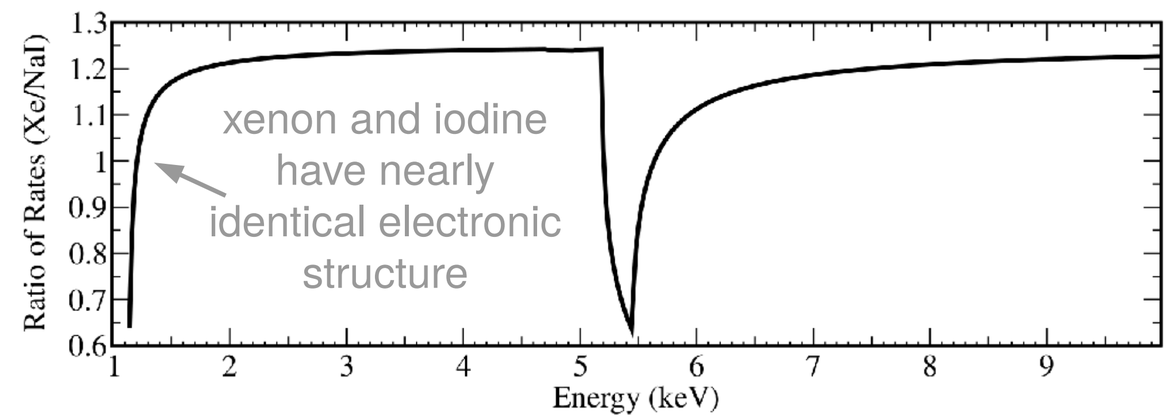
Signal Conversion

- Assume axial-vector coupling of WIMPs to electrons, compute relative rate in Xe and NaI

Model: Kopp *et al.*, Phys. Rev. D 80, 083502 (2009)

Xe/NaI rate: Aprile *et al.*, Science vol. 349 no. 6250 pp. 851-854 (2015)

Also considers Luminous and Mirror DM models



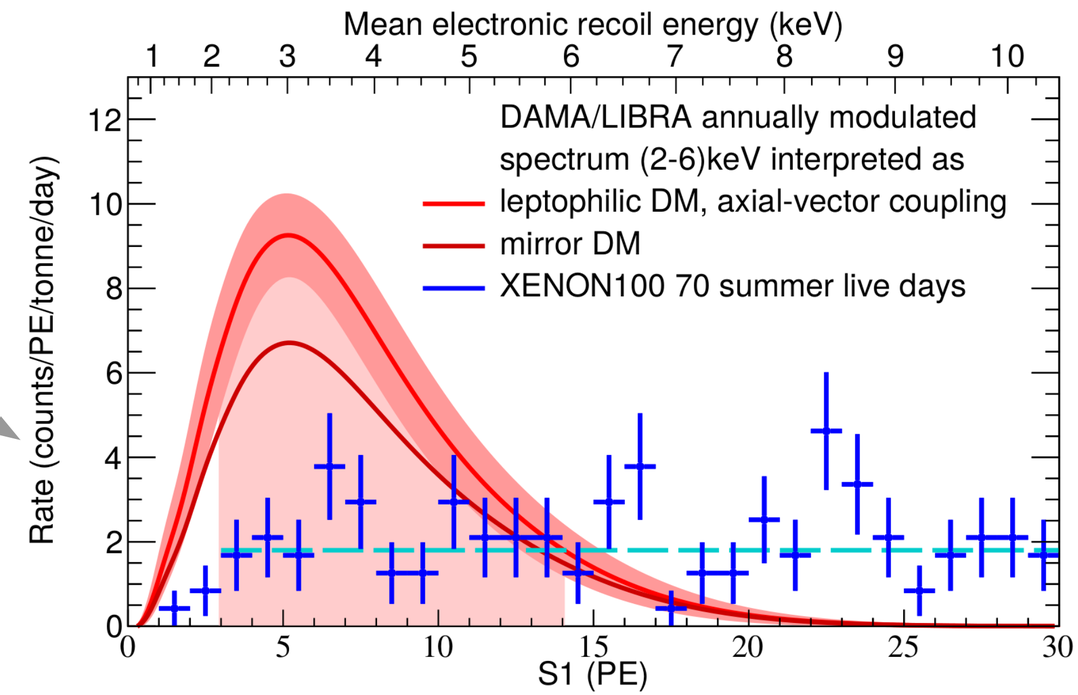
- Find expected spectrum in XENON100 from DAMA/LIBRA observation, accounting for
  - relative rate and energy scale conversion
  - S1 generation (Poisson process)
  - PMT single pe resolution
  - Measured cut acceptance
  - DAMA/LIBRA stat. uncert. and XENON100 uncert.

Measured rate (acceptance applied)

Total rate

A [Events/(keV · tonne · day)]

DAMA/LIBRA expected (axial-vector): 11.5 ± 1.2 stat ± 0.7 sys



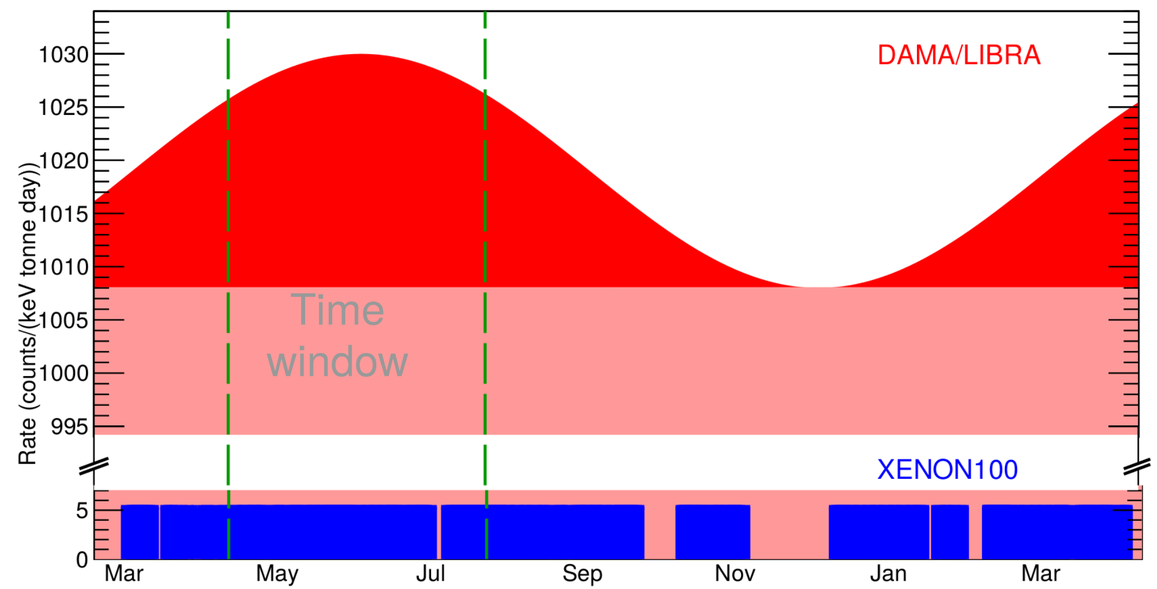
DAMA/LIBRA Comparison

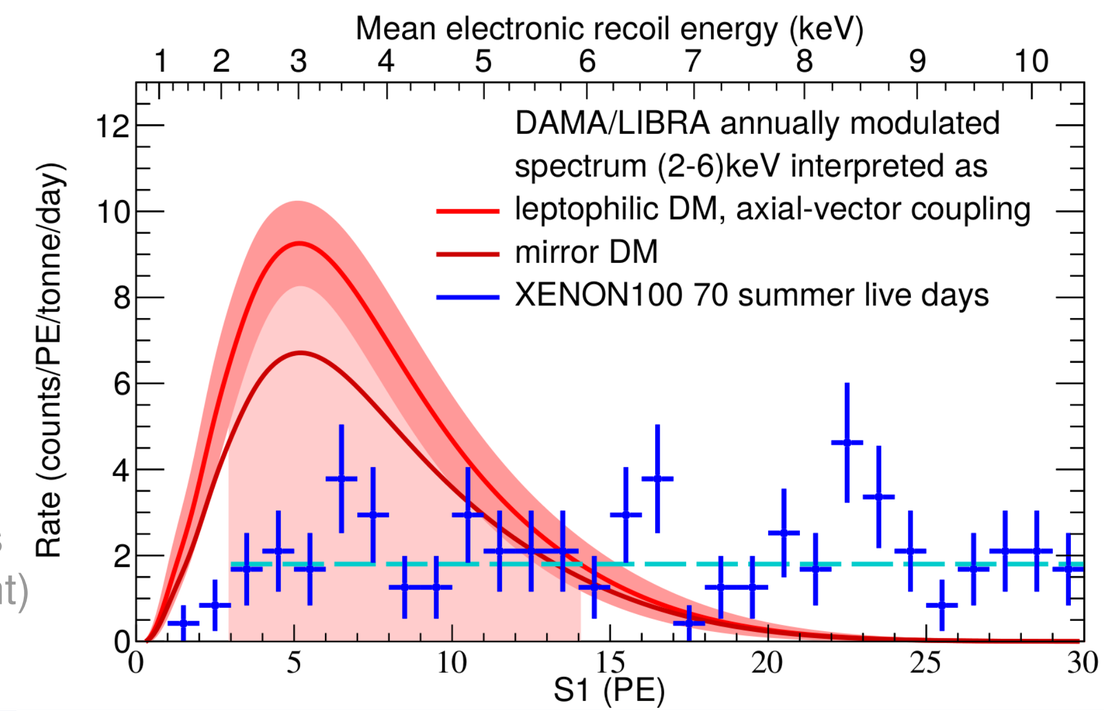
Exclusion – Average Rate

- Assume *all* events in XENON100 are signal
- Average rate in XENON100 ~2x lower than DAMA/LIBRA modulation *fraction*
- Integrate rate during optimized time window around June 2, and use for exclusion:
  - Mirror Dark Matter: **3.6σ**
  - Luminous Dark Matter: **4.6σ**
  - Axial-vector coupling to electrons: **4.4σ**

>3σ even assuming ~4.5σ downward deviation of yield measurements *or* zero light yield below 2.9 keV (in contradiction with direct measurement)

Aprile *et al.*, Science vol. 349 no. 6250 pp. 851-854 (2015)





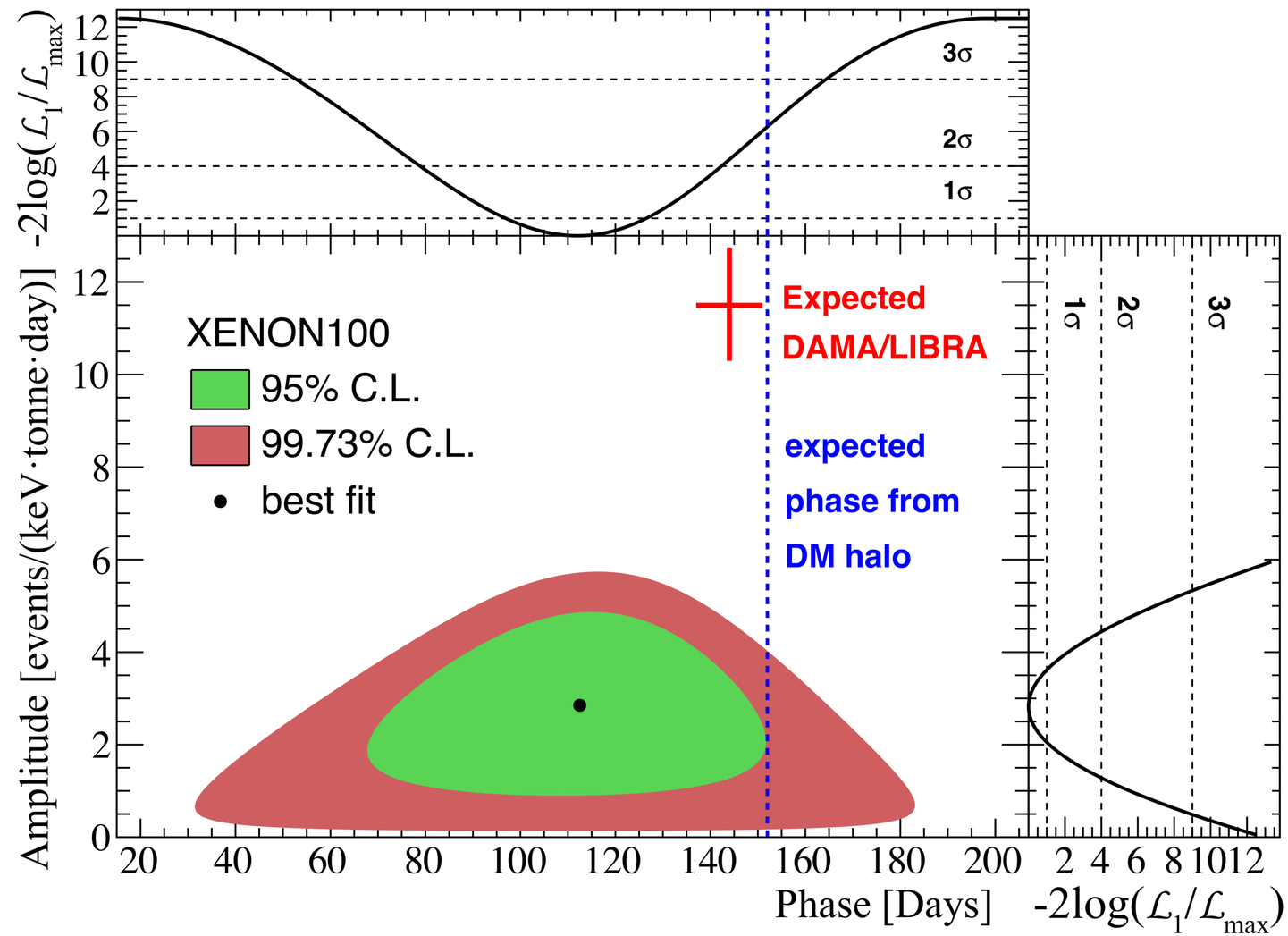
DAMA/LIBRA Comparison

Exclusion – Varying Rate

$$f(t) = \epsilon(t)\left[C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right]$$

- PL method to compute discrepancy of expected DAMA/LIBRA *A* with XENON100 best-fit
  - *Fix P*= 365.25 days, ϕ =144 ± 7 days (May 24)
  - Uncertainties constrained by data
  - *Add* constraint term to likelihood, $\mathcal{L}_\phi$
- Interpretation of DAMA/LIBRA signal as ERs (axial-vector coupling) **excluded at 4.8σ**

Aprile *et al.*, Phys. Rev. Lett. 115, 091302 (2015)



A [Events/(keV · tonne · day)]

DAMA/LIBRA expected (axial-vector): 11.5 ± 1.2 stat ± 0.7 sys

XENON100 best-fit: 1.9 ± 0.8 stat

DAMA/LIBRA Comparison

Summary

- Best-fit annual modulation amplitude >4x *lower* than DAMA/LIBRA modulation
- *Phase shifted* ~1 month from DAMA/LIBRA
- Local significance comparable for single *and* multiple scatter events (and *phases in agreement*)
- Interpretation of DAMA/LIBRA as WIMP-induced ERs strongly challenged

Models Excluded

Axial-vector coupling to electrons (4.8σ)	Aprile *et al*., Phys. Rev. Lett. 115, 091302 (2015)
Mirror Dark Matter (3.6σ) Luminous Dark Matter (4.6σ)	Aprile *et al*., Science vol. 349 no. 6250 pp. 851-854 (2015)

Conclusion

- Benchmark for stability of LXe dark matter detectors
- Challenges interpretation of DAMA/LIBRA modulation as ERs from WIMPs

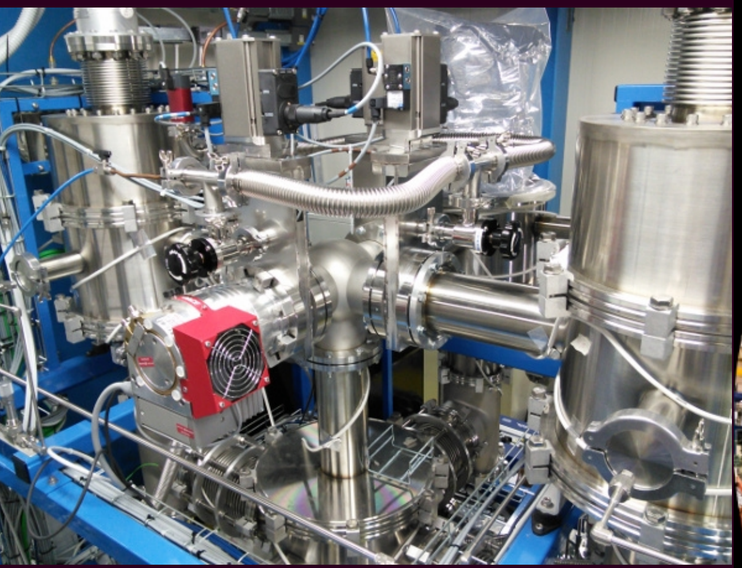
Axial-vector coupling to electrons (4.8σ)	Aprile *et al.*, Phys. Rev. Lett. 115, 091302 (2015)
Mirror Dark Matter (3.6σ) Luminous Dark Matter (4.6σ)	Aprile *et al.*, Science vol. 349 no. 6250 pp. 851-854 (2015)

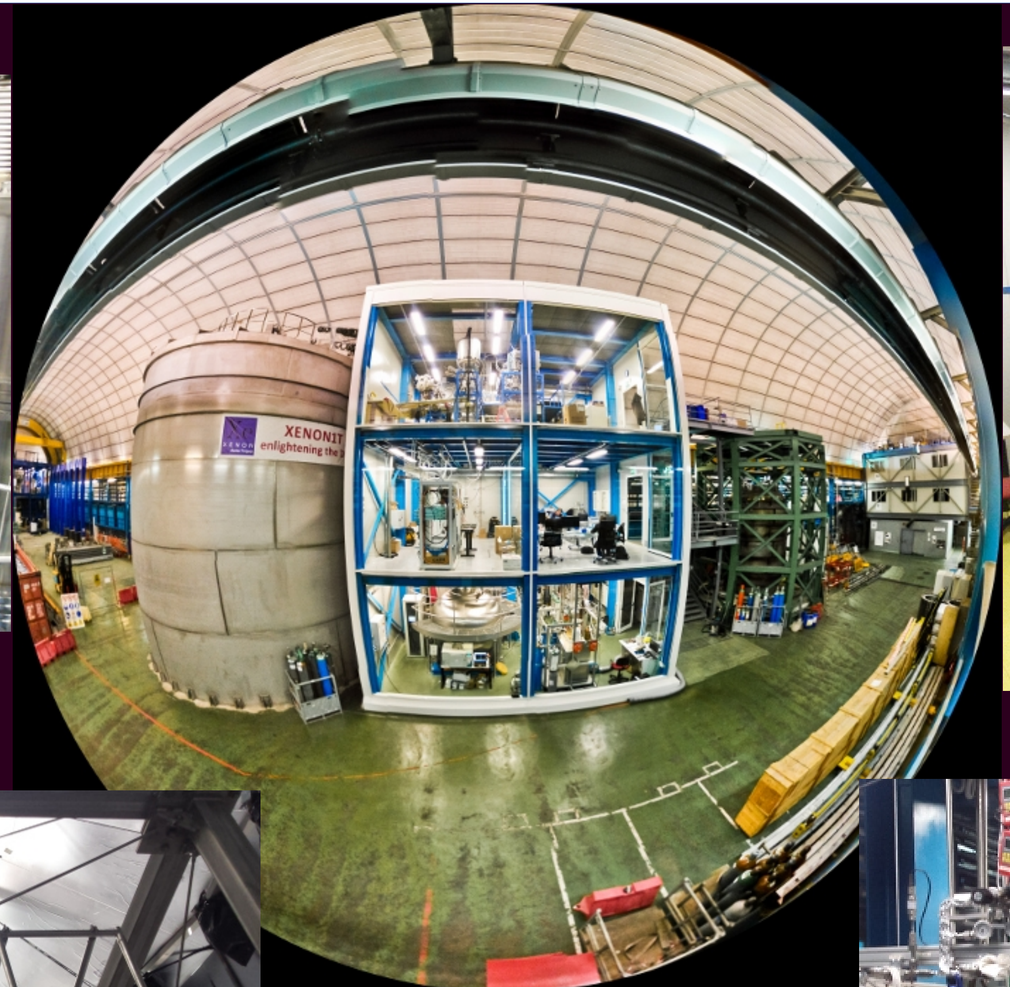
Improvements in progress

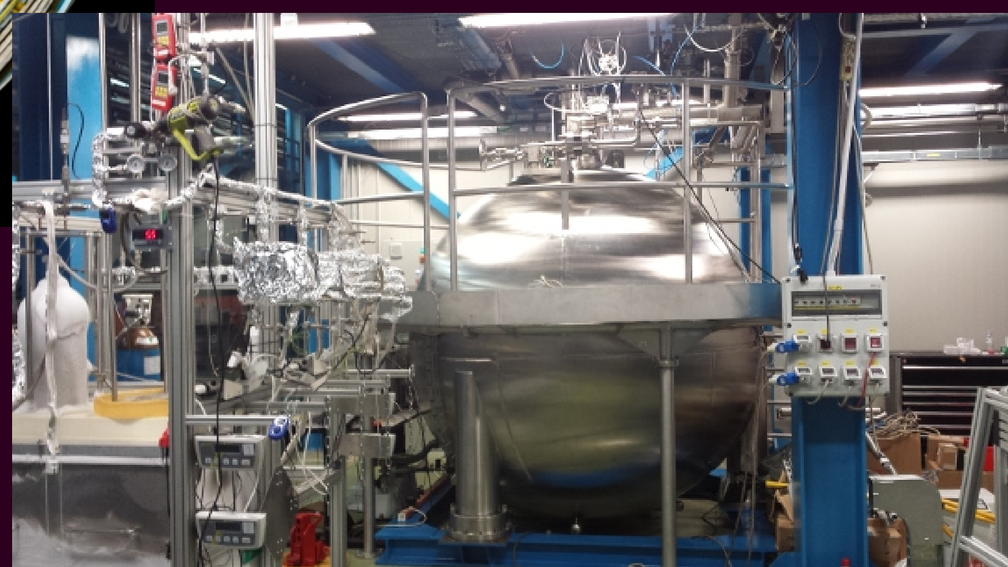
- *More* XENON100 data (153 additional live days)
- *Lower uncertainty* on energy scale (new calibration measurements)
- *More* diagnostic tools for Kr contamination
- and...

Conclusion

... an even bigger, better detector - XENON1T!







Extra

Detector Stability

Rn-Kr Correlation

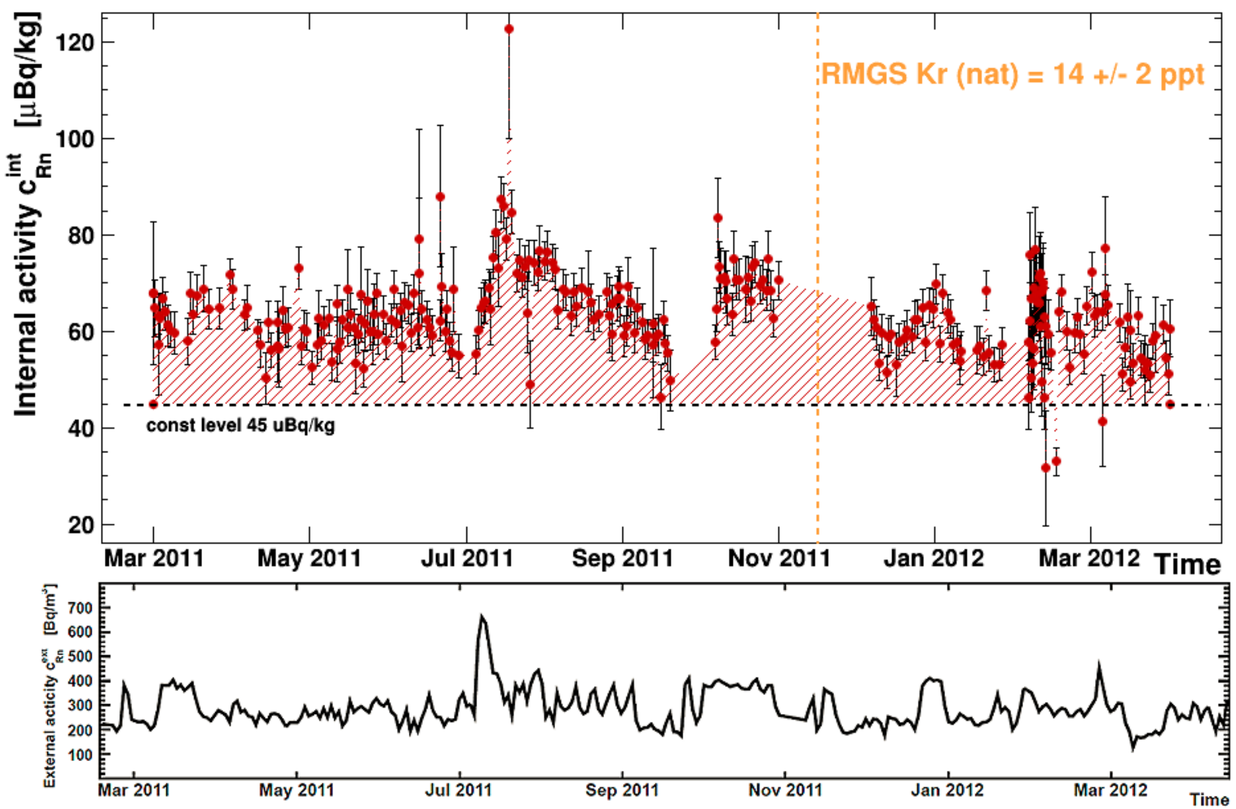
Air leak ~10^{-5} torr*l/s

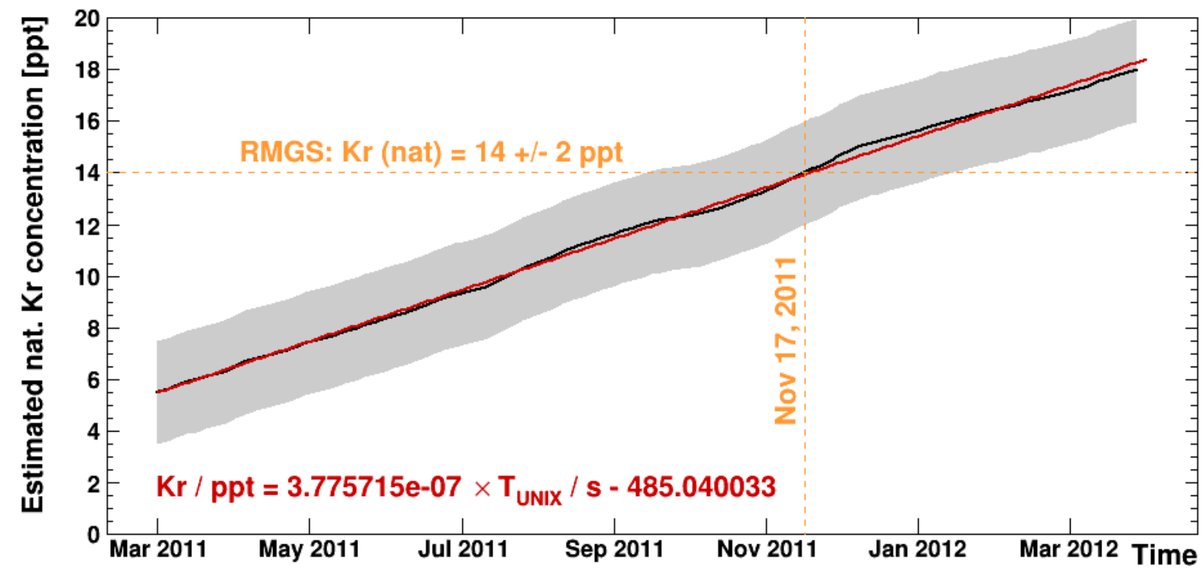
air → ^{85}Kr: $t_{1/2}$ = 10.8 years → builds up

air → ^{222}Rn: $t_{1/2}$ = 3.82 days → decays away

$$f(t) = \epsilon(t)\left[C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right]$$

K = 2.54±0.53×10^{-3} (events/(keV·tonne·day))/day





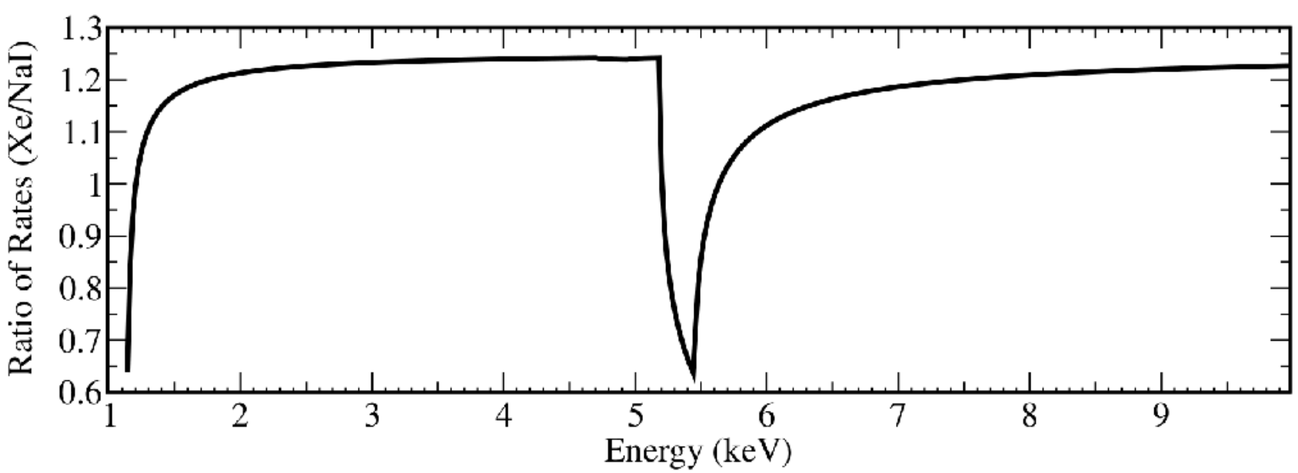
DAMA/LIBRA Comparison

Expected rate from WIMP-induced ER

- keV recoils from inelastic scatter of >1GeV WIMPS with momentum ~MeV
- Interaction rate from Kopp et al. (x2 to account for electron spin) Kopp *et al.*, Phys. Rev. D 80, 083502 (2009)
- Sum contribution from each atomic shell (integrate momentum wave function)
- Largest rate from 3s shell of Iodine (Na 100x smaller)
- Xe and I overall very similar electron structure
- Negligible dependence on WIMP mass

Other Models Considered

- ◊ Mirror Dark Matter: scale by ratio of (number of loosely bound electrons · number of target atoms)
- ◊ Luminous Dark Matter: scale by target density ratio



Aprile *et al.*, Science vol. 349 no. 6250 pp. 851-854 (2015)

ER Rate Periodicity

PL Method Details

Basic method: Olive *et al.*, Chin. Phys., C38 (2014), 090001

Rate

$$f(t) = \epsilon(t)\left[C + Kt + A\cos\left(2\pi\frac{(t-\phi)}{P}\right)\right]$$

Normalized by *D*

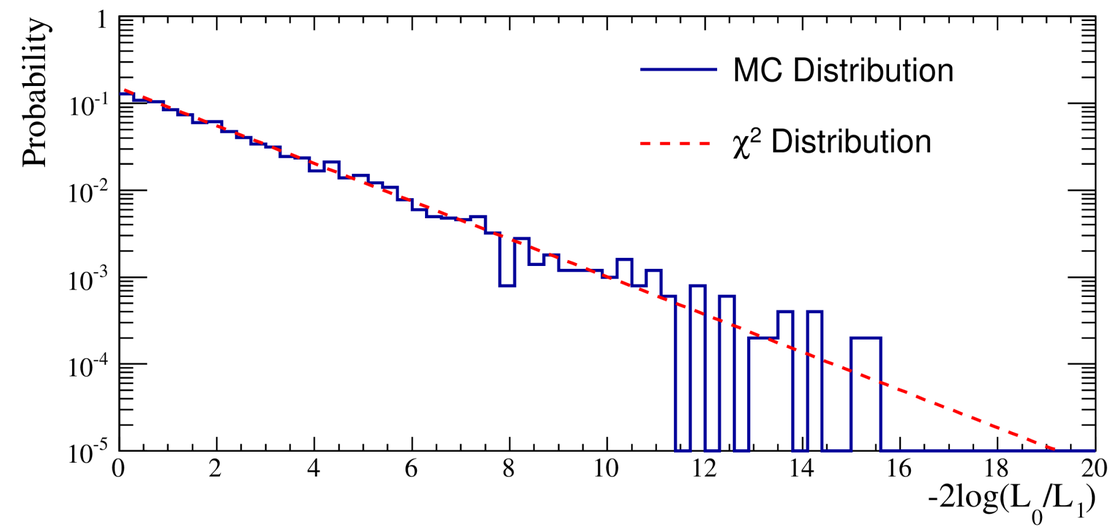
Normalization factor

$$D = C \times \sum_{j=1}^{m}(T_E^j - T_S^j) \times \epsilon\left(\frac{T_S^j + T_E^j}{2}\right) + \frac{K}{2} \times \sum_{j=1}^{m}(T_E^{j\,2} - T_S^{j\,2}) \times \epsilon\left(\frac{T_S^j + T_E^j}{2}\right)$$
$$+ \frac{A \times P}{2\pi}\sum_{j=1}^{m}\epsilon\left(\frac{T_S^j + T_E^j}{2}\right) \times \sin\left(\frac{2\pi}{P} \times (T_E^j - \phi)\right)$$
$$- \frac{A \times P}{2\pi}\sum_{j=1}^{m}\epsilon\left(\frac{T_S^j + T_E^j}{2}\right) \times \sin\left(\frac{2\pi}{P} \times (T_S^j - \phi)\right)$$

Likelihood function

$$\mathcal{L} = \left(\prod_{i=1}^{n}\tilde{f}(t_i)\right)\mathrm{Poiss}[n|N_{\mathrm{exp}}(E)]\mathcal{L}_\epsilon\mathcal{L}_K\mathcal{L}_E$$

Local significance, 500 days



2 d.o.f. = 7 total parameters – 4 constraints – 1 fixed parameter
(*ε, φ, C, K, A, P, E*) (likelihood factors) (*P*)

Global significance