A Symphony of Scintillation

Noble **E**lement **S**imulation **T**echnique

for Geant4

http://nest.physics.ucdavis.edu

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on behalf of the entire NEST development team, of the University of California, Davis, Davis, CA, USA, Lawrence Livermore National Laboratory, Livermore, CA, USA, and the University of California, Los Angeles, CA, USA

University of Minnesota, Minneapolis, Friday 11-11-11

The People of the NEST Team

UC Davis, LLNL, and UCLA, in California

A small but passionate group of individuals who love the work

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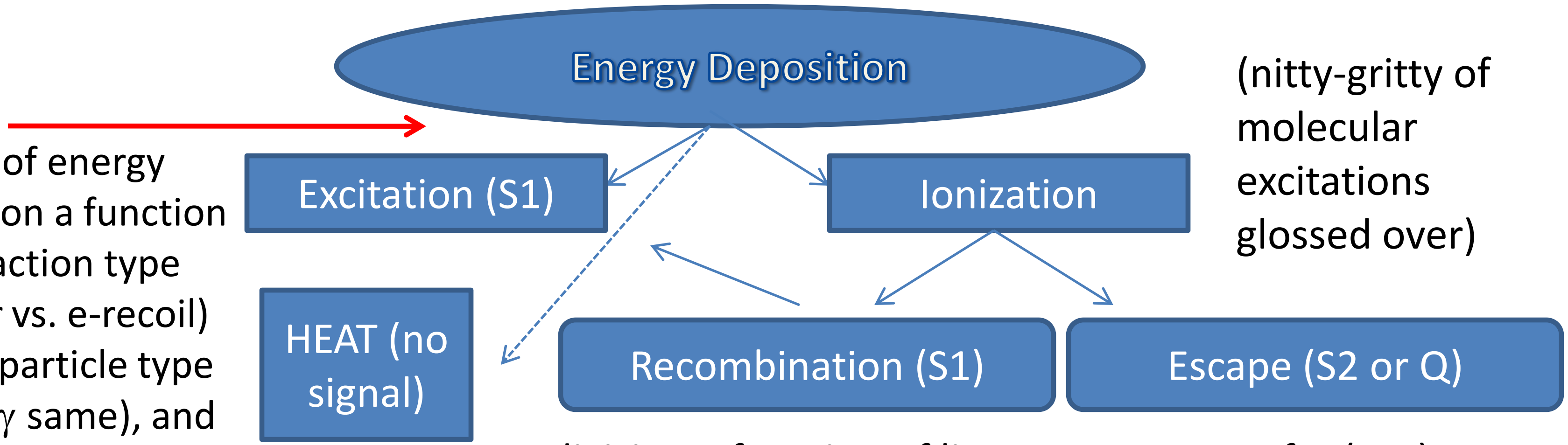
Why simulate scintillating noble elements well?

- Direct dark matter detection or calibration for it (past, present, future experiments)
  - LUX, XENON, ZEPLIN, LZ, WArP, DarkSide, ArDM, XMASS, DARWIN, MAX, Xürich, Xed, XeCube, PANDA-X, PIXeY, DEAP, CLEAN, ….. 1- and 2-phase
- Double beta decay ($0\nu\beta\beta$, $2\nu\beta\beta$) projects too
  - EXO, NEXT (both ^{136}Xe-enriched)
- Positron Emission Tomography (PET) scans for medical applications: detect 511 keV γ's
- Other particle detection applications, e.g., collider experiments (MEG, Olive, et al.)

The Purpose and Scope of NEST

- Create full-fledged simulation based on a physical, albeit also heuristic/quasi-empirical approach
- Comb the wealth of data for liquid and gaseous noble elements for different particles, energies, and electric fields, and then combine everything
- Aid the many dark matter, double beta decay, and other experiments which utilize this technology to be on the same or comparable page for simulations
- Bring added realism to the simple model that is present now in Geant4 for scintillation
- Explore backgrounds at low energy by expanding Geant4 physics to be more accurate when you go to a low energy regime: $O(1)$ keV and even lower
- Have to start somewhere: LXe, for sake of LUX

Basic Physics Principles



(nitty-gritty of molecular excitations glossed over)

division of energy deposition a function of interaction type (nuclear vs. e-recoil) but not particle type (e.g., e ,γ same), and not a function of the parent particle's kinetic energy

(the infamous $\mathscr{L}$ value)

division a function of linear energy transfer (LET) or stopping power (dE/dx), because of ionization density considerations, and of the electric field magnitude

- Heat loss for nuclear recoils (Lindhard effect), while electron recoils relatively easier to deal with
- Start simple: no exotic energy loss mechanisms (like "bi-excitonic" collisions). Explains the data?

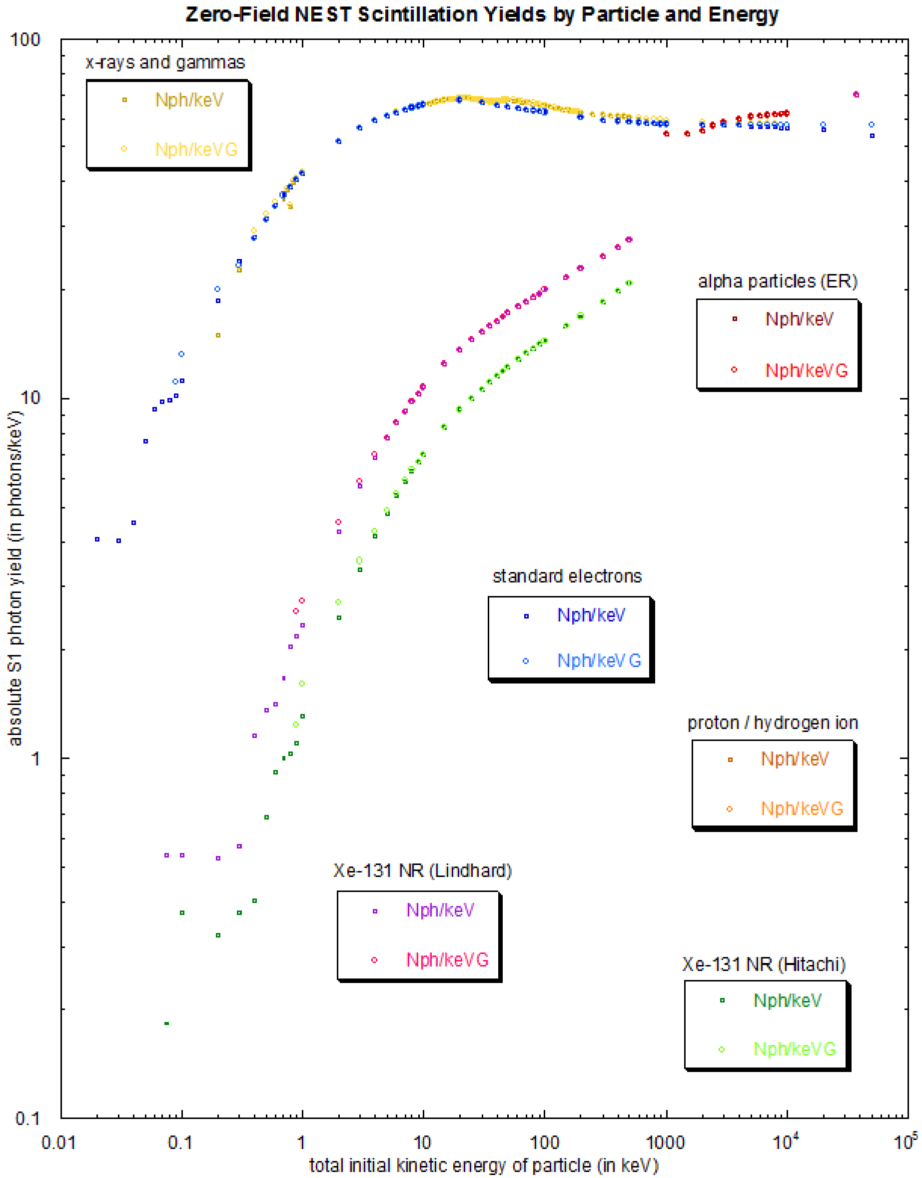
Basic Physics Principles

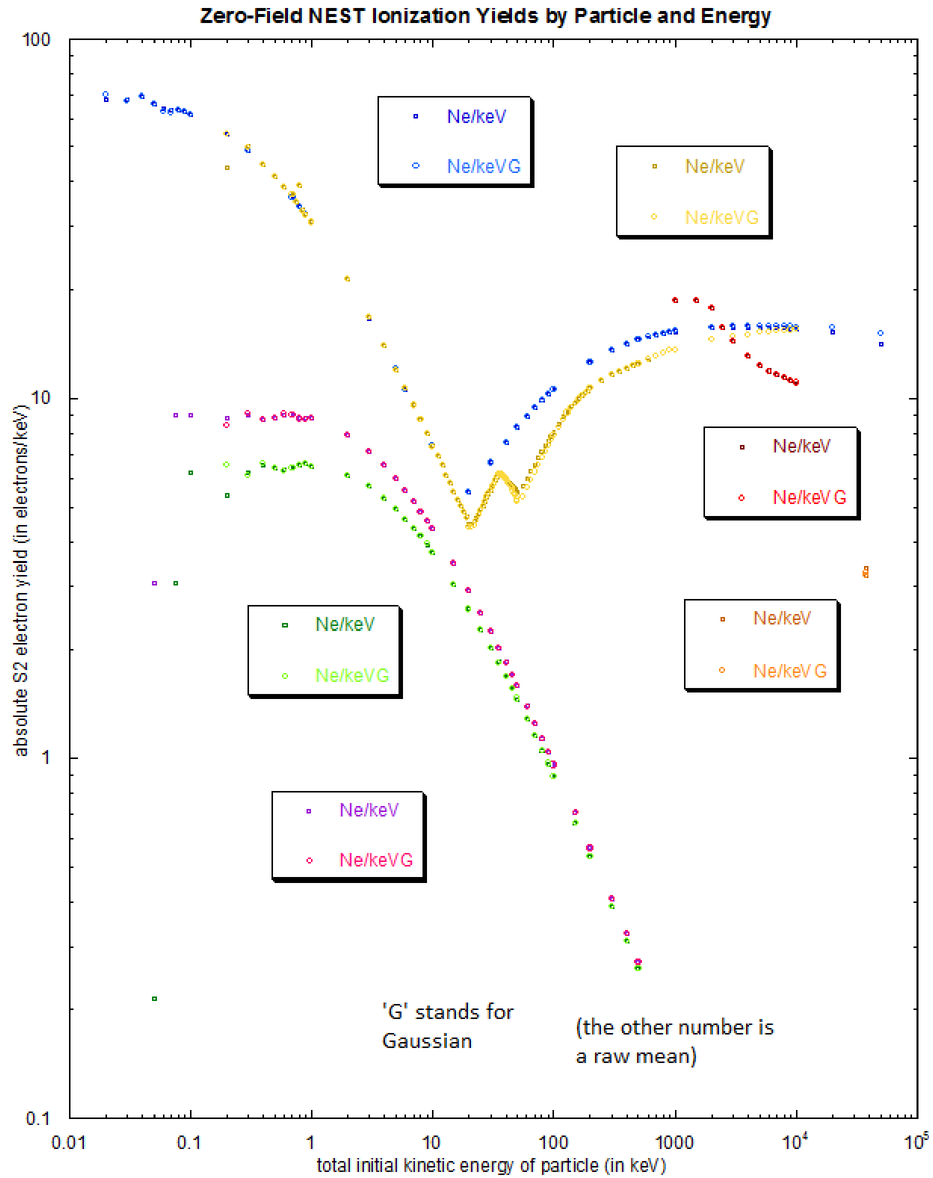
- Cornerstone: There is ONE work function for production of EITHER a scintillation photon or an ionization electron. All others derive from it.
- $W = 13.7 \pm 0.2$ eV $(N_{e-} + N_{\gamma}) = E_{dep} / W$

  C.E. Dahl, Ph.D. Thesis, Princeton University, 2009
- Two recombination models, for different E regimes
  - Thomas-Imel ”box” model (*O*(10) keV and lower)
  - Modified Birks’ Law of Doke (*O*(100) keV and up)
- Recombination probability makes for non-linear yield: 2x energy does not mean 2x light, charge
- Excellent vetting against much past data

Putting it All Together to Predict the Yield

First: Let's look at zero-field scintillation yield from various particles





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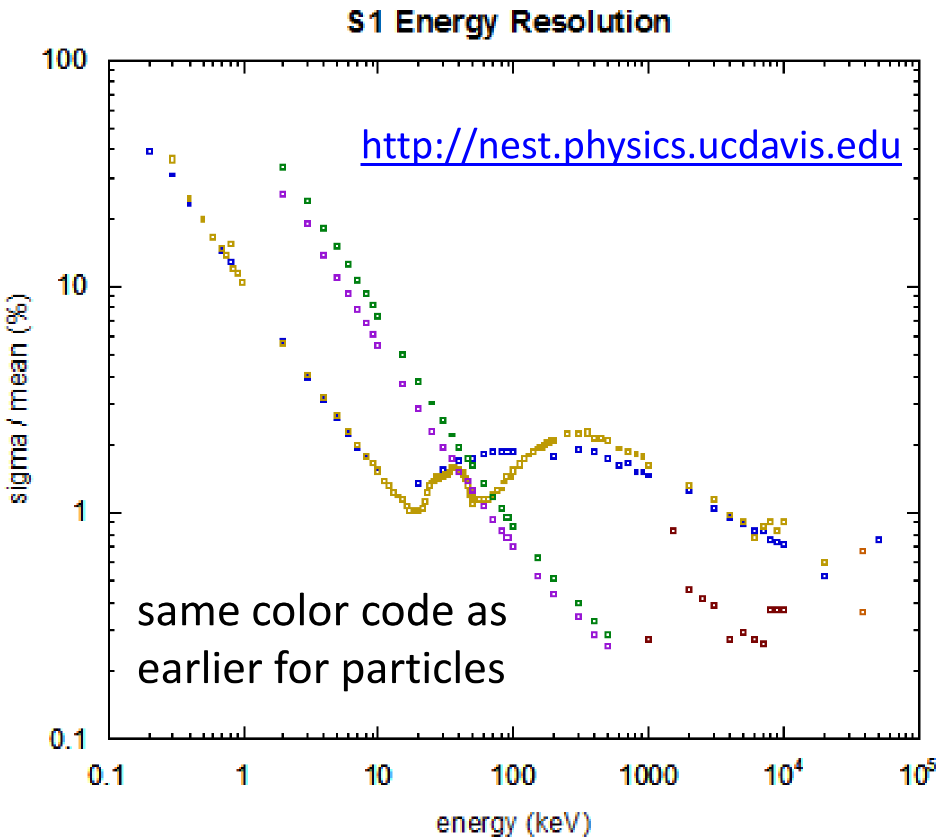
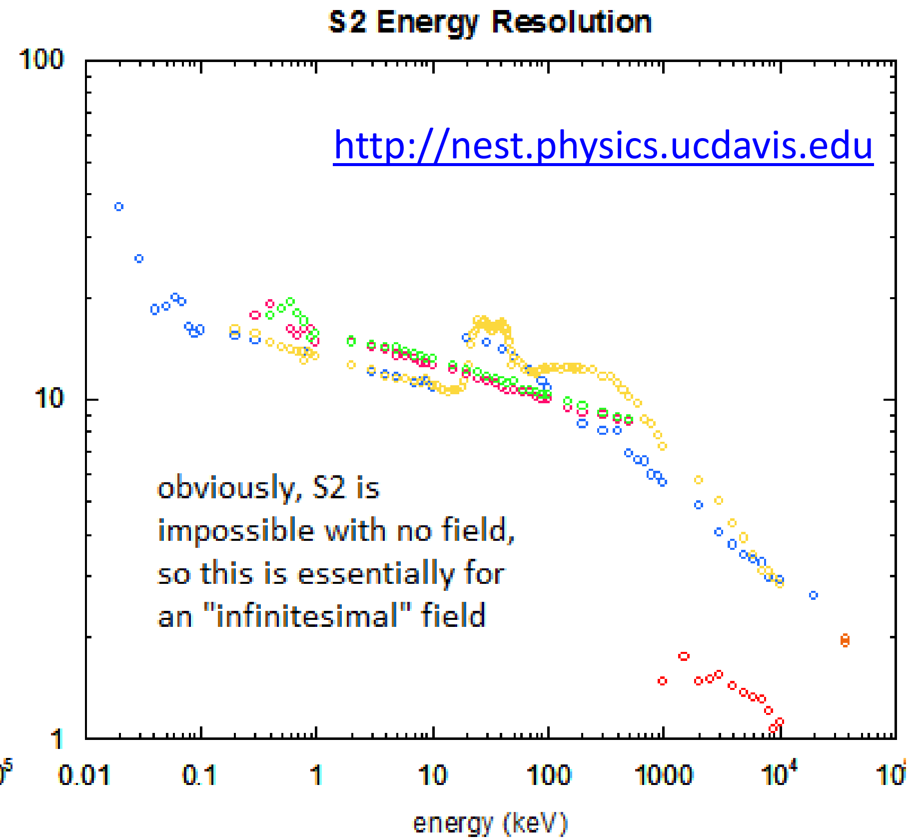
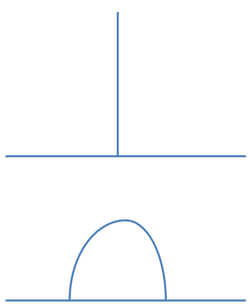
Energy Resolution

Preliminary NEST Predictions for Zero Electric Field



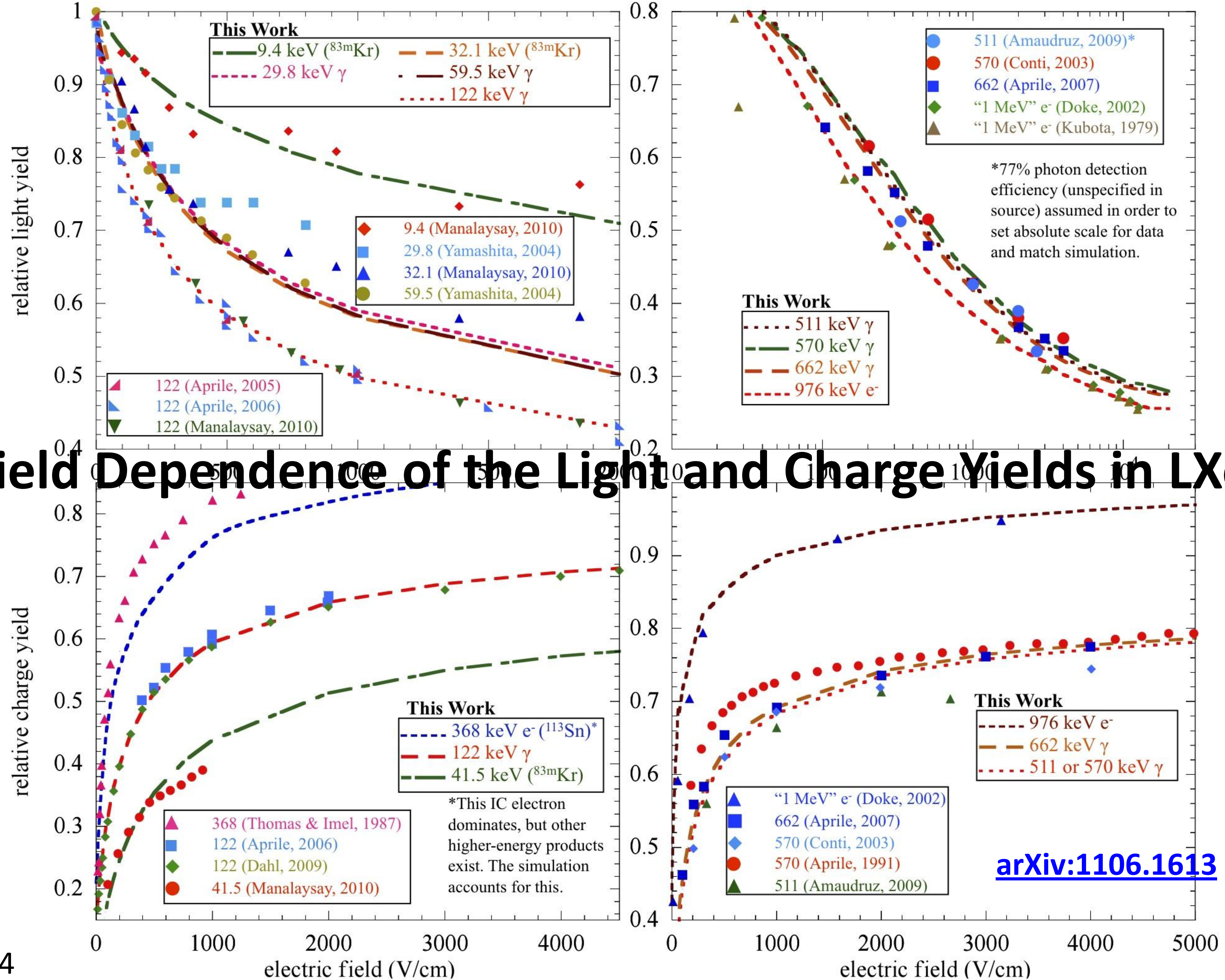




The sources of INTRINSIC non-perfect resolution, at all electric fields

- Fano factor (extremely small effect until lower energies)
- Binomial fluctuations in the recombination probability
- Binomial fluctuations in the numbers of excitons versus ions (small)
- Particle track history, including stochastic dE/dx effects
- Dependence of recombination probability on track angle (?)

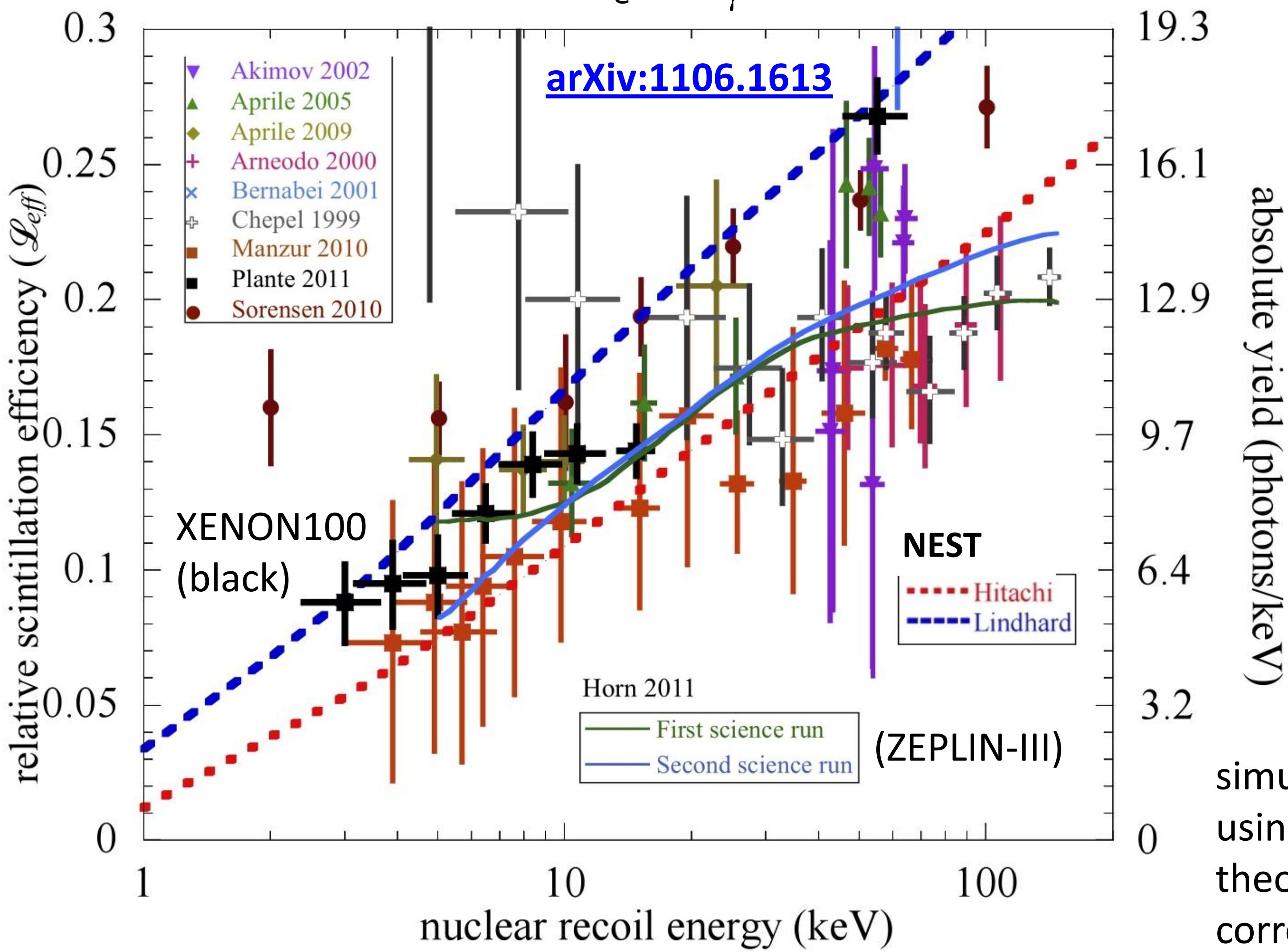
Field Dependence of the Light and Charge Yields in LXe



arXiv:1106.1613

The Tricky Nuclear Recoil Issue: LXe

$(N_{e-} + N_\gamma) = \mathbf{L(E)} * E / W$



prediction with simulations based on electron recoil numbers, NOT a direct fit

(other axis is relative to 122 keV gamma's yield, as is traditional)

simulated yield using Lindhard theory or the Hitachi correction to it

This is likely the strongest prediction, with the simplest assumptions, ever devised!

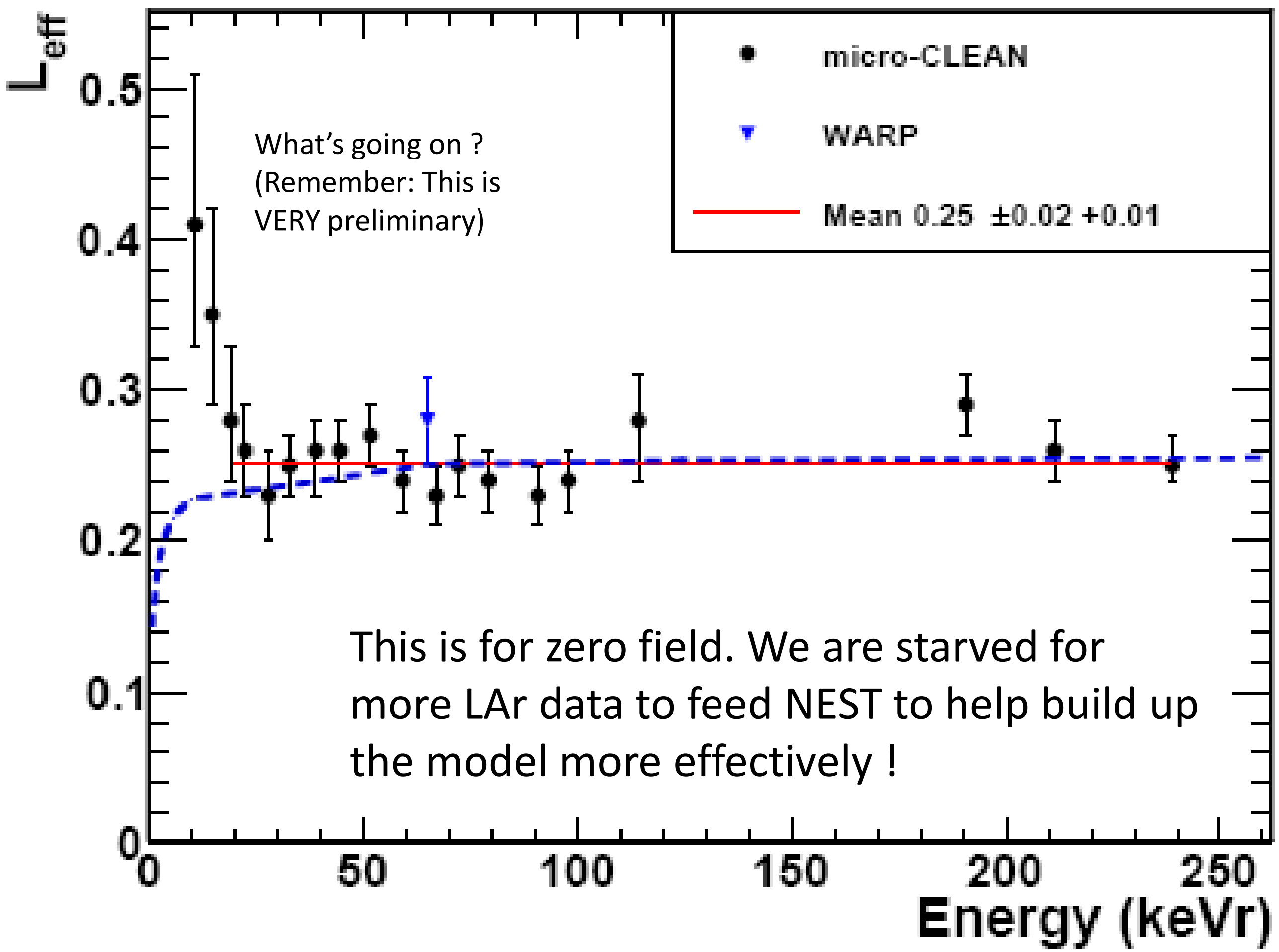
Very Preliminary LAr Result for NR Light Yield

Using a flat eye-balled valued for L(E)
plus the Thomas-Imel box model
of recombination, with an ansatz
calculation for its one free parameter

Yield higher than in Xe. *Why?*

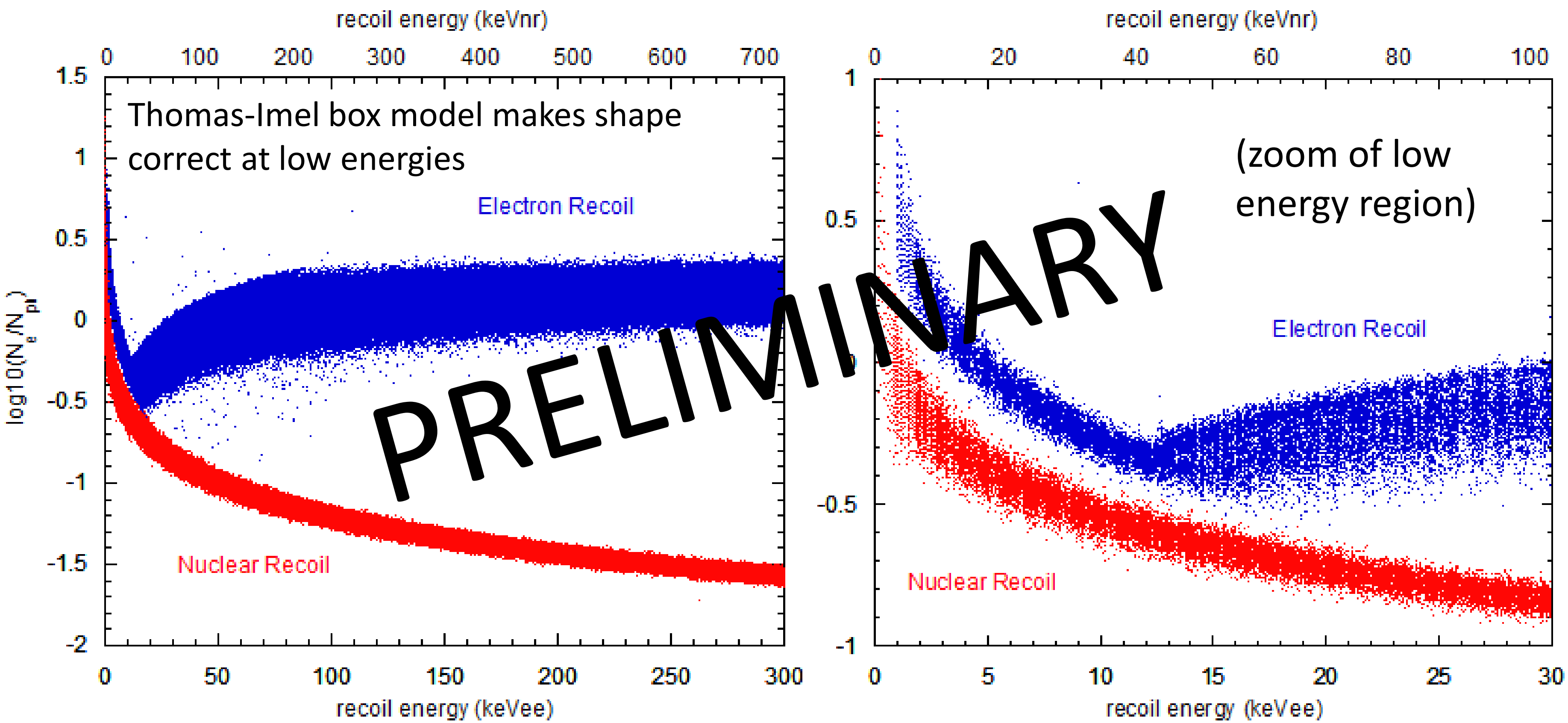
<u>Two main reasons:</u>

Smaller Z and A, greater initial exciton to ion ratio



What Can NEST Do For You?

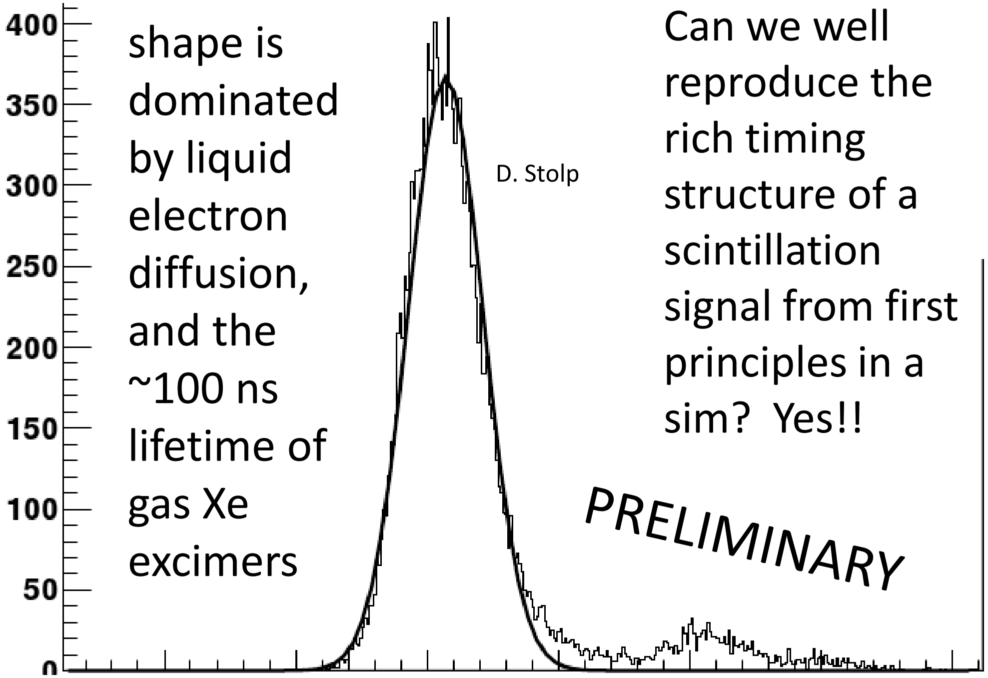
Example simulated NR, ER bands in S2/S1 space from LUX (with LUXSim - see Kazkaz' talk)



NO artificial smearing, Gaussian or otherwise, was added to NEST to yield the result depicted.

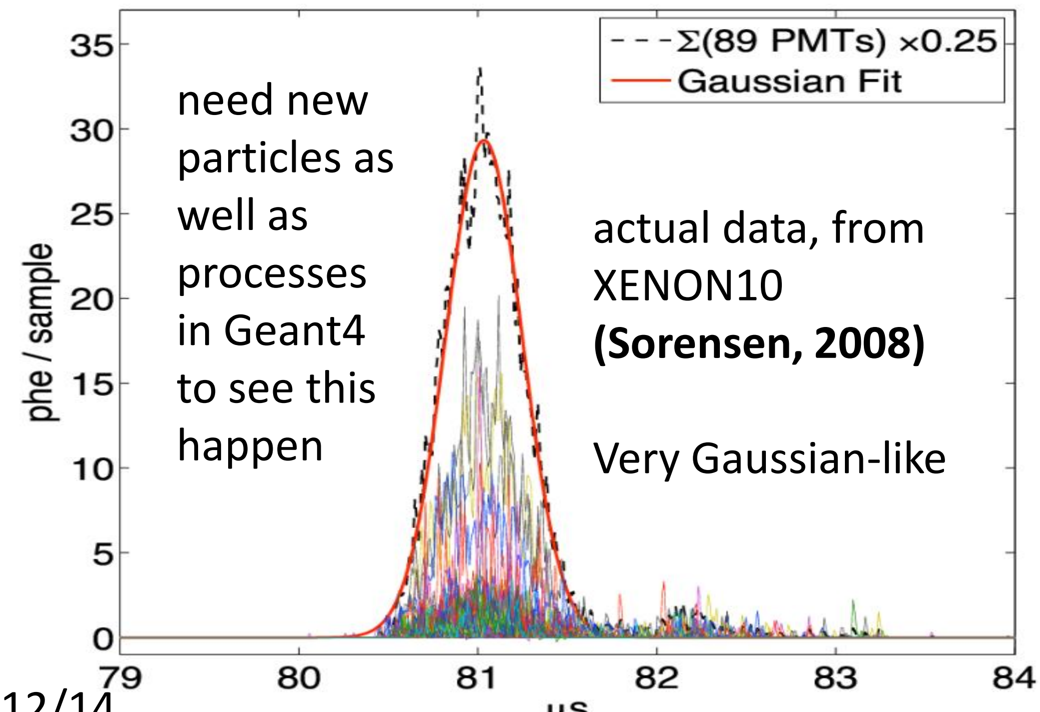
Now it has become possible, with NEST, to study/predict the discrimination power of your experiment before you even built it or calibrate, with a reliable simulation.

Understanding the Raw Pulse Shapes (S1, S2)



shape is dominated by liquid electron diffusion, and the ~100 ns lifetime of gas Xe excimers

Can we well reproduce the rich timing structure of a scintillation signal from first principles in a sim? Yes!!

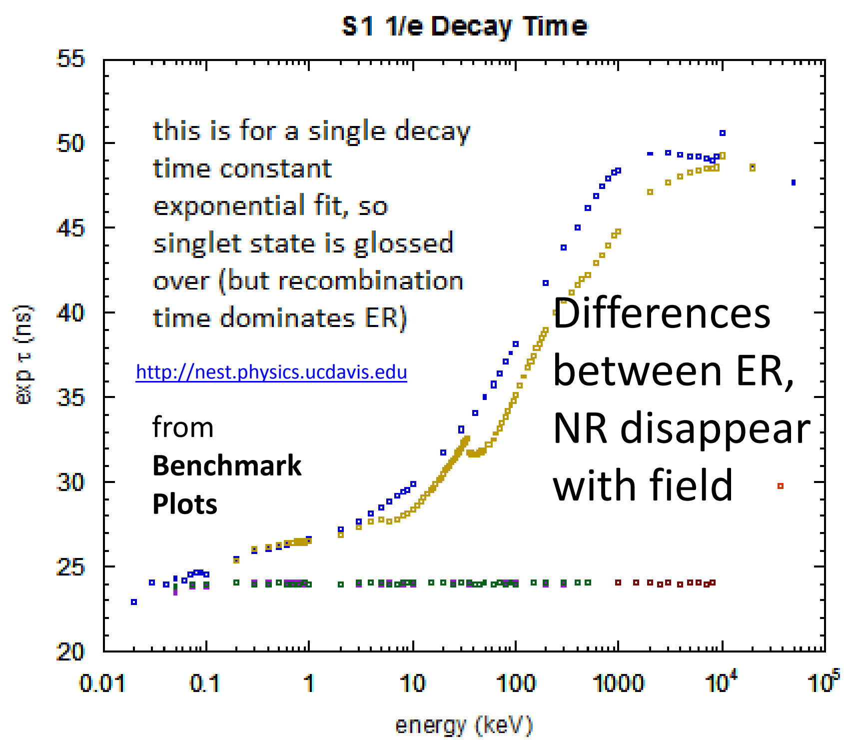


need new particles as well as processes in Geant4 to see this happen

actual data, from XENON10 **(Sorensen, 2008)**

Very Gaussian-like

single, triplet lifetimes incorporated for S1, as well as the recombination time, which is varied versus ionization density and the electric field magnitude



this is for a single decay time constant exponential fit, so singlet state is glossed over (but recombination time dominates ER)

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from **Benchmark Plots**

Differences between ER, NR disappear with field

Interfacing with GEANT

- Upgrade to **G4Scintillation** physics process, called **G4S1Light**, available for download on-line; speaking with GEANT about inclusion in upcoming version
- Another new G4 physics process: **G4S2Light** soon, utilizing a new species of electron (“thermal”)
- Resolving geometrical bugs: I want to talk to the representatives of GEANT present here today
  - Not all photons collected when reflectivities set to 100%
  - Volume borders “fuzzy” at *O*(0.1 mm) level
- Bugs solvable, and *you can dial in a particle type and energy, set your electric field, and watch your sims give reliable results with relative ease*

Status and Future

- Fully simulating DAQ chain (pulse shaping effects)
- Detector effects: QE, PMT gain variation, etc.
- Representatives of many collaborations already members of the NEST mailing list, and downloading
- No more rules of thumb, nor extrapolations from past detectors: build your geometry and go
- Drag and drop NEST into your sim with minimal effort, and get regular updates with more features
- Next: GXe, L/GAr, Ne, He, Kr, solids – complete set someday soon? ALL noble elements…

References

- For all of the references used in this talk, please simply consult the full bibliography of

M. Szydagis et al., NEST: A Comprehensive Model For Scintillation Yield in Liquid Xenon

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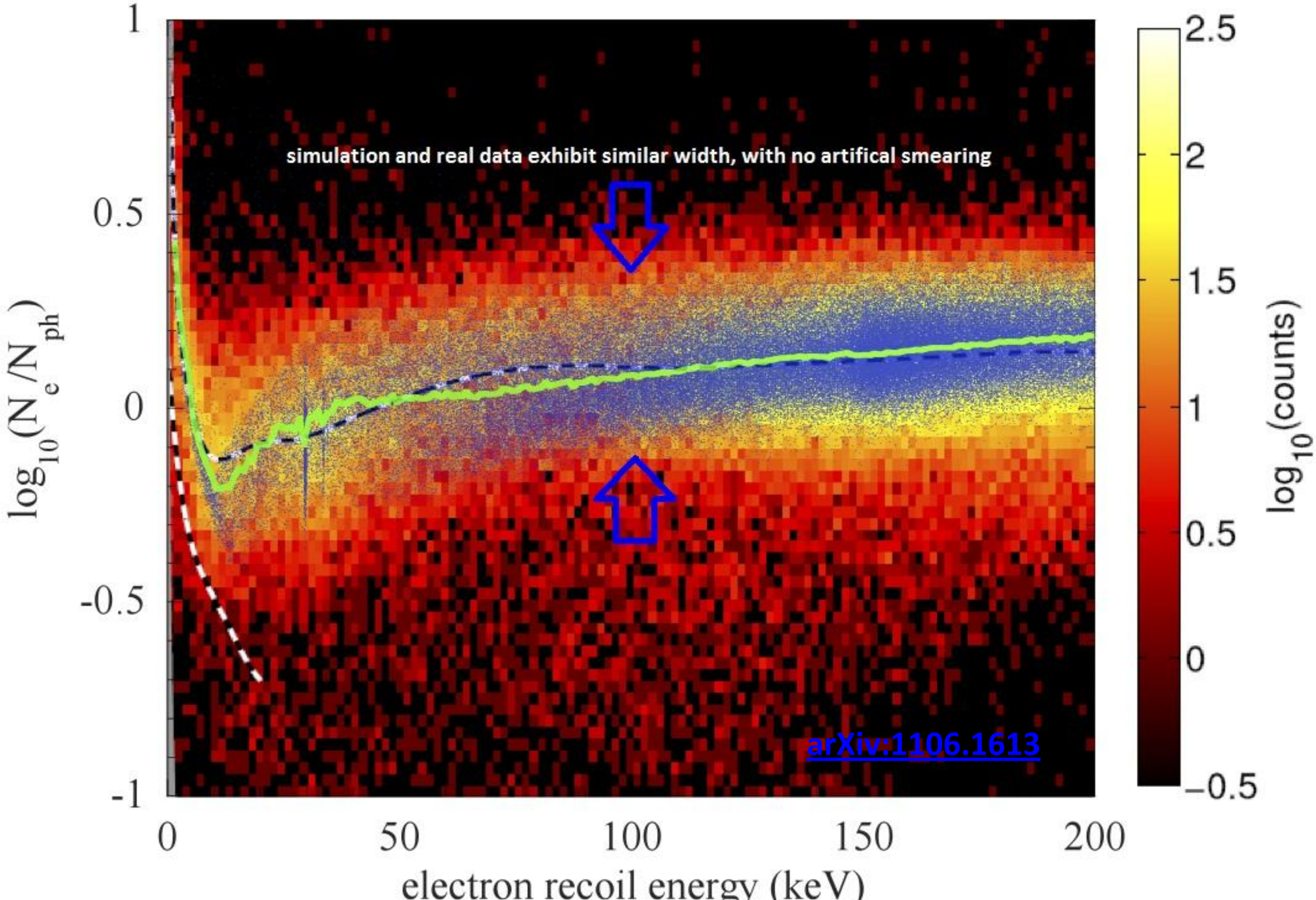
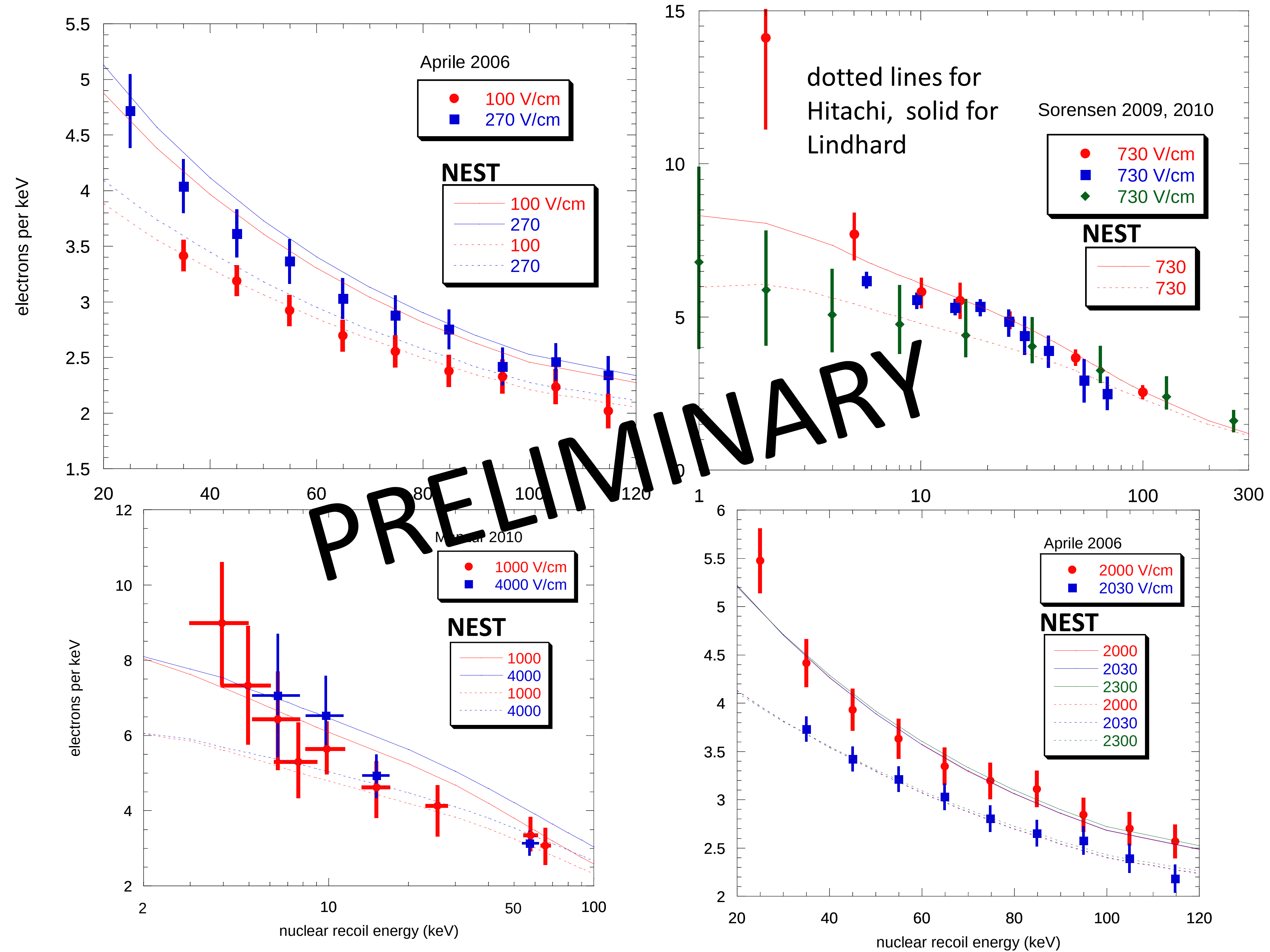
Also, visit us on the arxiv at:

arxiv:1106.1613

Bonus Slides



simulation and real data exhibit similar width, with no artifical smearing
arXiv:1106.1613
$\log_{10}(N_e/N_{ph})$
electron recoil energy (keV)
$\log_{10}$(counts)
1
0.5
0
-0.5
-1
0
50
100
150
200
2.5
2
1.5
1
0.5
0
−0.5



electrons per keV
Aprile 2006
100 V/cm
270 V/cm
NEST
100 V/cm
270
100
270
dotted lines for Hitachi, solid for Lindhard
Sorensen 2009, 2010
730 V/cm
730 V/cm
730 V/cm
NEST
730
730
PRELIMINARY
1000 V/cm
4000 V/cm
NEST
1000
4000
1000
4000
electrons per keV
nuclear recoil energy (keV)
Aprile 2006
2000 V/cm
2030 V/cm
NEST
2000
2030
2300
2000
2030
2300
nuclear recoil energy (keV)