Development of Cryogenic Tracking Detectors for Low-energy Solar Neutrinos

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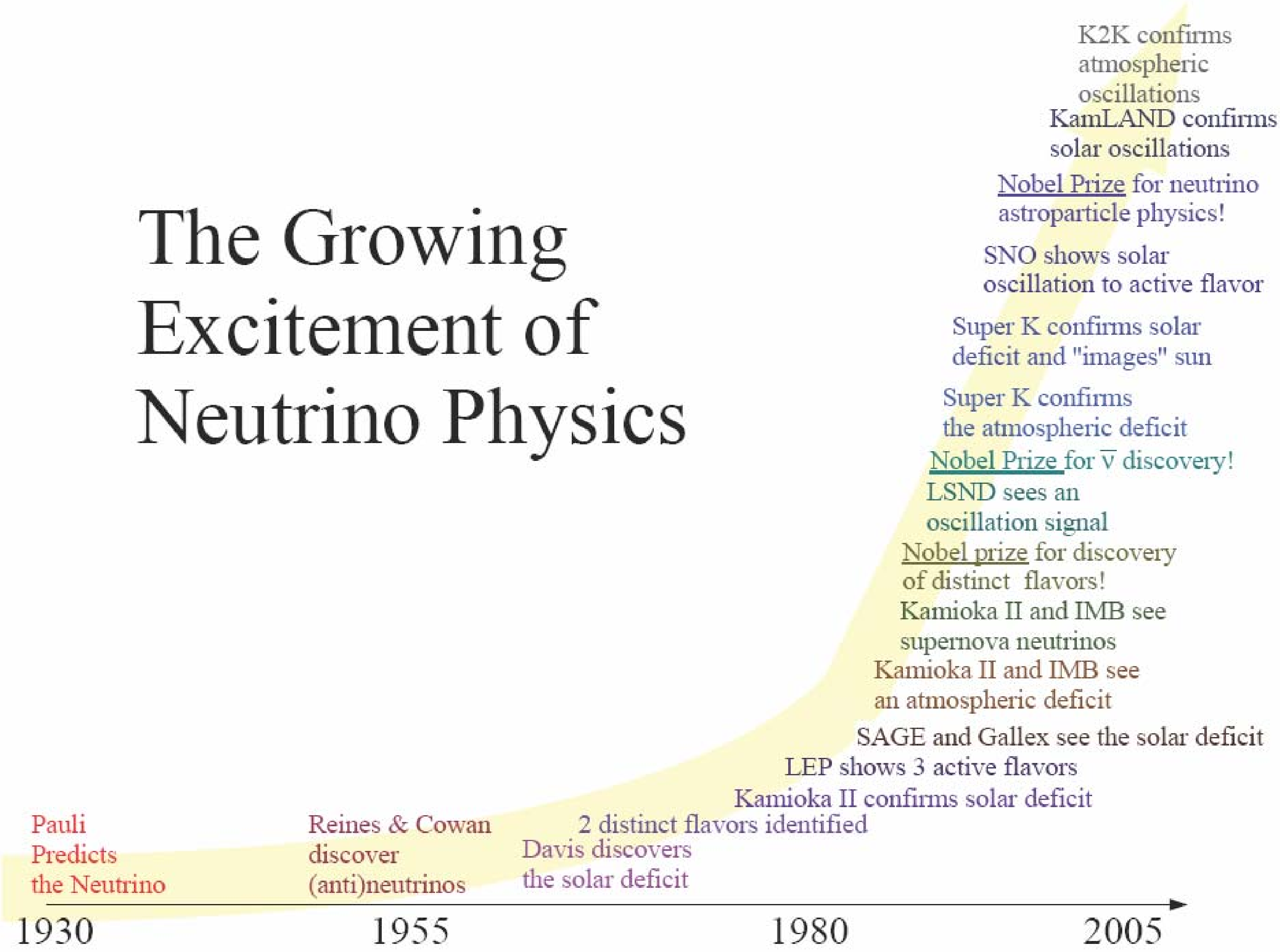
Outline

- Accessing the low energy solar neutrino spectrum
- The Electron Bubble TPC concept
- R&D progress
- Next steps: towards a cubic-meter prototype

The Growing Excitement of Neutrino Physics



Pauli
Predicts
the Neutrino

Reines & Cowan
discover
(anti)neutrinos

Davis discovers
the solar deficit

2 distinct flavors identified

Kamioka II confirms solar deficit

LEP shows 3 active flavors

SAGE and Gallex see the solar deficit

Kamioka II and IMB see
an atmospheric deficit

Kamioka II and IMB see
supernova neutrinos

Nobel prize for discovery
of distinct flavors!

LSND sees an
oscillation signal

Nobel Prize for $\overline{\nu}$ discovery!

Super K confirms
the atmospheric deficit

Super K confirms solar
deficit and "images" sun

SNO shows solar
oscillation to active flavor

Nobel Prize for neutrino
astroparticle physics!

KamLAND confirms
solar oscillations

K2K confirms
atmospheric
oscillations

Evidence of ν oscillation:

- Our understanding of neutrinos has changed in light of new evidence:
- Neutrinos no longer massless particles (though mass is very small)
- Experimental evidence from different phenomena:

Solar

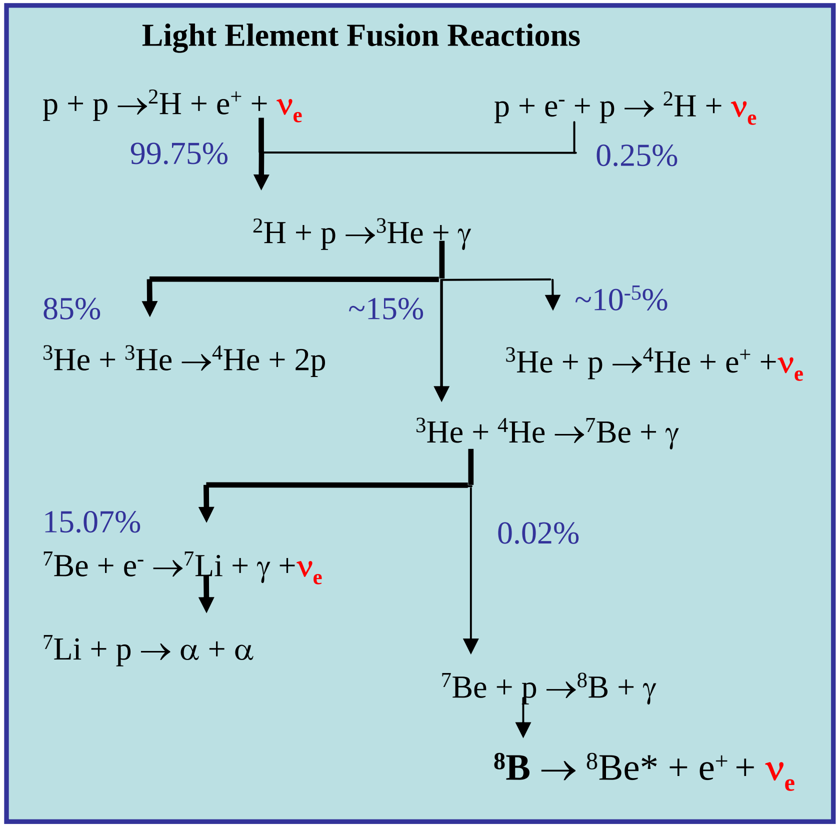
Atmospheric

Accelerator

Reactor

- Data supports the interpretation that neutrinos *oscillate*.

- Solar Standard model provides a theory about the inner workings of the Sun.
- Neutrinos from the sun allow a direct window into the nuclear solar processes



Light Element Fusion Reactions

$p + p \rightarrow {}^2H + e^+ + \nu_e$

99.75%

$p + e^- + p \rightarrow {}^2H + \nu_e$

0.25%

${}^2H + p \rightarrow {}^3He + \gamma$

85%

~15%

~10^{-5}%

${}^3He + {}^3He \rightarrow {}^4He + 2p$

${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

15.07%

0.02%

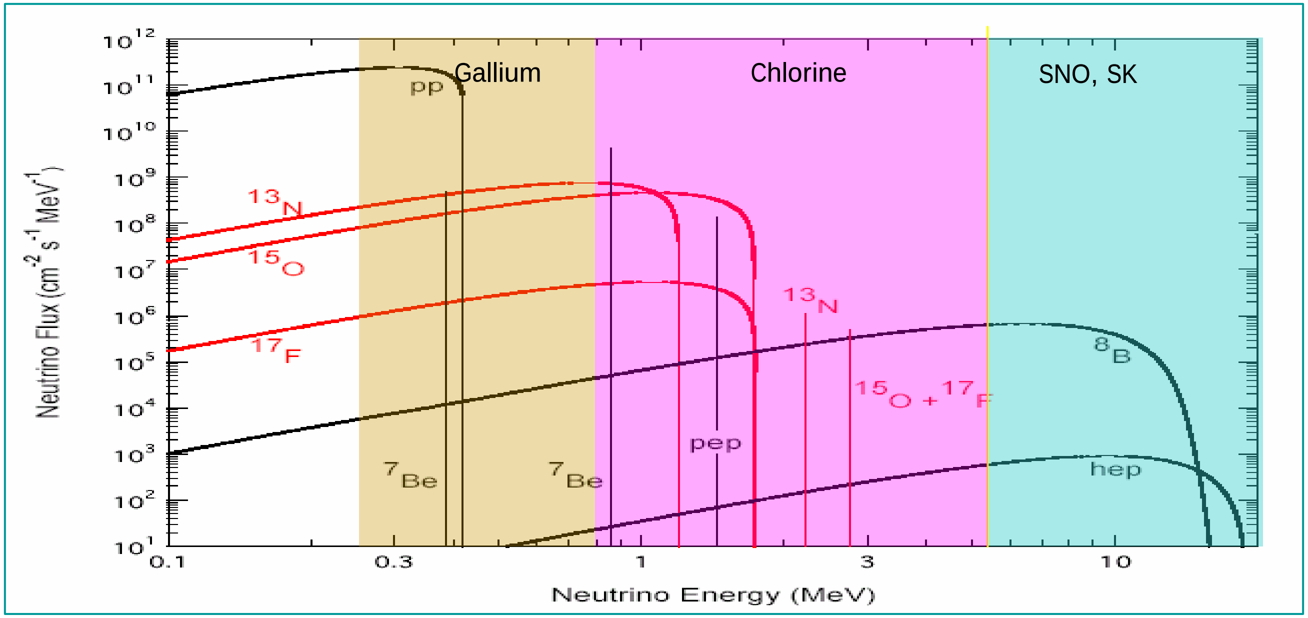
${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

${}^7Li + p \rightarrow \alpha + \alpha$

${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8\mathbf{B} \rightarrow {}^8Be^* + e^+ + \nu_e$

Solar neutrinos over full (pp) spectrum



- In particular, a precision, real-time measurement of the pp neutrino spectrum down to the keV range
- Precision measurements of oscillation effect matter/vacuum dominated regimes
- SSM uncertainty on the pp flux ~ 1% → aim for “1%” measurement
- Insights into the inner working of the Sun. Comparison of the neutrino luminosity to the photon luminosity should be =1.

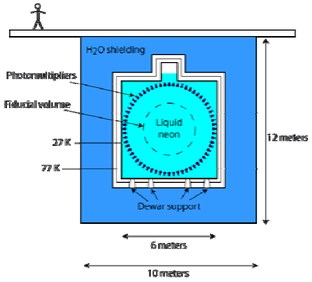
Who’s in the low-energy solar neutrino game?

LENS $E\nu>114$KeV

Low Energy Neutrino Spectroscopy

HERON $E_\nu<100$Kev

Helium Roton Observation of Neutrino



CLEAN $E_\nu>100$KeV

Cryogenic Low Energy Astrophysics with Noble gases

Physics Motivation cont’d

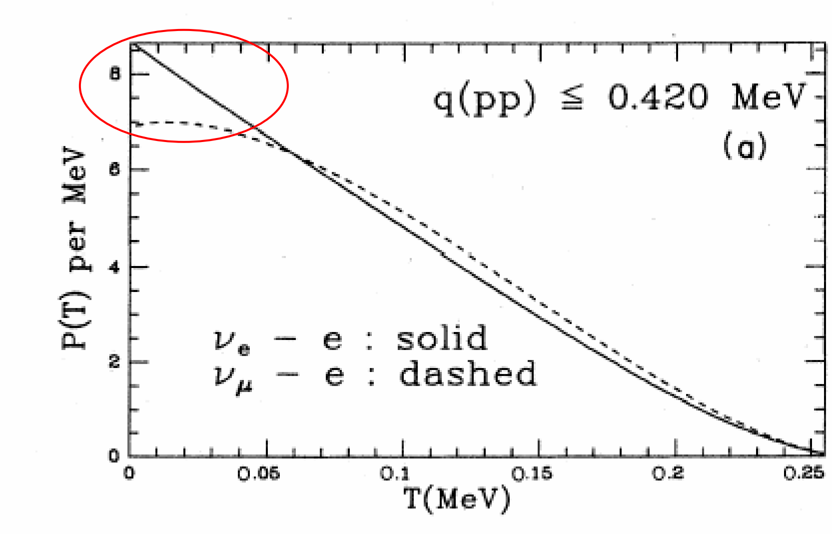
Physics Program

- Physics Focus is the real-time, full spectrum measurement of pp fusion solar neutrinos
- “light” Dark Matter scattering on modest target mass, for example GeV mass neutralino

Signal Sources Ordered by visible energy of track, E_X

- E_X = 10-30 MeV; isolated and “upward-going” electrons; presumably from supernovae. Little background, a single event, with ν direction measured to ~1 degree, is meaningful, at least as a trigger to look elsewhere at associated phenomena.
- E_X<10 MeV proton; from scattering of neutrons on the ~1% hydrogen quenching dopant, very useful feature of our detector, since this is an important background for DM experiments without high resolution tracking: the neutrons-proton scatter cross section is large and the track clearly identified, typically centimeters long and densely ionizing
- E_X <228 KeV electron; from scattering of pp fusion neutrino, E_X<50 Kev electrons are sensitive to neutrino flavor
- E_X<40 KeV nuclear recoil from WIMP, range very different from electron, very different coherent scattering on helium and neon, and spectrum depends on WIMP mass (and is measurable for masses even below 1 GeV, unlike scattering on Ge and Xe)

Detection via elastic scattering



Bahcall

- Elastic scattering: measure energy and angle of recoil electrons to determine incident neutrino energy
- Most of scattered electrons are < 100 keV; flavor dependence < 50 keV
- A few hundred scatters per ton per year → O(25) ton-year exposure needed
- Cross-sections for ν_μ and ν_τ scattering down by a factor of ~ 4
- Higher energy neutrinos "for free"

Detector requirements

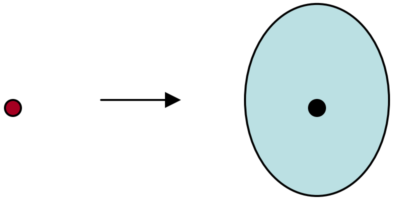
- ~ O(10) tons fiducial mass
- "Condensed" phase target medium to give reasonable volume for this mass
- Excellent (sub-mm) spatial resolution for low energy tracks → range, electron ID, plus pointing, at least for higher energy recoils
- To maintain this resolution if drifting over long distances, need very low diffusion
- Good energy resolution
- Very high purity → long drifts, and low background from medium
- Goal of reaching keV level implies need for some gain, presumably in gas phase
- (Self-) shielding
- Excellent background rejection, in particular of γ's via Compton cluster ID
- Ideally, a slow drift to ease readout of large number of volumes → feasible in principle in low-background environment underground

Detection medium: helium/neon

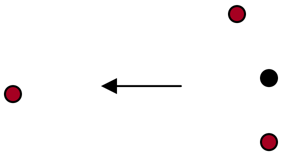
- In liquid phase, these low-Z materials offer good compromise between volume-to-mass consideration and desire to minimize multiple scattering
- Very low boiling points → excellent purity, since impurities freeze out
- In the case of thermal charge carriers, diffusion is proportional to $\sqrt{T}$, so low temperature is very advantageous
- In liquid phase and in dense, cold gas, electrons are localized in nano-scale electron bubbles
    - Bubble size leads to low mobilities, of order 10^{-3} -10^{-2} $cm^2 sec^{-1} V^{-1}$, and slow drifts
    - Electron bubbles remain thermal for E fields up to ~ 40 kV/cm, and field-ionize around 400 kV/cm
    - In two-phase system, bubbles are trapped at the liquid-vapor interface, before tunneling out on a timescale dependent on T and E

Compare L Argon to L Helium, H_2

- An electron near a large atom:



- An electron near a He/H_2 atom (Pauli)



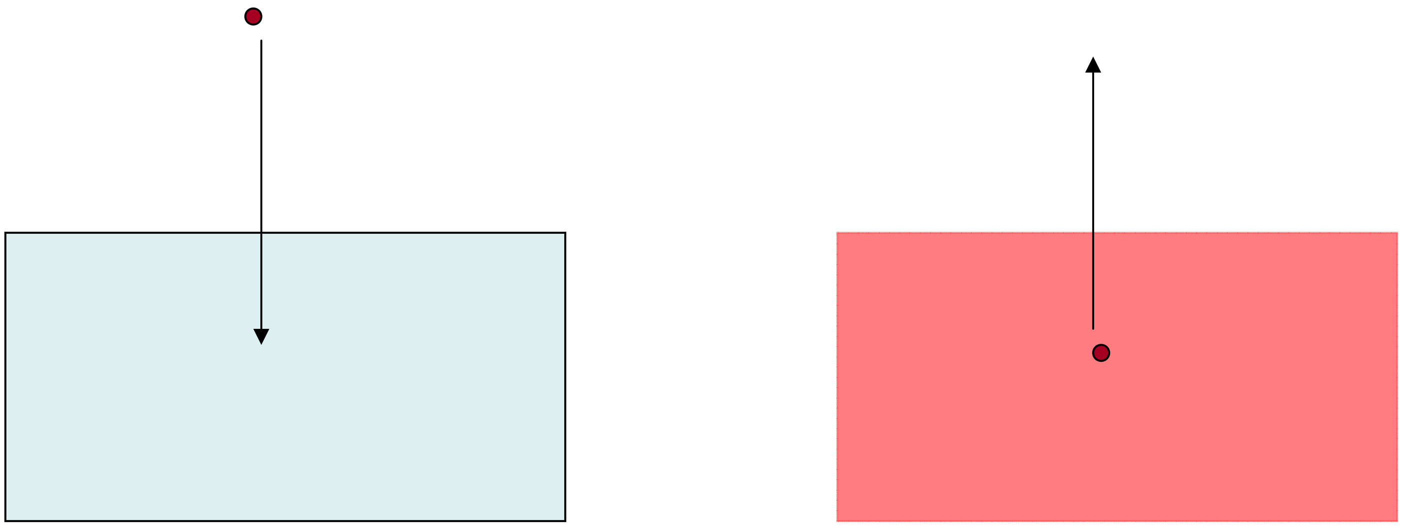
Work Functions

L Argon

W = + 1.4eV

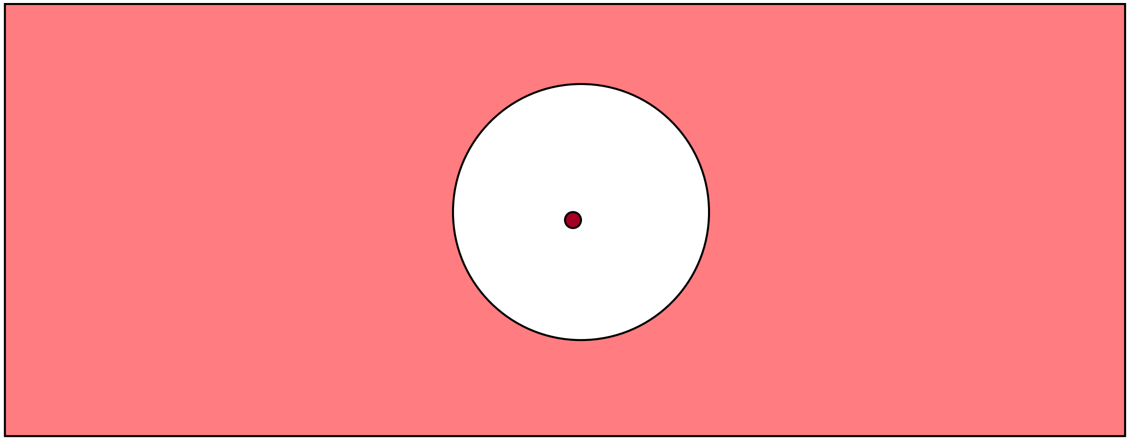
LHe (LNe)

W = - 0.9eV (-0.6)



Fate of an electron in LHe/LNe

- If an electron is created suddenly in the body of LHe/LNe in the presence of an electric field, it will start to move with a large mobility as in Argon, but the repulsive force with the liquid will soon blow a hole in the liquid, creating a cavity empty of helium/neon atoms, containing only the electron:
- Scale: nanometers; a "mesoscale" object!
- Like an ion, it drifts very slowly.

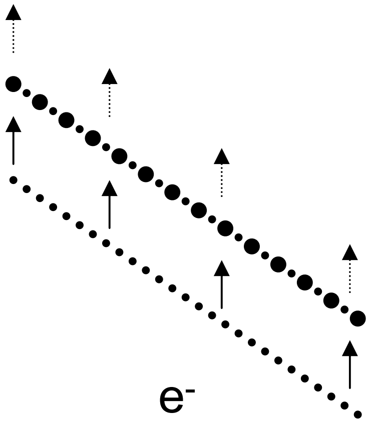


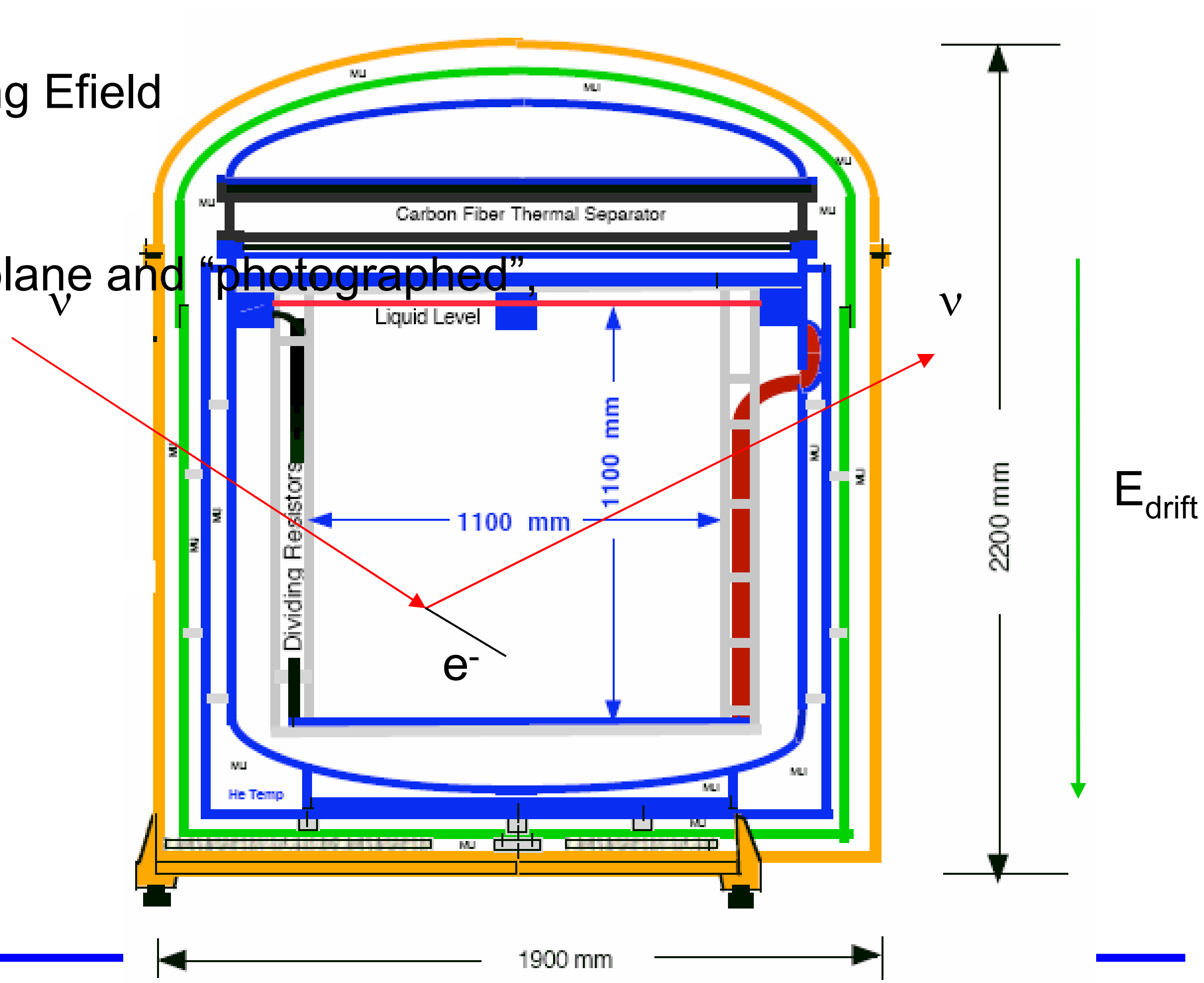
Experimental approach: an electron bubble TPC

- For a homogeneous medium, one dimension must use a drift → Time Projection technique
- Slow drift (e.g. 10 cm/sec) of electron bubbles in these fluids allows high resolution in drift direction with moderate data rate
- Signals “stored” in detector volume, and read out one plane at a time in drift direction, at a rate of 10’s-100’s Hz
- Zero suppression in low-rate, low-background environment gives further large reduction in data rate
- Depth measurement from diffusion broadening of track width $\sigma=\mathrm{sqrt}(2kTd/eE)$
- Need gain if we are to access keV energies → we have chosen Gas Electron Multipliers (GEMs) as the most promising avenue for our R&D program
- Avalanche process in the GEMs offers both charge and light as potential bases for readout schemes – we are focusing on optical readout

An Event:

1. Neutrino scatters on a target electron
2. Electron ionizes medium
3. Ionized electrons drift along Efield
4. Ebubbles form
5. Ebubbles drift to readout plane and "photographed", one plane at a time



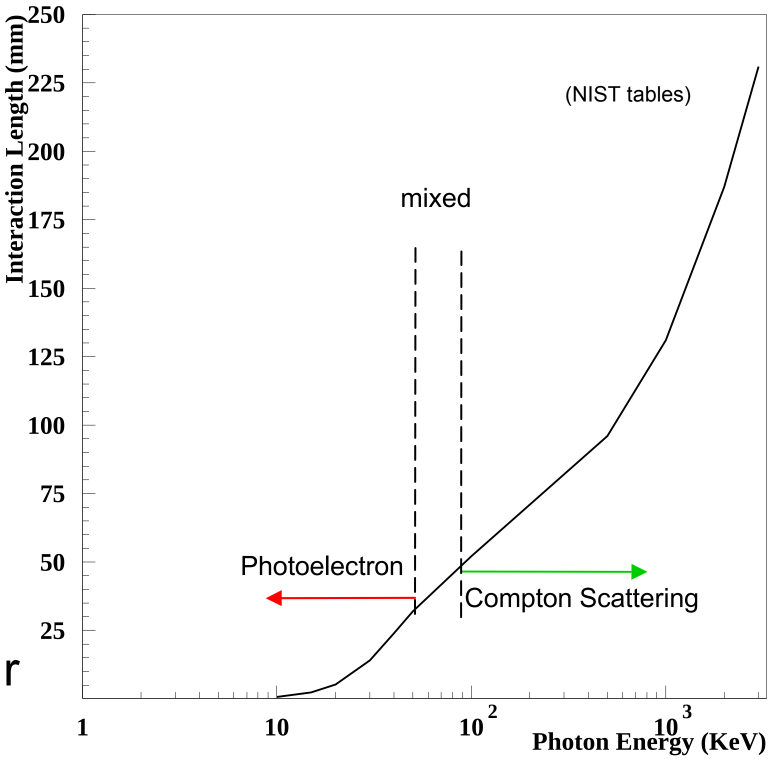


Backgrounds

- No radioactive isotopes in detector medium
- No solubility of heavier molecules in LHe, whereas H_2 dissolves in LNe (useful!) → impurities freeze out
- Micropore filters shown to be effective in removing “dust”
- Good energy and spatial resolution give powerful capability for recognizing “Compton clusters” of several scattered electrons from external γ’s in the MeV range
  - Each secondary photon from successive scatters has a lower energy, and a decreased absorption length, leading to events with a number of scattering vertices easily recognized as a Compton cluster
  - Calculations indicate rejection factors of order 100’s – 1000’s, depending on the source and the fiducial cut → ongoing studies
  - Irreducible background from MeV γ’s with (improbable) single scatters in the keV range in fiducial volume
- Self-shielding, in LNe, effective for lower energy γ’s
- 3D-reconstruction defines fiducial volume – track width from diffusion gives reasonable depth measurement, in particular at top, where backgrounds from the readout plane can be cut

LNe is self shielding

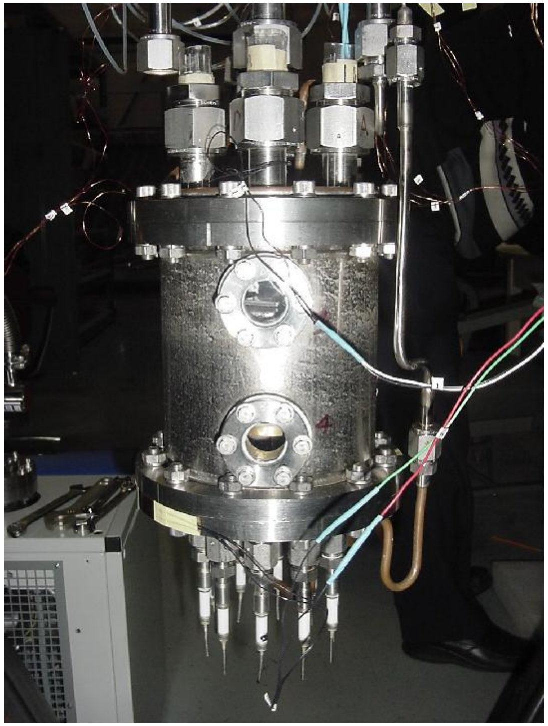
1. LNe allows for self shielding in the active tracker volume.
2. Spatial resolution (100 μm) allows a Compton cluster of several electrons to be identified.
   - Below 50KeV in the Compton chain all the energy goes into the next interaction as a photoelectron and the chain stops. Hence the last gap is O(1cm).



What’s left is one’s irreducible background!

- Photons which penetrate deep into our active fiducial volume.

Recent results from Cryogenic Test Facility at BNL



- 1 < T < 300K; P up to 10 bar
- Field cage
- Windows, transmitting from IR to UV
- Various ionizing particle sources
- Operation with LHe, LNe, or other fluids of interest

Build a Cryogenic *Fluid* Tracker

↓

Single Phase Liquid

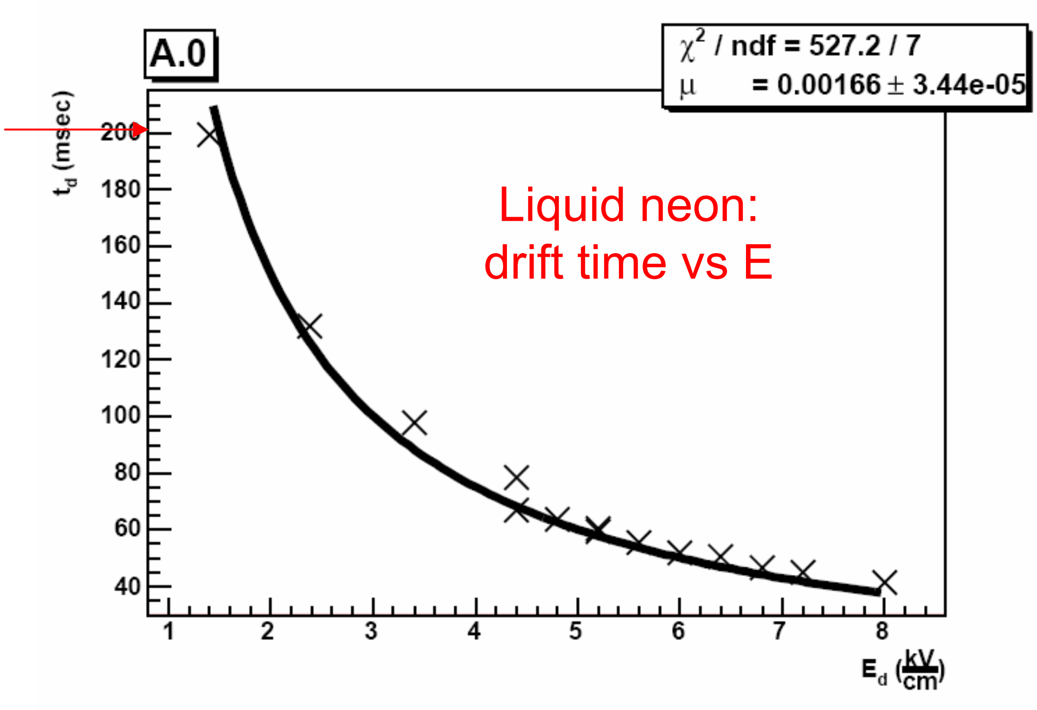
No gain (charge/light) in Liquid

- New detector technologies

↓

2-Phase detector

Low-mobility carriers observed in liquids



200 msec

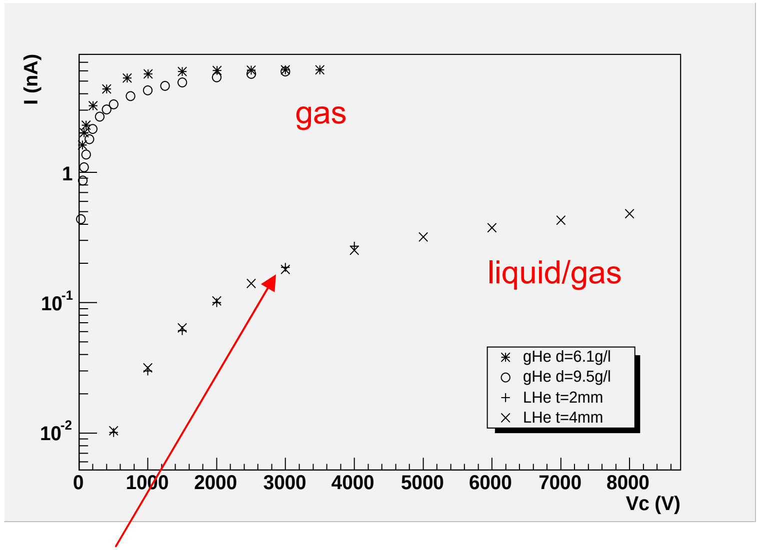
Liquid neon:
drift time vs E

- Measured drift velocities consistent with known electron bubble mobilities
- Long lifetimes! Excellent purity achieved easily

Surface behavior and trapping times

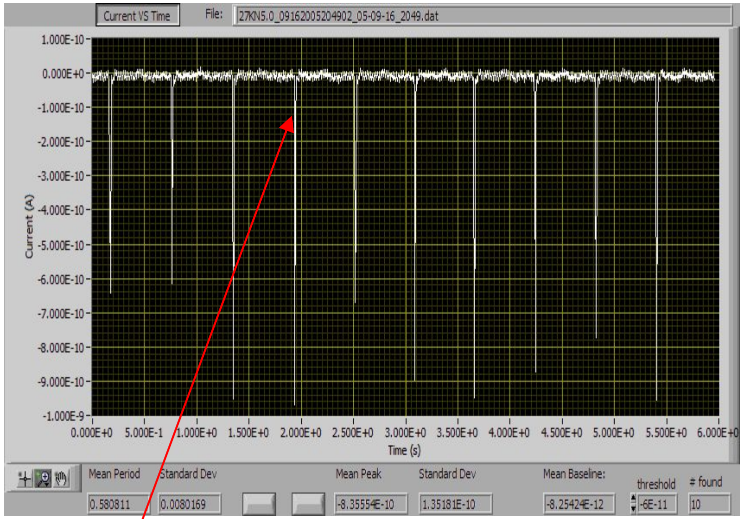
- Experimentally:
  - Establish “steady-state” with ionization charges from an alpha source being drifted to the surface, and ejected into vapor phase
  - Measured current is related to surface trapping time:

Helium



Expected monotonic increase of I with $E_{surface}$ → trapping times ~ msec, and tunable

Neon



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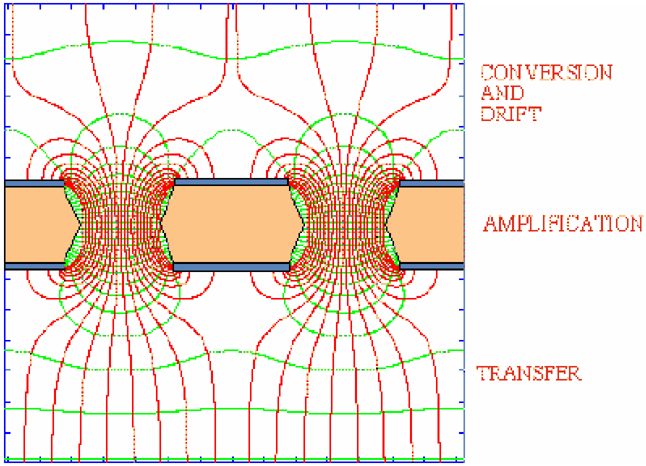
Mean Period	Standard Dev	Mean Peak	Standard Dev	Mean Baseline:	threshold	# found
0.580811	0.0080169	-8.35554E-10	1.35181E-10	-8.25424E-12	-6E-11	10

Periodic droplet ejections from surface (visible!) → trapping times ≥ sec

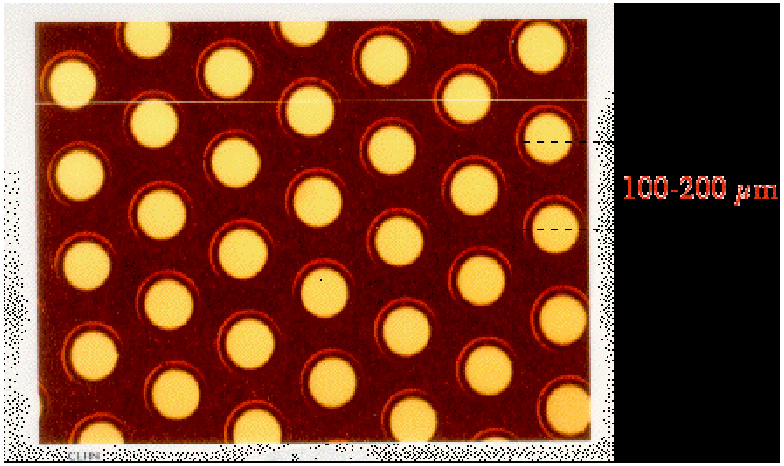
- Suitable trapping times at LHe surface, but too long for LNe at 1 Bar

GEM gain

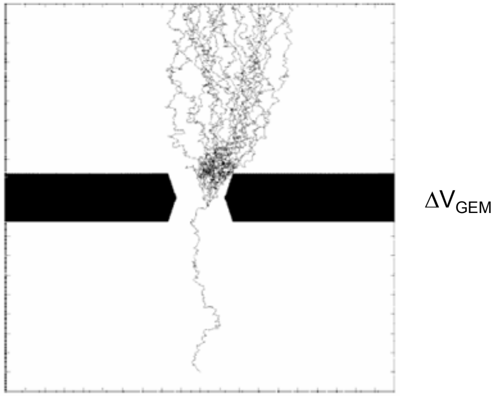


Gas Electron Multipliers
- Copper foils surrounding Kapton
- Amplification takes place in holes where the fields are maximized

Conical or Cylindical Holes ~ O(50μm)

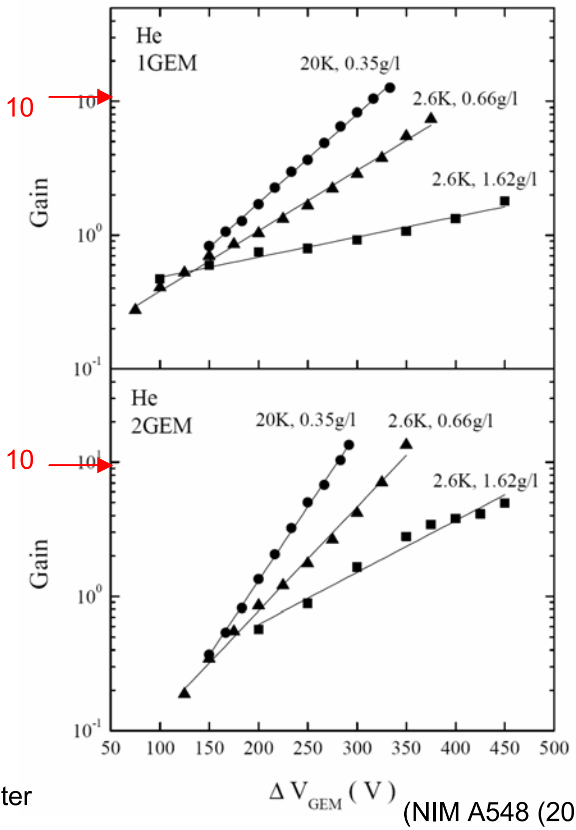


Garfield Simulation of GEM avalanche

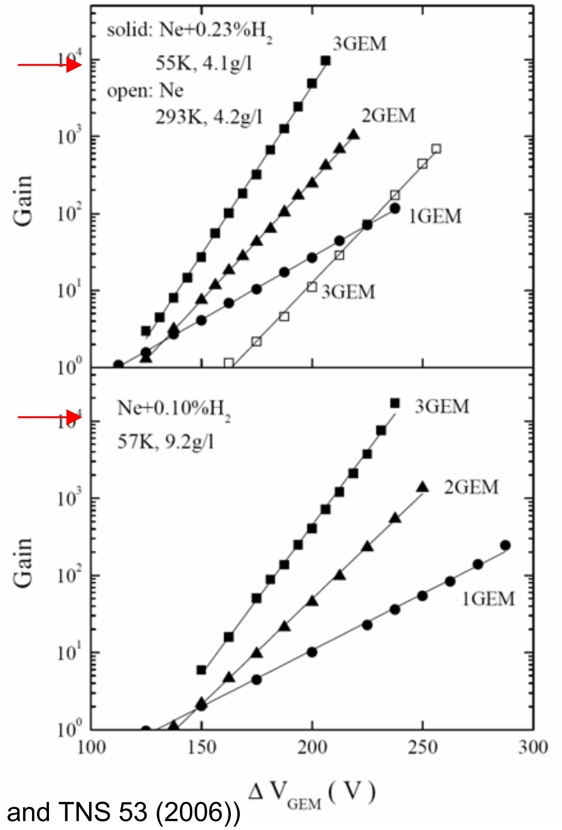


Gain from GEMs in vapor

Helium



Neon



Gain > 10^4
maintained
at ~ 30K

CERN GEMs
30x30mm
140μm hole pitch
50μm hole diameter

(NIM A548 (2005) 487-498 and TNS 53 (2006))

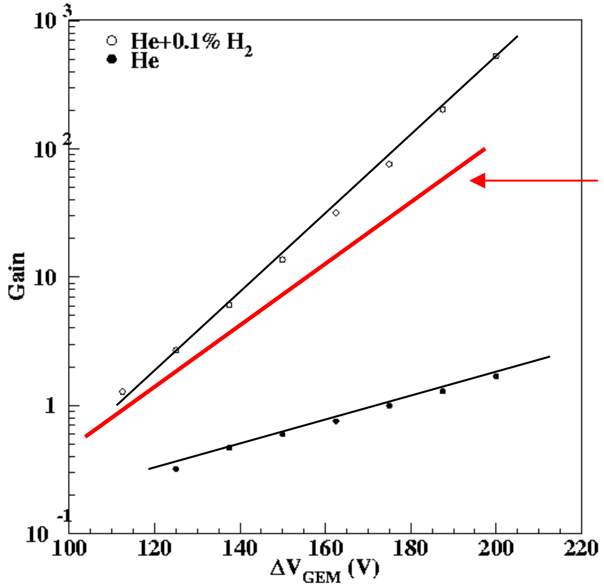
- Modest gain in He vapor; large gain (> 10^4) in Ne vapor with addition of fraction of H_2 → operate at temperatures where finite H_2 vapor pressure
- With hydrogen doping, both He and Ne give gains > 10^4 in 3-GEM configuration
- Little true temperature effect - impurities play important role at high temperatures

Purity & the addition of H_2 to He

Penning: $e + He \longrightarrow e + He^m$

$He^m + \text{Impurity} \longrightarrow \text{Impurity}^+ + e$

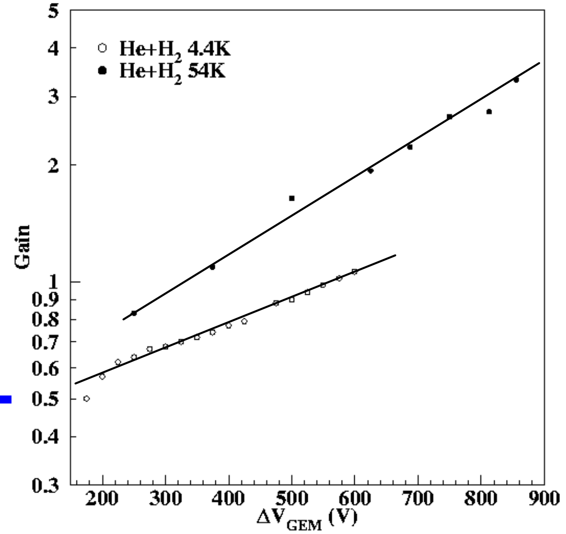
- To test the impurity hypothesis, subsequent runs purified the Helium gas supply through Oxisorb + (Rare Gas) Heater Getter.
- The drop in gain could be compensated by the controlled addition of known impurity (H_2) at High temperatures.
- Gain still drops at LHe temperatures as the vapor pressure of H_2 decreases.



2GEM 77K
ρ=0.00055g/cm³

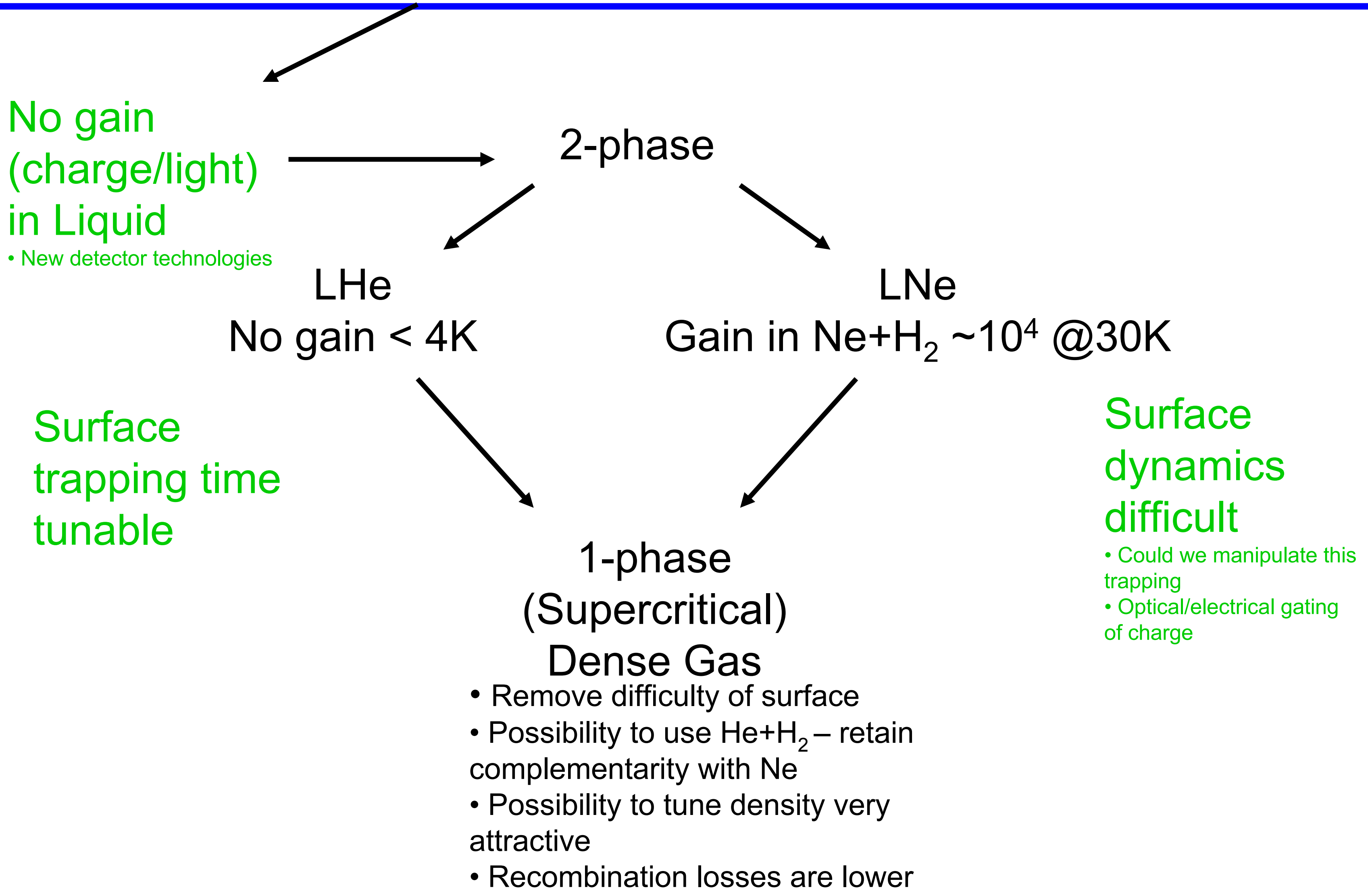
He from Gas Bottle 99.999% purity

TNS 53 (2006)



1GEM
ρ=0.0017g/cm³

Build a Cryogenic *Fluid* Tracker



No gain (charge/light) in Liquid

- New detector technologies

2-phase

LHe
No gain < 4K

LNe
Gain in Ne+H_2 ~10^4 @30K

Surface trapping time tunable

Surface dynamics difficult

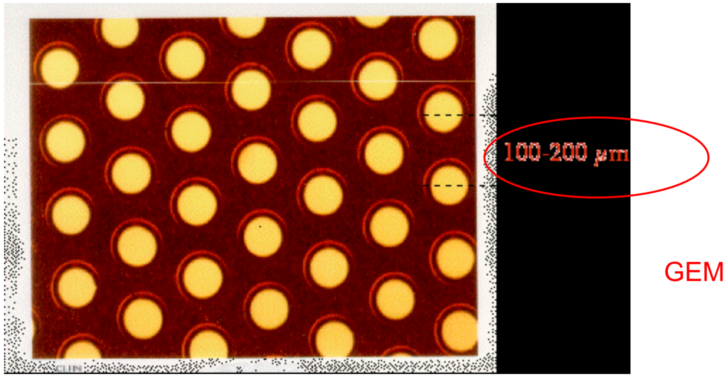
- Could we manipulate this trapping
- Optical/electrical gating of charge

1-phase
(Supercritical)
Dense Gas

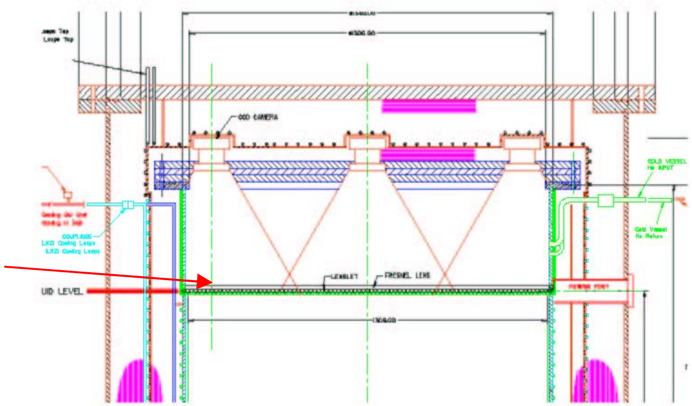
- Remove difficulty of surface
- Possibility to use He+H_2 – retain complementarity with Ne
- Possibility to tune density very attractive
- Recombination losses are lower

GEM-optical readout concept

- Could use 2D array of amplifiers to detect charge, however electronics with good performance at low temp. are not readily accessible in standard silicon processes
- Avalanche produces light as well as charge - triplet excitation produces significant visible (plus IR?) component



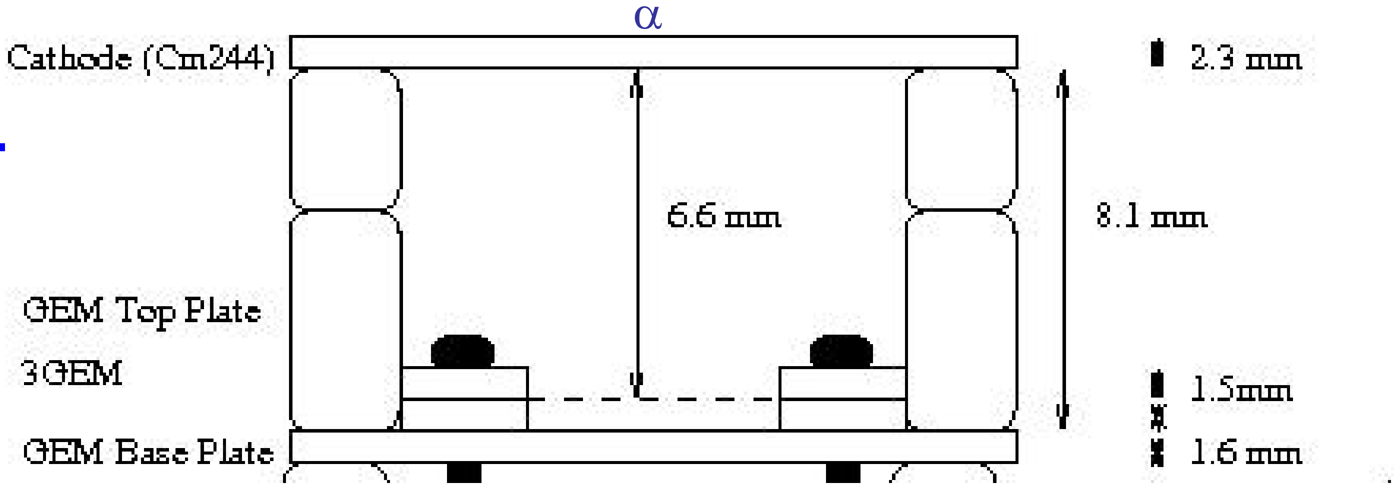
(back-illuminated, not avalanches!)



GEM+lenslet

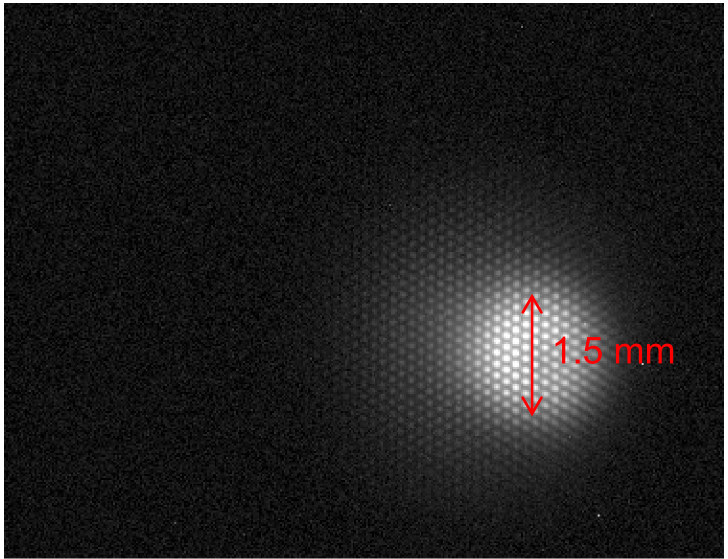
- Calculations indicate transport efficiency of a few %, making use of lenslets matched to GEM holes
- Use commercial CCD cameras, sitting at ~ 50K

α tracks:

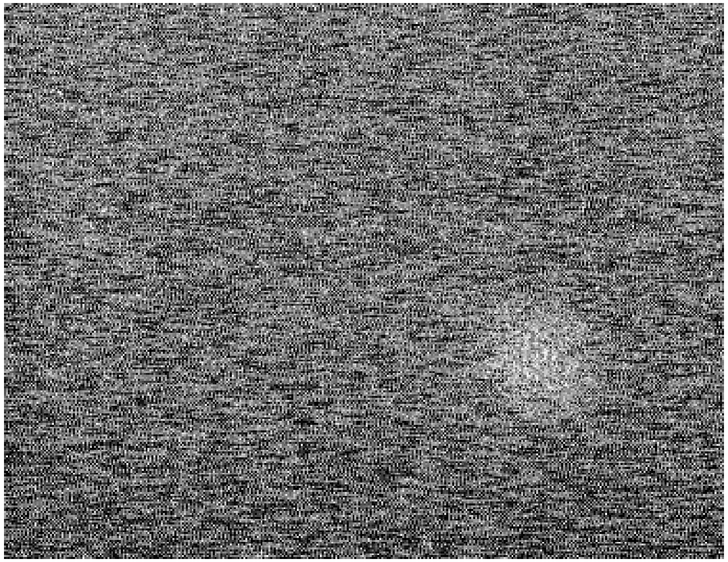


- Uncollimated alpha source, ~ 10 kHz rate, in Ne + 0.01% H_2 at 78K (charge gain ~ 10)

60 sec exposure (~ 600k alphas!):



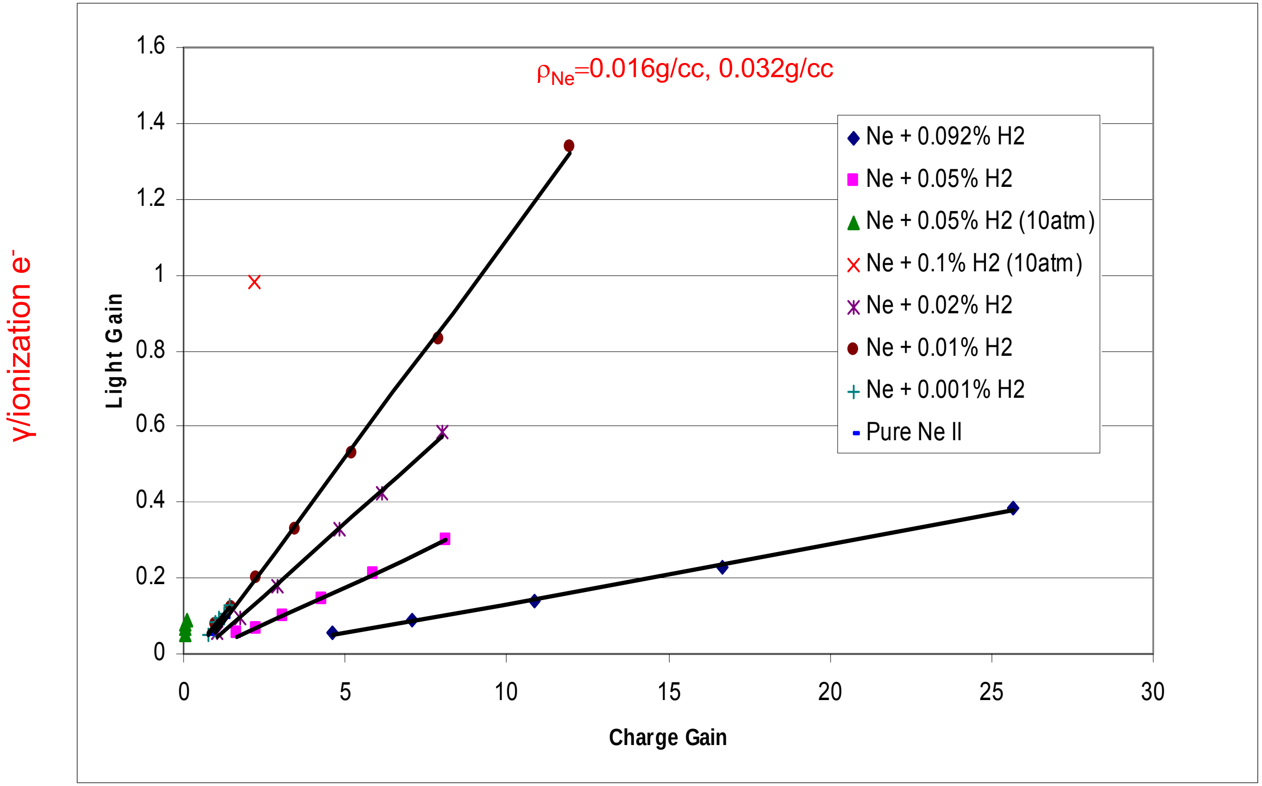
1 msec exposure (~ 10 alphas):



- Non-optimal geometry, with ionization from many alphas occupying only a few GEM holes, limits available gain in this configuration

Light yield and spectrum

- Initially, studies with alpha tracks in neon-based mixtures at 78K
- Light registered with PMT.



**Triple GEM

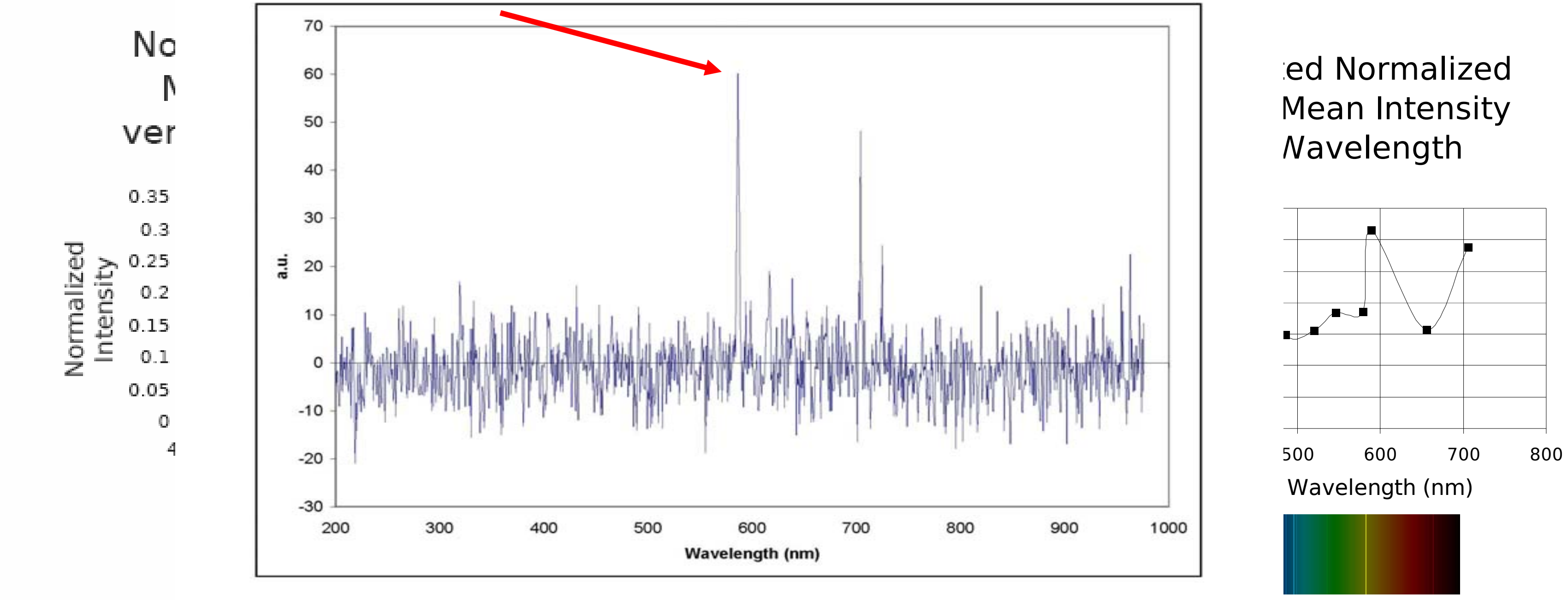
(systematic errors on light yield not included)

- Highest charge gain achieved in Ne + 0.1% H_2
- Highest (relative) light yield for Ne + 0.01% H_2 → can obtain visible light yield from GEM holes of ≥ 1 photon per avalanche electron
- Much lower visible yield from helium-based mixtures (need to measure IR)

- Use narrow band filters to look at spectrum of visible light using CCD.
- CCD QE~10% at 850nm

-0.01% H_2

585nm Main emission line in Ne spectrum @ 77K

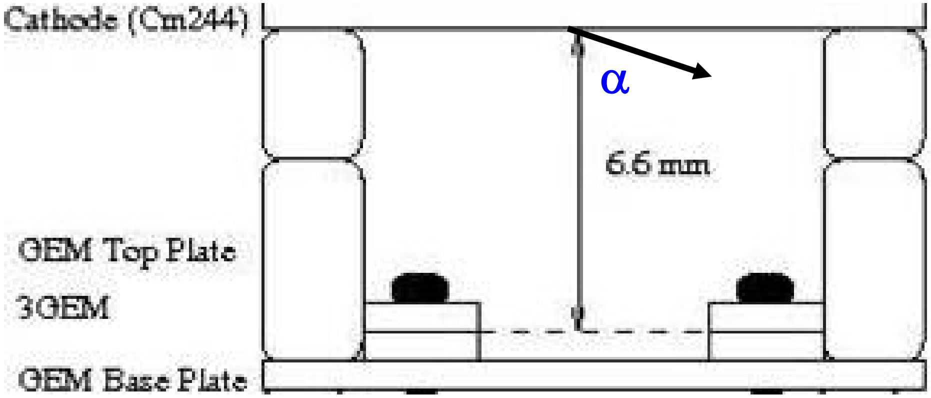


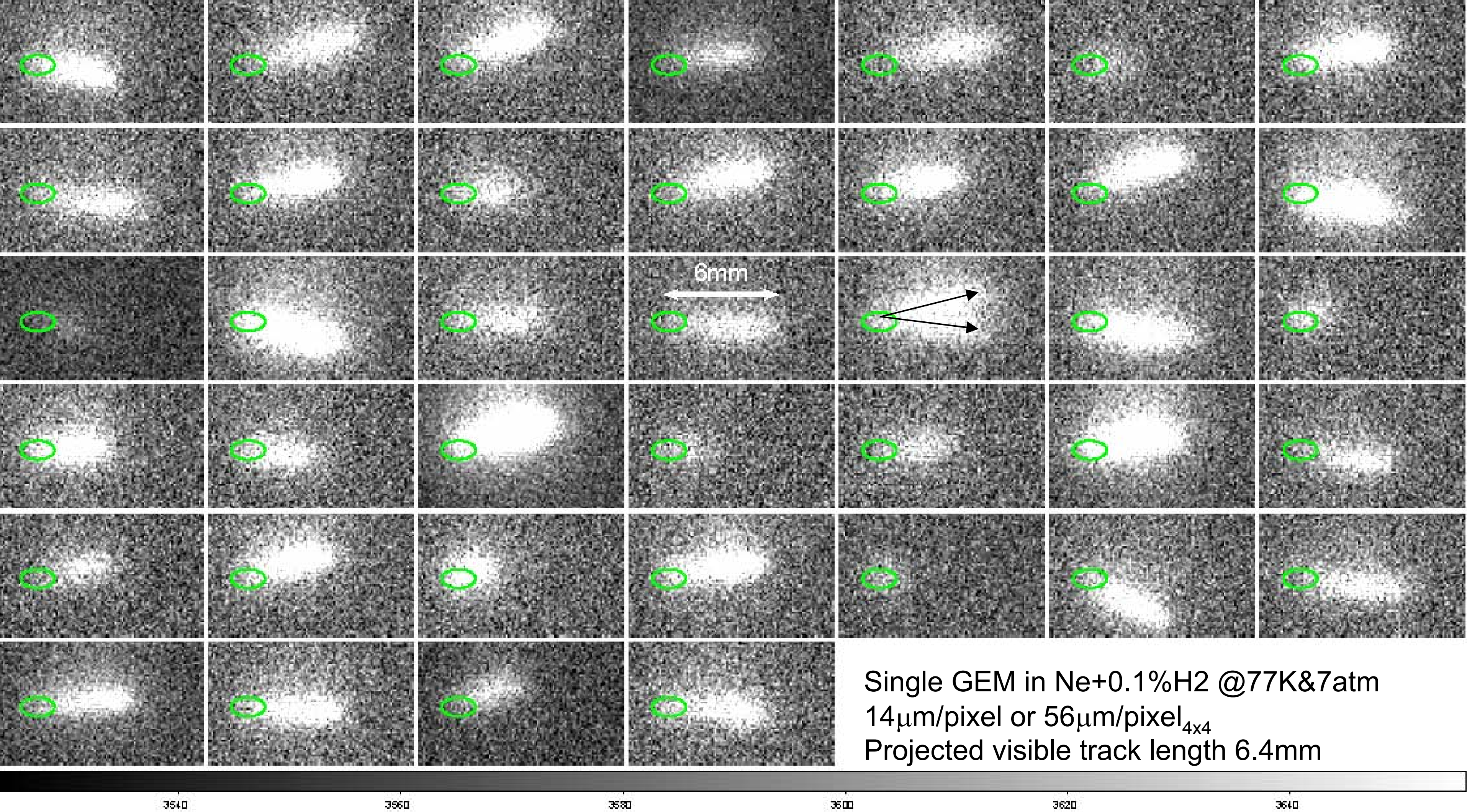
Conclus

- H_2 does not influence emission spectrum in Ne.
- Harder to get light in He even with the addition of H_2.

α tracks:

- Collimator reduced source rate & collimated αs coming out at 35deg to the plane of the cathode
  - Rate ~ O(5-10)Hz
- Charge gain >10^4 achieved in a single GEM, due to reduction in charge density although in a single GEM



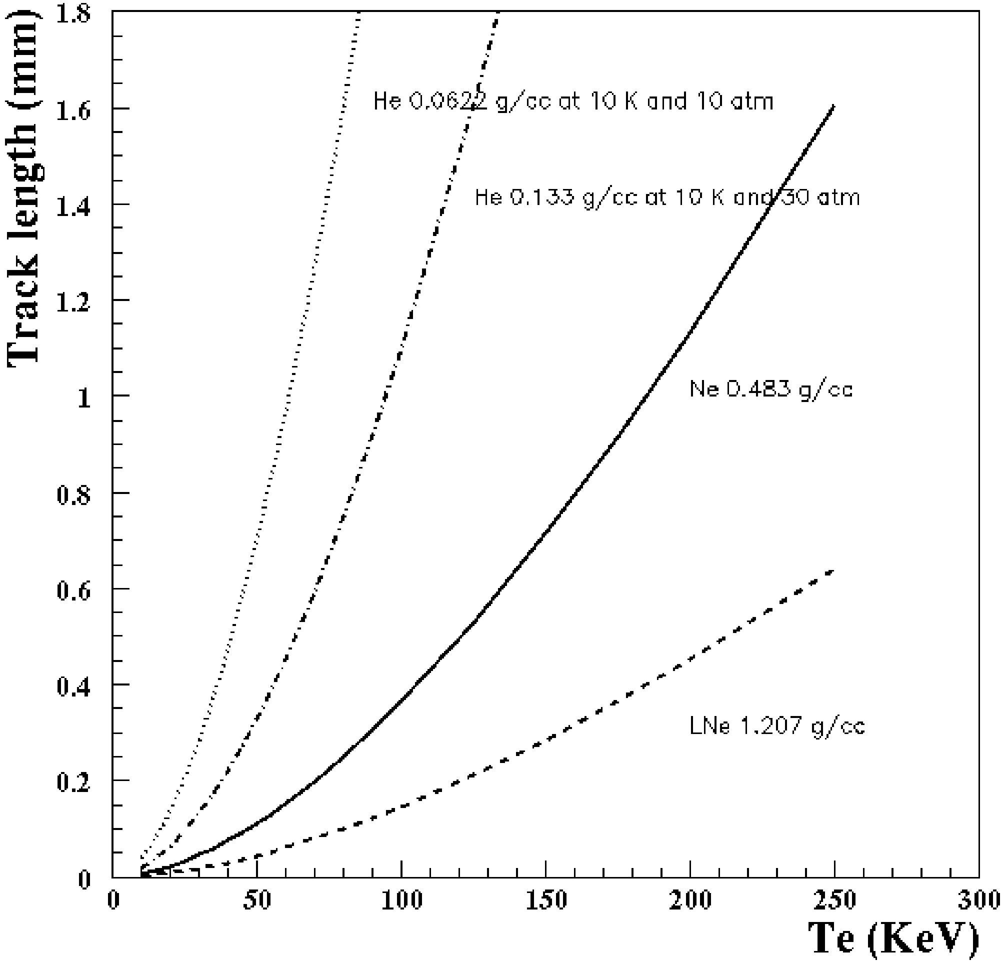


Single GEM in Ne+0.1%H2 @77K&7atm
14μm/pixel or 56μm/pixel$_{4x4}$
Projected visible track length 6.4mm

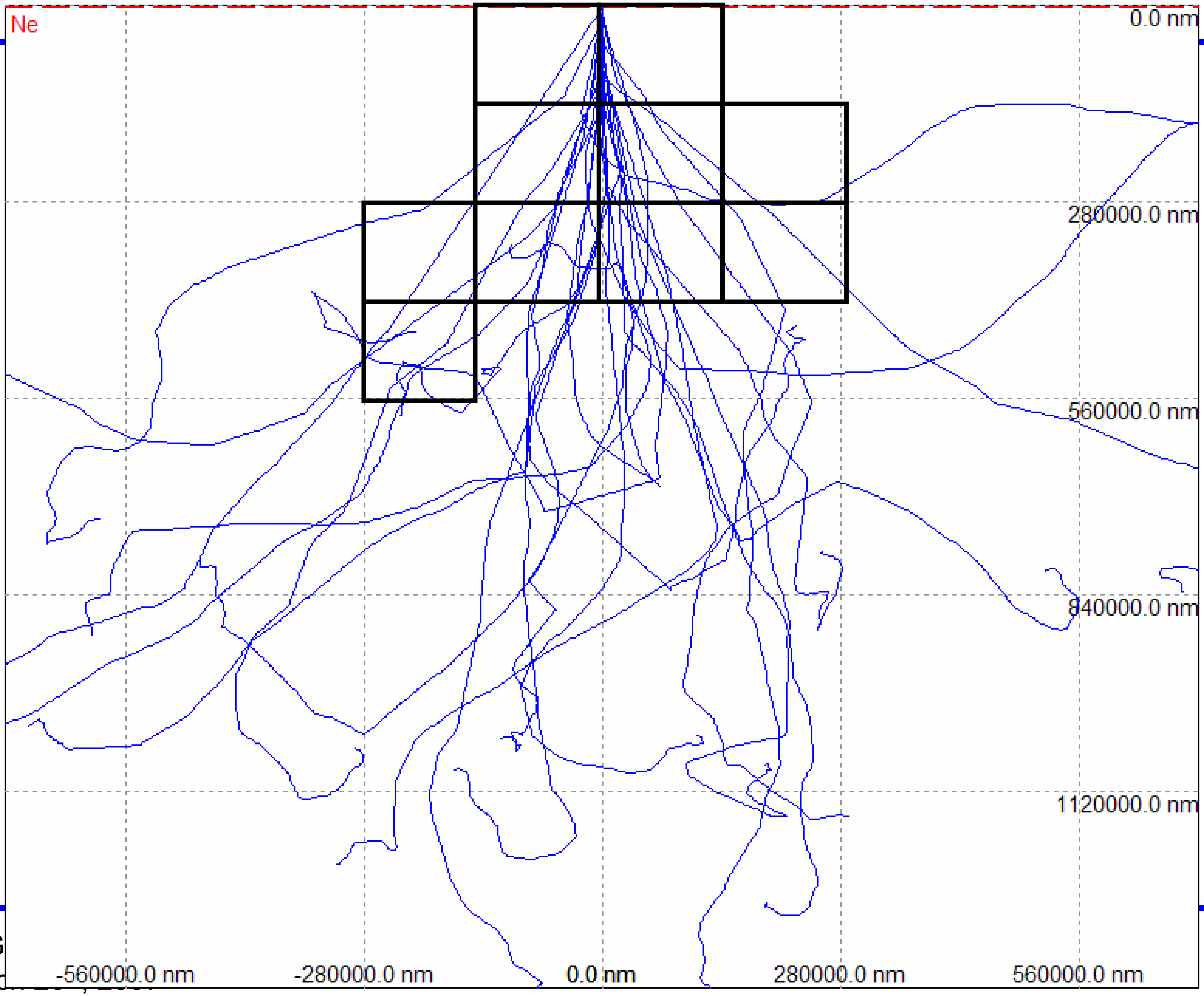
Pedesal~3565

- No alignment of GEM holes on multiple GEM structures is performed
- Single vs Triple GEM did not reduce the width of the tracks.
  - Track width dominated by couloumb spread of the charge.
  - No localization of electrons in these conditions so diffusion is not thermally driven.

Range for 250keV recoil electron

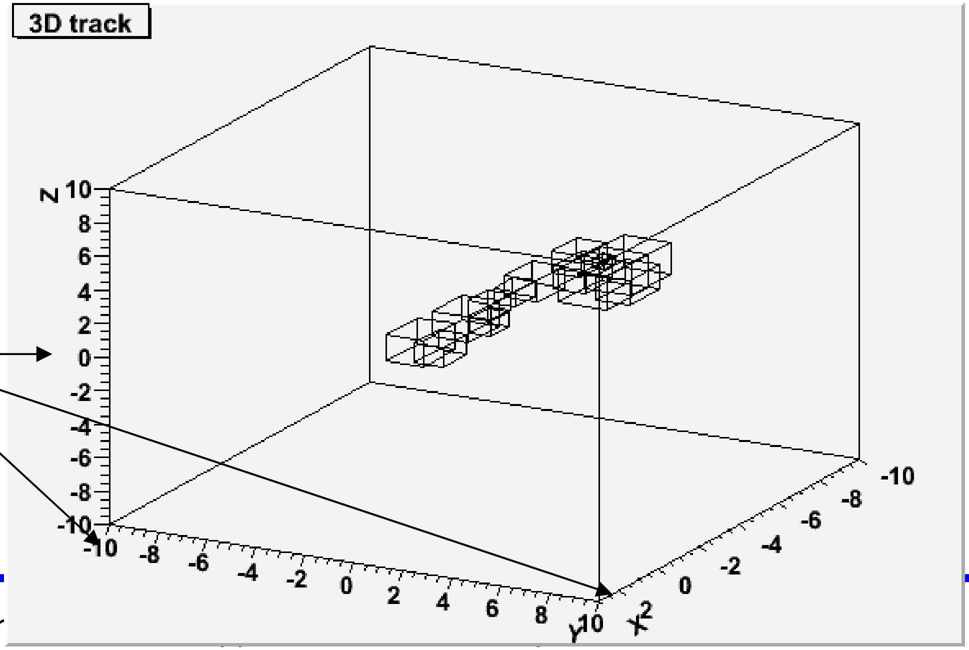


Visualization Casino simulation of 25 events in 0.483g/cc of Ne

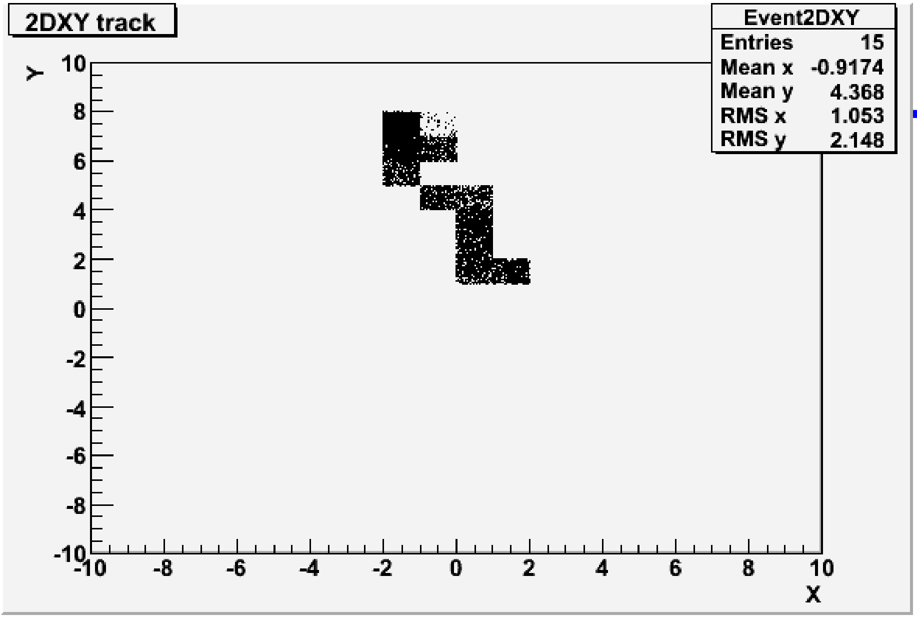


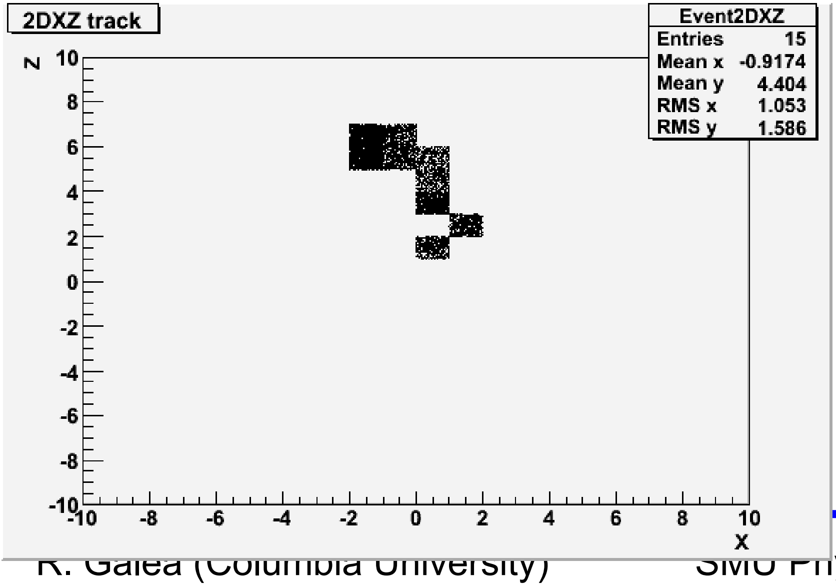
Pointing Accuracy

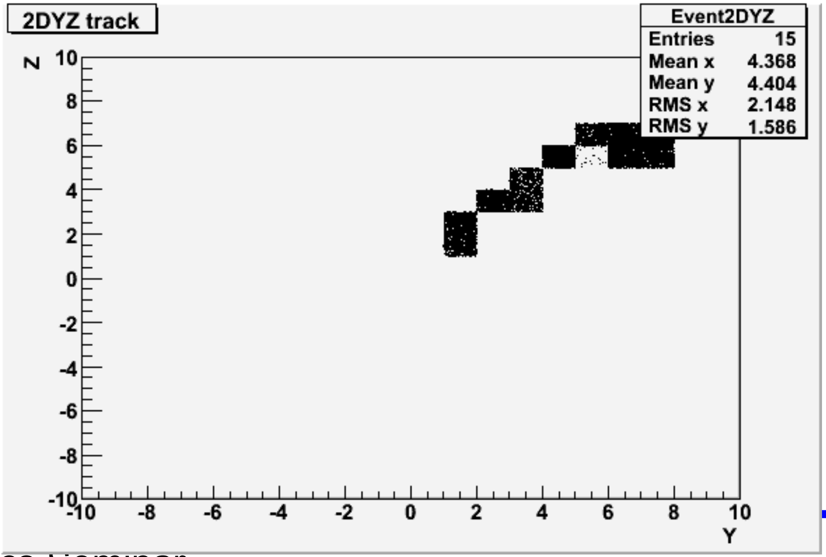
- Geant 4.7.1 Simulation
- 30000 e^- with T=250KeV in 0.483 g/cc Ne starting at (0,0,0) in the direction (1,1,1)
- Ionizations are *assigned* in 140μm^3 voxels (representing resolution)
- electrons are not drifted. At some point some smearing can be done to make things worse.
- The assumption is made that clustering and reconstruction algorithms of the DAQ deliver a set of hits that would potentially represent a track

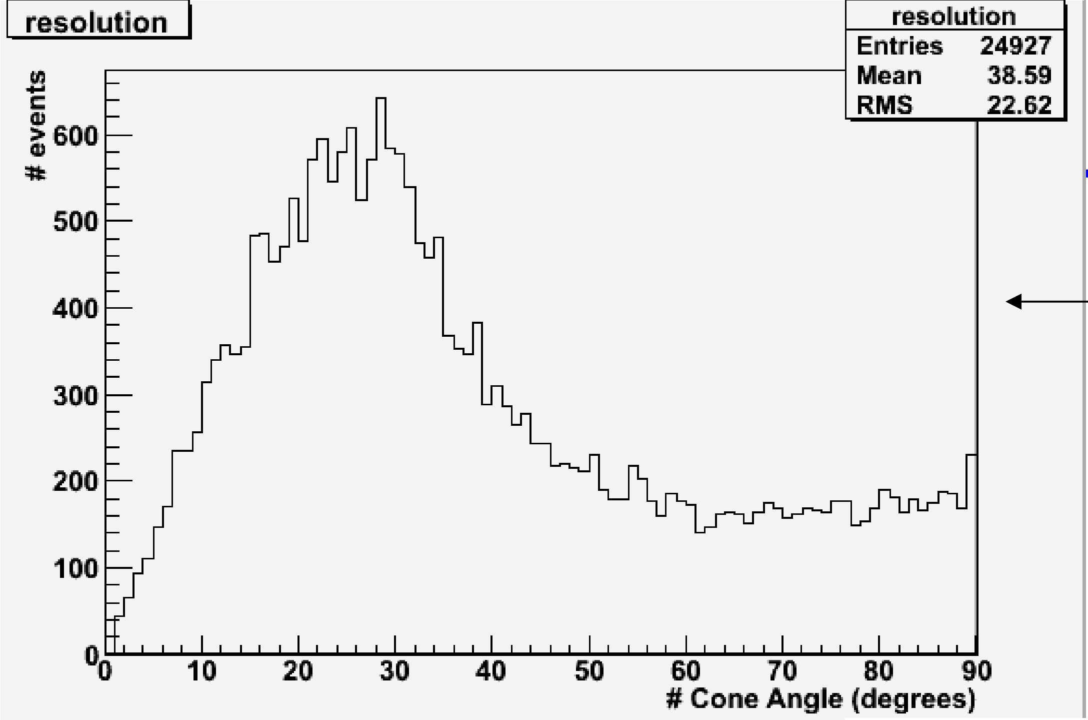


Units of 140μm

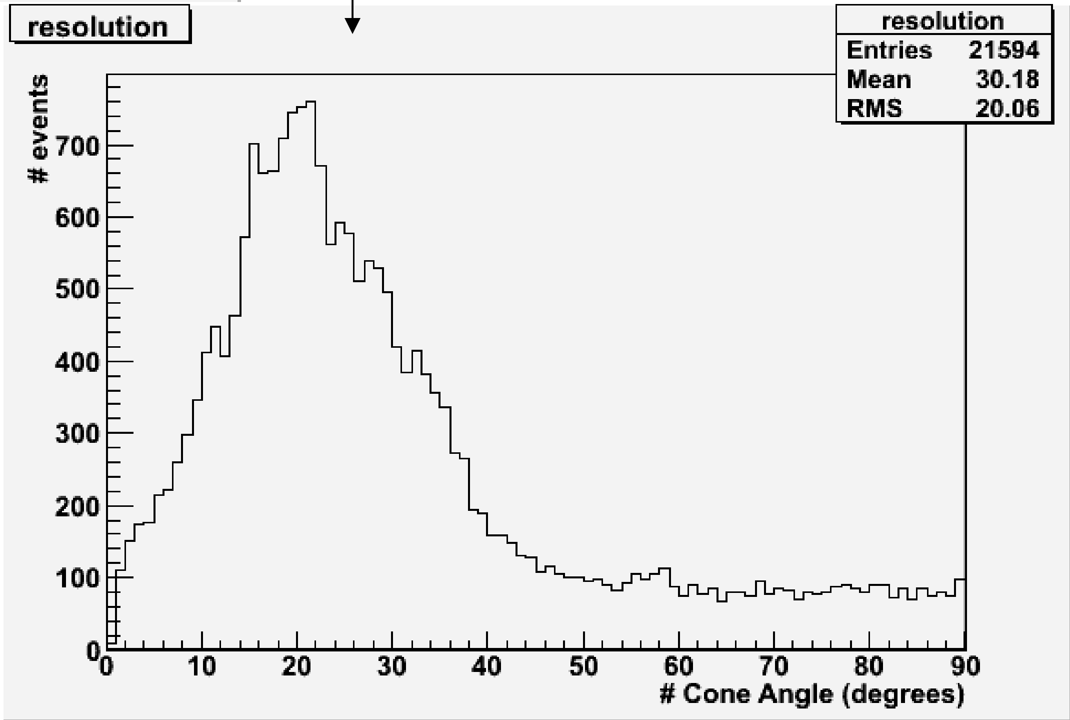

2DXY track
Event2DXY
Entries 15
Mean x -0.9174
Mean y 4.368
RMS x 1.053
RMS y 2.148
Y
X
-10 -8 -6 -4 -2 0 2 4 6 8 10

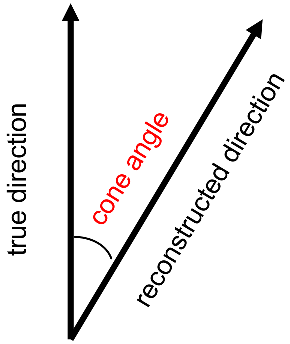

2DXZ track
Event2DXZ
Entries 15
Mean x -0.9174
Mean y 4.404
RMS x 1.053
RMS y 1.586
Z
X
-10 -8 -6 -4 -2 0 2 4 6 8 10


2DYZ track
Event2DYZ
Entries 15
Mean x 4.368
Mean y 4.404
RMS x 2.148
RMS y 1.586
Z
Y
-10 -8 -6 -4 -2 0 2 4 6 8 10



- Fit projections xy, yz, xz.
- errors weighted by energy of pixels/total
- all hits
- first 3 or 4 hits





Summary of R&D results to date

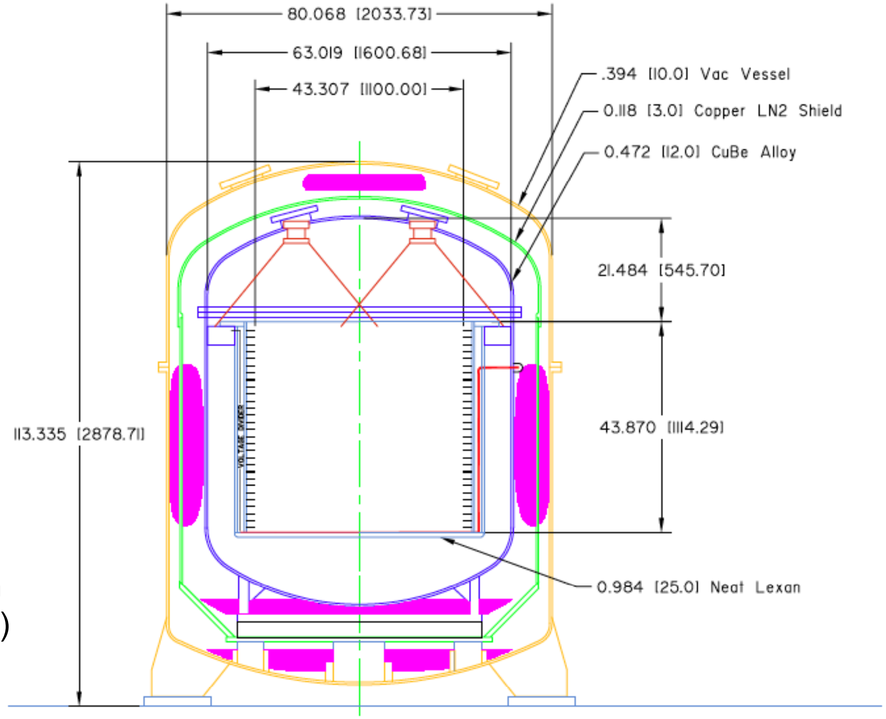
- Localized carriers observed in LHe, LNe – long drift times (at least 200 msec) measured, confirming high purity of fluids
- Measurements of surface transfer show suitable trapping times for LHe, but inconveniently long times for LNe, at least at 27K → higher temperatures, or single-phase medium if Ne
- Large, stable gains, up to 10^4, available in GEM structures, with small fraction (0.01 – 0.1%) of H_2 → operating temperatures above ~ 10K → single-phase medium if He
- Can achieve visible photon yields of > 1 photon per avalanche electron from GEM holes in neon-based gas mixtures
- Visible light yields from helium-based mixtures lower – need to measure IR yield (normal helium discharge has a bright line at ~ 1 μm)
- Successful initial CCD imaging of alpha tracks at cryogenic temperatures – individual track images very soon, followed by verification with electron tracks at T ~ 30-40K

Baseline: supercritical neon

- Initial ideas based on two-phase detector:
  - Insufficient gain in vapor phase for He
  - Trapping time at surface too long for Ne at 1 Bar
- Single-phase supercritical fluid:
  - Electrons are still localized and thermal
  - Removes difficulties of surface
  - Ability to tune density very attractive
  - Recombination losses lower

- Supercritical neon:
  - Density ~ 0.48 g/cc (T ~ 45K, P ~ 26 bar) → electron mobility ~ $6 \times 10^{-2}\ \mathrm{cm^2 sec^{-1} V^{-1}}$
  - Recoil track lengths for pp neutrinos up to ~ 2 mm
  - Keep option to run with supercritical helium: longer/straighter tracks, pointing for lower energies, systematic checks; but smaller target mass and reduced self-shielding

Design of cubic-meter prototype

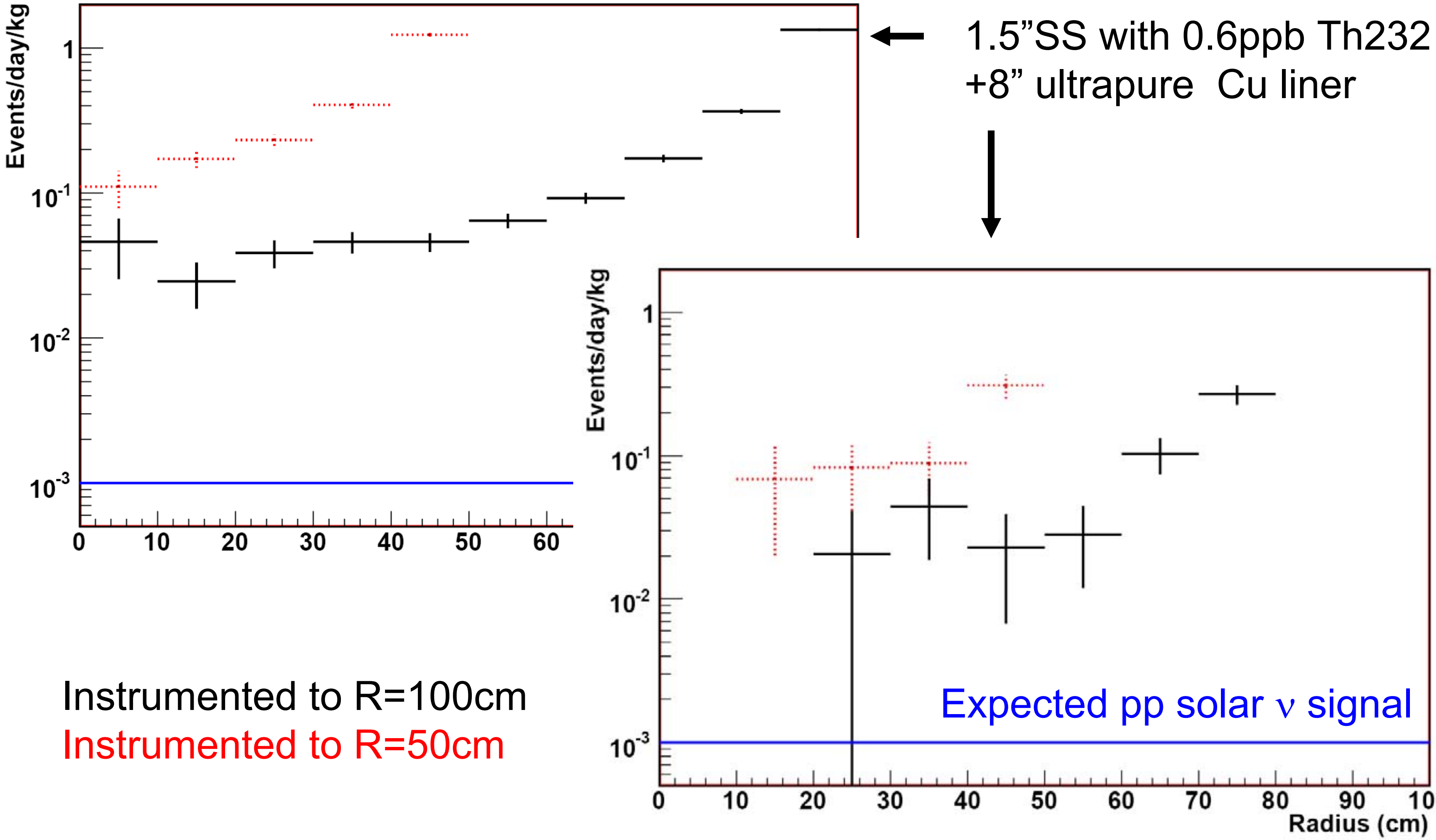


1 Cubic Meter 30 Bara Supercritical Neon Design

One possible design
J. Sondericker (BNL)

- Goals:
  - Detect neutrino interactions
  - Measure backgrounds/self-shielding performance
  - Develop analysis techniques
  - Explore scaling issues

Radial dependence of Irreducible Backgrounds from single compton scatters from 2.614MeV γ from the Th232 decay chain



1.5”SS with 0.6ppb Th232
+8” ultrapure Cu liner

Expected pp solar ν signal

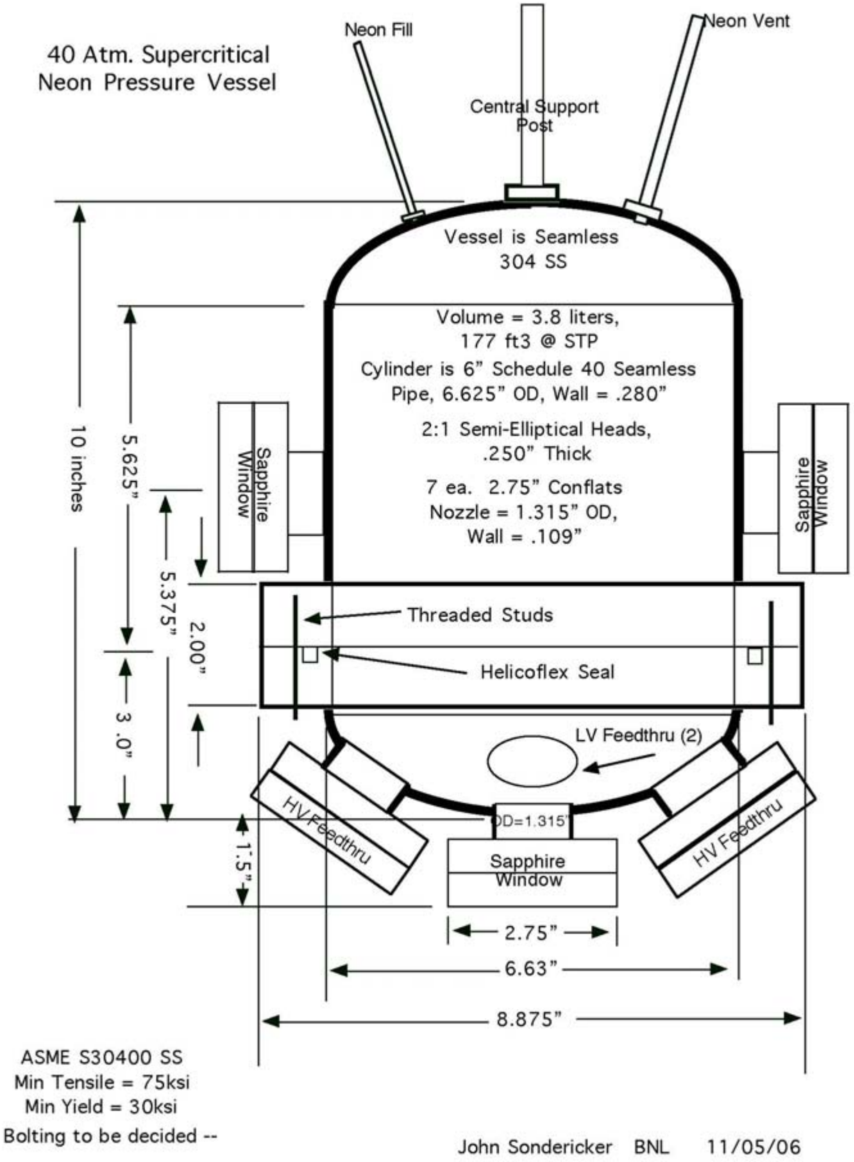
Instrumented to R=100cm

Instrumented to R=50cm

Conclusions

- Good progress in measuring fundamental parameters for an electron bubble TPC detector
- Next steps:
  - Measurements and imaging in supercritical Ne (He)
    - Supercritical Ne will require an upgrade to existing infrastructure
    - But existing Test Chamber can demonstrate ebubble behavior in GEM avalanche in critical density He
  - Continued R&D on optical readout based on lenslets and CCD camera → goal is full 3D track reconstruction with electron bubbles/slow drift
  - Ongoing development of the cubic-meter prototype – small enough to be transportable, with test phase at BNL before move to an underground site
- Techniques we are developing may be useful for a range of other applications requiring measurement (tracking) of very small signals in large volume detectors
  - Dark Matter
  - Coherent neutrino scattering
  - Double Beta decay

Upgrade of present System



Design of small 3.8 litter High pressure cold vessel.

Compatible with present setup.

To be build in '07.