The eBubble Detector for Solar Neutrino Detection

Raphael Galea

Columbia University Nevis Labs

BNL Instrumentation Seminar

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

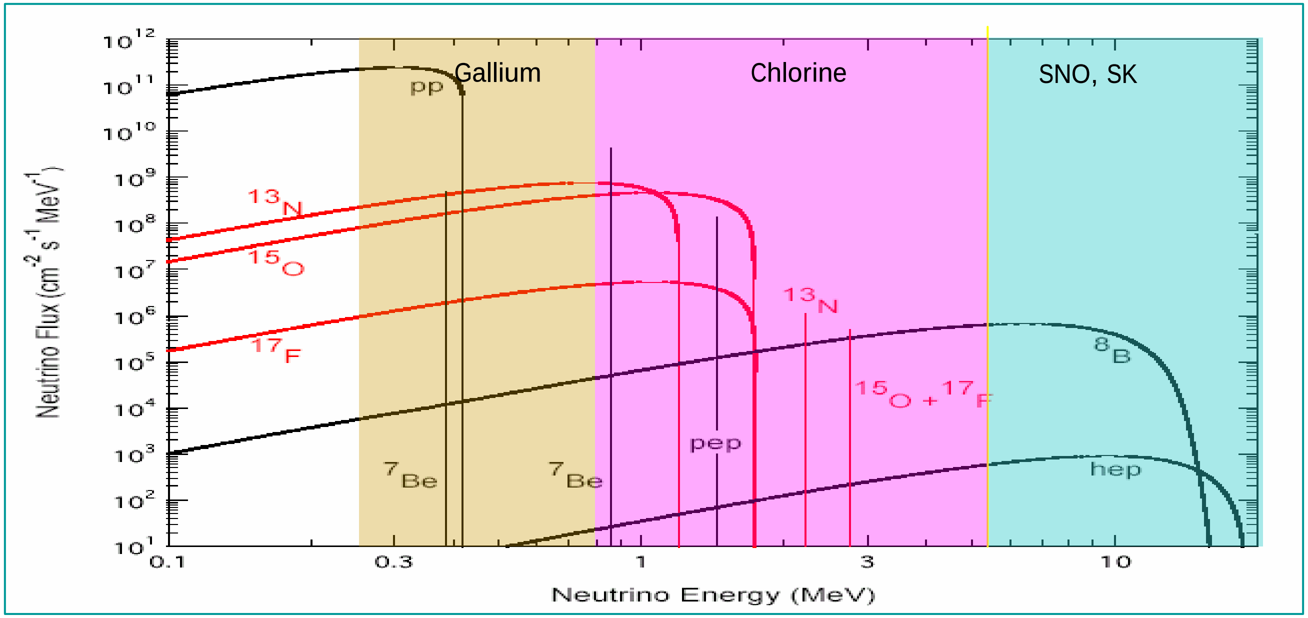
Columbia/Nevis: J. Dodd, R. Galea, W. Willis

BNL: R. Hackenburg, D. Lissauer, V. Radeka, M. Rehak, P. Rehak, J. Sondericker, P. Takacs, V. Tcherniatin, B. Yu

Budker: A. Bondar, A. Buzulutskov, D. Pavlyuchenko, R. Snopkov, Y. Tikhonov

SMU: R. Stroynowski, A. Liu, M. Christainsen

Solar neutrinos over full (pp) spectrum



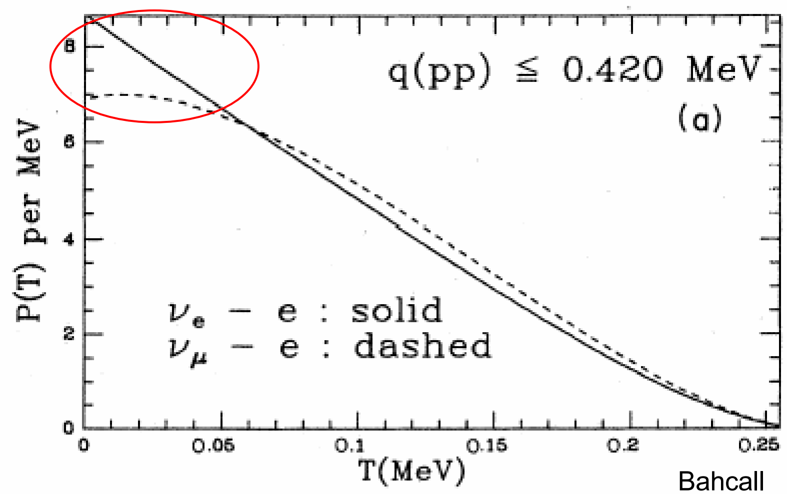
- In particular, a precision, real-time measurement of the pp neutrino spectrum down to the keV range
- Precision measurements of oscillation effect matter/vacuum dominated regimes
- SSM uncertainty on the pp flux ~ 1% → aim for “1%” measurement
- Insights into the inner working of the Sun. Comparison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

Physics Motivation cont’d

E_x is the visible track energy

- 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
- E_X<40 KeV nuclear recoil from WIMP (Dark Matter), range very different from electron and spectrum depends on WIMP mass – similar technique used in the DRIFT experiment

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

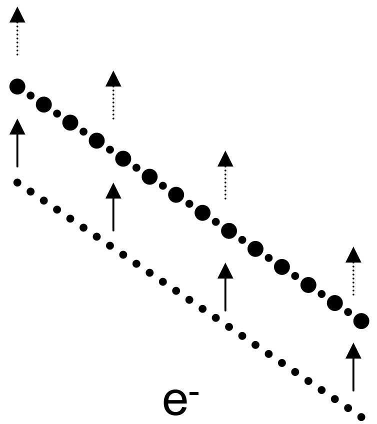
- In liquid phase, these low-Z materials offer good compromise between volume-to-mass consideration and desire to minimize multiple scattering
- Very low boiling points → excellent purity, since impurities freeze out
- In the case of thermal charge carriers, diffusion is proportional to $\sqrt{T}$, so 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} $cm^2sec^{-1}V^{-1}$, 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

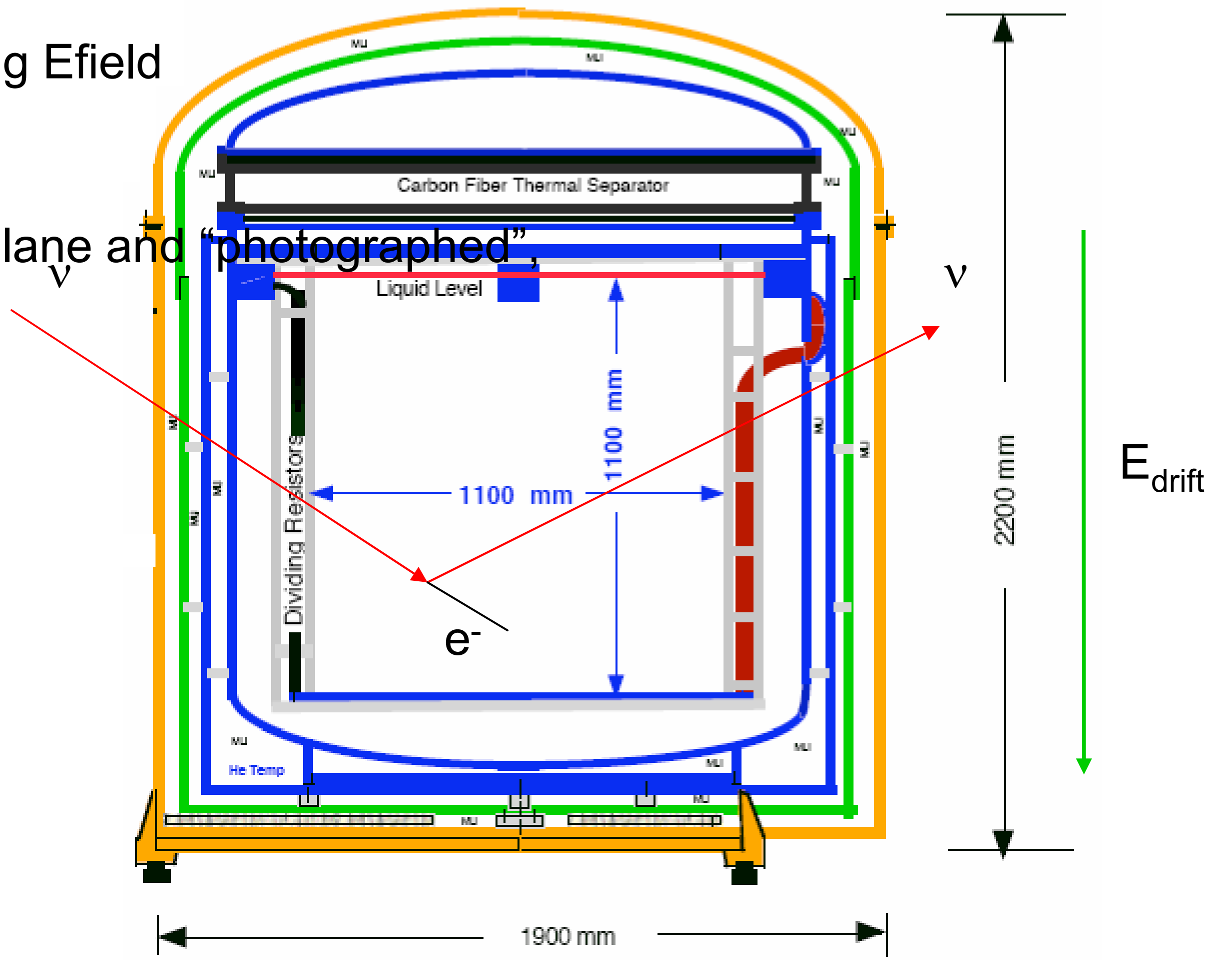
Experimental approach: an electron bubble TPC

- 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
- 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

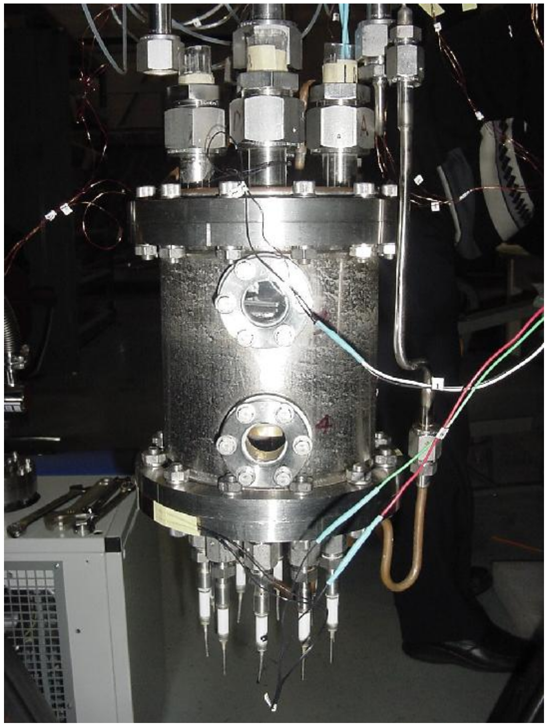




Backgrounds

- 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

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

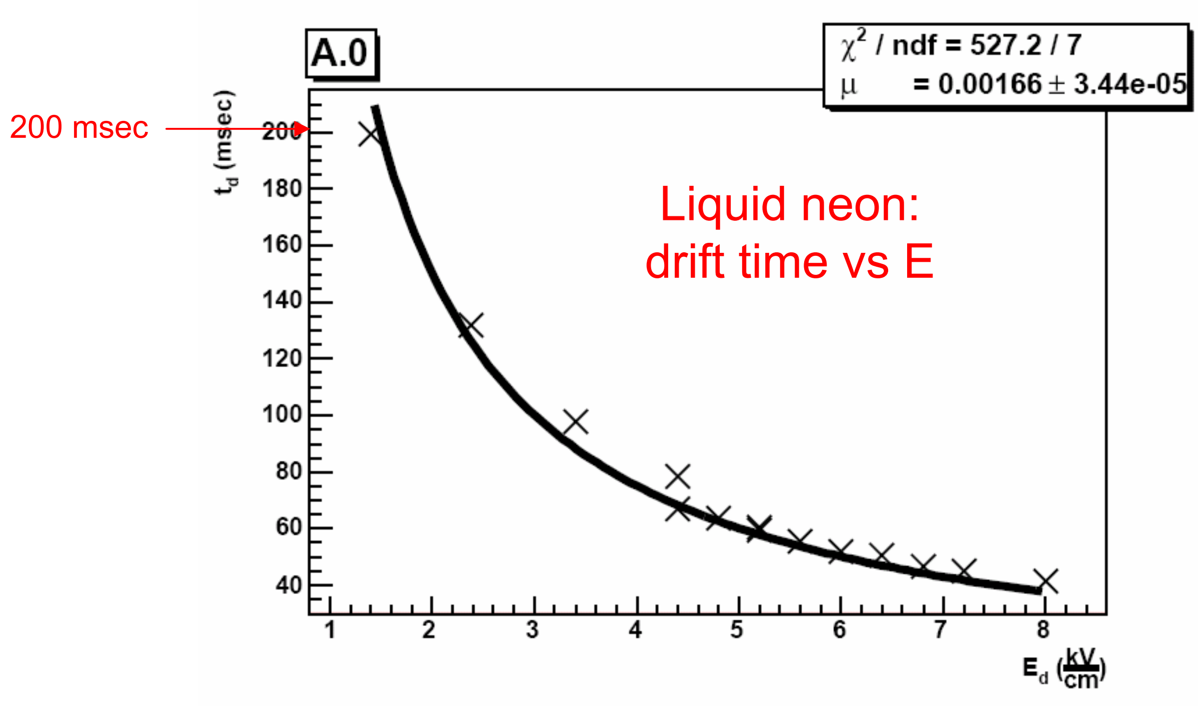
No gain (charge/light) in Liquid

- New detector technologies

↓

2-Phase detector

Low-mobility carriers observed in liquids

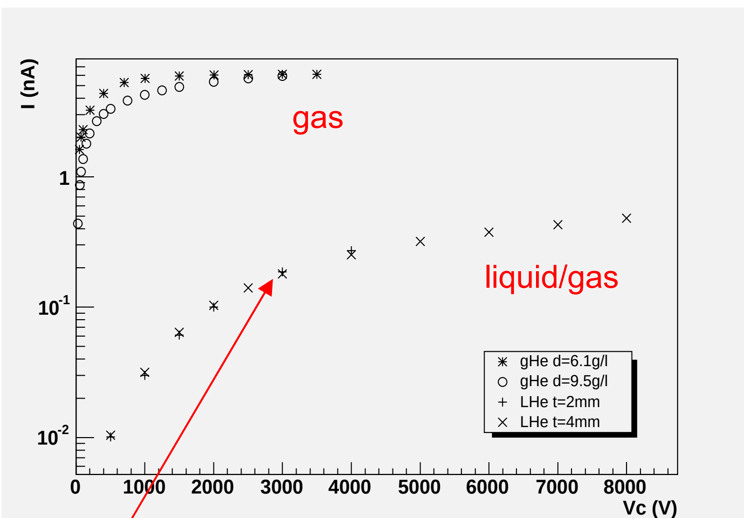


- Measured drift velocities consistent with known electron bubble mobilities
- Long lifetimes! Excellent purity achieved easily

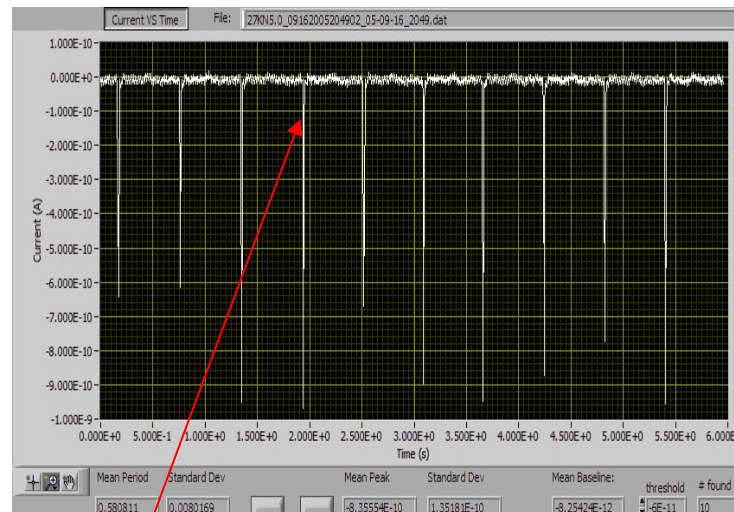
Surface behavior and trapping times

- 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



Neon

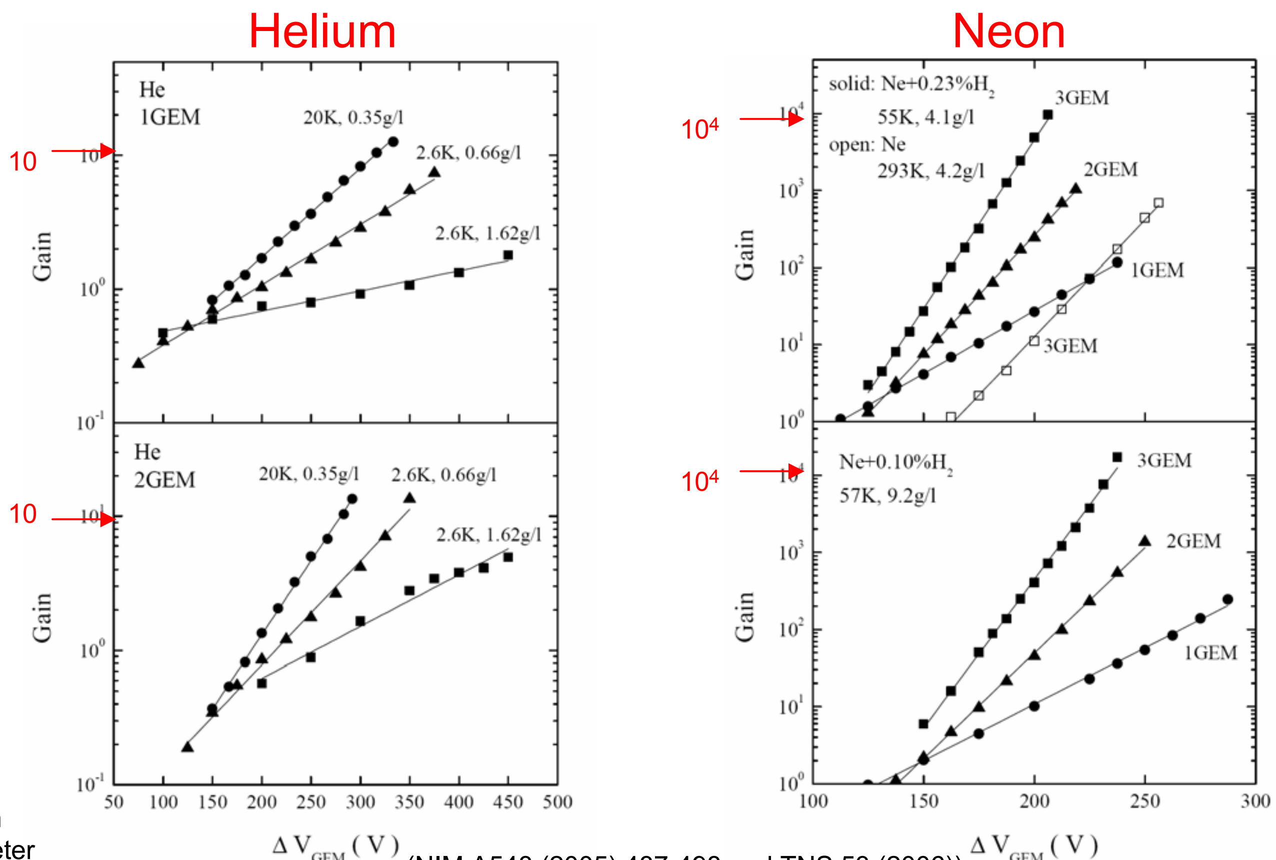


Expected monotonic increase of I with $E_{surface}$ → trapping times ~ msec, and tunable

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

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

Gain from GEMs in vapor



Gain > 10^4 maintained at ~ 30K

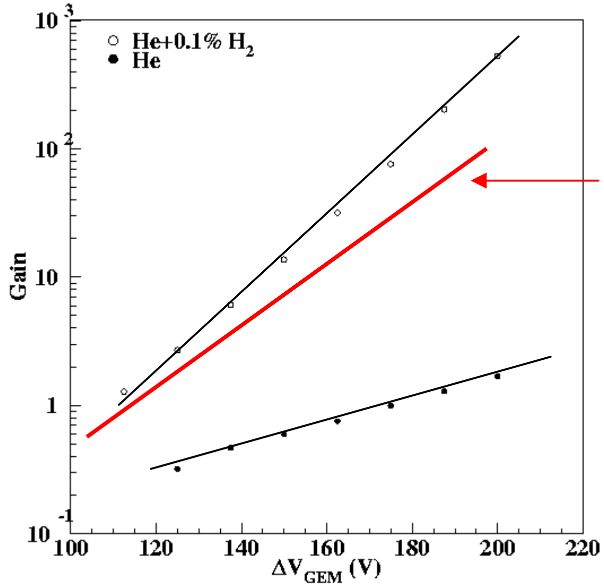
CERN GEMs
30x30mm
140μm hole pitch
50μm hole diameter

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

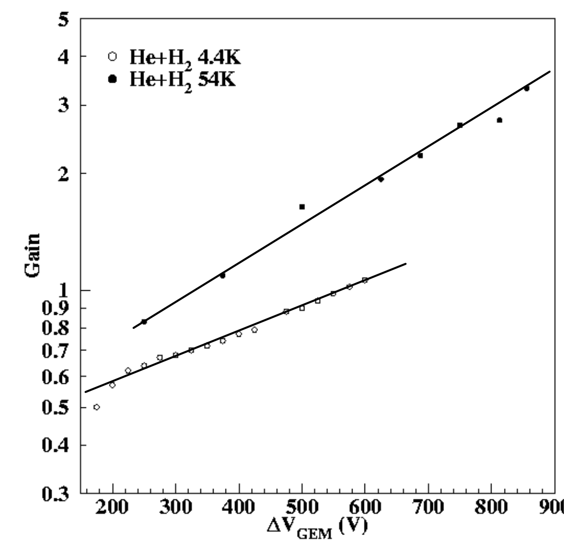
- Modest gain in He vapor; large gain (> 10^4) in Ne vapor with addition of fraction of H_2 → operate at temperatures where finite H_2 vapor pressure
- With hydrogen doping, both He and Ne give gains > 10^4 in 3-GEM configuration
- Little true temperature effect - impurities play important role at high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

Purity & the addition of H_2 to He

- 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.



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

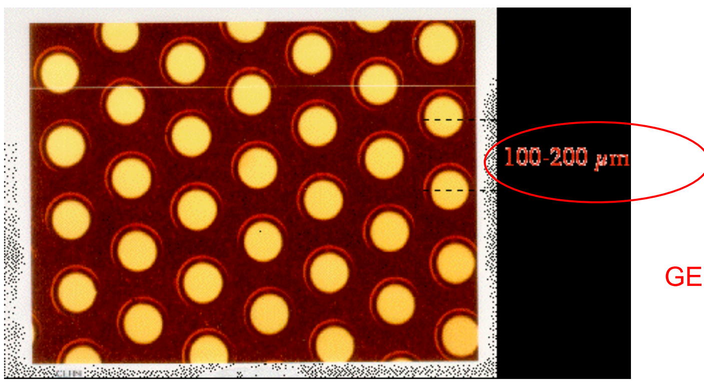
Surface dynamics difficult
- Could we manipulate this trapping
- Optical/electrical gating of charge

1-phase
(Supercritical)
Dense Gas

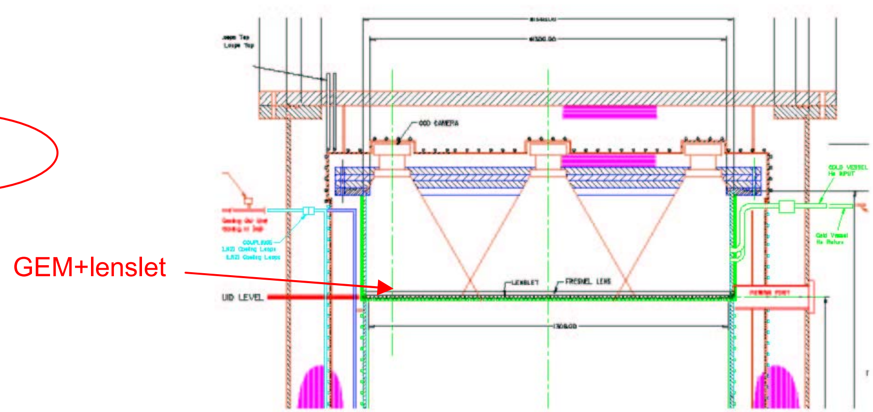
- Remove difficulty of surface
- Possibility to use $He+H_2$ – retain complementarity with Ne
- Possibility to tune density very attractive
- Recombination losses are lower

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

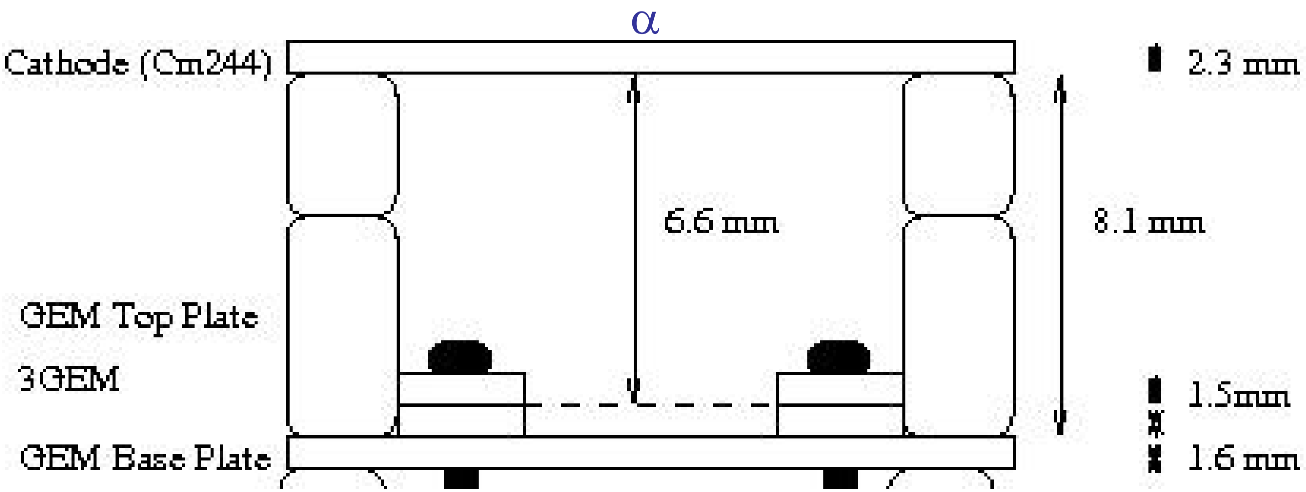


(back-illuminated, not avalanches!)



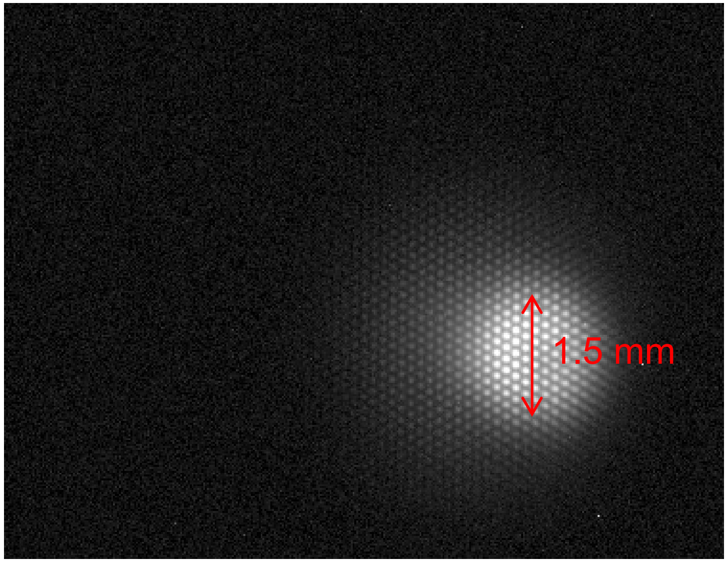
- Calculations indicate transport efficiency of a few %, making use of lenslets matched to GEM holes
- Use commercial CCD cameras, sitting at ~ 50K

α tracks:

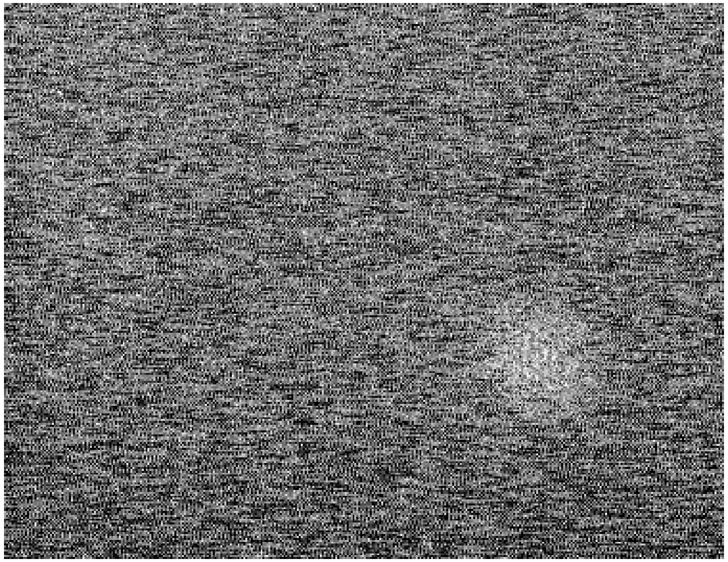


- Uncollimated alpha source, ~ 10 kHz rate, in Ne + 0.01% H_2 at 78K (charge gain ~ 10)

60 sec exposure (~ 600k alphas!):



1 msec exposure (~ 10 alphas):

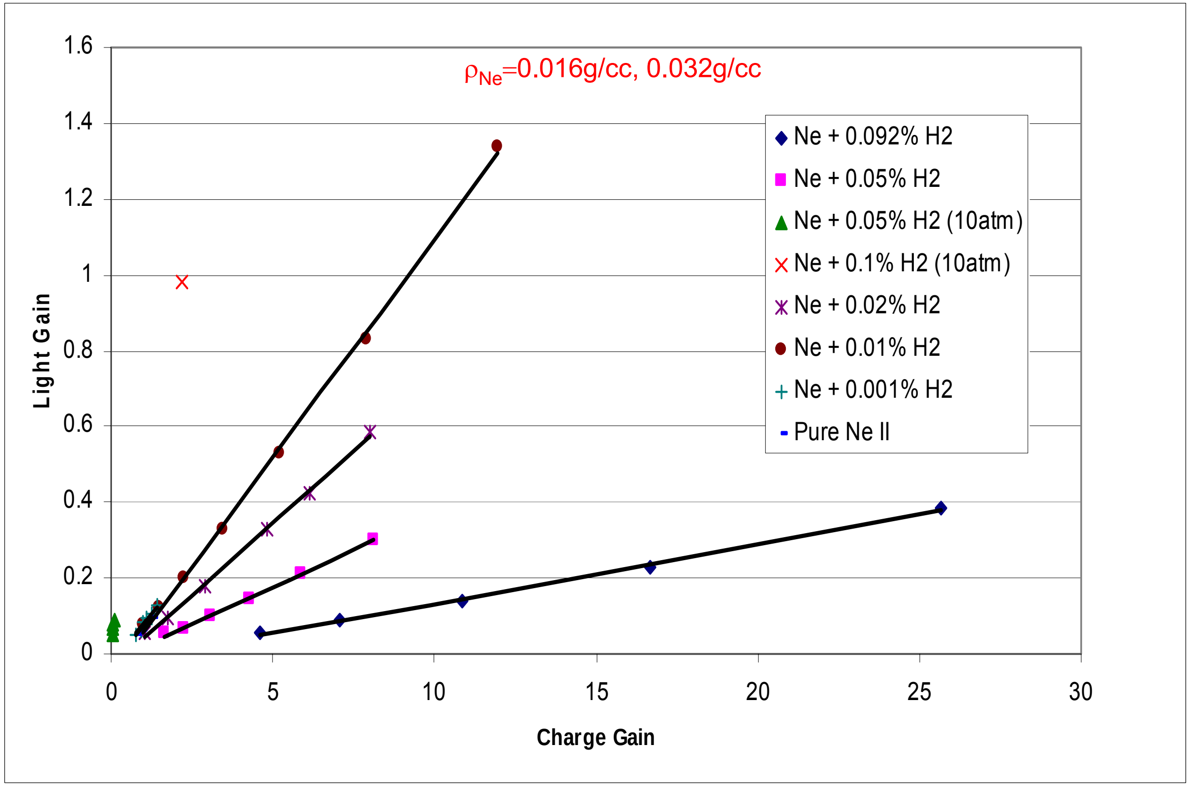


- Non-optimal geometry, with ionization from many alphas occupying only a few GEM holes, limits available gain in this configuration

Light yield and spectrum

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

γ/e

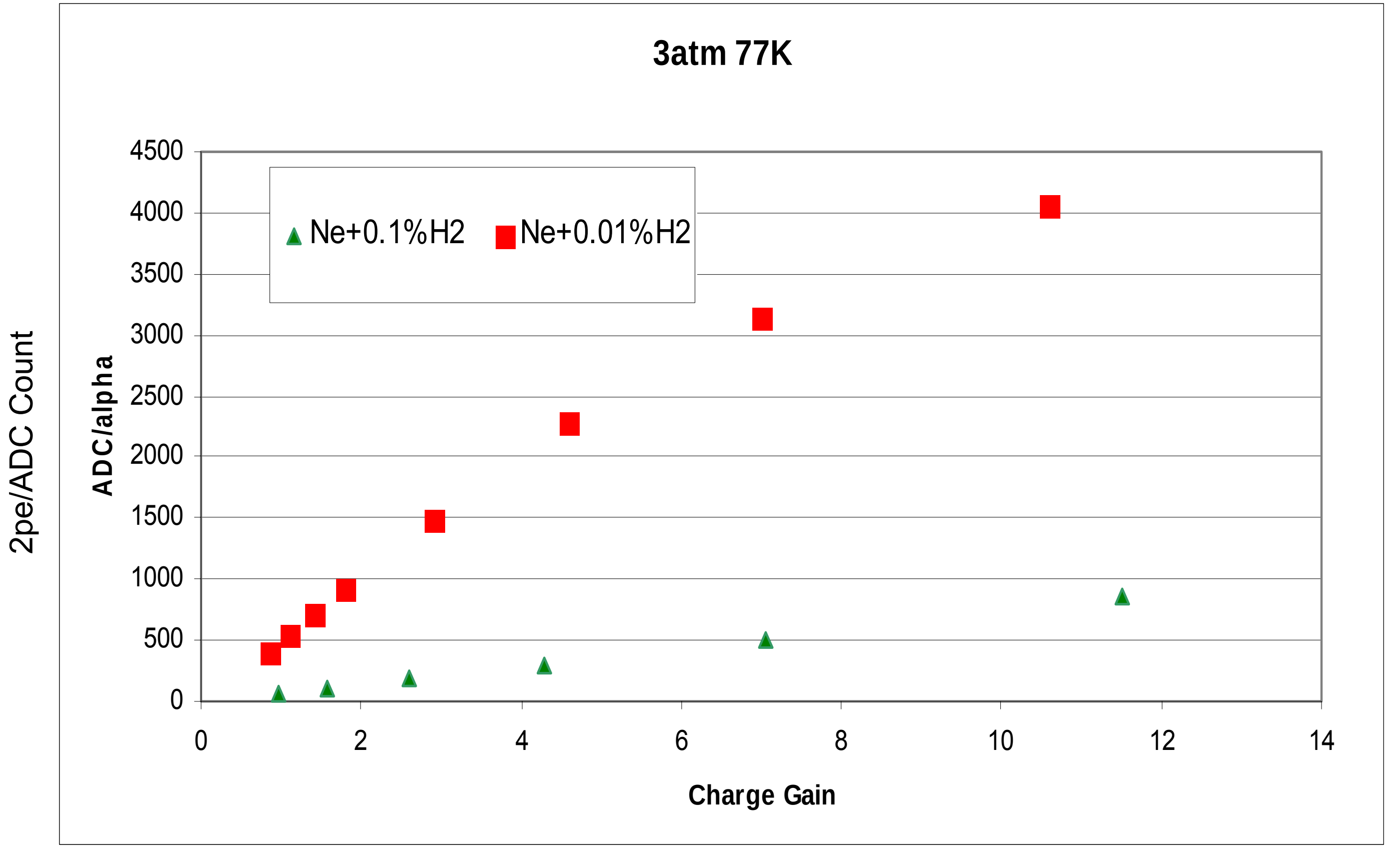


**Triple GEM

(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)

CCD Gas measurements:

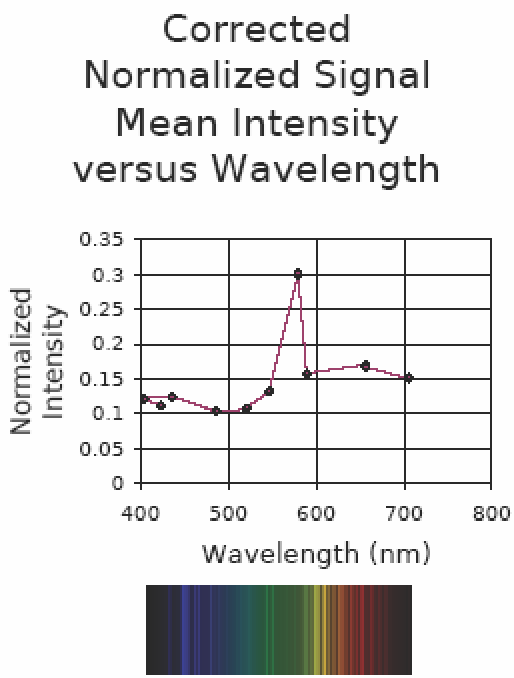


R_α=10 KHz

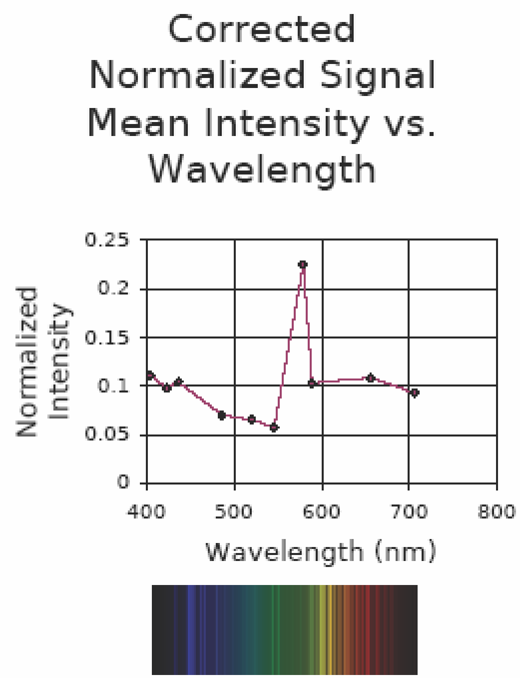
• In this configuration charge gain limited to O(10) before single damaging discharge occurs

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

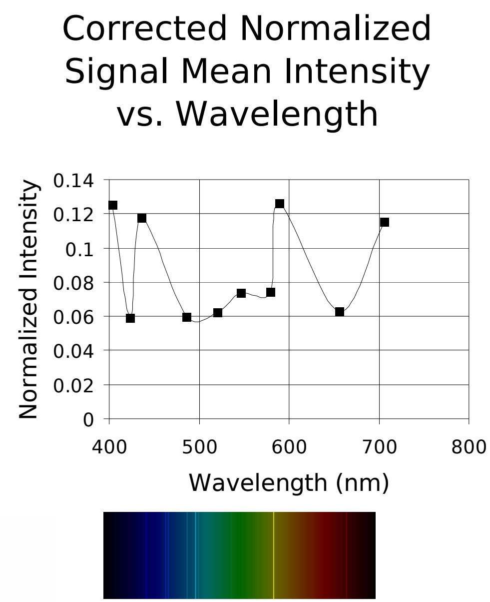
Ne+0.1% H_2



Ne+0.01% H_2



He+0.01% H_2

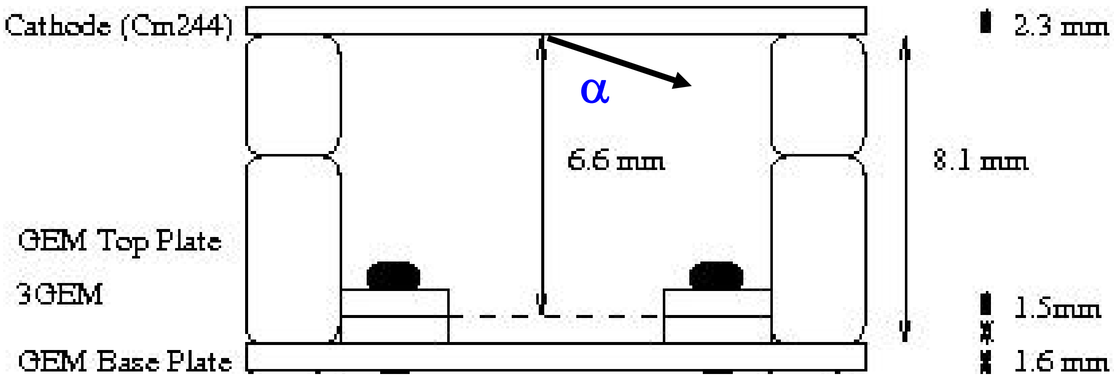


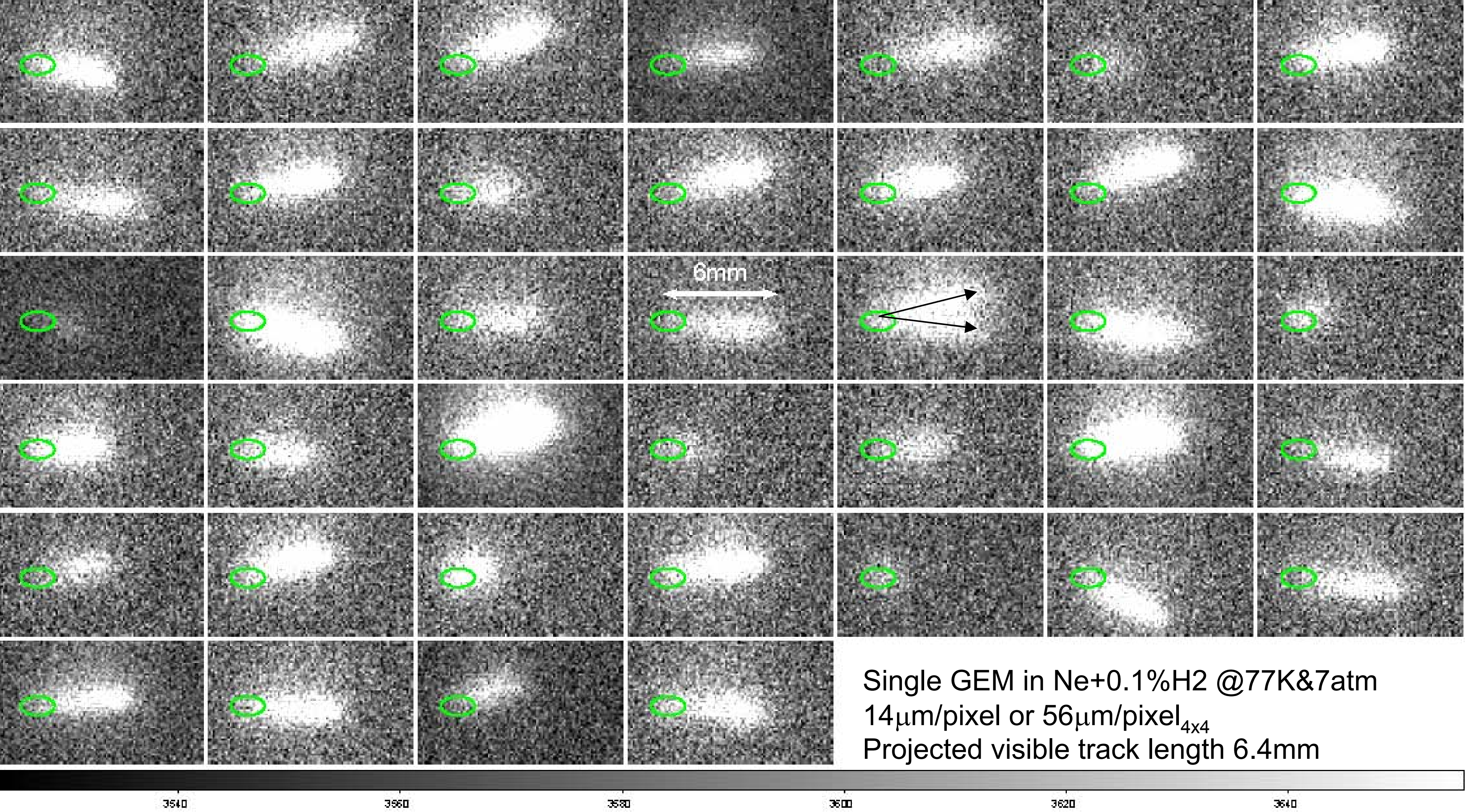
Conclusions:

- 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





- 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.

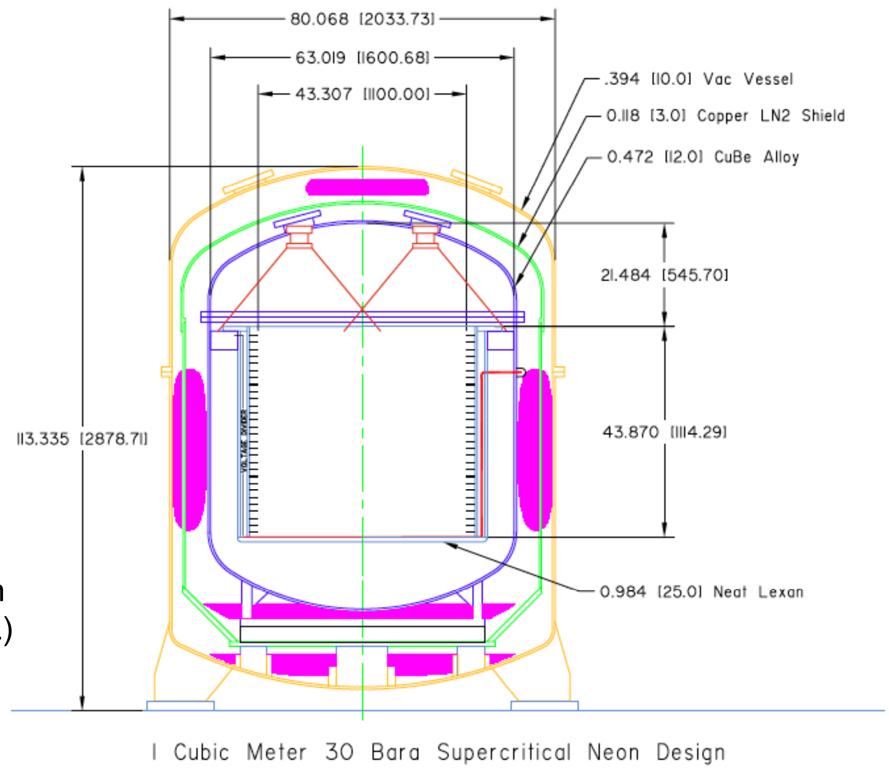
Summary of R&D results to date

- 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 ~ 6×10^{-2} $cm^2 sec^{-1} V^{-1}$
  - 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

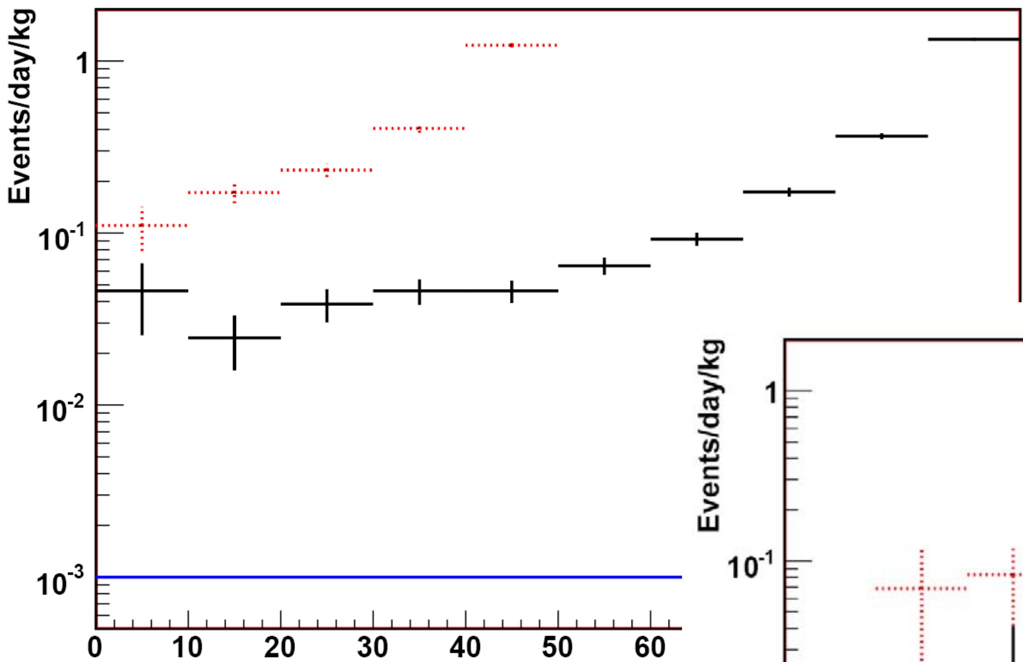
Design of cubic-meter prototype



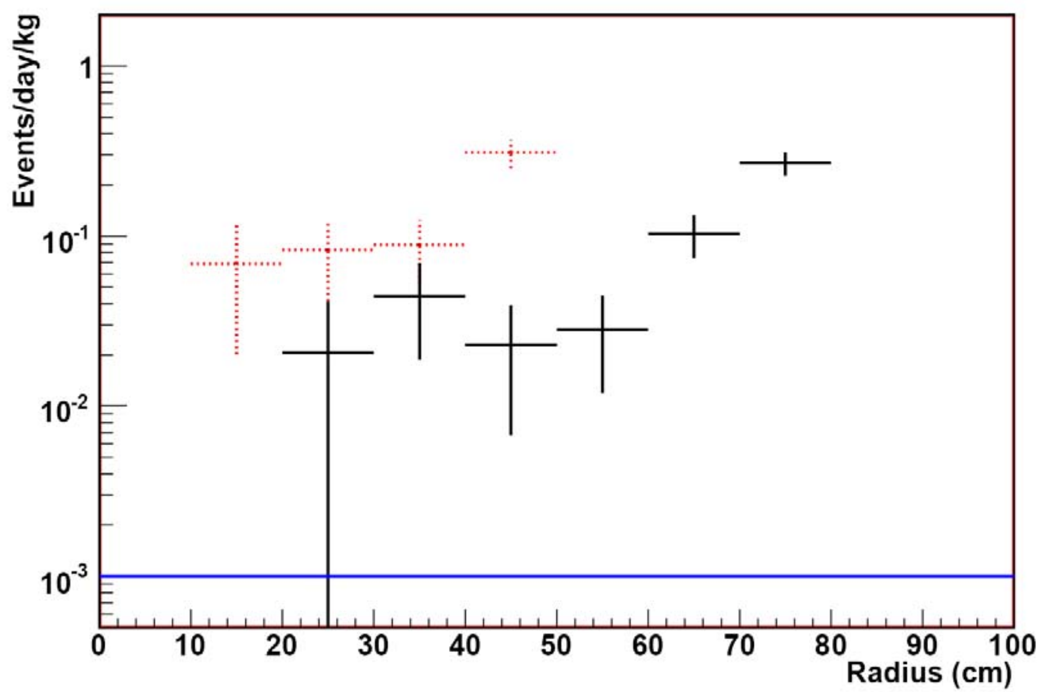
One possible design
J. Sondericker (BNL)

- 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



Instrumented to R=100cm
Instrumented to R=50cm

Expected pp solar ν signal

Conclusion

- 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