Whatever happened to Solar ν's?

Whatever happened to Bubble Chambers?

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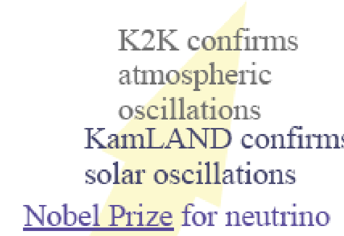
Bubble Chambers making a comeback in Dark Matter detection

• Large Multi-ton chambers were built in the 50s-80s.

• New Superheated liquid Bubble Chambers provide low energy thresholds for dark matter detection

• Ebubble is not a Bubble Chamber but a Chamber that utilizes electron Bubbles
  • Still a tracker
  • Time Projection Chamber

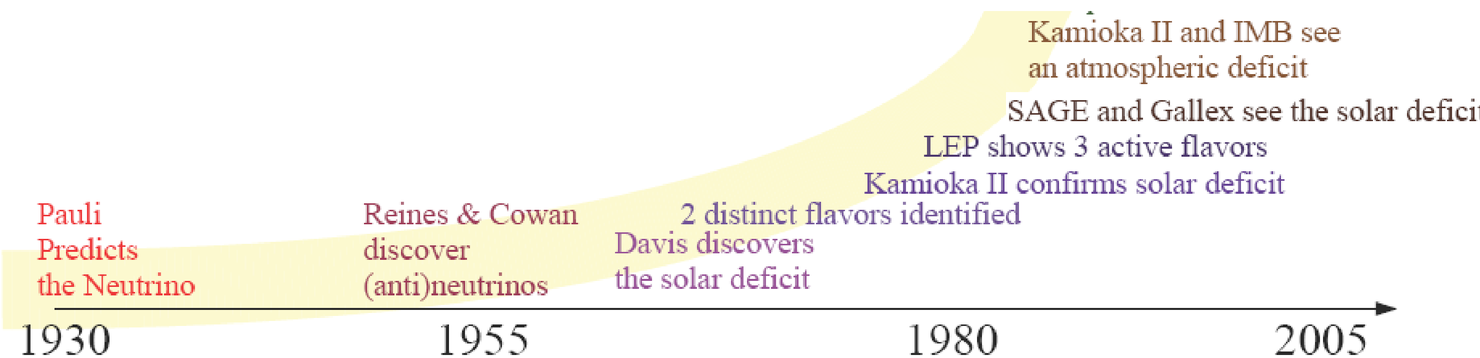
COUPP & PICASSO



Third (of 3) APS Recommendations:

"We recommend development of an experiment to make precise measurements of the low-energy neutrinos from the Sun."

"A precise measurement of the low-energy neutrino spectrum would test our understanding of how solar neutrinos change flavor, probe the fundamental question of whether the Sun shines only through nuclear fusion, and allow us to predict how bright the Sun will be tens of thousands of years from now."



Disclaimer: Just my impression…

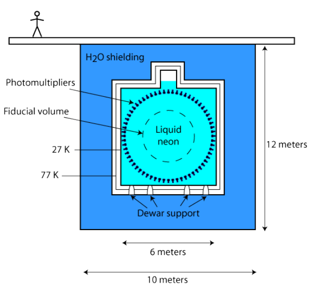
In 2005, Solar ν's were the hot topic…

LENS   Eν>114KeV

Low Energy Neutrino Spectroscopy

HERON E_ν<100Kev

Helium Roton Observation of Neutrino



CLEAN E_ν>100KeV

Cryogenic Low Energy Astrophysics with Noble gases

+ MOON and others

- What happened?
  - Dark Matter became *hotter*
  - *John Bahcall passed away*

Evidence of ν oscillation:

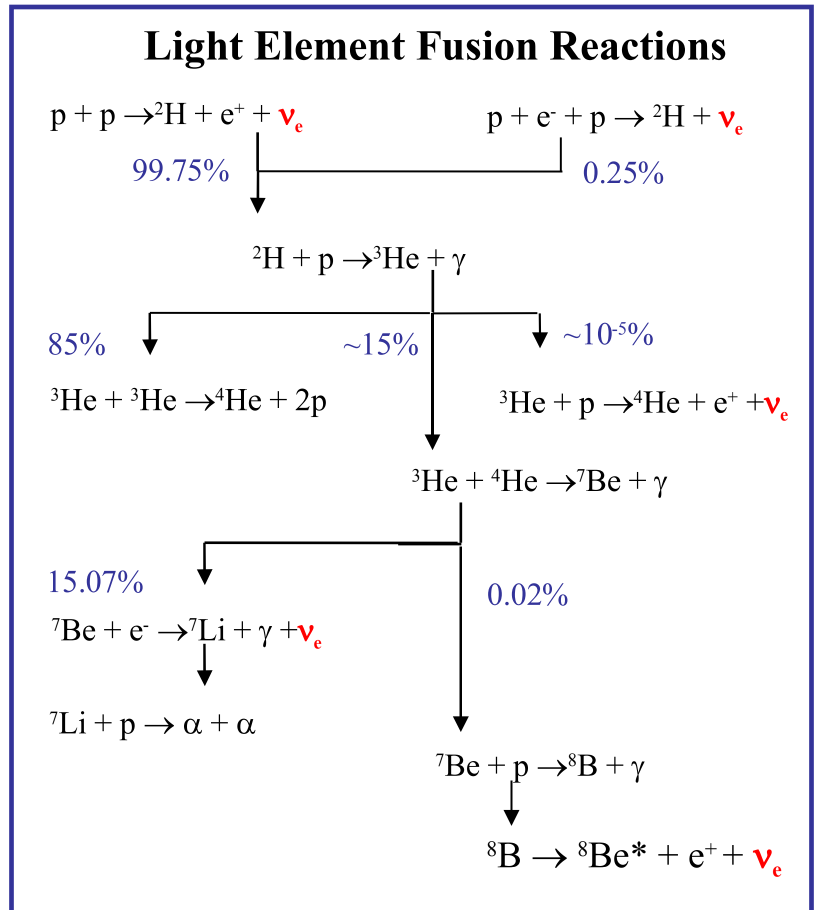
- Solar Standard model provides a theory about the inner workings of the Sun.
- Neutrinos from the sun allow a direct window into the nuclear solar processes

- 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 →

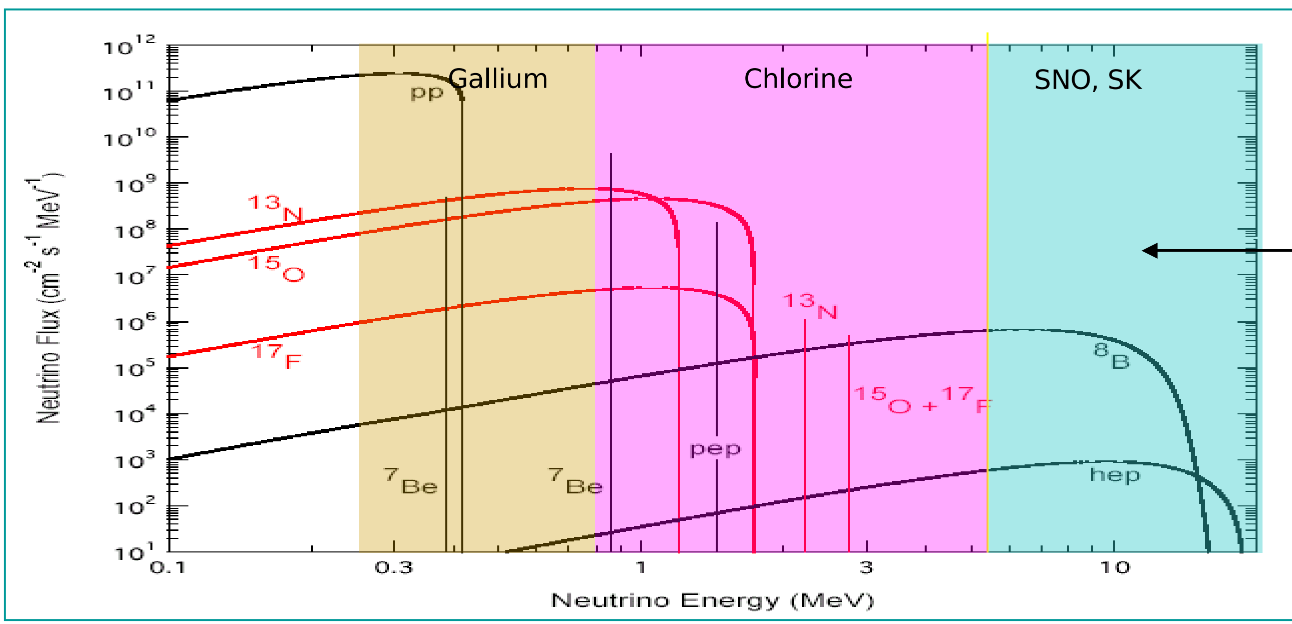
Atmospheric
Accelerator
Reactor

- Data supports the interpretation that neutrinos *oscillate*.



Real-time measurement of low-energy spectrum

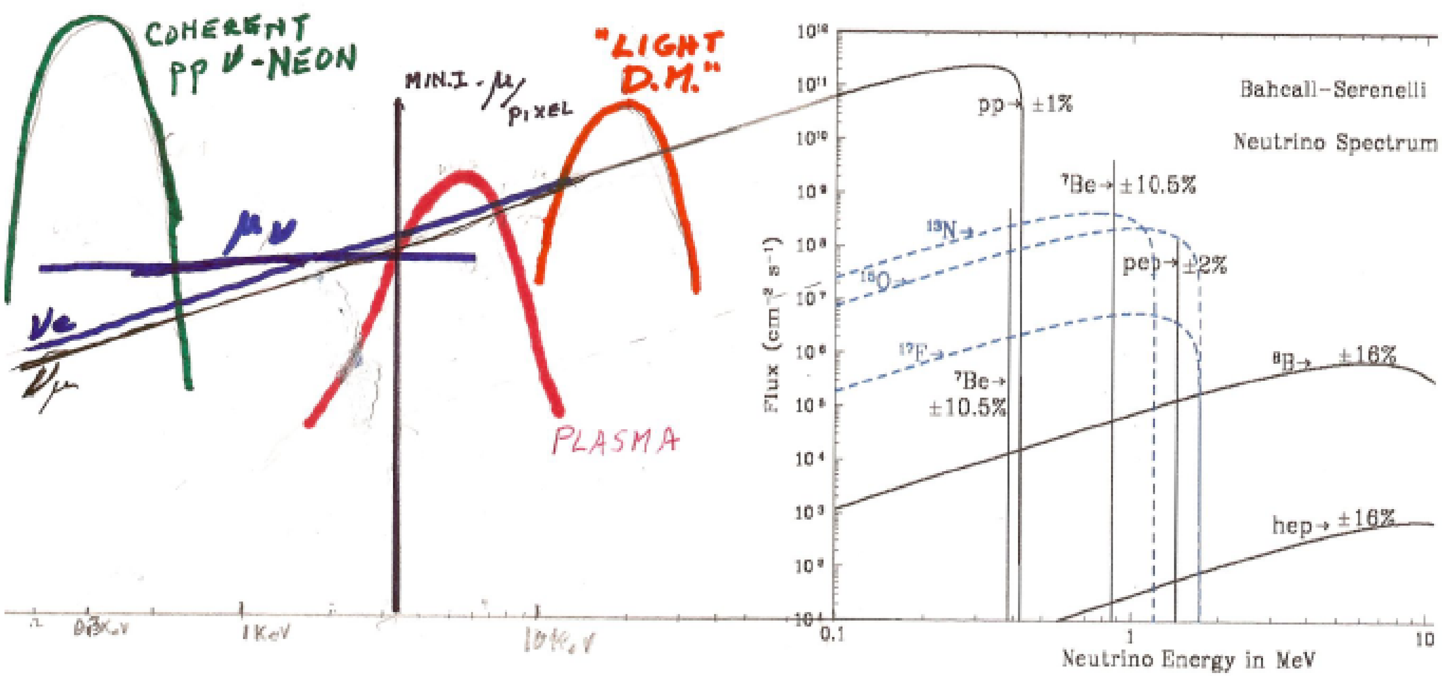
- Most solar neutrinos come from proton-proton fusion reactions, with an average energy about ten times lower than the threshold of the current real-time experiments in the MeV range; we aim to reach the KeV range
- The Standard Solar Model gives an accurate estimate of the number of these neutrinos at the source, allowing precision measurements of neutrino disappearance and matter effects from the spectrum of neutrinos observed through the scattering on target electrons
- The comparison of neutrinos from different reactions provides unique information on the physics of the Sun



0.01% of total flux

Neutrino Landscape

Neutrinos: "Always room at the bottom" - R.F.



B.Willis

Neutrino magnetic moment

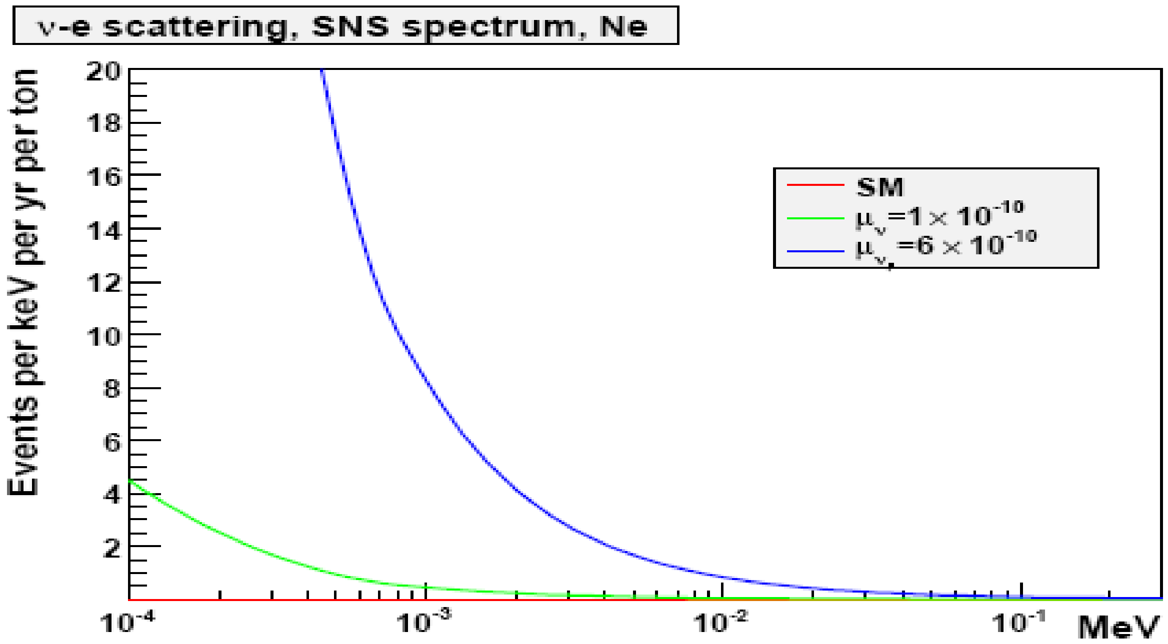
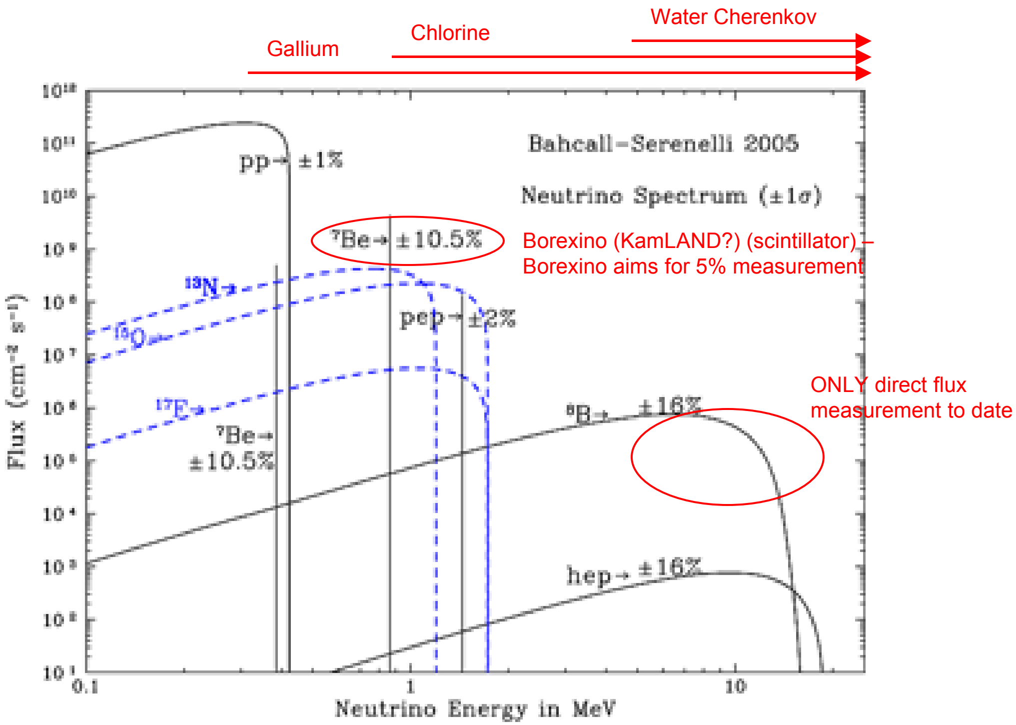


Figure 2: Differential yield at the SNS in neon as a function of electron recoil energy. Red line: Standard Model expectation. Green line: yield including magnetic moment contribution for $\mu_\nu = 10^{-10}\mu_B$ for both ν_e and $\bar{\nu}_\mu$. Blue line: yield including magnetic moment contribution for $\mu_\nu = 10^{-10}\mu_B$ for ν_e and $\mu_\nu = 6 \times 10^{-10}\mu_B$ for $\bar{\nu}_\mu$.

K.Scholberg

Solar neutrinos

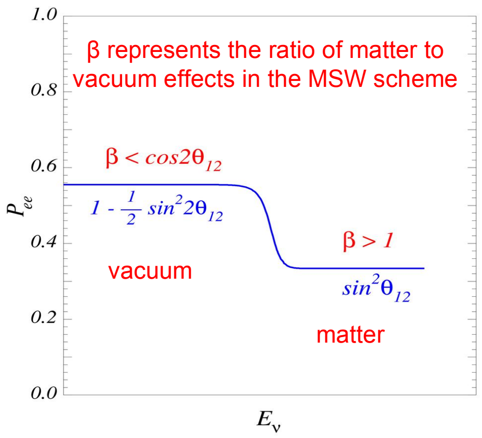
- Main goal is precision measurement of pp neutrino flux and spectrum

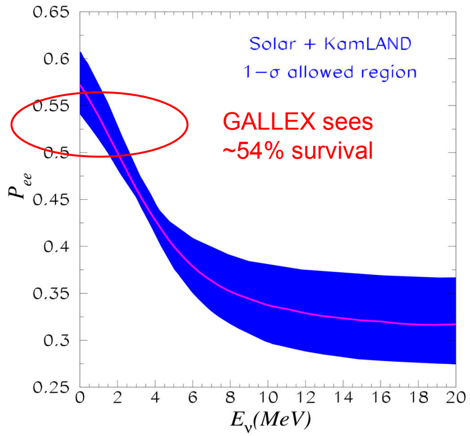


- Measurement of higher-energy neutrinos "for free"
- Depending on fluid density/tracking performance, higher energy neutrinos may provide pointing

Solar neutrinos

- Comparison with existing precision measurement of ^{8}B flux will demonstrate transition between vacuum- and matter- dominated oscillations - for solar neutrinos, transition occurs ~ 2 MeV

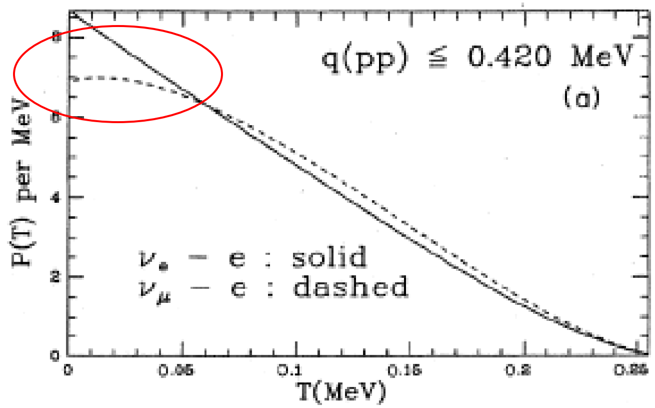




- Non-standard mechanisms?
- Check whether neutrino and photon luminosities agree
- Do fusion reactions account for all of the energy release?
- (Modestly) improved measurement of θ_{12} with 1% measurement of pp flux

Solar neutrinos

- Neutrino detection by elastic scattering of ν on target electrons:



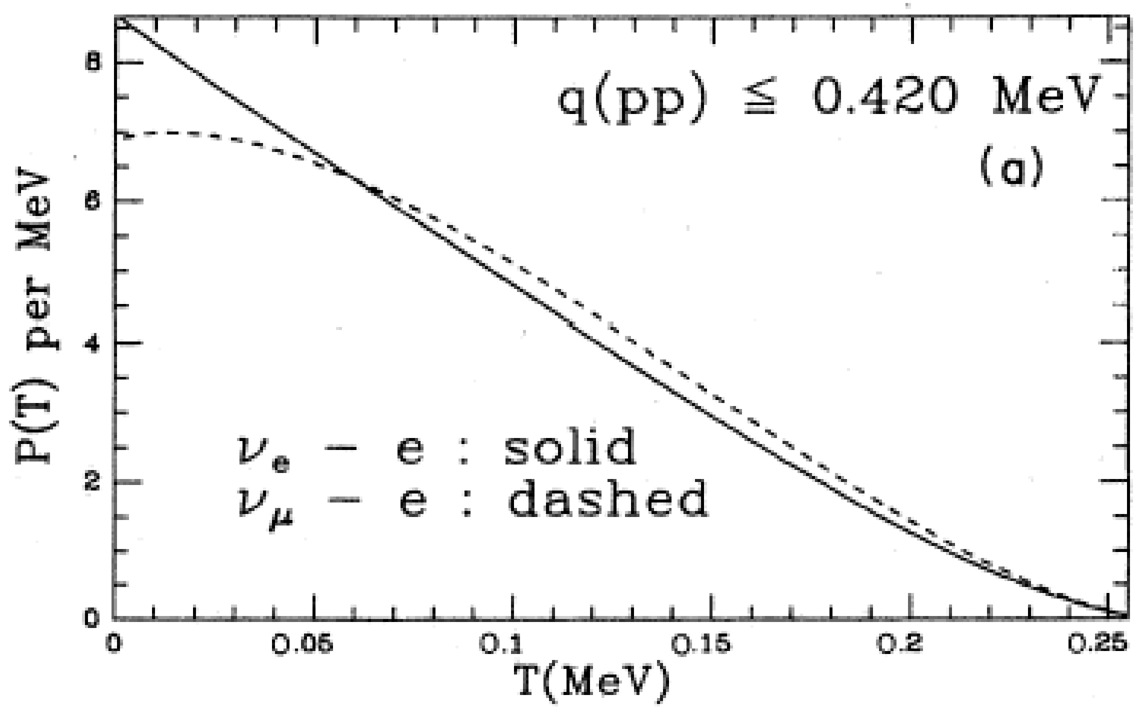
- Expected rate for pp neutrinos is about 700 elastic scatters per ton per year, without oscillation
- This reduces to ~ 400 events per year, if LMA/MSW is correct
- Exposure of at least 25 ton-yr needed for 1% measurement of flux (neglecting efficiencies, energy threshold, backgrounds,…)
- Scattering rates for ν_μ and ν_τ down by a factor of ~ 4
- Most of the scattered electrons are < 100 keV
- Flavor dependence of spectral shape < 50 keV

Electron recoil energy spectrum from scattering of p-p neutrinos.

$\nu + e^- \longrightarrow \nu + e^-$

Probability P(T) of producing electrons with different recoil kinetic energies (T) as a function of the kinetic energy (T).

Bahcall, Rev. Mod. Phys. **59**, 2, 1987.



• note that the electron energy spectrum is a convolution of the neutrino spectrum with the scattering energy partition.

Detector Requirements

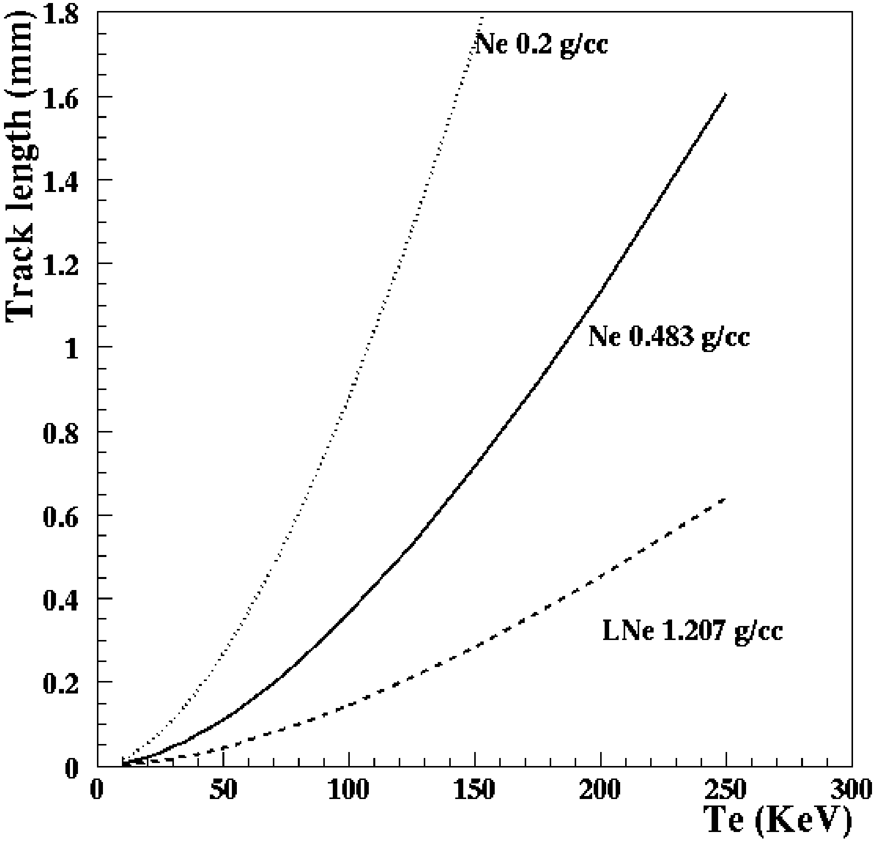
- ~ O(10) tons fiducial mass
- "Condensed" phase target medium to give reasonable volume for this mass
- Excellent (sub-mm) spatial resolution for low energy tracks → range, electron ID, plus pointing, at least for higher energy recoils
- To maintain this resolution if drifting over long distances, need 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: Neon(Helium)

- 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

Tracking in the Cryogenic Fluids:Neon (Helium)

- Requirements for He/Ne detector
  - A target mass sufficient to detect neutrino events O(0.5) tons -> long drift ~1m
    - At least 0.5T, 1 m^3 Ne fiducial volume ~100 solar neutrino events per year.
  - Good (0.1-0.5 mm) spatial resolution to allow range determination, track direction and Compton clusters
    - Lowest radiation loss to minimize multiple scattering for 100-300KeV electrons, visible range down to ~200KeV
  - Great purity, to allow long drift path
    - No intrinsic radio-impurities
    - Easily purified
  - Slow drift, due to localization, to allow a huge number bits to be read out
  - Good energy resolution
  - Low background

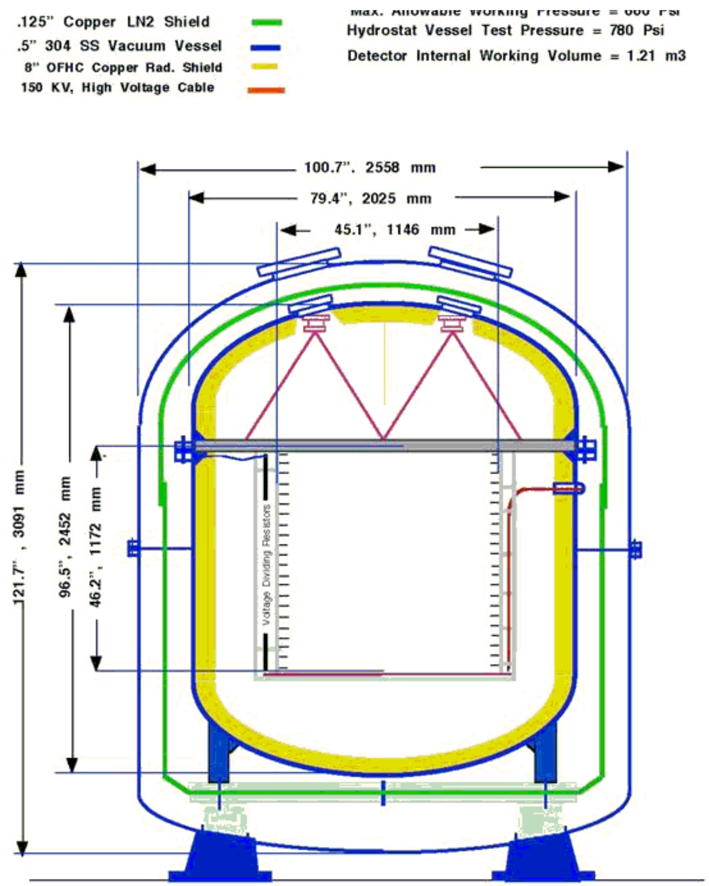


Readout! A new method needed

- Consider $1m^3$ with 1m drift in a Solar Neutrino Detector: there are 8×10^9 voxels to read for $(0.5mm)^3$ voxel.
- Drift at 10 cm/s through 1m in 10 seconds (we have simulated convection). Diffusion:

$$= \sqrt{\frac{2kTd}{eE}}$$

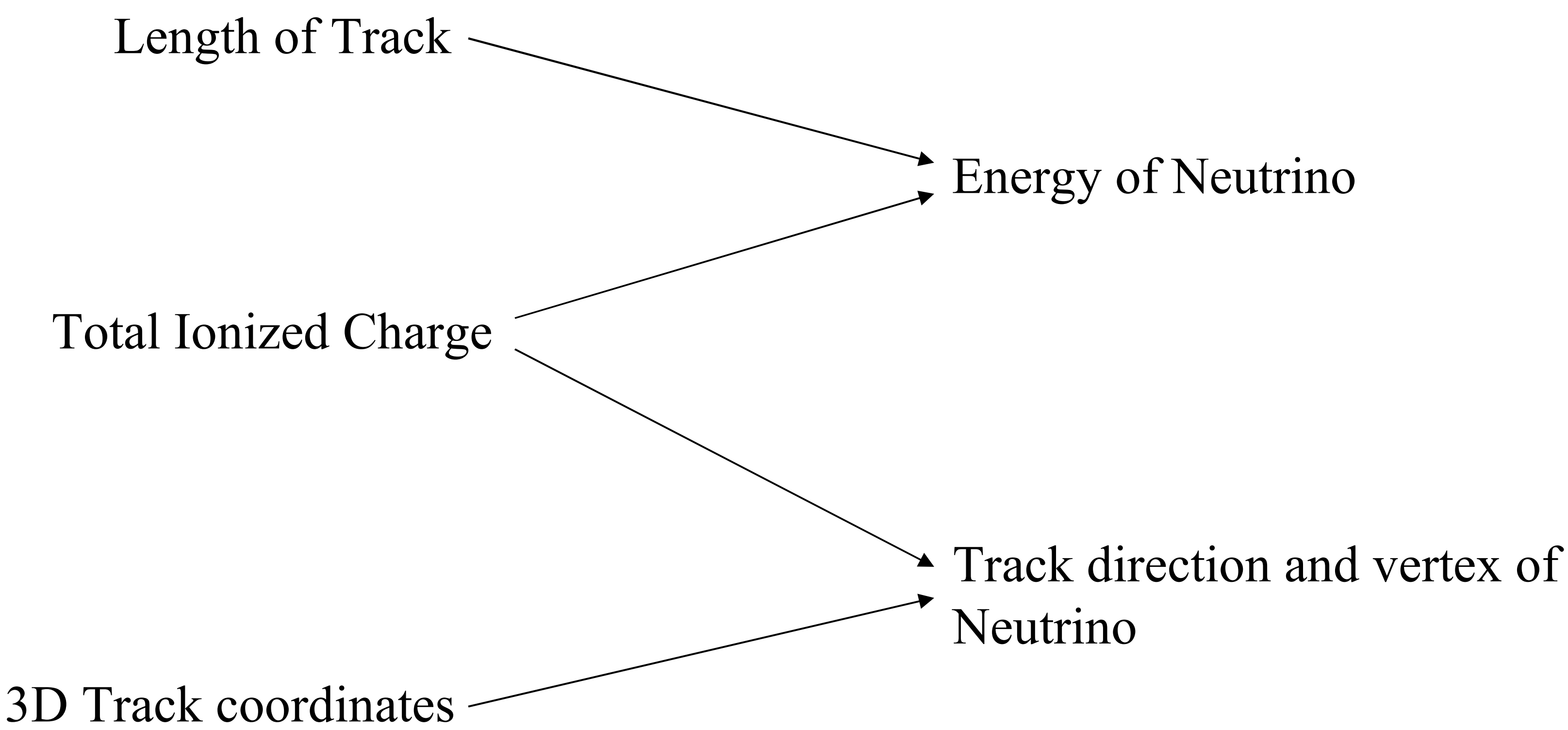
- Slow drift time is very useful! signals are stored in the detector volume and we deal with them one plane at a time, every 5 milliseconds (slower than TV).
- Zero suppression reduces this to < a few kHz.
- We obtain gain by amplifying in **G**as **E**lectron **M**ultipliers (**GEM**s).
- We use an optical readout, described below, observing light from a **GEM** avalanche detector, giving gain about 100



Columbia University in the City of New York

Tracks

Information from Tracks: Note that many tracks are too short to measure length



Electron Bubbles

- When electrons from a radioactive source are fired into a vat of helium, repeated interactions with the electrons of the helium atoms slow them down until, finally, they grind to a halt. The intruding electrons do not attach themselves to helium atoms as a third electron.
- The Pauli exclusion principle makes sure of that, because it forbids more than two electrons from sharing the same quantum state. Faced with helium atoms whose electrons have bagged the lowest energy state-the ground state-an interloper with no spare energy has no choice but to lodge in the space between atoms. There it clears a bubble of space around itself-an electron bubble.
- Electron bubbles form only in certain types of fluids, those in which the van der Waals force of attraction between atoms is weak enough to allow an electron to push them apart. (Helium, Hydrogen and Neon)
- At very low temperatures in helium, an electron bubbles displaces more than 700 helium atoms, creating a cavity around O(2nm) across. Inside this cavity quantum mechanics rules, ensuring that the electron can occupy only a limited set of energy states.

Mobilities

- eBubble mobility depends on density and temperature

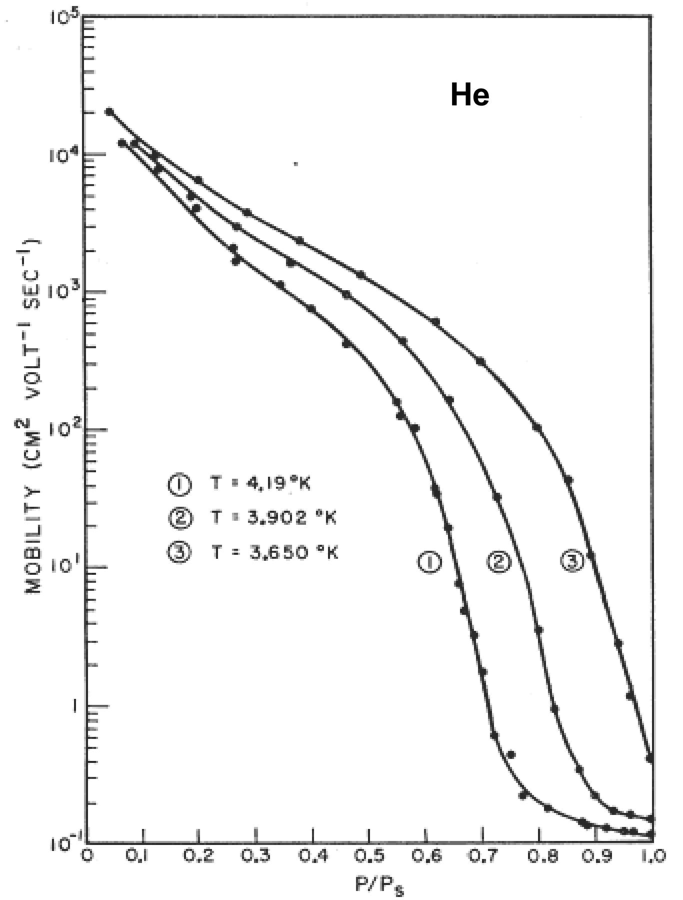
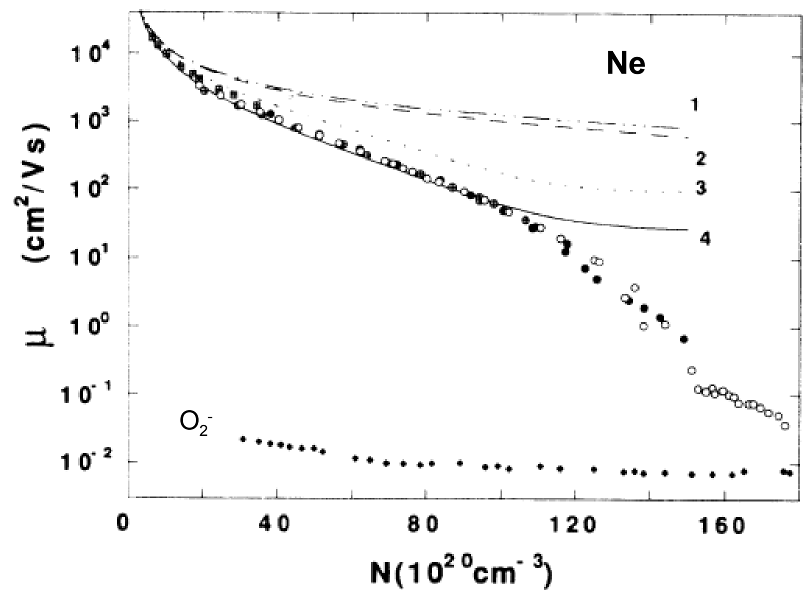


FIG. 5. Mobility versus pressure at constant temperature. The solid curves have no theoretical significance.

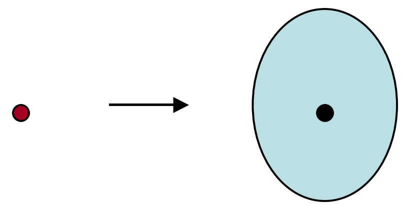
J.Levine and T.M.Sanders, Phys.Rev 145 (1967) 138.



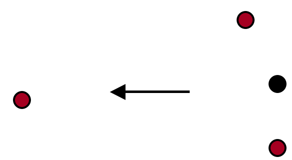
A.F.Borghesani and M.Santini,, Phys. Rev. A42, 7377, (1990).

Compare L Argon to L Helium, H_2

- An electron near a large atom (Ar):



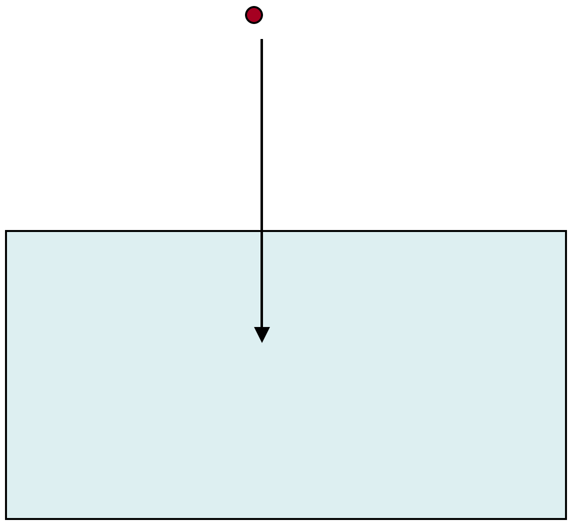
- An electron near a He/H_2 atom (Pauli)



Work Functions

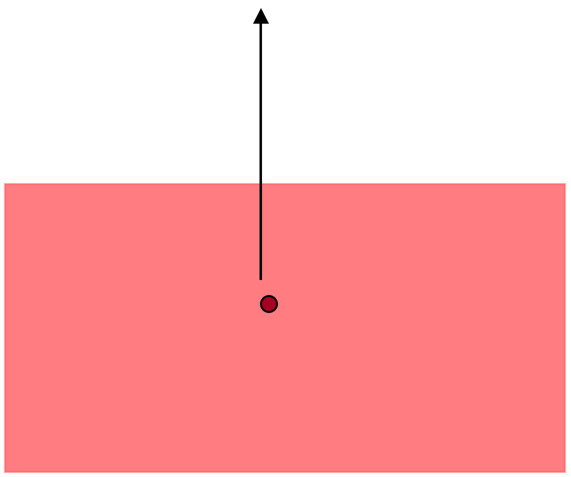
L Argon

W = + 1.4eV



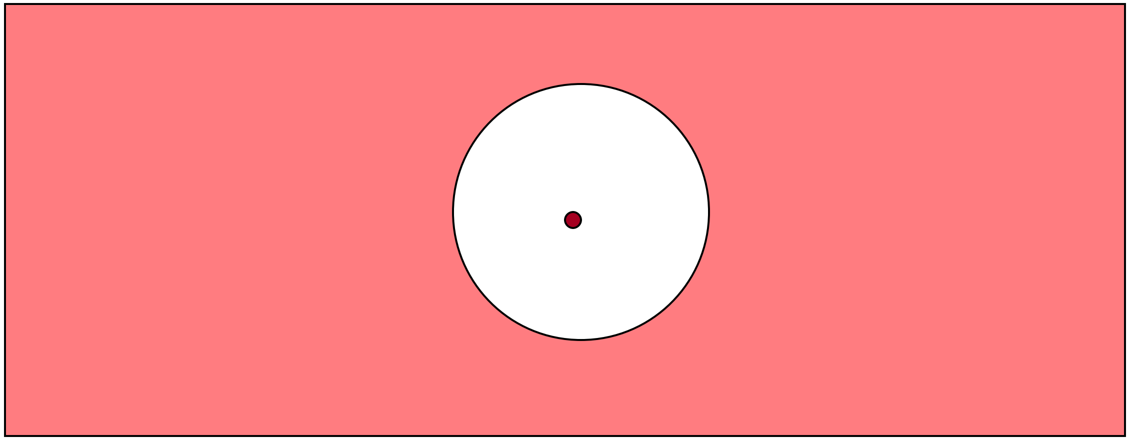
LHe (LNe)

W = - 0.9eV (-0.6)



Fate of an electron in LHe/LNe

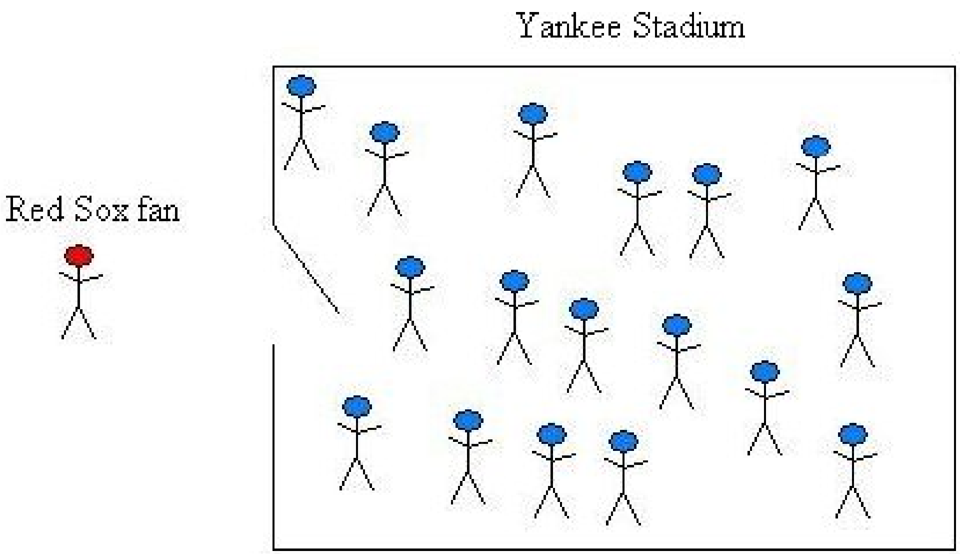
- If an electron is created suddenly in the body of LHe/LNe in the presence of an electric field, it will start to move with a large mobility as in Argon, but the repulsive force with the liquid will soon blow a hole in the liquid, creating a cavity empty of helium/neon atoms, containing only the electron:
- Scale: nanometers; a “mesoscale” object!
- Drift slowly like ions.
- A massive charge carrier, like an ion, remains thermal for much higher E.
- Diffusion is thermally driven; lowering the temperature T cuts diffusion.



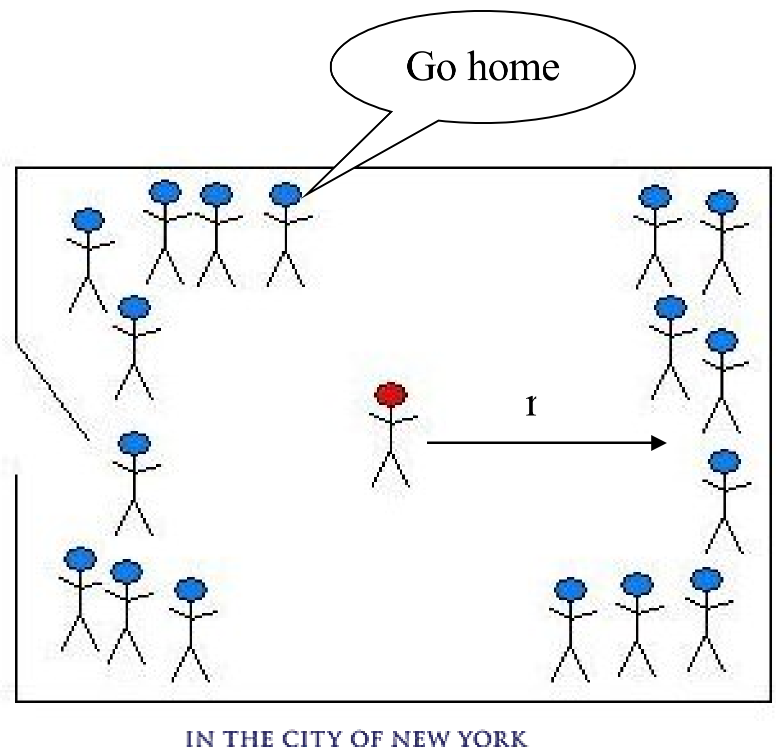
REU ANALOGY! (C.Beal & R.Wilson)

e-Bubbles

… A Social Metaphor



A Red Sox fan enters Yankee Stadium…



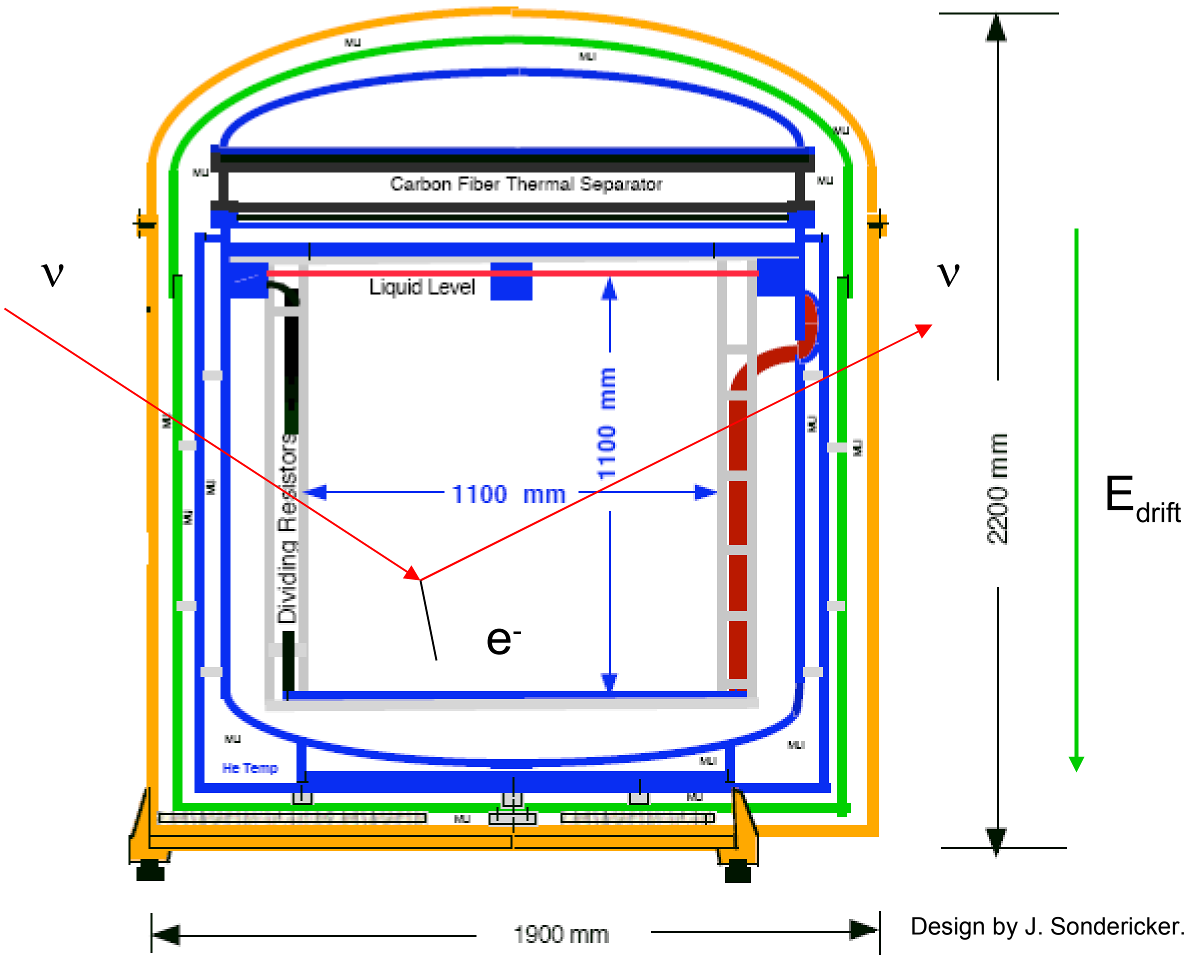
And the “Red Sox Fan”-Bubble phenomenon may be observed…

Ebubble:

1 m^3 phase I Tracker:

$\nu + e^- \longrightarrow \nu + e^-$

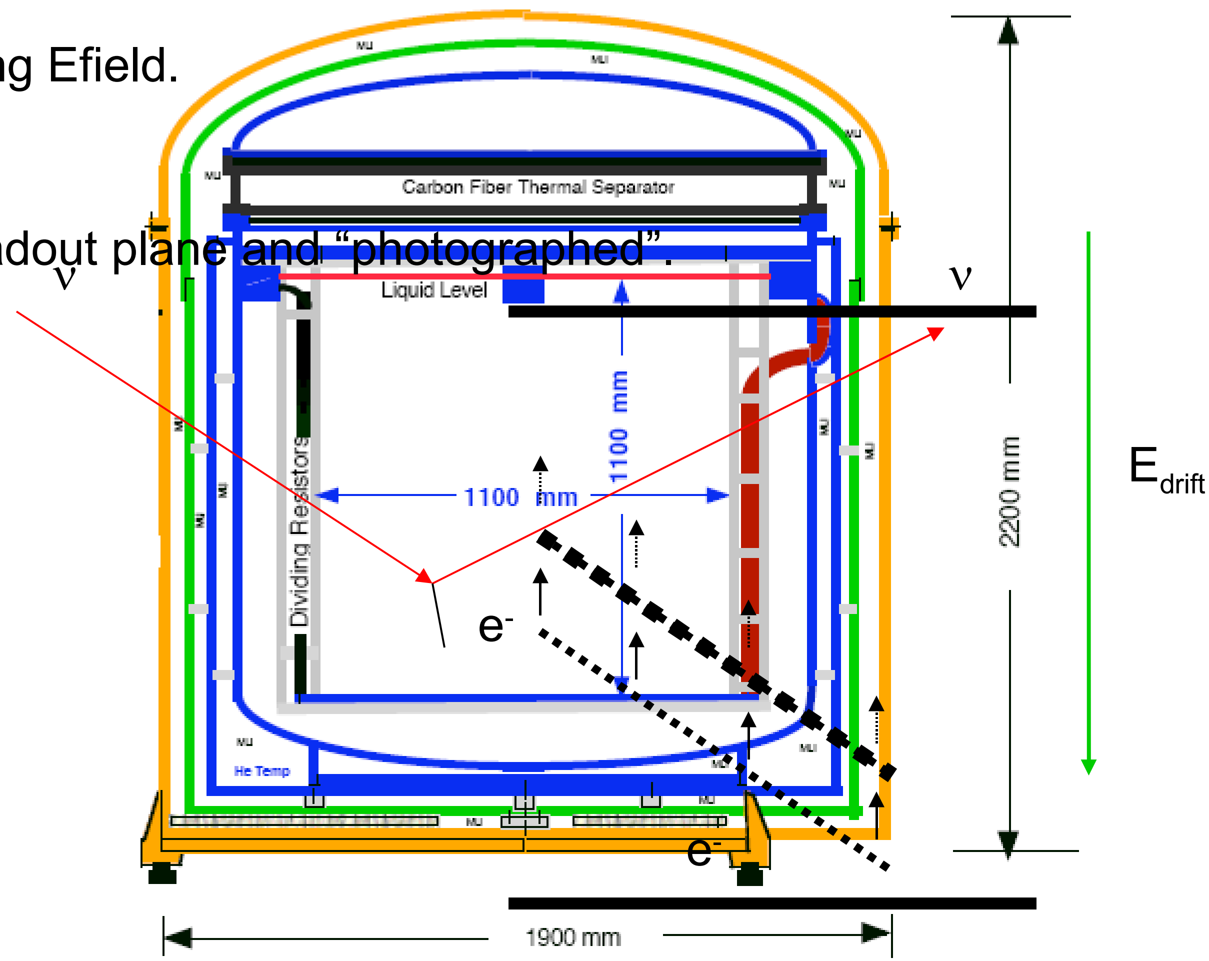
- Detect elastic scattering of neutrinos on target electrons
- image the scattered electron
- Scattered electron ionizes the medium and that charge is drifted to some readout plane



Design by J. Sondericker.

An Event:

1. Neutrino scatters on a target electron.
1. Electron ionizes medium.
1. Ionized electrons drift along Efield.
1. Ebubbles form.
1. Ebubbles drift to some readout plane and “photographed”.



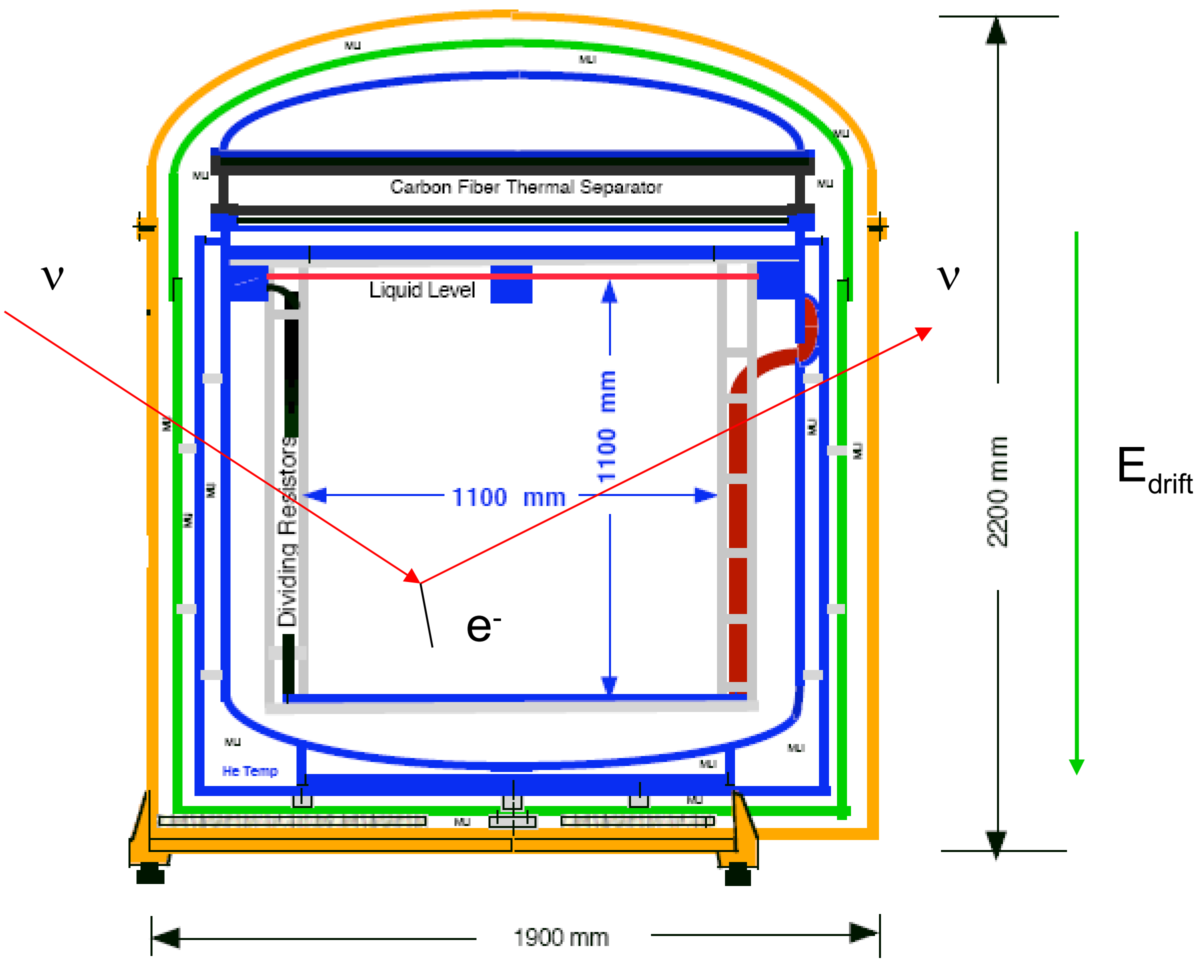
Design by J. Sondericker.

1 m^3 phase I Tracker:

- Readout one voxel worth of charge at a time (image one plane in that time)
- X & Y coordinates from 2D segmented readout plane
- Z (d) coordinate by measuring diffusion

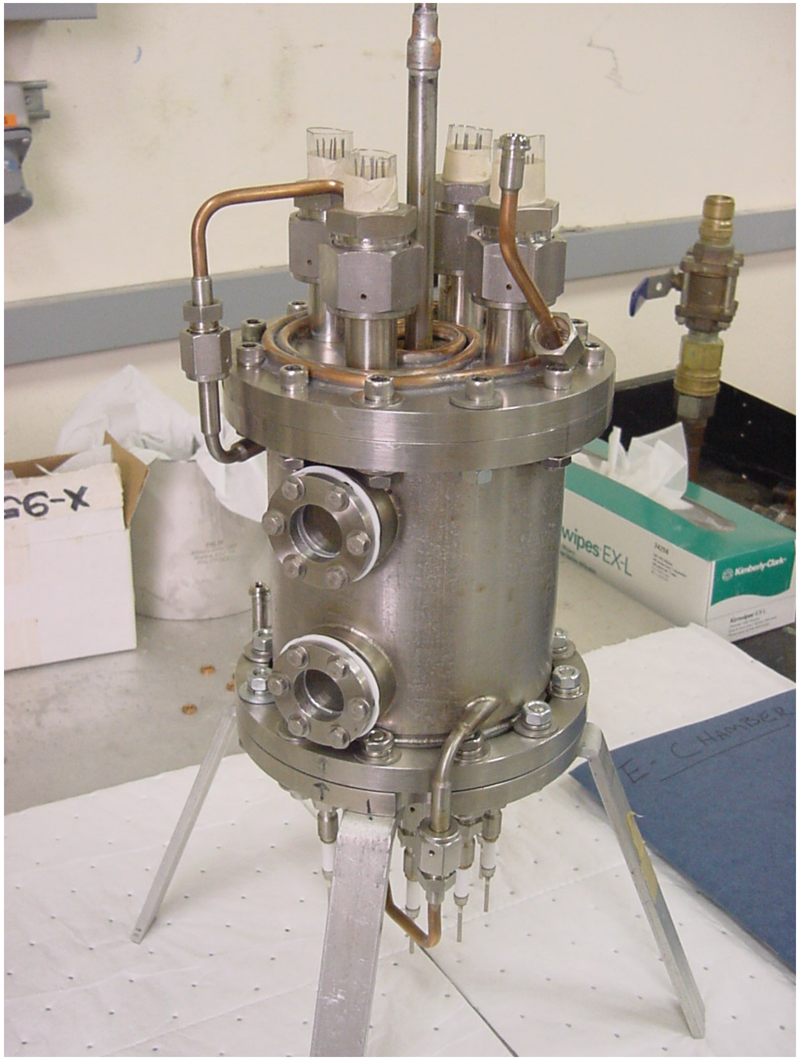
$$=\sqrt{\frac{2kTd}{eE}}$$

- Signals are very small so we need gain (amplify)



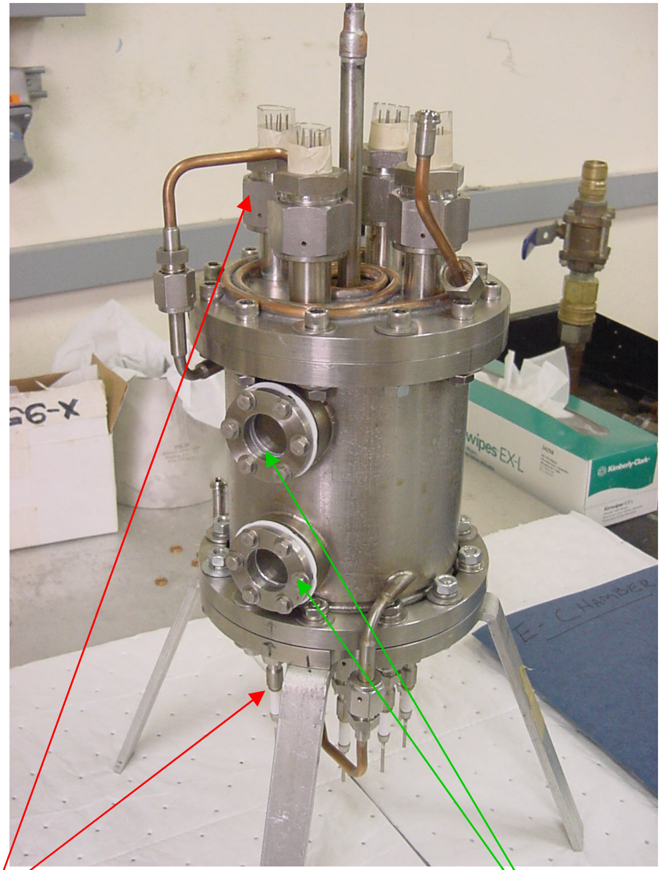
Design by J. Sondericker.

Prototype eBubble Detector



COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

10 cm test cell & cryostat



It is possible to operate at temperatures and pressure over a wide range, ~1K-300K and up to ten atmospheres.

Used to investigate the properties of ebubbles which will give us access to low-energy solar neutrinos.

HV & LV feedthrus

5 Windows

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

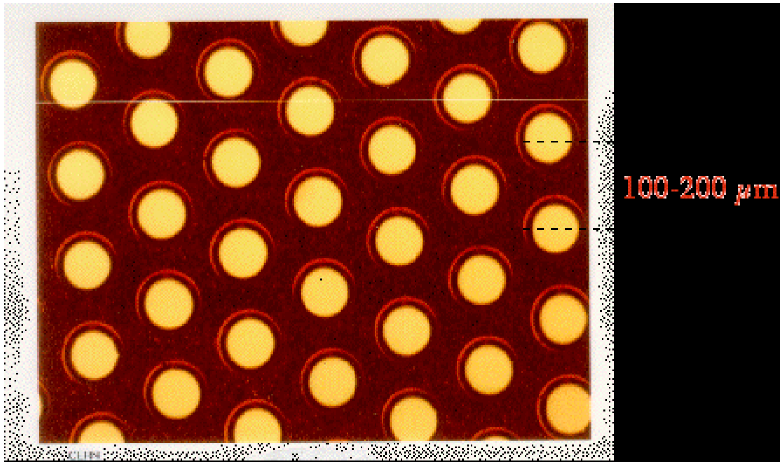
1-phase
(Supercritical)
Dense Gas

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

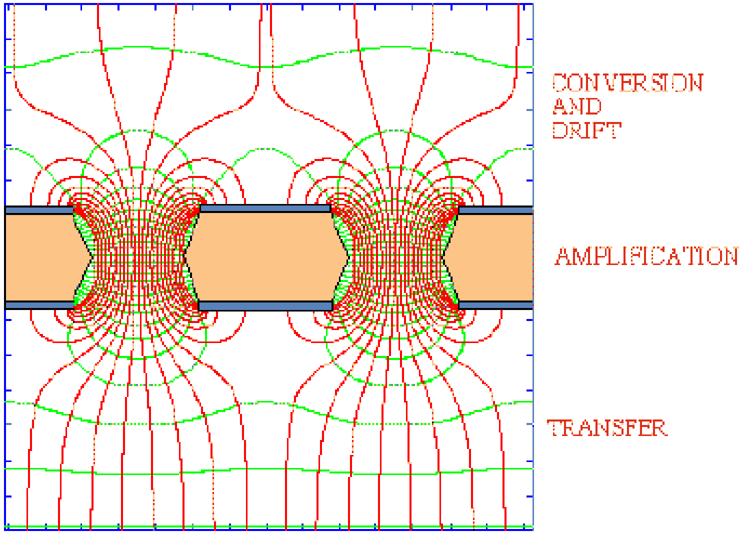
We need GAIN to see O(KeV) electrons

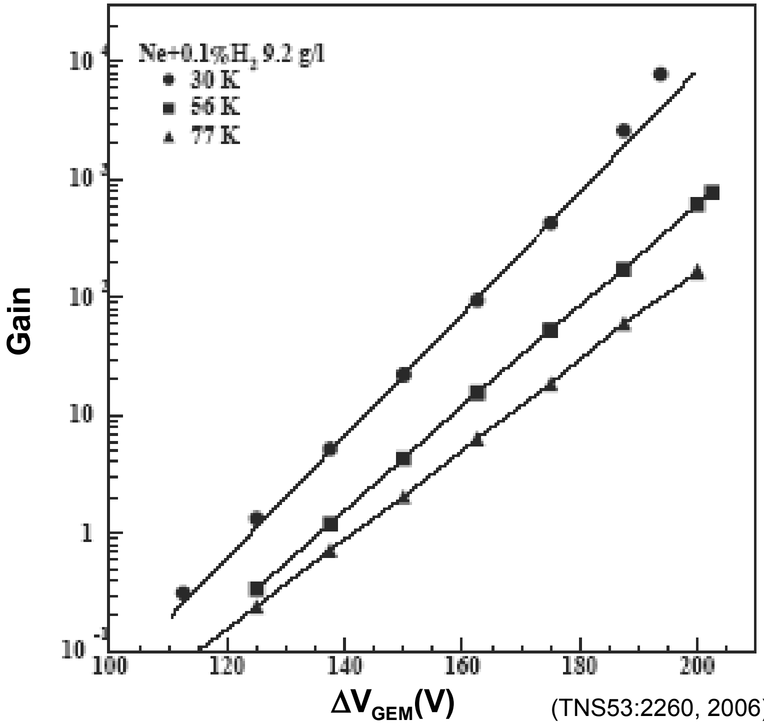
- We need avalanche gain to reach the few KeV threshold required by the physics
- We did not achieve avalanche gain in the liquid.
- We achieved gain in vapor above the liquid, through collaboration with Alexei Buzulutskov at Novosibirsk. Gain in Helium/Neon & Penning mixtures in GEM detectors was achieved.
- We also note that the avalanche is known to produce light, which is intended as our baseline read-out mode.
- This also motivated us to look at the behavior of the electrons at the liquid-vapor interface. Transition time very tunable at a LHe interface and not dynamic at a LNe interface.

GEM readout



Gas Electron Multipliers
- 2D Readout
- mechanically self-supporting
- access to both surfaces of the structure





(TNS53:2260, 2006)

CCD camera, with internal electronic gain

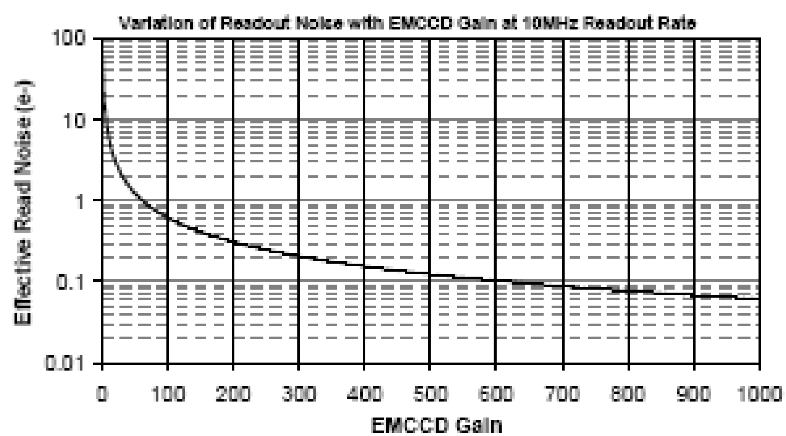
CCD Selection:

Want to be fast enough and sensitive enough to demonstrate the TPC technique using e-bubbles in Critical density Ne (26atm & 44K).

Andor technology:
iXon with EMCCD
DU-897: $34K.

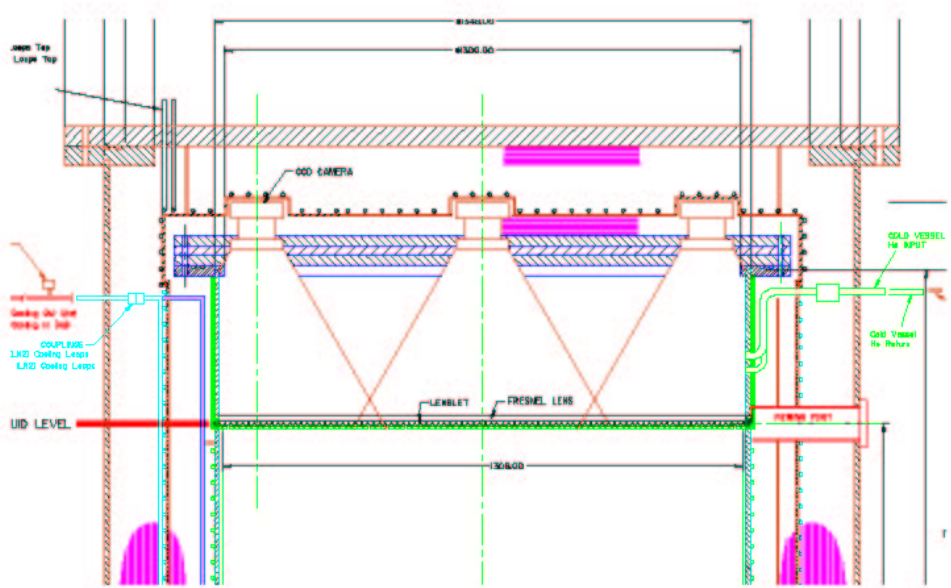
		Full frame rate: (NxN) [Hz]		
DU-897	Pixel size(um)	512x512	256x256	128x128
1x1	16	35	68	132
2x2	32	68	132	248
4x4	64	131	246	439

- Noise & EMCCD Gain



Back Illuminated :
QE=92.5% at 600nm

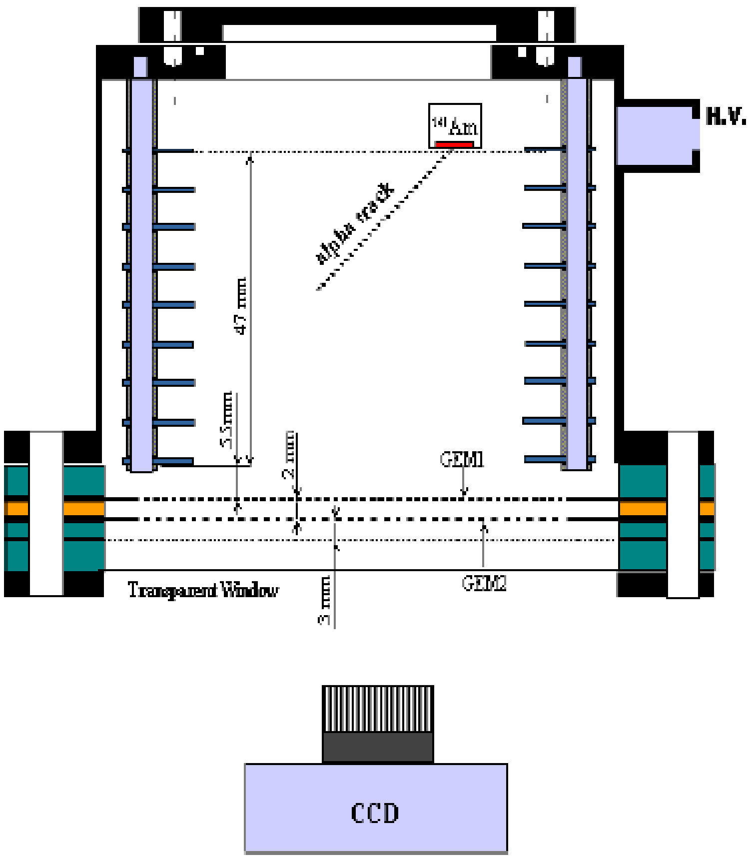
Lenslet optics for GEM readout



Lenslet array, plus Fresnel lens, to focus light from GEM holes onto camera plane.
Optical efficiency ~5%

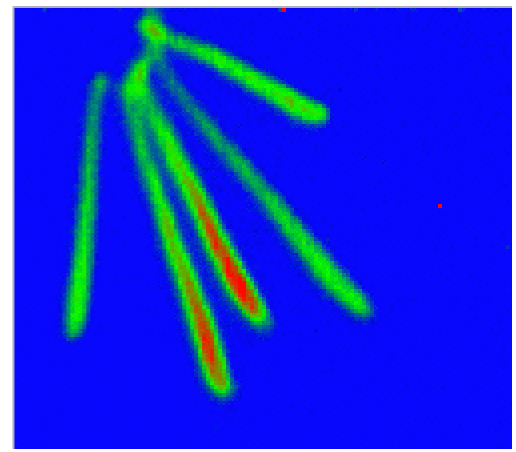
Policarpo et. al.

IEEE Nucl. Sc. Symposium Lyon 2000



Imaged alpha tracks in GEM

- Ar & Ar+CF4 mixtures

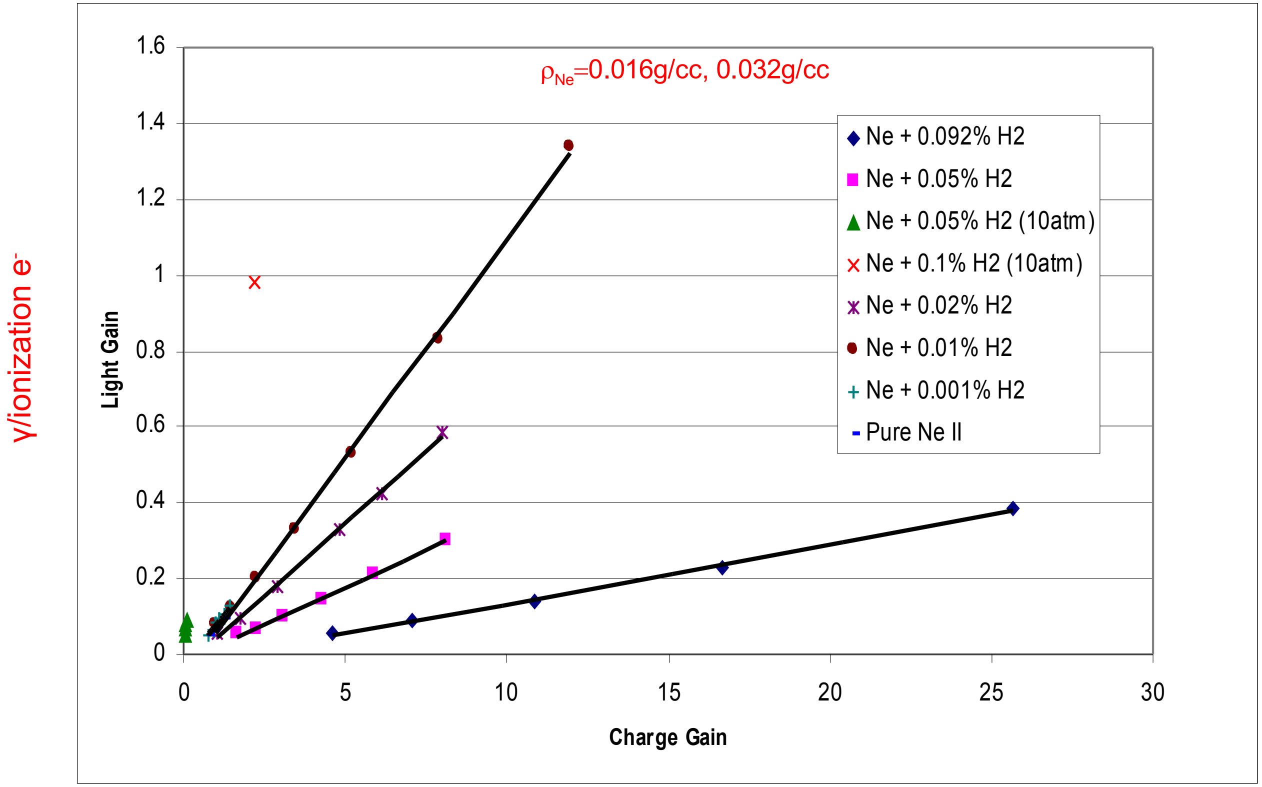


Use light instead of charge:

- long cables to bring out signals add noise
- Standard electronics stopped functioning below 40K.
- Expensive to instrument each GEM hole

Light yield and spectrum

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



**Triple GEM

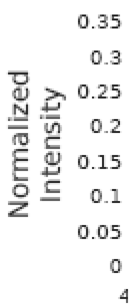
(systematic errors on light yield not included)

- 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)

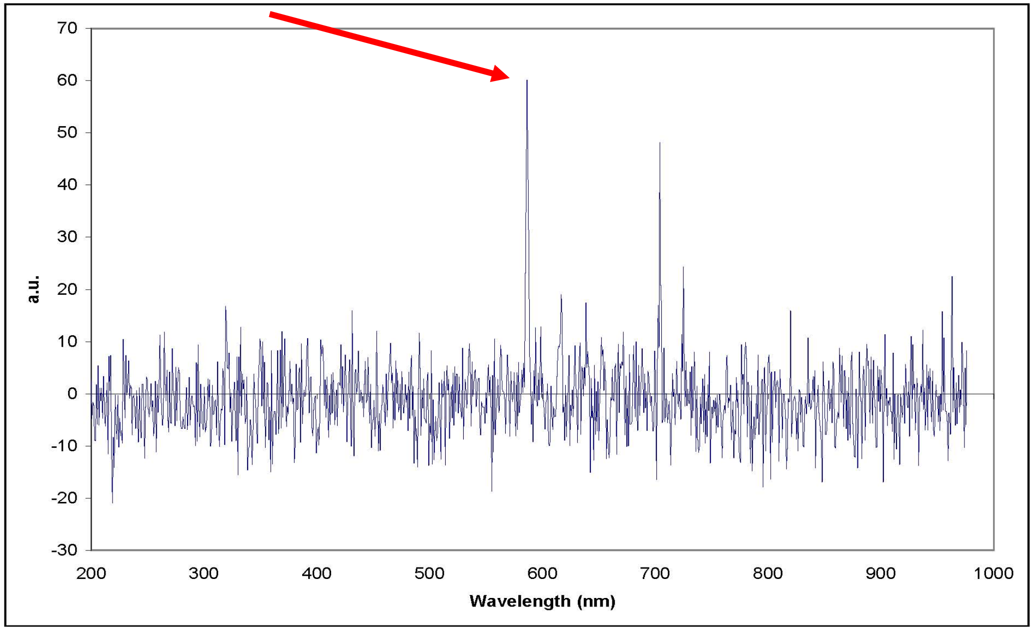
- Use narrow band filters to look at spectrum of visible light using CCD.
- CCD QE~10% at 850nm

-0.01% H_2

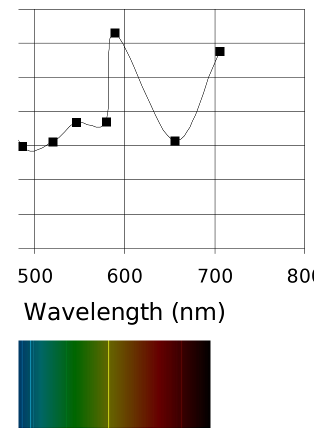
No
M
ver



585nm Main emission line in Ne spectrum @ 77K

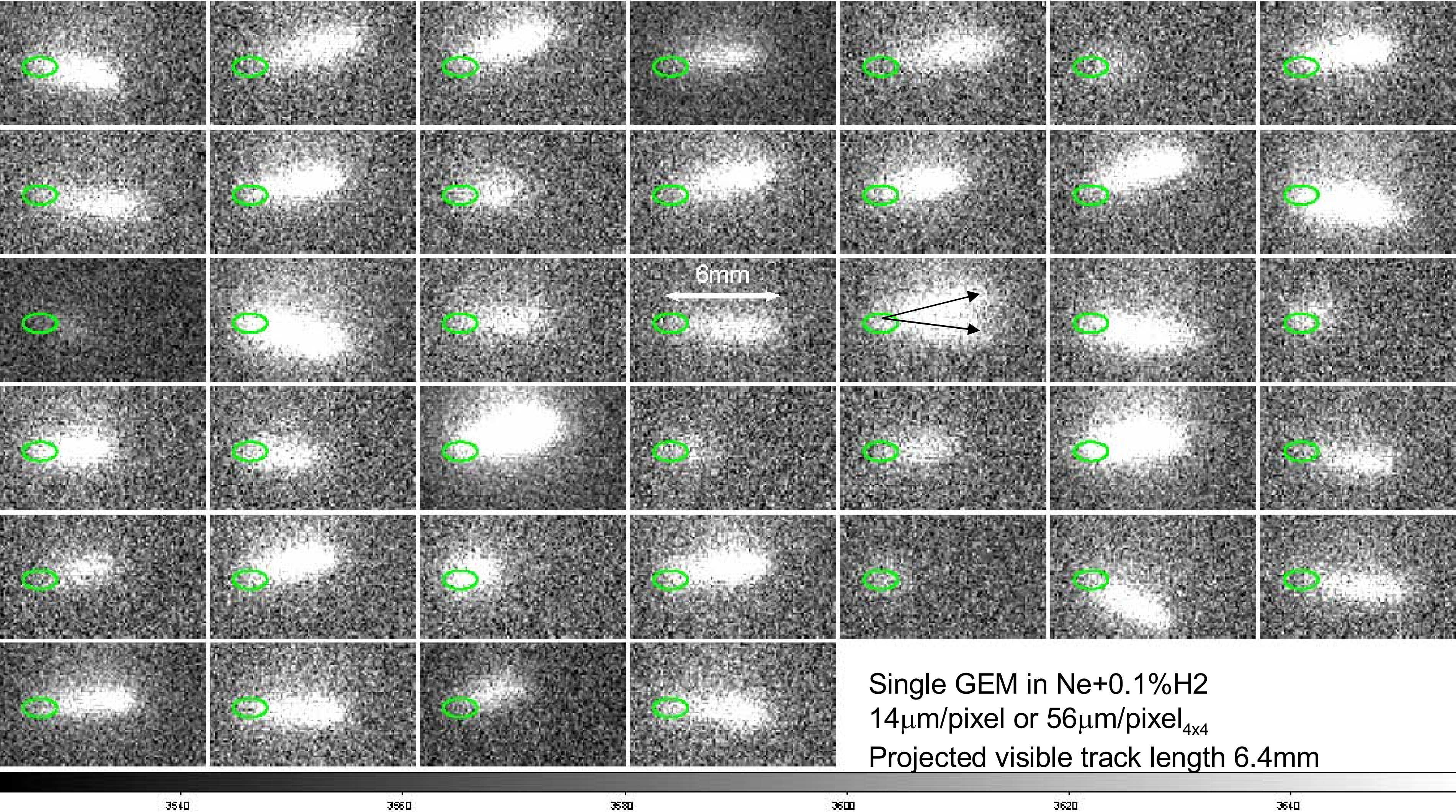


:ed Normalized
Mean Intensity
Wavelength



Conclus

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

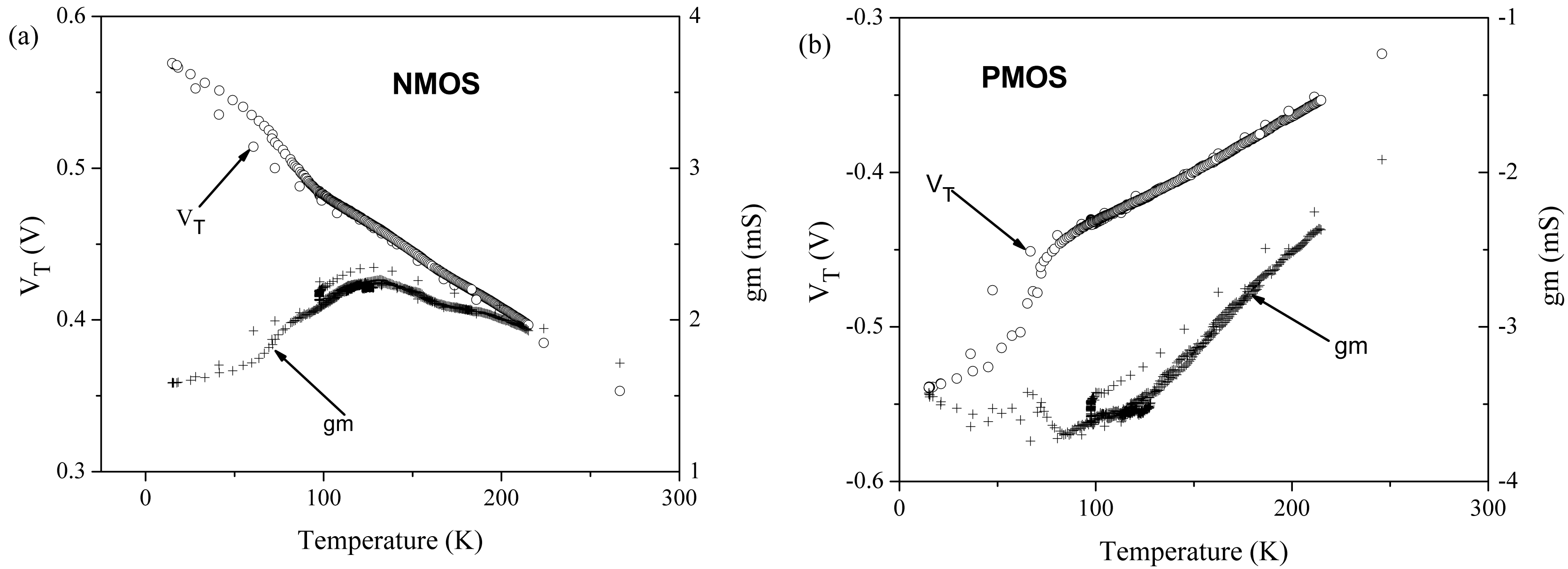


Single GEM in Ne+0.1%H2
14μm/pixel or 56μm/pixel$_{4x4}$
Projected visible track length 6.4mm

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.
  - No localization of electrons in these conditions so diffusion is not thermally driven.

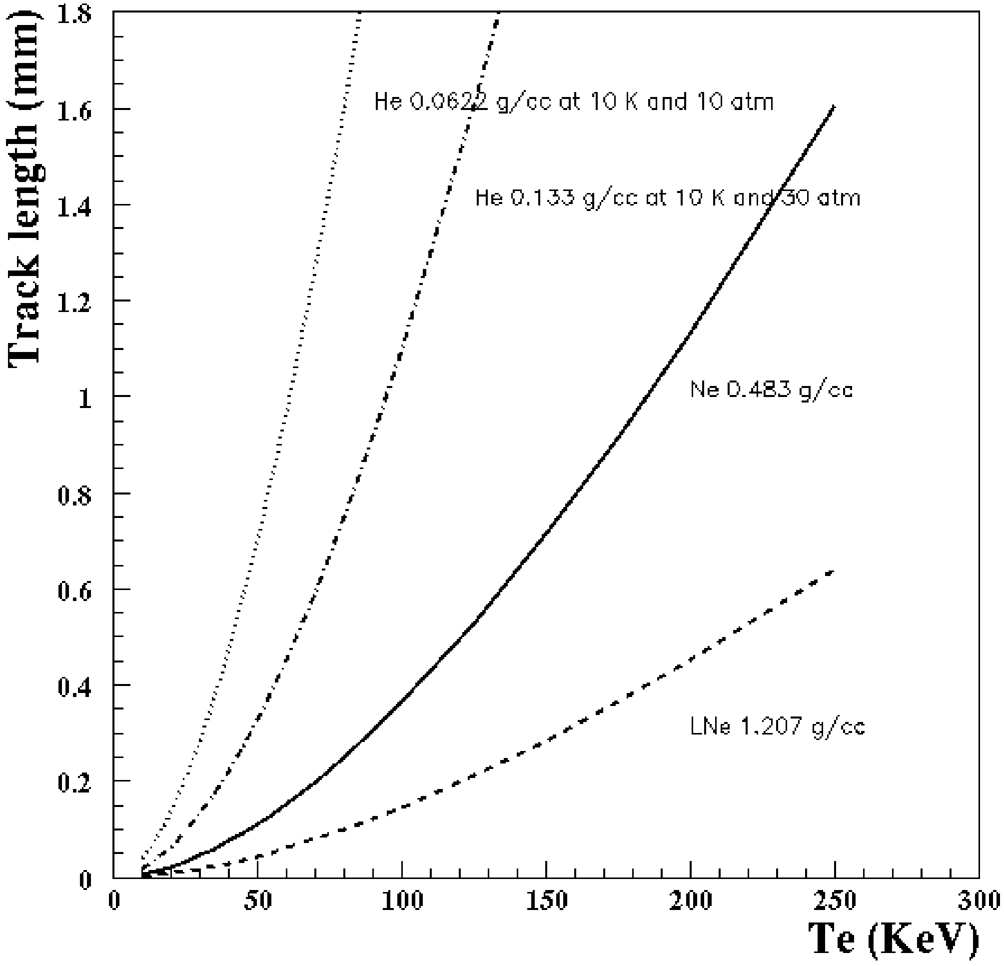
Electronics aside:
Development of cryogenic SoS-based 0.25μm electronics performance



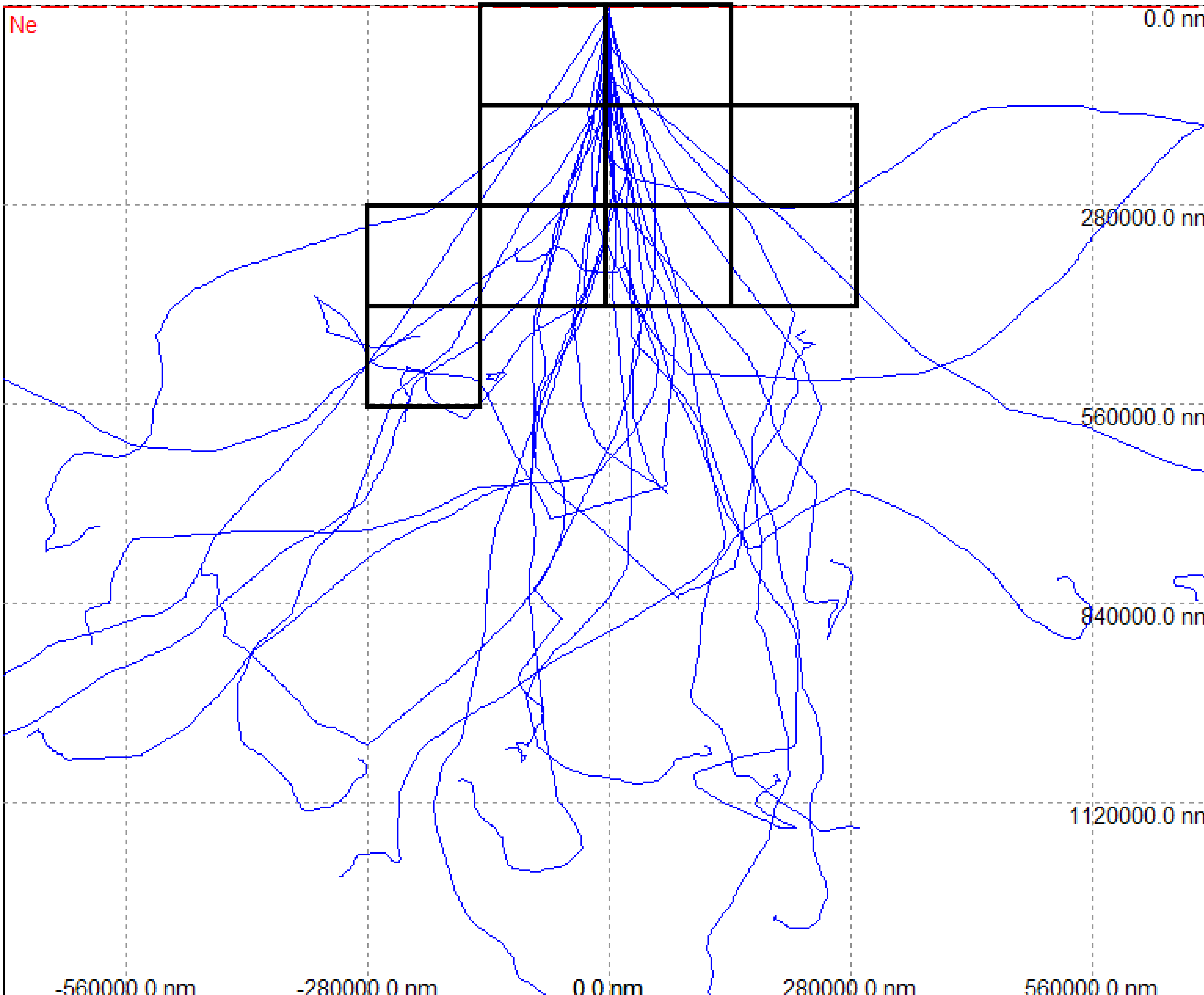
The threshold voltage (V_T) and transconductance (gm) as functions of temperature of NMOS (a) and PMOS (b) transistors.

- All transistors survived multiple cooling cycles down to 11K and any variations were within manufacturing tolerances.
- Circuit: Ring oscillator functioned down to 20K.

Range for 250keV recoil electron

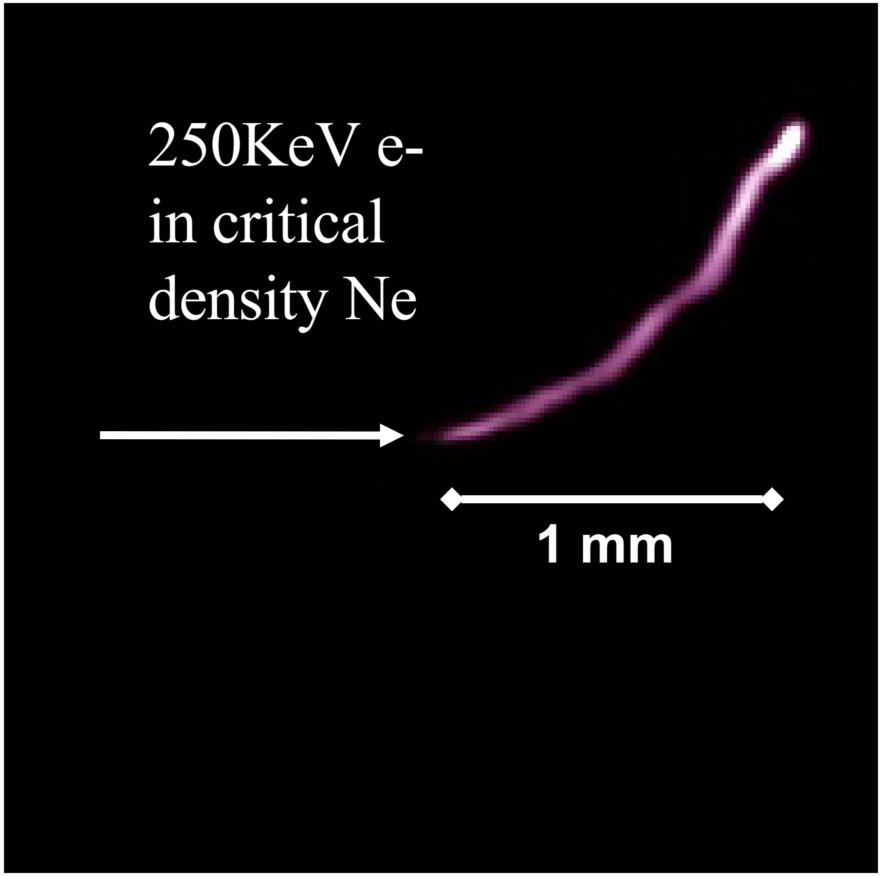


Visualization Casino simulation of 25 events in 0.483g/cc of Ne

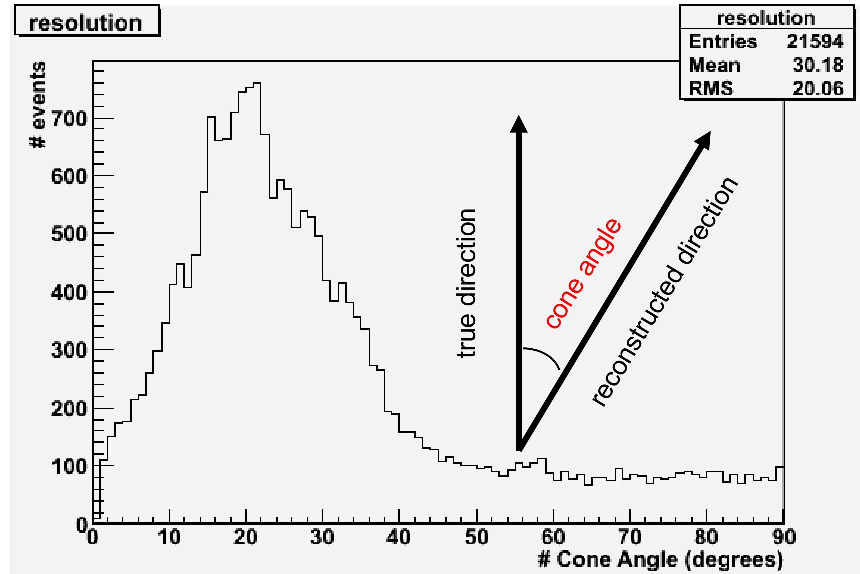


Sim track

Simulation of electron tracks



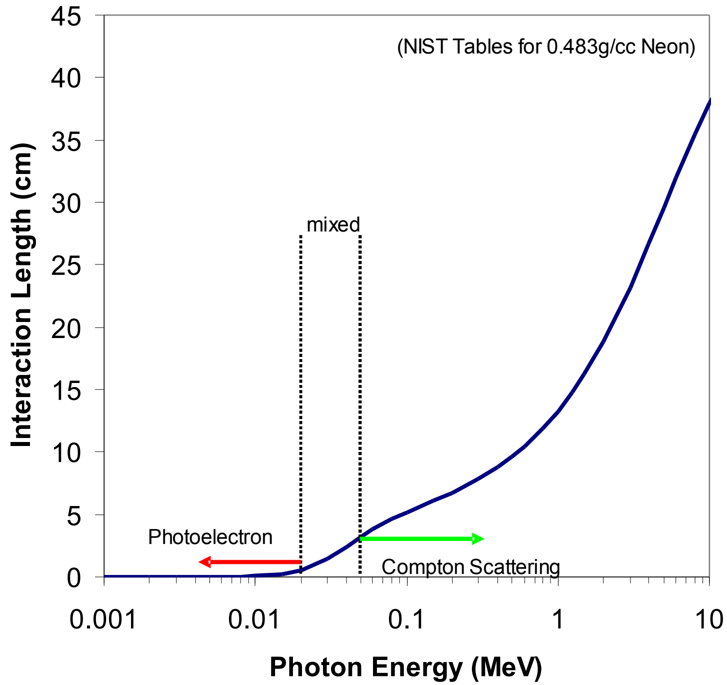
- Fit projections xy, yz, xz. errors weighted by energy of pixels/total
- first 3 or 4 hits



Compton Background vs Energy

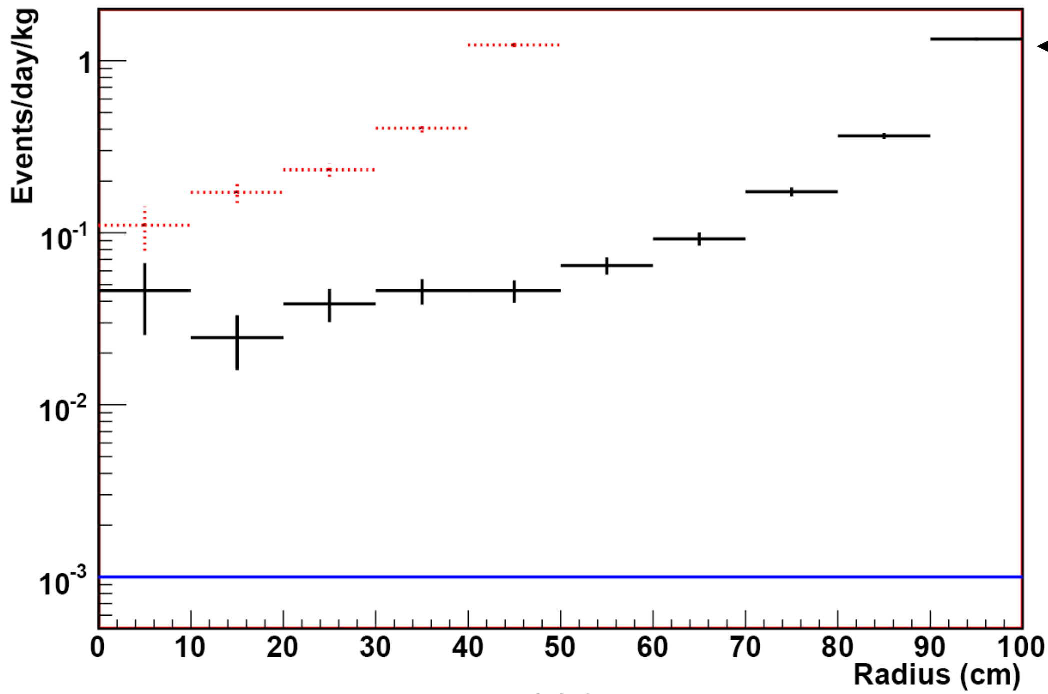
- Even though we have a high flux, the interaction cross sections are small so the detected event rates will be small.
- What are the sources of main background?
  - Cosmic radiation – Add shielding/go deep underground
  - Natural radioactivity in ground and air – Purity
- Whatever isn't removed can it still be identified!
  - Unique signatures in detector
    - (He) Tracks pointing to the sun are signal.
    - (Ne) Dense enough to act as it's own shield.

Identify Compton clusters
• an MeV γ will typically Compton scatter multiple times.



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

- Backgrounds from MeV γ's with improbable single KeV electron scatters



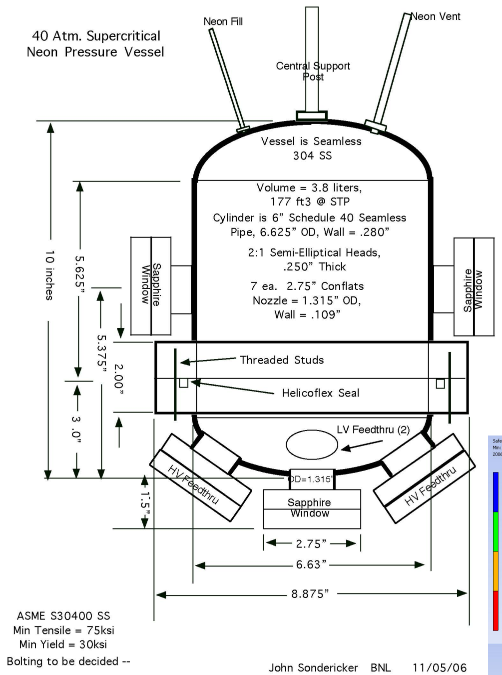
1.5"SS with 0.6ppb Th232

Expected pp solar ν signal

Instrumented to R=100cm

Instrumented to R=50cm

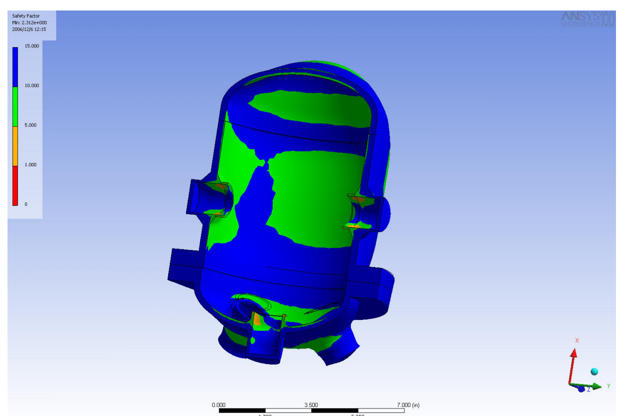
Upgrade of present system to allow wider pressure range



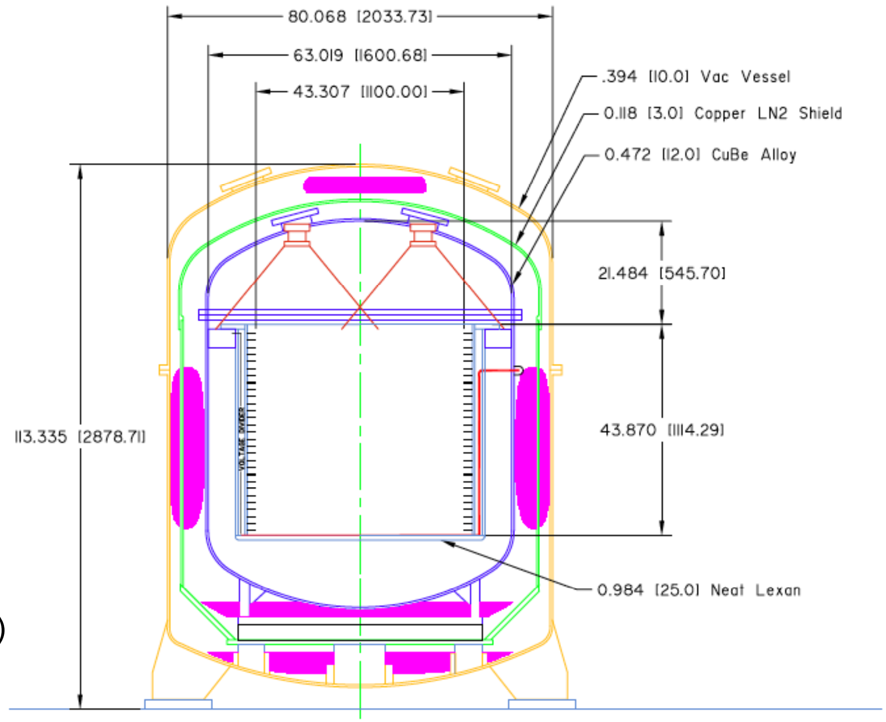
Design of small 3.8 litter High pressure cold vessel.

Compatible with present setup.

Finished in December ’07.



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

Near Term Program: Demonstrate TPC technique

- 36eV of ionization gives 1 e^--ion pair
- measure under baseline conditions

- GEM avalanche gain $>10^3$
- measure under baseline conditions

- 1 photon per avalanche e-
- measure under baseline conditions

- Geometric acceptance 10^{-3}

results in ~40 eV of ionization gives 1 photon in the camera acceptance

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- Optical efficiency with microlens <6%
- R&D on microlens

results in ~40 eV of ionization gives 10 photons in the camera acceptance

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