Measurements of the Intrinsic Quantum Efficiency and Visible Reemission Spectrum of Tetraphenyl Butadiene Thin Films for Incident Vacuum Ultraviolet Light

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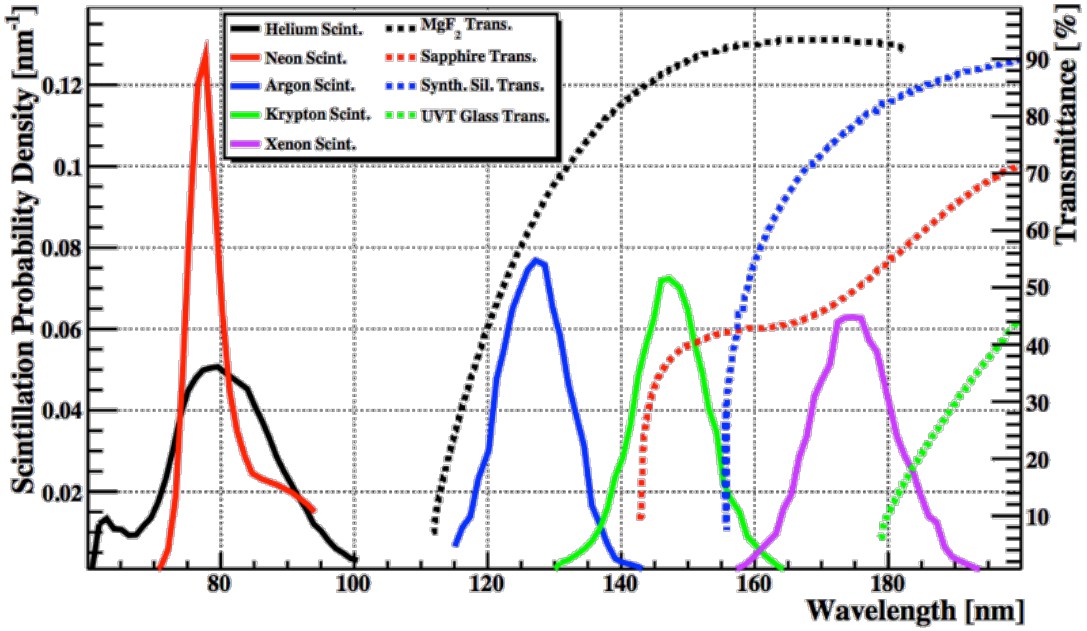
Noble Liquid Detectors

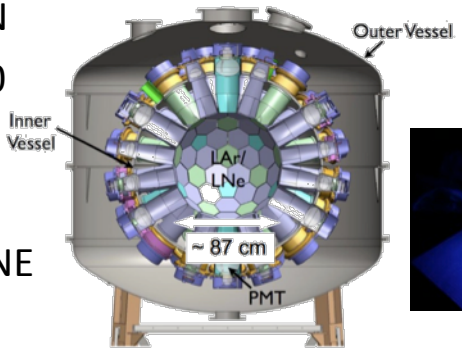
- Scintillation/Ionization Target Medium
  - Low energy threshold
  - High light yield
- Scalability
  - Readily available
  - Commercially available purification systems
- Pulse Shape Discrimination
- Single or dual phase

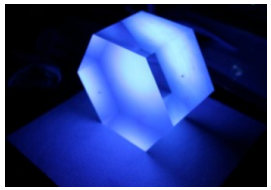


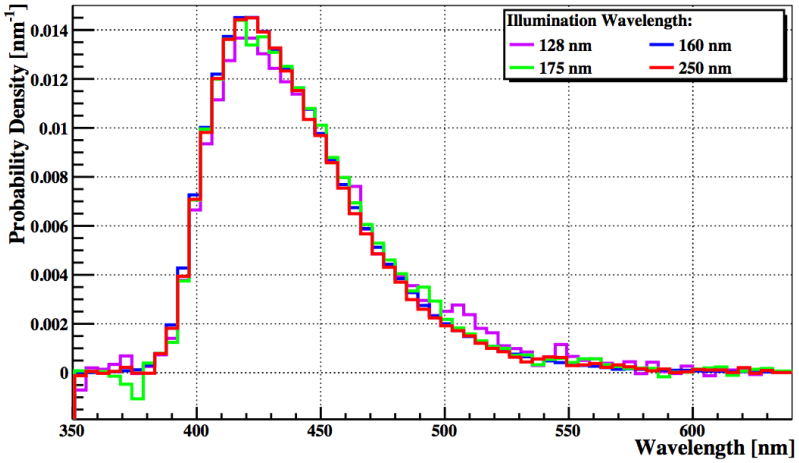
Gehman et al., Nucl. Instrum. Meth., A654:116-121, 2011

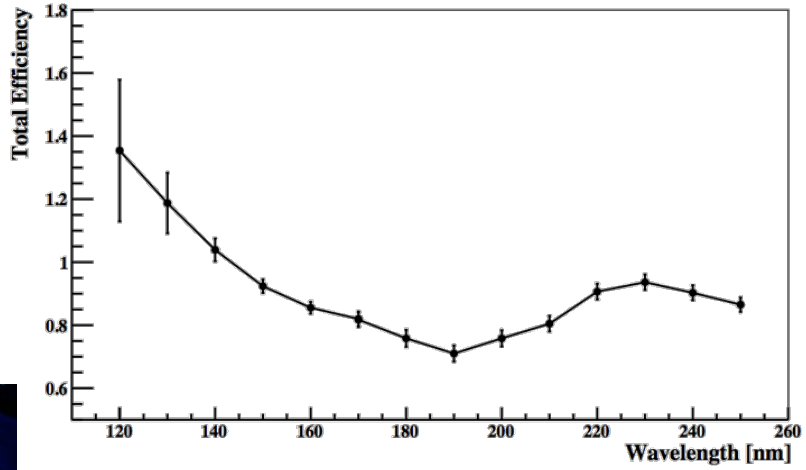
Tetraphenyl Butadiene (TPB)

- TPB is a common wavelength shifter in neutrino and dark matter physics experiments
- It absorbs UV light and reemits in the visible spectrum
- Used to convert UV scintillation light to visible light for detection with photomultiplier tubes (PMT).
- A few of the collaborations using TPB:
  - MiniCLEAN
  - DEAP 3600
  - DarkSide
  - DUNE
  - MicroBooNE









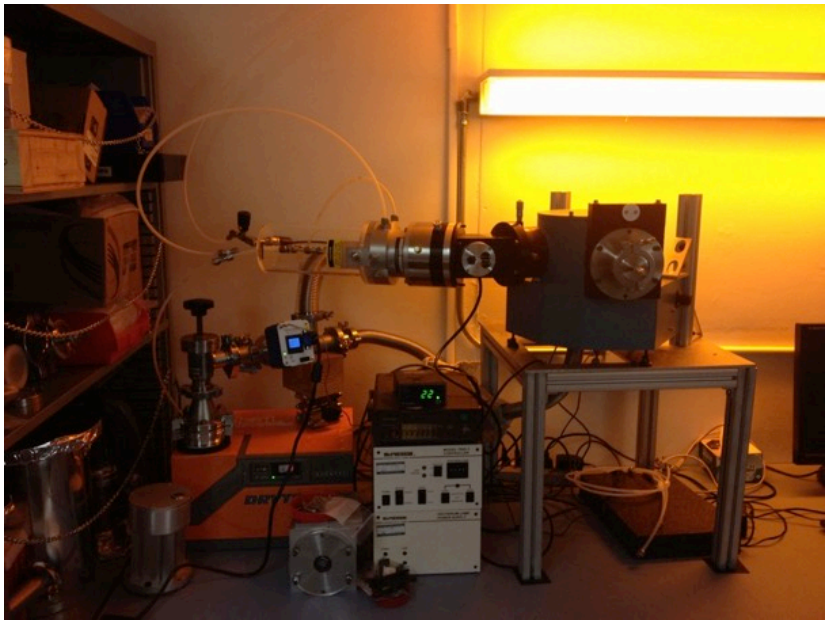
Gehman et al., Nucl. Instrum. Meth., A654:116-121, 2011

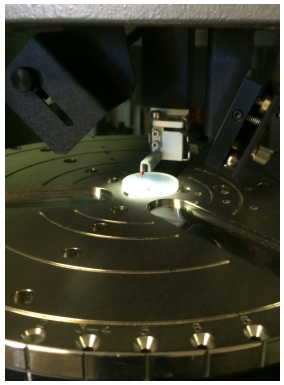
Results to be Presented

- Reemission Spectrum of TPB from 45 to 250 nm
- Absolute Wavelength Shifting Efficiency (WLSE) of TPB
  - As function of sample thickness and incident VUV wavelength (45 to 250 nm)
- Intrinsic Quantum Efficiency (QE) Extraction
  - Using a microphysical Monte Carlo simulation and thickness dependence of WLSE to extract QE of TPB

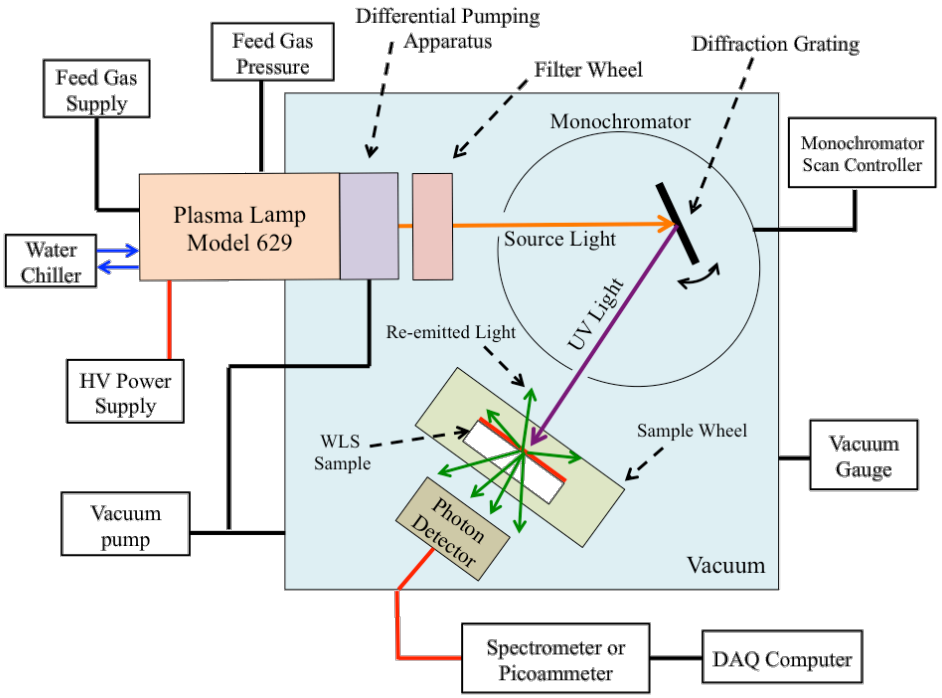
Details of this work can be found in arXiv article 1709.05002

Experimental Apparatus and Sample Fabrication





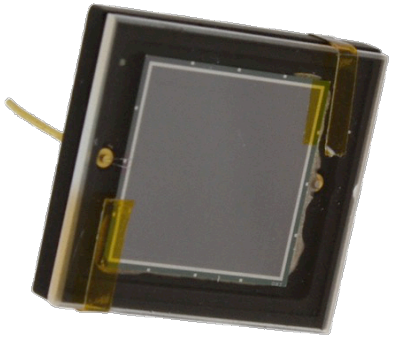
Sample fabrication performed used equipment in Molecular Foundry at LBL and Dr. Dan McKinsey Lab at UC Berkeley



Key Points:

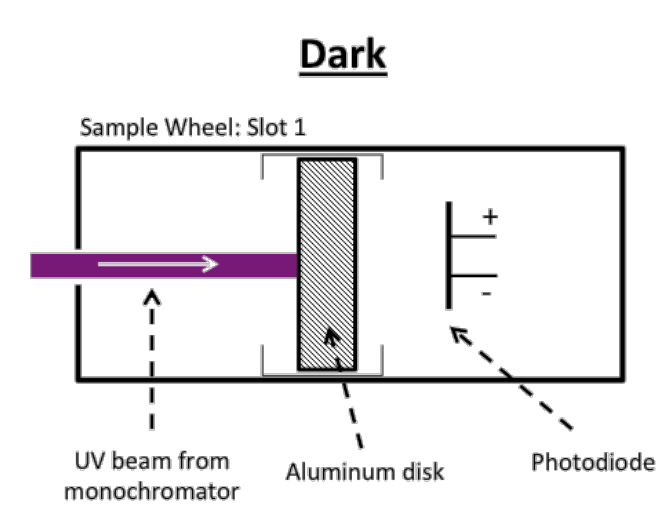
- Broad spectrum UV and visible light emitted by lamp and focused onto diffraction grating in a monochromator.
- Select UV wavelength with diffracting grating and expose samples.
- Collect remitted photons from WLS.

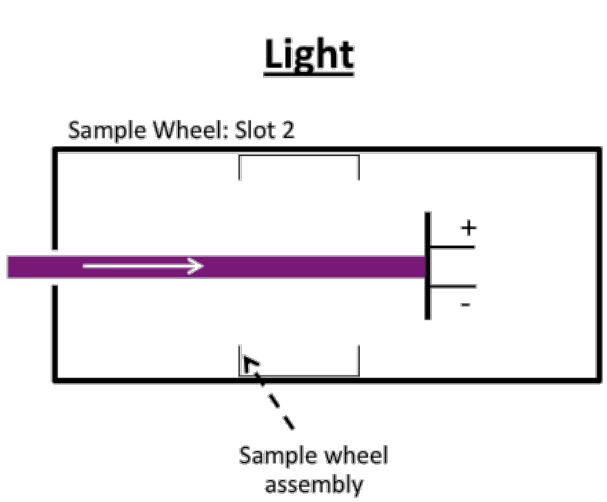
Photon Detection

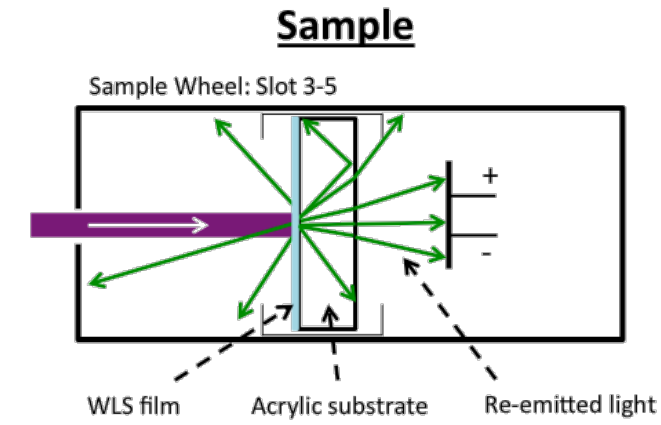


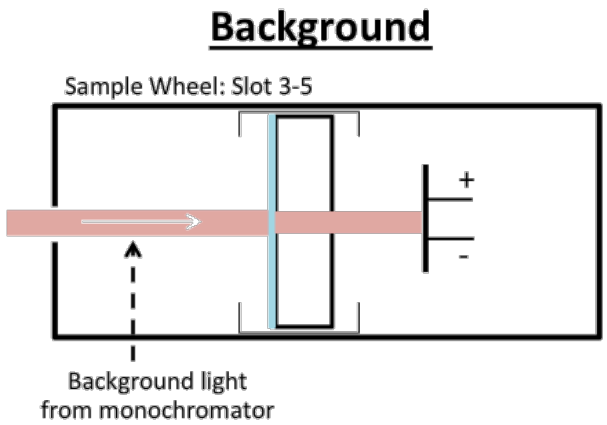
UV Photodiode
Opto Diode - AXUV 100G
1 cm x 1 cm active area
NIST Calibrated Response
50 to 1100 nm

Spectrometer
Ocean Optics - QE65000
Range = 200 to 1000 nm

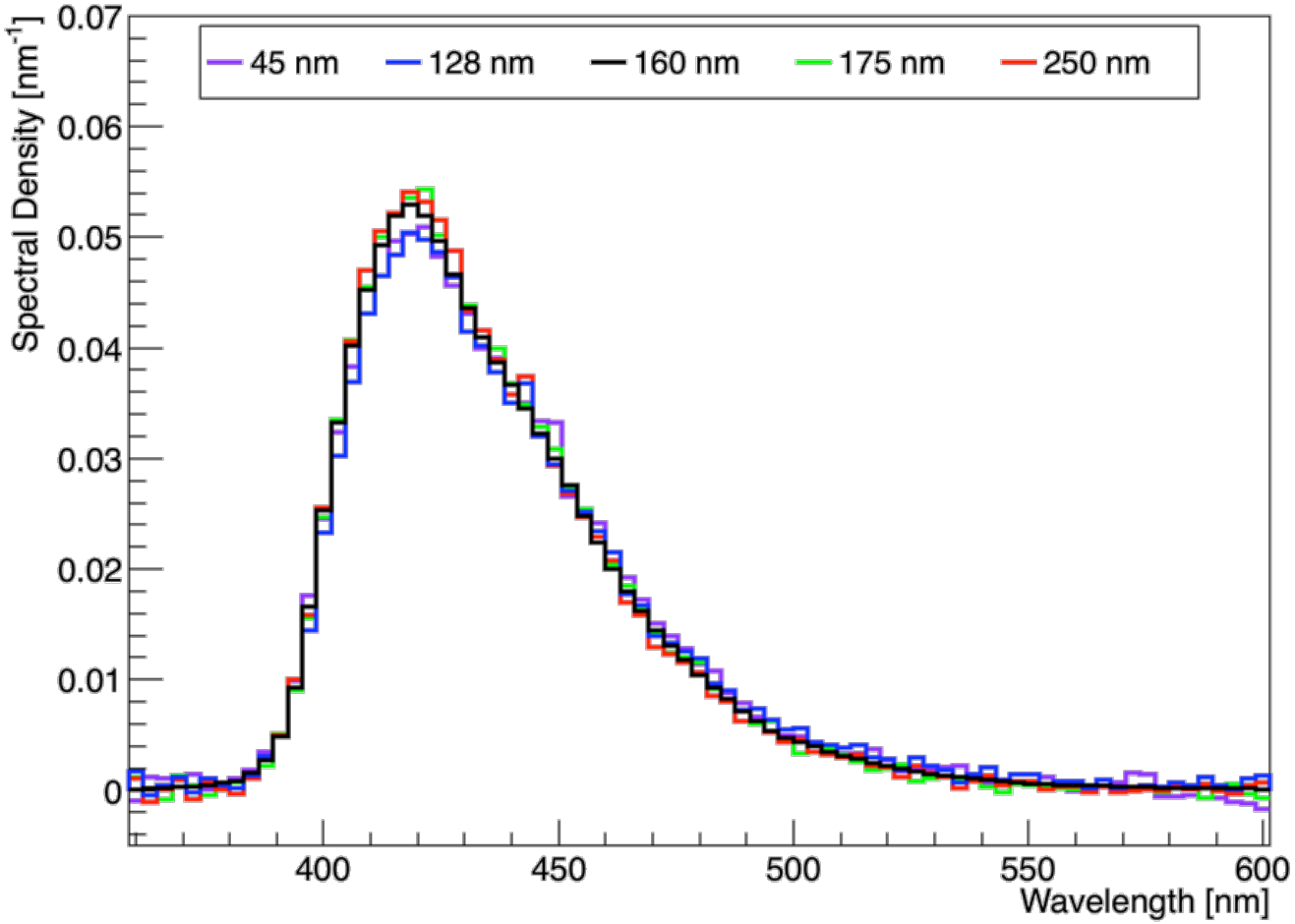








TPB Reemission Spectrum



Measured TPB Reemission spectrum for a 1.8 μm thick TPB sample for several choices of incident light.

Evaluating the Absolute Wavelength Shifting Efficiency

Reemitted Light Photocurrent

Dark and Background photocurrent corrections

Photodiode Response

Incident light Spectrum

$$\beta_{i,exp}(\lambda) = \frac{I_{\mathrm{TPB}}(\lambda) - I_{\mathrm{corr}}(\lambda)}{I_{\mathrm{light}}(\lambda) - I_{\mathrm{corr}}(\lambda)} \times \frac{\int d\lambda' \frac{hc}{\lambda'} R(\lambda') M(\lambda - \lambda')}{\int d\lambda'' \frac{hc}{\lambda''} R(\lambda'') P(\lambda'')}$$

Photon Ratio

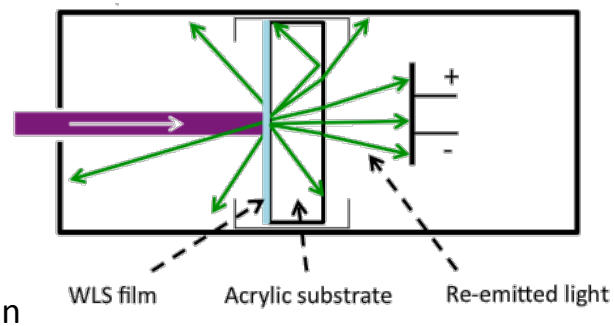
Incident Light Photocurrent

TPB Reemission Spectrum

$$\varepsilon_i(\lambda) = \beta_{i,exp}(\lambda) \times \frac{1}{A_i}$$

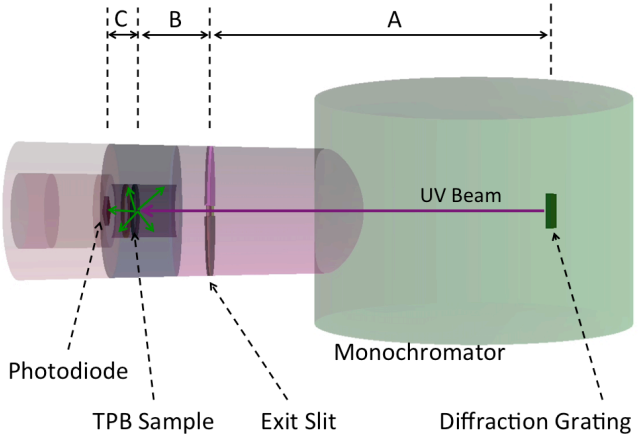
Absolute WLSE

Geometric Acceptance Fraction Determined from simulation

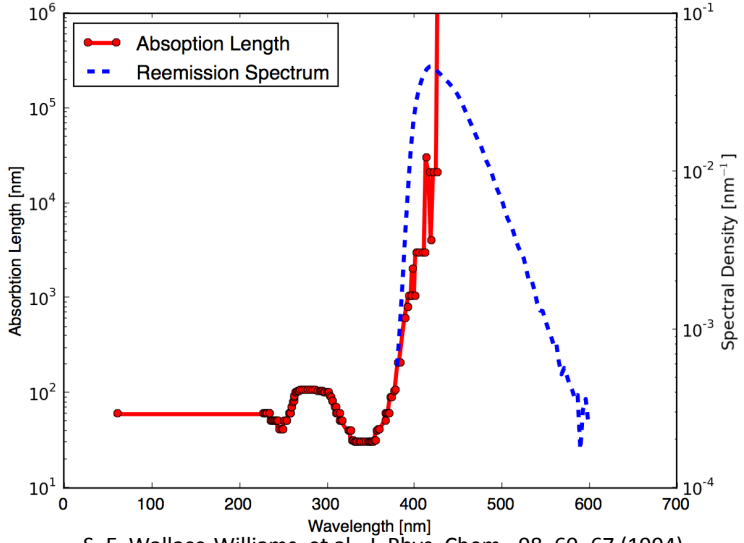


Monte Carlo Simulation

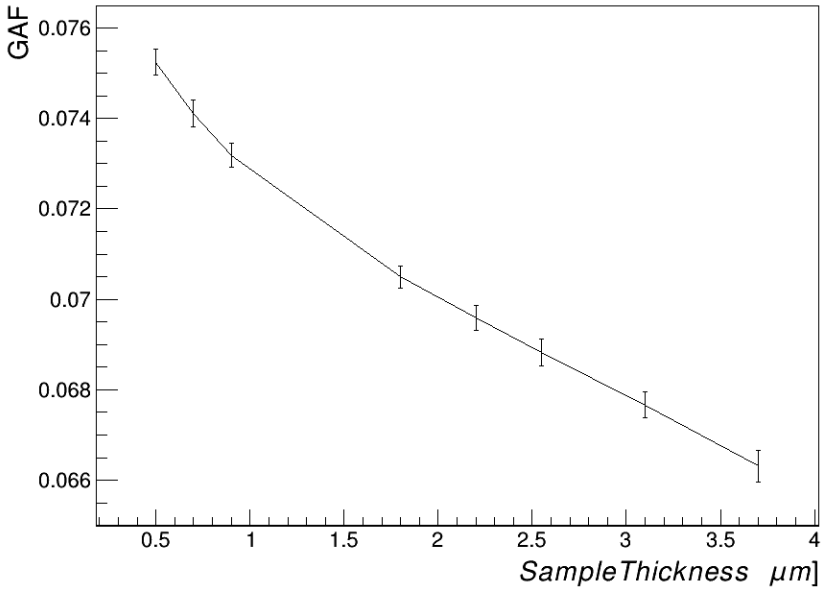
A detailed Geant4-based microphysical simulation of the setup and TPB is performed using MiniCLEAN RAT.



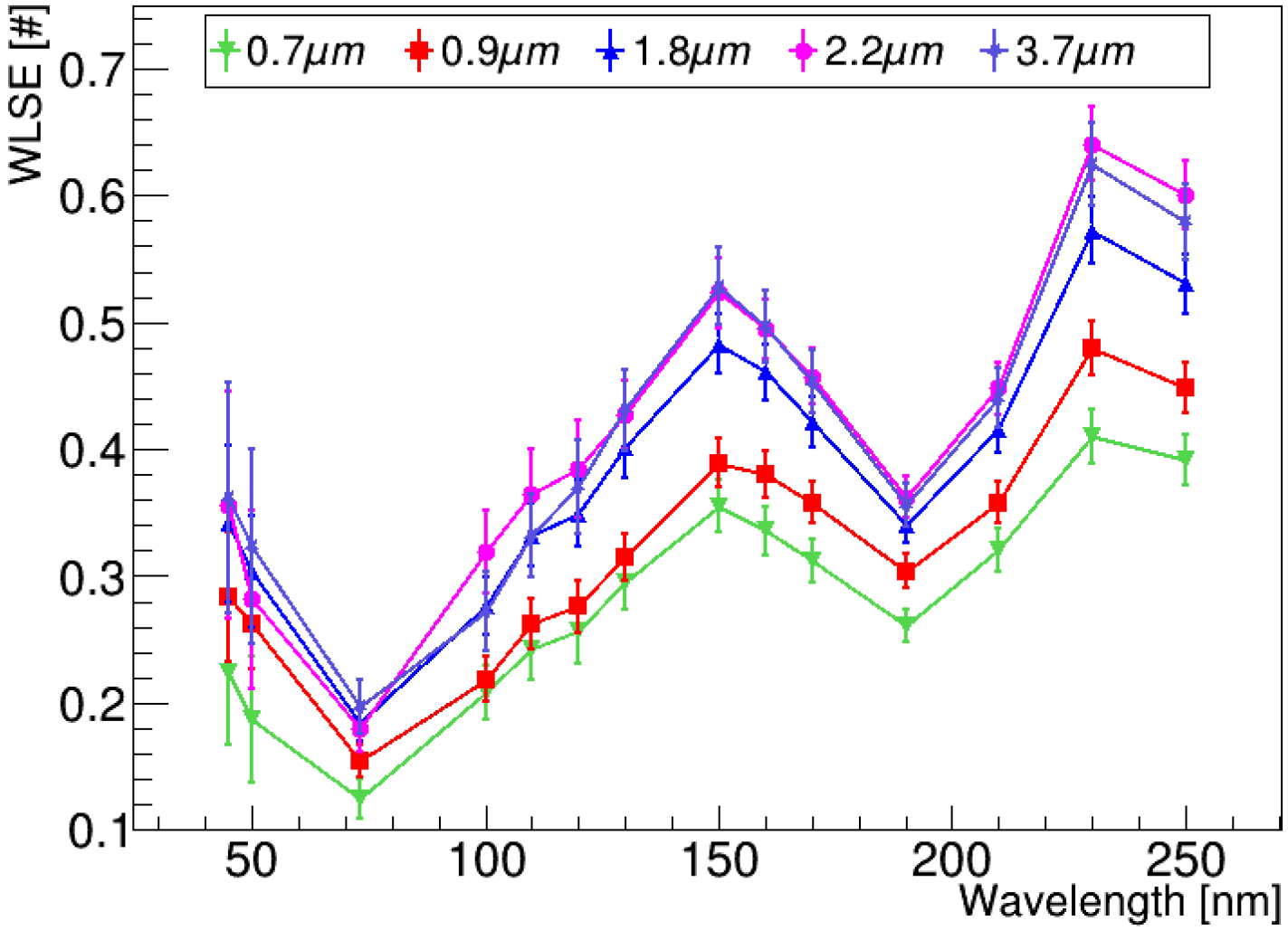
- TPB is modeled as a solid and uses optical parameters from the literature.
  - TPB intrinsic QE is the only free parameter in simulation
- The simulation is used to:
  - Determine the geometric acceptance fraction
    - Depends on sample and setup optics
  - Calculate a photon ratio for direct comparison to data. Provides a way to extract preferred QE



S. E. Wallace-Williams, et al., J. Phys. Chem., 98, 60–67 (1994).

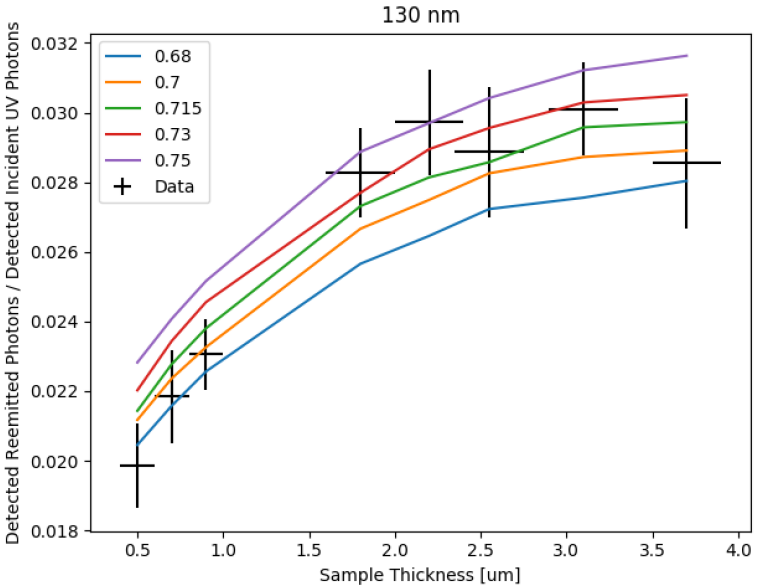


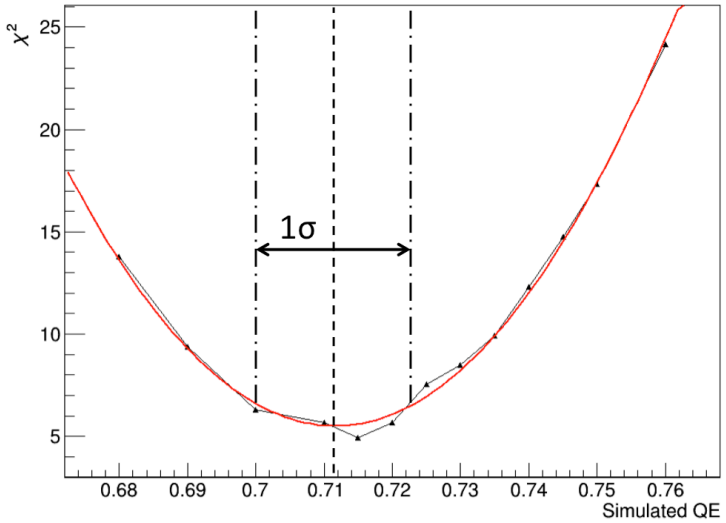
Absolute Wavelength Shifting Efficiency



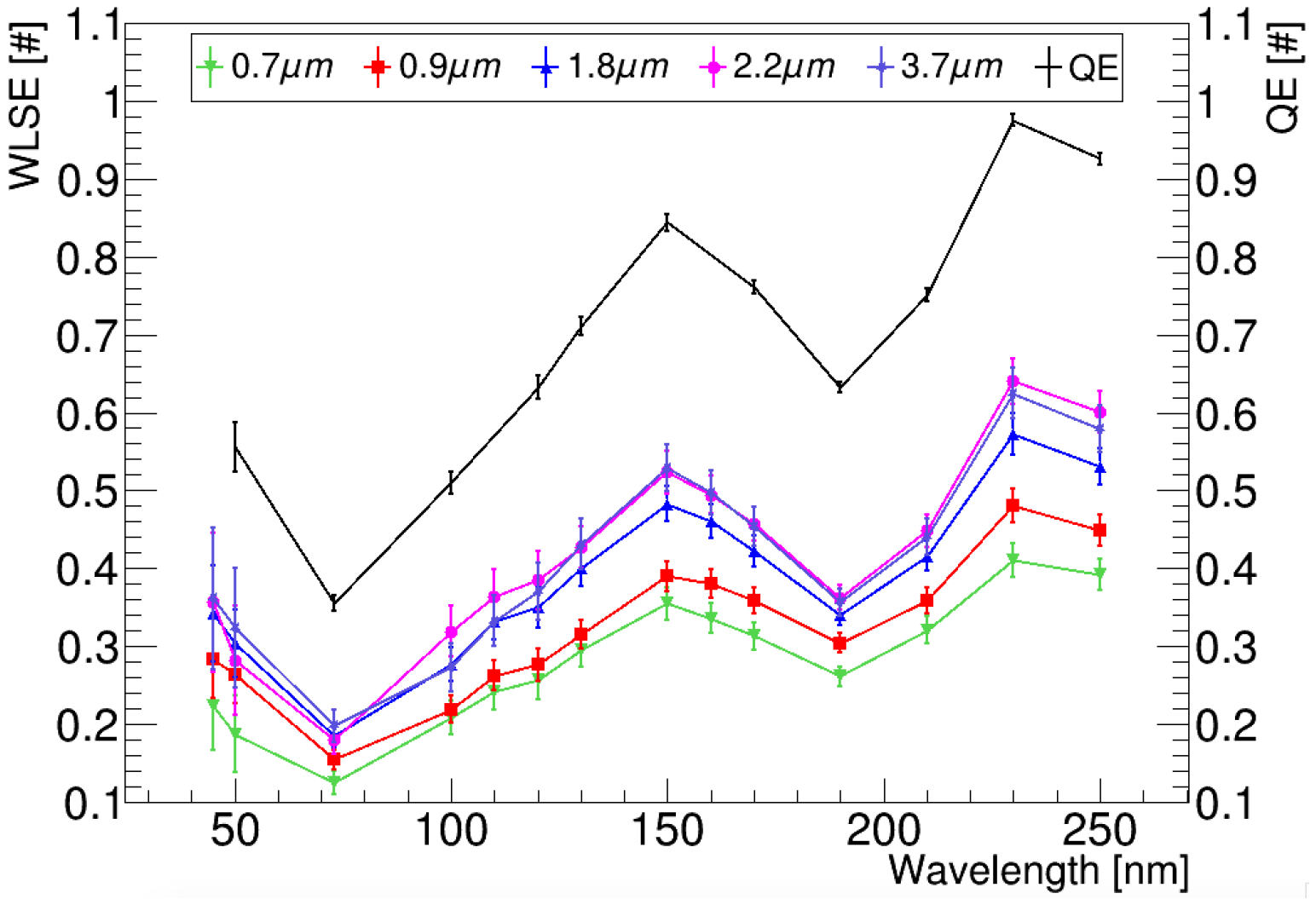
Intrinsic Quantum Efficiency Extraction

- Determine the same photon ratio using simulation for several candidate values of QE.
  - Only free parameter adjusted in simulation is TPB QE
- Compute χ^2 difference between simulation and data to determine favored QE for each wavelength.
  - Minimum of a parabola fit
  - +/- 1σ bounds set by $\Delta\chi^2 = 1$

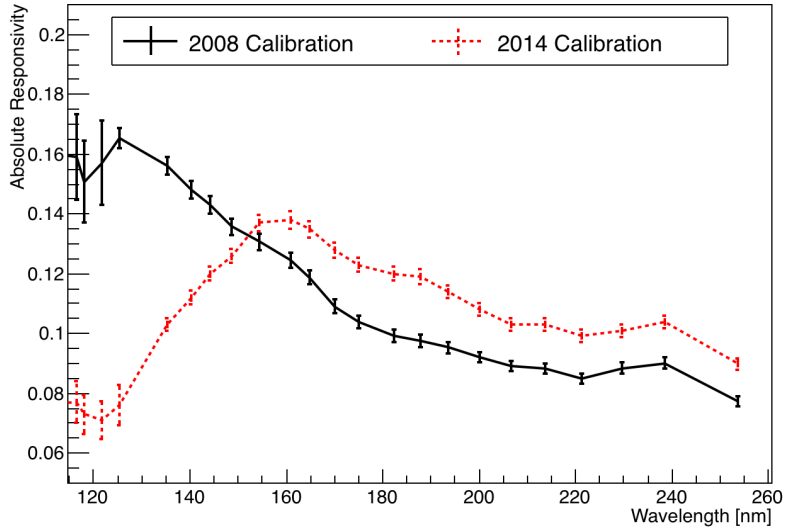


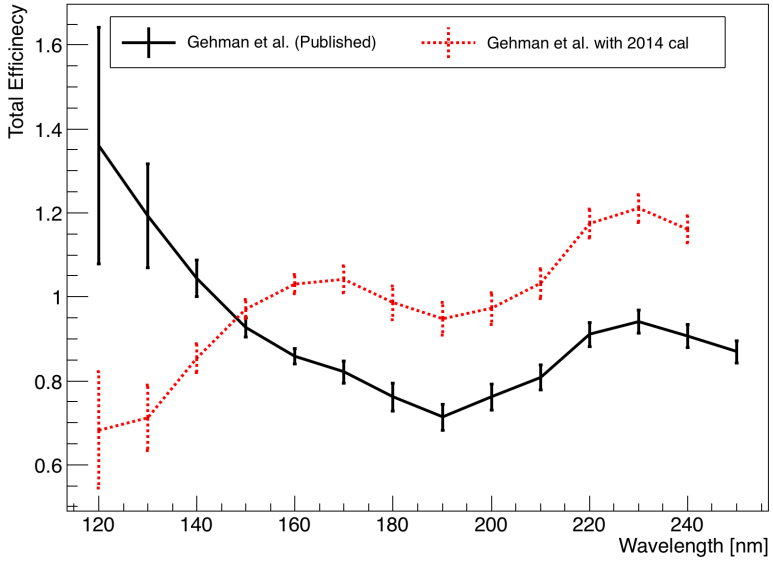


TPB Intrinsic Quantum Efficiency

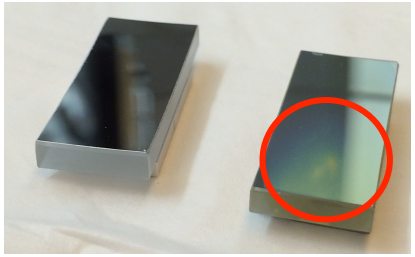


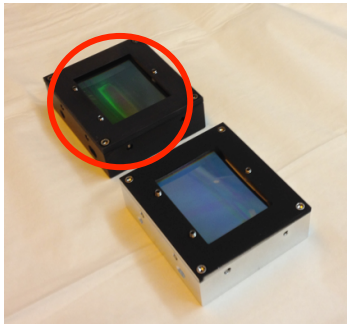
Difference in Efficiency Measurements





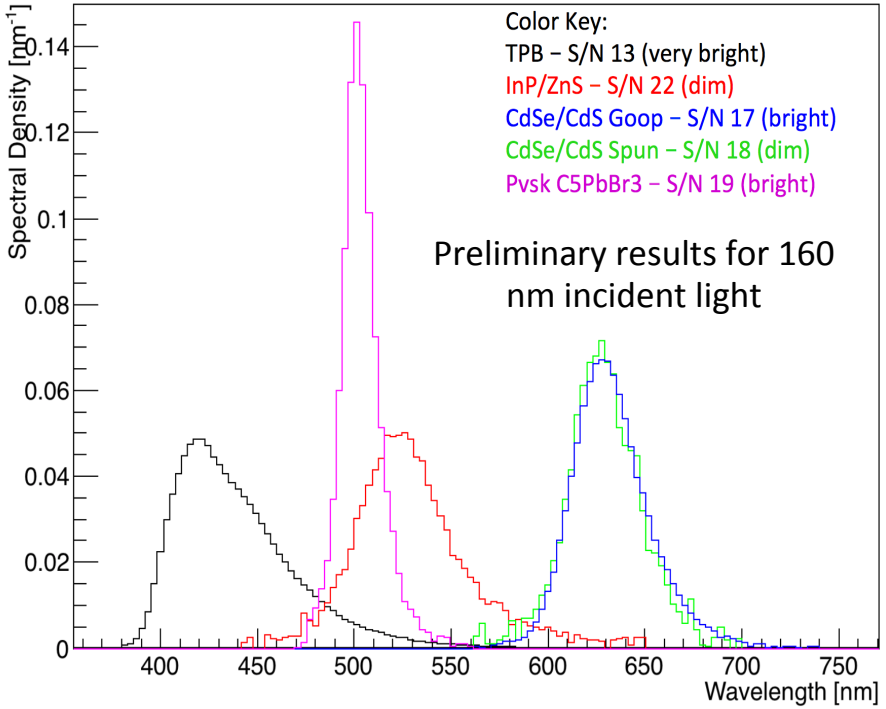
- Difference between this work and Gehman's 2011 publication is explained by a photodiode calibration drift and differences in model.
- We have a good handle on systematics and photodiode calibration
  - Tracking PD calibration
  - Improved simulation and modeling
  - Multiple configurations allows overlapping crosschecks
  - Excellent background controls
  - Multiple samples and fab access
  - Minimum exposure per sample
  - 2 batches of TPB and vacuum storage

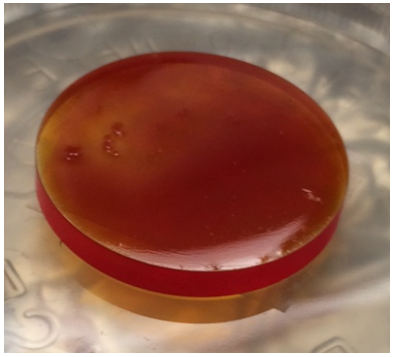


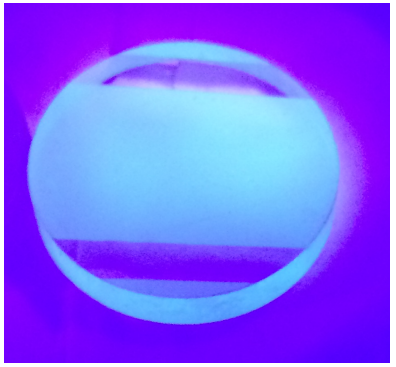


Current and Future Measurements

- TPB WLSE degradation as a function of VUV exposure time
- Angular distribution of reemitted photons
- Nanoparticle WLS alternatives to TPB
  - We have investigated several nanoparticle species produced by Paul Alivisatos' group (UC Berkeley physical chemistry)
  - Reemission Spectrum
  - WLSE relative to TPB







Conclusions

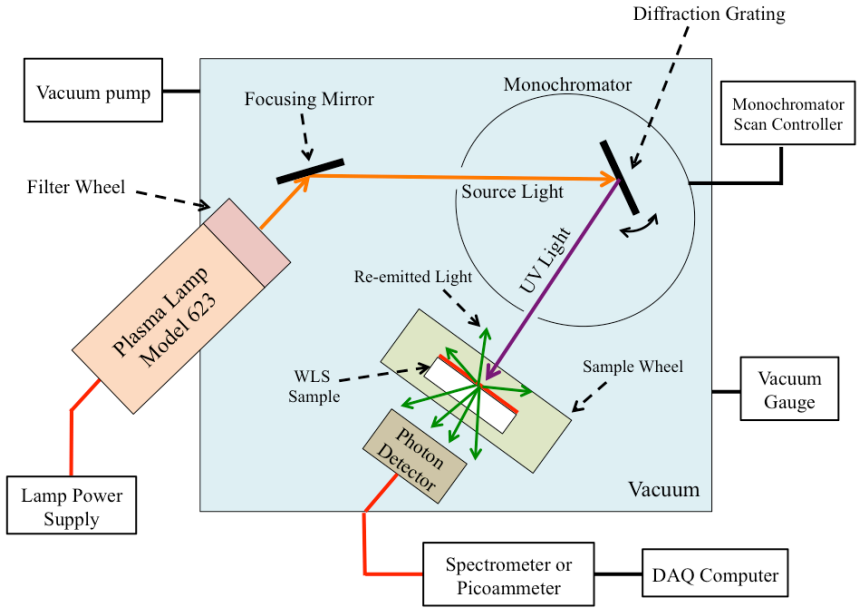
- First extraction of intrinsic TPB quantum efficiency, not sample-dependent
- Measurement of TPB reemission spectrum in new low wavelength regime (45 to 250 nm)
- Measurement of the WLSE of TPB samples with improved precision and in a new low wavelength range (45 to 250 nm)

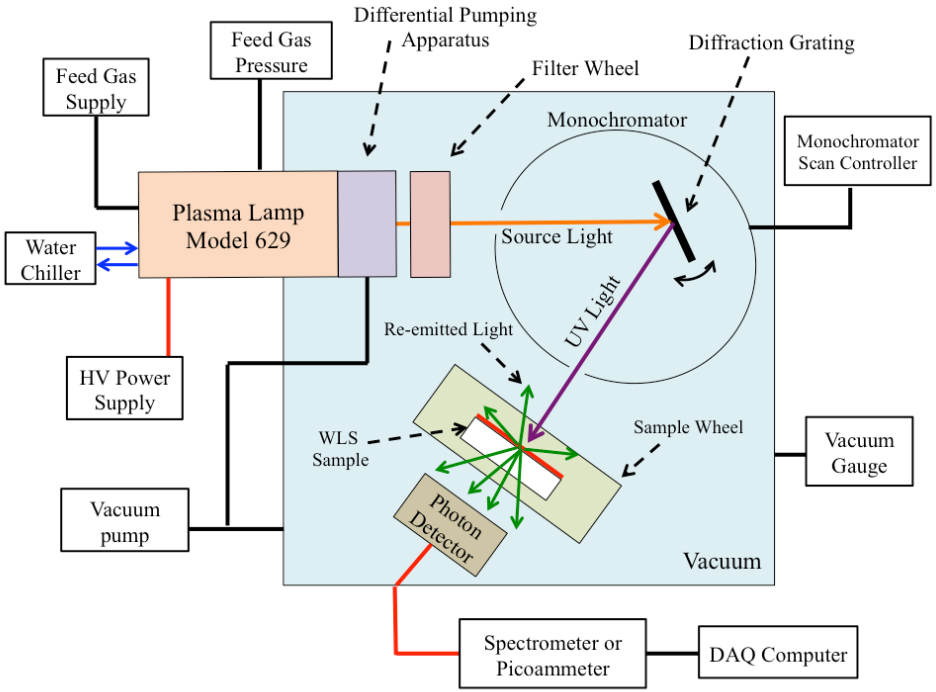
Details of this work can be found in arXiv article 1709.05002

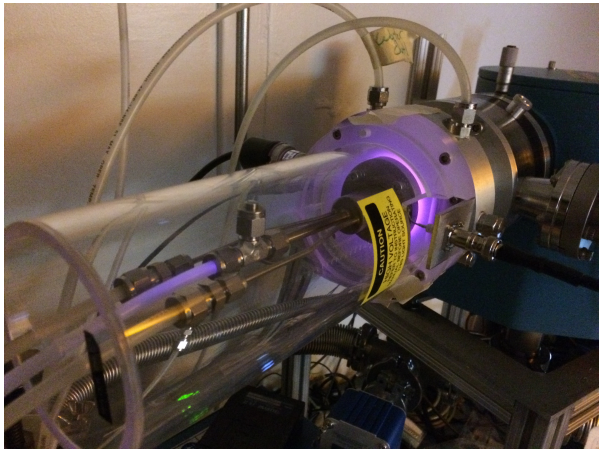
Acknowledgments

- This work was supported by the Office of High Energy Physics of the U.S. Department of Energy under contract DE-AC02-05CH11231
- Work at the Molecular Foundry was supported by the Office of Science, Office of Basic Energy Sciences, of the U.S. Department of Energy under Contract No. DE- AC02-05CH11231.
- The Ocean Optics spectrometer, McPherson monochromator, deuterium light source, lamp power supply, monochromator motor controller, and two photodiodes are kindly on loan from Dr. K. Rielage and Los Alamos National Laboratory.
- We thank the MiniCLEAN collaboration for their permission to use MiniCLEAN RAT and Dr. Thomas Caldwell for his input on modeling TPB in Mini- CLEAN RAT.
- We thank the Dr. Daniel McKinsey group at University of California at Berkeley for the use of their thermal evaporator and for valuable discussion.

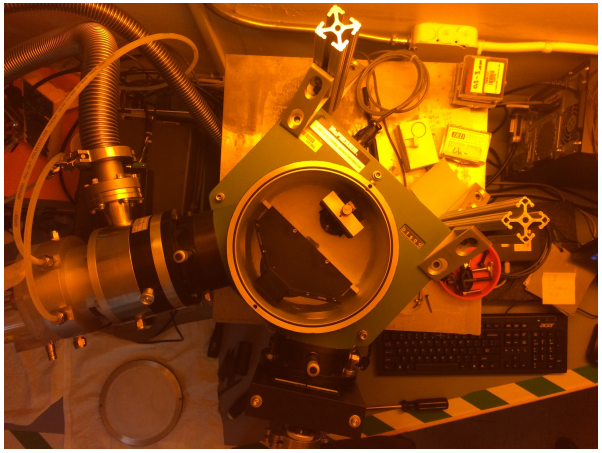
Back Up Slides



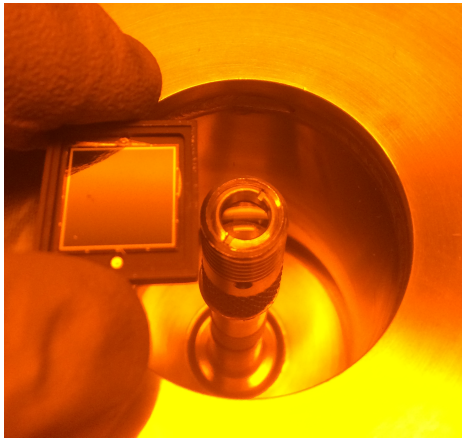




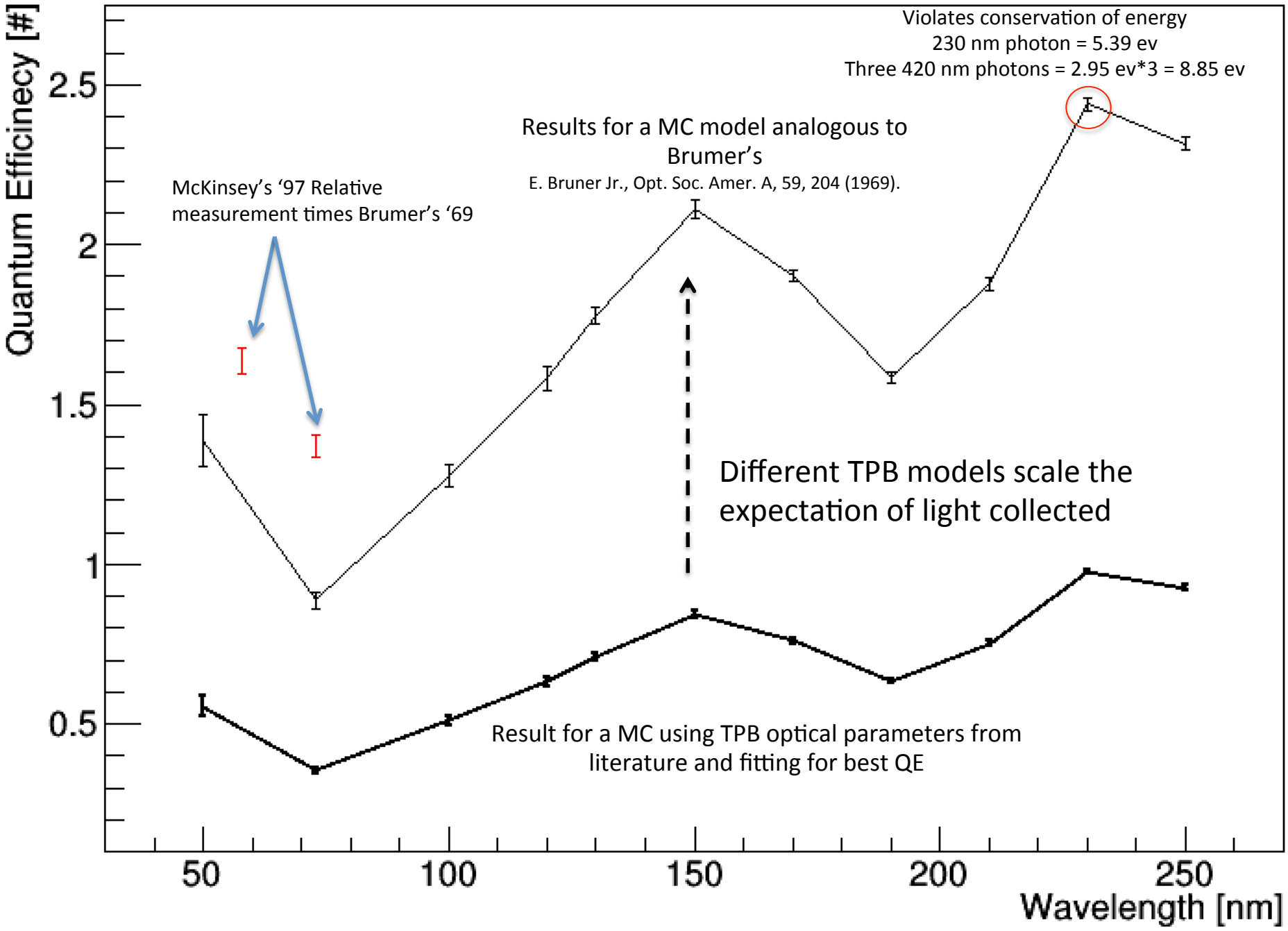
Windowless Lamp with N2



Top down view of monochromator

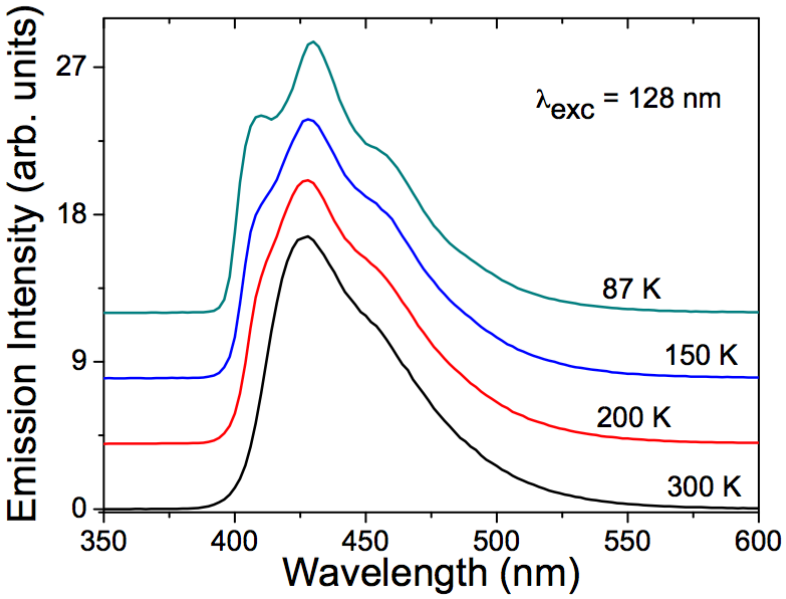


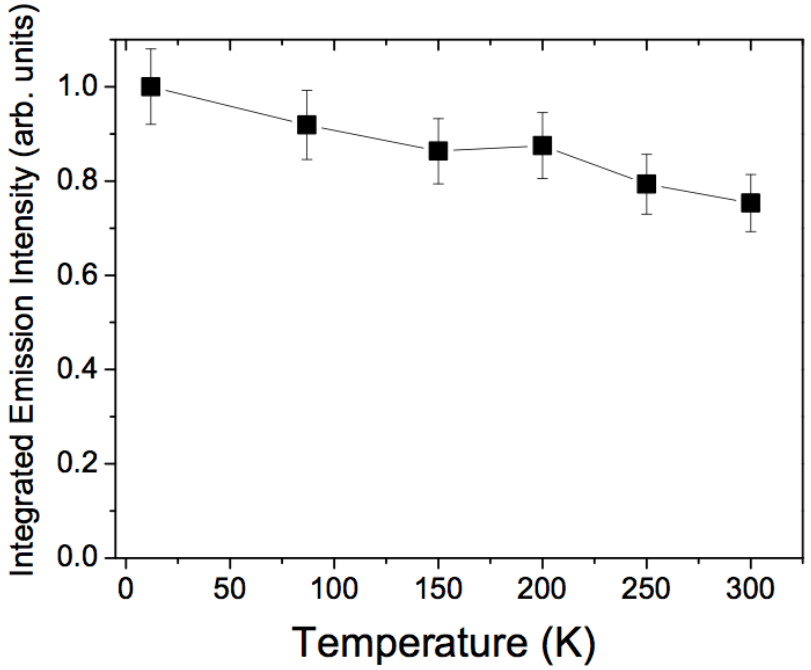
Optical feed through and photodiode


Violates conservation of energy
230 nm photon = 5.39 ev
Three 420 nm photons = 2.95 ev*3 = 8.85 ev
Results for a MC model analogous to Brumer's
E. Bruner Jr., Opt. Soc. Amer. A, 59, 204 (1969).
McKinsey's '97 Relative measurement times Brumer's '69
Different TPB models scale the expectation of light collected
Result for a MC using TPB optical parameters from literature and fitting for best QE
Quantum Efficinecy [#]
Wavelength [nm]
0.5
1
1.5
2
2.5
50
100
150
200
250

VUV-Vis optical characterization of Tetraphenyl-butadiene films on glass and specular reflector substrates from room to liquid Argon temperature

R. Francini[a], R.M. Montereali[b], E. Nichelatti[c], M.A. Vincenti[b], N. Canci[d], E. Segreto[d], F. Cavanna[e,f,*], F. Di Pompeo[e], F. Carbonara[g], G. Fiorillo[g], F. Perfetto[g],





Our work is at room temperature. R. Francini et. al suggests that emission intensity goes up at LAr temperature.

Simulation Inputs

- Photon absorption lengths in TPB
  - S. E. Wallace-Williams, et al., J. Phys. Chem., 98, 60–67 (1994).
- Flat index of refraction for TPB of 1.67
  - IOR from similar compounds and from calculations
- Scattering Length in TPB
- Acrylic substrate properties from supplier
- Measured reemission spectrum of TPB