Collection of Vacuum Ultraviolet Scintillation Photons in in Noble Gas Detectors

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BNL Seminar
Upton, NY
November 4, 2013

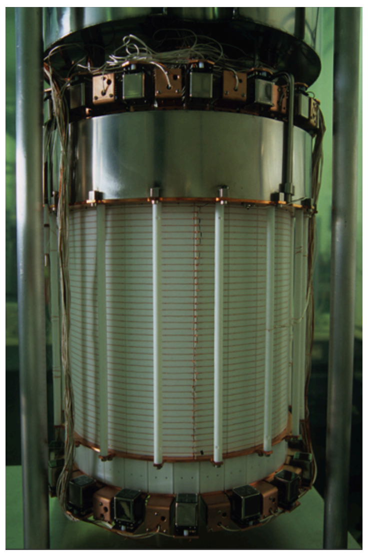
Outline

- Noble gas detectors and VUV scintillation: why is this so hard???
- Turning difficult photons into easy ones for fun and profit
- Recent results:
    - Absolute measurements are hard to come by...
    - Deuterated TPB
    - Lots of fluors
    - R&D for large area collectors
- Some cool new ideas (one that seems to work and one that really doesn't):
    - Bulk volume doped WLS additives
    - High-frequency transparent filters?

Noble Gas Detectors

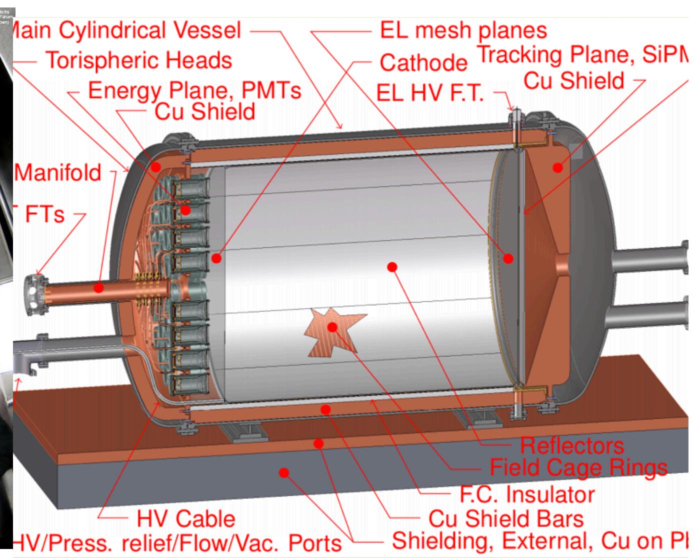
... are increasingly central to a broad range of physics programs:

XENON100

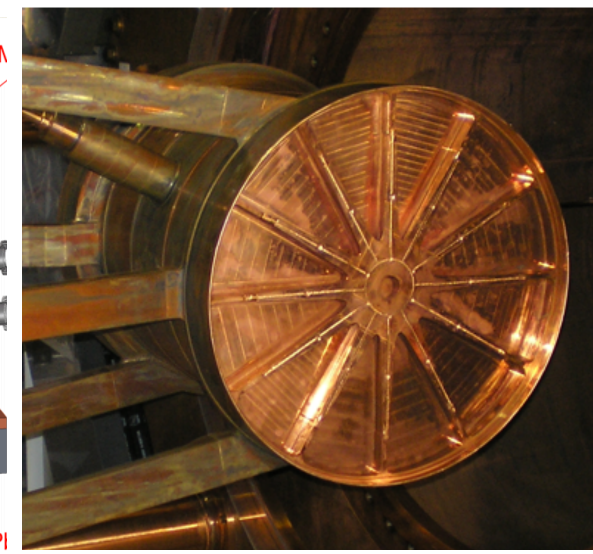


LUX

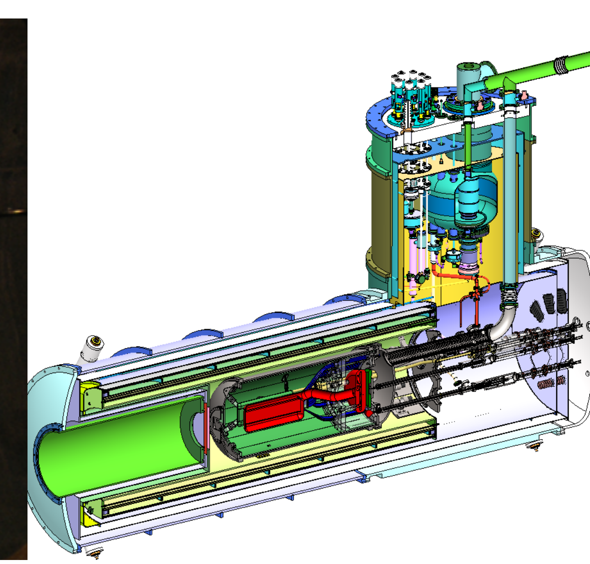
NEXT



EXO



nEDM

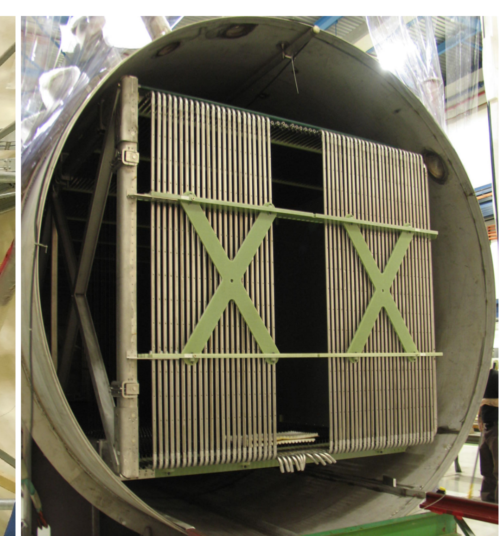


XMASS

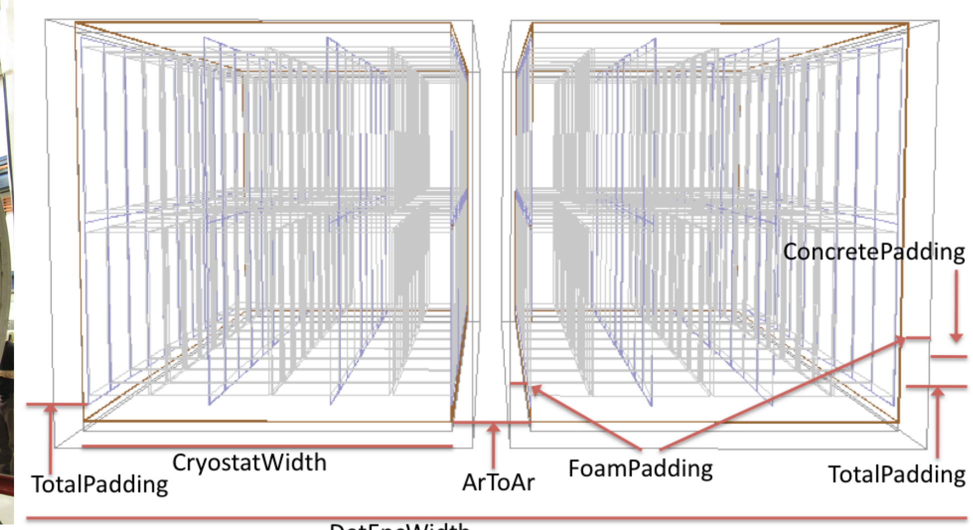
MiniCLEAN

DEAP-3600

MicroBooNE



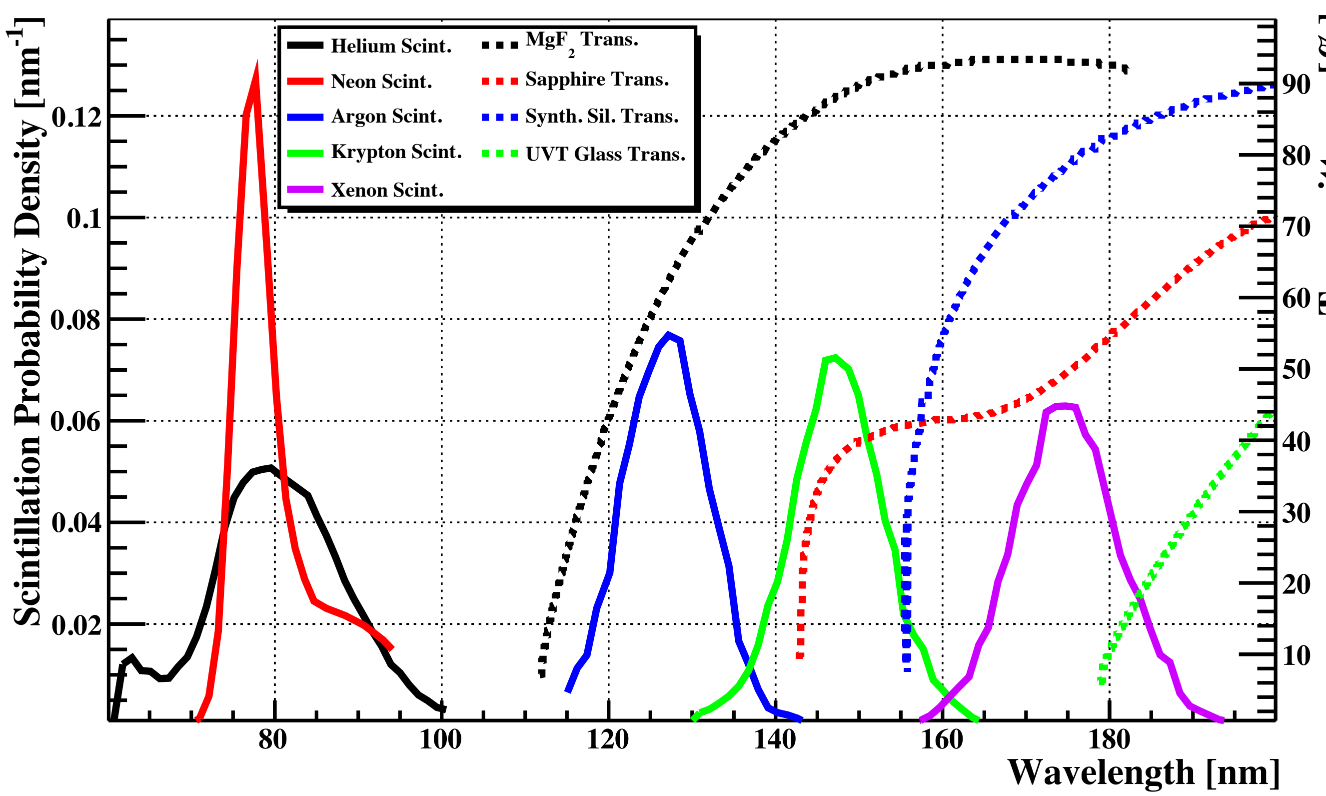
LBNE



Noble gas scintillation:

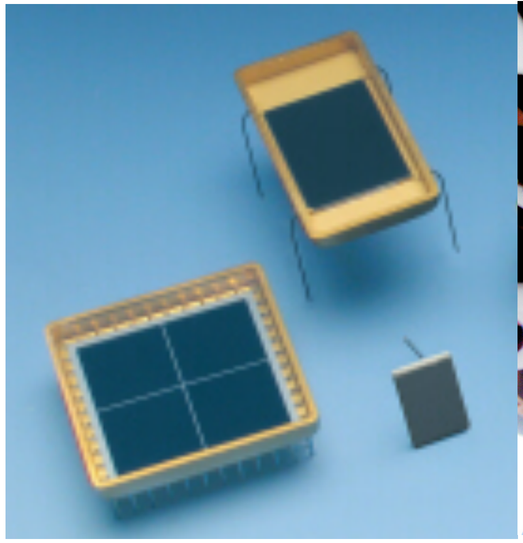
- High-scintillation light yield (20-40 photons/keV)
- High density (1.2 - 3.0 g/cm^3) in liquid phase
- Excellent energy resolution in gas phase
- Transparent to their own scintillation light
- Ionization/tracking capability (digital bubble chamber!)
- Particle ID:
  - scintillation light time structure
  - dE/dx in ionization tracks

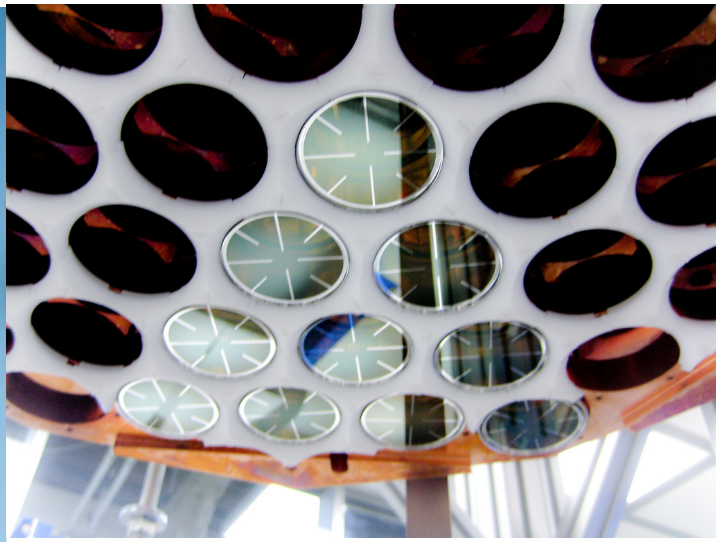
- Liquid phase requires cryogenic temperatures
- Scintillation light is *very* short wavelength (vacuum ultraviolet, 80 - 175 nm)
  - Rayleigh scattering ($\sigma \sim \lambda^{-4}$),
  - VUV light is strongly absorbed by almost everything...



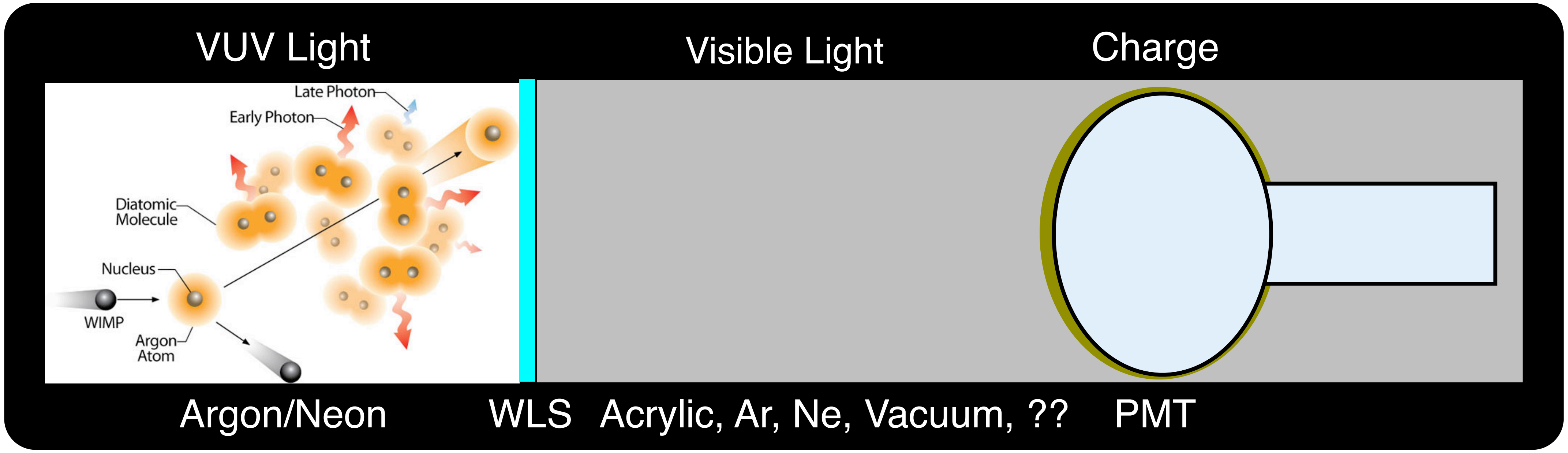
What to do with these troublesome photons?

- Some devices are directly sensitive to them
  - Solid state devices can be sensitive down to below 100 nm. Small area, often slow
  - Some PMTs sensitive down to 160 nm, UV-transmitting window limits area





- Usually, you need a wavelength shifting film:



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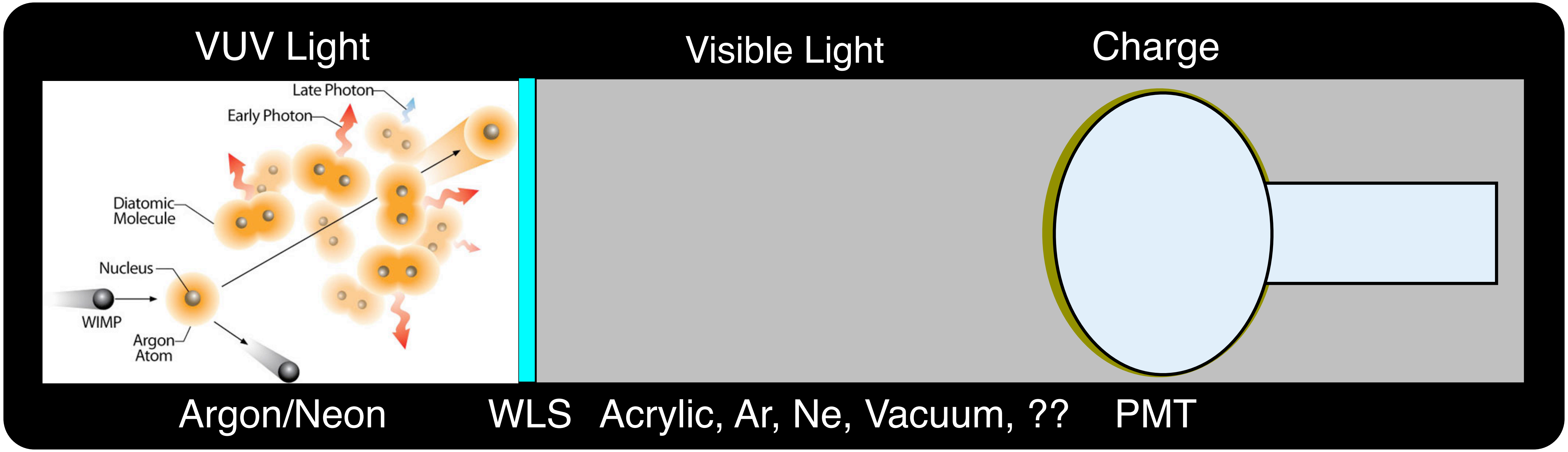


When you do this, you get "easier to detect" photons, but you give up all of your direct light

Any analysis that requires detailed understanding of your optical train becomes a bit more complicated

WLS Molecules for Dummies

- UV absorption pushes the molecule from the S_0 to the S_1 state.
- S_1 then decays through the T_1 state, leading to a shift in the wavelength of emitted fluorescence light from the absorbed UV.

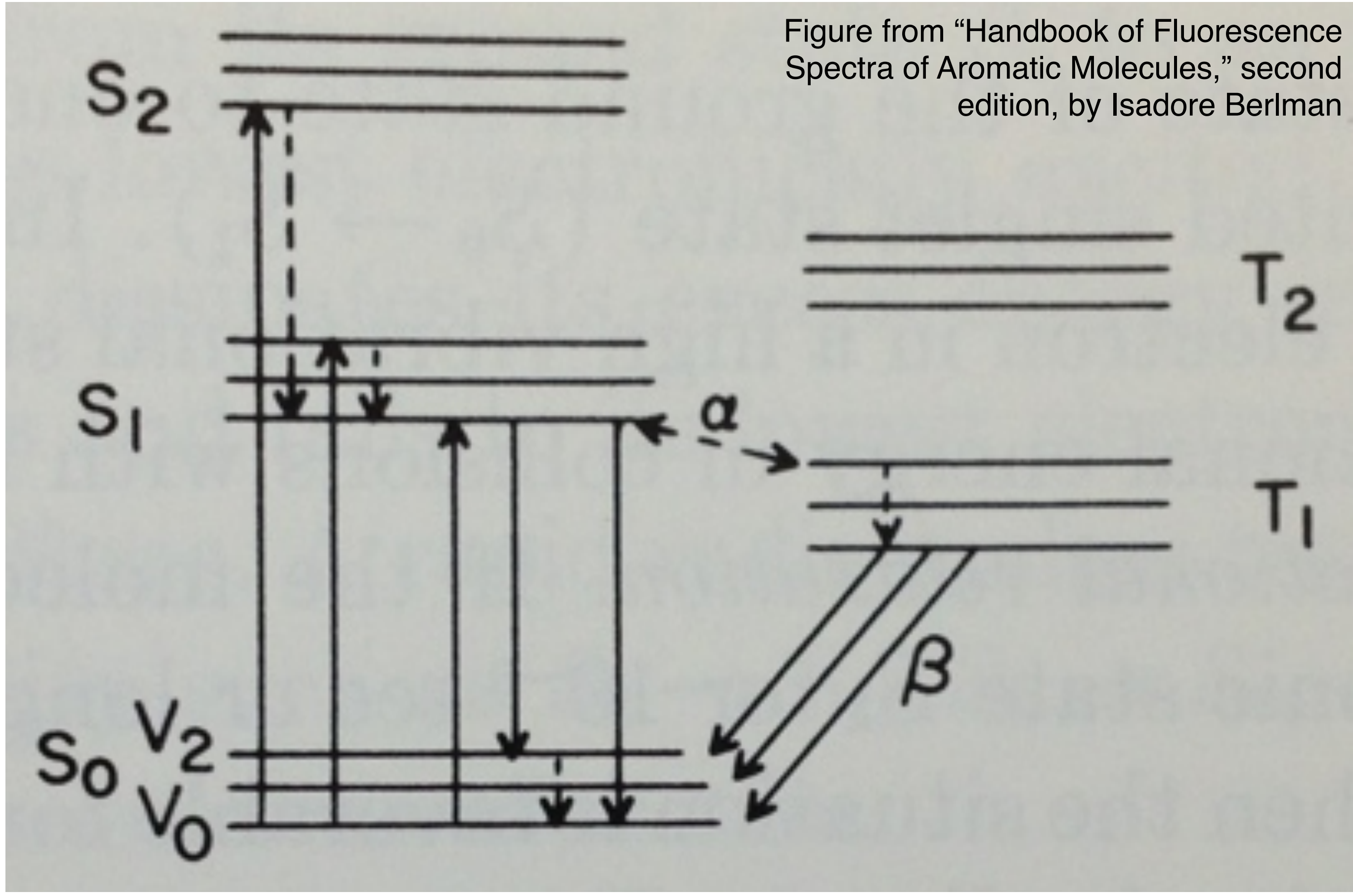


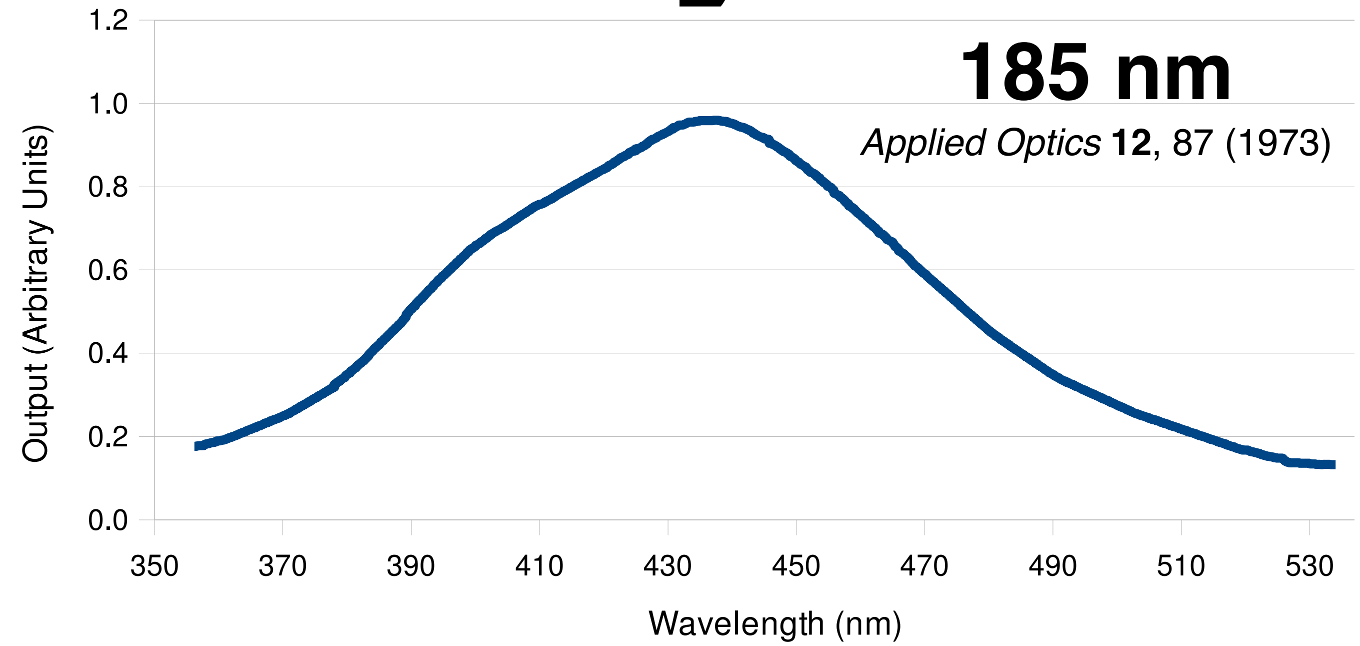
Figure from "Handbook of Fluorescence Spectra of Aromatic Molecules," second edition, by Isadore Berlman

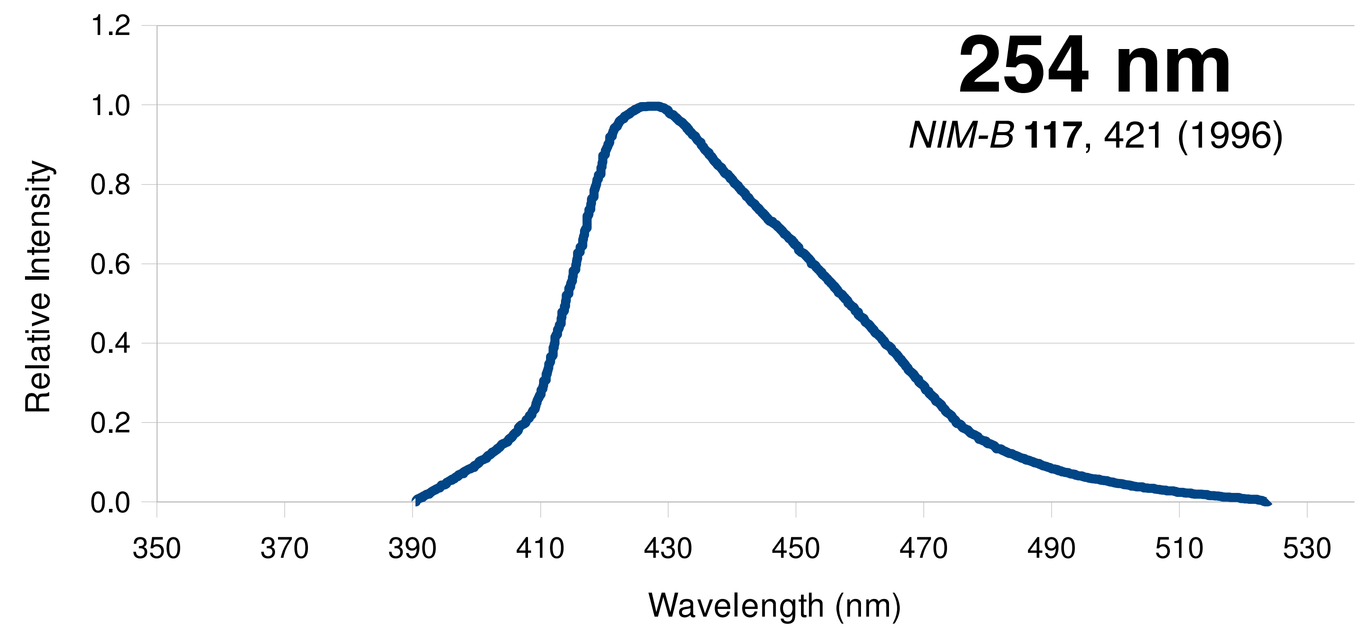
Cartoon diagram of Singlet/spin 0 states (left) and triplet/spin 1 states (right) for some fluorescent molecule. Each electronic state is composed of many closely spaced vibrational and rotational states.

- This is called the Stokes Shift.
- Happens when the time for relaxation of all the vibrational/rotational states is much faster than the time for changing electronic states.

Hasn't Someone Done All This Already?

- Yes, but…
- There was a lot of ambiguity in the shape of the re-emission spectrum as a function of input wavelength
- Previous efficiency measurements were made relative to other fluors whose absolute efficiency was uncertain to about a factor of three!





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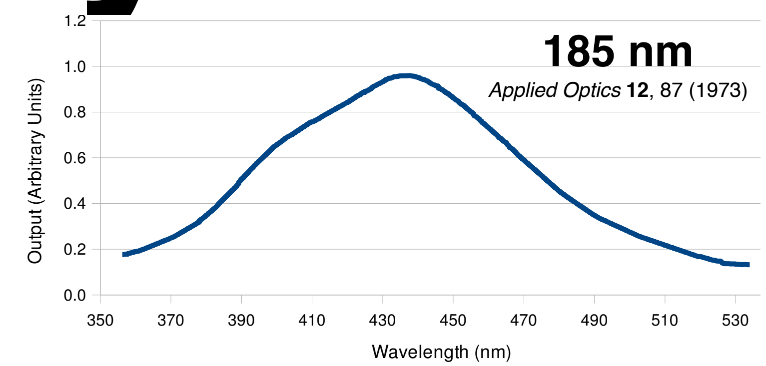
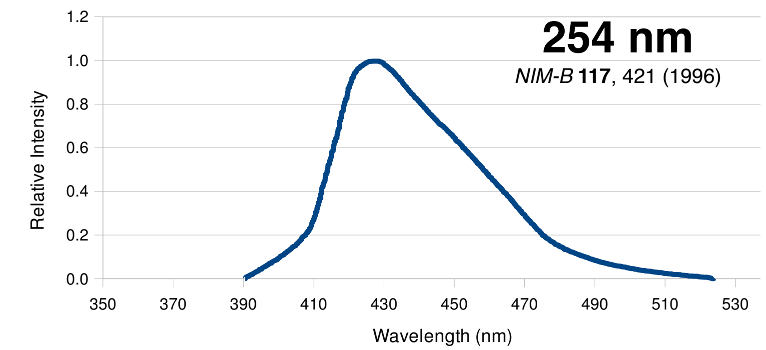




Absolute Efficiency [%]			Layer Thickness
2537 Å	1216 Å	304 Å	[mg / cm^2]
99	94		2–4
	62–80	41	5
65	38		2
50			1–2
64			6
25			?
60			2 mm[a]

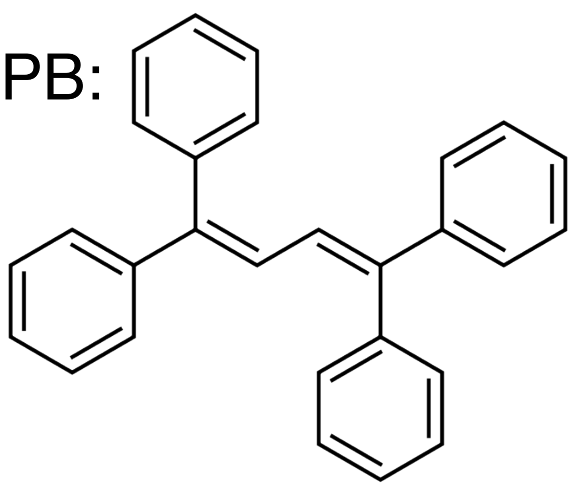
[a]Sample was a plaque pressed 2 mm thick

Table reproduced from "Techniques of Vacuum Ultraviolet Spectroscopy," James A. R. Samson, ©1967

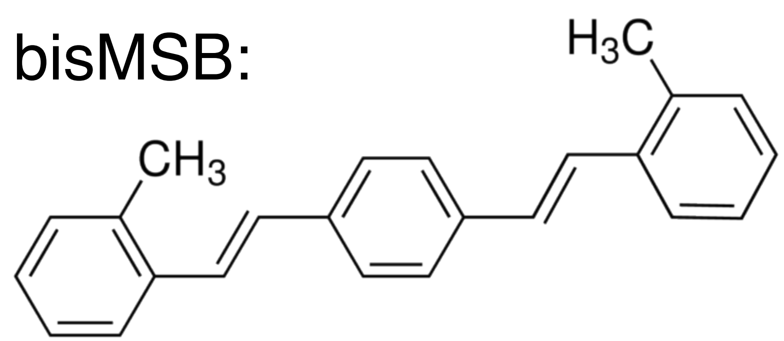
The Usual Suspects

- The most common choice is Tetraphenyl Butadiene (TPB)
  - J. Inst. 8 (2013) 01013
  - Nucl. Inst. Meth. A 654,(2011) 116
- There are a bunch of others that we look at though!

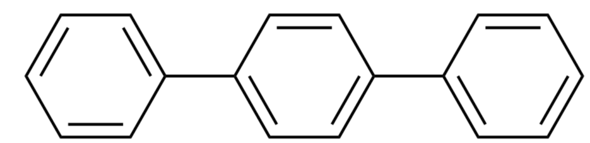
TPB:

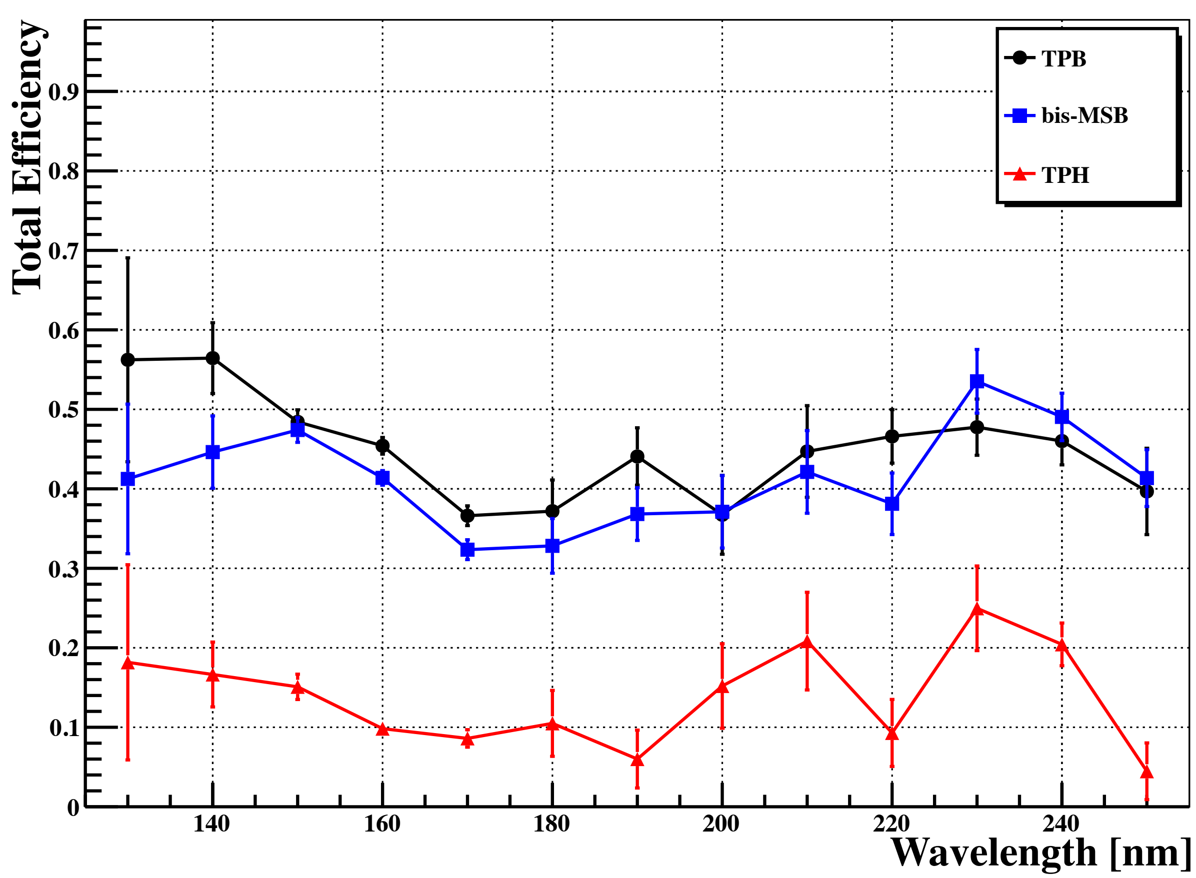


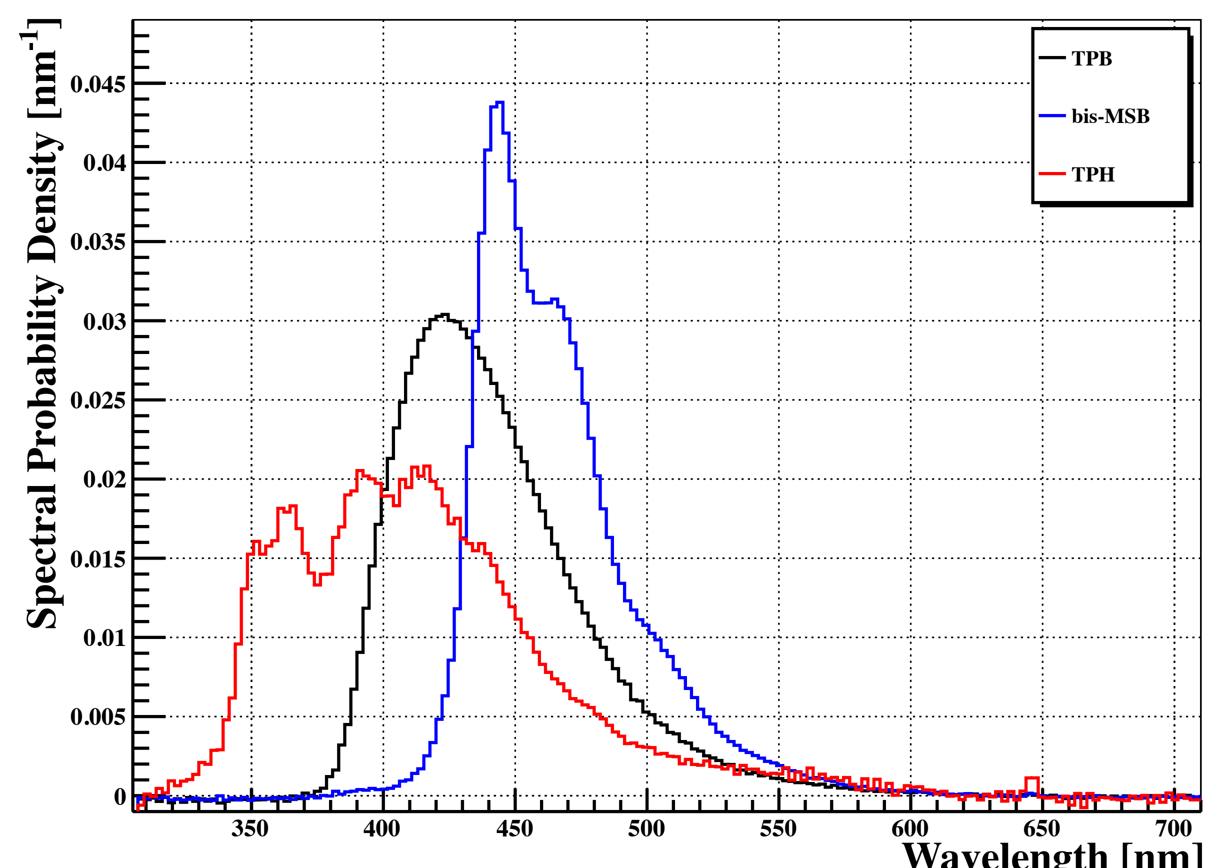
bisMSB:



TPH:

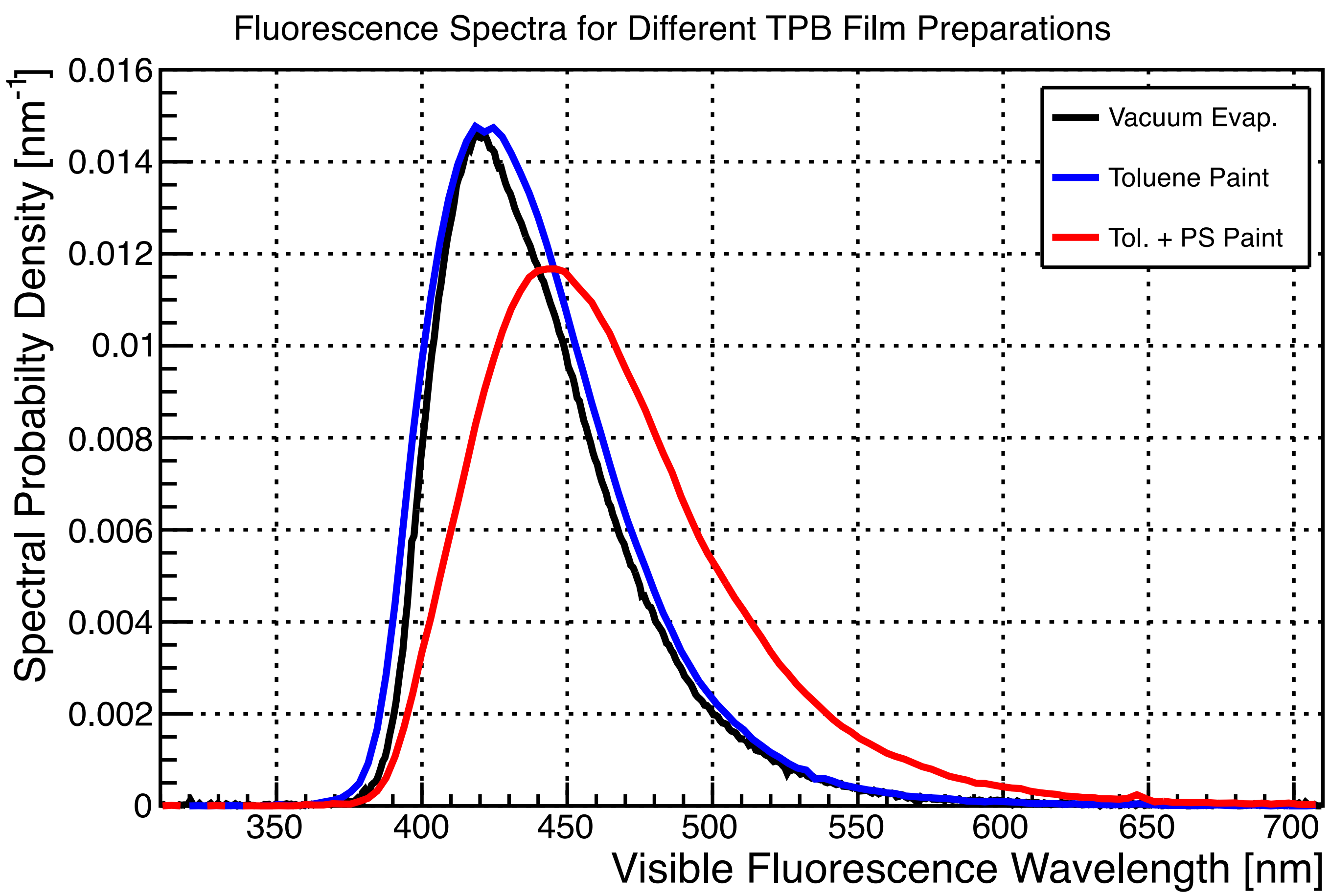


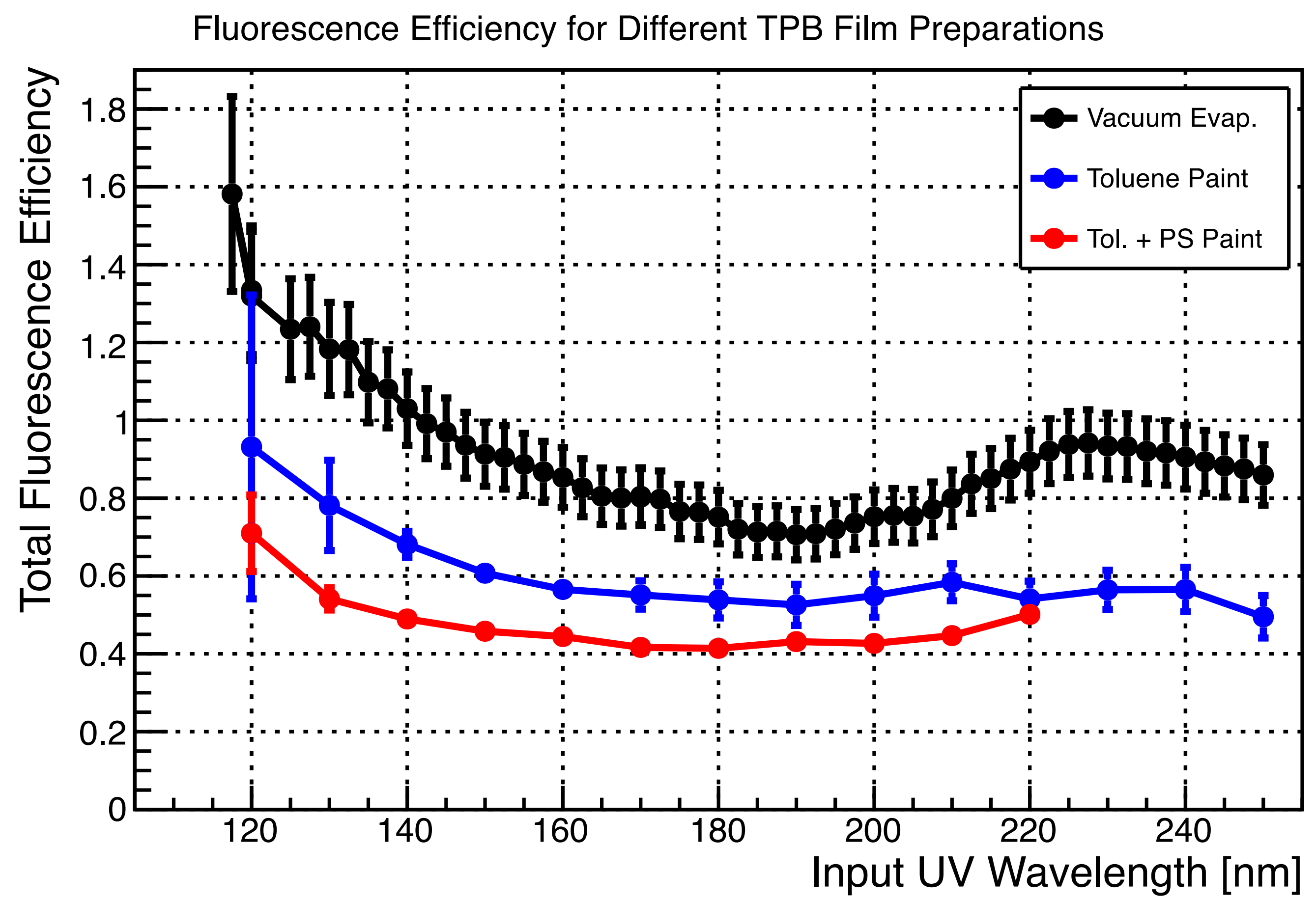




Details Matter!

- The details of how a WLS film (TPB or otherwise) make a difference in the optical response.
    - Vacuum deposited films tend to shine brighter and bluer, but be more fragile.
    - Solvent deposited films are dimmer and redder, but much more robust.

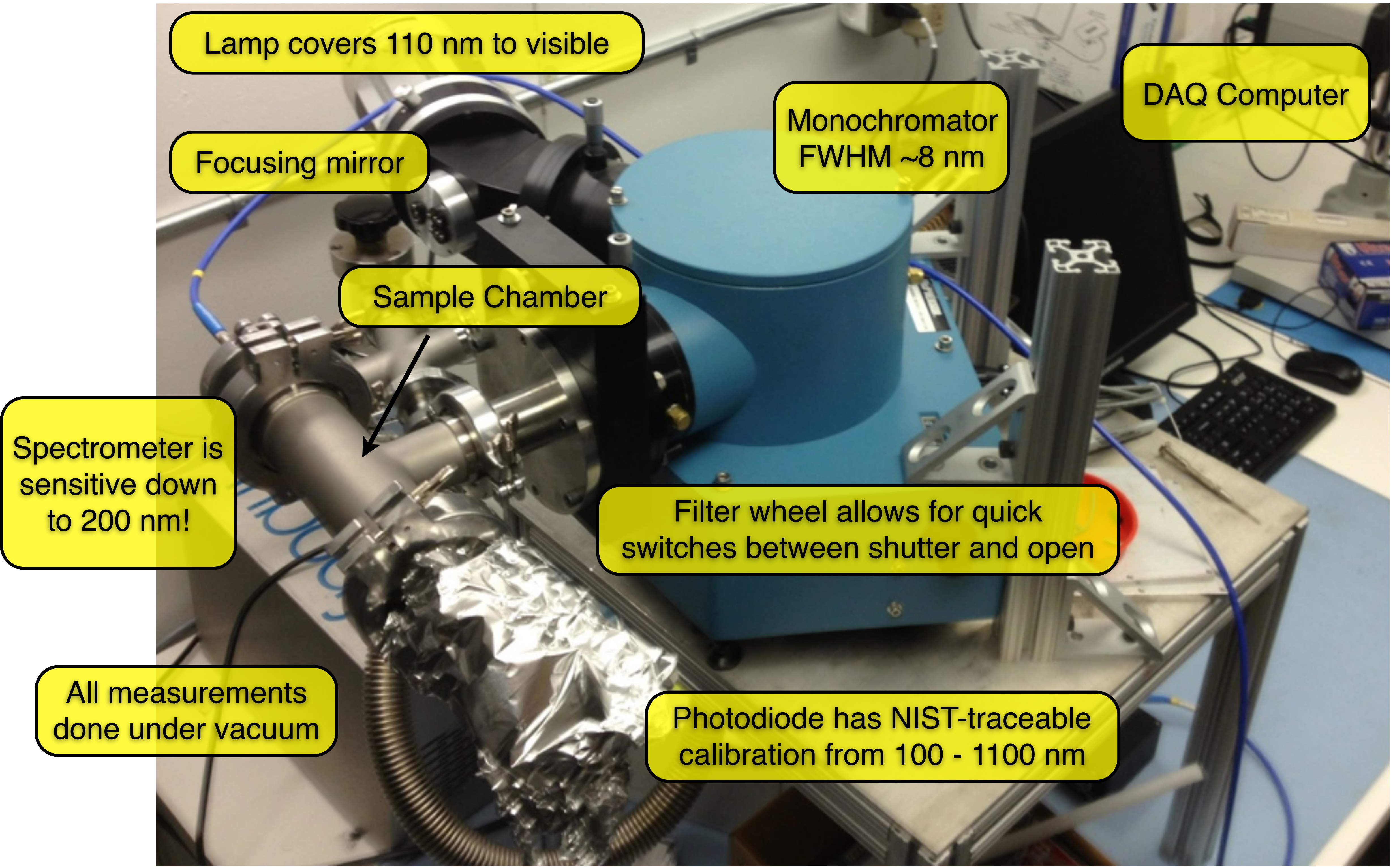




Recent Results

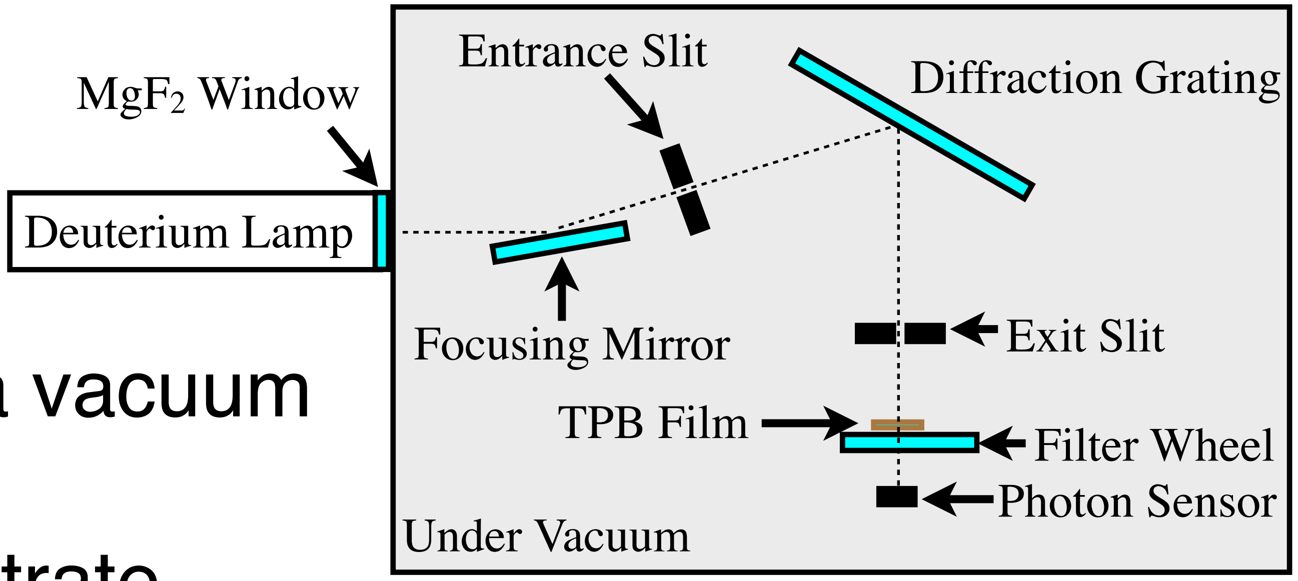
Experimental Apparatus

This is what our instrument looks like:



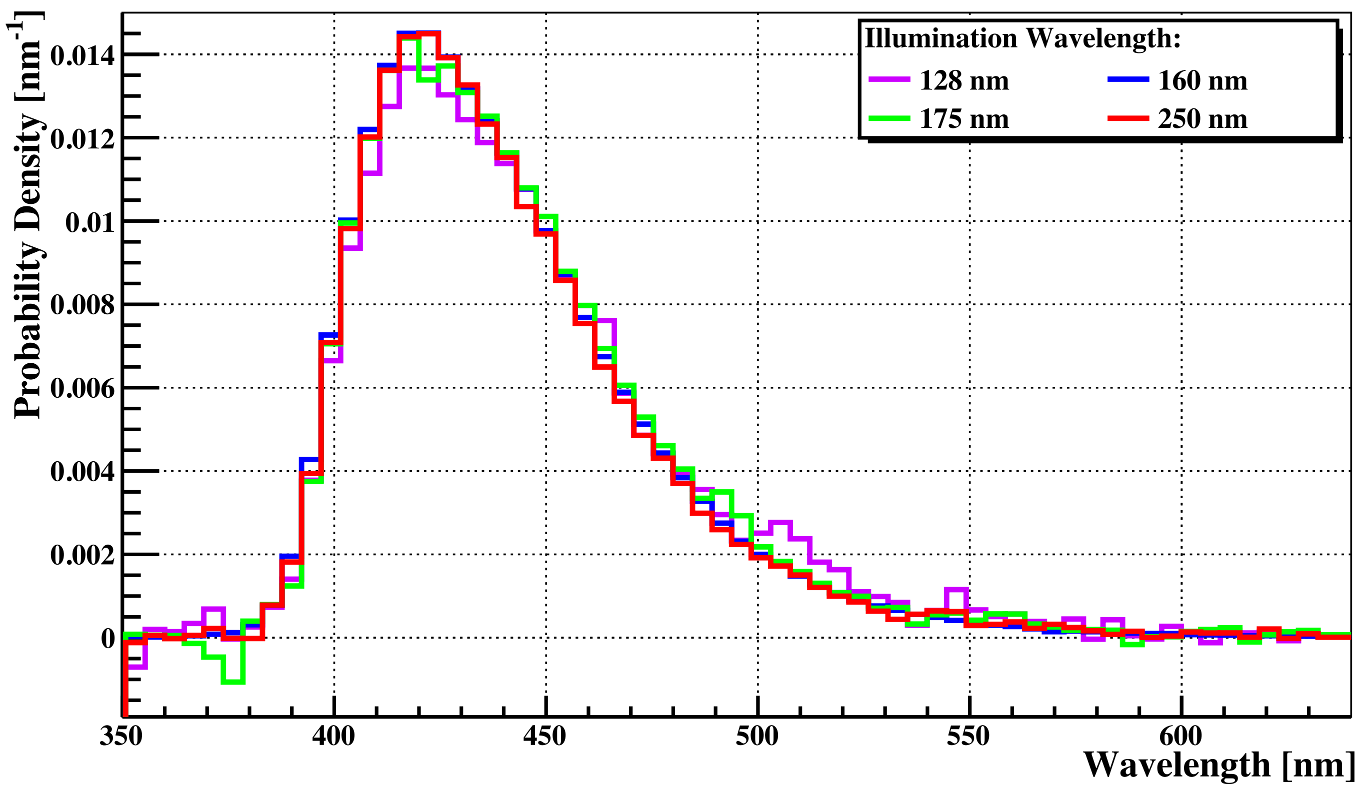
Absolute Efficiency

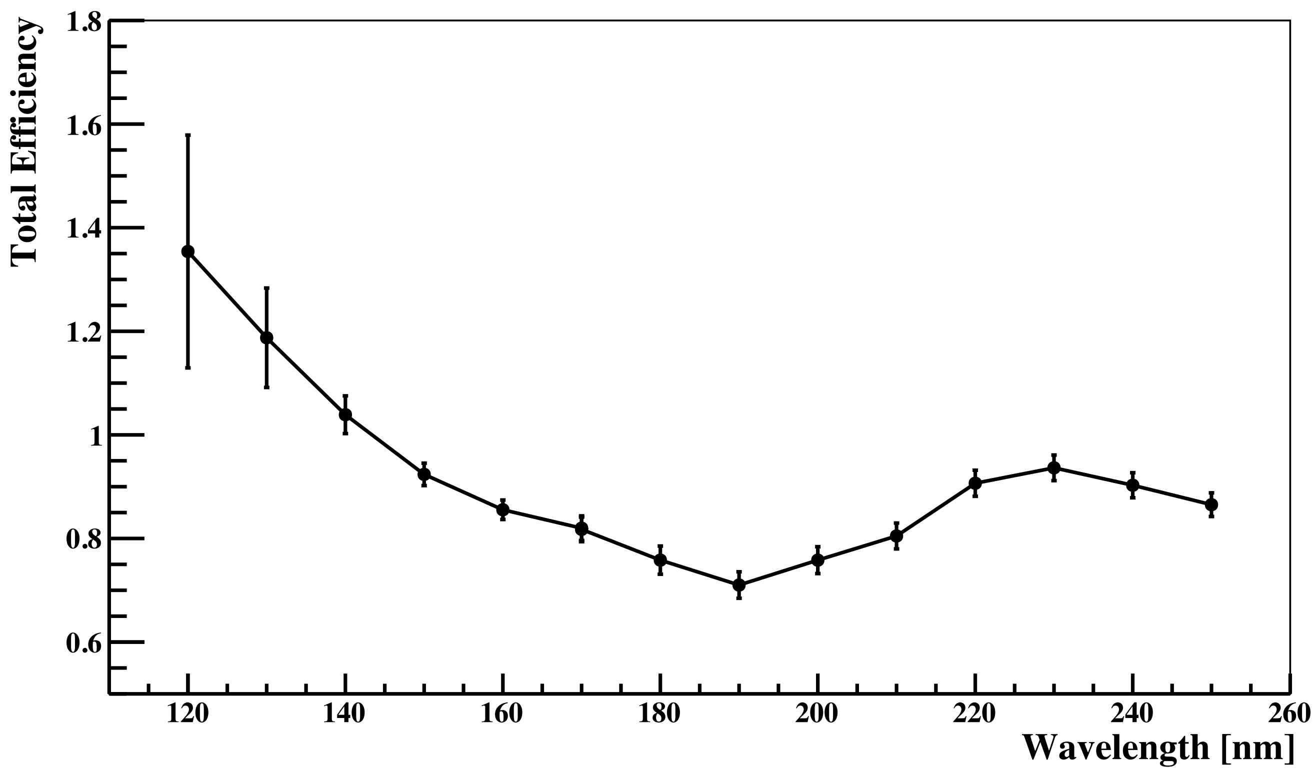
- Made the first absolute efficiency measurements: *Nucl. Inst. Meth. A* **654** (2011) 116 (arXiv:1104.3259)



- Looked at fluorescence light from a vacuum evaporated film (0.1 - 0.3 mg/cm^2) transmitted though the acrylic substrate.

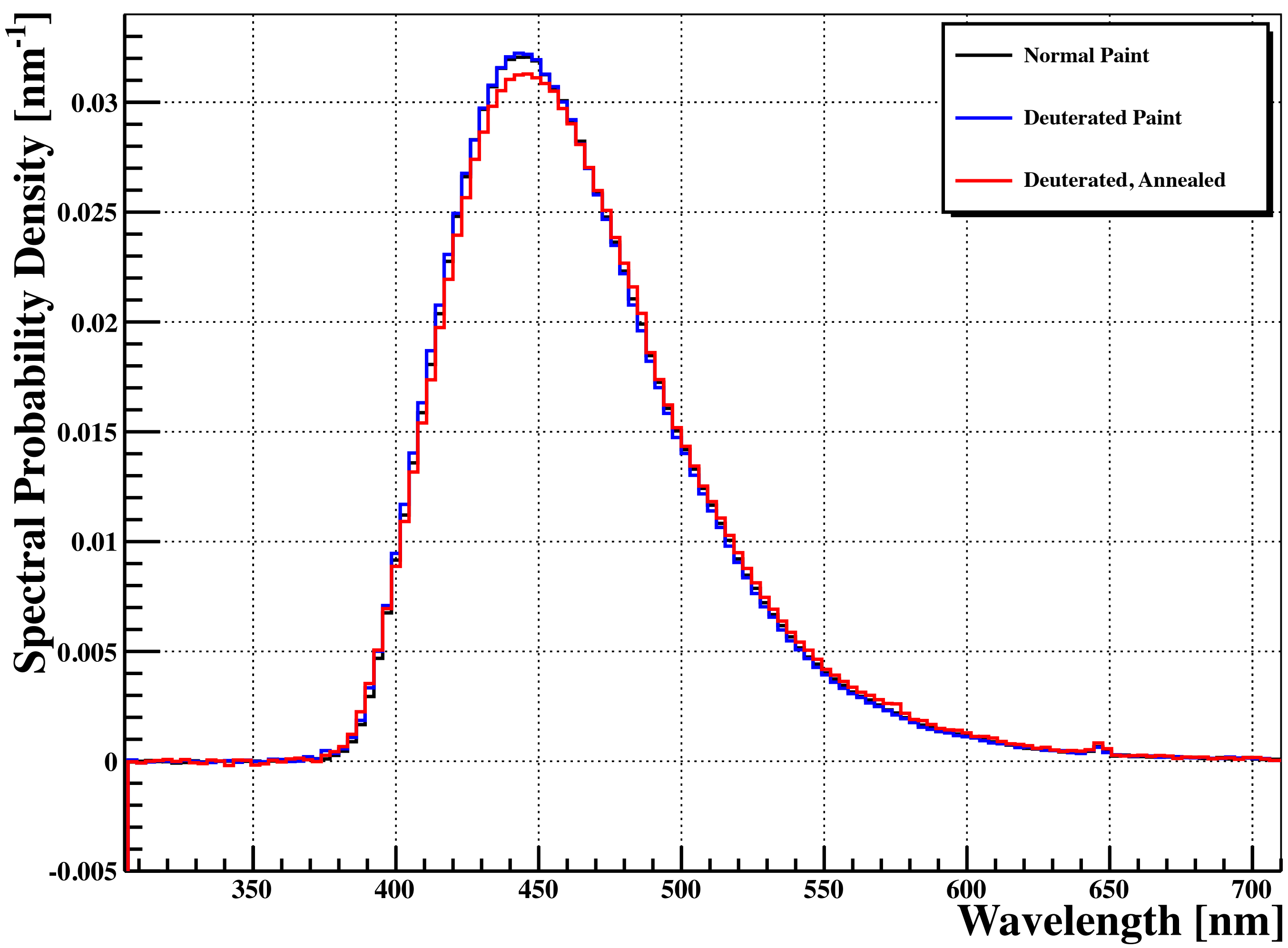
- Saw no real dependence on film thickness. No change in fluorescence spectrum on input wavelength

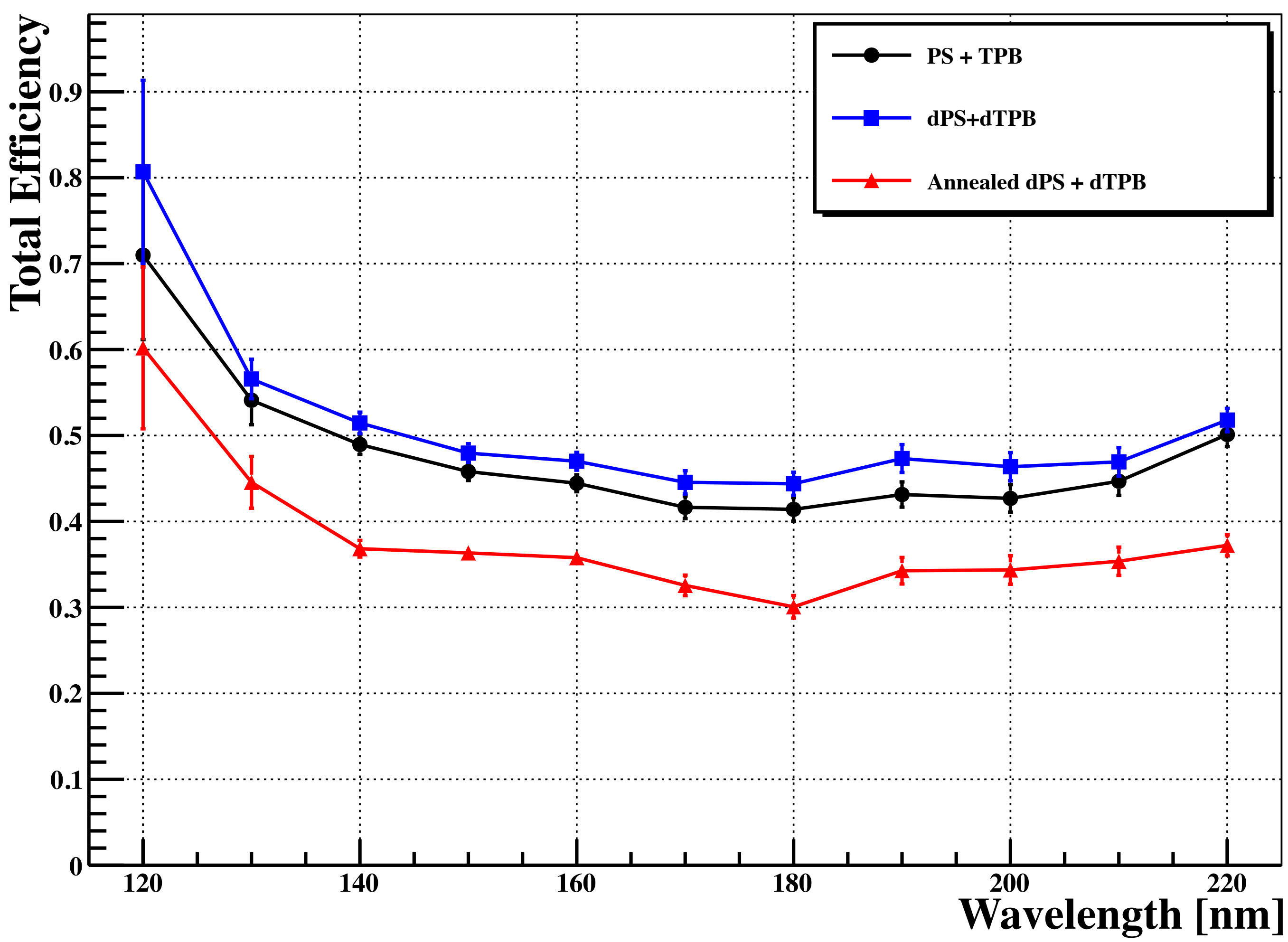




Deuterated TPB

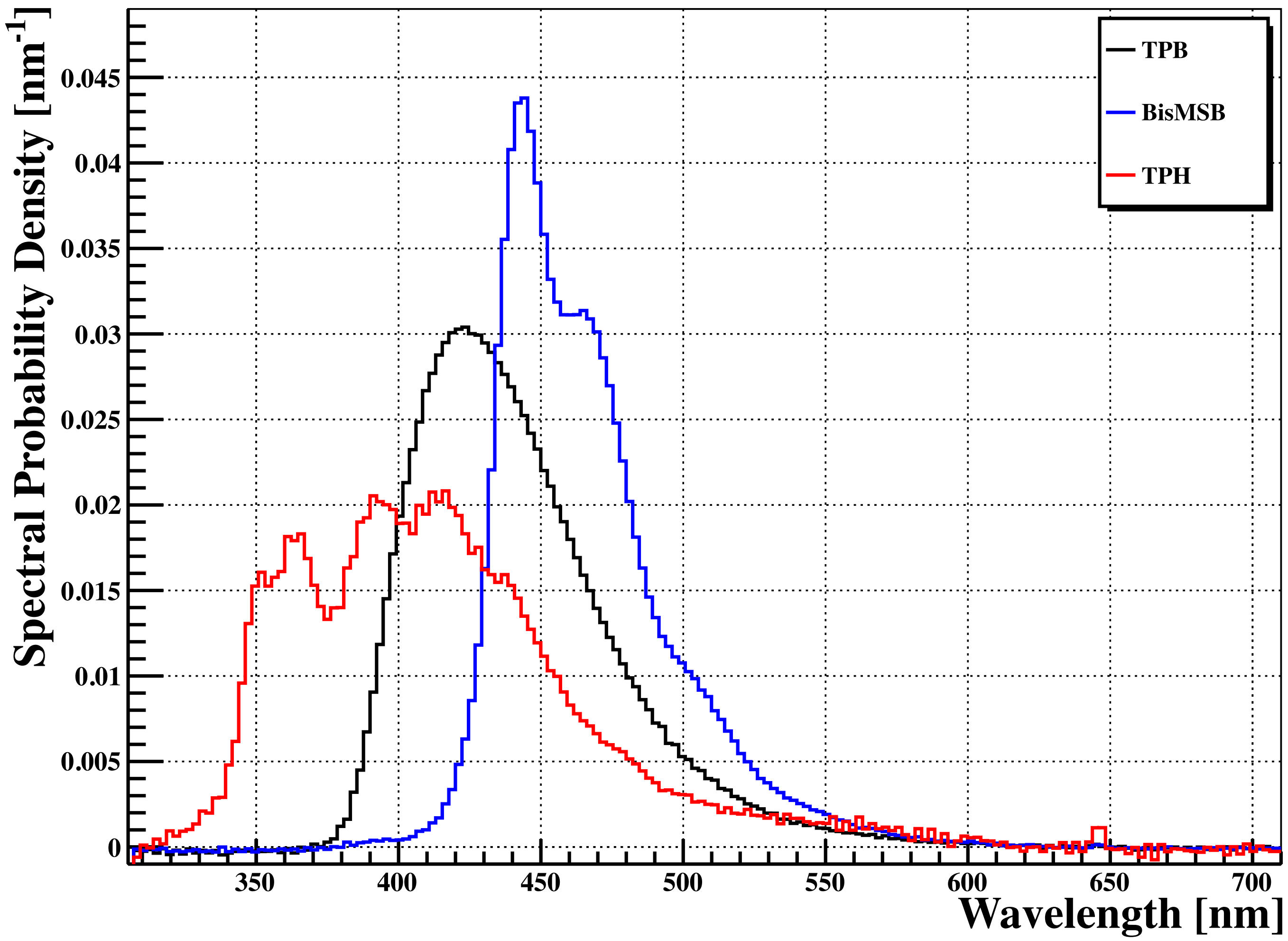
- Studied the properties of deuterated and annealed TPB films (related to nEDM experiment)
- arXiv:1302.3210, *J. Inst.* **8** (2013) P04024
- Deuterated TPB ≈ normal TPB; annealing lowers efficiency by 20-30% but does not affect spectrum much

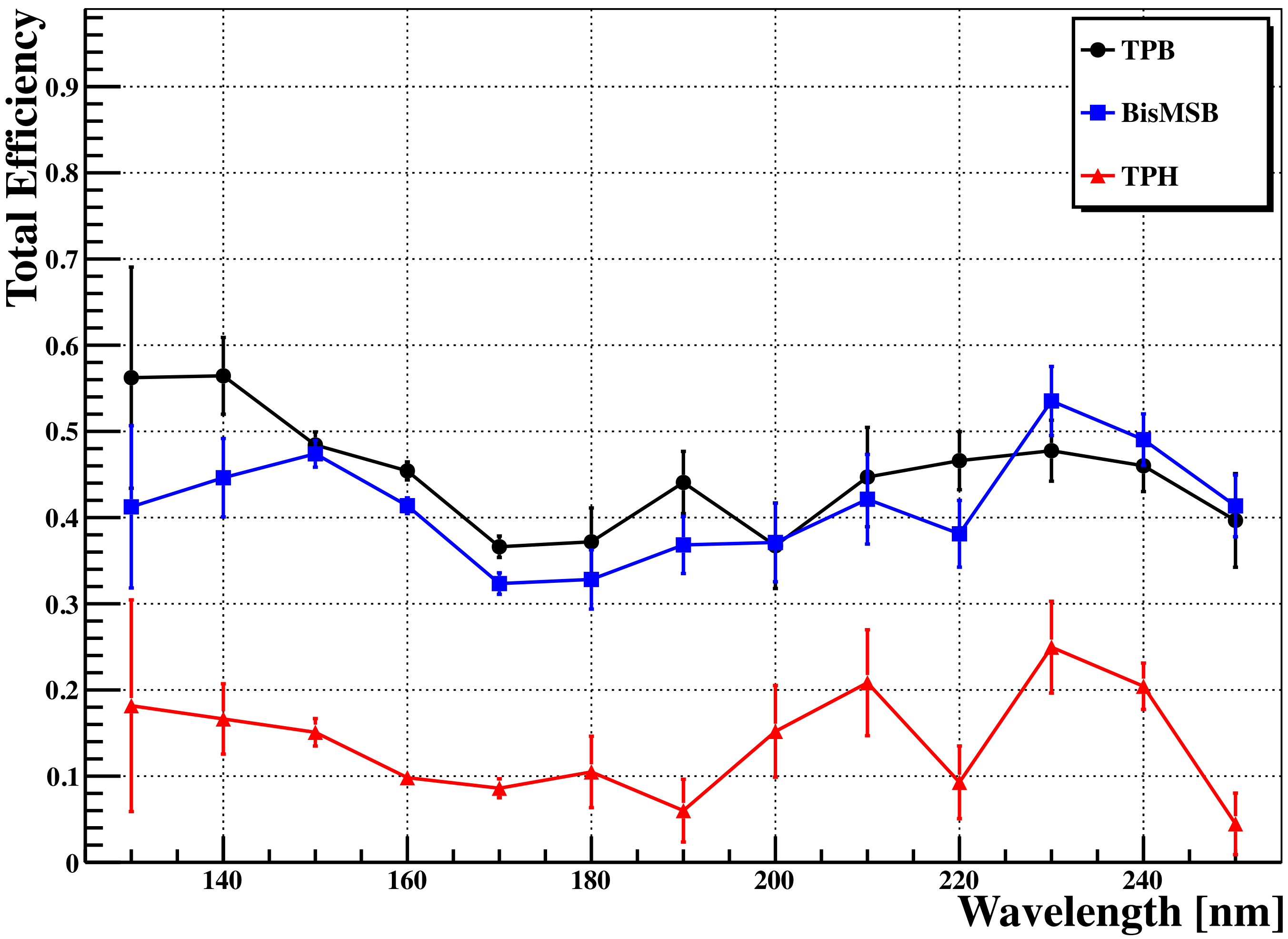




More Fluors

- Recently did absolute measurements for two more fluors: BisMSB* (of interest for LBNE) and TPH† (because I had some in my lab...)
- BisMSB is a very promising alternative to TPB, but doesn't dissolve in Toluene as well--looking into evaporation





* BisMSB = 1,4-Bis(2-methyl-styryl)benzene †TPH = p-Ter-phenyl

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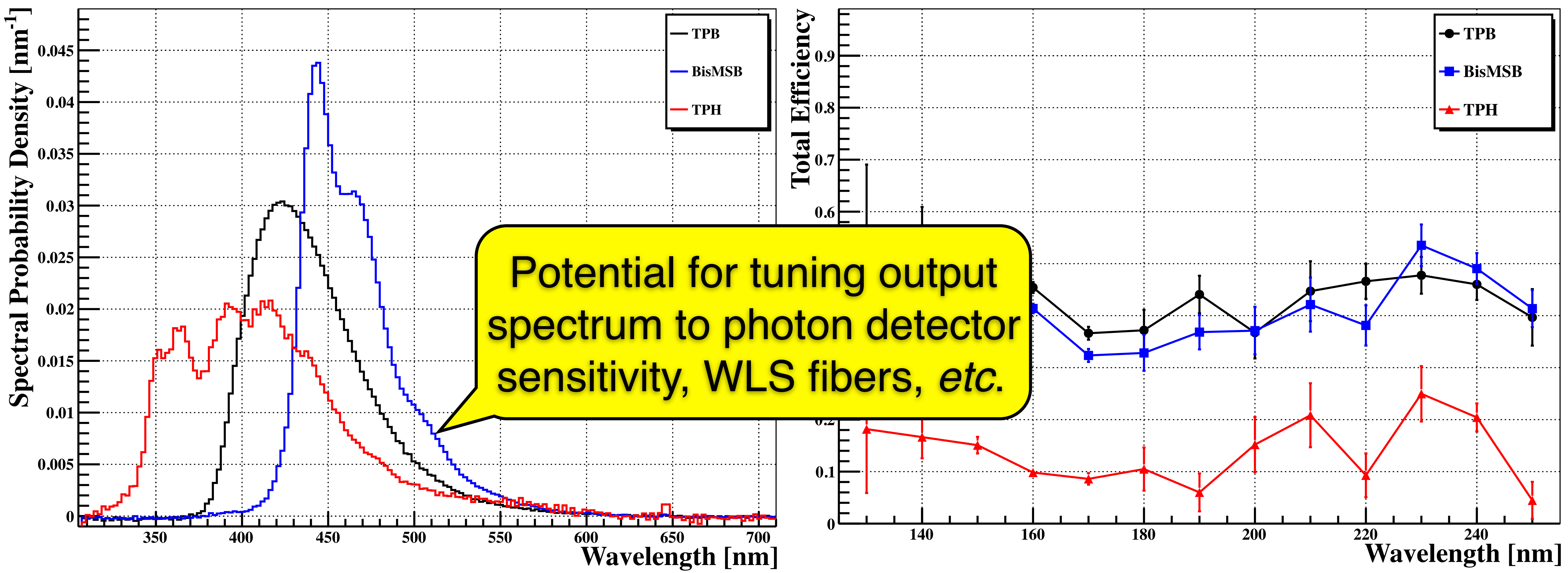

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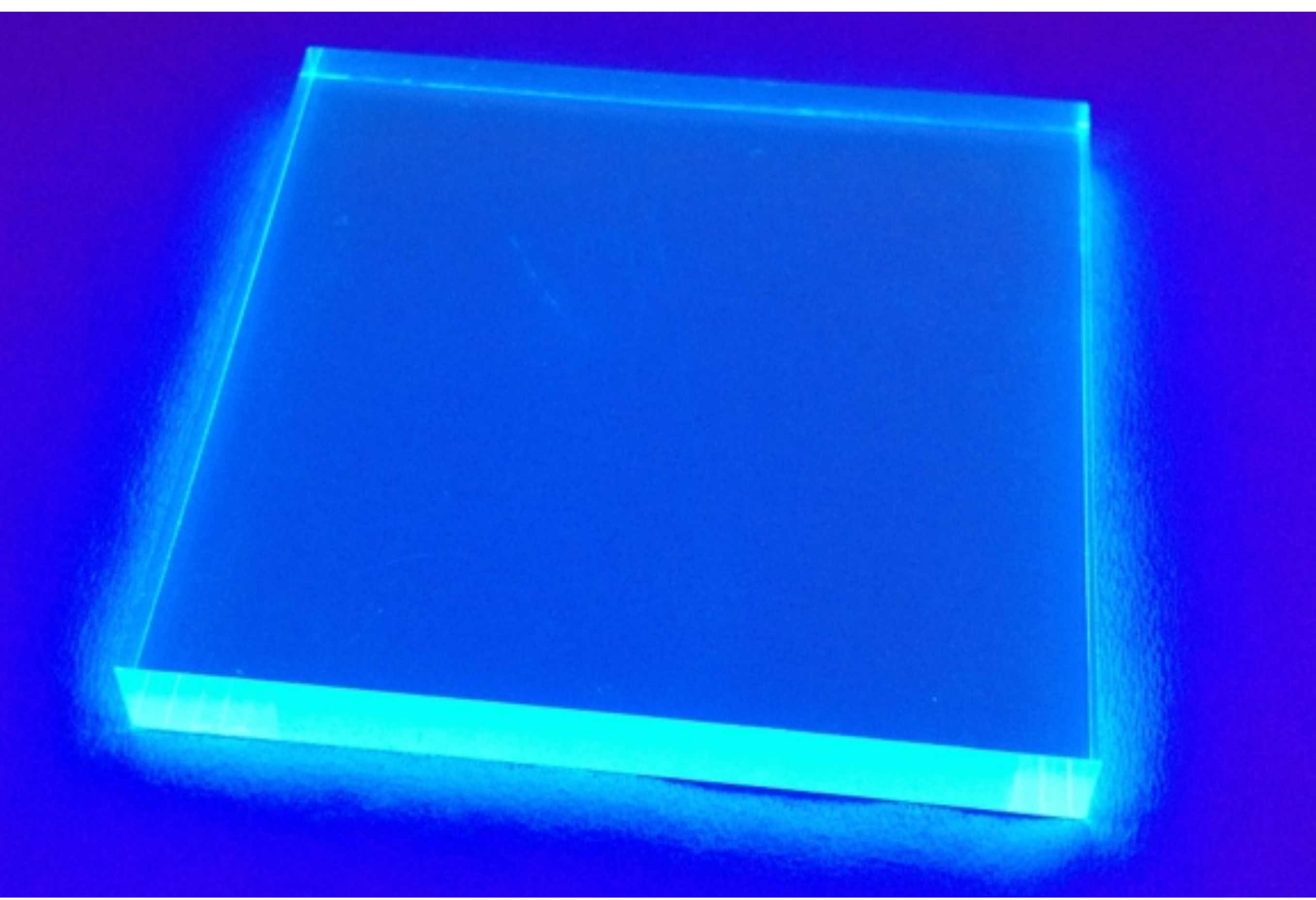
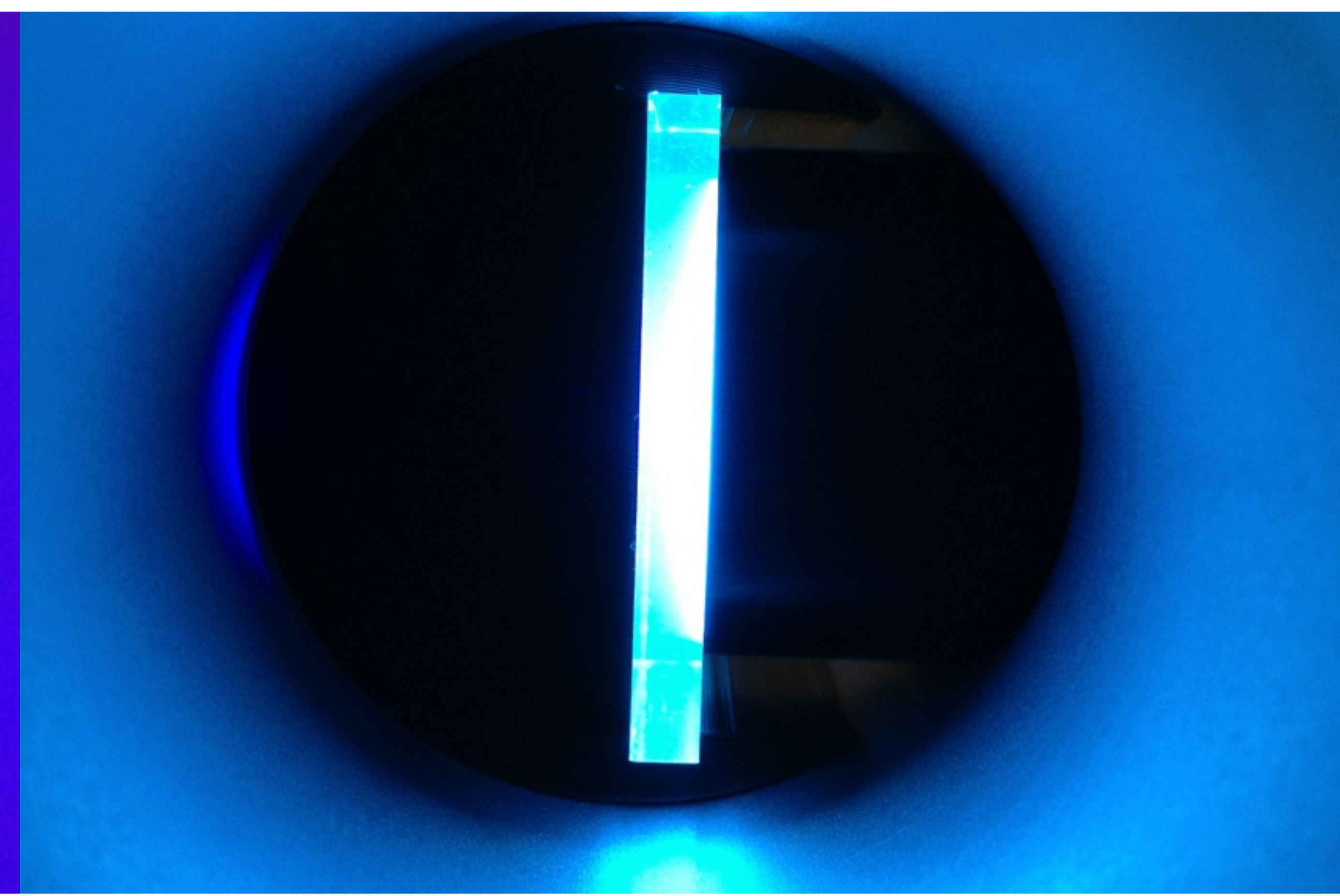
Large-area paddles

- Investigating plastic light guides doped with WLS during manufacture (instead of coating outside)
- Started with 1.5” square tiles, read out from the edges
- Doping with TPB and BisMSB at 0.01, 0.1 and 1.0% by mass





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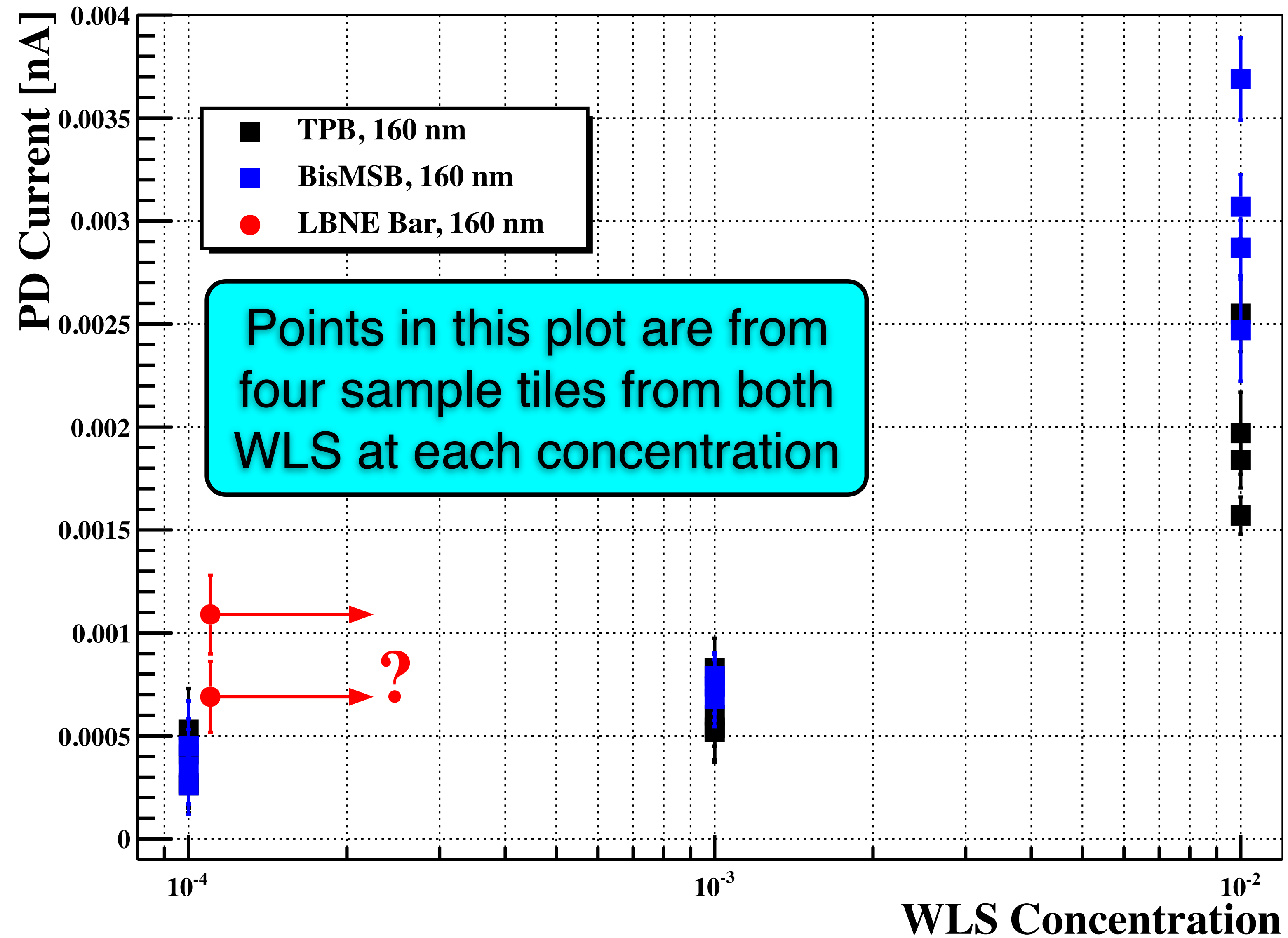
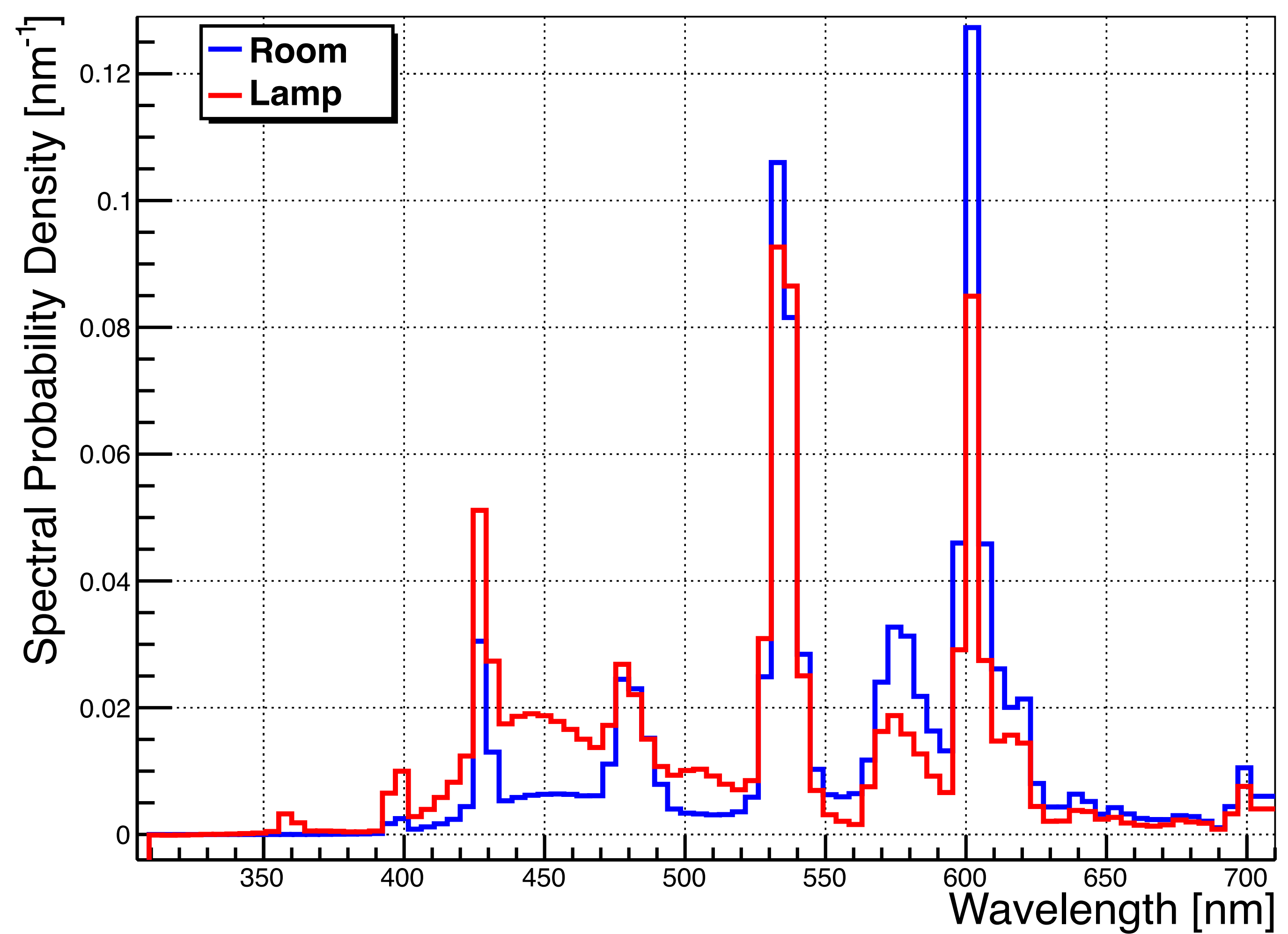
Clearly, more WLS is better, so we’re scaling up to test paddles for LBNE prototype detectors this summer with 1% of each WLS.



Aging Tests

- Using these tiles for some exposure tests to look for degradation due to exposure to fluorescent room lighting
- Used a fluorescent desk lamp inside a dark box to give controlled doses of indoor lighting



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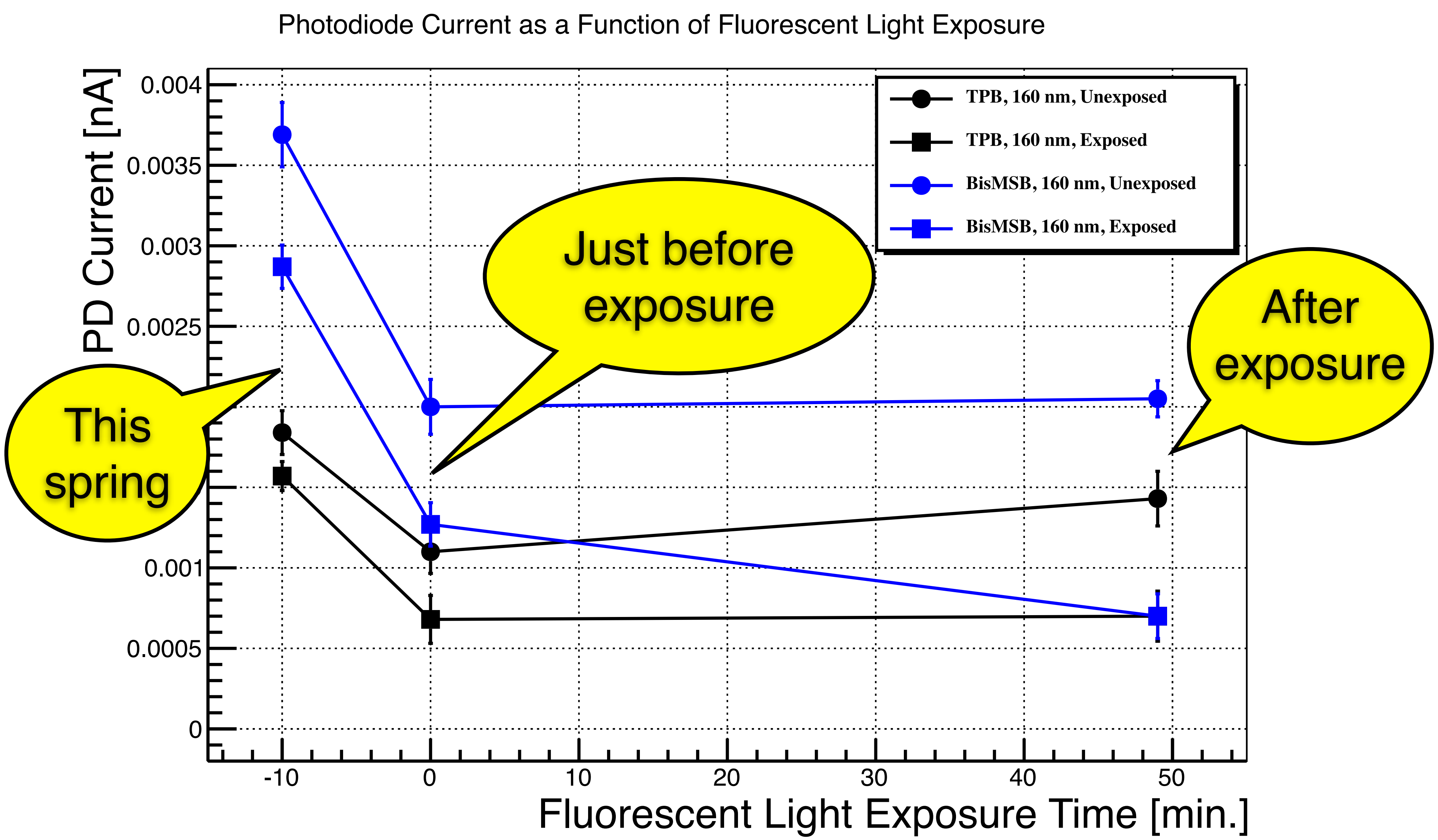

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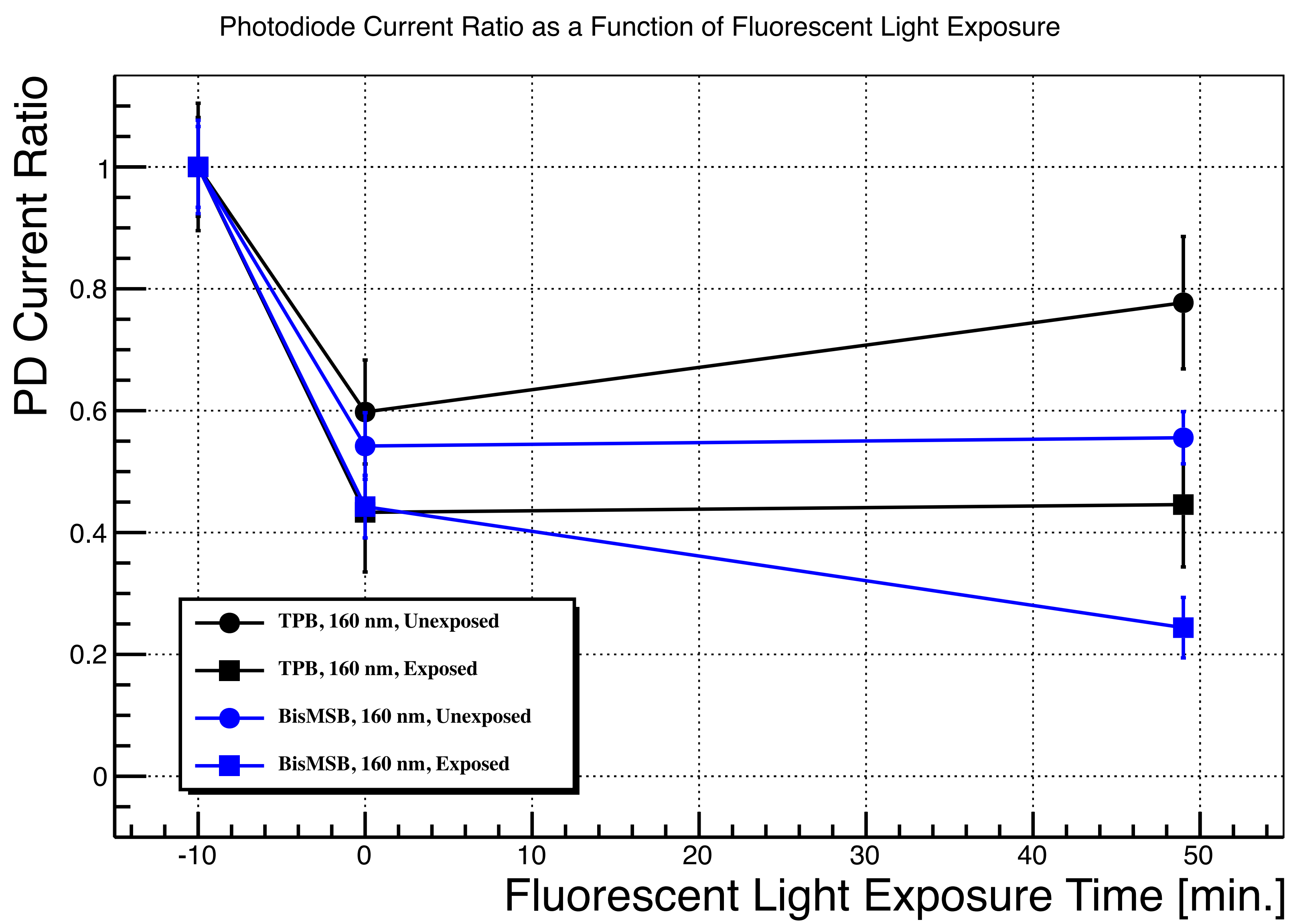
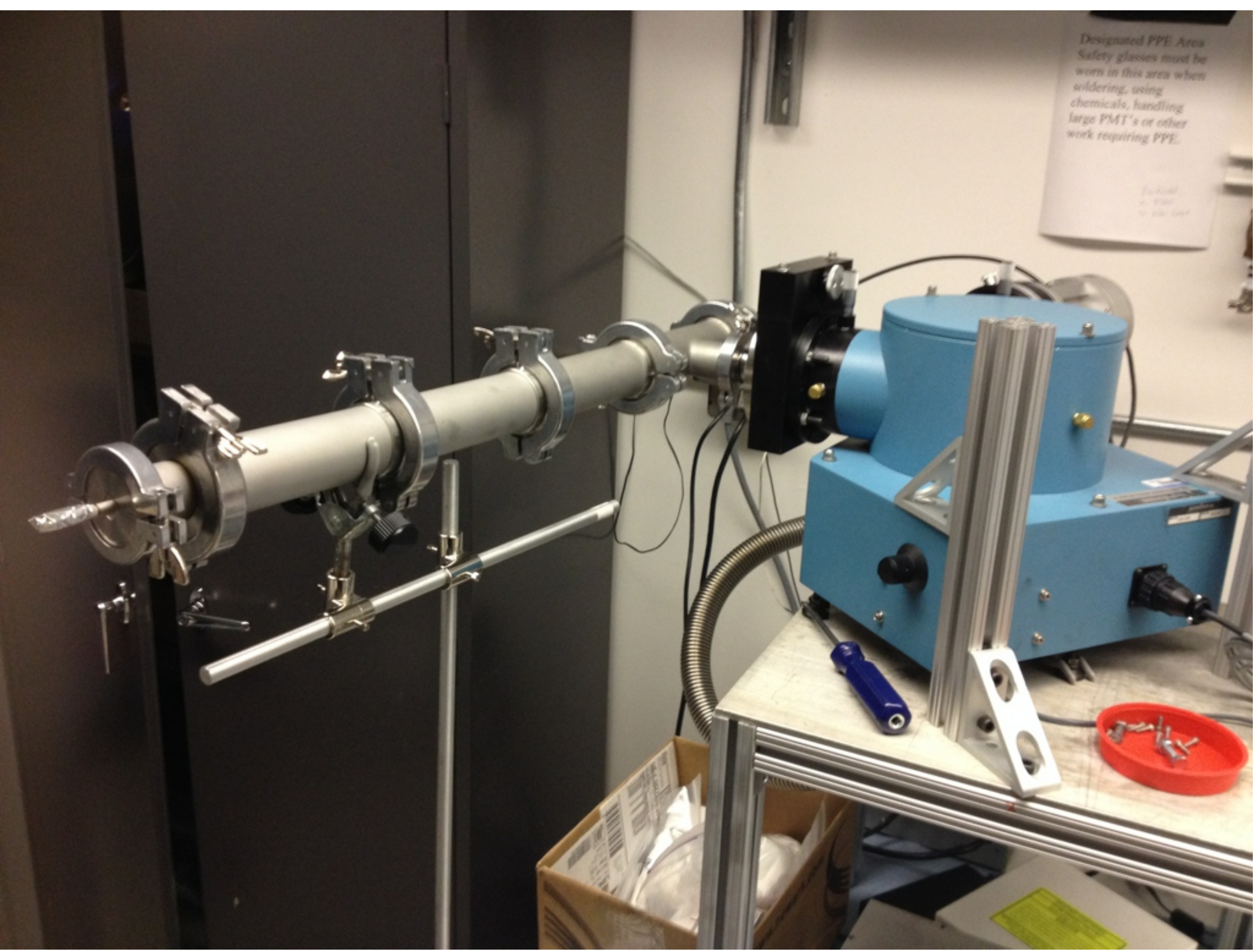
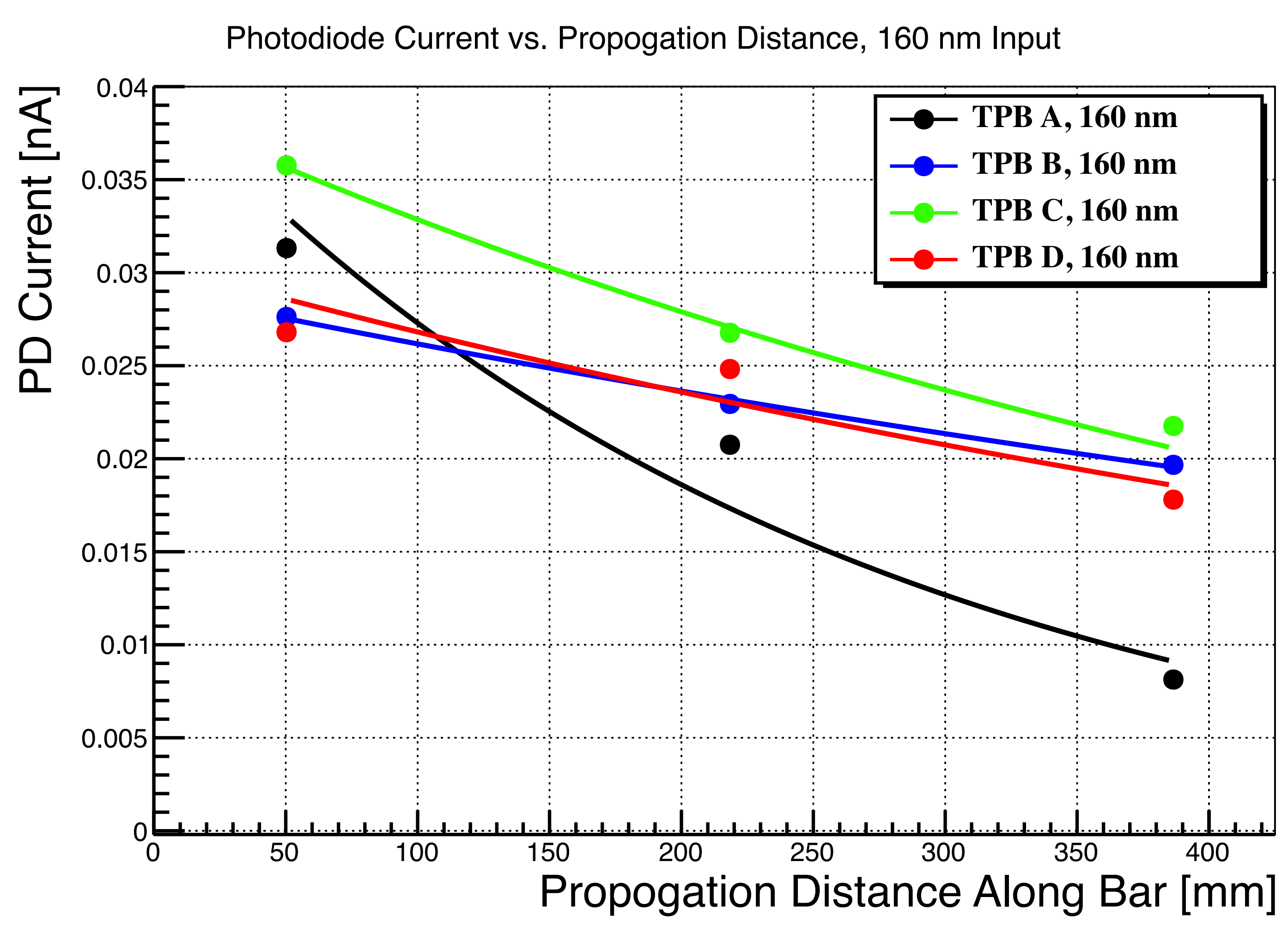


Scaling up!

- Recently got WLS doped bars that match the LBNE baseline (25 x 6 x 525 mm)
- Measuring the fluorescence yield at the end of the bar resulting from illumination at three points along its length
- Also bought some wider panels to experiment with fiber readout





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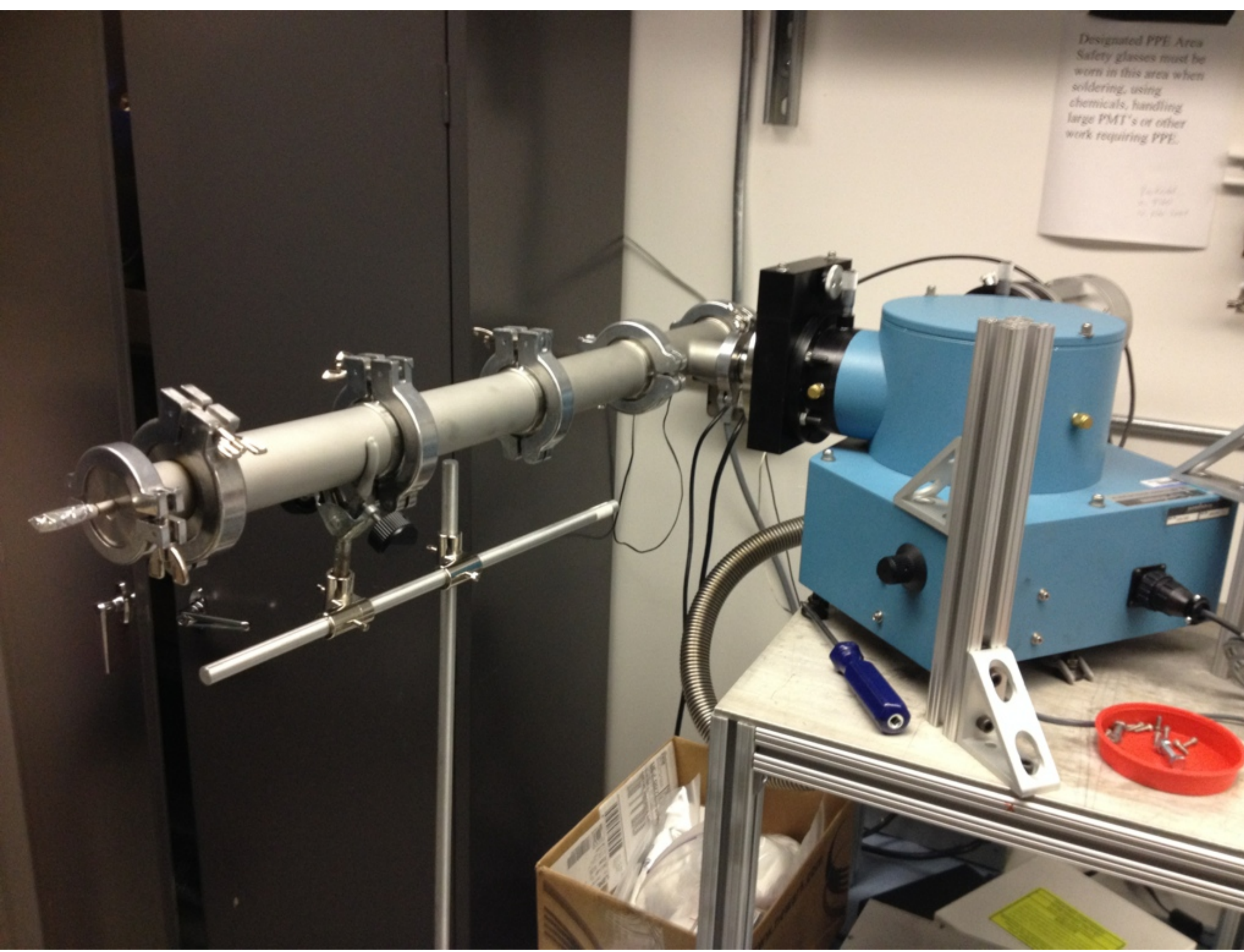

Fl. Yield [nA]	Att. Len [mm]
0.040 ± 0.00051	260.8 ± 4.1
0.029 ± 0.00020	981.1 ± 29.8
0.039 ± 0.00030	611.6 ± 17.8
0.030 ± 0.00022	779.4 ± 16.7

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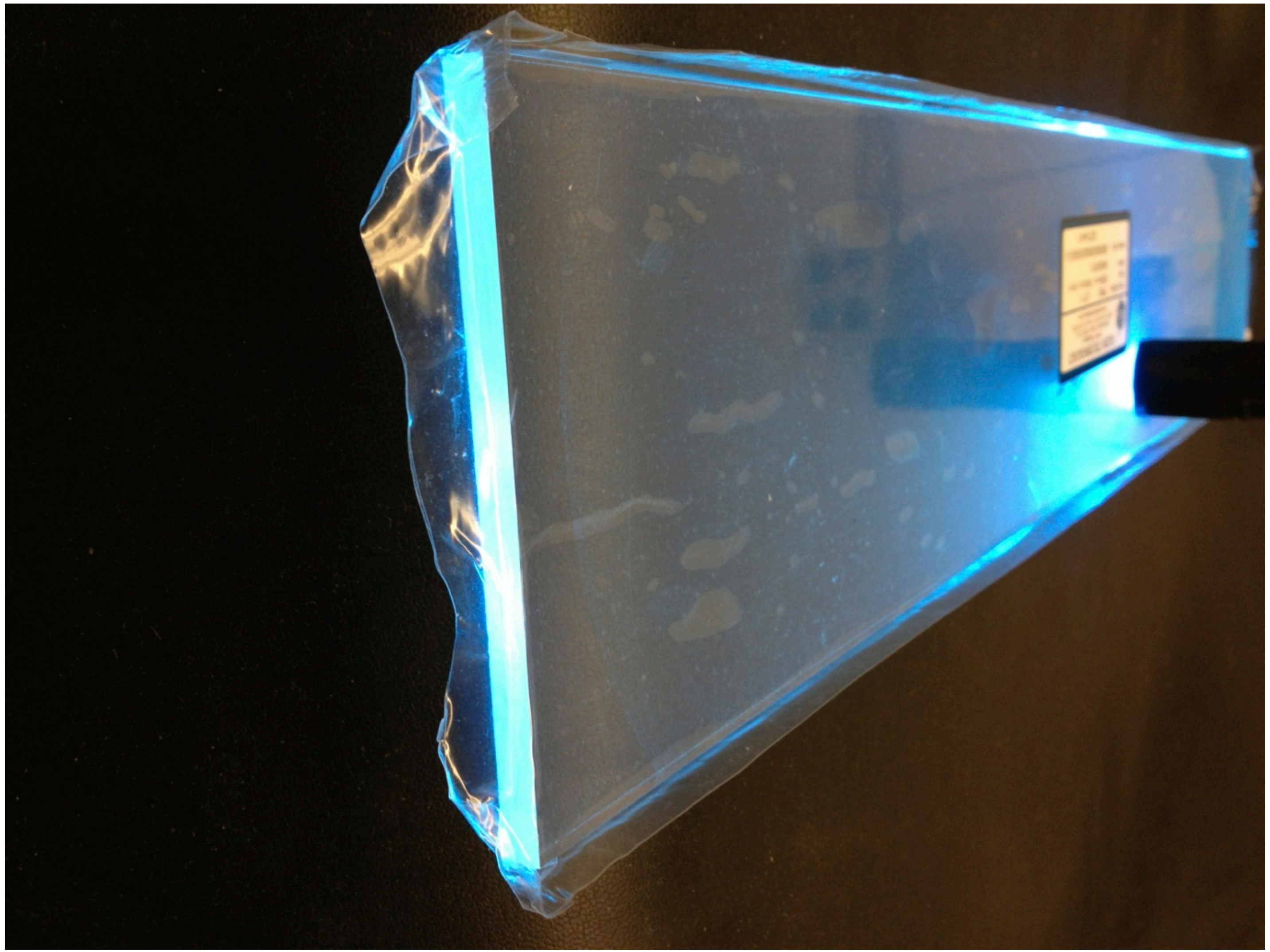
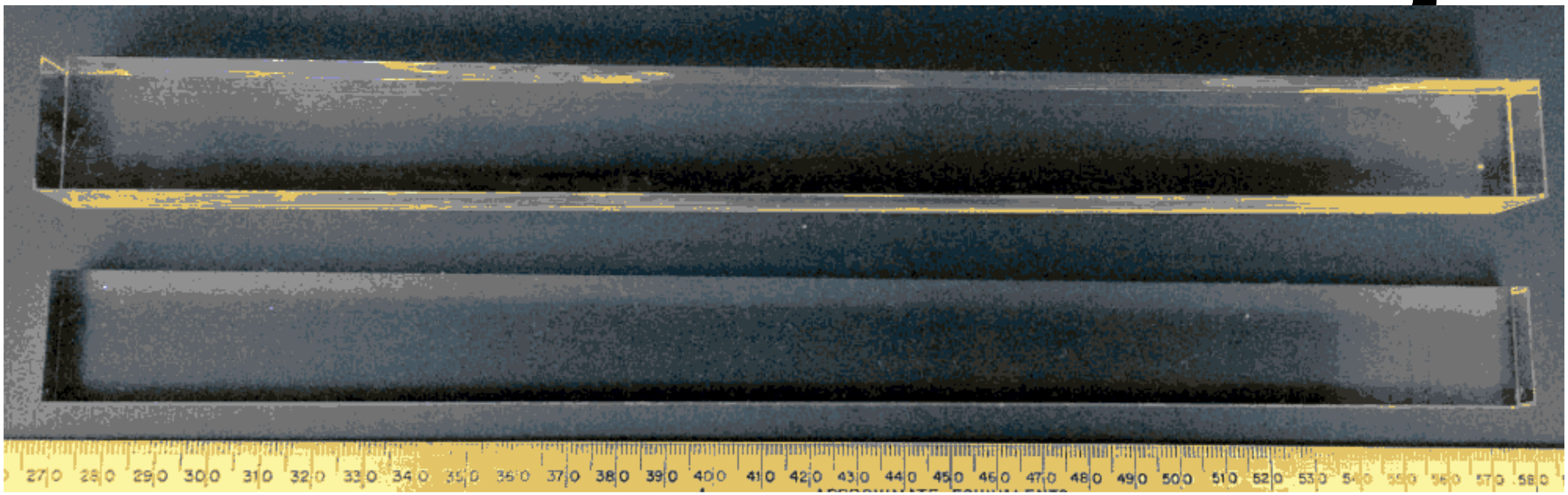
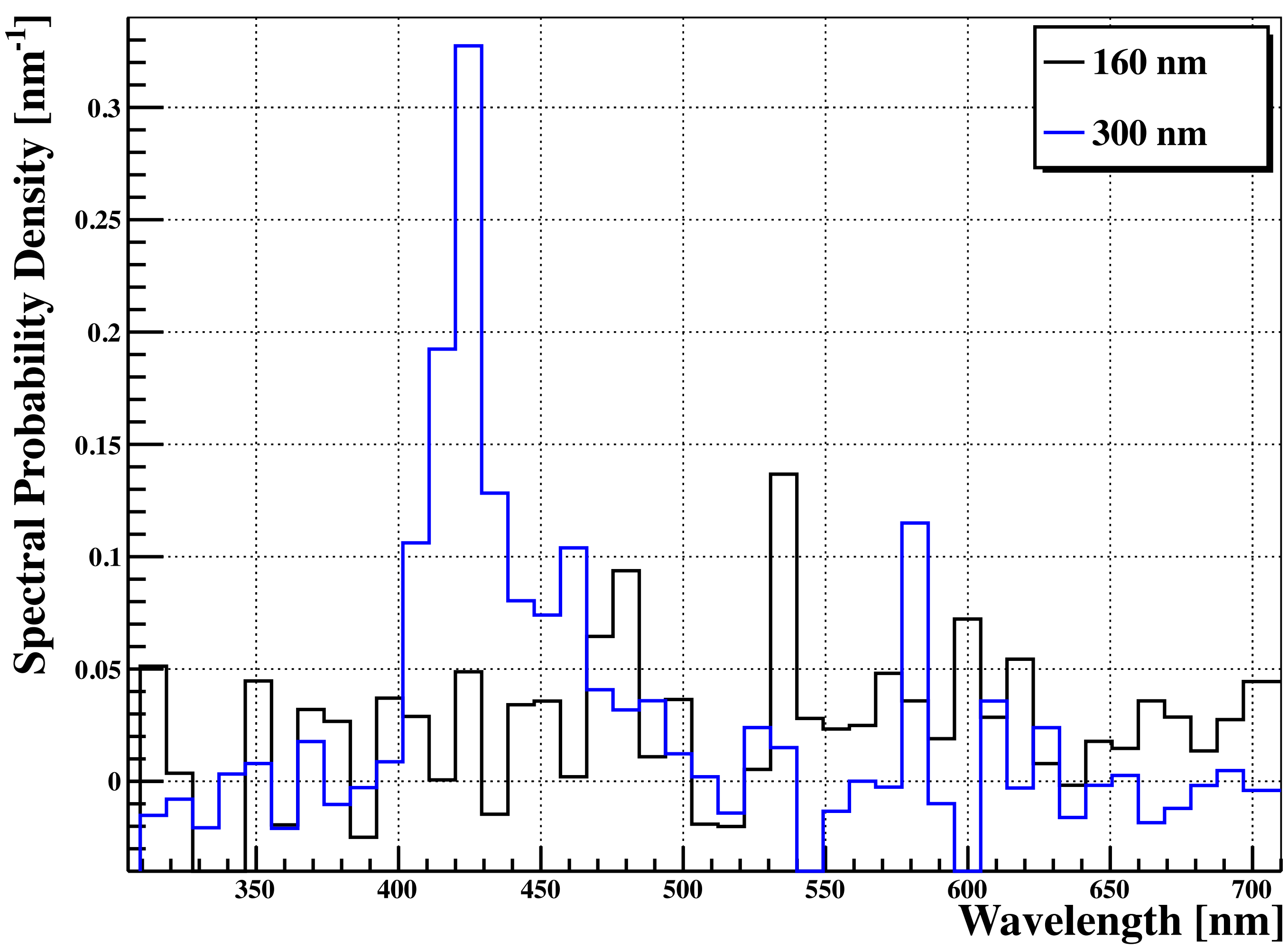
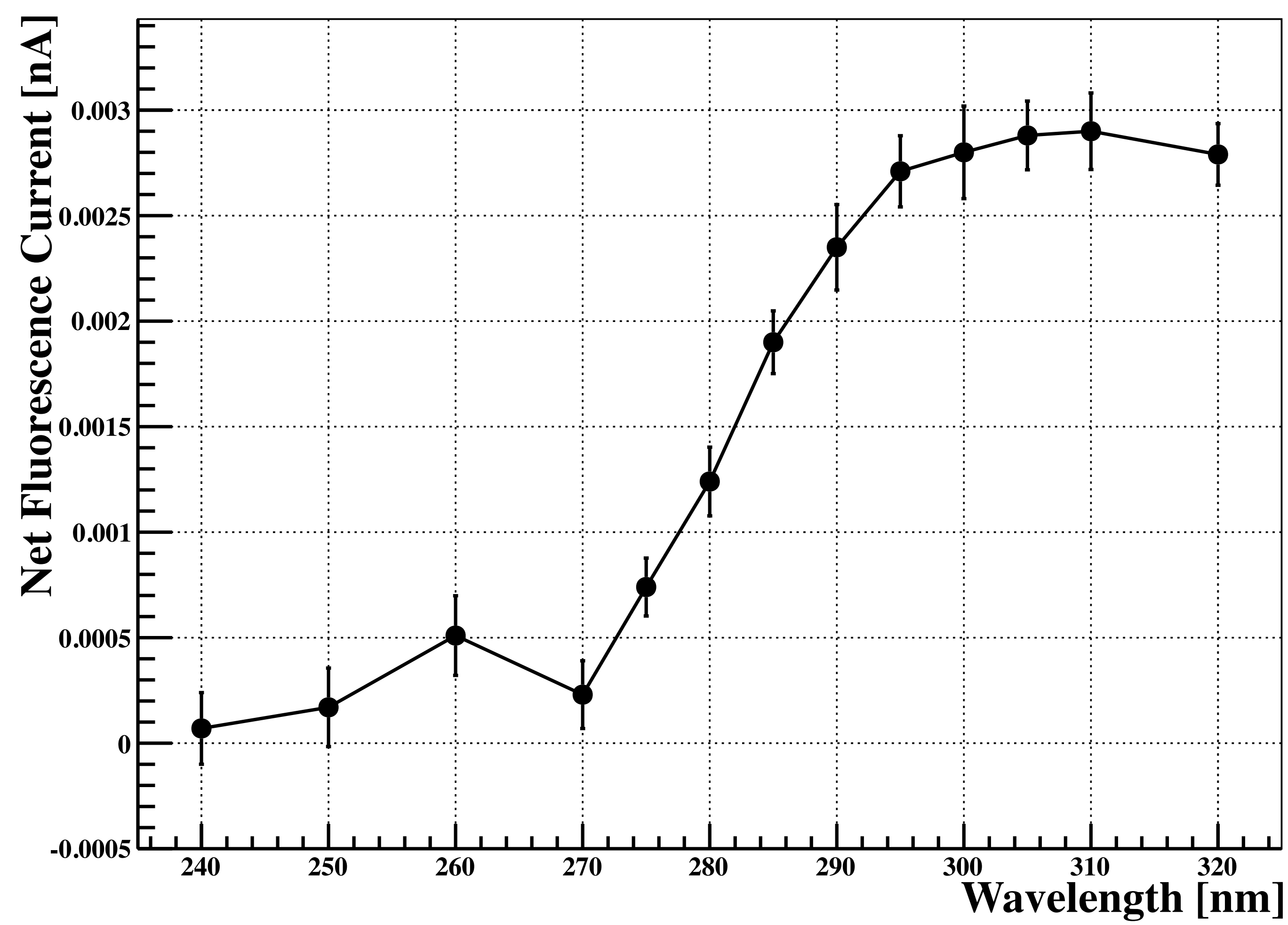


WLS Bars From Eljen

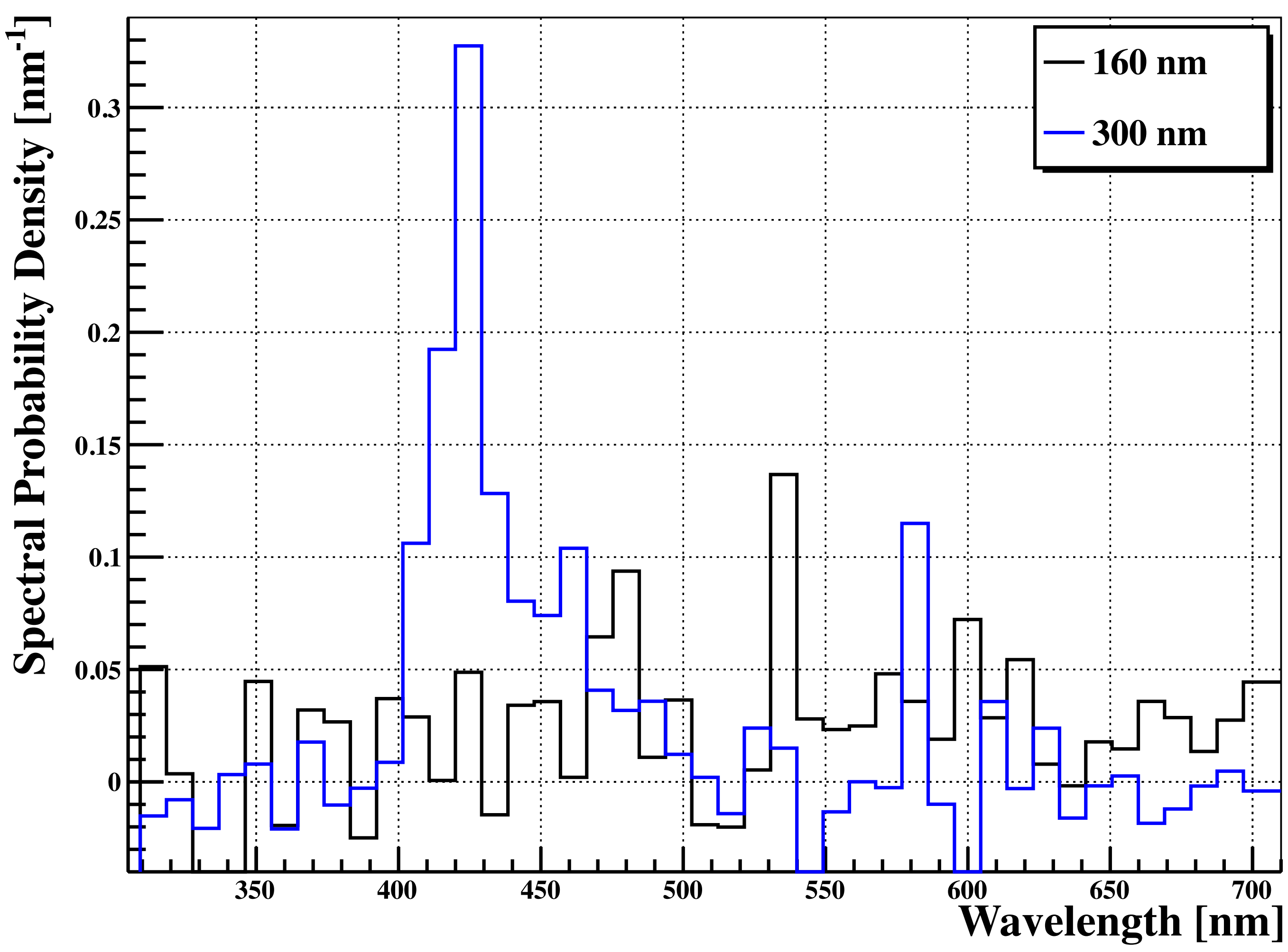


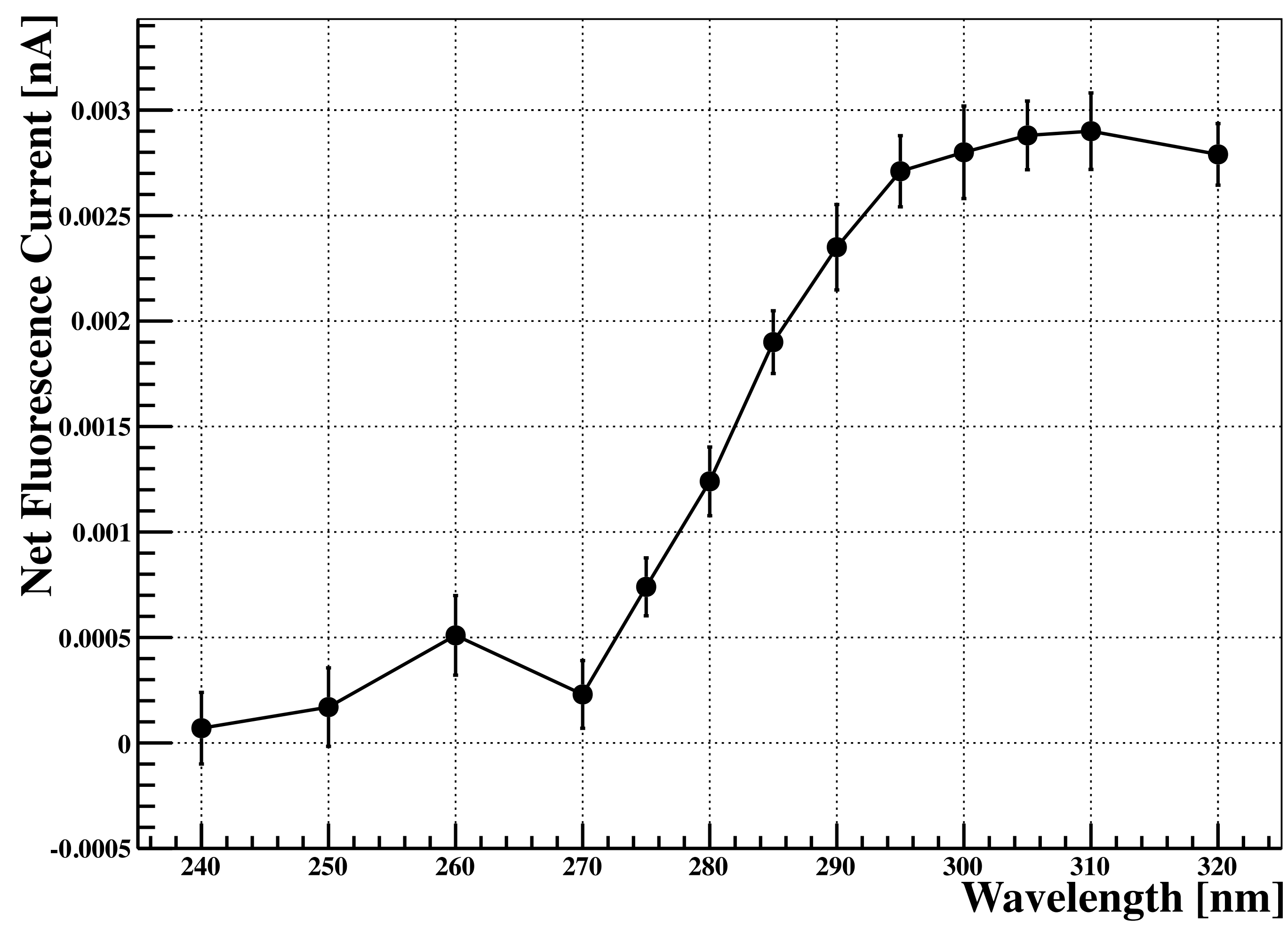




WLS Bars From Eljen

- Commercial WLS coated bars from Eljen (both silvered on one end)
- **1” x ½” x 12” PMMA *doped* with EJ-299-15**
- 1” x 1” x 12” *coated* with EJ-298B





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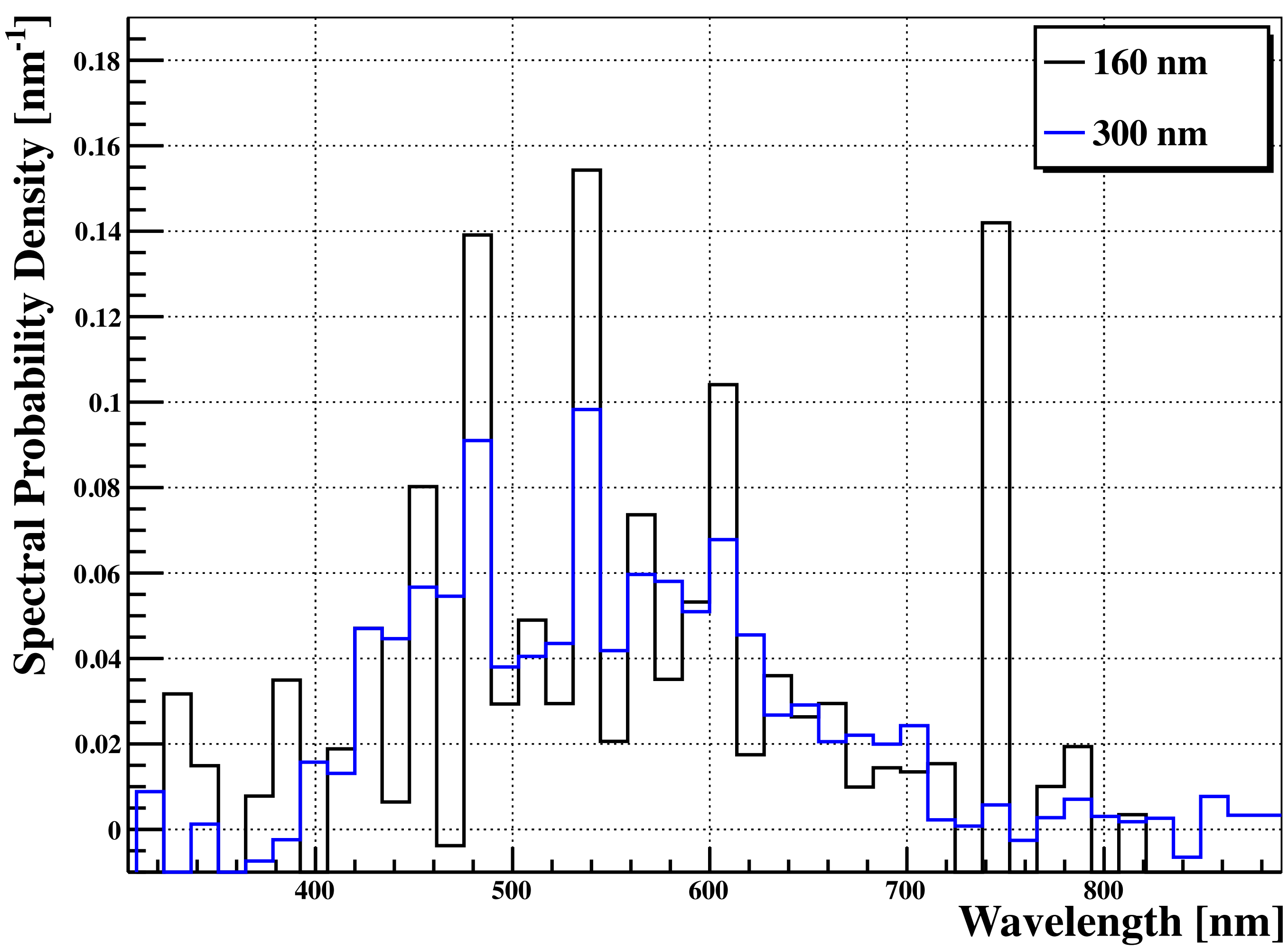
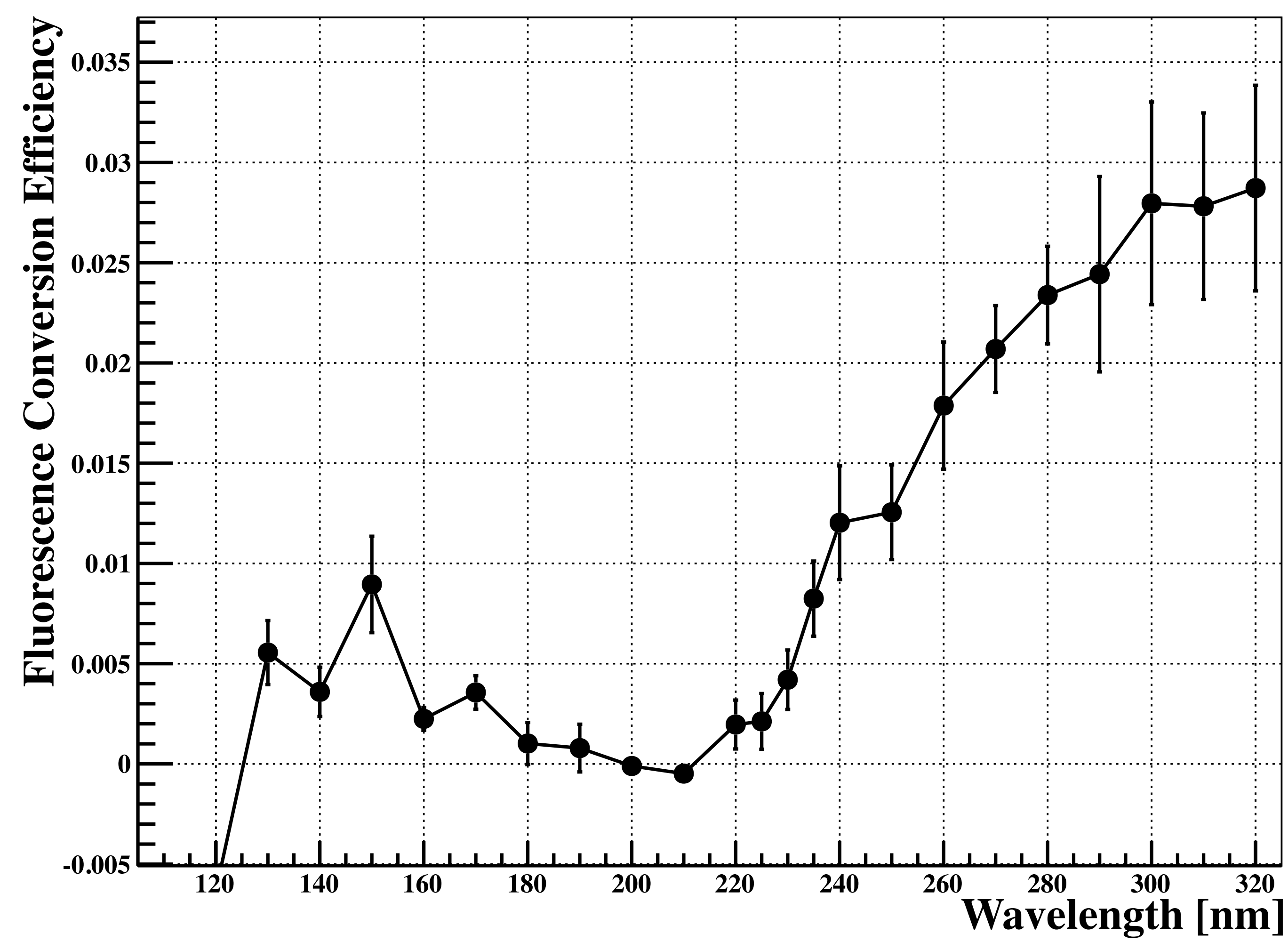
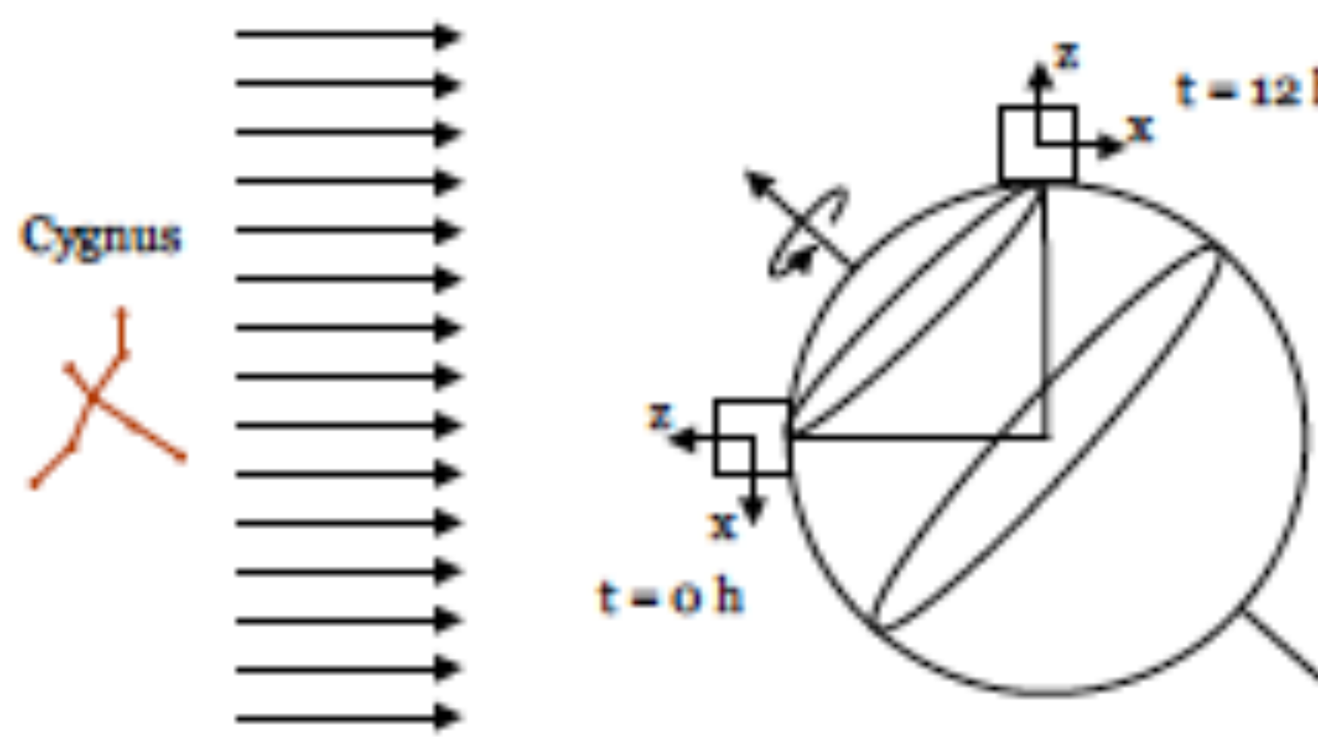




Some Cool New Ideas

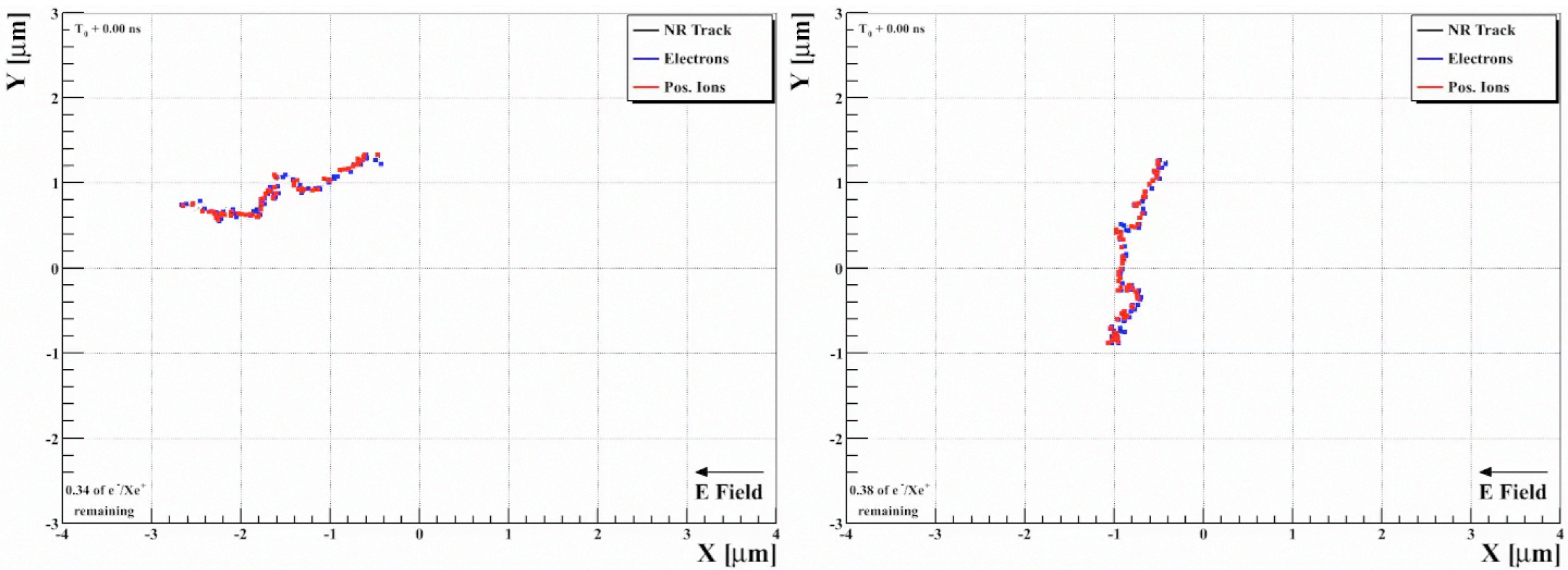
Directional Dark Matter

- Xenon is a nice target for dark matter, and gas rather than liquid phase has some advantages
- Track directionality would make a very strong case for direct detection of dark matter
- Most current experiments try for directionality by imaging the nuclear recoil track:
  - Very diffuse detectors (low target mass)
  - High energy threshold
  - Poor track image quality



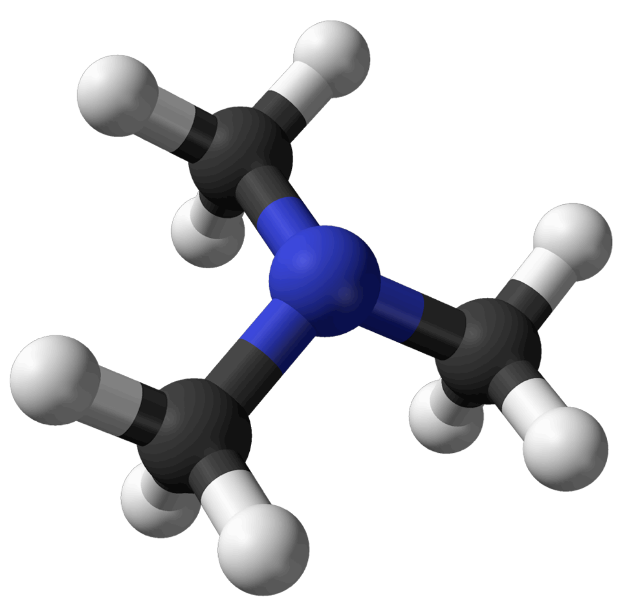
A Different Approach!

- Use *columnar recombination* (CR) to extract track direction...
- Requires ionization electrons drift back through parent track:
    - Depends on angle between drift field and track direction
    - Other recombination types are independent of this angle

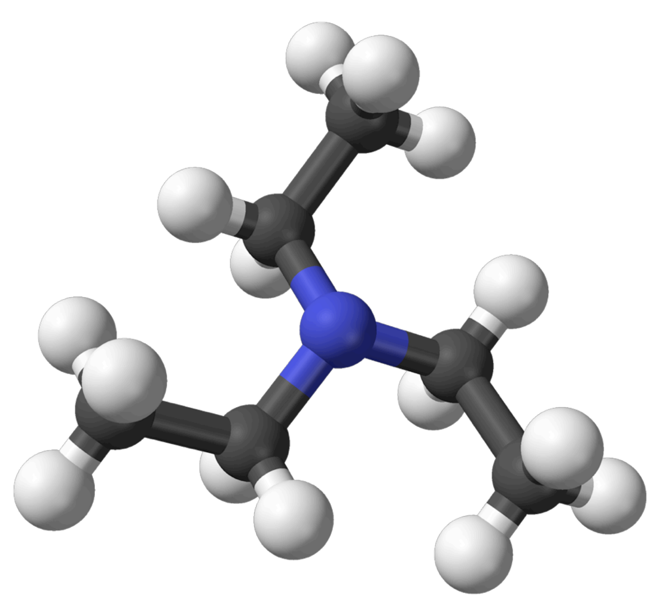


Two Birds With One Stone

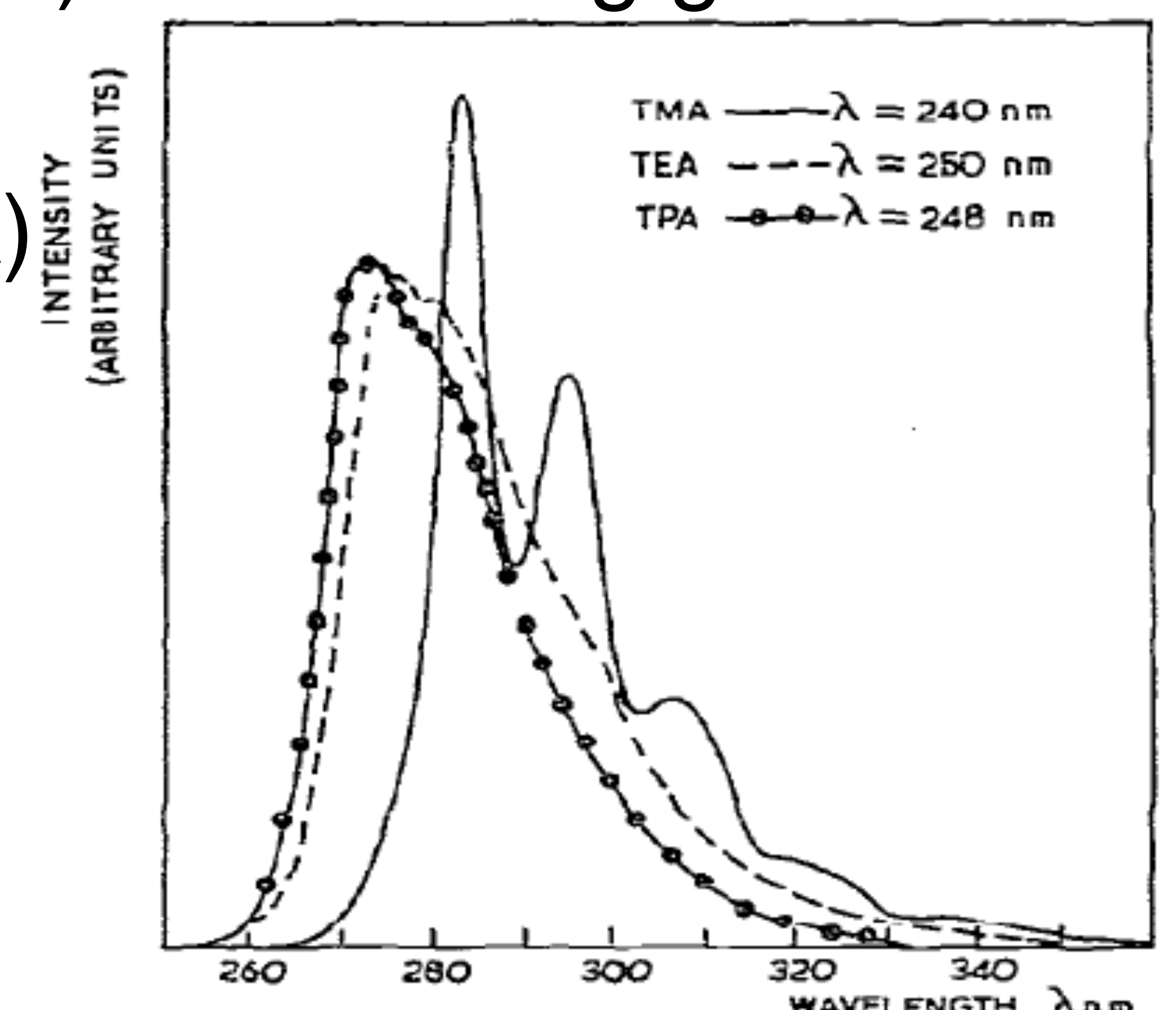
- To extract the CR signal from a HPXe gas detector, we need two things:
  - Penning additive to convert excitations into ionizations
  - WLS that absorbs at 173 nm and fluoresces at ≈ 300 nm
- Provenance! Tri-methyl-amine (TMA) is a Penning gas known to fluoresce efficiently at 300 nm!
- also possible: Tri-*ethyl*-amine (TEA)



TMA



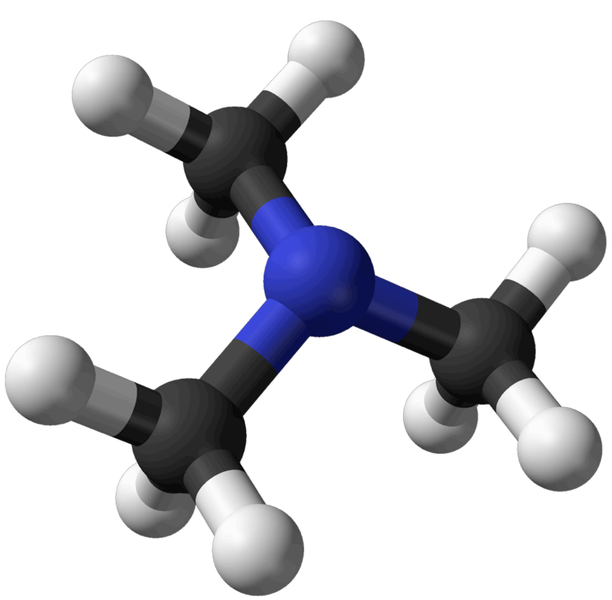
TEA



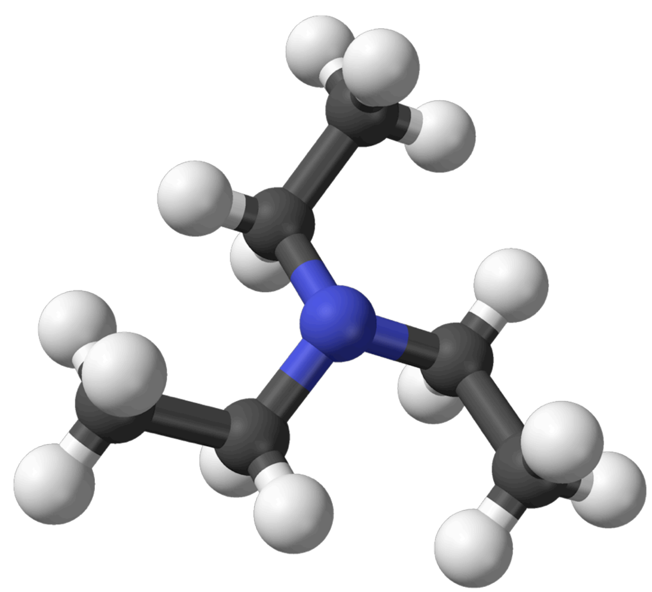
Two Birds With One Stone

- To extract the CR signal from a HPXe gas detector, we need two things:
  - Penni… …xcitations into ionizations
  - W… …oresces at ≈ 300 nm
- P… …Penning gas known to…
- also possib… …ne (TEA)

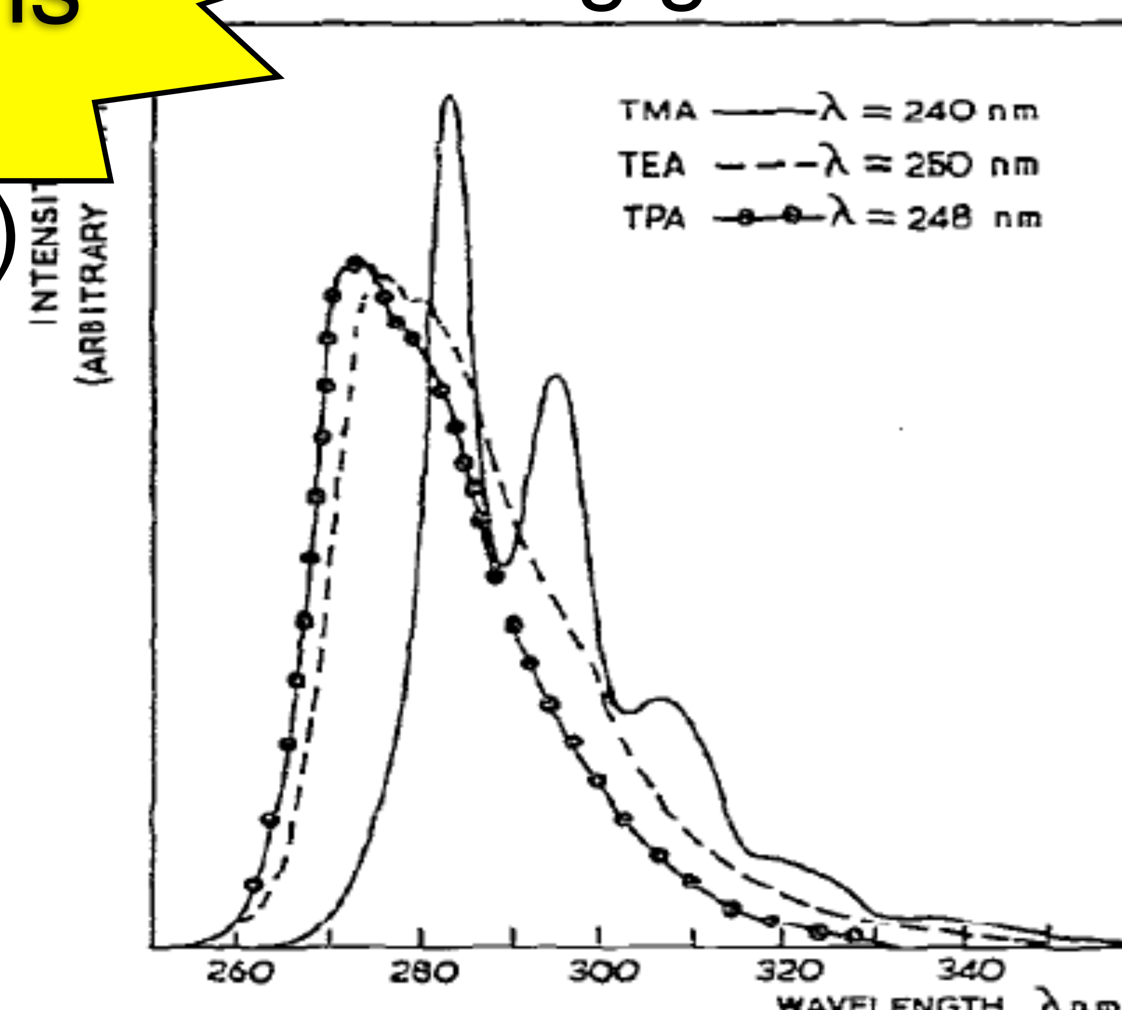
Bonus!
these molecular additives help cool the ionization electrons and reduce diffusion



TMA

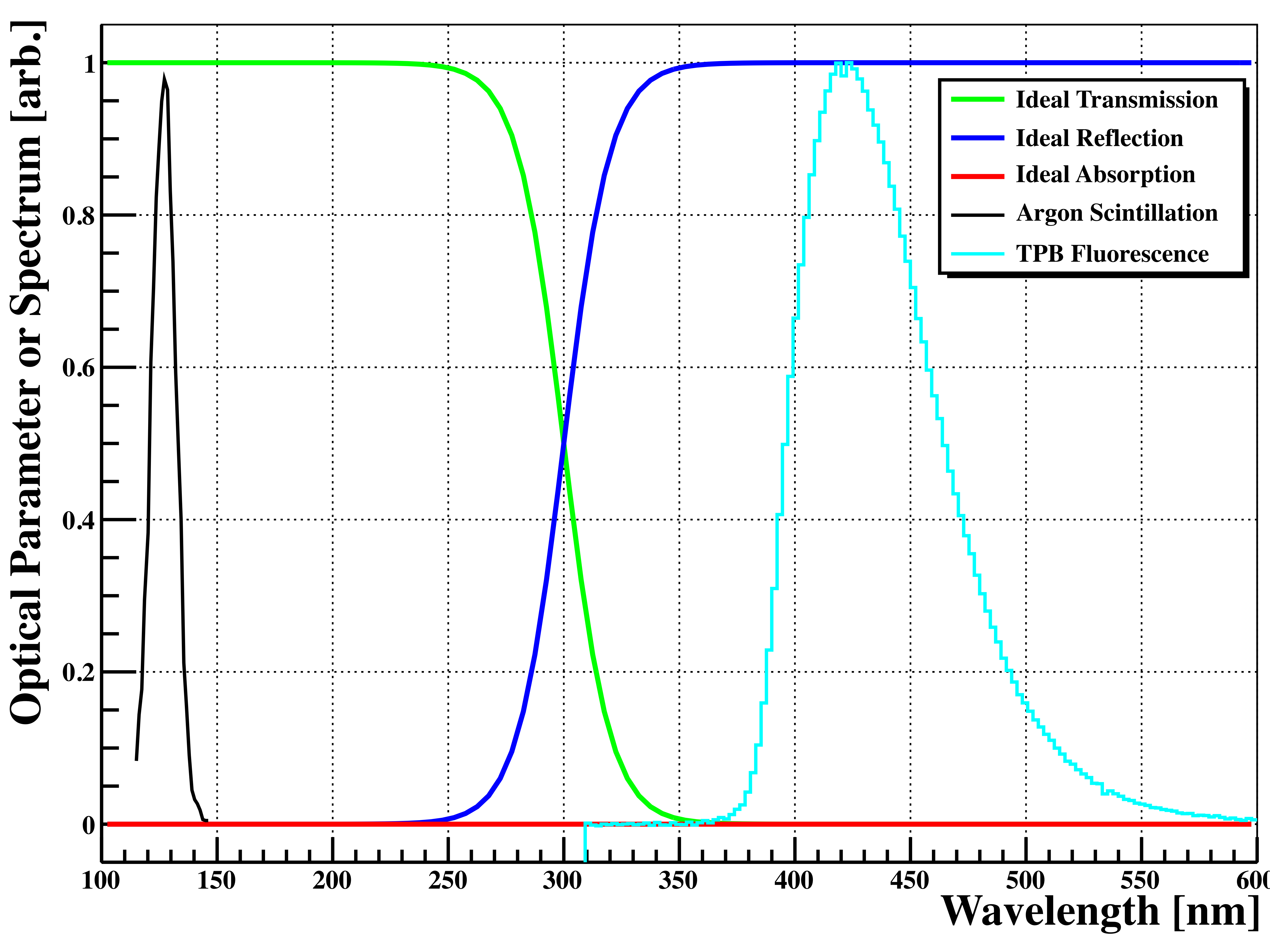


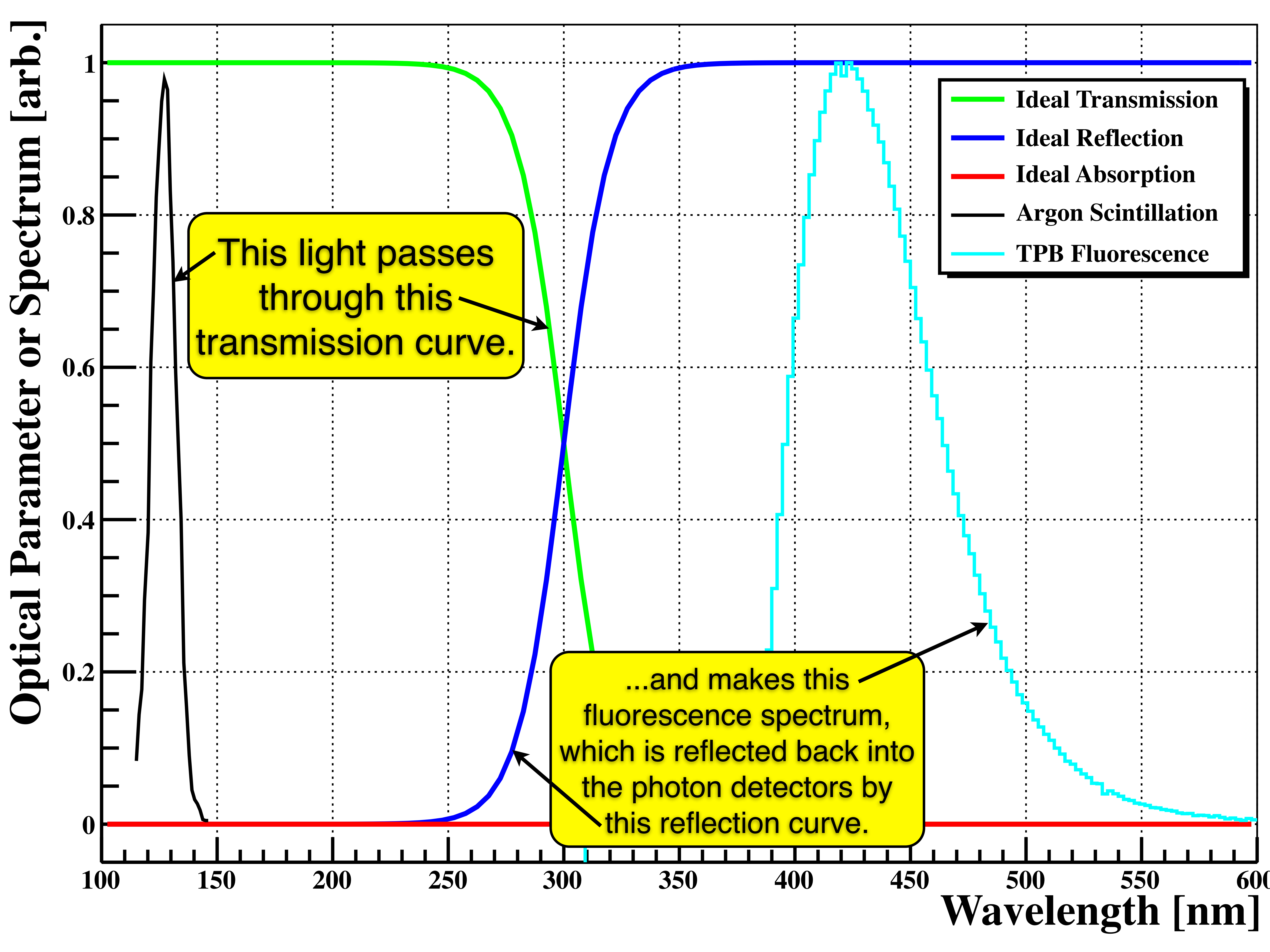
TEA



A “high pass” Filter

- Even if your WLS is *perfect*, it fluoresces in 4π, so you lose half the light no matter what (much more, in practice if fluorescence light must be transported through a light guide to your detector)
- We want some material that is transparent to VUV scintillation, highly reflective for visible fluorescence light, and absorptive nowhere...
- But does such a material really exist?


Optical Parameter or Spectrum [arb.]
Wavelength [nm]
Ideal Transmission
Ideal Reflection
Ideal Absorption
Argon Scintillation
TPB Fluorescence
0
0.2
0.4
0.6
0.8
1
100
150
200
250
300
350
400
450
500
550
600



Optical Parameter or Spectrum [arb.]
Wavelength [nm]
Ideal Transmission
Ideal Reflection
Ideal Absorption
Argon Scintillation
TPB Fluorescence
This light passes through this transmission curve.
...and makes this fluorescence spectrum, which is reflected back into the photon detectors by this reflection curve.

A “high pass” Filter

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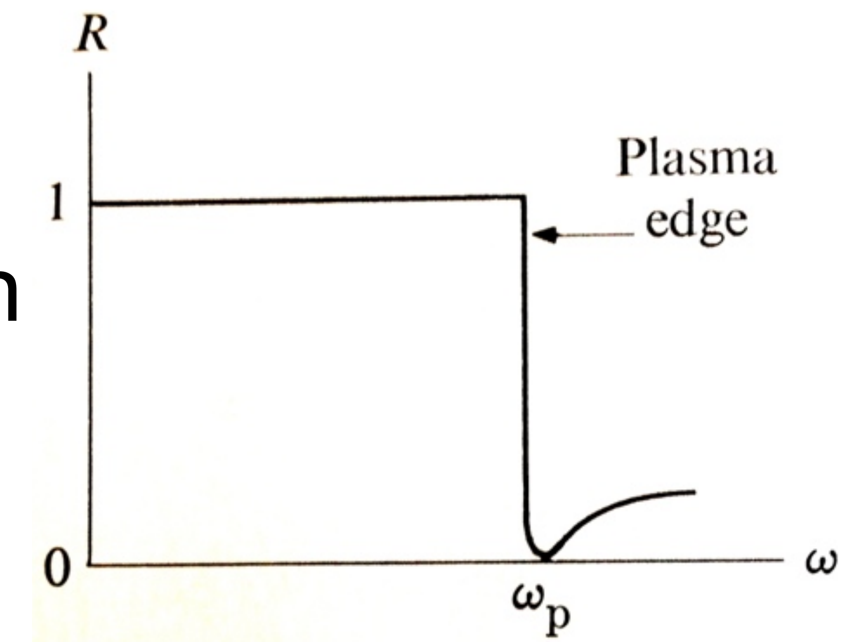
- But does such a material really exist?

What about metallic films?

- If you pick the right metal, it's shiny in the visible, but what about the UV transmission
- Exploit the plasma frequency! $\omega_p^2 = \frac{Ne^2}{\epsilon_L m^*}$
  - Conduction electrons in metal act like a plasma of free electrons.
  - Finite e$^-$ mass means that photons with too high a frequency can't move them around, and therefore don't interact (transmission!)

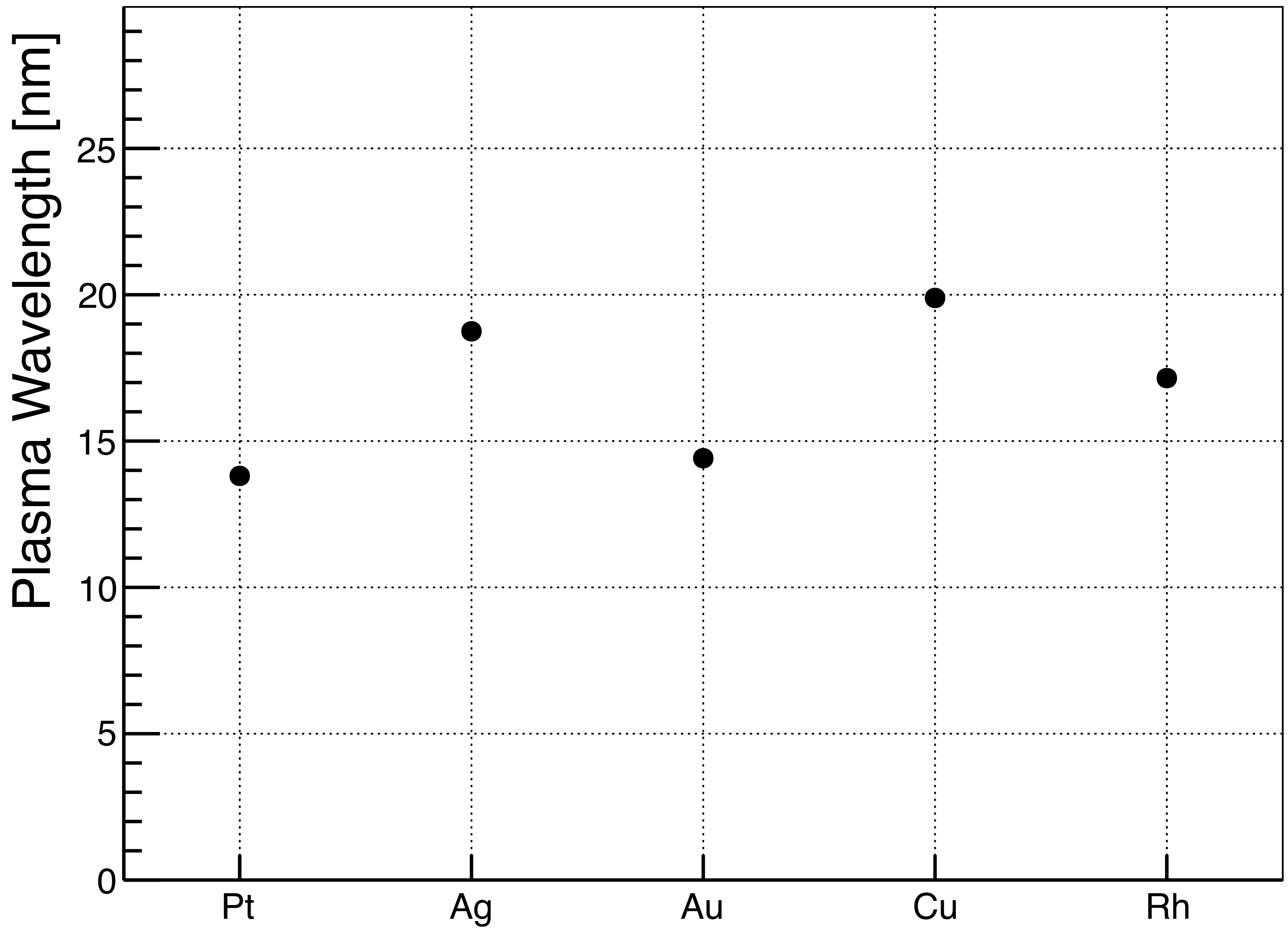


- If we pick a metal with the right plasma frequency, we can coat the WLS with it and recover much of the fluorescence light emitted back into the detector.
- Absorption can still hurt us though, especially for large paddles read out from the side

Why doesn't this work?

- This effect turns on at too short a wavelength...
- You can parameterize the wavelength corresponding to the plasma frequency as:

$$\frac{40.1 \text{ nm}}{\sqrt{\frac{\rho}{\text{g/cm}^3}\frac{Z}{A}}}$$



Conclusions

- Lots of new detectors are coming on line that require the detections of VUV photons,
- but VUV photons are a real pain to deal with...
- So don’t do it if you can get away with shifting them to a more manageable wavelength!
- These are fun measurements to do once you have the infrastructure in place, so...
- if there’s a fluor or detector setup you would like to investigate, talk to me or send me an email, and we’ll figure out how to fine tune and characterize the design!

Thank you for your attention
Any questions?