Fluorescence Efficiency and Visible Re-emission Spectrum of Tetraphenyl Butadiene Films at Extreme Ultraviolet Wavelengths

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BERKELEY LAB

Outline:

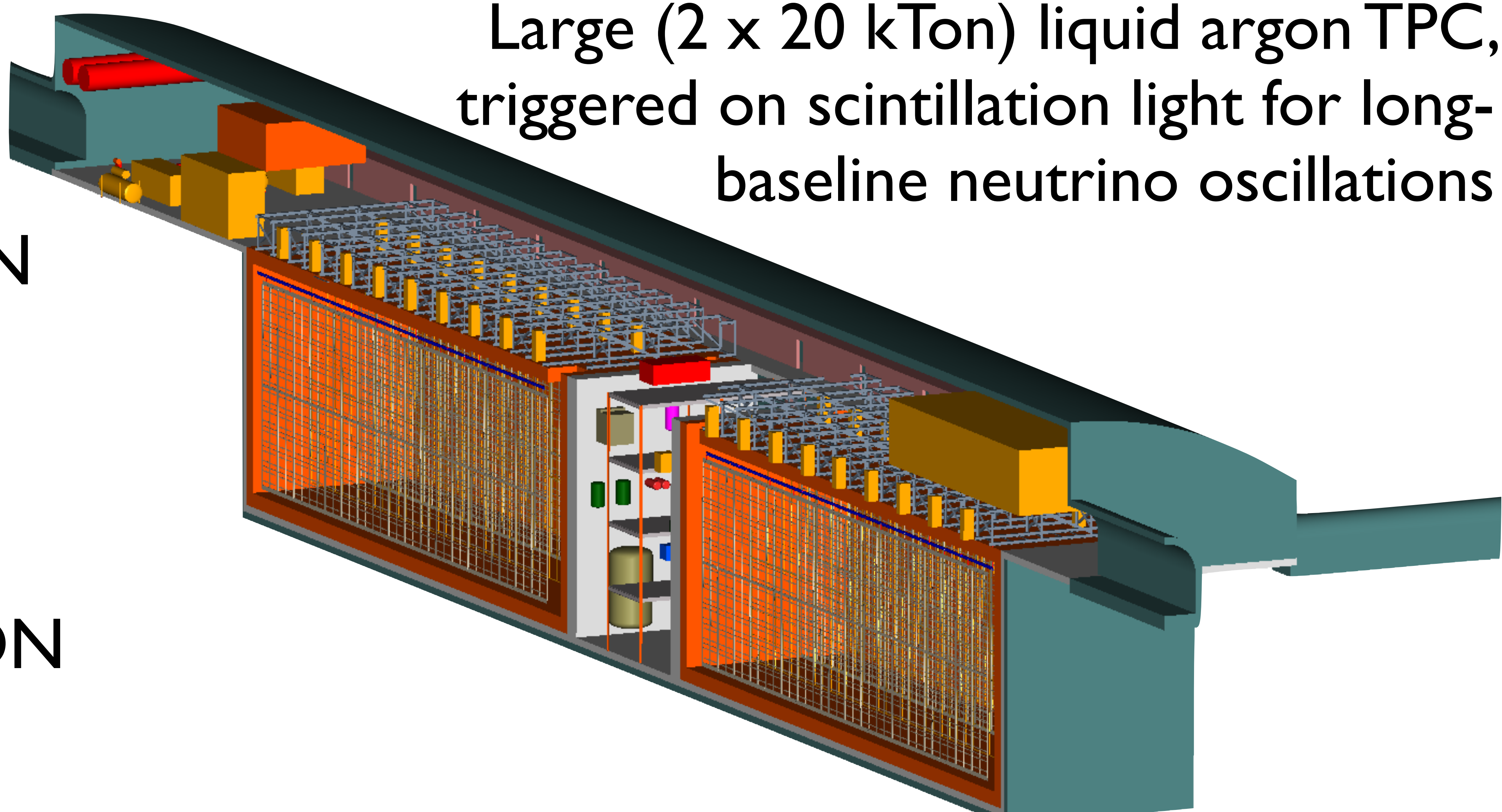
- Noble gas detectors and scintillation light
- Wavelength shifting films (TPB), and previous work
- Our work:
    - Experimental apparatus and systematic checks
    - Visible re-emission spectrum
    - Absolute fluorescence efficiency
- Plans for future work at LBL
- Conclusions

Noble Gas Detectors and Scintillation Light

Handling 100-nm or so photons is a pain in the neck!

Noble Gas Detectors

- Long history of use in proportional counters and TPCs
- Quite a few proposed ones that will also collect scintillation light:
  - LBNE
  - NEXT
  - CLEAN
  - nEDM
  - LUX
  - XENON



Large (2 x 20 kTon) liquid argon TPC, triggered on scintillation light for long-baseline neutrino oscillations

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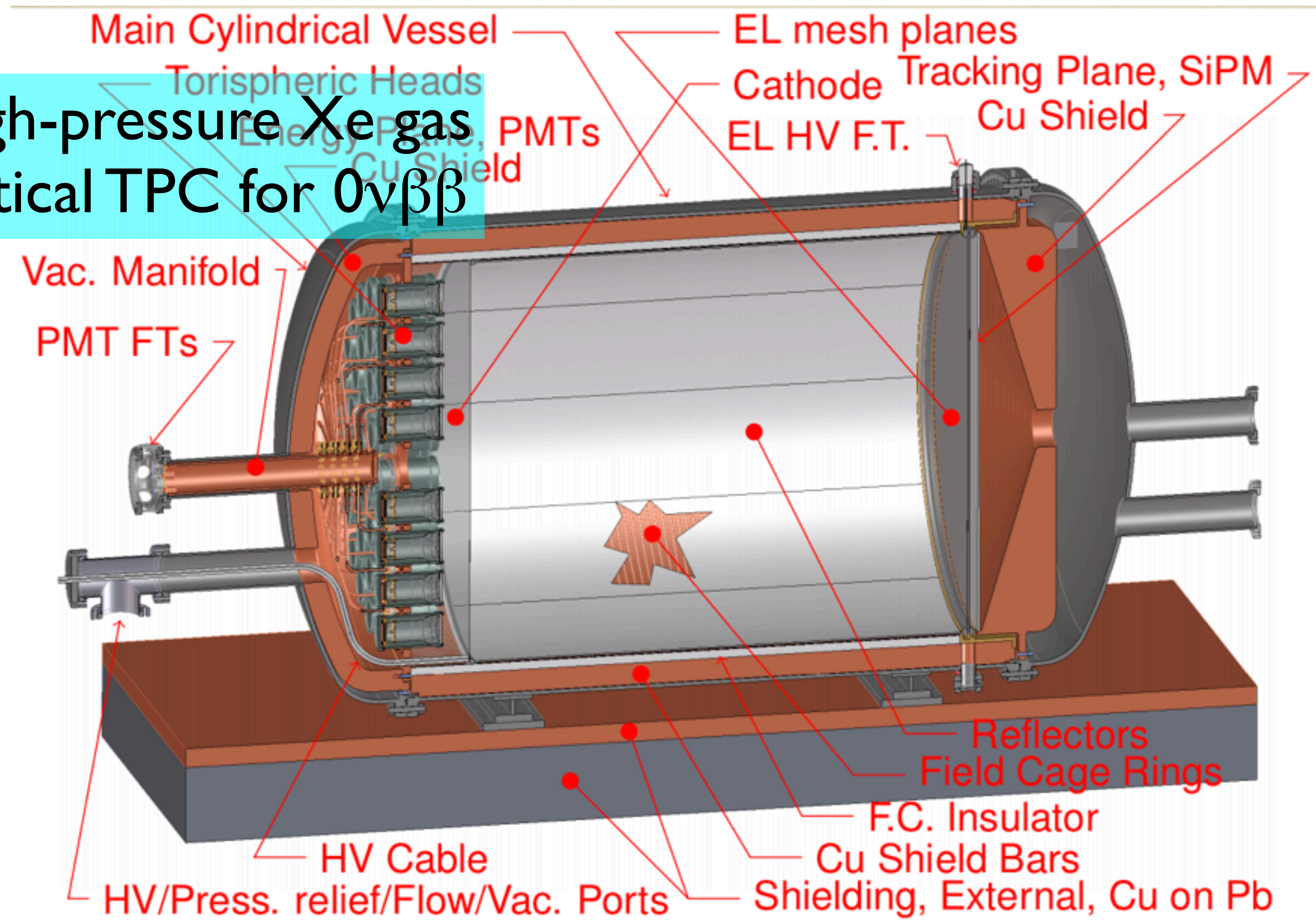
High-pressure Xe gas optical TPC for $0\nu\beta\beta$



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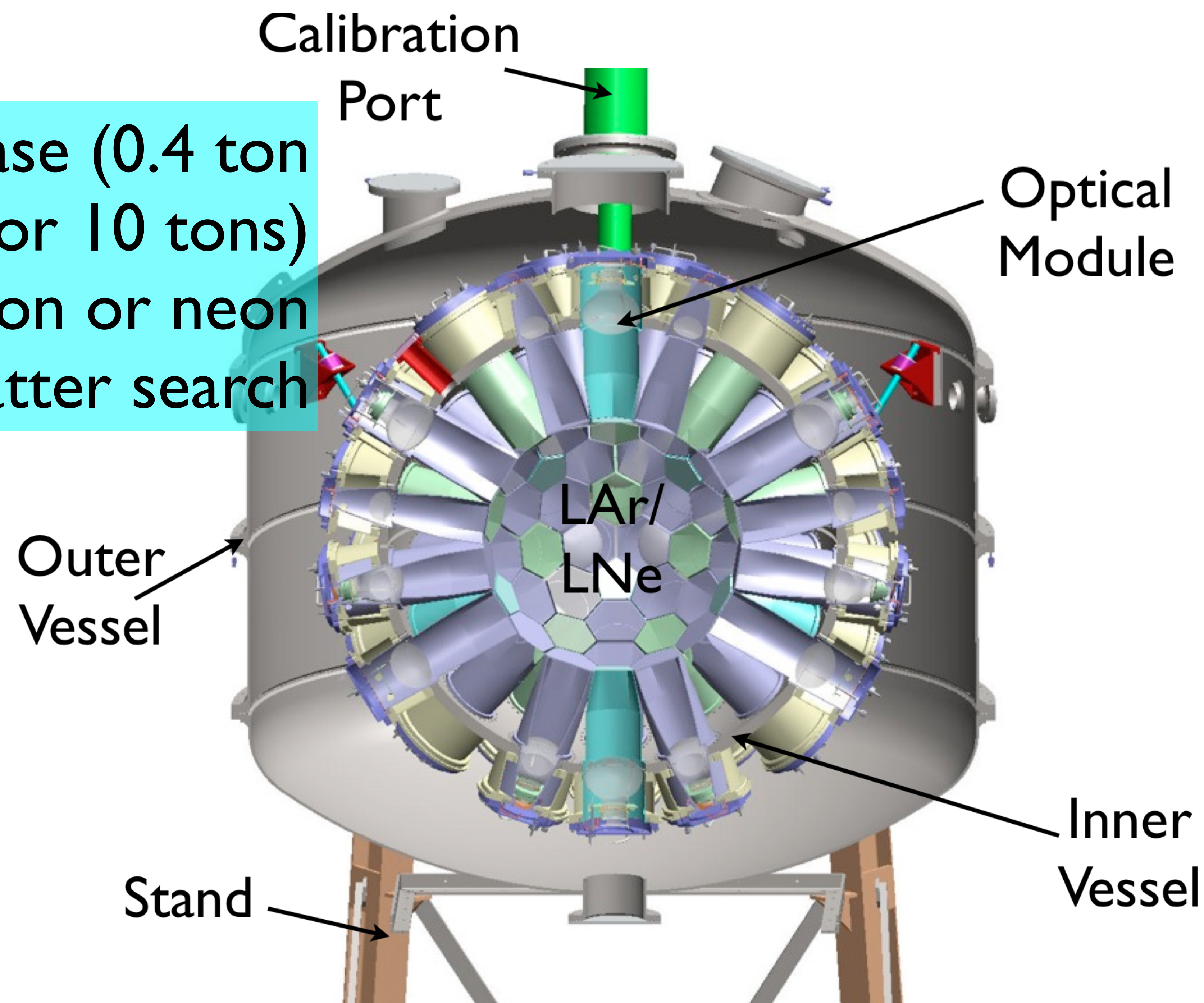
Single-phase (0.4 ton now, plans for 10 tons) liquid argon or neon dark matter search



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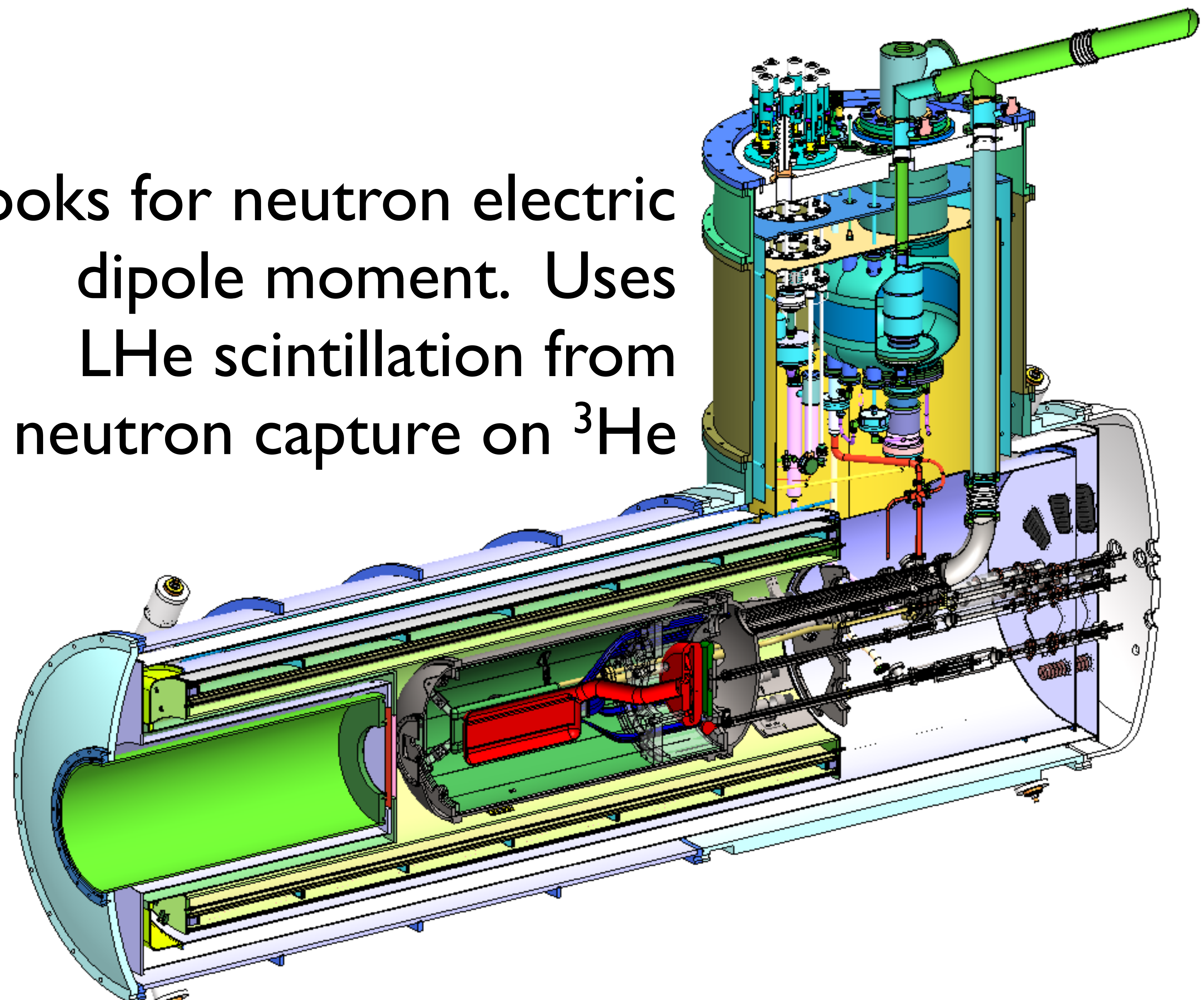
Looks for neutron electric dipole moment. Uses LHe scintillation from neutron capture on ^{3}He



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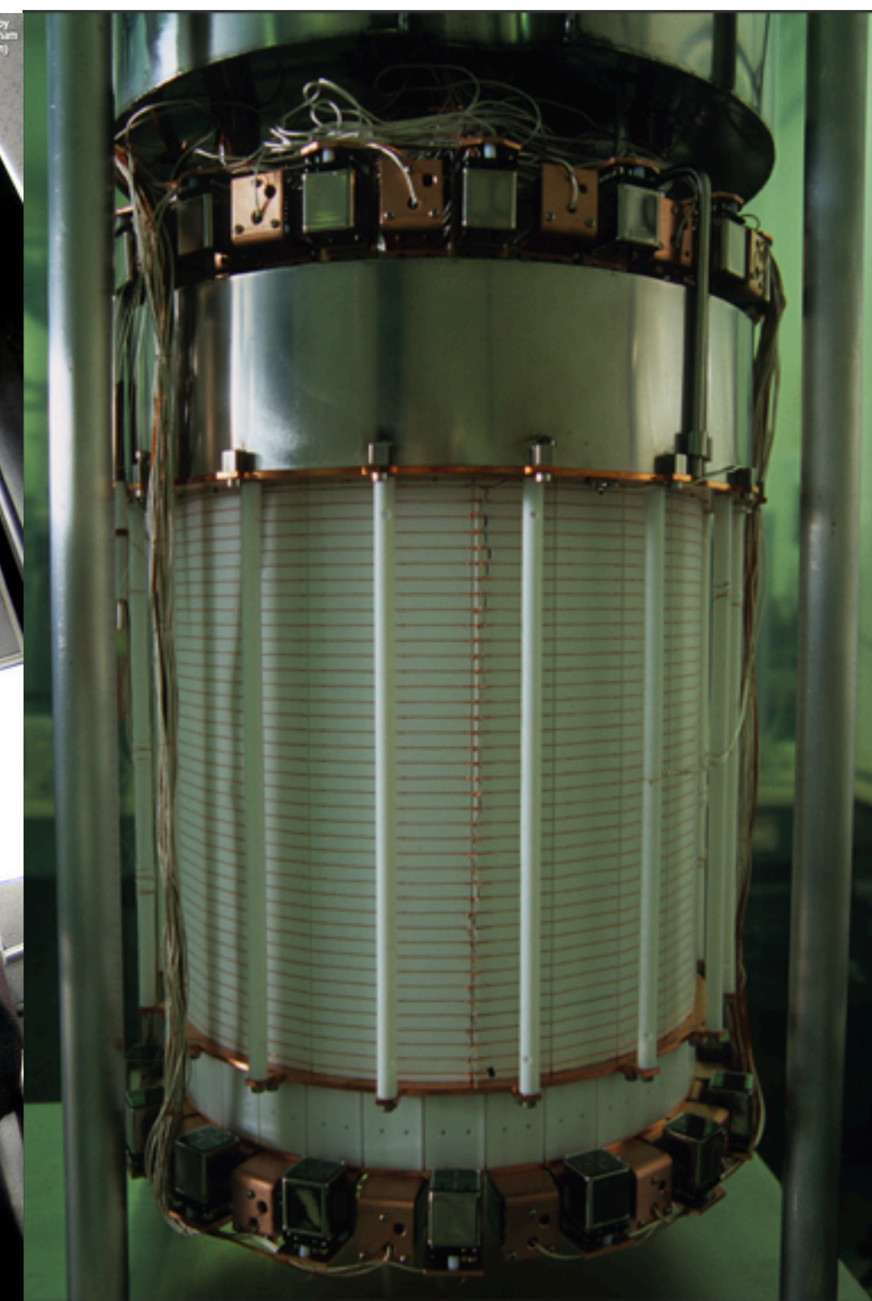
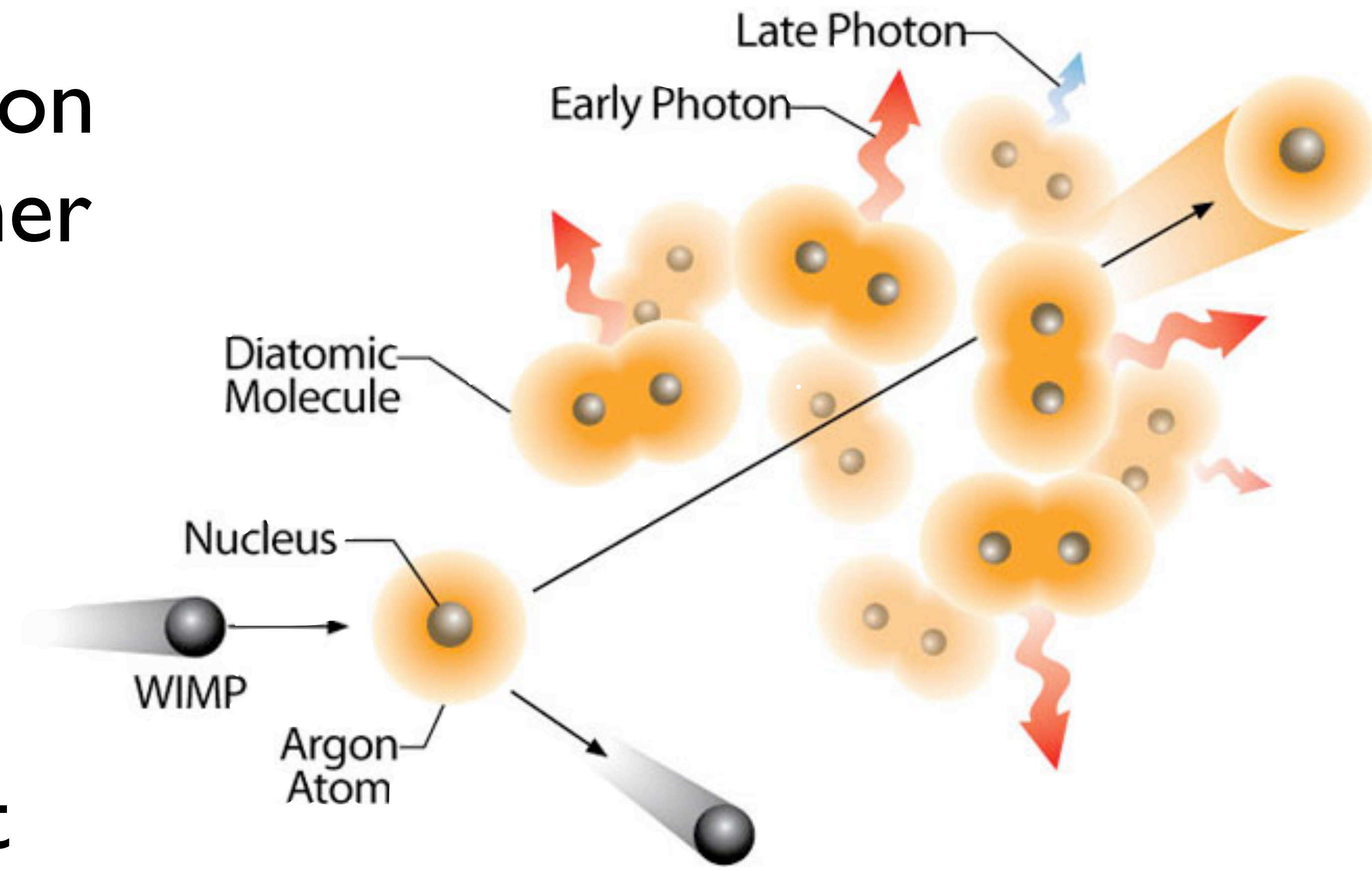
Dual-phase LXe TPC
for dark matter



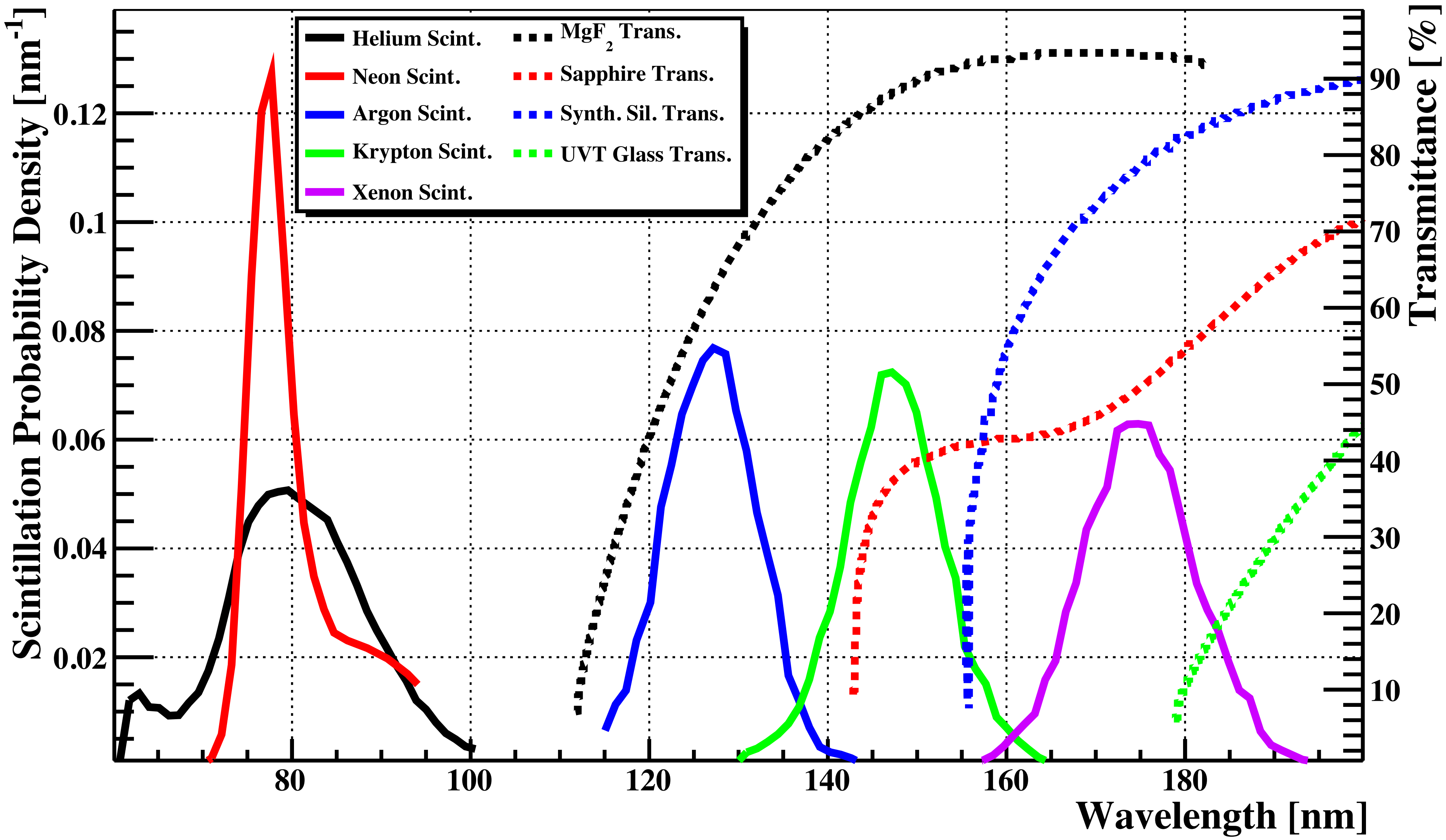
Noble Gas Scintillation

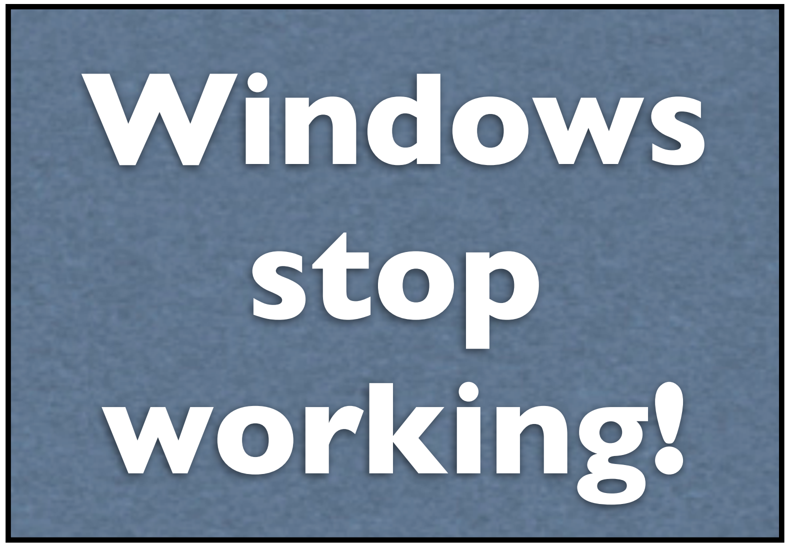


- Noble gasses create scintillation light differently than most other materials
- Scintillation light comes from the breakup of dimers where one partner atom is either excited or ionized by incident radiation
- This leads to two important consequences:
  - Near perfect transparency to its own scintillation light
  - Two scintillation time constants: one from dimer breakup involving excited atoms (prompt light, few ns) and one from ionized atoms (later light, tens of ns to few μs)

Here's the problem...

- The scintillation light is well into the extreme ultraviolet!
- Short enough wavelength that everything interacts with them, but not energetic enough to penetrate like x rays



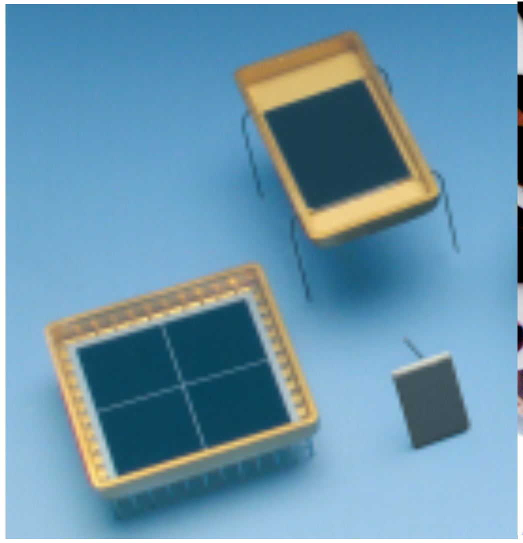


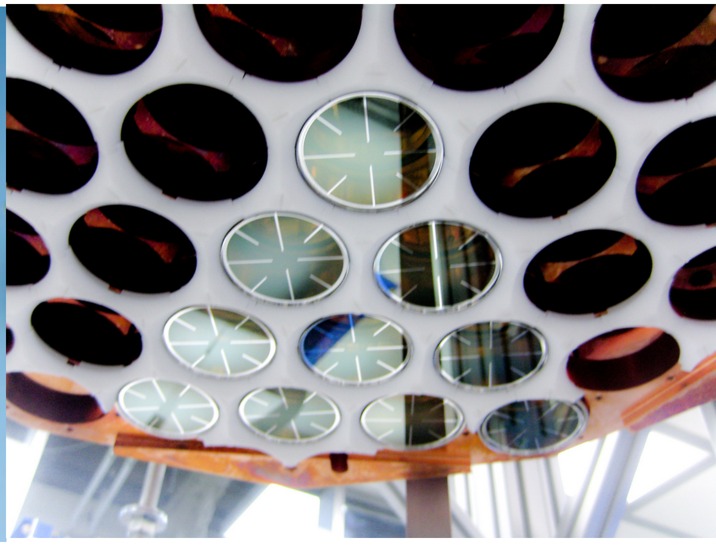
Wavelength Shifting Films and Previous Work

Why has no one done this before???

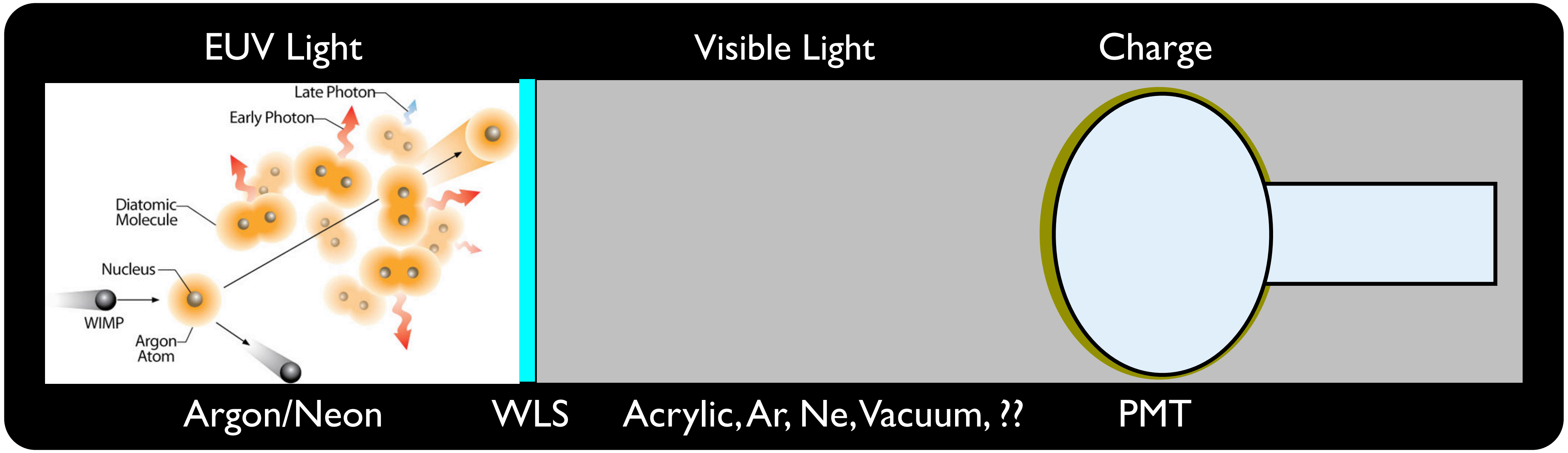
What to do with these troublesome photons?

- 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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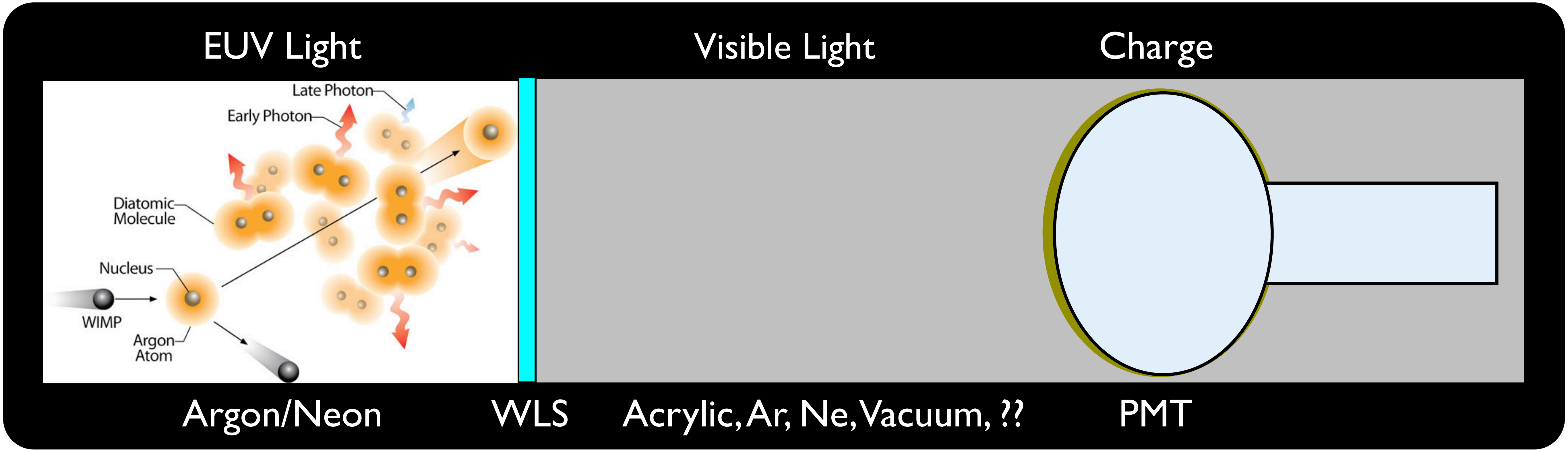
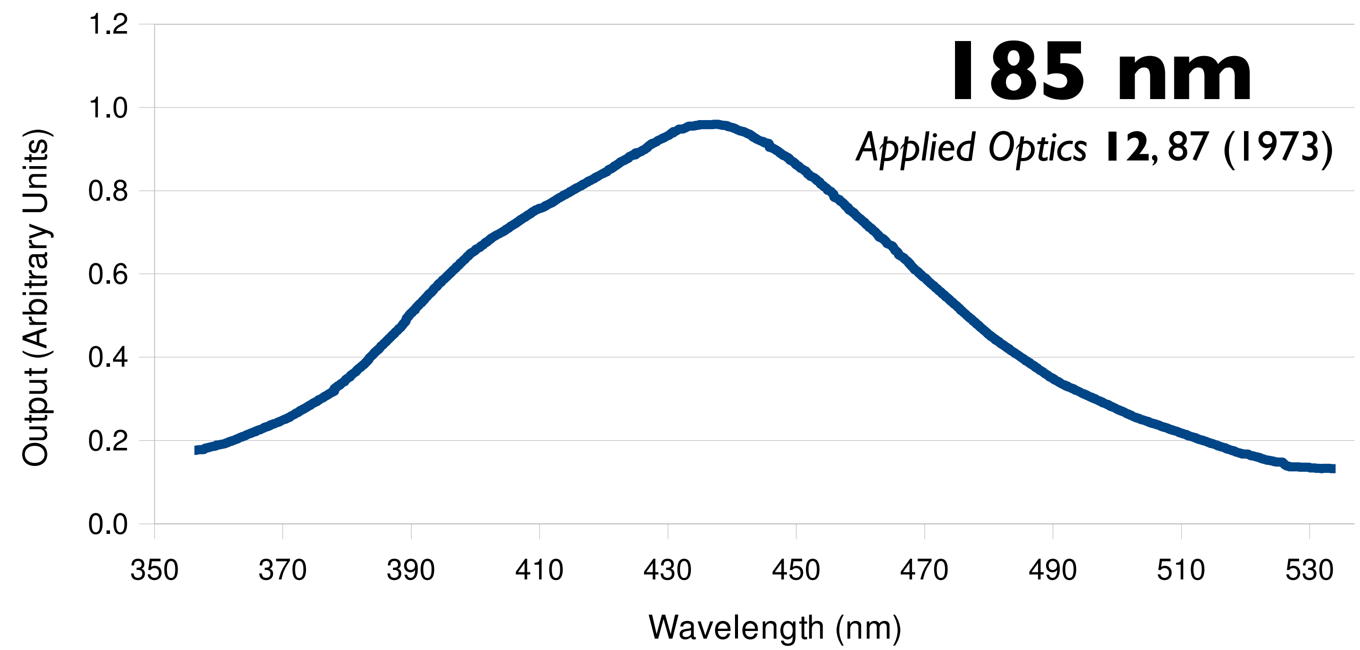


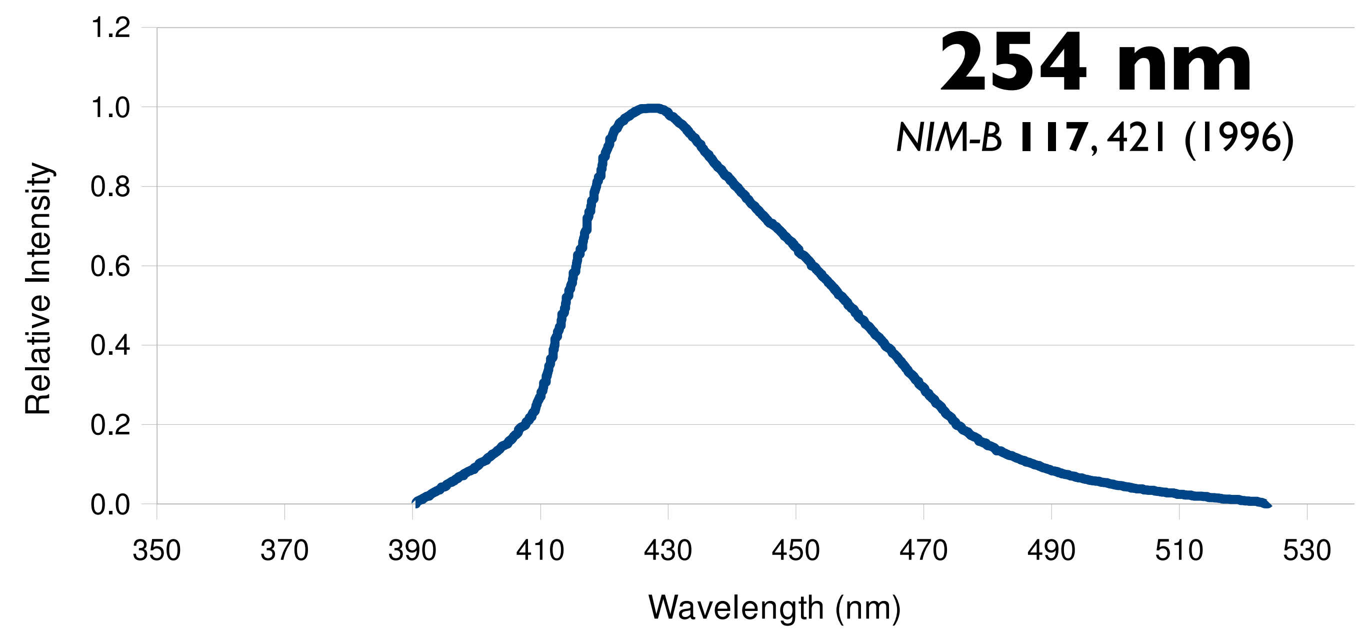
When you do this, you get "easier to detect" photons, but you give up all of your direct light

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

Hasn't Someone Done 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 two!





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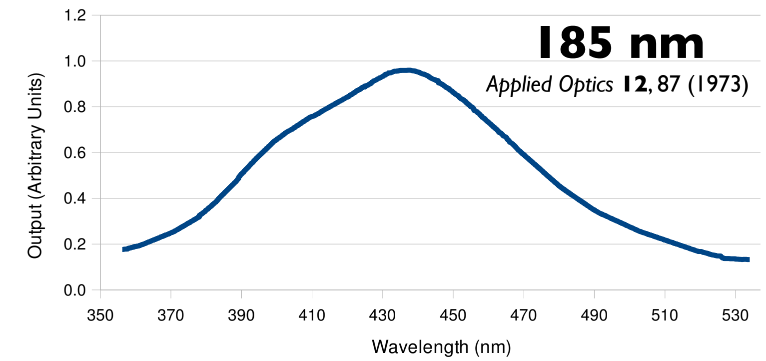

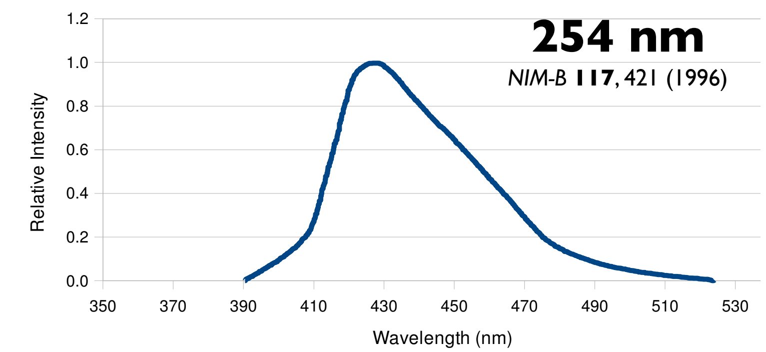

Absolute Efficiency [%]			Layer Thickness
2537 Å	1216 Å	304 Å	[mg / cm^2]
99	94		2–4
	62–80	41	5
65	38		2
50			1–2
64			6
25			?
60			2 mm[a]

[a] Sample was a plaque pressed 2 mm thick

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

Our TPB Study

How I spent a good chunk of last year...

Experimental Apparatus

Since we are observing individual photons, we care about the efficiency as a ratio of photon rates.

$$\epsilon(\lambda) = \frac{\boxed{I_{\mathrm{TPB}}} - \boxed{I_{\mathrm{dark}}}}{\boxed{I_{\mathrm{lamp}}} - \boxed{I_{\mathrm{dark}}}} \times \boxed{g} \frac{\int d\lambda' \frac{hc}{\lambda'} \boxed{C(\lambda')} \boxed{S(\lambda - \lambda')}}{\int d\lambda'' \frac{hc}{\lambda''} \boxed{C(\lambda'')} \boxed{R(\lambda'')}}$$

- Measured by us
- Measured by IRD/NIST
- Calculated from our measurements

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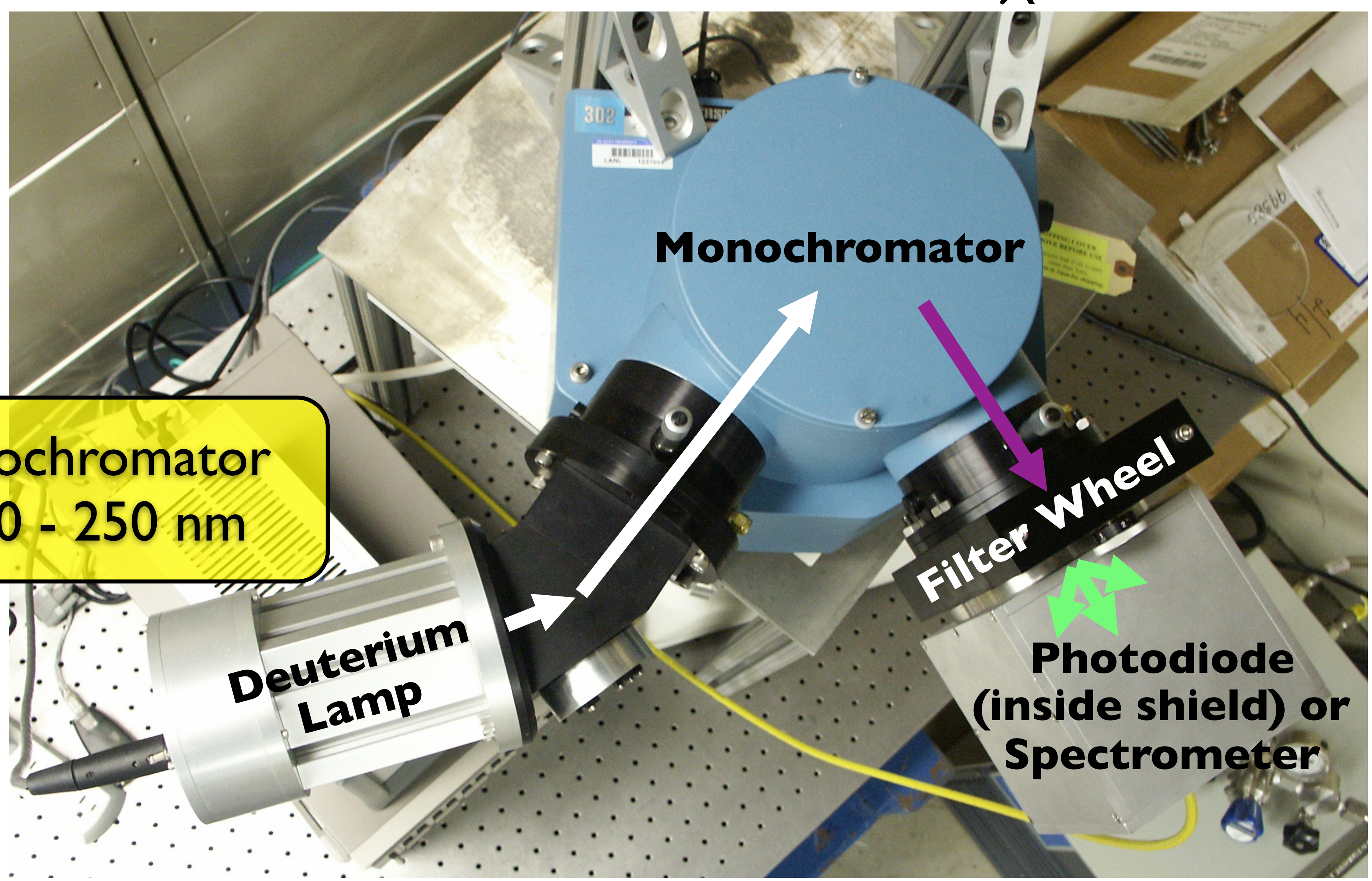

Lamp/Monochromator covers 110 - 250 nm

Experimental Apparatus

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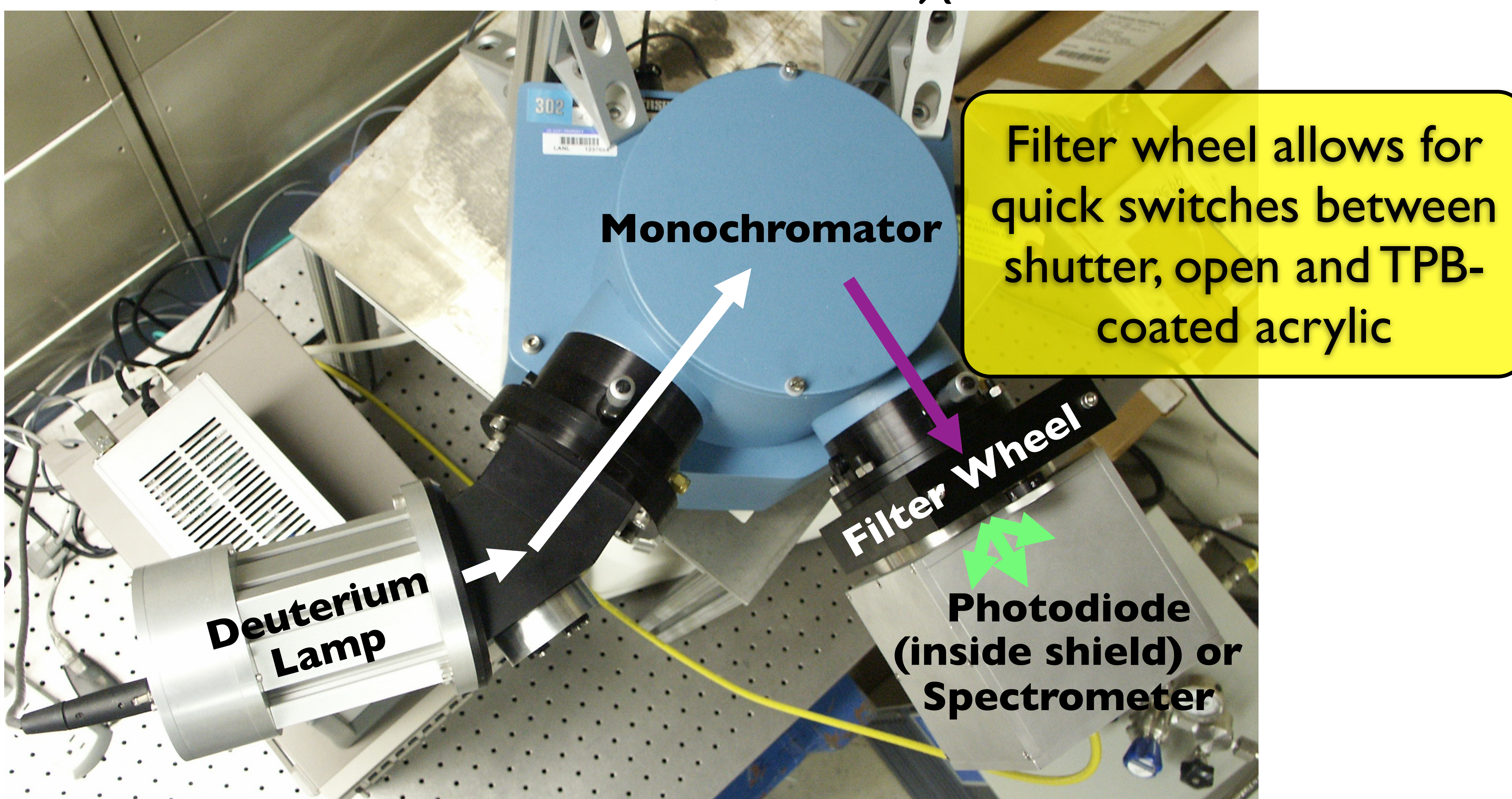

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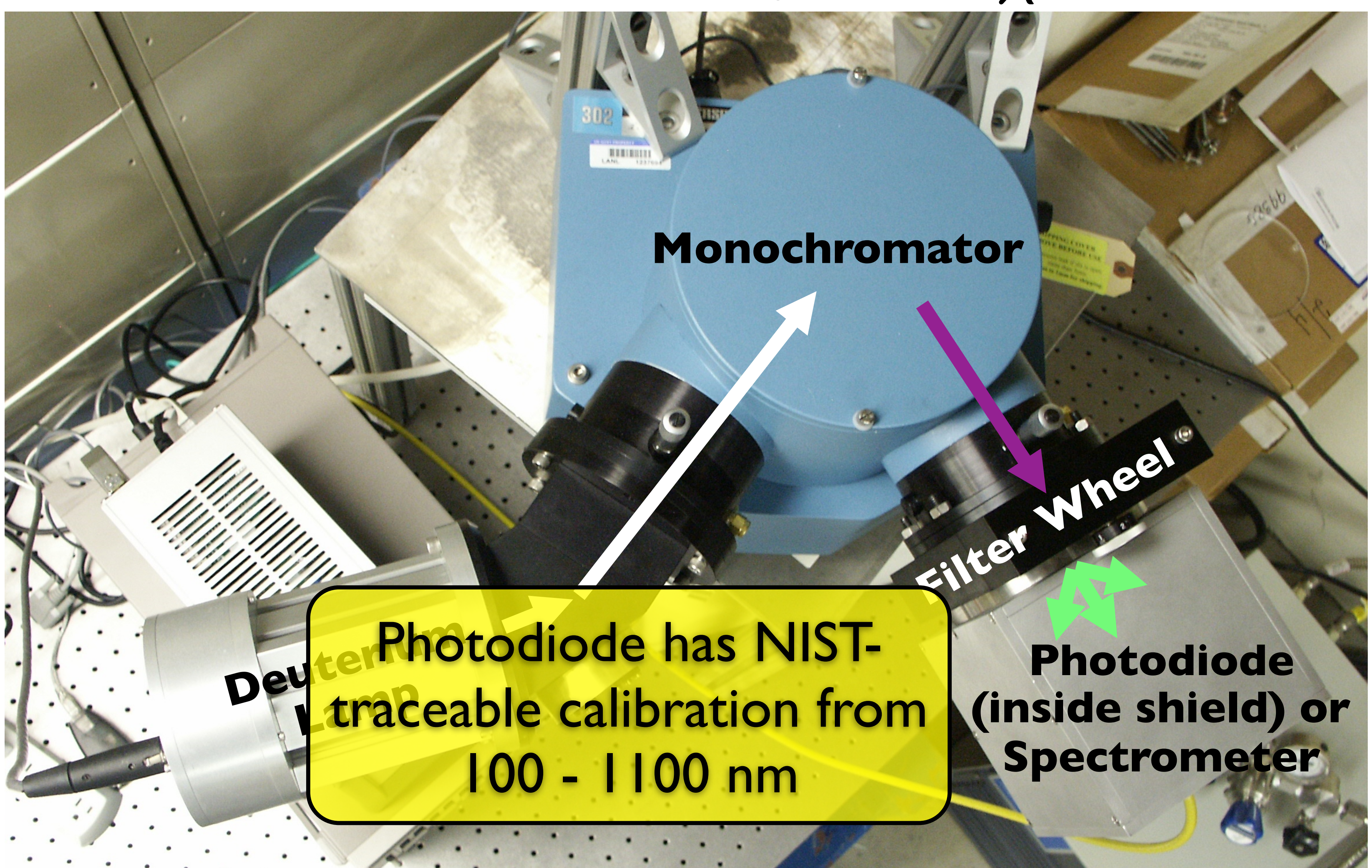
Since we are observing individual photons, we care about the efficiency as a ratio of photon rates.

$$\epsilon(\lambda) = \frac{I_{\rm TPB} - I_{\rm dark}}{I_{\rm lamp} - I_{\rm dark}} \times g \frac{\int d\lambda' \frac{hc}{\lambda'} C(\lambda') S(\lambda - \lambda')}{\int d\lambda'' \frac{hc}{\lambda''} C(\lambda'') R(\lambda'')}$$



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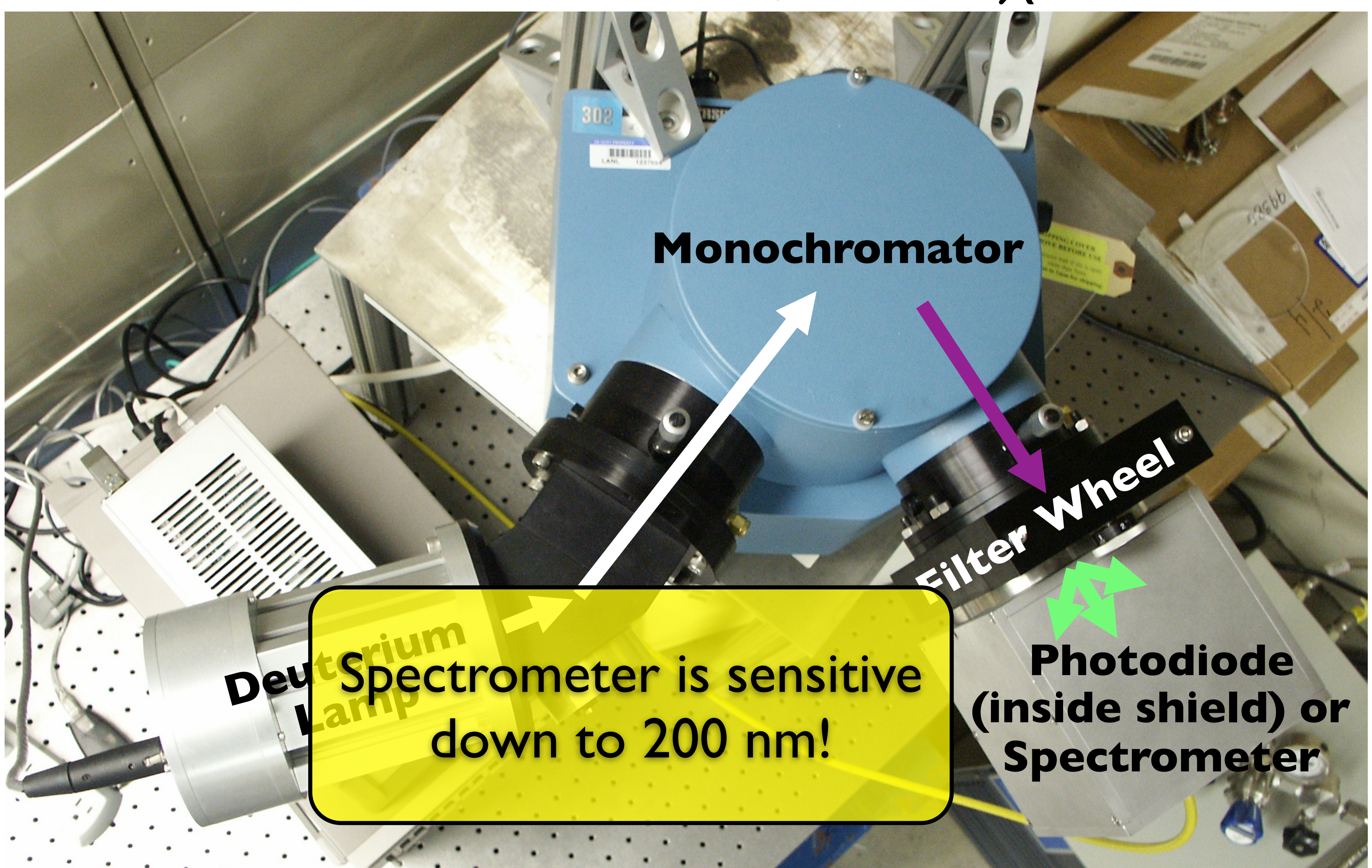
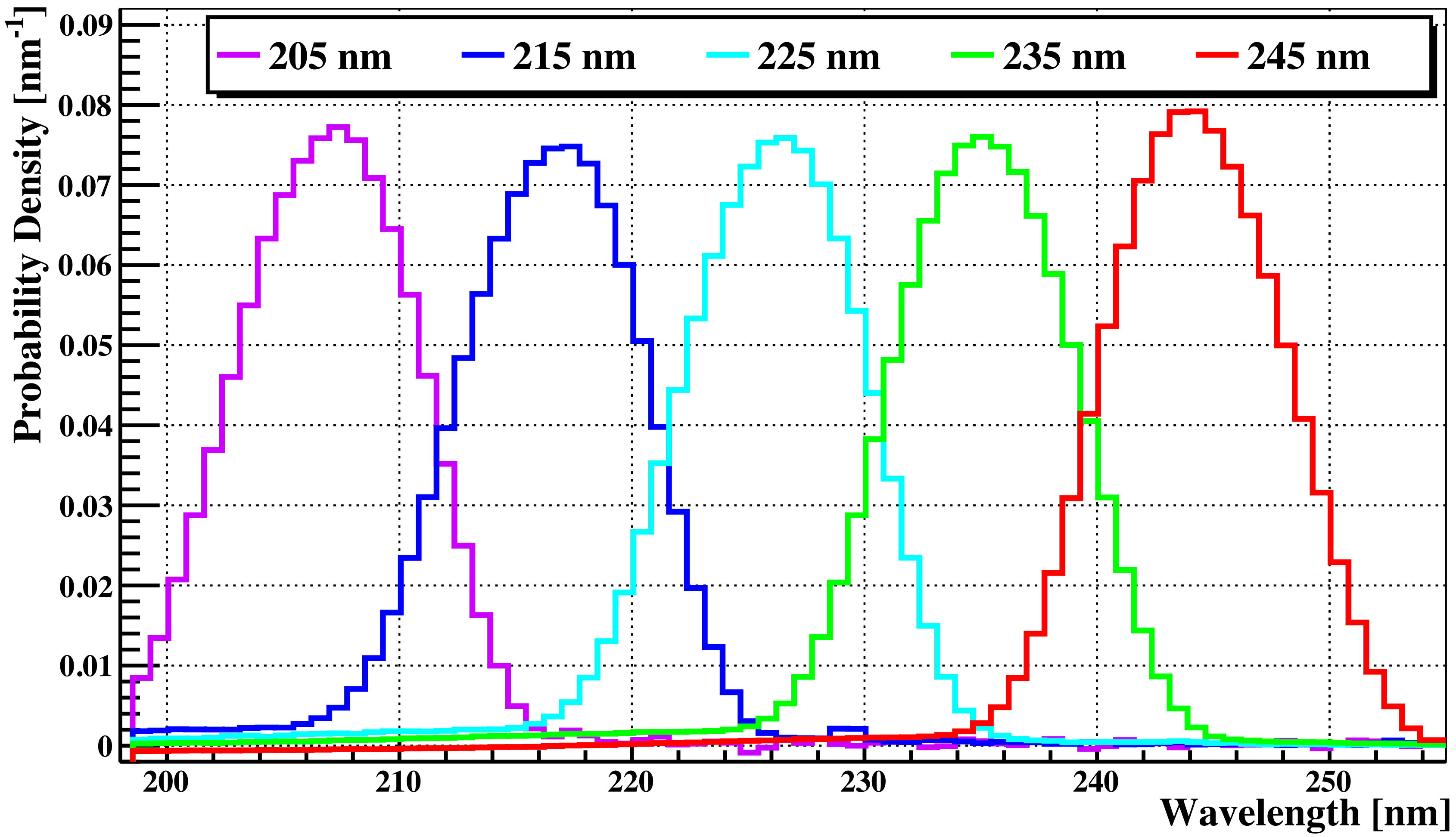


Systematic Checks

- Light source resolution: 8.5 ± 0.5 nm
- TPB film thickness: 1.5 ± 0.05 μm (thin film reflectometry)
- Acrylic (substrate) transmittance
- Optical train (lens, fibers, feedthroughs) transmittance
- Photodiode response (measured by IRD and NIST)



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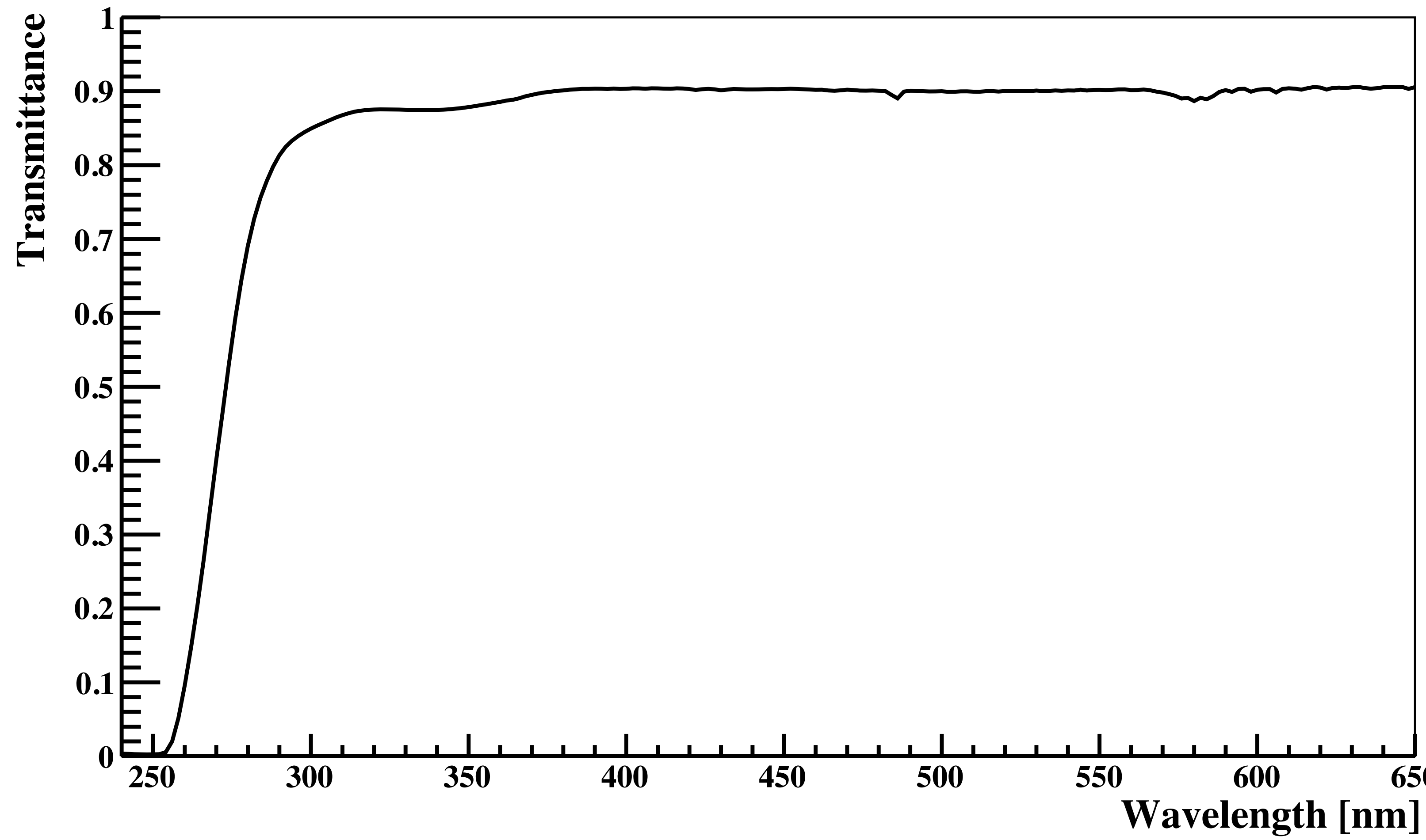

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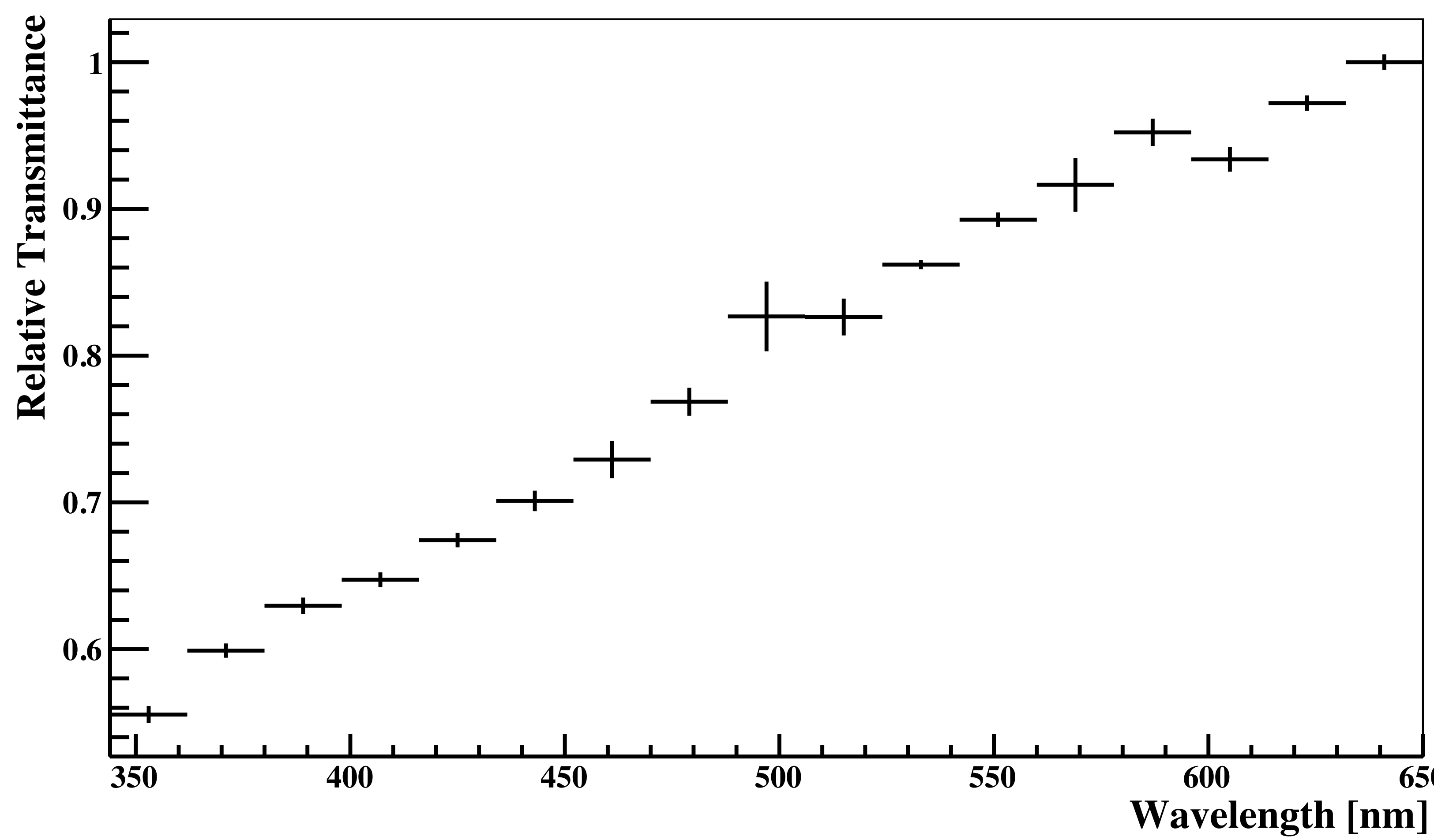

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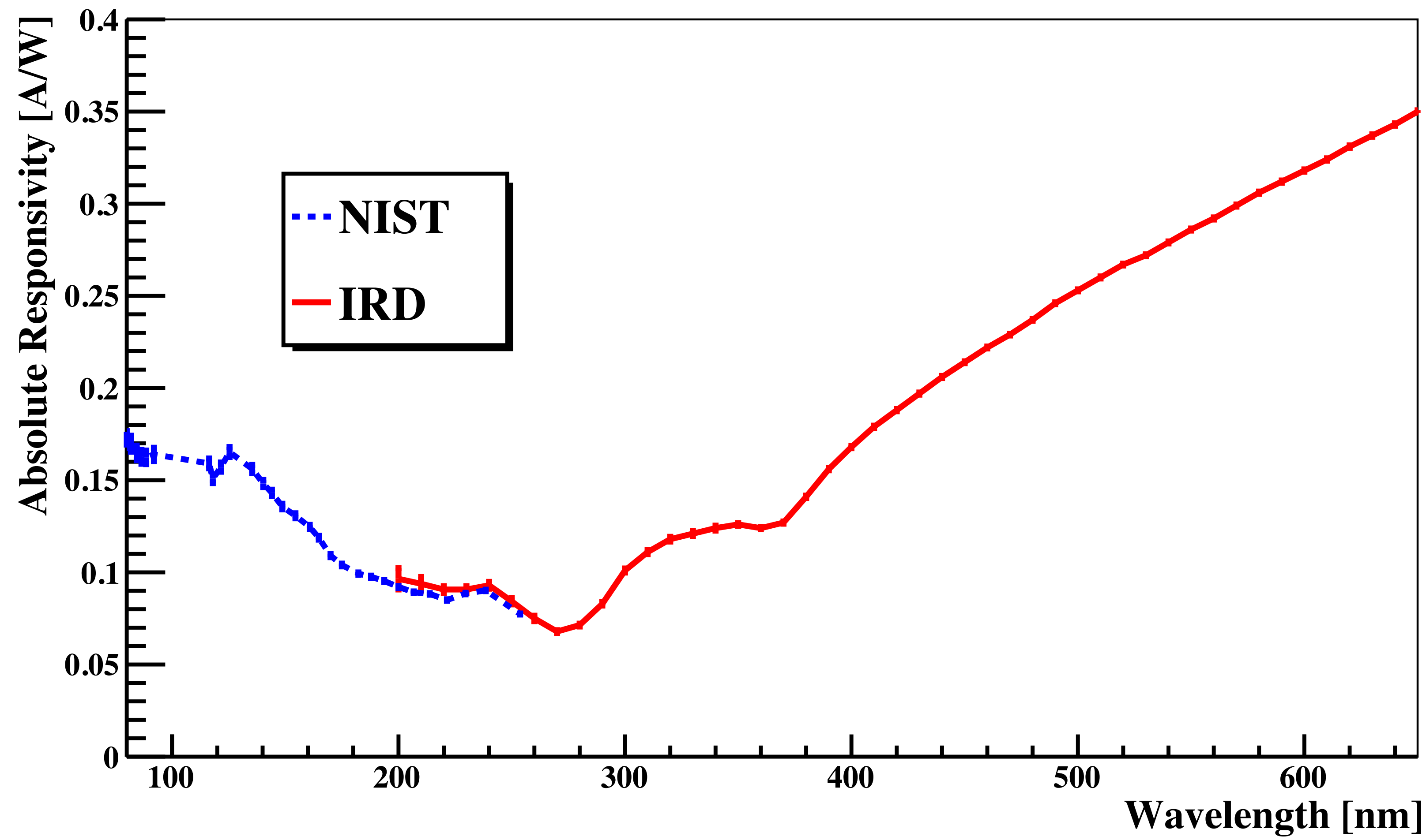
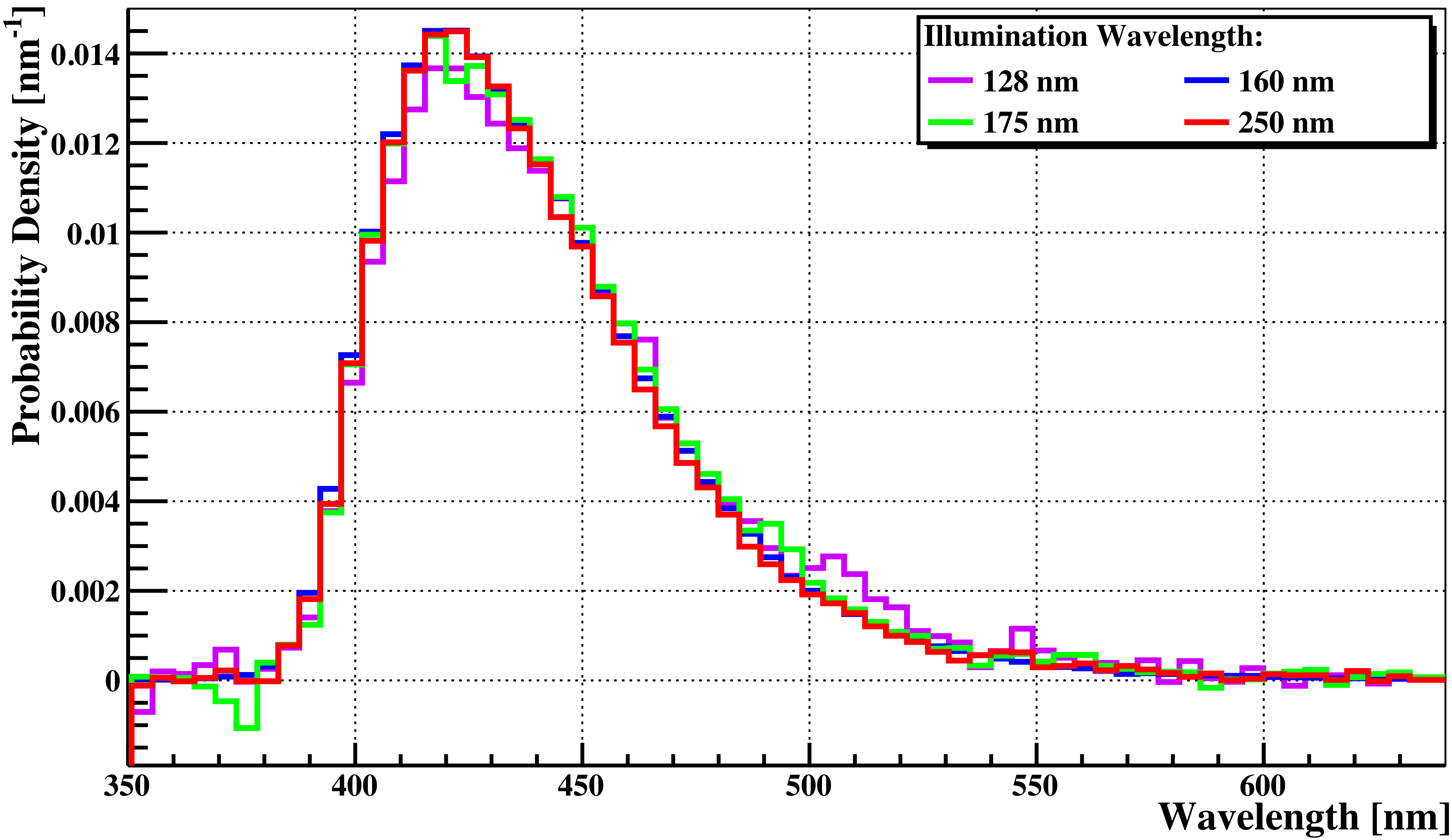
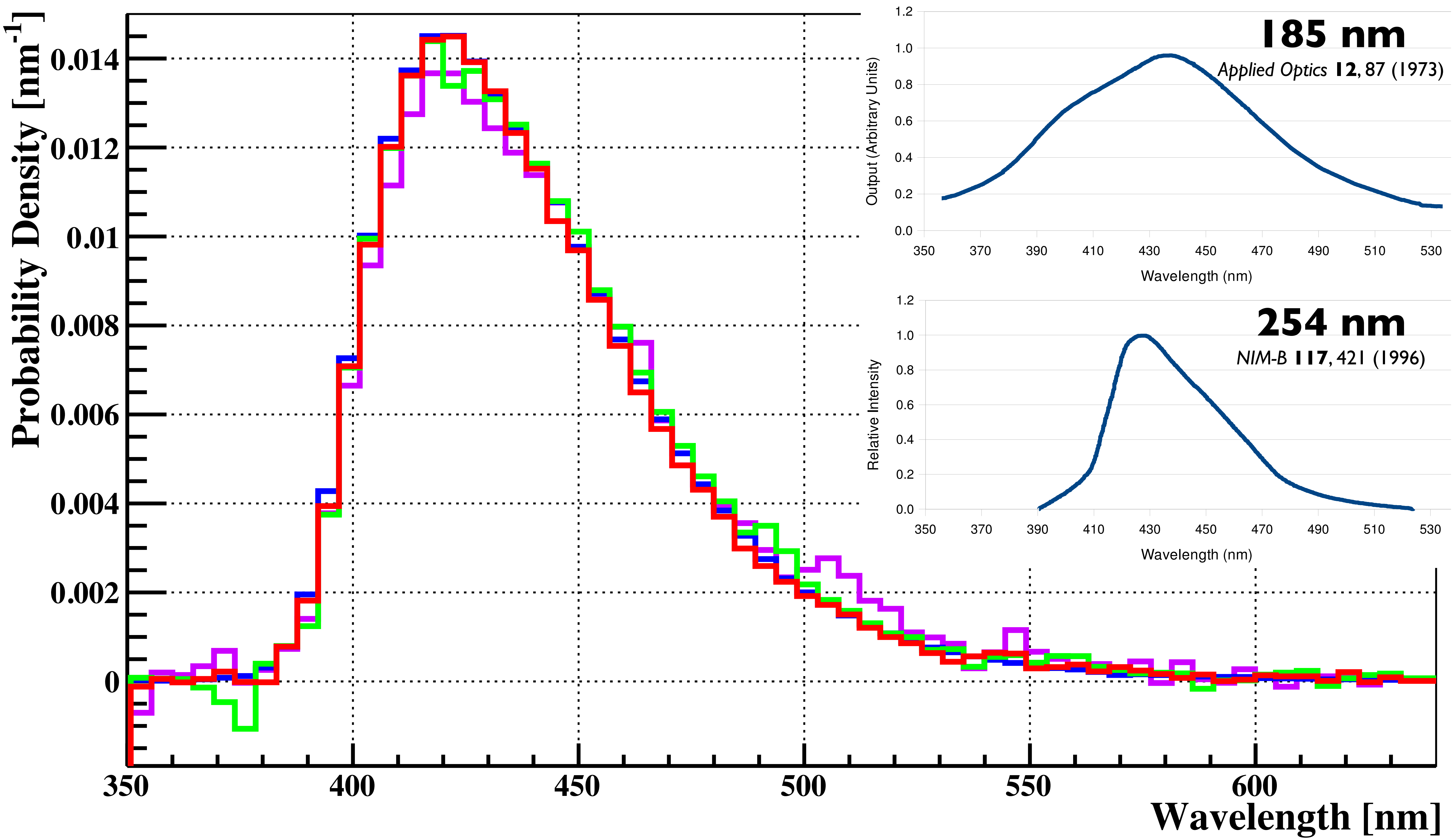


Visible Re-emission Spectrum



No strong wavelength dependence!

Visible Re-emission Spectrum

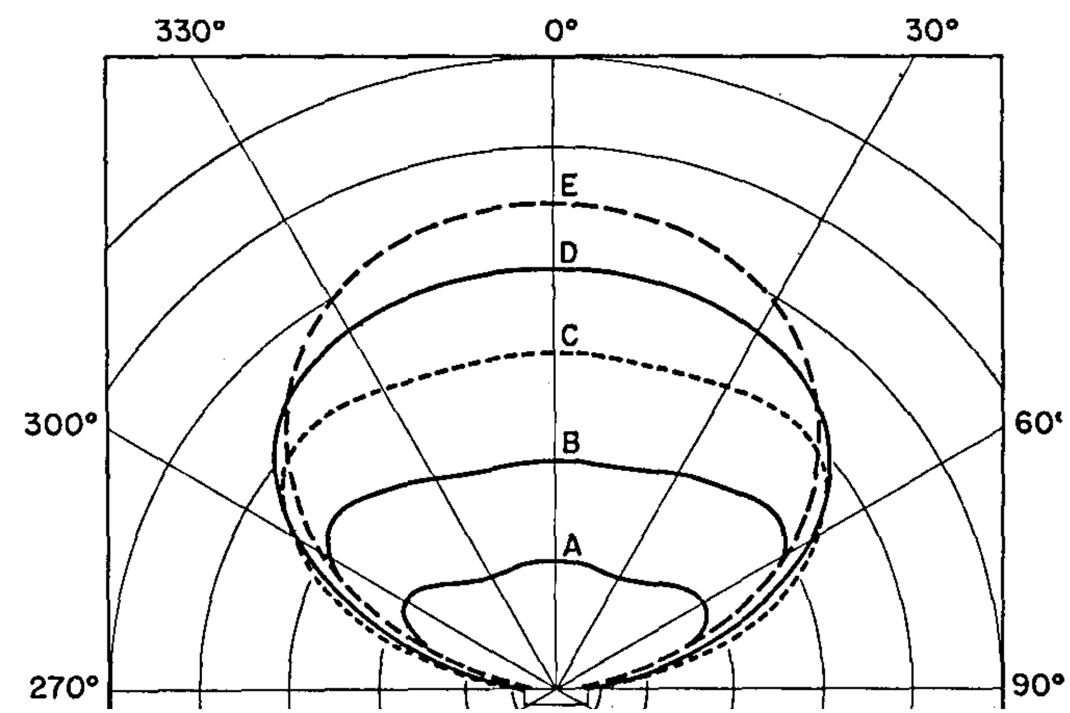


No strong wavelength dependence!

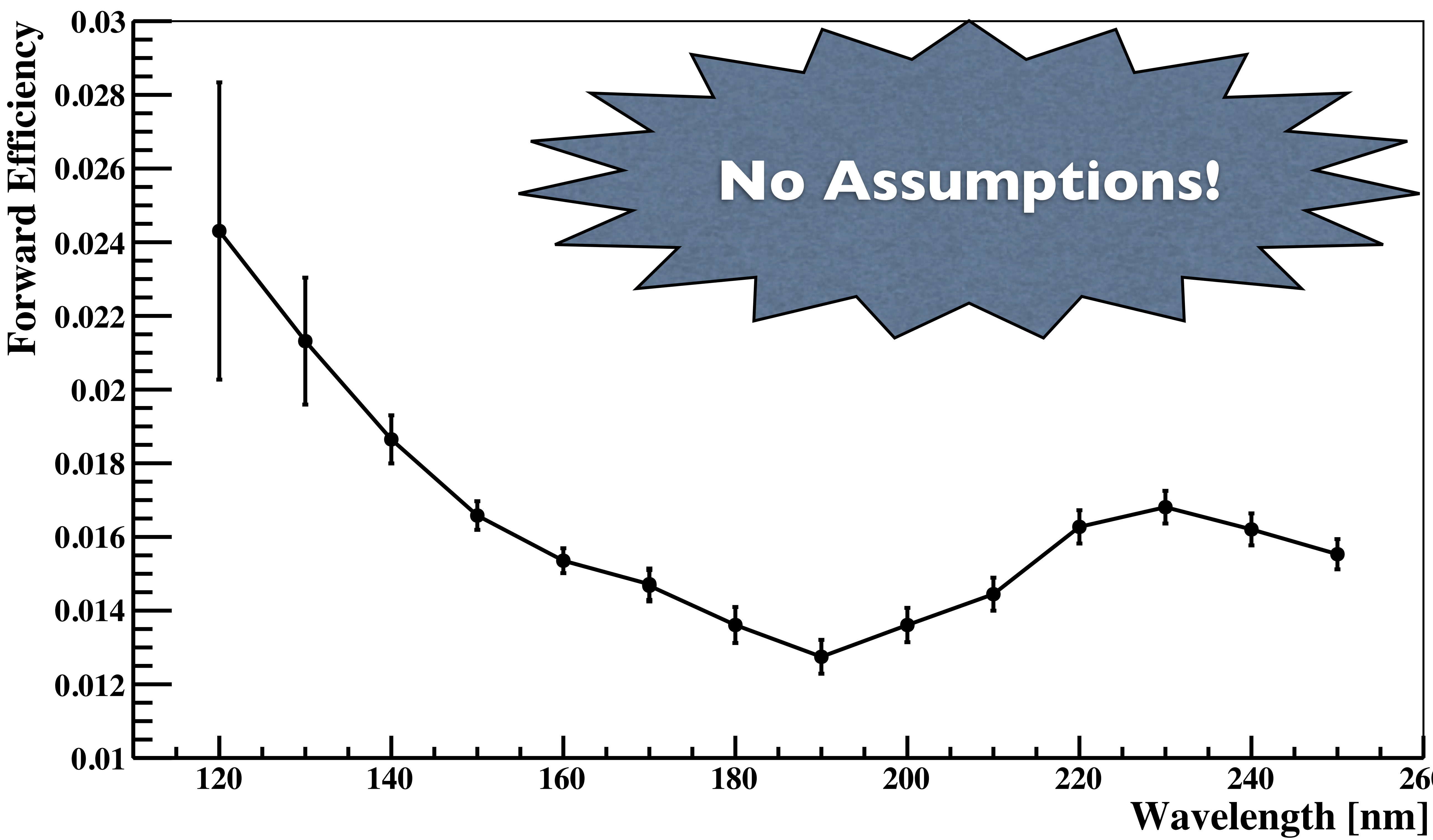
Fluorescence Efficiency

- The absolute efficiency calculation adds one more ambiguity: *angular distribution of re-emission light*
  - No published measurements for TPB!
  - Most naive assumption (isotropic re-emission) gives unphysically high efficiencies
- Found published angular distribution for *Sodium Salicylate* (the "other fluor" from a few slides ago)
- Follows Lambertian (cosine) distribution
- Calculated "Forward Efficiency" (re-emission at 0°, no assumptions) and total efficiency (more useful, requires Lambertian assumption)

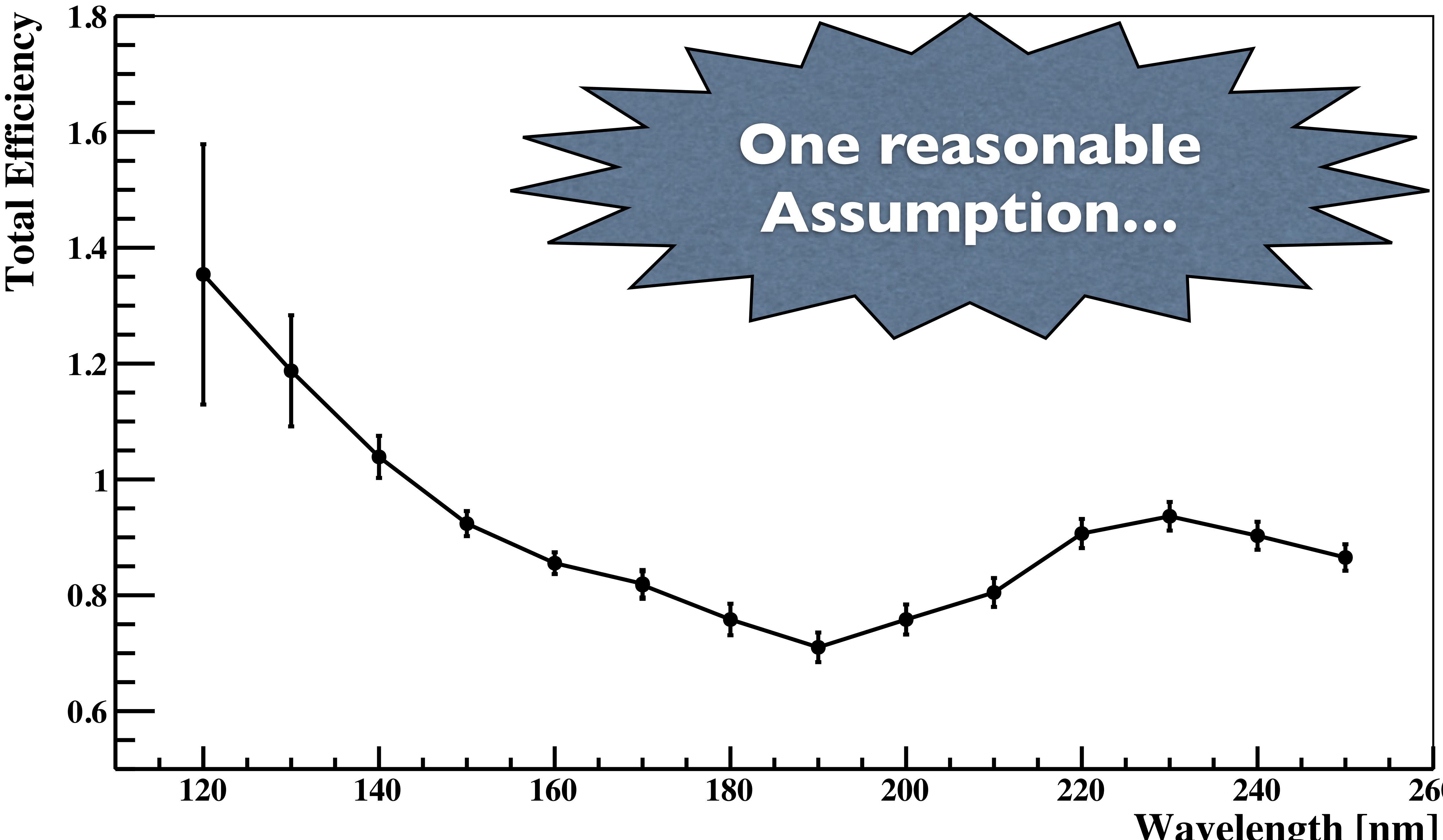
J. Opt. Soc. Am., **54**, 747 (1964), Fig. 3



Forward Fluorescence Efficiency



Total Fluorescence Efficiency

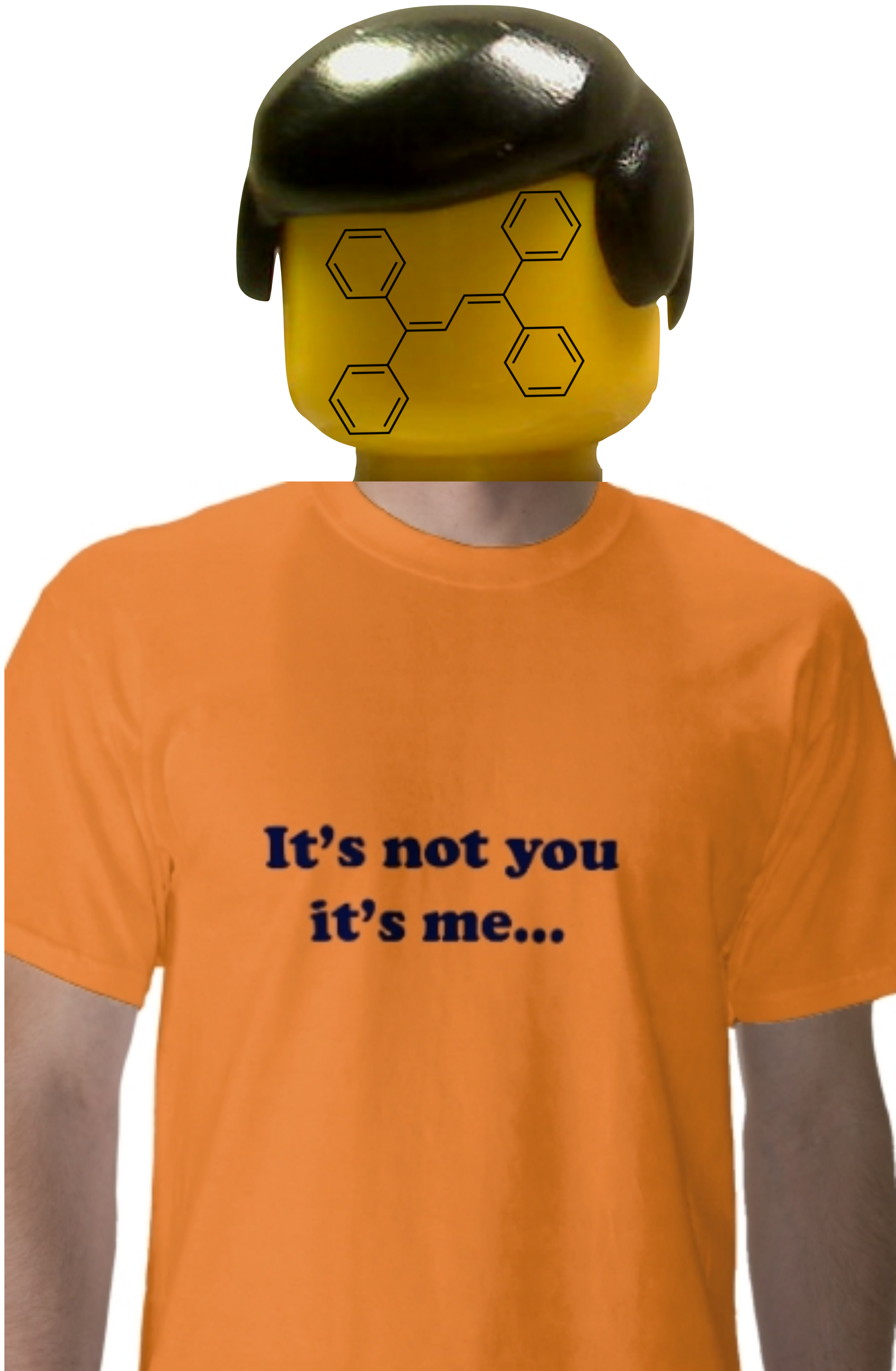


Plans for Future Work at LBL

How I would like to spend a good chunk of next year...

Other WLS Films?

- Vacuum deposited TPB nicely, and it's been well studied. Why would we try something else?
  - TPB is kind of expensive ($113/5g)
  - Vacuum deposited films are a fragile
- There are ways of making more robust TPB films
  - *so far*, at the expense of fluorescence efficiency
  - Other ways of doing solvent dilution/ painting, coating paddles with embedded fibers
- There are plenty of other fish in the sea... TPH, Bis-MSB, PPO/POPOP, other organics with a few phenyl groups



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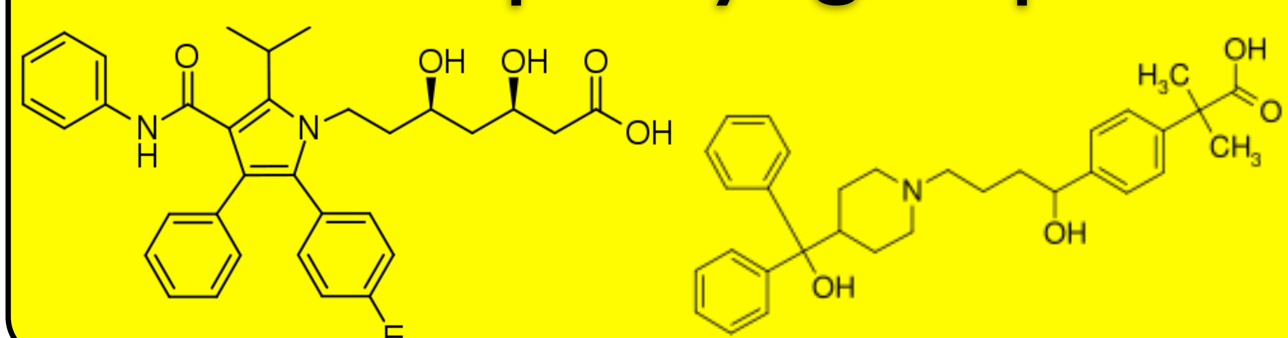
on/

Lipitor and Allegra also have lots of phenyl groups!



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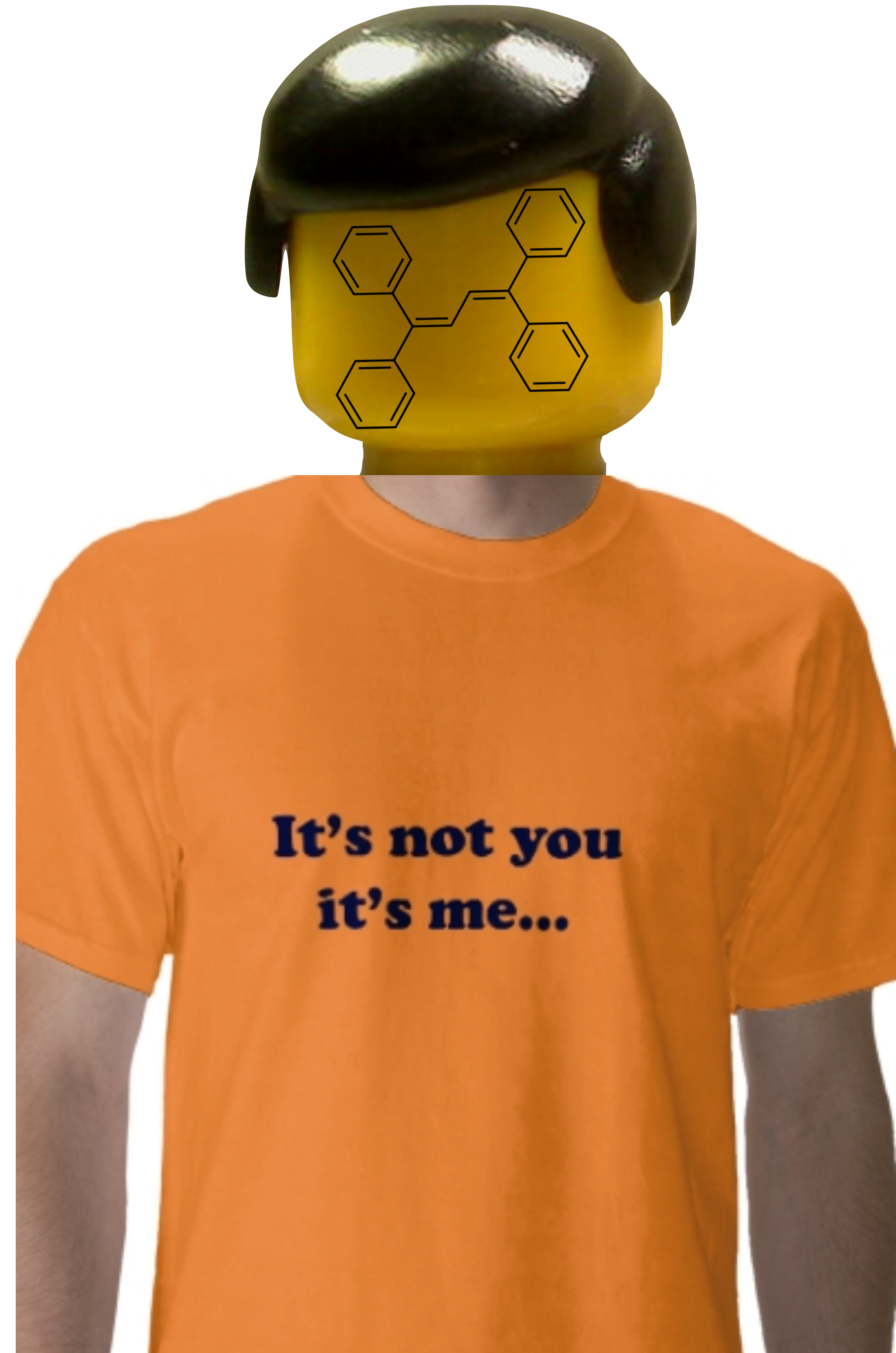
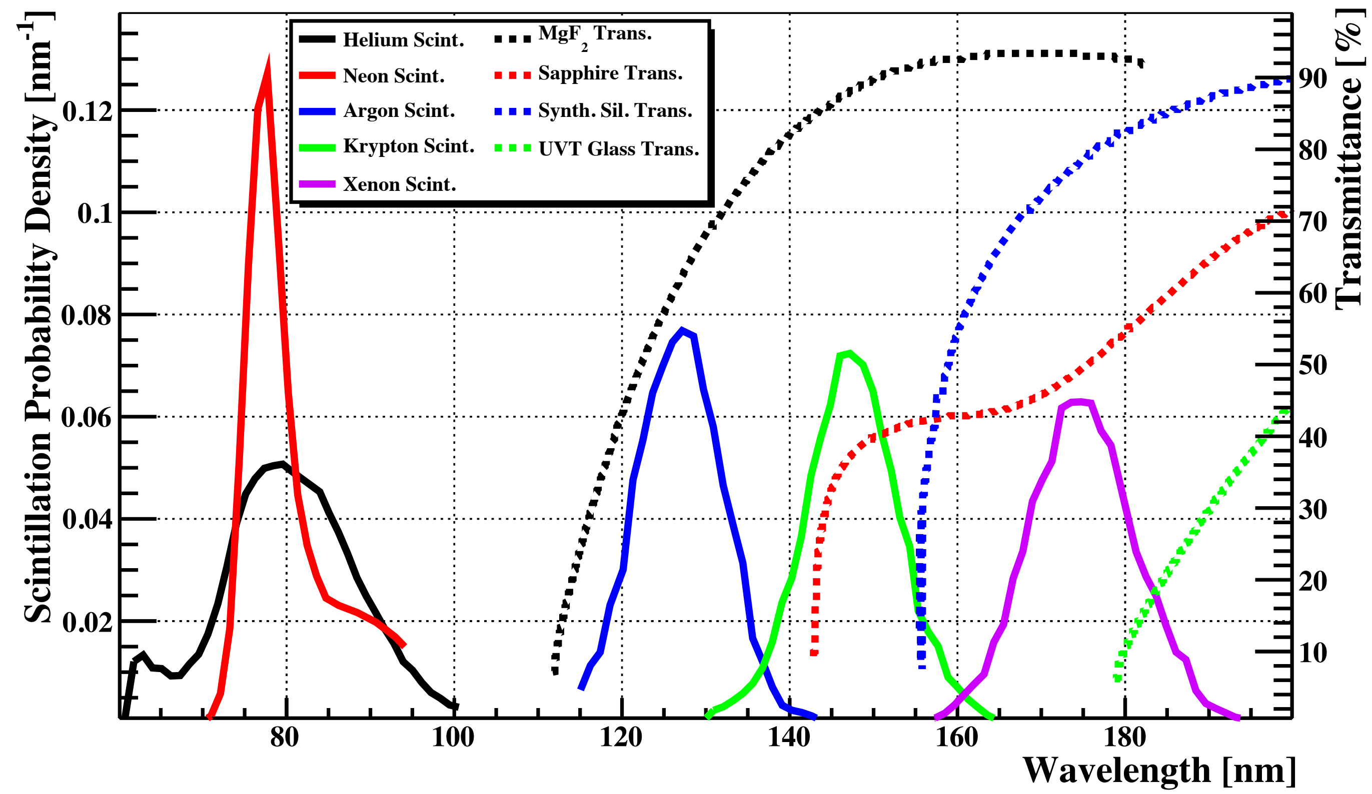


Push Fluorescence Studies Down to below 80 nm

- The MgF_2 window on our lamp limited the short wavelength range of our measurements
- This would make these measurements applicable to neon and helium
- Brighter intensity at 128 will shrink down the uncertainty at short wavelength.
- Can also change gases to get different spectra for different measurements...
- More comprehensive understanding of fluorescence behavior



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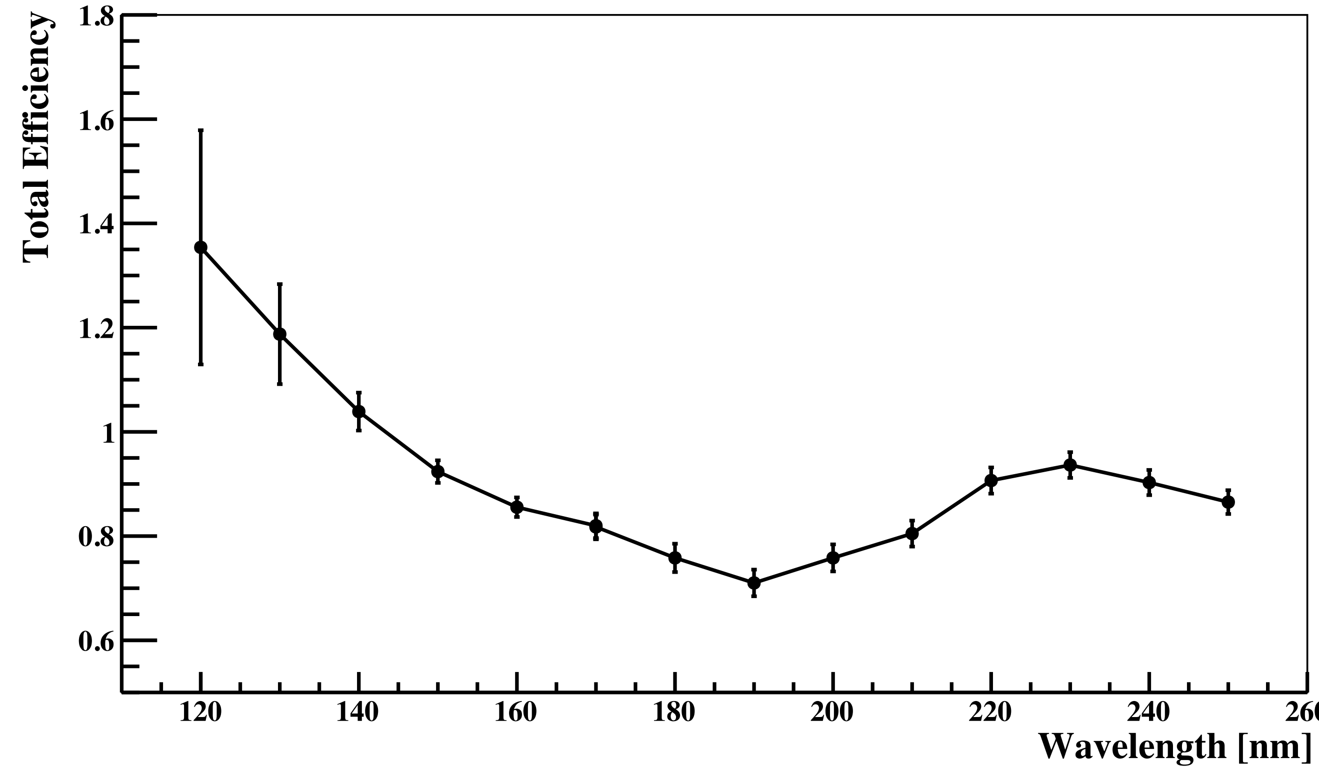
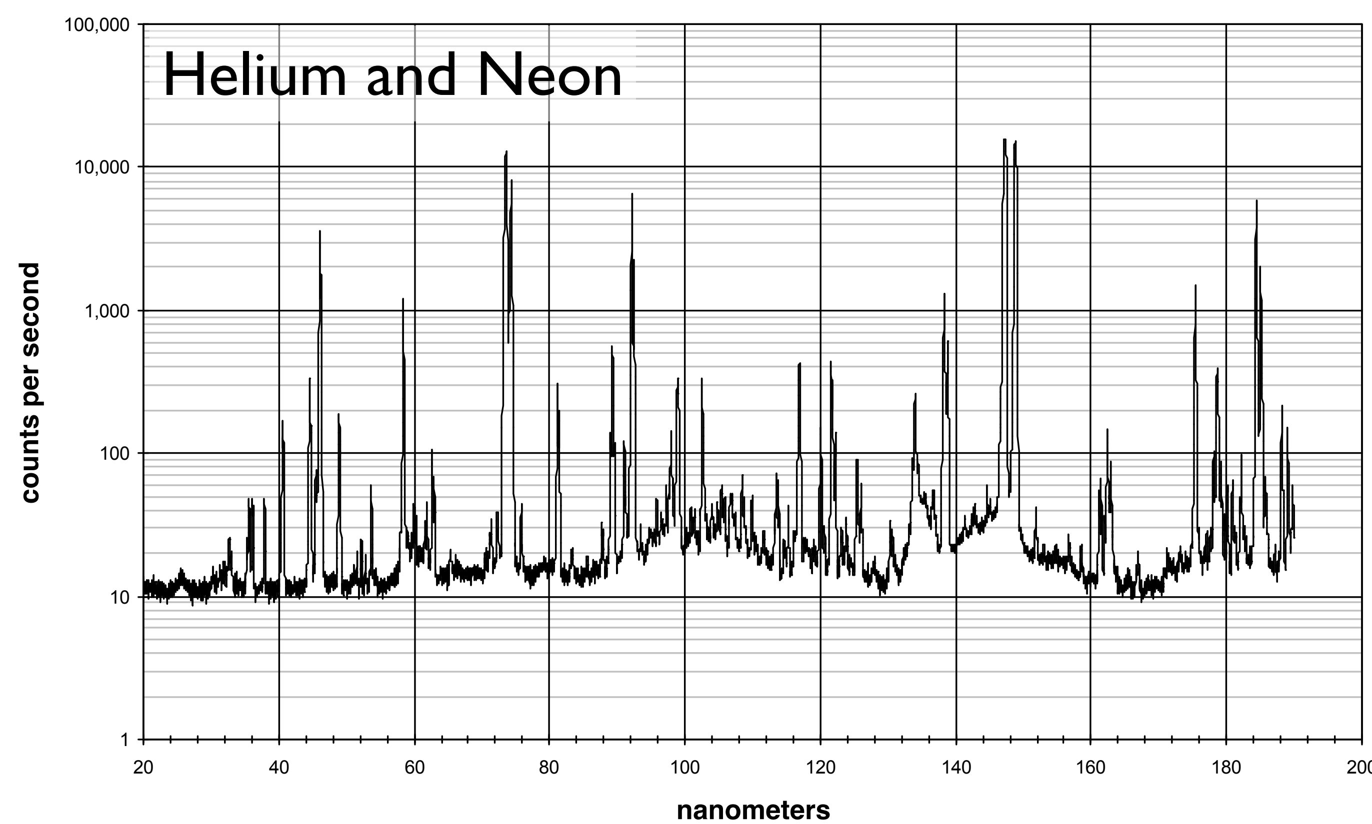
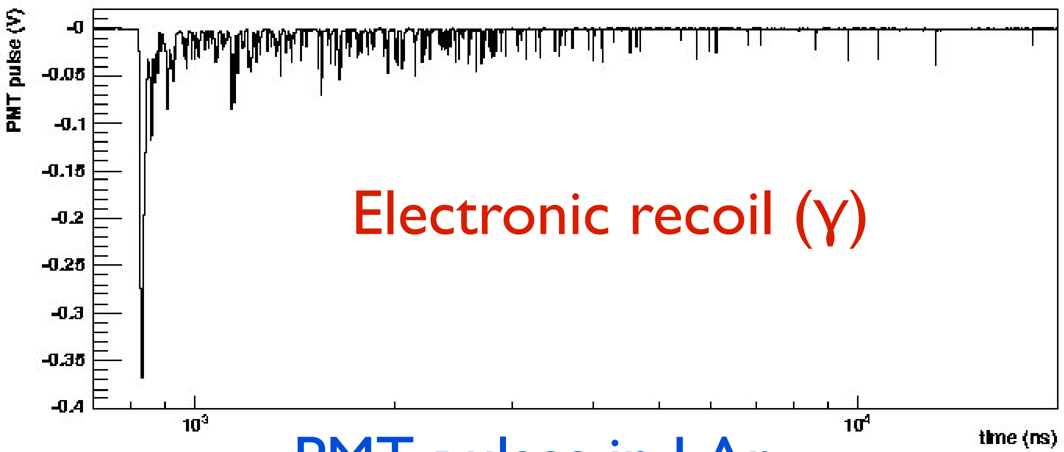


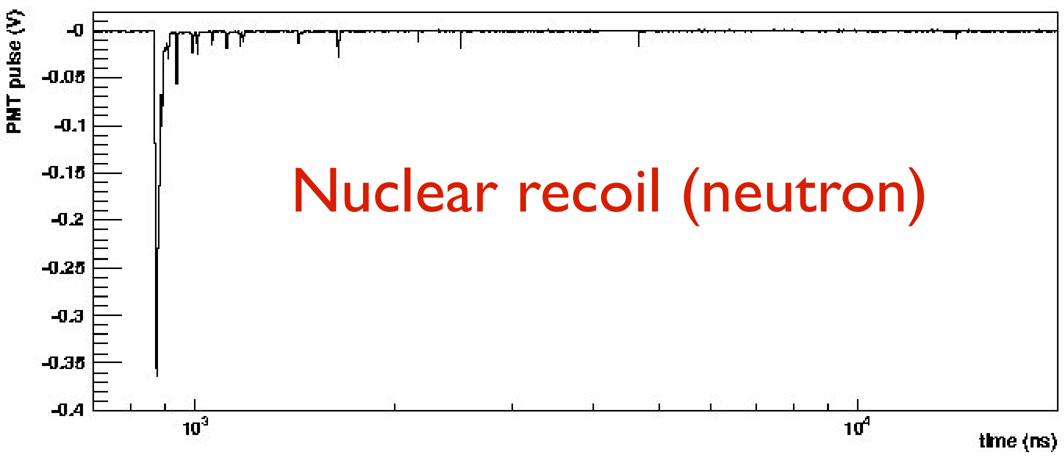


Fluorescence Time Structure

- Pulse shape analysis (singlet vs. triplet light) is one nice way of tagging nuclear and electron recoils



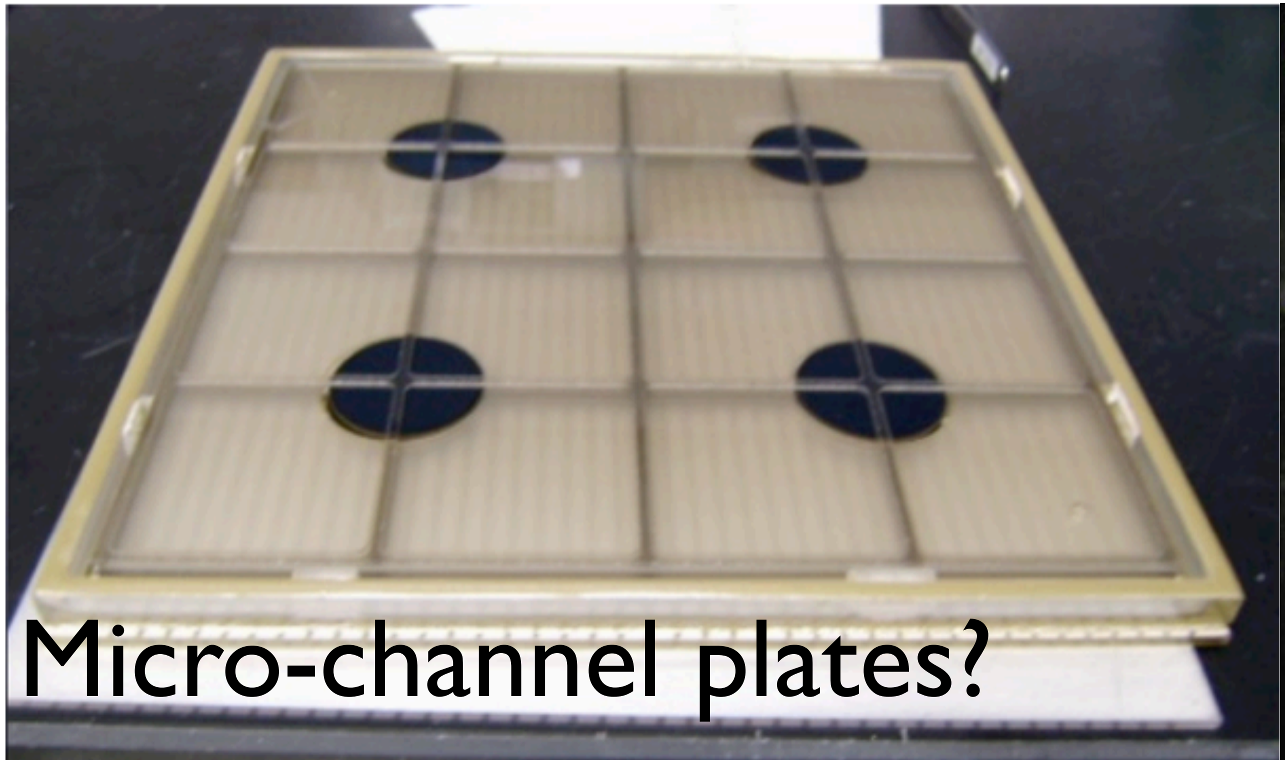
PMT pulses in LAr

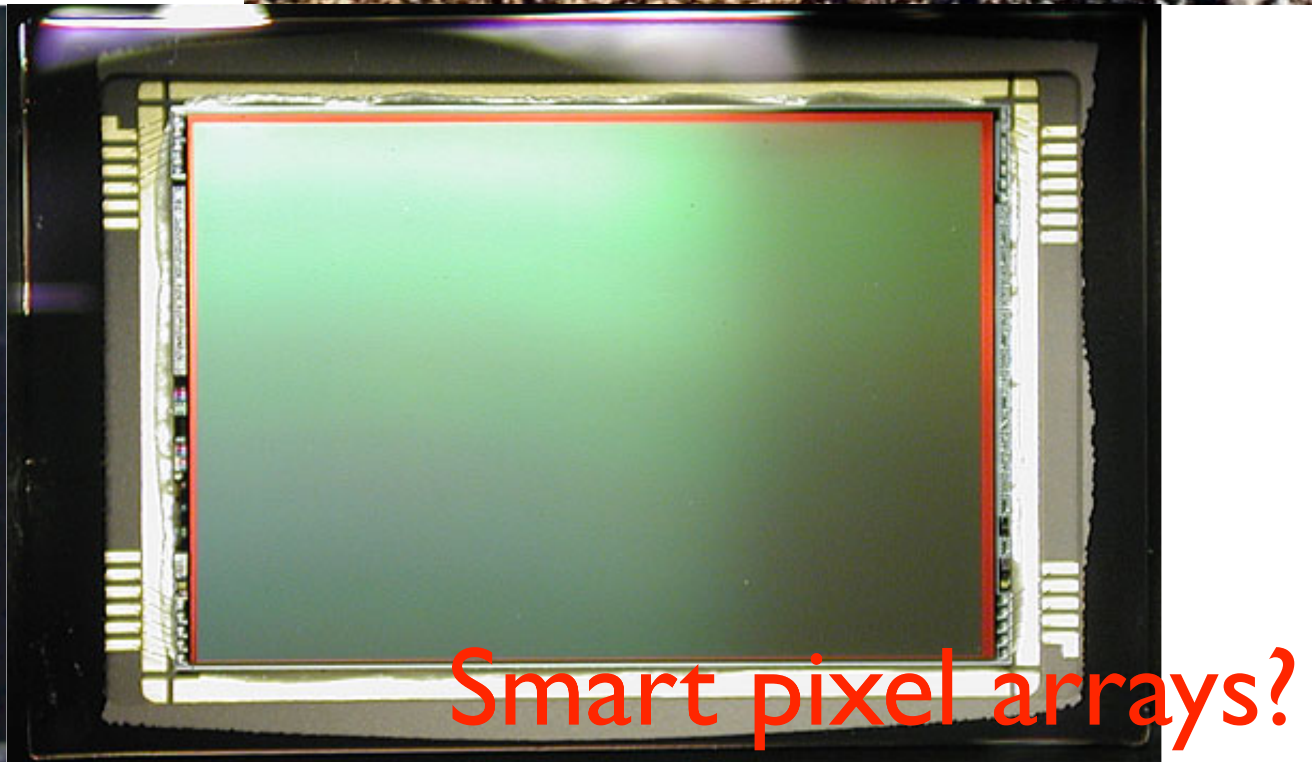


- How good a job can you do?
  - Are you limited by PMT response, or WLS?
  - Is there a temperature response?
- This is actually quite important if you're trying to model your PSA response for design of readout electronics, *etc.*

Something Completely Different?

- Wouldn't it be nice to not have to launder all of our light through a wavelength shifter?
- The alternatives clearly have problems, but maybe it's time for another look!





Conclusions

- Detection of EUV photons is about to be *really* important to a lot of interesting particle and nuclear physics experiments
- There are some nice optical measurements and detector development projects that can dramatically influence the design and scope of these experiments
- EUV photon detection problems are *not*, in general interchangeable: right design for neutrino oscillation $\neq$ $\beta\beta$ or dark matter
- Multi-disciplinary laboratories are well-positioned to contribute mightily to this problem!!!

Thank you for your attention!

Any questions?