Ideas for Non-Imaging Light Collection

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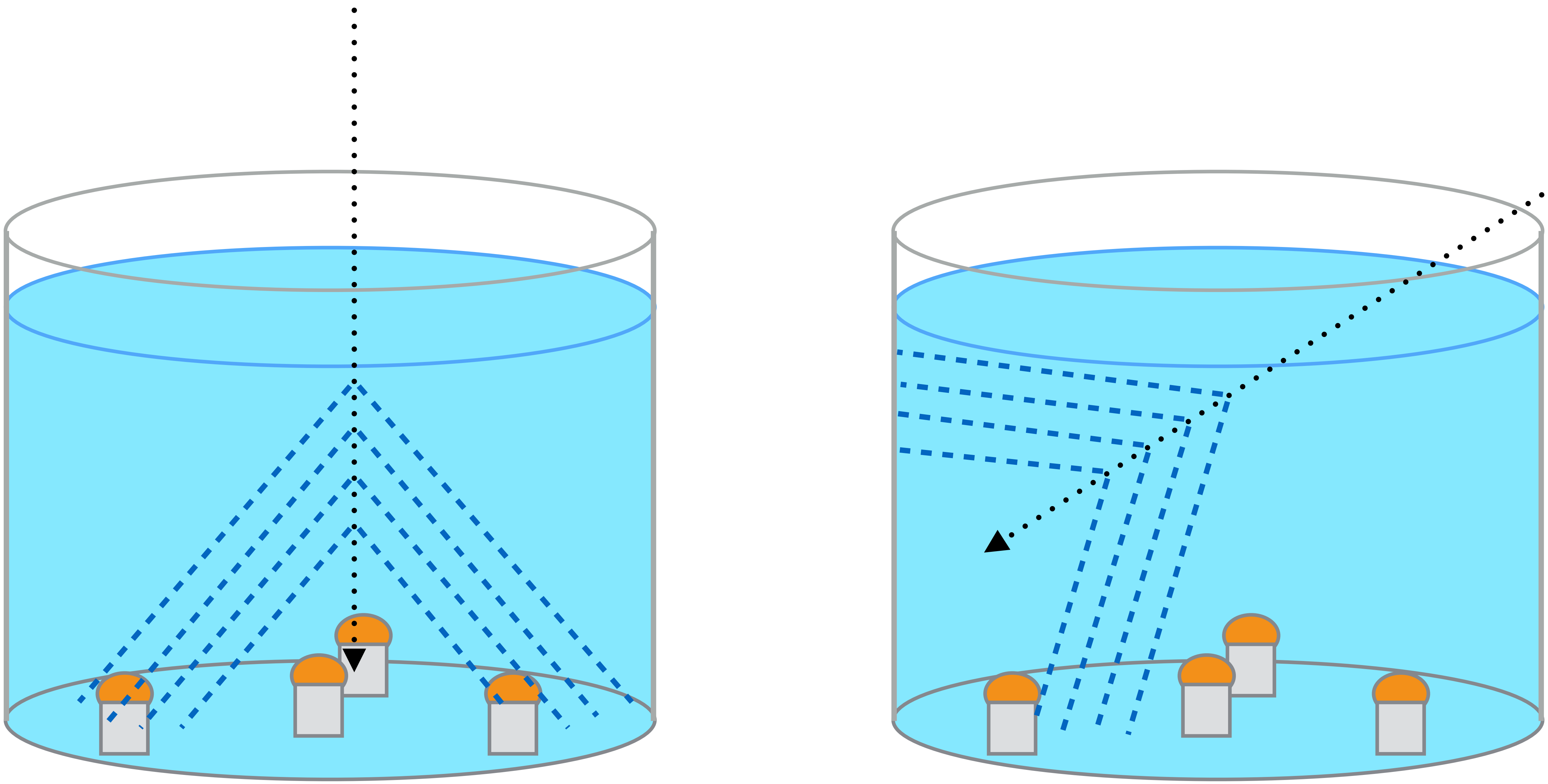
Improving LC in WCDs

- It would be nice to improve the photon collection efficiency of light sensors in HAWC-like WCD arrays
  - More photons = better (always?)
  - Background suppression improves with N_{hit}
  - Perhaps reduce total number of photosensors needed, which is important for holding down costs
- **Note**: @ HAWC trigger threshold we're actually particle starved, not photon starved. You can tell just by looking at sub-TeV CORSIKA showers. So going to very high altitude **is** quite important!

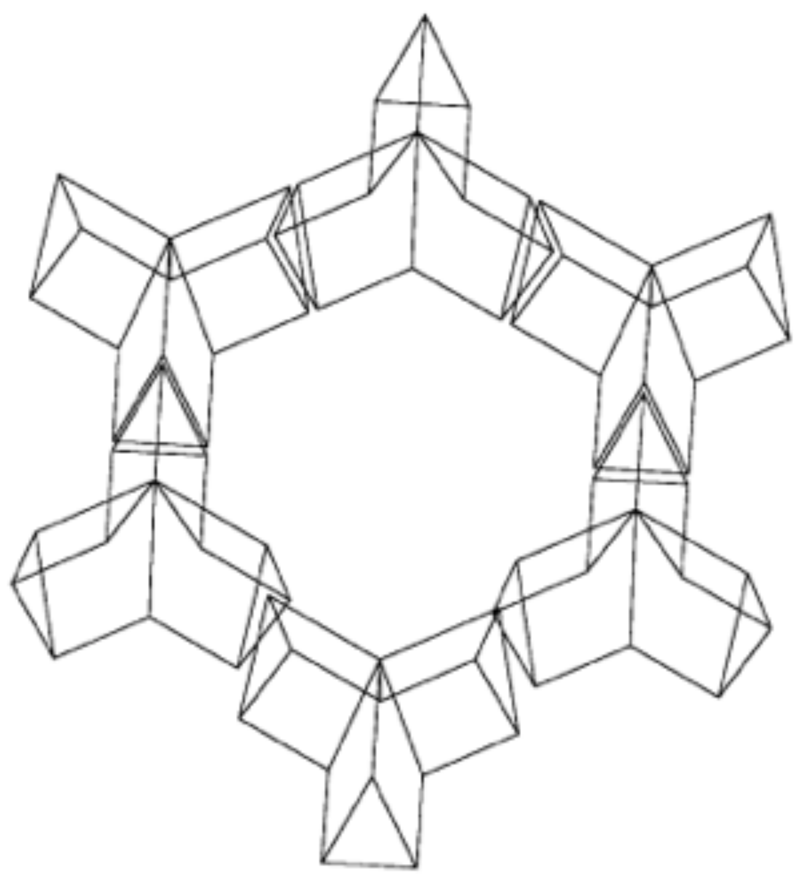
Why >1 PMT Used?

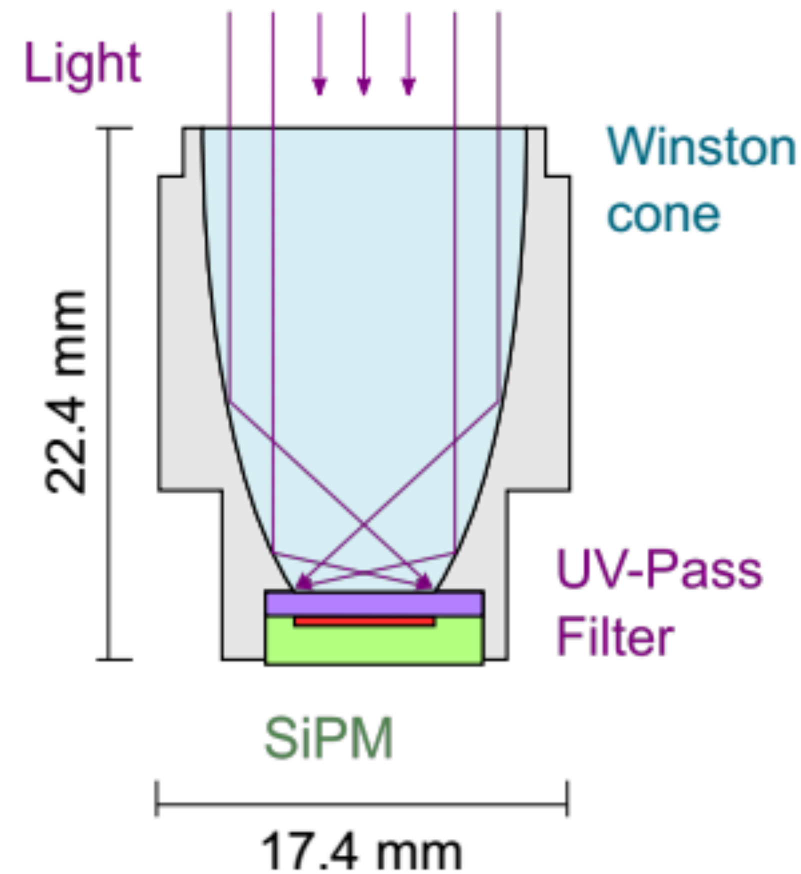
- Want tall WCDs, but that's expensive. In shorter tanks need sensors at rim to view inclined particles



Non-Imaging LC

- Geometric concentration: use Winston cones with PMTs to collect light and/or make the photocathode response more uniform

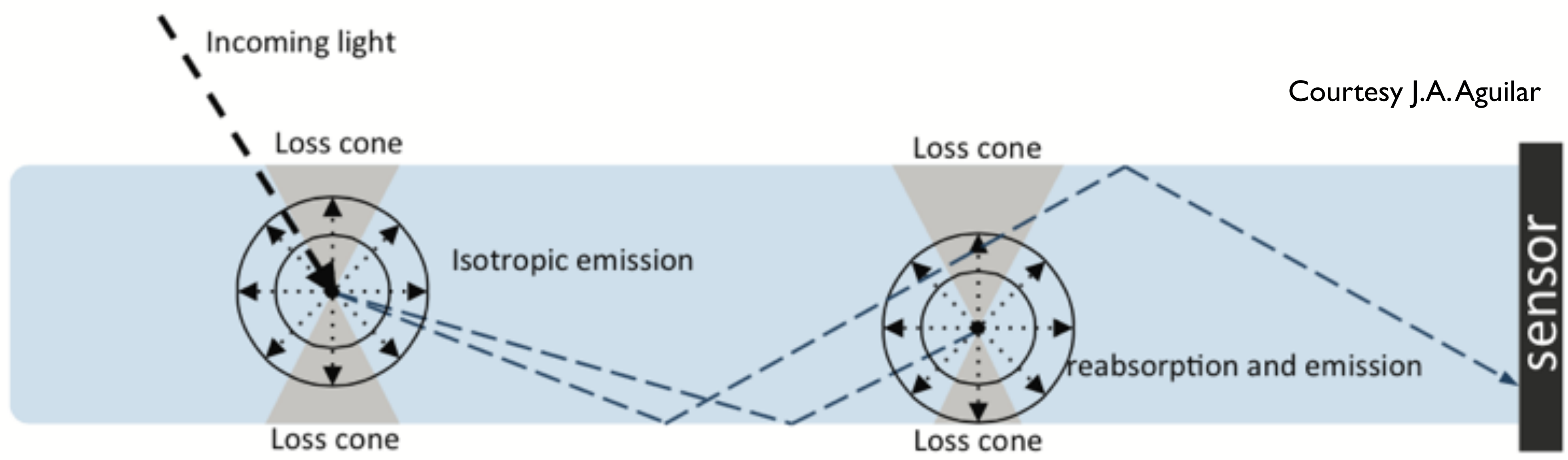




- Concentration ratio: bound by $C \leq n^2 \sin^2\vartheta_{out} / \sin^2\vartheta_{in}$

Inelastic Concentration

- Use a material that absorbs high-energy photons and isotropically re-emits low-energy photons

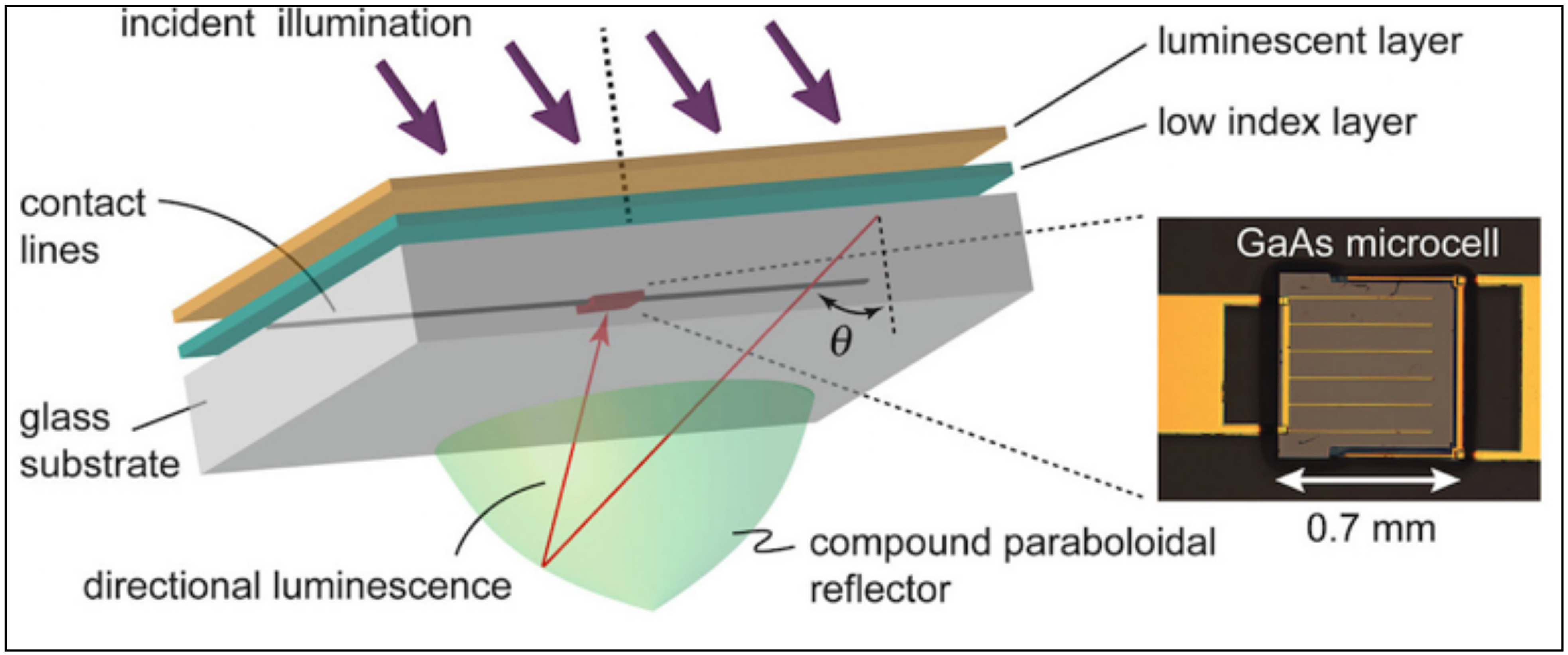


- Wavelength shifter (WLS): concentrate light at peak response of photosensor, usually >400 nm
- Use total internal reflection to guide light to sensor. Note the light losses outside the TIR region

Combined Approach

- Lots of work on this topic in the field of solar cell optimization: non-imaging luminescent concentrators

Y. Shen et al., ACS Photonics 1:746, 2014

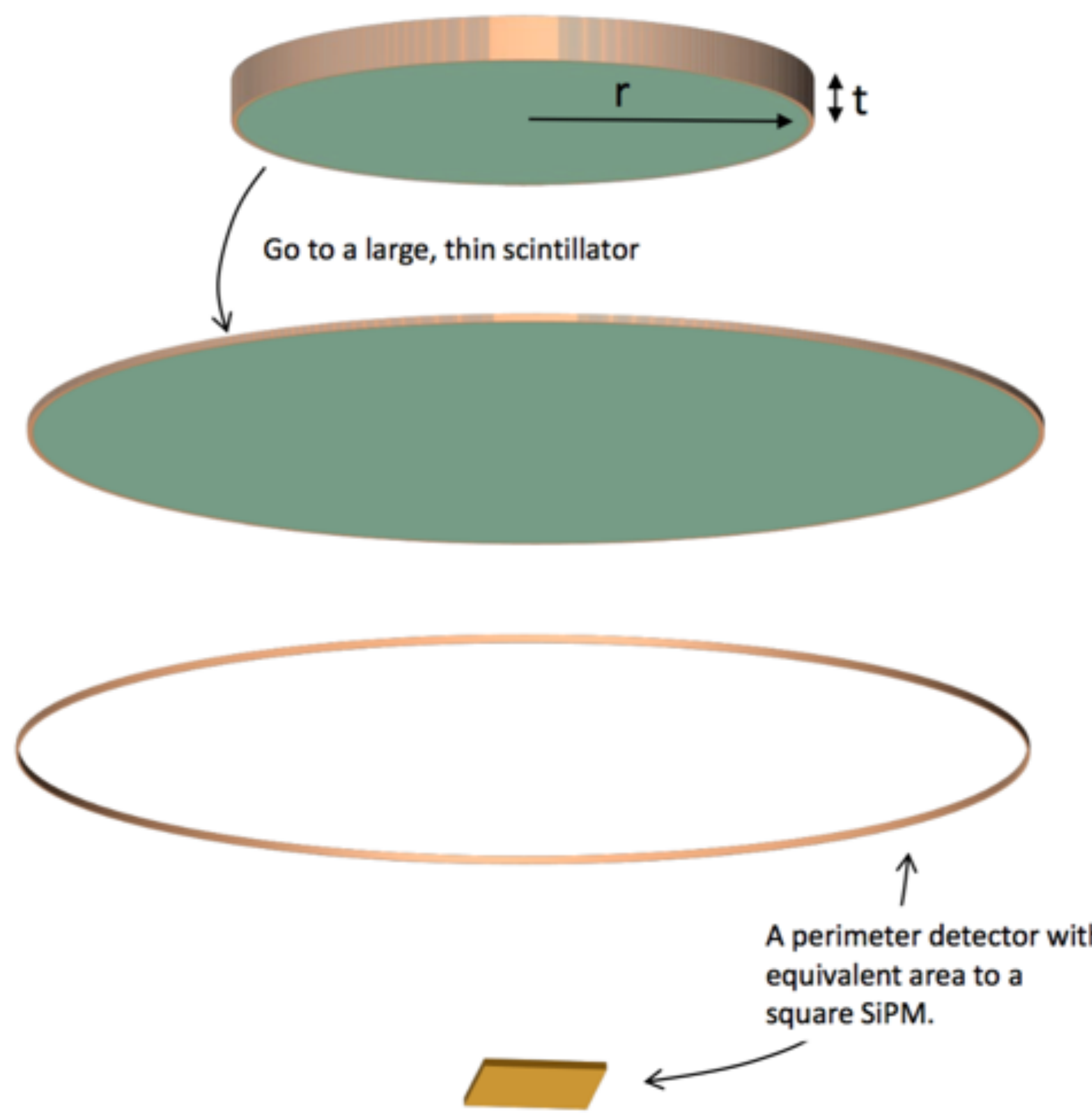


- Development of novel WLS materials with anisotropic emission: eliminate loss cones, boosting the LC efficiency. Combine with geometric concentration for high gain

Edge-on vs Face-on Readout

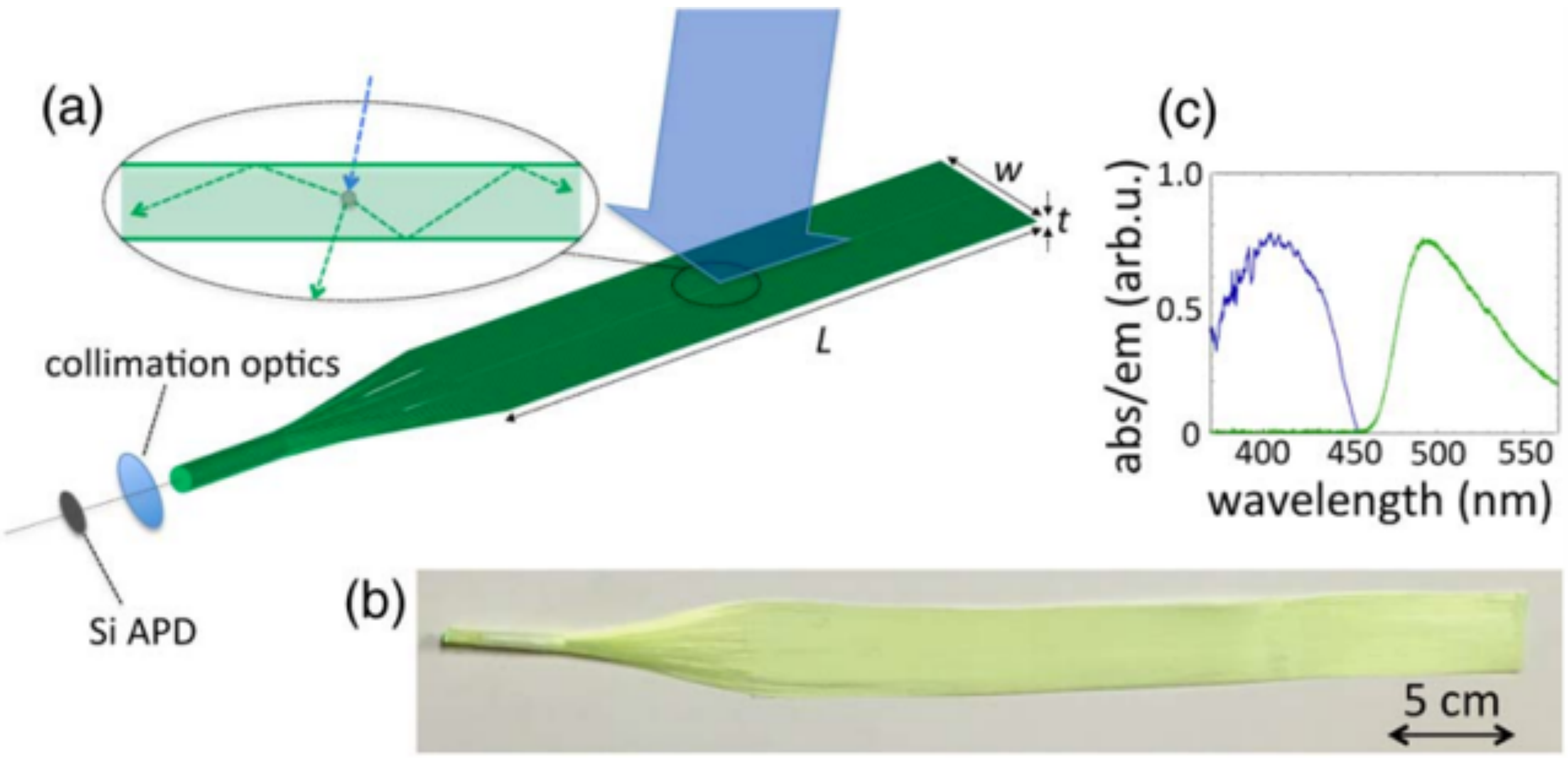
- In a flat LC we'd want to read out along the edge where TIR concentrates all the photons
- Ideally: make the panel extremely thin so that the area to edge ratio is huge
- Gain scales like $G \sim r/t$, and $t \sim 1\ \mu m$ for anisotropic LC, so in principle $G \sim 10^3$

Courtesy N.C. Giebink



Back to the Real World

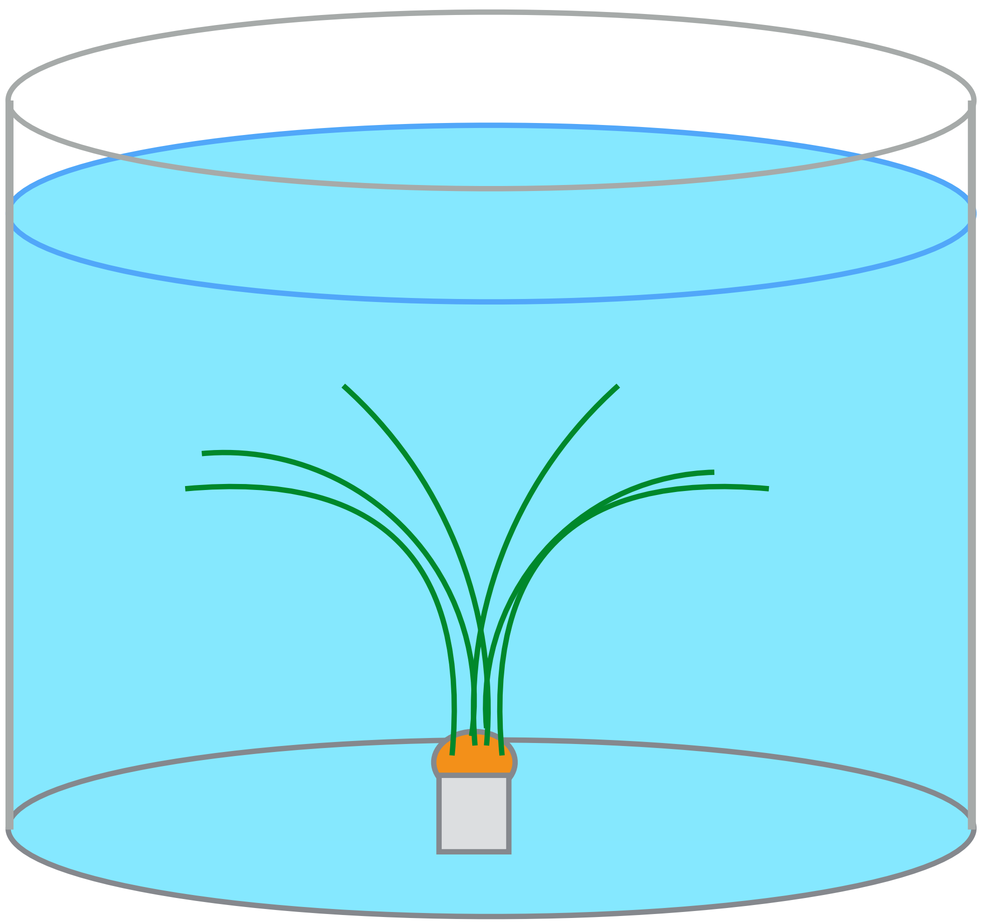
- Unfortunately, it's hard to stretch a photosensor into a one-micron hoop. Also, a flat sensor is a bad choice if wide angular acceptance is required (poor A_{eff} @ large zenith)
- Alternative from the field of solar luminescent concentration: optical fiber concentrators



Fiber Concentrator Gain

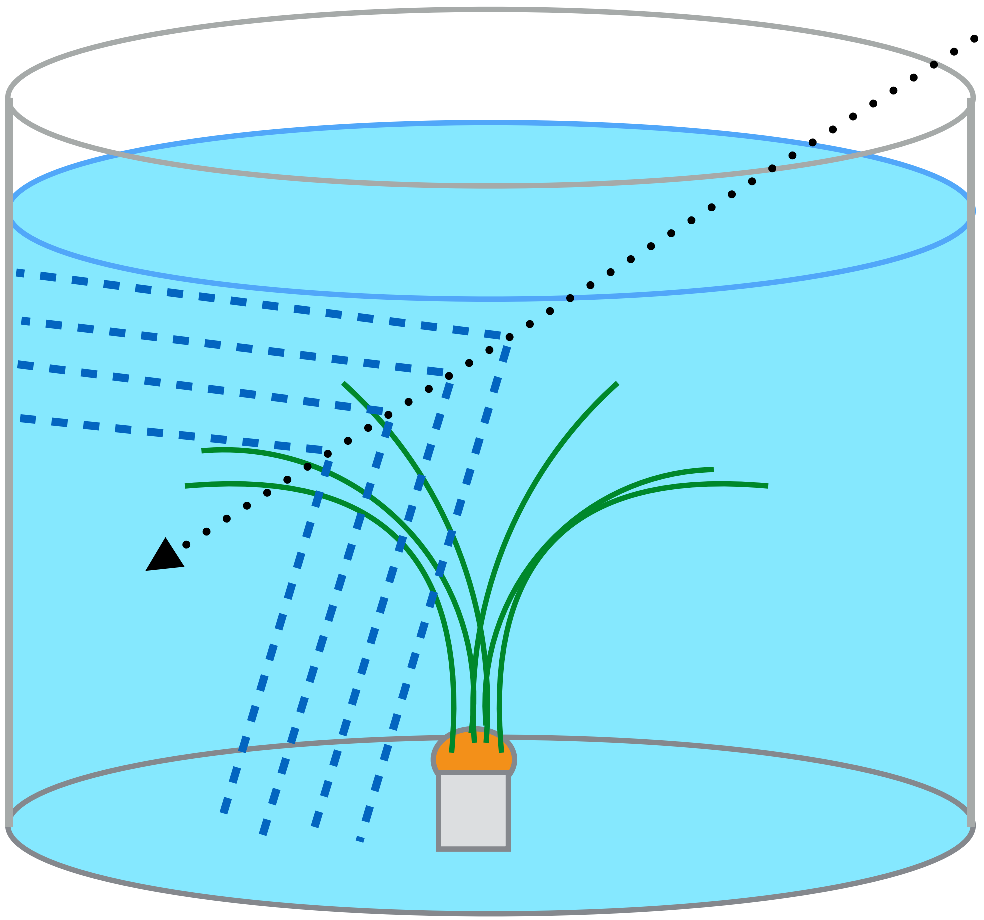
- Gain of WLS fiber LC goes like $G \sim A_{fibers}/A_{SiPM} \cdot \eta_{opt}$
- A_{fibers} scales with number of fibers. Can easily get huge area ratio with respect to photosensor while arranging the fibers in any desired shape
- η_{opt} is the optical efficiency of the system: fluorescence quantum yield, absorption losses, fiber shadowing, and reflection losses at surfaces. Typical is η_{opt} <1%, with measurements of $G \sim 10$ reported in the literature
- May be able to boost η_{opt} to 10% with clever choice of materials. Active research ongoing in solar community

Fiber Concentration



- Can we fill the tank with a non-imaging collector that channels light to a single photosensor?
- E.g., a "fiber flower" or "fiber mop"
- Have 3D shape with effective area that does not rapidly decrease with zenith angle

Fiber Concentration



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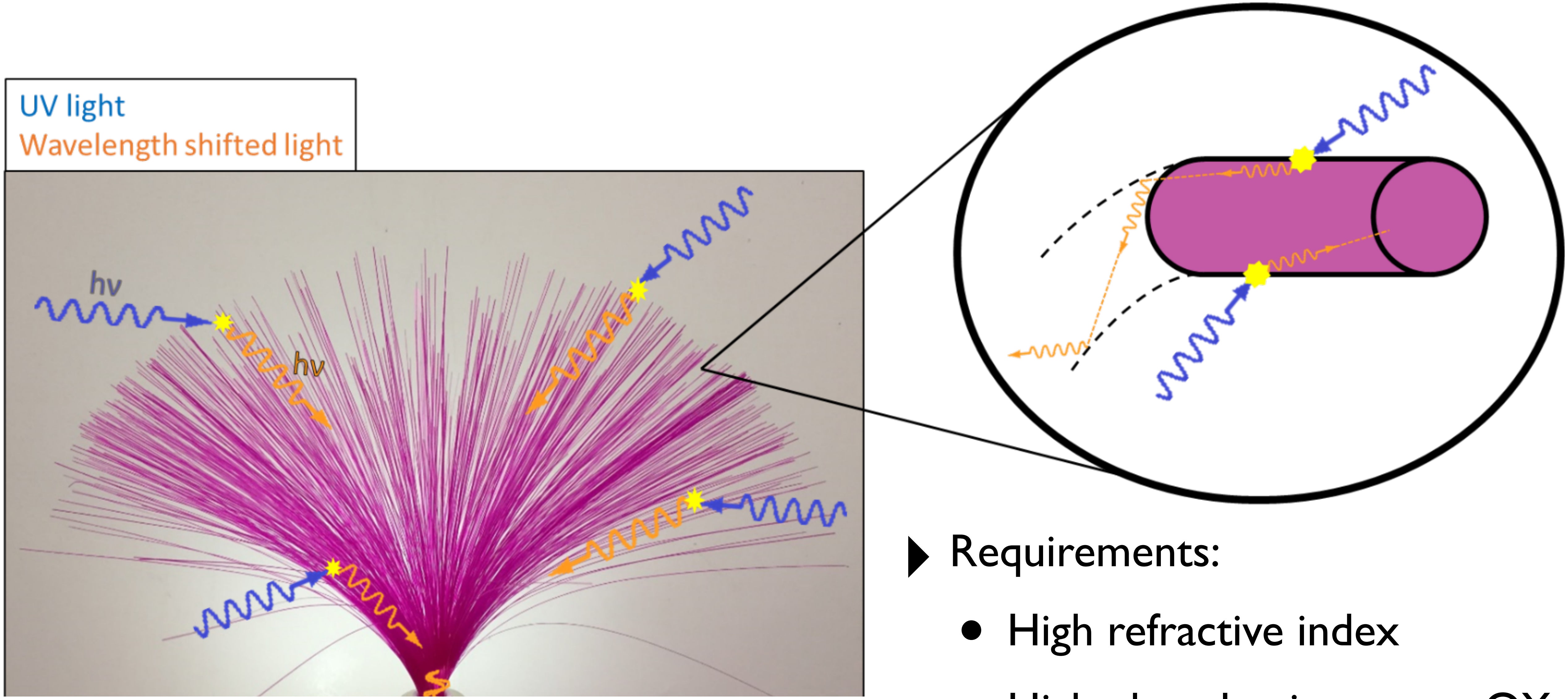
Fiber Light Concentrator

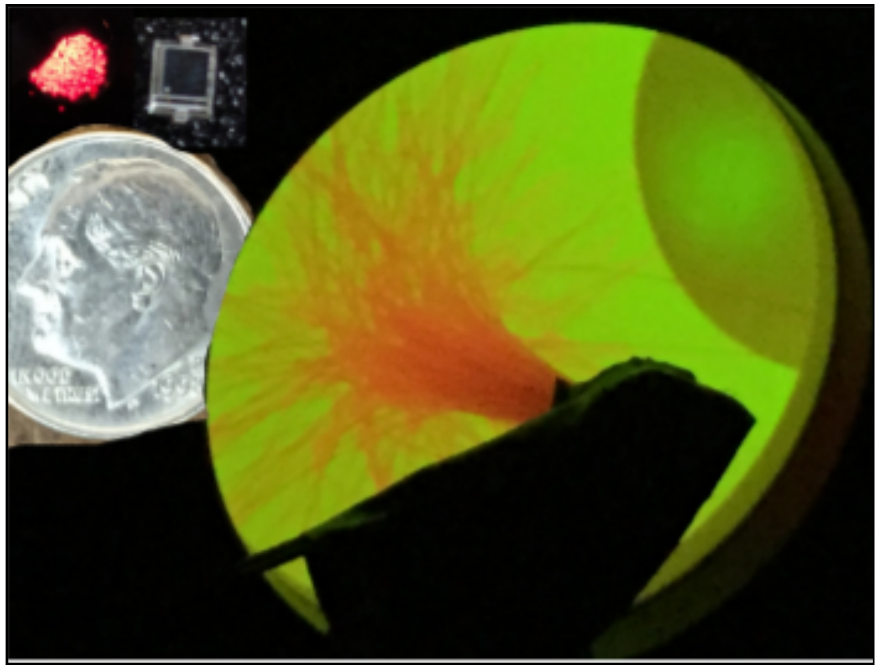


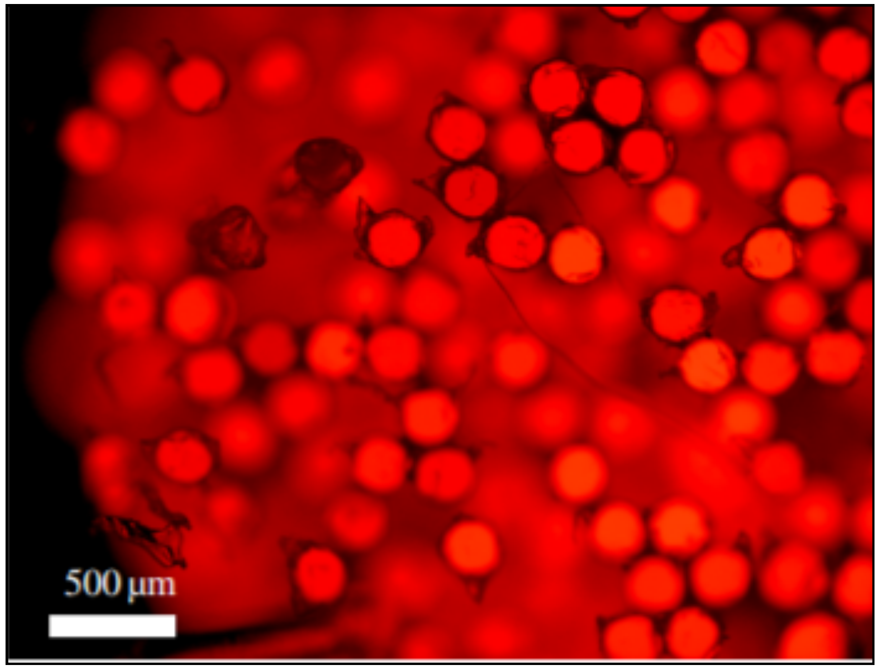
Courtesy N.C. Giebink

- Requirements:
  - High refractive index
  - High photoluminescence QY
  - Fast radiative decay (<1 ns)
  - Strong absorption < 400 nm
  - Long-term stability in water

Prototype @ PSU

Courtesy N.C. Giebink

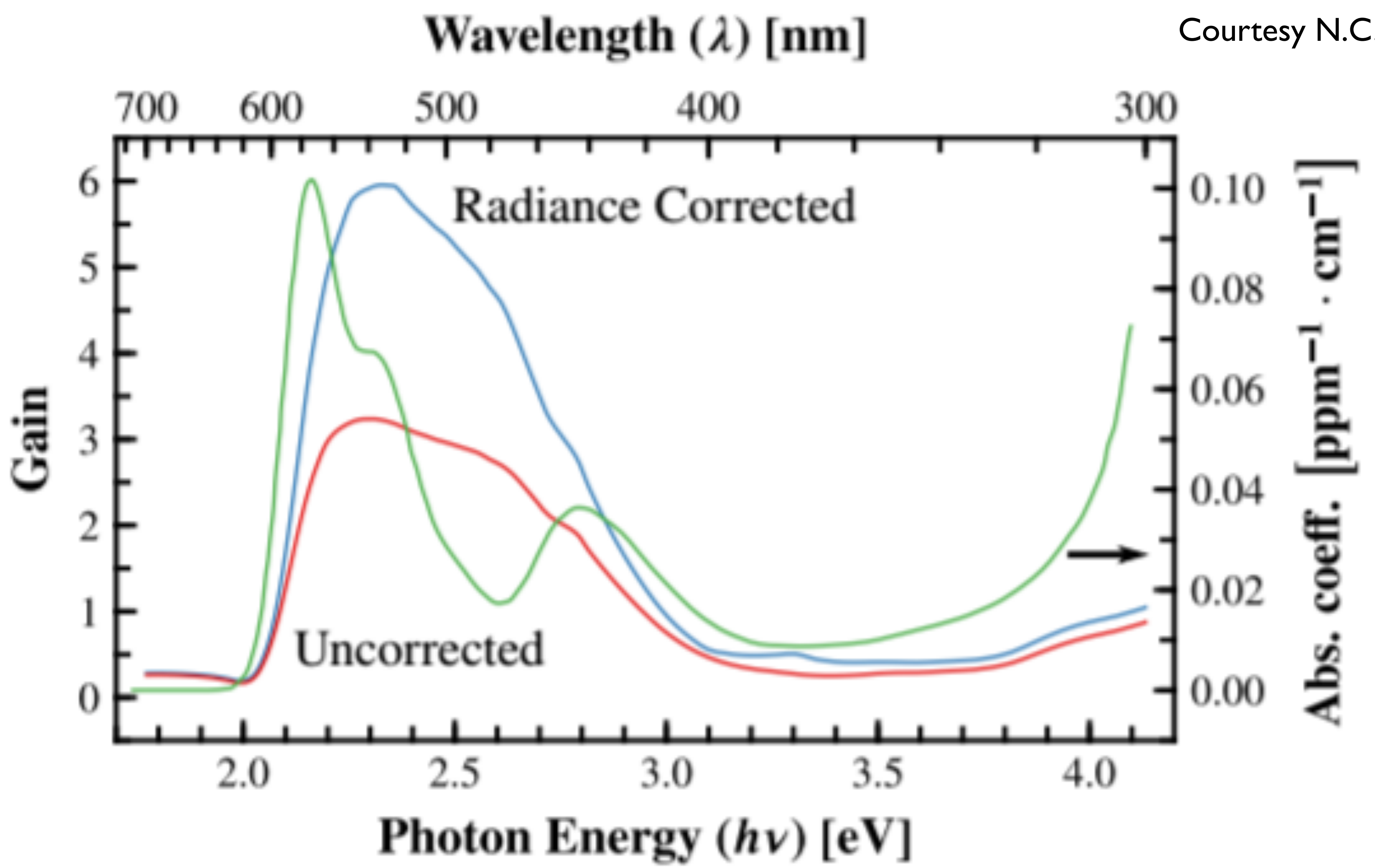




- PSU: PMMA coated with fluorescent material in the lab. Looking for very speedy polymers (sub-ns fluorescence τ_{decay})
- Getting some feedback on materials from solar concentrator community
- My lab: Kuraray WLS fibers left over from T2K R&D

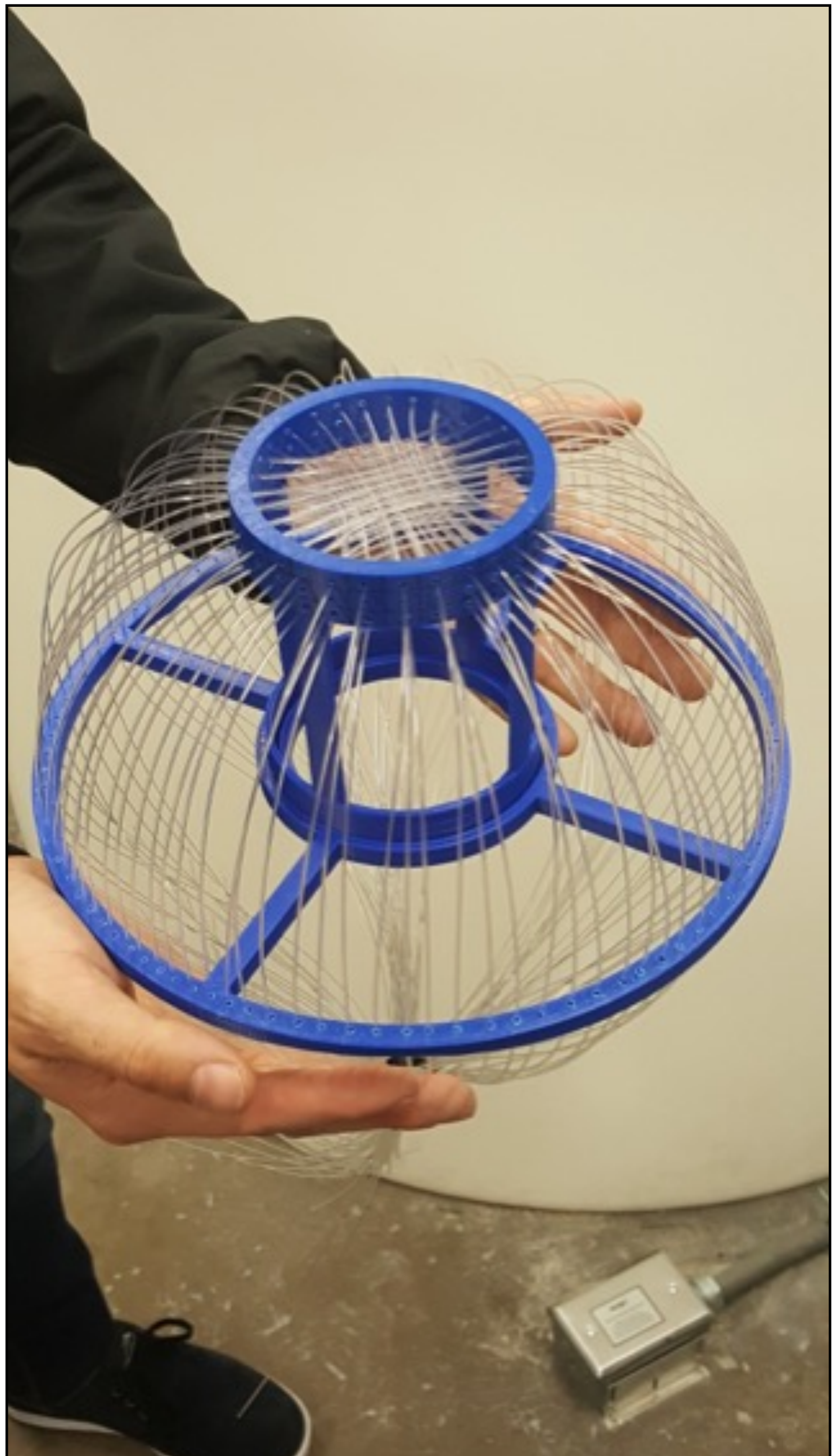
PSU Fiber Flower Gain

Courtesy N.C. Giebink, A.J. Grede



- Gain of fiber flower measured inside integrating sphere
- Naïvely expect $G > 100$. Optical efficiency matters a lot

U of R "Concentrator"



- More rigid fiber concentrator with a hemispherical shape
- 3D-printed frame made by UR undergraduate Alex Johnson
- Threaded with 1-mm PMMA fibers ordered from amazon.com. Easy to scale to larger sizes
- Will replace plain PMMA with Kuraray WLS or fibers from PSU. From literature, expect geometric gains of 3x to 10x

Summary

- Combination of geometric and inelastic light concentration ("luminescent concentrators") could have benefits for future WCD arrays
  - Maintain or improve WCD photon detection efficiency with fewer photosensors, cables, readout channels, etc.
  - Bare WLS fiber concentrators allow for flexible 3D designs. Physical robustness is surprisingly good!
- Lab measurements: $G \sim 10$. Optimizing the fluorescent materials may provide very substantial gains in the future
- Synergies with solar concentrator community, where very similar design problems exist. Work is ongoing