LUMINESCENT SOLAR CONCENTRATORS

A BRIGHT IDEA FOR SOLAR ENERGY CONVERSION?

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3rd Generation PV workshop

Heriot Watt University
24 March 2010

Introduction

☆ *Diffuse* solar irradiation is a underused resource for photovoltaics (PV)

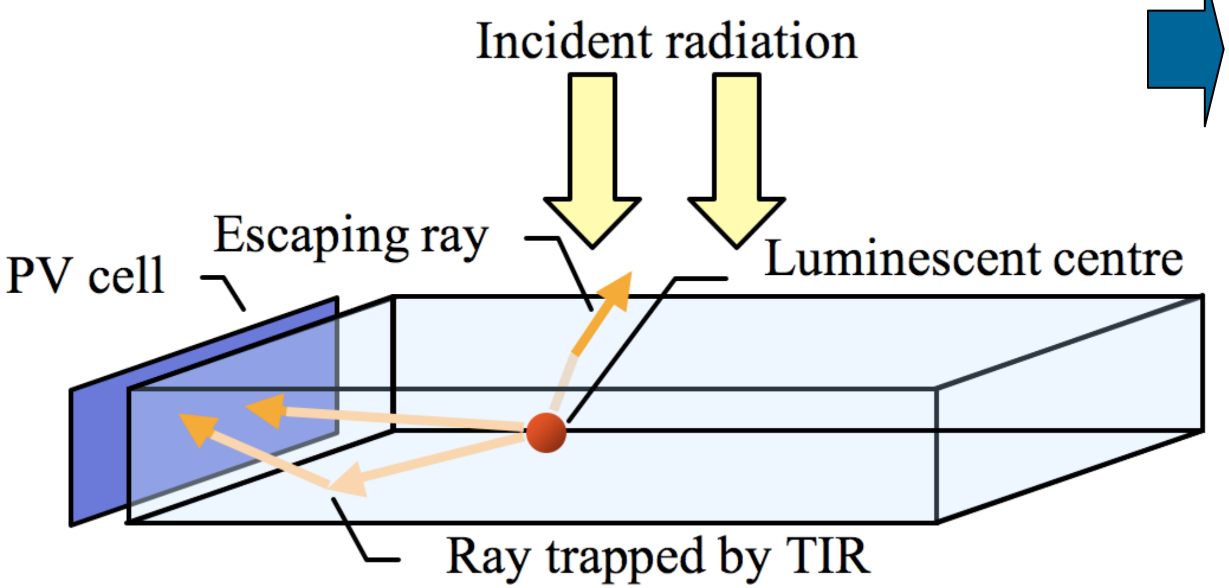
- particularly at high latitudes
- conventional optical concentrators

☆ Polymer based PV materials utilise *diffuse* irradiation owing to low *n*

- fabrication of cheap, large area modules

☆ In the UK over 7× as much solar energy falls on buildings as is consumed inside and over half of this is diffuse

Luminescent Solar Concentrator (LSC)



☆ Reduce the costs of PV electricity

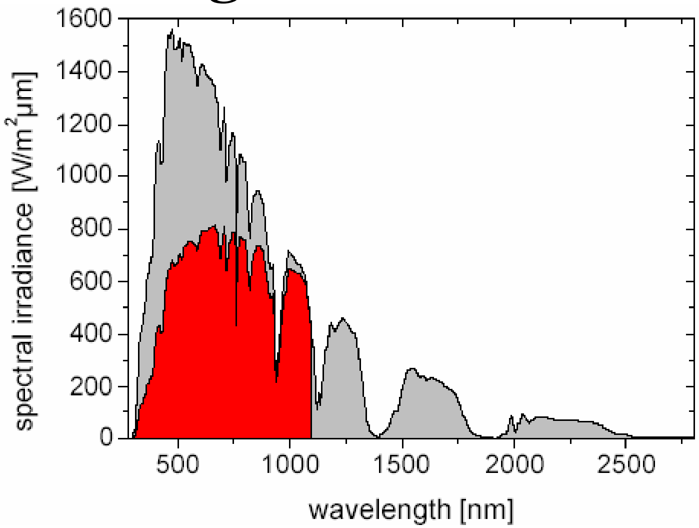
☆ Collects direct and diffuse light

☆ Non-tracking

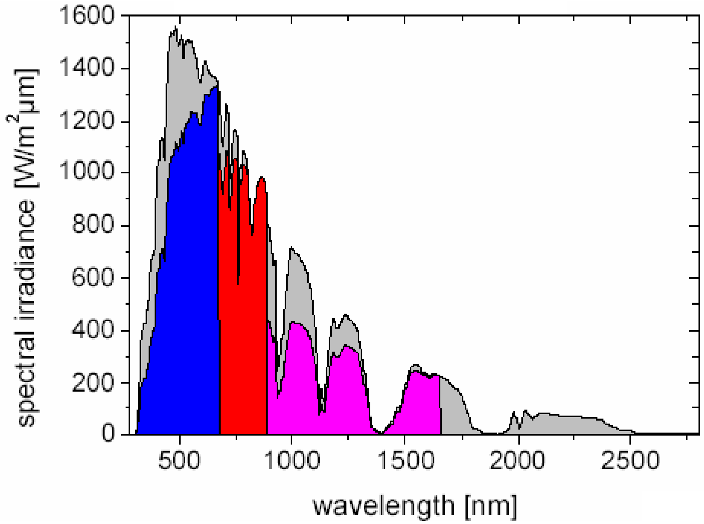
☆ Ideally suited to building integration

Materials and Architectures

Single LSCs



Stacked LSCs



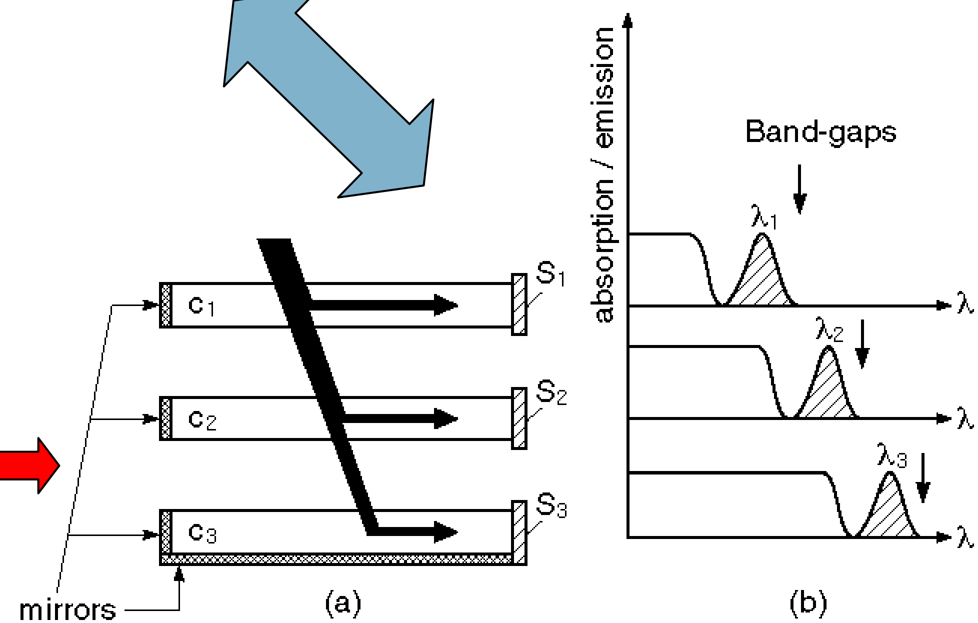
DYES

- ☆ High $Q_e \sim 95\%$
- ☆ Available in a wide range of colours
- ☆ Narrow absorption spectra
- ☆ Stability

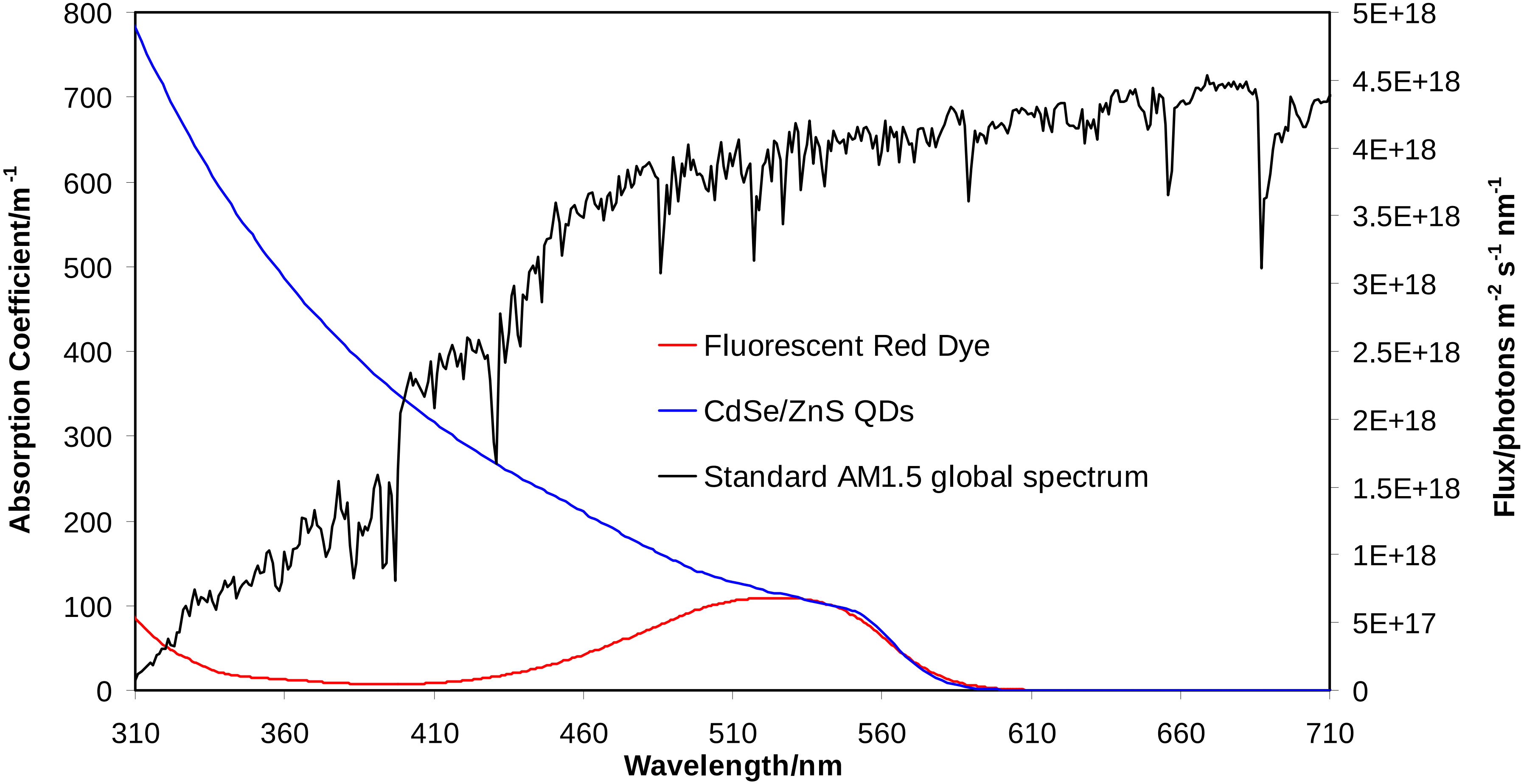
NANOCRYSTALS

- ☆ Broad absorption spectra
- ☆ Stable
- ☆ **Tuneable**
- ☆ Relatively high $Q_e > 80\%$

Narrow band emission reduces thermalisation losses in an attached PV cell



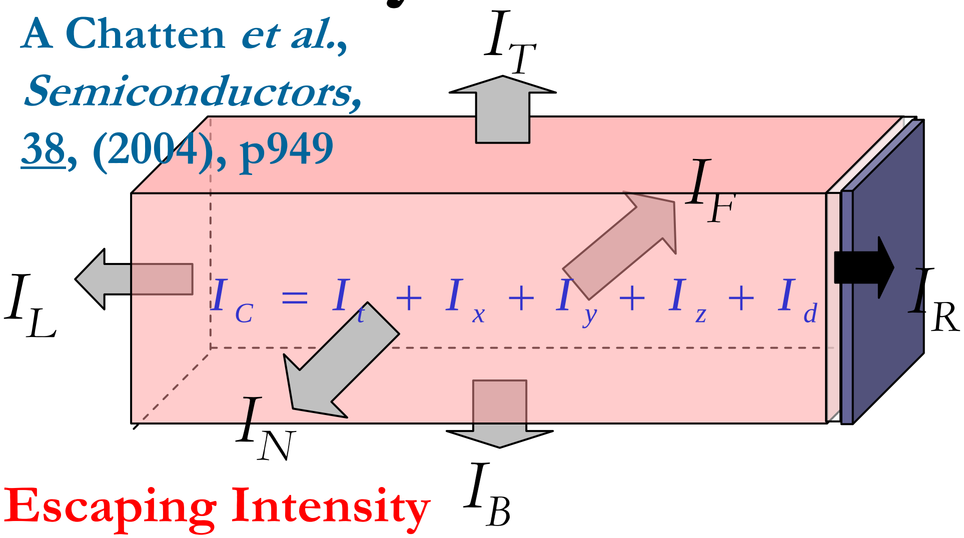
Solar Photon Harvesting



- QDs absorb 42.3% of the photons out to E_g (700nm) whereas the red dye absorbs only 23.5%
- 10×10×0.5cm red dye doped LSC ($Q_e = 0.95$) $J_{SC} = 207$ A m^{-2}
- 10×10×0.5cm QD doped LSC ($Q_e = 0.85$) $J_{SC} = 268$ A m^{-2} up 29%

Thermodynamic Model

A Chatten *et al.*, *Semiconductors,* 38, (2004), p949



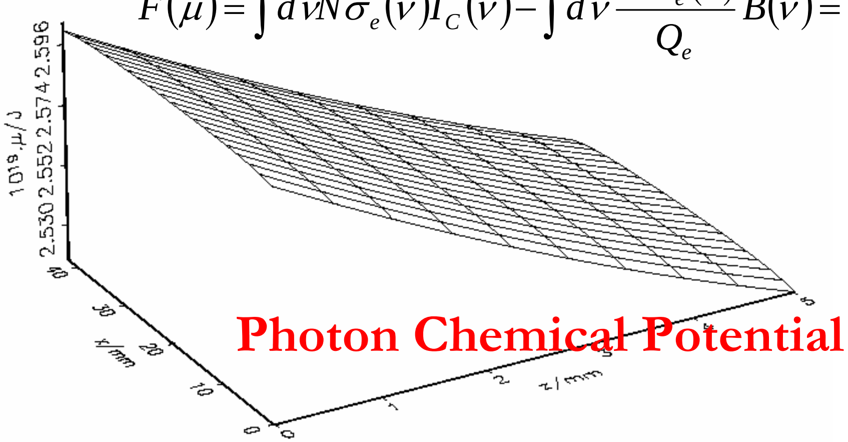
Escaping Intensity

$$I_x(x,y,z) = \frac{\Omega_c \lambda_e \cosh\left(\lambda_a x + \frac{\alpha_L}{2}\right)}{2\pi \sinh\left(\lambda_a L + \alpha_{LR}\right)} \int_0^L dx' \cosh\left[\lambda_a (L - x') + \frac{\alpha_R}{2}\right] B(x',y,z)$$

$$- \frac{\Omega_c \lambda_e}{2\pi} \int_0^x dx' \sinh\left[\lambda_a (x - x')\right] B(x',y,z)$$

Detailed Balance

$$F(\mu) = \int d\nu N \sigma_e(\nu) I_C(\nu) - \int d\nu \frac{N \sigma_e(\nu)}{Q_e} B(\nu) = 0 = A - E_C$$



Photon Chemical Potential

1) Start with Chandrasekhar's general radiative transfer equation

2) Use the methods of Schwartzchild and Milne to generate diff. eqns.

3) Integrate the diff. eqns. for the fluxes

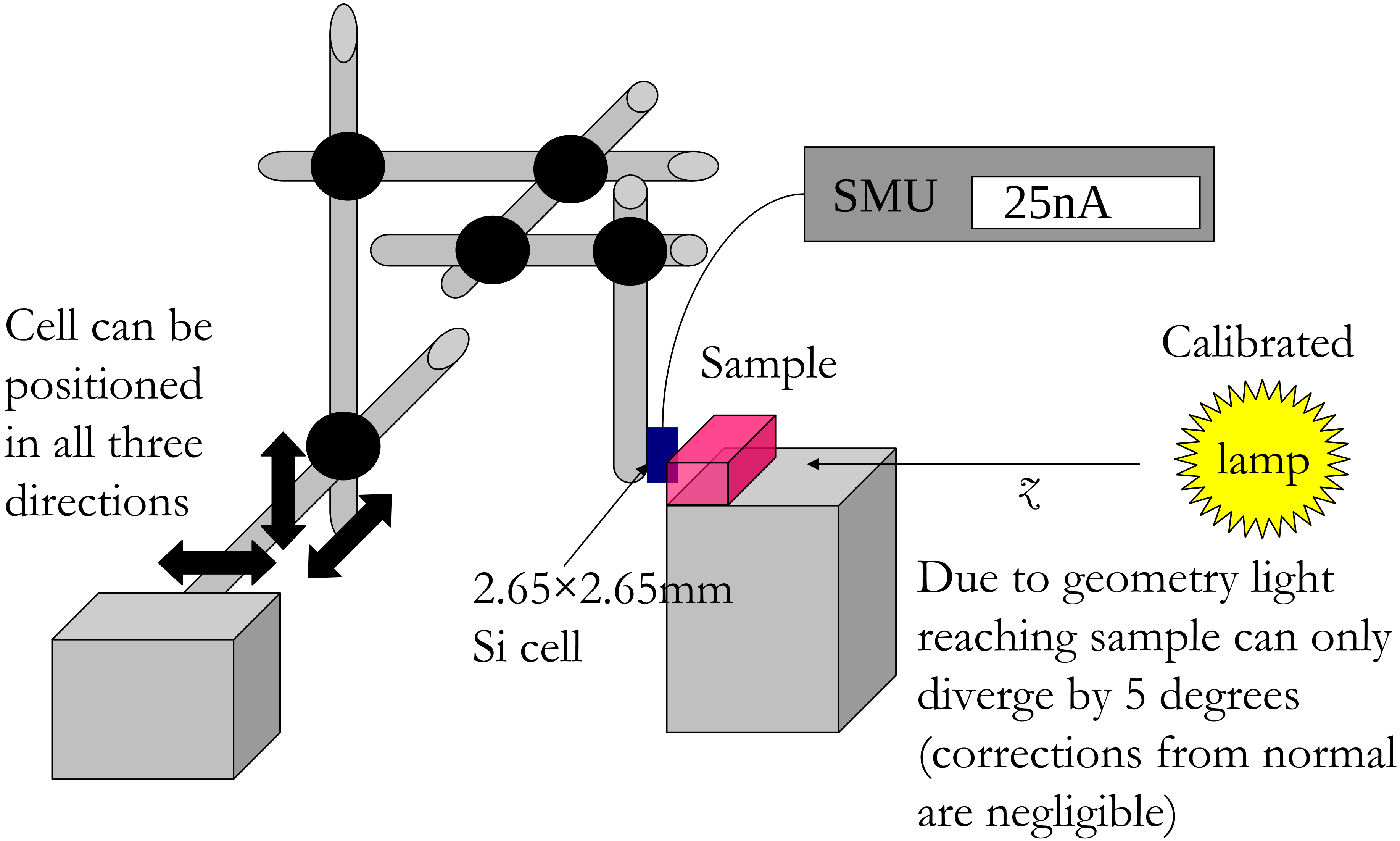
4) Evaluate the resulting expressions at the surfaces

5) Apply appropriate boundary conditions considering reflection and transmission at the surfaces

6) Derive expressions for the intensities within the LSC and fluxes exiting the surfaces

Experimental set-up

- Illuminate test concentrator, module or stack with a calibrated lamp
- Measure short circuit current density J_{sc} generated in a calibrated PV cell



Results – Short Circuit Currents (QD-LSCs)

- Stacked concentrators - red and yellow Nanoco QDs ($0.3 < Q_e < 0.6$)

Sample		Fit Q_e(%)
IC Yellow		**56 ± 3**
IC Red		**6.5 ± 1**
Fh-IAP Yellow		**69 ± 15**
Fh-IAP Red		**25 ± 2**

- IC samples – UV polymerised
- Fh-IAP samples – thermally polymerised

Andreas Büchtemann

Luminescence quantum efficiency - processing dependent

Test concentrators 4.5×1.5×0.5cm

Layer IC plates	Experimental J_{sc} mA/m^2	Predicted J_{sc} mA/m^2
top	2.6 ± 0.2	2.4 ± 0.2
bottom	1.0 ± 0.2	1.0 ± 0.2

Layer Fh-IAP plates	Experimental J_{sc} mA/m^2	Predicted J_{sc} mA/m^2
top	0.6 ± 0.2	0.5 ± 0.2
bottom	2.6 ± 0.2	2.5 ± 0.2

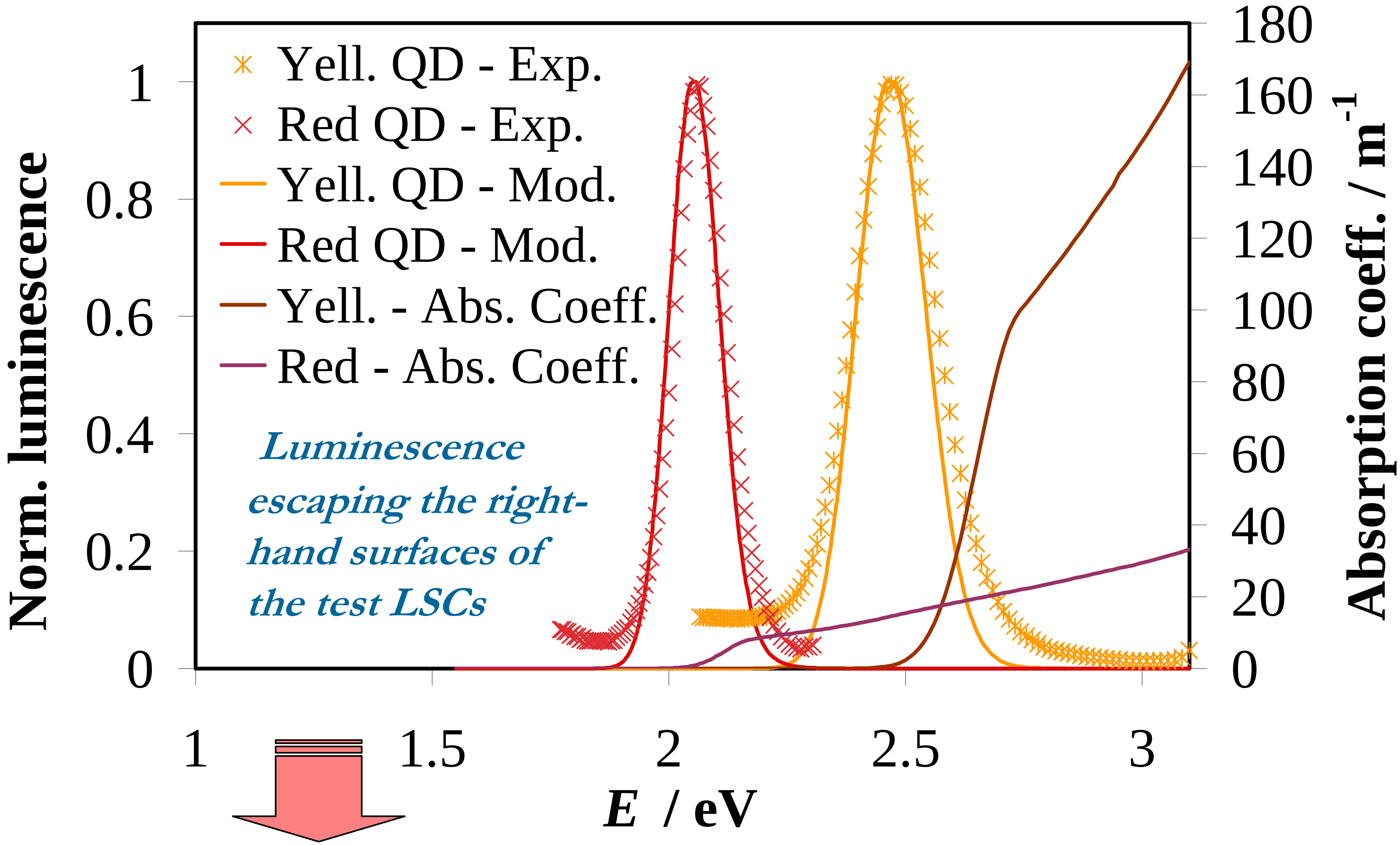
Layer IC plates	Experimental J_{sc} mA/m^2	Predicted J_{sc} mA/m^2
top	1.3 ± 0.2	1.3 ± 0.2
bottom	1.1 ± 0.2	1.3 ± 0.2

good agreement with the thermodynamic model

D J Farrell *et al.*, *Proc. IEEE 4th WCPEC*, (Waikoloa, Hawaii, 2006), p217

Results – Luminescence (QD-LSCs)

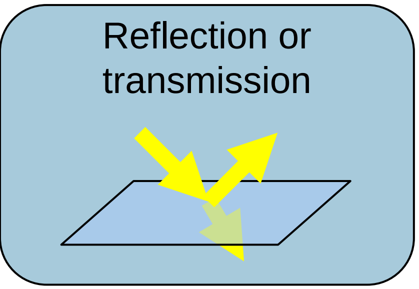
- Red and yellow Nanoco QD doped test LSCs

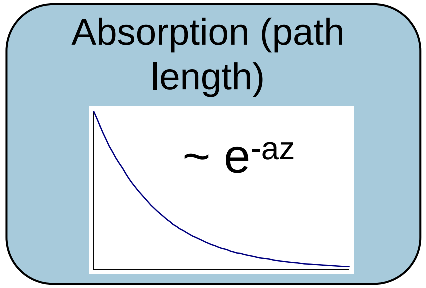


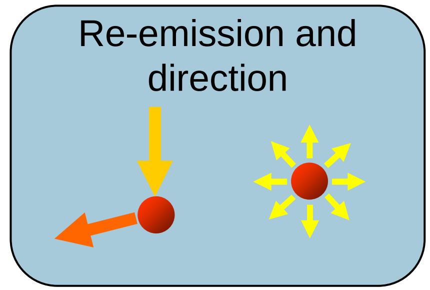
- Good agreement between the shape and position of the predicted and observed luminescence

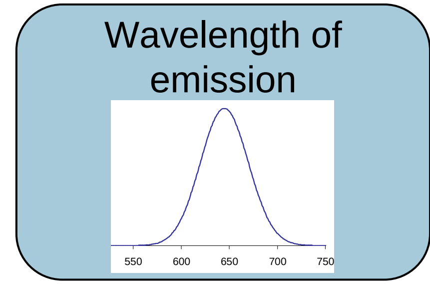
Raytrace Model

- Monte Carlo method to trace photons using geometrical optics
- Random numbers determine outcome of events:







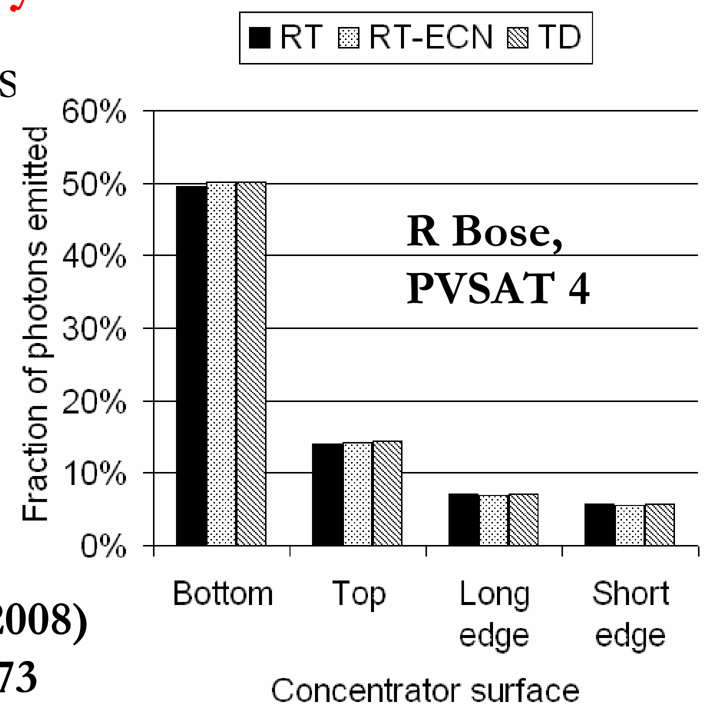


Comparison between thermodynamic and ray-trace models

- Bayer Fluorescent Red and Yellow doped LSCs
- Uniformly illuminated by a lamp
- Photon distributions, PL, J_{SC}

Agreement better than 1% absolute!

also conmpared with RT models from DIT and UCB

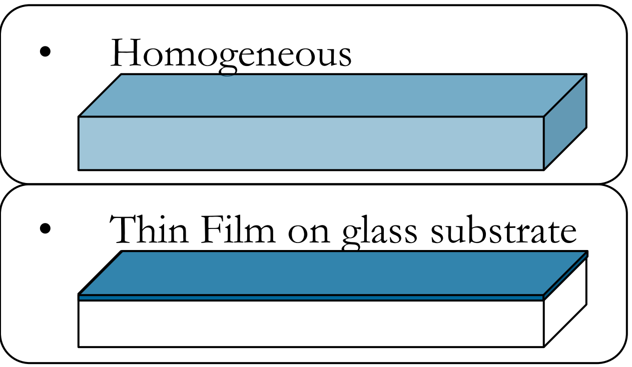


M Kennedy et al., *Proc. 23rd EUPVSEC* (Valencia, Spain, 2008) and WGHM van Sark et al., *Optics Express* 16 (2008) p21773

Thin- Film LSCs

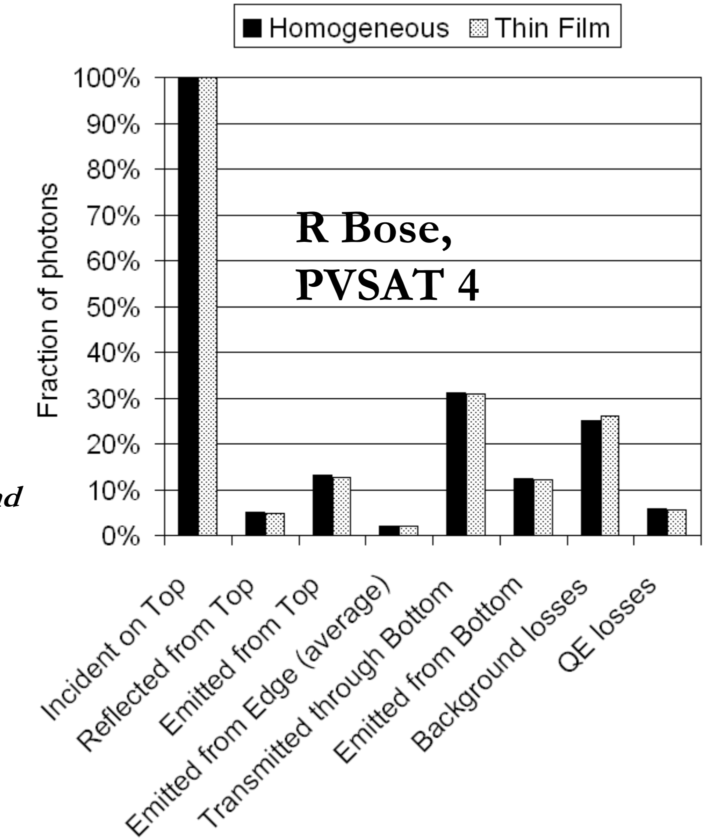
☆ Proposed to minimise re-absorption losses

C F Rapp and N L Boling, *Proc. 13th IEEE PVSC*, p690 (Washington, USA, 1978)



SAME!

see R Bose *et al.*, *Proc. 22nd EUPVSEC* (Milan, Italy, 2007) p210



R Bose, PVSAT 4

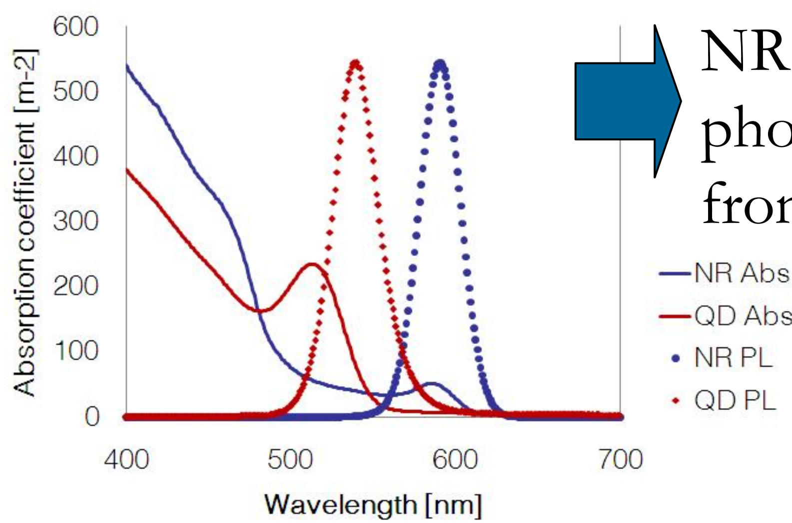
☆ May also reduce costs by allowing the use of cheaper substrates

Nanorod Doped LSCs

☆ CdSe/CdS nanorods provided by CNR-INFM and UCB

☆ Reduce reabsorption losses

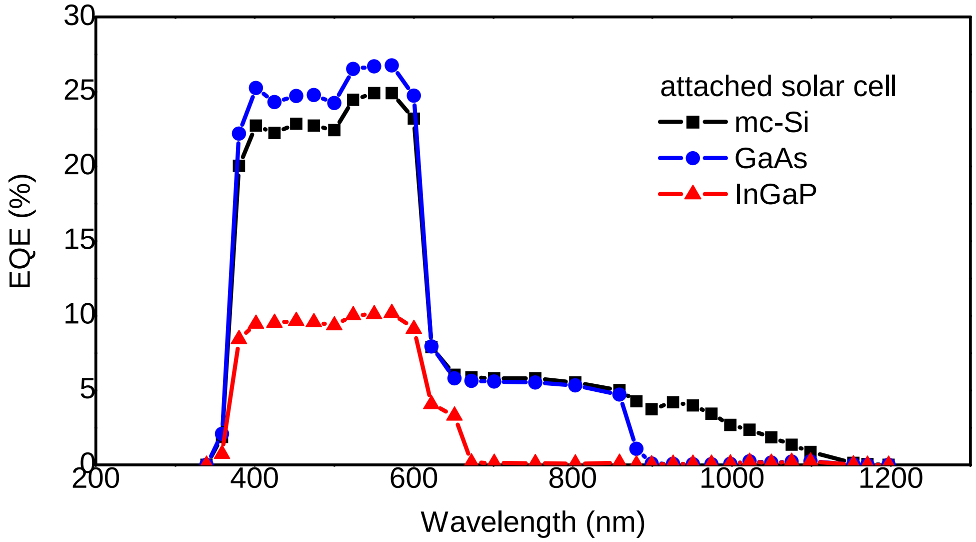
☆ LQE of 70%



NRs double % of photons emitted from the LSC edges

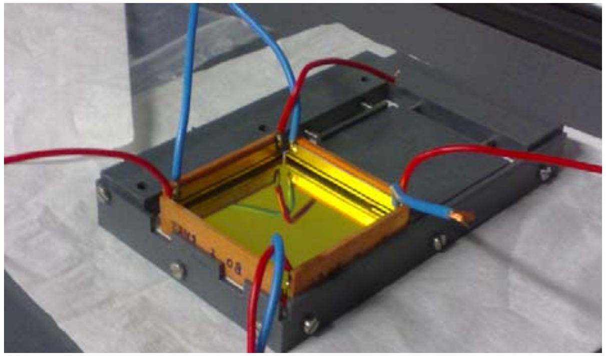
R Bose *et al.*, *Proc. 33rd IEEE PVSC* (San Diego USA, 2008)

World Record 7.1% Efficient LSC



L H Slooff *et al., Phys. Stat. Solidi (RRL)*, 2, 257 (2008)

- Lumogen F Red 305 from BASF (a Perylene) and Fluorescence Yellow CRS 040 from Radiant Color (a Coumarine)
- Matrix material PMMA (Plexit 55), back surface diffuse reflector (R=97%)
- Fabricated at Fh-IAP, characterised at ECN



M Pravettoni, EC JRC

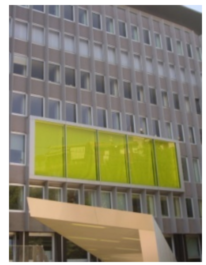
- Devices tested at ESTI
- 1 GaAs cell + mirrors (G=10)
- 4 GaAs cells (G=2.5)
- IV curve with two class A simulators
- External Quantum Efficiency (EQE)
- Correction to STC (T=25°, AM1.5g, 1000 Wm^{-2})

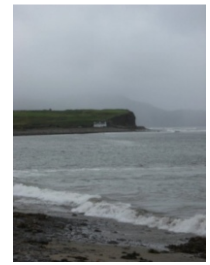
4 GaAs cells in parallel

Specific Annual Energy Yield: A Comparison

- Data in kWh/Wp
- 30cm Red 305 doped LSC module with attached mc-Si cells: PCE 3.5%
- Optimally-inclined conventional, non-concentrating, fixed modules

M Pravettoni, EC JRC





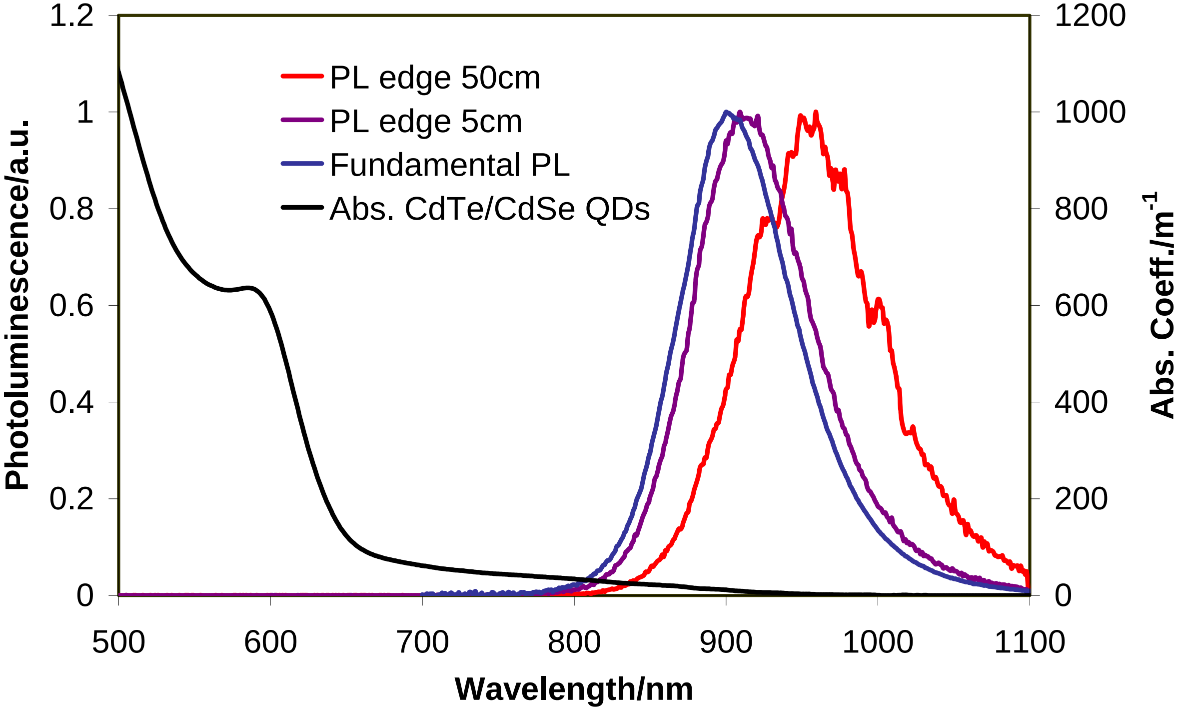
	Milan	Dublin	Famagusta
LSC @ 90 deg	**0.89**	**0.66**	**0.95**
mc-Si	1.06 +19%	0.81 +23%	1.32 +39%
thin-film (CIS)	1.09 +22%	0.83 +26%	1.37 +44%

Cost Aspects – dye doped LSC

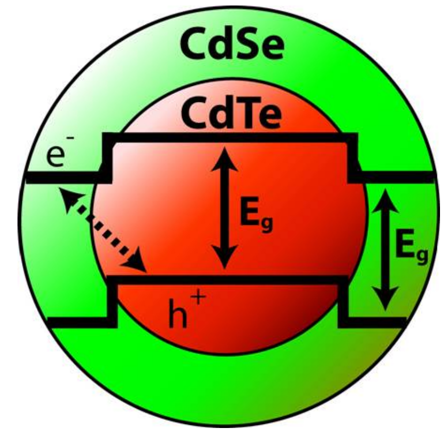
- Detailed cost analyses indicate ~2 Euros per Wp
- Competitive with other technologies

New QDs with Emission Matched to Si

- ☆ CdTe/CdSe QDs minimise re-absorption losses through the large effective red-shift and have NIR emission matched to Si



R Koole, University of Utrecht



BUT these QDs are not air stable yet

Thin-film on solar glass with 4 Si cells

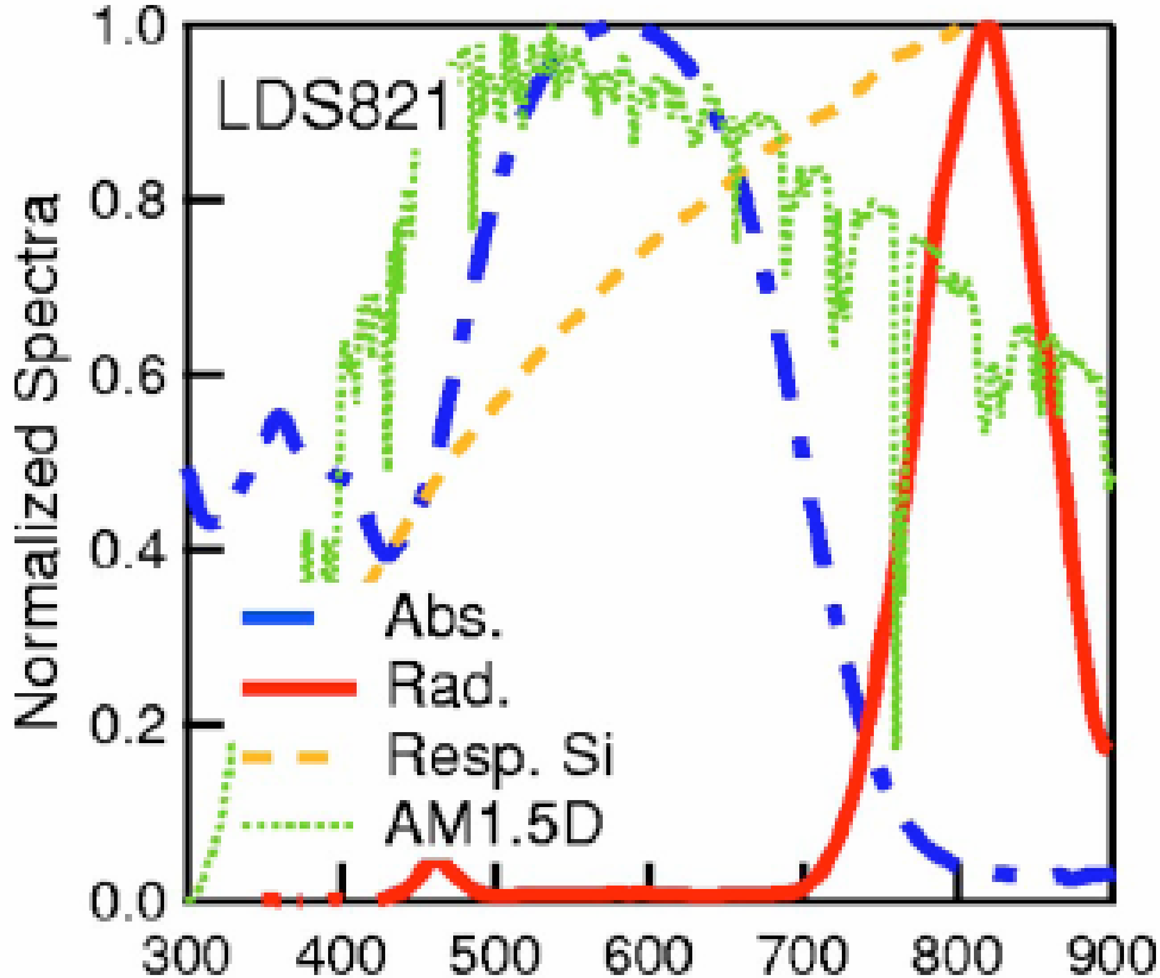
- ☆ Efficiency of 4% for 50cm LSC
- ☆ With LQE of 80%
- ☆ 30% more photons emitted from each edge of the LSC compared to a similar Red 305 doped LSC

New Approaches: Conjugated Polymer LSC

☆ Conjugated polymers have intrinsically large Stokes shifts leading to lower reabsorption losses

New collaboration with Martin Heeney's group in the Department of Chemistry

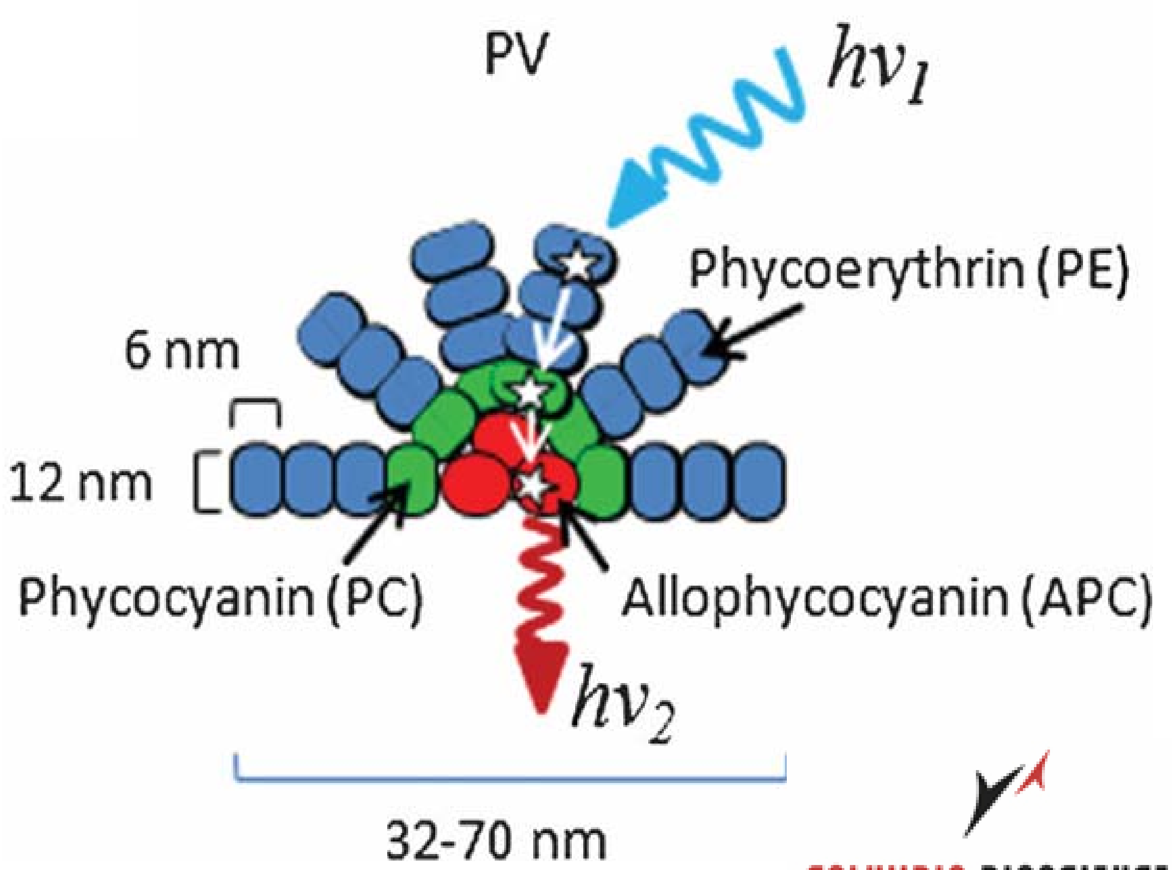
Conjugated polymers may also be aligned by deposition on rubbed substrates ➡ potential for beneficial directional emission



Further advantage if want to utilise energy transfer - distance dependence $\sim r^4$ rather than the usual $\sim r^6$

New Approaches: Phyco-LSC

- Phycobilisomes are antennae proteins from algae that absorb blue-green light and emit red and exhibit efficient FRET

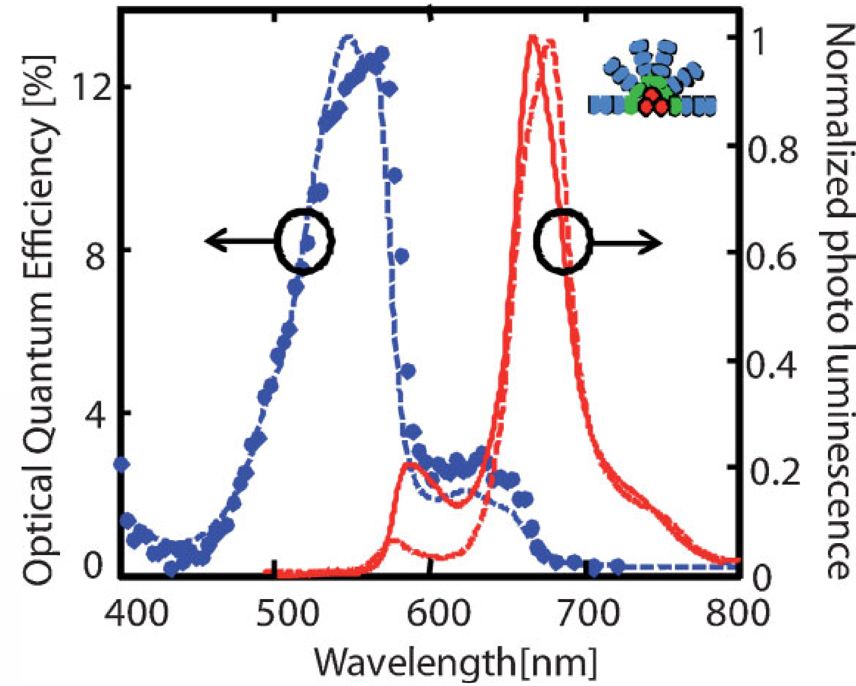


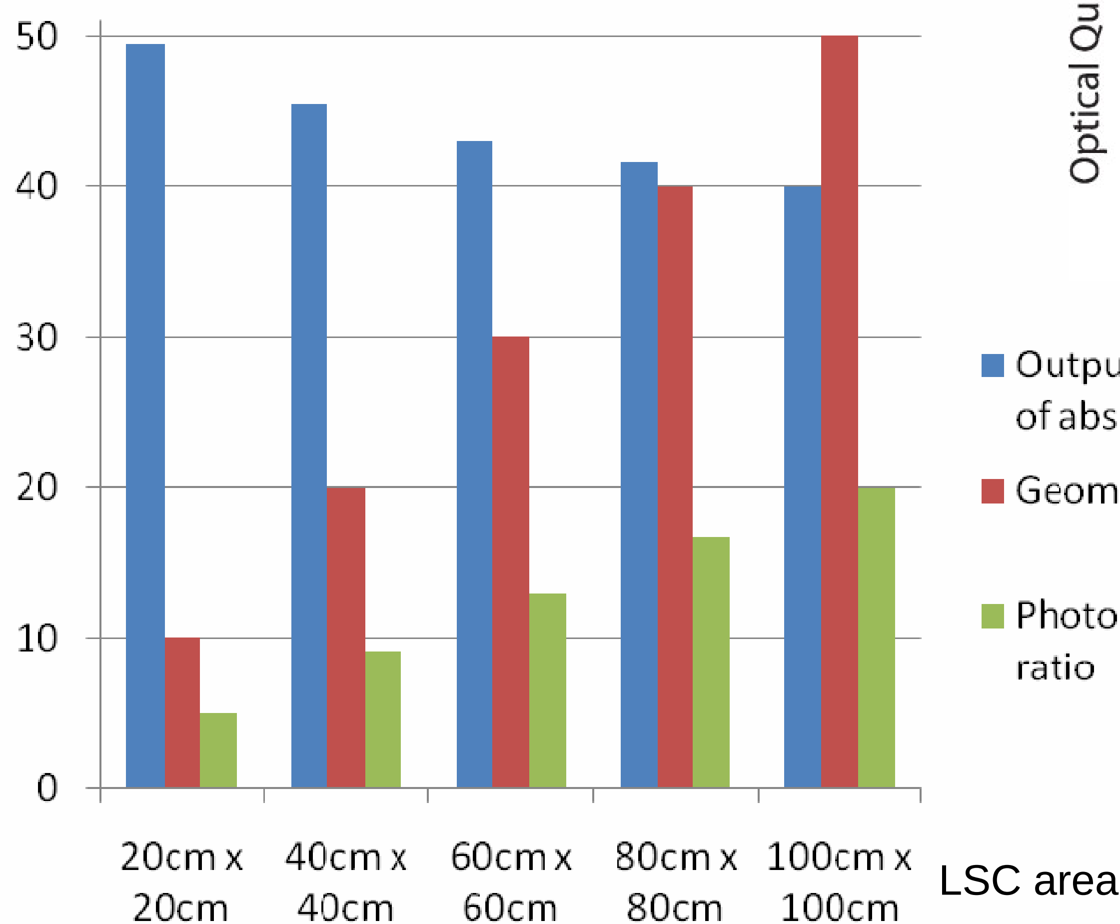
COLUMBIA BIOSCIENCES

Rob Walters NRL

New Approaches: Phyco-LSC

- Large Stokes shift
- 95% Q_e



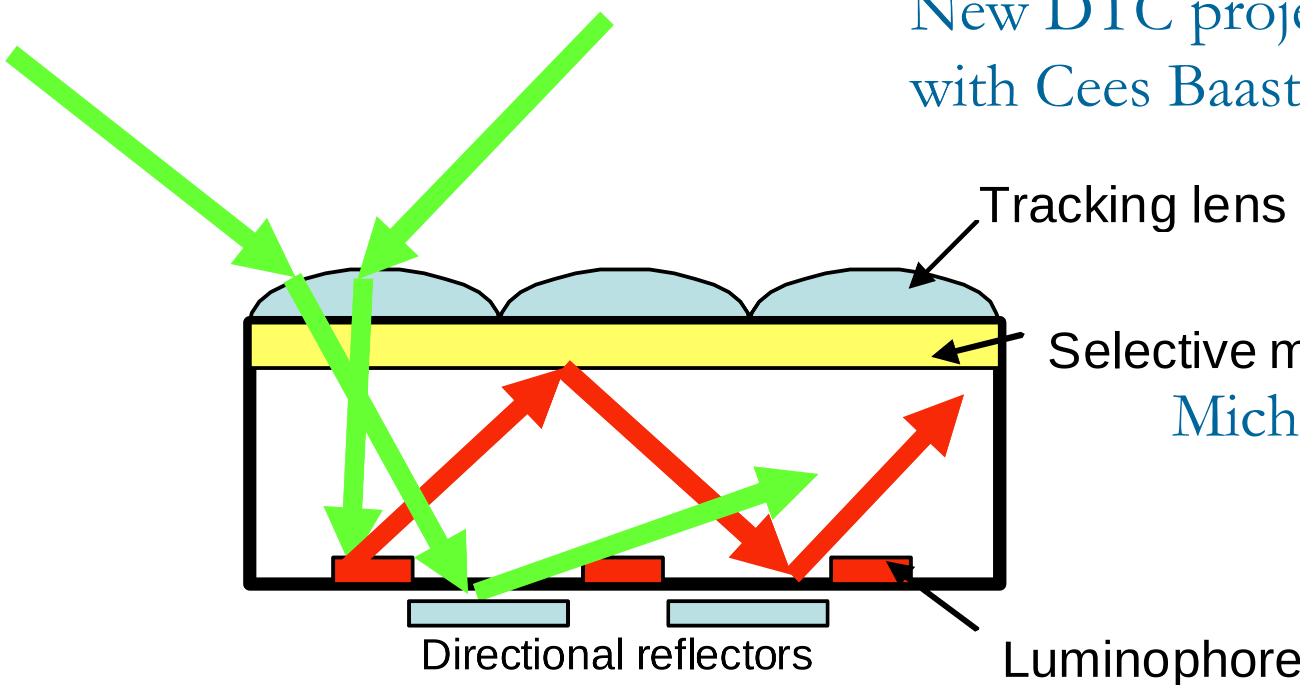


Preliminary raytrace simulations of a 5mm thick phyco-LSC

New Approaches: Advanced Optical Designs

- ☆ Patterned luminescent films should dramatically reduce reabsorption losses
- ☆ BUT require lenses to focus the light onto islands so only direct light can be efficiently harvested

- ☆ Combine with nano-optical elements for optimal light management

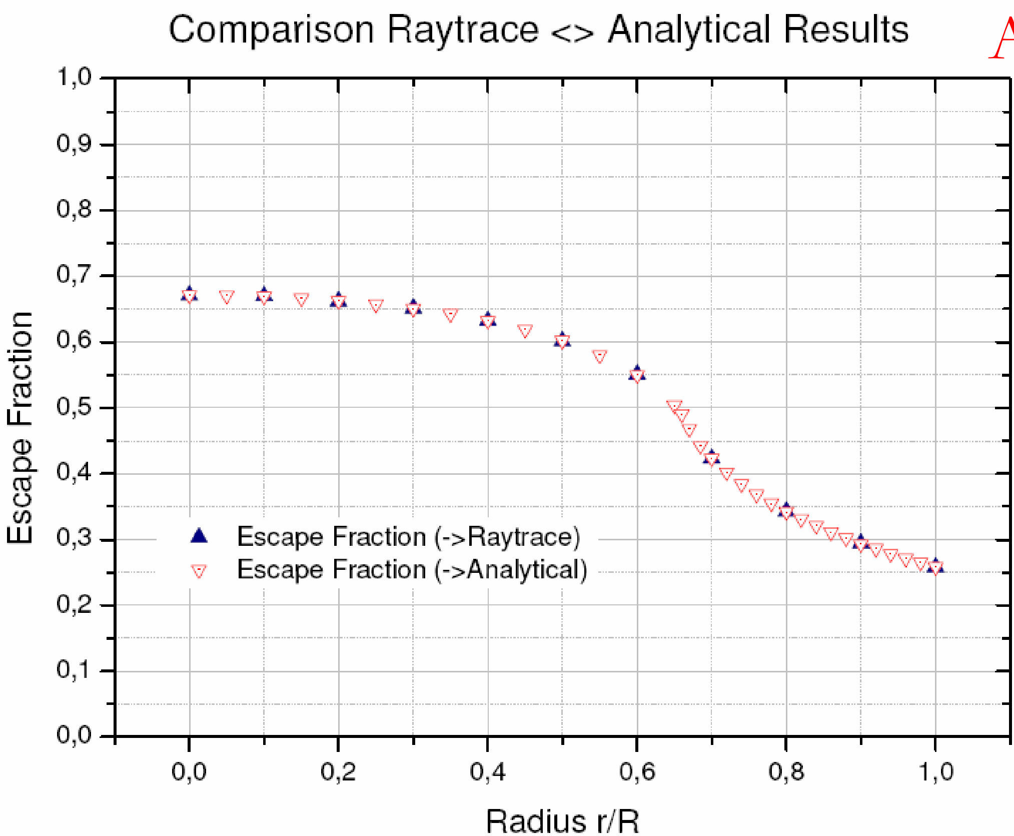


New DTC project in collaboration with Cees Baastiaansen

QMU and TUE

Michael Debije

New Approaches: Cylindrical LSCs

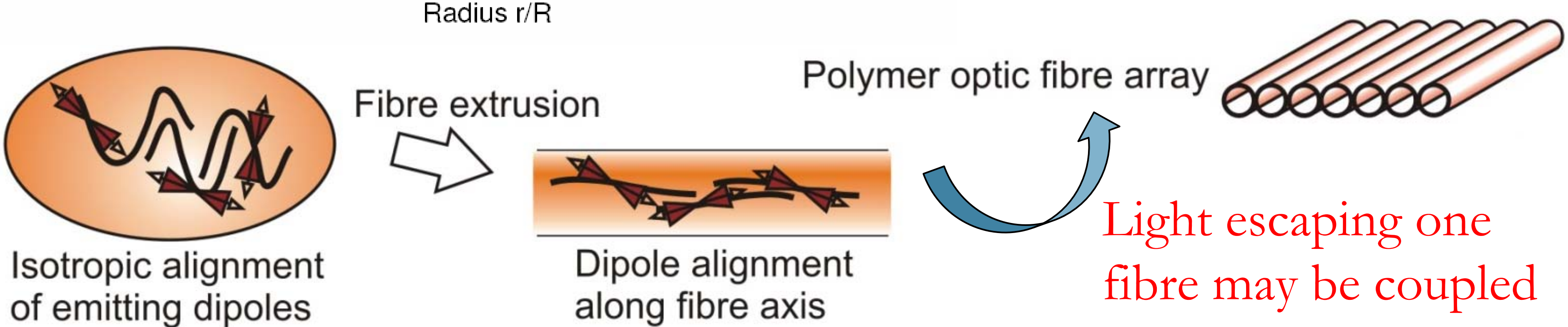


Al Buckley University of Sheffield

- In a cylinder escaping probability is position dependent

- Approaches the ~25% for a planar LSC when emission is near the surface

BUT



Light escaping one fibre may be coupled into neighbours

Aligned dipole emit preferentially into guided modes

SolarStructure Concept

• In the UK – over **60%** electricity used **in buildings**

Power Generating Windows

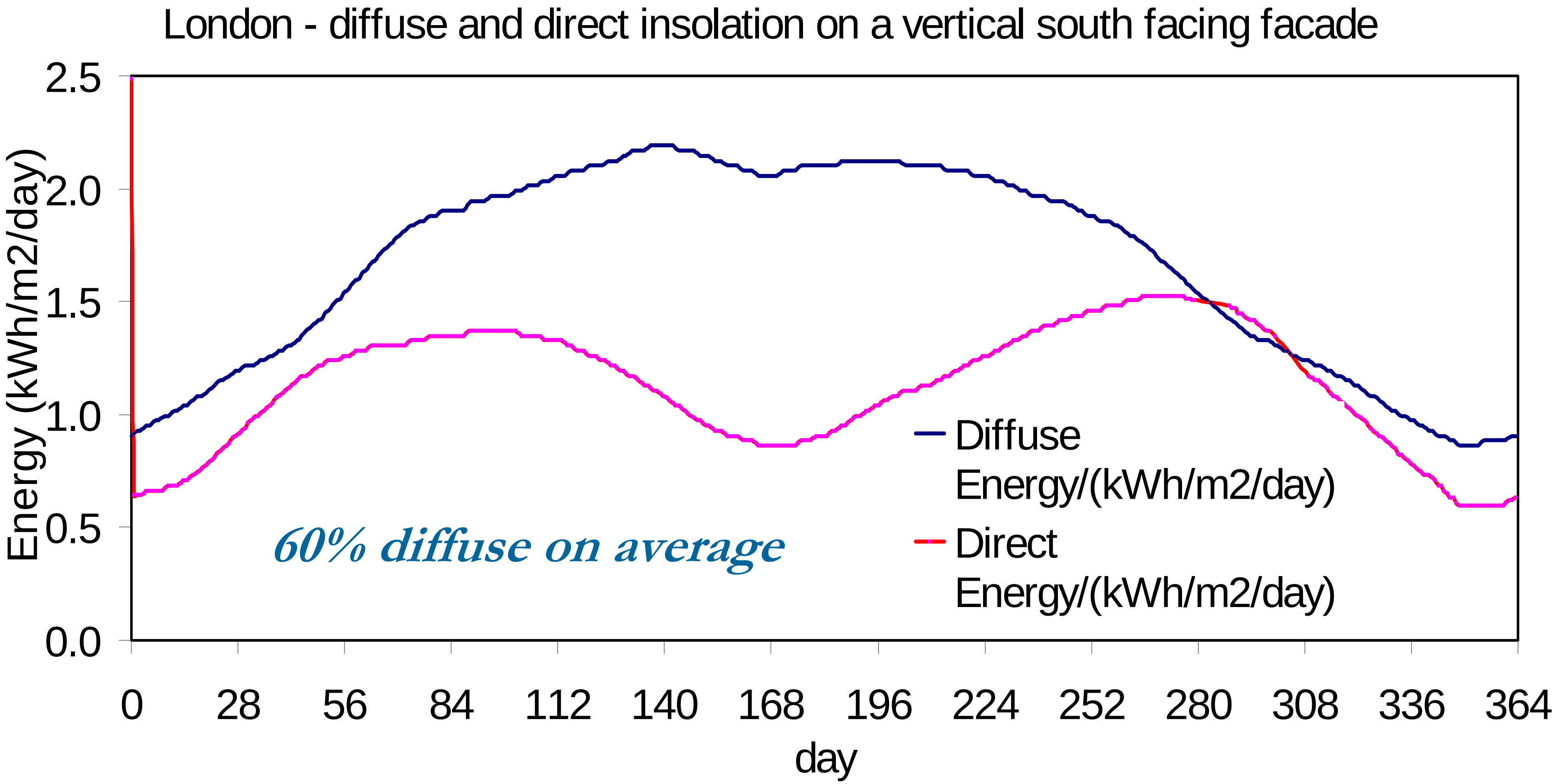
- No transmission of direct sunlight
- Reduce glare and a/c requirement
- Max diffuse sunlight - for illumination
- No need for lights when blinds working
- (2 – 3)× power from Silicon BIPV
- Electricity at time of peak demand
- Cell cooling in frame - hot water

Barnham, Mazzer, Clive, *Nature Materials*, **5**, (2006), p161

Solar Insolation in London

☆ **Solar insolation model** by Massimo Mazzer

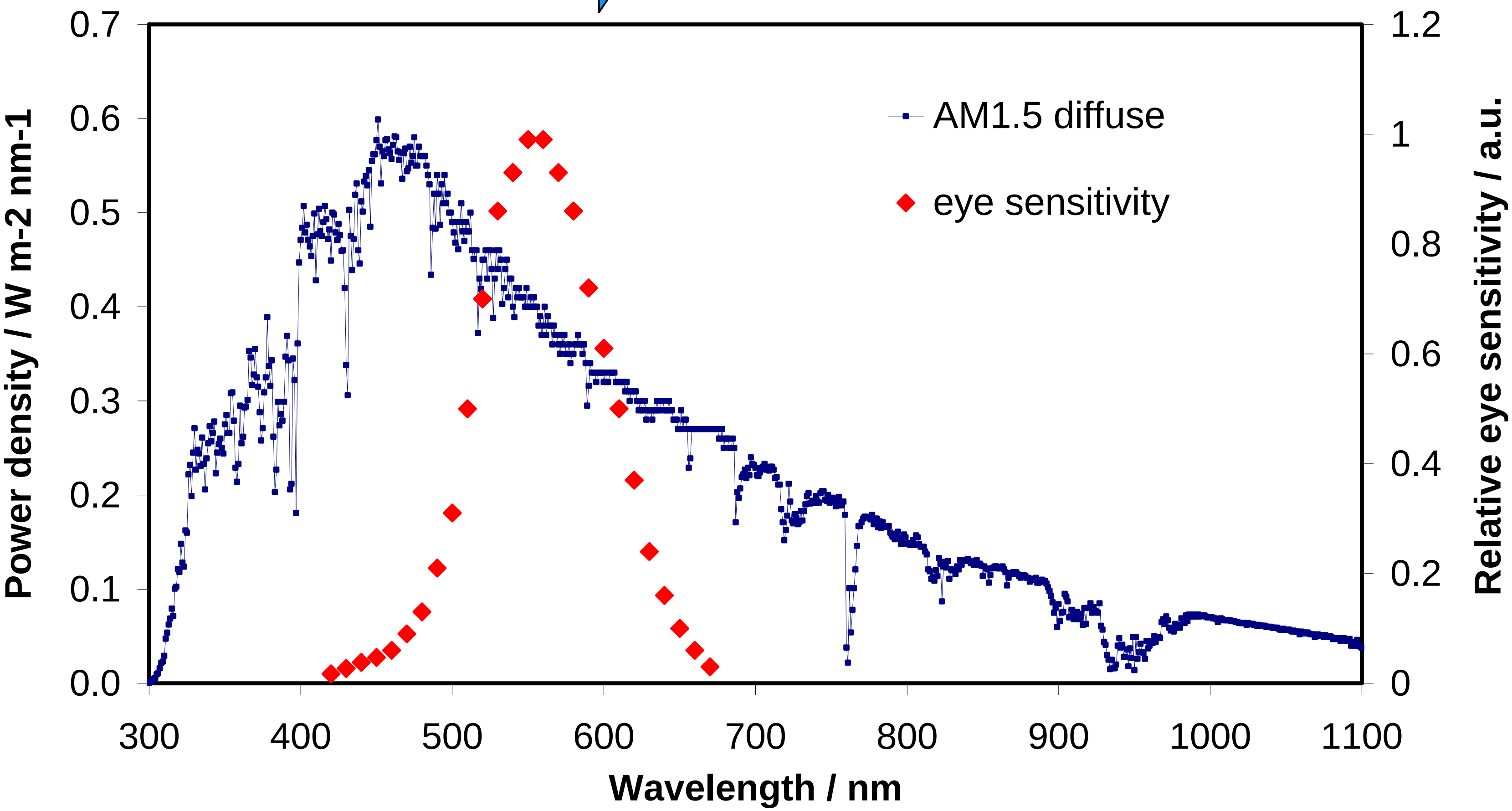
Standard NREL insolation software BIRD used to provide the daily and yearly solar insolation with appropriate parameters for aerosol absorption and humidity from a NASA database.



Blue Sky Window

☆ The highest building integrated photovoltaic power generation density will therefore be achieved by making optimal use of both the diffuse and direct components of sunlight

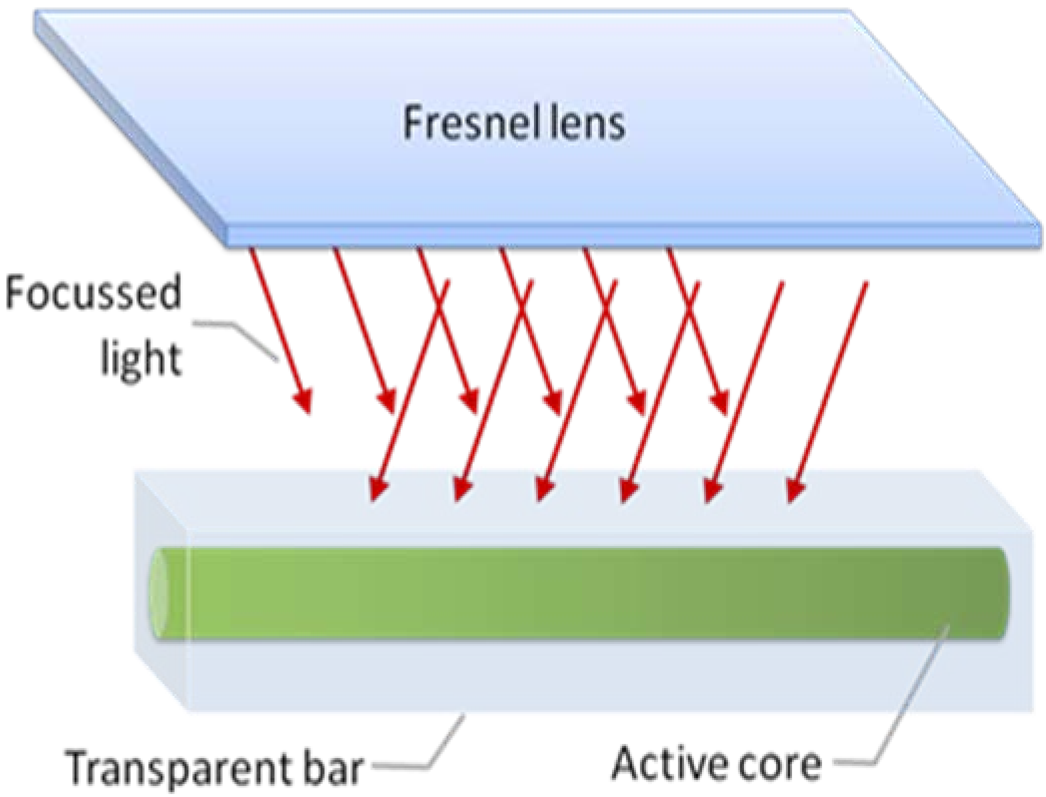
☆ The high concentration tracker blind described above only harvests the direct sunlight ➡ **Add a "transparent" LSC**



Initial Lightbar Simulations

The aim of the composite lightbar is to reduce re-absorptions and associated losses between the point of light absorption and emission out of the ends

To quantify potential benefits



- Incident spectrum: AM 1.5d
- Doping density scaled to give identical absorption in both homogeneous and composite bars
- Light at normal incidence over diameter of core (composite) / width of bar (homogeneous)
- Length of bar: 1m

1cm bar with 0.5mm core: 32% of absorbed light emitted from the ends

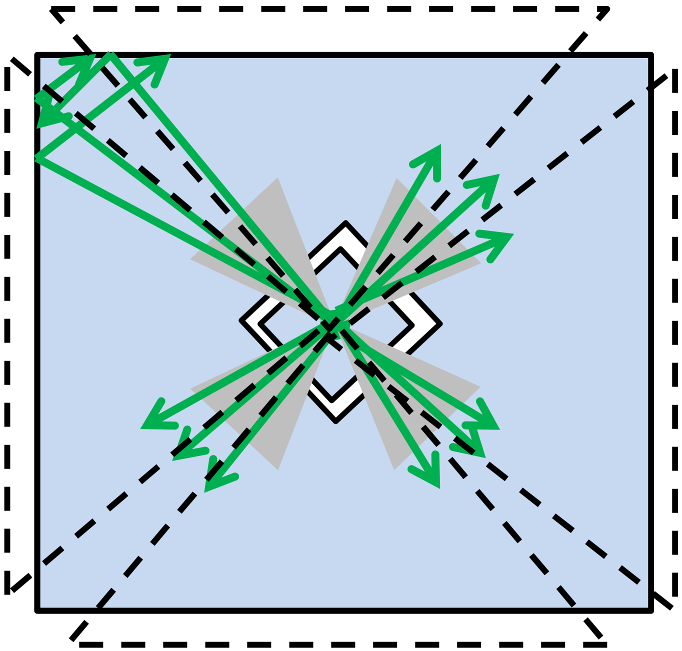
Homogeneous: 25% of absorbed light emitted from the ends

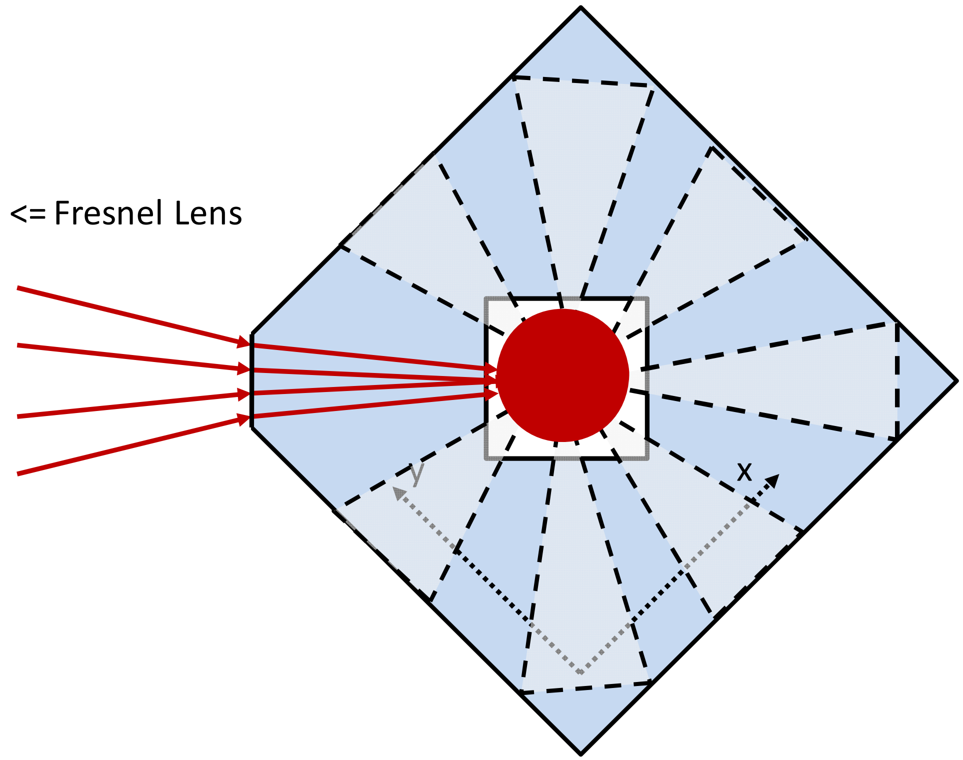
➡ Composite 30% better with half as many reabsorption events!

Advanced Lightbar Designs

Carl Poelking

How do we manage to inject photons into trapped modes?





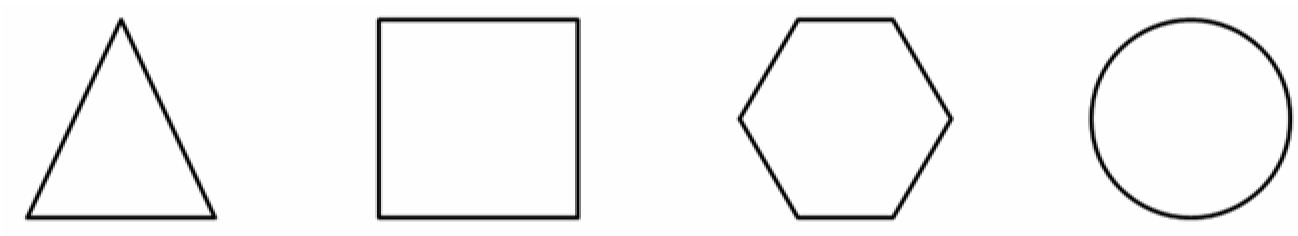
Injection mostly into trapped modes?

To allow light in-coupling

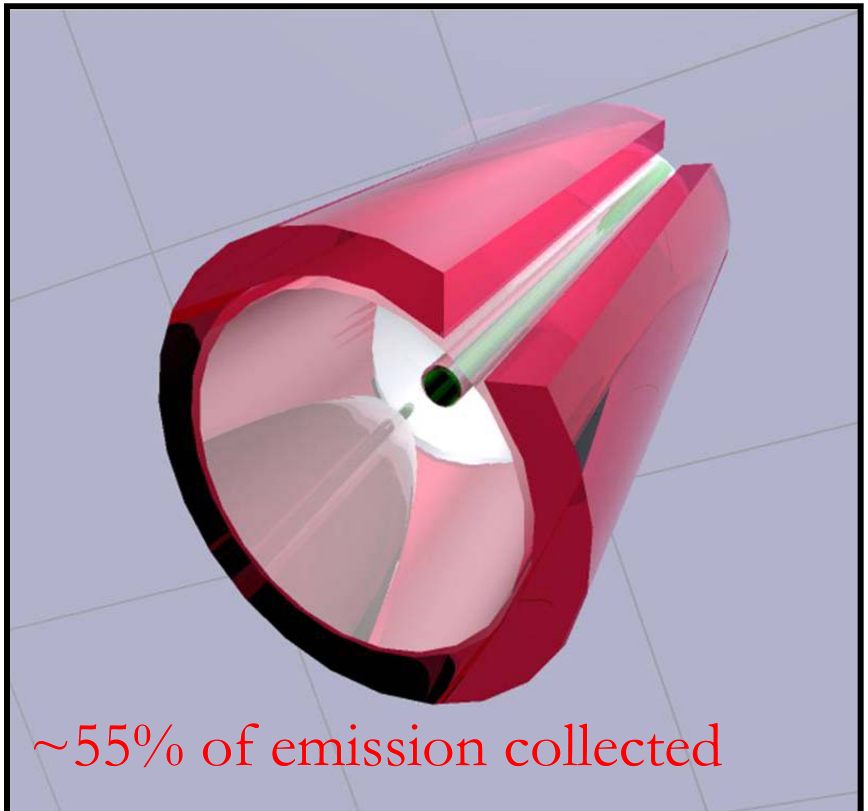
Looks excellent in 2D but in 3D find ~45% of emitted photons collected

Advanced Lightbar Designs

better waveguiding



better trapping (on 1st emission)



- subcylinder doped with dye A
- located as close as possible to the barrel of the parent cylinder
- undoped parent cylinder waveguide
- trenched cylinder shell doped with dye B
- emission of dye A matched to absorption of dye B

Conclusions

- ☆ Developed self-consistent 3D thermodynamic models and ray-trace models of the LSC
- ☆ Results show that the models can predict the luminescence and total flux escaping each surface providing tools for optimisation of the LSC
- ☆ Currently the highest efficiency LSC is organic dye doped but new materials have advantages
  - tunability
  - stability
  - reabsorption
  - potential for directed emission
- ☆ New architectures and advanced optical designs provide the potential for PCE > 10%
- ☆ Combination of LSC and high concentration technologies provides the potential for sustainable buildings