Another Semiconductor Revolution: This Time It's Lighting!

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Invited Plenary Presentation
Spring Meeting of the German Physical Society
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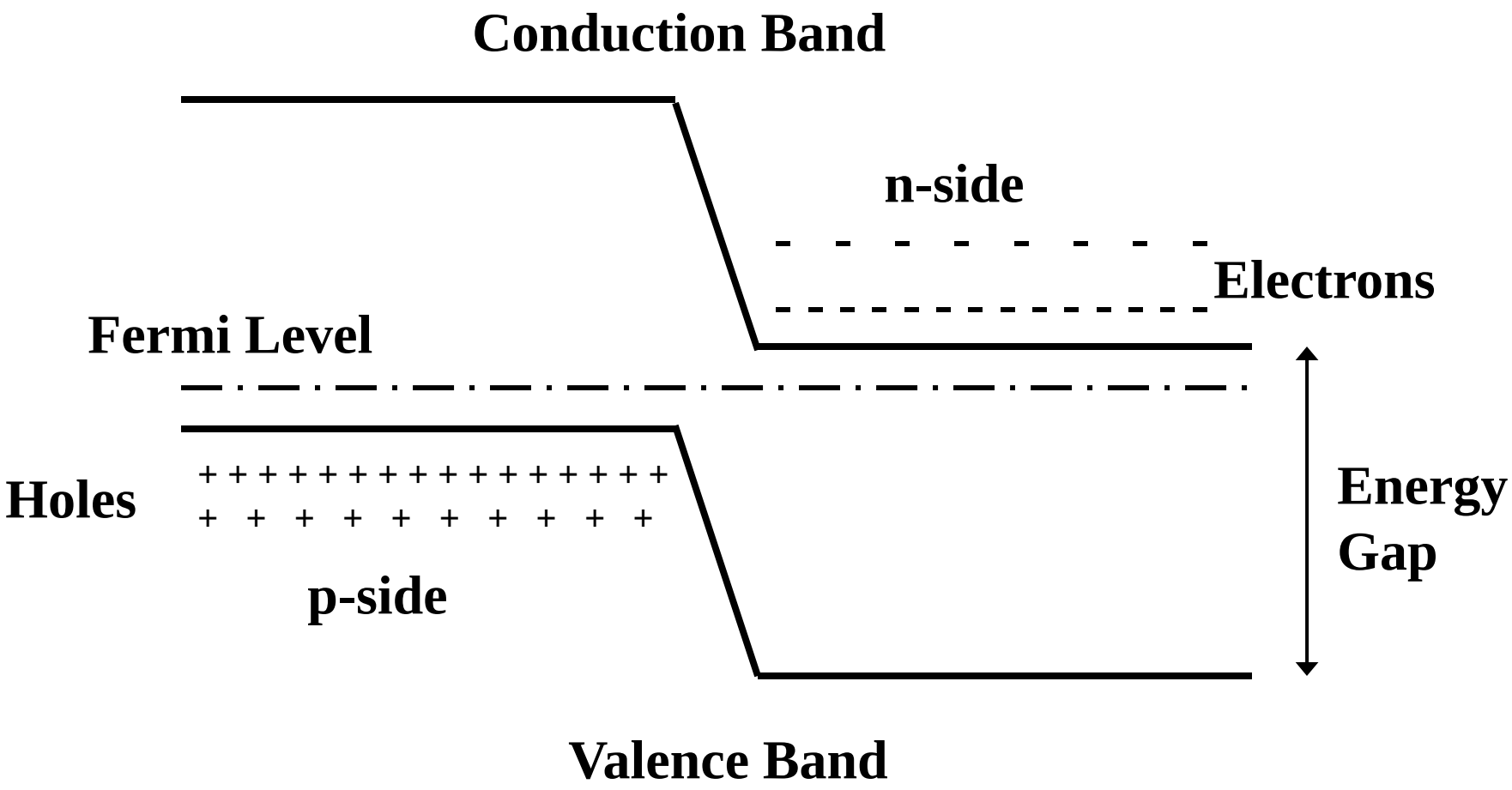
Agenda

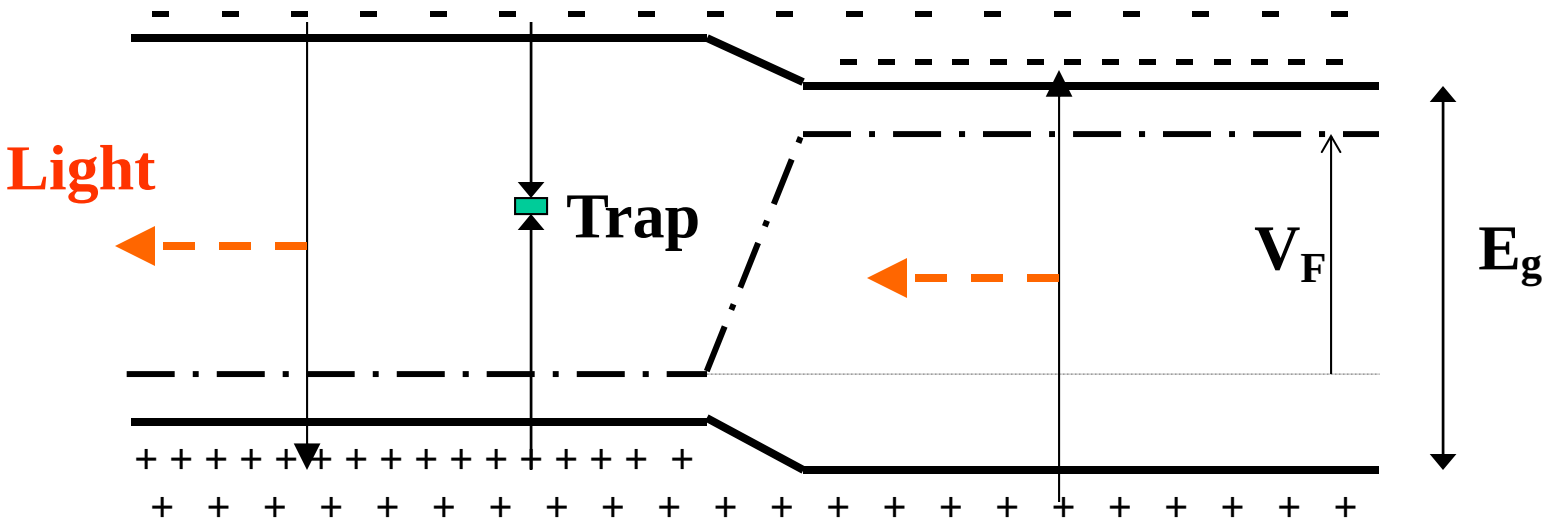
Physics of LED Light Generation
Brief LED History
Current Performance
Vision for Next Two Decades

- **Impact on Lighting Industry**
- **Energy Savings**
- **Environment**

We must accelerate this revolution!



pn Junction at Zero Bias



Electron-Hole Recombination

pn Junction at Bias V_F

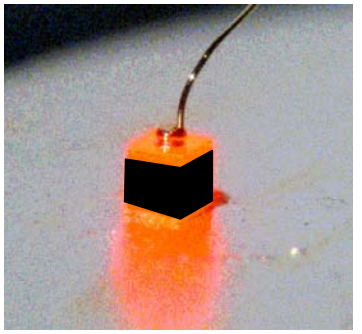
Quantum Efficiency of LEDs

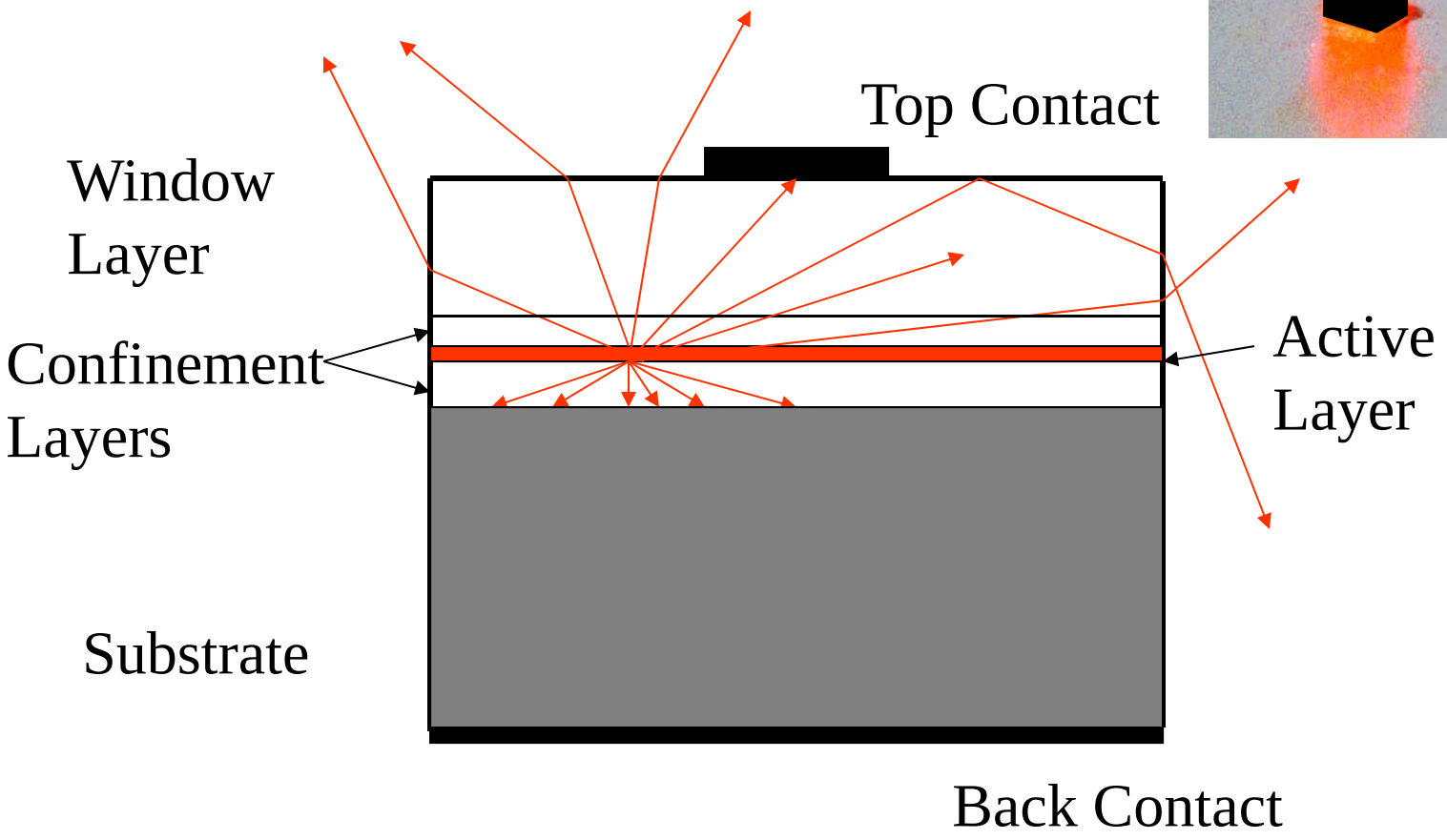
Internal Quantum Efficiency

$$\tau_{int} = \tau_n/(\tau_n + \tau_r)$$

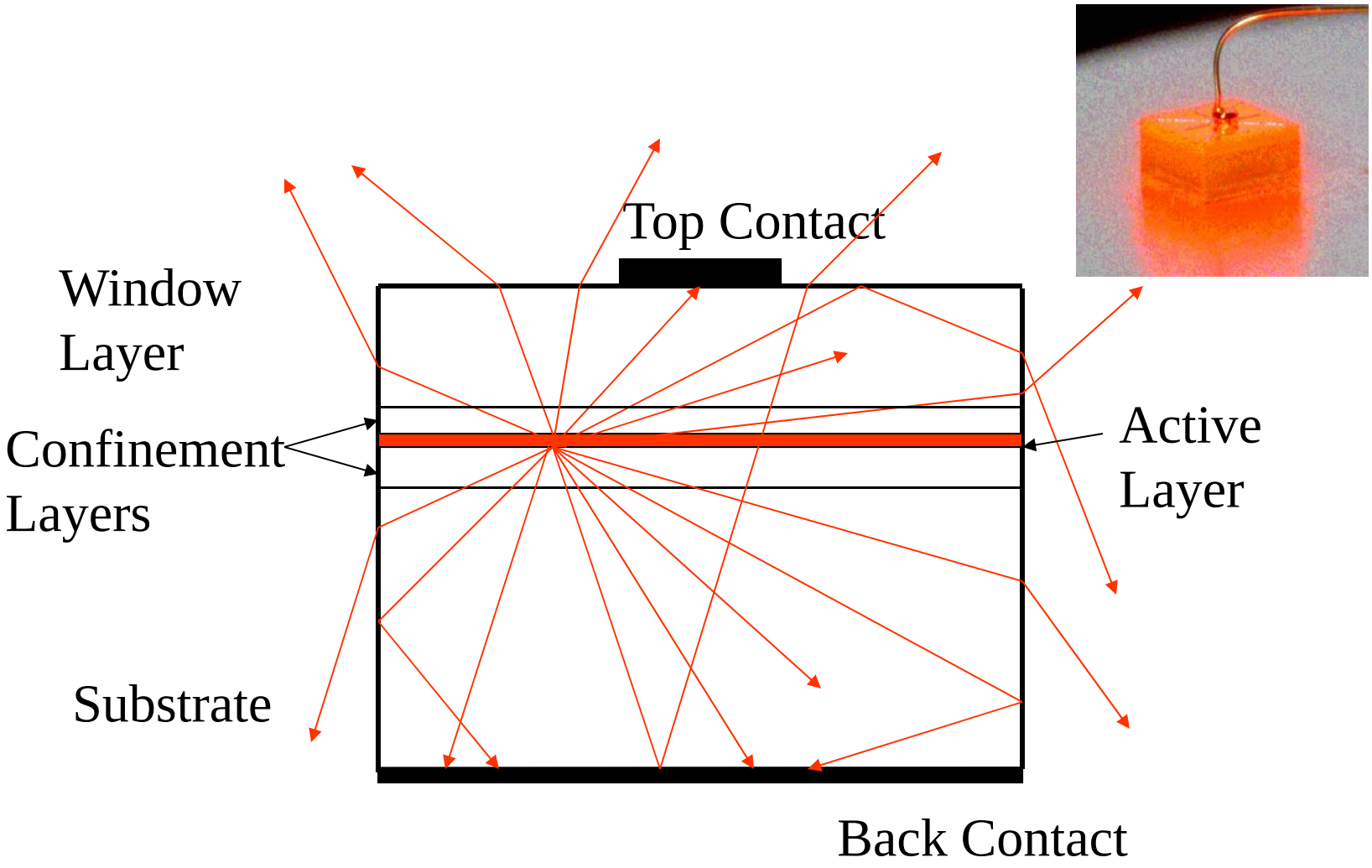
External Quantum Efficiency

$$\tau_{ext} = \tau_{int} \bullet \tau_{extraction}$$





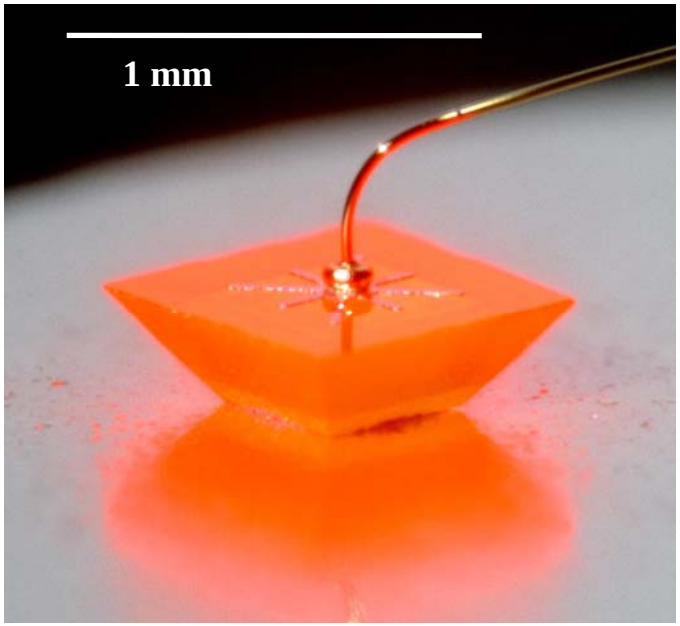
Light Extraction: Absorbing Substrate

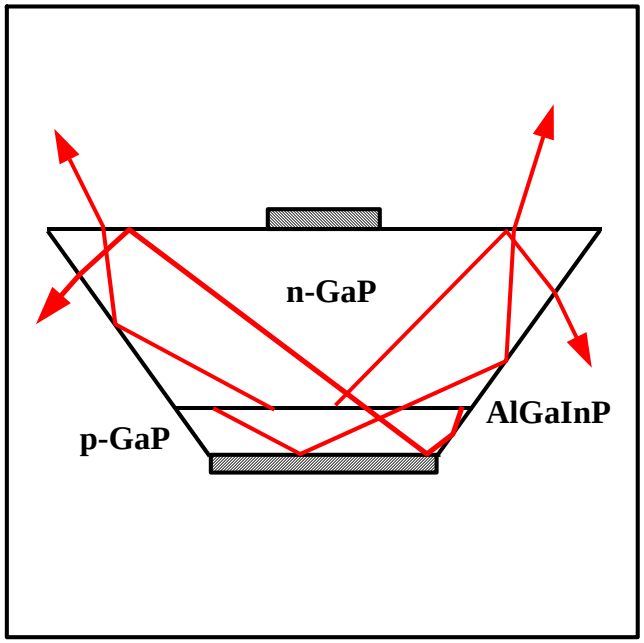


Light Extraction:Transparent Substrate

High-Power TS AlGaInP LEDs

AlGaInP/GaP Truncated-Inverted-Pyramid (TIP) LED





Lighting Efficacy for LEDs

Luminous Efficacy (lm/W)

$$\eta_{lum} = 683 \bullet R_{eye} \bullet \tau_{int} \bullet \tau_{extraction}$$

Lighting Efficacy (lm/W)

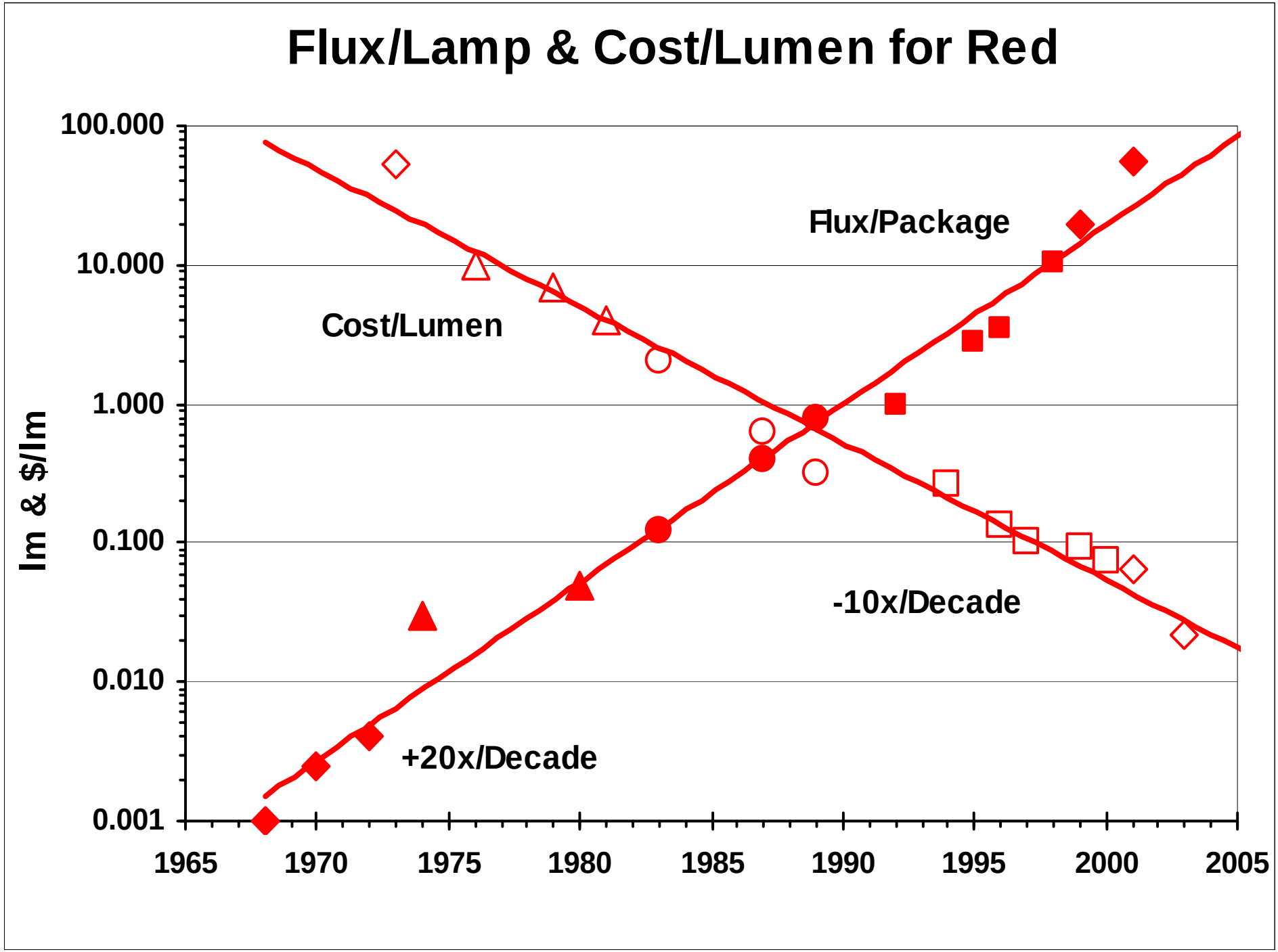
$$\eta_{lighting} = \eta_{lum} \bullet \eta_{distribution}$$

Distribution Efficiency

LED lamps are a cold point source:

- **Close proximity reflectors**
- **Close proximity lenses**
- **Superior beam control**
- **Compact design**

LED lamps save 20-50% in light distribution!

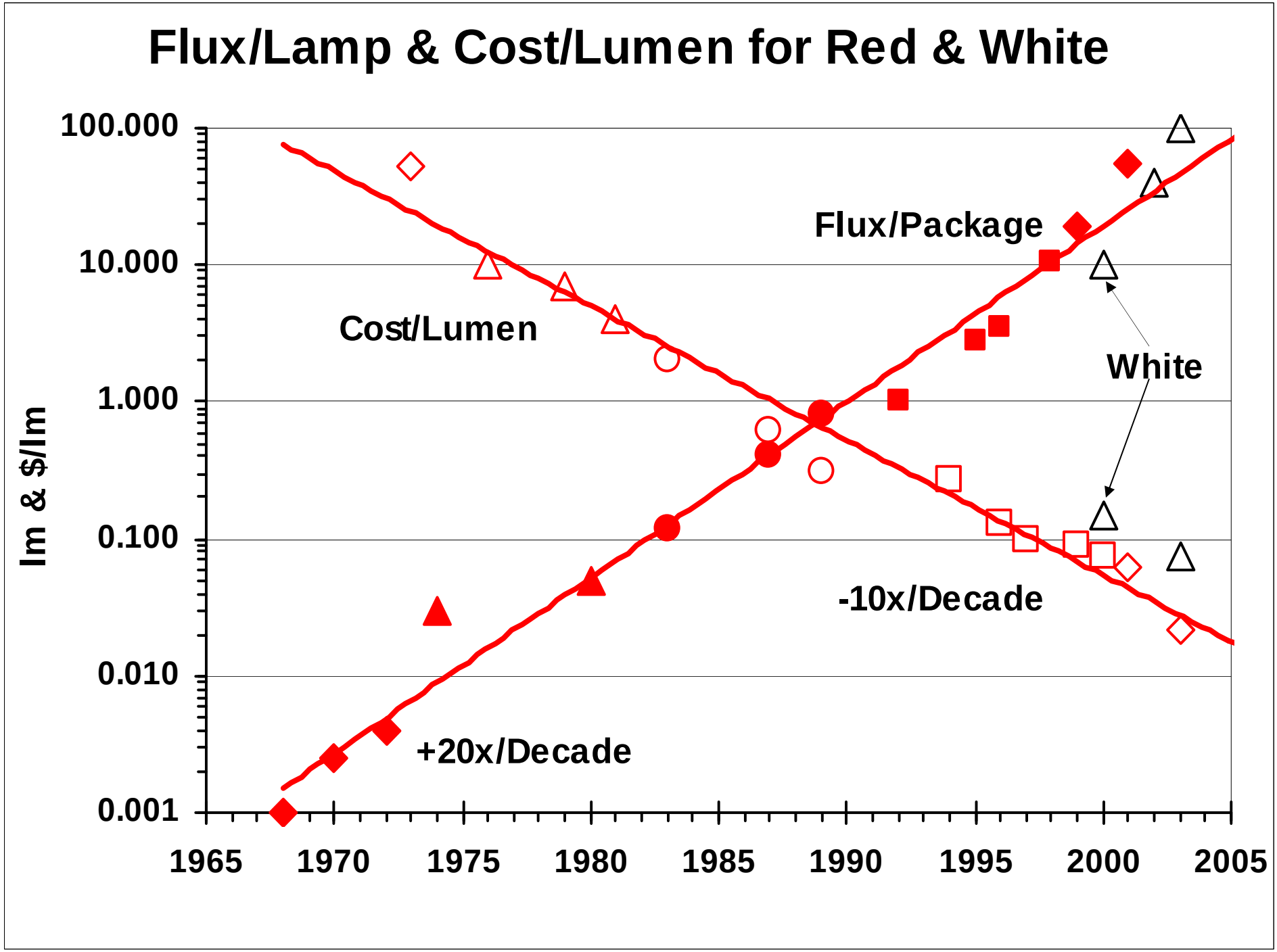

Flux/Lamp & Cost/Lumen for Red
100.000
10.000
1.000
0.100
0.010
0.001
lm & $/lm
1965
1970
1975
1980
1985
1990
1995
2000
2005
Flux/Package
Cost/Lumen
-10x/Decade
+20x/Decade

Significance of Red Data to White Performance

Eye Sensitivity:

- **Red at 625nm** **0.35**
- **Green at 525nm** **0.85**
- **Blue at 665nm** **0.09**

Conclusion: Red ≈ White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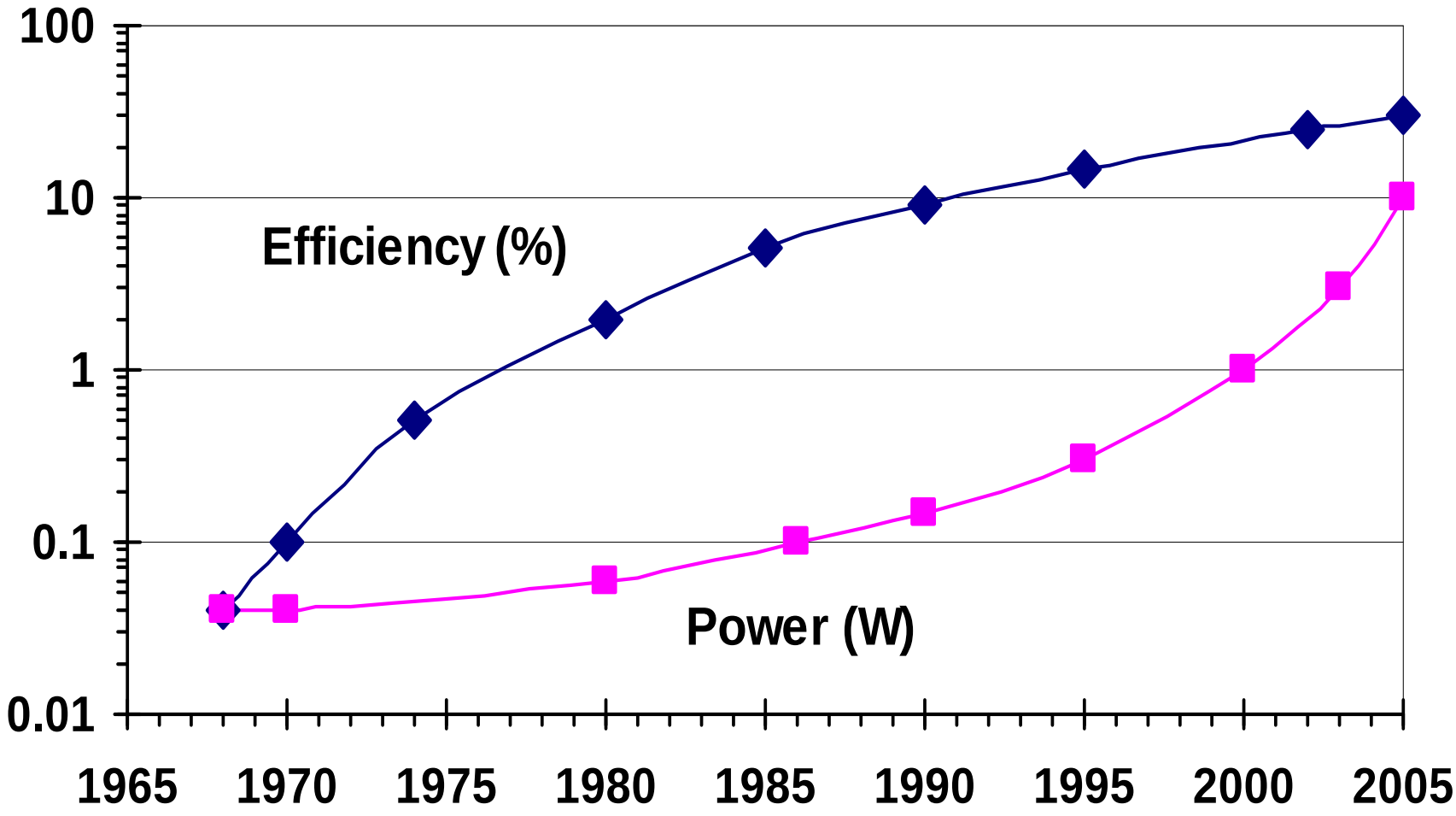
Approx. Contribution to Red Flux

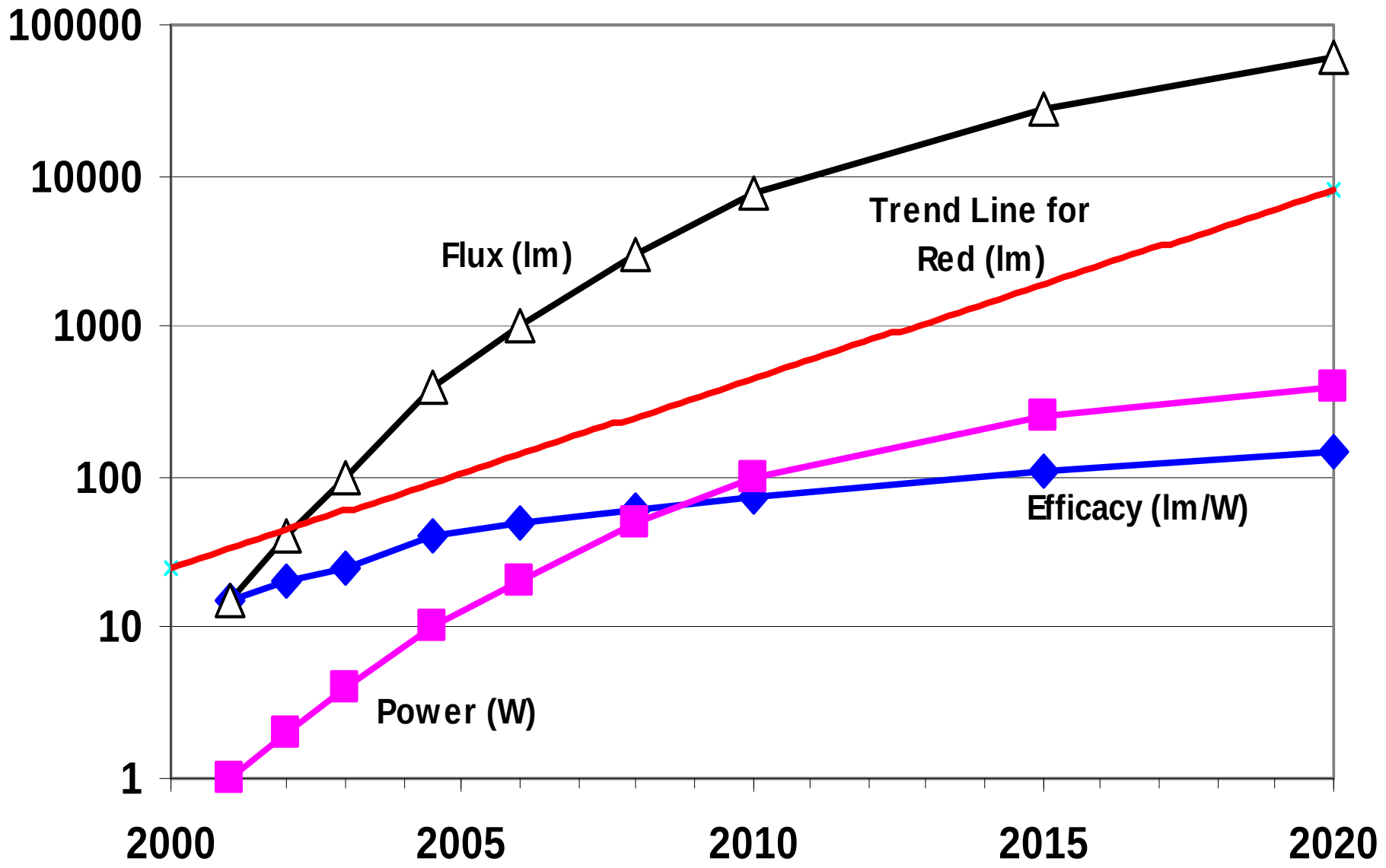


2005-25 Performance

Analogies to Moore's Law:

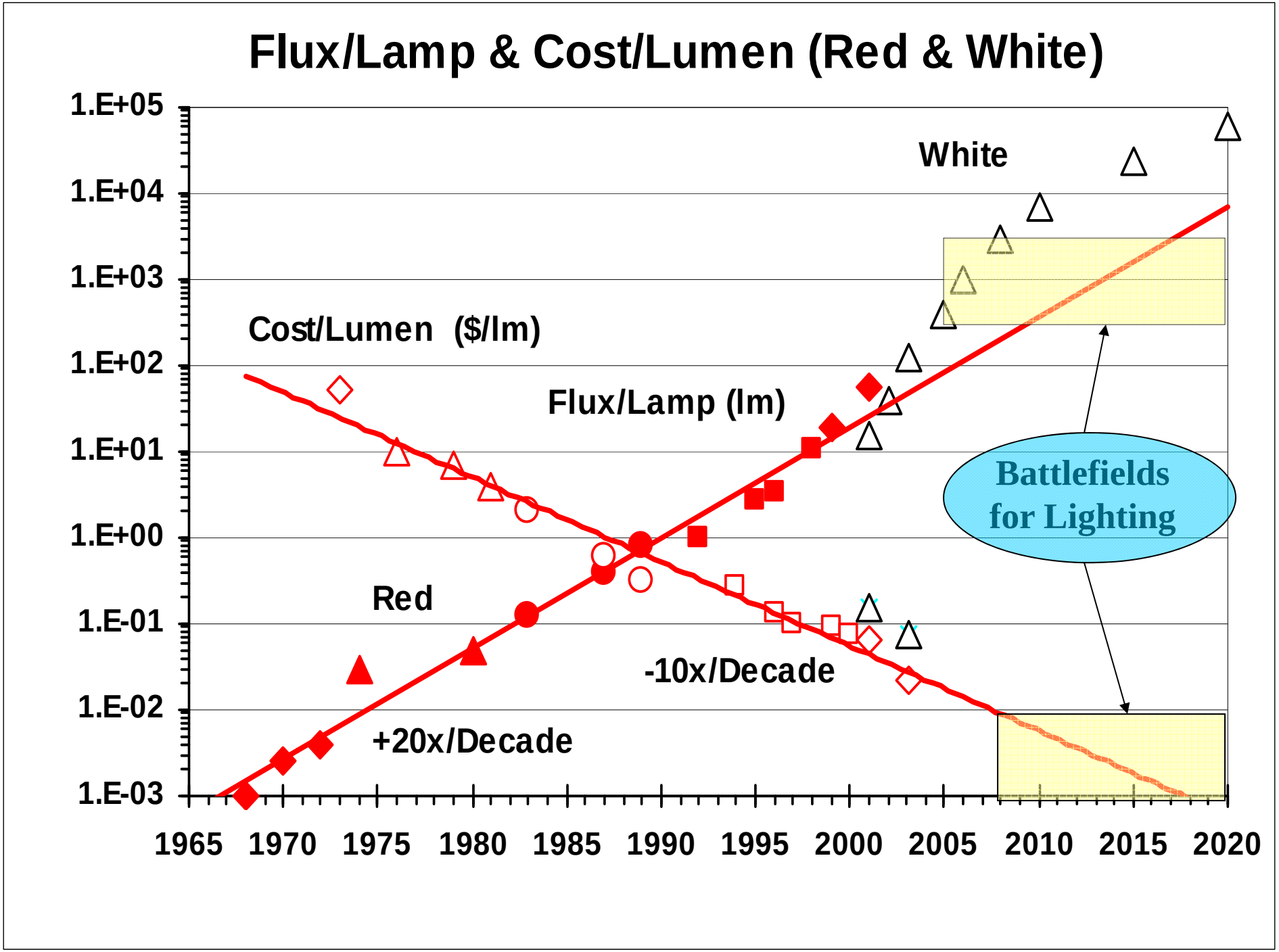
- **How long will the trend continue?**
- **What are the technology drivers?**
- **Where is the "Brick Wall"?**

White LED Performance Projection



Preliminary Conclusions

- **Efficacy will saturate at 150-250 lm/W (Physics)**
- **Input power will saturate at 200-500W (Market)**
- **Lamp flux will top out at 30-100klm/lamp**


Flux/Lamp & Cost/Lumen (Red & White)
1.E+05
1.E+04
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-02
1.E-03
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
2020
White
Cost/Lumen ($/lm)
Flux/Lamp (lm)
Battlefields for Lighting
Red
-10x/Decade
+20x/Decade

Vision

By 2015, LEDs will have a dynamic range from 0.1mlm to 10Mlm

LEDs will attack all lighting applications on the surface of the earth from the dimmest indicators to sports stadiums with:

- Superior color control
- Large dimming range without loss of efficiency
- Lowest power consumption
- Compact design
- Long lamp life
- Competitive life system costs everywhere!

There will be a couple of exceptions!

Exceptions

- **Fireflies:** **Low weight and un-tethered mobility**
- **Lightning:** **Spectacular display, for free**
- **Sun:** **Lots of light at zero cost**

Energy Savings

US Consumption for Lighting	**60GW**
Incand./Halogen @ 15 lm/W	**24GW**
FL & HID @ 75 lm/W	**36GW**
Max. potential Savings @ 150 lm/W	**40GW**

Carbon Emission Savings

(USA only)

Conversion Ratio:

1GW ≅ 4Mt of coal/year

Max. Coal Reduction:

40GW ≅ 160Mt of coal/year

20% of US Coal Production!

Why Government Support?

The benefit/risk ratio is unfairly distributed:

	Benefit	**Risk**
Consumer	**60%**	**10%**
Economy	**15%**	**5%**
Environment	**15%**	**5%**
LED Industry	**10%**	**80%**

The consumer receives most of the benefits and the LED industry carries most of the risk!

Taxpayer’s Payback

US Government Investment = 500M$ over 10 Years

US Consumer Savings Potential = 40B$/Year in 25 Years

Probability of Success = Extremely High (>90%)

This is an offer the taxpayer cannot afford to refuse!

For Europe, the numbers are lower but still compelling!

Perspective

History of Lighting

- **Campfire**
- **Torch**
- **Candle**
- **Oil Lamp**
- **Gas Light**
- **Incandescent Lamp**
- **Misc. Discharge Lamps**
- **LED Lamps**

I predict that semiconductor lamps will be the dominant lighting technology for the current millennium!

I am too old to be proven wrong within my life time!

Summary

A revolution in lighting will happen during the early part of the 21st century!

How much are we willing to accelerate this revolution?

The results will be worth the disruptions and early costs!