

# **Advanced Photodetection Concepts**

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**Work supported by National Nuclear Security  
Administration (NNSA), Office of Nonproliferation  
Research and Engineering, DOE, and**

**two Advanced Detector Awards, Office of Science, DOE**

# Very rare and/or weak radiation phenomena

- **Nuclear Nonproliferation and Homeland Security**
- **Proton Decay**
- **Neutrino Physics**
- **Geo-neutrino Physics**
- **Neutrino Astrophysics**
- **Gamma-ray Astronomy**  
(low detection threshold + wide acceptance angle)
- **Ultra-high energy cosmic rays ( $>10^{19}$  eV)**
- **Neutrinoless Double Beta Decay (e.g. SuperNemo)**
- **Dark Matter Search**

# DETECTION OF NUCLEAR MATERIALS

## VIA RADIATION

**INTRINSIC (n,  $\gamma$ ,  $\nu$ )**

**- HE Uranium**

**- 'Any-Grade' Plutonium**

**Weak radiation**

**INDUCED ( $\gamma$ )**

**NEUTRON ACTIVATION**

**Limited to low (harmless)**

**doses**

**DETECTION SYSTEMS**

**→ VERY LARGE  
(EMBEDDING)**

**Every bit of  
radiation is  
PRECIOUS**



**REQUIREMENTS ON  
NUCLEAR DETECTION SYSTEMS**  
(containers, vehicles etc.)

**→ VERY LARGE AREA**  
(EMBEDDING the OBJECT)

**→ MANY DETECTORS**  
(COMPREHENSIVE)

- INDUSTRIALLY MASS-PRODUCED**
- INEXPENSIVE**
- ROBUST and RELIABLE**
- EASILY DEPLOYABLE**

# MONITOR

HOMELAND DEFENSE & SECURITY

Homeland Security ♦ Defense ♦ Energy ♦ State

Anti-Terrorism, Counterterrorism, First Response, Force Protection & Physical Security Technologies

Volume 8 No. 14

July 17, 2006

— INSIDE HIGHLIGHTS —

|   |    |
|---|----|
| The Senate unanimously passed the FY07 Homeland Security Appropriations bill July 13 amid a torrent of criticism from lawmakers of the management of the Dept. of Homeland Security, its prioritization of problems and the lack of overall preparedness. . . . .   | 2  |
| The Dept. of Homeland Security awarded three contracts July 14 for development of its Advanced Spectroscopic Portal to supplement current radiation portal monitors by reducing false alarm rates. . . . .  | 4  |
| Legislation introduced by House Homeland Security Committee Ranking Member Bennie Thompson (D-Miss.) June 29 to strengthen transportation security days could be brought to the top of Congress's agenda after the devastating attacks in India earlier this month. . . . .                               | 6  |
| A House Homeland Security subcommittee passed legislation July 11 to strengthen chemical facility security across the country that is generally in-line with that proposed in the Senate Homeland Security and Government Affairs Committee bill reported out last month. . . . .                         | 6  |
| Researchers at the University of California, Davis working on a prototype gamma ray detector are incorporating flat screen technology used in televisions that they believe could reduce the cost of such detectors 100-fold and enable their use in a variety of homeland security applications. . . . . | 7  |
| The Dept. of Homeland Security released guidance July 6 for nearly \$400 million in grants available in FY06 to protect critical infrastructure sites across the country, including transit systems, seaports and chemical facilities. . . . .  | 8  |
| The Dept. of Homeland Security unveiled its National Infrastructure Protection Plan June 30, outlining the roles of various government agencies, the private sector, and academia in securing key facilities within the United States. . . . .  | 9  |
| The government's Interagency Security Committee should develop and distribute guidance for ensuring facility security, as current assessments do not accurately reflect the performance of security efforts, according to a Government Accountability Office letter report released July 7. . . . .       | 9  |
| The Department of Homeland Security's National Asset Database is too large and includes several questionable facilities, the Department's Inspector General contends in a recent report, saying the faults "could lead to inefficient use of limited homeland security resources." . . . . .              | 10 |
| Despite recent technology advances in nuclear detectors, the core of the nuclear detection capabilities along U.S. borders remains in the hands of 100 volunteers at three Dept. of Energy national laboratories. . . . .   | 11 |
| <i>Perspectives</i> . . . . .   | 12 |
| <i>Wrap Up</i> . . . . .  | 13 |
| <i>Solicitations</i> . . . . .  | 14 |
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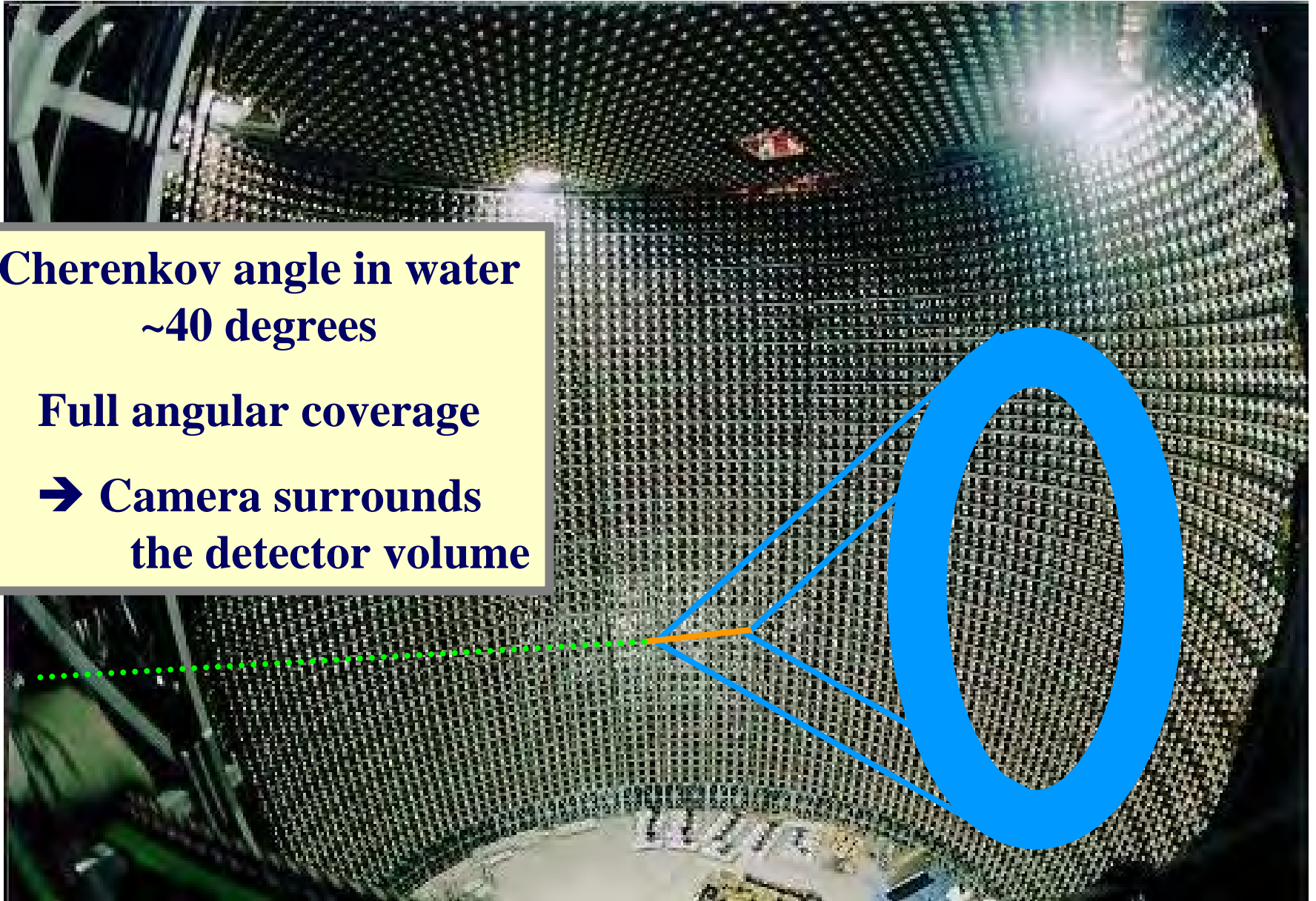
**REP. BENNIE THOMPSON (D-MISS.) ON CHEMICAL PLANT SECURITY . . . . . Pg. 12**

# The Unbeatable Reality of Mr. Liouville

**Cherenkov angle in water  
~40 degrees**

**Full angular coverage**

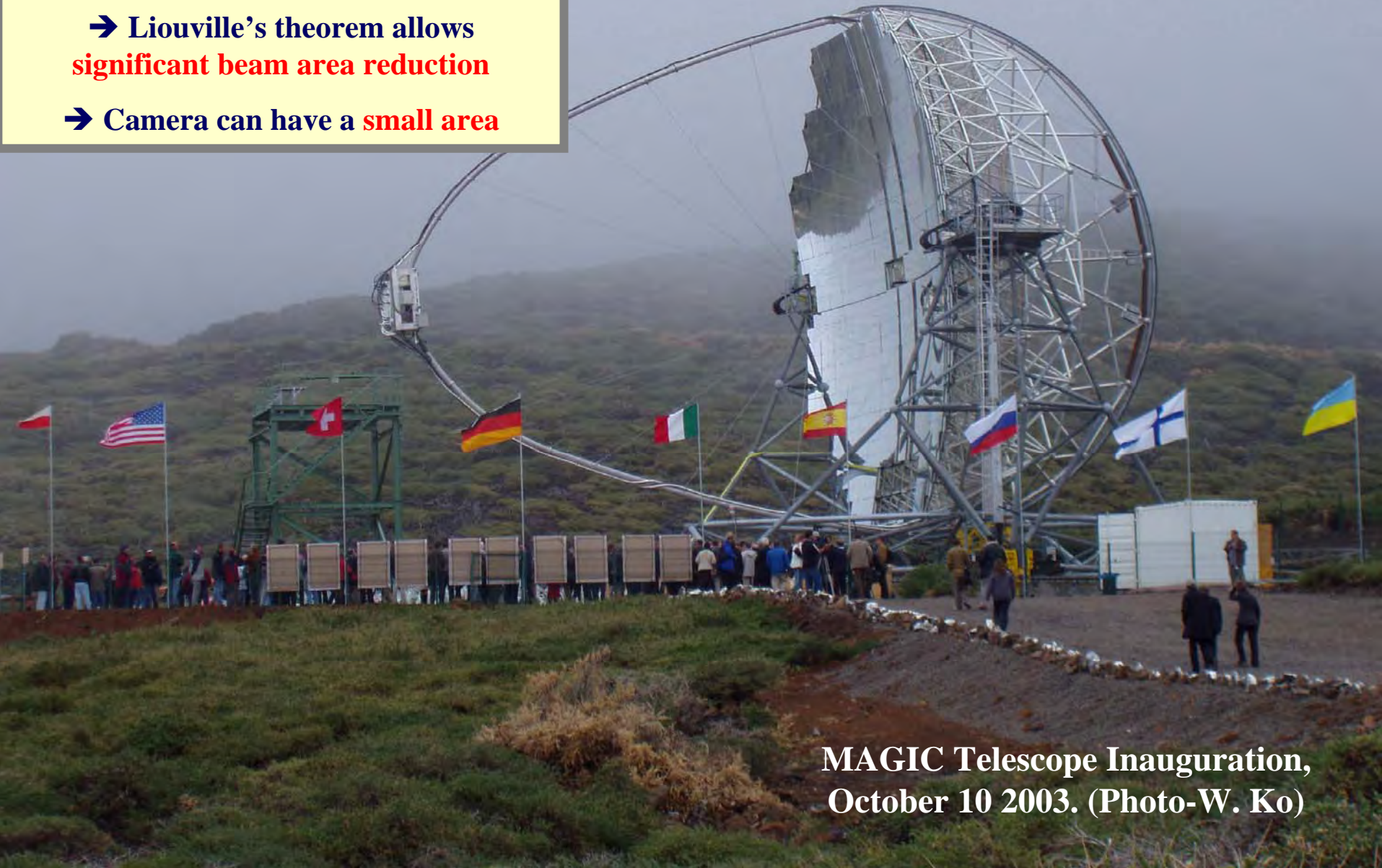
**→ Camera surrounds  
the detector volume**



**Cherenkov angle in air  $< 1$  degree, also well defined observational direction, and small angular spread in the EM shower**

**→ Liouville's theorem allows significant beam area reduction**

**→ Camera can have a small area**



**MAGIC Telescope Inauguration,  
October 10 2003. (Photo-W. Ko)**



**Irreducibly Large Illuminated Area**



**strong internal signal concentration**

**Vacuum**

**( photon → photoelectron → 'no more Liouville' )**

# WHY

- (1) THE PMT COST IS HIGH
- (2) THE QUANTITY IS LIMITED

?

**50% - DYNODE COLUMN**

**50% - GLASS BULB**

→ **HAND-MADE COMPONENTS**

→ **CLOSED CONFIGURATION**  
(a PMT is partly 'made in itself')

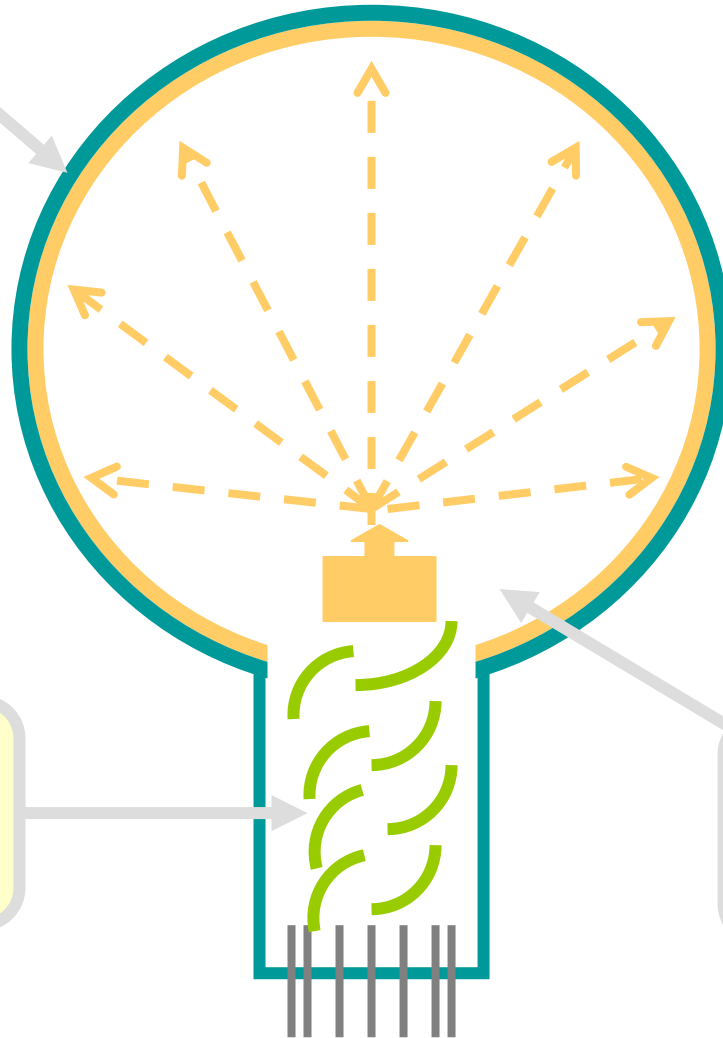


**Every PMT – ‘its own factory’**

**handmade**

**handmade**

**Cs, K, Na, Sb**



# A GLASS TUBE FACTORY

~100 x



# SciFi PMT DYNODE FACTORY



# Development of Other Vacuum Devices



~1960



~2000

**Production Cost '07 < \$500/m<sup>2</sup>**

# OUR GOAL

**to introduce a new Technology for**

**industrial mass production**

**of large quantities**

**of large photosensors**

**based on modified existing technologies**

**+ FOCUS on some 'REAL' (non-physics)  
MARKETS**

**ENCLOSURE:  
FLAT-PANEL TV**



**3 existing  
mass-production  
technologies**

**PHOTON→ELECTRON  
CONVERSION:  
CLASSICAL  
PHOTOCATHODE**

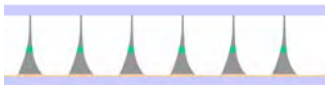
**ELECTRON DETECTION:  
SEMICONDUCTOR  
Scintillator + Geiger-MODE  
AVALANCHE  
DIODE  
'Light Amplifier'**



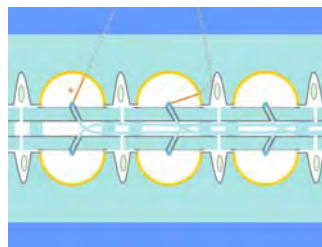
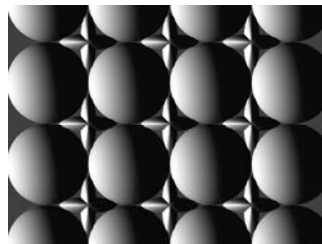
# Advanced Photosensors

**ULTIMATE:  
FLAT-PANEL**

**ReFERENCE**

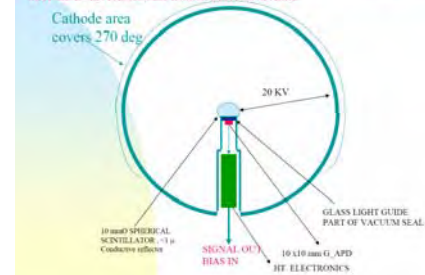


**ArcaLux**



**INTERMEDIATE:  
HEMISPHERICAL  
Light Amplifier**

A SPHERICAL SOLUTION WITH SPHERICAL SCINTILLATOR, SIMPLE PRODUCTION  
5 STERAD, MINIMAL TIME JITTER, ELECTRONICS CAN BE LOCATED IN STEM  
MAY BE EVEN PRODUCED INSIDE BENTOS SPHERE



**CANDESCENT**  
Field-Emission Display R&D Company, San Jose, CA



**\$ 600 Millions**



**5-inch  
prototypes**



**TECHNOLOGY**

**R&D EQUIPMENT**

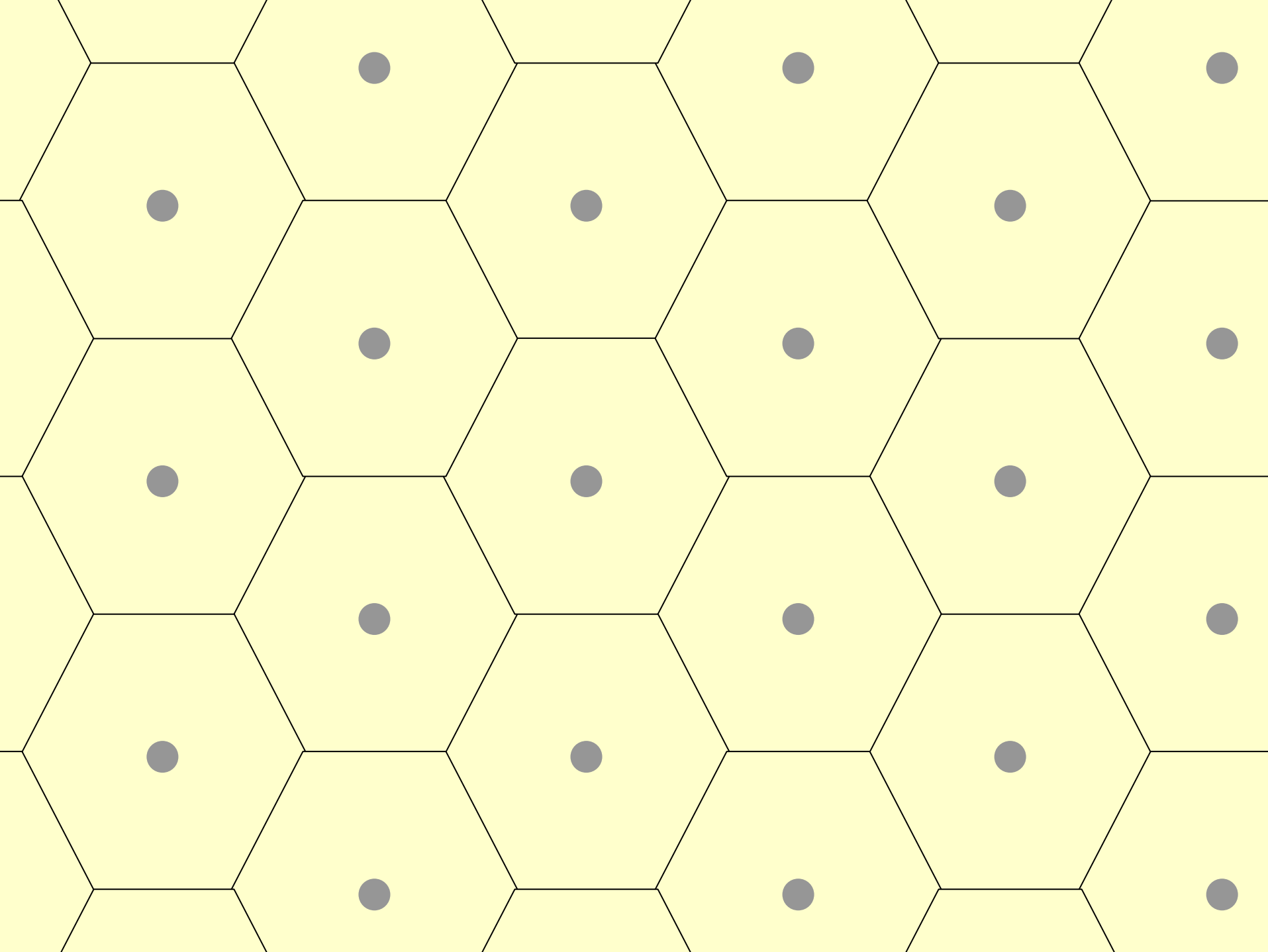


**CANON-TOSHIBA  
SED Display (2006)  
~1 m<sup>2</sup>**

**Our LAB @  
UC Davis**

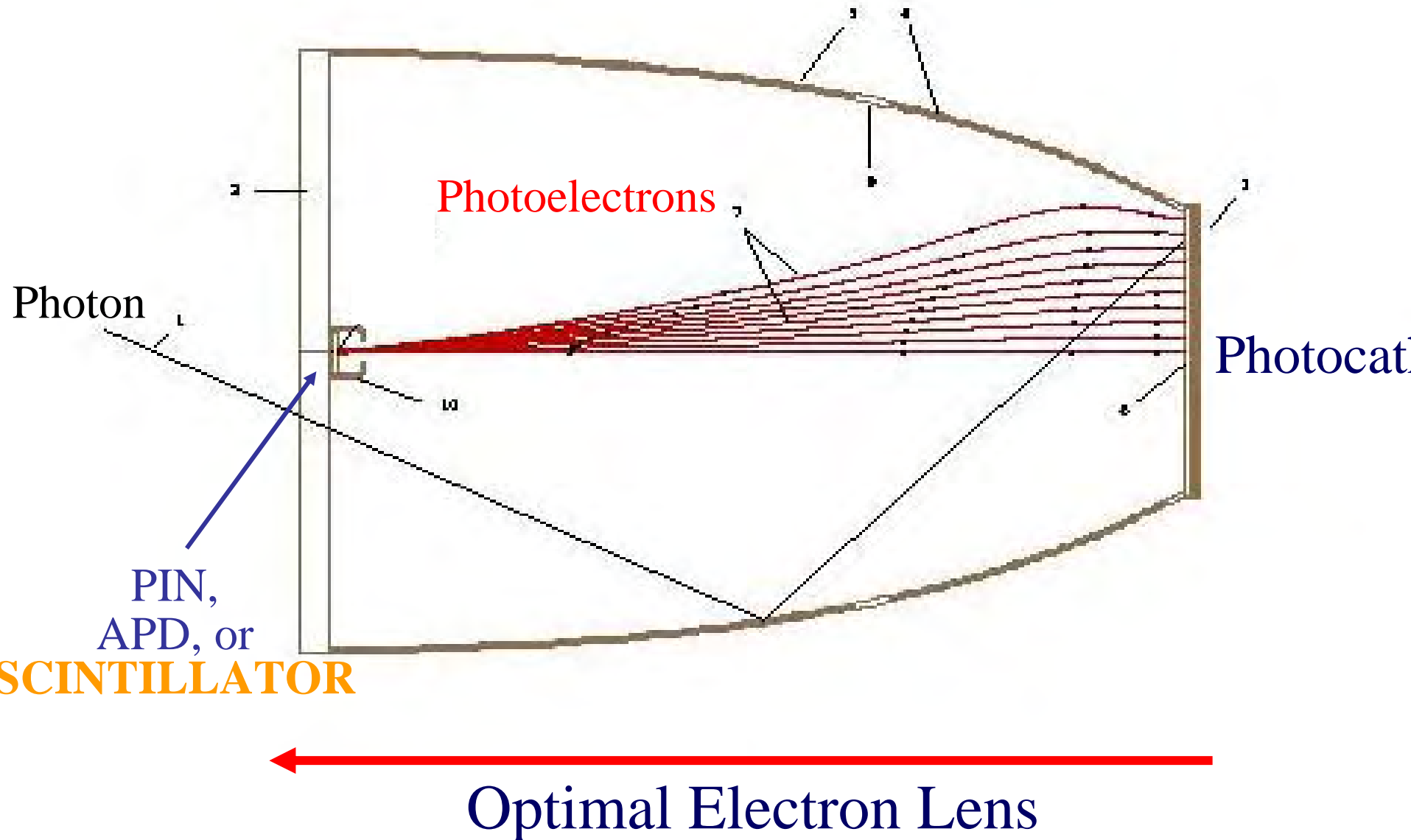
**\$ 2 B**

**>>\$ 1 M**



# Ideal Light Concentrator

(takes the maximum of Liouville!)



# Ideal Light Concentrator

(takes the maximum of Liouville!) 



Photon 

PIN,  
APD, or  
SCINTILLA

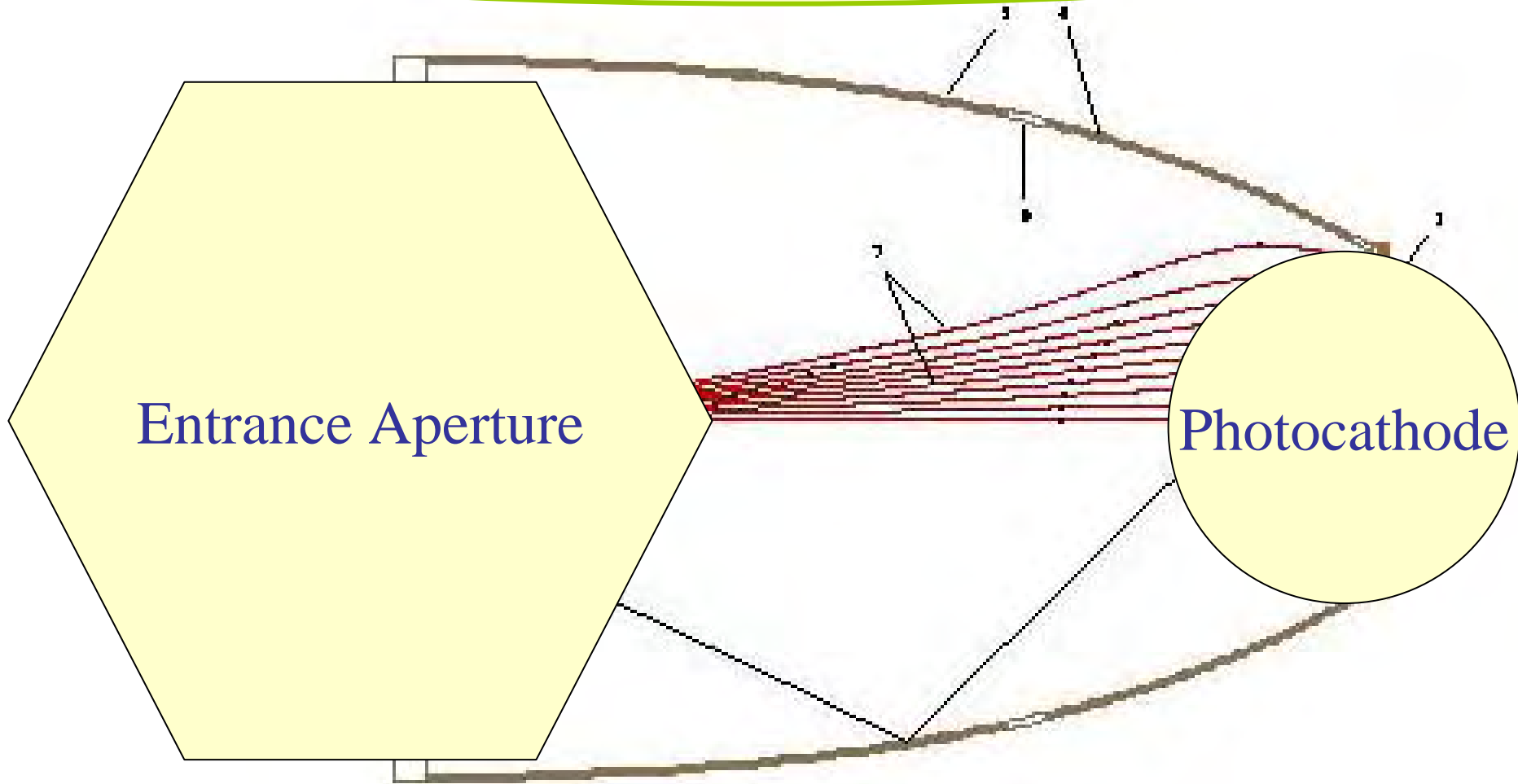
otocat

  
Optimal Electron Lens

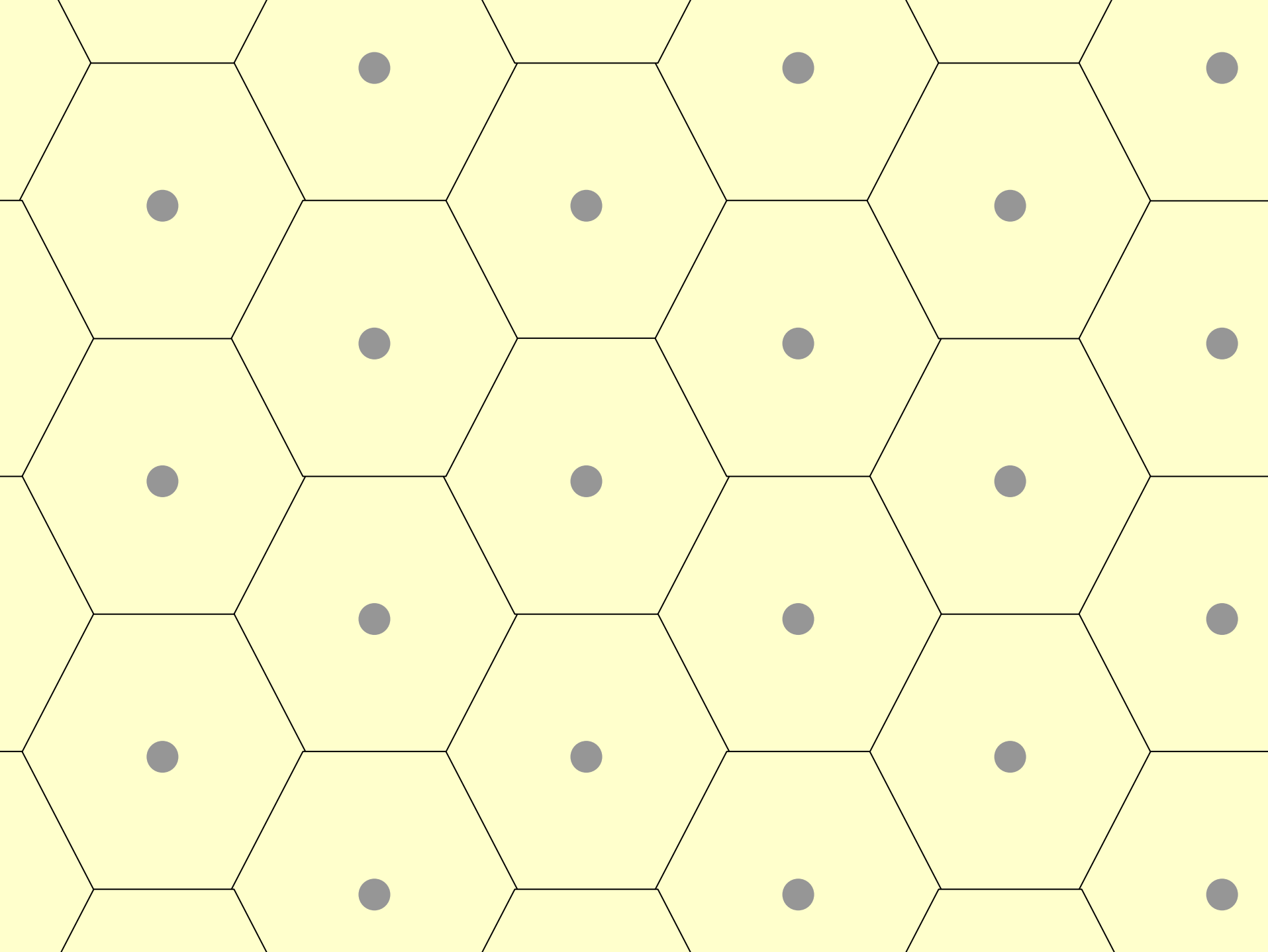




# Very Important: Hexagonal Packing







# HAMAMATSU

PRELIMINARY DATA  
NOV. 1998

## PHOTOMULTIPLIER TUBE R7517

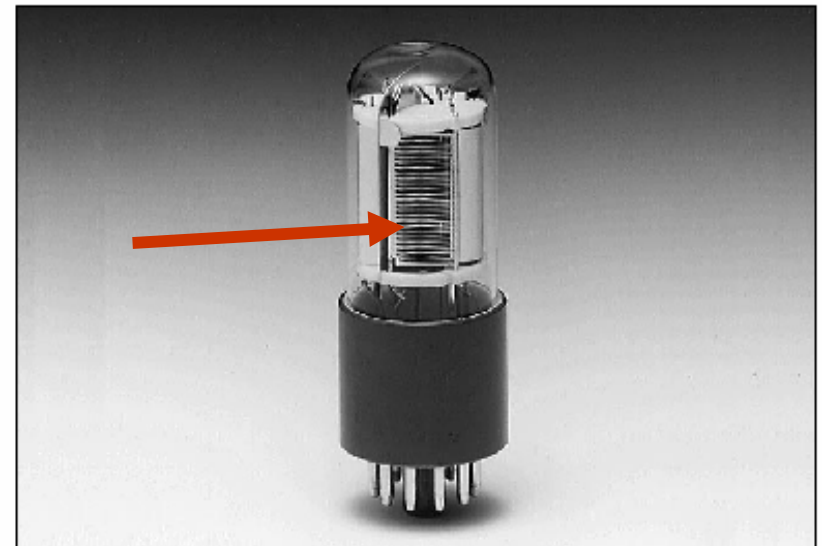
### High Q.E., Bialkali Photocathode 28mm (1-1/8 Inch) Diameter, 9-Stage, Side-On Type

#### FEATURES

- Spectral Response..... 185 to 760 nm
- High Cathode Sensitivity
  - Luminous ..... 160  $\mu\text{A}/\text{lm}$  Typ.
  - Radiant at 420nm ..... 105 mA/W Typ.
  - Quantum Efficiency at 220nm ..... 40% Typ.
- High Anode Sensitivity (at 1000V)
  - Luminous ..... 1600A/lm Typ.
  - Radiant at 420nm .....  $10.5 \times 10^5$  A/W Typ.

#### APPLICATIONS

- Fluorescence Spectrophotometers
- Fluorescence Immuno Assay
- SO<sub>2</sub> Monitor (UV Fluorescence)

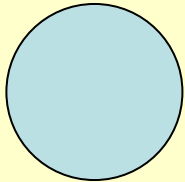


# PROTOTYPE DEVELOPMENT

UNSEALED 1-PIXEL

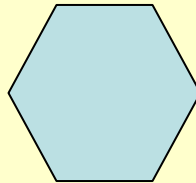
SEALED PANELS  
(7 pixels, 5 inch)

CYLINDRIC

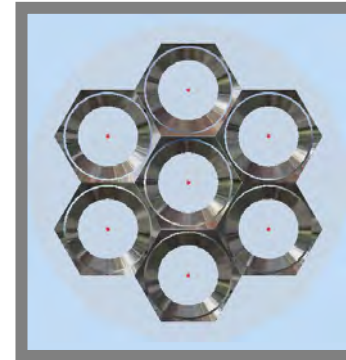


2001-2002

HEXAGONAL



2003



SEALED

with  
In/Au

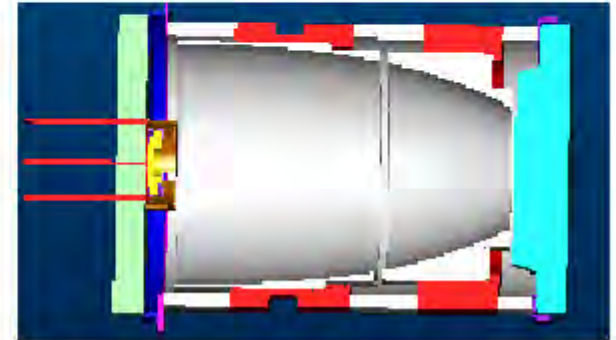
SEALED

with  
SOLDER  
GLASS

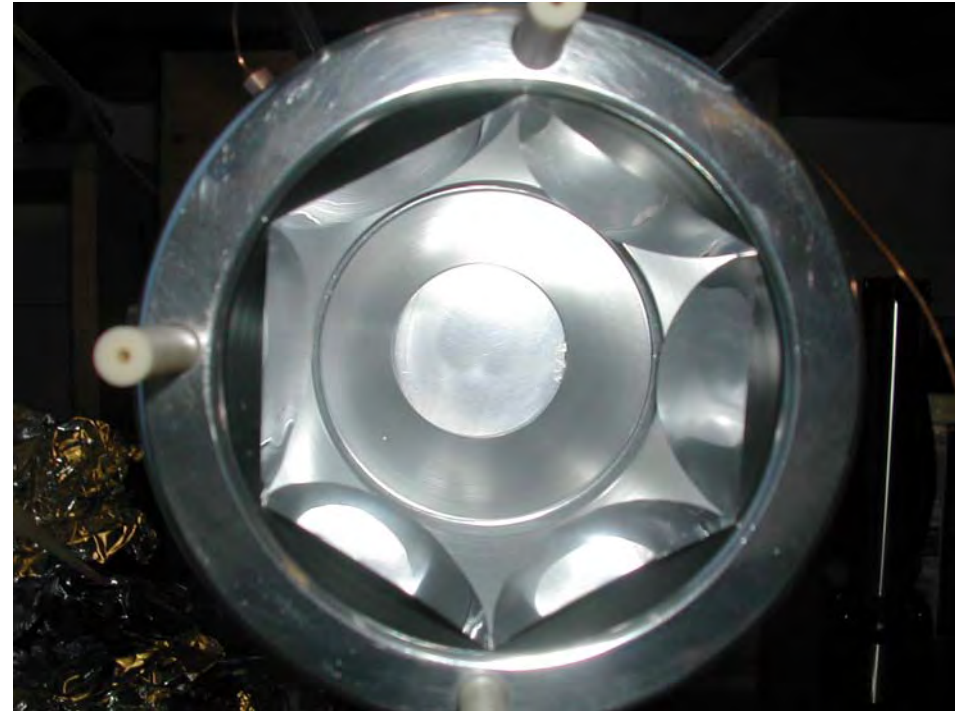
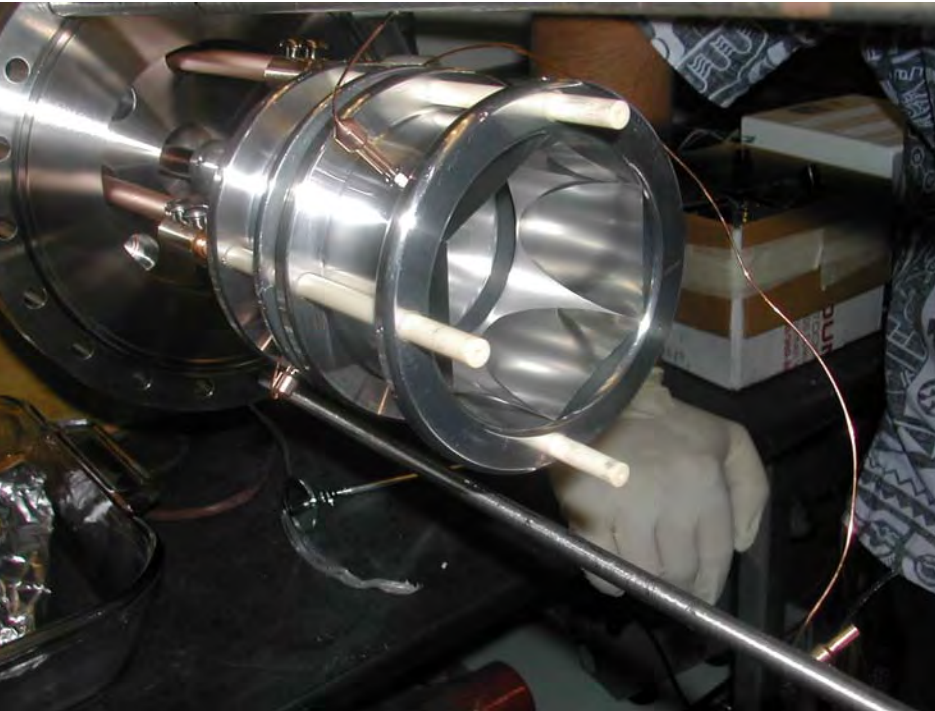
Equipment (**Candescent**,  
**Litton Night Vision**) ~\$2M

# ReFERENCE Tube Design

- Reflection mode GaAs cathode (12.5mm used)
- Sapphire input window 25mm aperture
- High voltage APD (API)
- Segmented Kovar CPCs for concentration and timing
- Size chosen to use standard parts and tooling
- Prototype device to test design concept with short time and internal funding
- Anticipate improved external QE 300-400nm and good QE out to 900nm



## 3<sup>rd</sup> ReFeRence Prototype



3" diameter, single pixel  
(successfully tested – see below)



**Strong signal concentration, factor ~ 1500**  
**(one of our goals)**

**Replaces the entire Dynode Column!**

**Provides ~100% Collection Efficiency!**

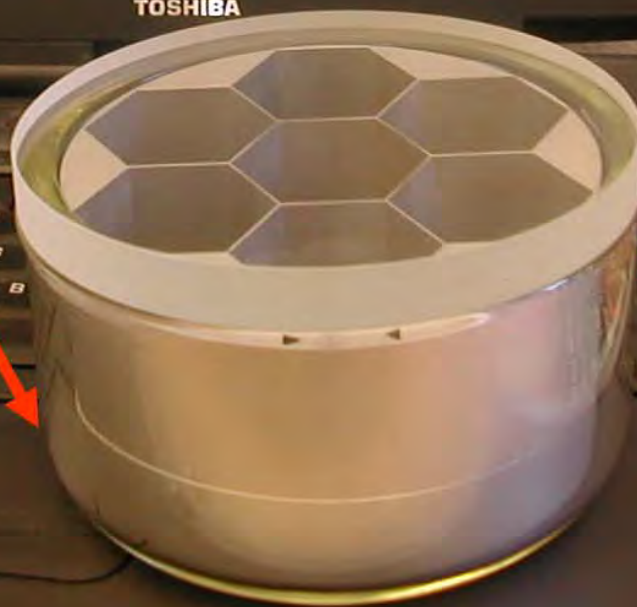
- **APD**
- **Scintillator + Fiber (both of small and comparable diameter → good coupling efficiency)**

*ReFERENCE Panel* Prototype (under construction)



**ENDPLATE**

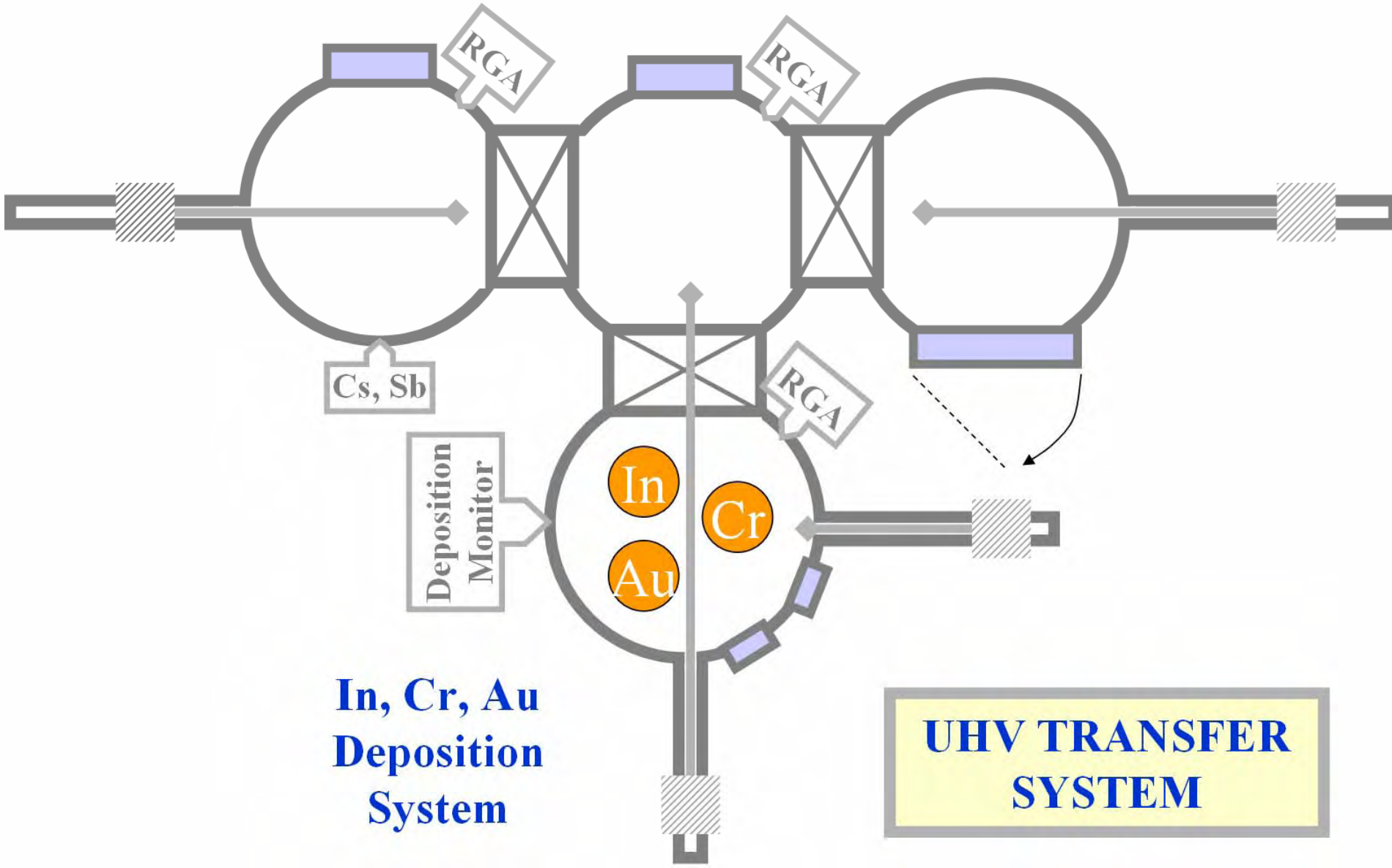
**TUBE  
BODY**



**Photocathode  
Deposition  
Chamber**

**Sealing  
Chamber**

**Load-Lock  
Chamber**

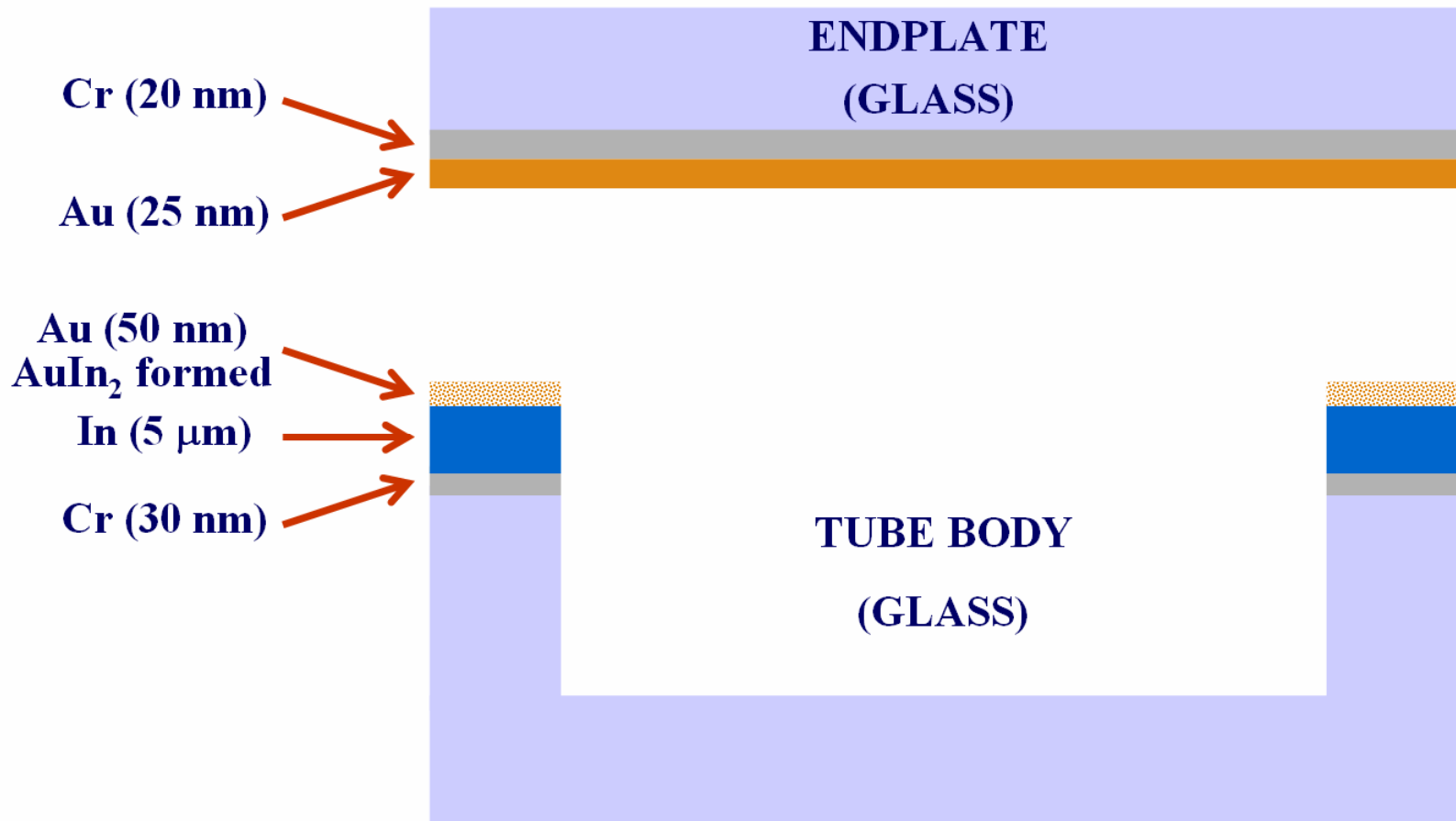


**In, Cr, Au  
Deposition  
System**

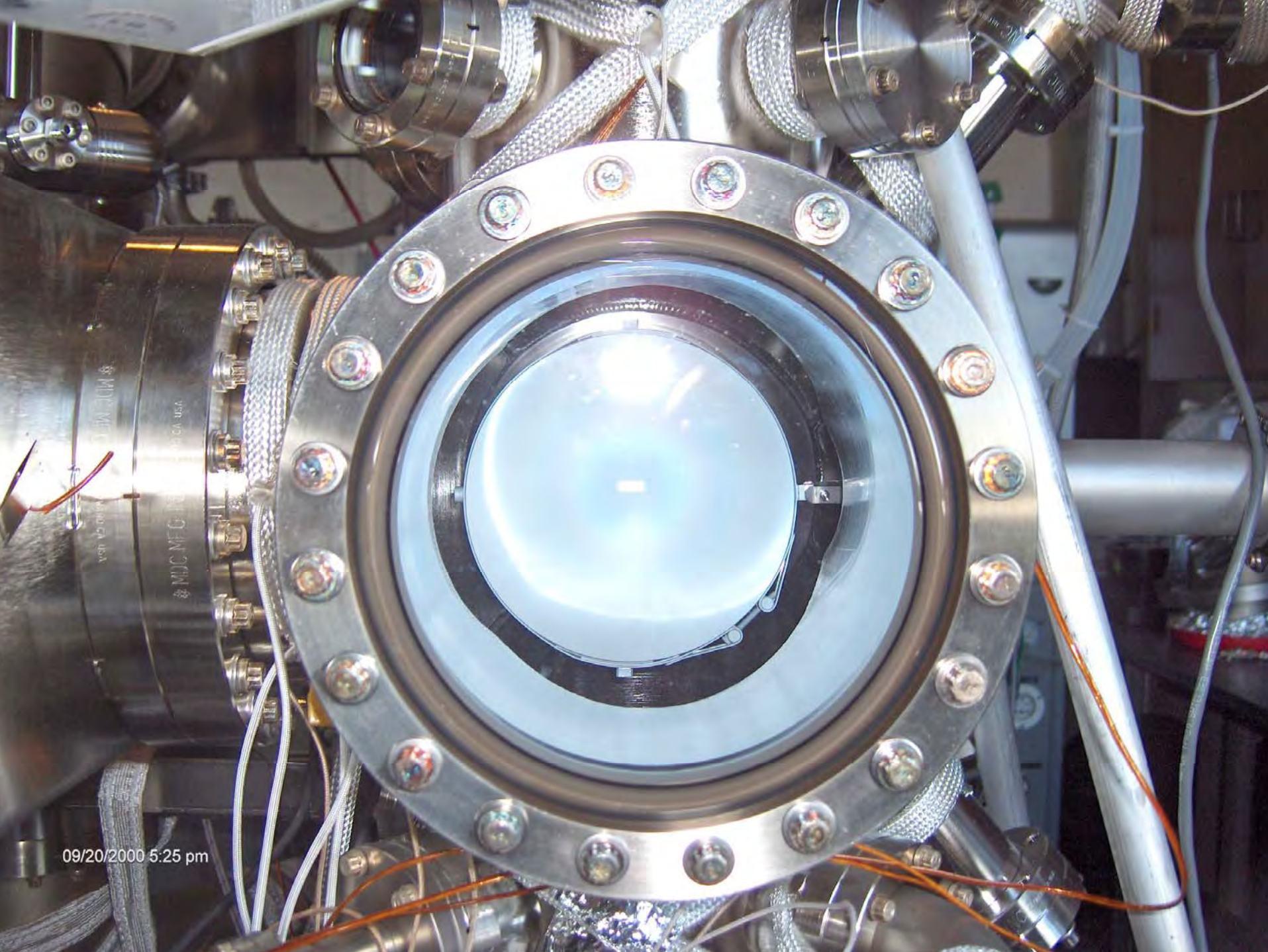
**UHV TRANSFER  
SYSTEM**



# New Oxide-Free Indium Sealing Method



See NIM-A paper, D. Ferenc, E. Lorenz et al. 2006

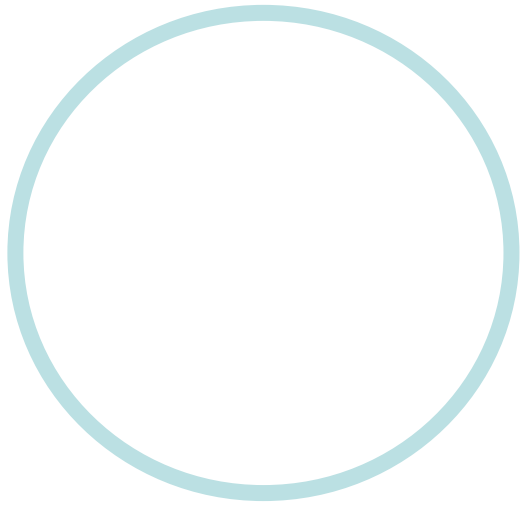


09/20/2000 5:25 pm

# **‘ArcaLux’**

**(*lat.* light box)**

- **Full angular acceptance**
- **Perfect optical coupling to thick layers of water or scintillator**
- **High ambient pressure**
- **Extreme robustness**
  - **SPHERICAL CONFIGURATION**
- **Immune to accidental exposure to high light intensities**
  - **LIGHT AMPLIFIER (G-APDS)**



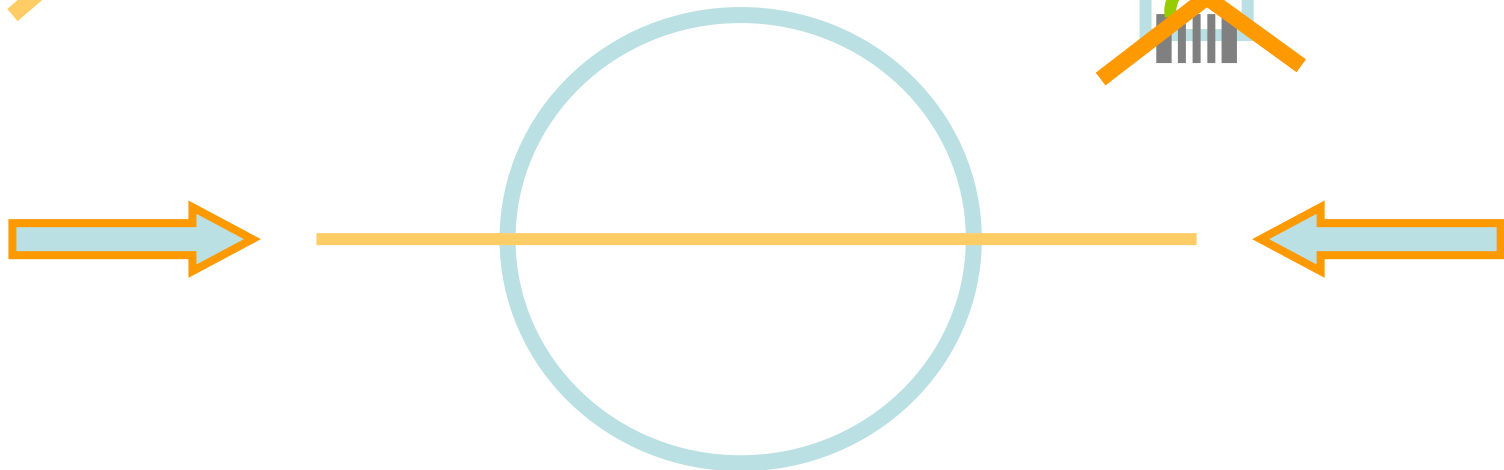
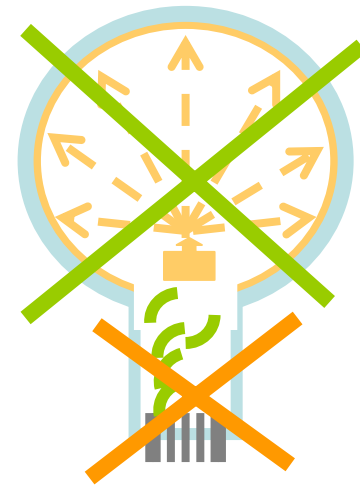
?

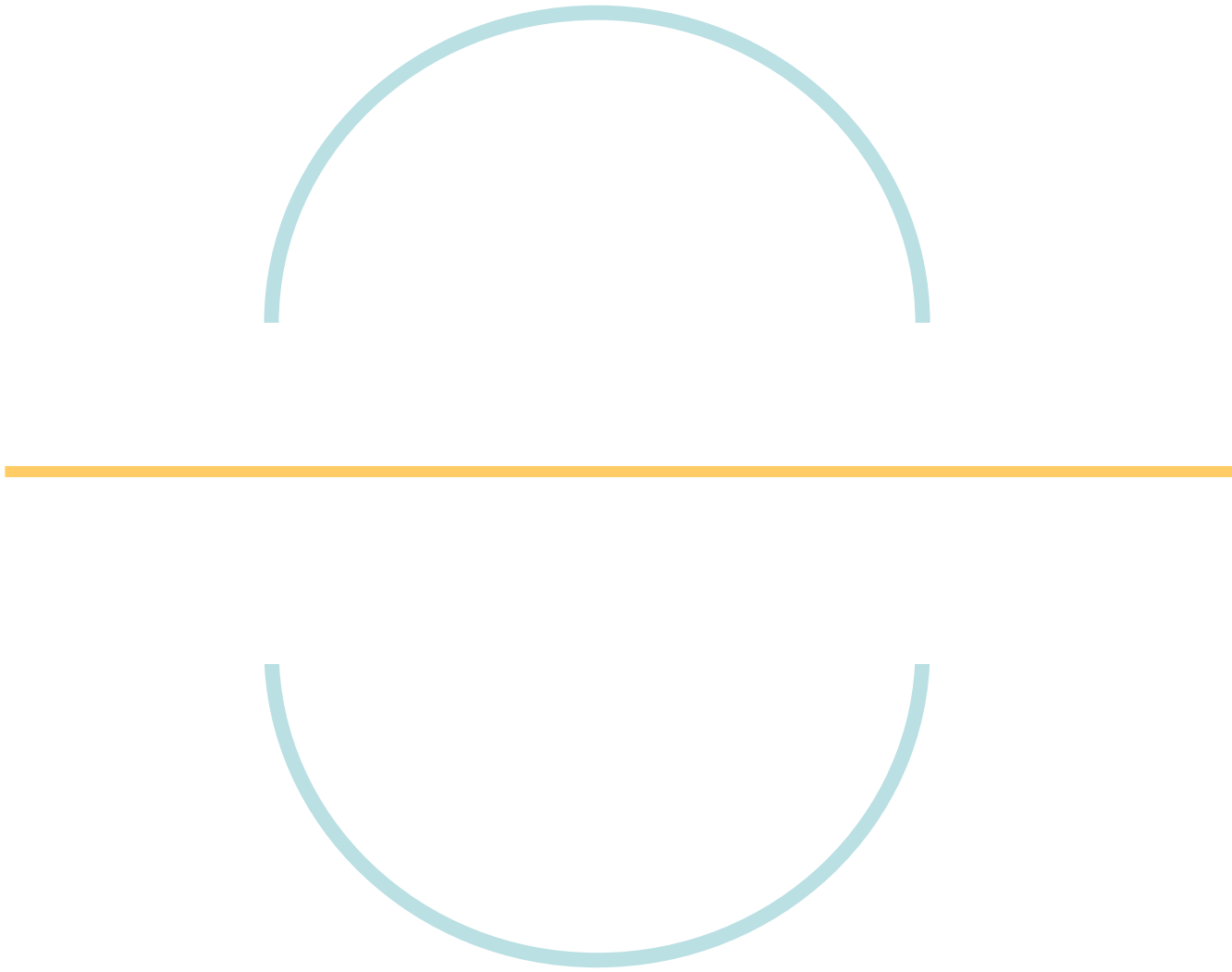


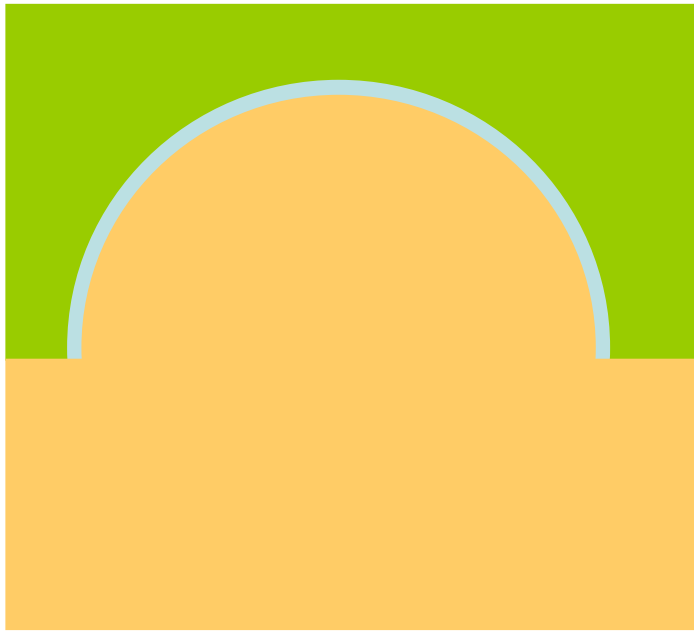
**Mass production**  
**High performance**

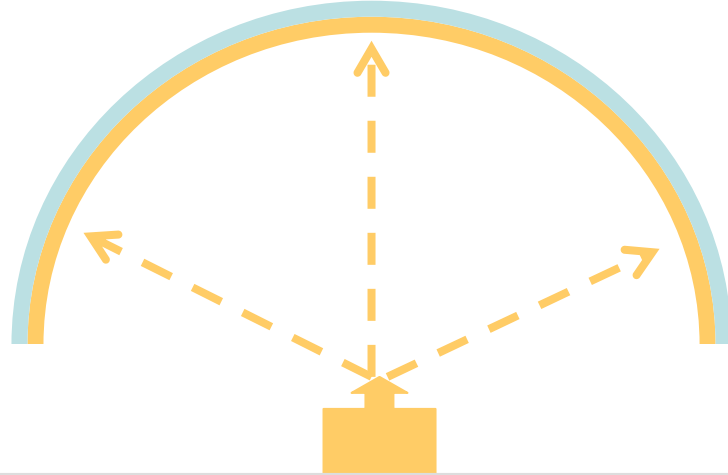
**COMPONENTS:**  
**Industrially**  
**mass-produced**

**ASSEMBLY:**  
**Production-line**









**vacuum**





?

## **Special marriage:**

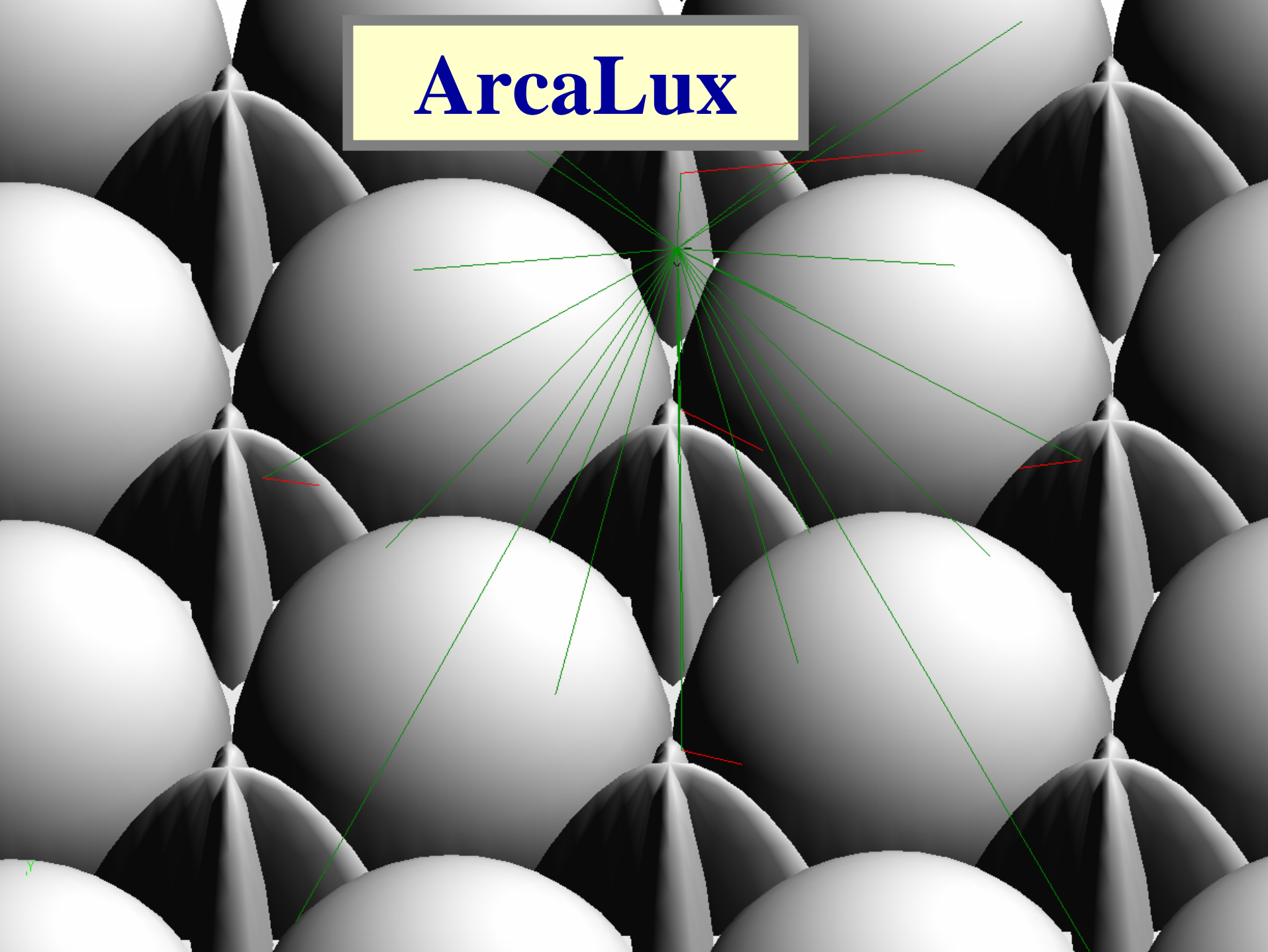
**~ 0% dead area**

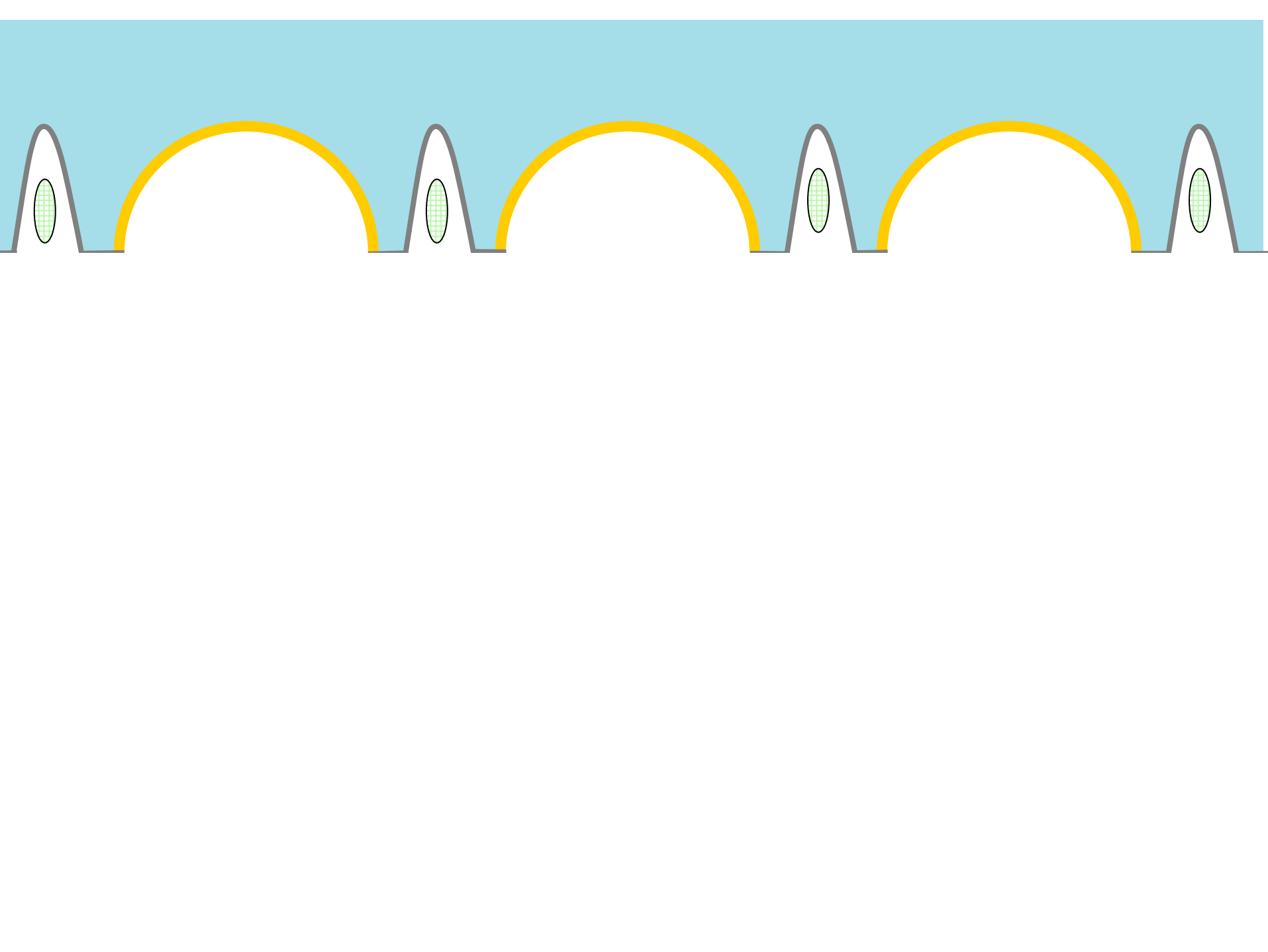
**Long-lasting – the internal pollution - internally absorbed**

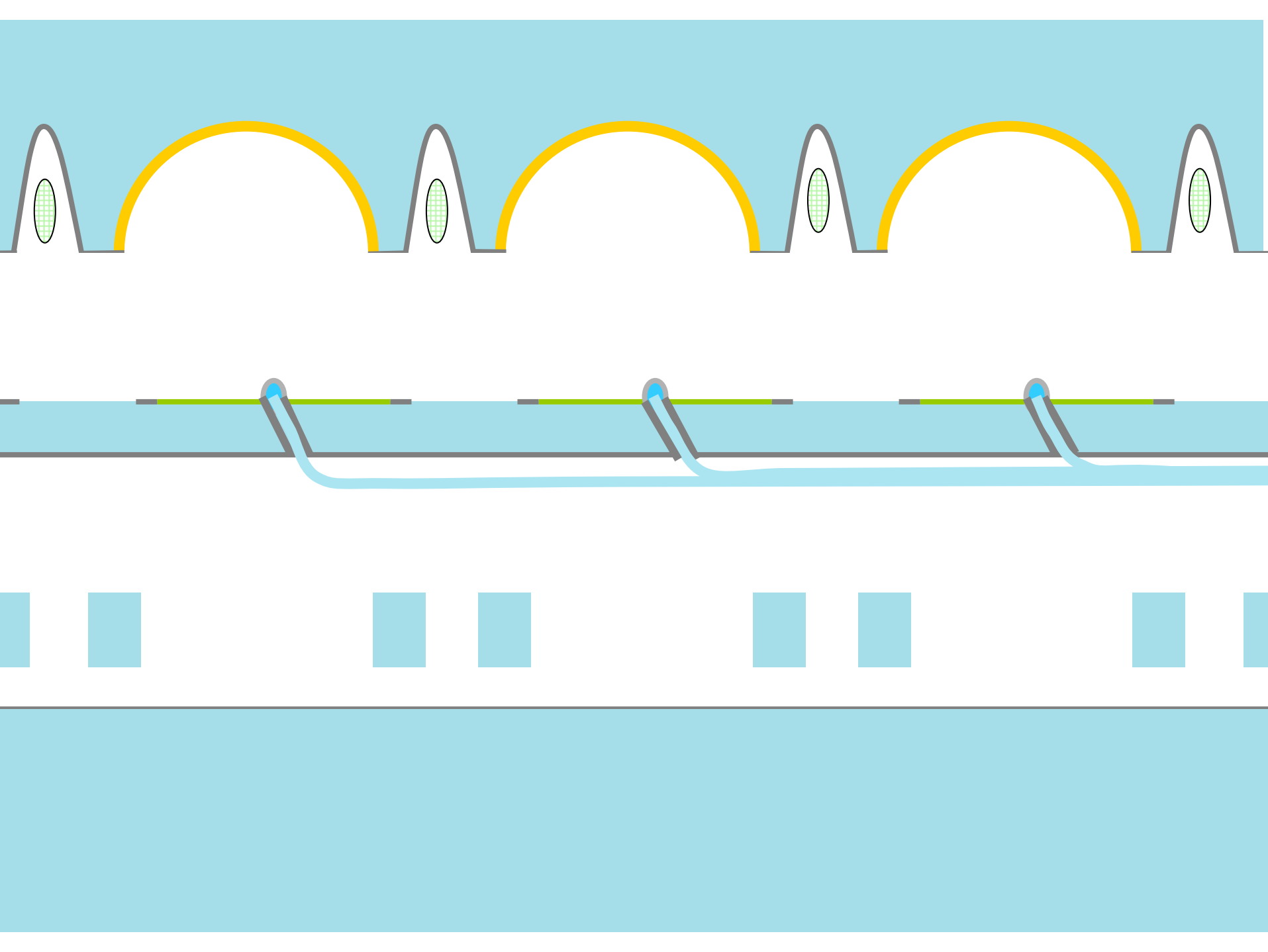
**Highly resistant to pressure from outside**

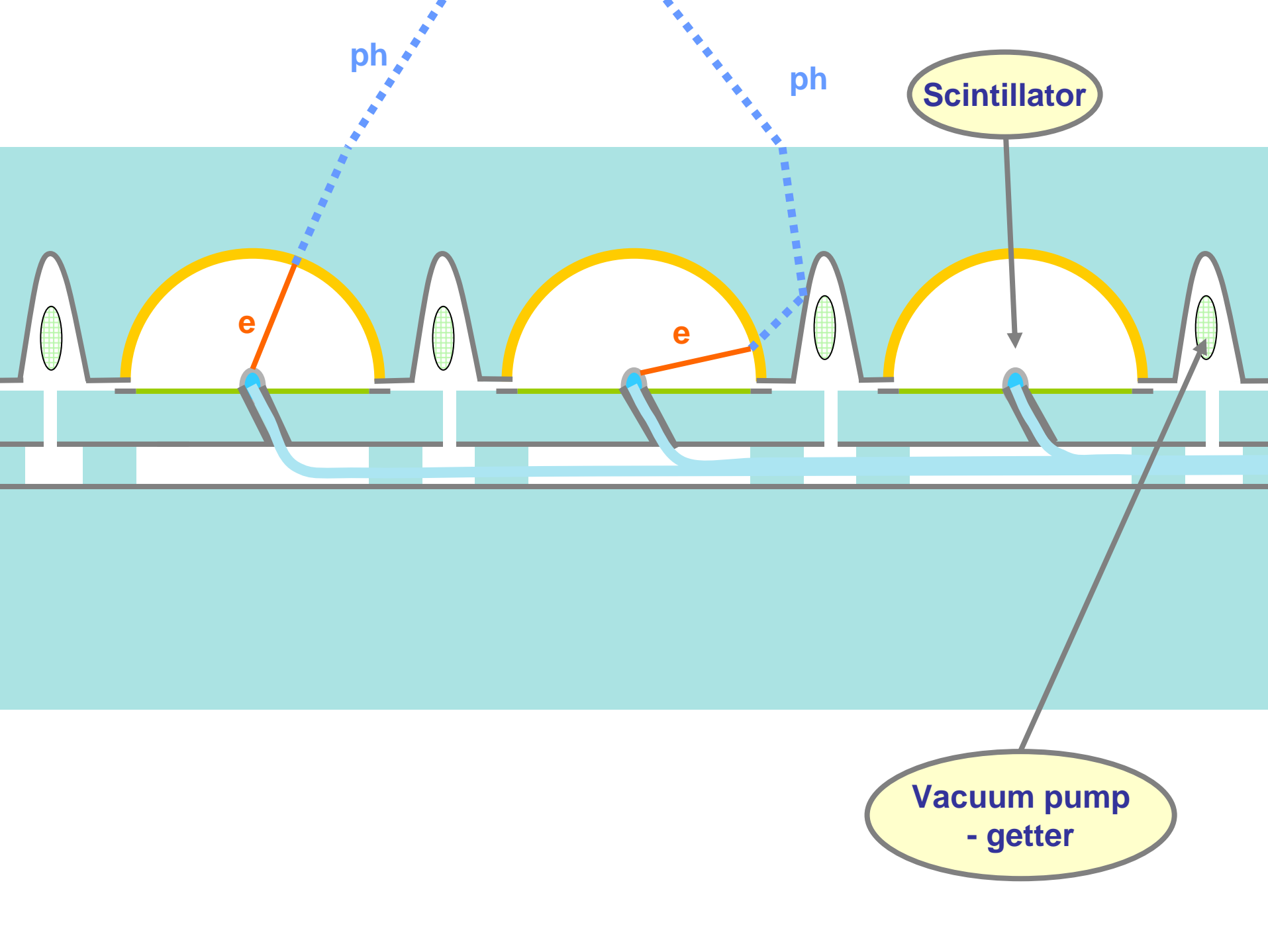
**Ready for mass-production**

# ArcaLux









ph

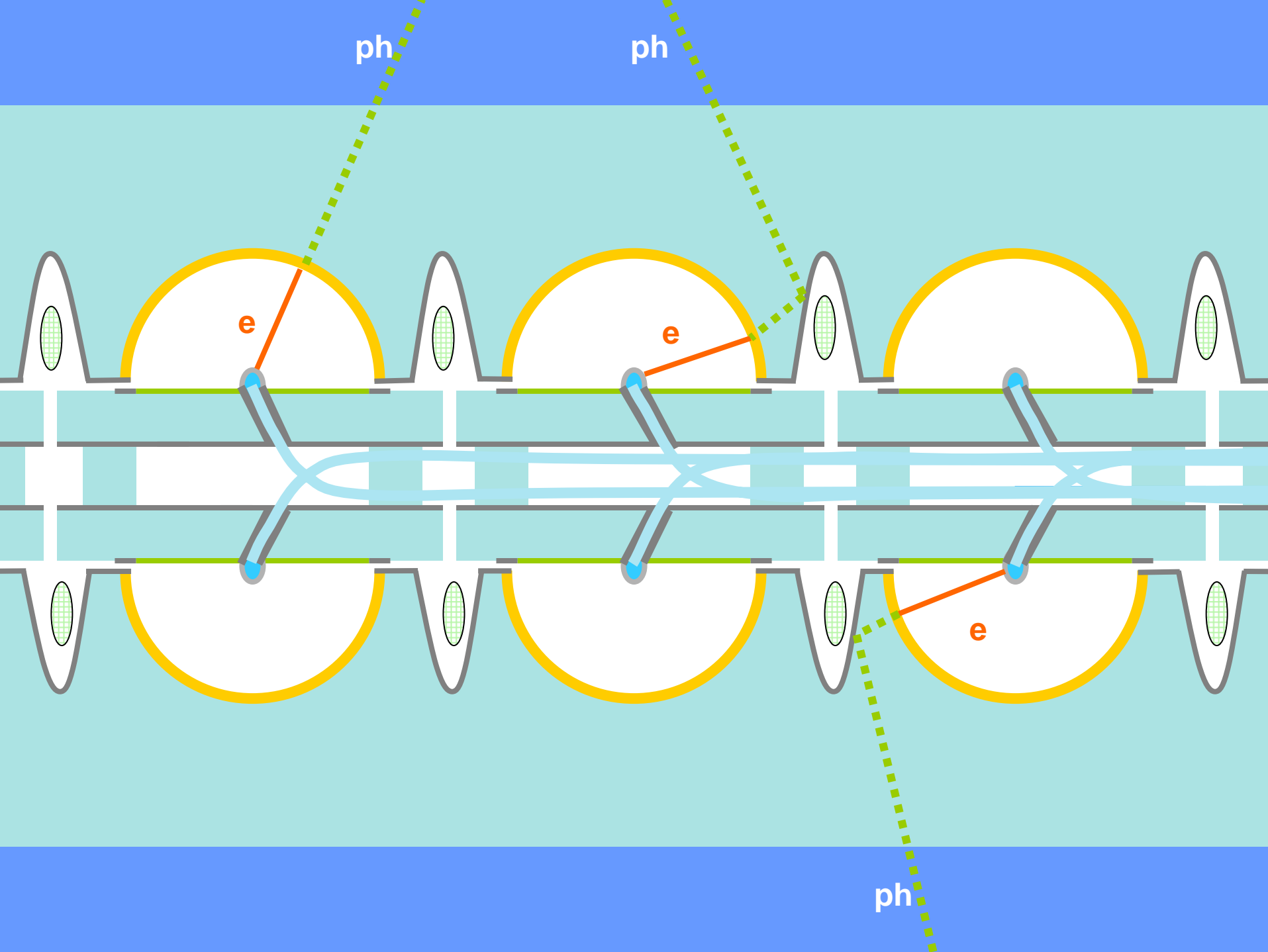
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Scintillator

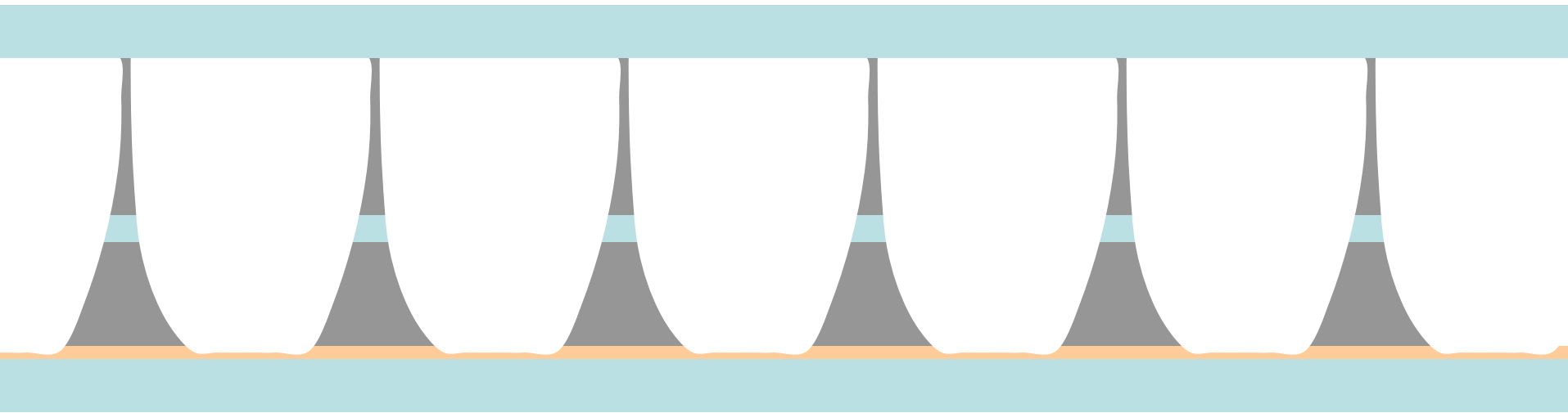
e

e

Vacuum pump  
- getter



# Flat-Panel Honeycomb Sandwich Camera Construction



**Industrial Production (no glass blowing etc.)**  
**Intrinsic Mechanical Stability, Low Buoyancy,..**

Ideal Light Concentrator = OK!



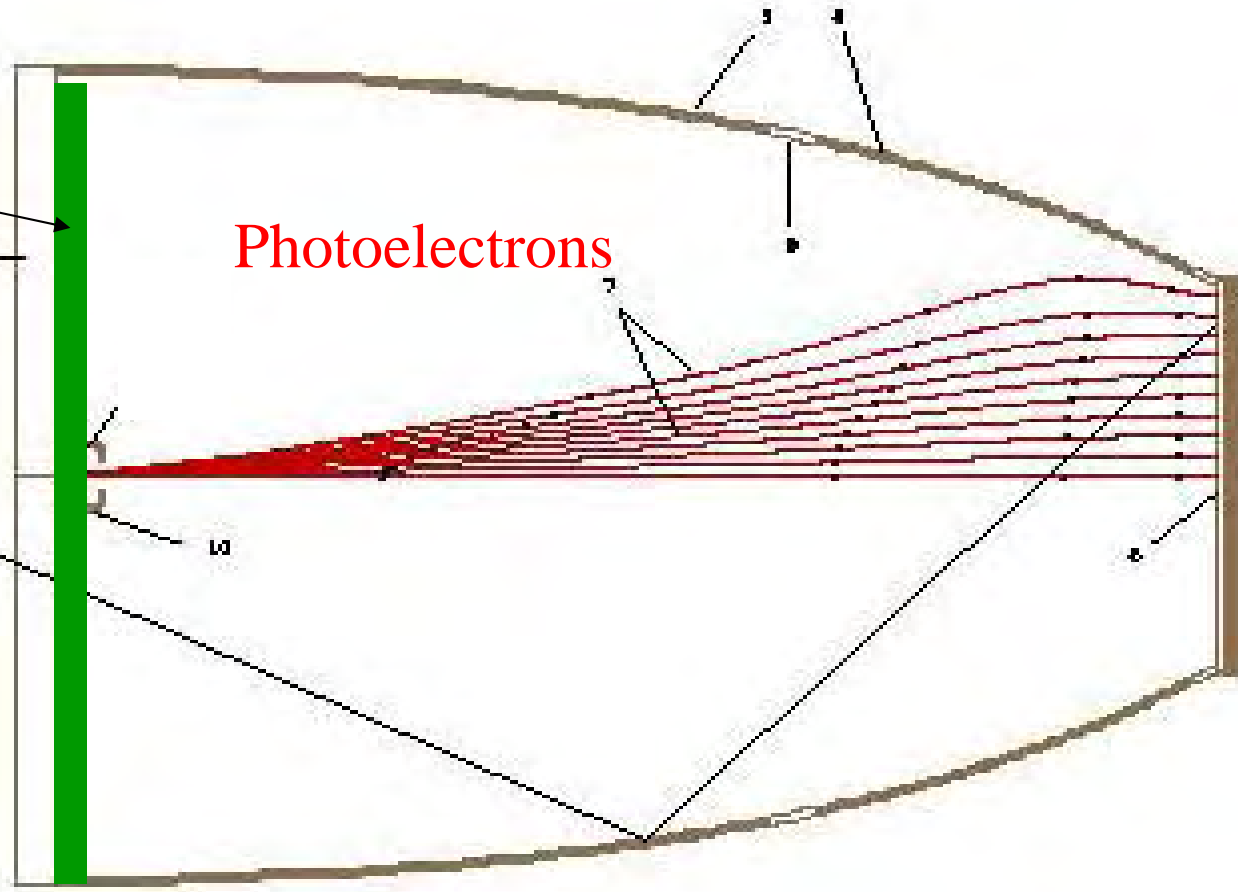
Phosphor Screen

Photon

Photoelectrons

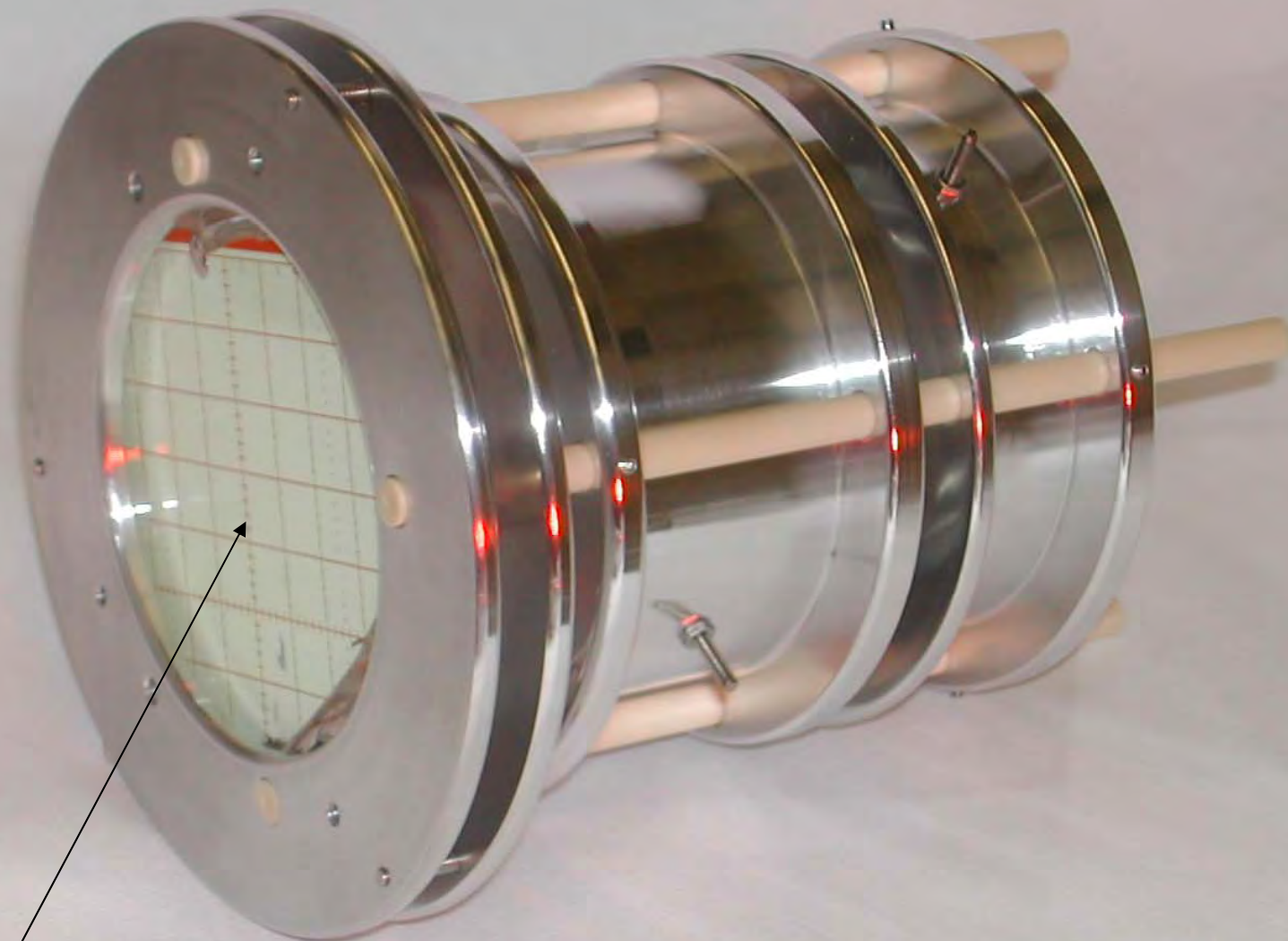
Photocat

verify

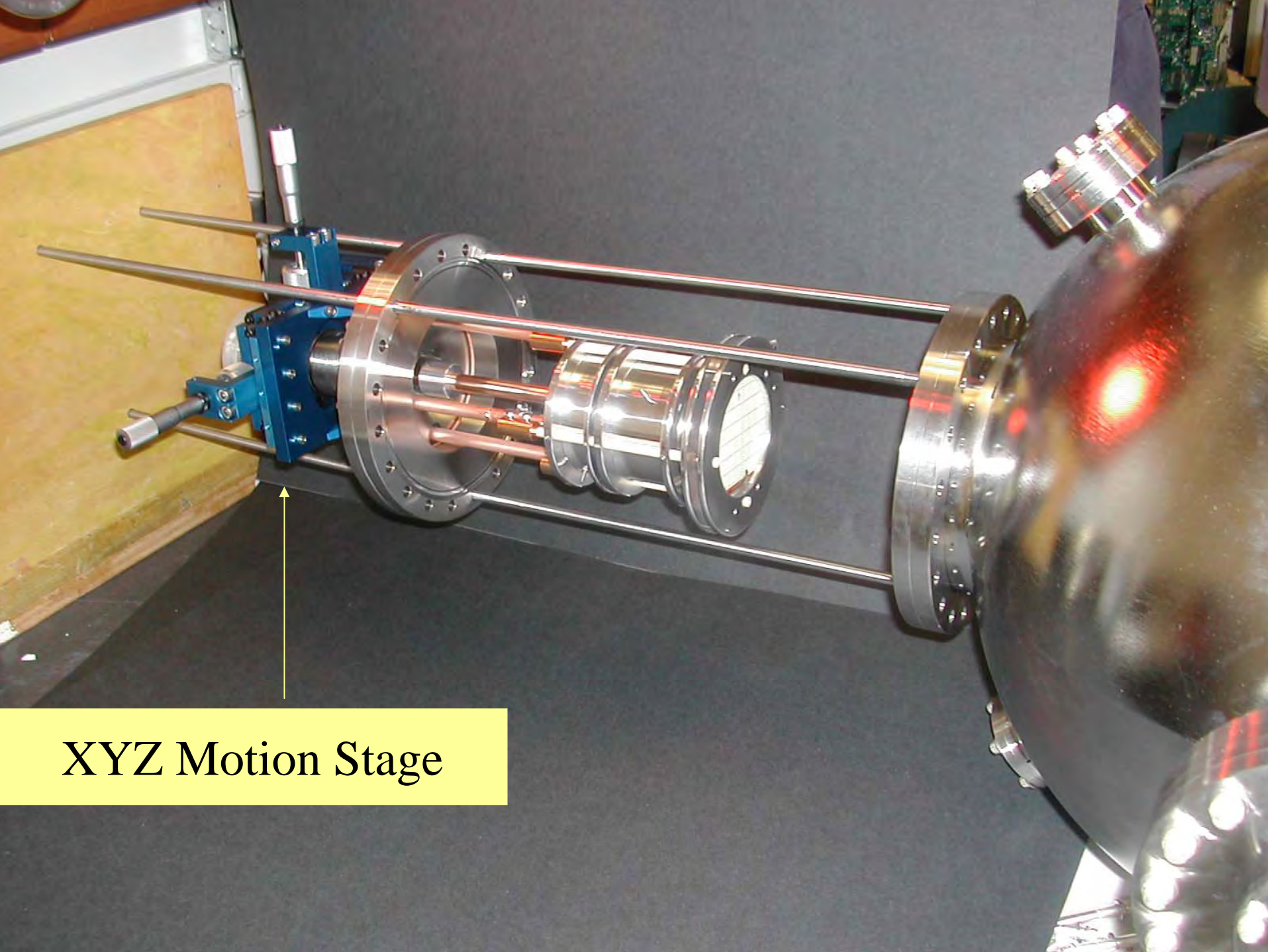


Optimal Electron Lens

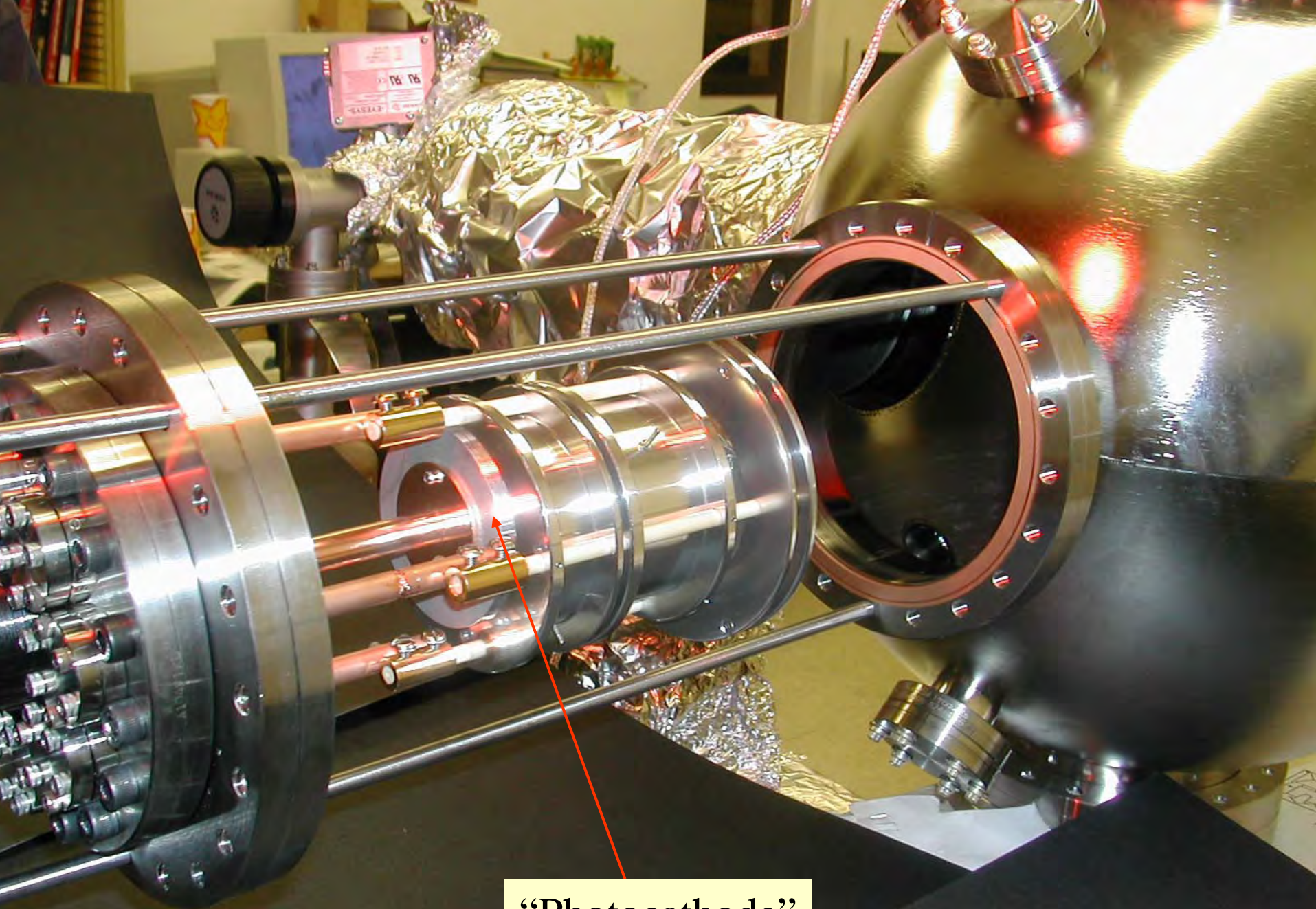




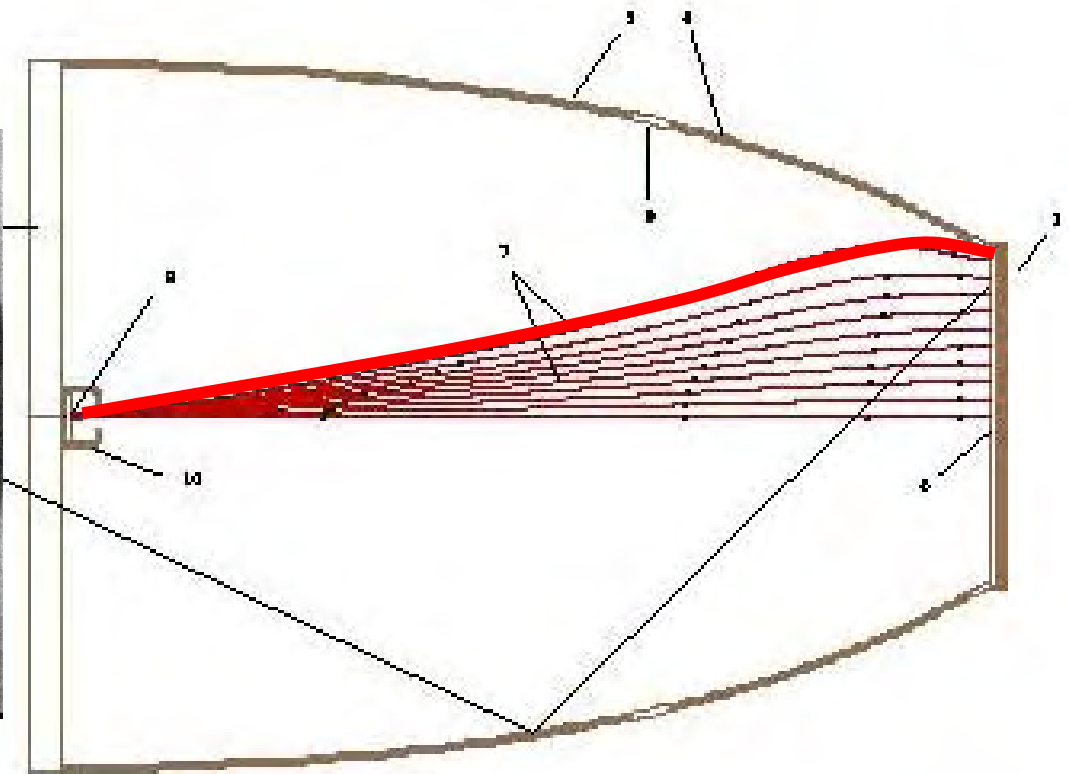
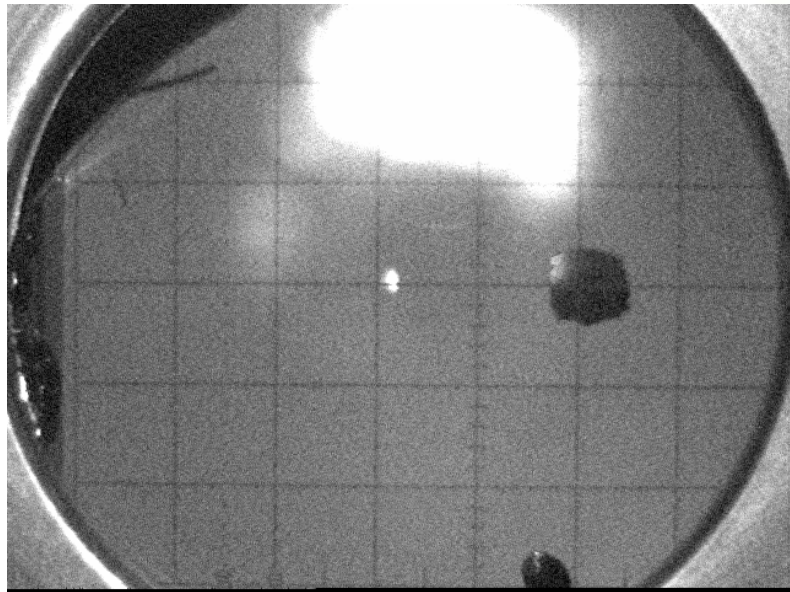
Phosphor Screen

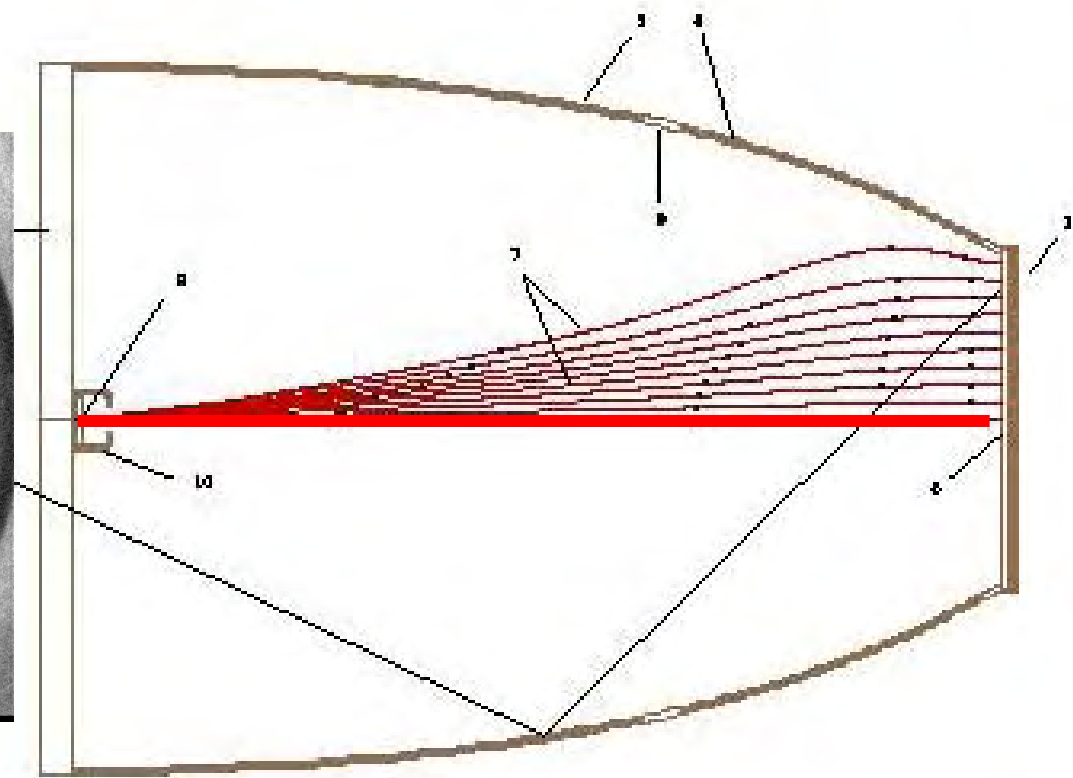
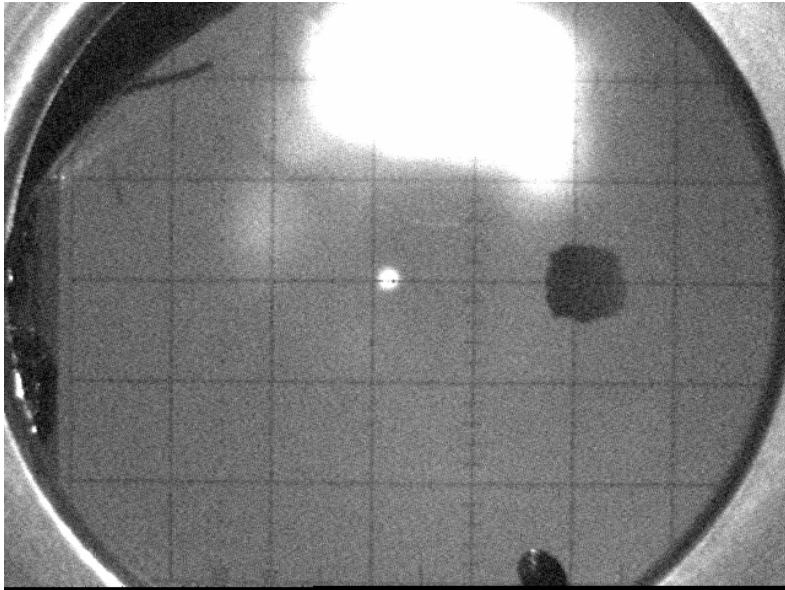


XYZ Motion Stage



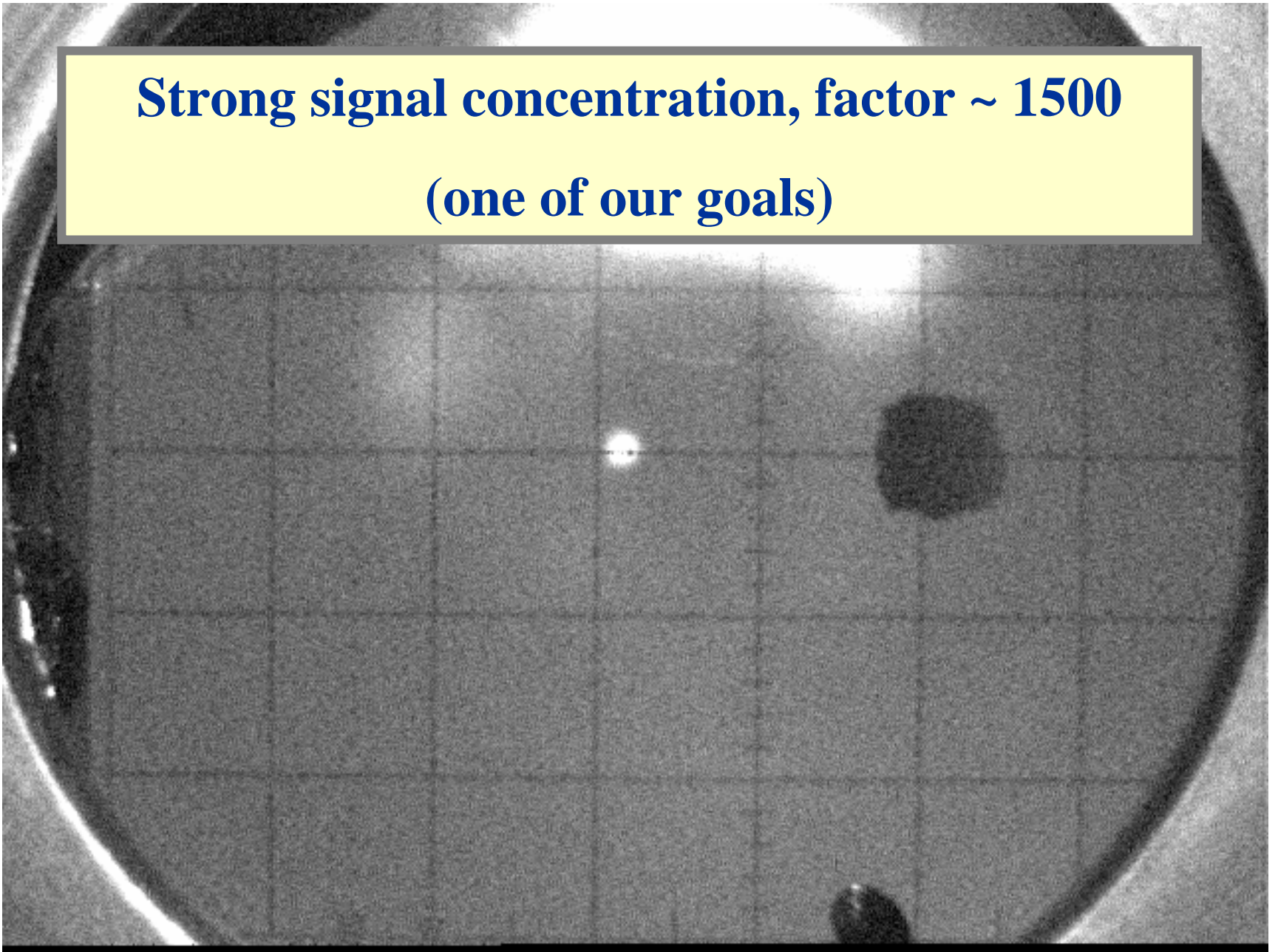
“Photocathode”



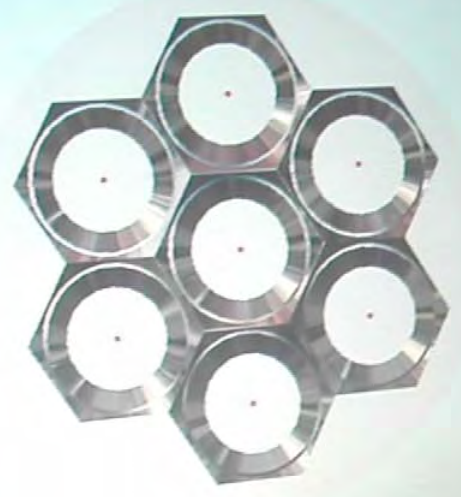


**Strong signal concentration, factor ~ 1500**

**(one of our goals)**



ReFerence Panel Prototype (under construction)



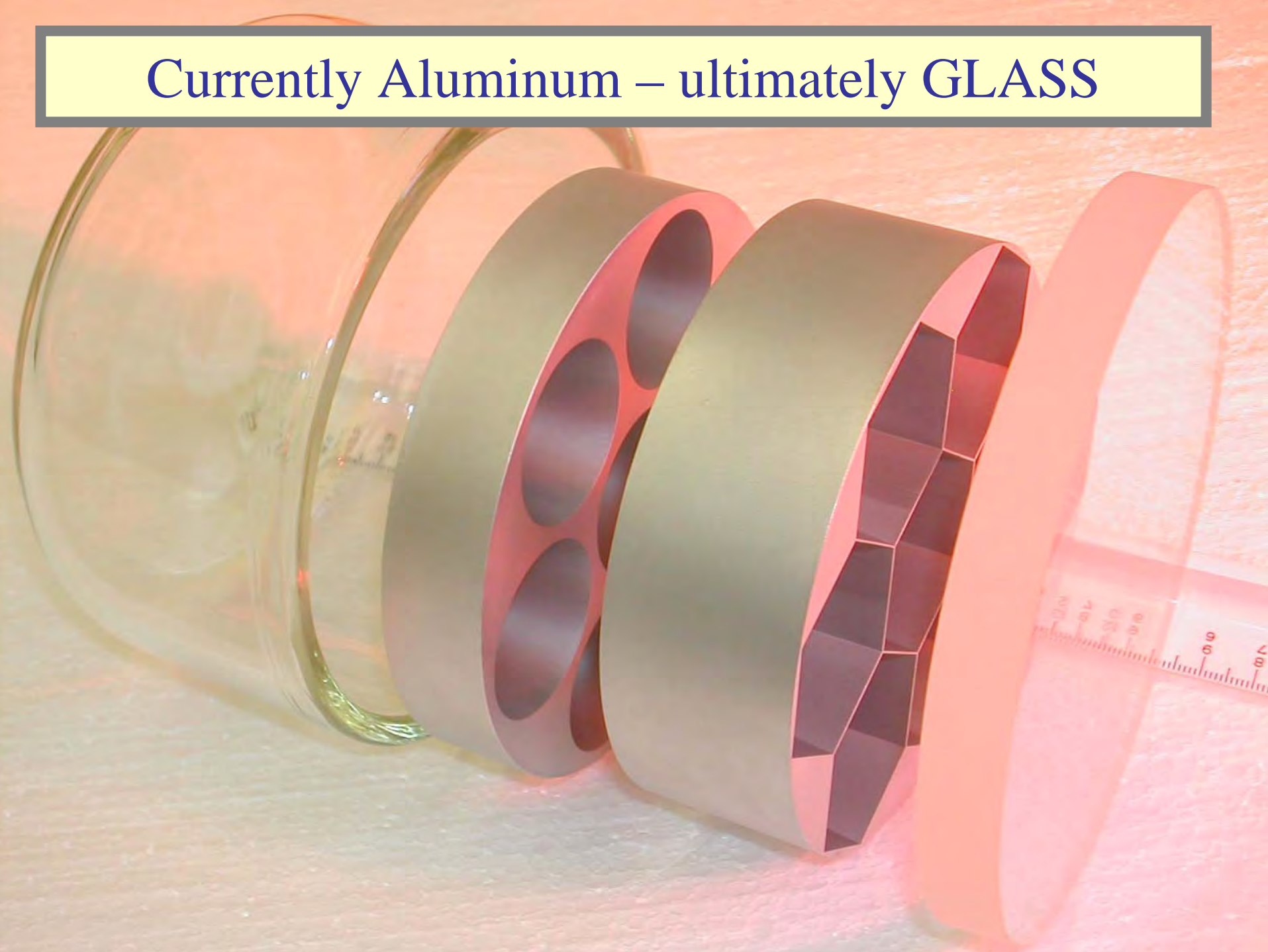
TOSHIBA



THE S  
on the Univers  
What is it  
Satellite

OTORIS  
Machine Vision  
udy in Co  
Contrast  
onic Crystal Fiber  
oled IR Det  
ring C

Currently Aluminum – ultimately GLASS

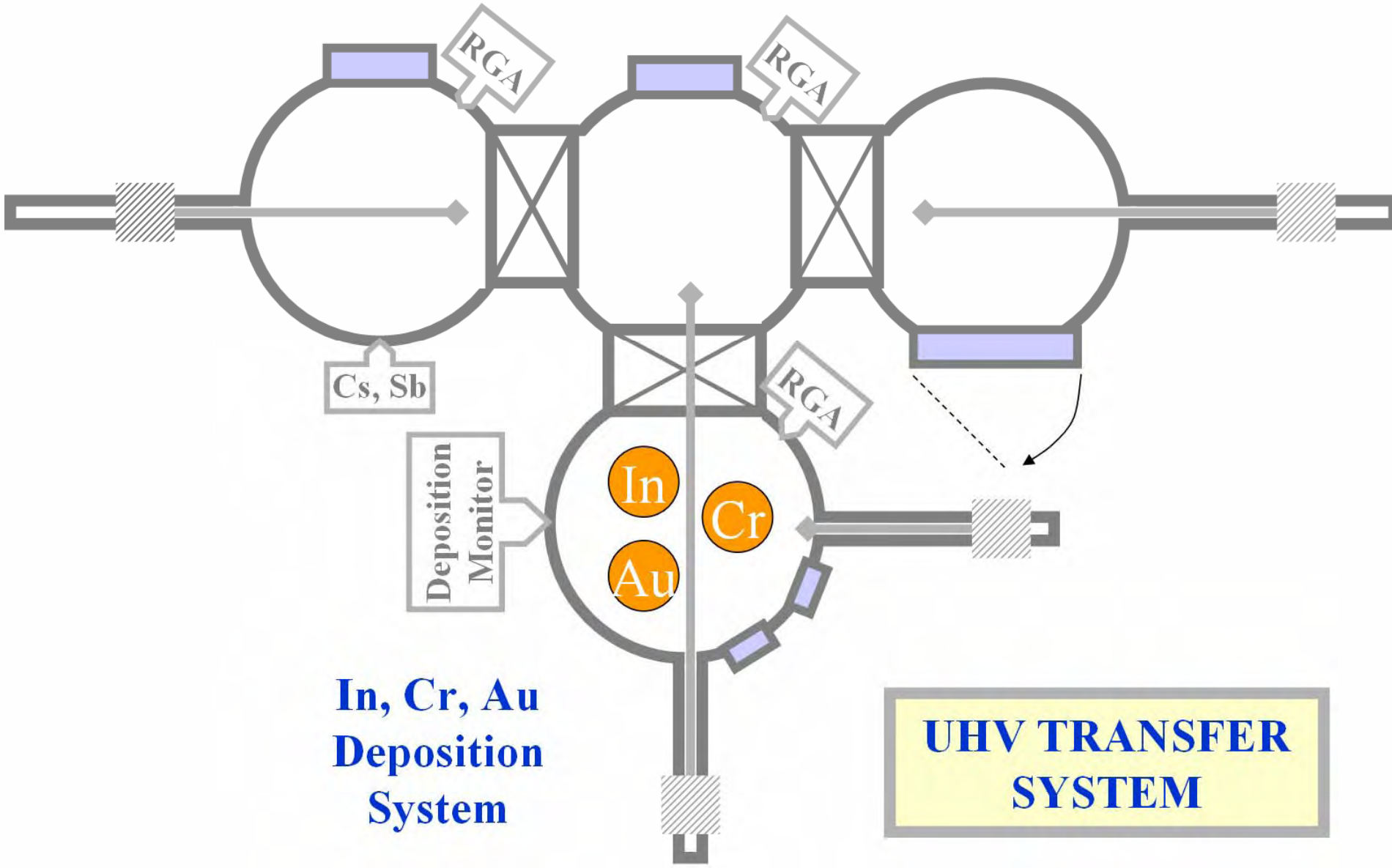




**Photocathode  
Deposition  
Chamber**

**Sealing  
Chamber**

**Load-Lock  
Chamber**



Cs, Sb

Deposition  
Monitor

**In, Cr, Au  
Deposition  
System**

In

Cr

Au

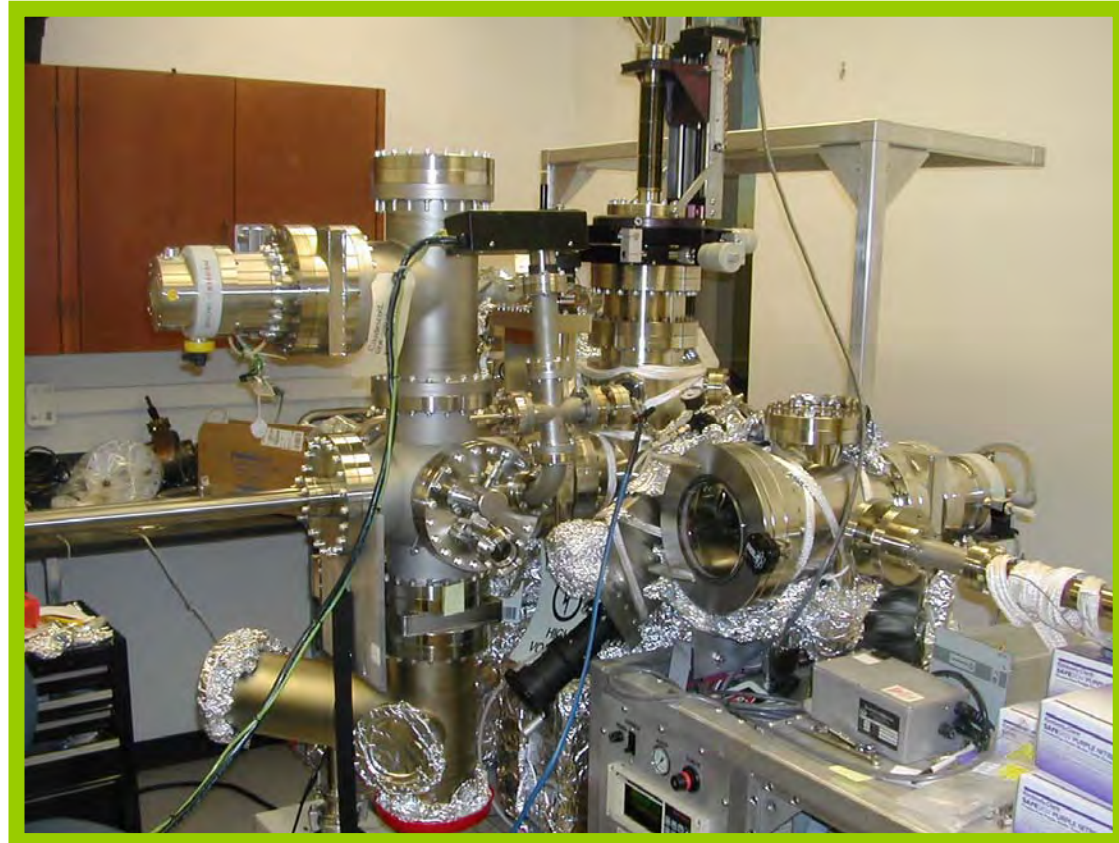
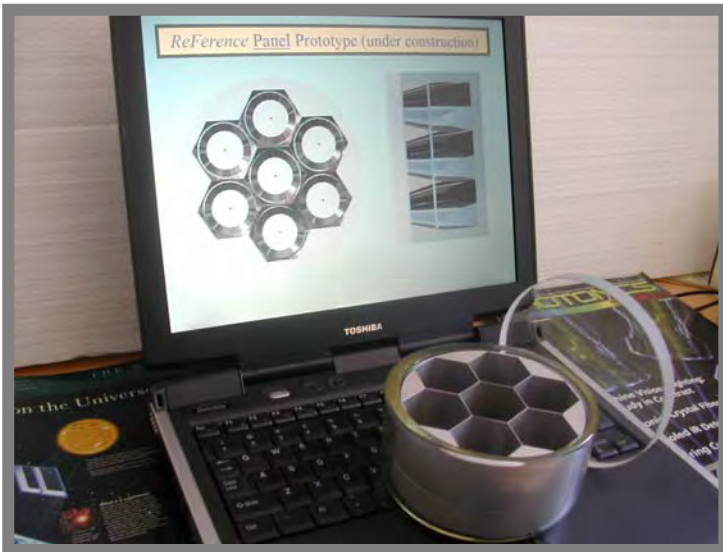
RGA

RGA

RGA

**UHV TRANSFER  
SYSTEM**

# 7-pixel 5-inch ReFeference Flat-Panel Prototype



**UHV Transfer System :**

- **Photocathode deposition**
- **Indium/Au/Cr deposition**
- **Vacuum sealing**



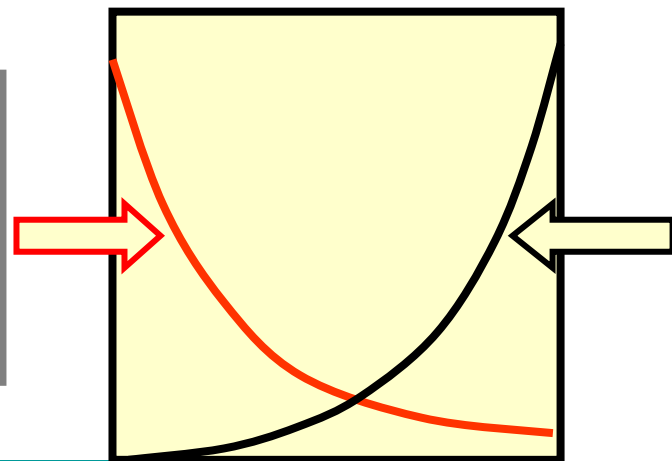
**Mass spectrometer**

**Sb evaporator**

**Cs, Na, K dispensers**

**Photocurrent  
monitor**

Photon Absorption  
(Electron Creation)



Probability for an  
Electron to Reach  
the Vacuum  
Surface  
(*Random Walk*)

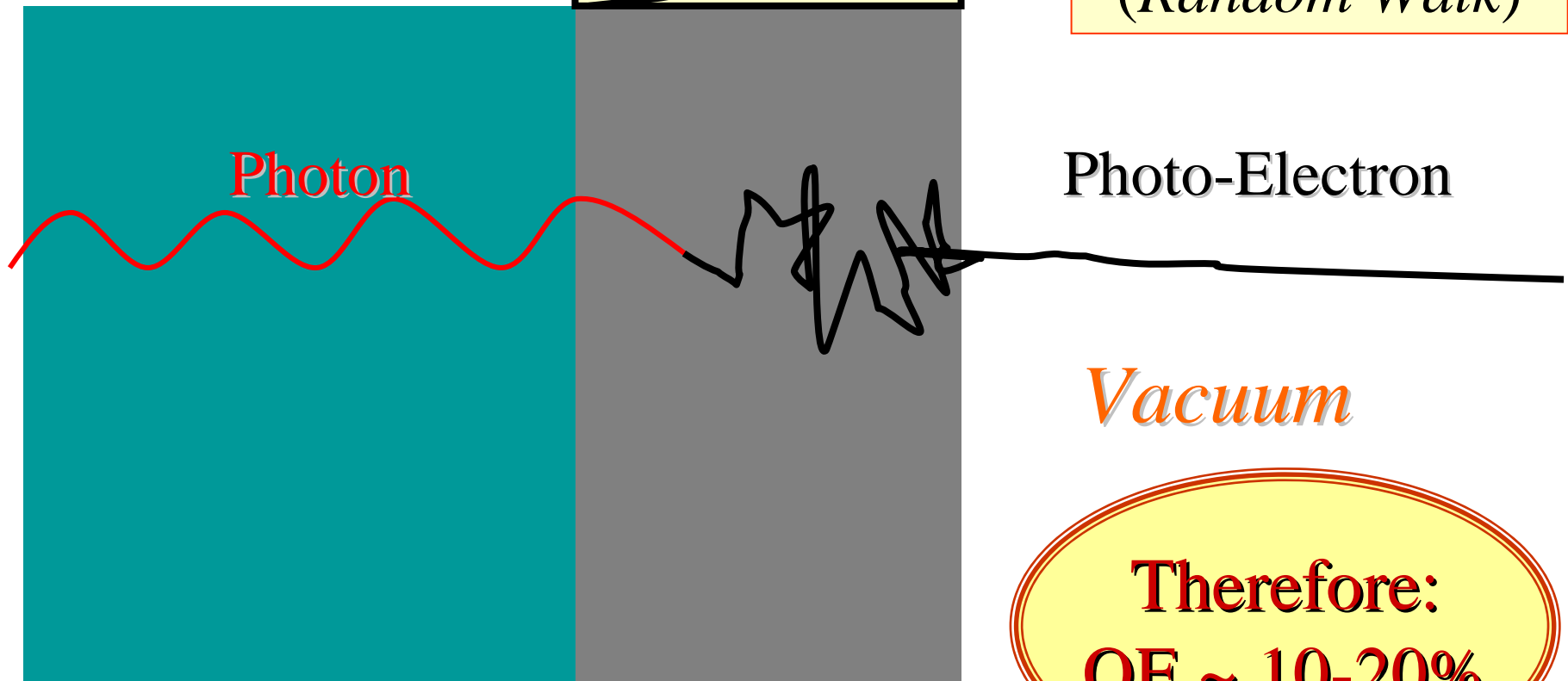


Photo-Electron

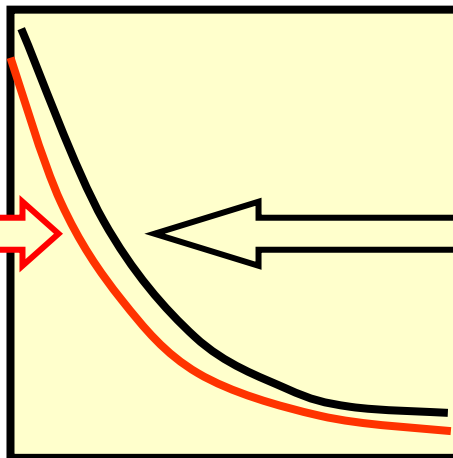
*Vacuum*

Therefore:  
QE ~ 10-20%

*Glass Window*

*Photocathode*

Photon Absorption  
(Electron Creation)



Probability for an  
Electron to Reach  
the Vacuum  
Surface  
(Random Walk)

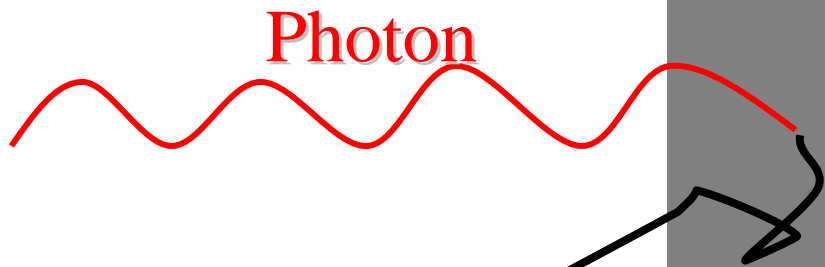


Photo-Electron

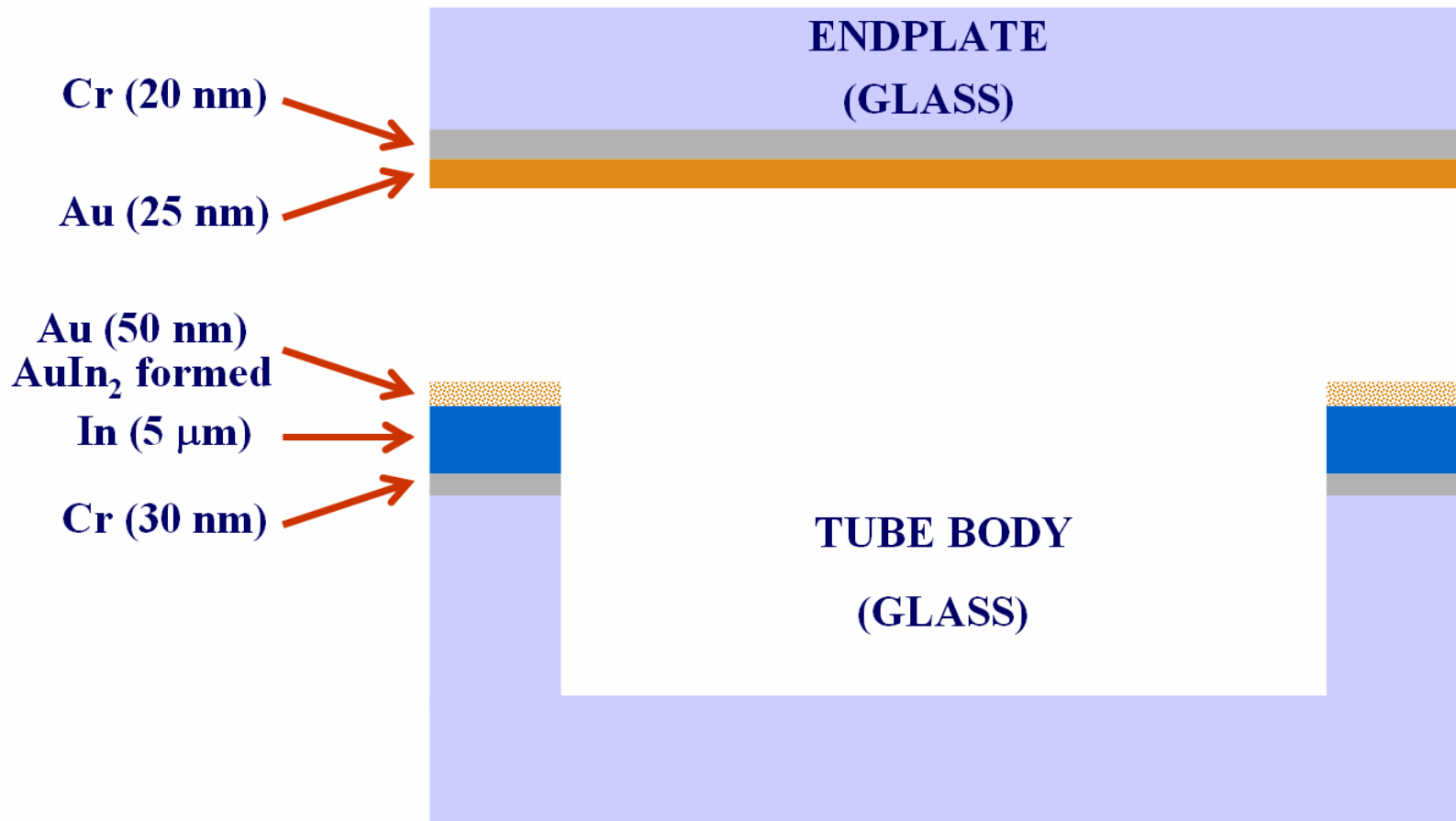
(e.g. Substrate,  
**Reflector**,...)

Vacuum

LOW  
PRODUCTION  
COST !

Photocathode

# New Oxide-Free Indium Sealing Method



See NIM-A paper, D. Ferenc, E. Lorenz et al. 2006 (in press)

ReFerence Panel Prototype (under construction)

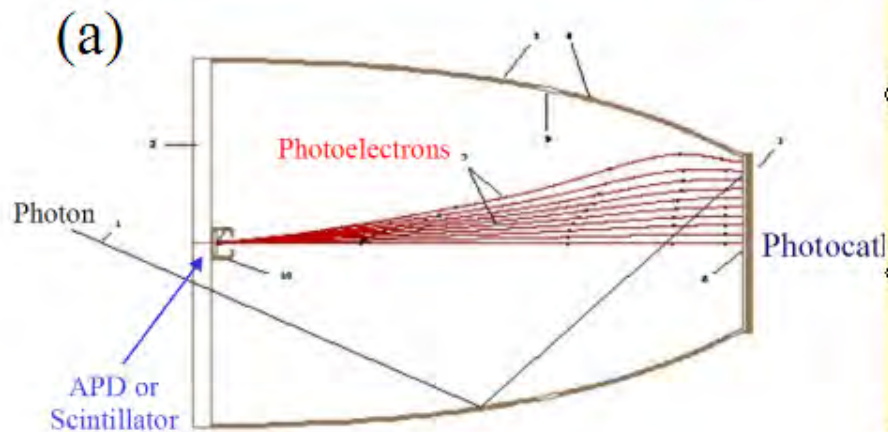


**ENDPLATE**

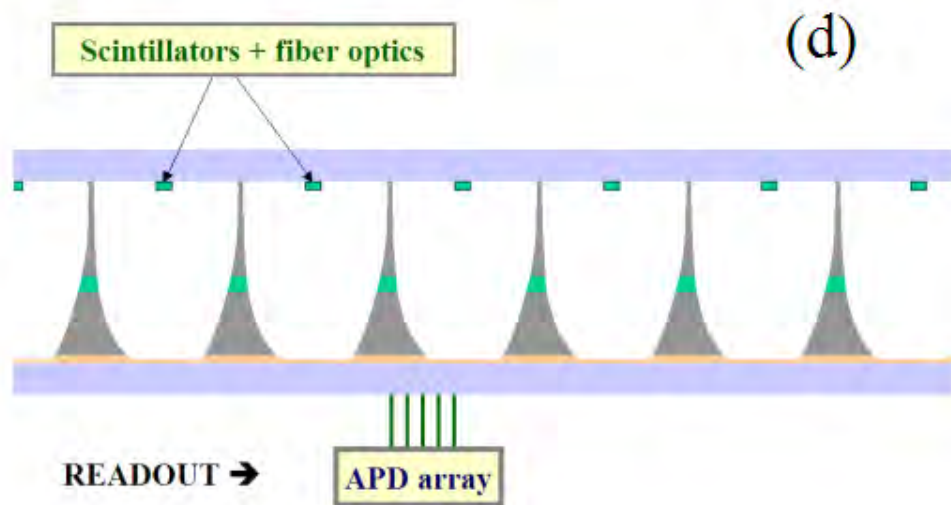
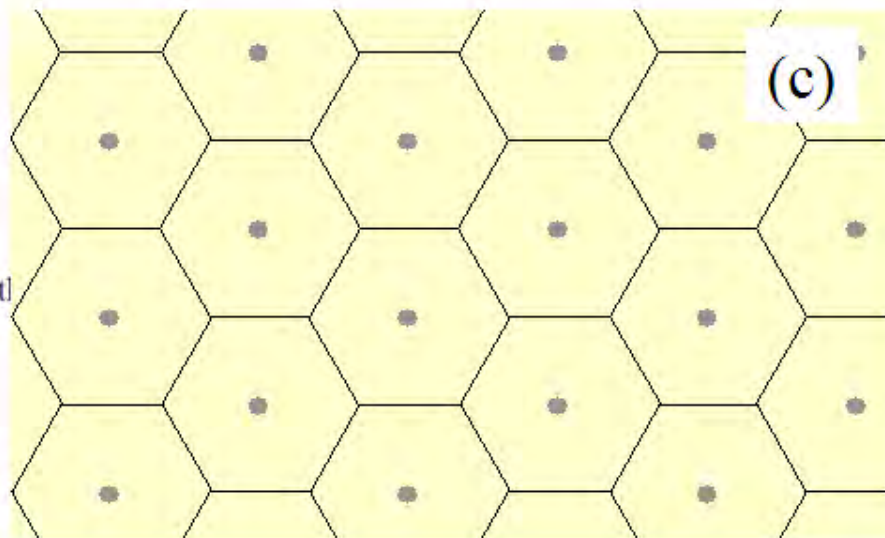
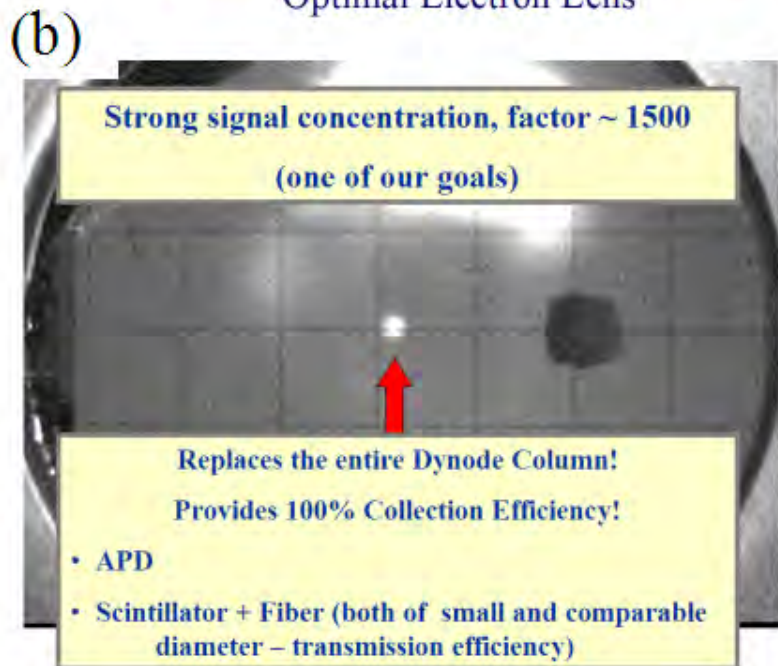
**TUBE  
BODY**



### Ideal Light Concentrator



### Optimal Electron Lens





# **‘ArcaLux’**

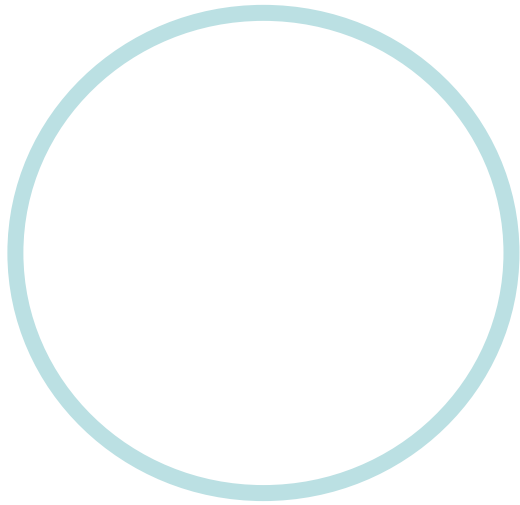
**(*lat.* light box)**

- **Full angular acceptance**
- **Perfect optical coupling to thick layers of water or scintillator**
- **High ambient pressure**
- **Extreme robustness**

**→ SPHERICAL CONFIGURATION**

- **Immune to accidental exposure to high light intensities**

**→ LIGHT AMPLIFIER (G-APDS)**



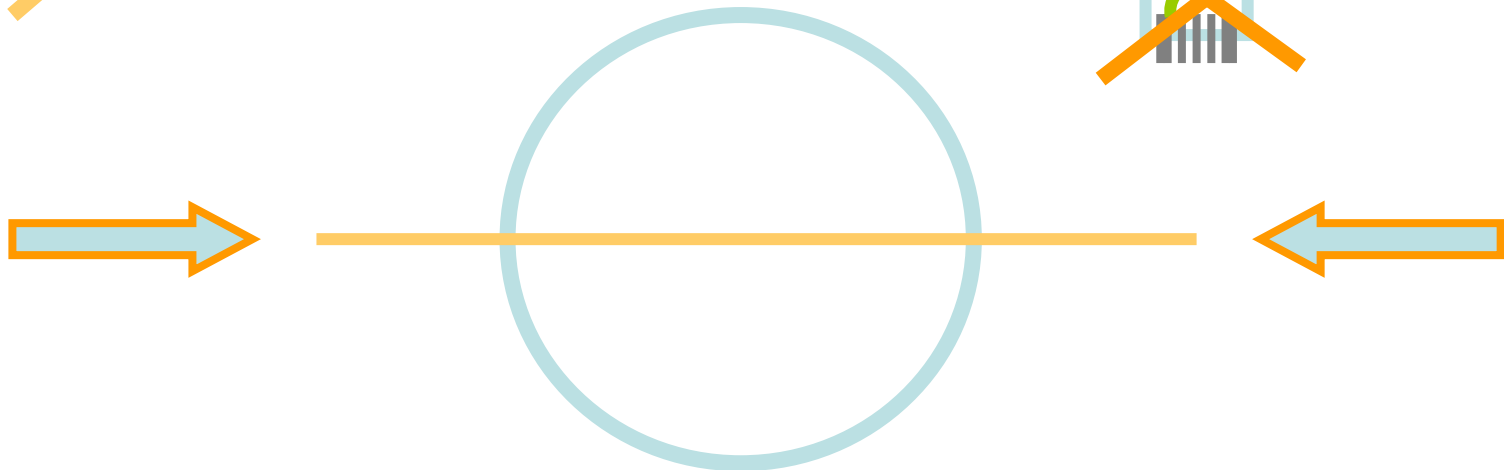
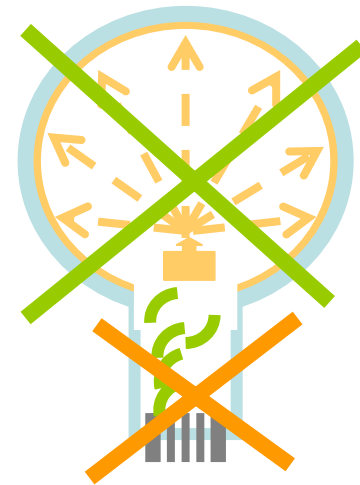
?

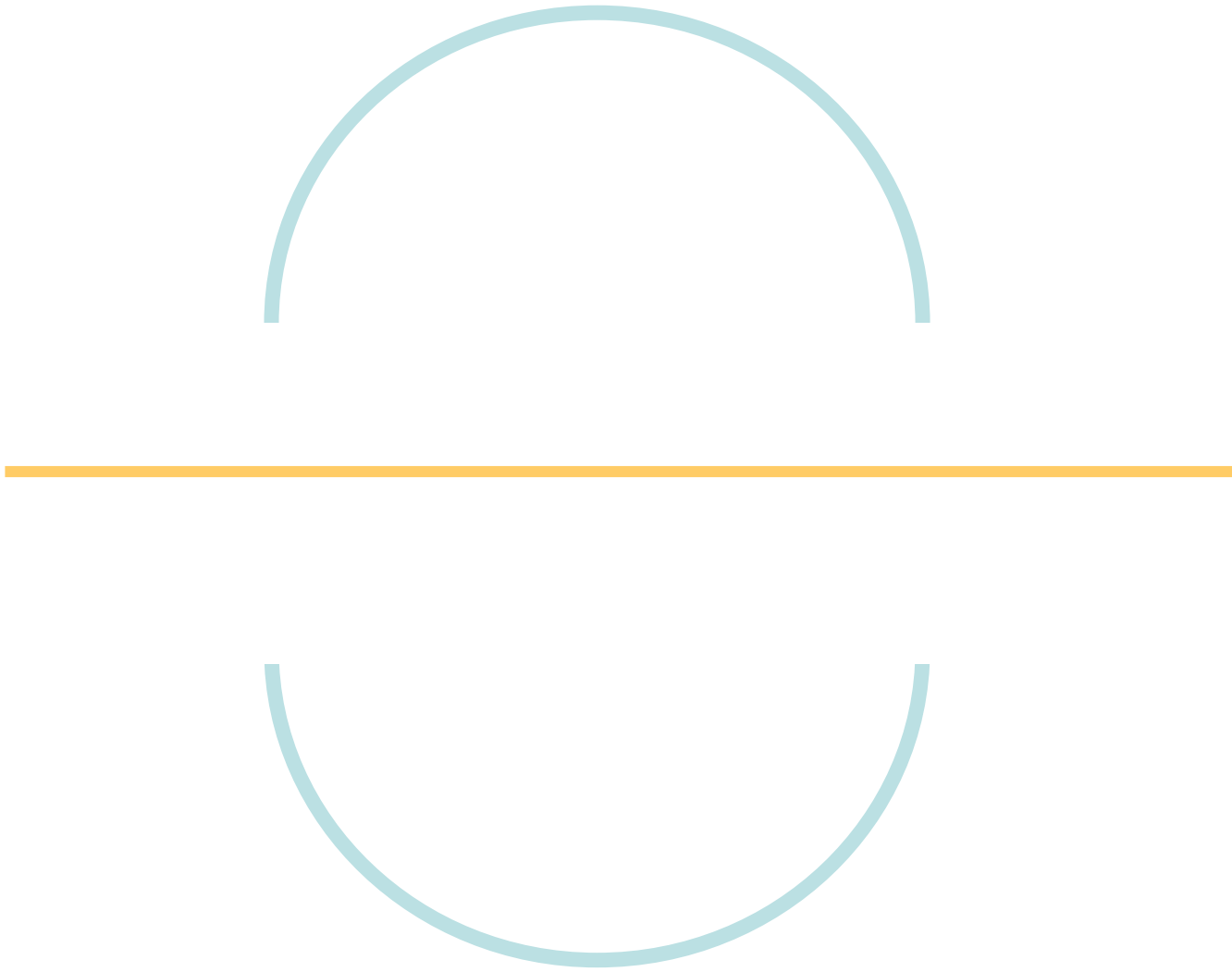


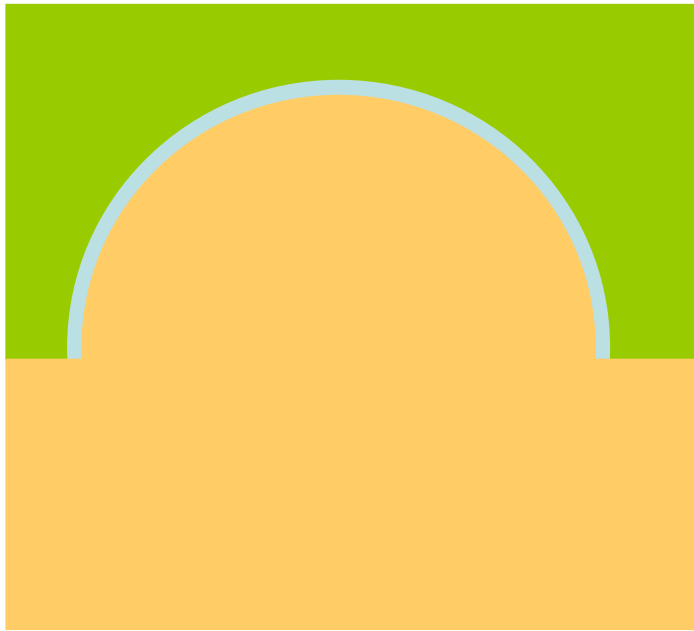
**Mass production**  
**High performance**

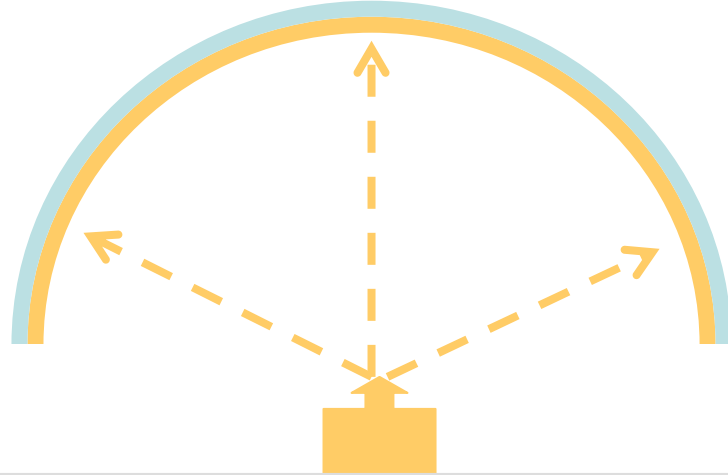
**COMPONENTS:**  
**Industrially**  
**mass-produced**

**ASSEMBLY:**  
**Production-line**









**vacuum**



?

## **Special marriage:**

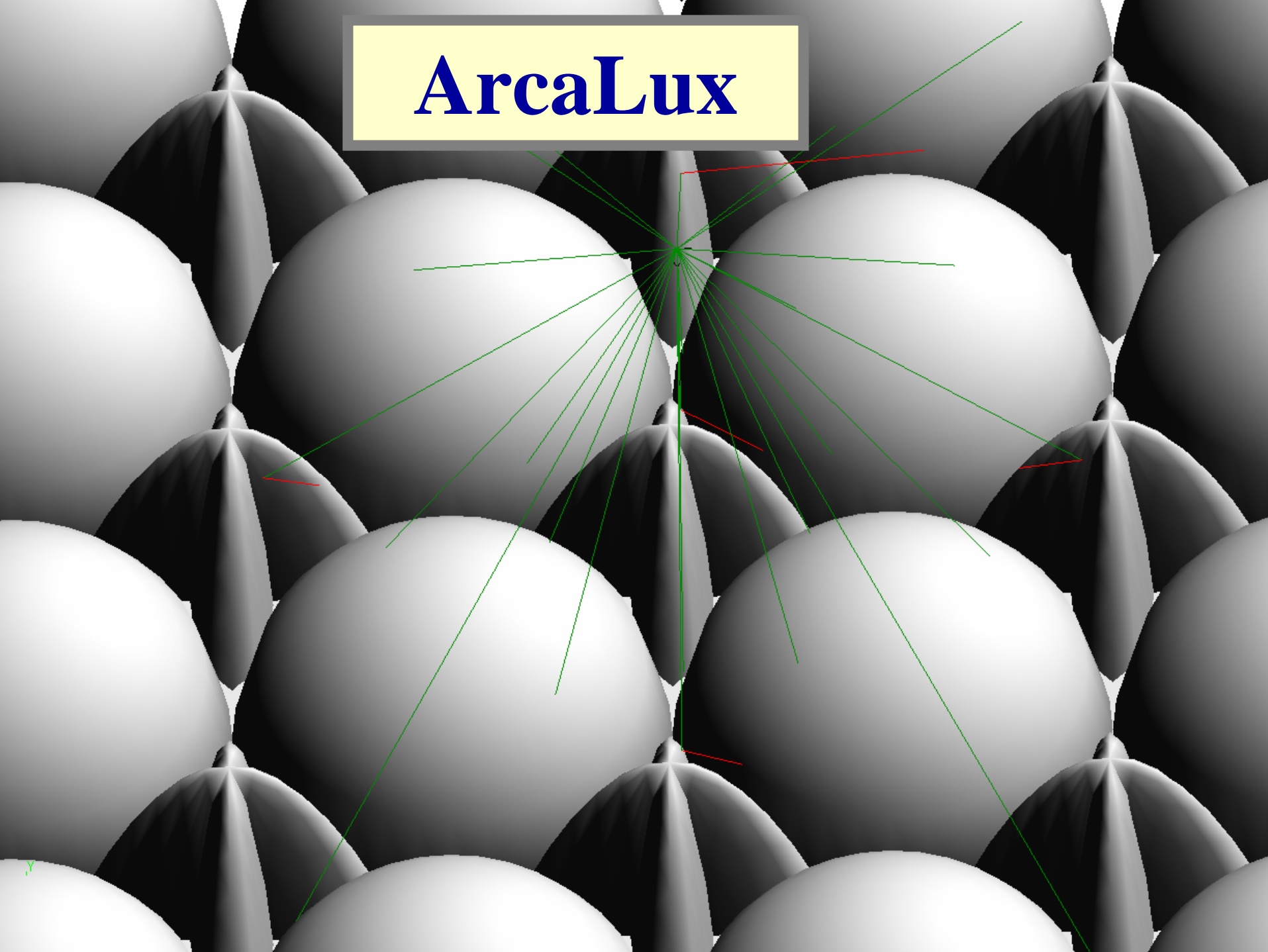
**~ 0% dead area**

**Long-lasting – the internal pollution - internally absorbed**

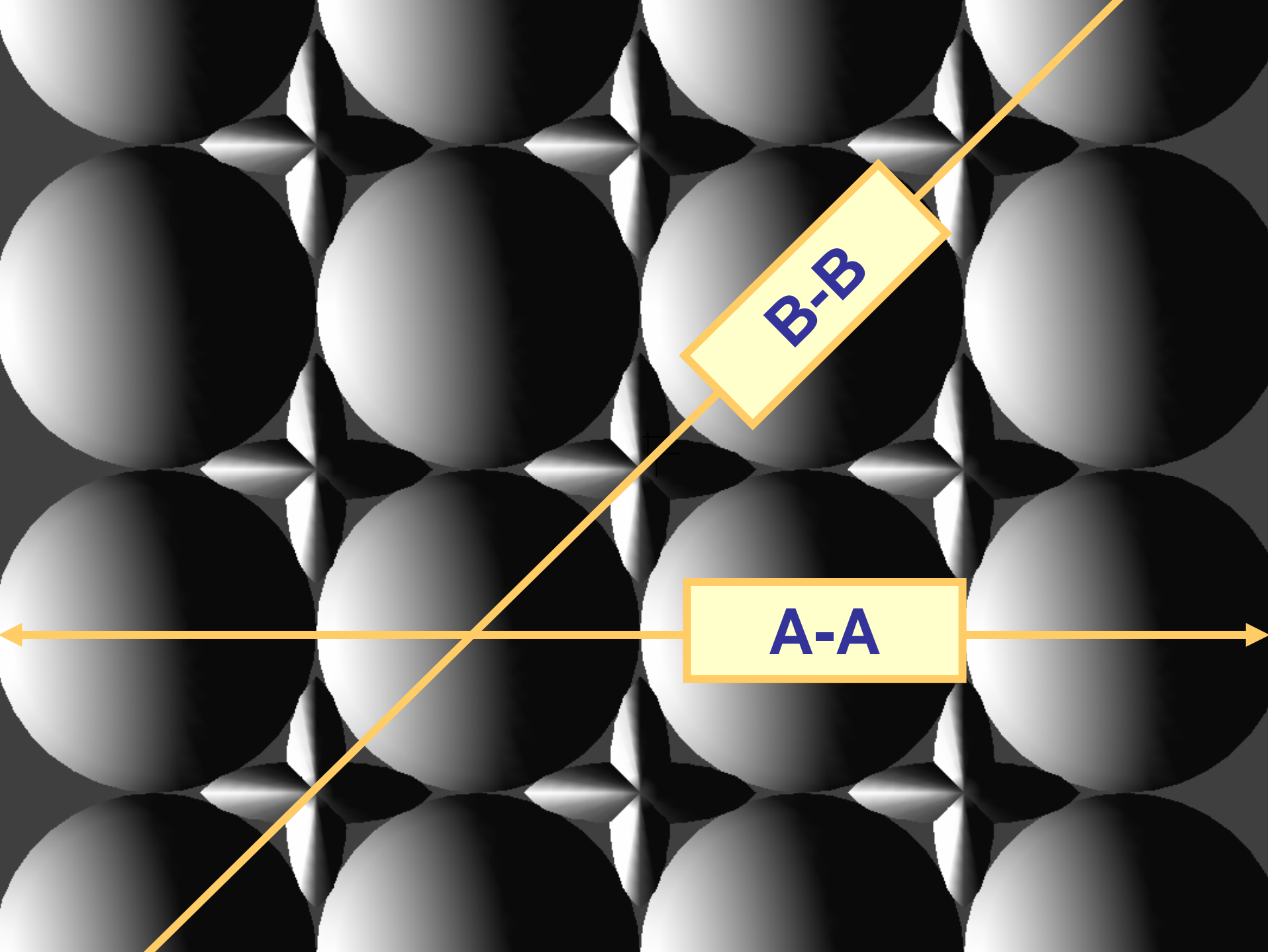
**Highly resistant to pressure from outside**

**Ready for mass-production**

# ArcaLux

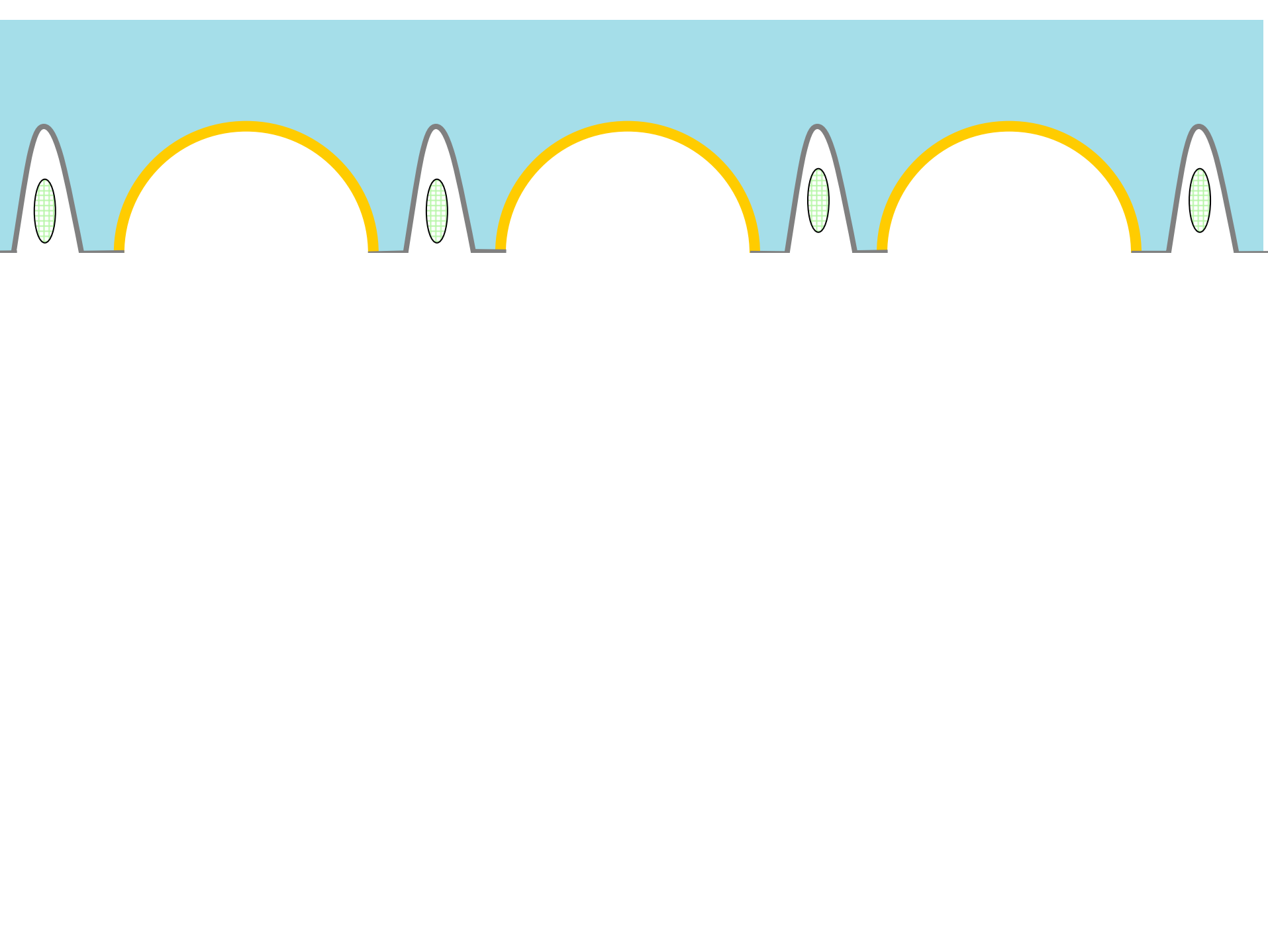


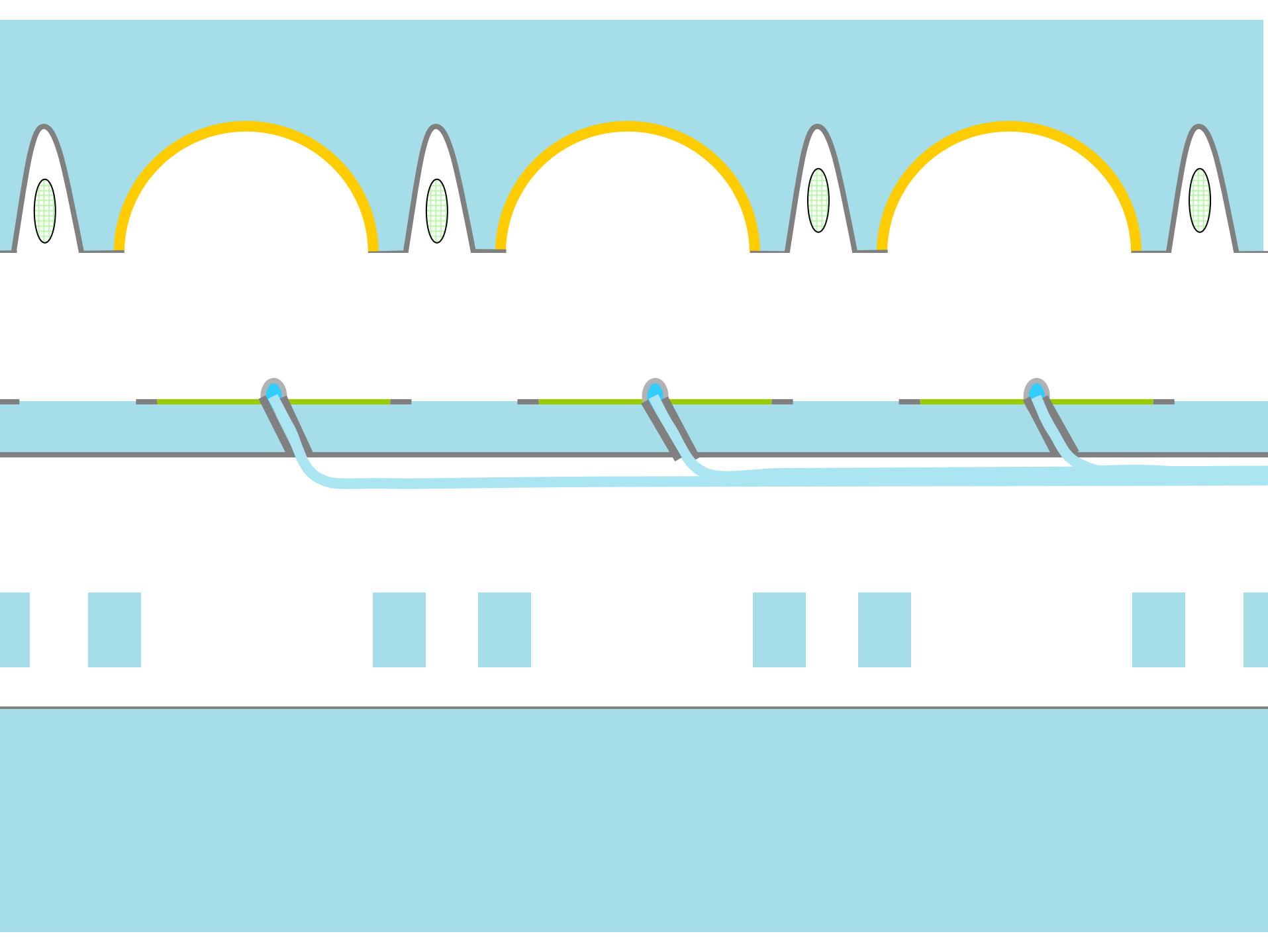


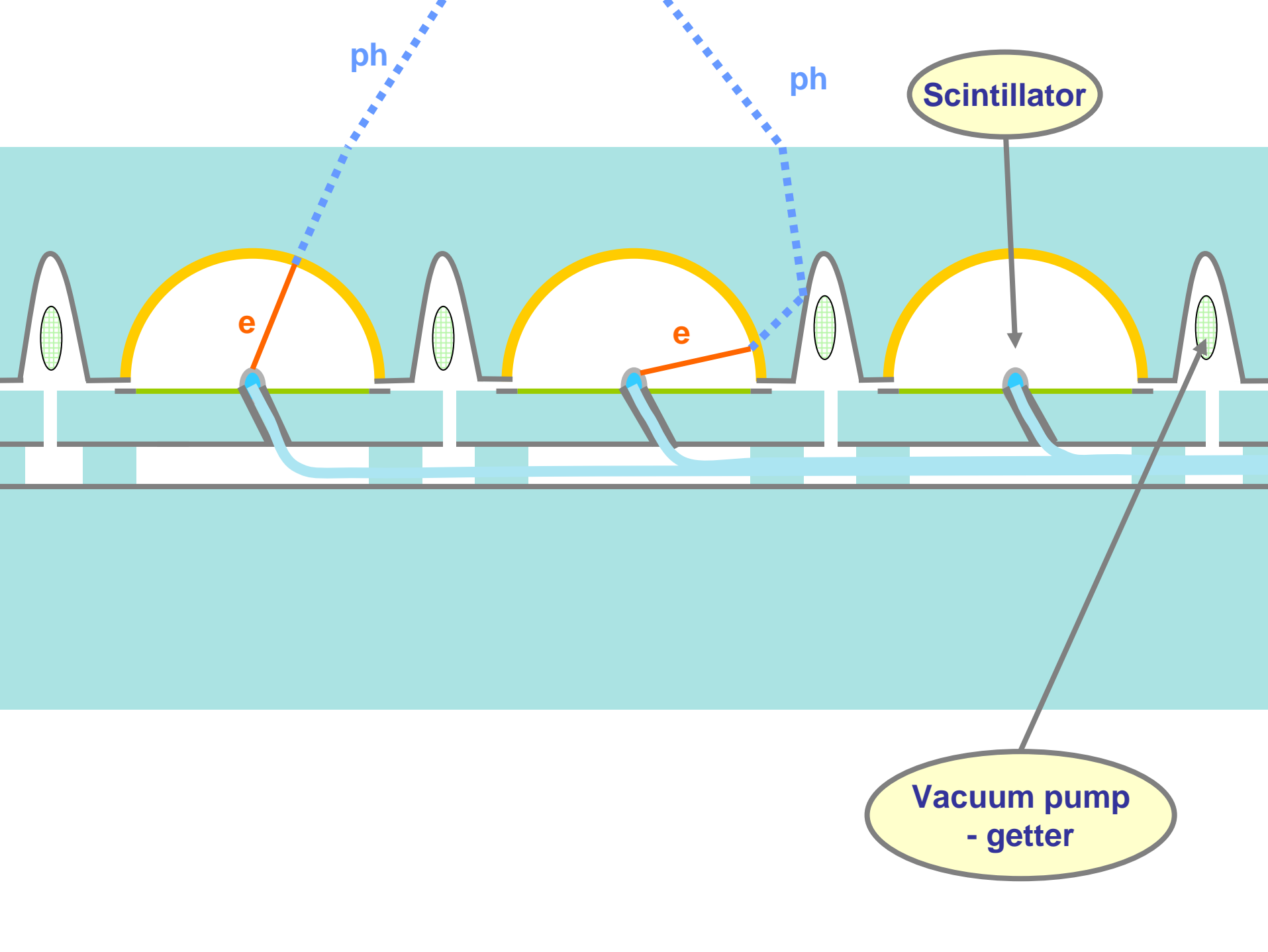


**B-B**

**A-A**







ph

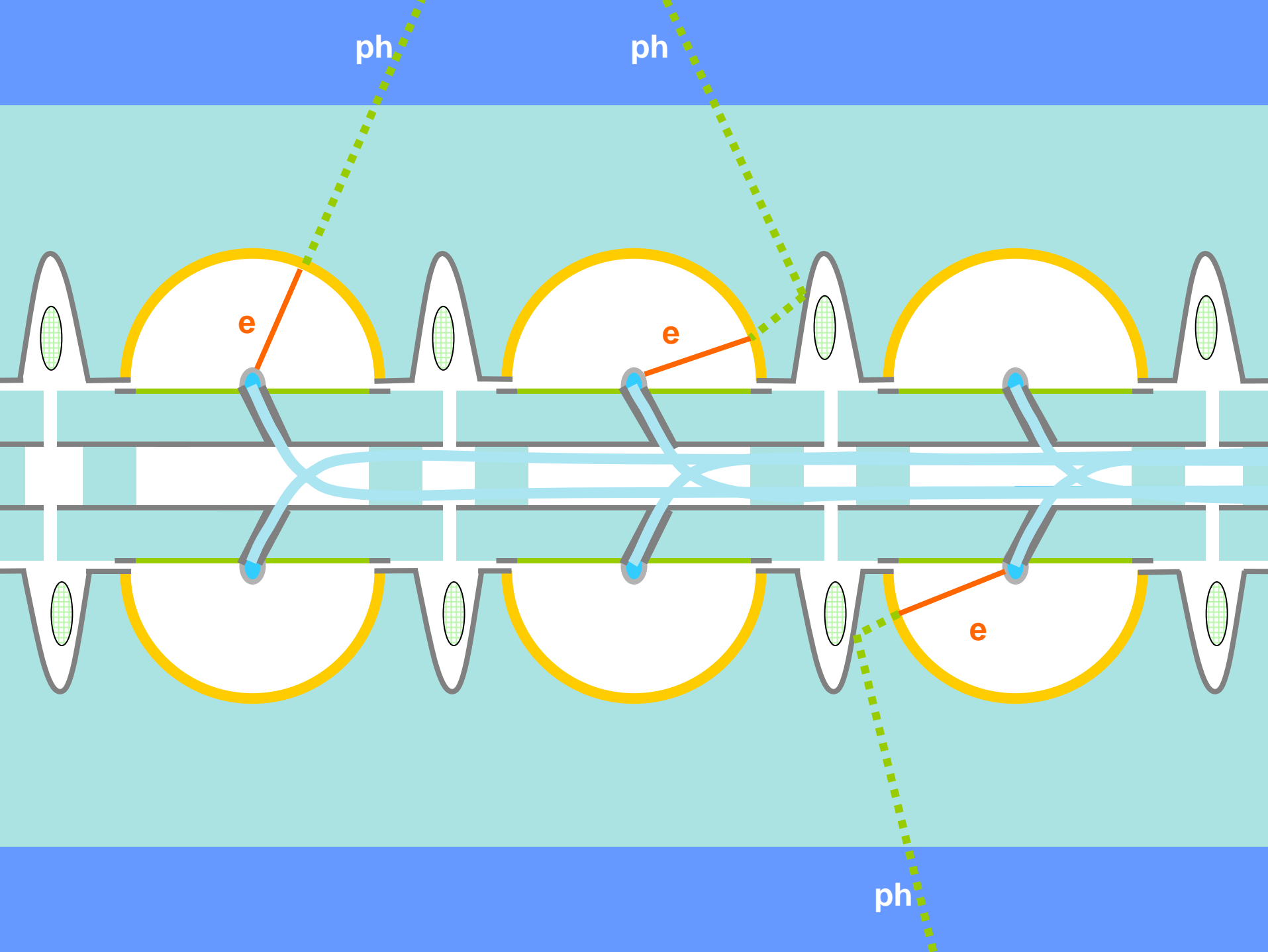
ph

Scintillator

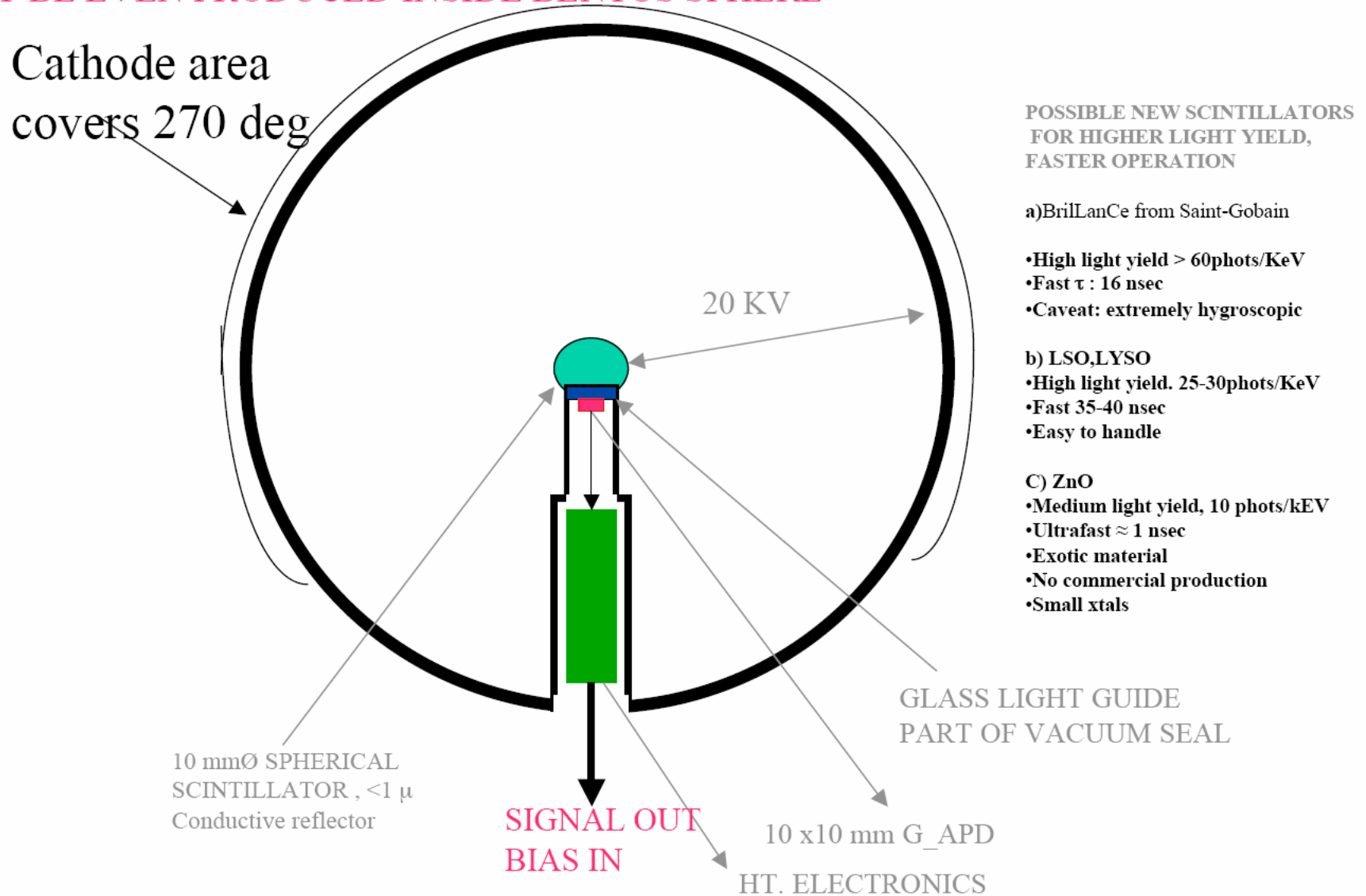
e

e

Vacuum pump  
- getter



A SPHERICAL SOLUTION WITH SPHERICAL SCINTILLATOR, SIMPLE PRODUCTION  
 5 STERAD, MINIMAL TIME JITTER, ELECTRONICS CAN BE LOCATED IN STEM  
 MAY BE EVEN PRODUCED INSIDE BENTOS SPHERE



# THE QUASAR

IMPROVED VERSION OF THE SMART PMT

- LARGE ACTIVE AREA/TOTAL VOLUME
- SYMMETRIC PHOTOELECTRON COLLECTION
- PRACTICALLY 100%PHOTOELECTRON COLL.EFFICIENCY
- NO NEED FOR BLEEDER CURRENT -> VERY LOW HT POWER
- ALREADY IN LONGTERM USE IN LAKE BAIKAL
- RELATIVELY CHEAP
- CAN DETECT SINGLE PHOTOELECTRONS,
- F-FACTOR  $\approx 1.3$

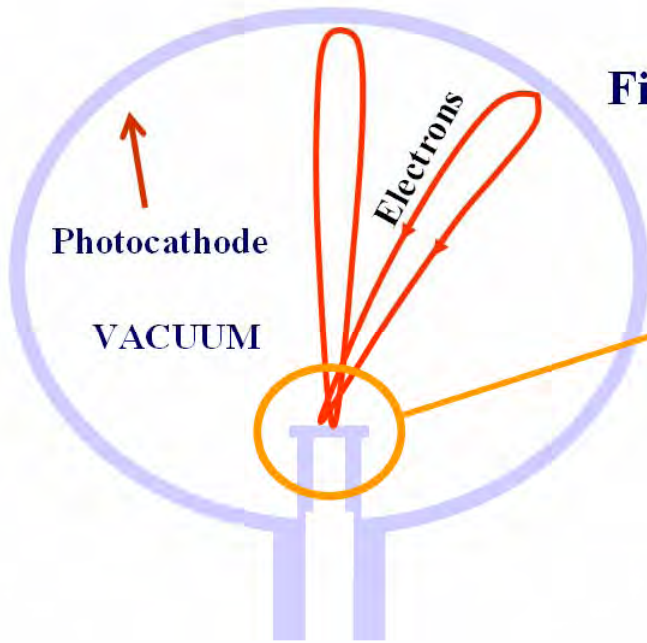
- CRYSTAL WITH LONG DECAY TIME
- RELATIVELY LOW LIGHT YEALD
- PRODUCTION STOPPED

THE FOLLOWING TESTS HAVE BEEN CARRIED OUT WITH A QUASAR

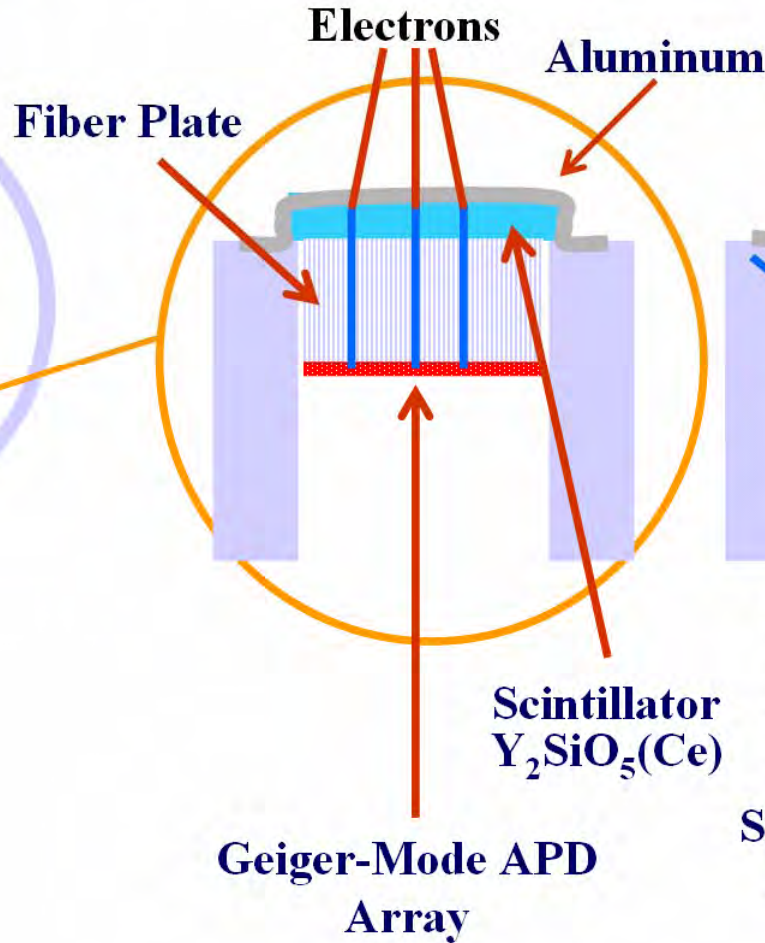
SECONDARY  
PMT TO READ OUT  
CRYSTAL



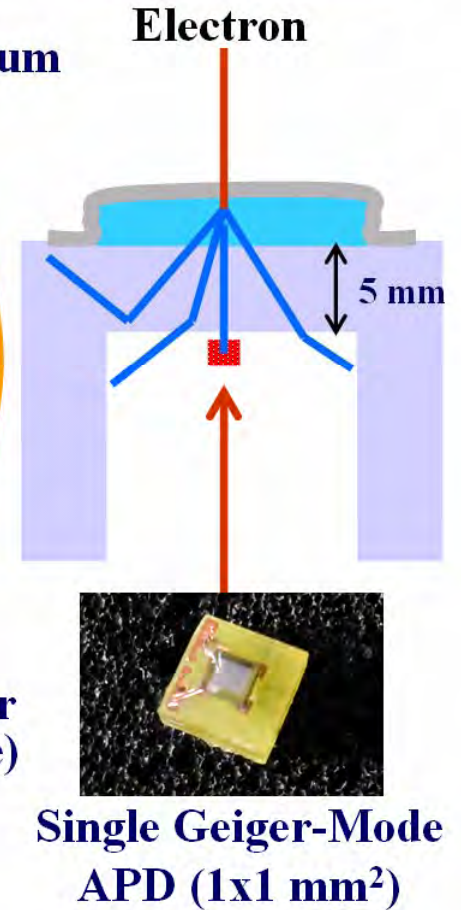
**HEMISPHERICAL  
LIGHT AMPLIFIER**



**THE  
ULTIMATE  
DESIGN**

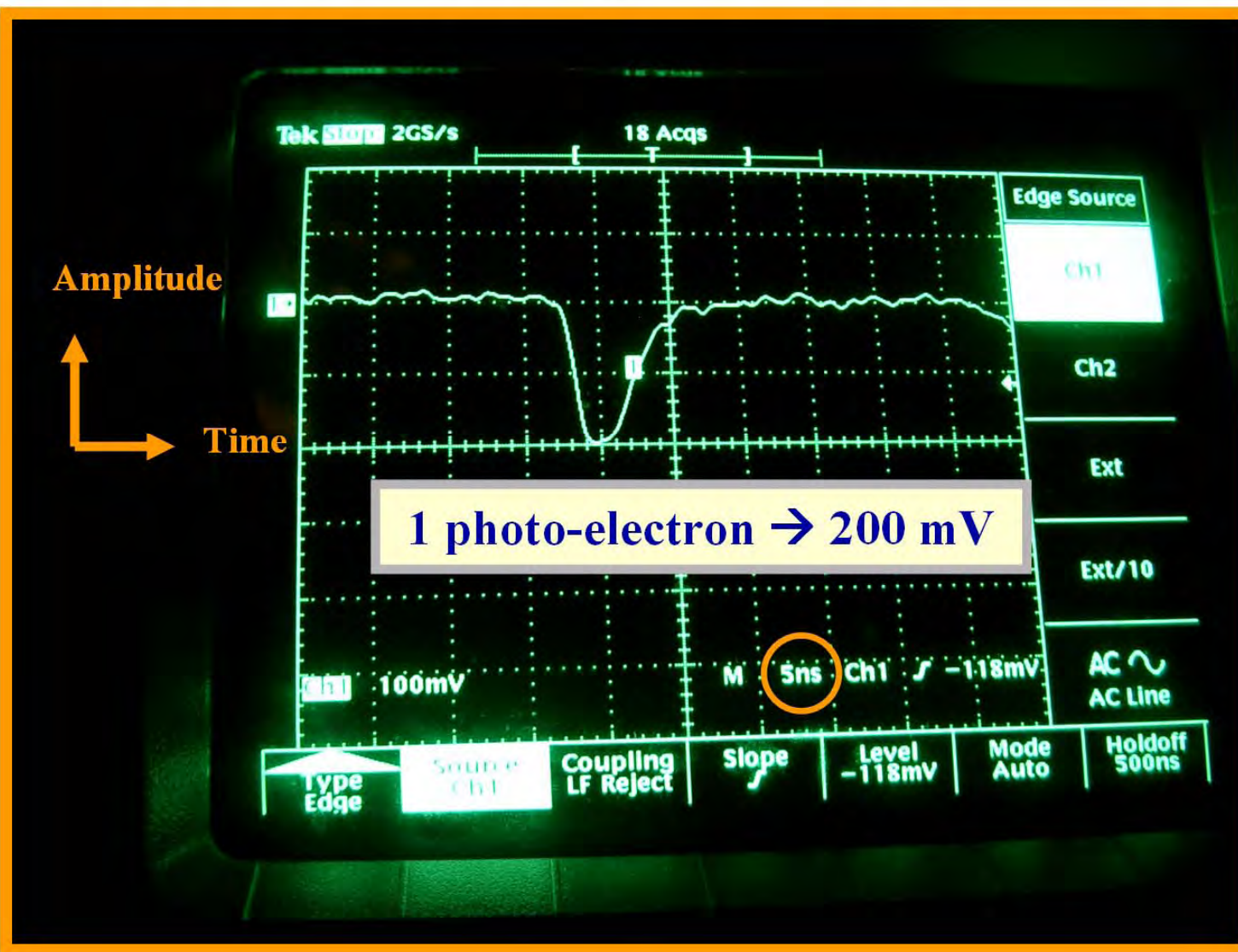


**CURRENT  
PROTOTYPE  
SETUP**





# A Typical Single-Photon Signal in the Geiger-mode APD



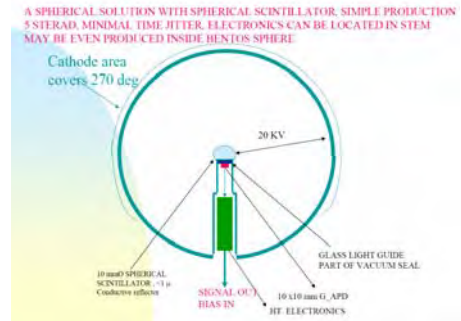
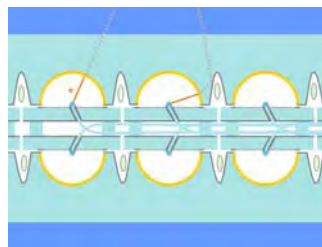
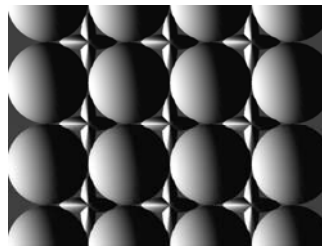
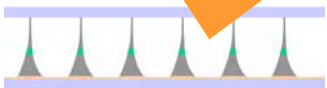
# Conclusion

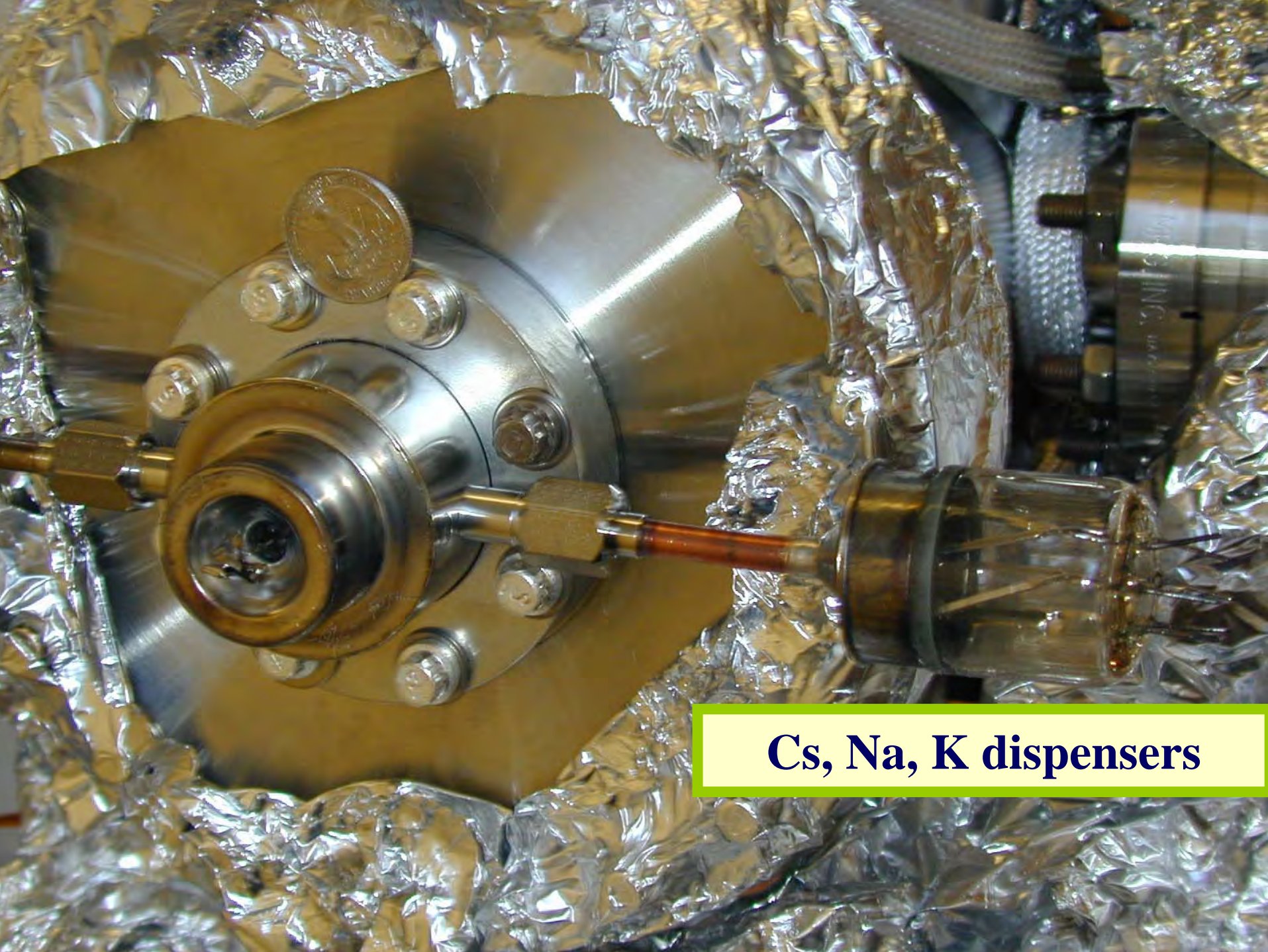
**ULTIMATE:  
FLAT-PANEL**

**INTERMEDIATE:  
HEMISPHERICAL  
Light Amplifier**

**ReFereNce**

**ArcaLux**





**Cs, Na, K dispensers**