Advanced Photodetection Concepts

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Eckart Lorenz

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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

ITRINSIC (n, γ, ν)

- HE Uranium
- ‘Any-Grade’ Plutonium

Weak radiation

INDUCED (γ)

NETRON ACTIVATION

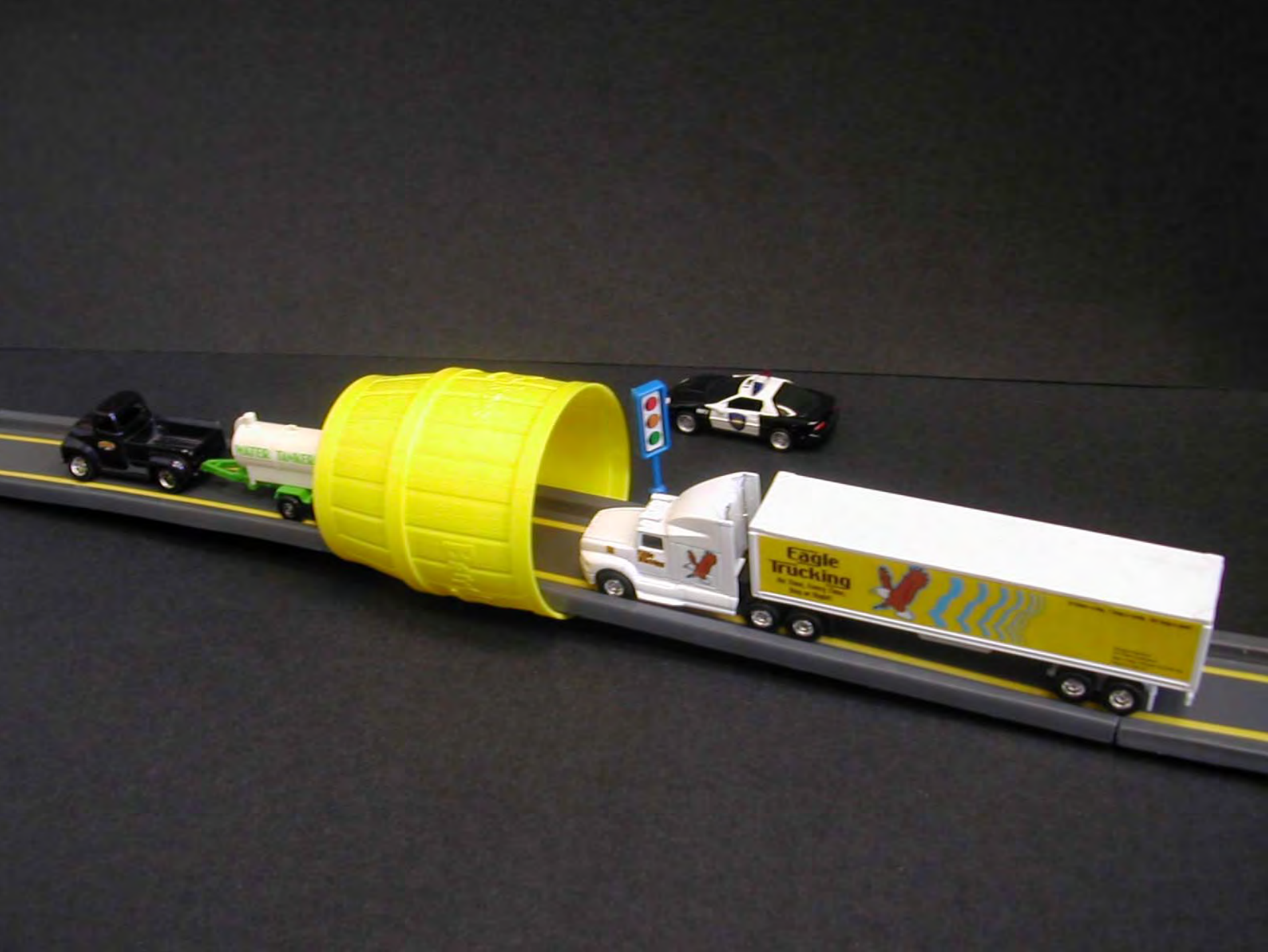
Limited to low (harmless) doses

DETECTION SYSTEMS

➔ VERY LARGE

(EMBEDDING)

Every bit of radiation is PRECIOUS


Eagle
Trucking

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 —

REP. BENNIE THOMPSON (D-MISS.) ON CHEMICAL PLANT SECURITY . . . . . Pg. 12

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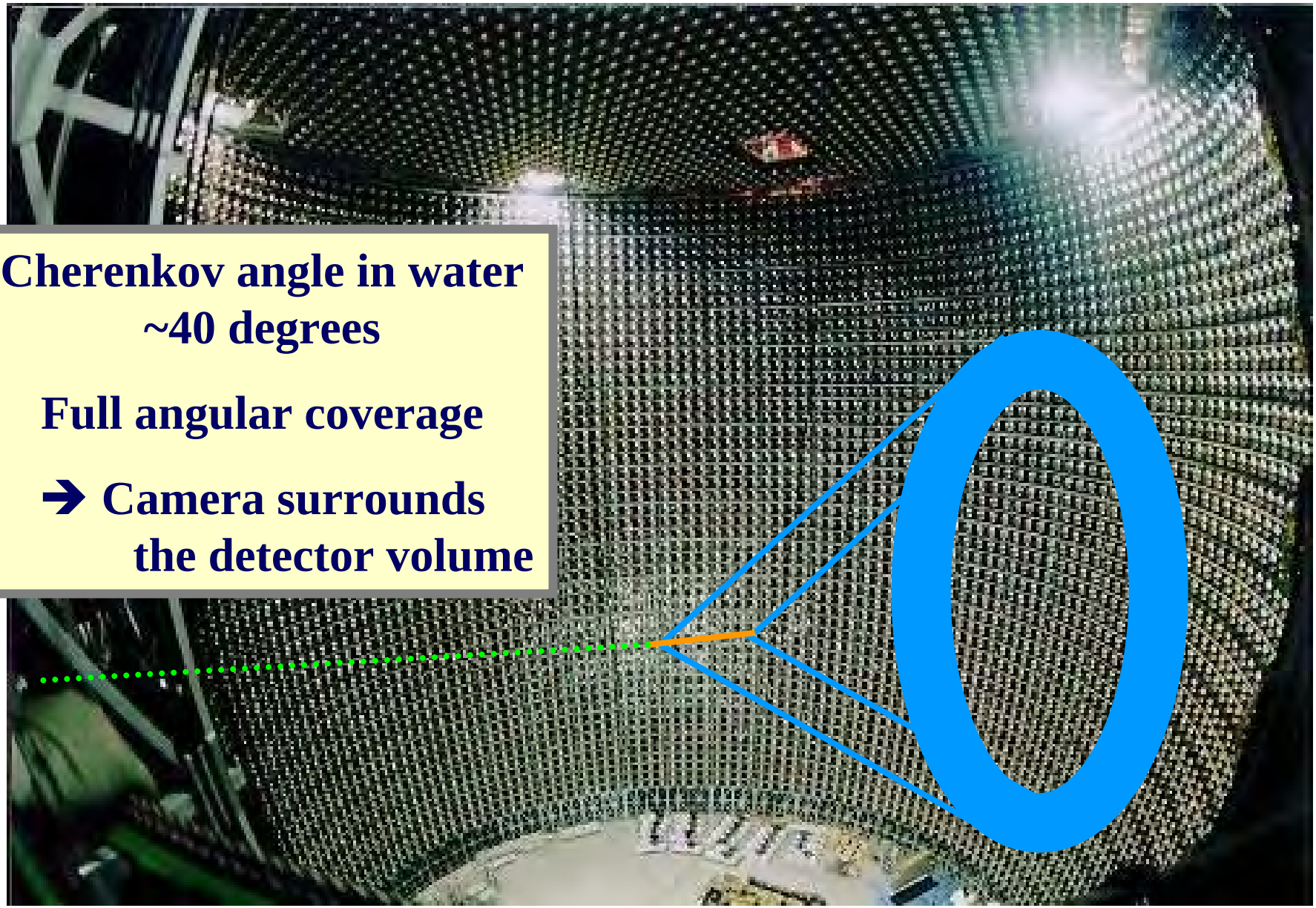
The Unbeatable Reality of Mr. Liouville



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)

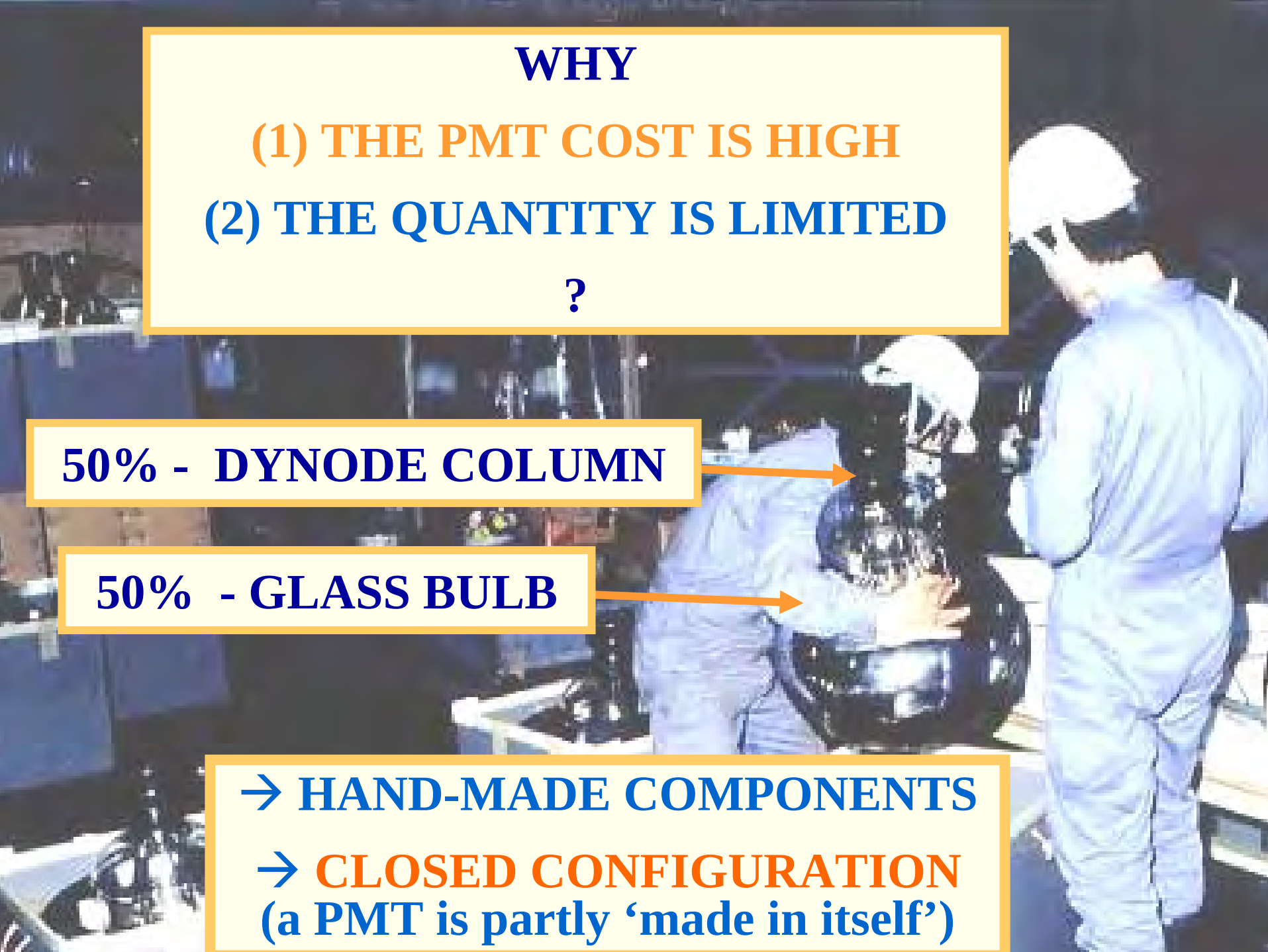
Irreducibly Large Illuminated Area

↓

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

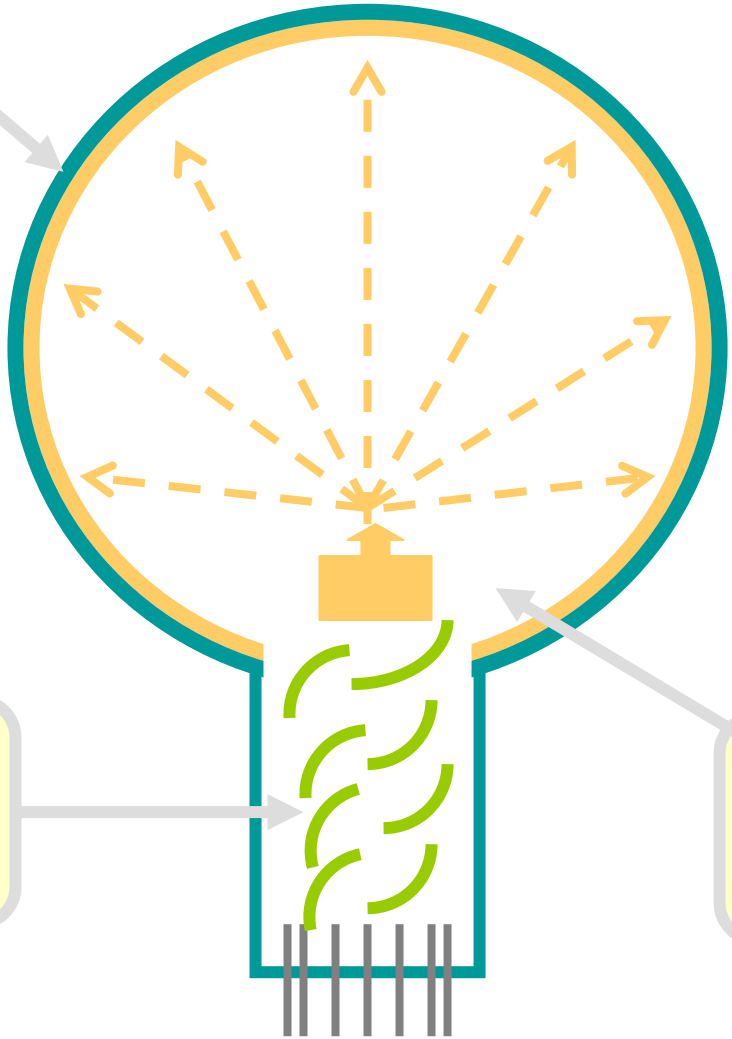
50% - GLASS BULB

→ HAND-MADE COMPONENTS

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

Every PMT – ‘its own factory’

handmade

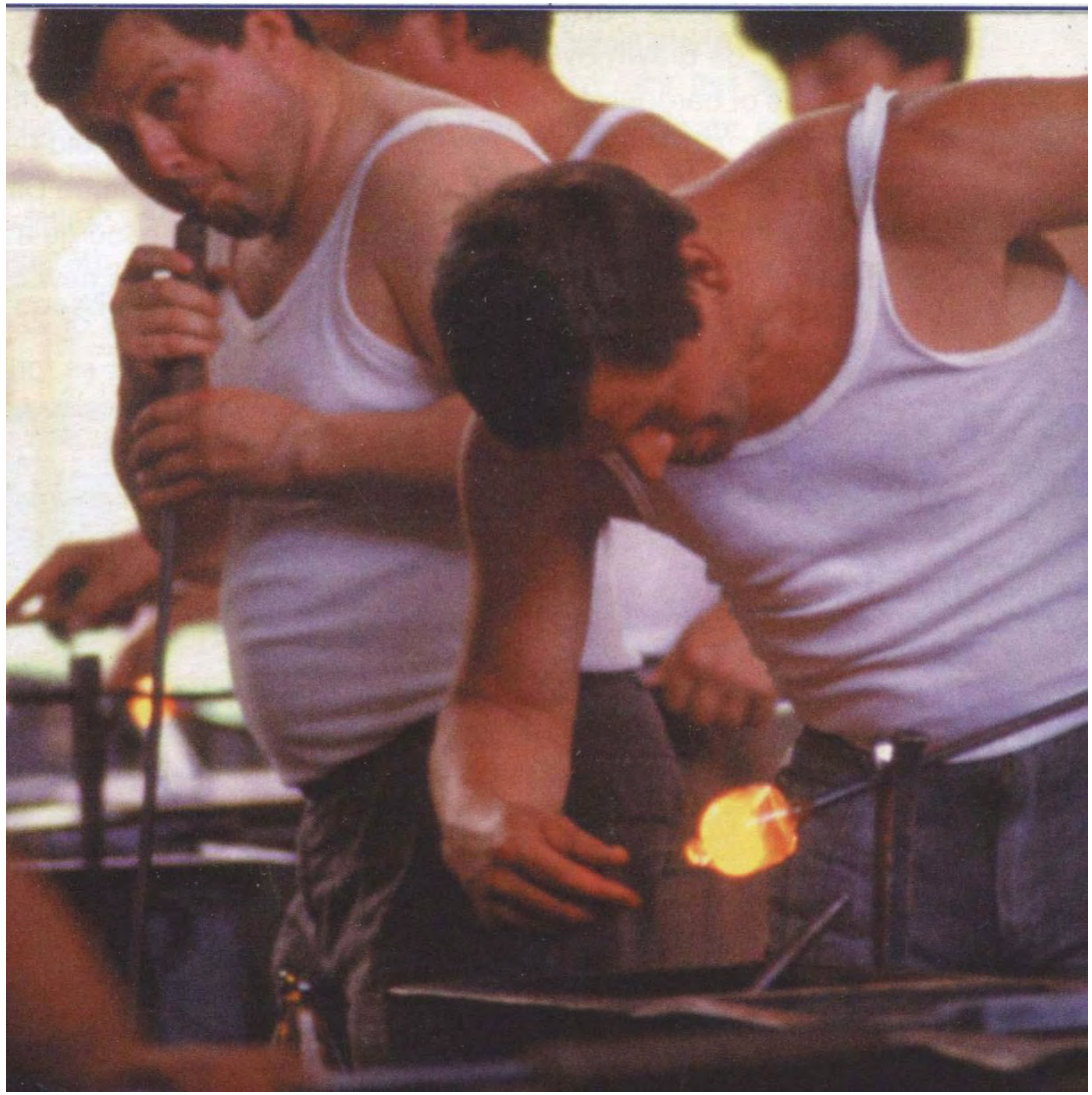


handmade

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^2

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

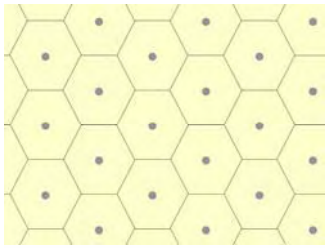
PHOTON→ELECTRON CONVERSION:
CLASSICAL PHOTOCATHODE

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

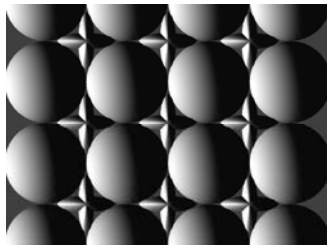
Advanced Photosensors

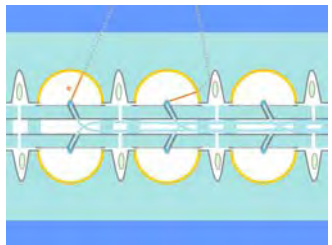
ULTIMATE: FLAT-PANEL

ReFerence

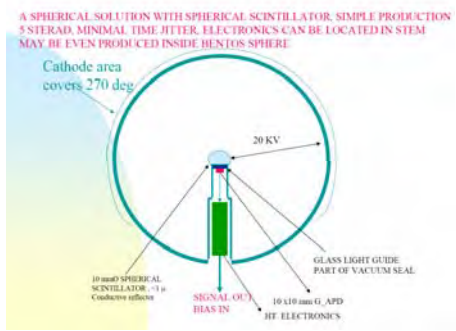


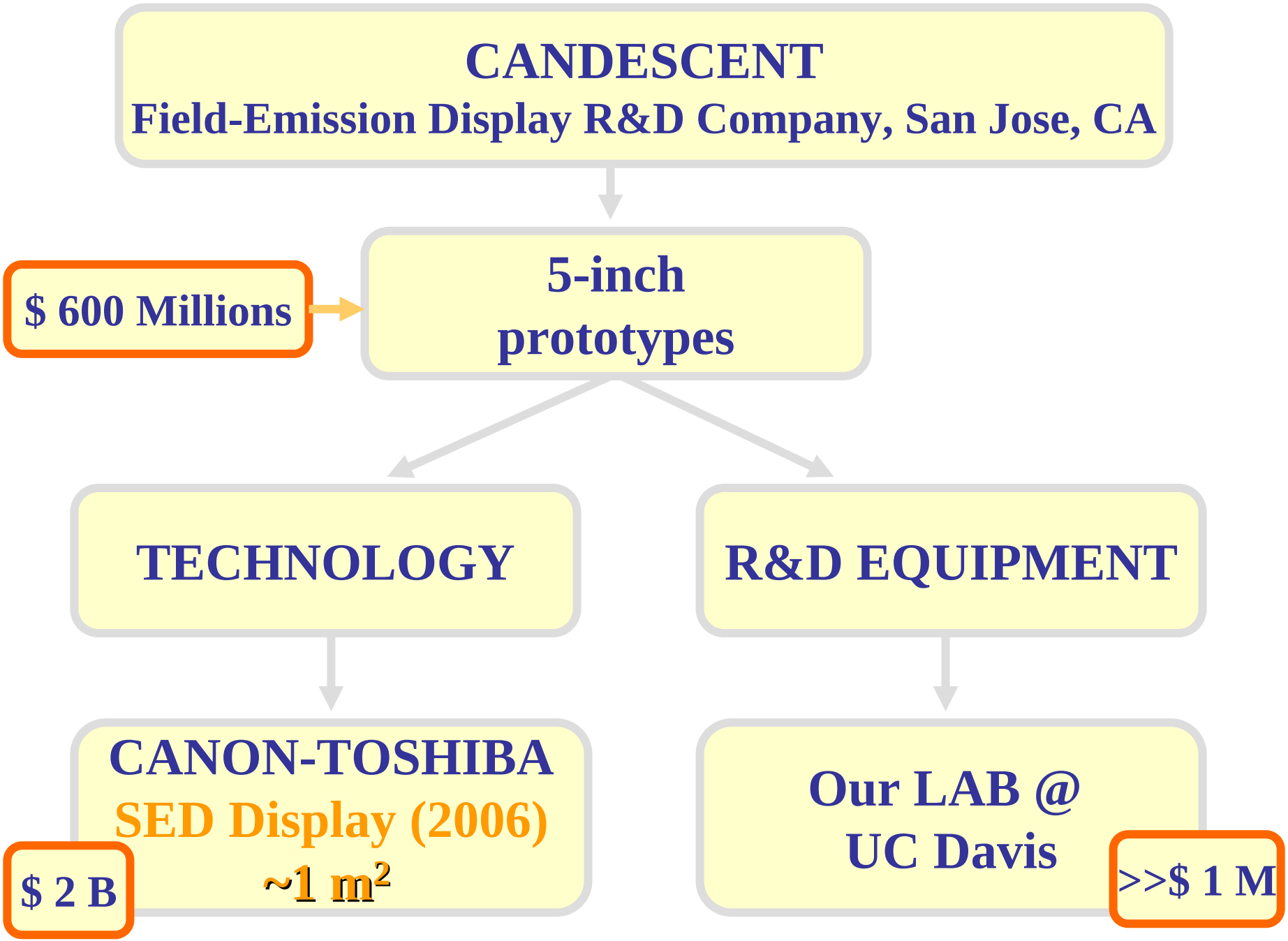
ArcaLux

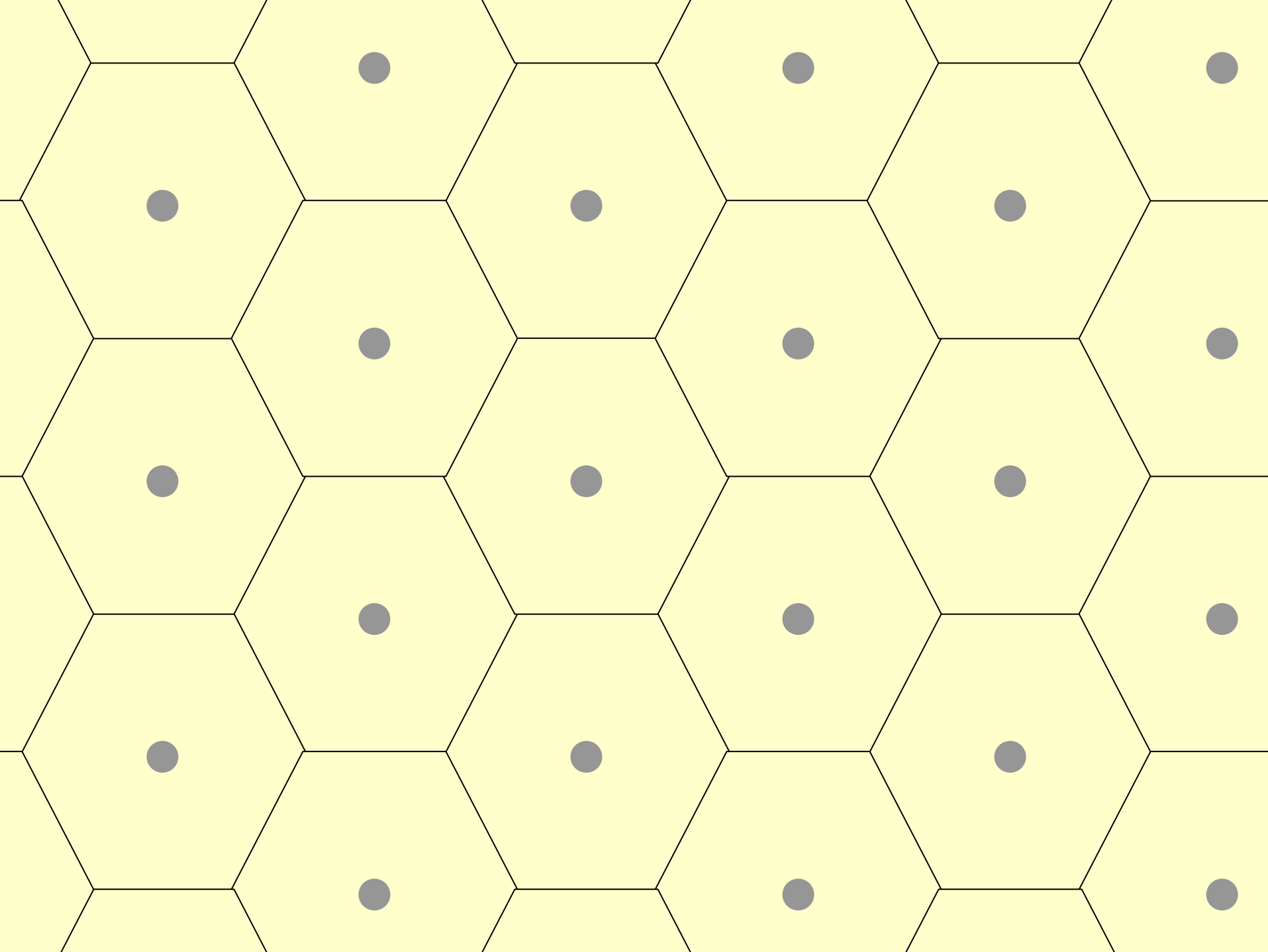




INTERMEDIATE: HEMISPHERICAL Light Amplifier

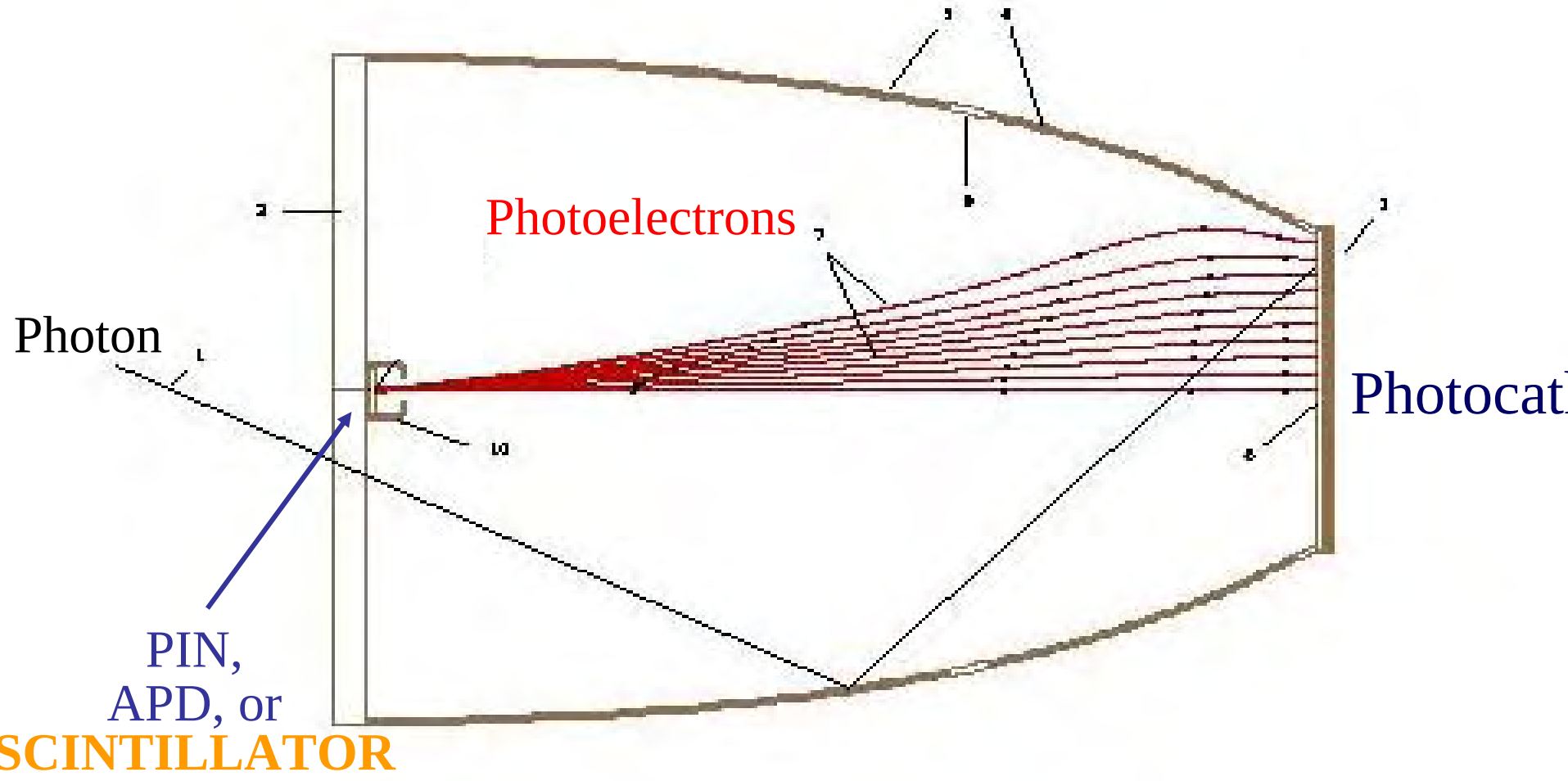



CANDESCENT
Field-Emission Display R&D Company, San Jose, CA
$ 600 Millions
5-inch
prototypes
TECHNOLOGY
R&D EQUIPMENT
CANON-TOSHIBA
SED Display (2006)
~1 m2
$ 2 B
Our LAB @
UC Davis
>>$ 1 M



Ideal Light Concentrator

(takes the maximum of Liouville!)



Optimal Electron Lens

Ideal Light Concentrator

(takes the maximum of Liouville!)

Photon

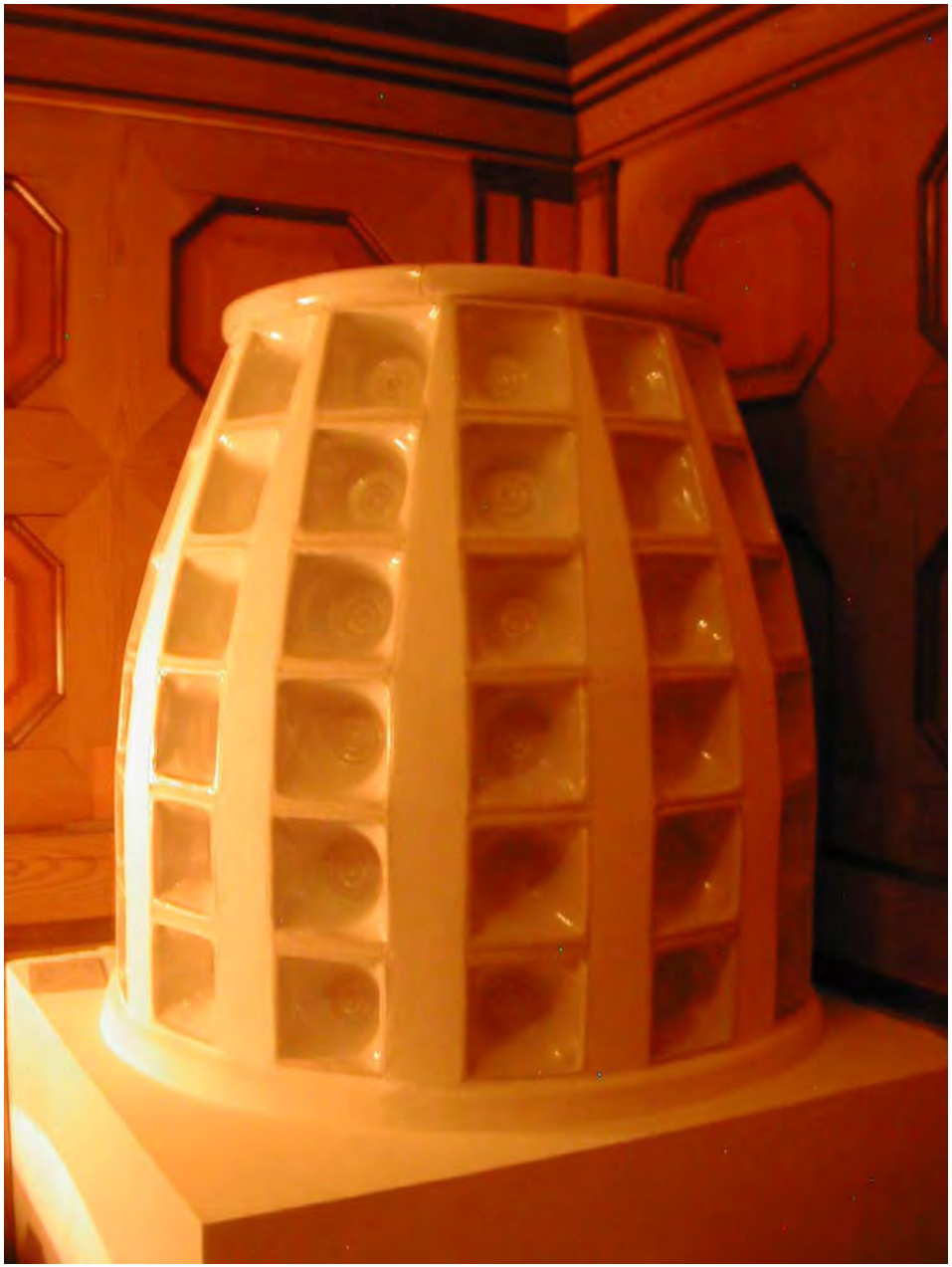
otocat

PIN,

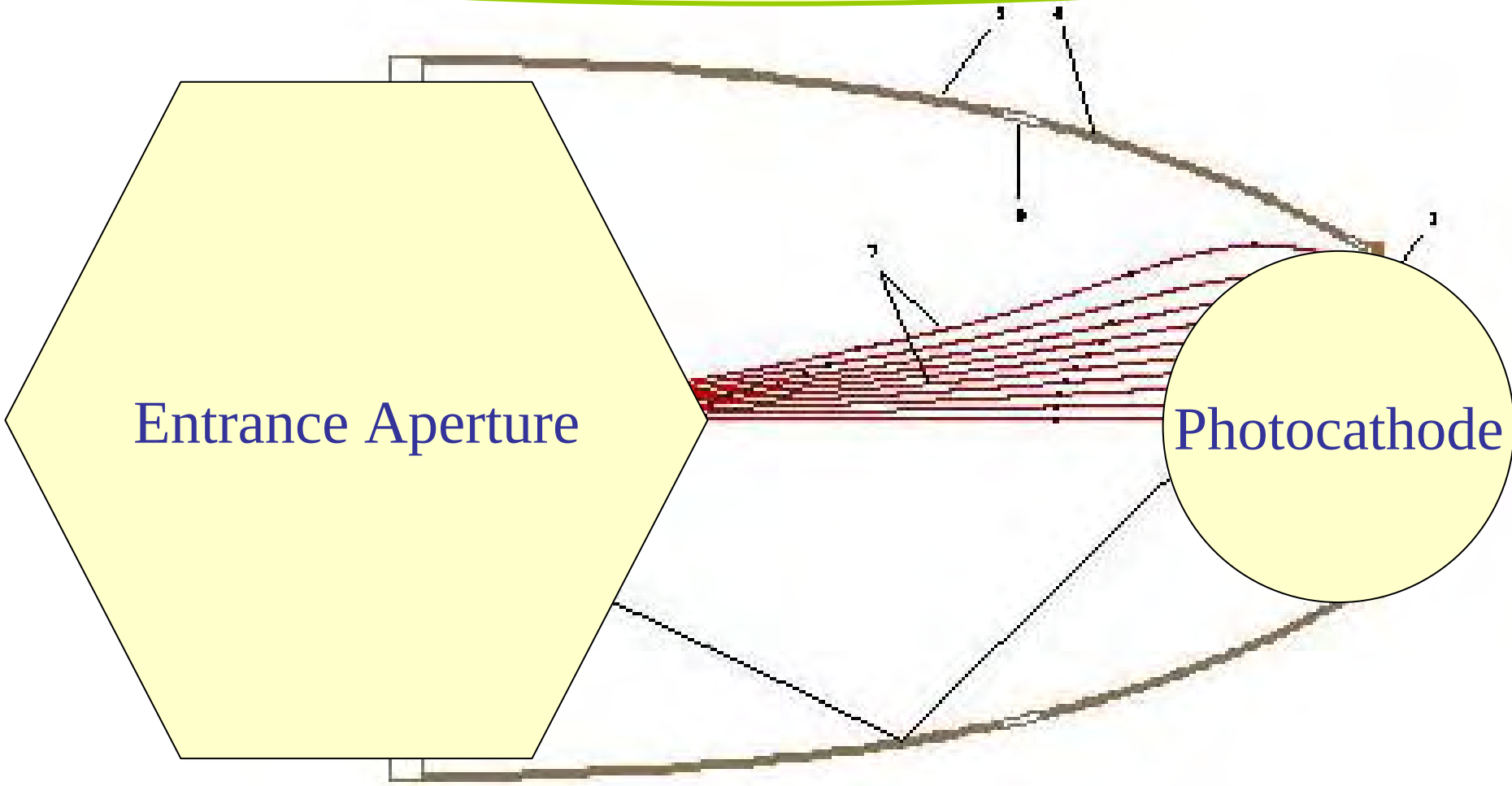
APD, o

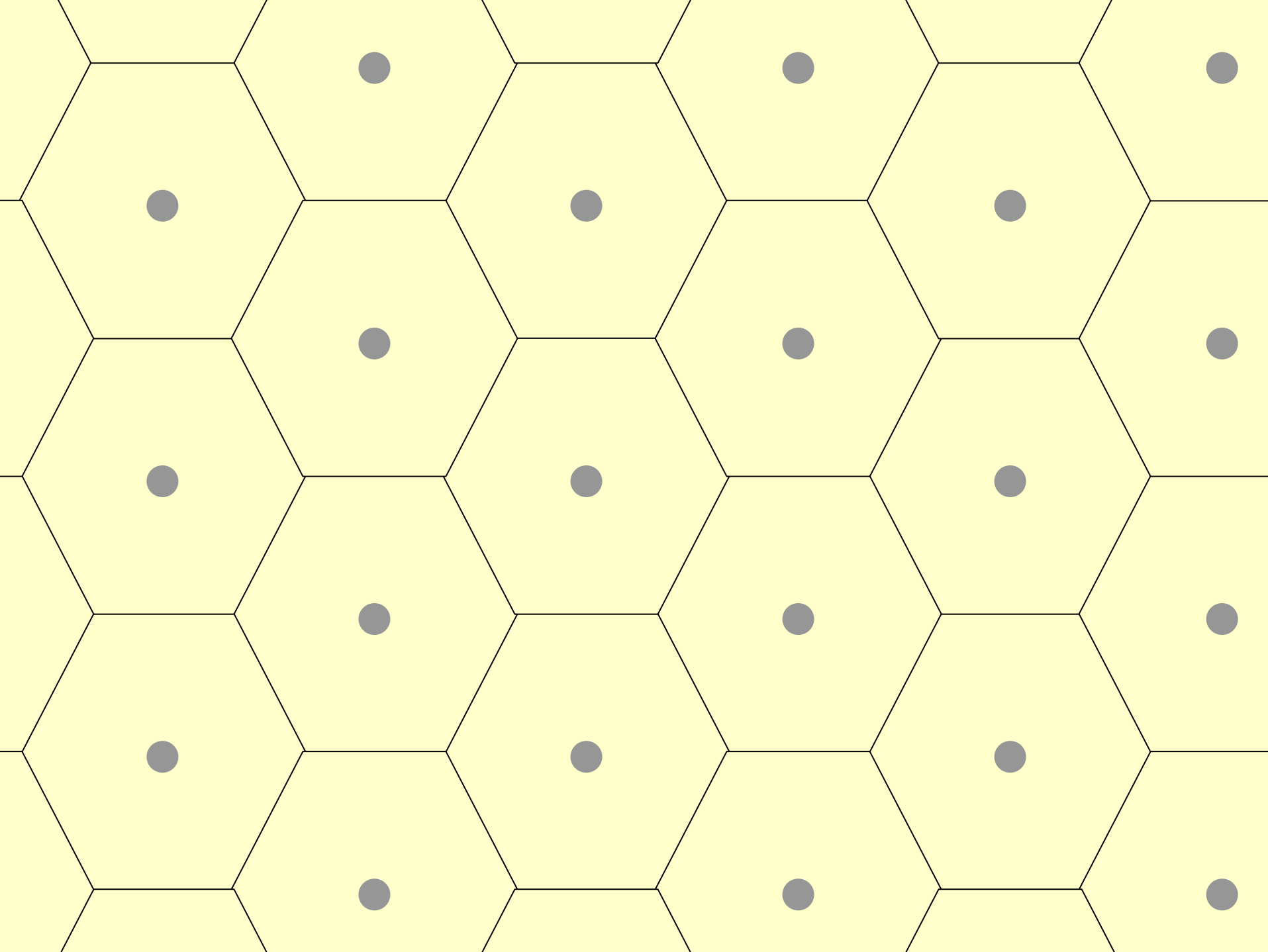
SCINTILLA

Optimal Electron Lens



Very Important: Hexagonal Packing





HAMAMATSU

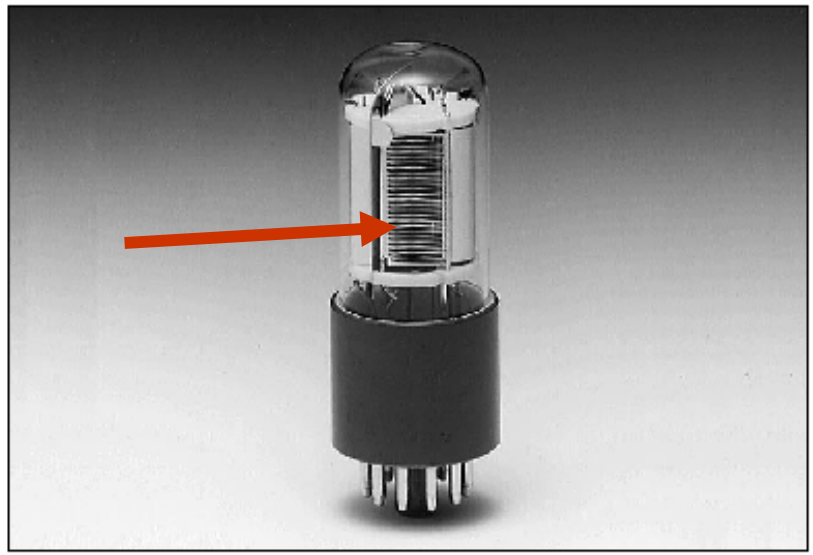
PRELIMINARY DATA
NOV. 1998

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 μA/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 ..... 10.5×10^5 A/W Typ.



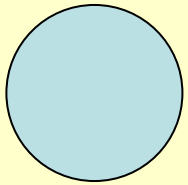
APPLICATIONS

- Fluorescence Spectrophotometers
- Fluorescence Immuno Assay
- SO_2 Monitor (UV Fluorescence)

PROTOTYPE DEVELOPMENT

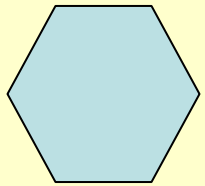
UNSEALED 1-PIXEL

CYLINDRIC



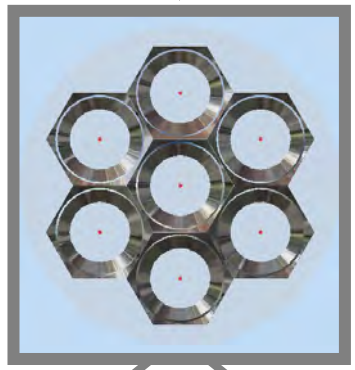
2001-2002

HEXAGONAL



2003

SEALED PANELS (7 pixels, 5 inch)



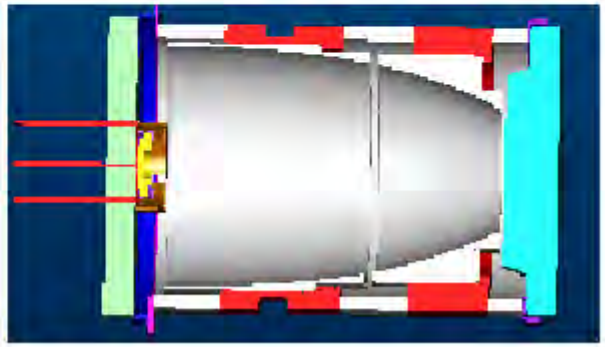
SEALED with In/Au

SEALED with SOLDER GLASS

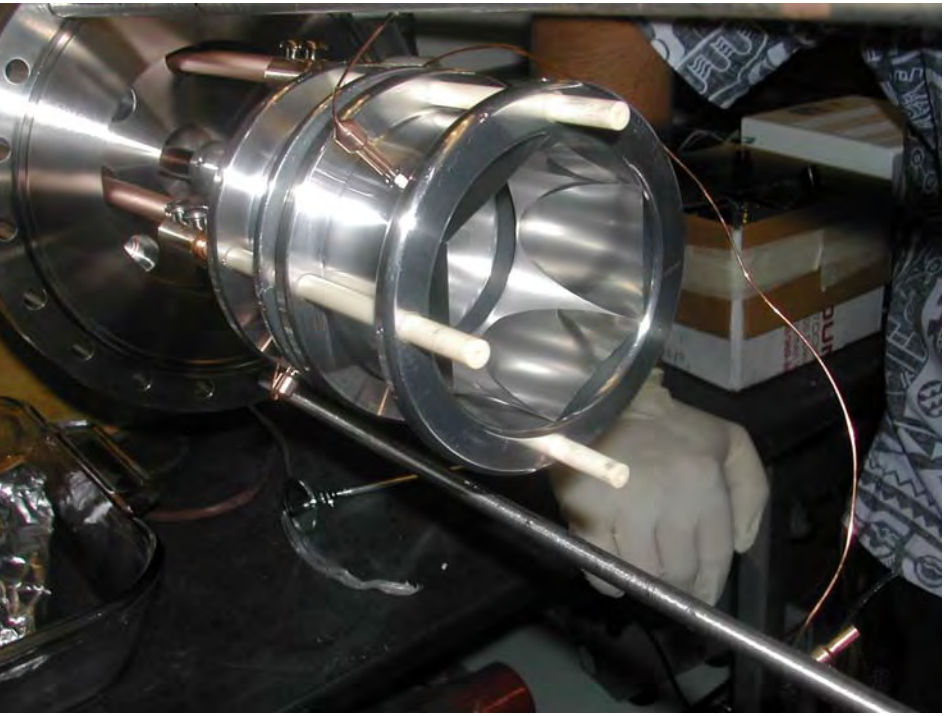
Equipment (Candescent, Litton Night Vision) ~$2M

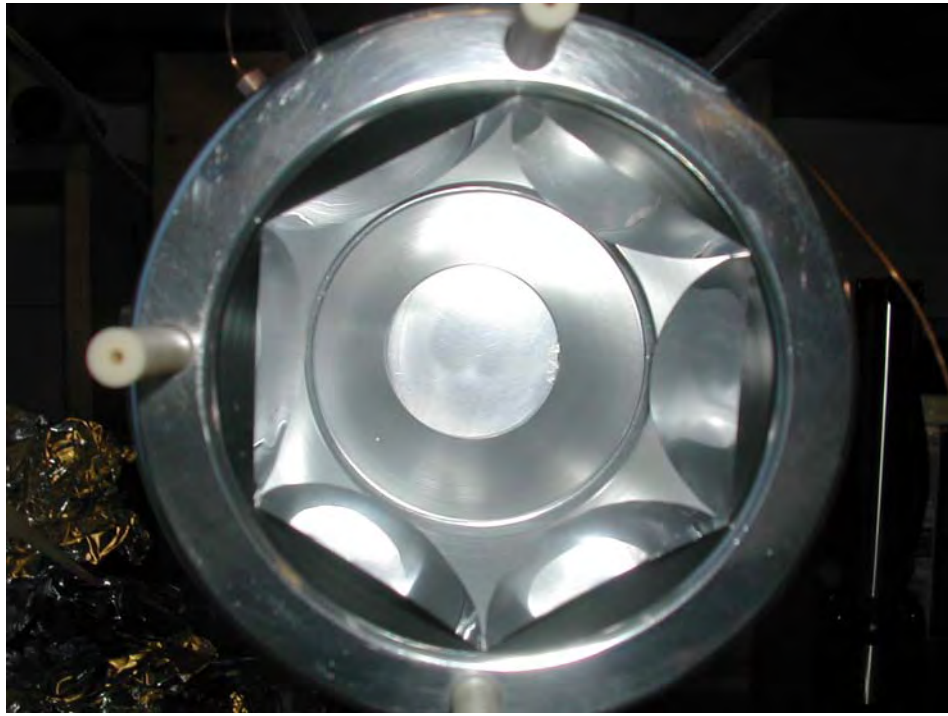
ReFerence Tube Design

- 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



3rd ReFerence Prototype



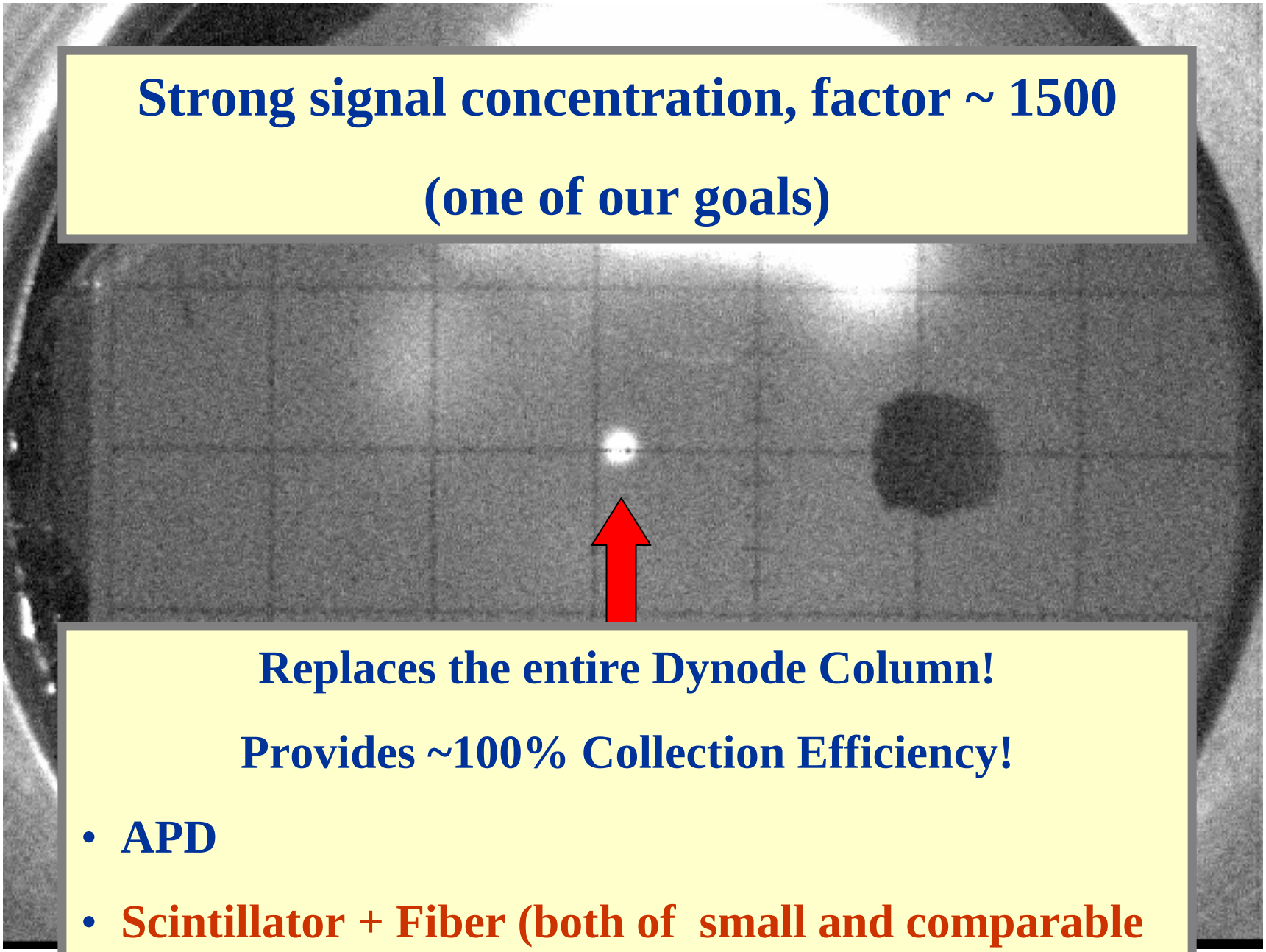


3” diameter, single pixel

(successfully tested – see below)

Strong signal concentration, factor ~ 1500

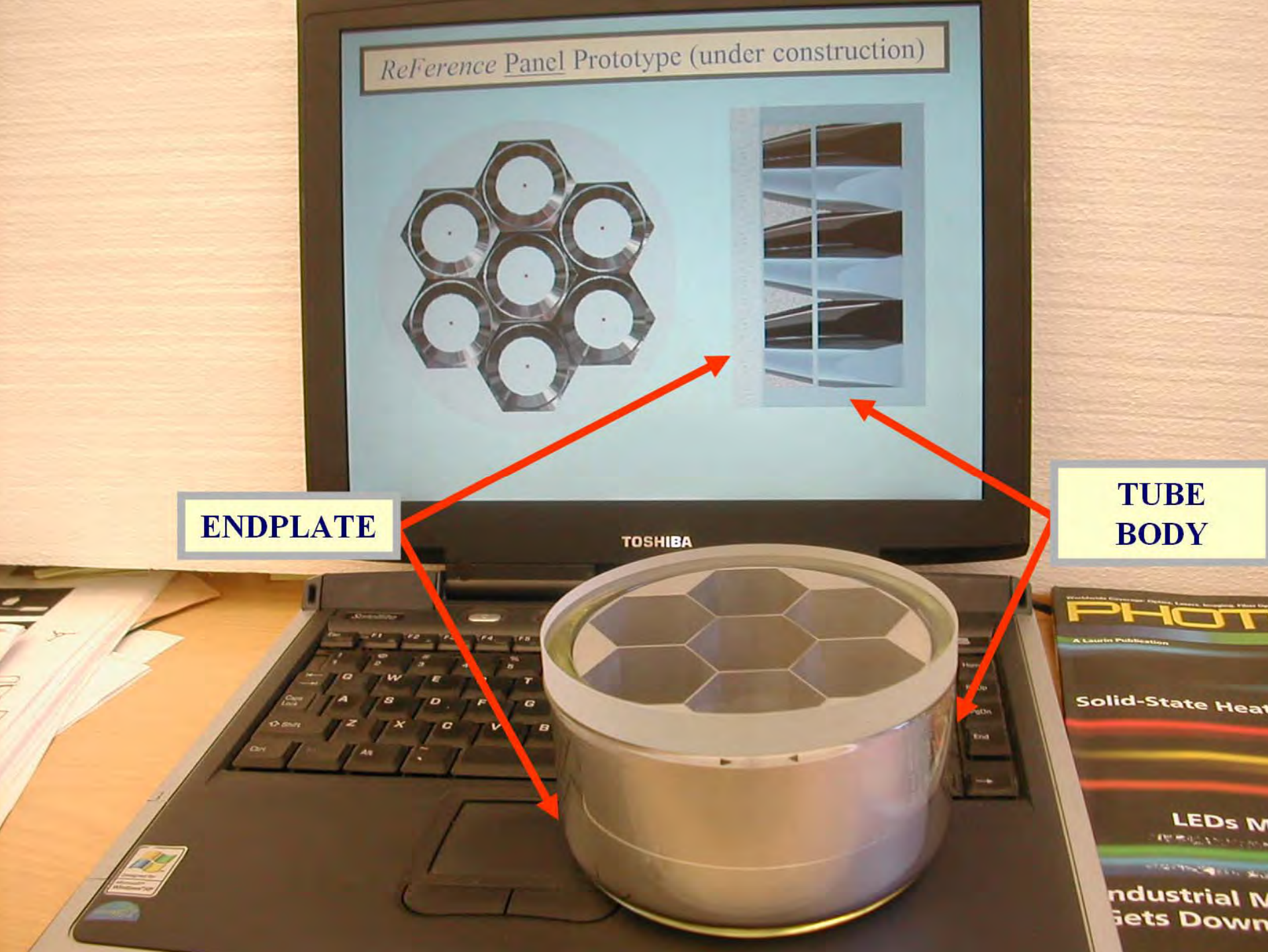
(one of our goals)

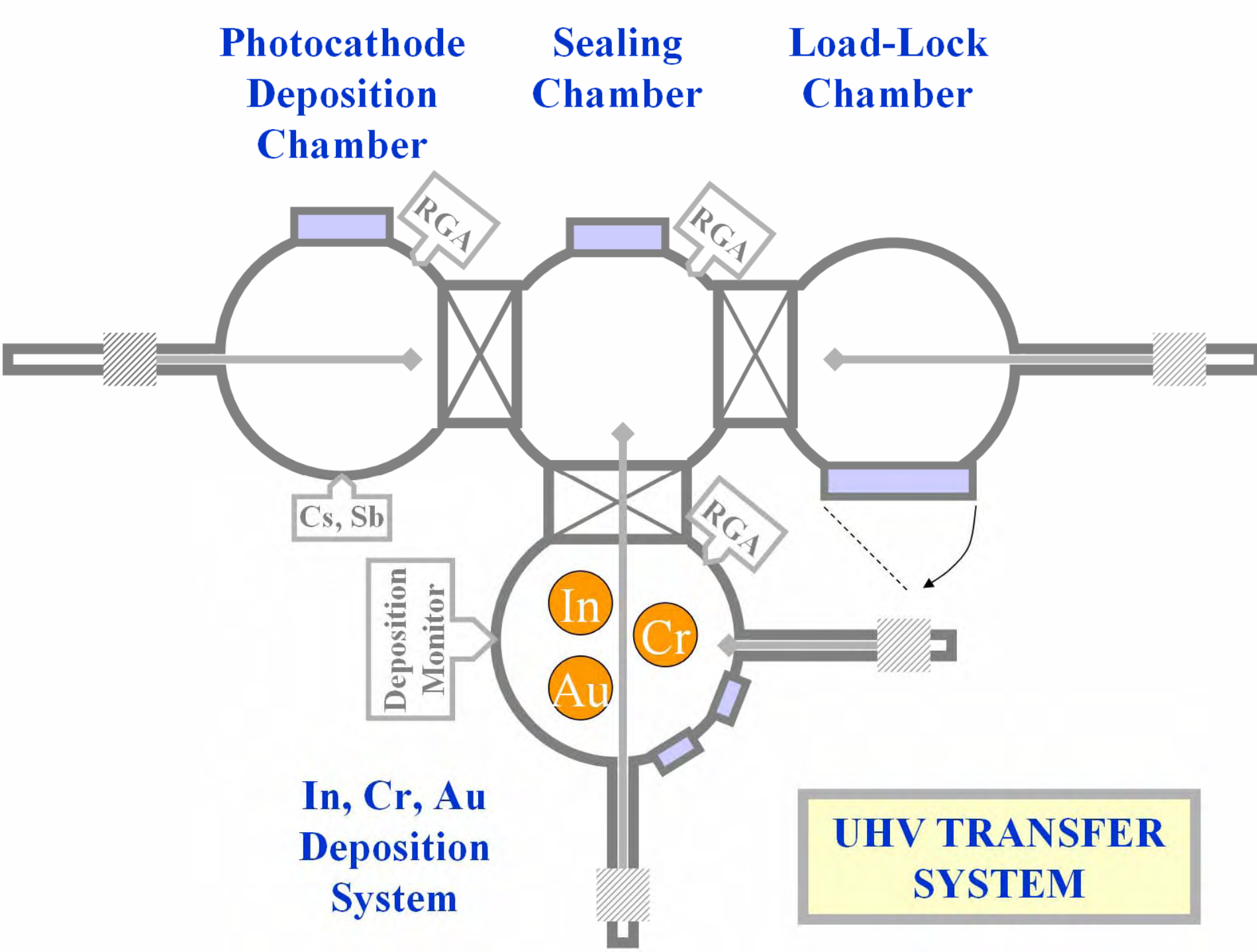


Replaces the entire Dynode Column!

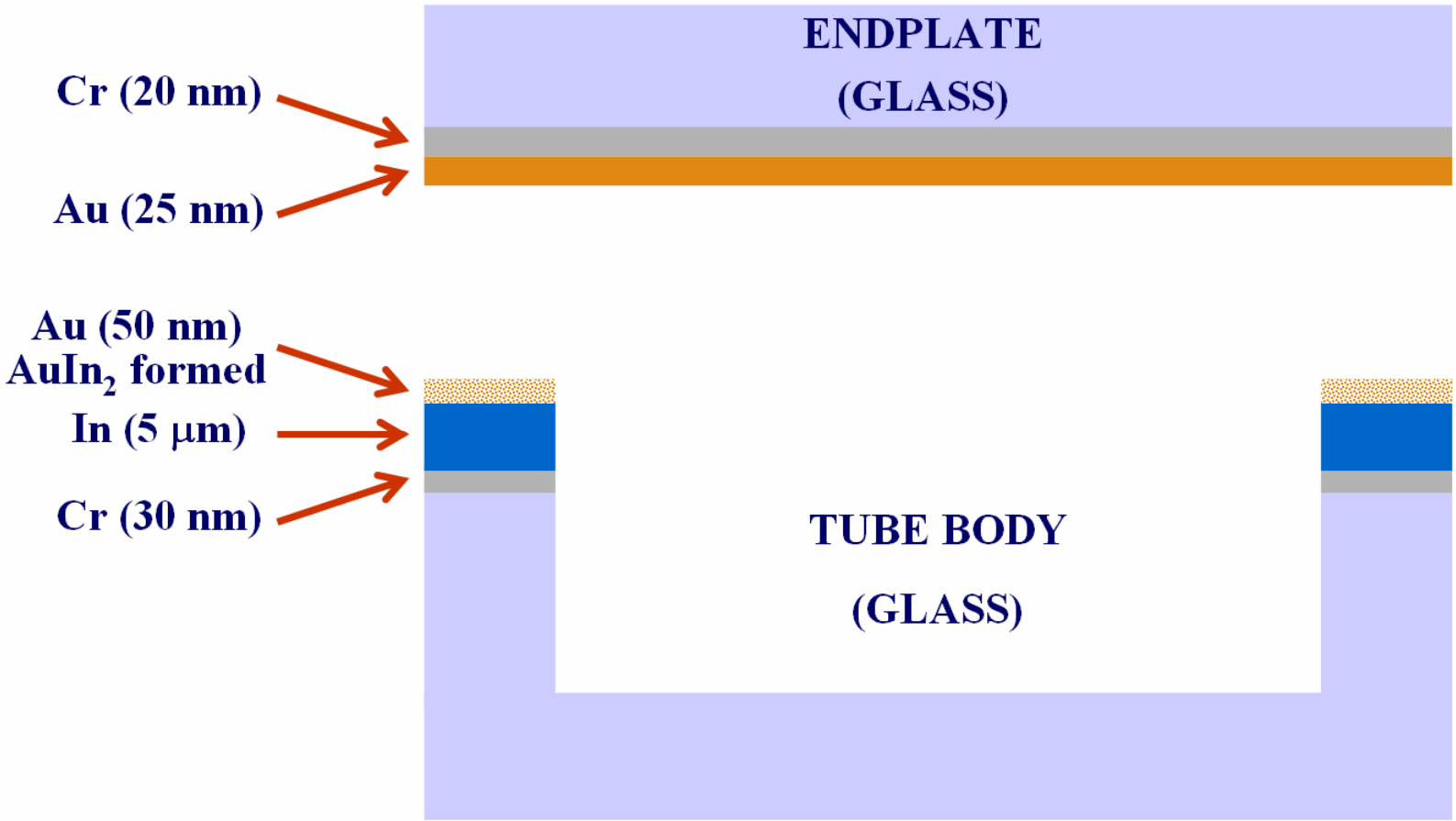
Provides ~100% Collection Efficiency!

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

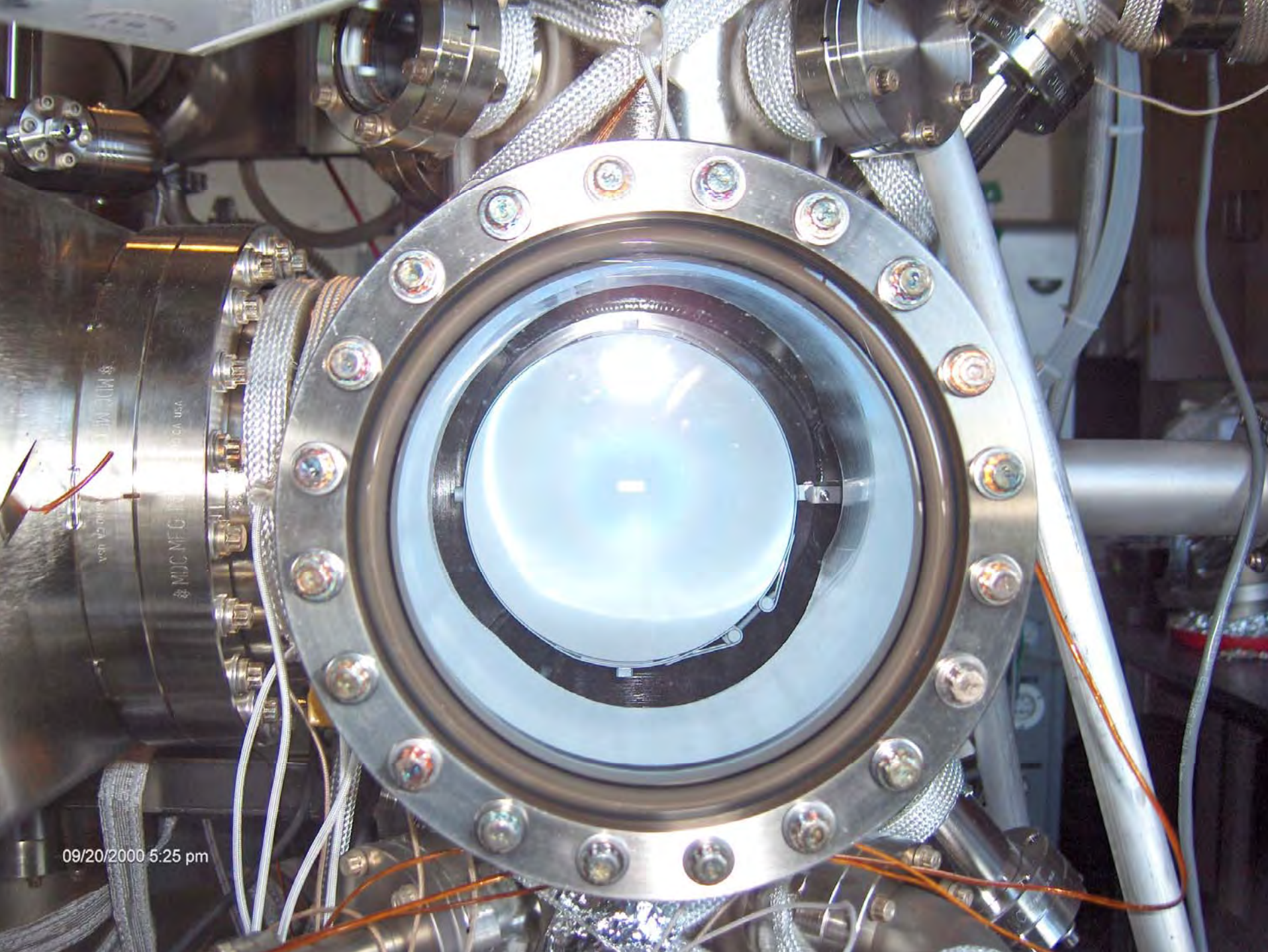

ReFerence Panel Prototype (under construction)
ENDPLATE
TUBE BODY
TOSHIBA
Solid-State
LEDs


Photocathode Deposition Chamber
Sealing Chamber
Load-Lock Chamber
RGA
RGA
RGA
Cs, Sb
Deposition Monitor
In
Cr
Au
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**

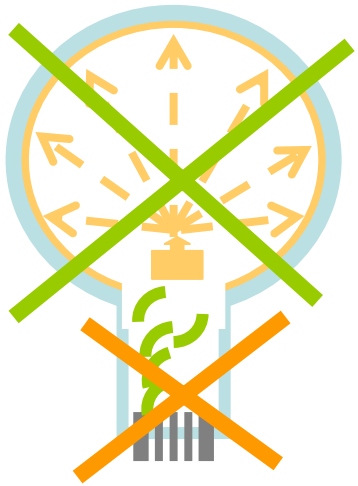
  ➔ LIGHT AMPLIFIER (G-APDS)

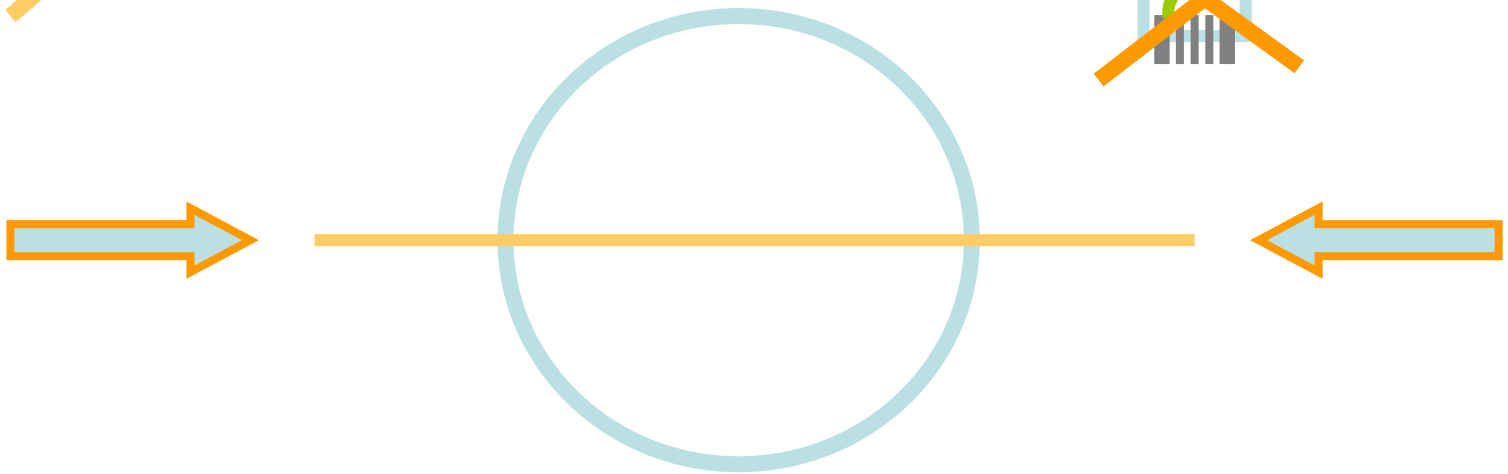
?

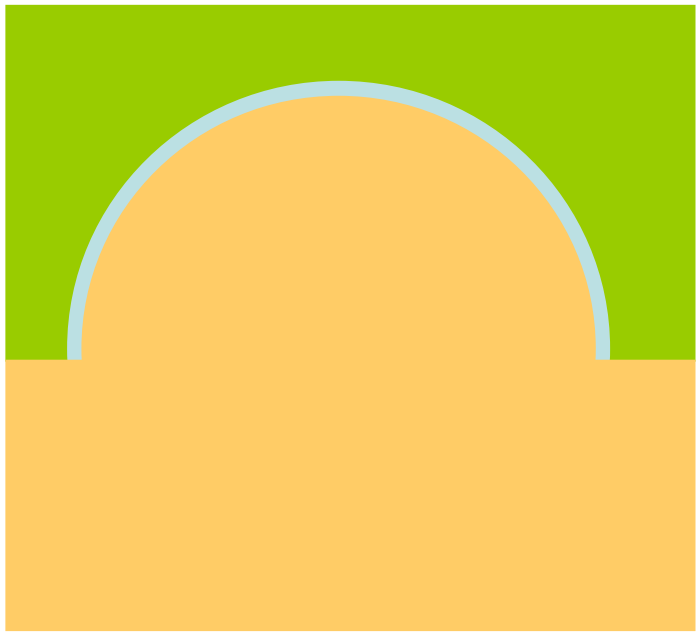
Mass production
High performance

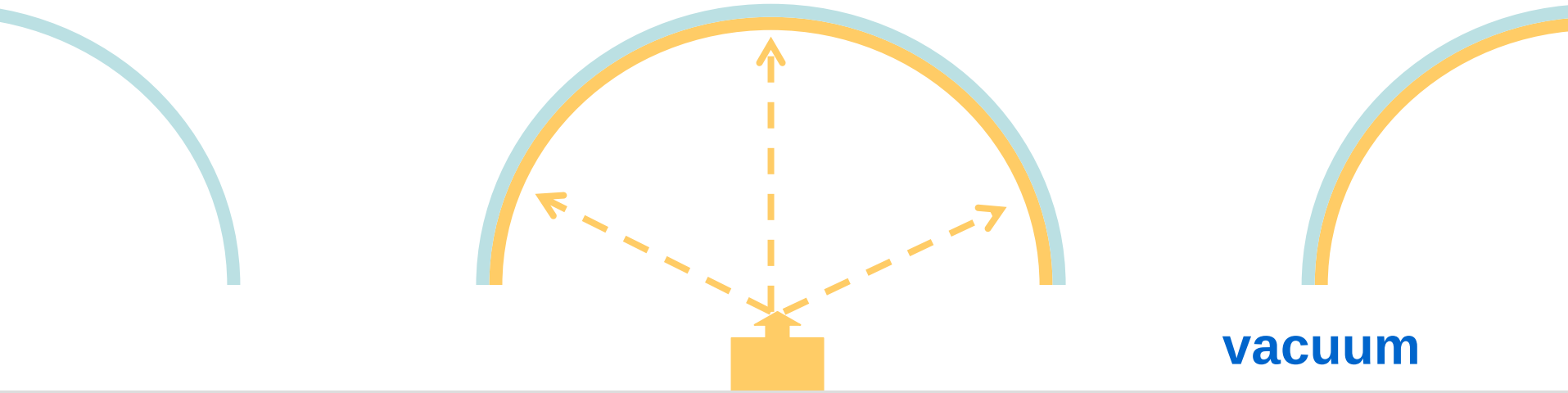
COMPONENTS:
Industrially mass-produced

ASSEMBLY:
Production-line








vacuum

?

Special marriage:

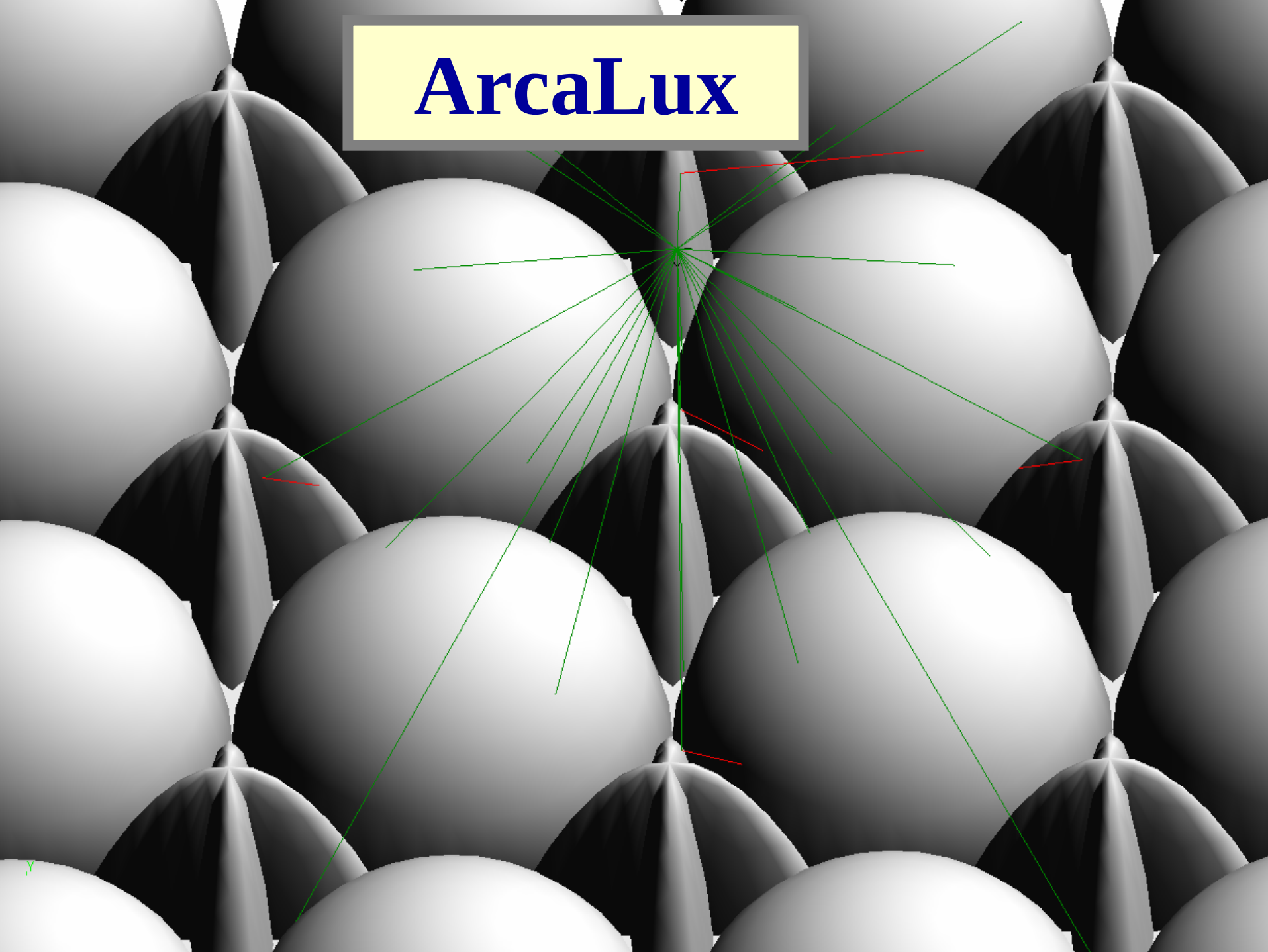
~ 0% dead area

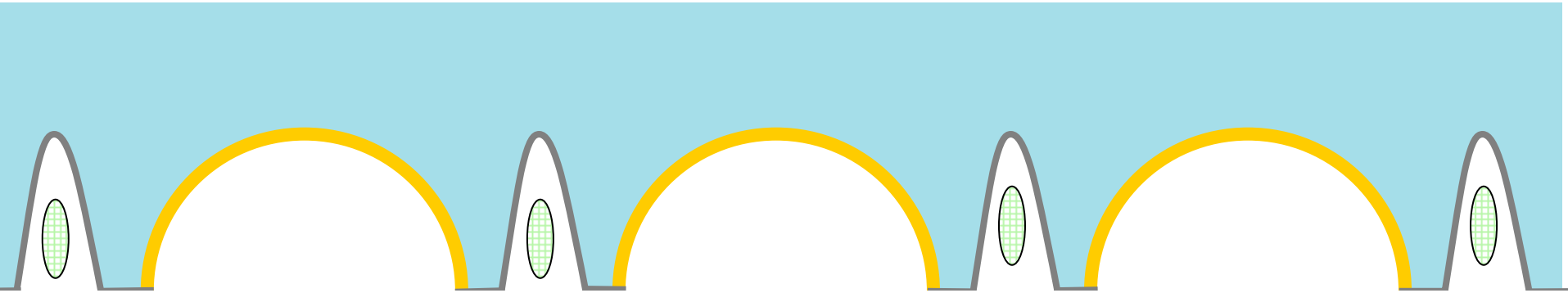
Long-lasting – the internal pollution - internally absorbed

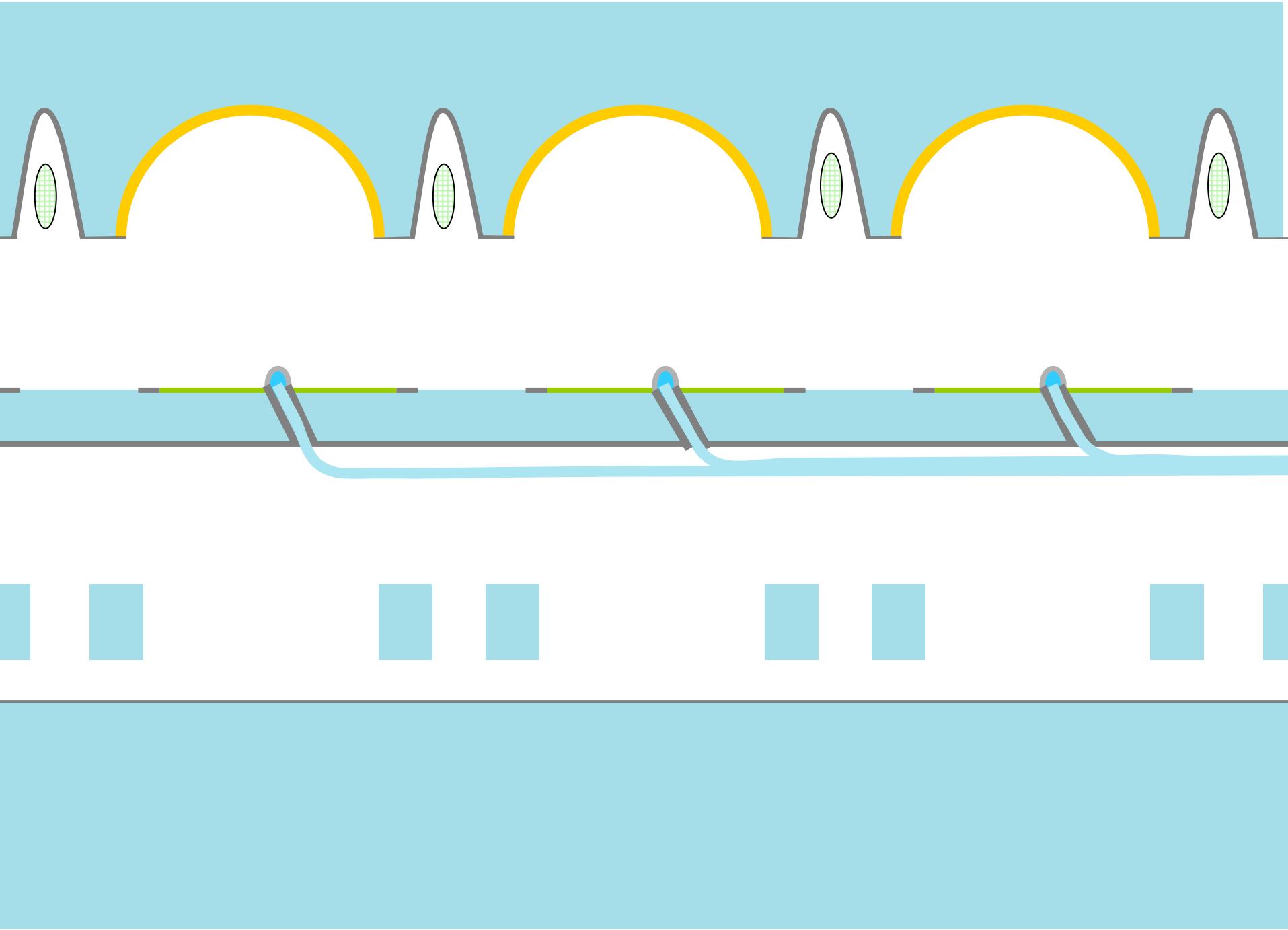
Highly resistant to pressure from outside

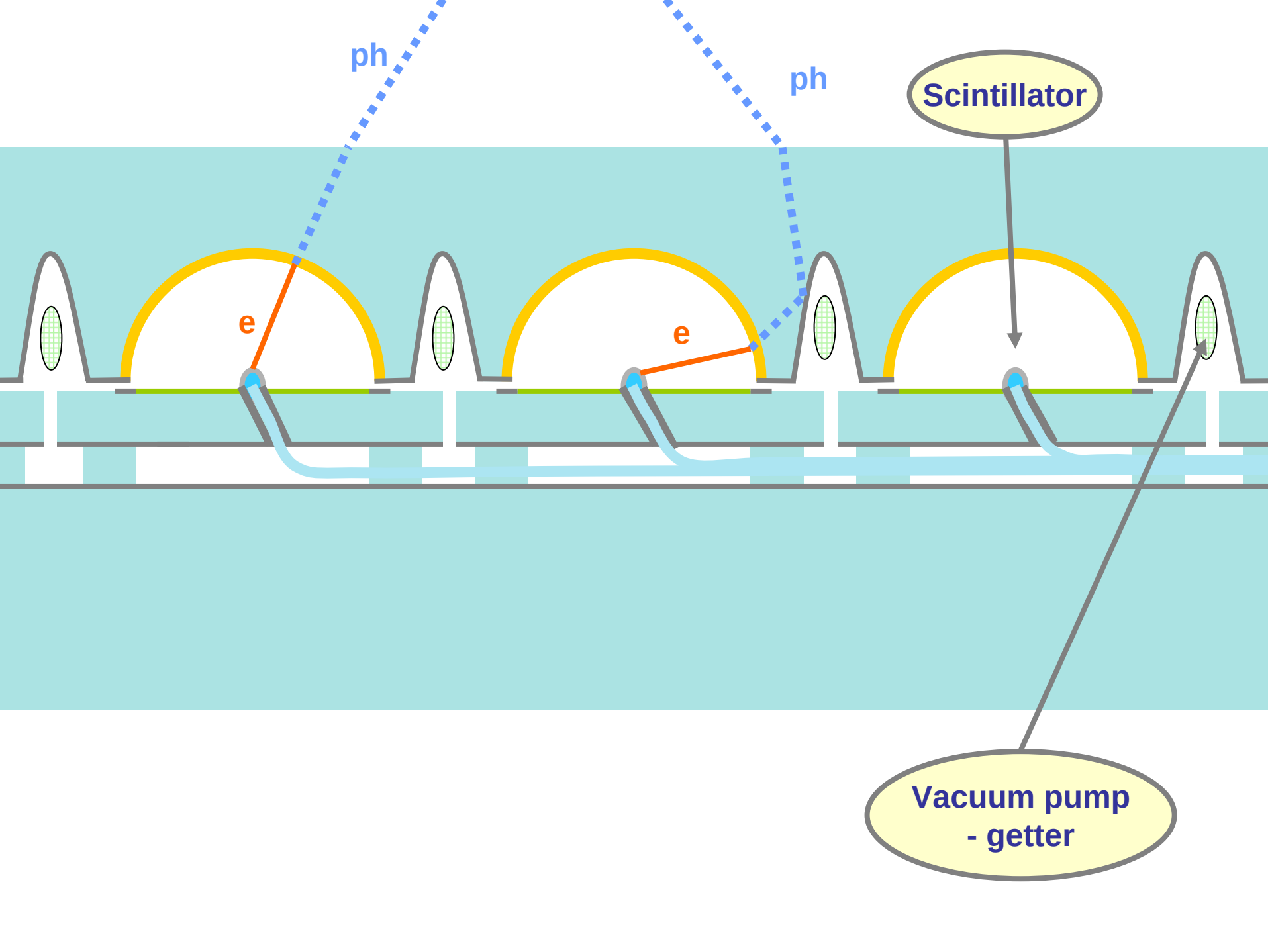
Ready for mass-production

ArcaLux





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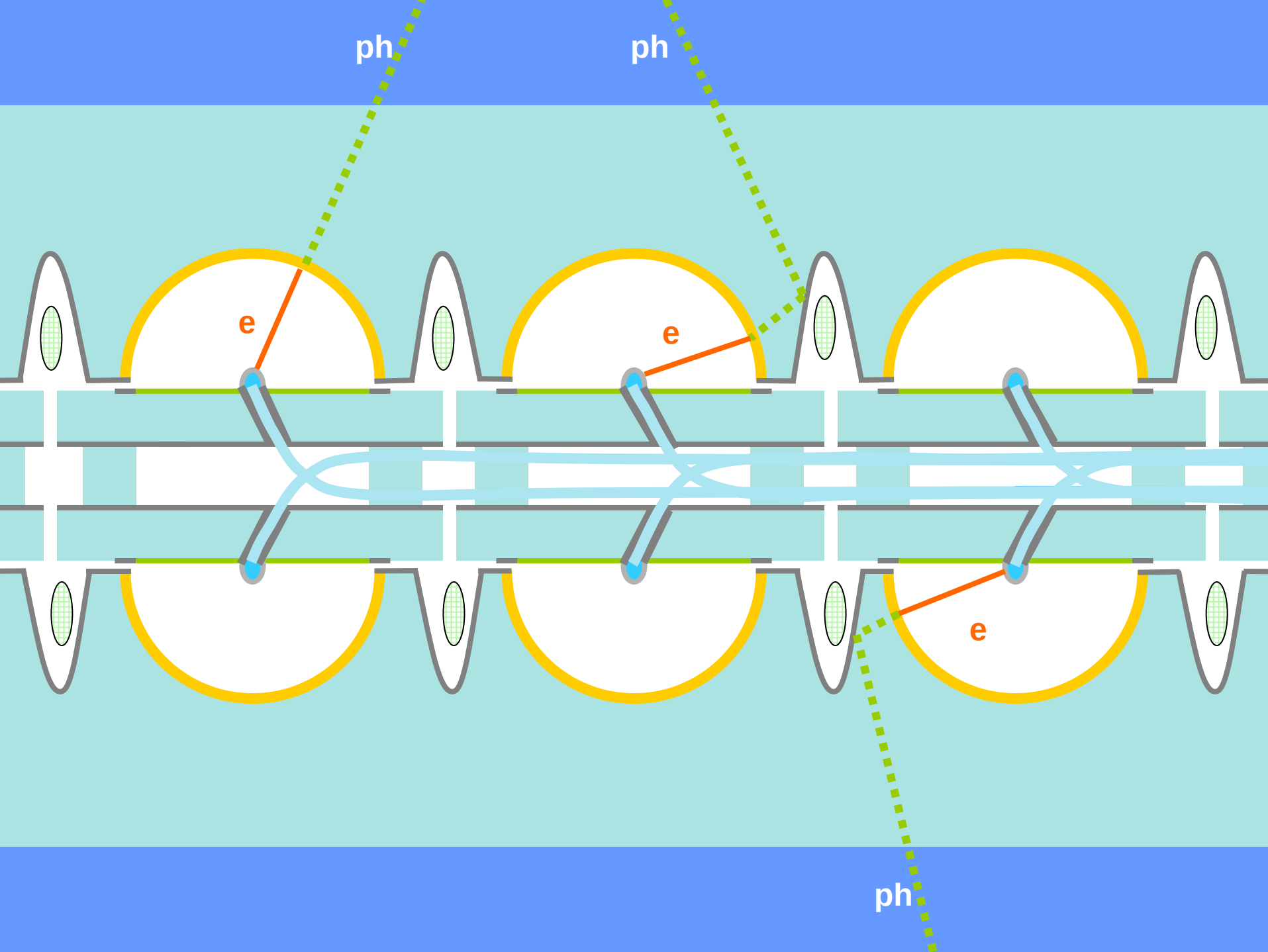
ph
Scintillator
e
e
Vacuum pump
- getter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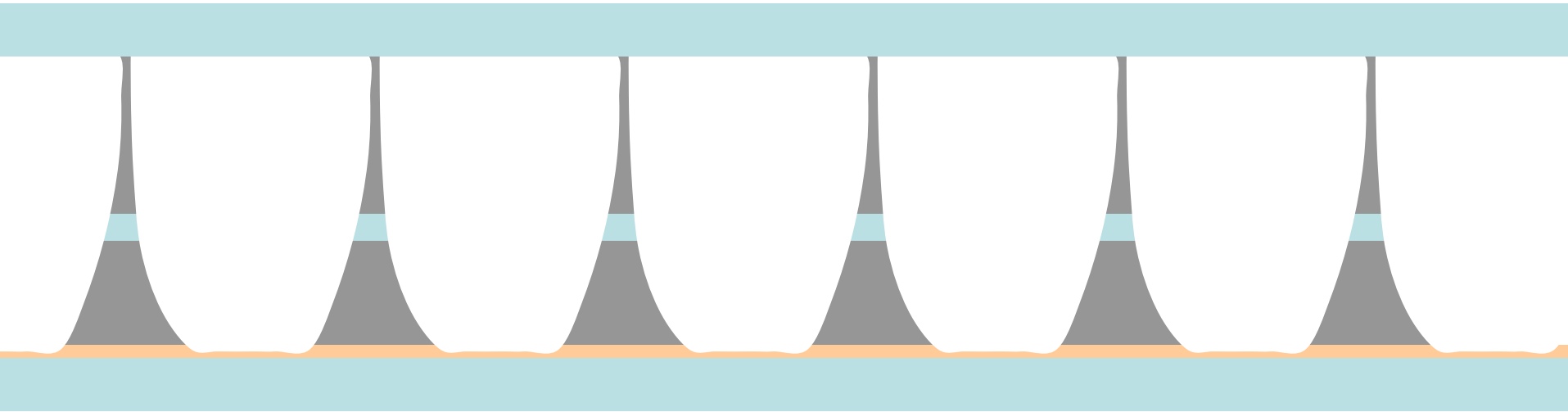
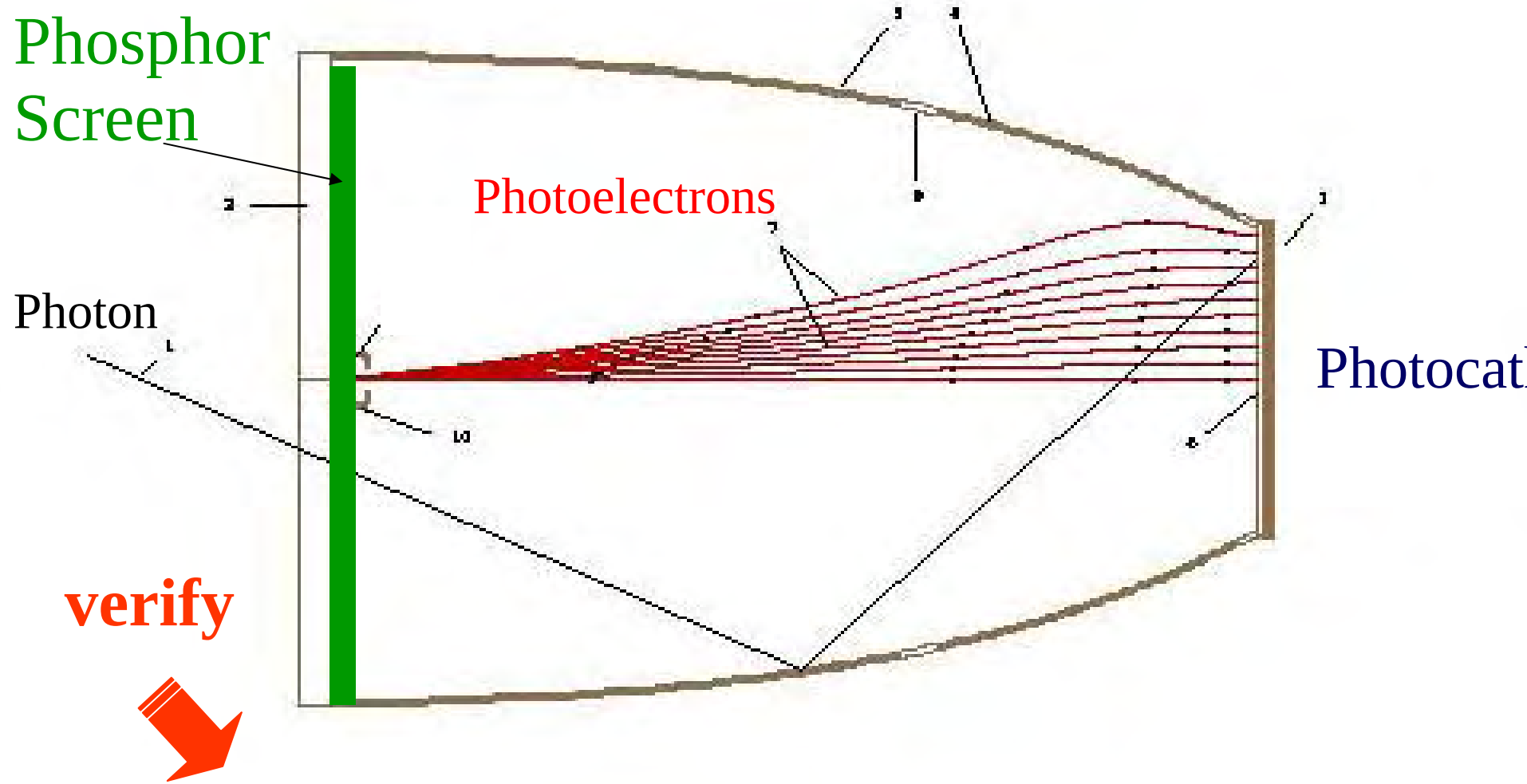
Flat-Panel Honeycomb Sandwich Camera Construction



Industrial Production (no glass blowing etc.)

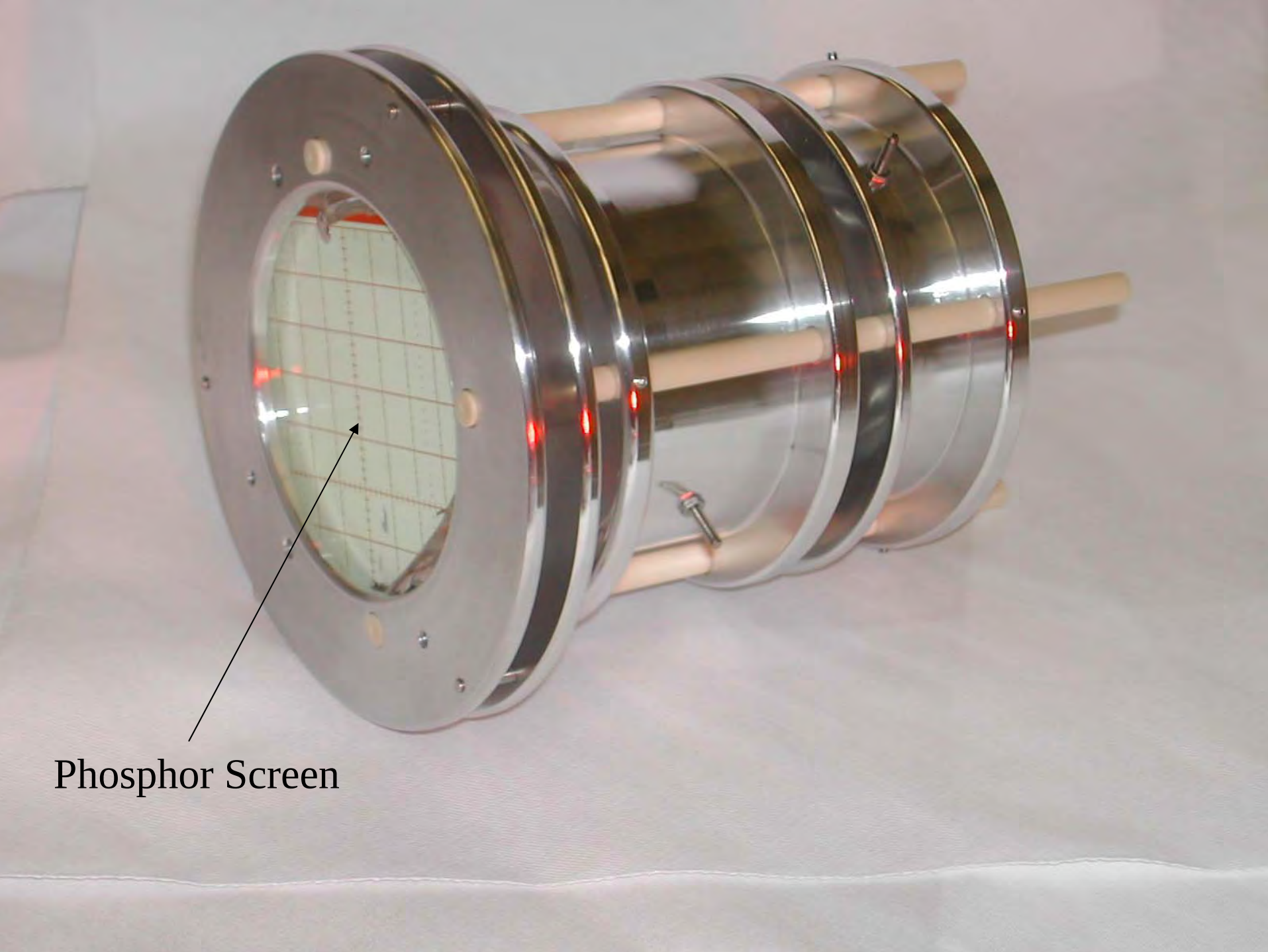
Intrinsic Mechanical Stability, Low Buoyancy,..

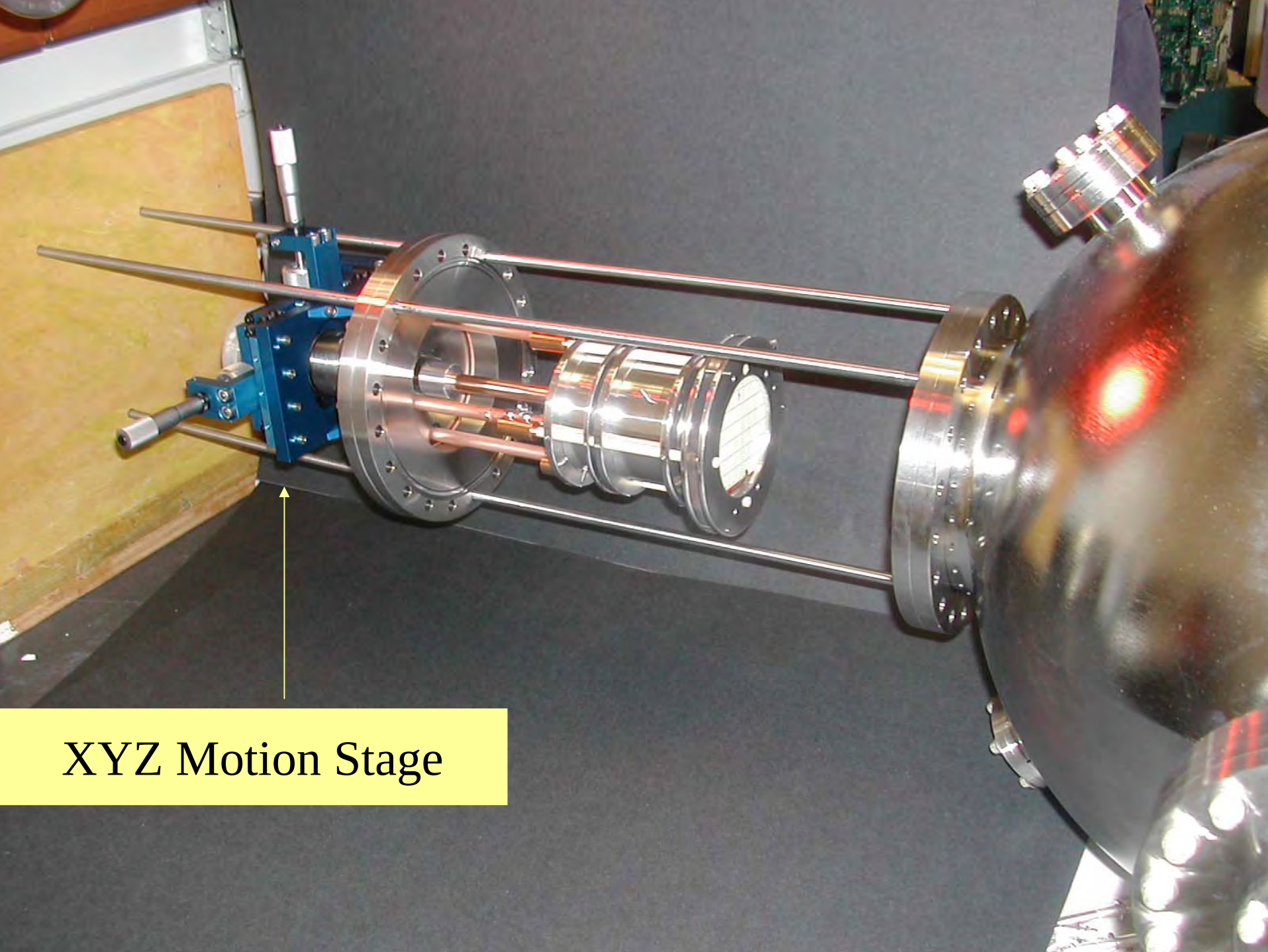
Ideal Light Concentrator = OK!

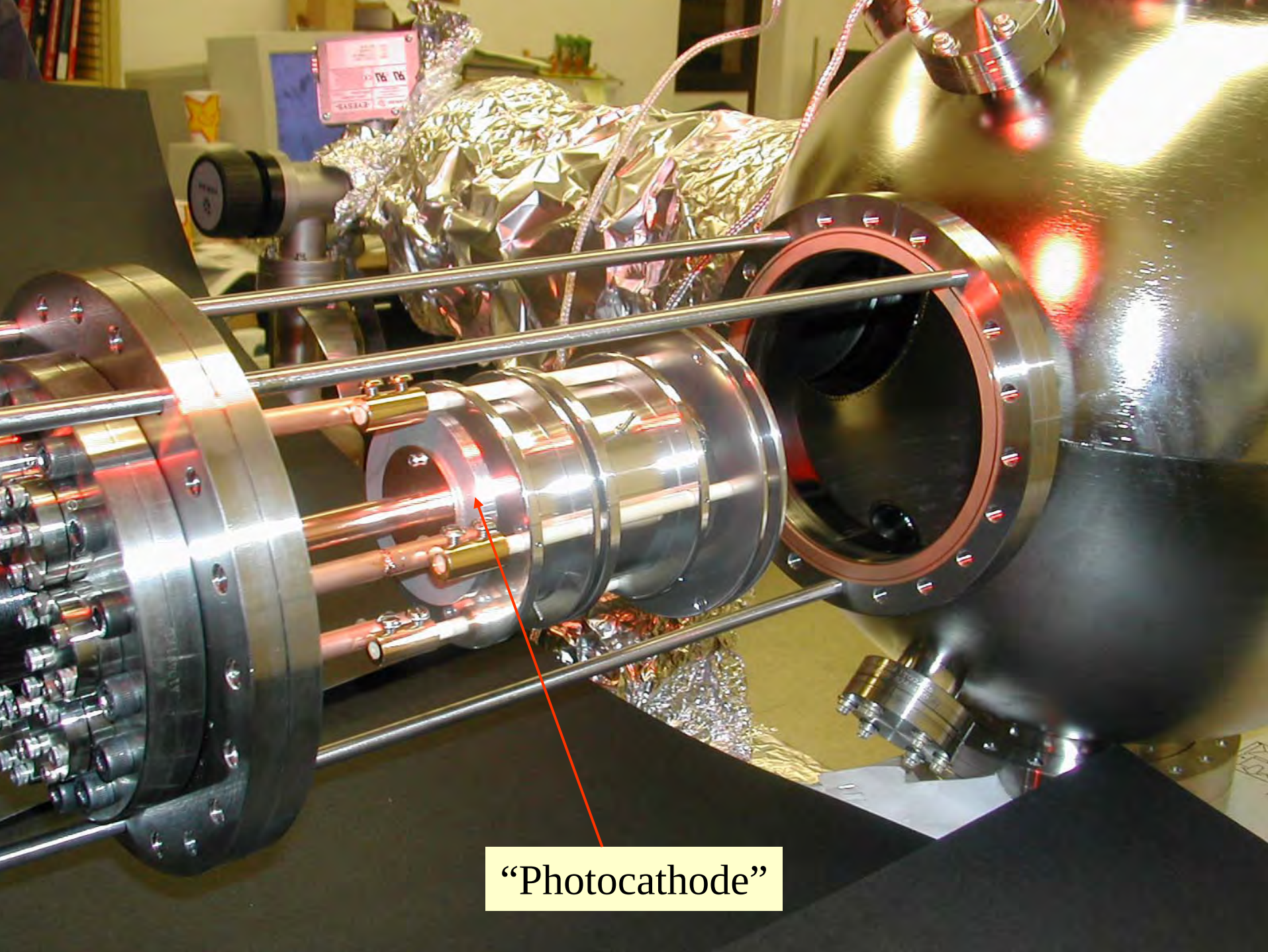


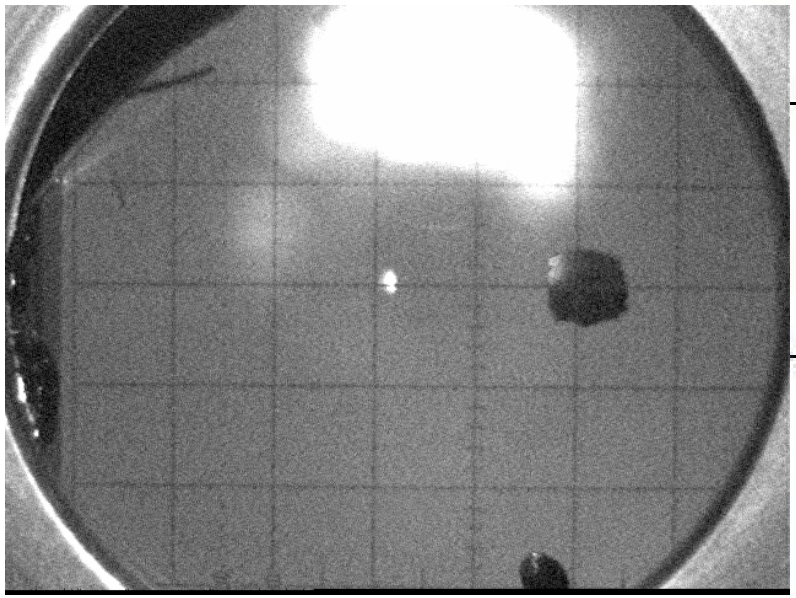
verify

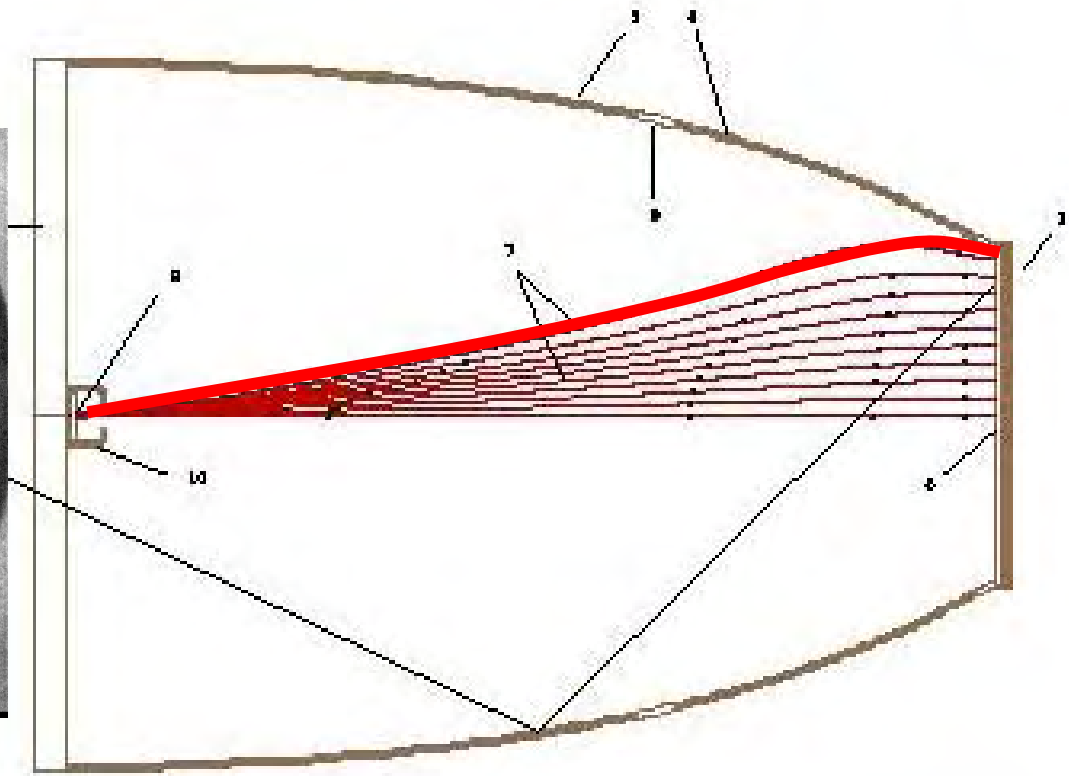
Optimal Electron Lens

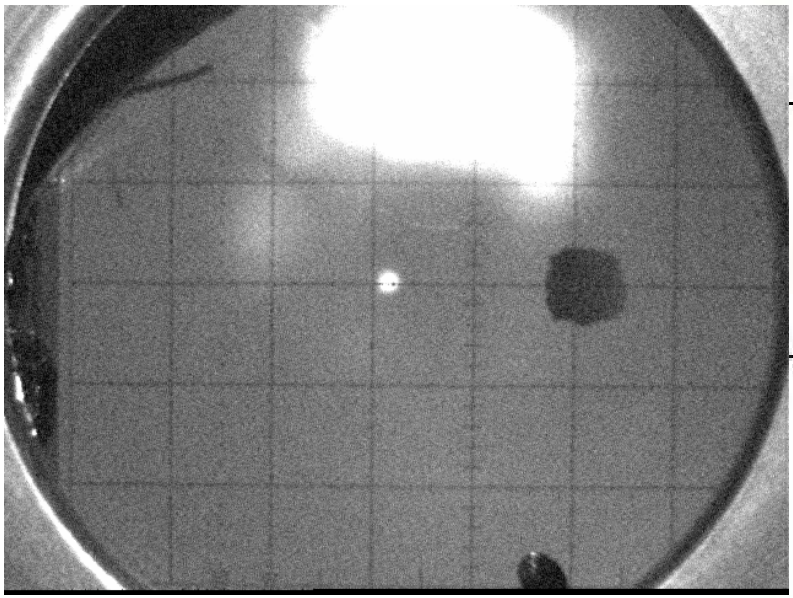

Phosphor Screen

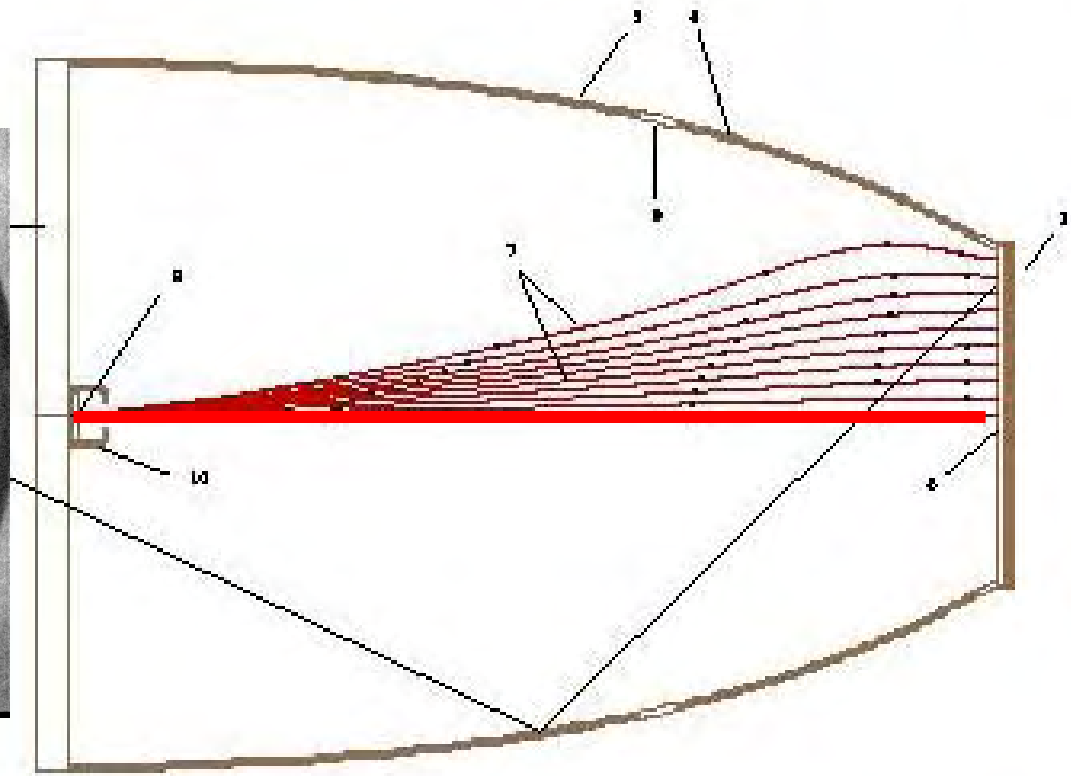

XYZ Motion Stage

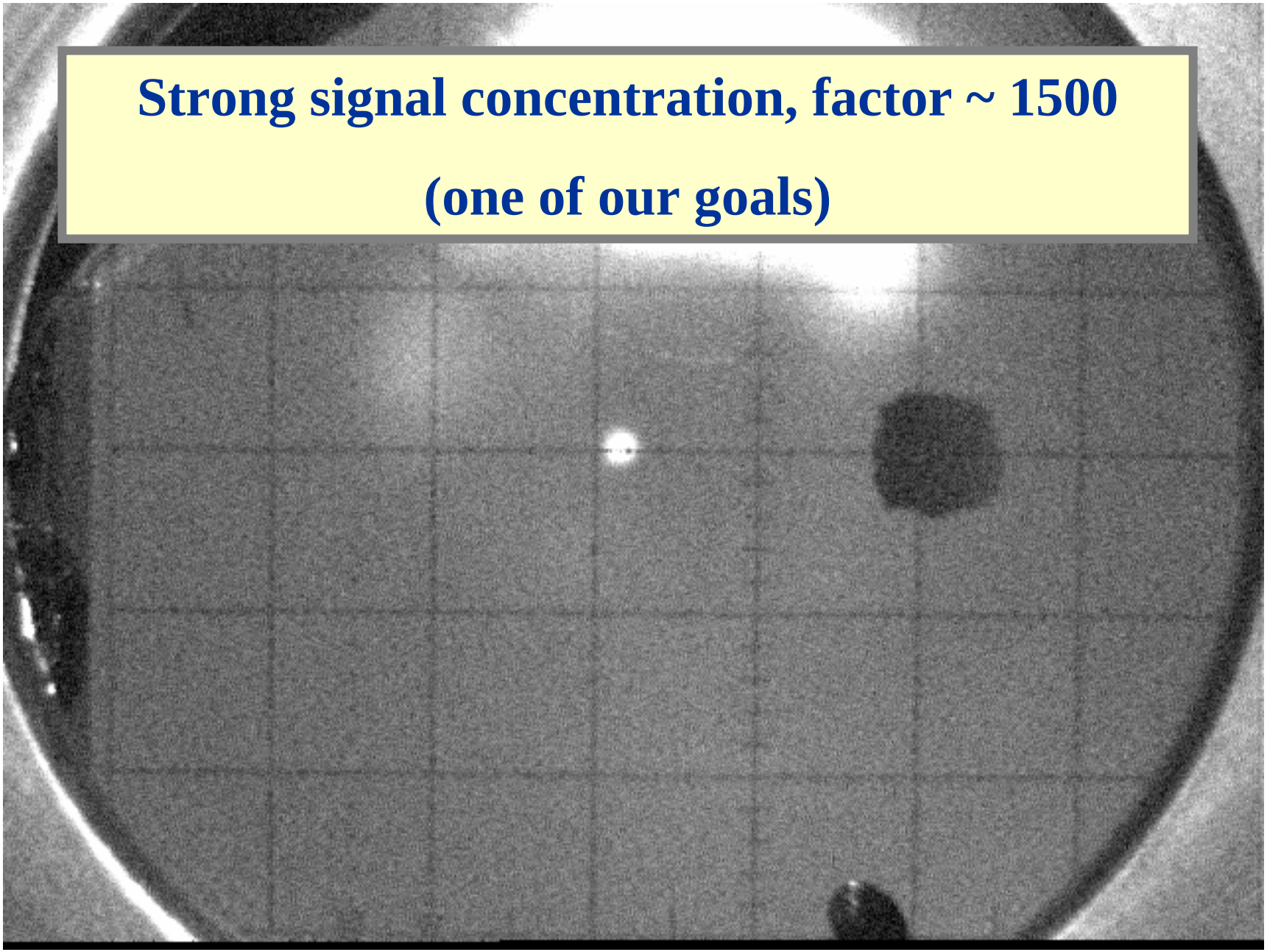

“Photocathode”

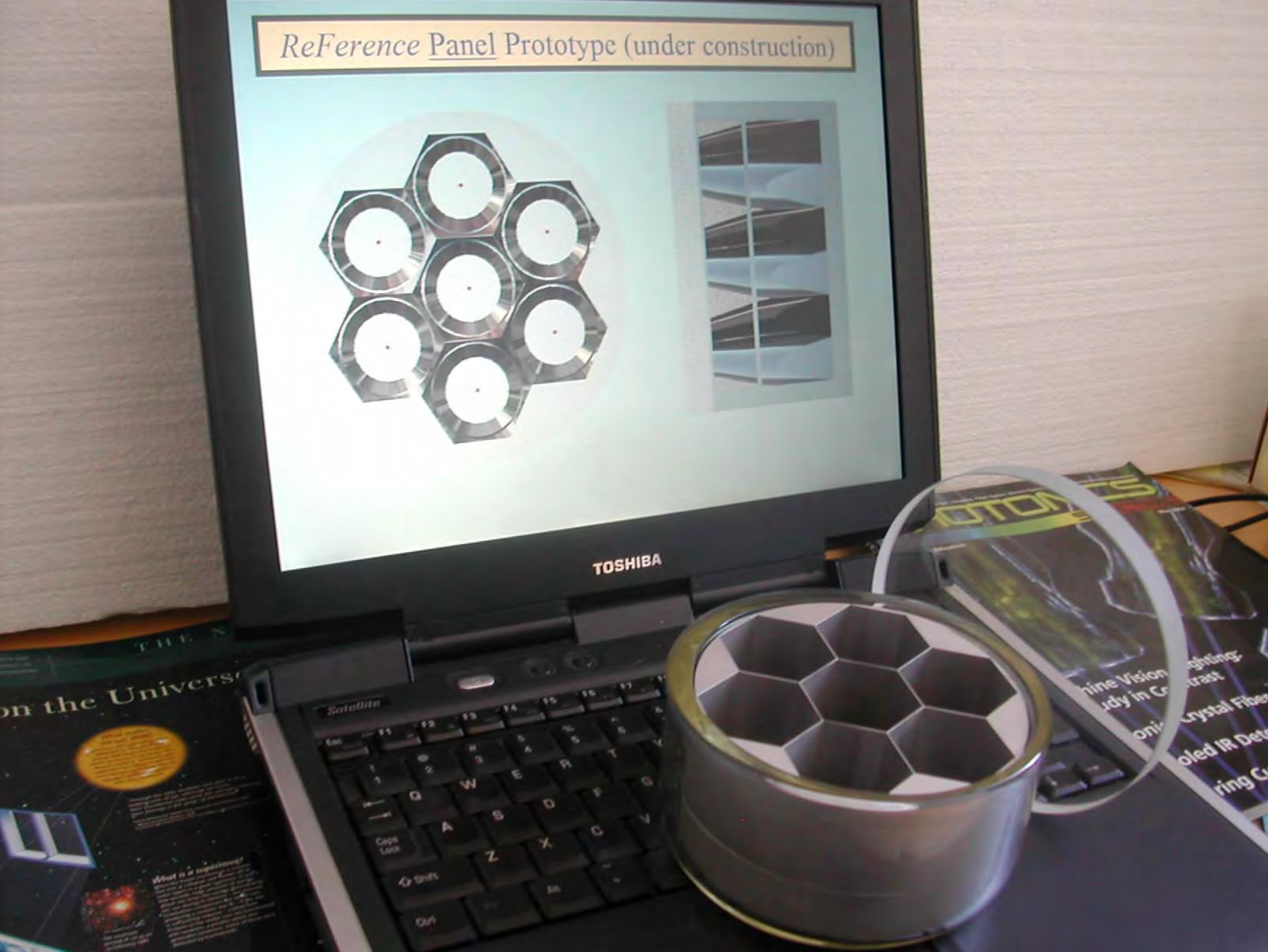




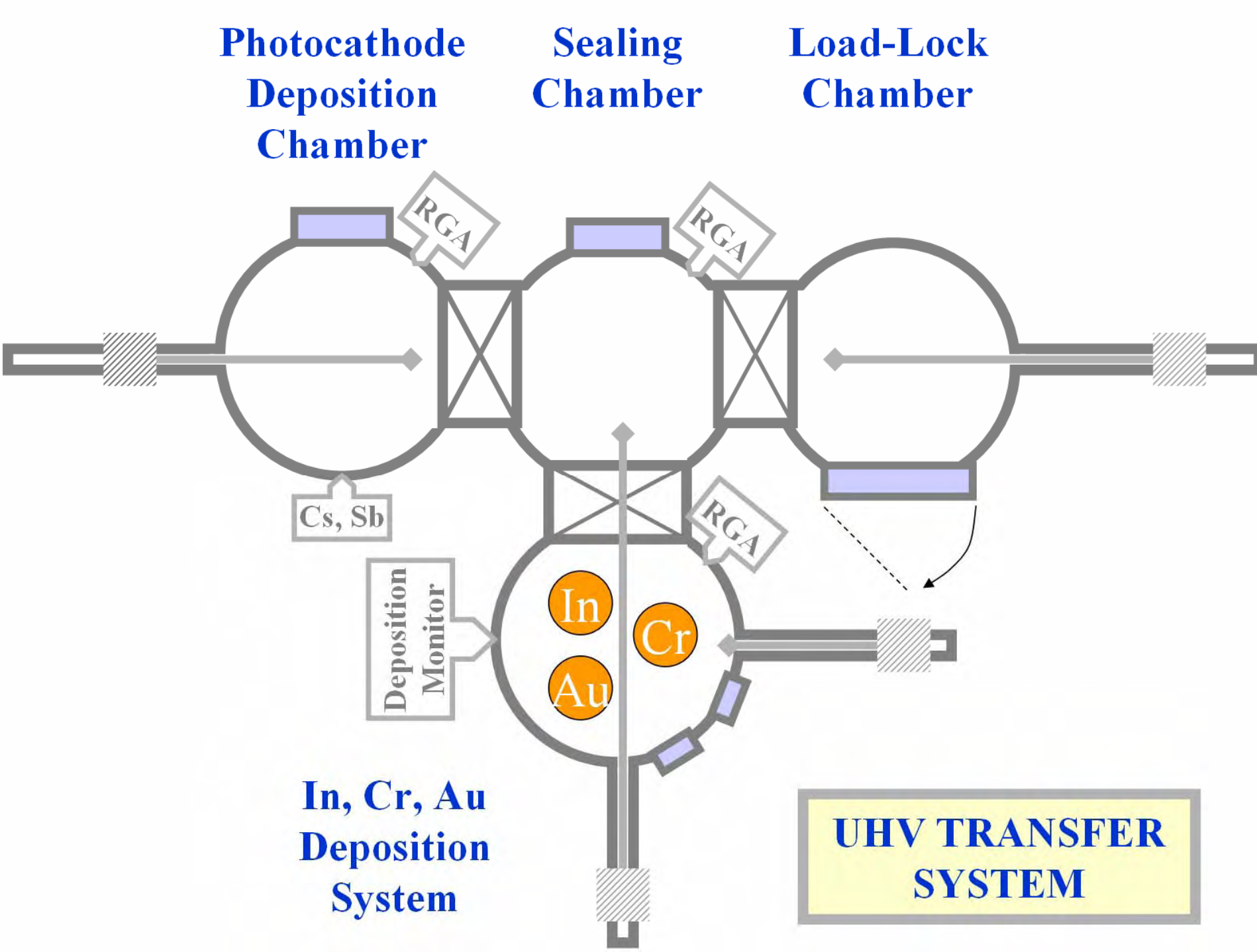



5
4
3
7
8
6

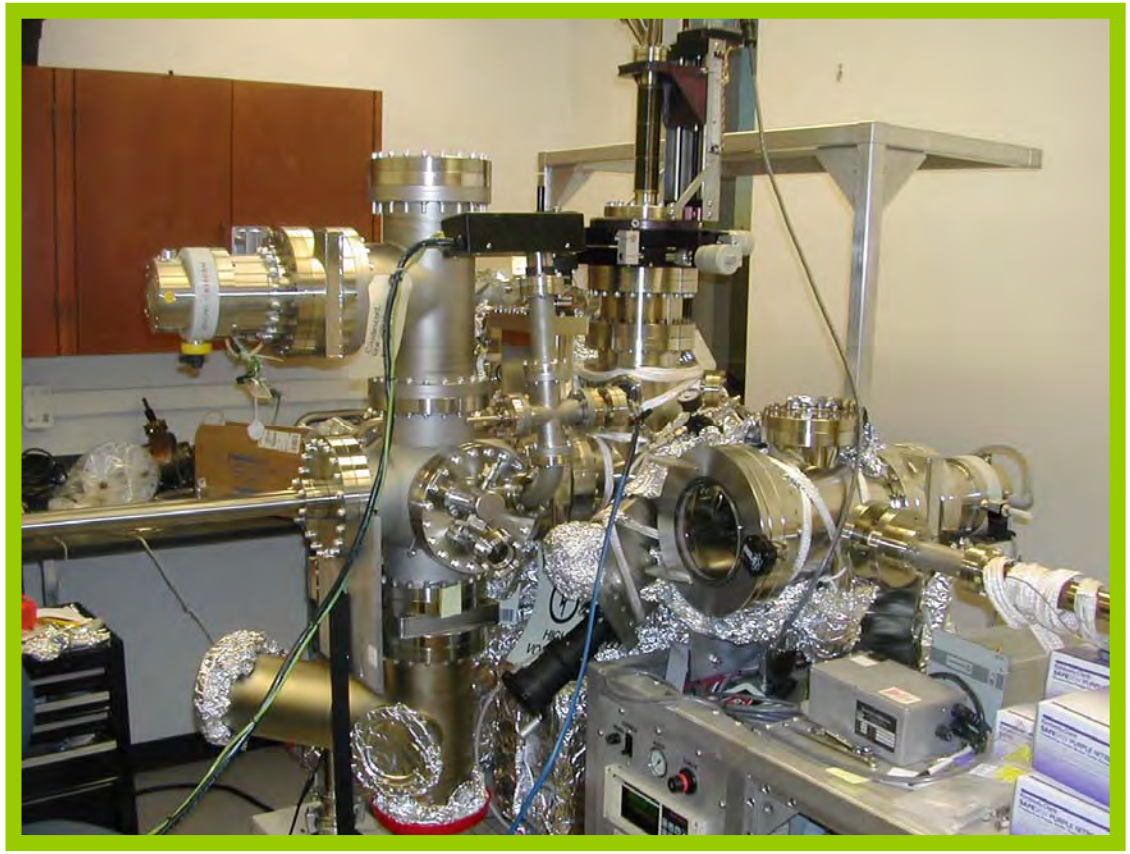

Strong signal concentration, factor ~ 1500
(one of our goals)


ReFerence Panel Prototype (under construction)
TOSHIBA
Satellite

Currently Aluminum – ultimately GLASS

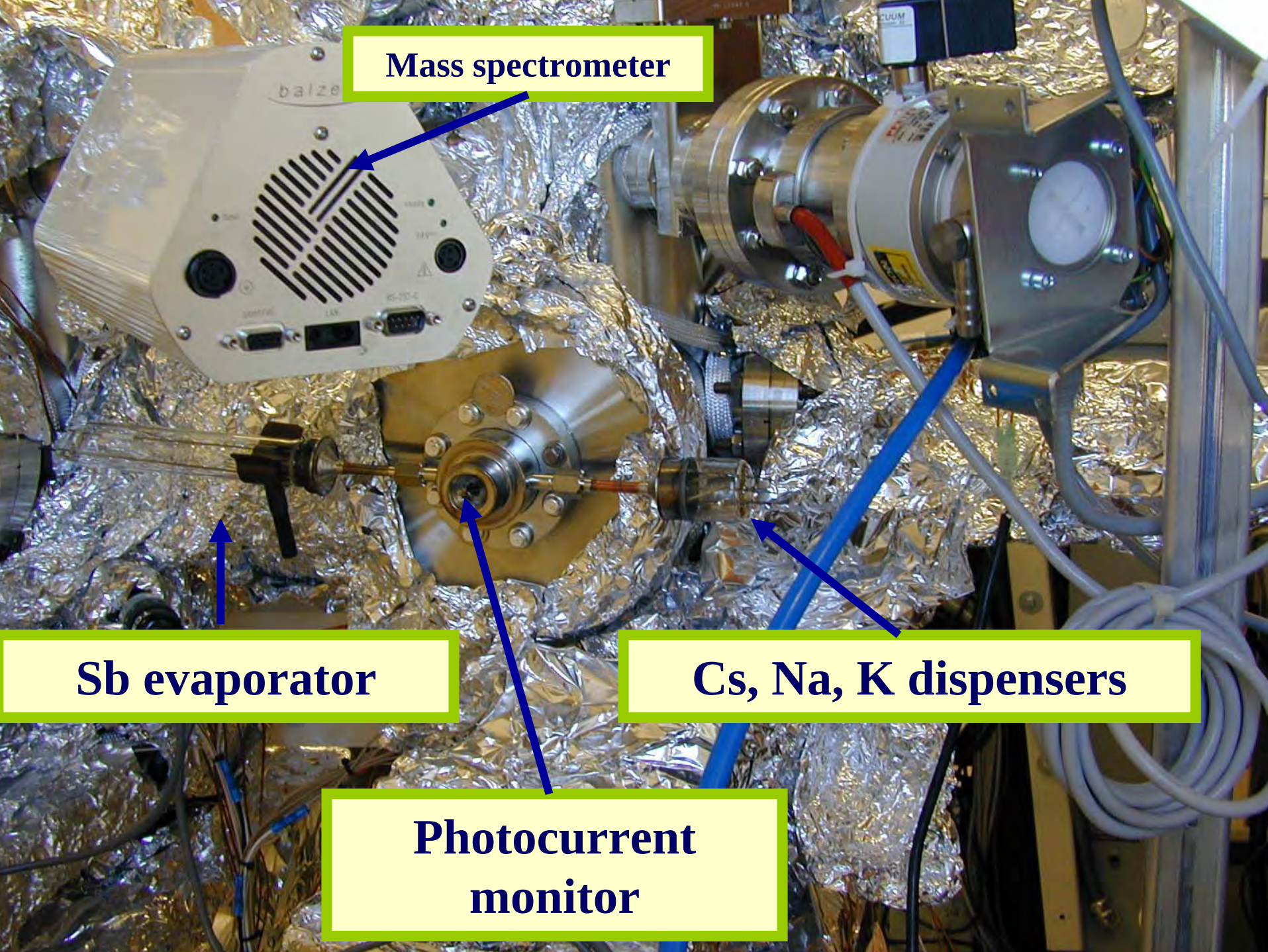

Photocathode Deposition Chamber
Sealing Chamber
Load-Lock Chamber
RGA
RGA
RGA
Cs, Sb
Deposition Monitor
In
Cr
Au
In, Cr, Au Deposition System
UHV TRANSFER SYSTEM

7-pixel 5-inch ReFerence Flat-Panel Prototype

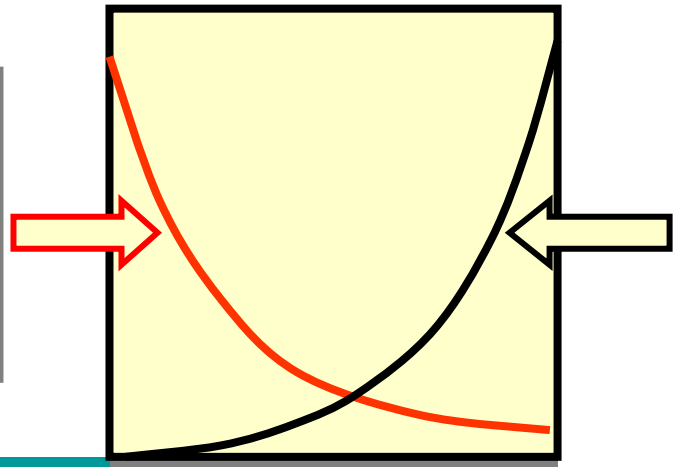


UHV Transfer System :

- **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*)

Photon

Photo-Electron

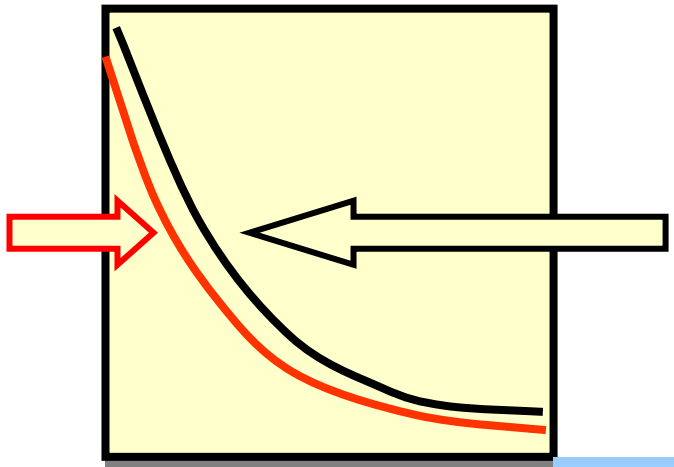
Vacuum

Therefore: QE ~ 10-20%

Glass Window

Photocathode

Photon Absorption (Electron Creation)



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

Photon

Photo-Electron

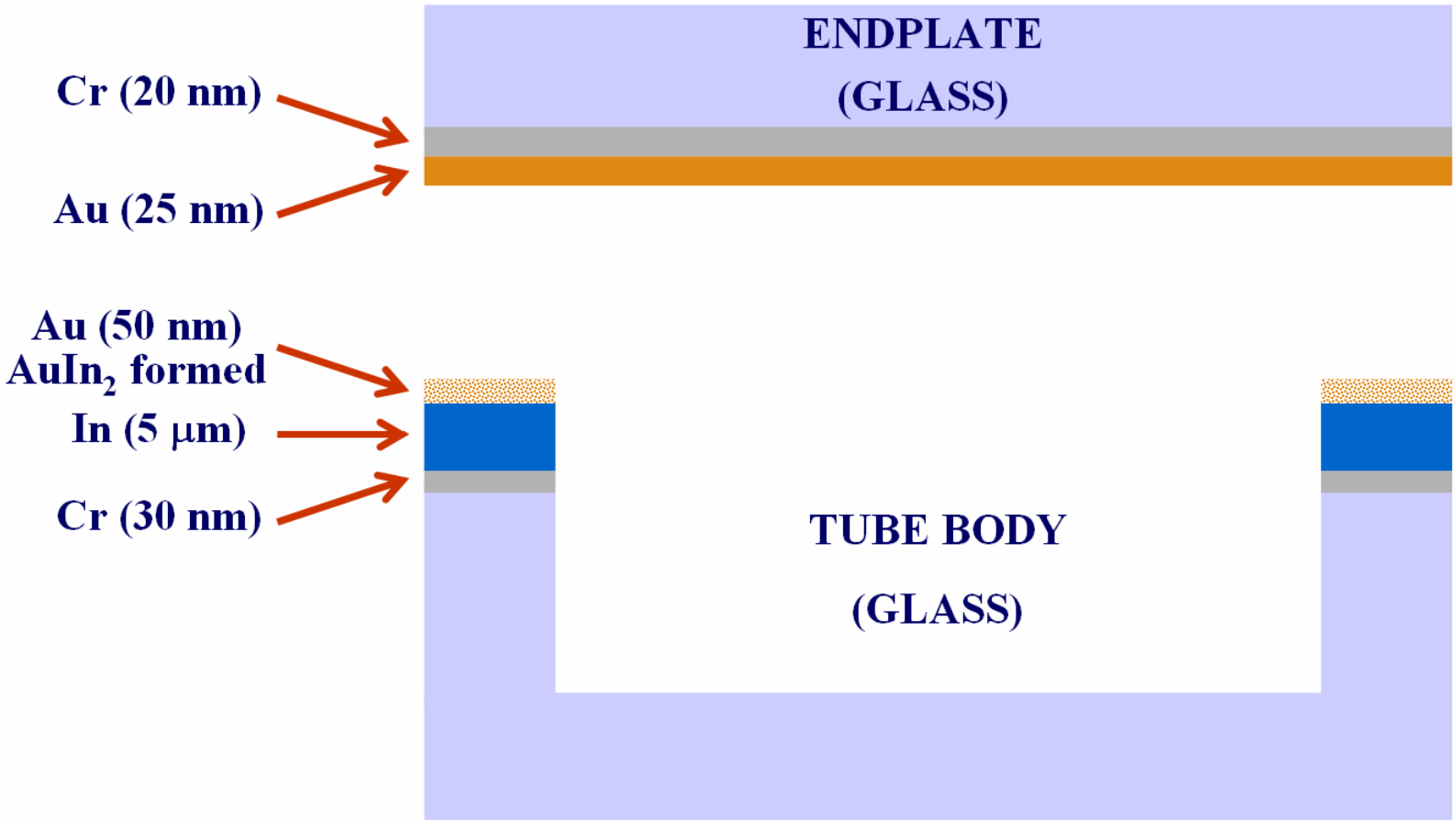
Vacuum

(e.g. Substrate, ***Reflector****,…)*

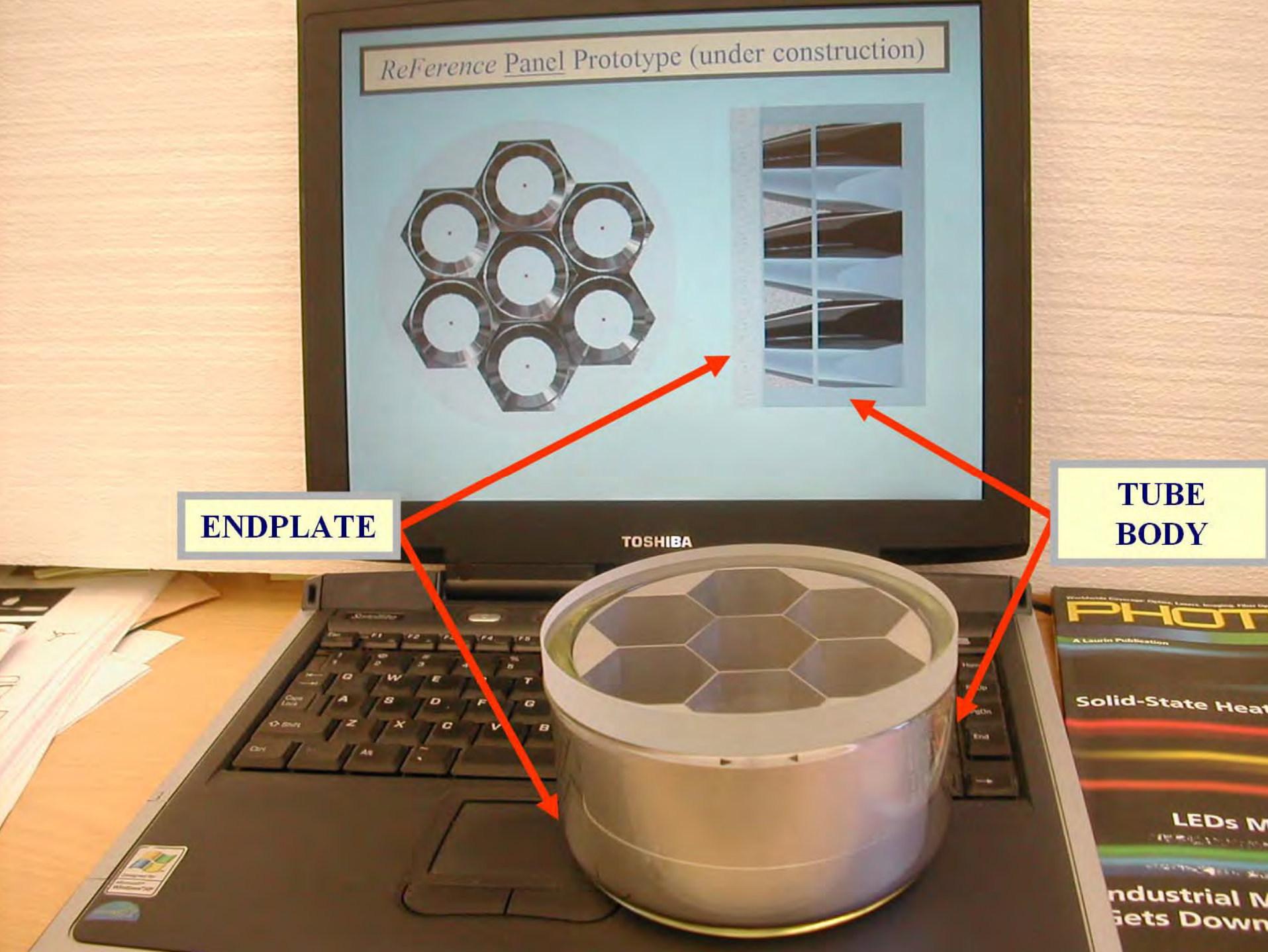
LOW PRODUCTION COST !

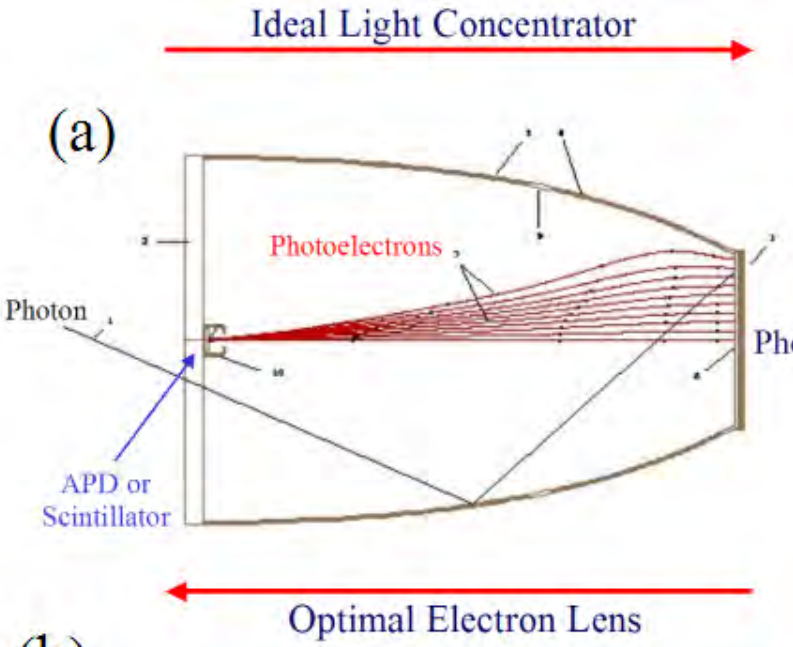
Photocathode

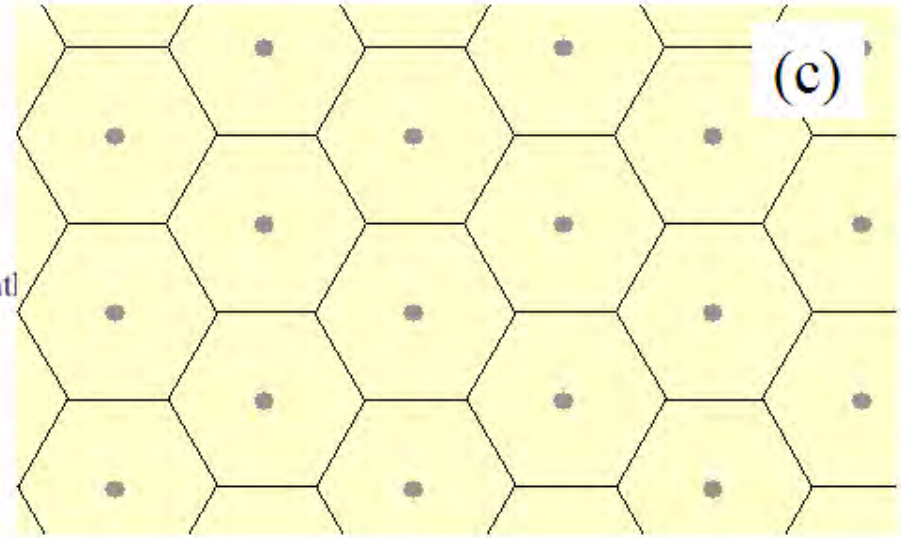
New Oxide-Free Indium Sealing Method

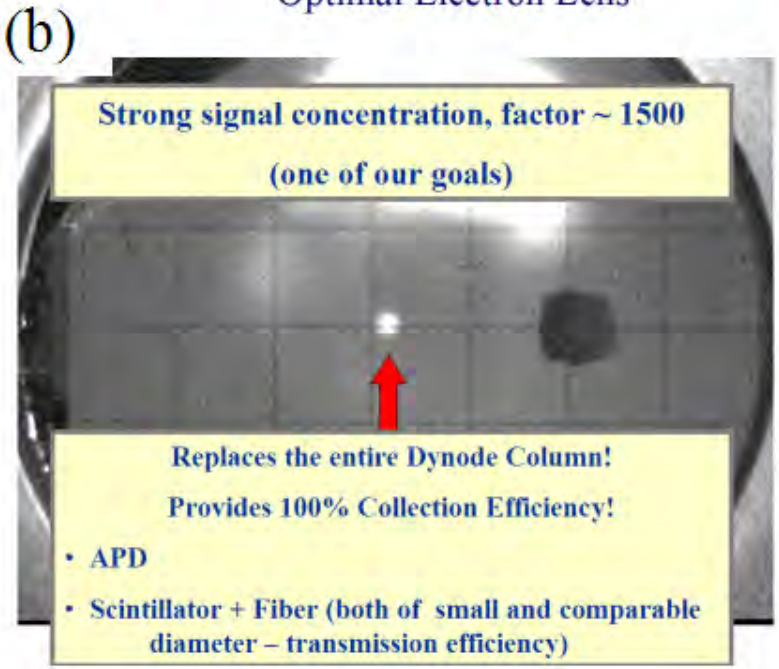


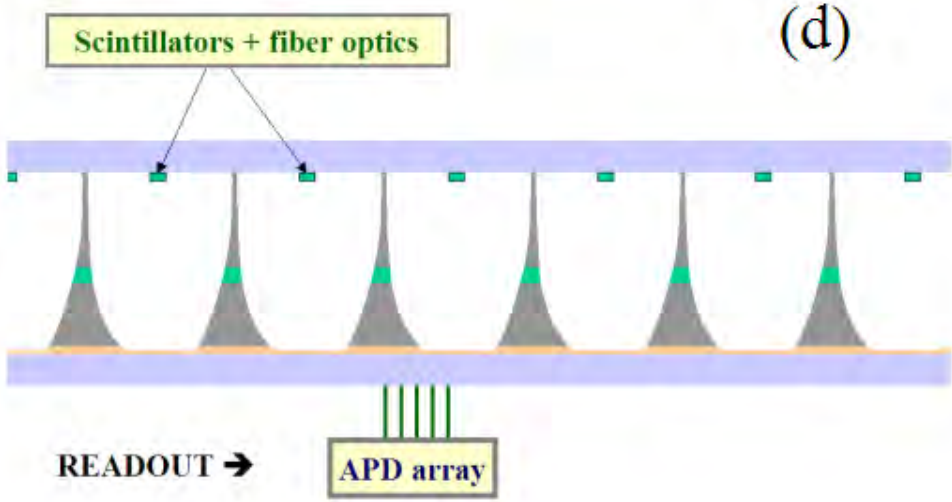
See NIM-A paper, D. Ferenc, E. Lorenz et al. 2006 (in press)


ReFerence Panel Prototype (under construction)
ENDPLATE
TUBE BODY
TOSHIBA
Solid-State
LEDs


Ideal Light Concentrator
(a)
Photoelectrons
Photon
Photocat
APD or
Scintillator
Optimal Electron Lens


(c)


(b)
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 – transmission efficiency)


Scintillators + fiber optics
(d)
READOUT ➔
APD array

‘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**

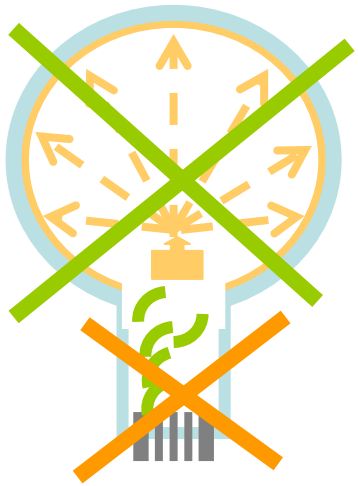
  ➔ LIGHT AMPLIFIER (G-APDS)

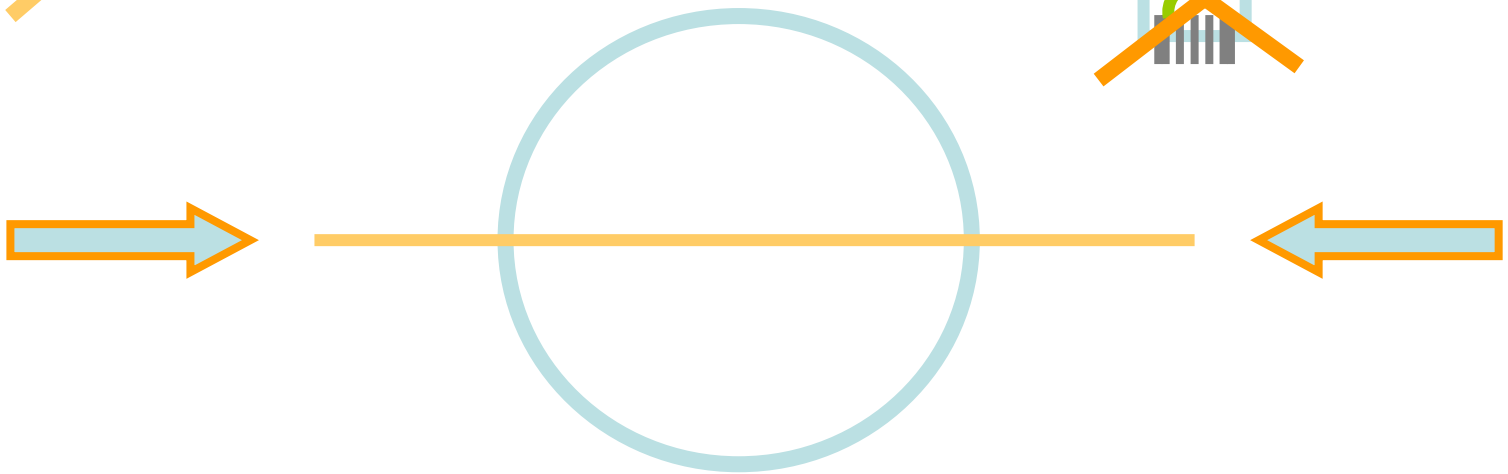
?

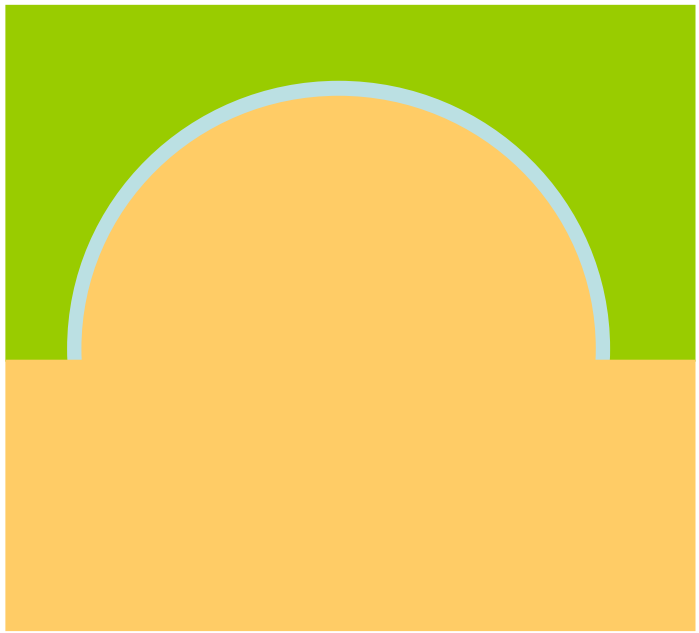
Mass production
High performance

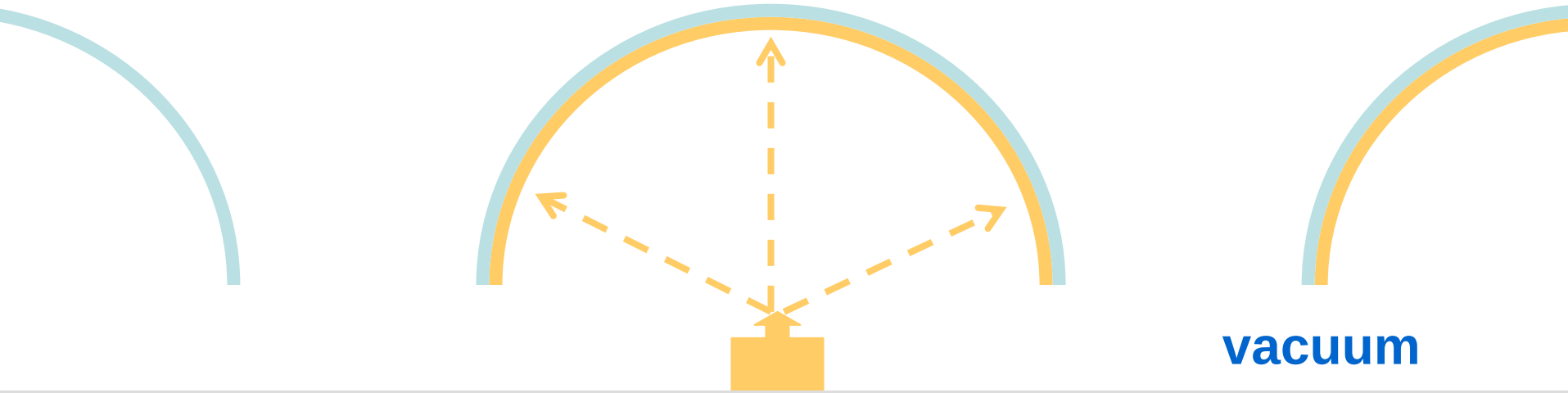
COMPONENTS:
Industrially mass-produced

ASSEMBLY:
Production-line








vacuum

?

Special marriage:

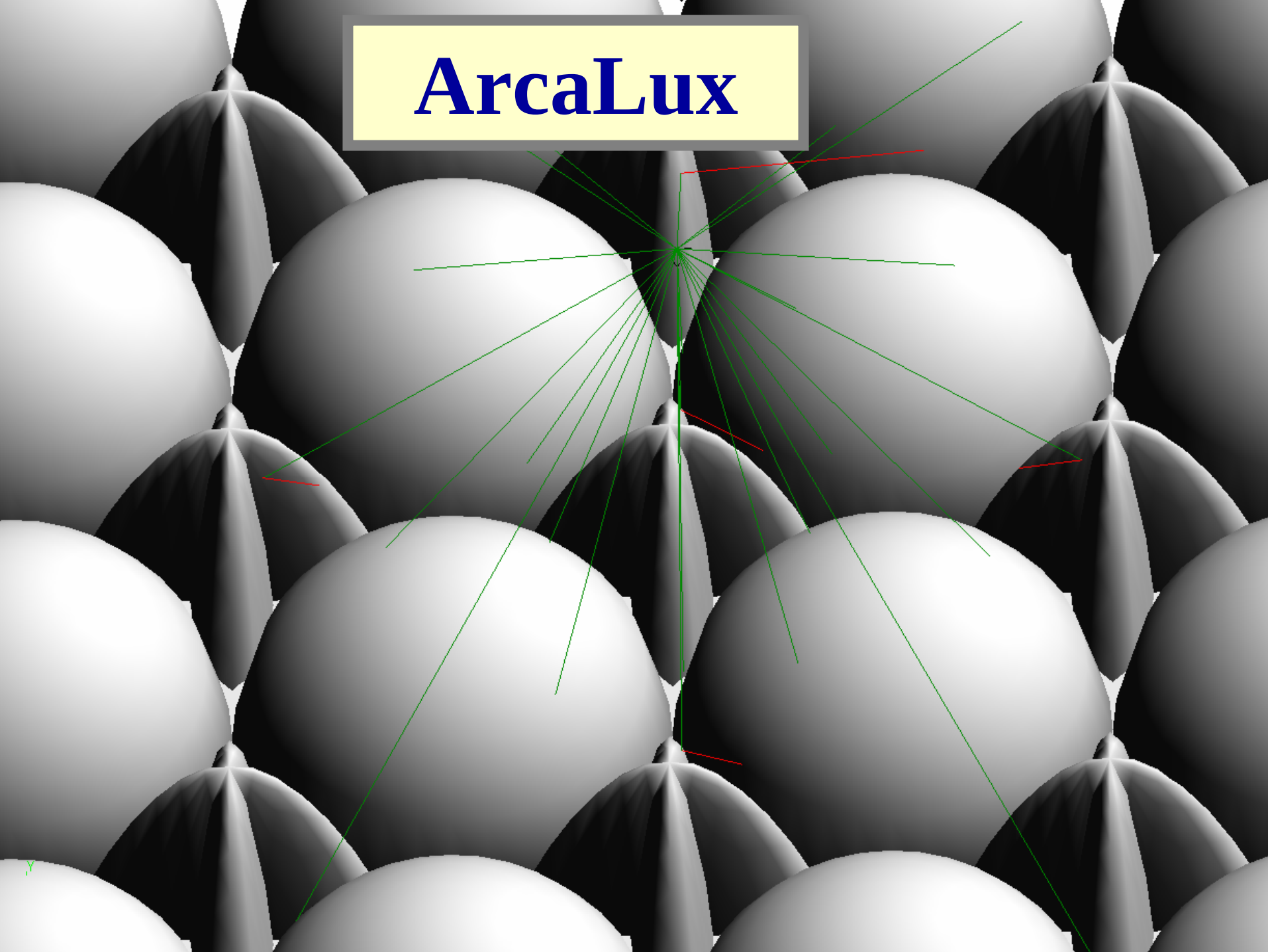
~ 0% dead area

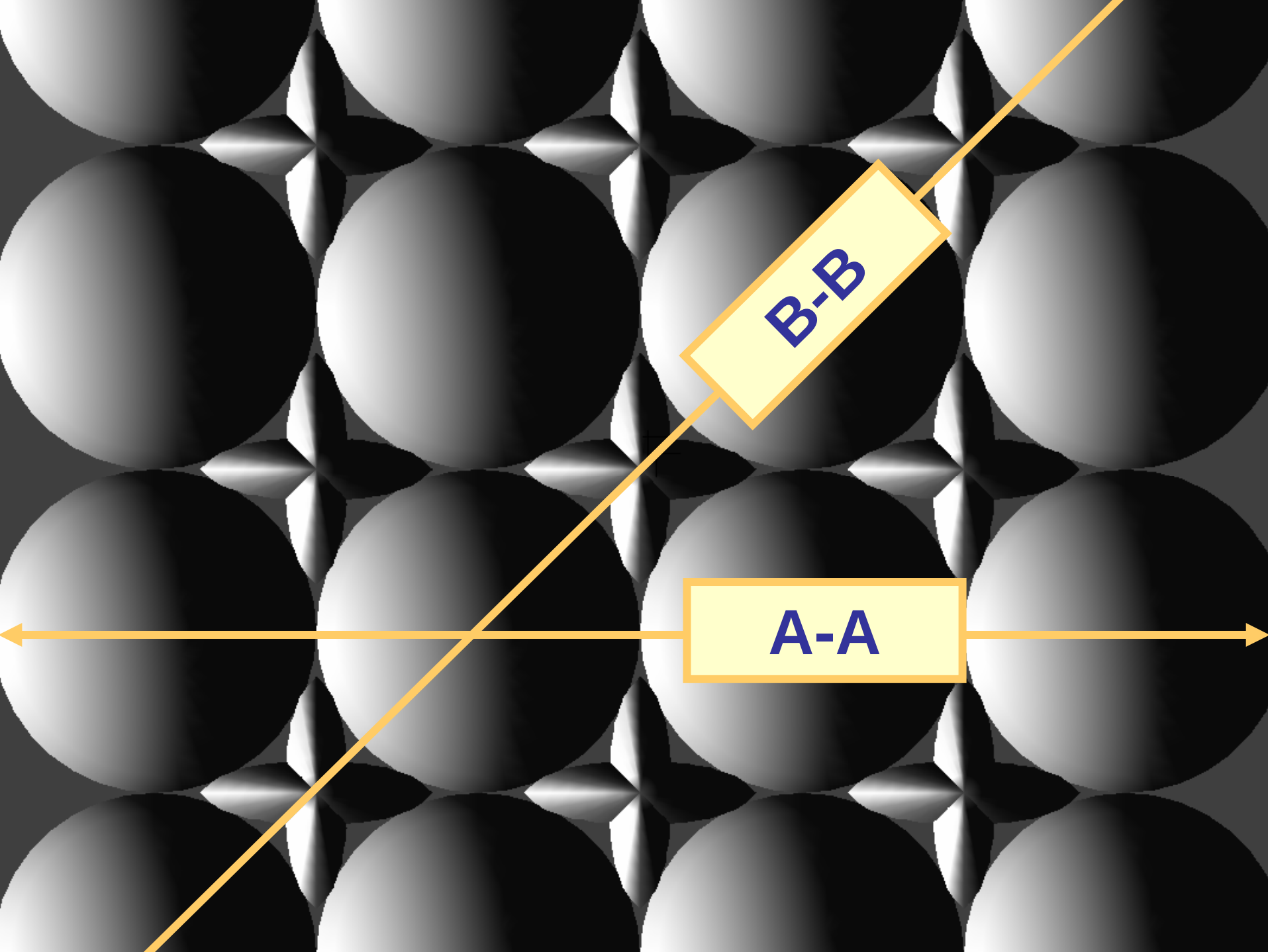
Long-lasting – the internal pollution - internally absorbed

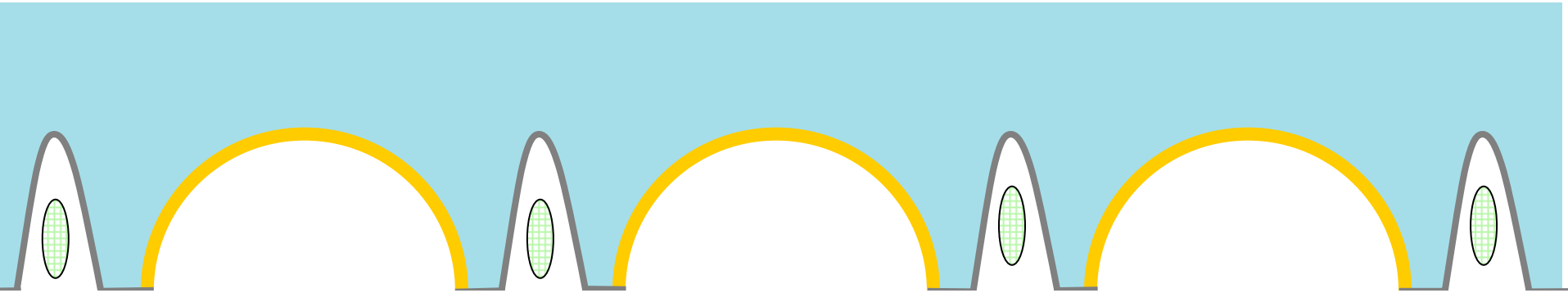
Highly resistant to pressure from outside

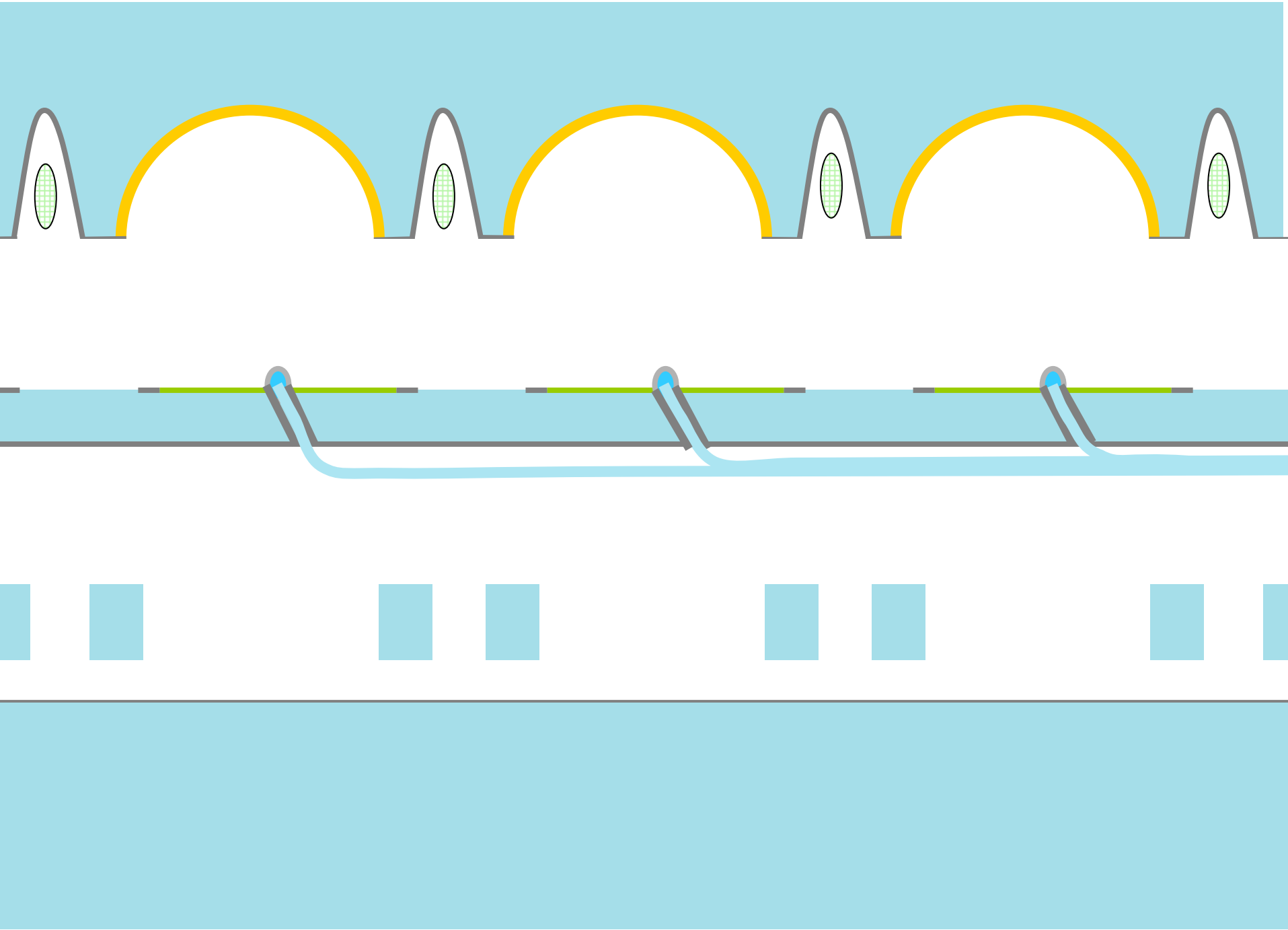
Ready for mass-production

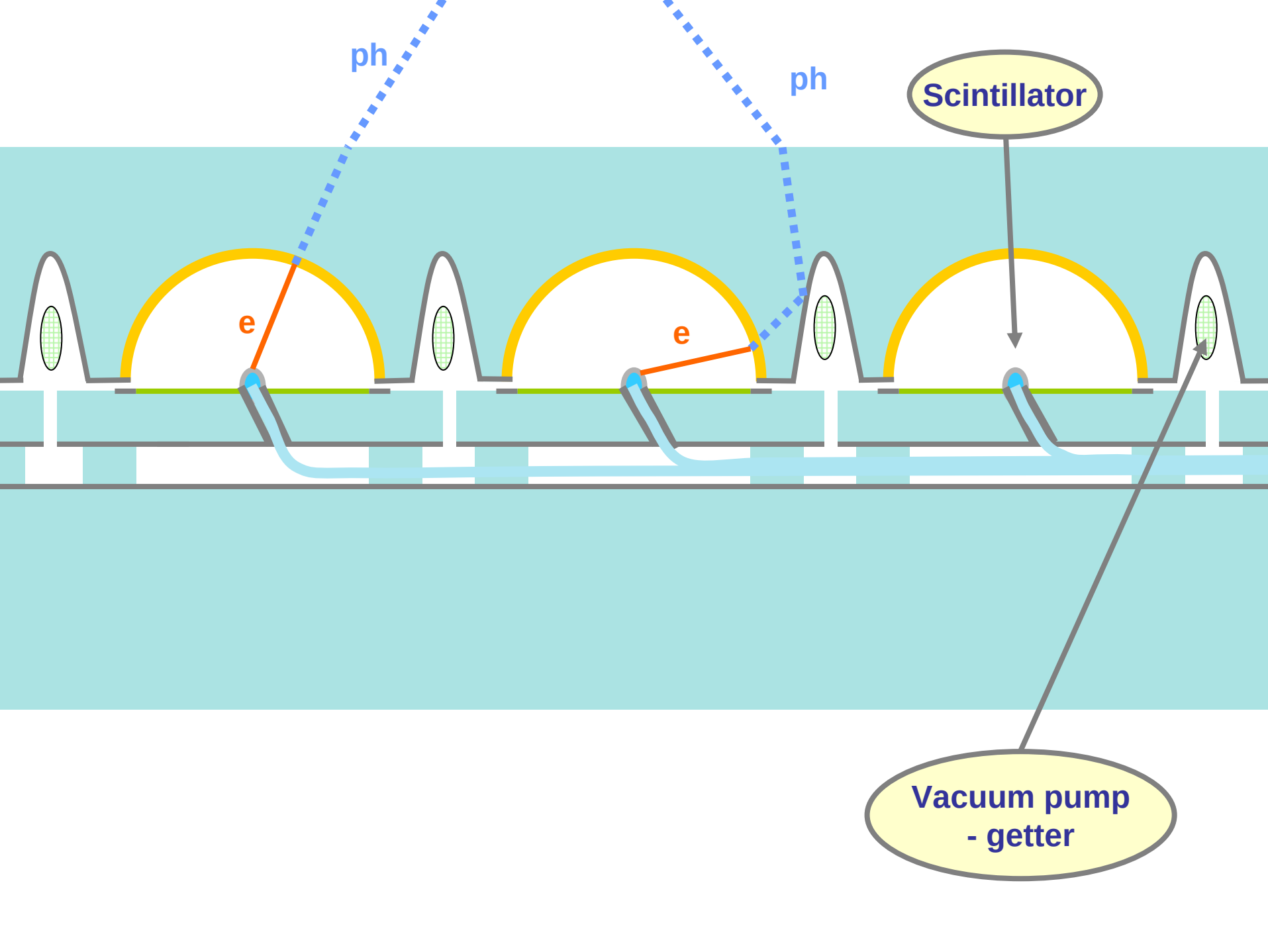
ArcaLux

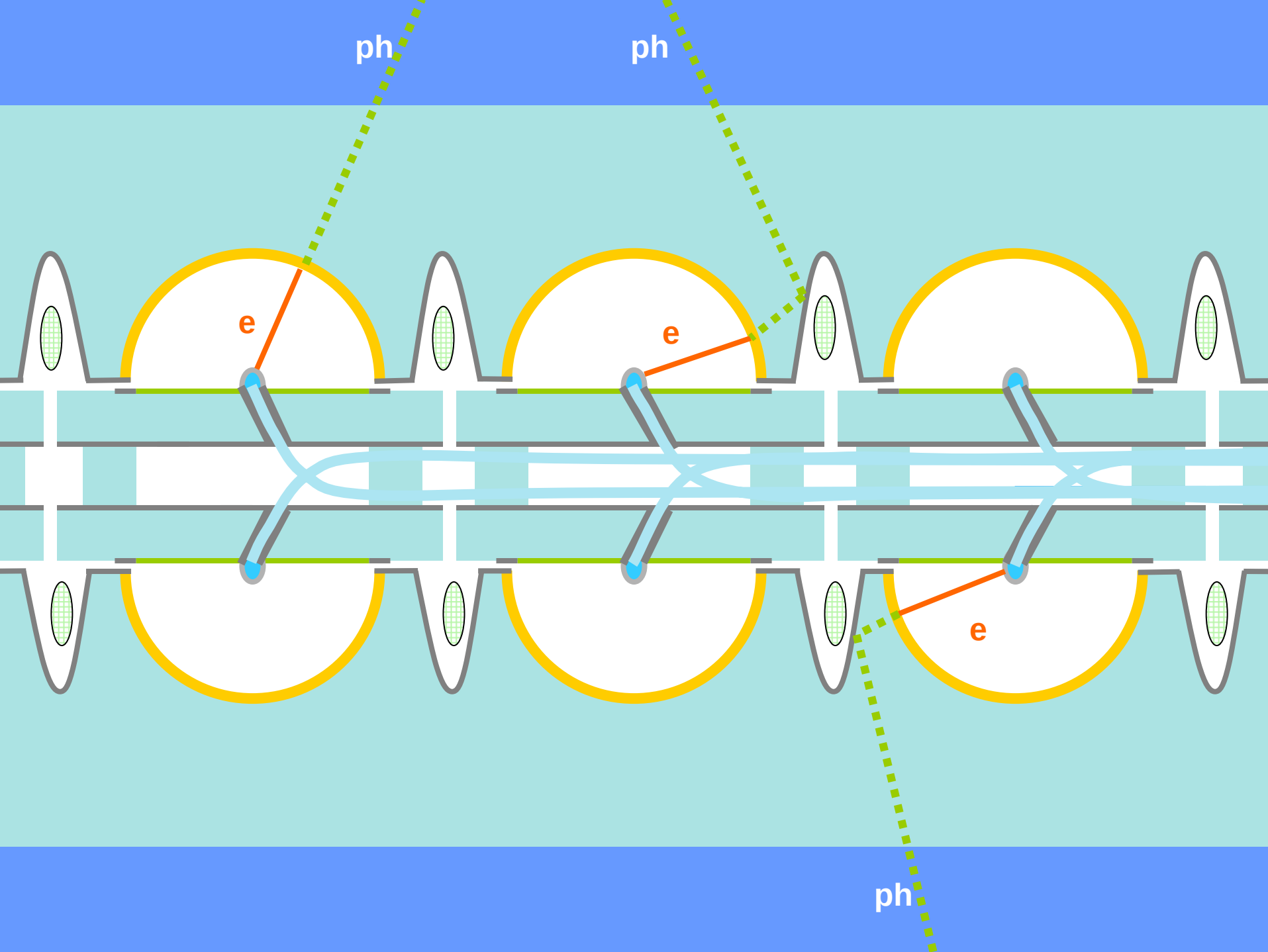



B-B
A-A






ph
ph
Scintillator
e
e
Vacuum pump
- getter


ph
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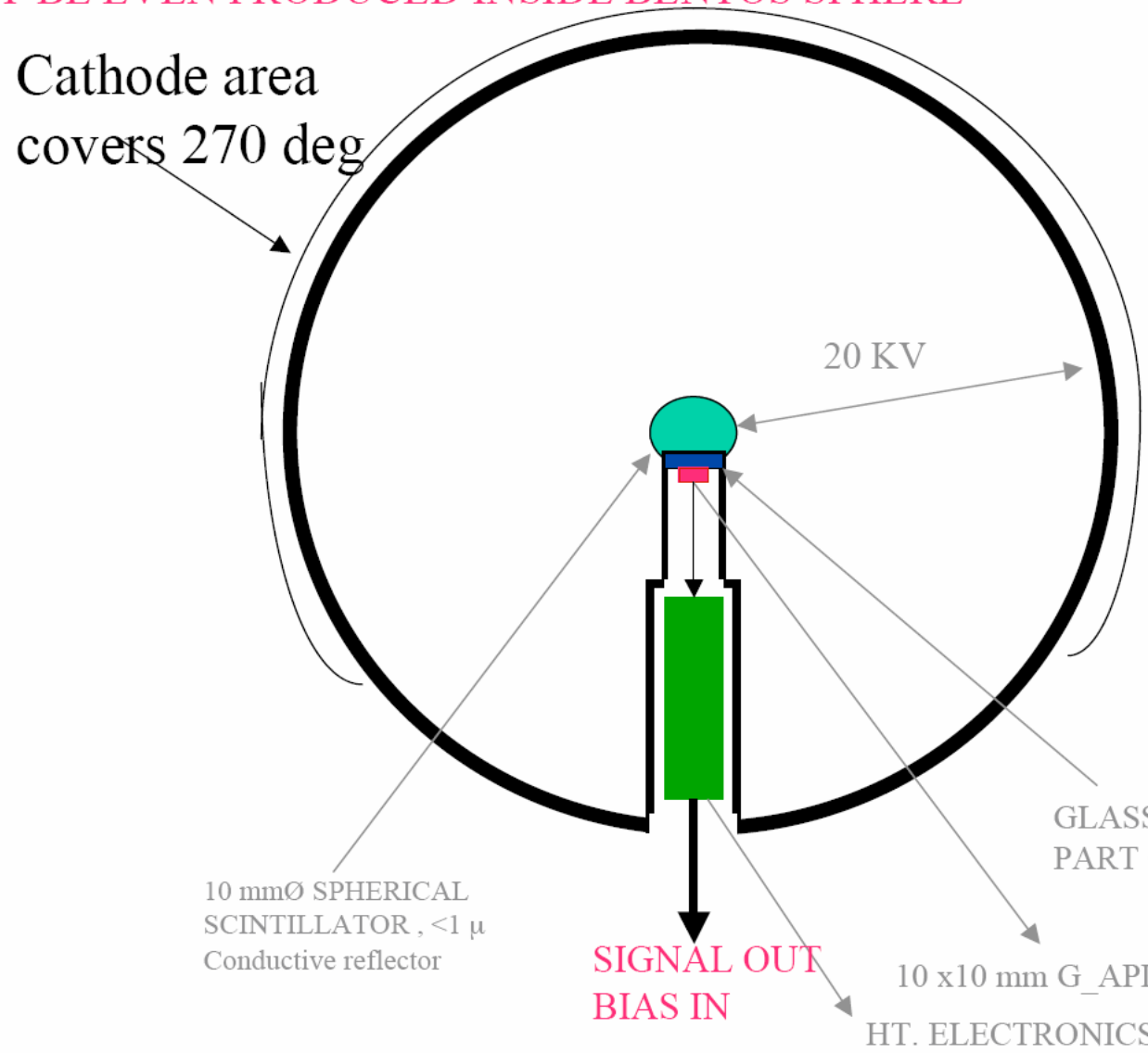
ph

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



POSSIBLE NEW SCINTILLATORS FOR HIGHER LIGHT YIELD, FASTER OPERATION

a)BrilLanCe from Saint-Gobain

- **High light yield > 60phots/KeV**
- **Fast τ : 16 nsec**
- **Caveat: extremely hygroscopic**

b) LSO,LYSO

- **High light yield. 25-30phots/KeV**
- **Fast 35-40 nsec**
- **Easy to handle**

C) ZnO

- **Medium light yield, 10 phots/kEV**
- **Ultrafast ≈ 1 nsec**
- **Exotic material**
- **No commercial production**
- **Small xtals**

E. Lorenz, D. Ferenc, Elba 2006, NIMA

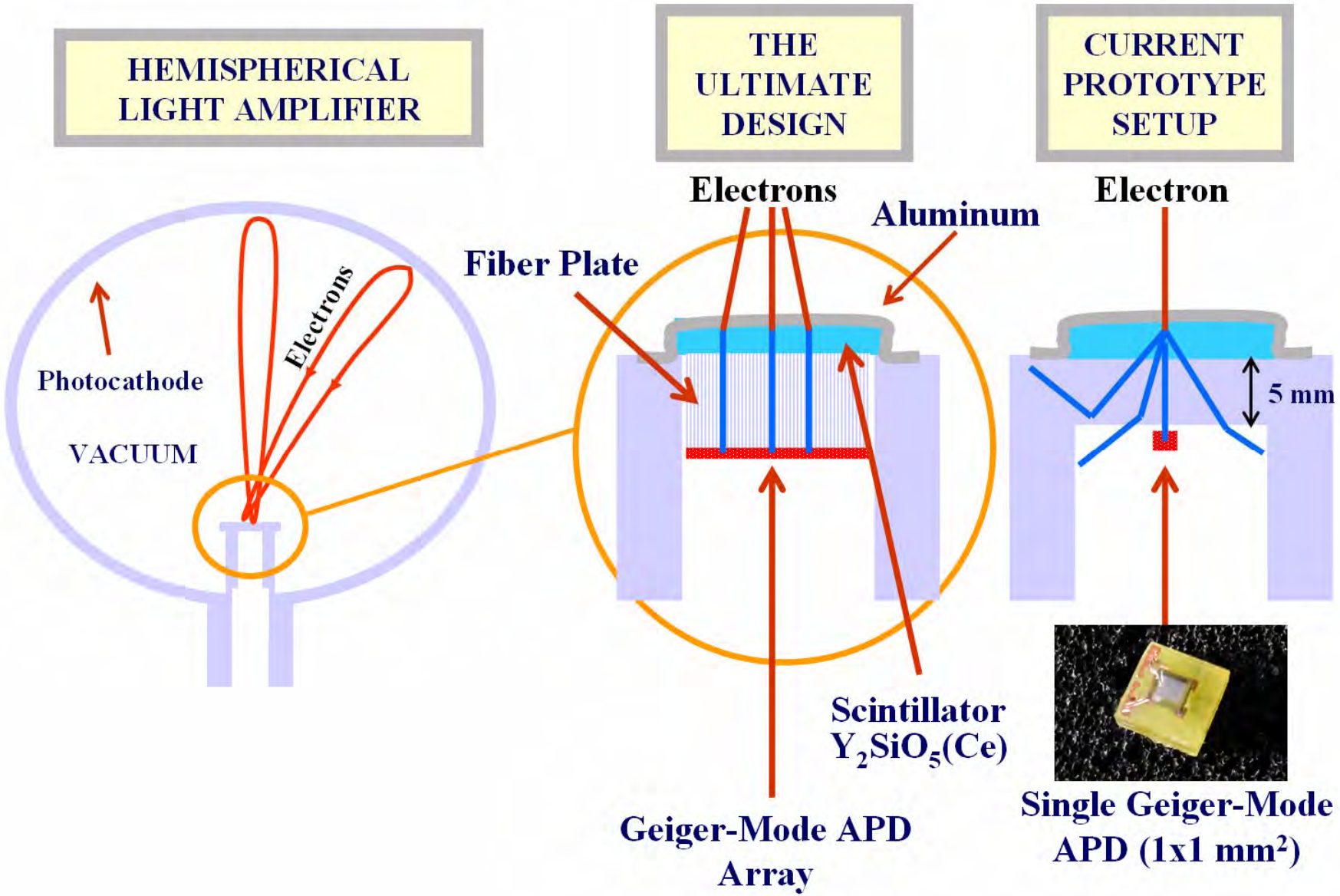
THE QUASAR

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 ≈1.3

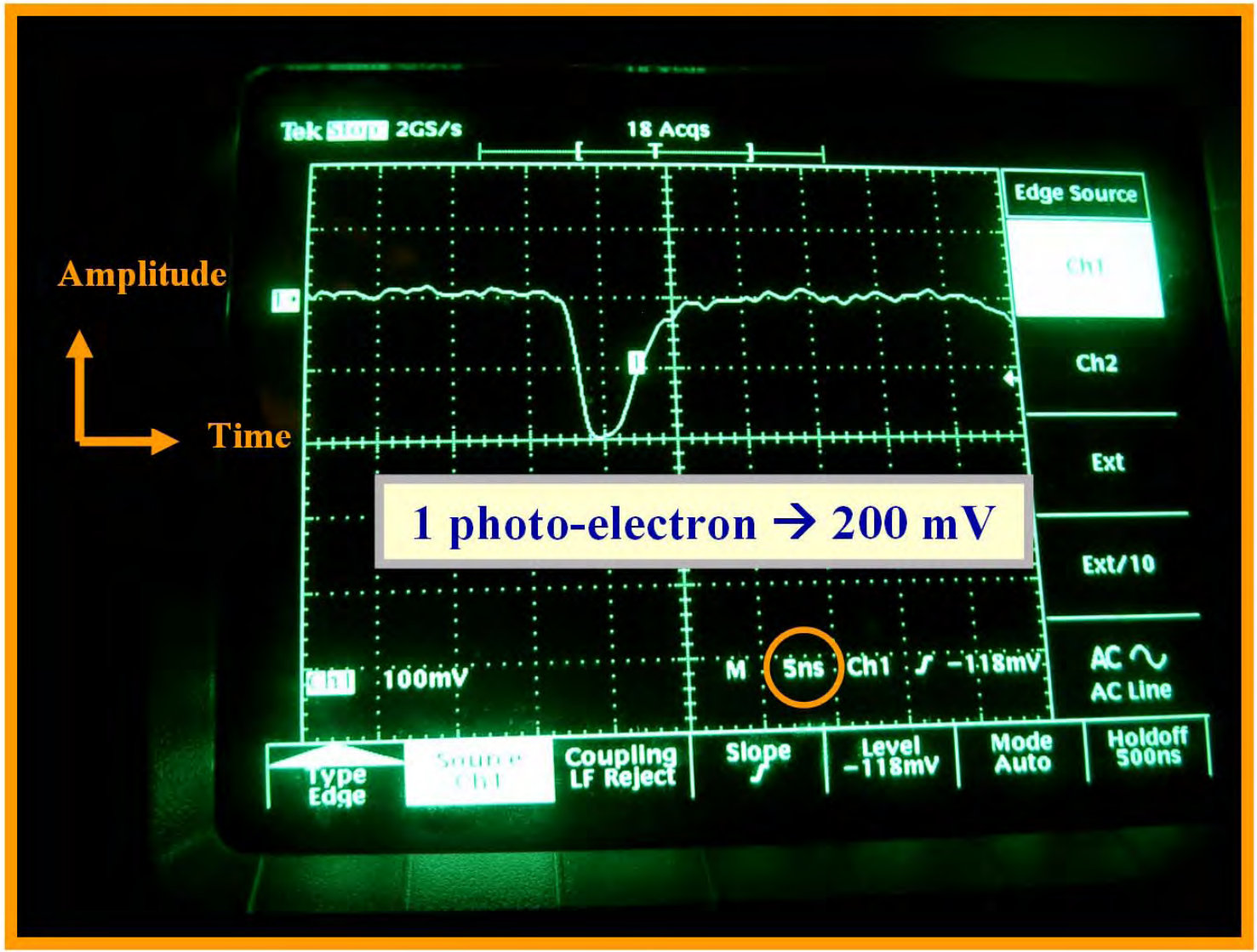
- CRYSTAL WITH LONG DECAY TIME
- RELATIVELY LOW LIGHT YEALD
- PRODUCTION STOPPED

THE FOLLOWING TESTS HAVE BEEN CARRIED OUT WITH A QUASAR



E. Lorenz, D. Ferenc, Beaune 2005, MIMA

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

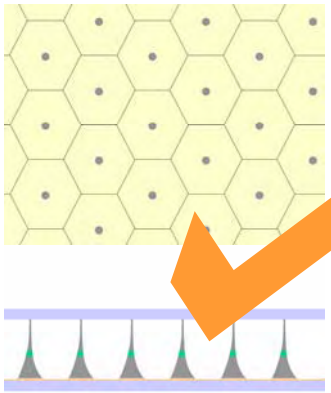


E. Lorenz, D. Ferenc, Beaune 2005, MIMA

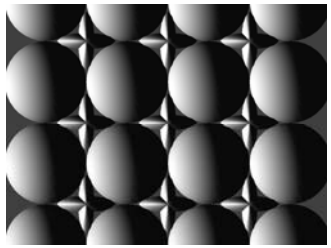
Conclusion

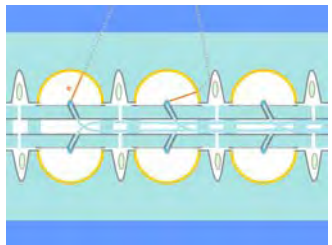
ULTIMATE: FLAT-PANEL

ReFerence

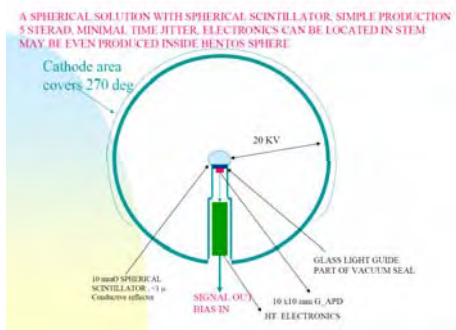


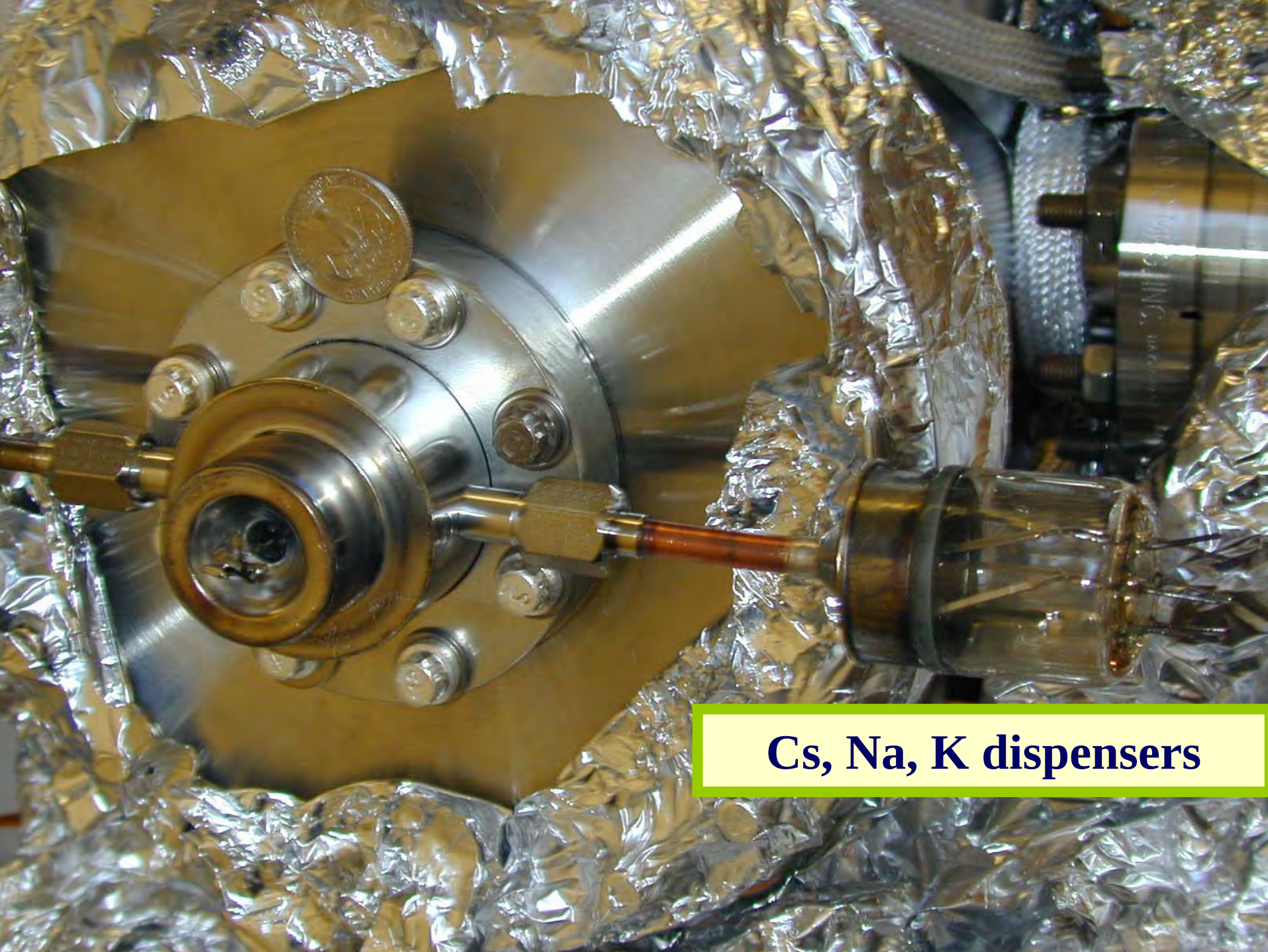
ArcaLux





INTERMEDIATE: HEMISPHERICAL Light Amplifier




Cs, Na, K dispensers