KEK

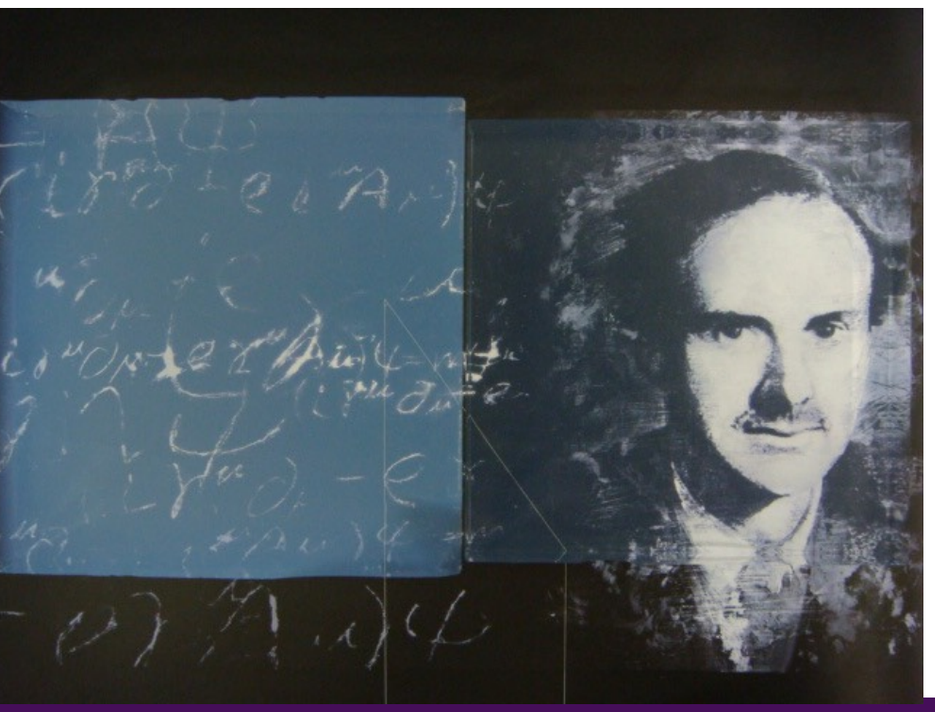
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

Status and Perspectives of High Quality Silica Aerogel

Ichiro Adachi

KEK

2018.08.03



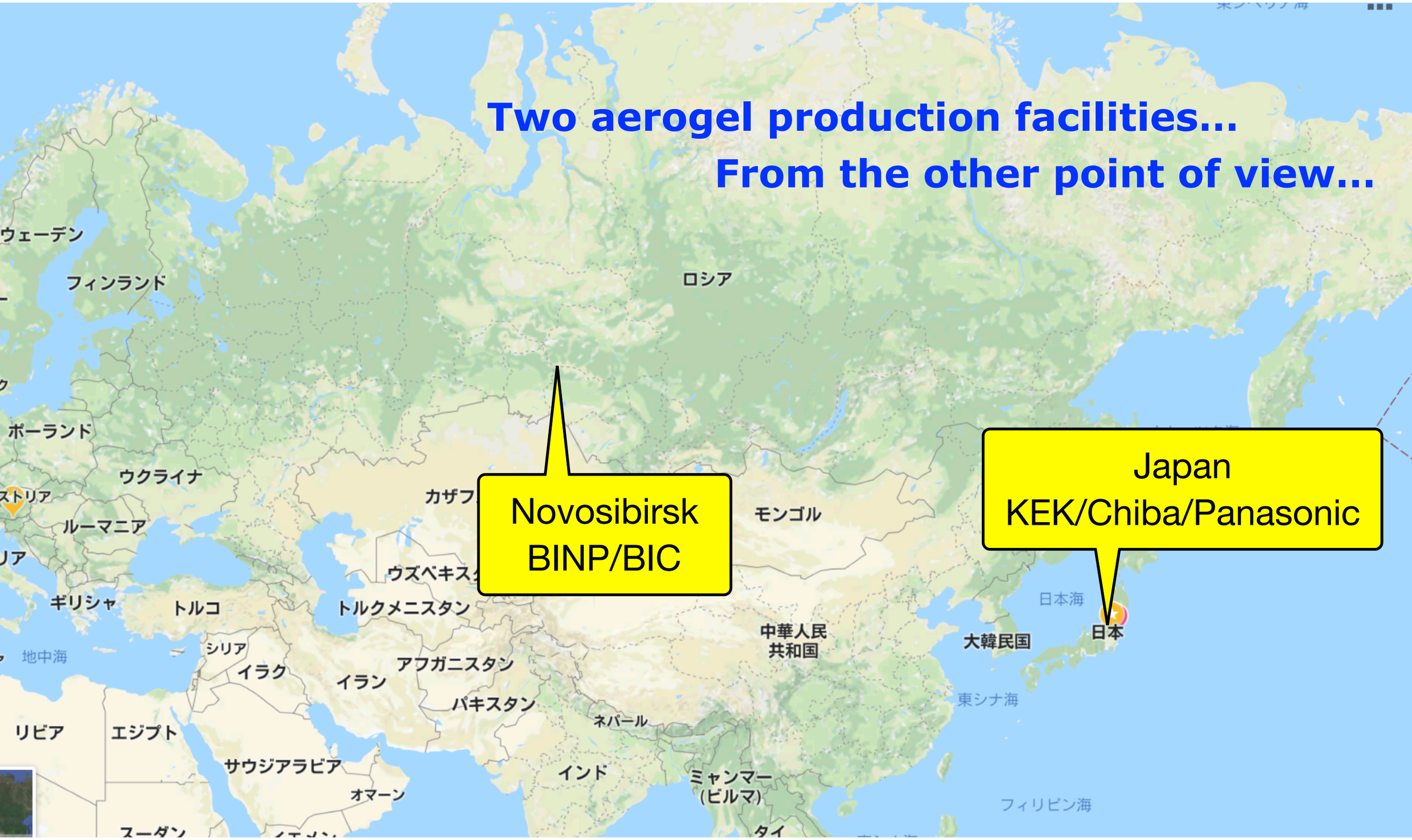
Cherenkov detectors with aerogel radiators

E.A.Kravchenko

Novosibirsk State University
Budker Institute of Nuclear Physics

We have already had a review talk !

Two aerogel production facilities...
From the other point of view...



Comment...

Belle aerogel Cherenkov counters

1991 KEK and Matsushita started joint effort in producing low refractive index silica aerogels.

- 1992 – seminar of A.Onuchin at KEK on aerogel threshold detector development
- 1994 – approval of KEKB with Aerogel Cherenkov Counters as baseline for PID
- Very intensive R&D both on aerogel production and detector design
- 1124 detectors equipped with 2024 Fine Mesh PMTs (2, 2.5, 3 inch)
- n=1.01—1.03, V_{Σ}=2000 l, high transparency hydrophobic aerogel
- Npe = 20—26(!)
- In operation 1998-2010
- **Full success of the project!**

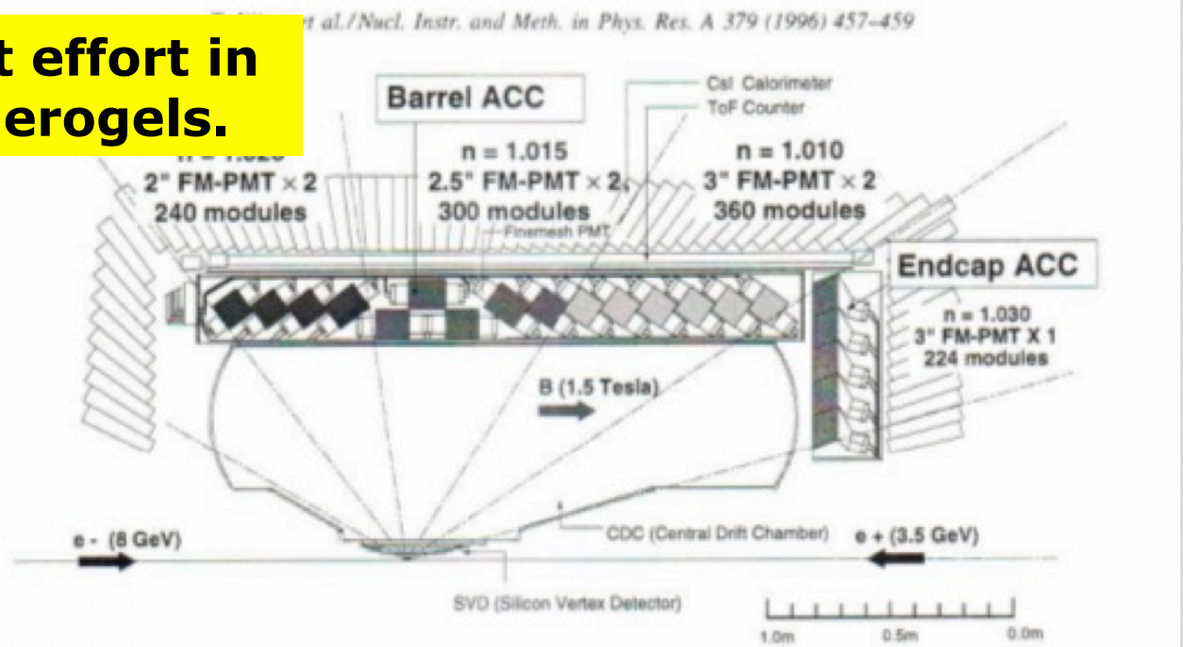


Fig. 1. Design of the BELLE aerogel Cherenkov counter system (as of March 1996).

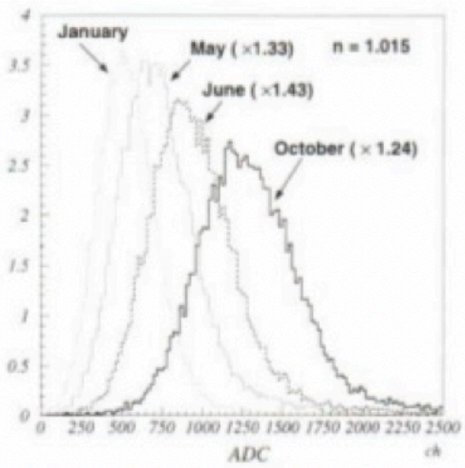
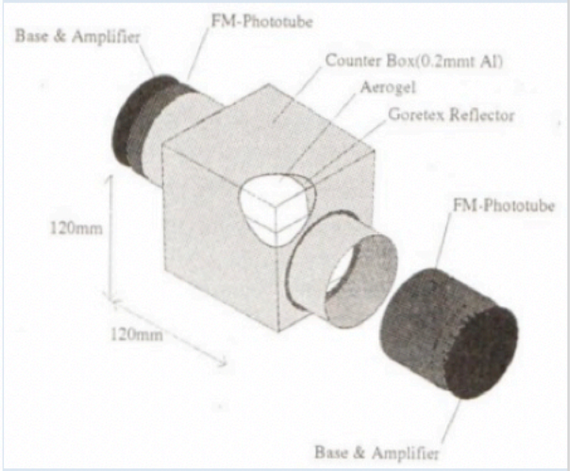


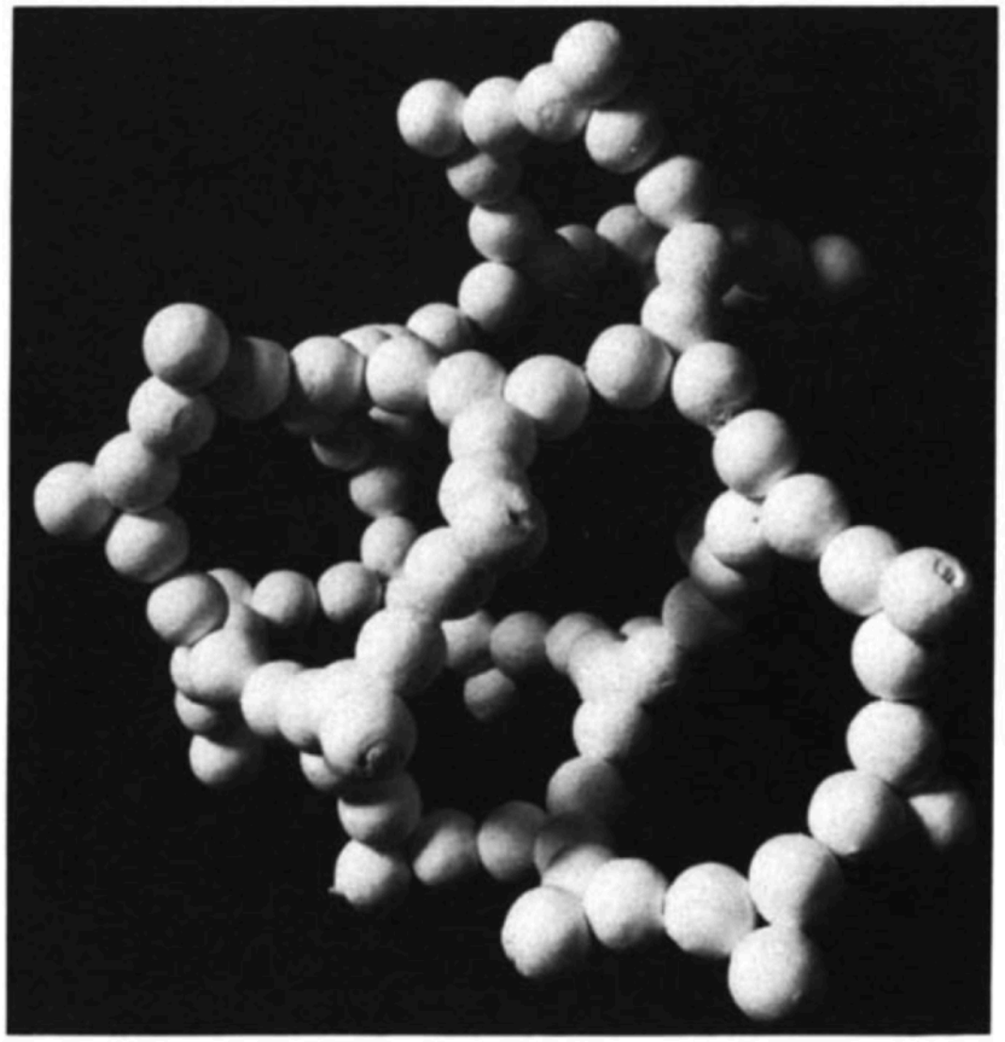
Fig. 2. Pulse height spectra obtained with $n = 1.015$ aerogels in beam tests in the past one year. The counter configuration and PMT gains are the same for all measurements.

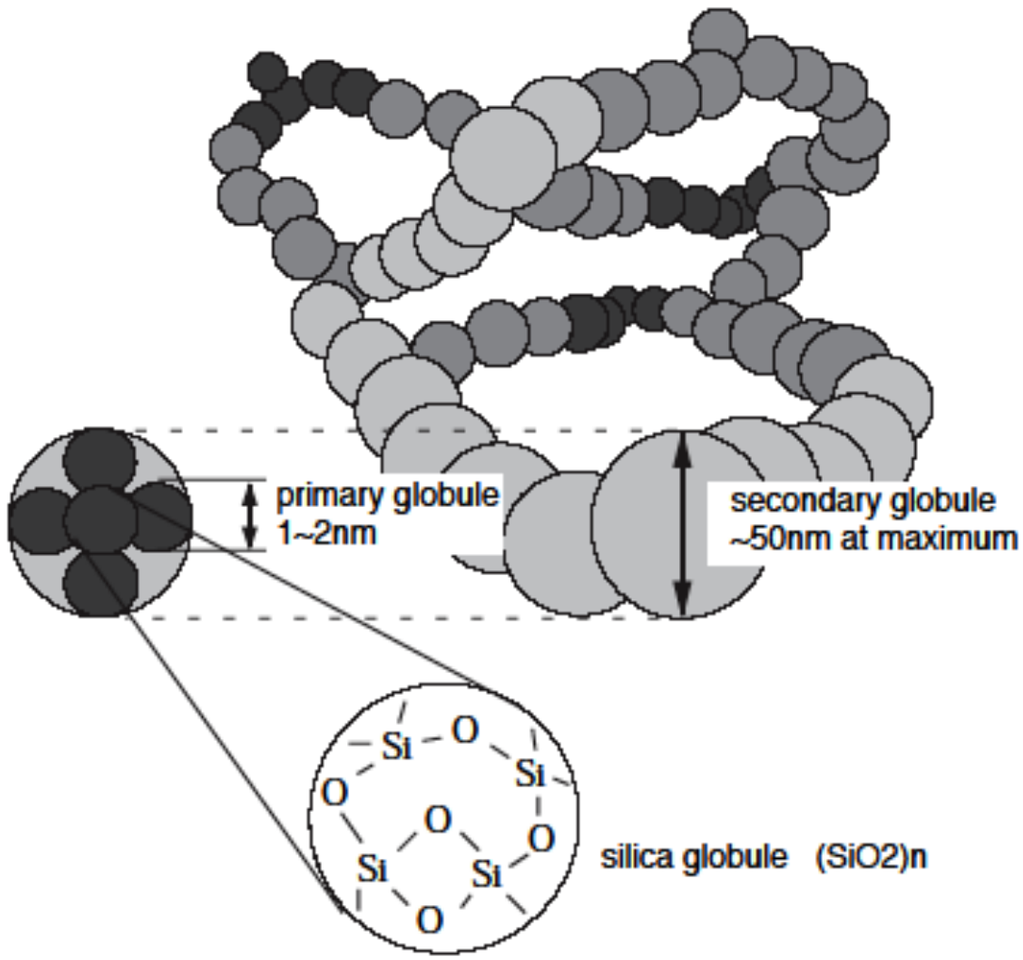


01.08.18 RICH2018, Moscow 12

Silica Aerogel

- Highly porous material of silica clusters
  - 3 dimensional network of $(SiO_2)n$
  - Micro-structure smaller than the wavelength of visible light.
  - More than 90 % air inside volume





Production Process

- Two subsequent reactions for sol-gel polymerization

$$n\mathrm{Si(OR)_4} + 4n\mathrm{H_2O} \longrightarrow n\mathrm{Si(OH)_4} + 4n\mathrm{ROH} \qquad \textbf{Hydrolysis}$$

$$n\mathrm{Si(OH)_4} \longrightarrow \underline{(\mathrm{SiO_2})_n} + 2n\mathrm{H_2O} \qquad \textbf{Condensation}$$

Alco-gel

- **Hydrophobic treatment**
  - **Introduced in 1990's at KEK**

- Aging
  - Stabilize 3D network of SiO_2 clusters

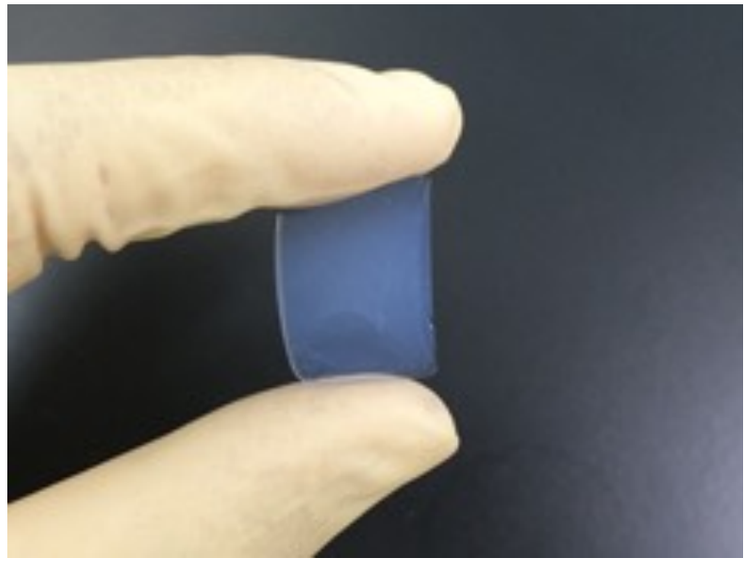
- Supercritical drying (SCD) to convert from alco-gel to aerogel.
  - Critical point
    - CO_2 : T=31℃ & P=7.4MPa
    - Methanol : T=240℃ & P=8.1MPa

Unique Features

- Excellent thermal insulator

thermal insulation window

- Fragile
  - Especially localized pressure
  - If pressure is widely uniform over aerogel surface, aerogel tiles posses some rigidity.



Optical Quality

- Refractive Index
  - Density (in other words)
  - **Fraction of silica clusters defines material density.**
- Transparency
  - Transmission length
  - Clarity parameters
  - **Uniformity and dimensions of silica clusters are related to transparency.**
    - For high transparency, synthesis parameters (gelling time etc) should be optimized.

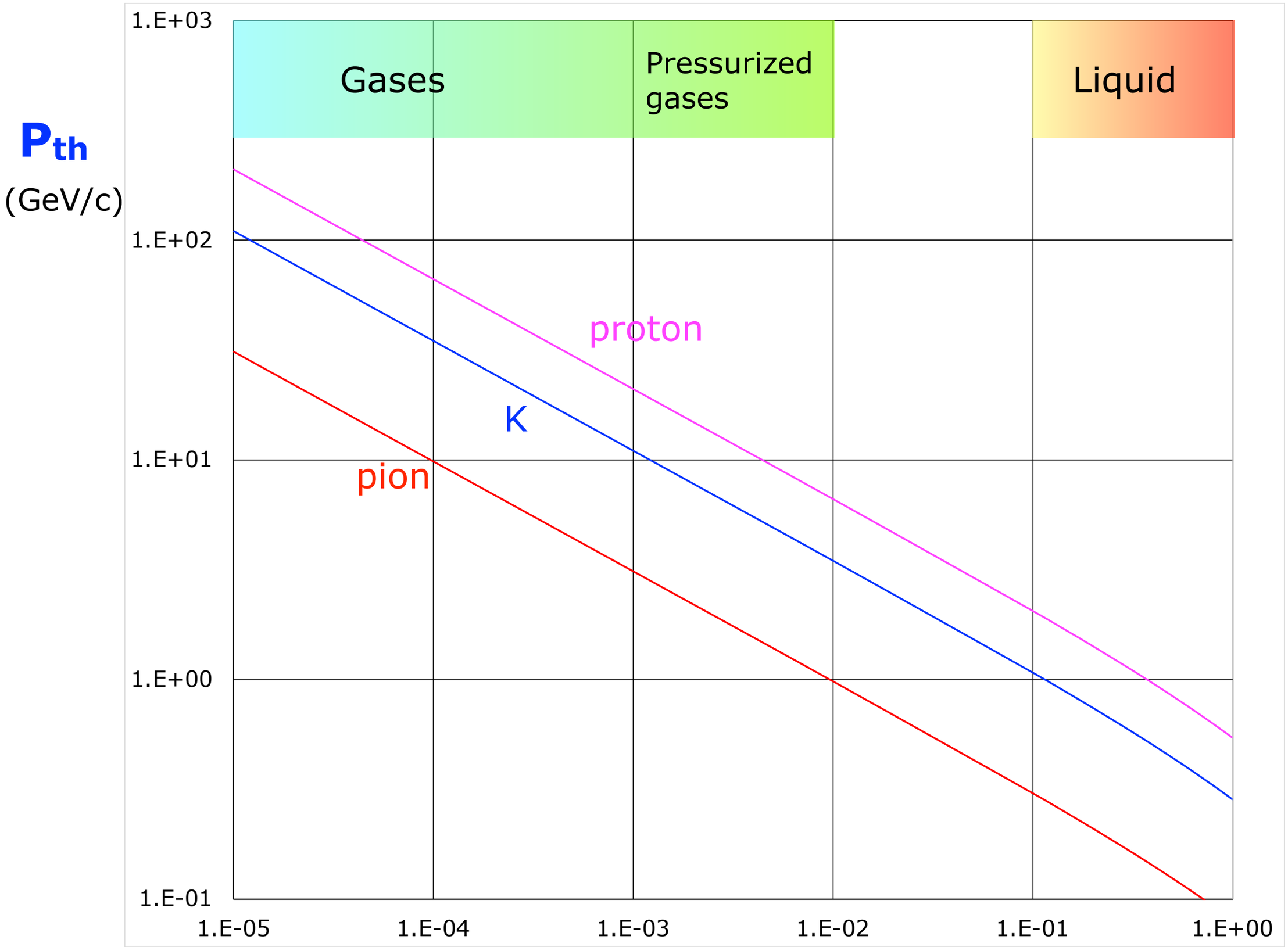
Refractive Index

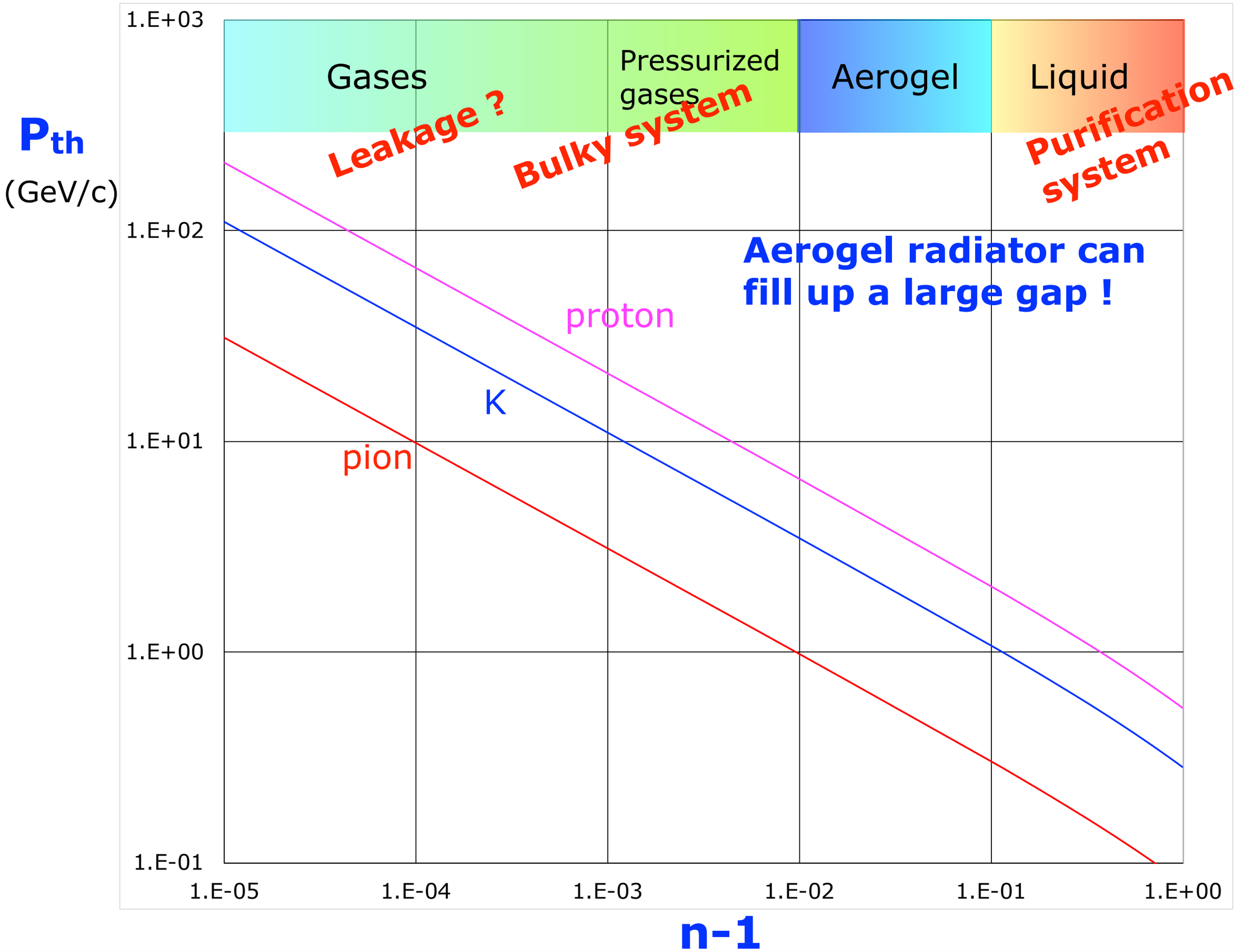
- Unique refractive index
  - It is related to quantity of SiO_2 clusters.

Cherenkov radiation

Threshold momentum P_{th} is related to refractive index (n) of radiator medium and incident particle mass (m) .

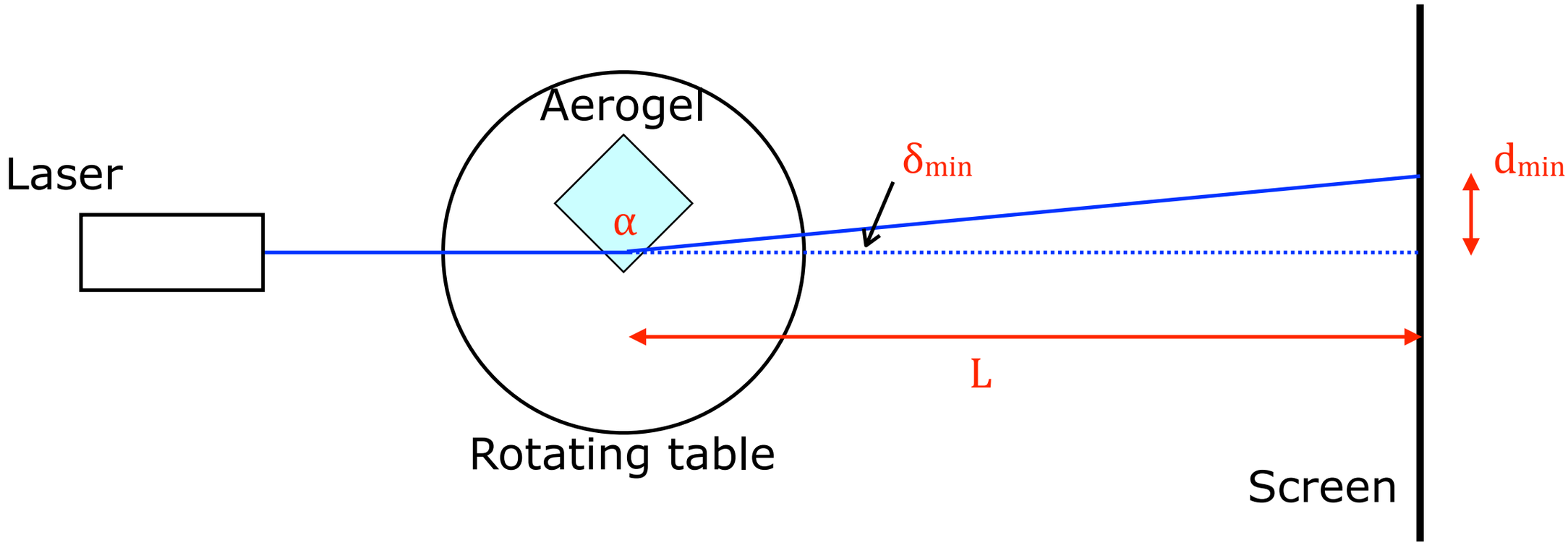
$$P_{th} = m / \sqrt{(n^2 - 1)}$$


Gases
Pressurized gases
Liquid
proton
K
pion
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
Pth
(GeV/c)
n-1


Pth
(GeV/c)
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
n-1
Gases
Pressurized gases
Aerogel
Liquid
Leakage ?
Bulky system
Purification system
Aerogel radiator can fill up a large gap !
proton
K
pion

Refractive Index Measurement

- Refractive index is calculated from a deflection angle in Fraunhofer method.



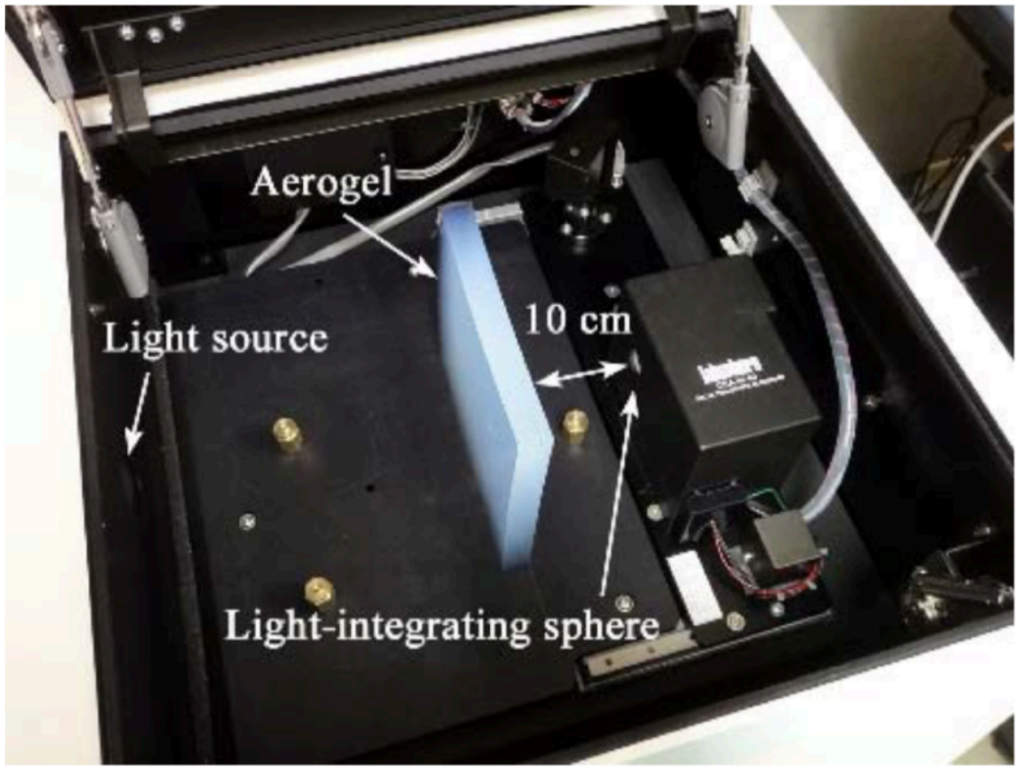
Prism formula

$$n = n_{air} \cdot \sin((\alpha+\delta_{min})/2)[1/\sin(\alpha/2)]$$

$$\delta_{min} = \tan^{-1}(d_{min}/L)$$

Transmittance

- Transmittance is measured using a spectrophotometer.
  - At KEK, aerogel tile is placed by 10 cm from a light-integrating sphere.



$T = T_0 \exp(-d/\Lambda)$

T_0: initial intensity
d : thickness
Λ : transmittance length

$\Lambda(\lambda) = -d/\ln(T/T_0)$

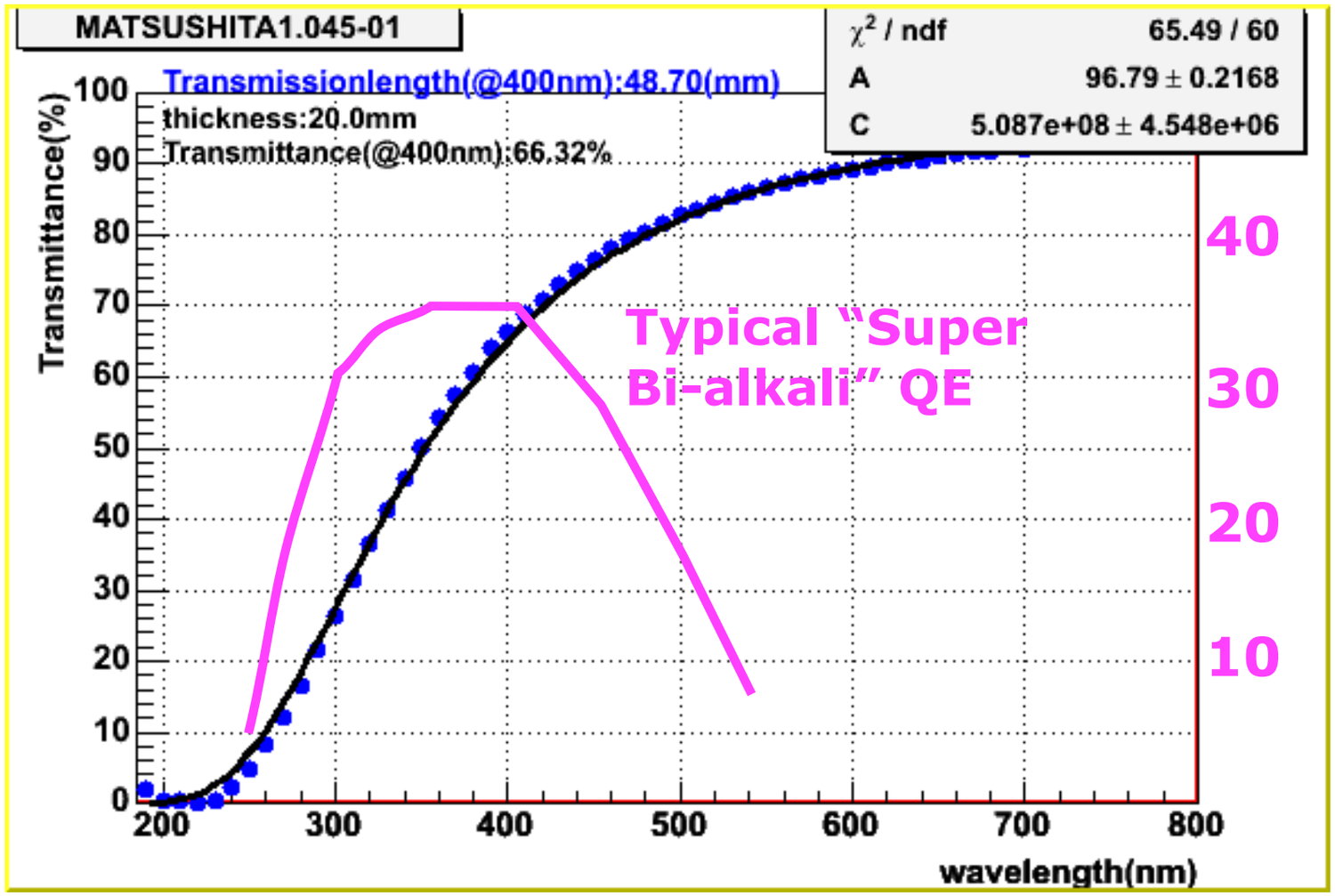
$\Lambda(\lambda=400nm)$ often used to characterize aerogel transparency

Λ depends on the position, where aerogel tile is placed in the spectrophotometer.

Clarity parameters also used.
$T = A \exp(-C \cdot t/\lambda^4)$

Transmittance

- Transparent for visible light region
- **This makes photon detection more straightforward.**



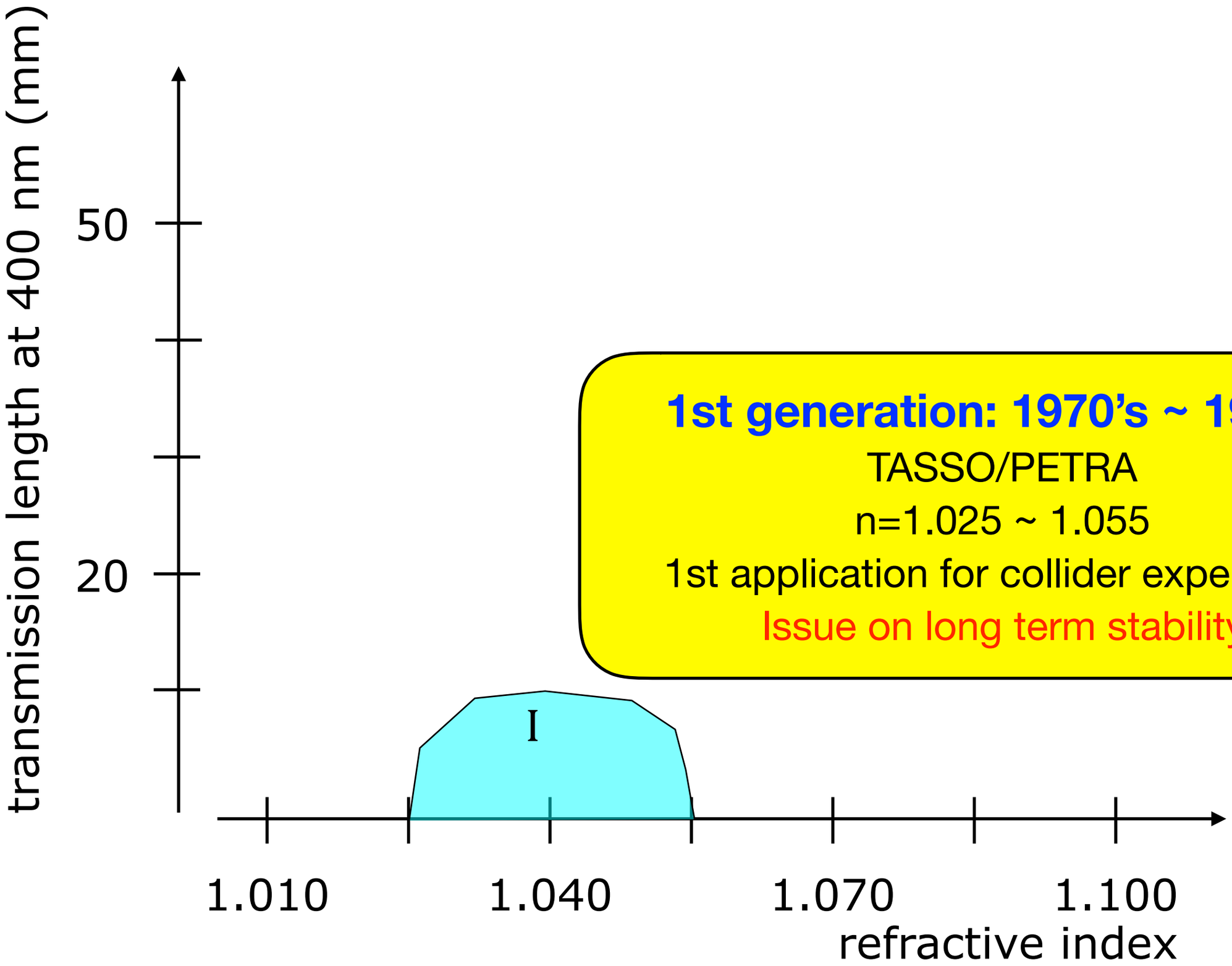
Aerogel Production Centers

- **Japan**
  - KEK/Chiba/Panasonic groups
    - Panasonic no longer deal with aerogel production.
    - Technological transfer to Japan Fine Ceramics Center (JFCC).
    - SCD is outsourced to Mohri oil company.
      - Facility with 70-liter dry volume
    - Chiba university has their own SCD facility.
      - Only academic center to handle aerogel production from synthesis steps to SCD.

- **Russia**
  - Budker INP and Boreskov institute of Catalysis.
  - Their own SCD facilities.
    - Please see a nice poster

History of Aerogel Radiator & Development of Cherenkov Counters

History of Aerogel Radiators



1st generation: 1970's ~ 1980's

TASSO/PETRA

n=1.025 ~ 1.055

1st application for collider experiment

Issue on long term stability

History of Aerogel Radiators

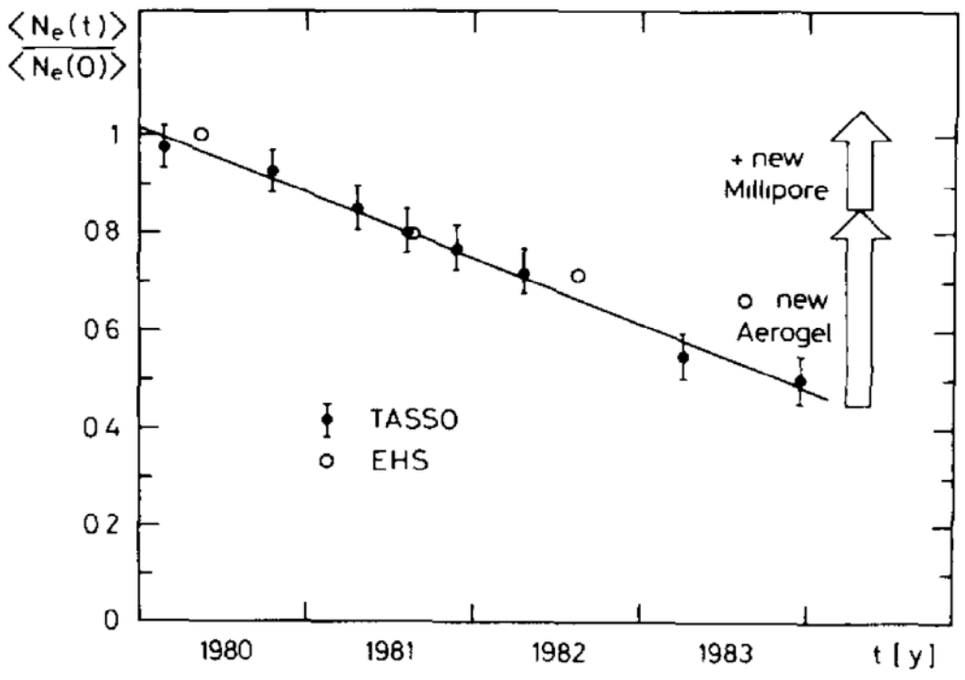


Fig. 24. Photoelectron yield of the TASSO aerogel counters for relativistic particles along the time of operation. The yield decreases with a slope of 0.5 yr^{-1}. The arrows show the improvement obtained when new aerogel and new millipore was recently installed in one cell. The data from the EHS detector [16] indicate a similar decrease but suggest an exponential decay with a time constant of 7.5 yr.

NIMA248(1986)118

N_{pe} decreased by 0.5/yr

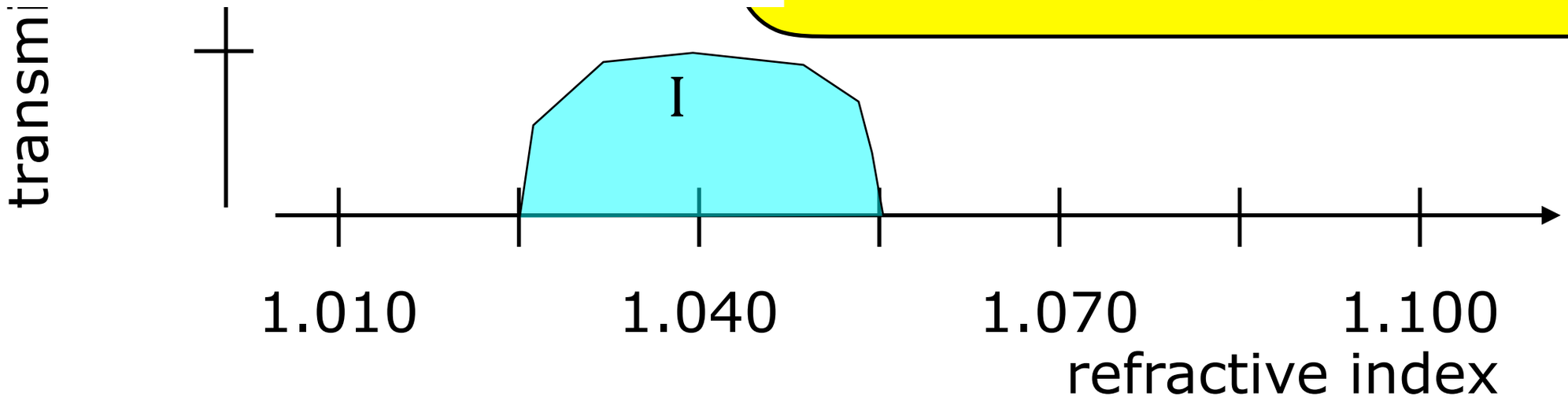
1st generation: 1970's ~ 1980's

TASSO/PETRA

n=1.025 ~ 1.055

1st application for collider experiment

Issue on long term stability



History of Aerogel Radiators

2nd generation: 1992 ~ 2002

Belle Aerogel threshold counter/KEKB

HERMES RICH/HERA

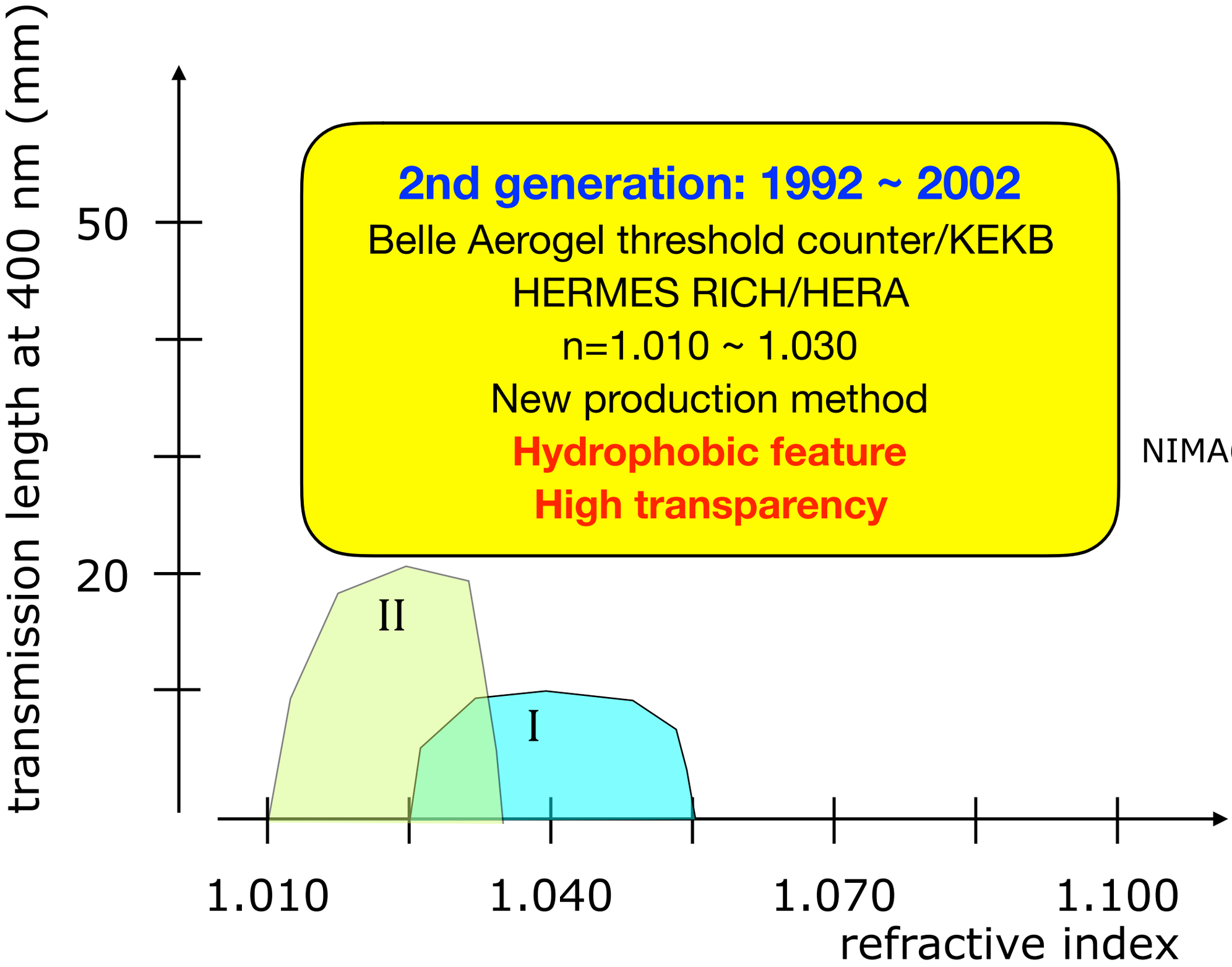
n=1.010 ~ 1.030

New production method

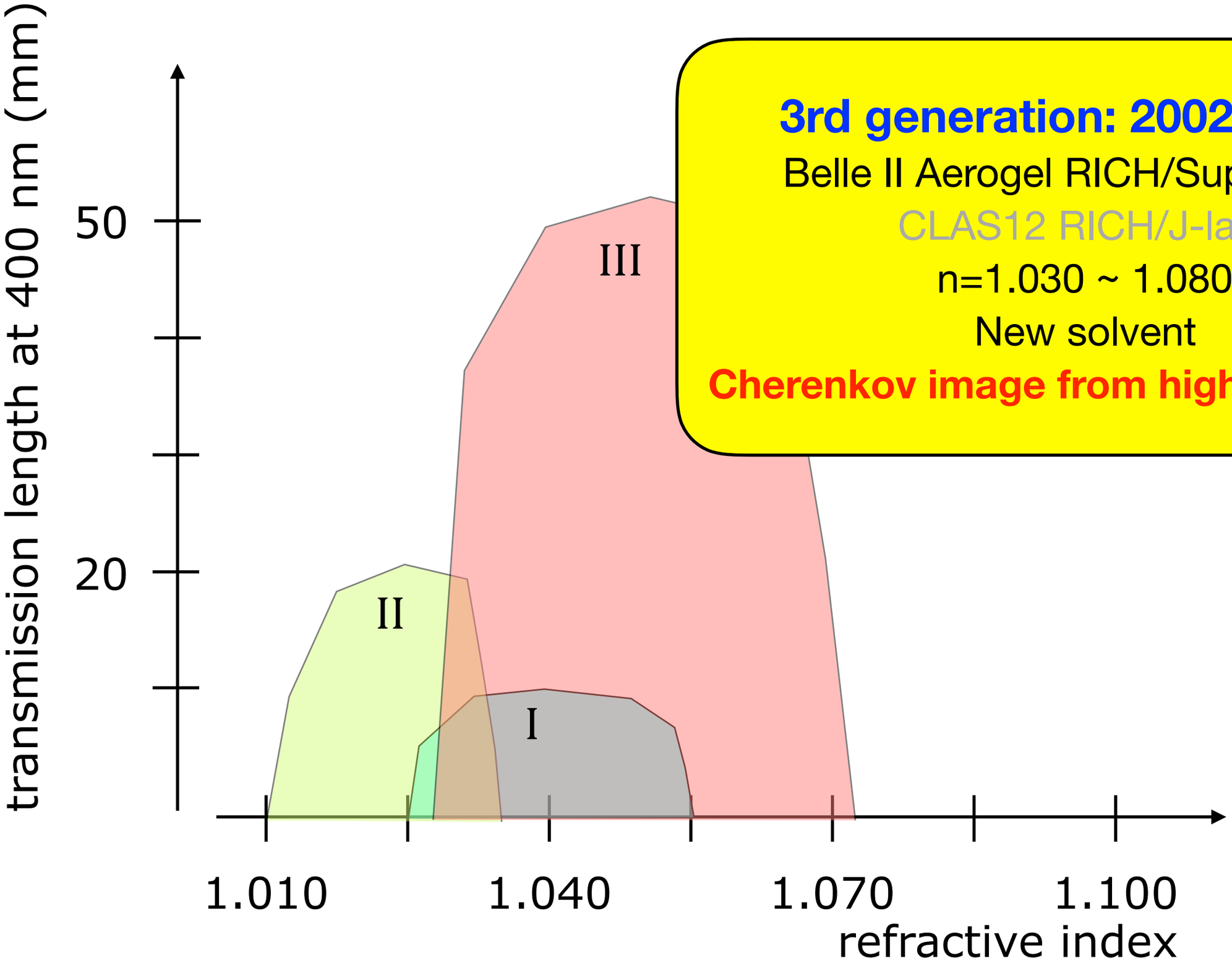
Hydrophobic feature

High transparency

NIMA668(2012)64



History of Aerogel Radiators



3rd generation: 2002 ~ 2014

Belle II Aerogel RICH/SuperKEKB

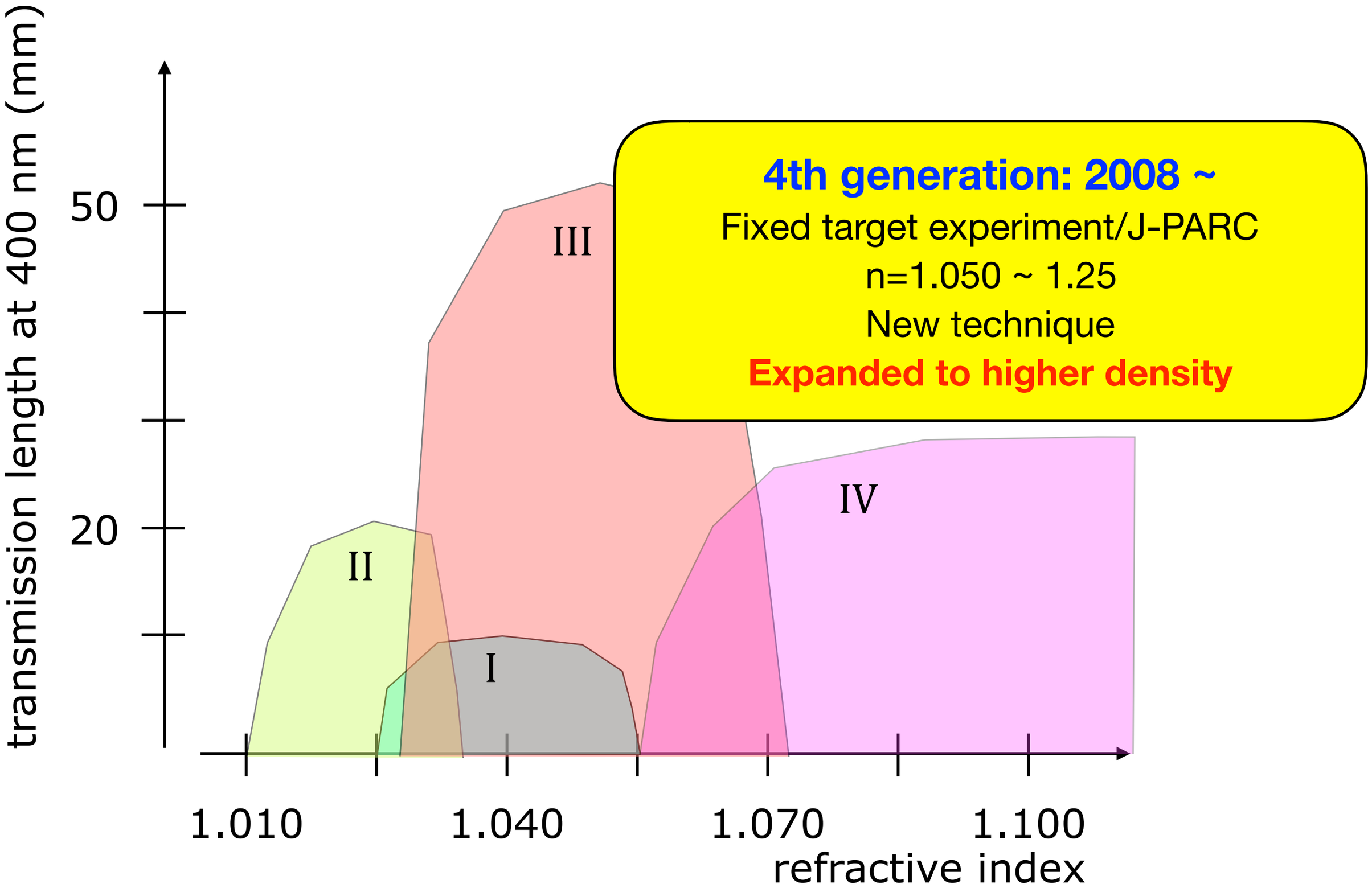
CLAS12 RICH/J-lab.

n=1.030 ~ 1.080

New solvent

Cherenkov image from high density gel

History of Aerogel Radiators



4th generation: 2008 ~

Fixed target experiment/J-PARC

n=1.050 ~ 1.25

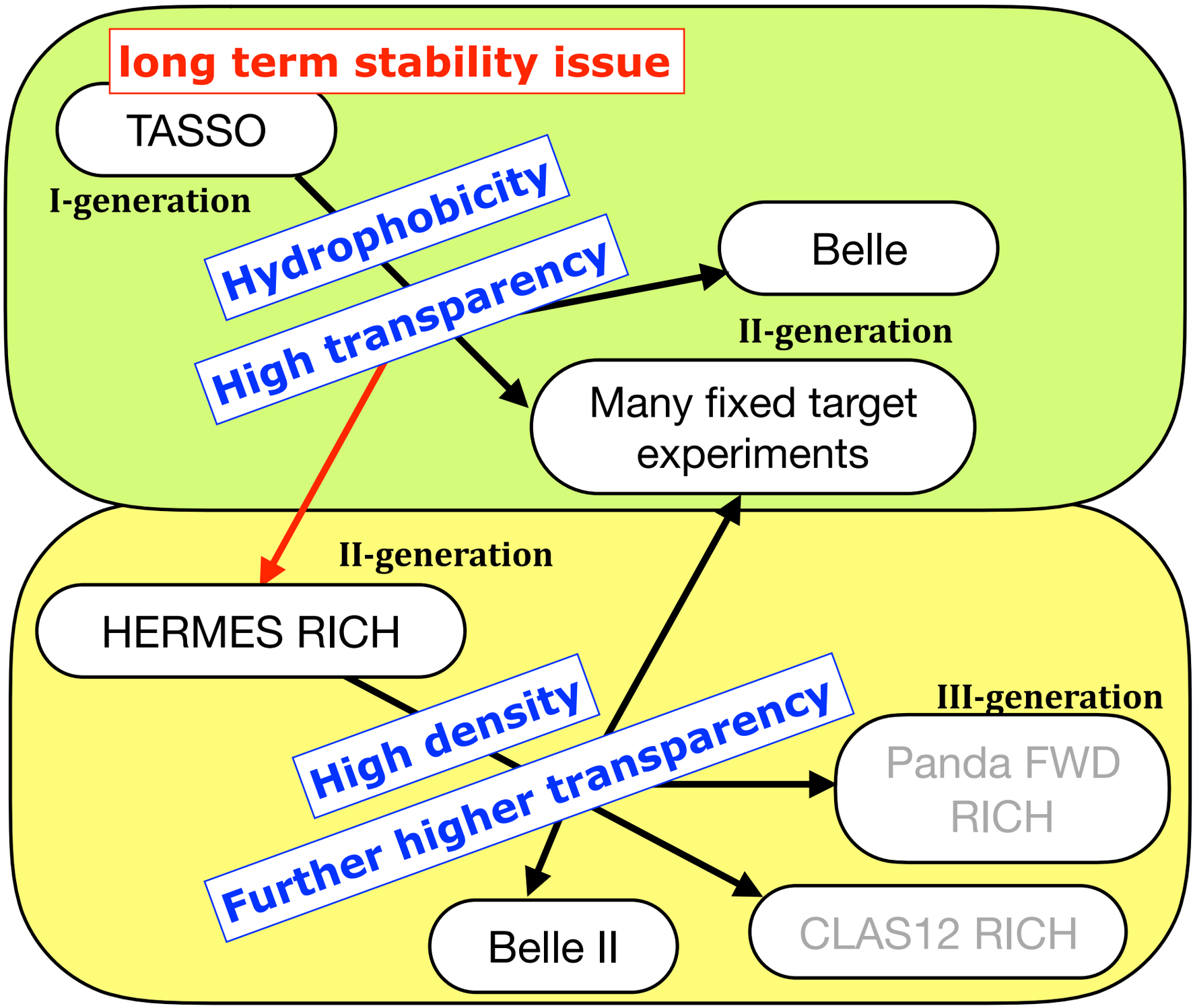
New technique

Expanded to higher density

Developments of Cherenkov Counters Based on Aerogel

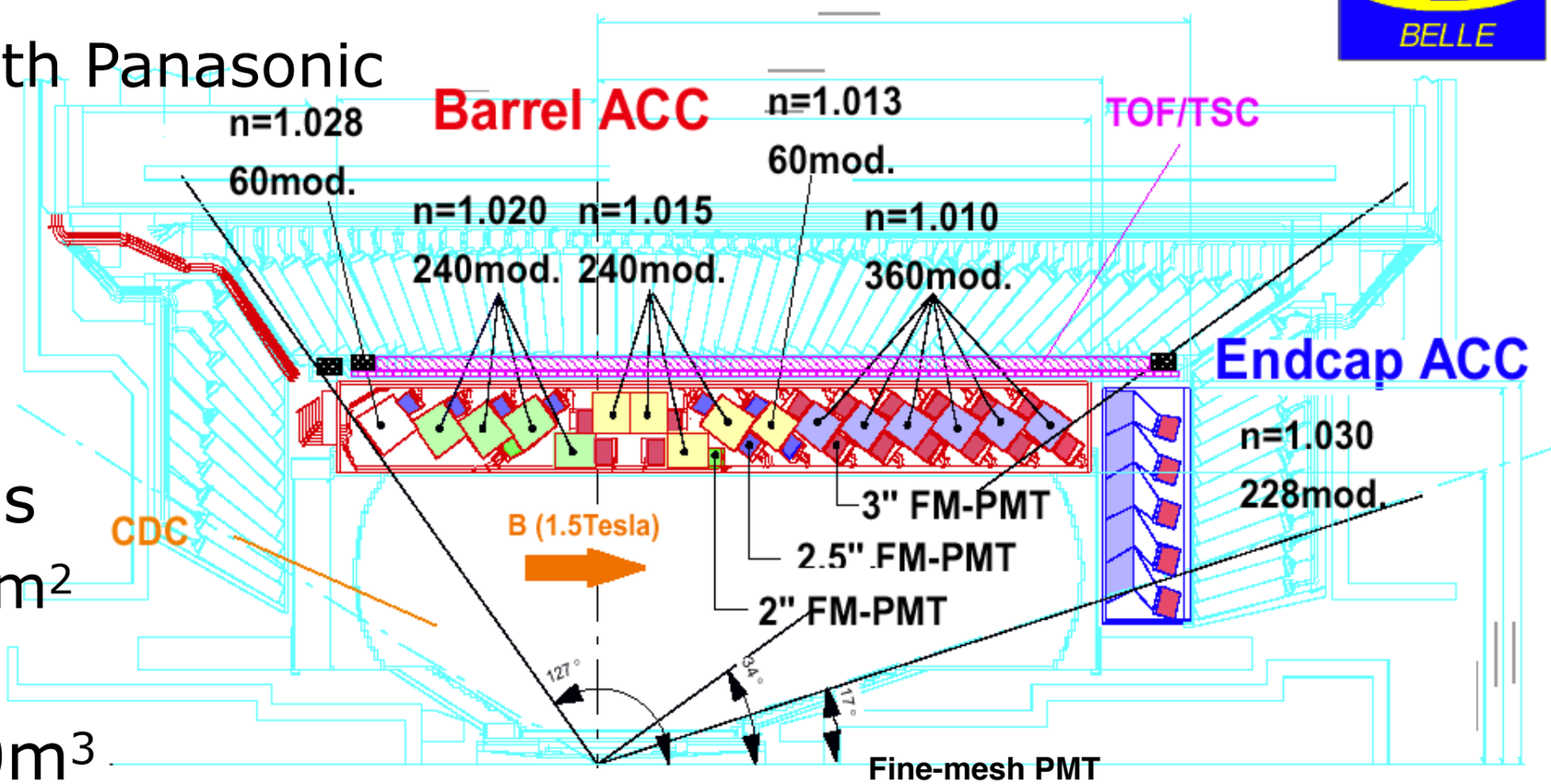
Threshold Counter

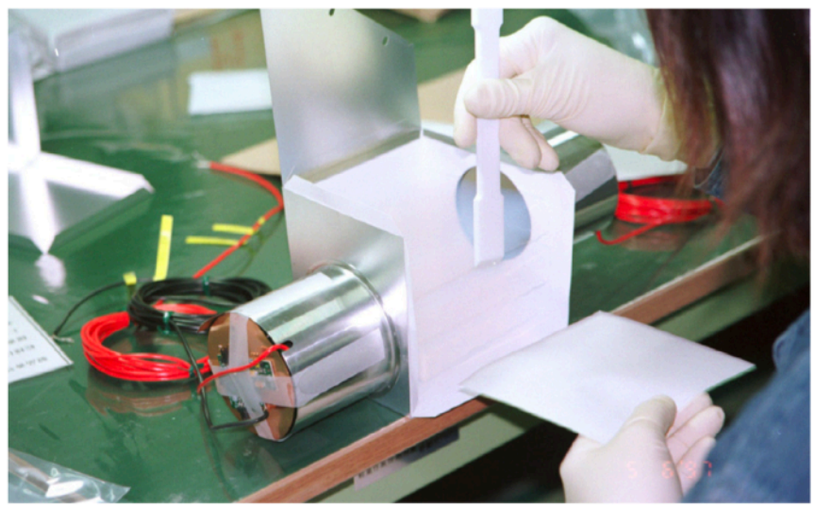
Imaging Counter

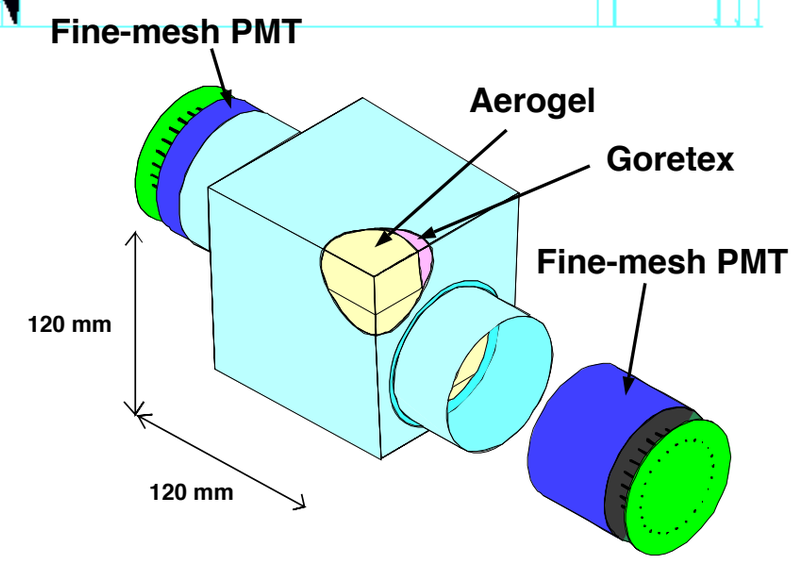


Belle ACC

- 1st large detector using the 2nd generation hydrophobic aerogels.
  - 1st corporation with Panasonic
- Low index
  - 1.010~1.030
- Tile size dimensions
  - ~100×100×20 mm^2
- Total volume ~ 1.0m^3
  - Home-made

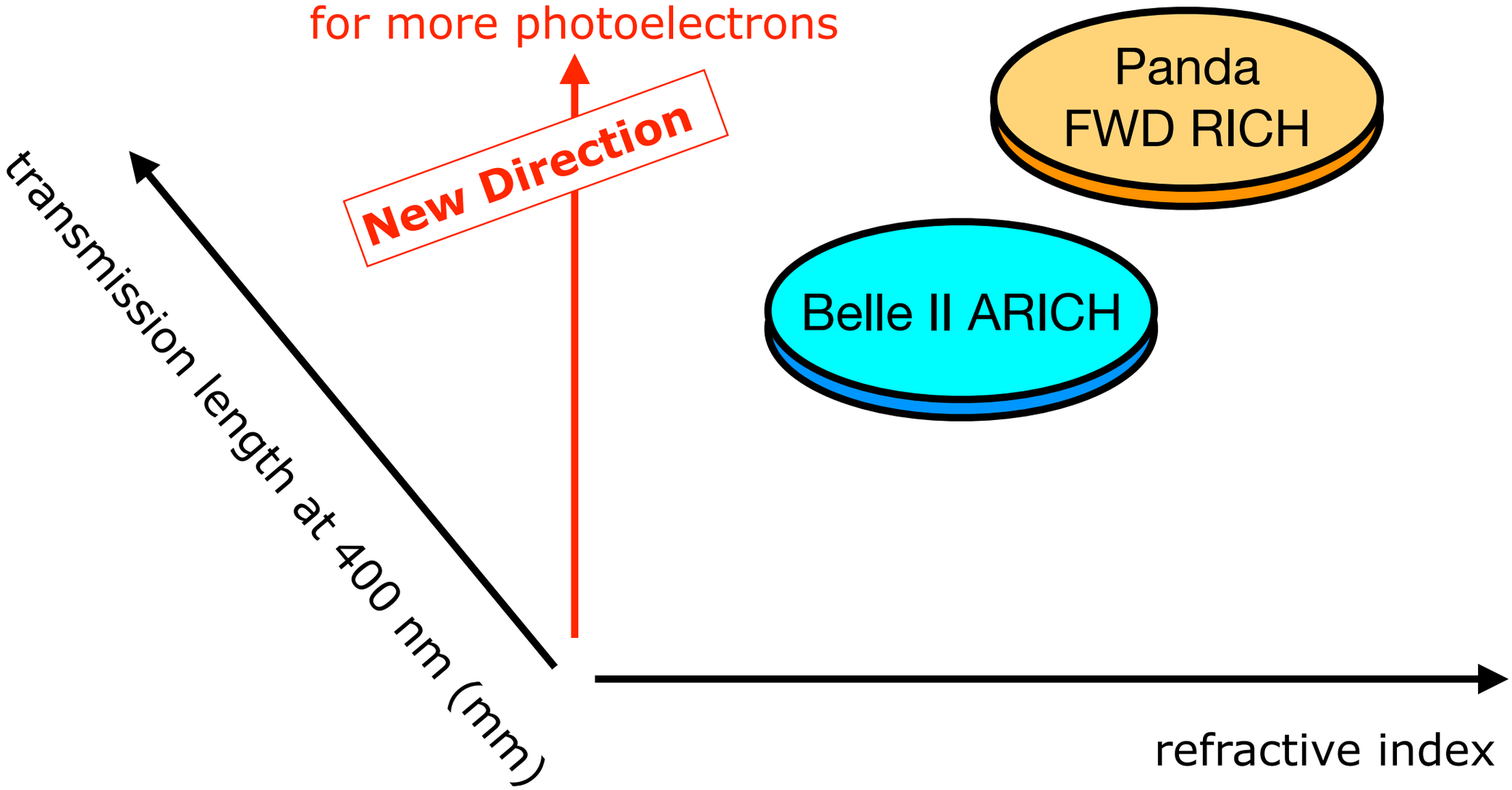






Highly transparent aerogels in the 3rd generation allows us to have another direction.

Refractive index in aerogel can be tunable.

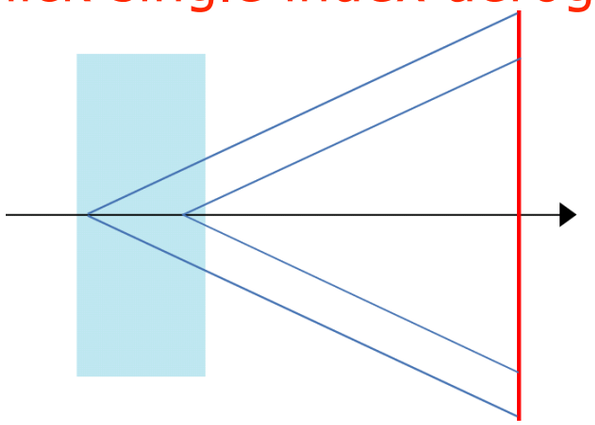


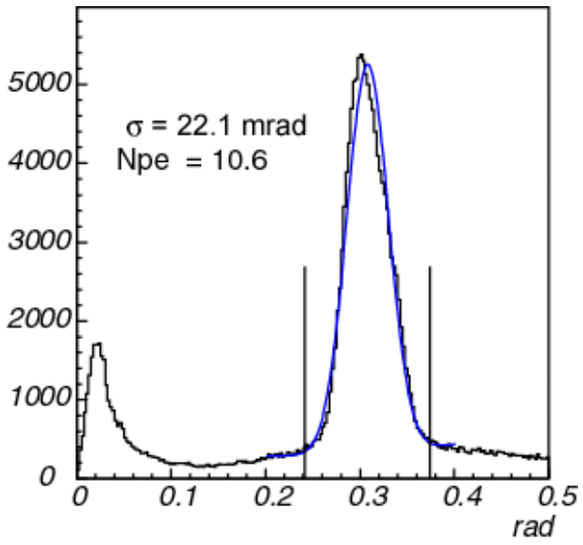
Belle II RICH

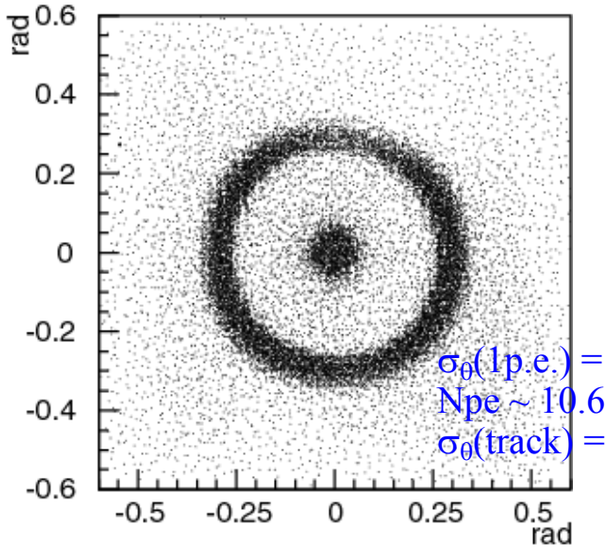
NIMA548(2005)383

- Aerogel in the 3rd generation used.
  - Highly transparent tiles with refractive index > 1.03
  - Dual Cherenkov radiators consisting of 1.045 (upstream) and 1.055 (downstream)

4cm thick single index aerogel

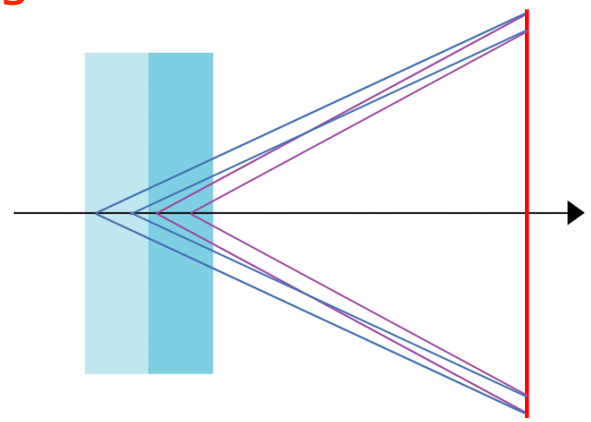


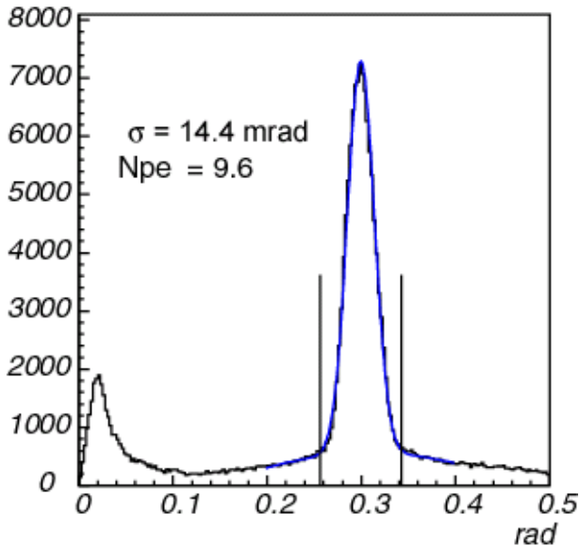


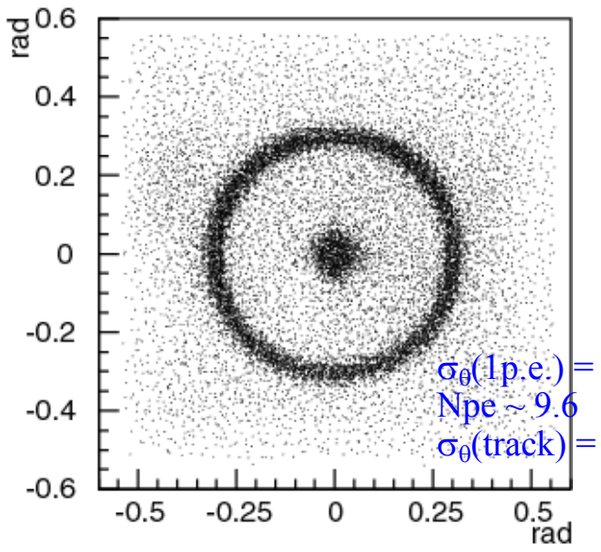


σ_0(1p.e.) = 22 mrad
Npe ~ 10.6
σ_0(track) = 6.9 mrad

Focusing 2cm+2cm dual aerogel

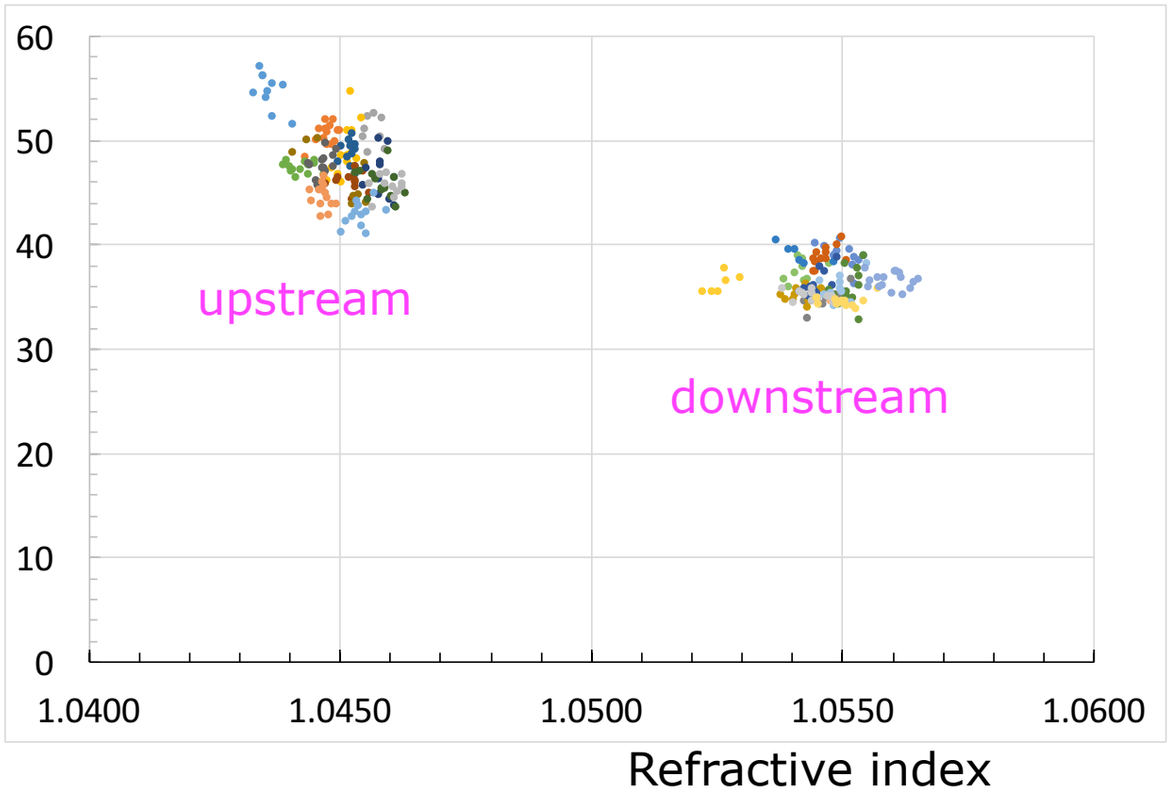


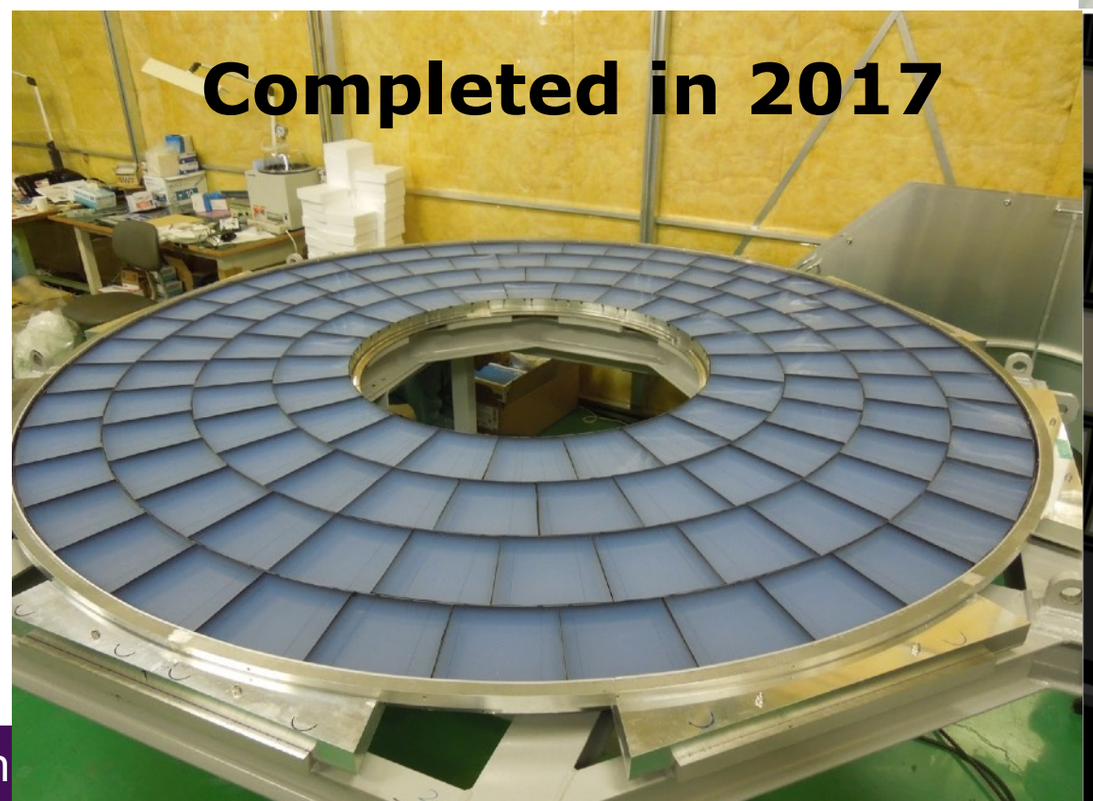


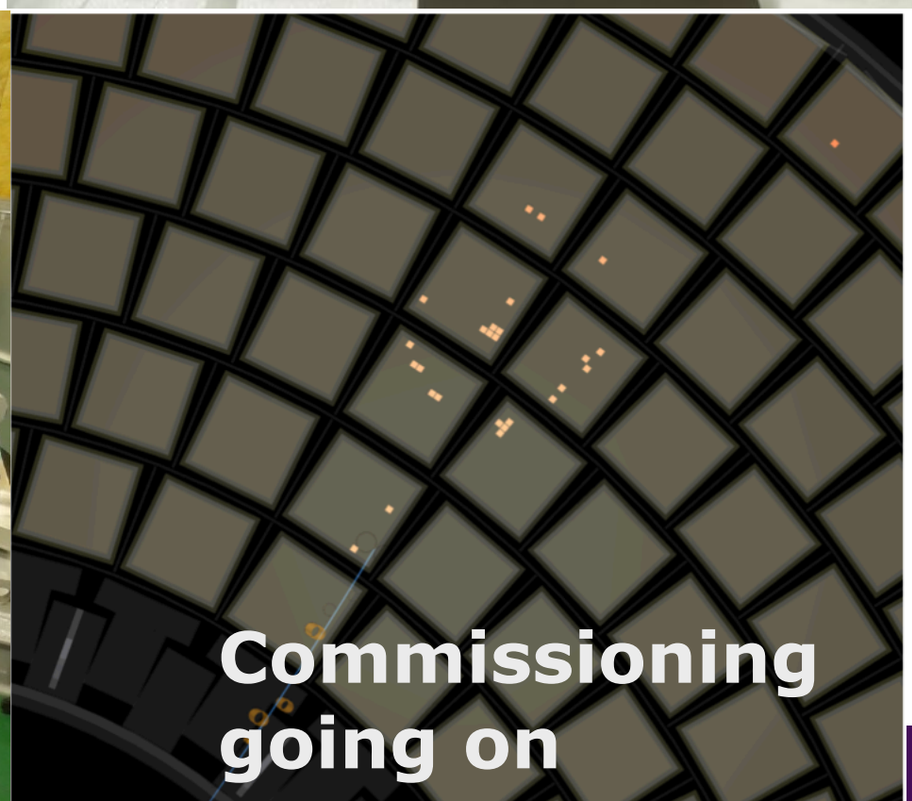


σ_0(1p.e.) = 14.4 mrad
Npe ~ 9.6
σ_0(track) = 4.8 mrad

Belle II RICH

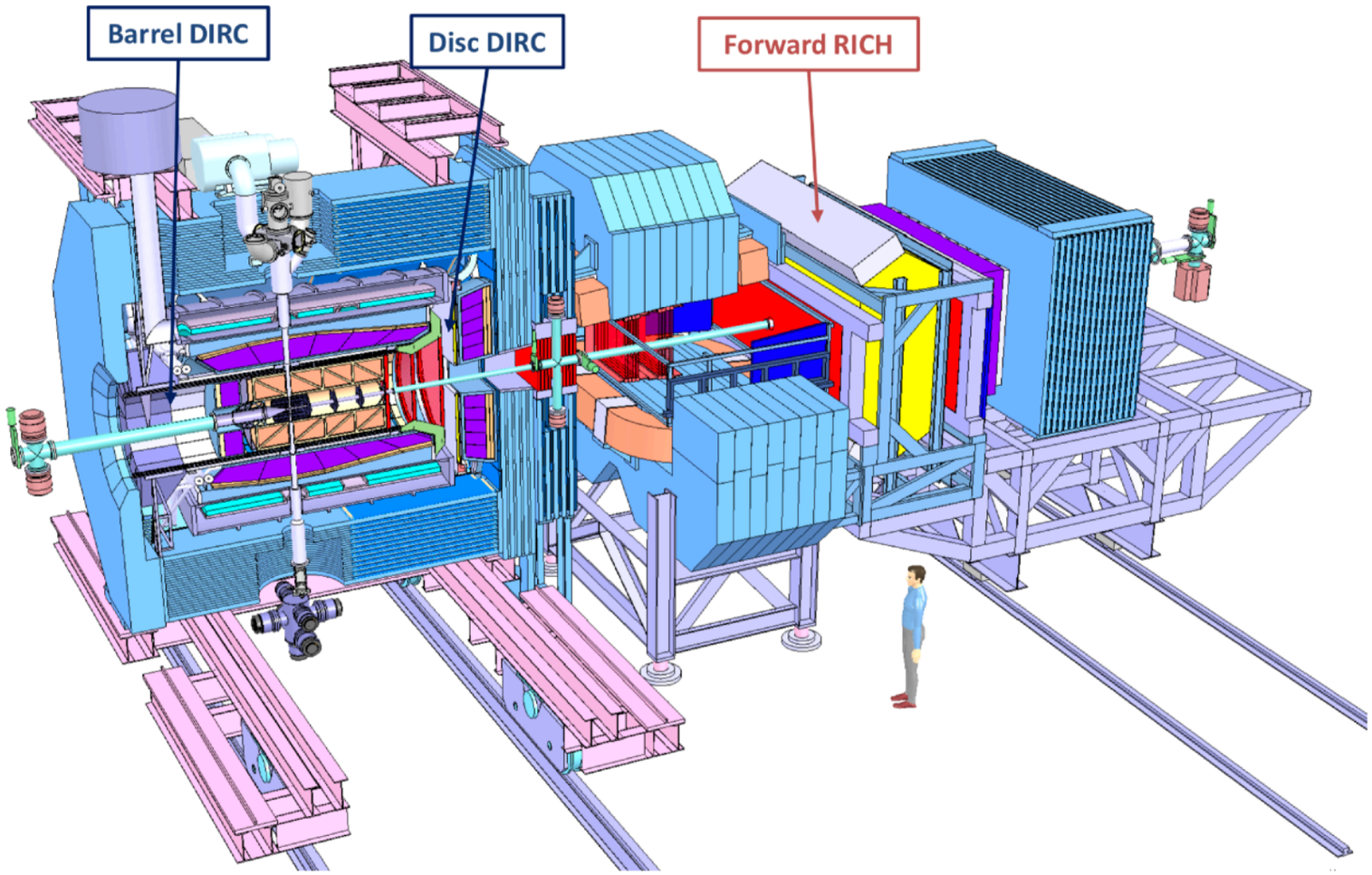




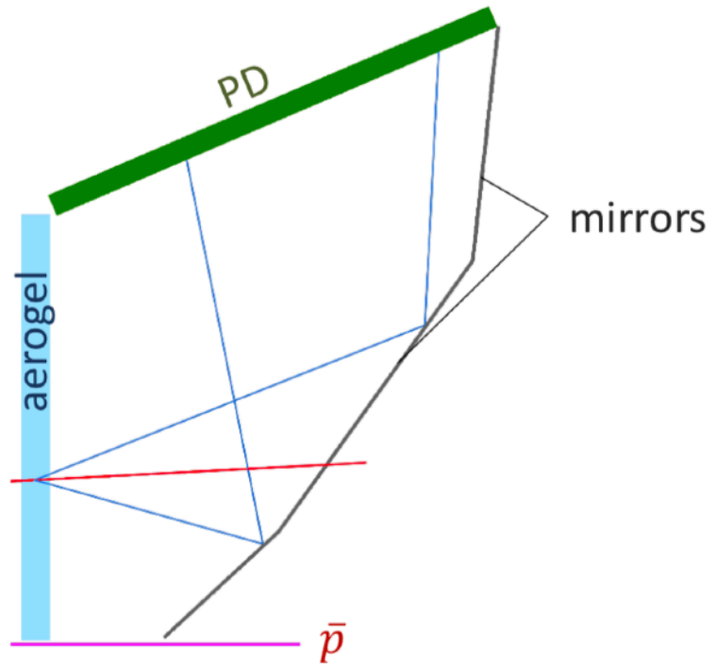


Talk by S.Kononov

Panda FWD RICH



Panda spectrometer

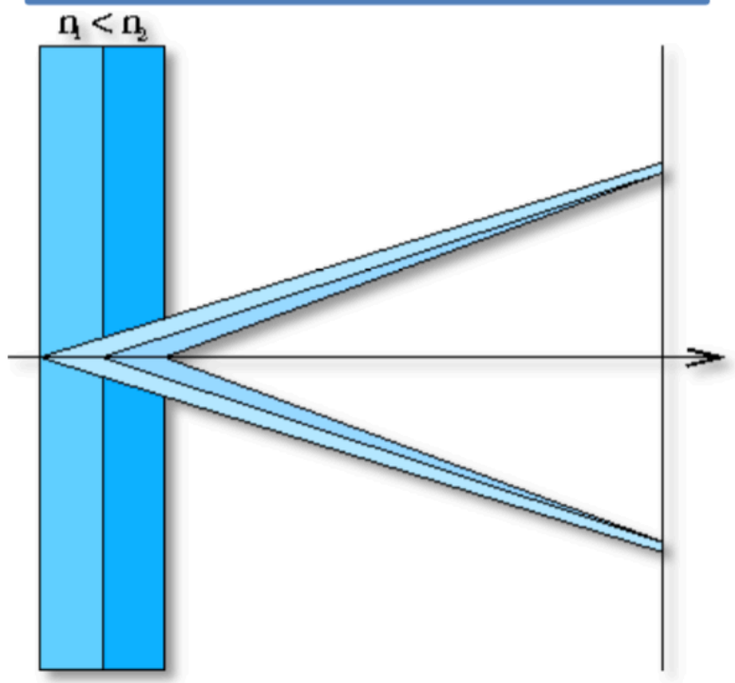


Radiator

- Focusing 2- or 3-layer aerogel
- 40 mm thick
- No gaseous radiator

Panda FWD RICH

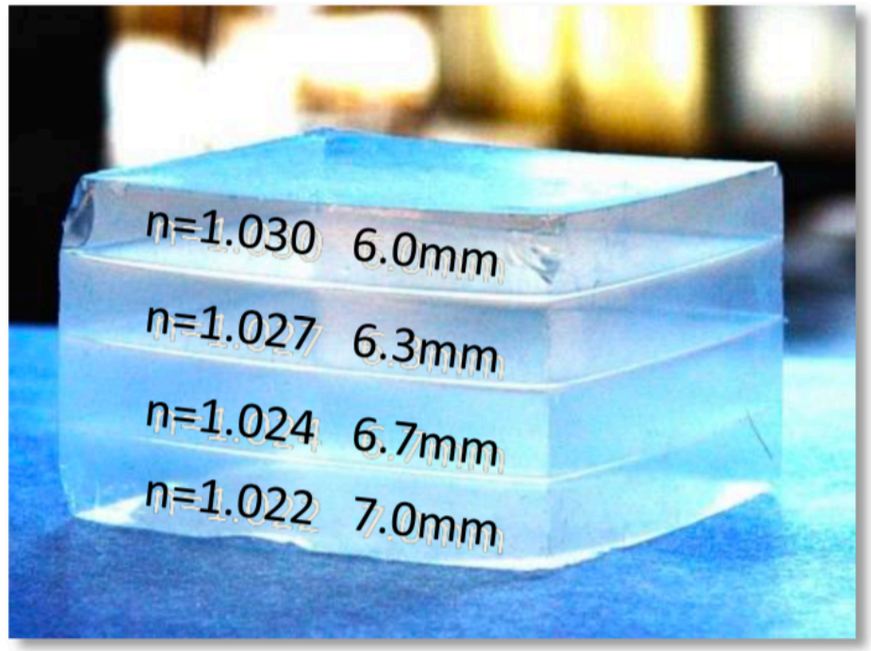
Single ring option



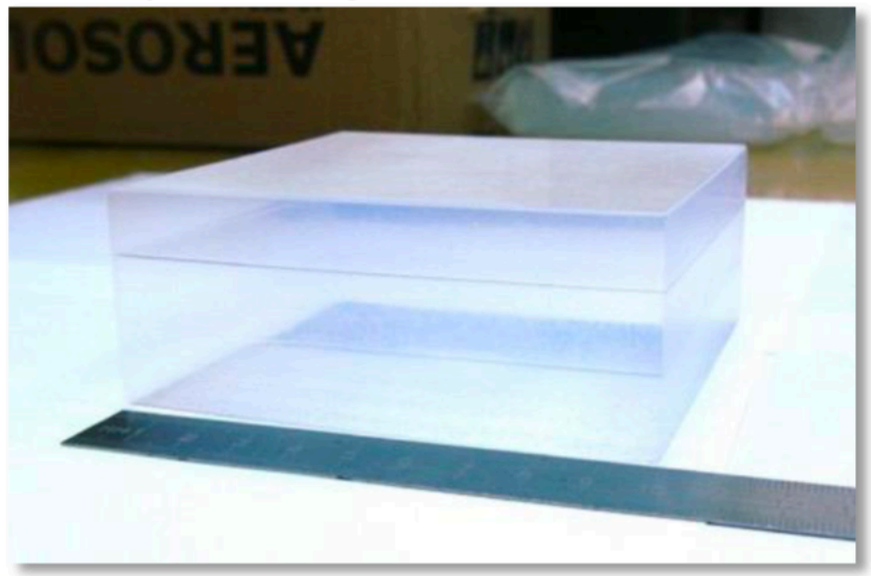
Focusing aerogel improves proximity focusing design by reducing the contribution of radiator thickness into the Cherenkov angle resolution

Multi-layer monolith aerogels have been being produced by the Boreskov Institute of Catalysis in cooperation with the Budker INP since 2004.

First sample of 4-layer aerogel



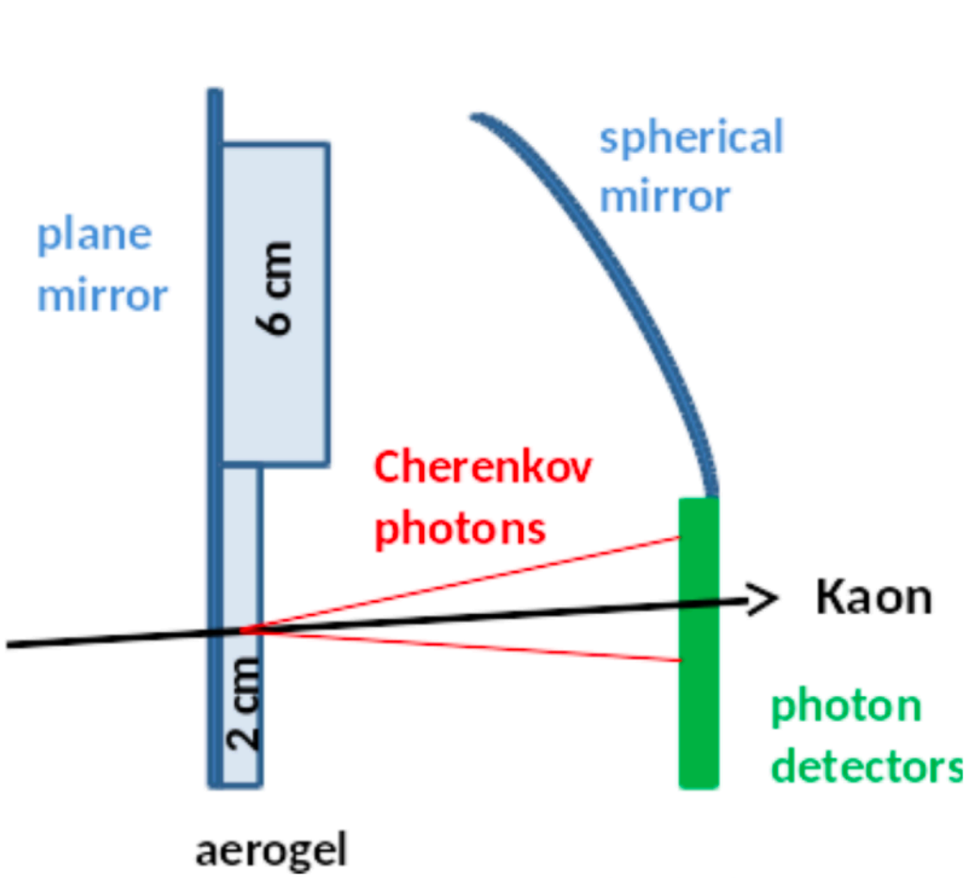
3-layer aerogel 115x115x41 mm^3

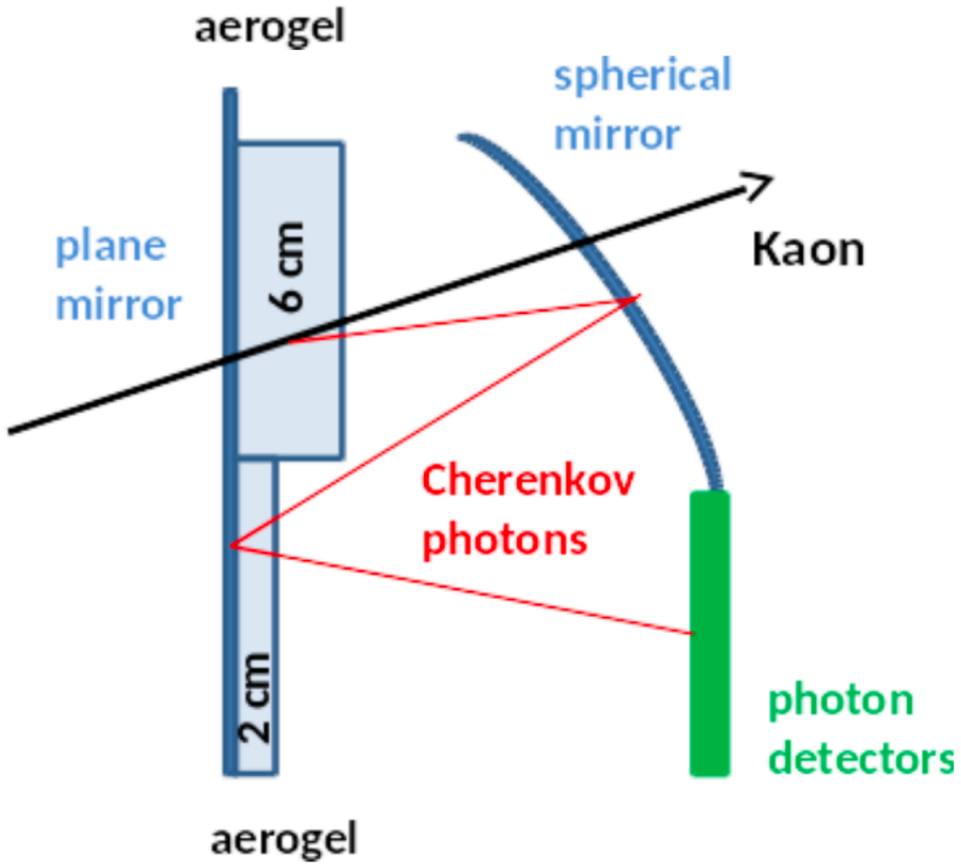


T.Iijima et al., NIM A548 (2005) 383
A.Yu.Barnyakov et al., NIM A553 (2005) 70

CLAS12 RICH

- Challenging design due to the constraints from the present CLAS spectrometer.
- 2 layers of 30 mm thick slice aerogels (n=1.05). Two reflections (one for spherical mirror and the other planer through aerogel medium) before photon detector



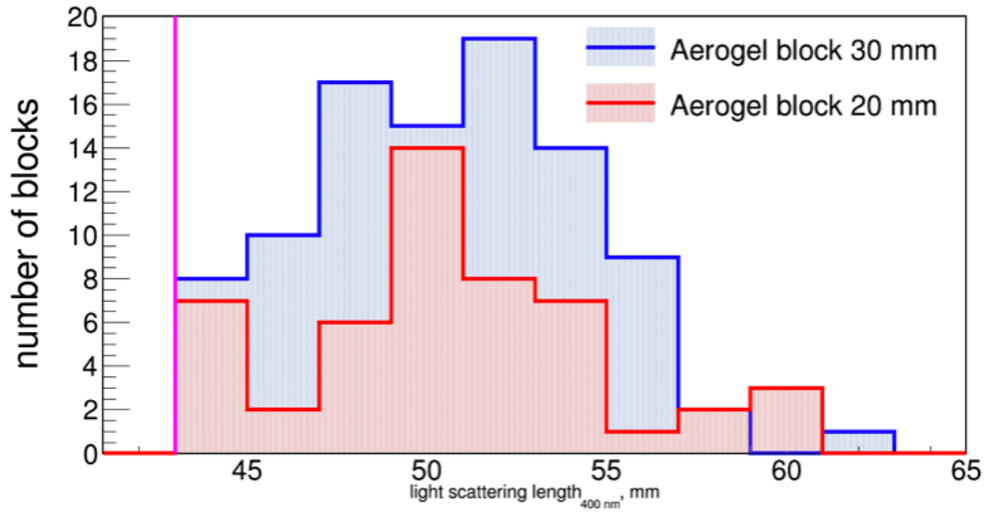


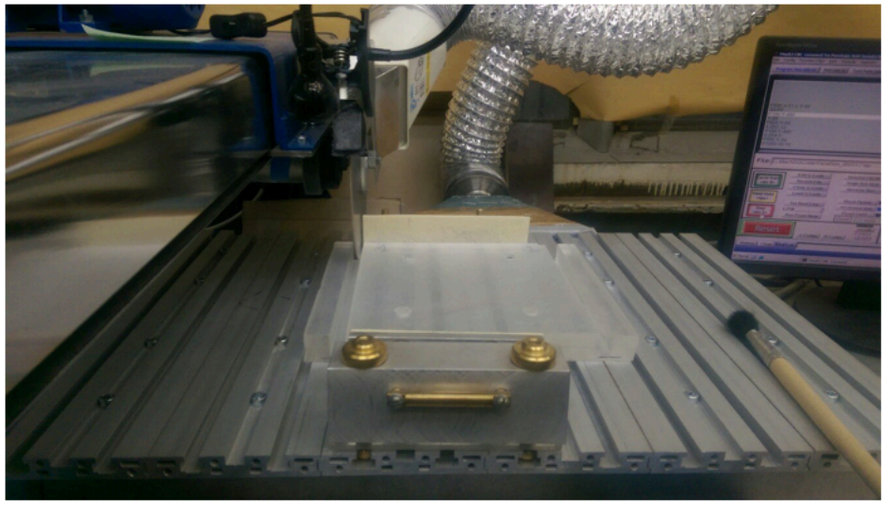
E. Kravchenko

CLAS12 RICH

Production of large aerogel tiles

- 200x200 mm², 20 and 30 mm thickness
- L_{sc}(400nm)>43 mm (mean ~50 mm)
- New CNC cutting machine (diamond wheel). The cutting accuracy is 0.25 mm.



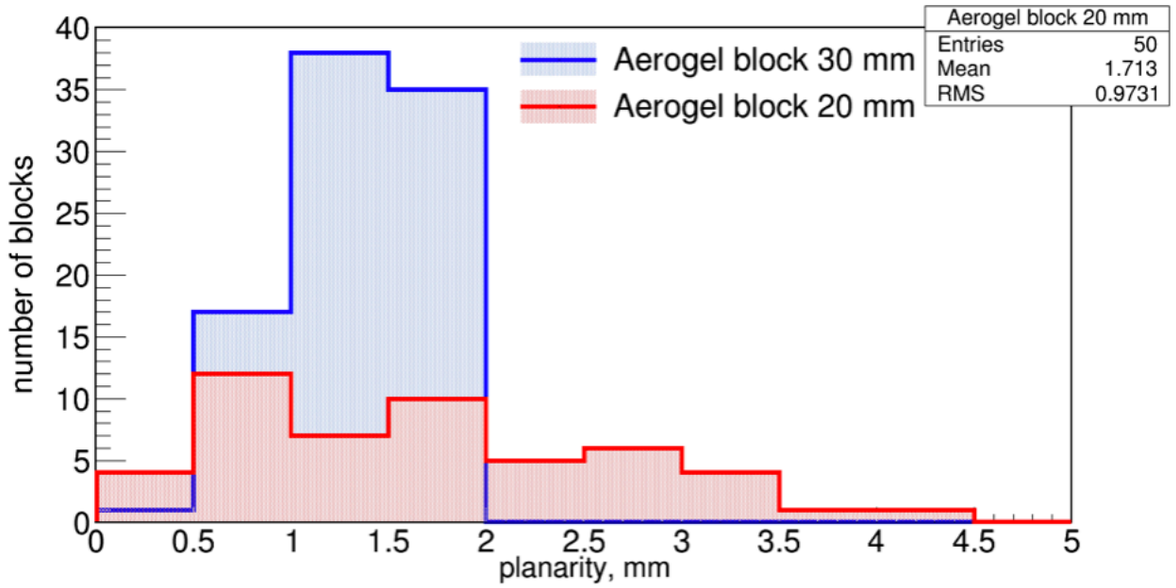


E. Kravchenko

CLAS12 RICH

Planarity of large aerogel tiles

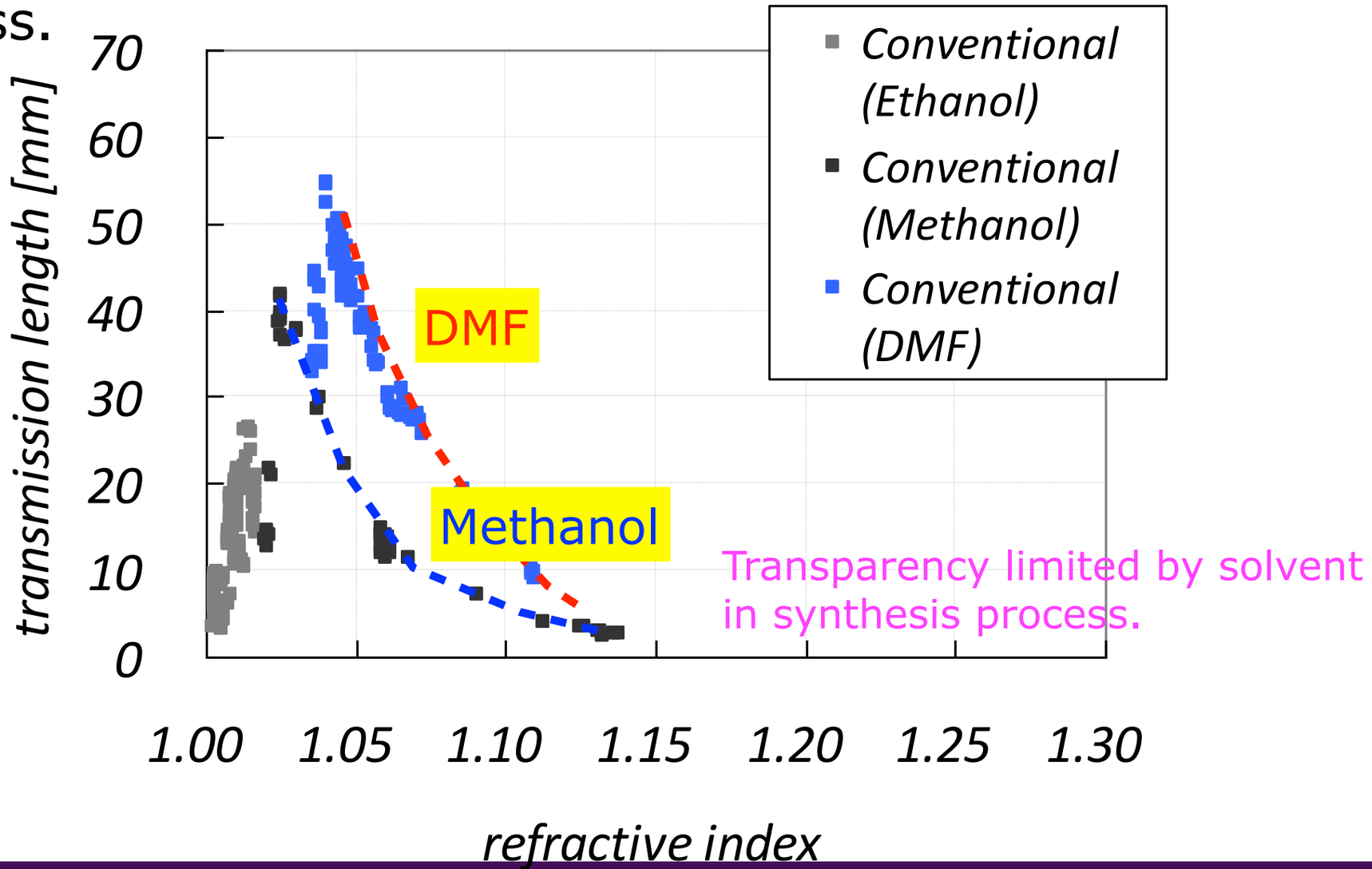
- The aerogel tile planarity is measured mechanically in 49 points (7x7 grid with step 30 mm). The planarity criteria is defined as the difference between the maximum and minimum values of the coordinate field after alignment procedure. Selection criteria:
  - the aerogel tile 30 mm, planarity up to 2 mm;
  - the aerogel tile 20 mm, planarity up to 4.5 mm, but the average planarity of all blocks does not exceed 3 mm.



Long-term stability
Monitoring is essential.

4th Generation

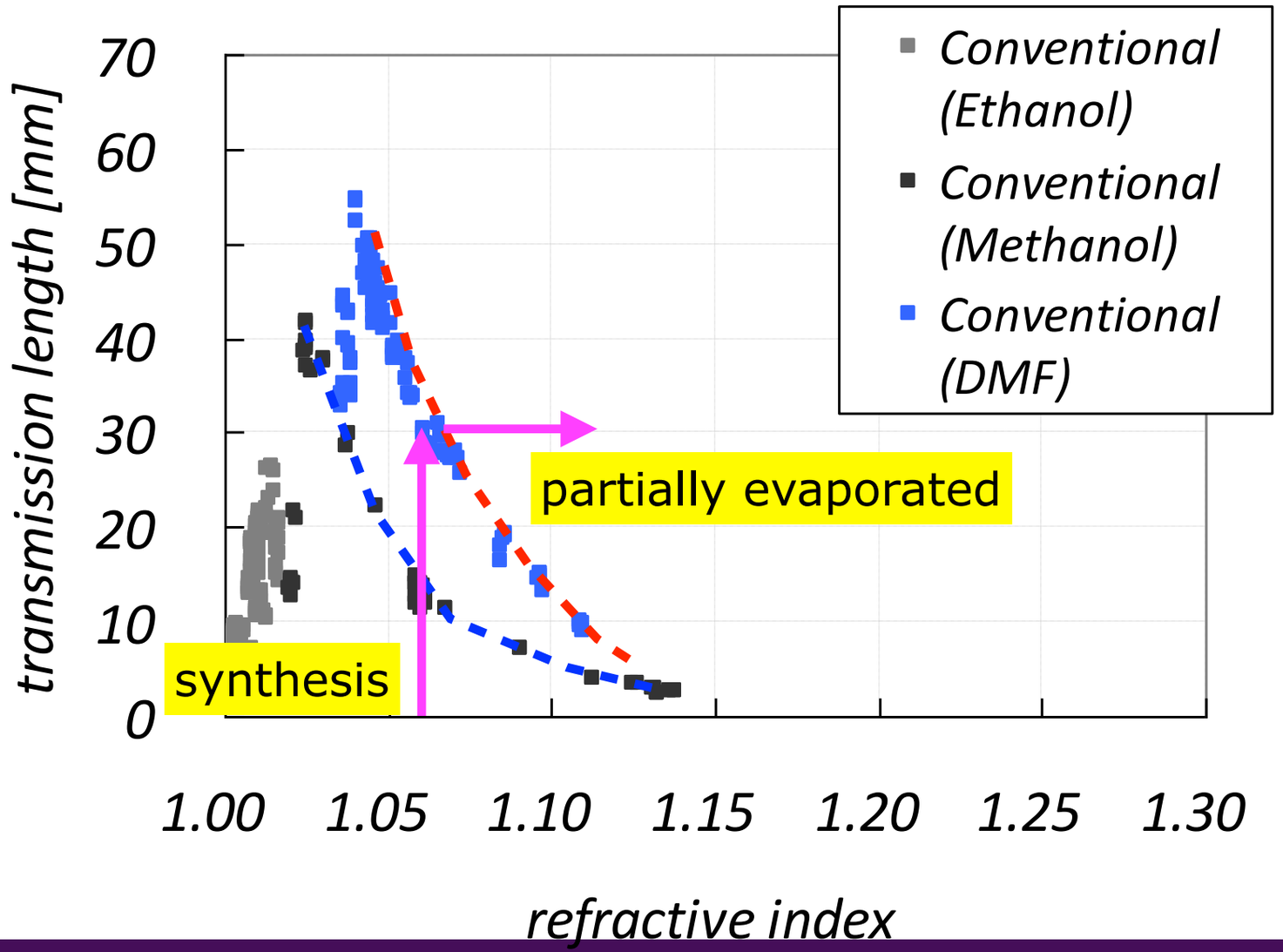
- High refractive index (>~1.14)
  - Transparency limited by solvent in synthesis step.
  - Difficult to produce alco-gels since too much silica particles can not undergo smooth gelation.
  - This results in non-transparent aerogel after supercritical drying process.



4th Generation

Synthesis process targeting n~1.06, then alco-gel obtained is partially evaporated in controlled environment to get target index(=density).

Pin-drying(PD) method by Chiba university group



4th Generation

Synthesis process targeting n~1.06, then alco-gel obtained is partially evaporated in controlled environment to get target index(=density).

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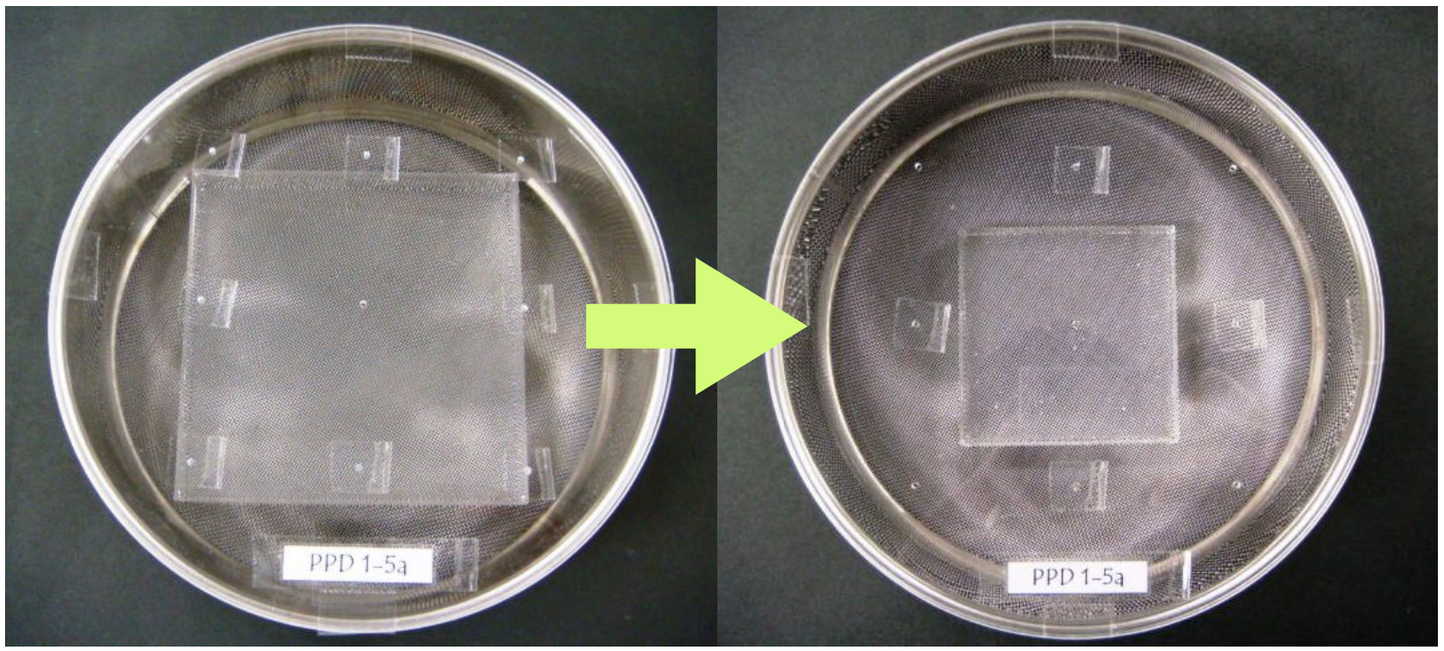
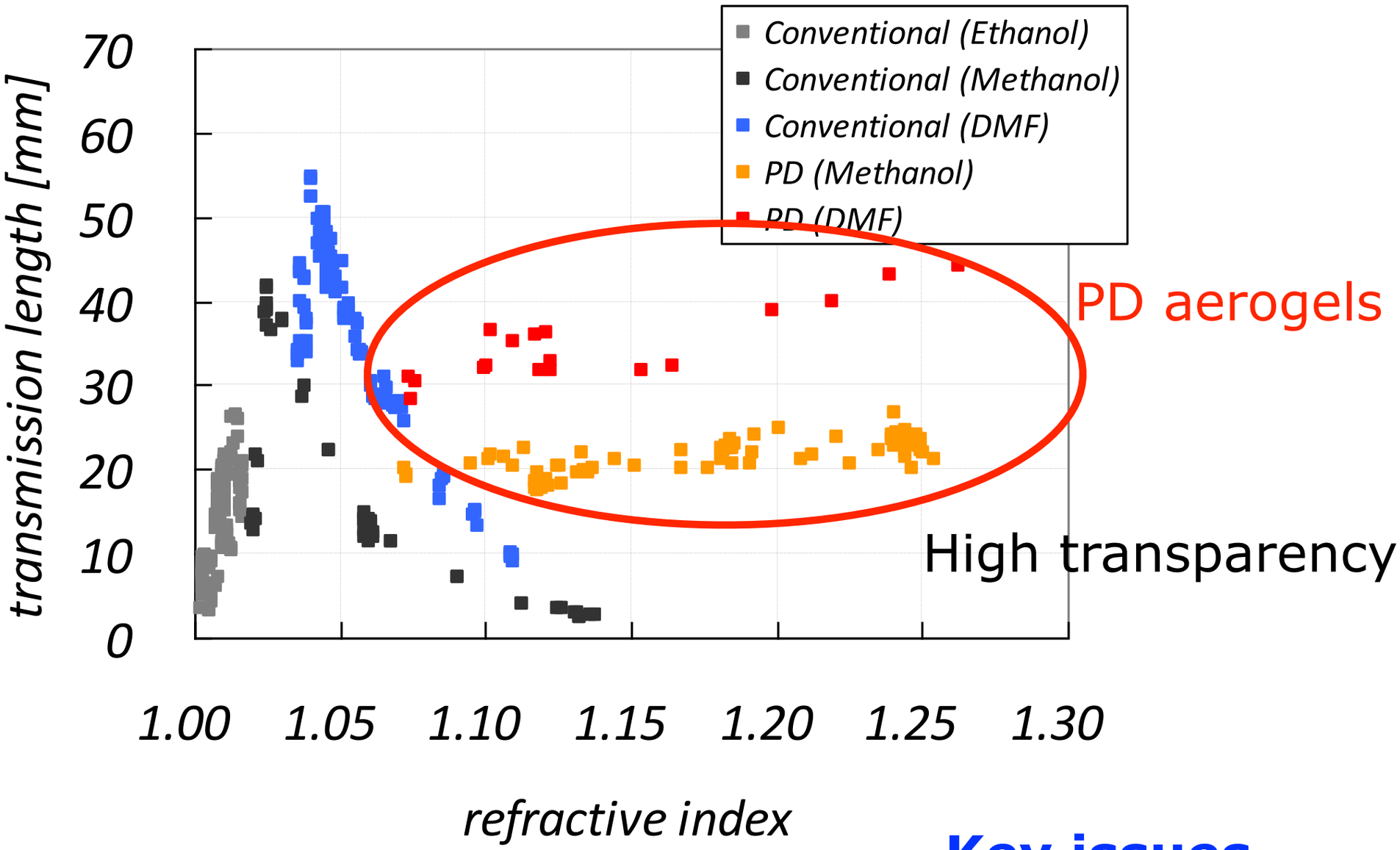


4th Generation



High transparency obtained !

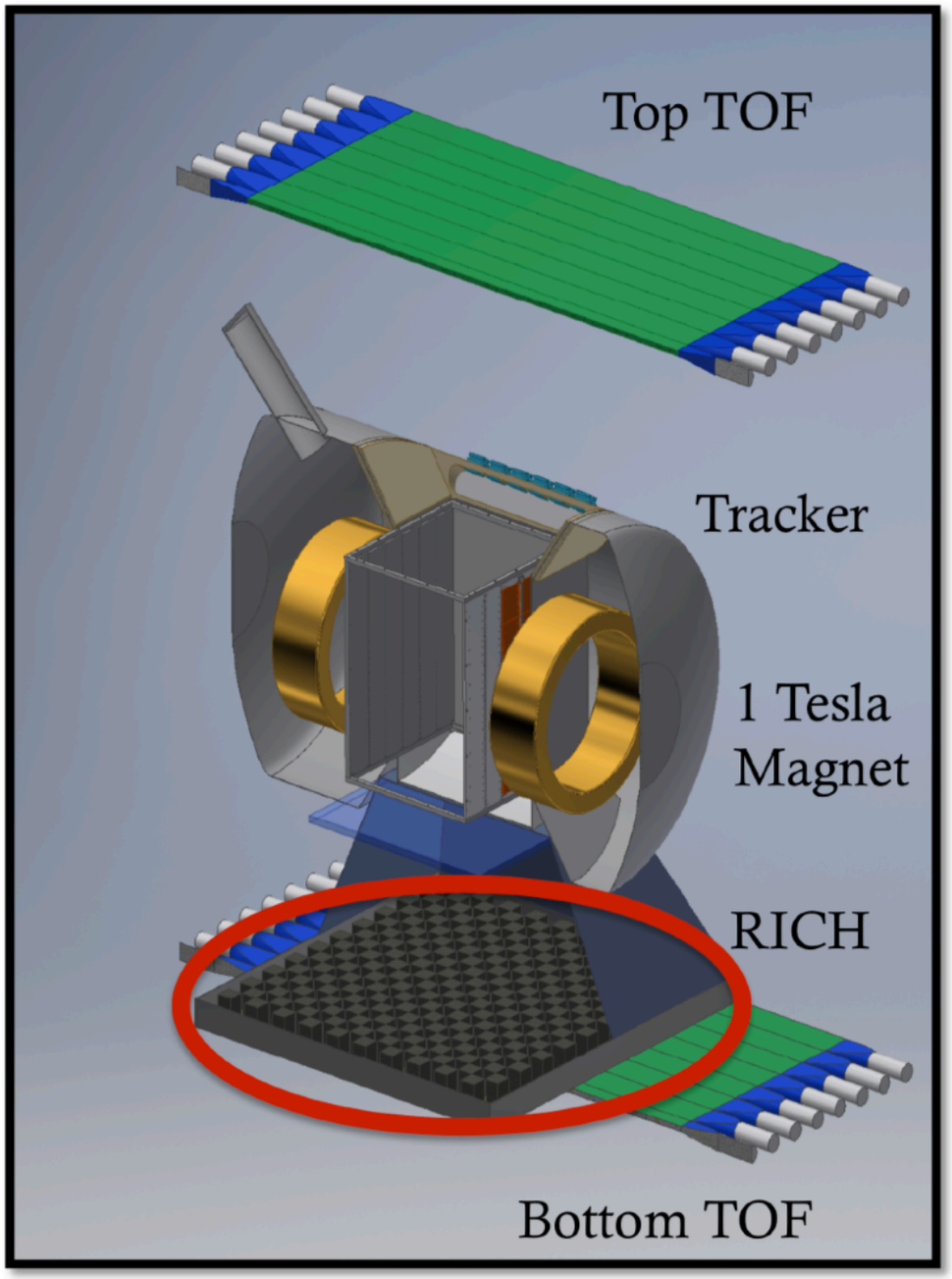
Key issues

Tile size and uniformity
Duration of production

Talk by M.Tabata

HELIX RICH

- HELIX is a magnet spectrometer for a balloon experiment around the south pole. Launch ~ 2019-2020.



Univ. Chicago …

The Ring-imaging Cherenkov Detector

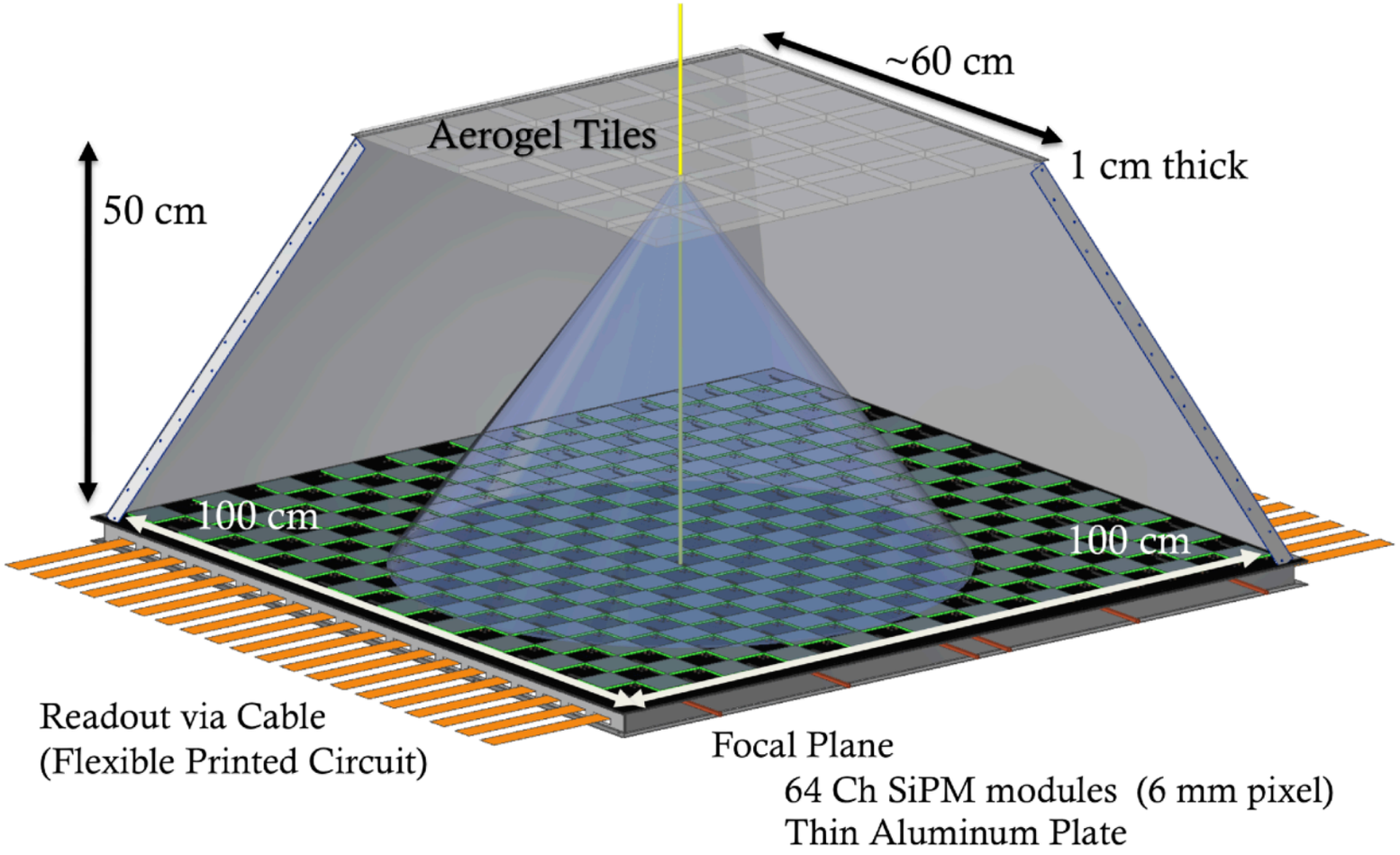
- Proximity-focused RICH w/ **SiPM** readout
- Design goal : **$\Delta\beta/\beta \sim 4\times10^{-4}$ for Z>3**
- Requires detector developments to reach goals

Presented at ICRC 2017

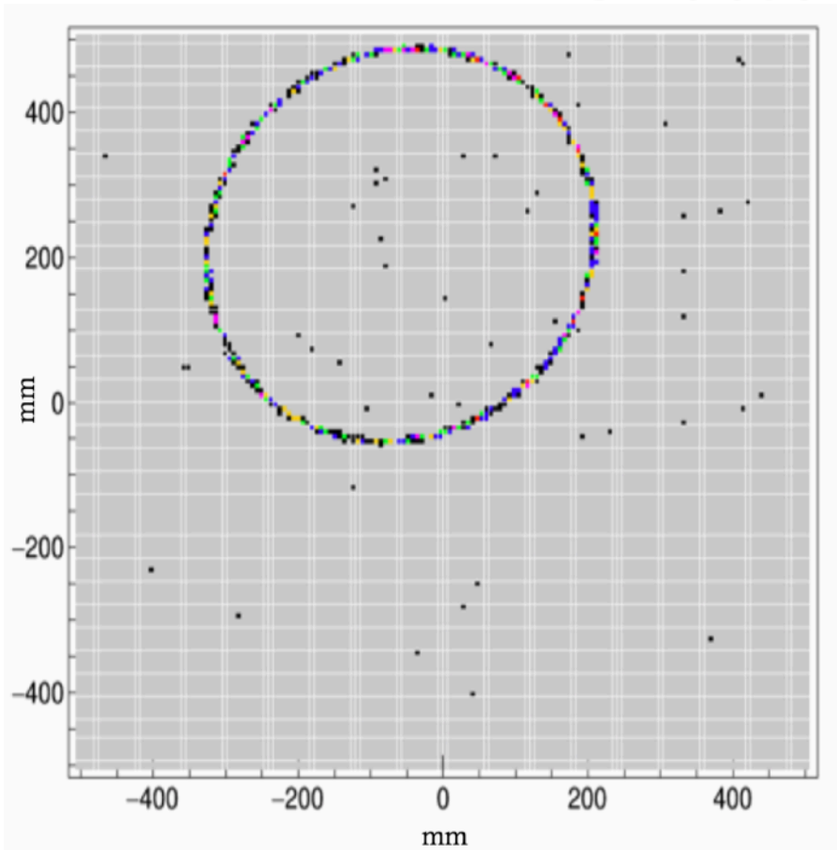
HELIX RICH

Cherenkov radiator system using 4th generation aerogel

- n=1.15 Aerogel from Chiba university group
- 36 tiles with 100×100×10mm^3
- Target transmission length at 400 nm > 30 mm



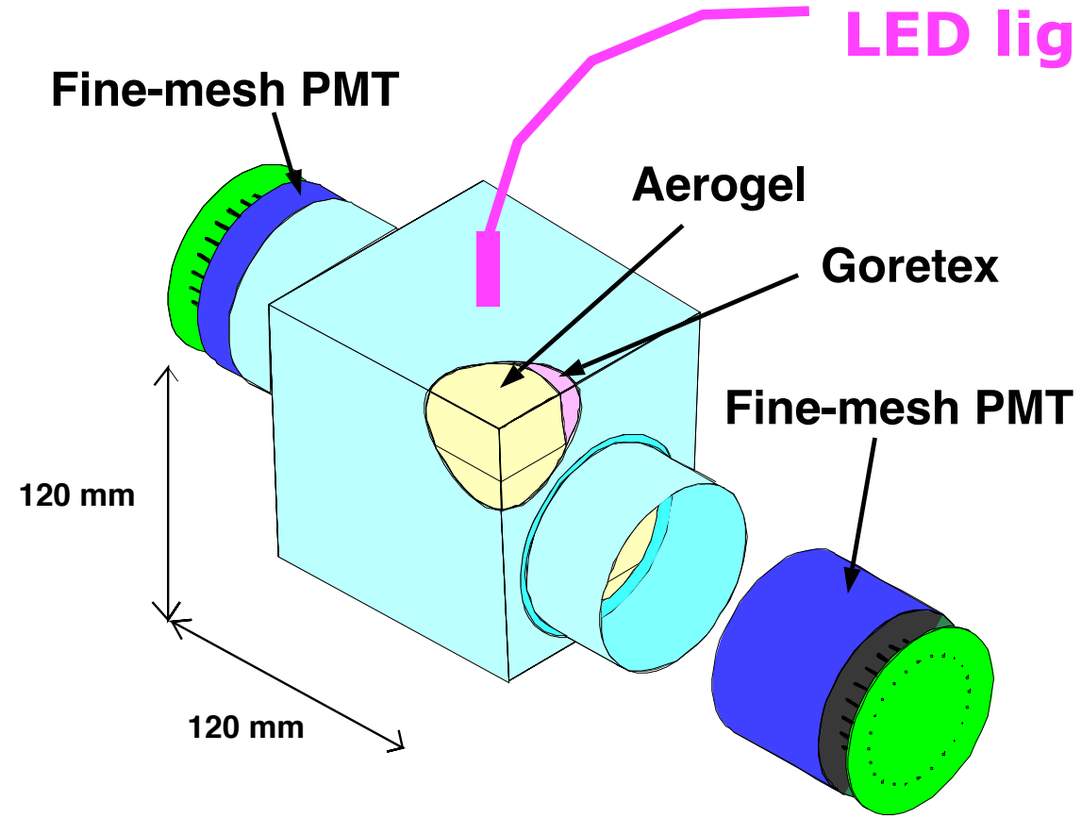
Simulation



Application Related Issues

Long-Term Stability

- In Belle aerogel Cherenkov counter we measured light output from PMTs for each counter by eliminating LED light.



Aerogel tiles of n=1.01-1.03
They are hydrophobic

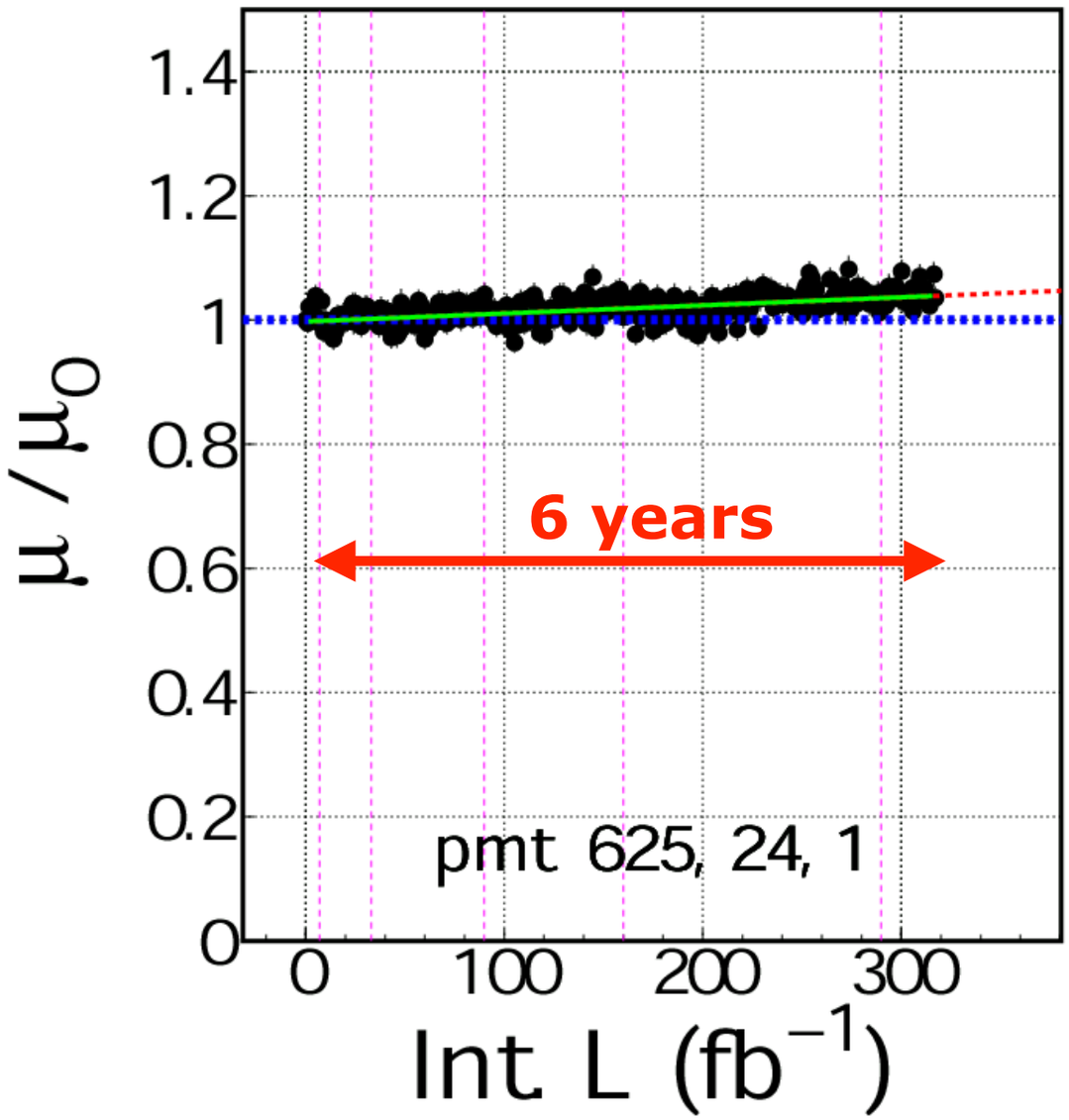
- Check long-term stability.

Long-Term Stability

- Very stable output has been obtained.

- This is a mixture of stabilities of:
  - Aerogel transparencies
  - PMT gain

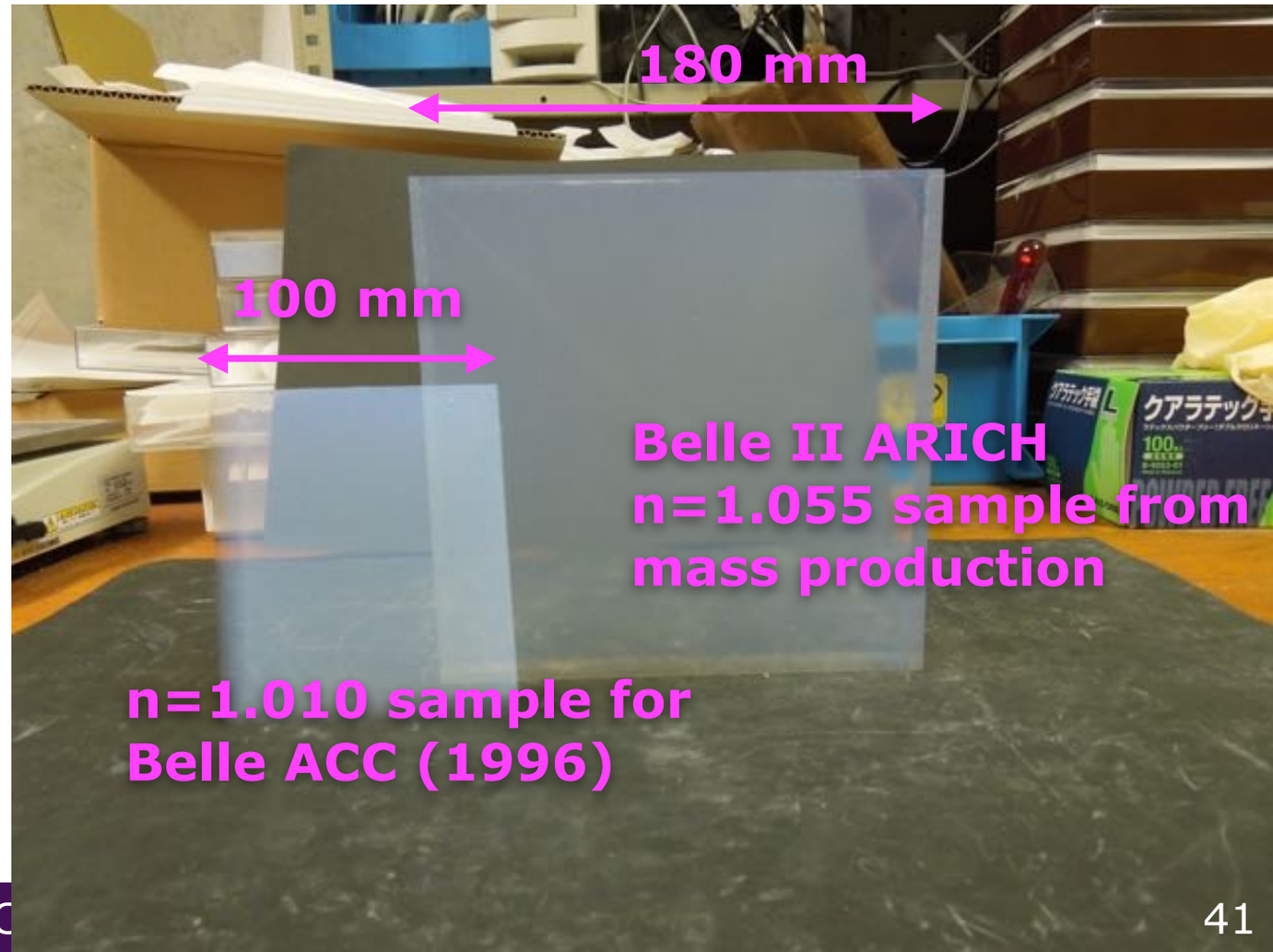
Transparency for hydrophobic aerogel tiles at Belle is stable.



Tile Dimensions

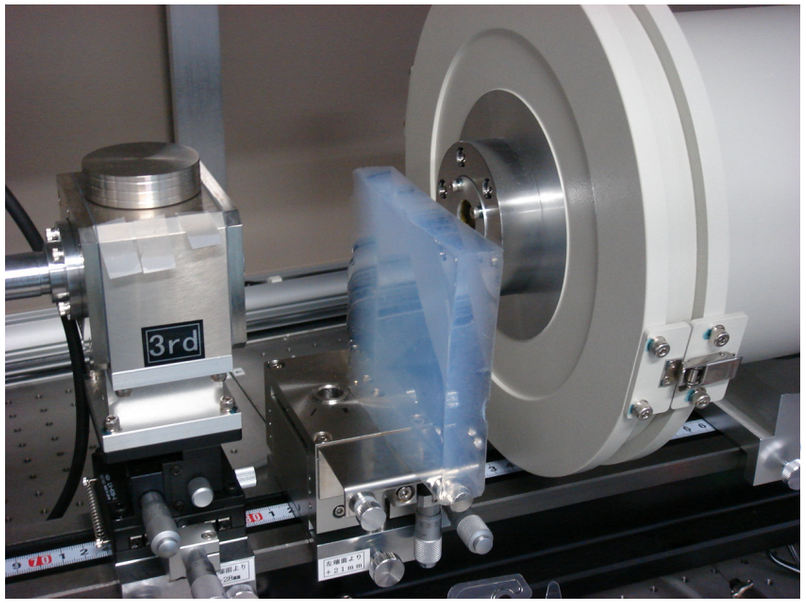
- If radiator medium needs to cover large area, basically big size tile reduces boundary region, where less Cherenkov photon yield is expected.
- Handling point of view, large tile needs more attention not only in production process but also in construction stage.
  - Crack-free yield/Tip-lost-at-corner yield/Related to thickness
  - Depends on tile index.
  - Optimizations in SCD step.
    - Pressure control

M.Tabata et al., The Journal of Supercritical Fluids, Vol.110, April 2016, Pages 183-192



Density Uniformity

- Uniformity scan was done using X-ray tomography device.



X-ray λ=0.156nm

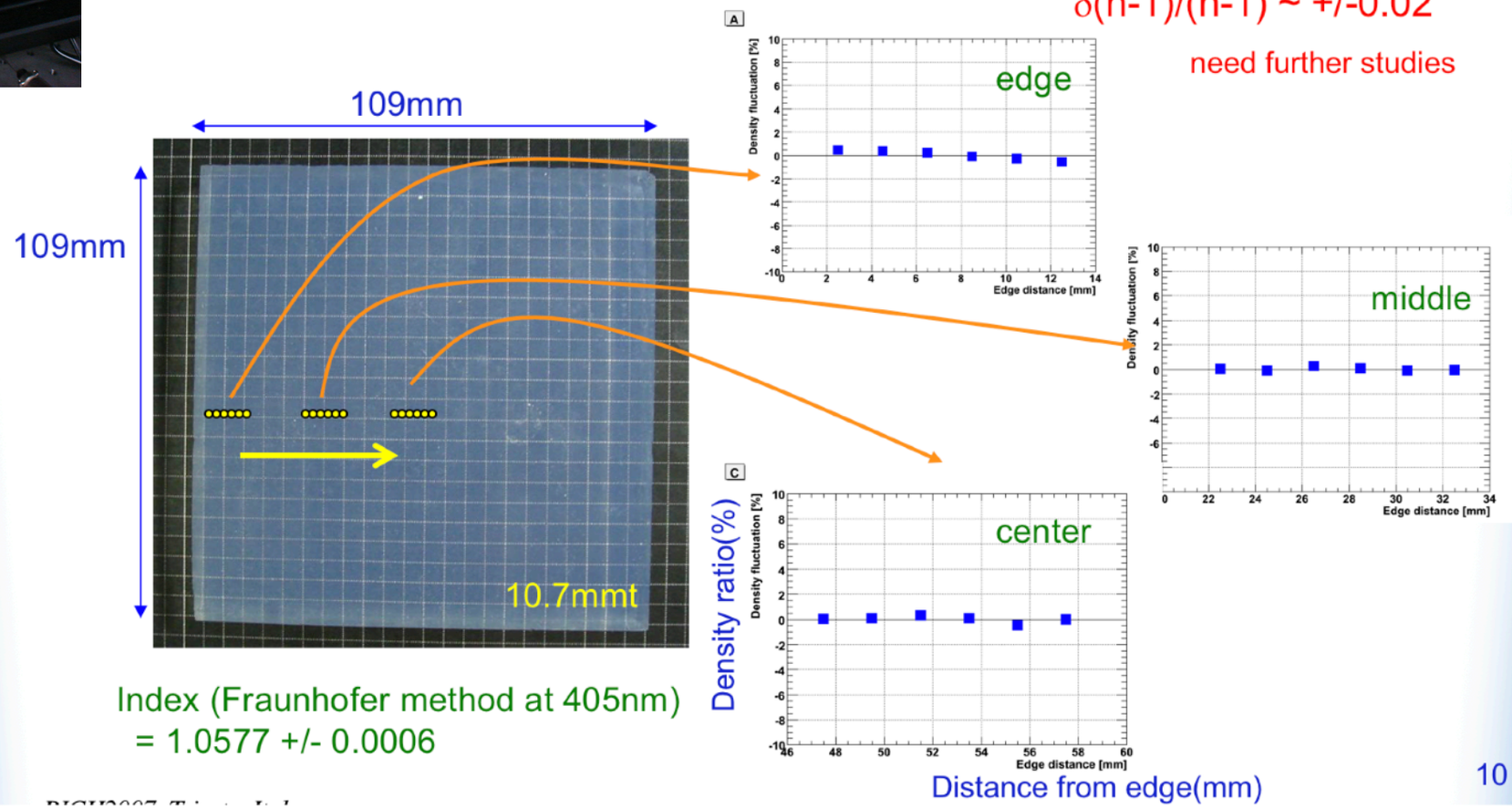
$\phi_{\text{beam spot}}$ < 1mm

density relative uniformity

preliminary value:

$\delta(n-1)/(n-1) \sim +/-0.02$

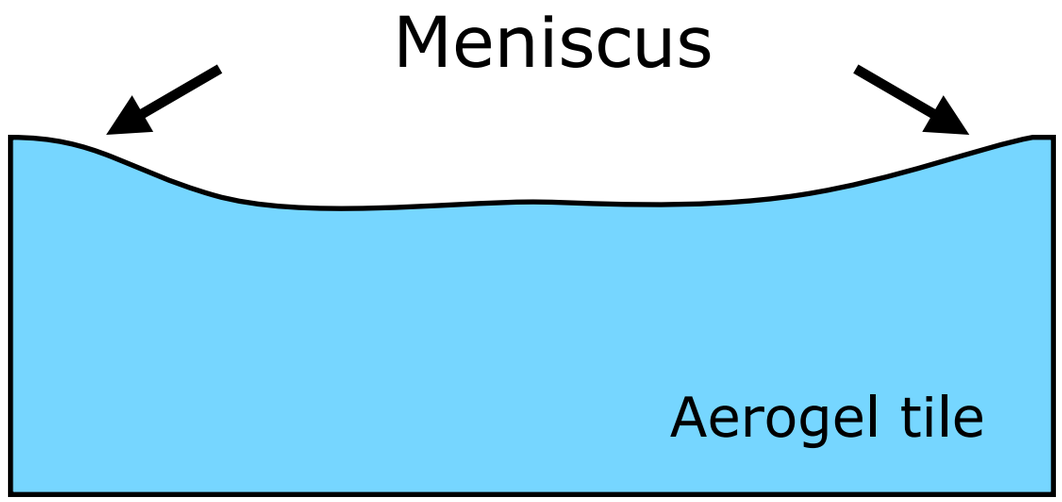
need further studies



Index (Fraunhofer method at 405nm)
= 1.0577 +/- 0.0006

Meniscus (1)

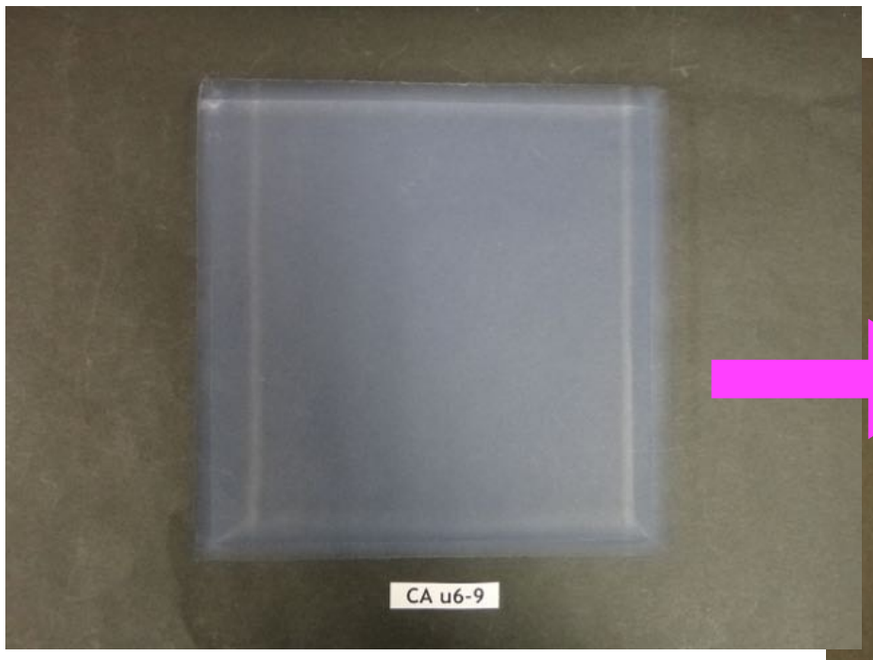
Aerogel tile has meniscus structure.
Meniscus structure partially related to production process.



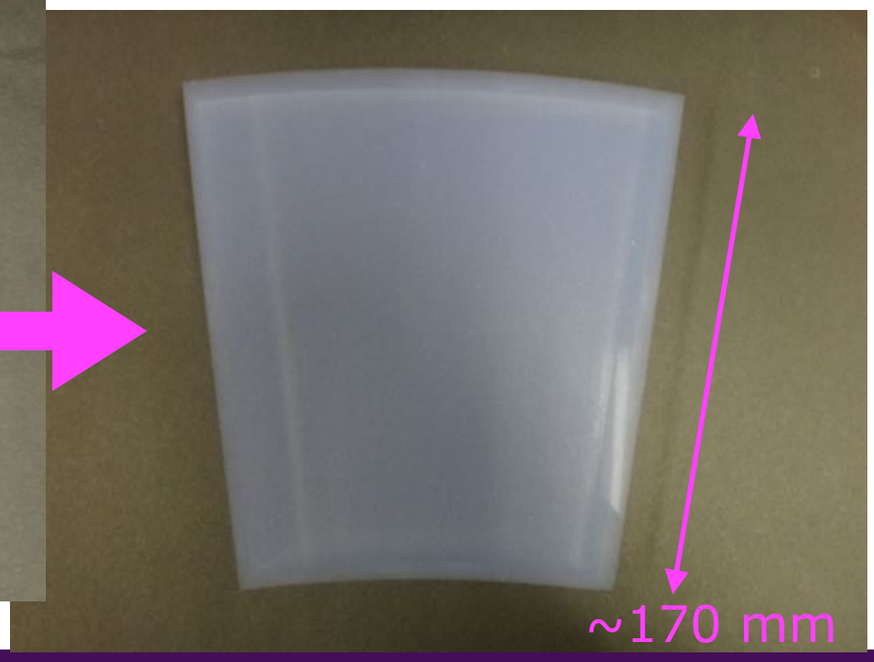
This could be a (*potential*) problem when Cherenkov radiator is organized by stacking # of aerogel tiles.

Meniscus (2)

- The best way is to remove tile edge regions, where there is meniscus.
- Hydrophobic feature allows us to use a water-jet machine without deteriorating optical transparency.
- In case of hydrophilic tiles, diamond cutter can be used for machining (like CLAS12 aerogels from BINP).



Belle II case

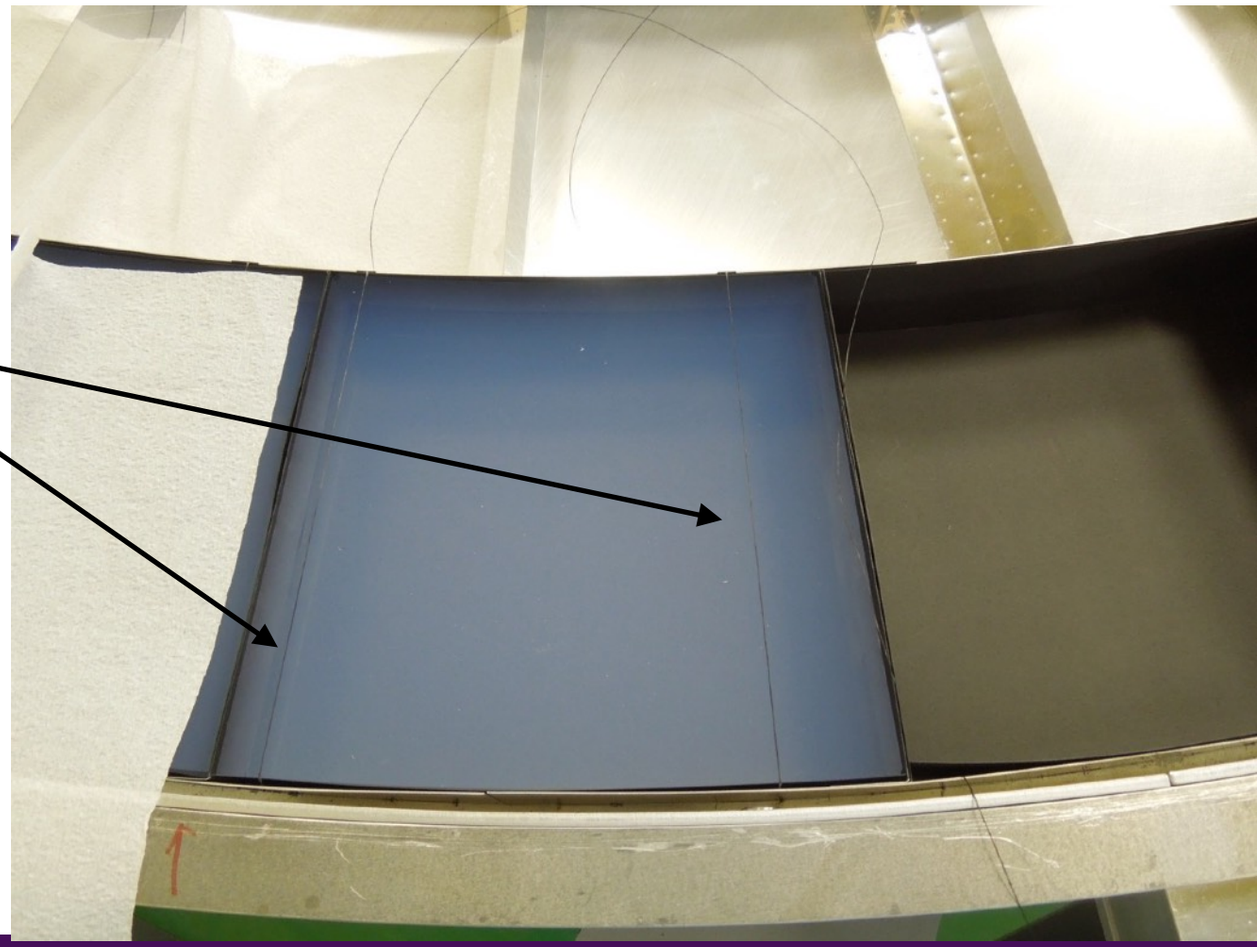


Housing

- To construct aerogel radiator system, each tile has to be fixed into the detector container.

- Aerogel is fragile and the way to fix tiles is rather limited.
  - Metal screws can not be used.
  - Wrapping transparent film and glue
  - Directly glue
    - One can not replace tiles.
  - Strings

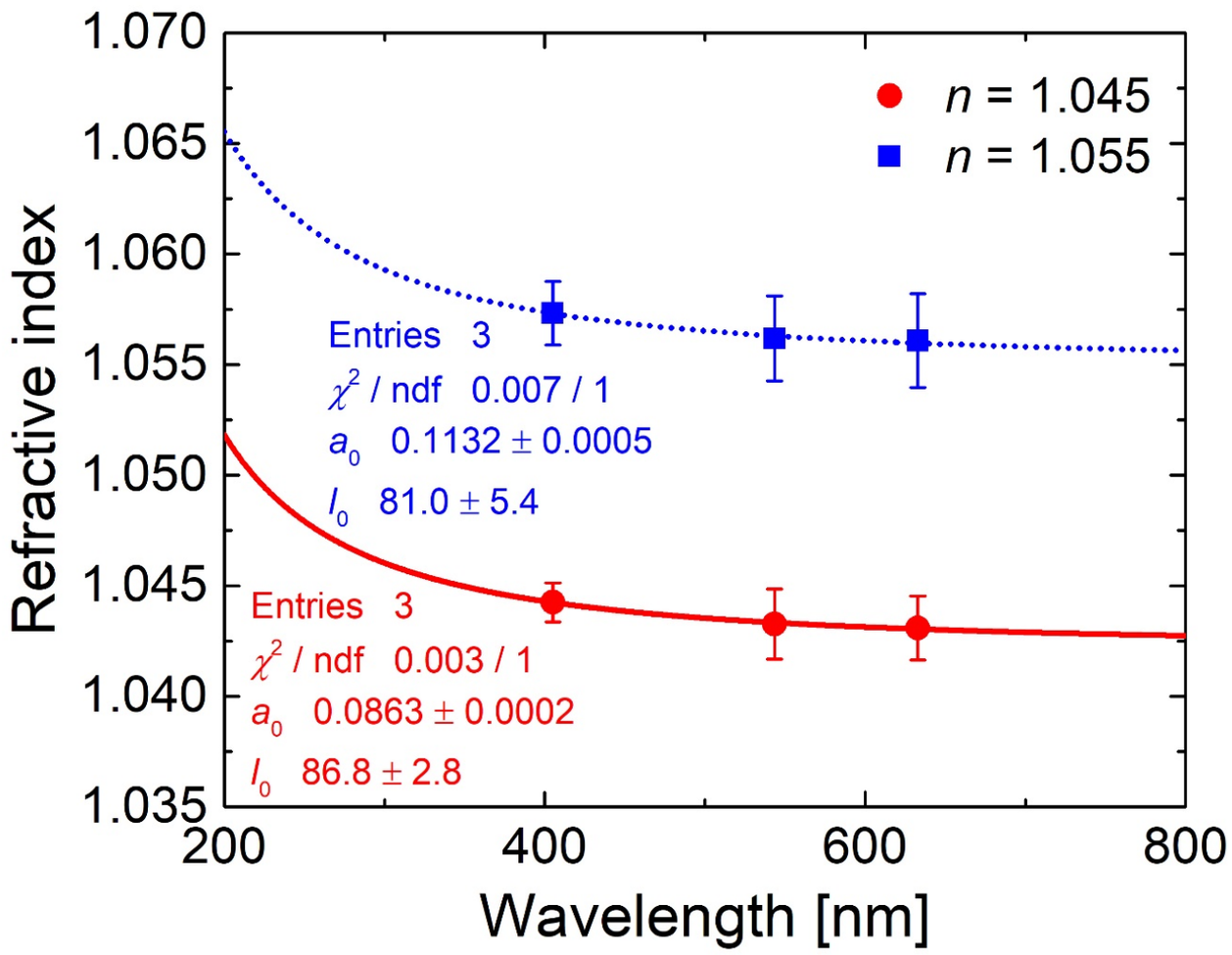
Belle II case
Glass fiber



It is not a problem, but (potential) worry…

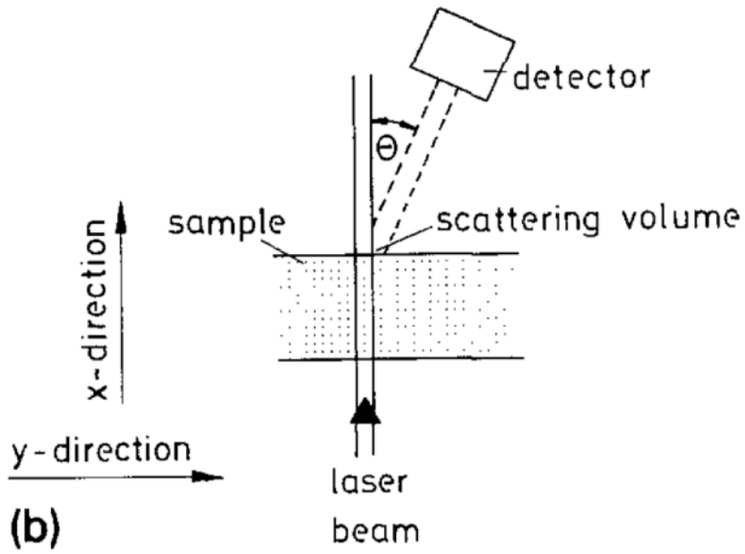
Chromaticity Dispersion

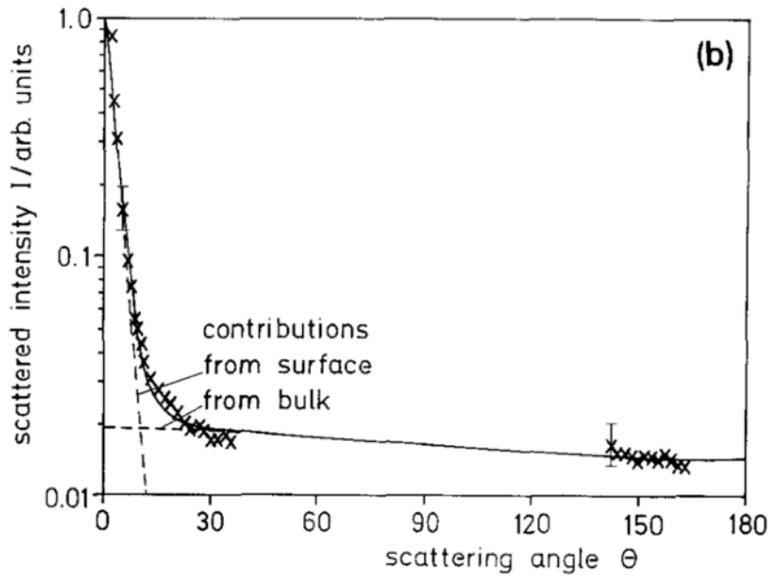
- Refractive index measured with lasers having different wave-length.
- Fitted with Sellmeier equation : $n^2 - 1 = a_0\lambda^2/(\lambda^2 - \lambda_0^2)$



Forward Scattering

- Forward scattering mainly on aerogel surface reported by P.Wang et al. in J. Non-Crys. Solids 145(1992)141.
  - Sharp peak in forward, unlike Rayleigh scattering.





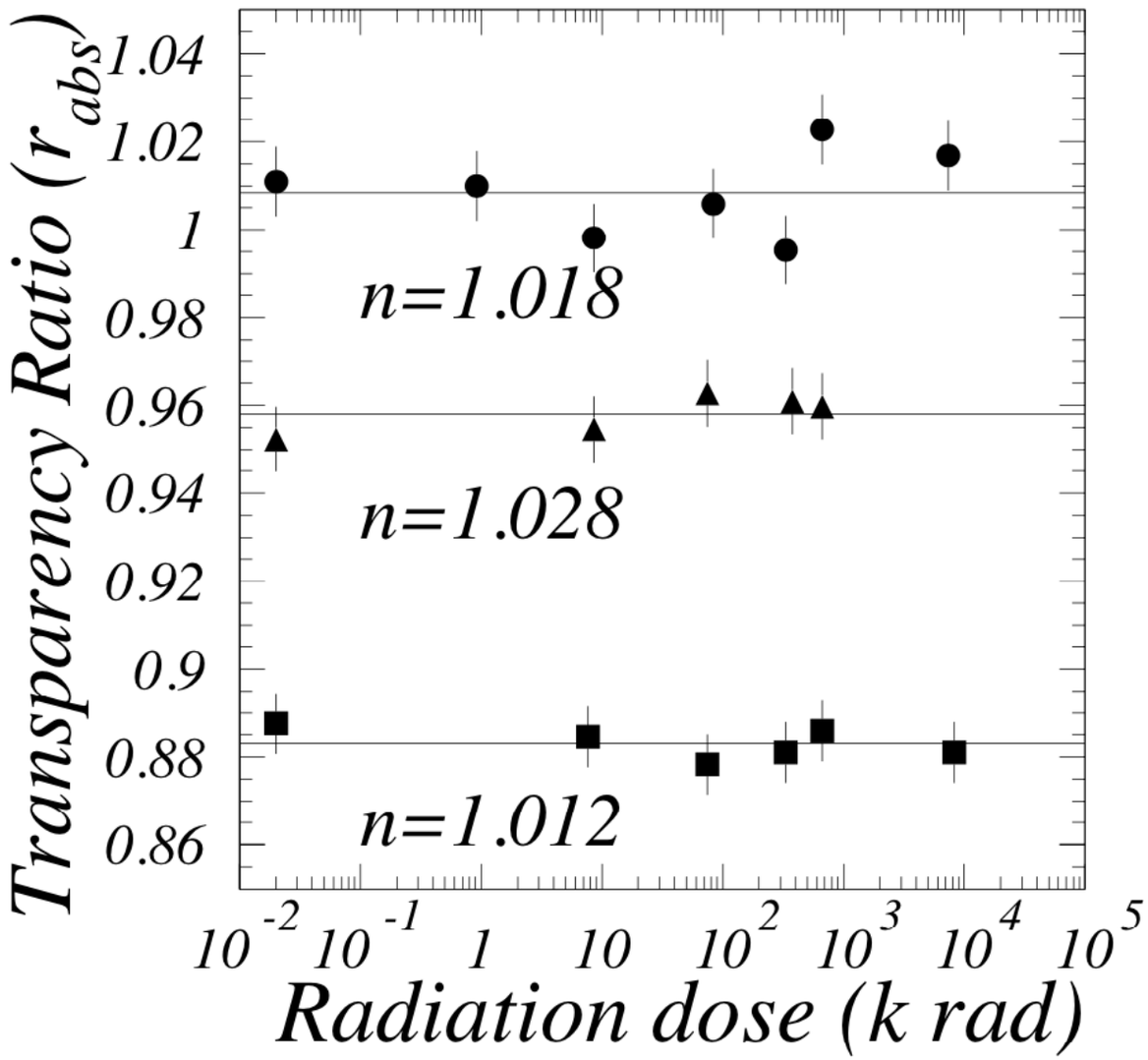
- Further systematic studies done by R. De Leo et al. NIMA457(2001)52. Matsushita aerogel used.

- This effect contributes as one of components in background.

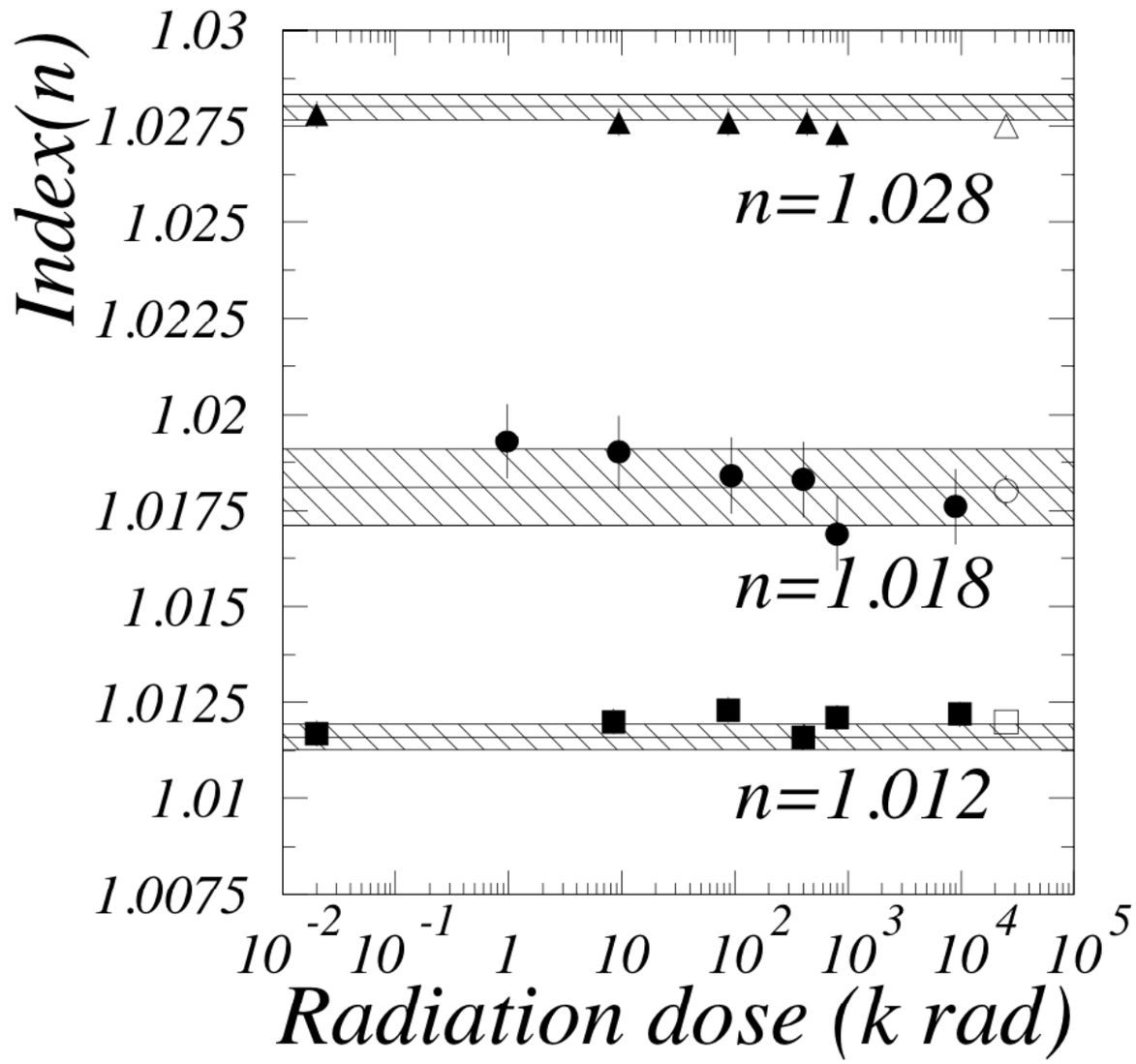
Need to measure this effect for recent samples

Radiation Damage

Transmittance



Refractive index

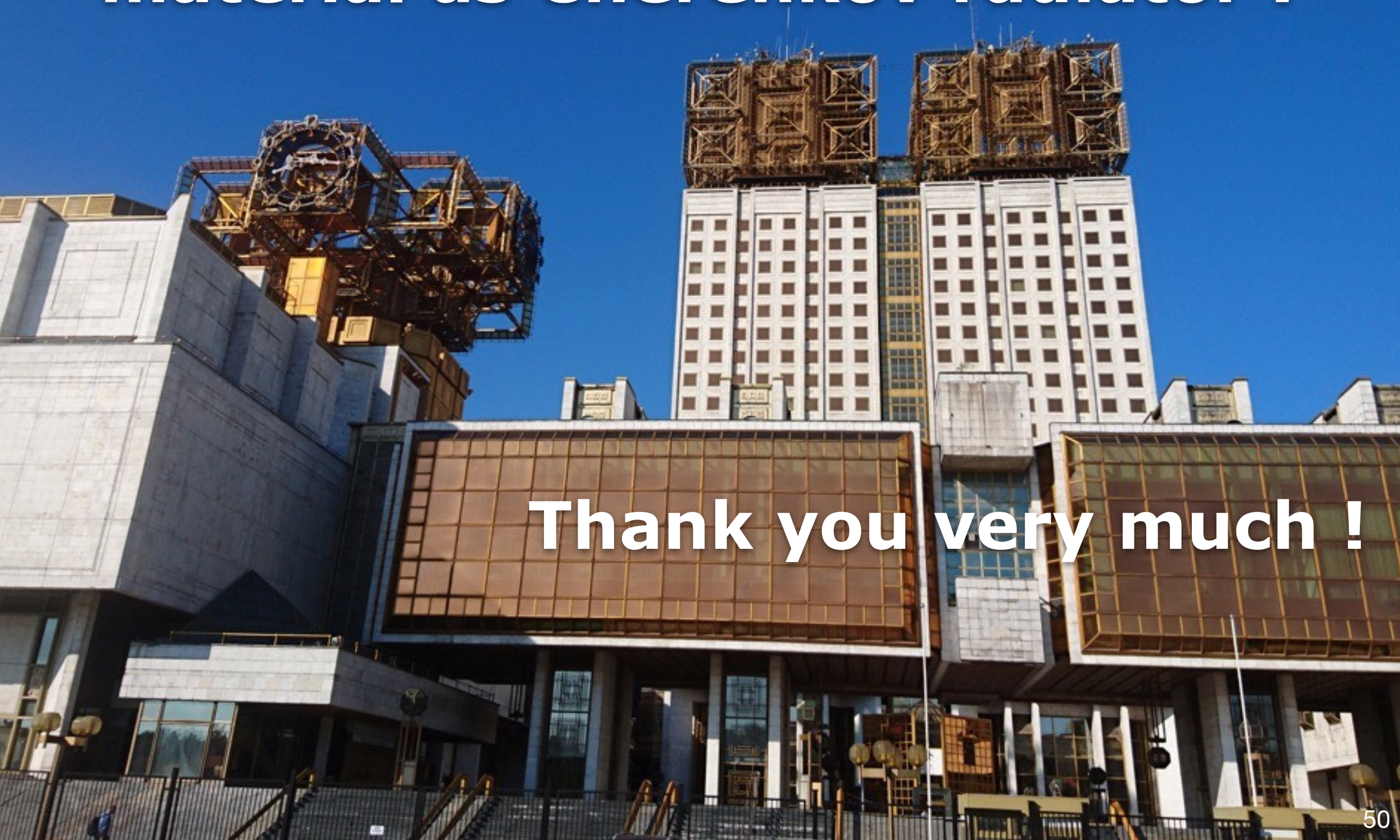


No deterioration up to 9.8 Mrad

Summary

- Aerogel is an unique material and has been developed as Cherenkov radiators since 1970’s.
- Aerogels in the new generations from Russia and Japan are widely used as Cherenkov detectors in various experiments.
- Transparent tile allows us to take the new direction.
  - Focusing scheme of multiple aerogel layers
- For the 4th generation aerogels, experience at HELIX RICH gives us further information on applications.

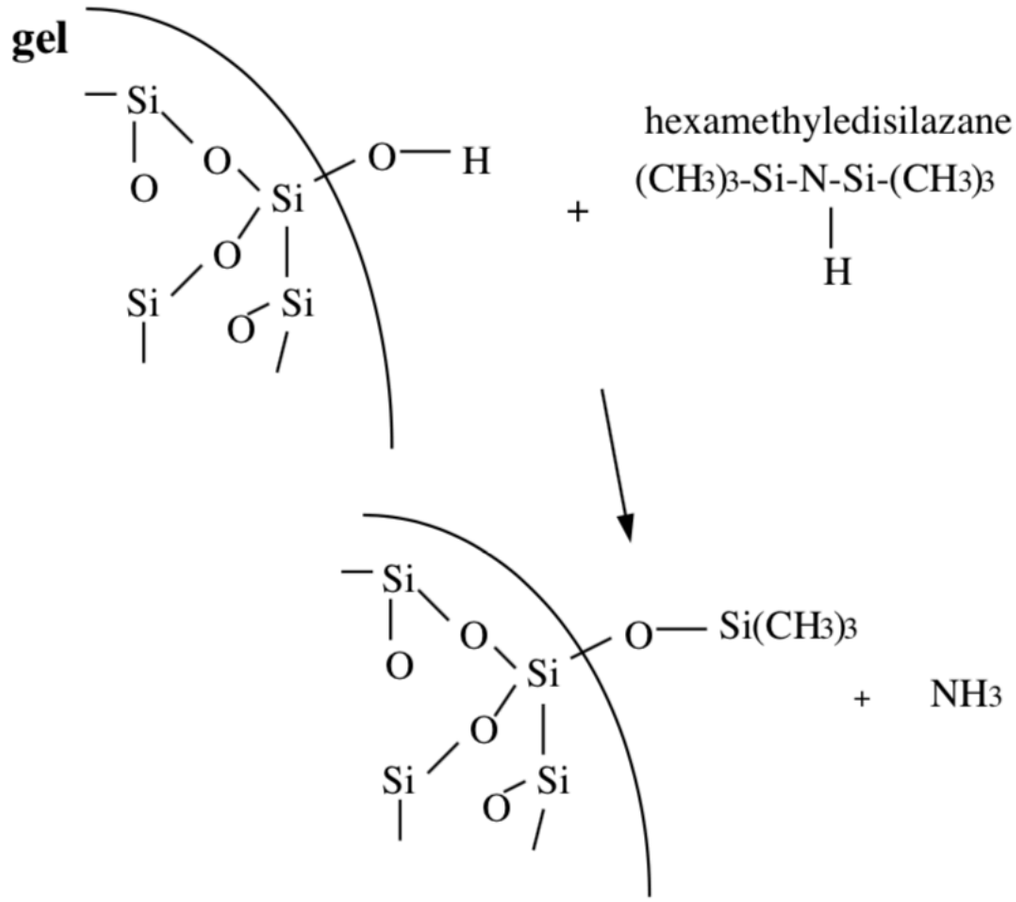
Silica aerogel is attractive material as Cherenkov radiator !



Thank you very much !

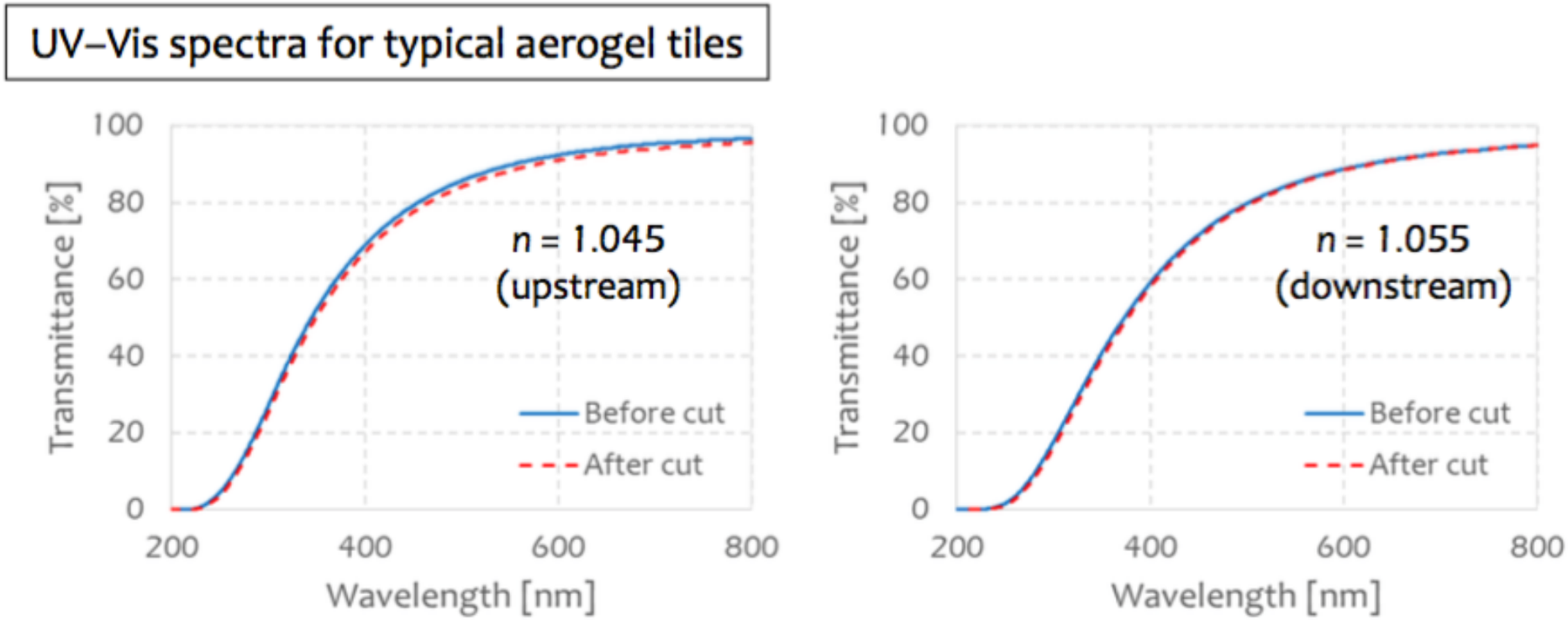
Hydrophobic Treatment

- -OH group in alco-gel is replaced into -O-Si$(CH_3)_3$
  - -OH group is likely to be charged and reacts with water.

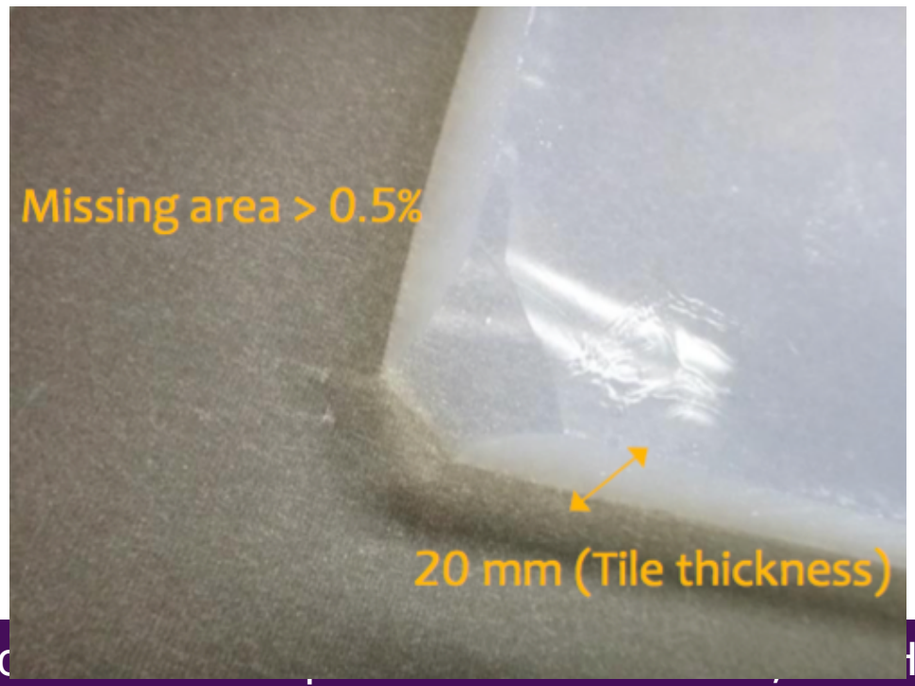


Tile Machining

No degradations in transparency due to this machining



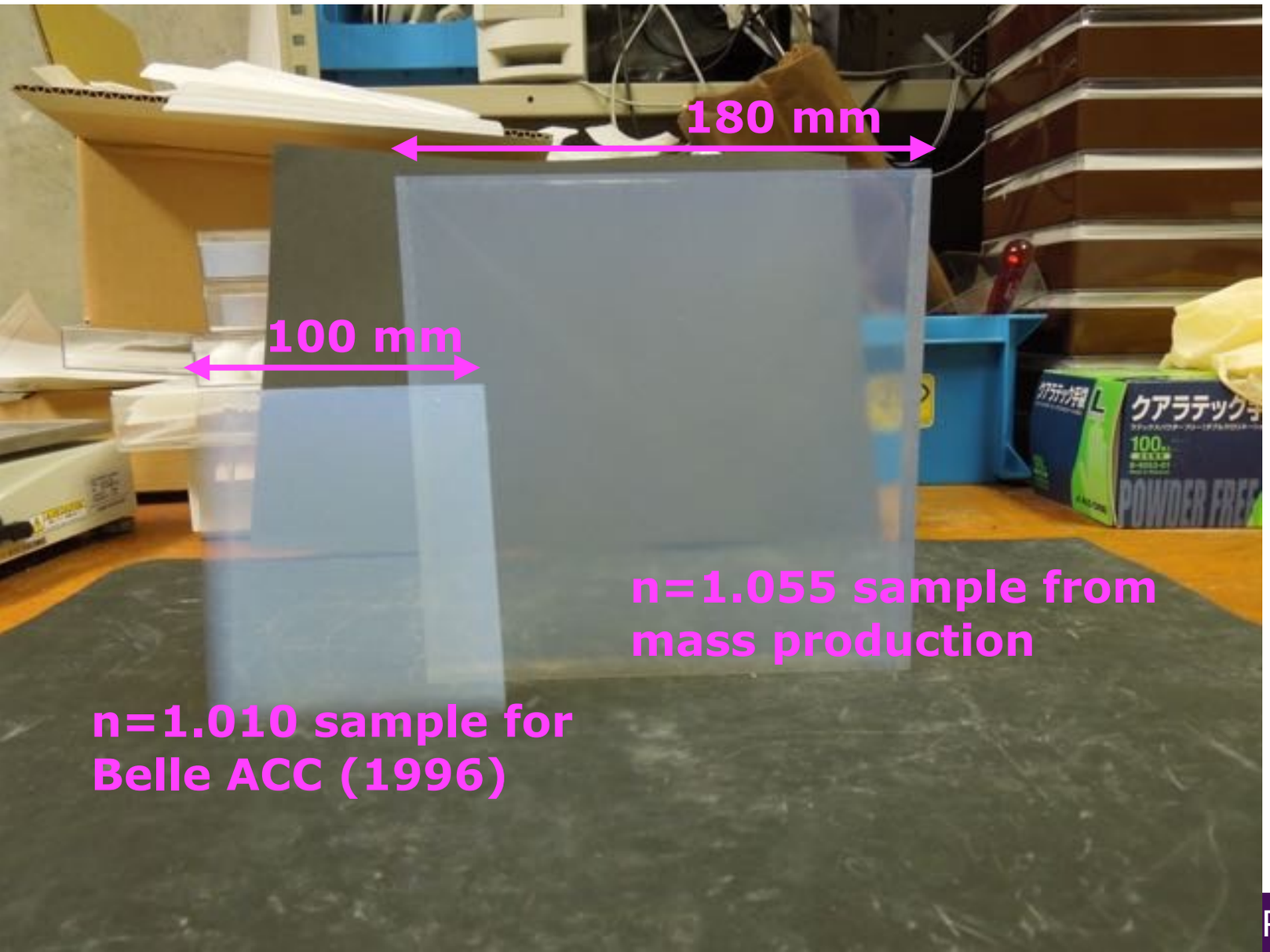
Small chips found in some tiles



If missing area > 0.4 % w.r.t. whole surface (~1.0 cm^2), the sample is removed from candidates.

New Aerogel Tile

- Large tile of 180×180×20 mm^3 with no cracks
  - Optimization of pressure control in supercritical drying process.
  - 3 times longer duration from operating point to atmospheric pressure introduced by Chiba university group.



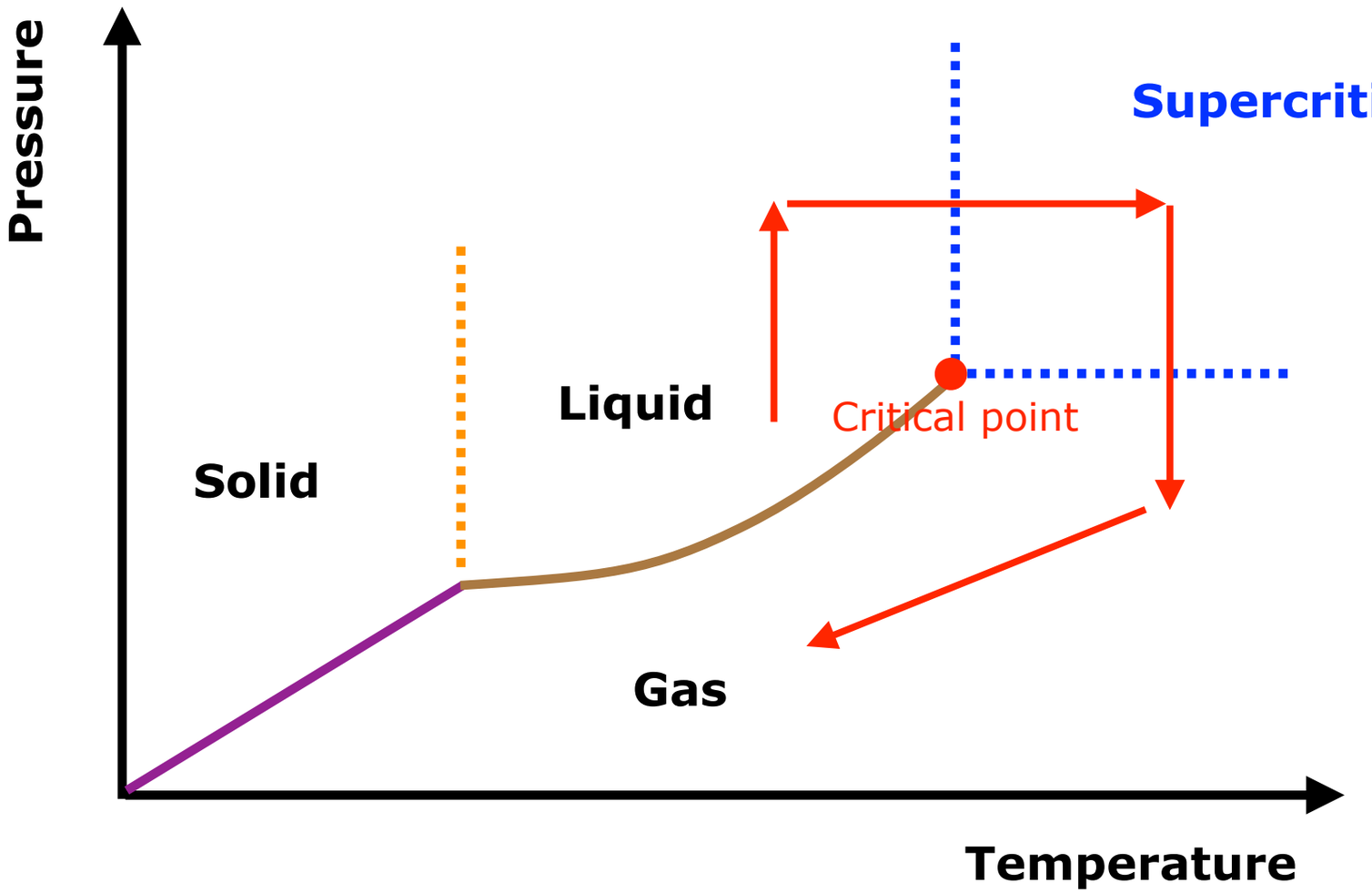
Crack-free yield ~ 87%

Drawback is to need more time for tile production.

M.Tabata et al., The Journal of Supercritical Fluids, Vol.110, April 2016, Pages 183-192

Supercritical Drying

Phase diagram



Drying through supercritical region, instead of passing through liquid-gas boundary.