

VIENNA 2010 SUMMARY

Amos Breskin

Pavel Rehak
December 5, 1945 – November 4, 2009



Pavel (BNL) pioneered far reaching new detector concepts and widely influenced many individuals and groups around the world.

His invention with Emilio Gatti of the silicon drift detector.

Used in STAR at RHIC and ALICE at LHC - it also revolutionized x-ray spectroscopic detectors.

The prime roles of our community:

- Study basic detector physics
- Conceive new detectors
- Build detector systems
- Educate the younger generation

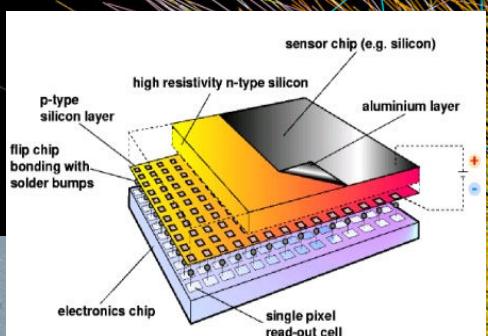
A fascinating, ever-growing field
With many multidisciplinary applications
Far behind Particle Physics!

resolutions

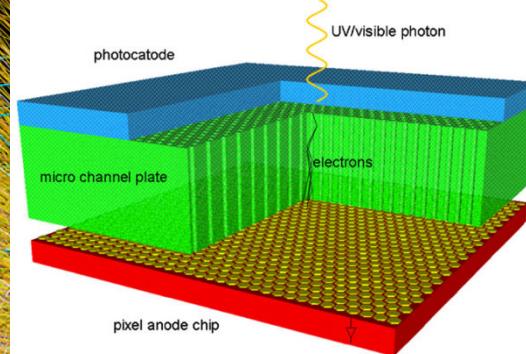
sizes

sensitivities

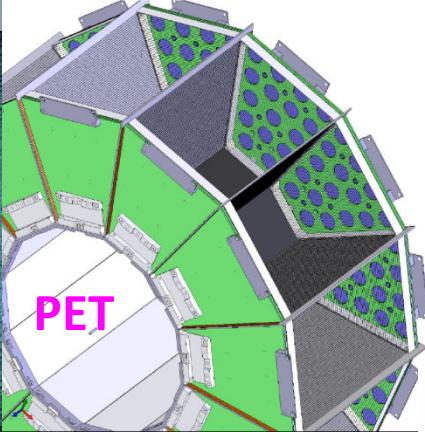
Medical



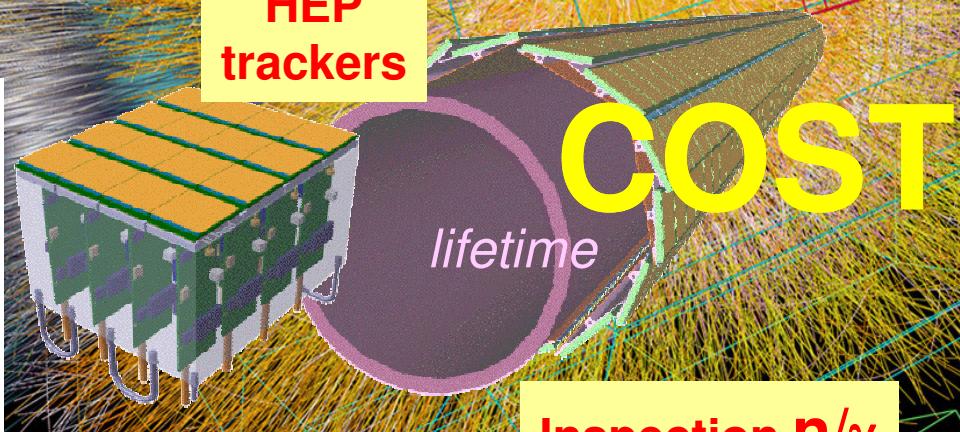
Astronomy



Astroparticle Physics



**HEP
trackers**

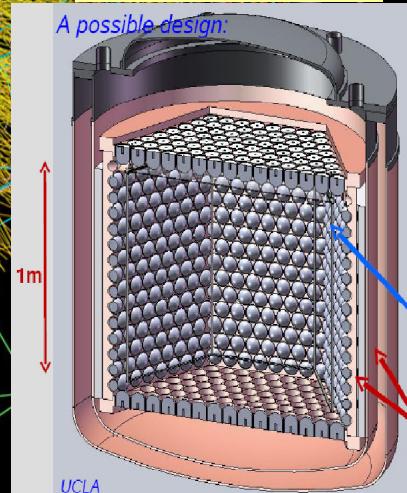


Inspection n/γ

fluxes



Dark matter



background

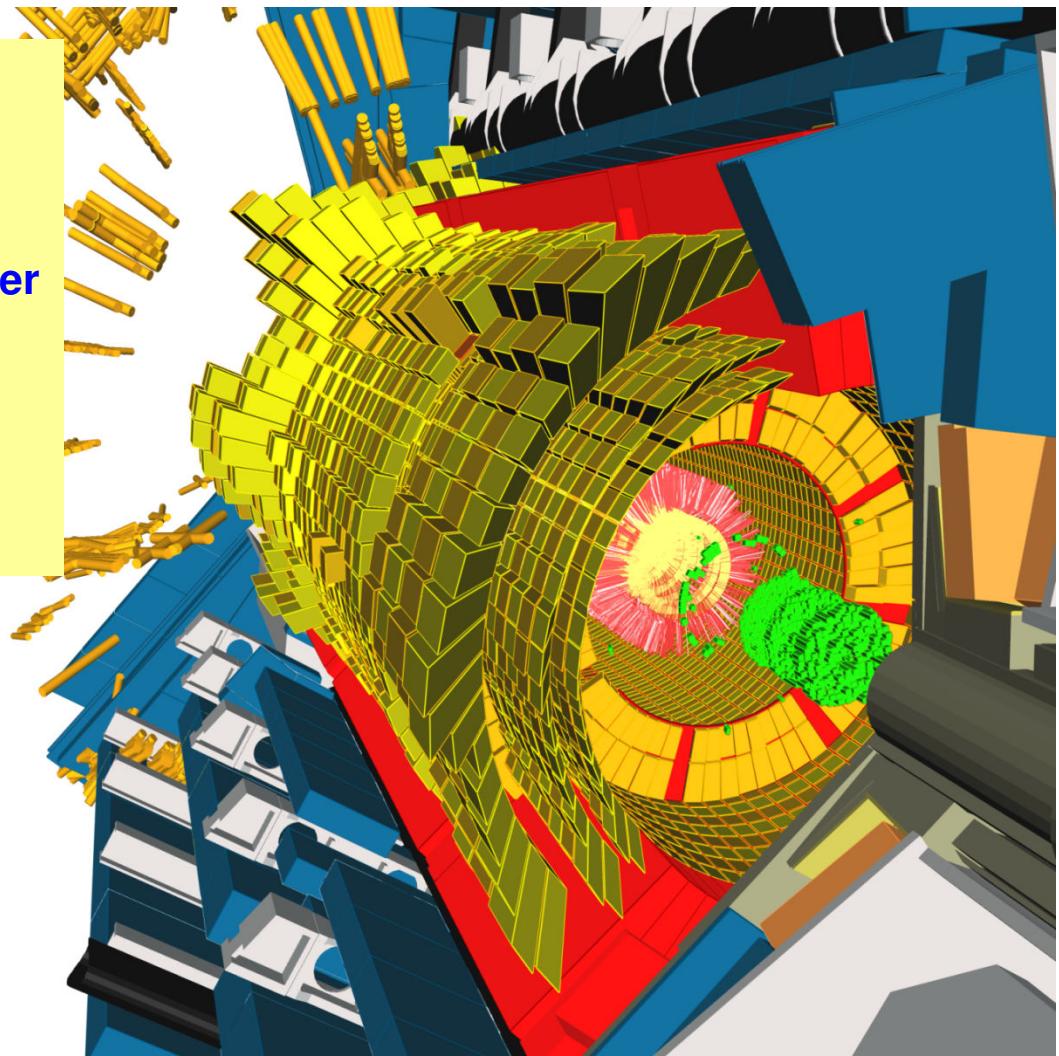
Nov 2009: First LHC runs
after many Vienna conferences...
BRAVO to all LHC detector designers & builders!!!

Si Pixels
Si strips
TRT
LAr EM calorimeter
Scintillator Tile hadronic calorimeter
MDT (Monitored Drift tubes)
RPC (Resistive plate chambers)
TGC (Thin gap wire chambers)
CSC (Cathode strip chambers)
ZDC (Zero degree calorimeter)

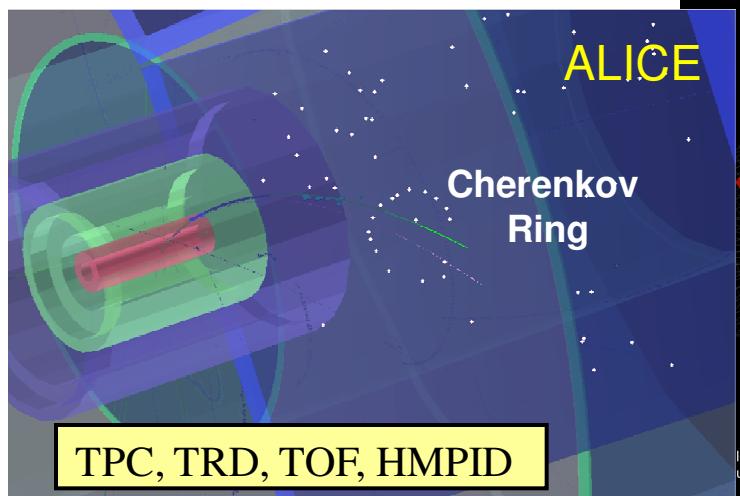
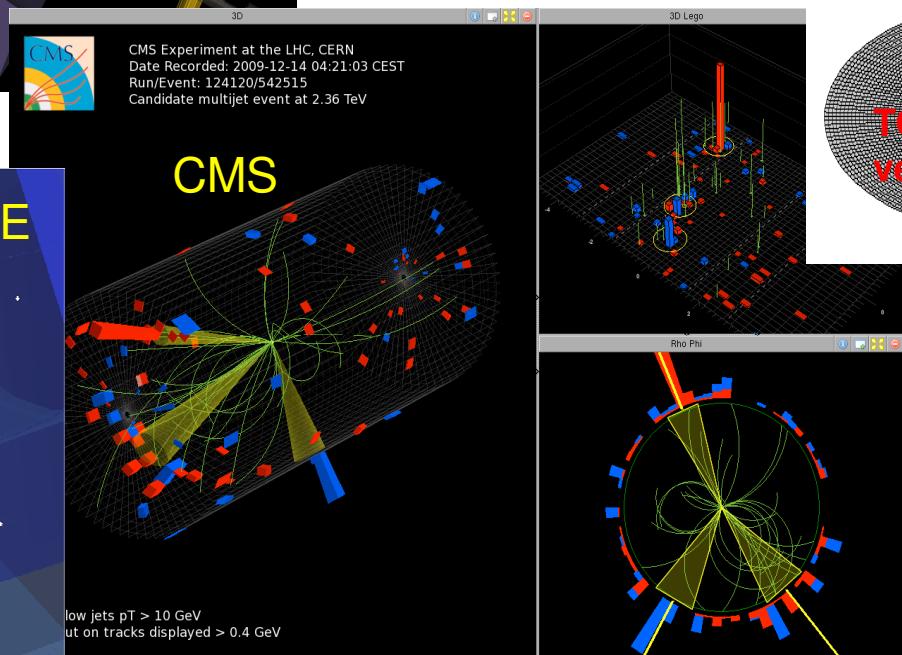
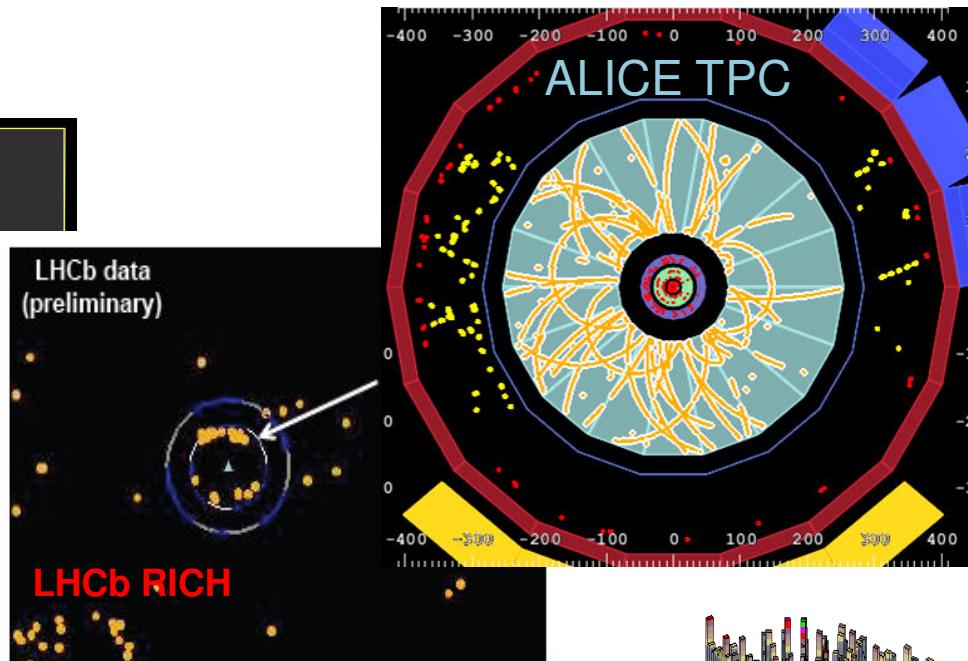
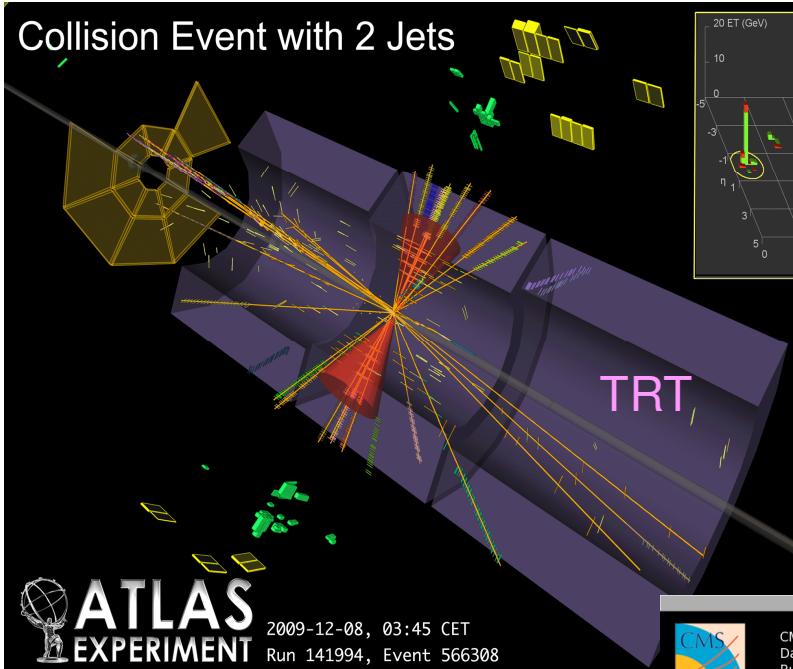
LHC DETECTORS
2008 *JINST* 3 2008 S08001-7



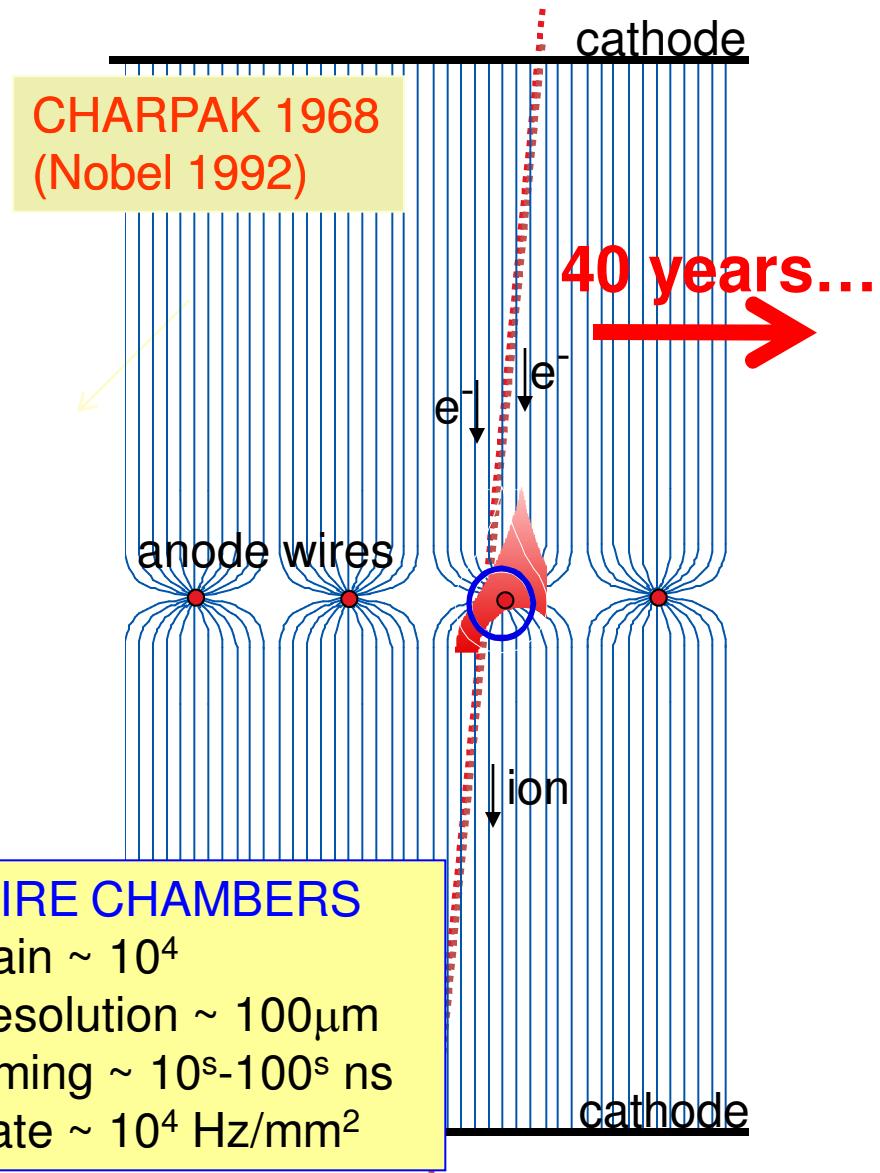
2009-11-20, 23:32 CET
Run 140370, Event 2666



LHC: first events - 2009

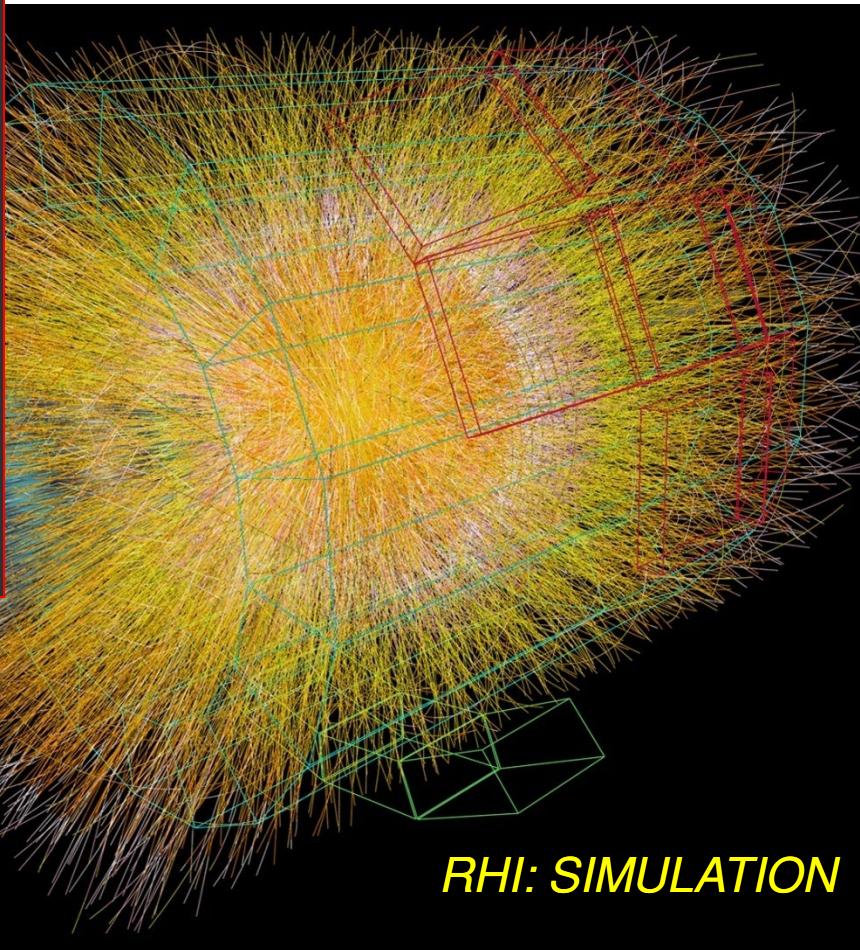


OLD GOOD VIENNA FRIENDS: WIRE CHAMBERS



Wires in ALICE

ALICE p-p event 2009



And next TPCs?

next?
next?
next?
next?
next?

Are we over with wires?

Solid-State Detectors

CMS

The large LHC trackers

- CMS

- 198 m² of Si, 9.3 M channels
- Inner Tracker: 4 barrel layers (TIB) and 3 disks per endcap (TID)
- Outer Tracker: 6 barrel layers (TOB) and 9 wheels both sides (TEC).
- Barrel: 2724 (TIB)+5208 (TOB)
- Endcap: 816 (TD)+6400 (TEC)
- 22 cm < R < 120 cm

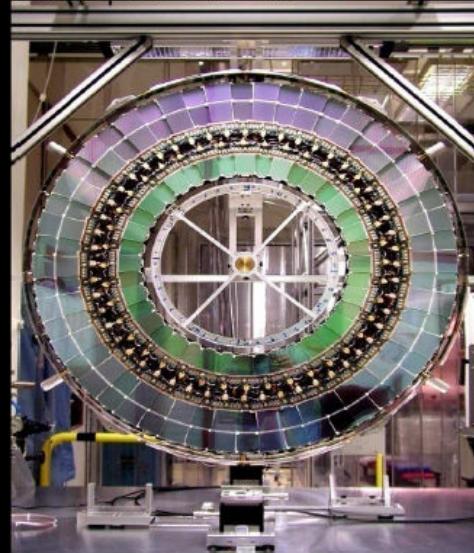


Daniela Bortoletto

TIPP 09

- ATLAS

- 61 m² of Si, 6.2 M channels
- 4 barrel layers and 9 disks in each endcap
- Barrel: 2112 modules (1 type)
- End-cap: 1976 modules (4 types)
- 30 cm < R < 52 cm



4

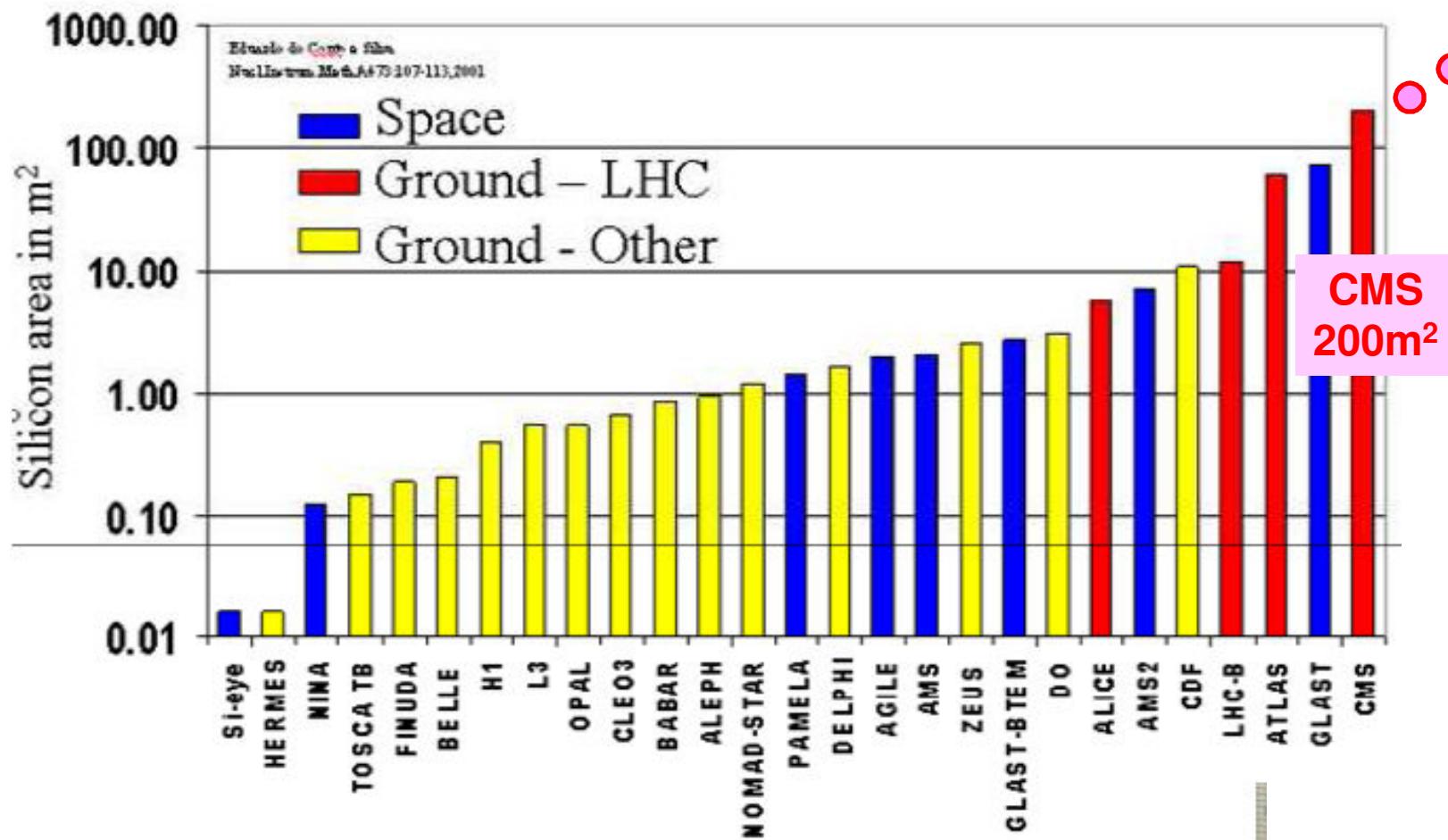
TRACKERS FOR NEXT GENERATIONS?

ILC, sLHC, B-factories, FAIR, space, Light Sources (XFEL)...

NEW TECHNOLOGIES, RAD-HARD MATERIALS, SPEED, RESOLUTIONS, SIZES...

Experiments with Silicon Detectors

?



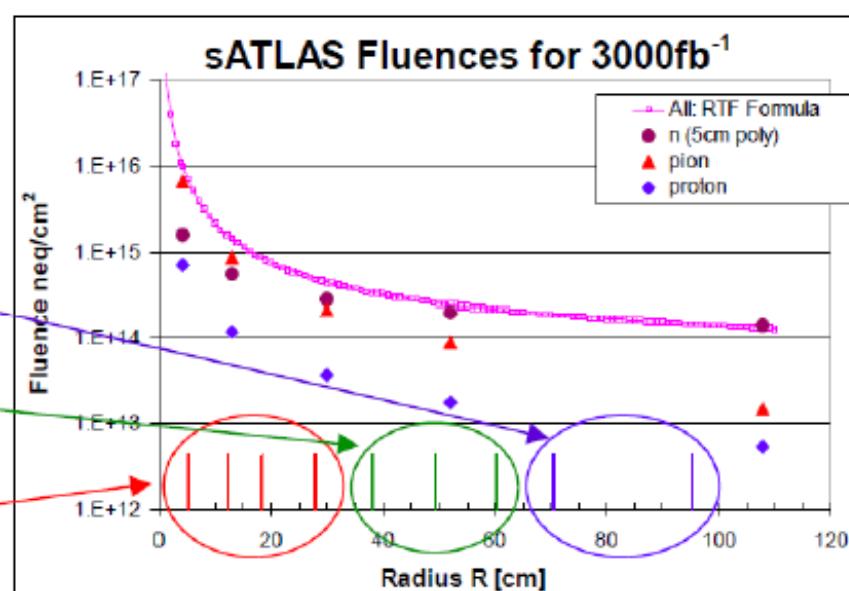
sLHC Trackers: sATLAS example

Radial distribution of sensors determined by Occupancy

Long Strips
(up to $4 \times 10^{14} \text{ cm}^{-2}$)

Short Strips
(up to 10^{15} cm^{-2})

Pixels
(up to 10^{16} cm^{-2})



sLHC:

Radiation hardness @ innermost layers: **$10^{16} \text{ neq}/\text{cm}^2$**

Material budget: **2-fold less than LHC ($1.5\text{-}2 X_0$)**

R&D: **3D Si, planar (n in p), diamond**

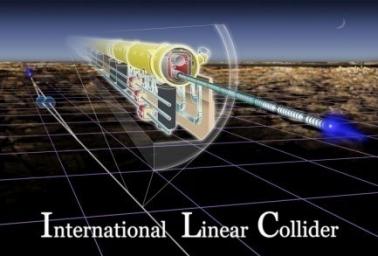
Rad-harder Si?:

n in p, FZ, MCZ, O-enriched?

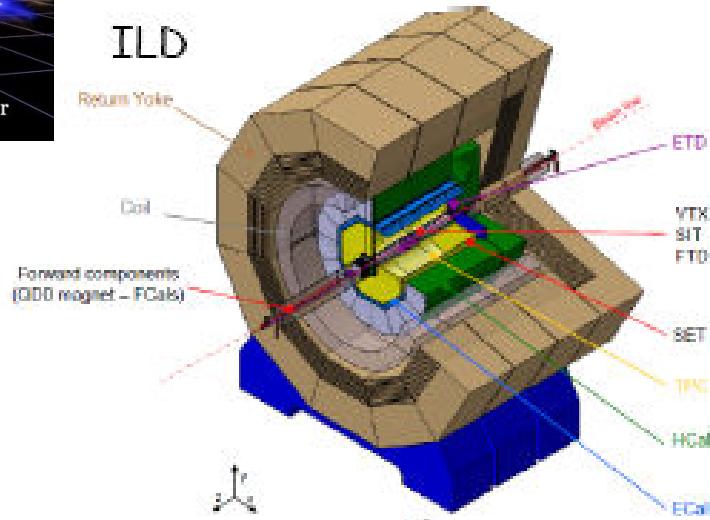
Rates: **320MHz \rightarrow 4-fold LHC**

But:
sLHC, ILC...
Ever?
15 years from now?

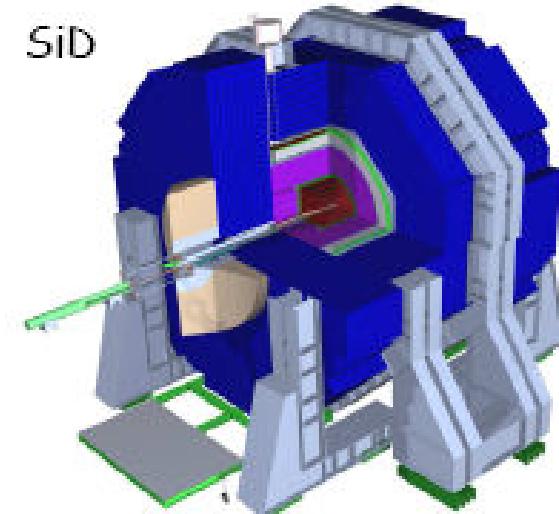
ILC detector concepts



International Linear Collider
Precision studies
of new physics



Vertex +Inner trackers: Si pads/strips
And TPC (with MPGDs)



All Si!

05-1TeV

Later, with CLICK technology: 3TEV

$2 \times 10^{34} \text{ cm}^2/\text{s}$

Many JETs!

Need:

Excellent vertexing ($3\mu\text{m}$) + robust tracking

Powerful high-resolution calorimetry → **Particle Flow** Concept!

→ Use tracking to “remove” charged particles + hit counting in DHCAL

CALICE: imaging CAL R&D

Pixel Sensors

NEED ACRONYMES DICTIONARY....!

- **CCD**

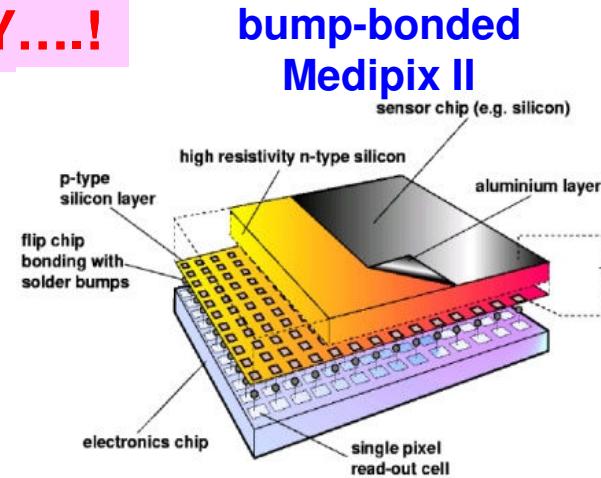
- CPCCD, FPCCD, ISIS (CCD/MAPS)

- **Hybrid**

- Sensors & readout chip fabricated separately
 - Different processes for sensor and readout
 - Fast, rad-hard, flexibility in circuit, but
 - Thick, large pixels, bump-bonding is cumbersome
- ATLAS pixel, CMS pixel, Alice SPD, Timepix, ‘3D’, diamond, etc

- **Monolithic**

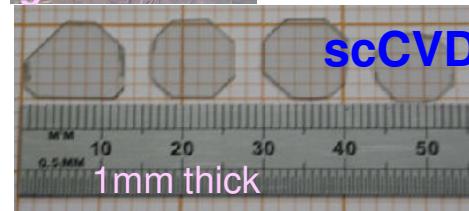
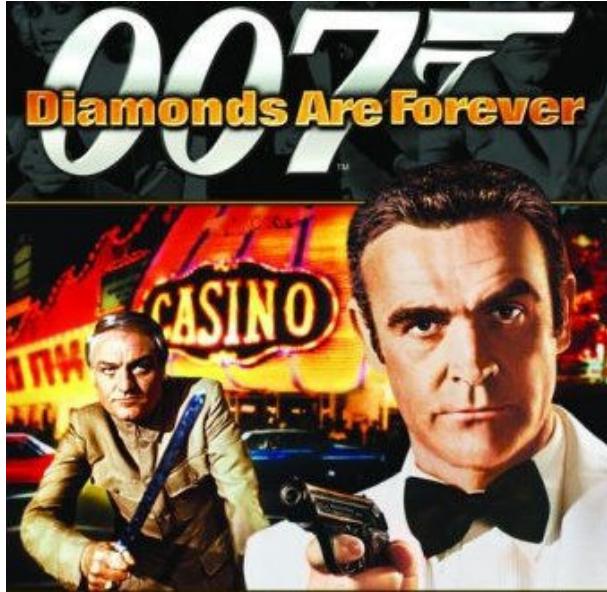
- Sensors and readout chip fabricated on single wafer
 - No bumps, high pixel density, thin, but
 - Type of circuitry is constrained (usually NMOS only)
- MAPS, DEPFET, Deep N-Well, SOI, CAP...
→ VERTICAL INTEGRATION



Pixel08 Workshop *JINST 2009, vol 5*

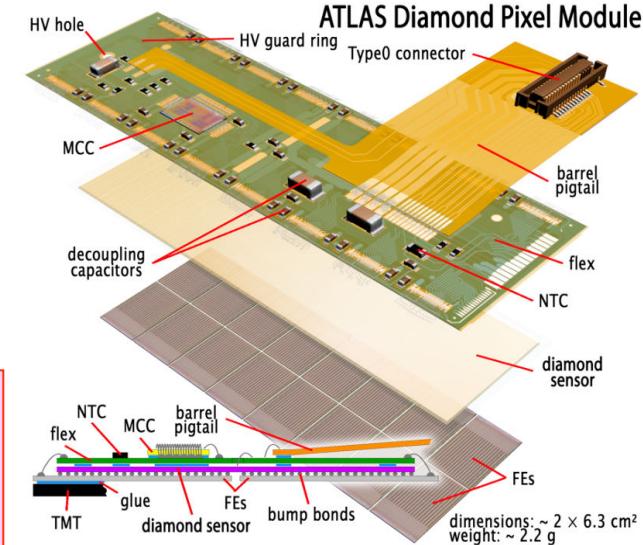
HARTMAN VCI2010 Rev on Si det “physics”

Diamond pixel sensors



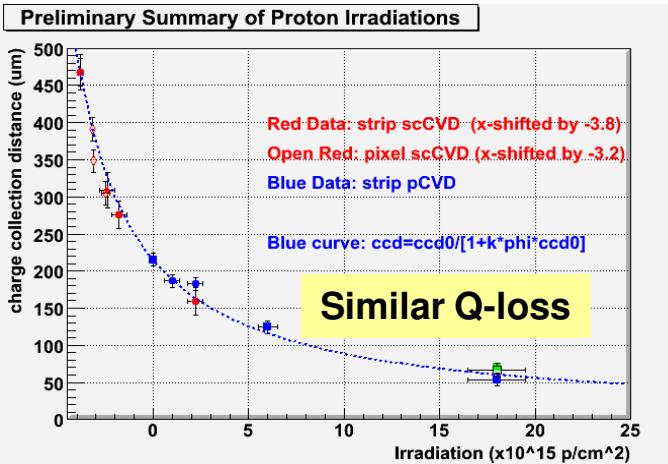
Poly-crystal CVD &
Single-crystal CVD

sLHC: high fluence
→ rad-hard pixels in central region



Module after bump bonding

Full module built with FE-I3 pixel chips
@ OSU, IZM and Bonn



Beam tests of modules:

pCVD:

14 μm , Eff. >97.5%

scCVD:

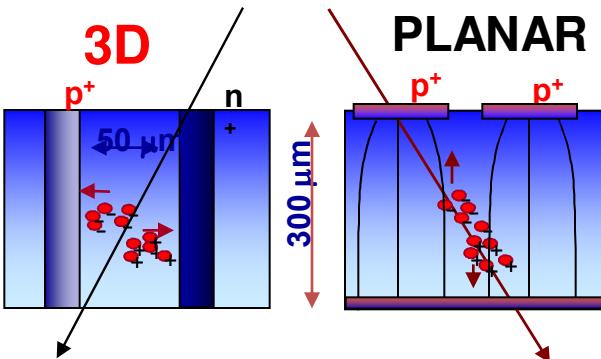
9 μm , Eff. 99.98%

Diamonds:
Still relevant with new aged-Si
Q-amplification data? Lange, Hartman VCI10'

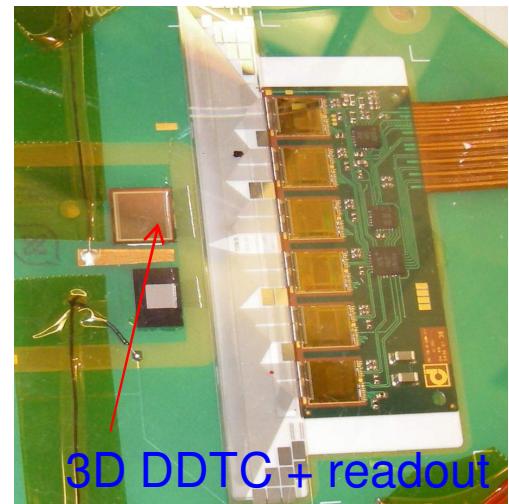
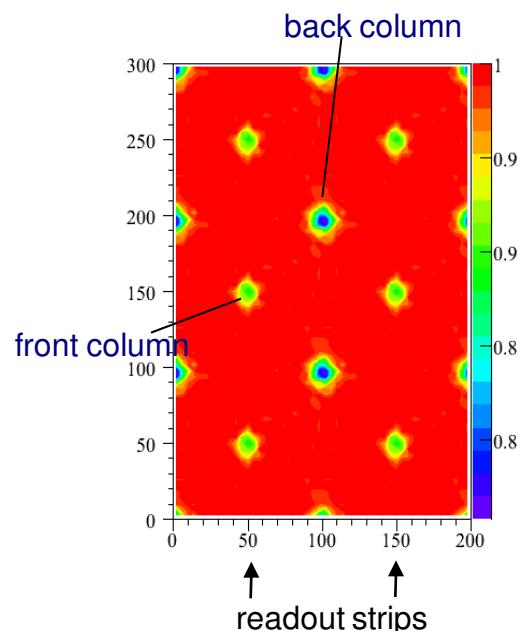
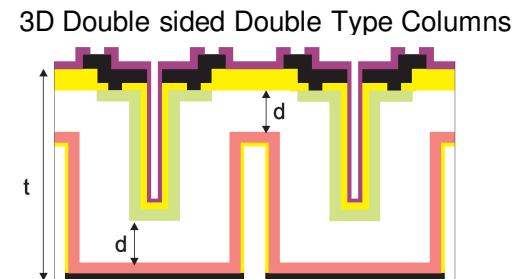
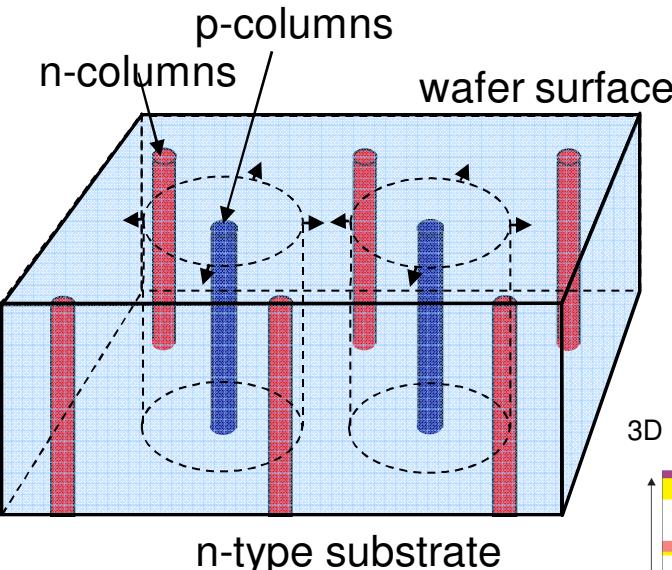
H. Kagan

3D Si detectors

Parzefall TIPP09



- Depletion & charge collection: **sideways – faster!**
- **Superior radiation hardness:**
 - Less trapping (**short collection**)
 - Full depletion V less affected by growing acceptor concentration
- Original 3D designs
 - Conceived as **pixel devices**
 - **Strips** by connecting rows of columns
- **Option for innermost layer in sLHC**



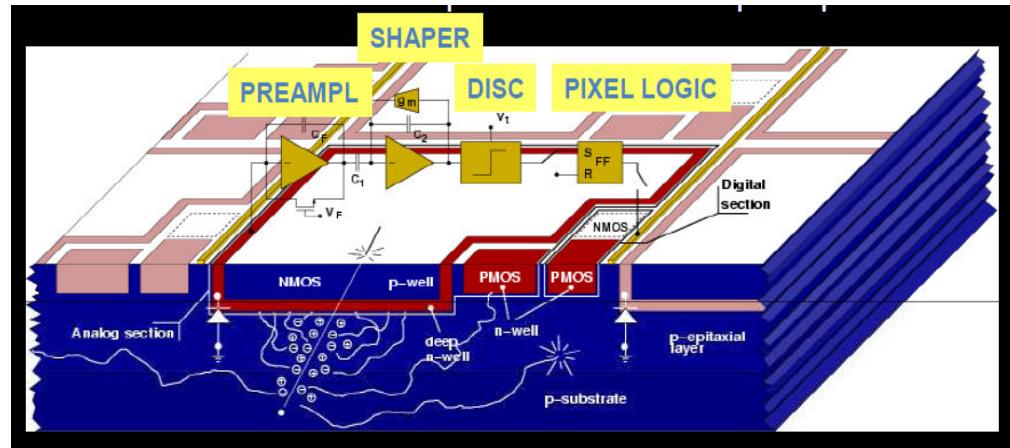
MIPS: 99% efficiency

Monolithic News

• Deep N-Well

Neri TIPP09

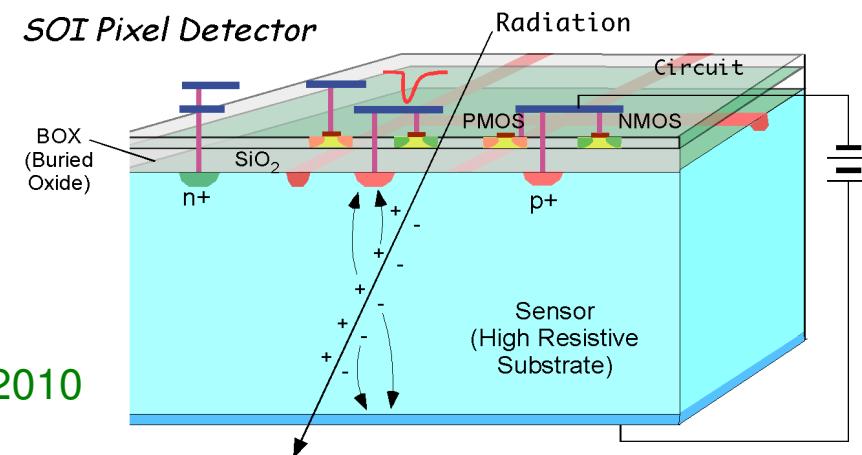
- PMOS can also be used.
 - Sensitivity loss under PMOS.
- R&D on **vertical integration**
Readout circuit in another layer



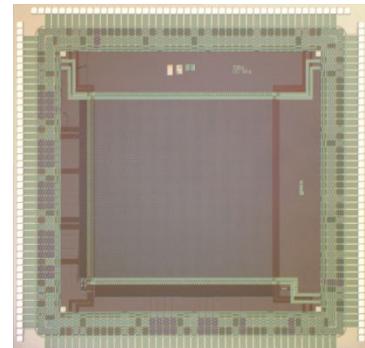
• SOI (silicon on insulator)

- Sensor active area very close to the read out circuit ($\sim 200\text{nm}$)
 - Sensor interferes with the readout circuit (back gate effect, cross talk)
- R&D on **vertical integration**

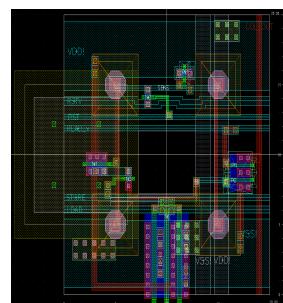
Arai TIPP09/VCI2010



128 x 128 pixels
5 x 5 mm²



20 $\mu\text{m} \times 20 \mu\text{m}$
pixel

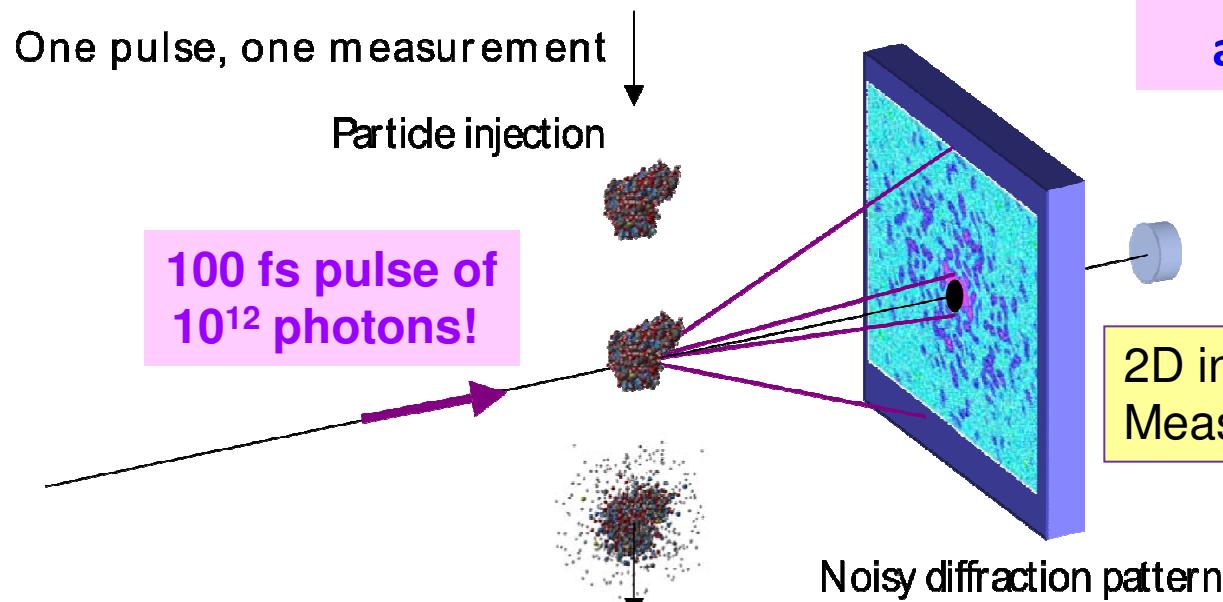


LIGHT SOURCES: XFEL - SINGLE-SHOT EXPERIMENTS

Due to high intensity sample gets destroyed

→ 1 new sample injected / 100 fs pulse

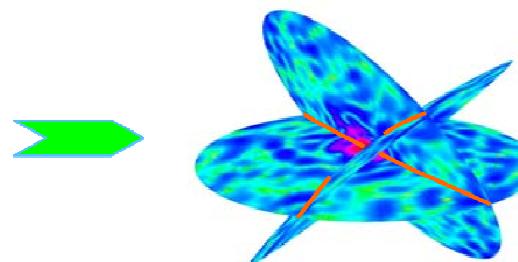
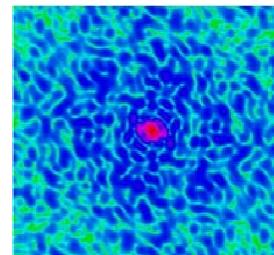
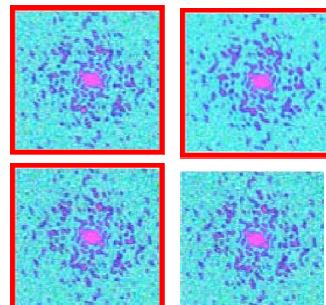
DESY-XFEL
27 000 bunches/s
at 4.5 MHz rep rate



Solve the well known
Phase Problem

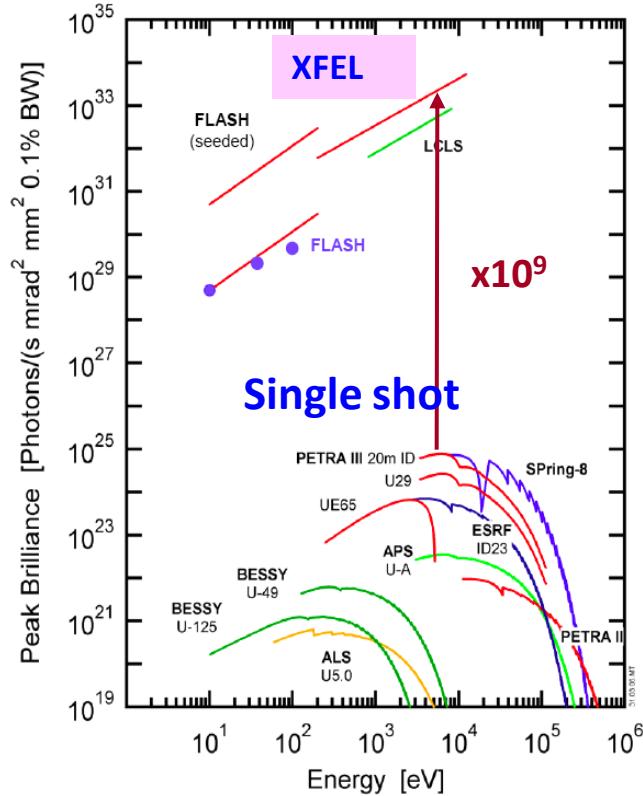
2D integrating detector
Measures single images

Combine 10^5 - 10^7 measurements

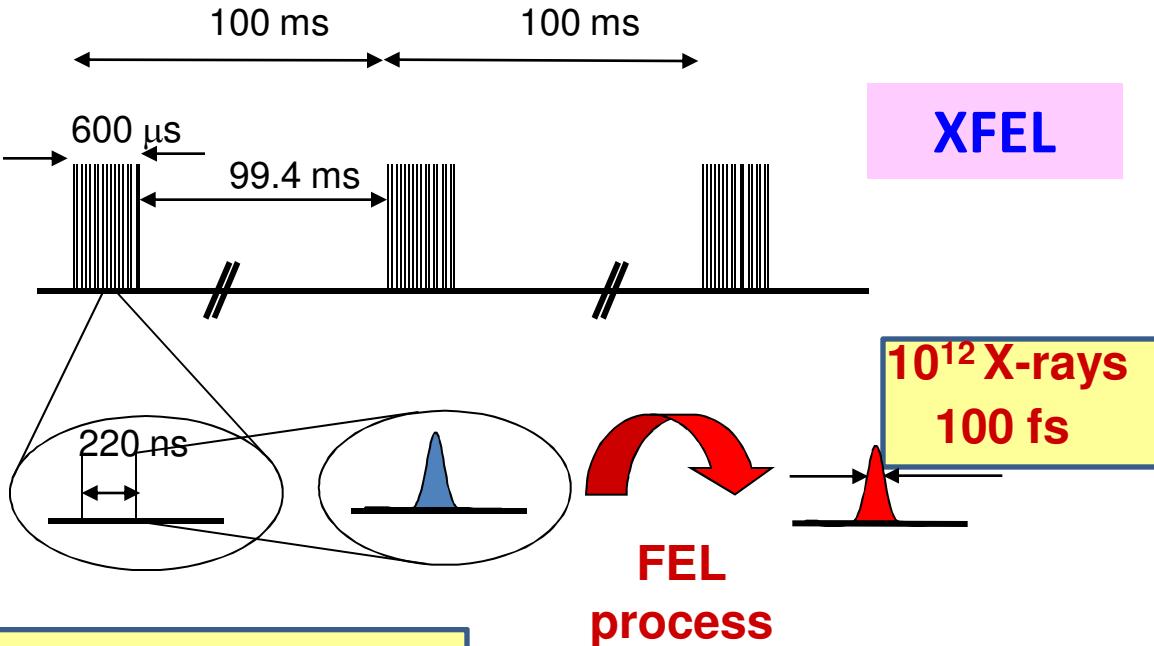


Graafsma / DESY

Light sources: Requirements and Specifications



Electron bunch trains; up to 2700 bunches in 600 μ sec, repeated 10 times per second.
→ **100 fsec X-ray pulses up to 27 000 bunches/s**



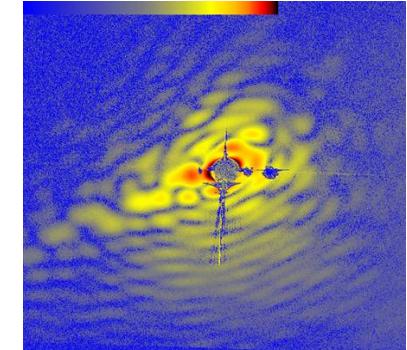
2D X-ray detector challenge

Requirements:

- 1k x 1k (4k x 4k) pixels
- “no noise”
- 10^4 ph/pixel/pulse
- Few 100 images/train
- Large dynamics

Consequences:

- Integration detectors
- Low noise
- In-pixel frame storage
- Multiple gains or
- Non-linear gain



Graafsma / DESY

LIGHT SOURCES – Detector examples

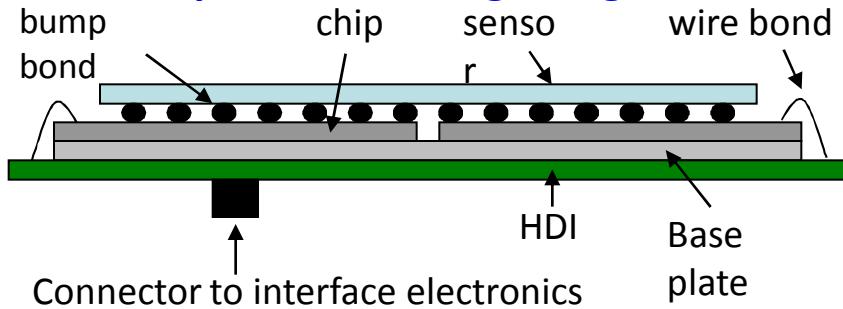
DSSC – DEPMOS with Signal Compression (MPI-HLL)

- **DEPFET /pixel**, small-area drift diodes
- **200 μm pitch**
- Very low noise (good for soft X-rays)
- non linear gain (good for dynamic range)
- per-pixel ADC
- digital storage pipeline

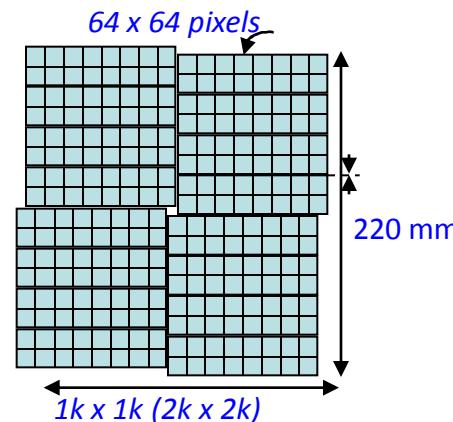


Graafsma / DESY

AGIPD - Adaptive Gain Integrating Pixel Detector (DESY)

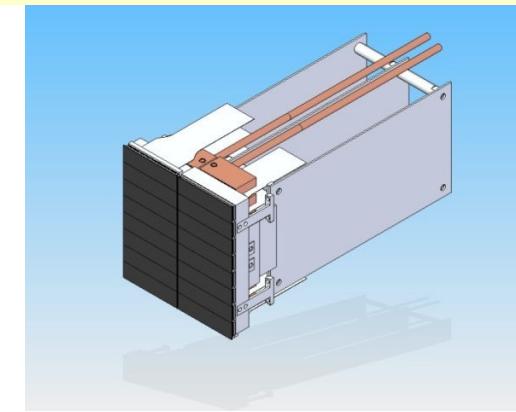


- **200 $\mu\text{m} \times 200 \mu\text{m}$ pixels**
- Up to 5 MHz framing speed
- Single-photon sensitivity at 12keV
- 2×10^4 dynamic range - 3 switched gains
- >200 images storage depth
- 128 x 256 monolithic tiles
- Flat detector



LPD – Large Pixel Detector (STFC - RAL)

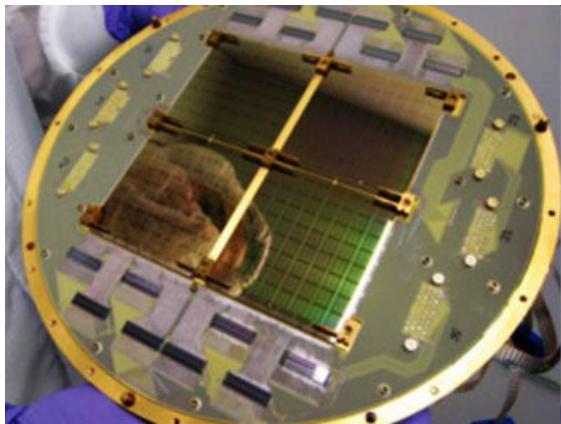
- Hybrid pixel technology
- **500 $\mu\text{m} \times 500 \mu\text{m}$ pixels**
- 10^5 dynamic range - 3 parallel gains
- 512 images storage depth
- analogue storage cells



See also **Bergamaschi VCI10' GOTTHARD** single-photon Counting, 8 μm resolution - SR

SOME SPACE TELESCOPE DETECTORS

Transition Edge Sensors Bolometers MW



BICEP2 focal plane with **512** polarization-sensitive antenna-coupled bolometers (credit: JPL)
Advanced SQUIDs

In one year
Fermi identified
almost **10 times**
more pulsars
than EGRET (in
10 years)

HgCdTe Large IR Arrays

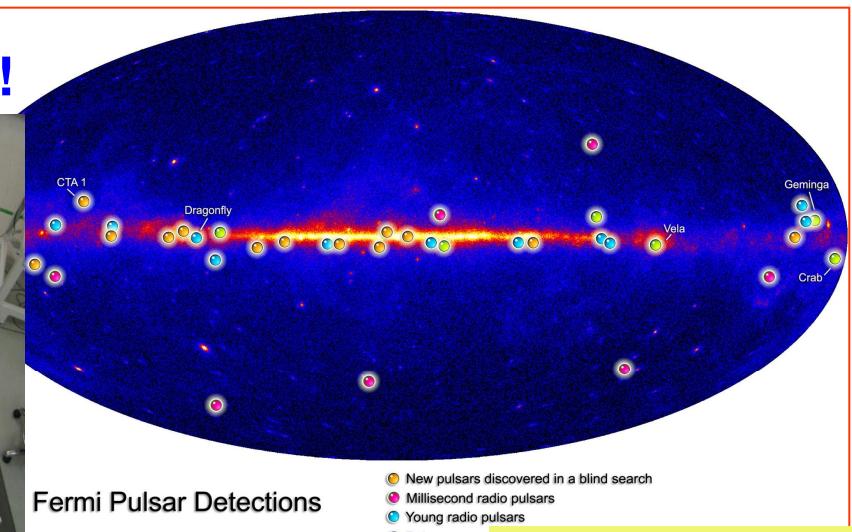
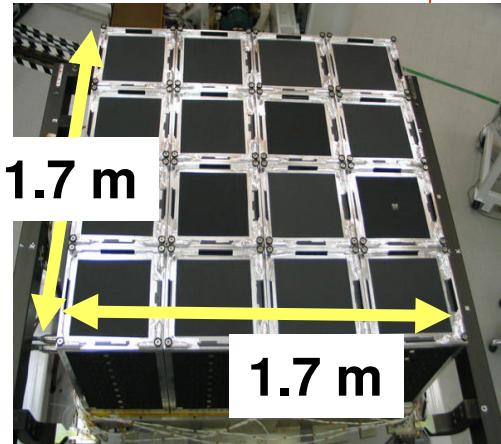


Hawaii 4RG
(Teledyne)

4096 x 4096
10 or 15 μm pitch

Fermi (GLAST) Large Area Telescope: γ Ray Pulsars

80m²Si microstrips!



Fermi Pulsar Detections

- New pulsars discovered in a blind search
- Millisecond radio pulsars
- Young radio pulsars
- Pulsars seen

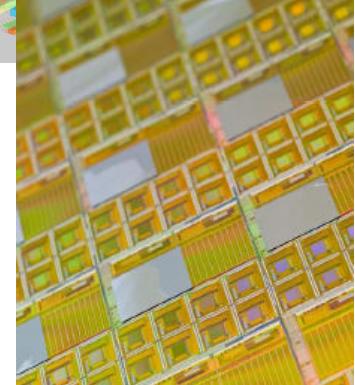
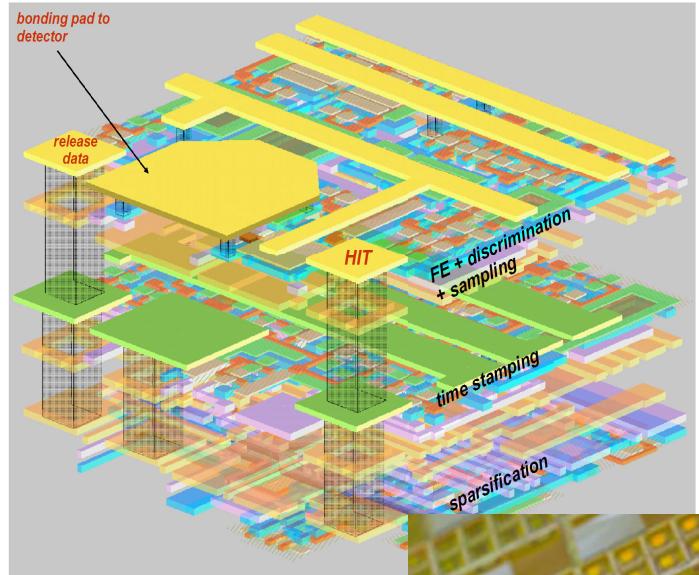
do Couto e Silva

Monolithic Vertically Integrated Pixel Sensors

- Technology is entirely industry-driven
- Vertical integration by
 - Via formation
 - Bonding
 - Thinning
- Process optimization of each layer

22 μm

VIP1: demonstrator chip for ILC Vertex



VIPS Facilitation Group

Initiative of CERN / KEK / FERMILAB

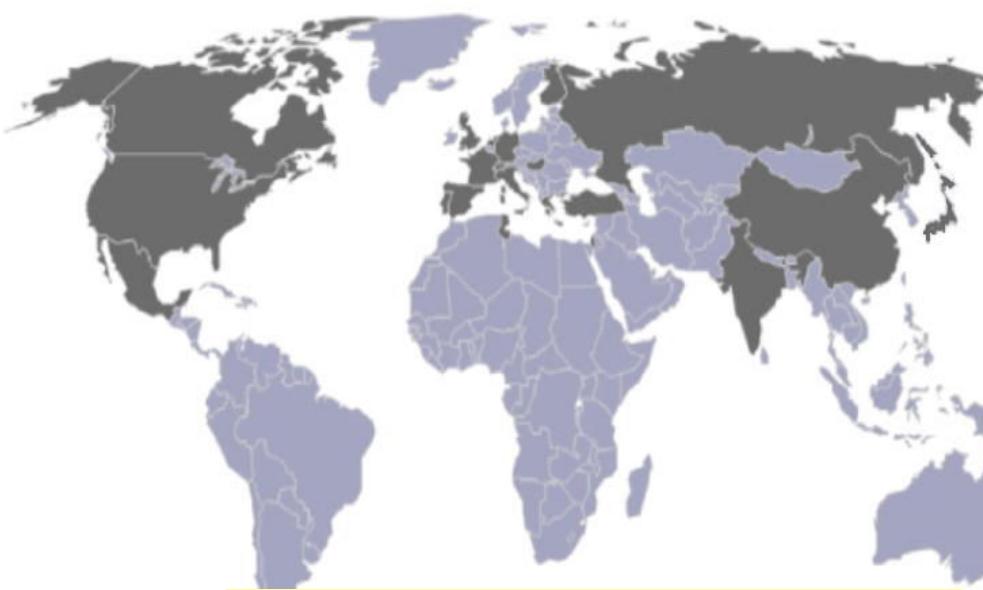
Goals :

- Understanding needs of HEP community
- Investigating needs of other communities
- Foster collaboration across different pixel R&D groups, to facilitate contacts and networking.

64 x 64 pixel array
of 20x20 μm

Gaseous Detectors

RD 51 : Development of Micro-Pattern Gas Detectors: Concepts & Technologies



**~70 institutes worldwide
~ 400 researchers**

RD51 aims at facilitating the development of advanced gaseous-avalanche detectors Concepts, technologies, electronics, simulations*

for basic and applied research

Co-Spokespersons: L. Ropelewski, M. Titov

CB Chair and Deputy: S. Dalla Torre, A. White

Management Board members: A. Breskin, I. Giomataris, F. Sauli, H. Taureg,

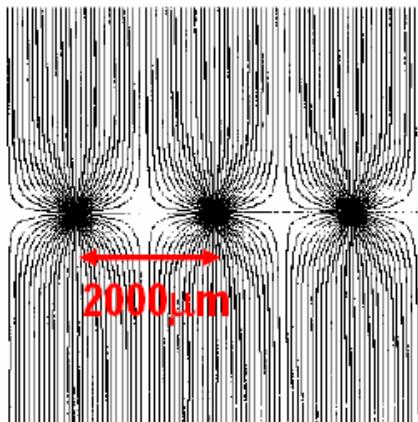
H. van der Graaf, P. Colas

**•Veenhof VCI10'
•Bhattacharya VCI10'**

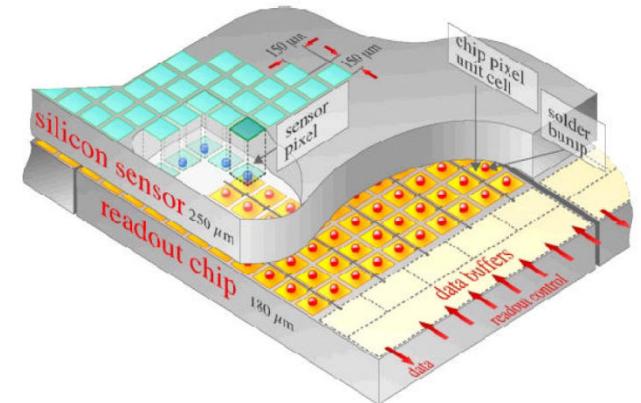
Public Web Site: <http://rd51-public.web.cern.ch/RD51-Public>

Closing the Gap between Gas and Silicon Detectors

MWPC

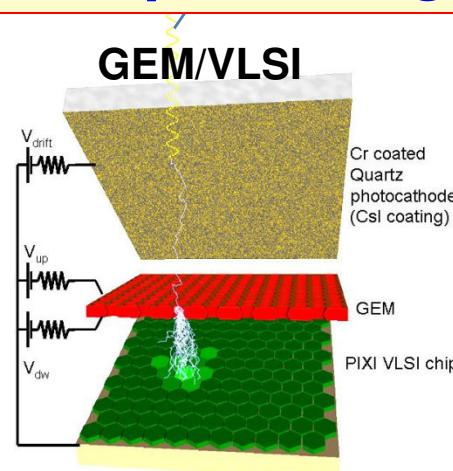


Novel Si-Pixels



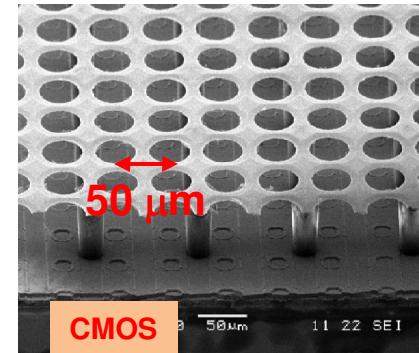
“micropattern” gaseous detectors

GEM/VLSI



Bellazzini 2002

Micromegas/CMOS



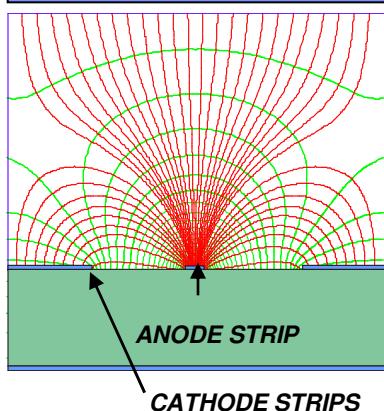
Van der Graaf 2008

MICRO-PATTERN GAS DETECTORS

A. Oed 1988

MICRO-STRIP CHAMBER MSGC

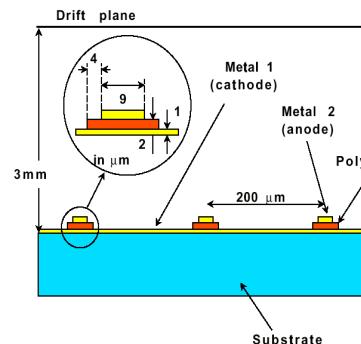
DRIFT ELECTRODE



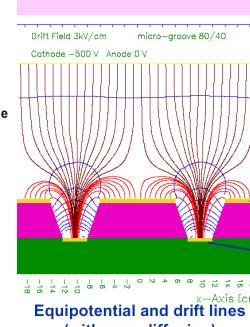
Drift + thin multiplication-strips
on insulator

Short anode-cathode Distance:
•Fast avalanche
•High-resolution
•Fast ion removal → high rates:

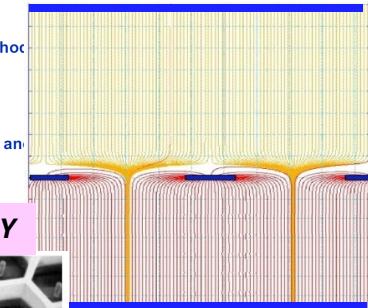
MICRO-GAP



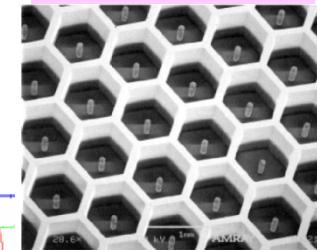
MICRO-GROOVE



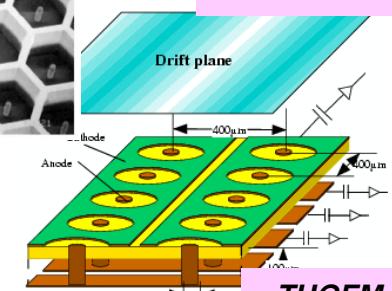
MICROMEGAS



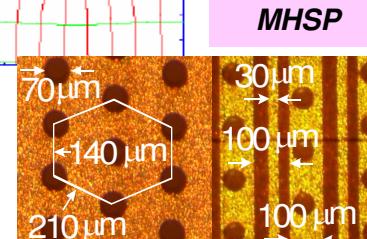
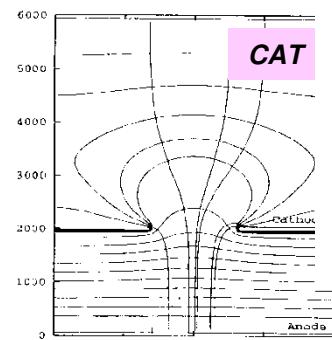
MICRO-PIN ARRAY



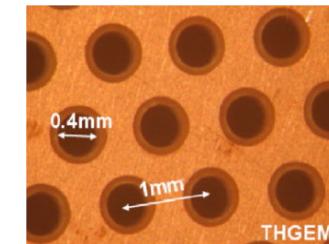
MICRO-PIXEL



CAT



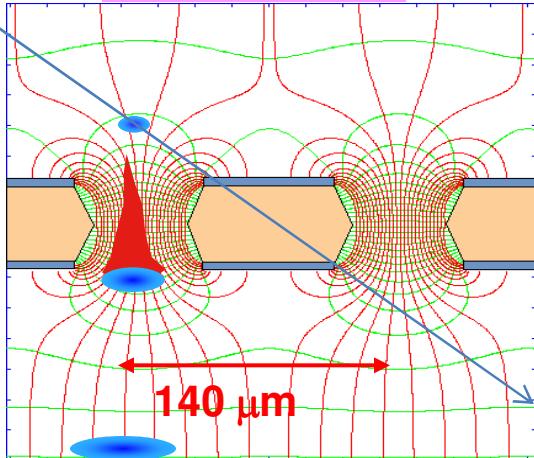
THGEM



MICRO-PATTERN GAS DETECTORS: MAIN PLAYERS

GAS ELECTRON MULTIPLIER (GEM)

Sauli 1997

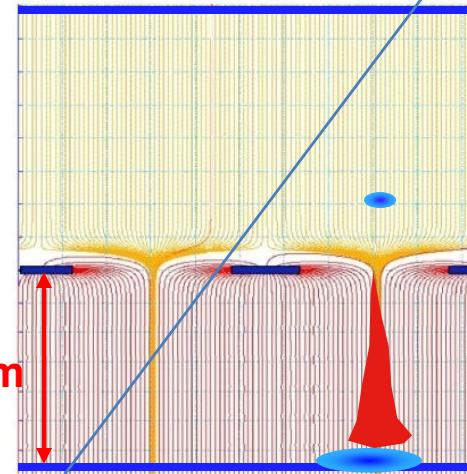


Thin, metal-coated polymer foil
+ high density of **60 μm holes**.
Each hole:
individual proportional counter

MICROMEGAS

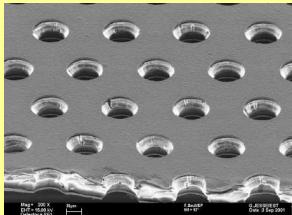
Giomataris 1998

<100 μm



Drift + micromesh
+ thin multiplication-gap
+ readout electrode

HOLE MULTIPLIERS → confined avalanche

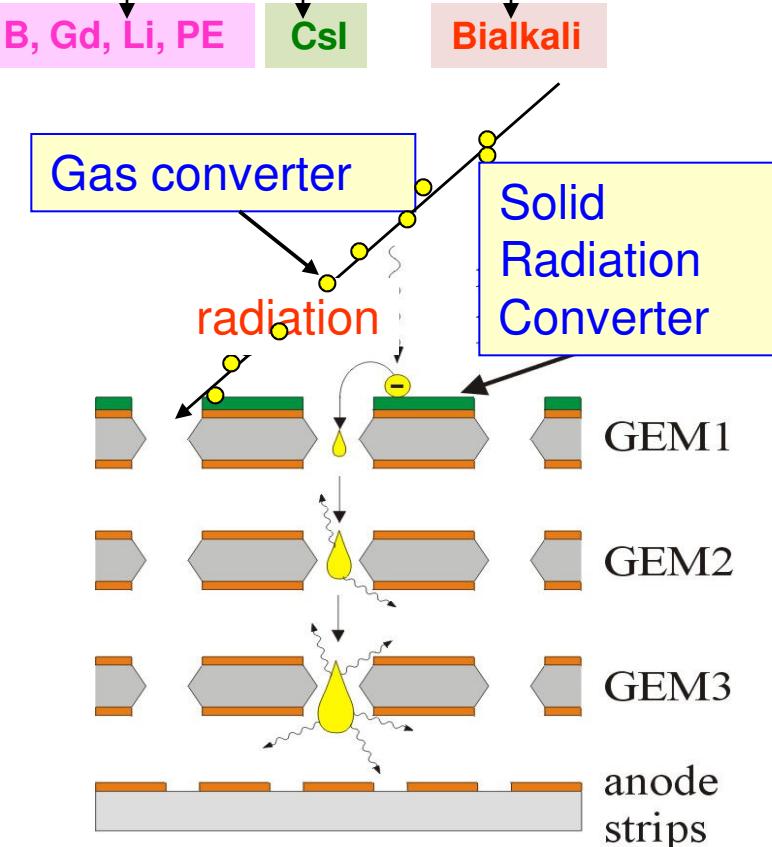


- Fewer secondary effects
- Multi-elements can be cascaded
- High gain also in noble gases
- Significantly **less** discharges
in presence of highly ionizing events

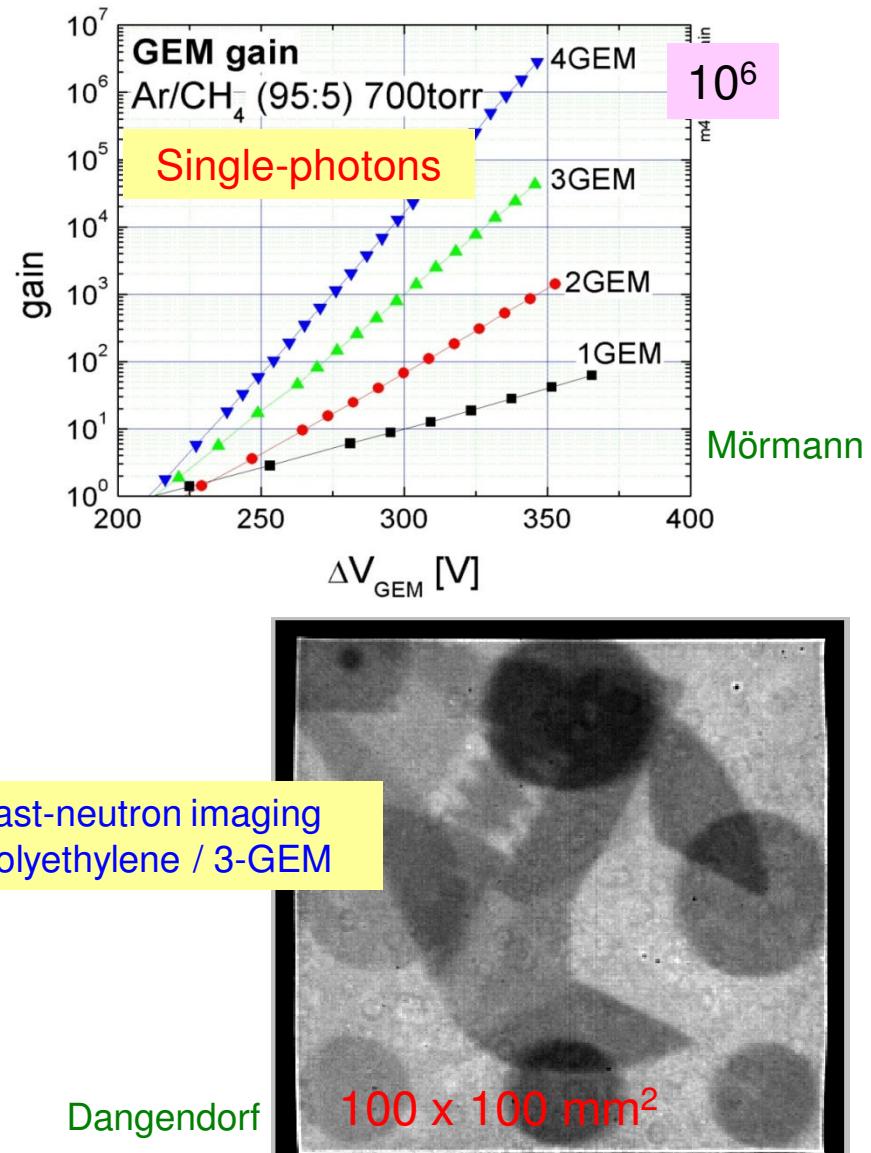
- Better ion blocking
- Better E-resolution
- No segmentation
- Discharges

cascaded-GEM detectors

Particle tracking, x-ray, thermal neutrons → gaseous radiation converter
neutrons, UV and visible photons → solid converters

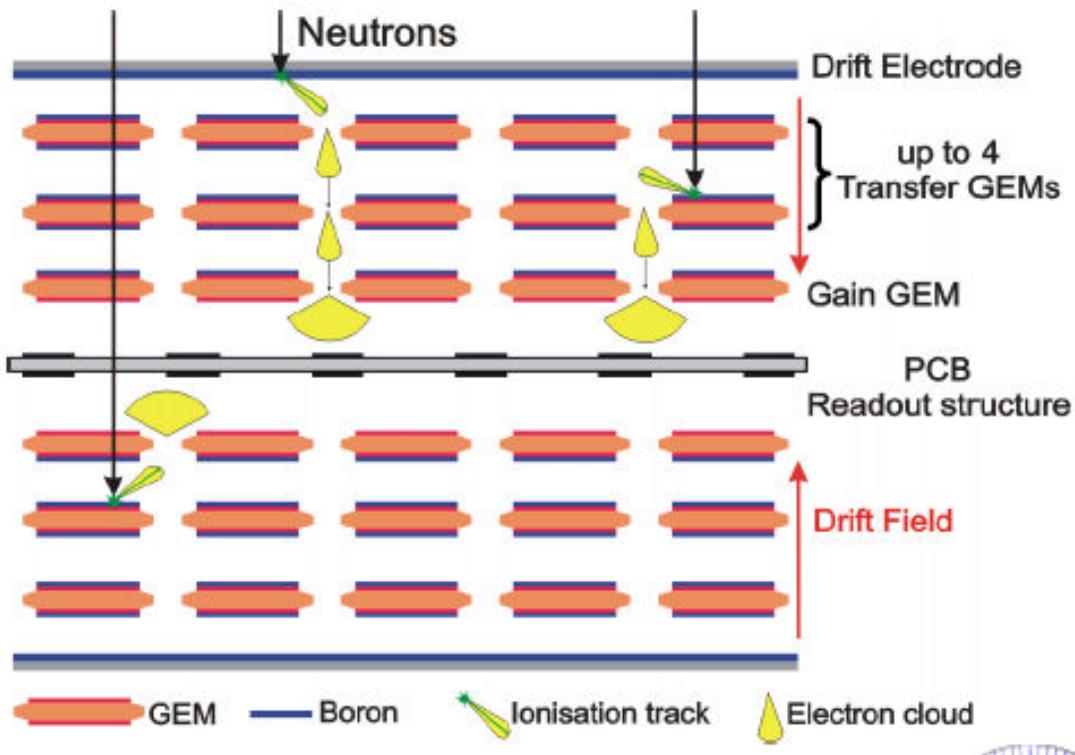


high gain and stability
→ single-electron sensitivity!



CASCADE: cascaded thermal-n detector

Klein VCI10'

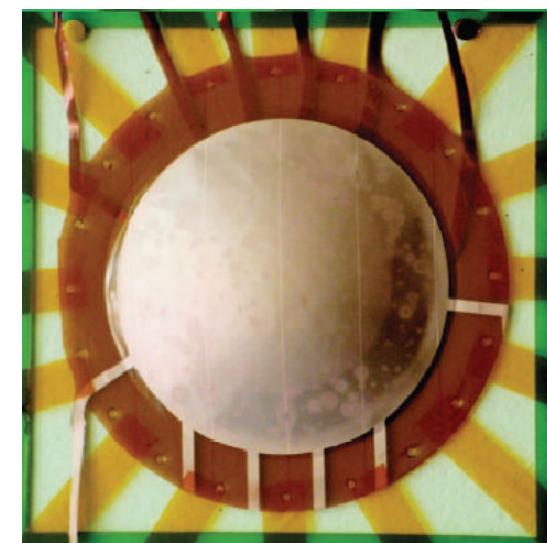
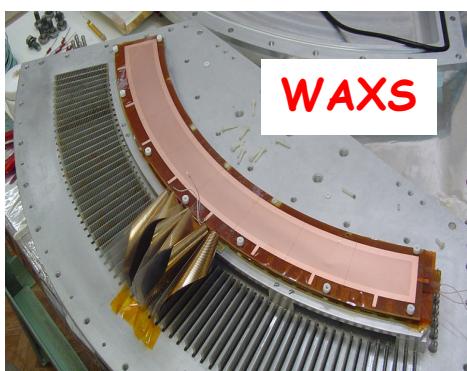
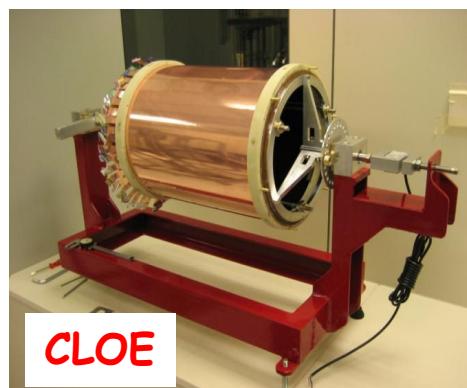
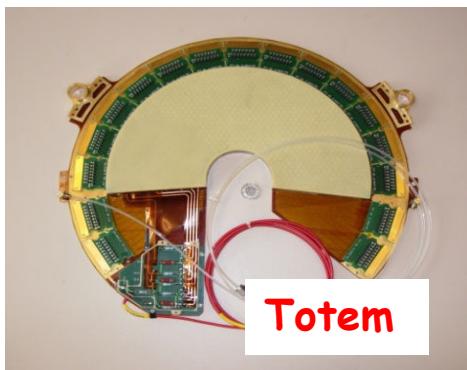
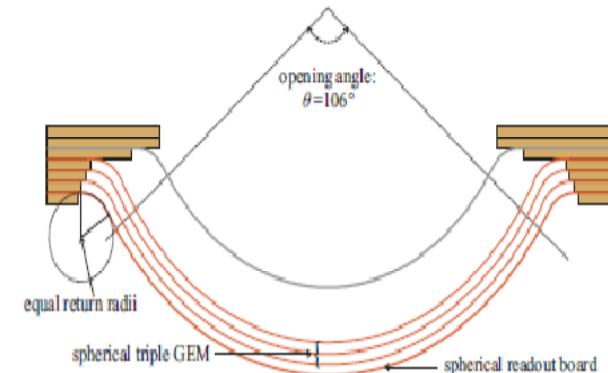
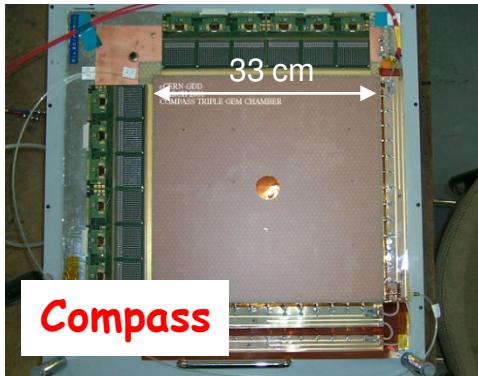


Fast electronics!

CIPix: 64 ch preamp/discriminator

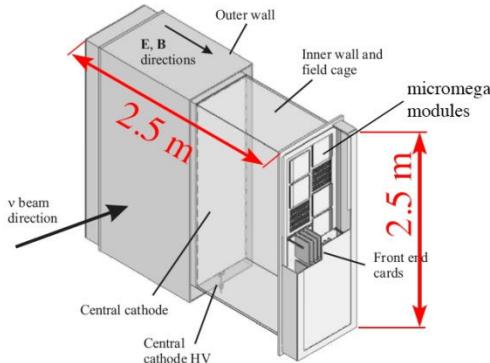
FPGA based readout

CASCADED GEMs

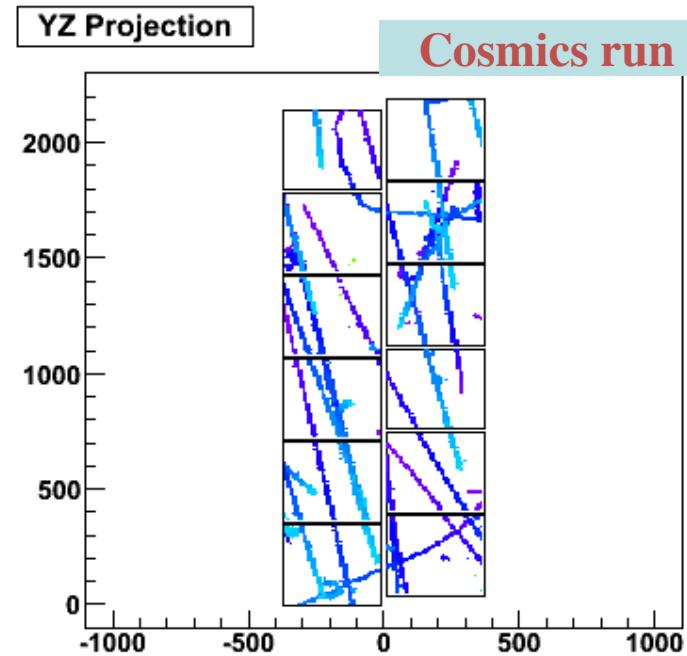
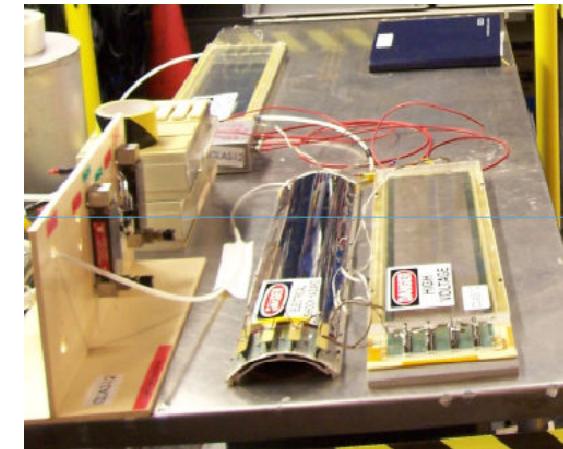


Spherical 3-GEM
X-ray diffraction

MICROMEGAS

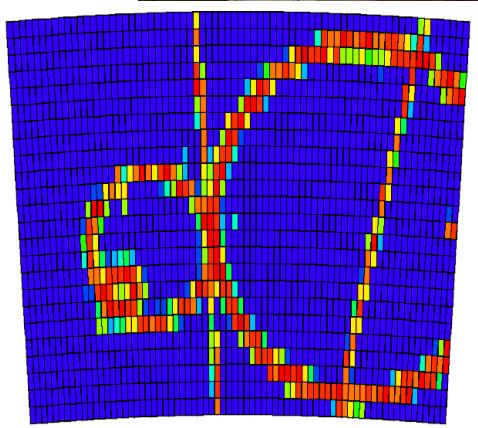
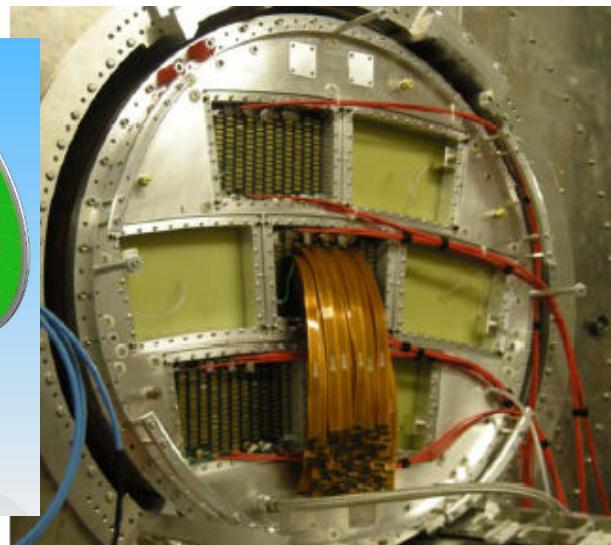
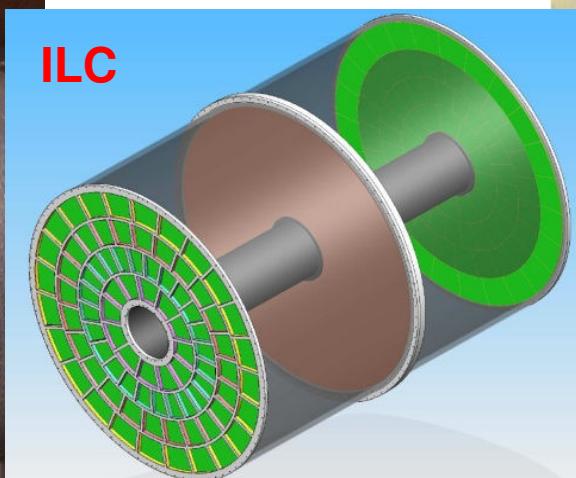
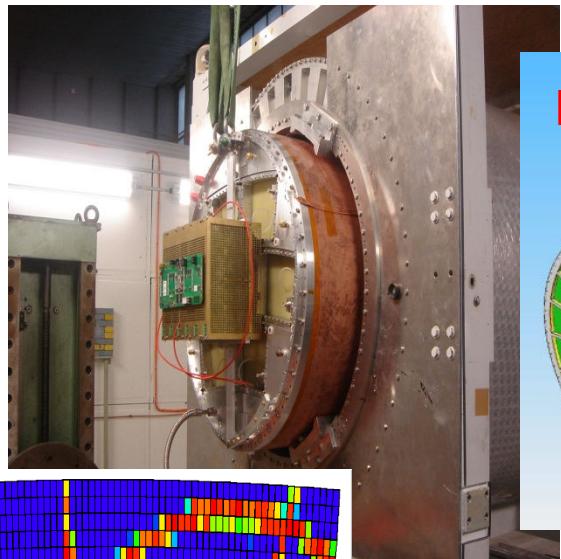


**Efforts made to reduce discharges:
Resistive mesh, segmentation,
resistive anodes...**



Curved Micromegas

R&D:
sLHC ATLAS - muons
ILC – Digital Hadron CAL
double beta decay
n-TOF
CAST...



ILC goal: 100 μm RMS

Beam tests at DESY: (EUDET project & RD51)

At B=4-5T

Both 3-GEM & Micromegas:

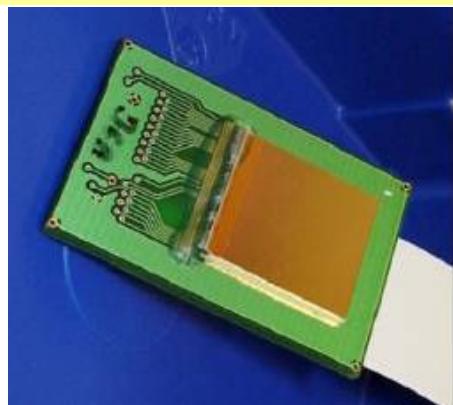
$\sigma_0 \sim 55 \mu\text{m}$

RD51

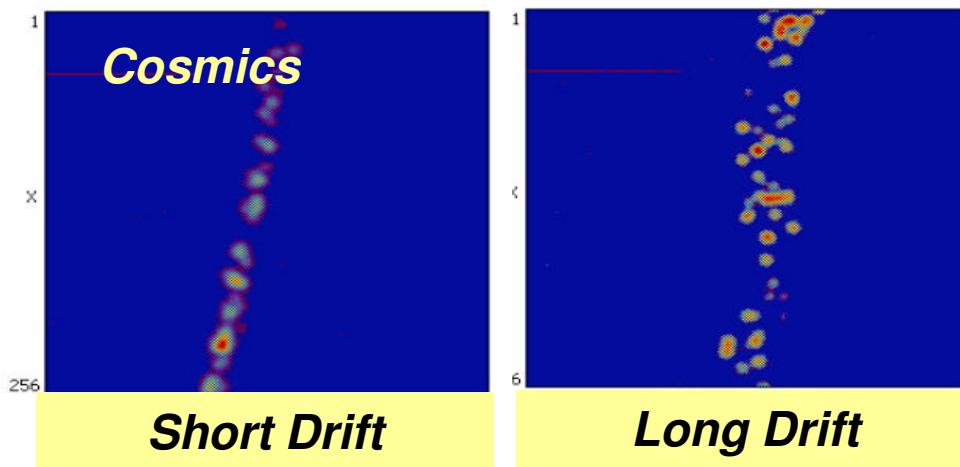
Dixit, Attie, Matsuda, De Lentdecker, 2009
Schade Vienna 2010

HYBRID-GEM TPC

TRIPLE GEM/TIMEPIX



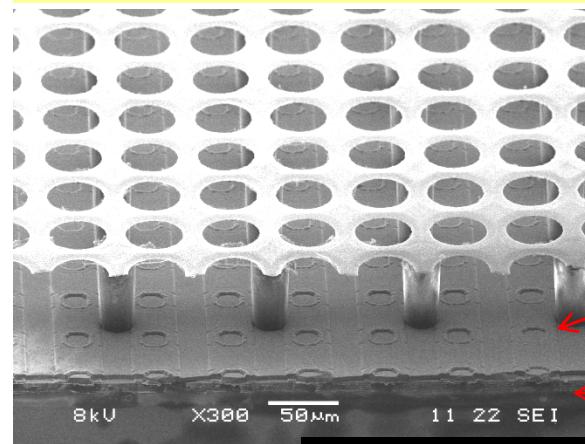
TIMEPIX Kaminski
256x256 pixels, $55 \times 55 \mu\text{m}^2$
14x14 mm 2 active area



HYBRID-MICROMEGAS : INGRID-GRIDPIX

INTEGRATED MICROMEGAS AND PIXEL SENSOR

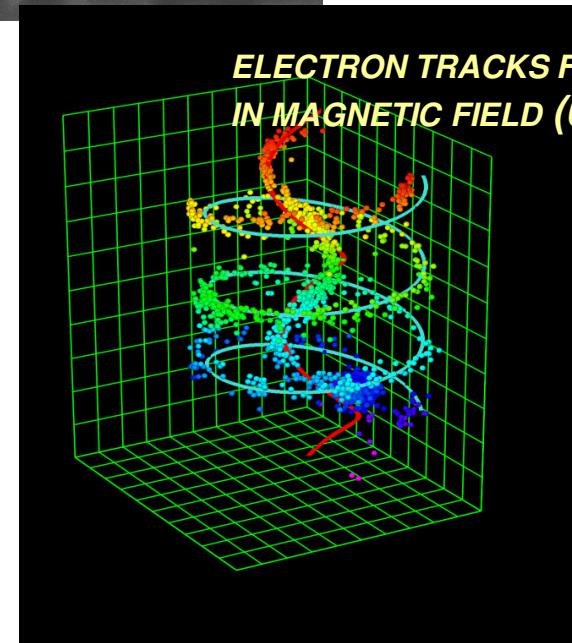
Post processing of TIMEPIX chip to form metal mesh on insulating pillars



Van der Graaf

Resistive-layer
against
spark-damage

CMOS-TIMEPIX



GOSSIP: THE ULTIMATE Gas-Hybrid?

EXPECTED HIGHLIGHTS:

Position resolution: **12 μm**

Radiation hardness: **excellent**

Material budget: **low**

Cooling: **relaxed**

Potential dangers:

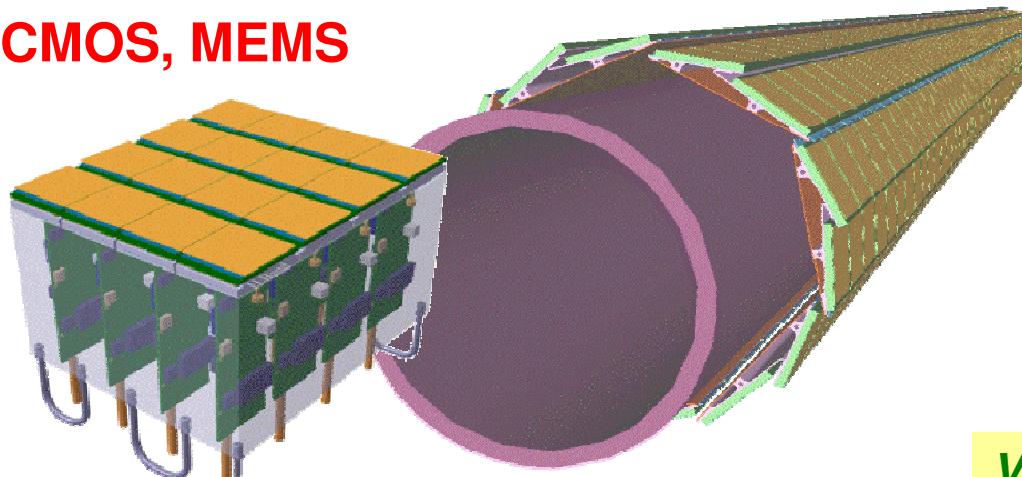
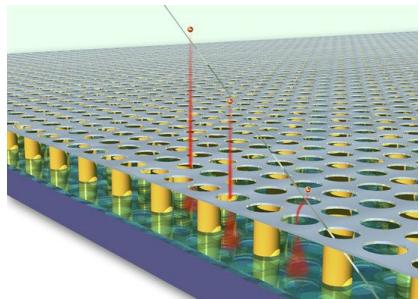
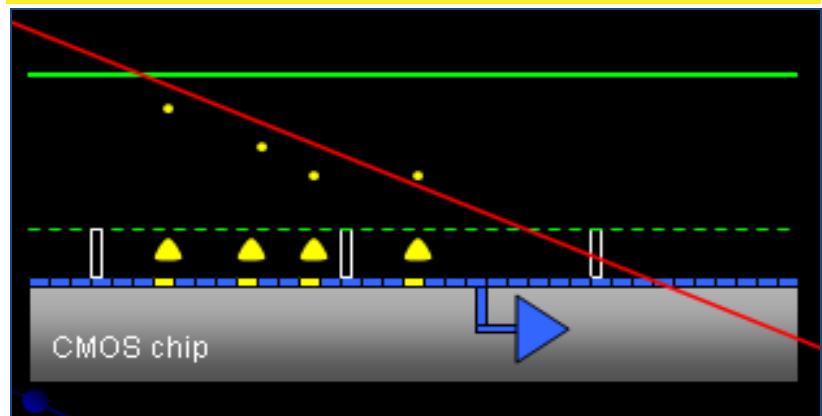
Gas detector: **aging?**

Discharge damage?

PRICE?

Simple processes: **CMOS, MEMS**

Gas On Slimmed SIlicon Pixels (GOSSIP)
Under study for **ATLAS SLHC** tracker



STOP!
MANY APPLICATIONS
DO NOT NECESSARILY NEED
 μm to tens μm
RESOLUTIONS !

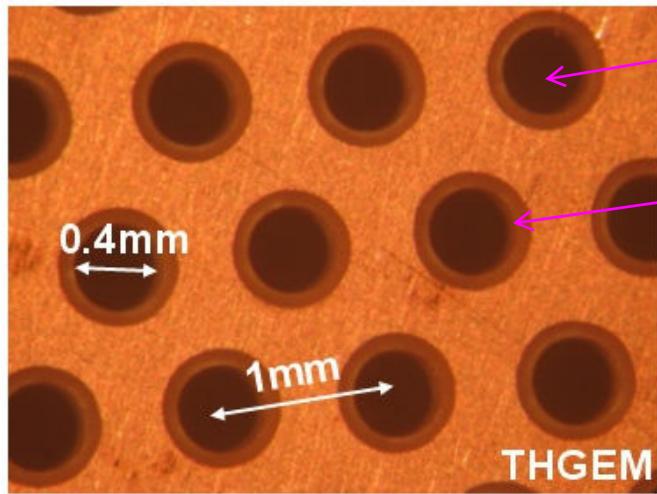
**calorimeters, RICH, external trackers,
large-volume rare-event detectors,
inspection systems...**

→ sub-mm to centimeters!

Thick Gas Electron Multiplier (THGEM)

~ 10-fold expanded GEM

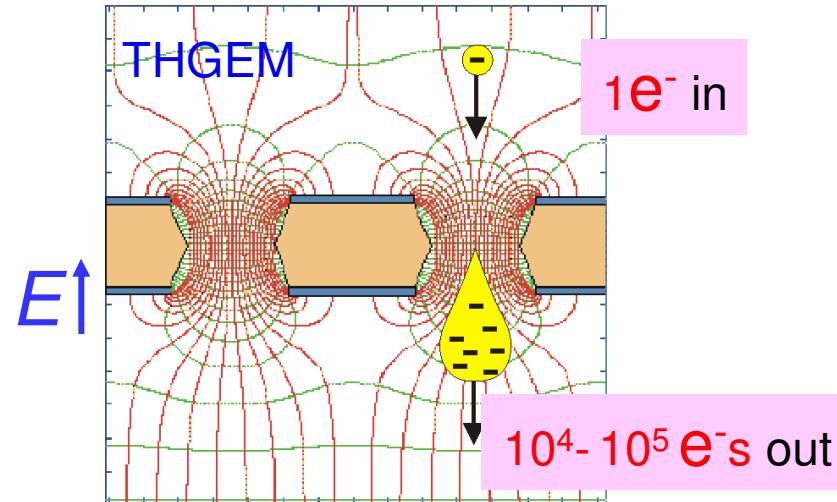
Chechik VIENNA 2004



Thickness 0.5-1mm

**SIMPLE, ROBUST, LARGE-AREA
Printed-circuit technology**

- Intensive R&D
- Many applications

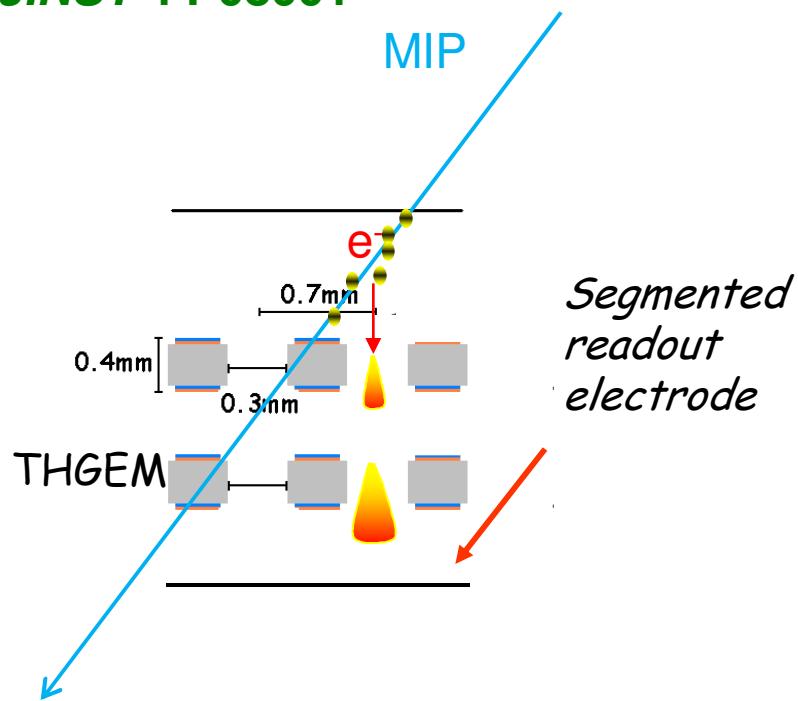


Double-THGEM: 10-100 higher gains

- Robust, if discharge no damage
- Effective single-electron detection
- Few-ns RMS time resolution
- Sub-mm position resolution
- >MHz/mm² rate capability
- Cryogenic operation: OK
- Broad pressure range: 1mbar - few bar

Gain: Single-THGEM in Ne-mixtures

2009 JINST 4 P08001

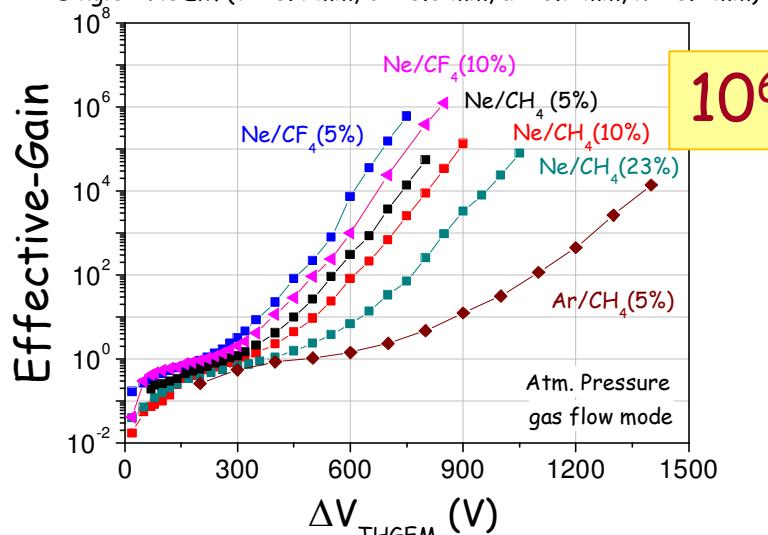


- High gain in Ne mixtures
- Operates in noble gases
- **2-THGEM: higher gains/lower HV**
- Large dynamic range

Soft x-rays: 2-THGEM Ne/5%: Gain $5 \cdot 10^5$ @ ~600V

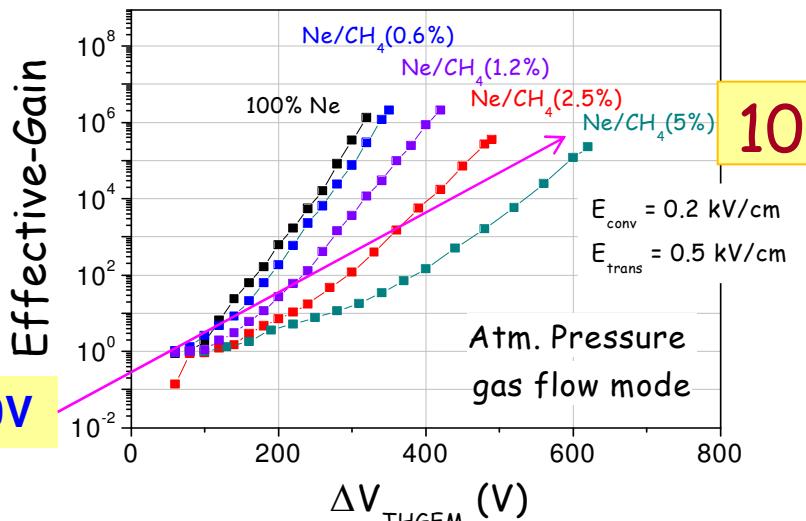
Single-THGEM / CsI PC / single UV-photons

Single THGEM ($t = 0.4 \text{ mm}$, $d = 0.3 \text{ mm}$, $a = 0.7 \text{ mm}$, $h = 0.1 \text{ mm}$)



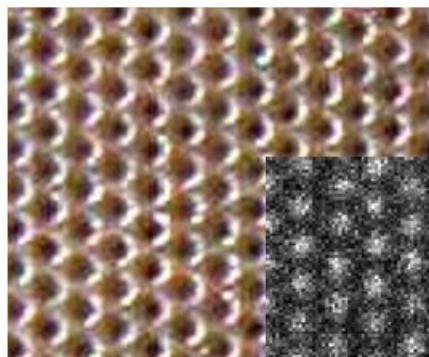
Double-THGEM / 9 keV X-rays

Double THGEM ($t = 0.4 \text{ mm}$, $d = 0.5 \text{ mm}$, $a = 1 \text{ mm}$, $h = 0.1 \text{ mm}$)

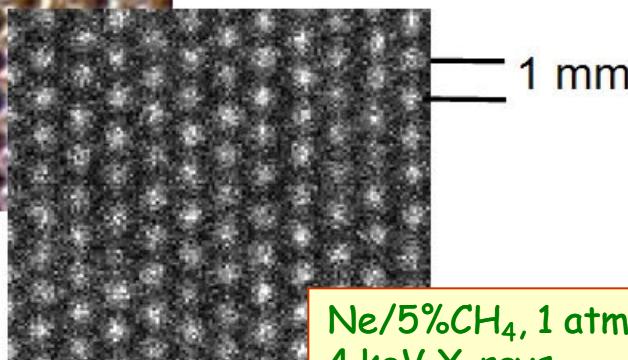


THGEM: 2D imaging results with soft X-rays

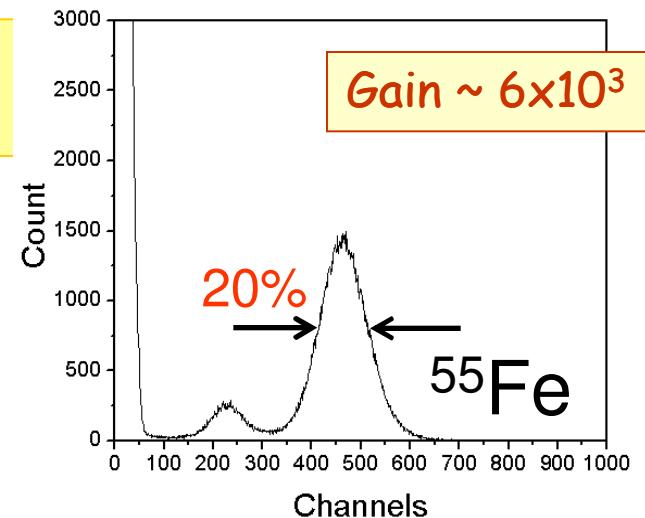
100x100 mm² double-THGEM



Gain uniformity
± 10%



Ne/5%CH₄, 1 atm
4 keV X-rays



Spatial Resolution (FWHM)

- | | |
|----------------------|----------------------------|
| Ar/5%CH ₄ | → 0.7 mm with 9 keV X-rays |
| Ne | → 1.4 mm with 9 keV X-rays |
| Ne/5%CH ₄ | → 0.3 mm with 4 keV X-rays |

THGEM: ONGOING APPLICATIONS:

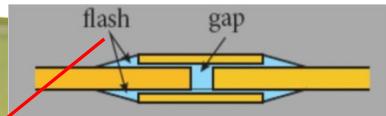
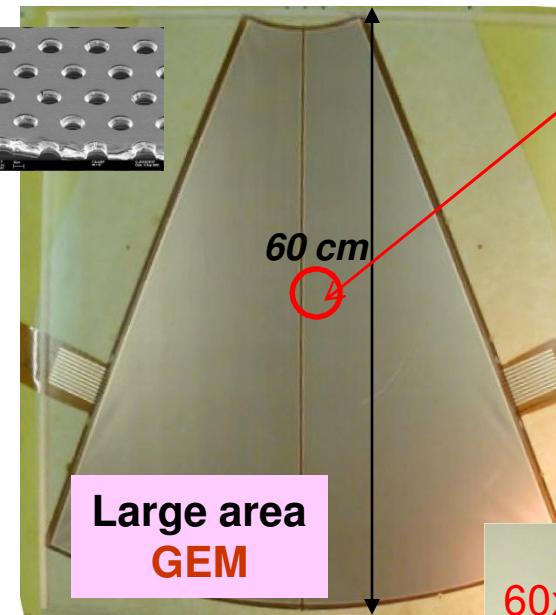
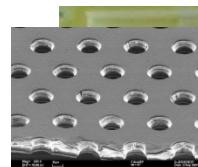
- UV detectors for RICH (COMPASS, sALICE)
- Fast-n imaging
- Cryo Gas-Photomultipliers for Noble-Liquid Scintillation and 2-phase detectors
- Sampling elements in Digital Hadron Calorimetry (DHCAL)
(competes with GEM, micromegas, RPC...)

RD51: Large gaseous multipliers

300x300mm² THGEM

90,000 0.5mm diameter holes
(Print Electronics, IL)

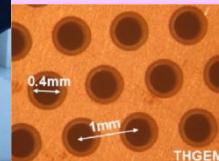
WEIZMANN



LARGE TOYS BY
RUI de OLIVEIRA!



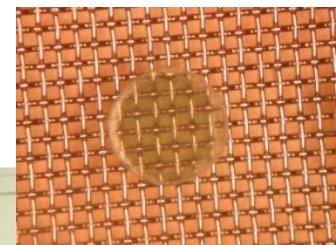
THGEM by industry:
square-meters possible



TRIESTE

600x600mm² THGEM

600,000 0.4mm diameter holes
(Eltos, IT)



60x150 cm



Large-area
BULK Micromegas

Other gas detectors:

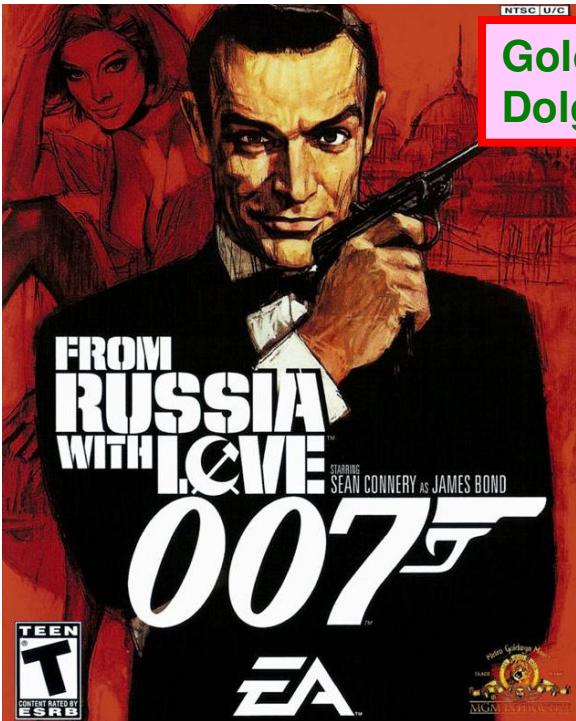
Naumann/FAIR: High-rate (500KHz/cm²) **CERAMIC RPCs**

Kiefer/CALICE: Large area (SQ m) GRPCs for ILC DHCAL

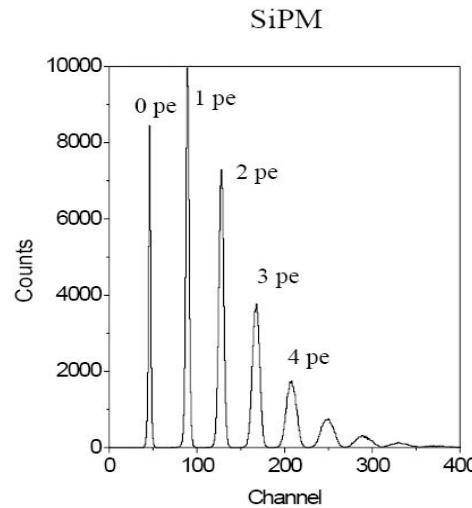
Photon detectors

Geiger-mode Avalanche Photodiodes

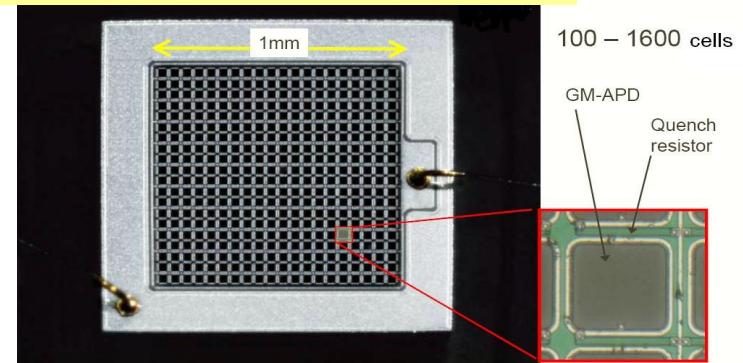
MRS APD, MAPD, SiPM, MPPC, SSPM, SPM, DAPD, PPD ...



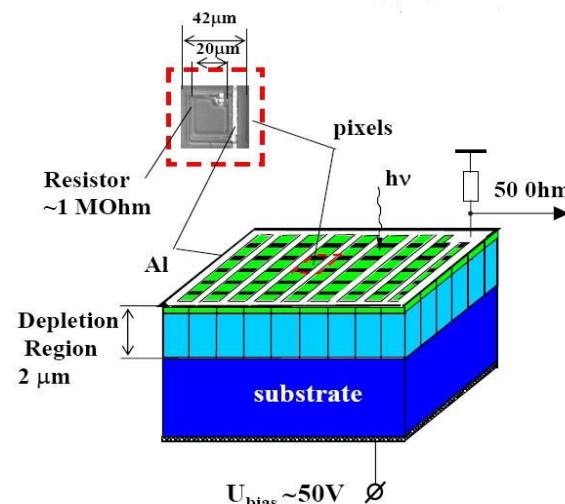
Golovin, Sadygov,
Dolgoshin...



MANY PRODUCERS!



APD –like, operated in Geiger mode;
subdivided into many cells connected via
limiting (quenching) resistors



- Gain: 10^5 - 10^7 → Single-photon sensitivity
- Quick recovery time
- Fast
- Output \propto number of fired cells (up to $40,000/\text{mm}^2$)
- PDE: QE \times geometrical factor 40-60% (peak)
- BUT: high dark current, cross talk, non-linearity...high cost!

G-APD: Where do we stand?

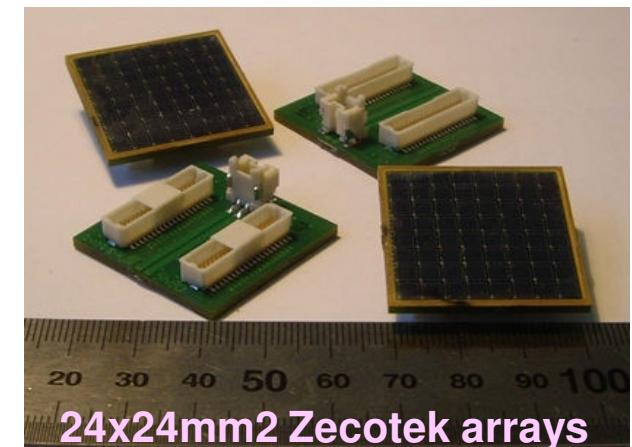
REVIEW: Renker & Lorenz
2009 *JINST* 4 P04004

Significant progress over the last 2-3 years:

- High PDE of 30-40% for blue-green light (CPTA/Photonique, Hamamatsu, Zecotek)
- Reduction of dark count at room temperature to 300 kHz/mm² (Hamamatsu, Zecotek)
- Low cross-talk <1-3% (CPTA/Photonique, MEPhI, STMicroelectronics)
- Low temperature coefficient of ~0.3%/C (CPTA/Photonique)
- Fast timing ~50 ps (RMS) for single photons (all)
- Large dynamic range with 15 000 – 40 000 pixels/mm² (Zecotek)
- “Large area” of 3x3 mm² (CPTA/Photonique, Hamamatsu, FBK, SensL, Zecotek, STMicroelectronics...) → reasonable arrays!
- High cost/area

Future

- PDE >50-60% @ 350-650 nm
- dark count rate <100 kHz/mm² at room temperature
- optical crosstalk <1%
- active area >100mm²
- high DUV sensitivity (PDE @ 128 nm ~20-40%)
- G-APD arrays: 6x6, 8x8 ...
- very fast position sensitive devices (**MAPS operated in Geiger mode**)
- radiation hard G-APDs -up to 10¹⁴ ÷ 10¹⁵ n/cm² (new materials: diamond?, GaAs?, SiC?, GaN ...)
- Digital sensors...
- Goal for cost ~1 \$/mm²



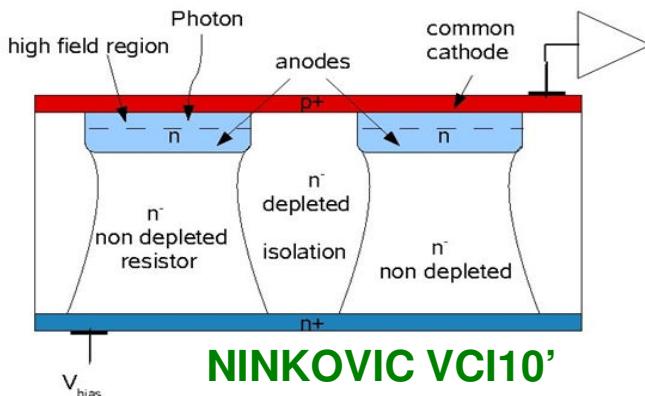
Applications:

Calorimetry, RICH, telescopes, PET, SciFi, Noble Liquids

G-APD NEWS

SiMPI: G-APD with bulk integrated quench resistors
(MPI-HLL Munich)

Geometric factor 0.75, **PDE 60%**

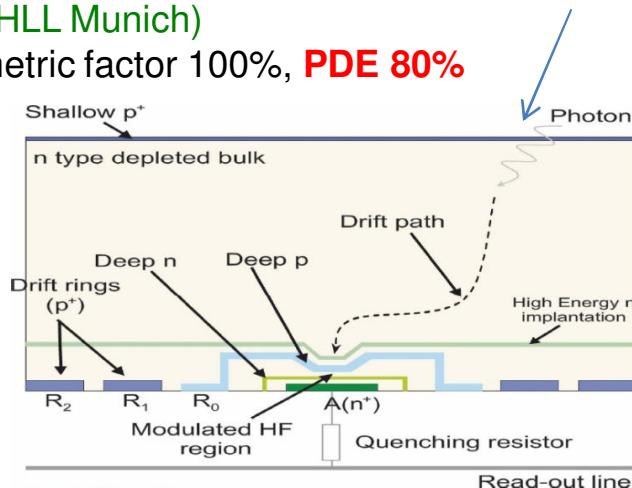


BID-SiPM: Back illuminated G-APD

Combination of drift diode & SiPM

(MPI-HLL Munich)

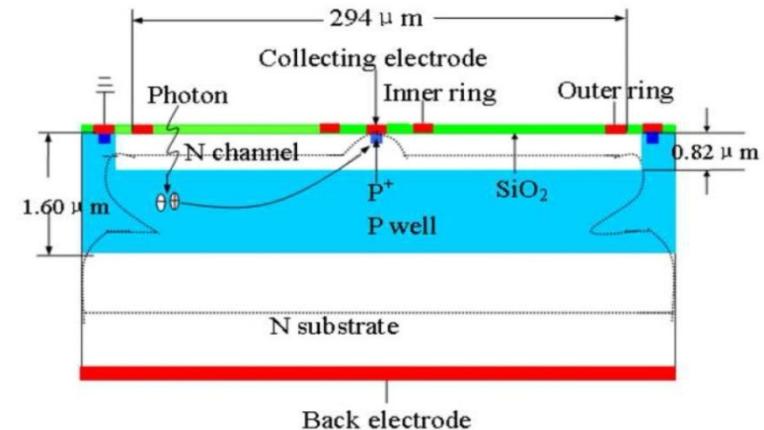
Geometric factor 100%, **PDE 80%**



Front illuminated G-APD (Wu, Beijing)

combination of drift diode and G-APD

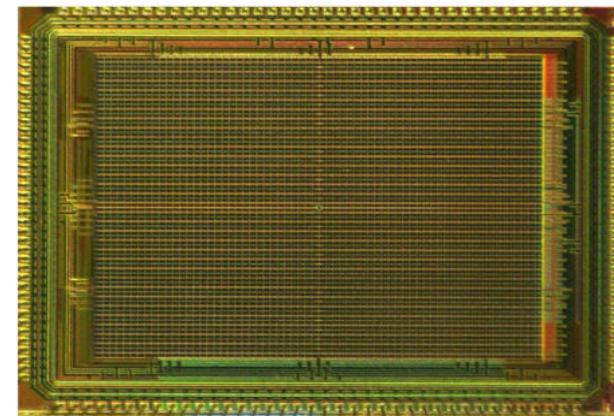
Small capacitance of multiplier; simple CMOS



Digital SiPM (Philips; IEEE 2009)

4x2047 pixels of $30 \times 52 \mu\text{m}$; fill factor 50%

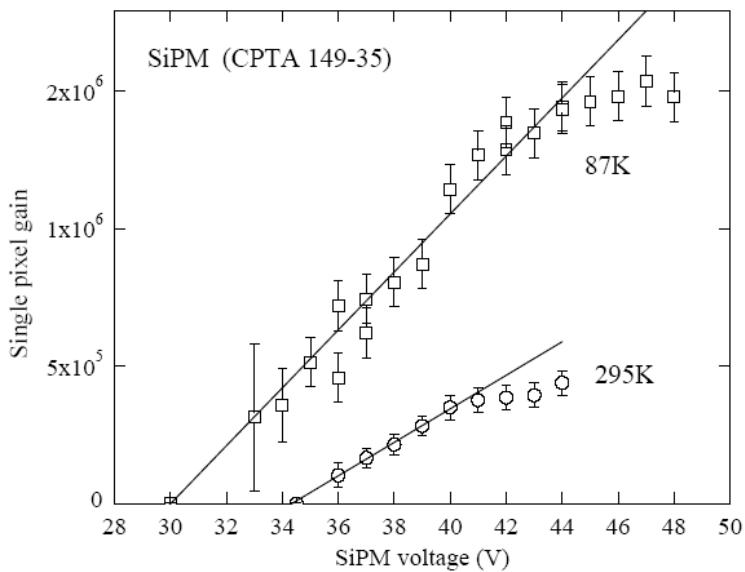
TDC **8ps** resolution, FPGA...



SiPM at cryogenic temperatures

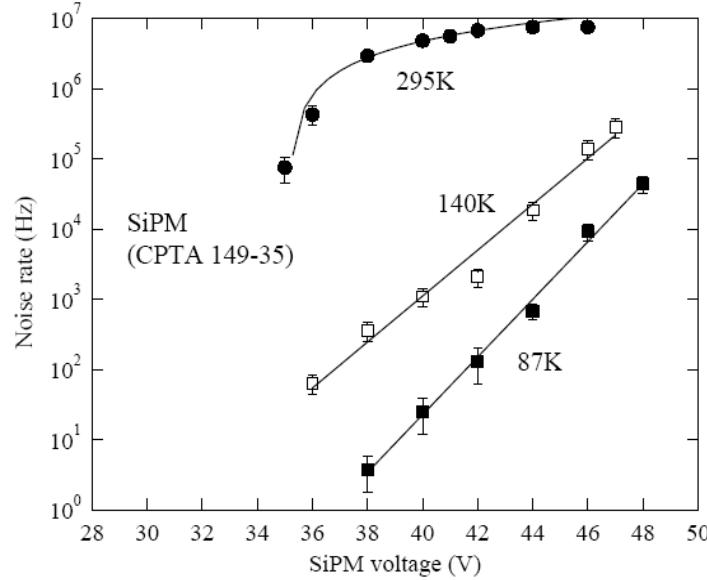
Buzulutskov VCI10'

X-ray-induced scintillations in Ar



Max gain @ 87K: ~4 times larger than @ RT

Noise rate



@ 87K: <1kHz ; increases exponentially with V
@ RT: >1MHz ; increases linearly with V

Potential readout of noble-liquid detectors?

See also Collazuol VCI10'

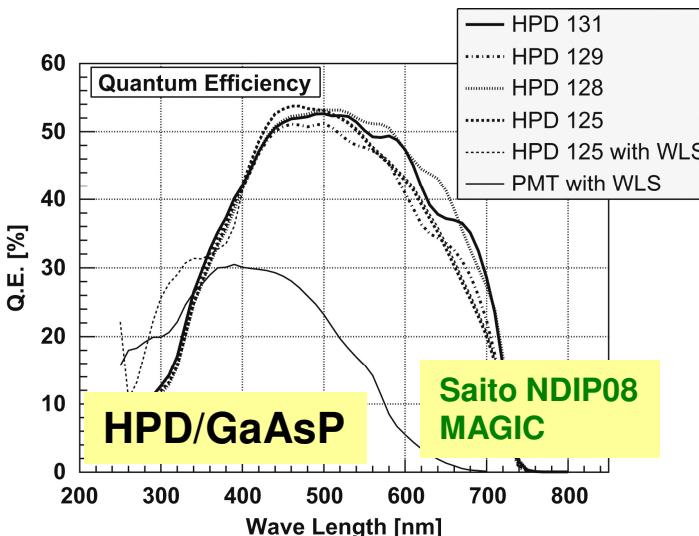
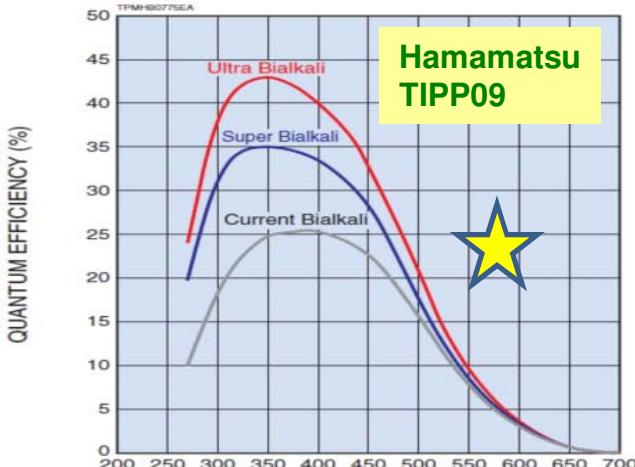
Vacuum photon detectors

High QE photocathodes (Hamamatsu)

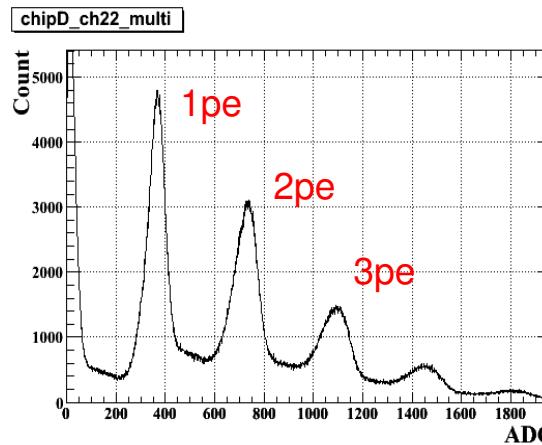
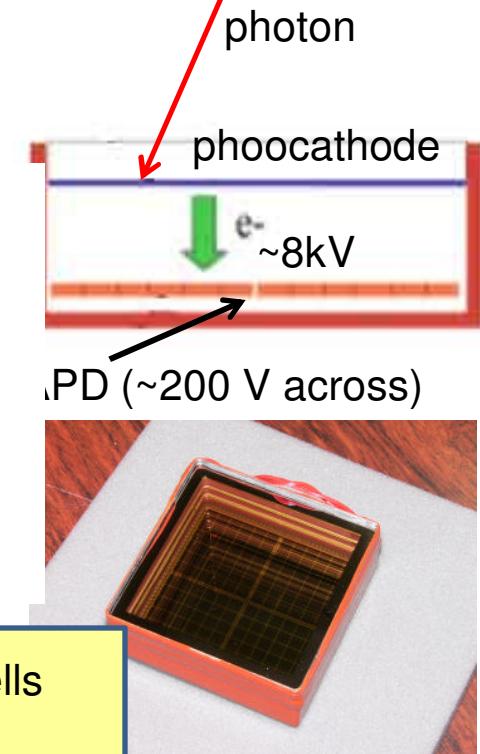
UBA (Ultra Bialkali) **QE = 43%**

SBA (Super Bialkali) QE = 35 %

(Regular Bialkali QE = 25%)



144ch HAPD for Belle-II Forward RICH Shiizuka



- $72 \times 72 \text{ mm}^2$, $5 \times 5 \text{ mm}^2$ cells
- Fill factor **67%**
- QE $\sim 30\%$
- Typical total gain $\sim 4 \times 10^4$
- Single-photon counting
→ better E-resolution than PMT
- $B \sim 1.5 \text{ T}$ OK
- Flat, compact, **SMALL**

LARGE VOLUME RARE-EVENT EXPERIMENTS

SK $\Phi 500\text{mm}$ Vac. PMT



$\sim 15,000$ PMTs



HYPER-K, LENA...> 100,000 PMTs!

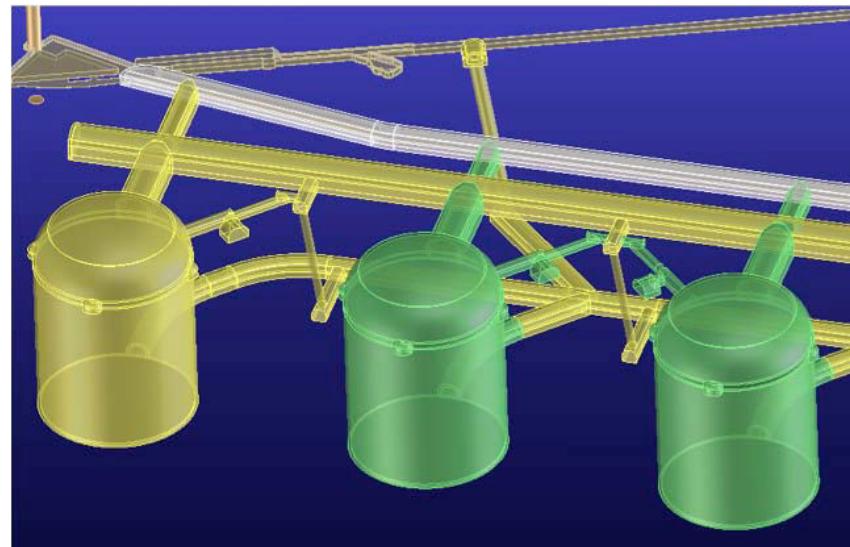


Super-K

**ALL PRODUCERS OF LARGE PMTs
(except Hamamatsu)
VANISHED!**

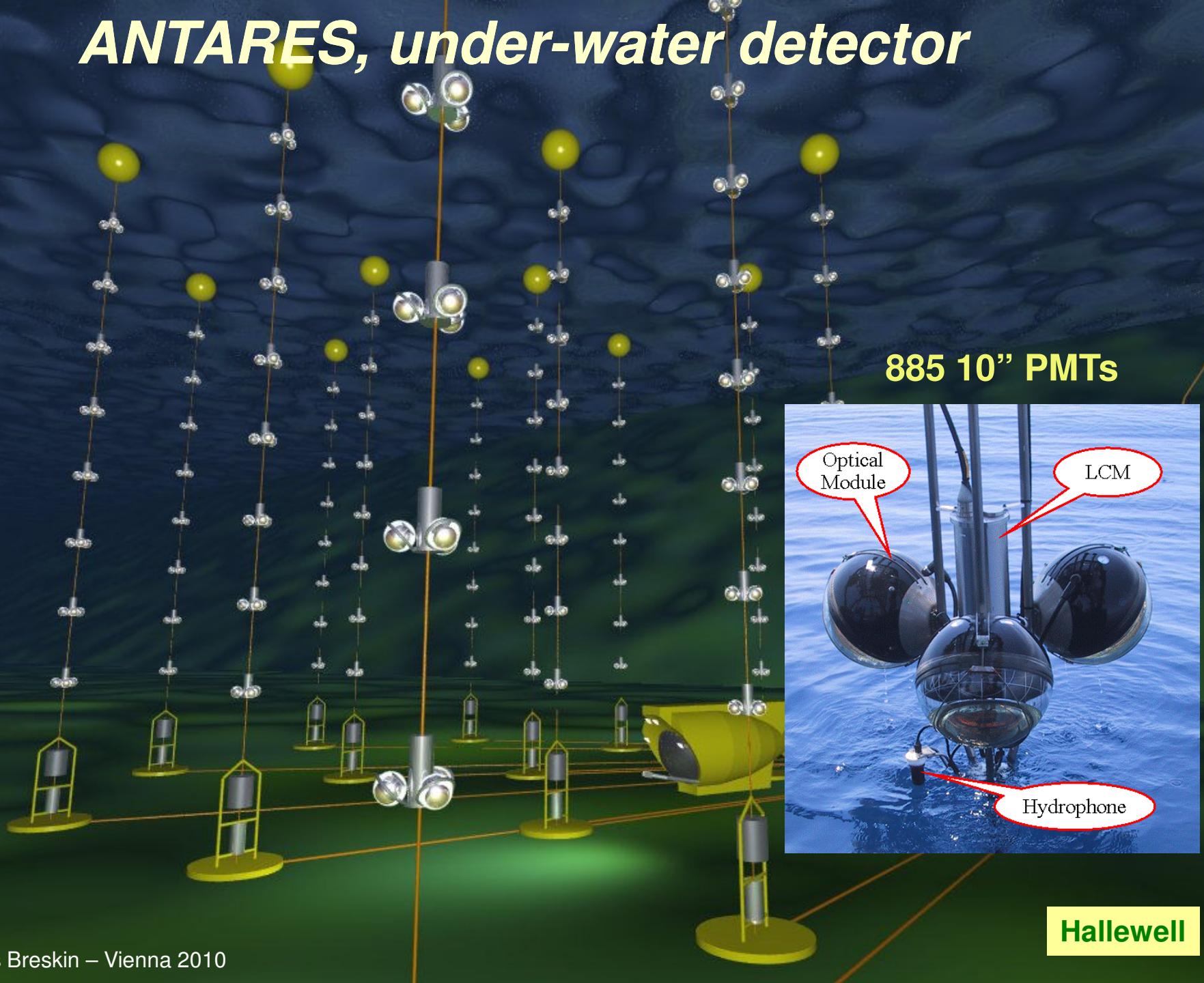
**WHO CAN PRODUCE?
WHO CAN AFFORD????
NEED NEW TECHNOLOGIES!**

Fermilab Long Baseline Neutrino Experiment LBNE

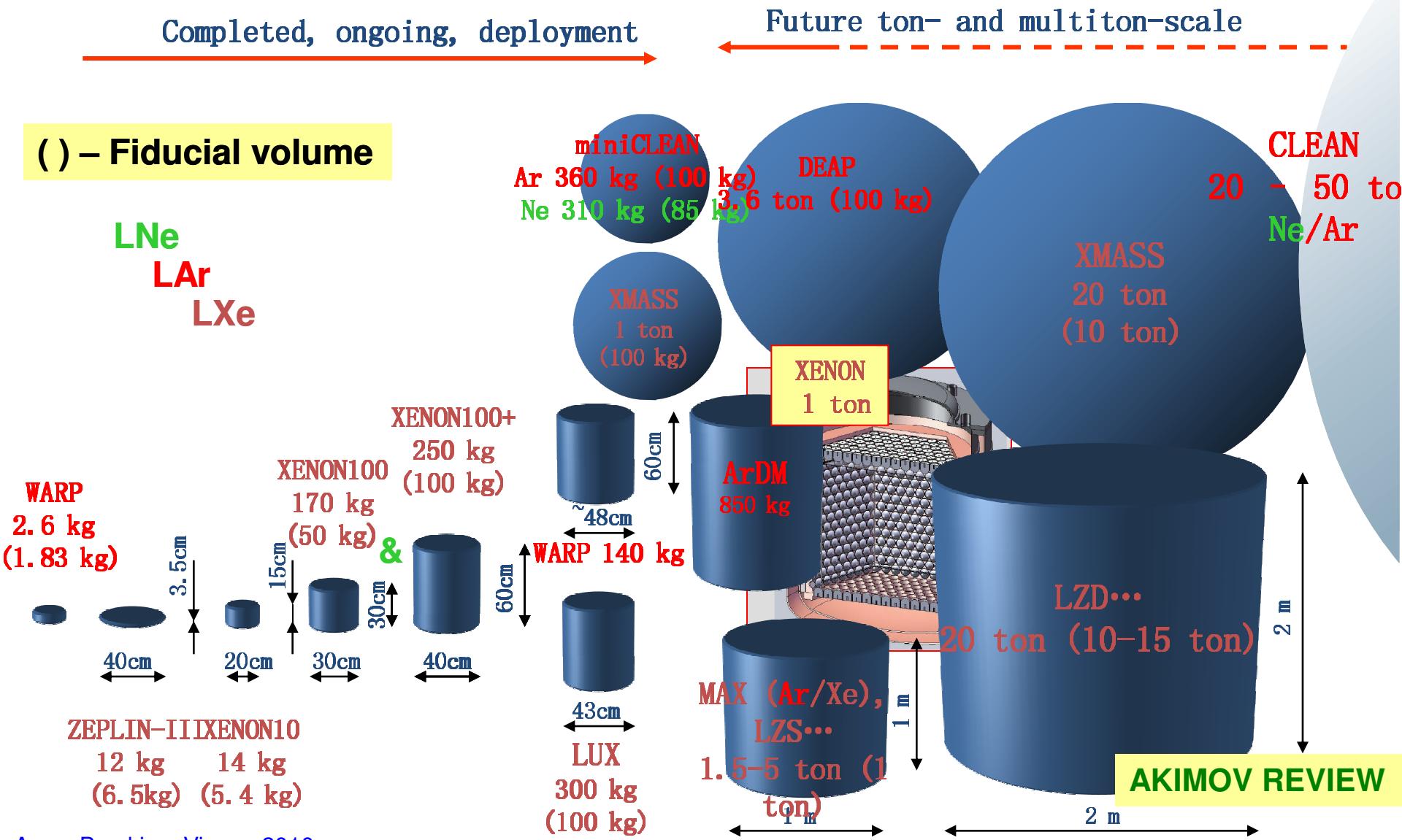


**300,000 m³ WATER + PMTs
12,000 m² of photon detectors per Each vessel**

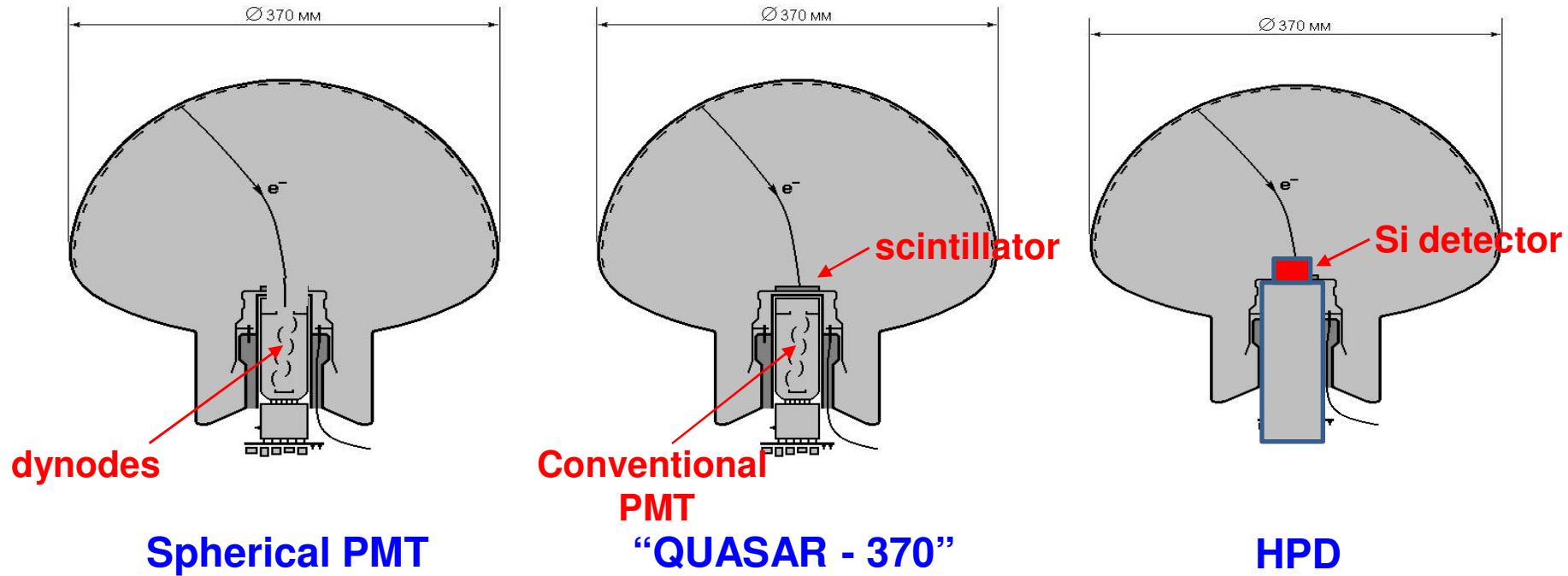
ANTARES, under-water detector



MANY NOBLE-LIQ DARK MATTER DETECTORS NEED RADIO-CLEAN PMT!

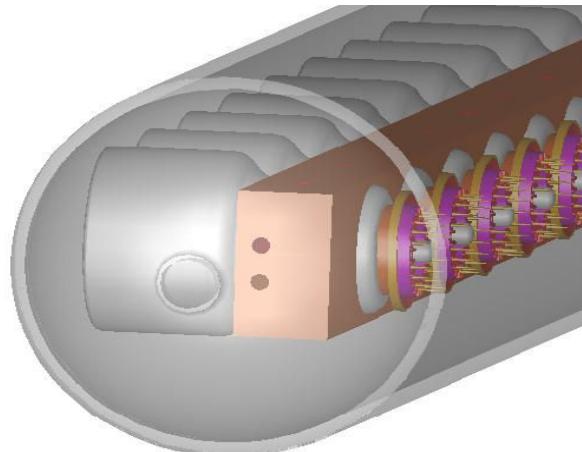


LARGE-AREA VACUUM PHOTON DETECTORS



VACUUM: BEWARE OF MAGNETIC FIELDS!

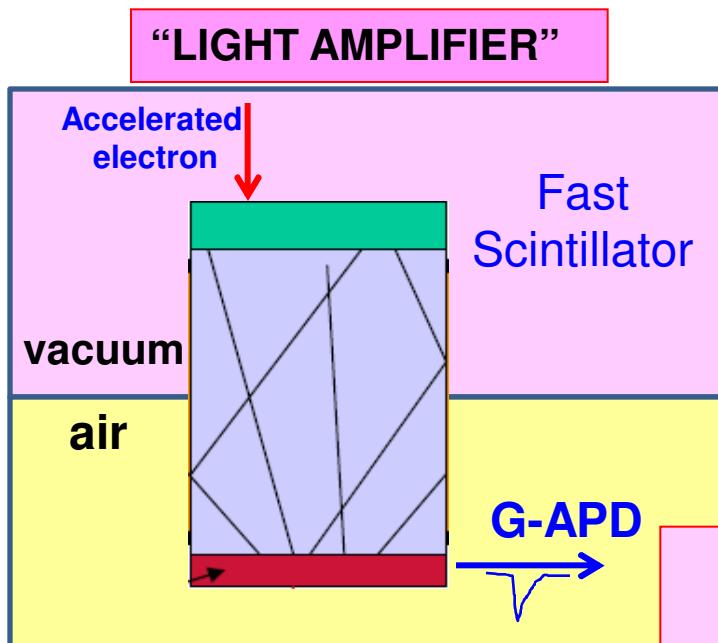
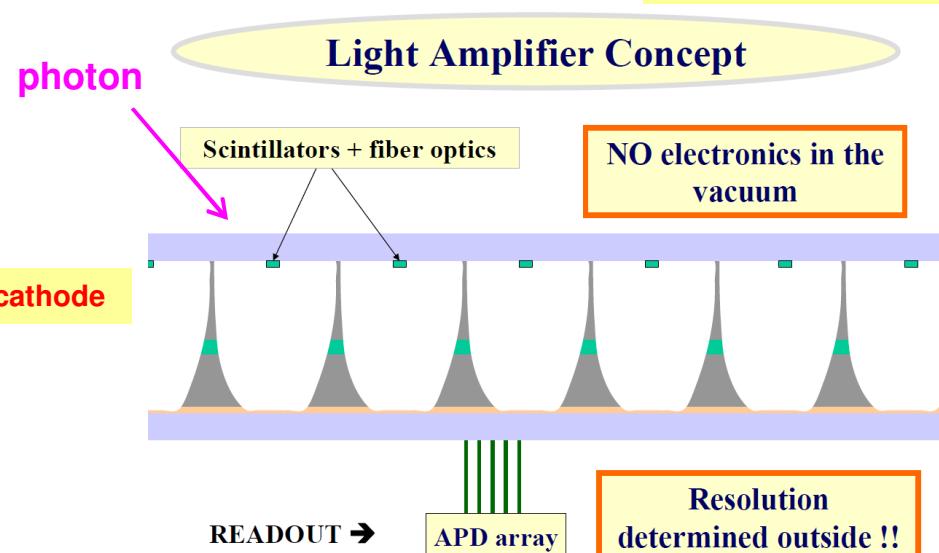
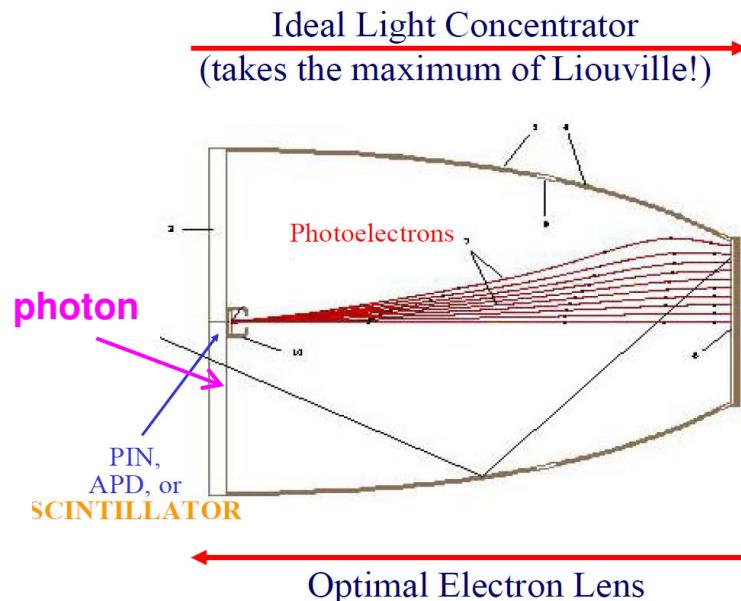
DREAM (?): 1\$/cm²



MANY SMALL PMTs IN TUBE...

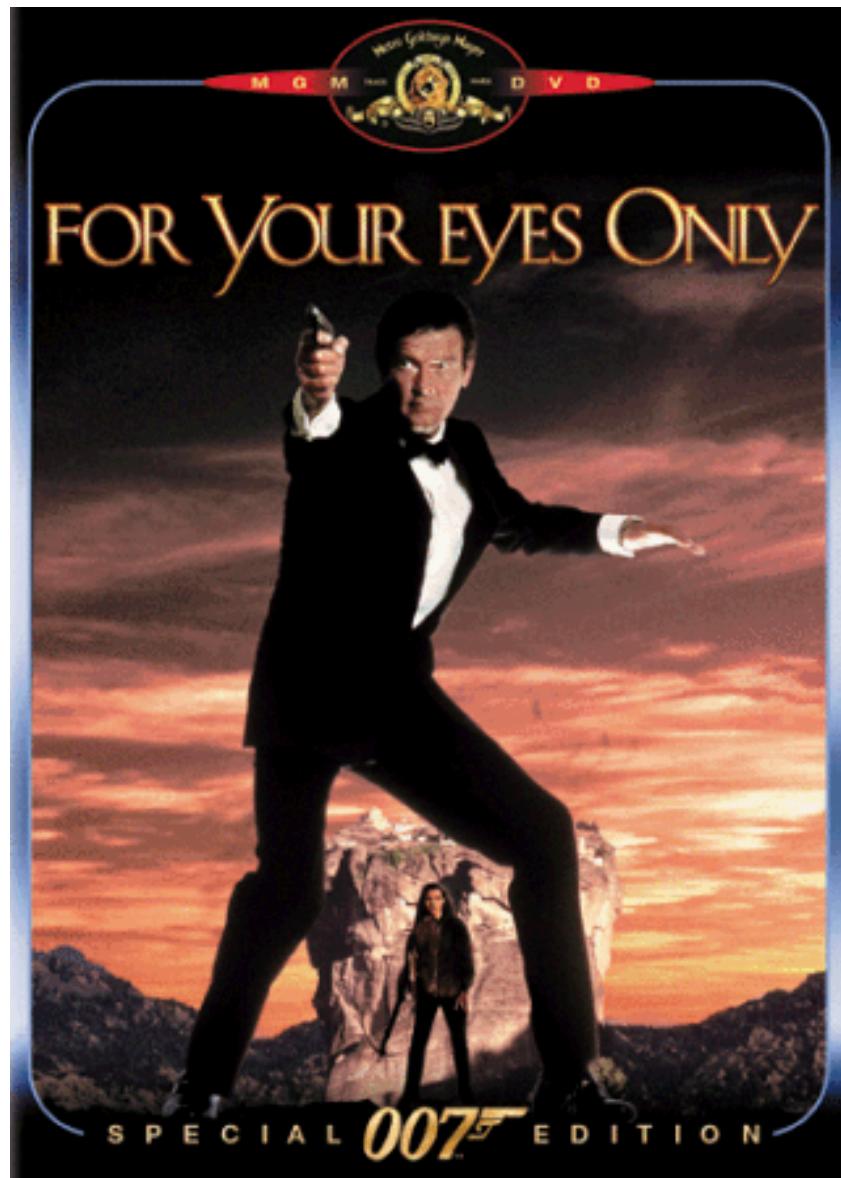
LARGE-AREA VACUUM PHOTON DETECTORS?

Ferenc LIGHT06

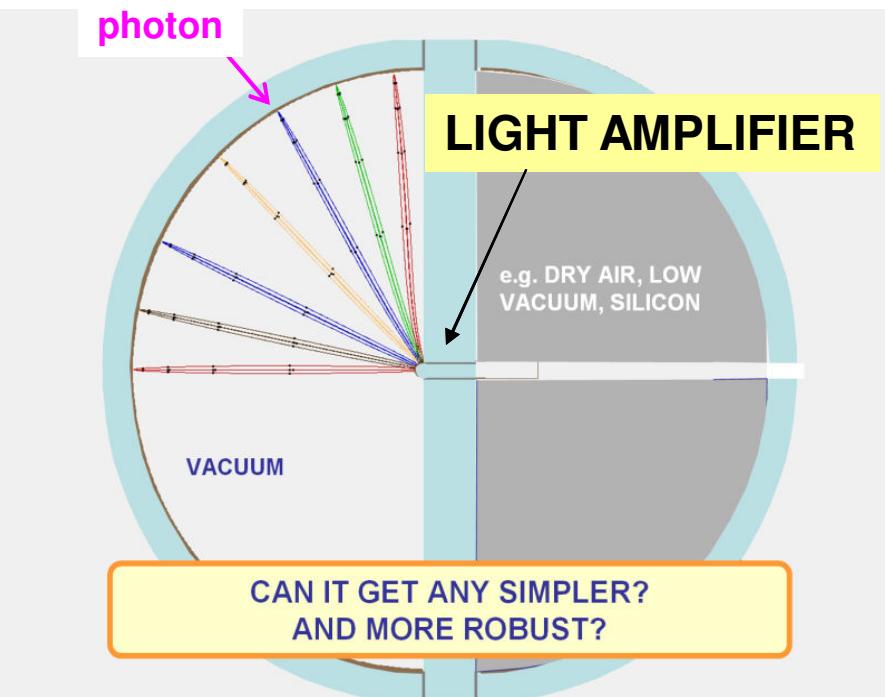


←Ferenc / Lorenz
NIMA 567(2006)166

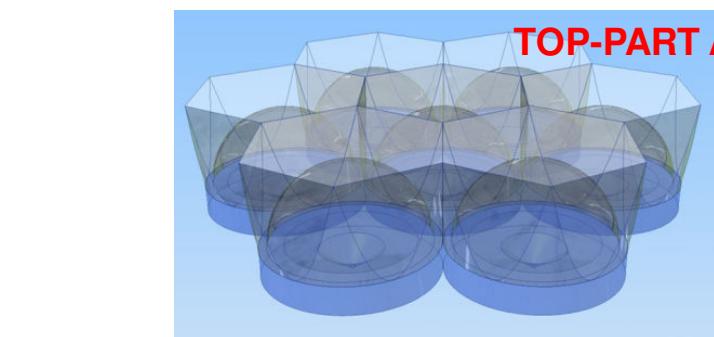




ABALONE



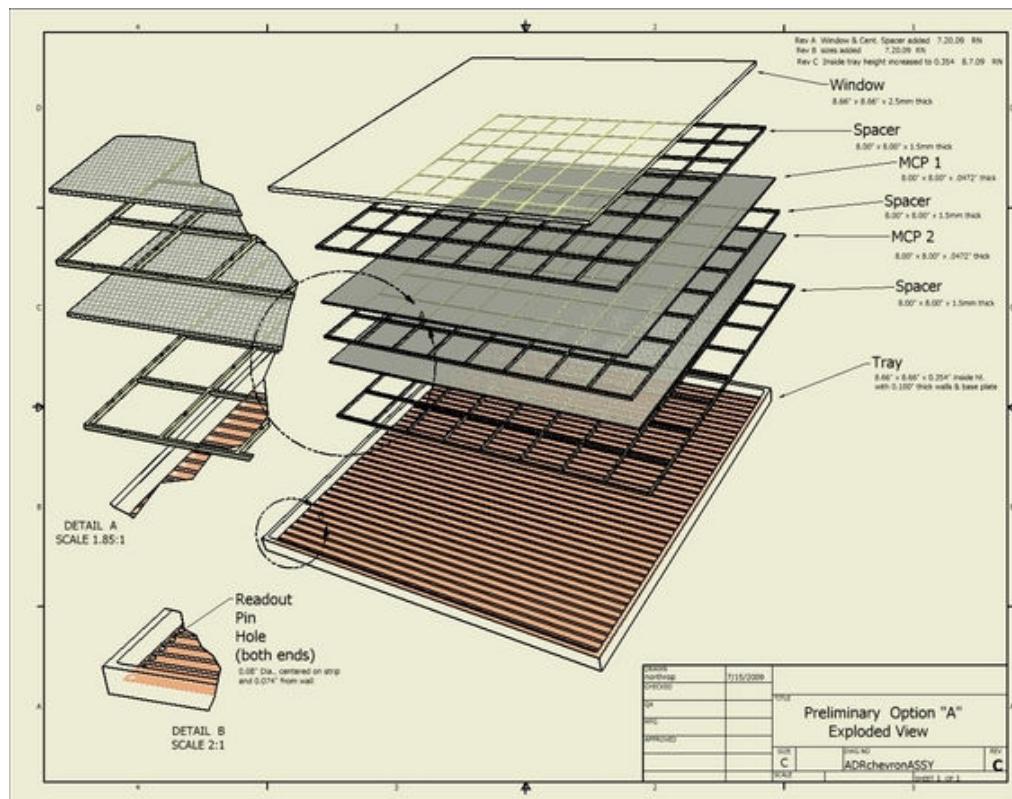
TOP-PART ARRAY



Daniel Ferenc, Patent pending

Large Area, flat, vacuum MCP-Photon detectors

The Large Area Picosecond Photodetector (LAPPD) Collaboration



Search for economic methods for large-area MCPs

- funded by DOE and NSF
- 4 National Labs
- 3 US small companies;

Lead by Henry Frisch, University of Chicago

Large-area Flat Gas-Photomultipliers GPM

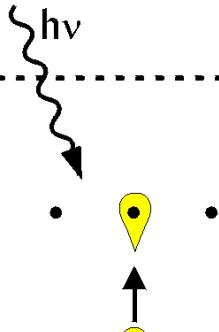
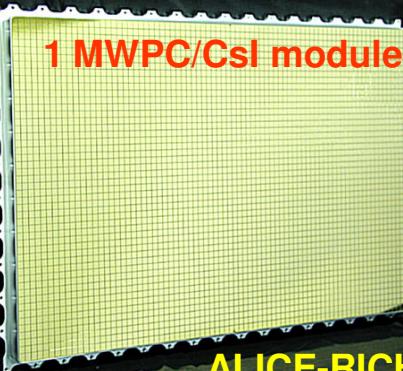
MWPC/CsI

mesh

wires

photocathode
(CsI)

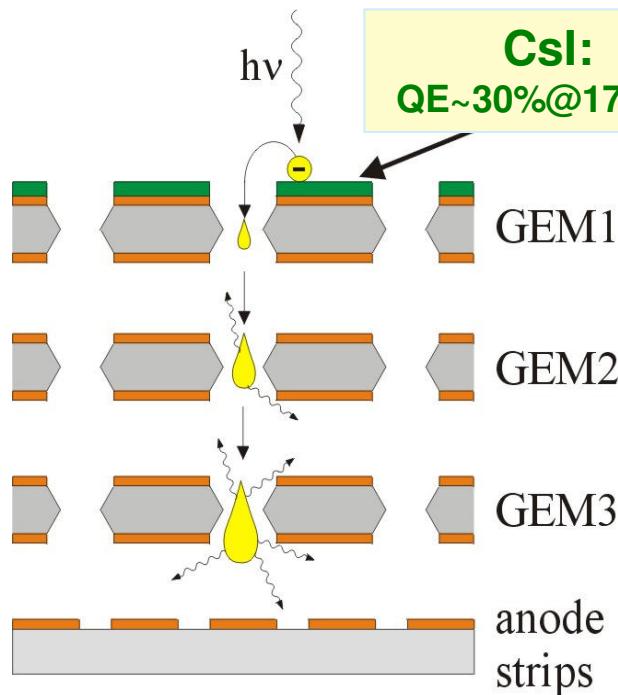
LHC-ALICE-RICH:
FIRST EVENTS



NEW: cascaded-GEM GPMs

A.B. et al, Weizmann

CsI:
QE~30%@170nm



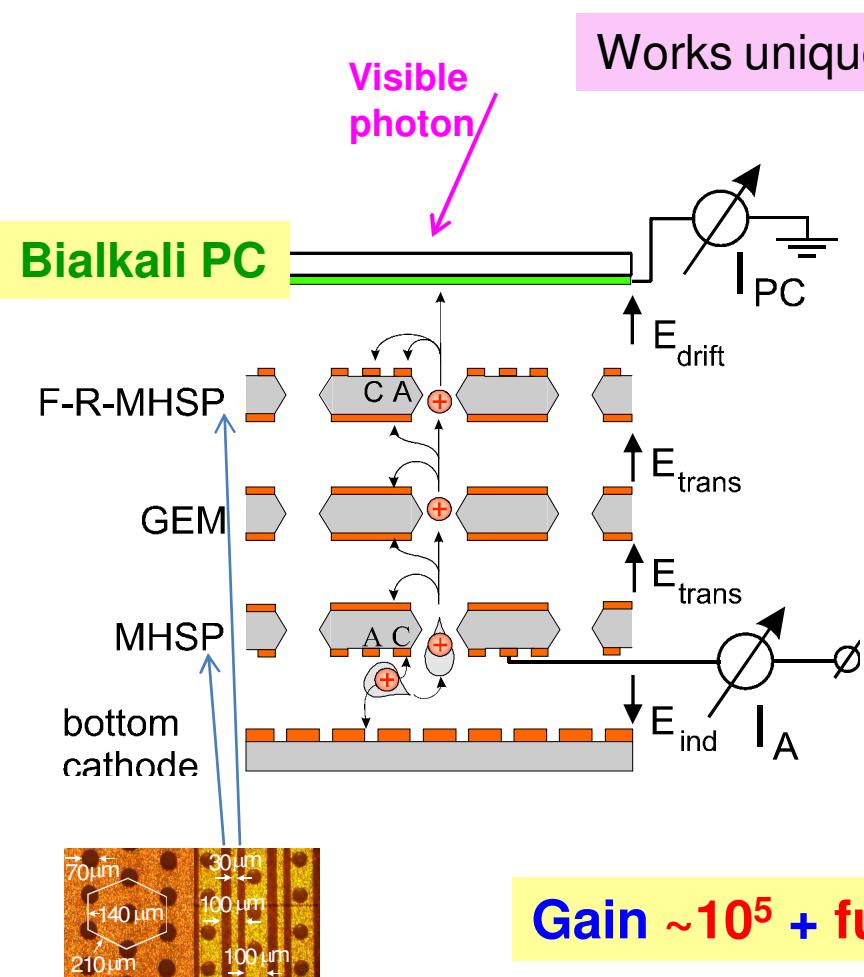
UV: CsI photocathode
Gain: $>10^6$

Single-photon sensitivity
100 micron resolution
OK in high B

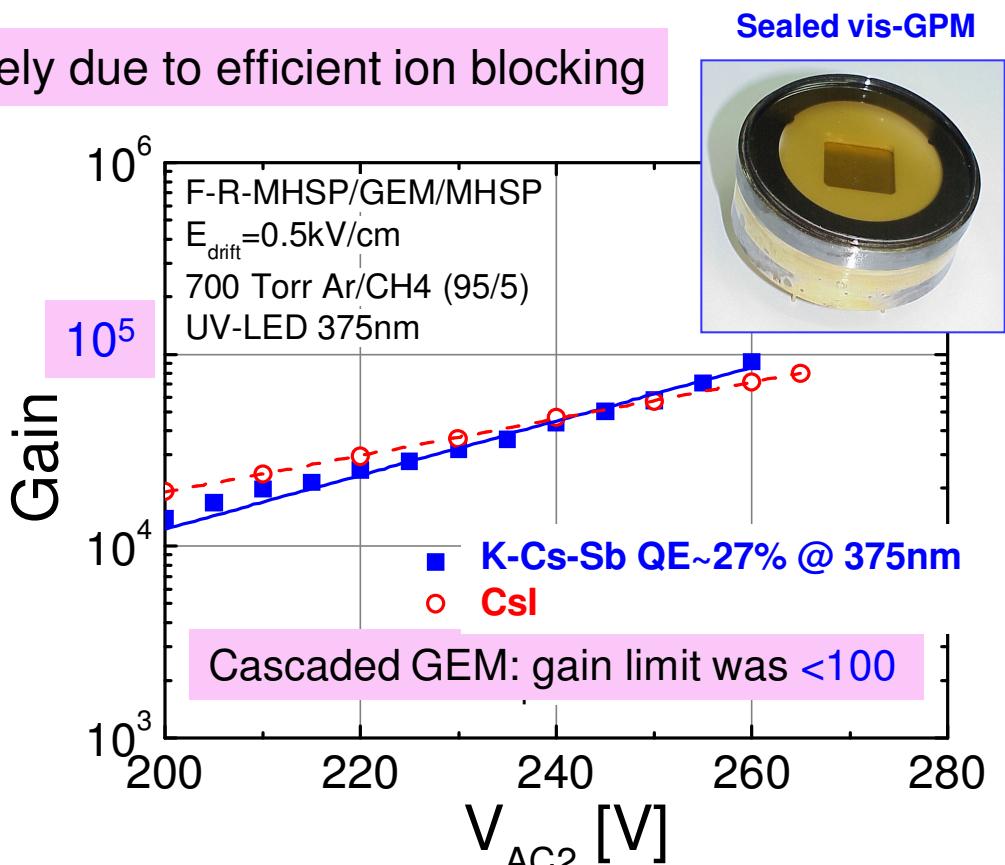
Main application: RICH

CHALLENGE: visible-light Gas Photomultipliers!

Cascaded patterned hole-multipliers with K-Cs-Sb photocathodes



Works uniquely due to efficient ion blocking



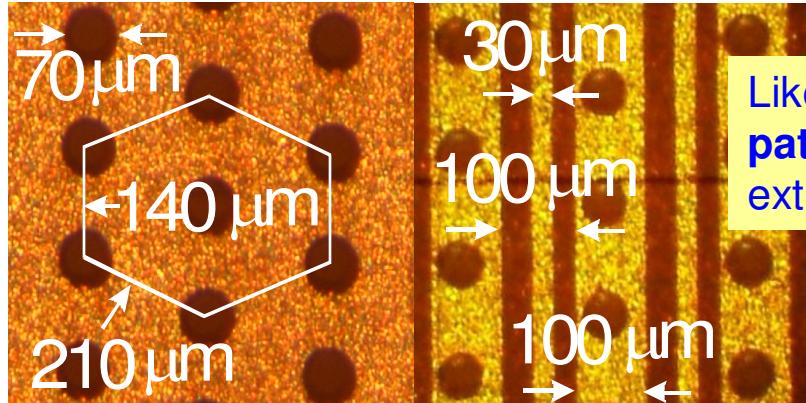
Gain $\sim 10^5$ + full photoelectron collection efficiency

- “flat-panel” large-area photon-imaging detectors insensitive to B
- numerous applications: RICH, large Astro experiments...

ION BLOCKING with PATTERNED HOLE MULTIPLIERS

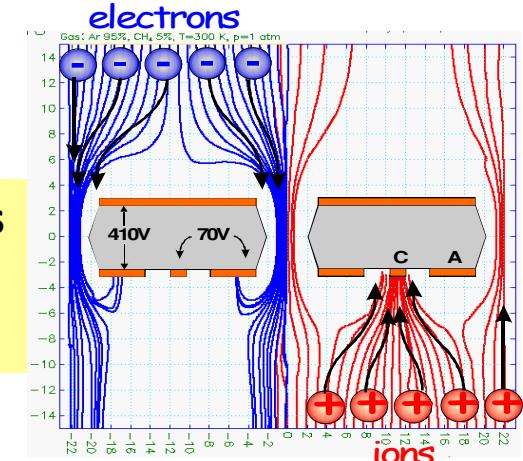
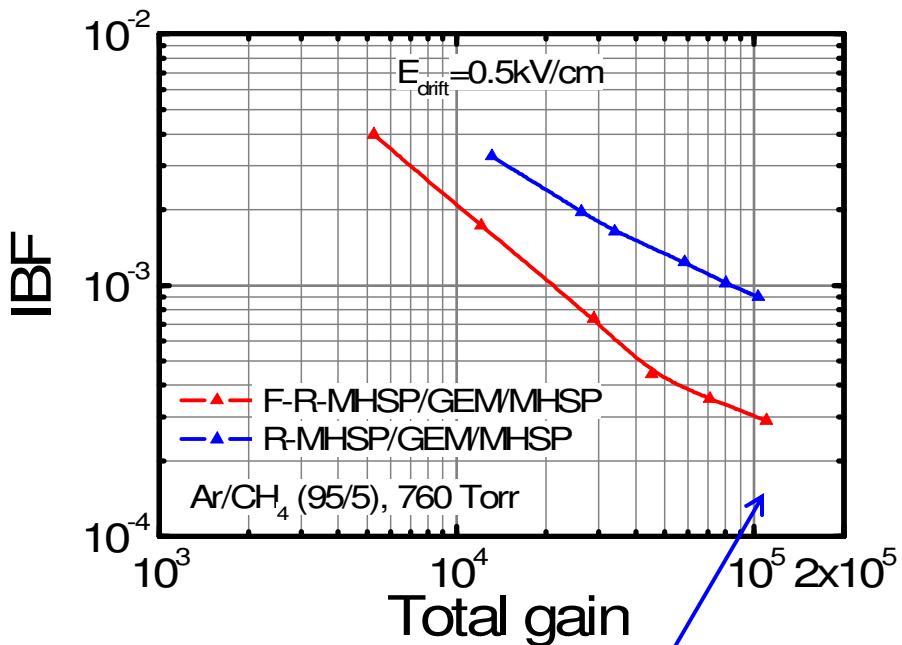
Weizmann/Coimbra/Aveiro

The Micro-hole & Strip plate (MHSP) **Veloso**

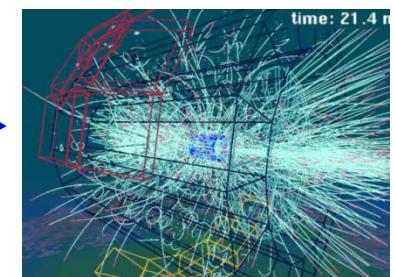
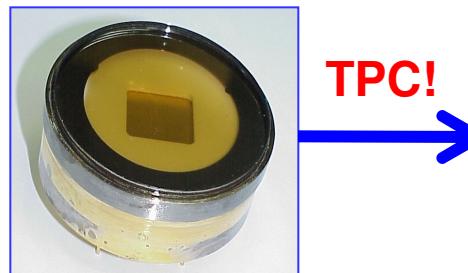


Like GEM, but with **additional patterned strip-electrodes**: extra gain OR **ion blocking**.

Ion deflection by strips between holes → efficient ion trapping



With MHSP/GEM cascade:
BEST ION TRAPPING : ~10⁻⁴
100 X better than 3-GEM
20 X better than Micromegas



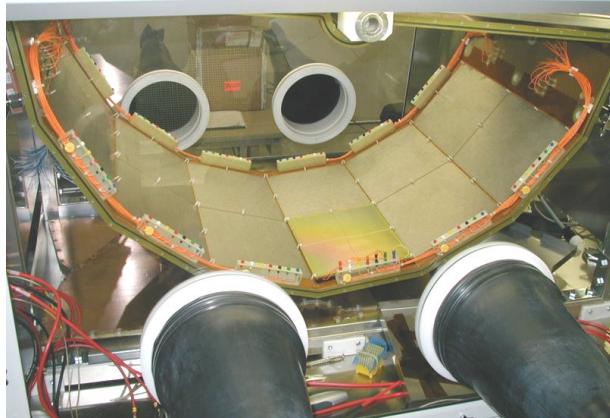
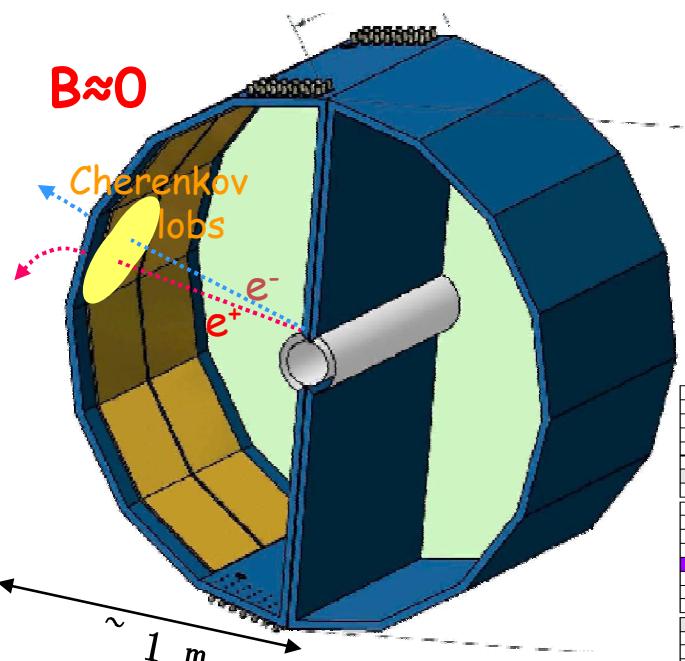
Lyashenko 2009

IBF = 3*10⁻⁴ @ Gain = 10⁵

Amos Breskin – Vienna 2010

PHENIX HBD: Hadron-Blind Cherenkov Detector

A. Milov et al.
J. Phys. G34, S701 2007



GEM size: $23 \times 27 \text{ cm}^2$
Total $\sim 1 \text{ m}^2$

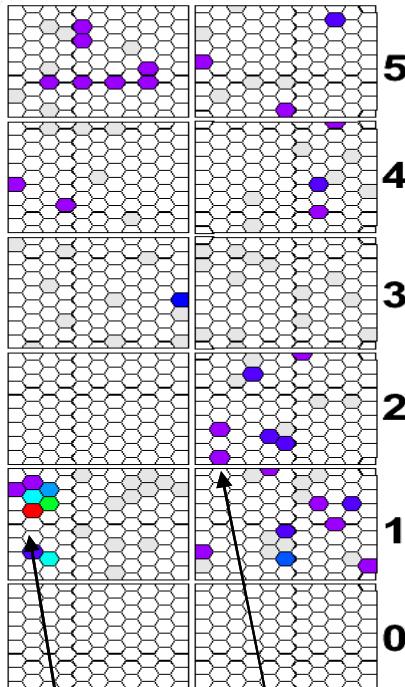
e^+e^- pair event

MIPS & CF_4 scintillation

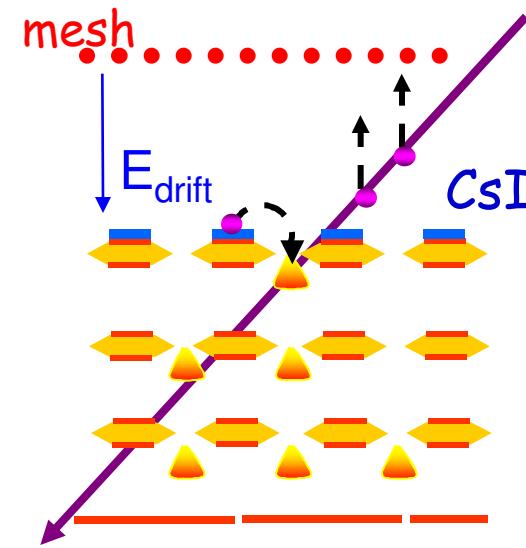
Windowless: CF_4 in radiator/detector

$N_0 \approx 840 \text{ cm}^{-1}$ (x6 larger than any e/π RICH)

200 GeV Au+Au collision

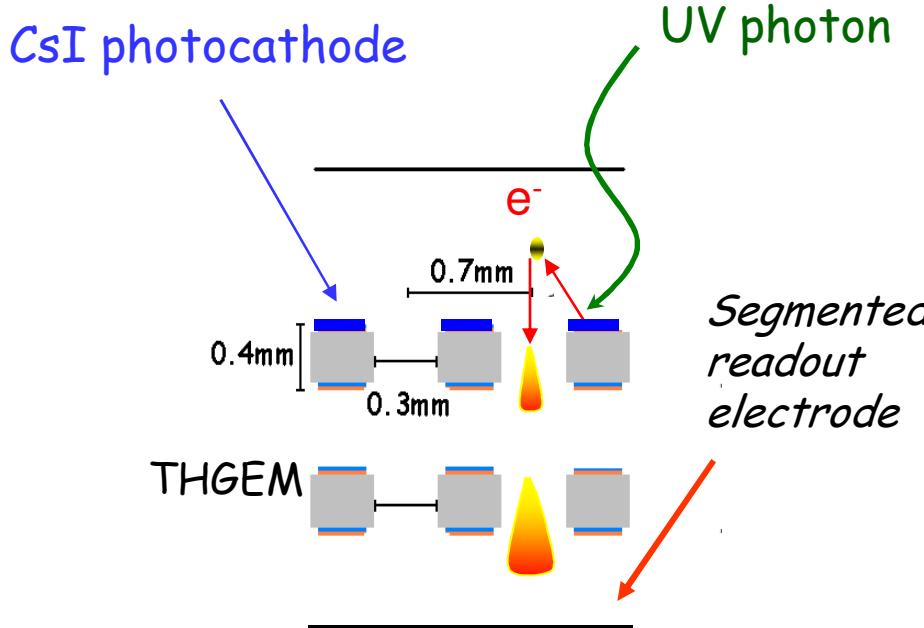


3-GEM + reflective CsI PC



REFLECTIVE PC + reversed E_{drift}
→ reduced sensitivity to MIPS

Double-THGEM photon-imaging detector → RICH

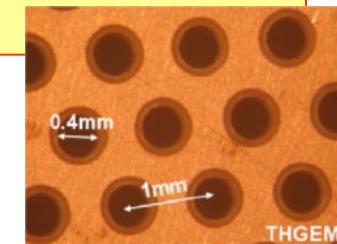


reflective CsI PC on top of THGEM

Important FACTS for RICH:

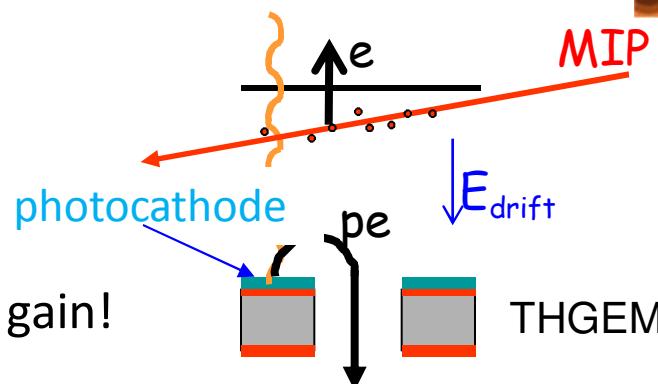
- Single-photon sensitivity
- Simple, robust, compact, large area
- Fast, good localization
- Photon detection efficiency :
~ 20% @ 170 nm

2010 JINST 5 P01002



& Unique:

- Slightly **reversed E_{drift}** (50-100V/cm)
- Good photoelectron collection
- low sensitivity to MIPs (~5%)
- background suppressing & higher gain!

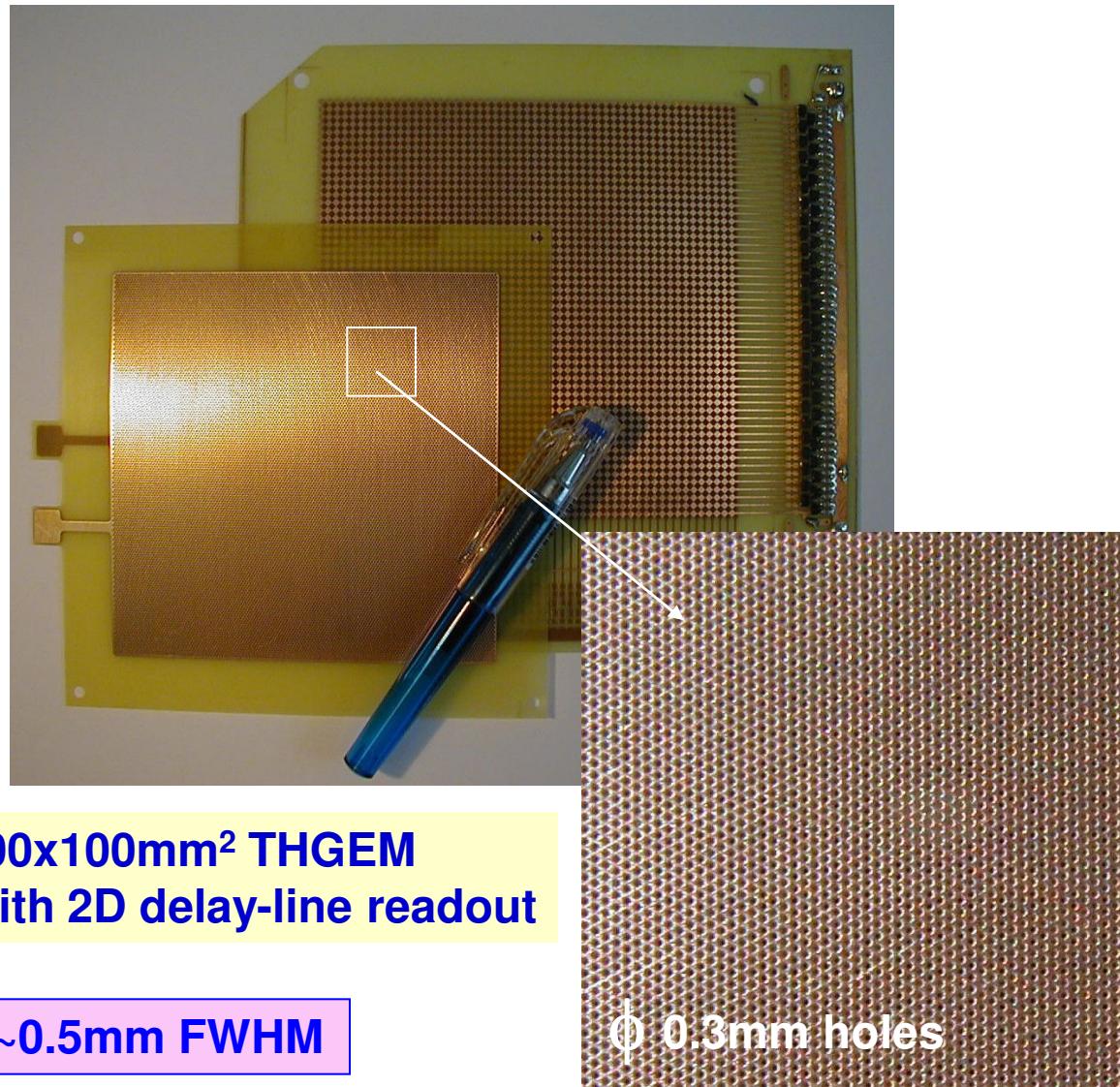
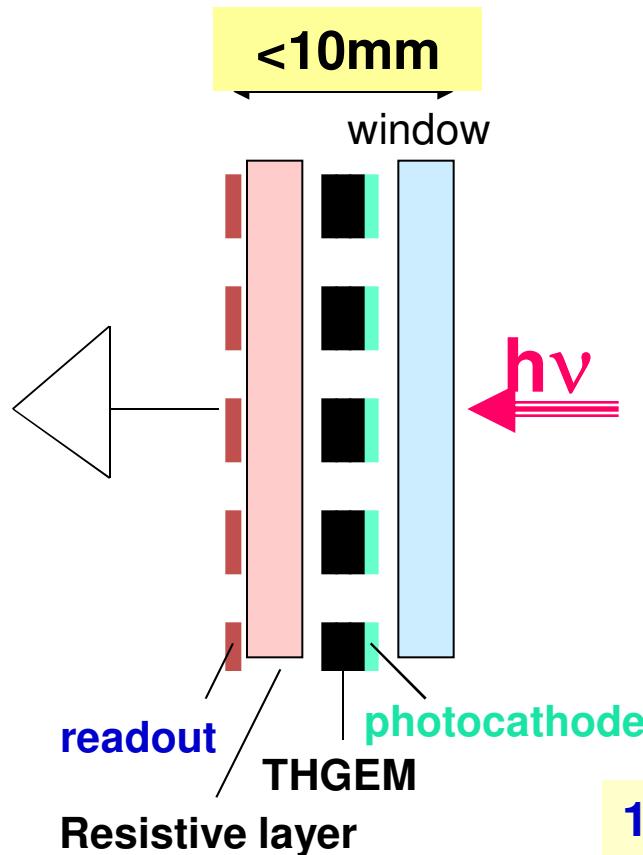


R&D for upgrade of COMPASS & ALICE RICH

1st results RD51 Nov 2009

A VERY FLAT UV DETECTOR

Cortesi 2007_JINST_2_P09002

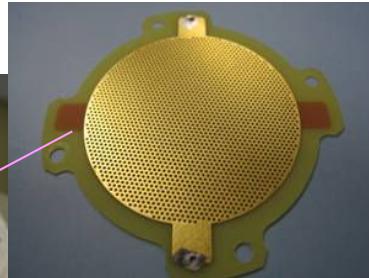
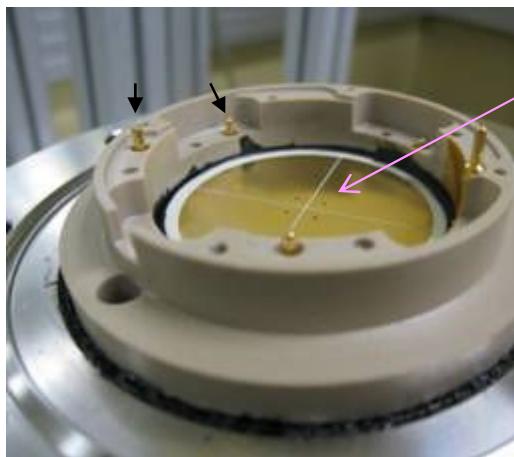


Localization resolution: ~0.5mm FWHM

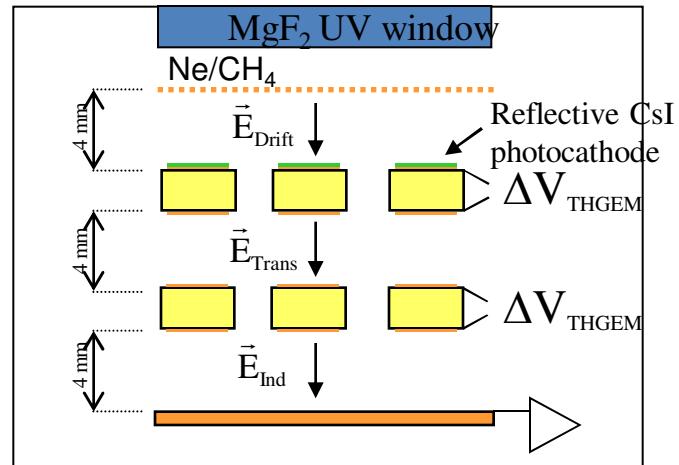
φ 0.3mm holes

Cryo-GPM for LXe Medical Compton Camera

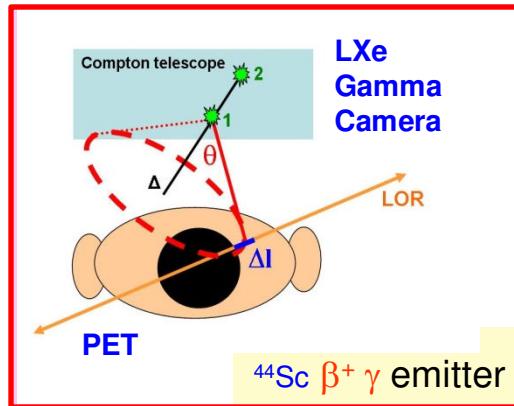
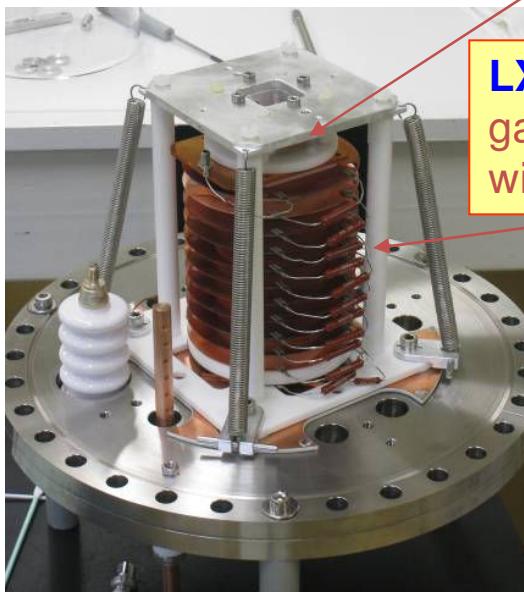
Subatech-Nantes/Weizmann



THGEM :
thickness = 400 μm
hole \varnothing = 300 μm
hole spacing = 700 μm
rim size = 50 μm



Double-THGEM layout



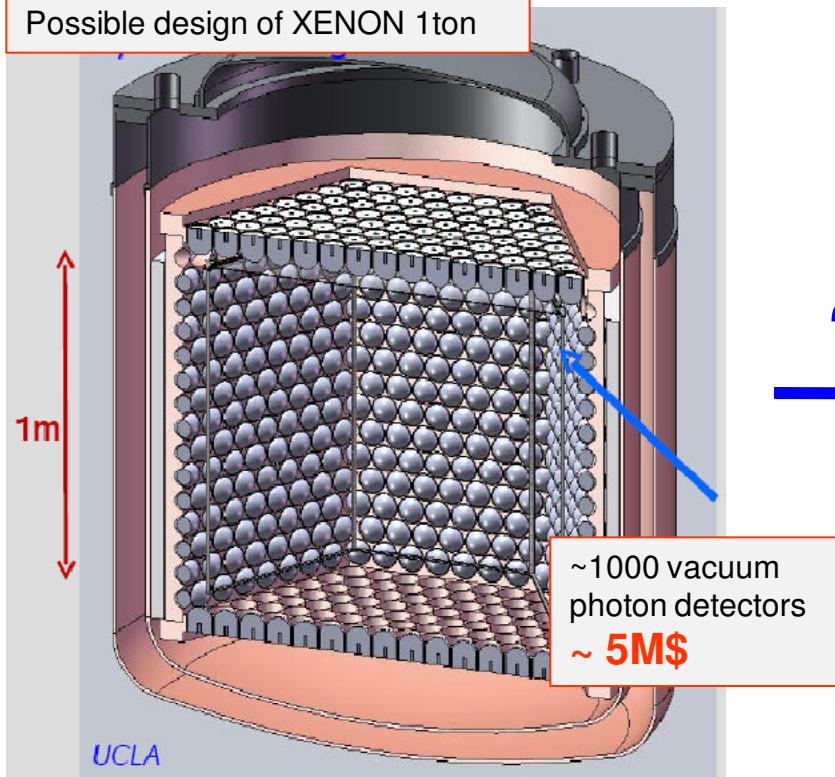
RT tests:
Gain: $\sim 10^7$
Cryo tests:
Soon!

2009 JINST 4 P12008

2-phase DM detectors

Aprile/XENON

Possible design of XENON 1ton



Possible design of the XENON 1 ton two-phase LXe DM TPC detector with ~ 1000 QUPID vacuum photon detectors. Background: 1mBq/tube

Expectation: < 1 WIMP interaction/Kg/Day

RD51: Weizmann/Nantes/Coimbra

THGEM GPM Detector Ne/CF4

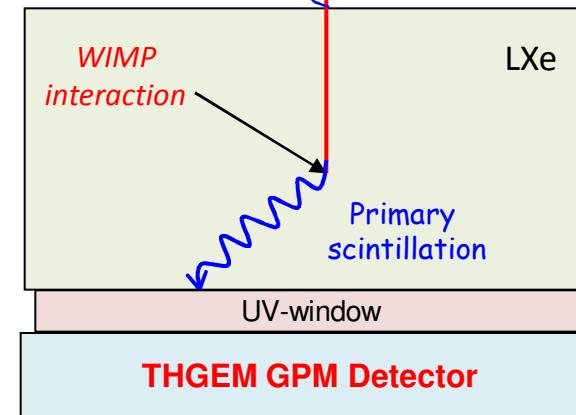
UV-window

Secondary scintillation

e^-

Xe

E_G



E_L

THGEM-GPM (gas photomultiplier):

- Simple, flat (save LXe), robust
- Low-cost
- Radio-clean ?
- Lower thresholds ?

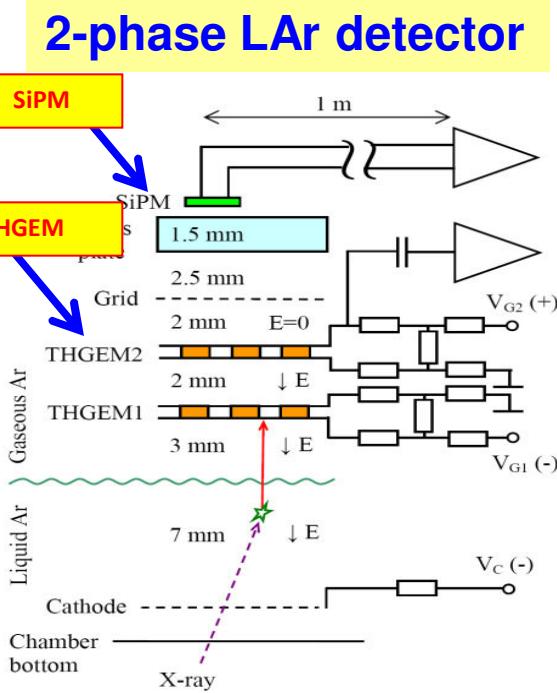
XENON100Kg: running!

PROBLEM:

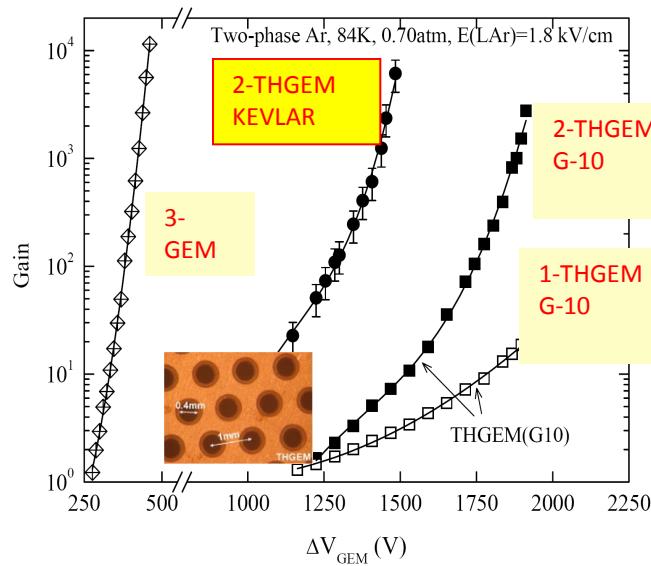
cost & natural radioactivity of multi-ton detectors! → **gas PMT?**

THGEM and THGEM+SiPM @ Cryo temperatures

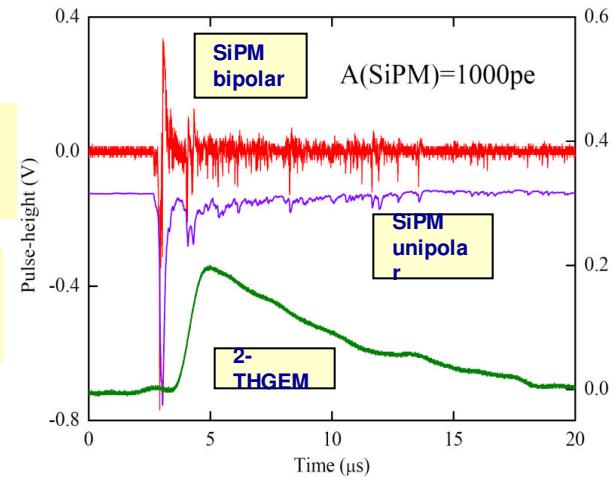
Buzulutskov
VCI 2010



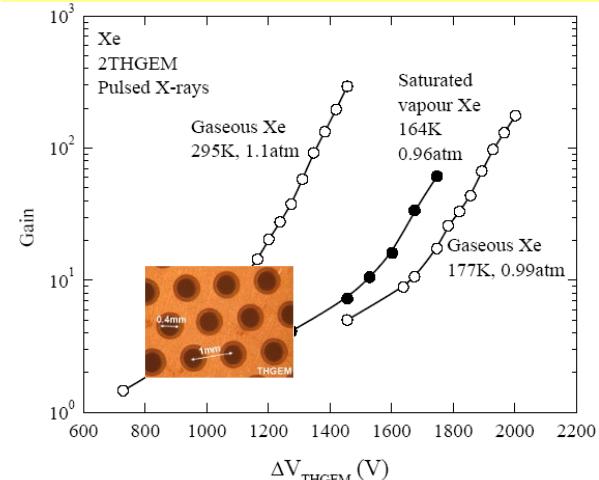
Stable operation in two-phase Ar, T=84K
Double-THGEM → Gains: 8×10^3



60 keV X-ray at 2THGEM gain=400
→ SiPM ~1000e before amplification!



Double-THGEM in Xe at cryogenic T.
Max. gain limit due to connector...



Two-phase detectors with THGEM+SiPM
→ ~1pe/initial e at THGEM gain=400 in Ar
→ N=N_{initial e's} × SiPM gain
Efficient readout of noble-liquid detectors?

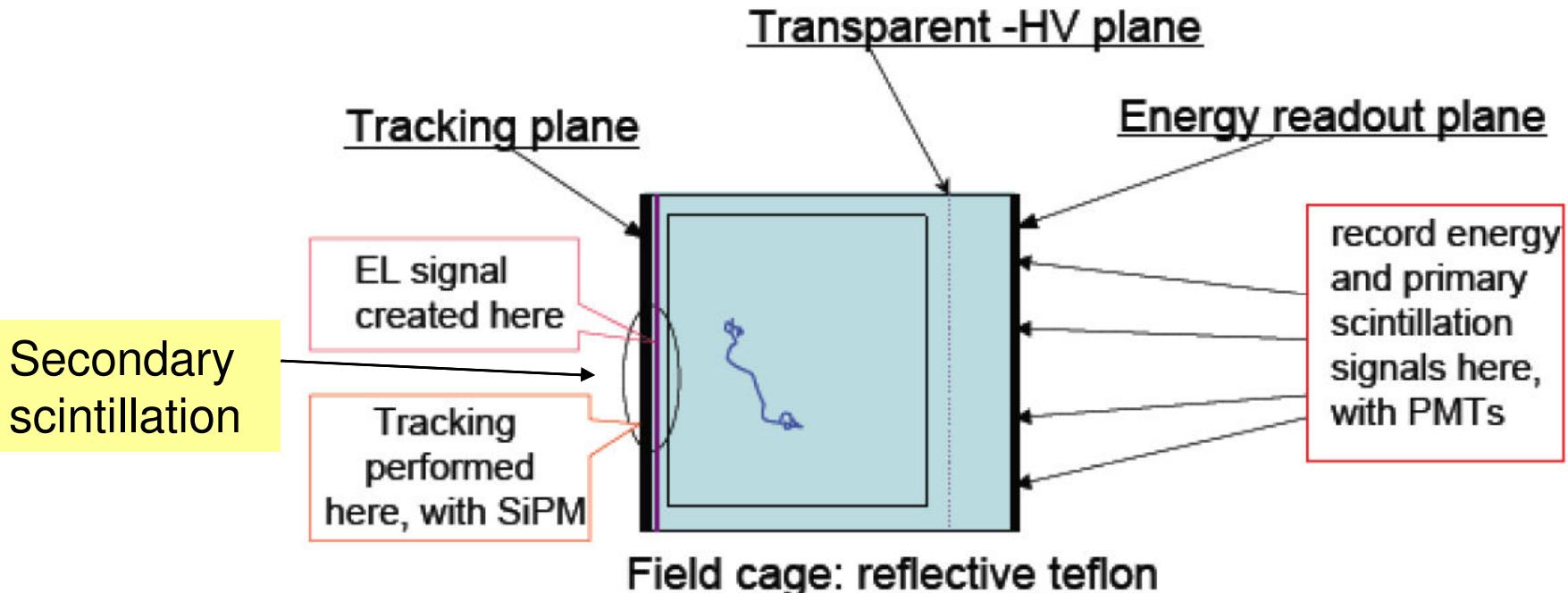
High-pressure Xe/SiPM detectors for 2- β decay

Neutrinoless 2-beta decay in 10 bar Xe **TPC/Scintillation/SiPM**
Need: **excellent E-resolution & topology**

High-pressure Xe gas can provide energy resolution much superior to liquid Xe.

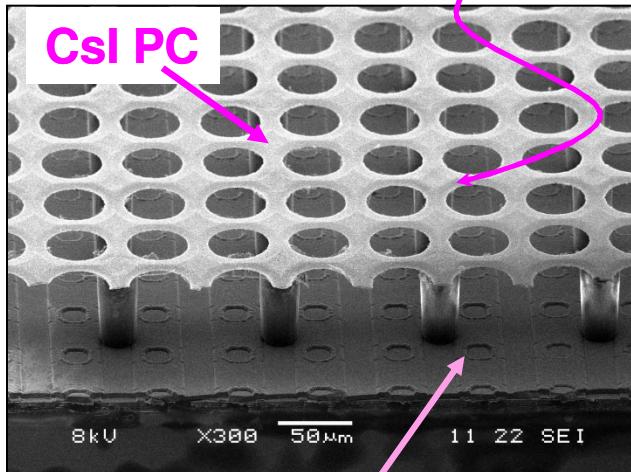
$E = 2.5 \text{ MeV} (= Q^{136}\text{Xe})$:

- High-Pressure Xe: $\Delta E / E \approx 3 \cdot 10^{-3}$ (Fano factor ≈ 0.15)
- Liquid Xe (EXO prediction): $\Delta E / E \approx 35 \cdot 10^{-3}$ (Fano factor ≈ 20)



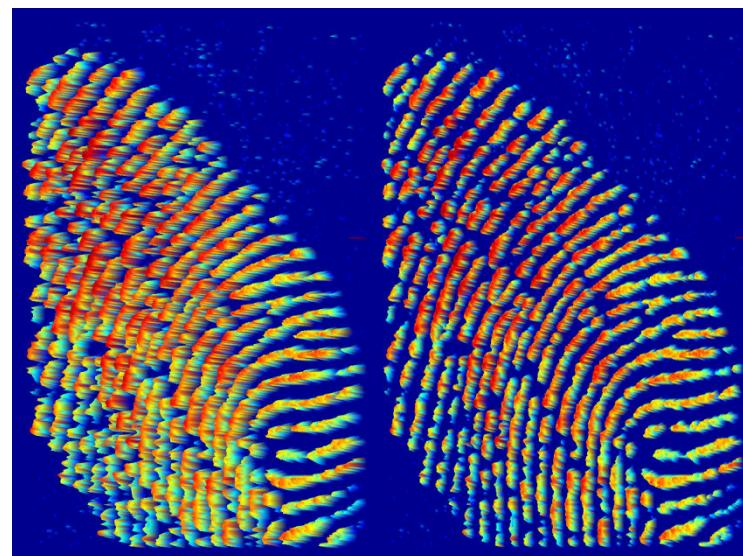
INGRID/CMOS PHOTON IMAGING DETECTOR

MICROMEGAS (InGrid)
covered with CsI

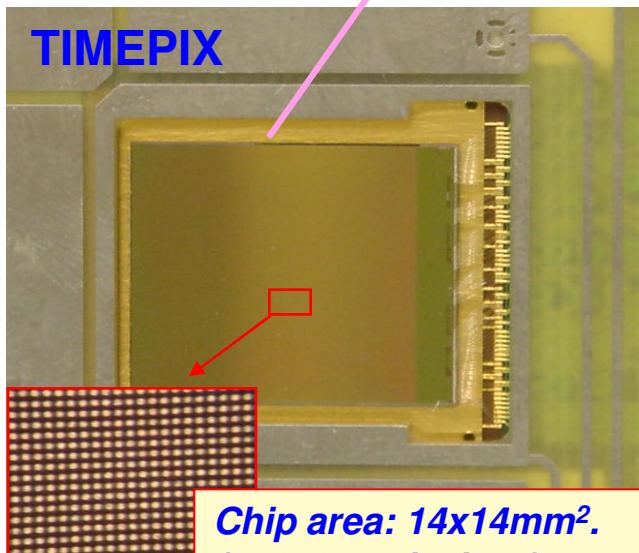


Ingrid without CsI

UV absorbed
by the
fingerprint
on the window



Fransen 2009

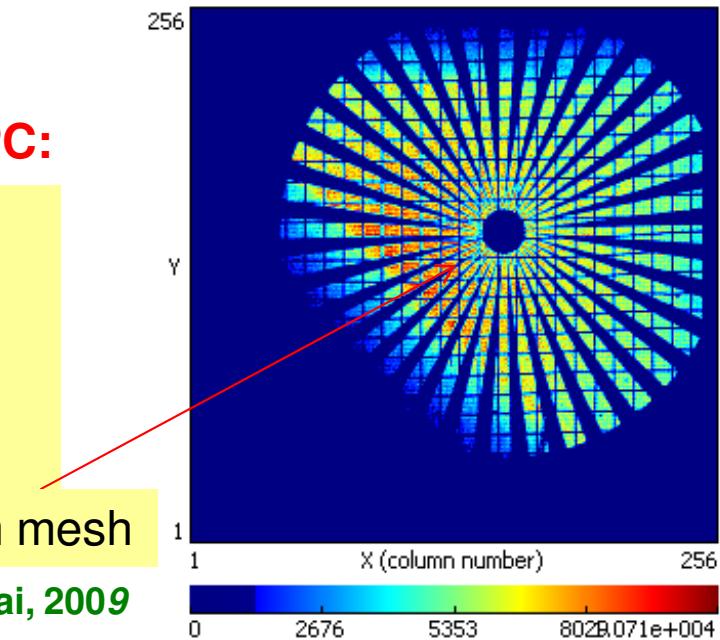


Ingrid with CsI PC:

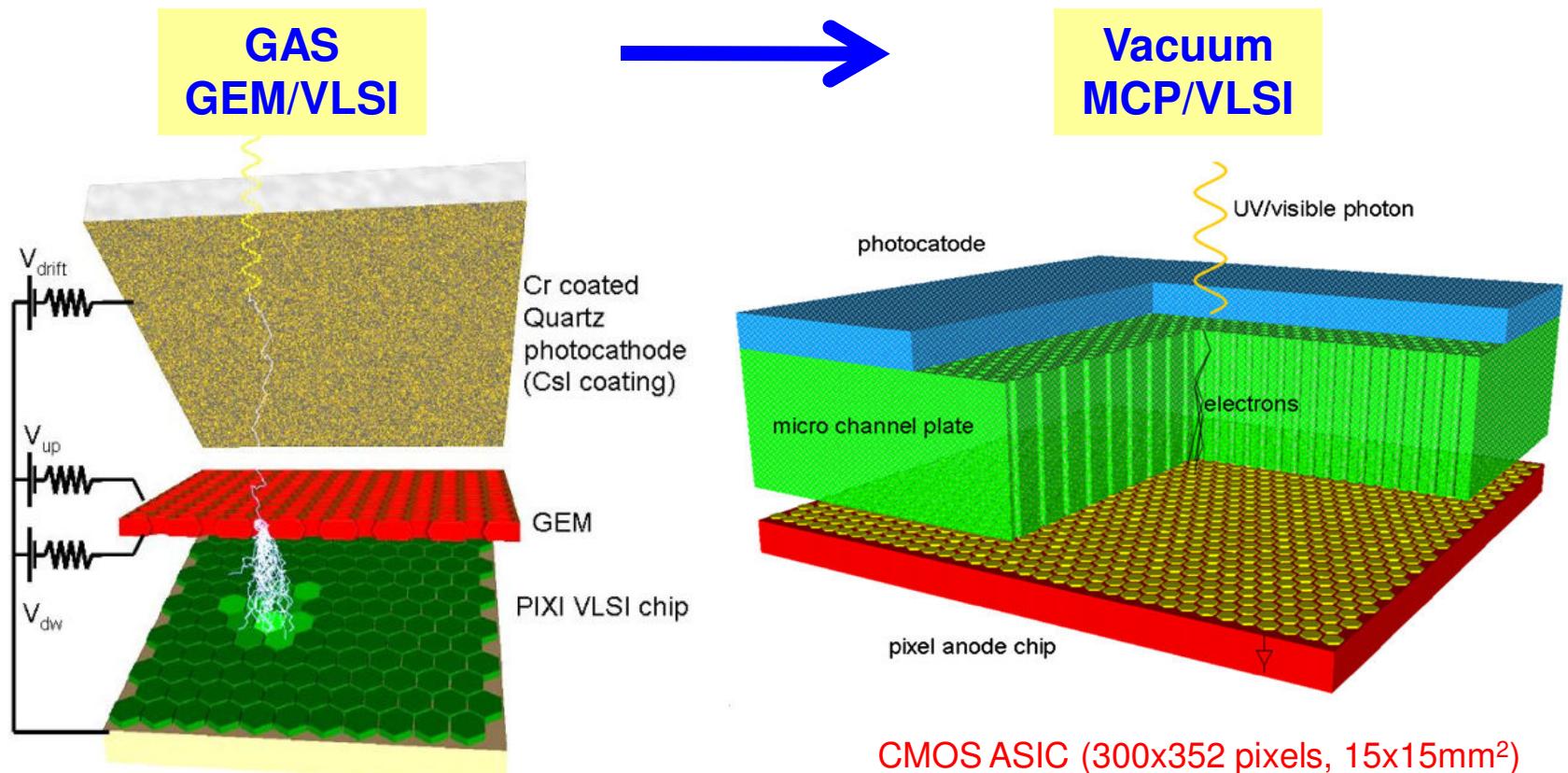
2D UV Image
of a 10mm
diameter mask
Few-micron
resolutions

50 μ m mesh

Melai, 2009



1 μm resolution vacuum photon detector



CMOS ASIC (300x352 pixels, 15x15mm²)

MCP: $\Phi 4$ micron pores

Single-photon resolution~ 1micron!

Bellazzini 2002

Bellazzini 2008

Important but not discussed

RICH & DIRC detectors

NAPPI Rev VCI10'

SEITZ VCI10': Important DIRC R&D for PANDA @ FAIR

DIRC2009 in *JINST*:

<http://www.iop.org/EJ/journal/-page=extra.proc3/jinst>

Others on photon detectors, Aerogel etc...

Tremsin VCI10'

Neutron imaging of magnetic fields

By neutron spin interactions

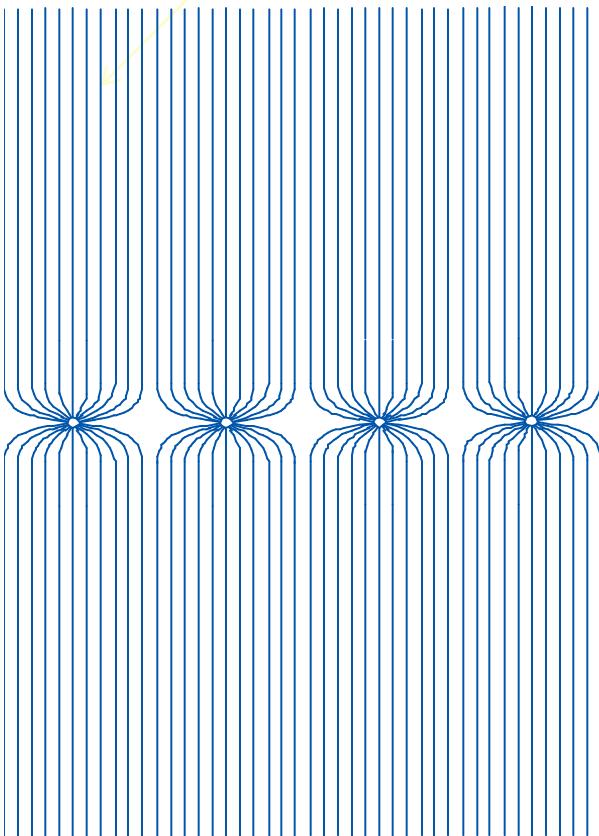
With **MCP/Medipix**



Towards “Wireless Vienna Conferences”?

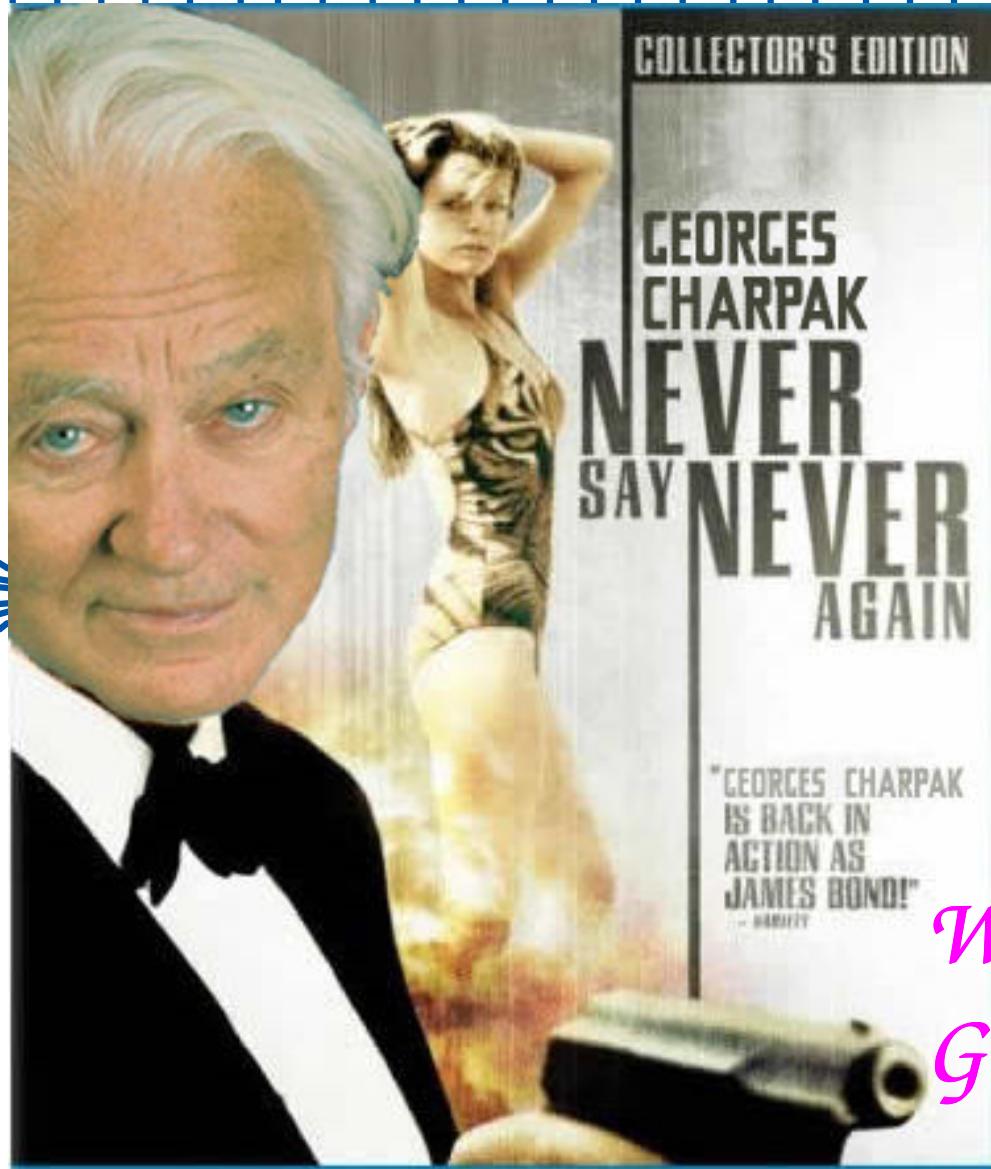
Old good wires?

Never again?



VCI10'

- **New TGCs for ATLAS upgrade (Etzion):**
Pads: trigger
Wires/strips: 60-80 micron localization
Stability: OK γ /n's
- **Tracking drift chambers @ PANDA/FAIR (Seitz)**
- **New MDT's for sATLAS (Kortner)**
- **3D drift chambers for DCBA 2- β decay (Ishikawa)**
- **Air-operated wire chambers (Peskov)**
Environmental monitoring



*We still love your wires,
Georges!*

Summary of summary...

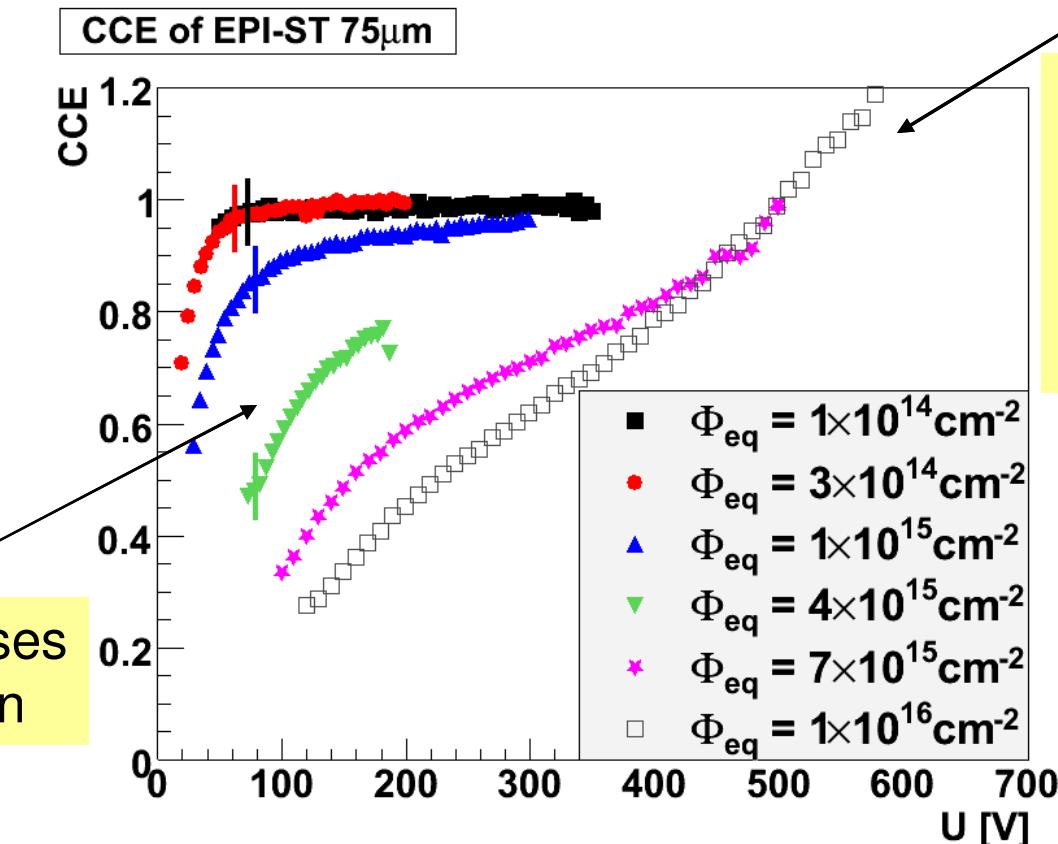
- Interesting Conference
- Good variety of talks, posters & reviews
- Focused on HEP...though many other fascinating applications!
- I limited myself to **some** of the topics presented and discussed **others** I find important
- sLHC & ILC are still “phantoms” - but B-factories, RHI, SR, space & ground astro-activities, medical etc – are good “customers”!
- Room for good R&D for training and motivating the younger generation!

We offer positions for students/post-docs...

Backup slides

Charge multiplication in aged Si

Collection losses
with irradiation



Q Multiplication
linear with V,
in irradiated Si!
→ in front side.

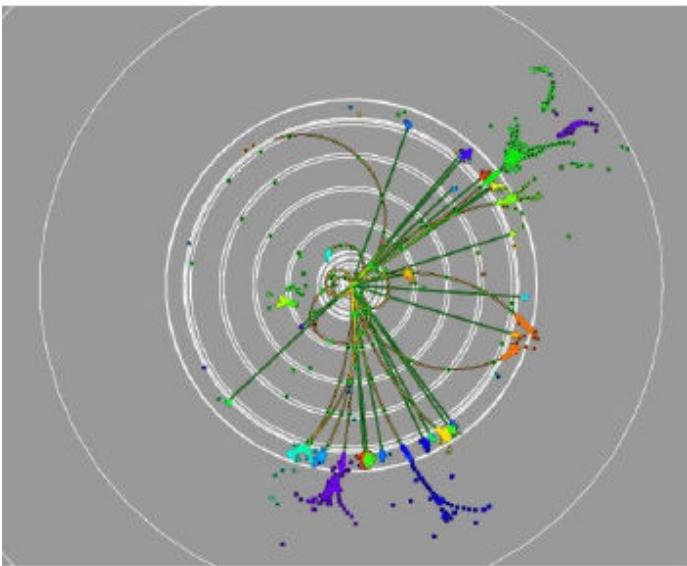
LANGE VCI10'

Digital Hadron Calorimetry

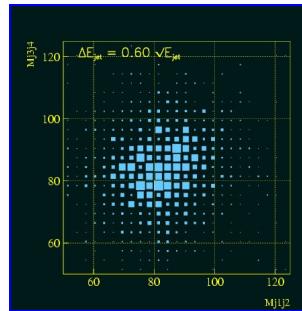
Digital calorimetry:

Particle Flow Algorithms:

associate “hits” with charged tracks, remove hits, measure neutrals in calorimeter using hits vs. energy

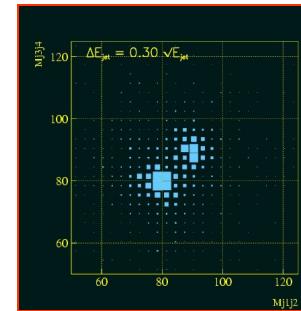


ILC: Separate W,Z boson masses on event-by event basis



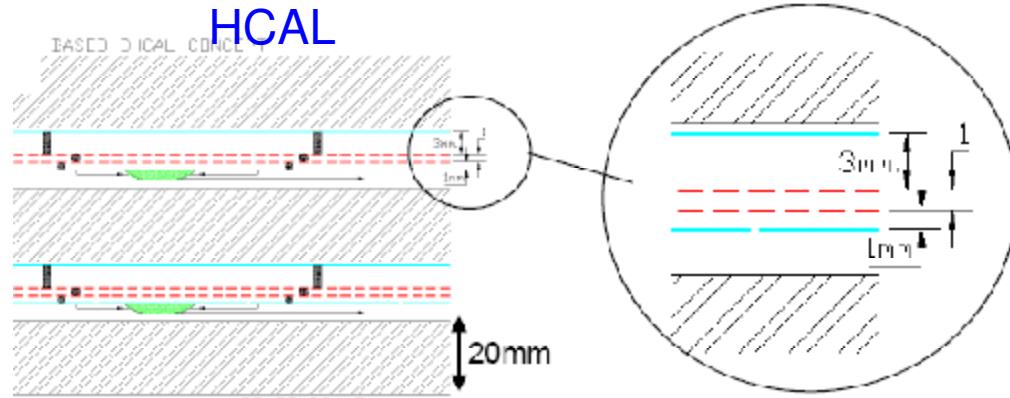
$60\%/\sqrt{E}$

Best JET
resolution with
traditional
calorimetry



Need $30\%/\sqrt{E}$

Generally need $\sigma/E_{jet} \sim 3-4\%$



2 sampling layers (out of 40) with GEM-based elements

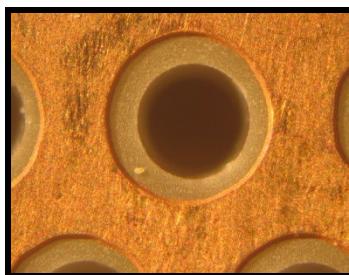
1m² GEM-HCAL proto in process (UTA)

Competitors DHCAL R&D: Micromegas, RPC, THGEM

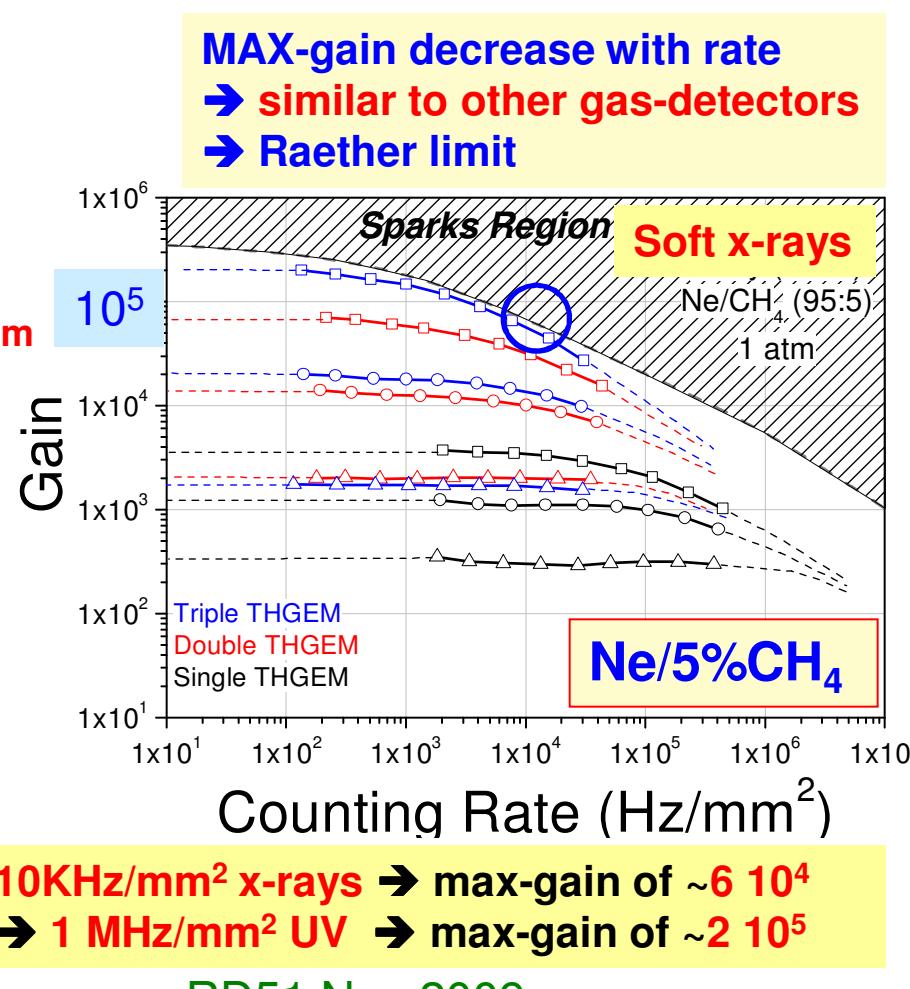
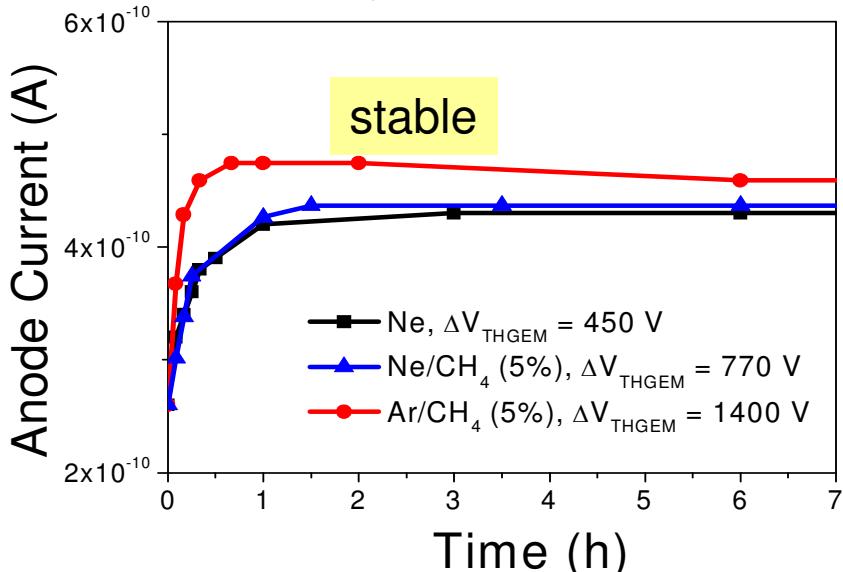
White UTA

THGEM: Gain stability & discharge limits

- GAIN-STABILITY (charging up, substrate polarization) function of :
substrate material, rim size around hole, HV value, gain, radiation flux, surface resistivity, mode of operation etc.
- Good stability (Trieste): Holes with no rim – but no-rim: 10-100 times lower gain
- New results in Ne-mixtures (much lower HV): **stability with rim**



Single THGEM ($t=0.4\text{mm}$, $d=0.5\text{mm}$, $a=1\text{mm}$, **rim=0.12mm**)
Gain = 10^4 , UV light, e^- flux $\approx 10 \text{ kHz/mm}^2$

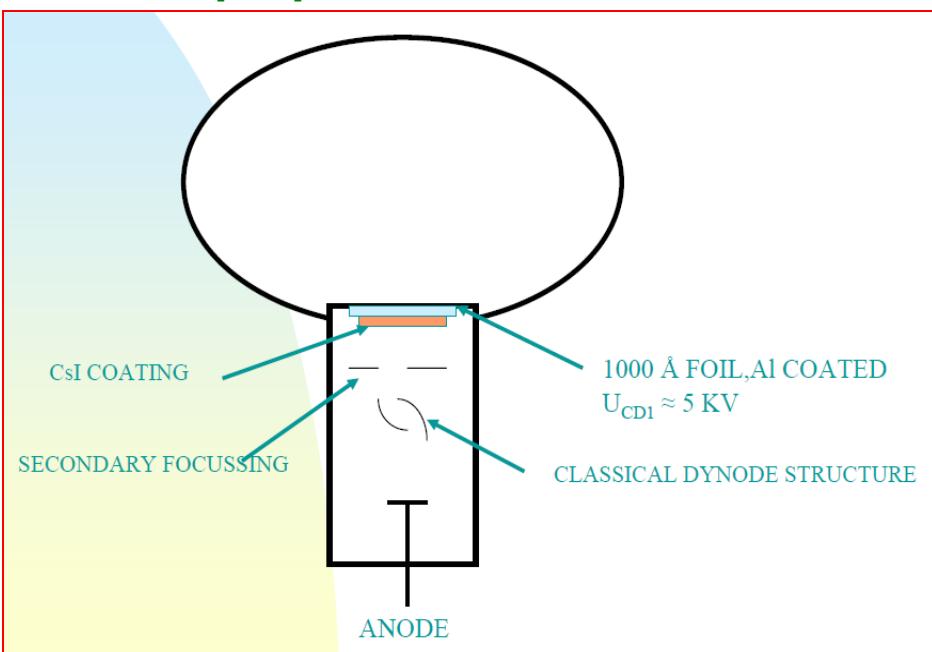


HOW TO MAKE LARGE-AREA PHOTON DETECTORS?

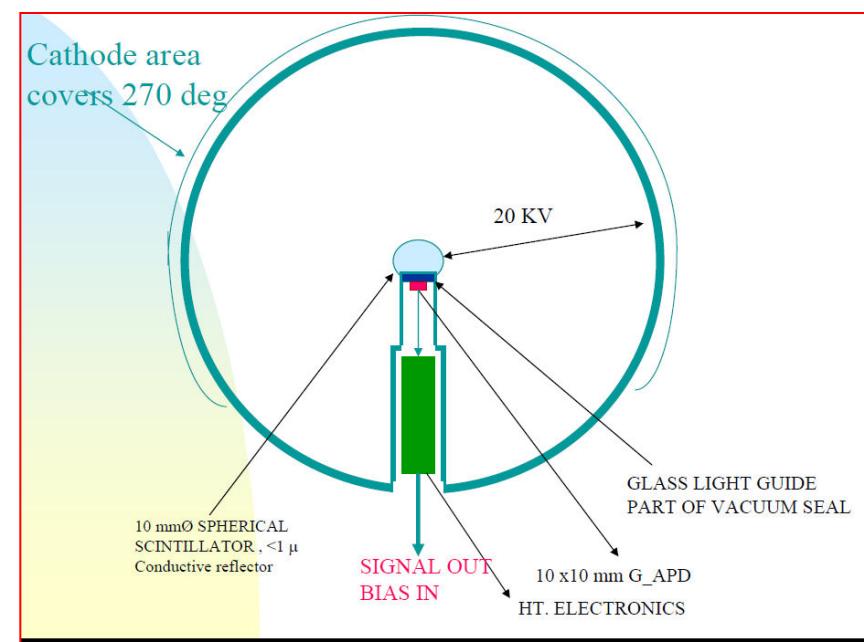
Eckart Lorenz LIGHT06:

THE VACUUM PMT IS AROUND FOR OVER 60 YEARS AND HAS ONLY SEEN MODEST IMPROVEMENTS (INCLUDING PRODUCTION METHODS) OVER THE LAST 50 YEARS: ITS AN 'ARCHAIC DEVICE'

Eckart proposed at LIGHT06:



Photoelectrons accelerated into CsI emitter;
Secondary electrons from CsI are focused & multiplied by dynodes.



Photoelectrons accelerated into fast spherical Scintillator; **light multiplied in a g-APD (SiPM).**