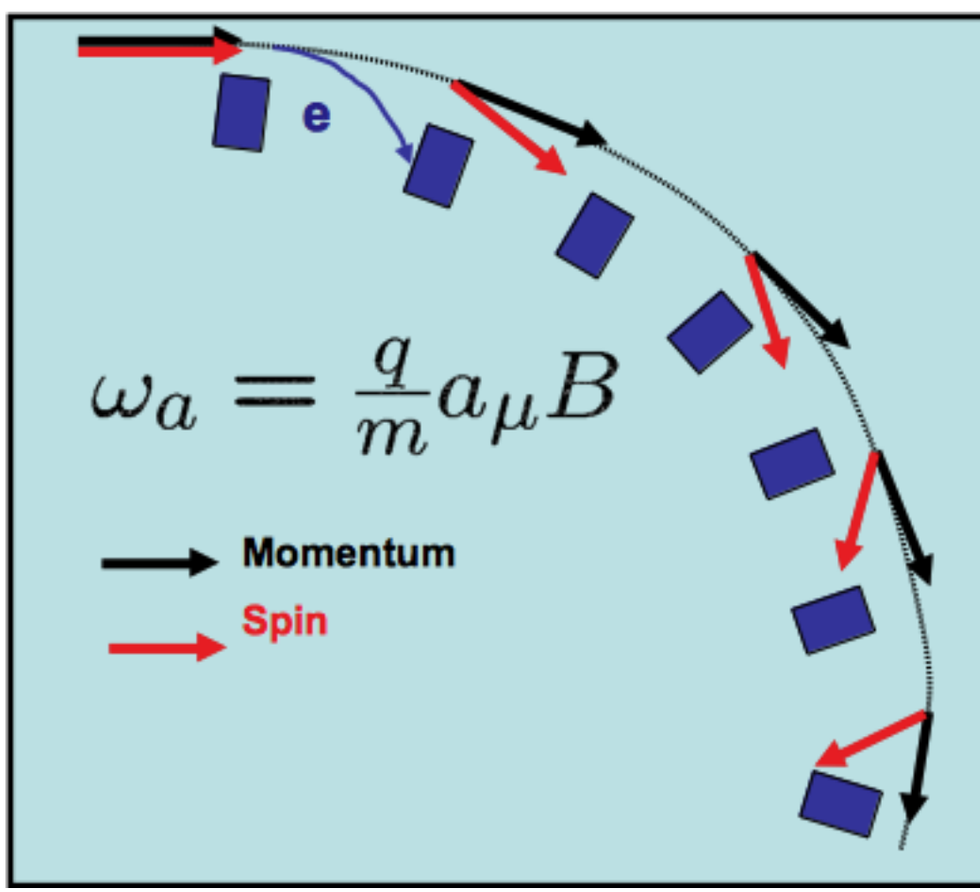
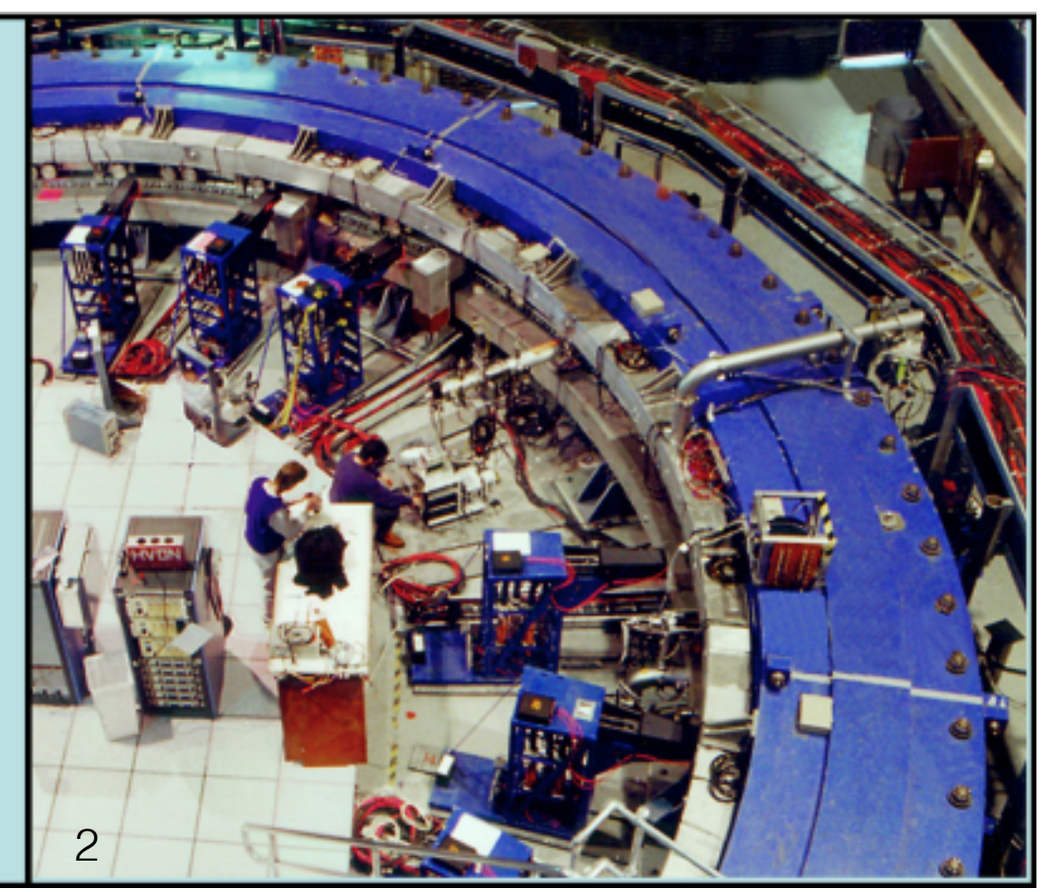
Future measurements of muon (g–2)

Jarek Kaspar, University of Washington

magnetic dipole moment of muon

- torque experienced in external magnetic field
- spin -> intrinsic magnetic dipole moment
- experiment measures how fast spin rotates

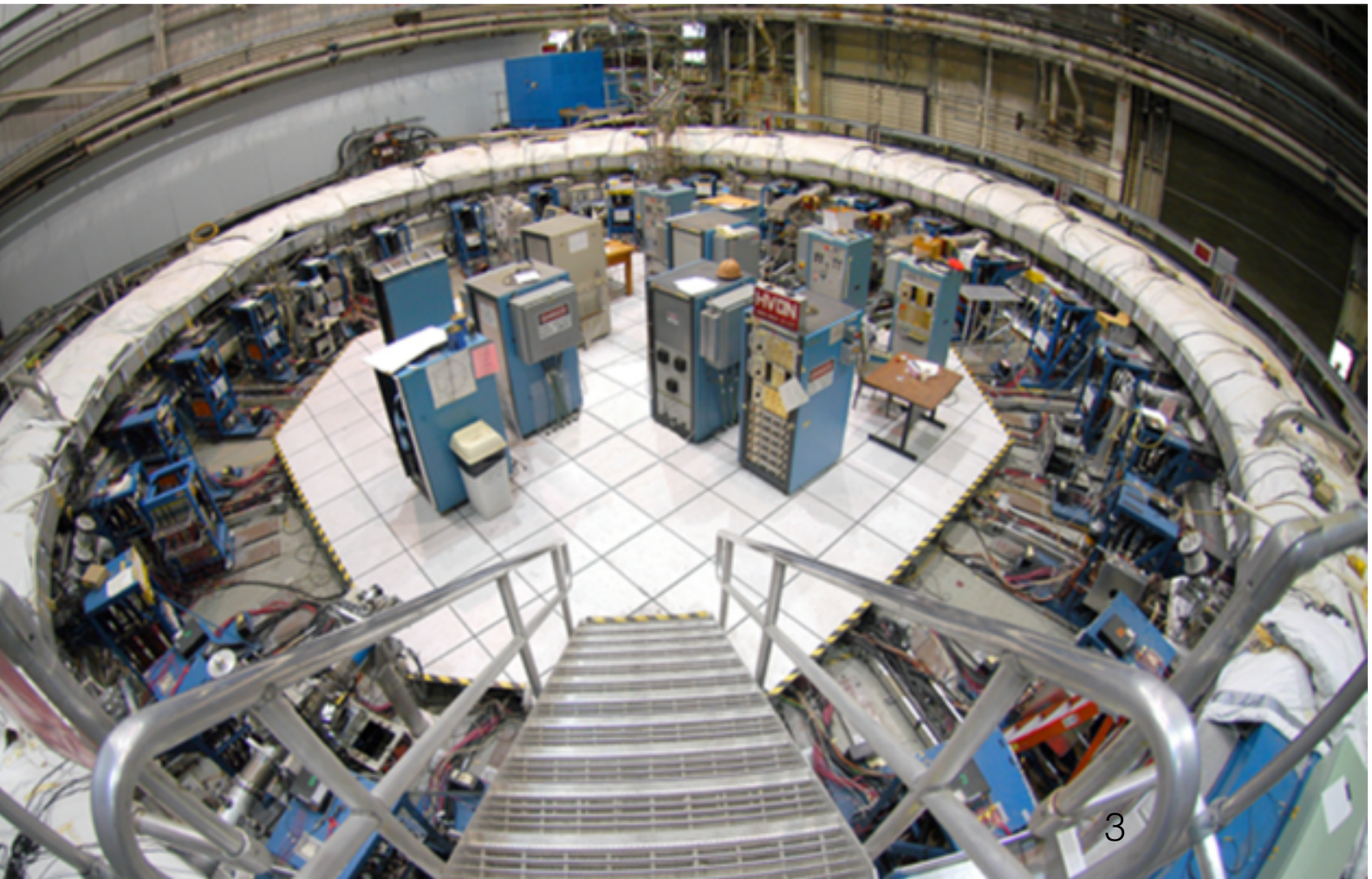




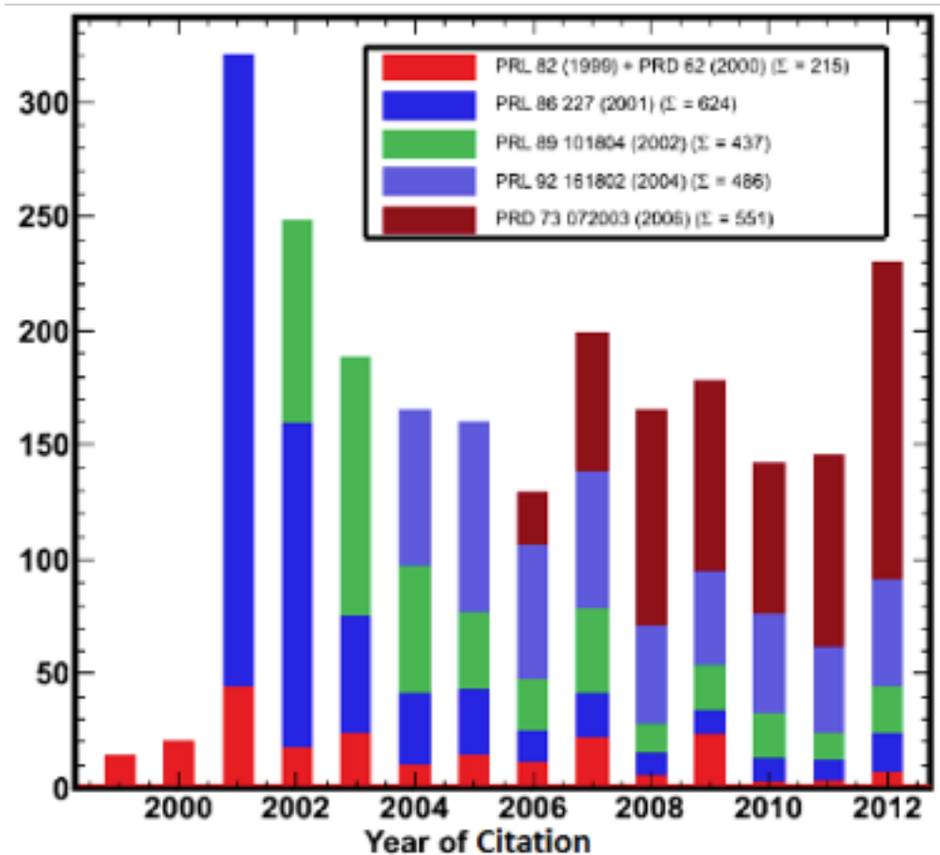
g – 2 experiment at BNL

E821 (1999 - 2006):
a_μ = 0.001 165 920 89 (63) (±0.54 ppm)
And a hint of New Physics ?

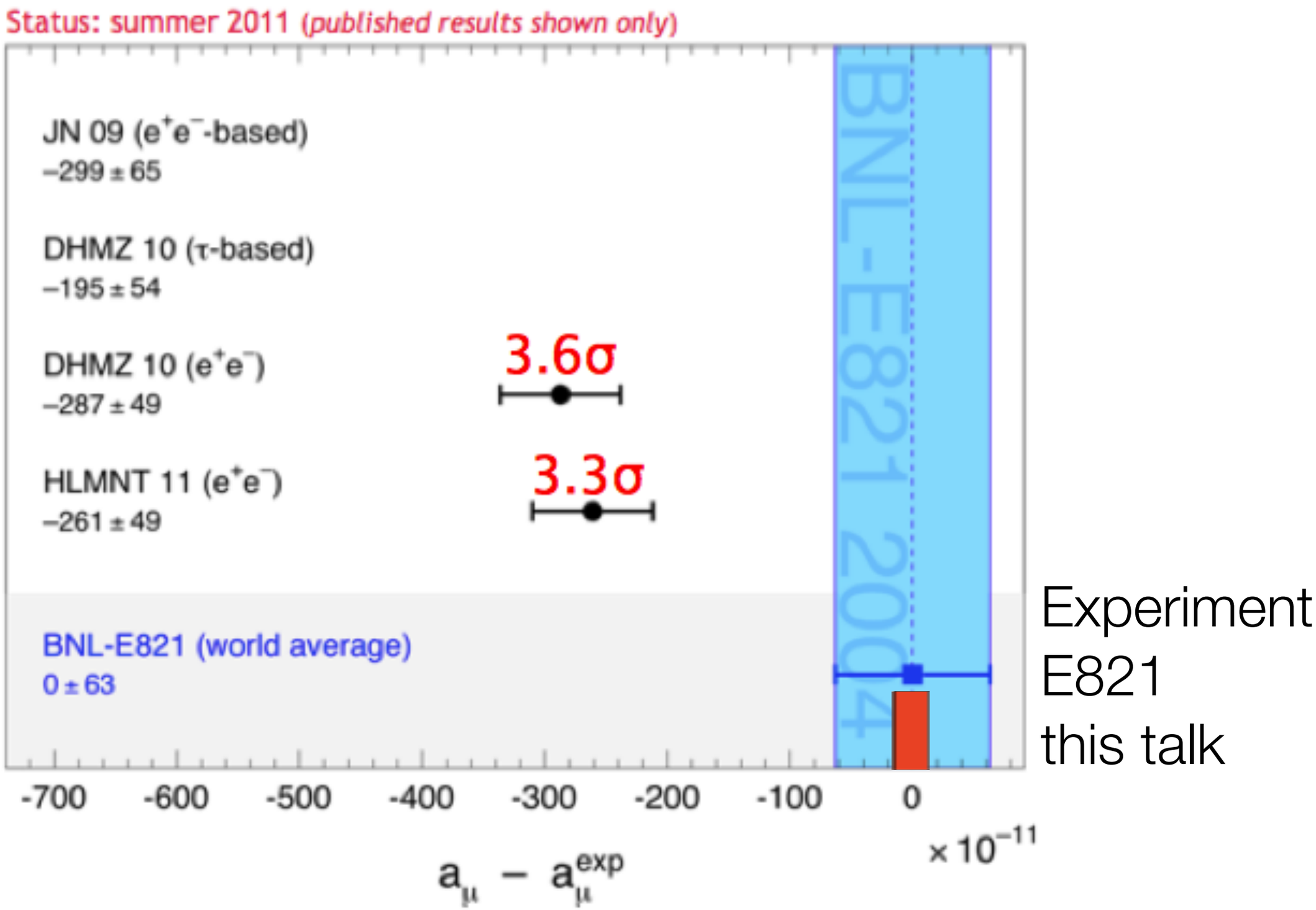
Figure 1.10: A picture from 1984 showing the attendees of the first collaboration meeting to develop the BNL g-2 experiment. Standing from left: Gordon Danby, John Field, Francis Farley, Emilio Picasso, and Frank Krienen. Kneeling from left: John Bailey, Vernon Hughes and Fred Combley.

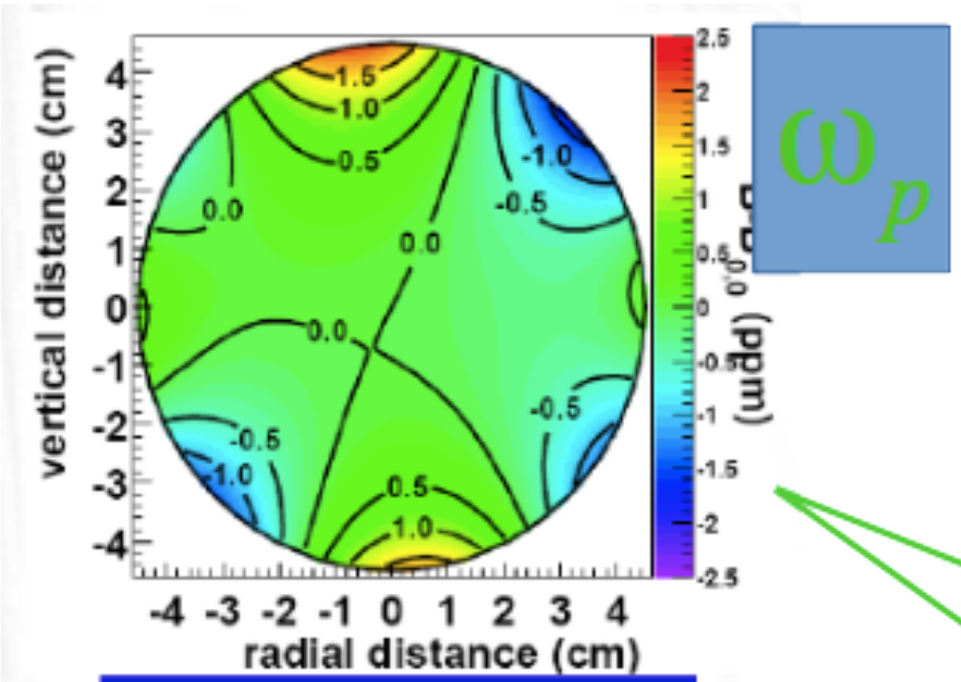


A highly cited result

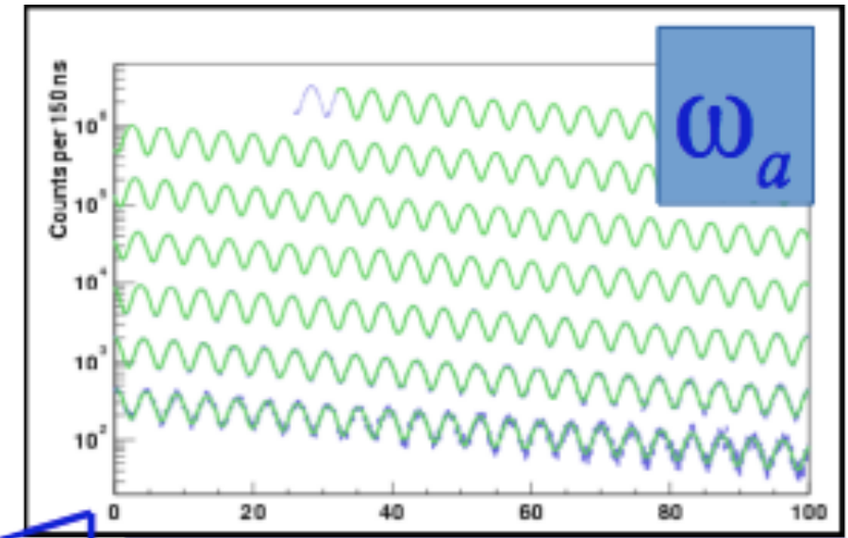


Standart Model prediction



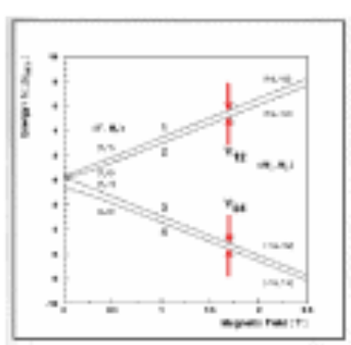


Our "Magnet"



Our conventional Detector, Electronics, and DAQ systems

$$a_\mu = \frac{\frac{\omega_a}{\omega_p}}{\frac{\mu_\mu}{\mu_p} - \frac{\omega_a}{\omega_p}}$$



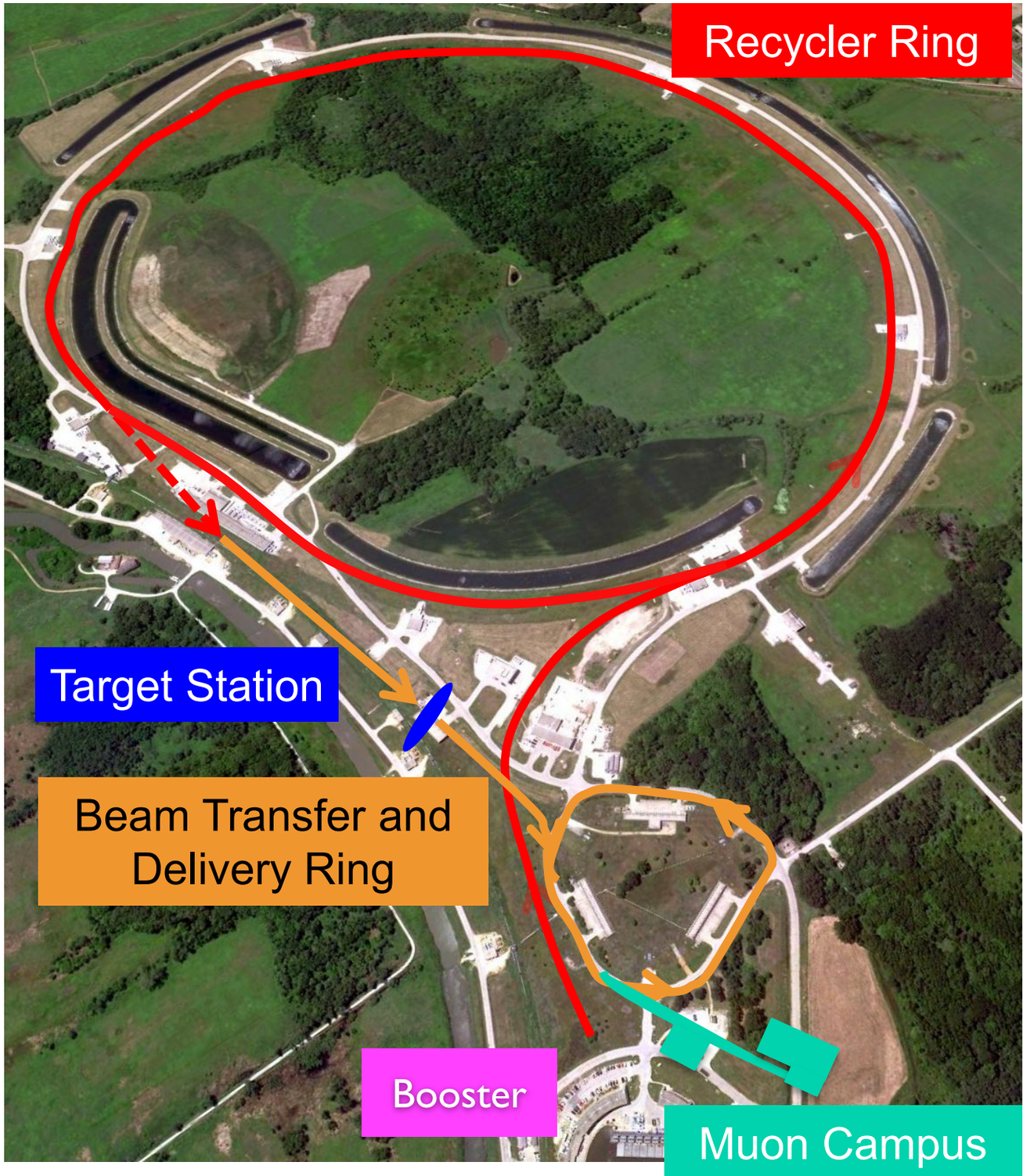
μ_μ/μ_p = 3.183 345 24(37) (120 ppb)
= *3.183 345 39(10) (31 ppb)*

External Muonium Hyperfine Expt.

principles of ω_a measurement

1. source of polarized muons (P violating pion decay)
2. precession proportional to *(g – 2)*
3. magic momentum
4. parity violating decay (positron reports on spin)

1. source of polarized muons

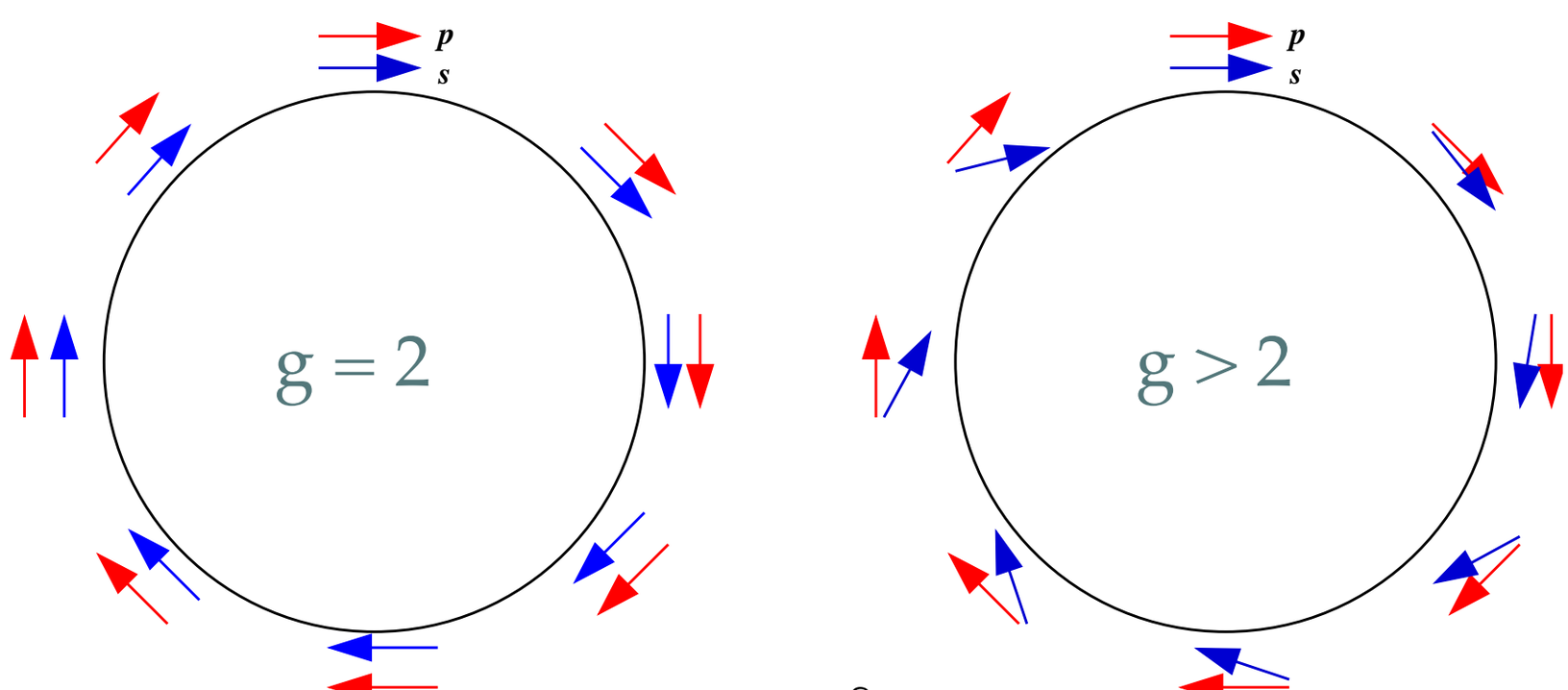


- Recycler
  - 8 GeV protons from Booster
  - Re-bunched in Recycler
  - New connection from Recycler to P1 line (existing connection is from Main Injector)
- Target station
  - Target
  - Focusing (lens)
  - Selection of magic momentum
- Beamlines / Delivery Ring
  - P1 to P2 to M1 line to target
  - Target to M2 to M3 to Delivery Ring
  - Proton removal
  - Extraction line (M4) to g-2 stub to ring in MC1 building

2. precession proportional to $g - 2$

$$\omega_C = \frac{eB}{mc\gamma} \qquad \omega_S = \frac{geB}{2mc} + (1-\gamma)\frac{eB}{\gamma mc}$$

$$\omega_a = \omega_S - \omega_C = \left(\frac{g-2}{2}\right)\frac{eB}{mc} = a\frac{eB}{mc}$$



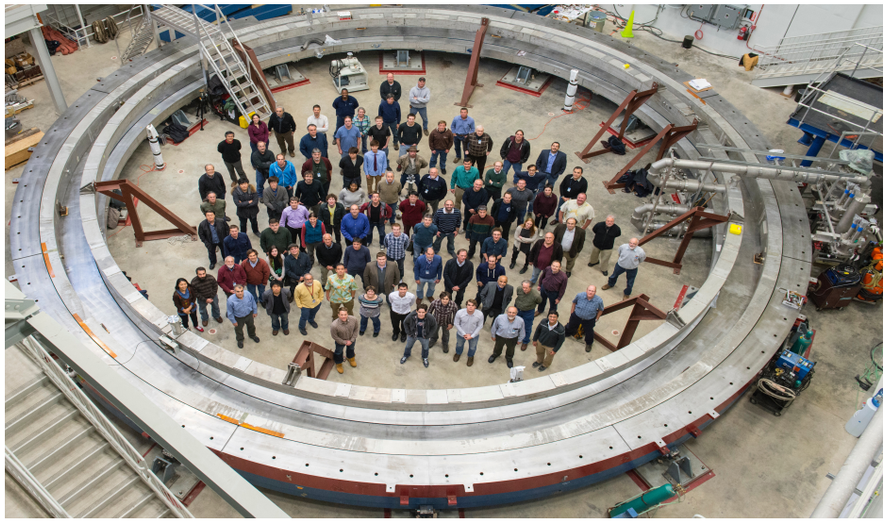
3. magic momentum

- electric quadrupole used for vertical focusing

$$\vec{\omega}_a = -\frac{e}{m}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta} \times \vec{E}}{c}\right]$$

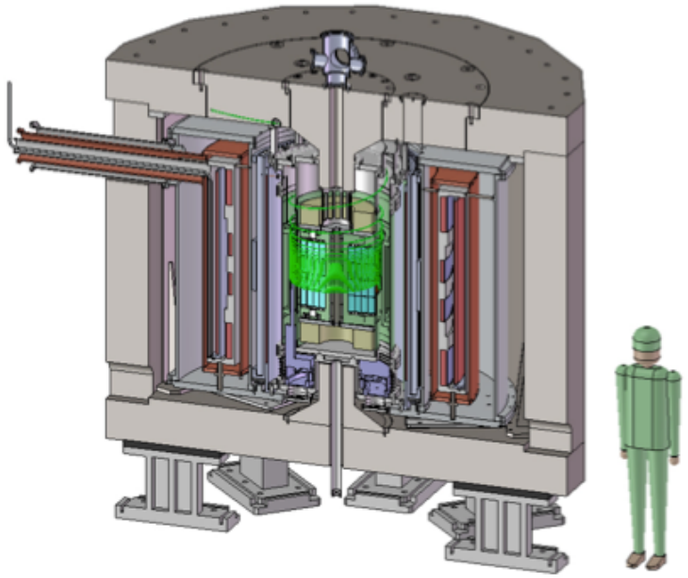
- either select γ = 29.3, muon momentum 3.094 GeV
- or don't use electric focusing

Fermilab E989 vs E34 J-PARC



- R 7m storage ring
- 1.45 Tesla magnetic field
- magic momentum: 3.09 GeV/c
- **high-rate muon beam**

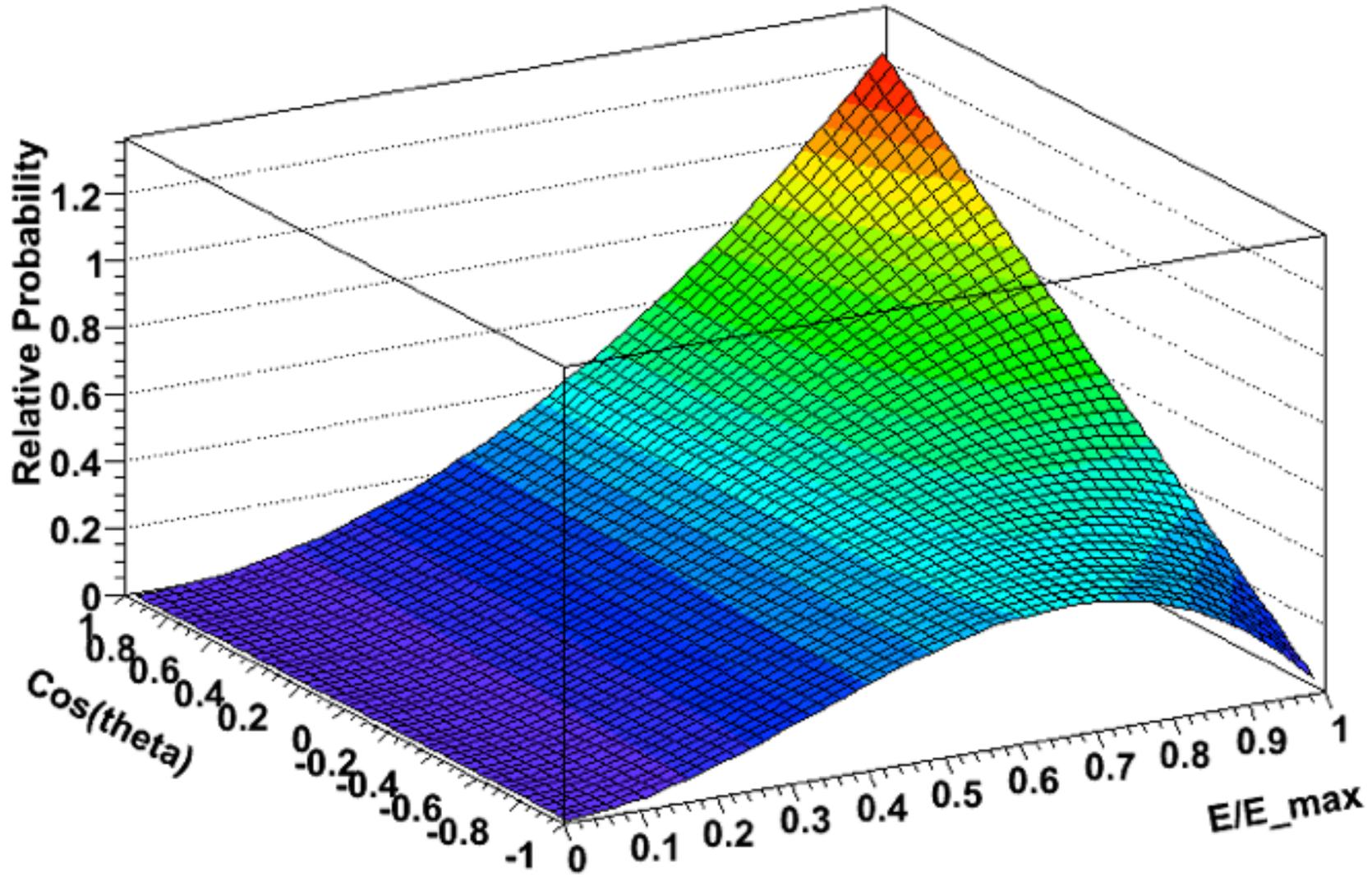
- Polarization ~ 97%
- Data taking 2017-2018
- 140 ppb by end of 2019



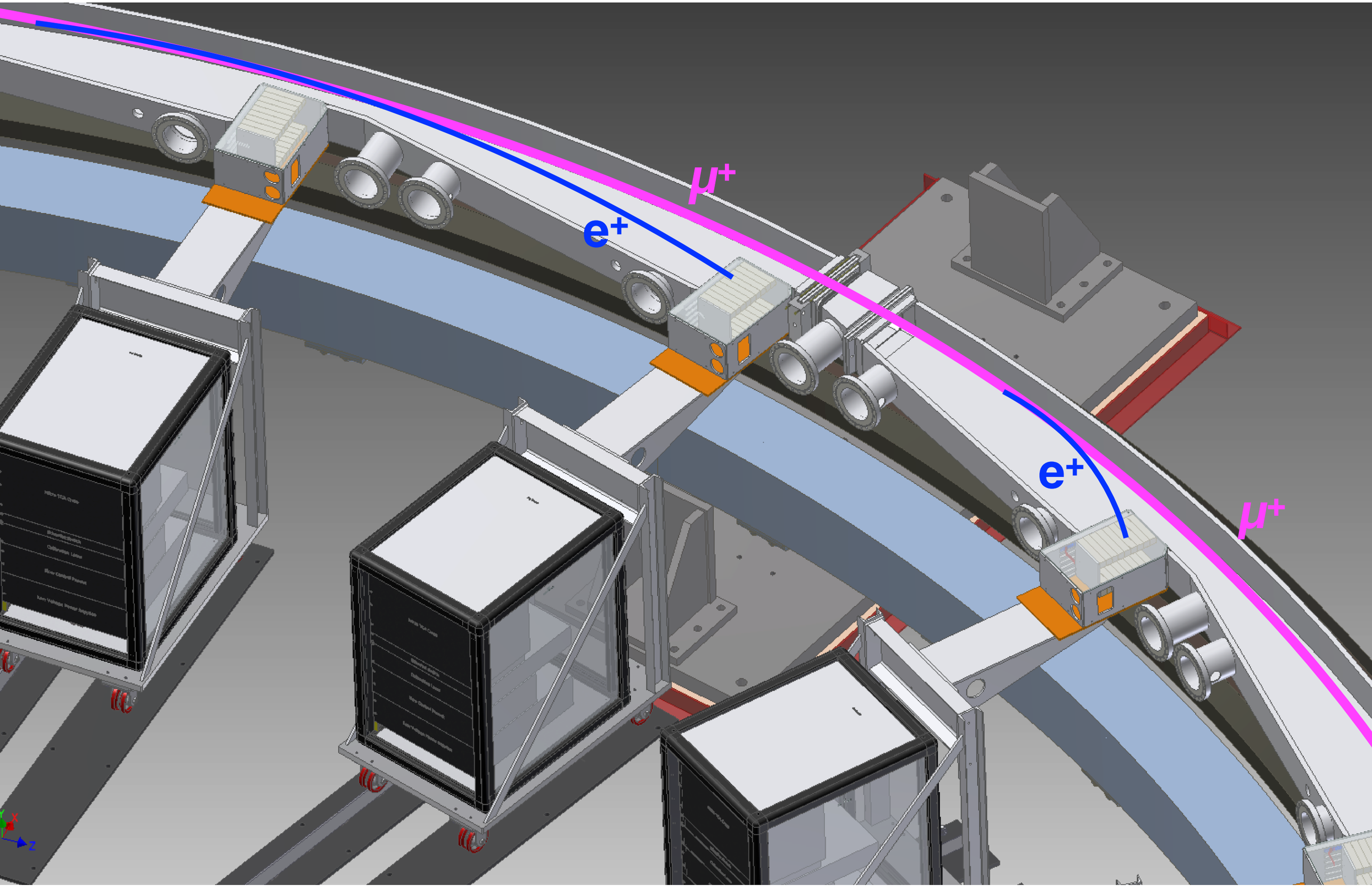
- R 0.33m storage ring
- 3 Tesla, no electric field
- surface muon beam,muonium,
  ~0.3 GeV/c muon beam
- **can control spin direction**

- Polarization ~ 50%
- Data taking 2019-2021
- 400 ppb by end of 2023

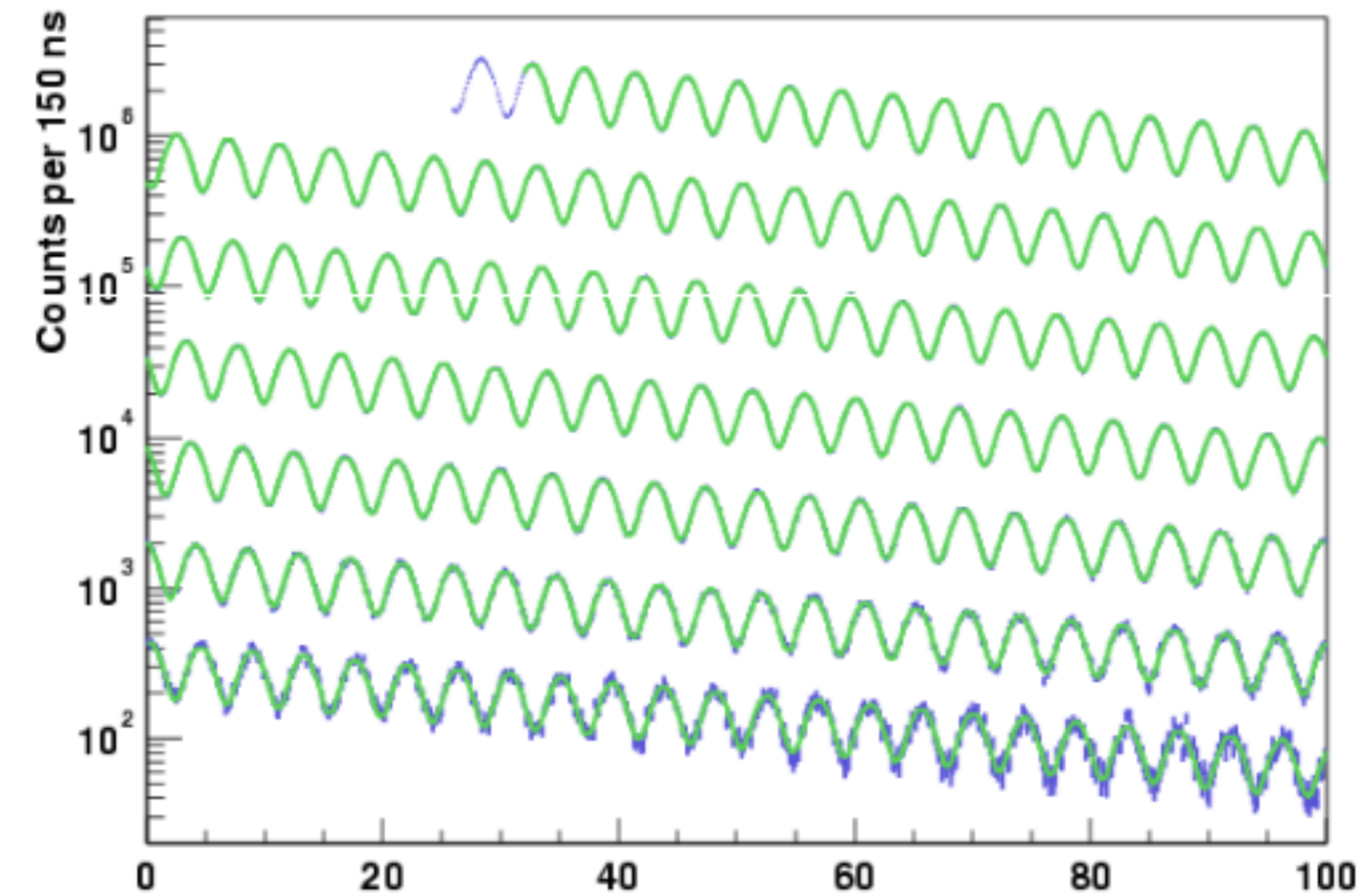
4. parity violating decay

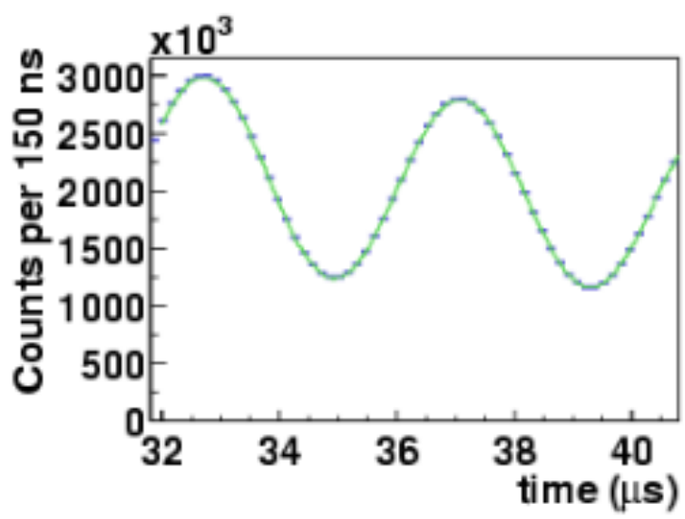


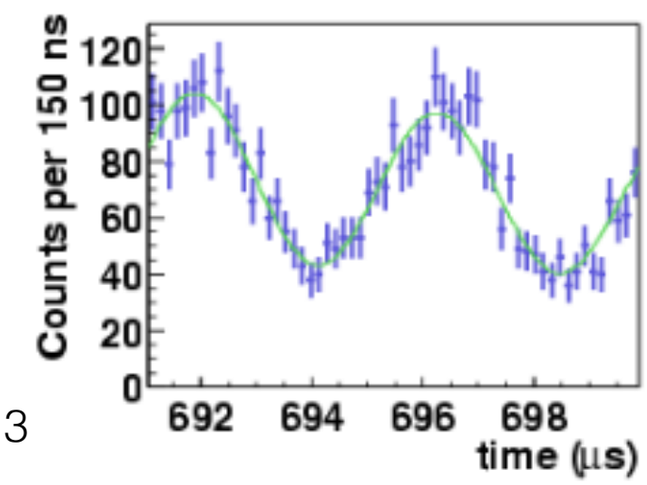
- muon -> electron and two neutrinos
- electron carries information on muon's spin
- positron prefers spin direction
- electron would prefer opposite direction

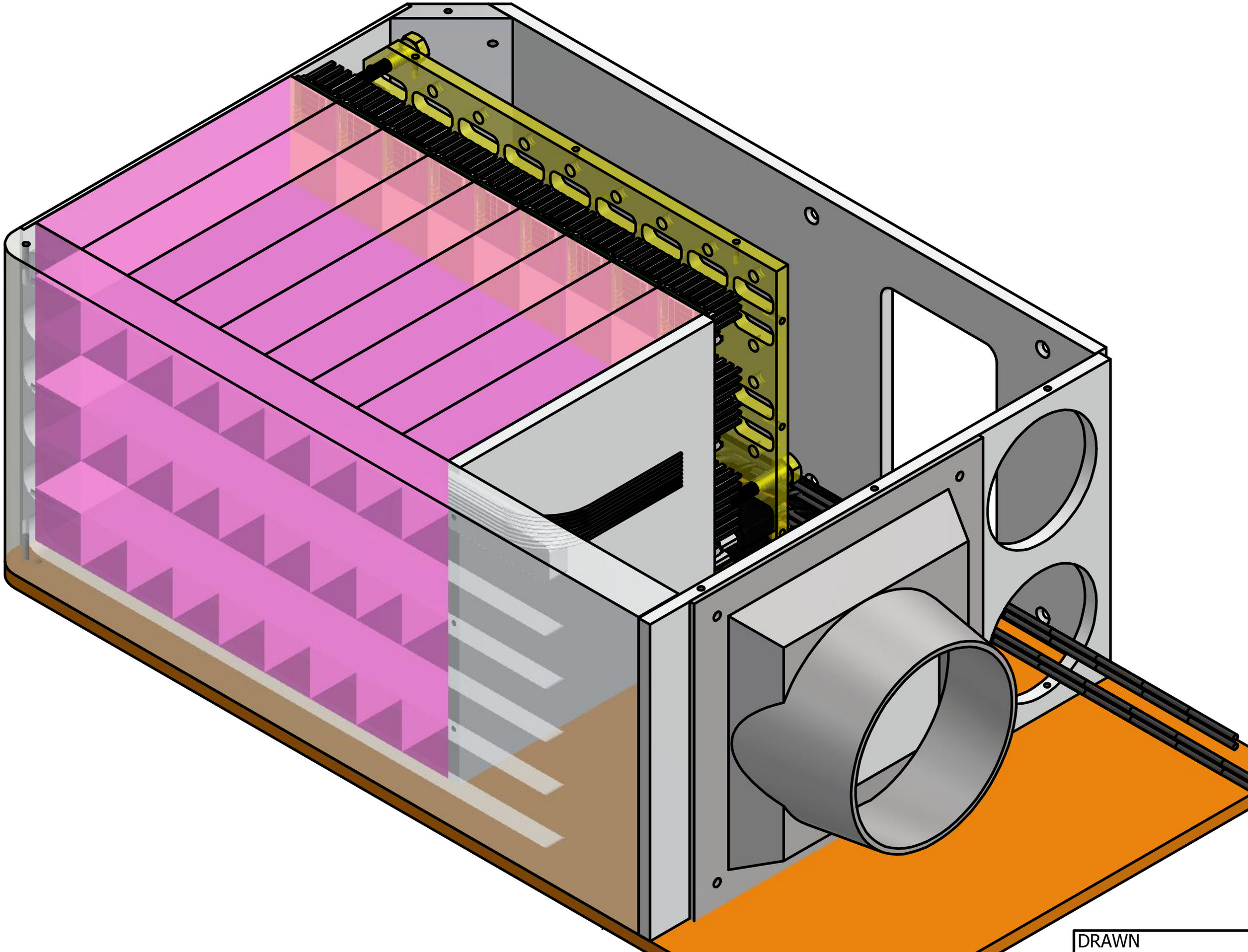

μ+
e+
e+
μ+

extract frequency ω_a

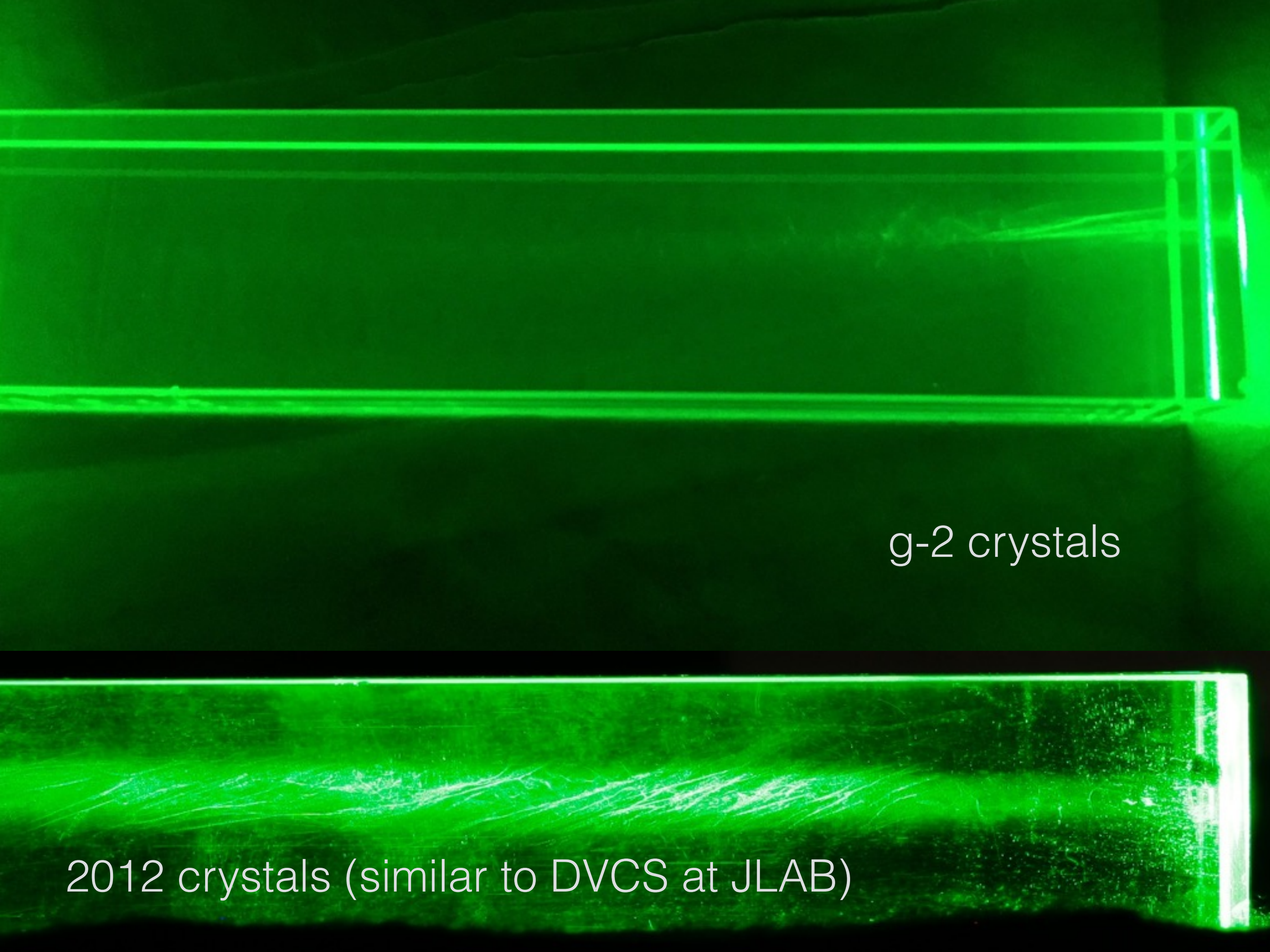


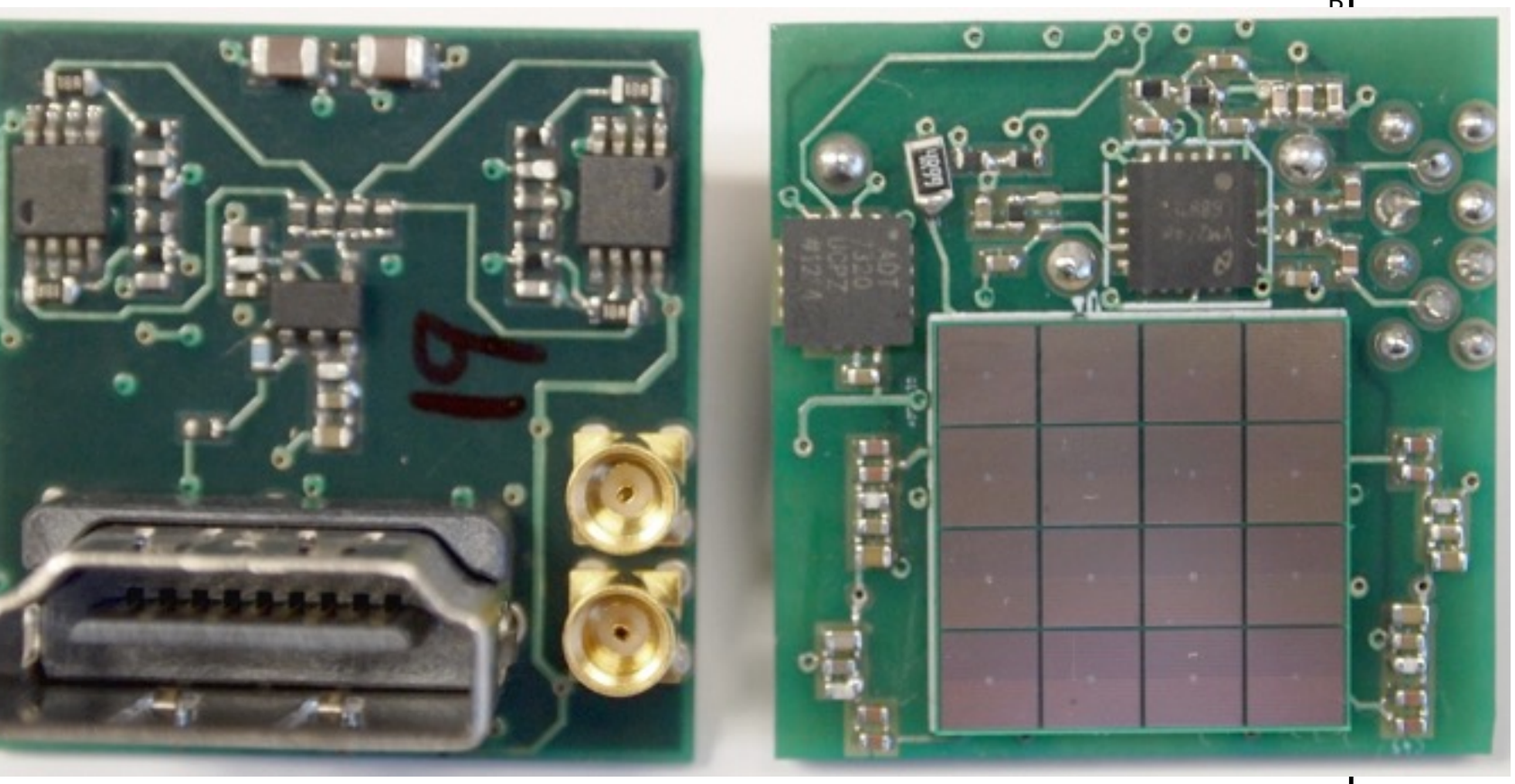


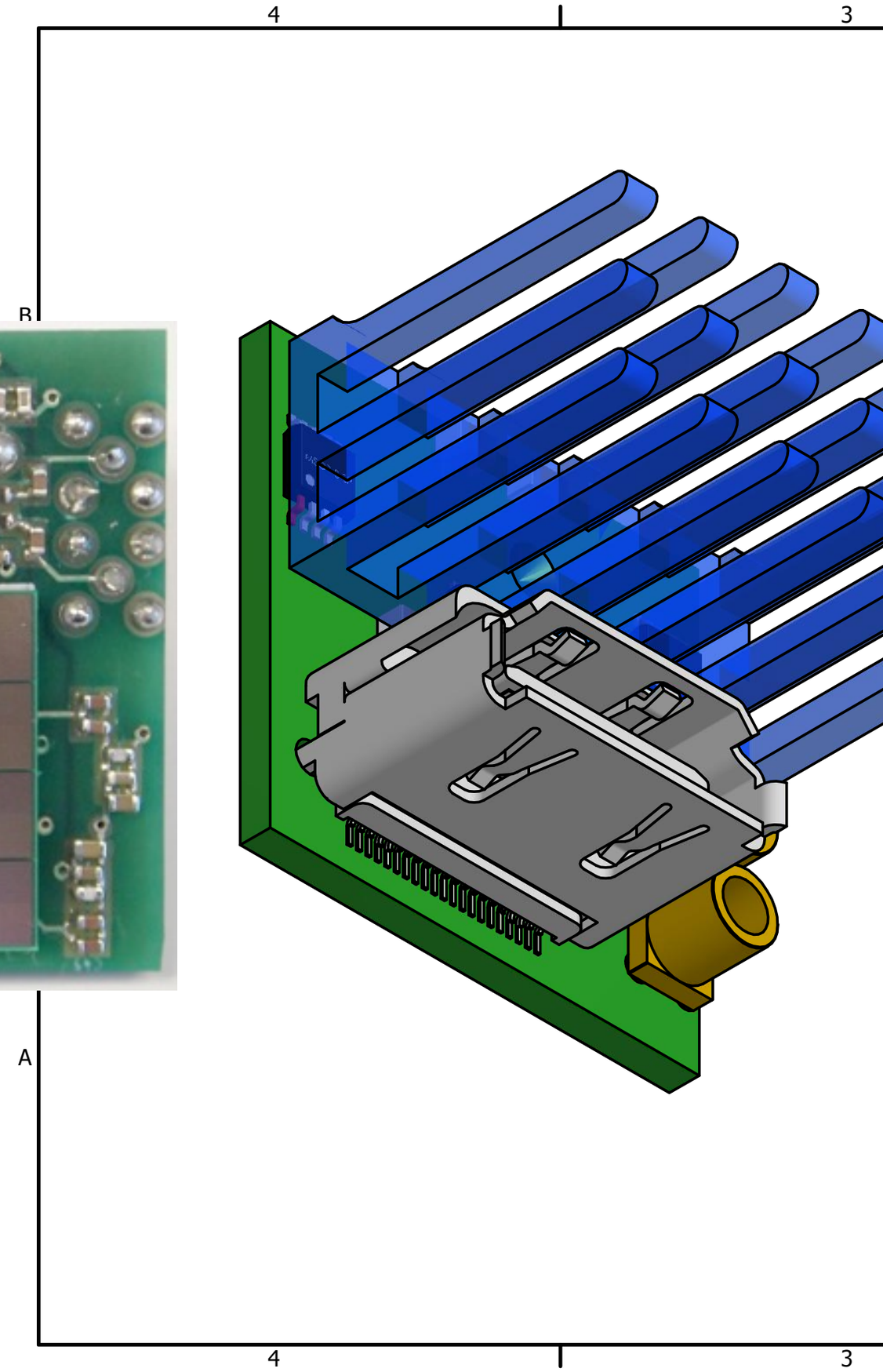




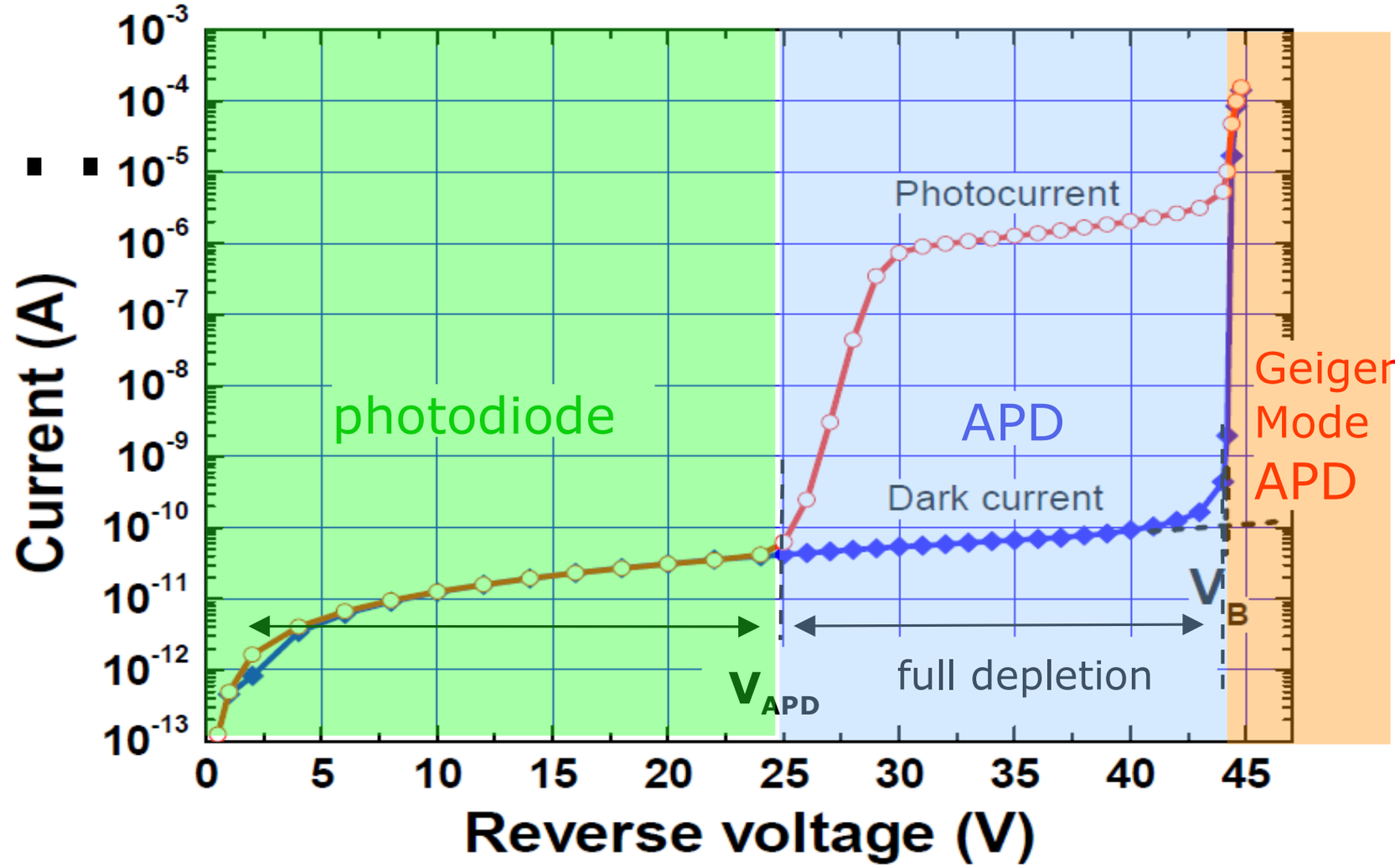
DRAWN


g-2 crystals
2012 crystals (similar to DVCS at JLAB)




4
3
B
A
4
3

A SiPM is…



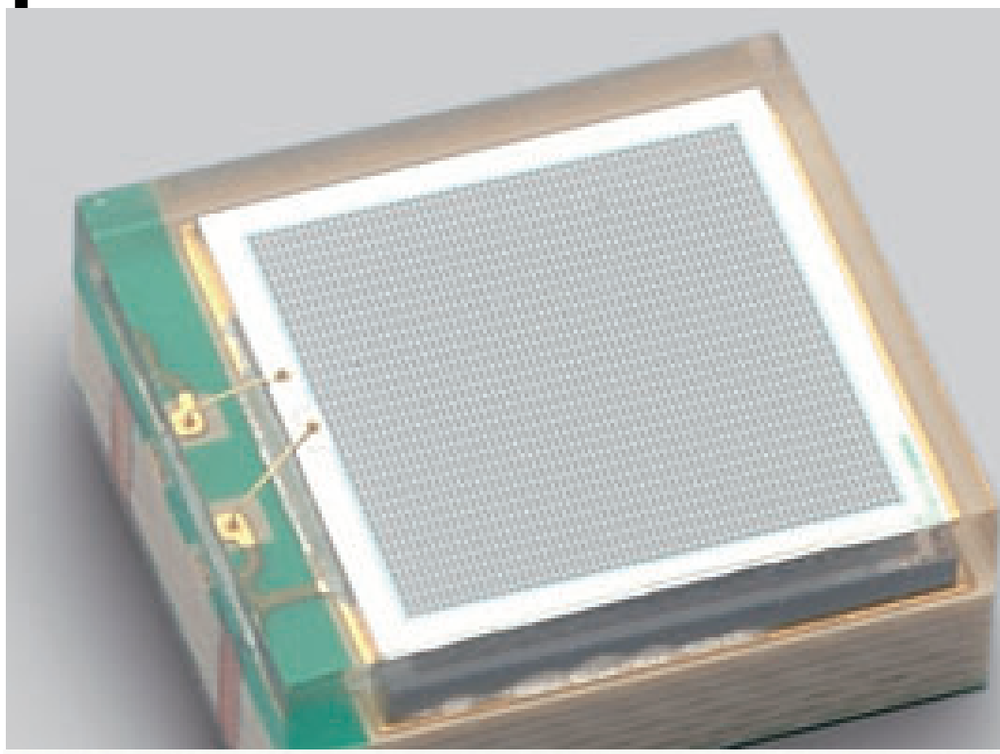
- take a photo-diode
- reverse-bias it above breakdown voltage (Geiger mode avalanche photo diode)
- add quenching resistor
- repeat many thousand times

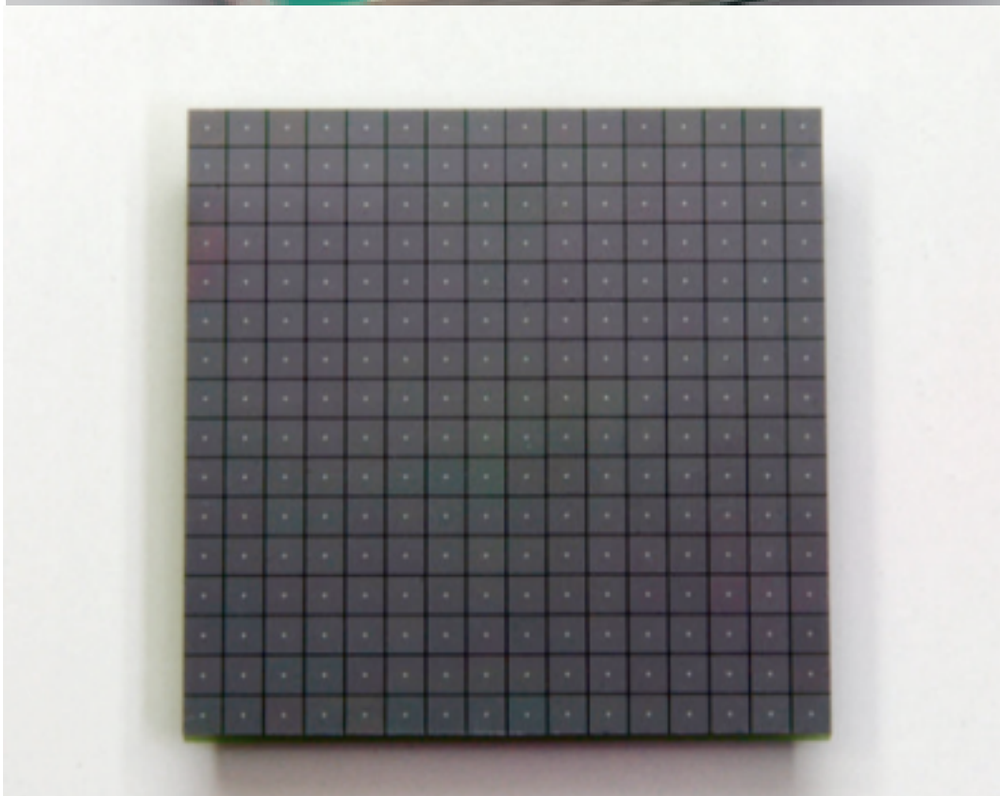
Huge variety of products

Hamamatsu
KETEK
SensL
Philips
ST Microelectronics

1x1 – 52 x 52 mm

10 – 200 um pixels

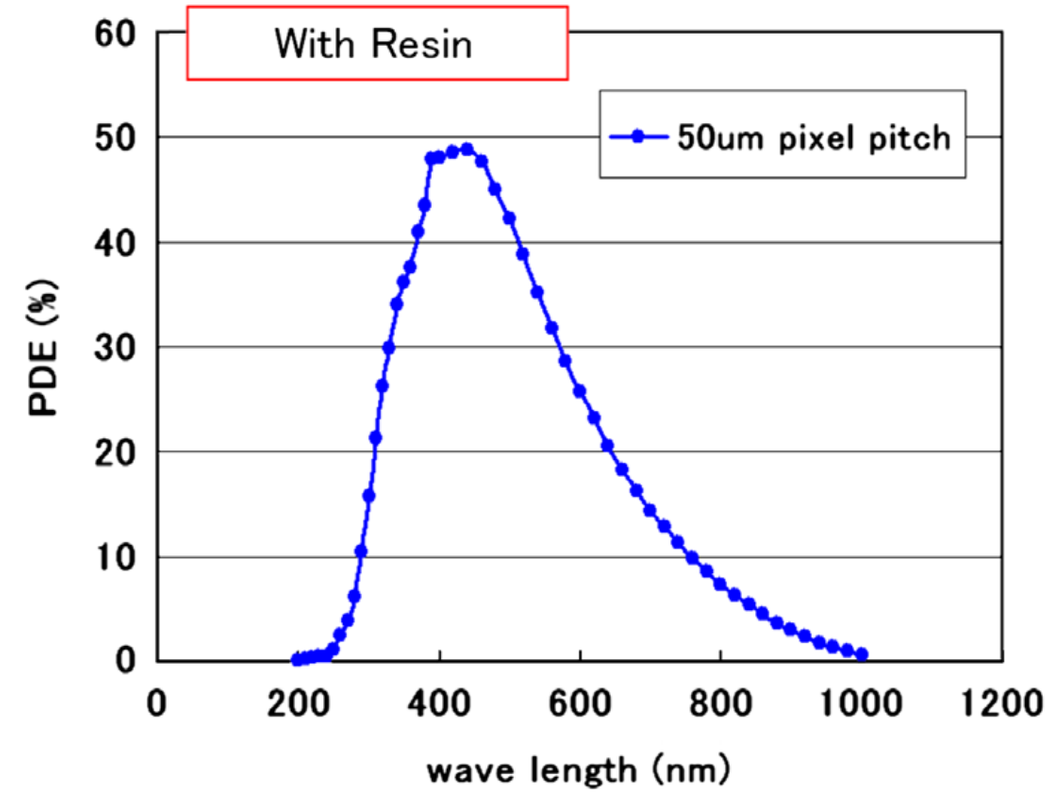




Theory of operation

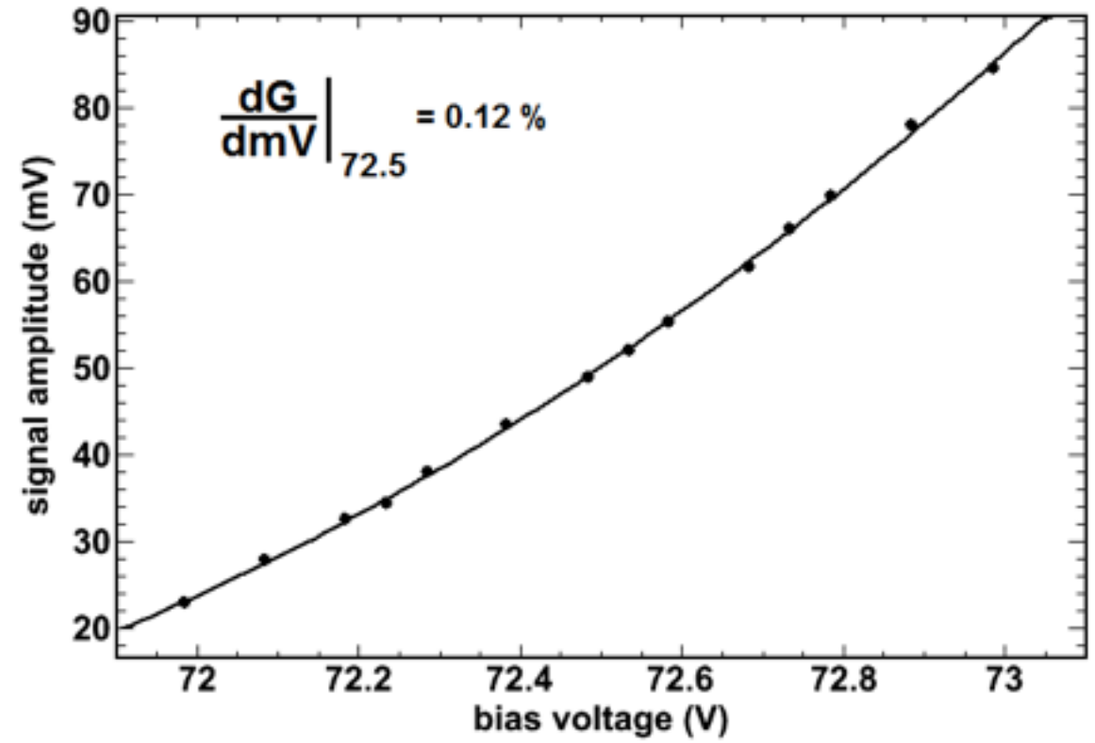
- each pixel is an independent detector
- when pixel fires, it delivers charge (~1e6 electrons) (regardless how many photons hit the pixel)
- then the pixel is dead for ~100 nsec (recovery time)
- many times more pixels on the device than photons

Advantages

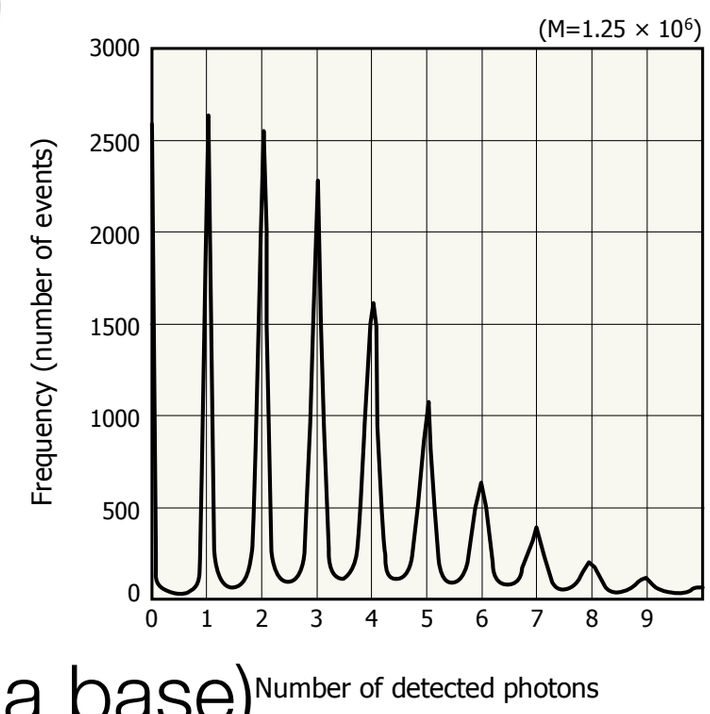


- fast like PMT, compact, cheap
- runs in magnetic fields, is non-magnetic
- high photo detection efficiency
- low voltage (typ. 40 or 70 V, diode orientation)
- much lower radioactivity than PMT

Disadvantages



- temperature dependence
  photo-effect (sec. order, cryo)
  probability electron triggers avalanche discharge
  gain (charge delivered by a pixel when it fires)
  breakdown voltage
  -> temperature monitoring
  -> in situ calibration
  (0,1,2 ph comb, or laser)



- batteries not included
  no standard pre-amplifier (think PMT without a base)

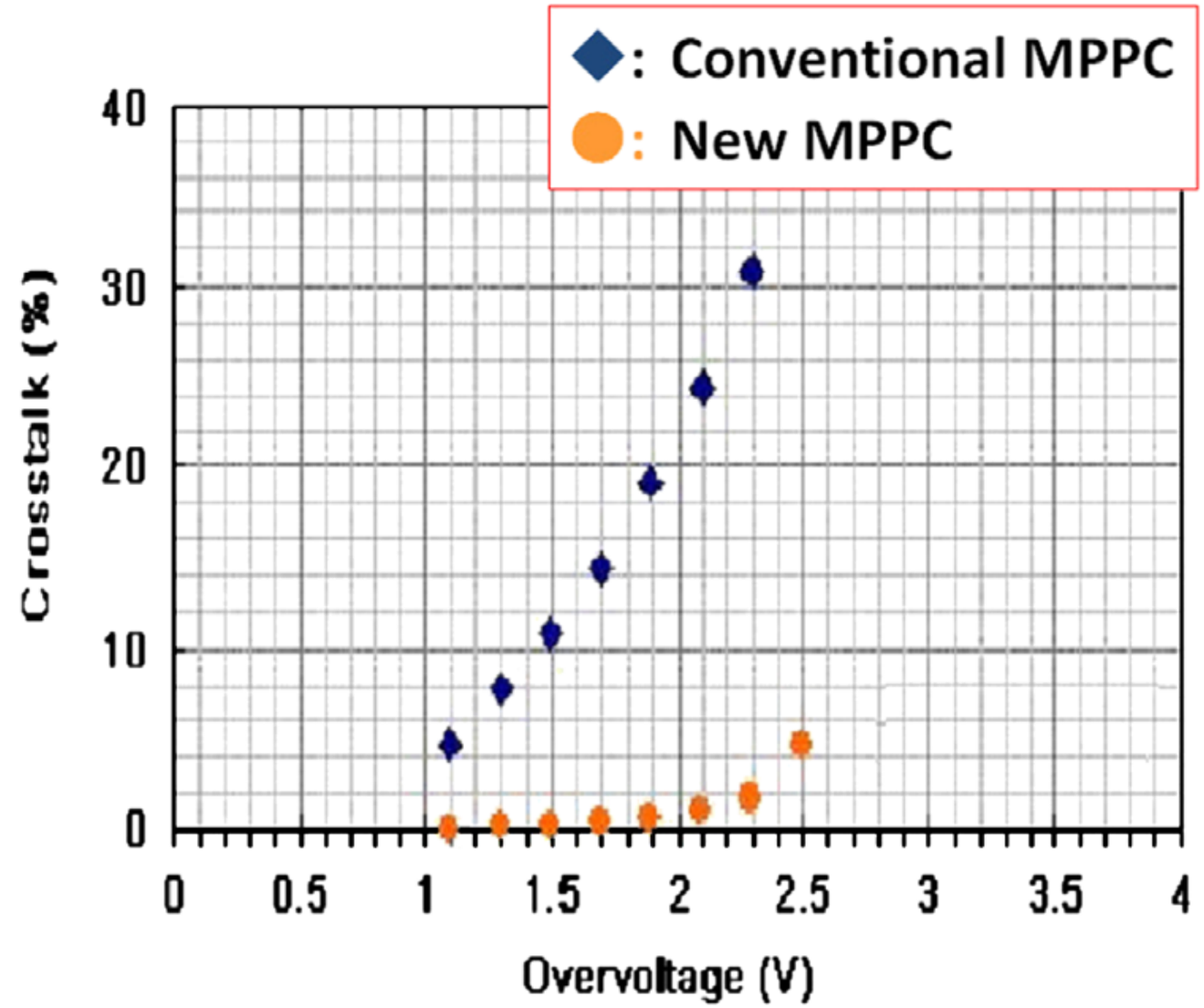
Heavy duty & Cryo compatible

- photon absorption length depends on temperature
- easy down to 100 K (SiPMs like that)
- modified runs well in LXe, LAr
  anti-reflective coating (UV eff), cryo comp package
  K.Sato NIM A 732, 2013 (427–430)
- charge carrier freeze-out < 50 K

Historical artifacts

- cross-talk -> optical trenches
- after-pulsing -> Si wafer purity
- high dark rate -> Si wafer purity
- slow pulses, pulse dependent on temperature -> metal (Ni) based quenching resistor
- high cost -> now often cheaper than PMT

cross-talk



- real photons emitted
  during avalanche discharge

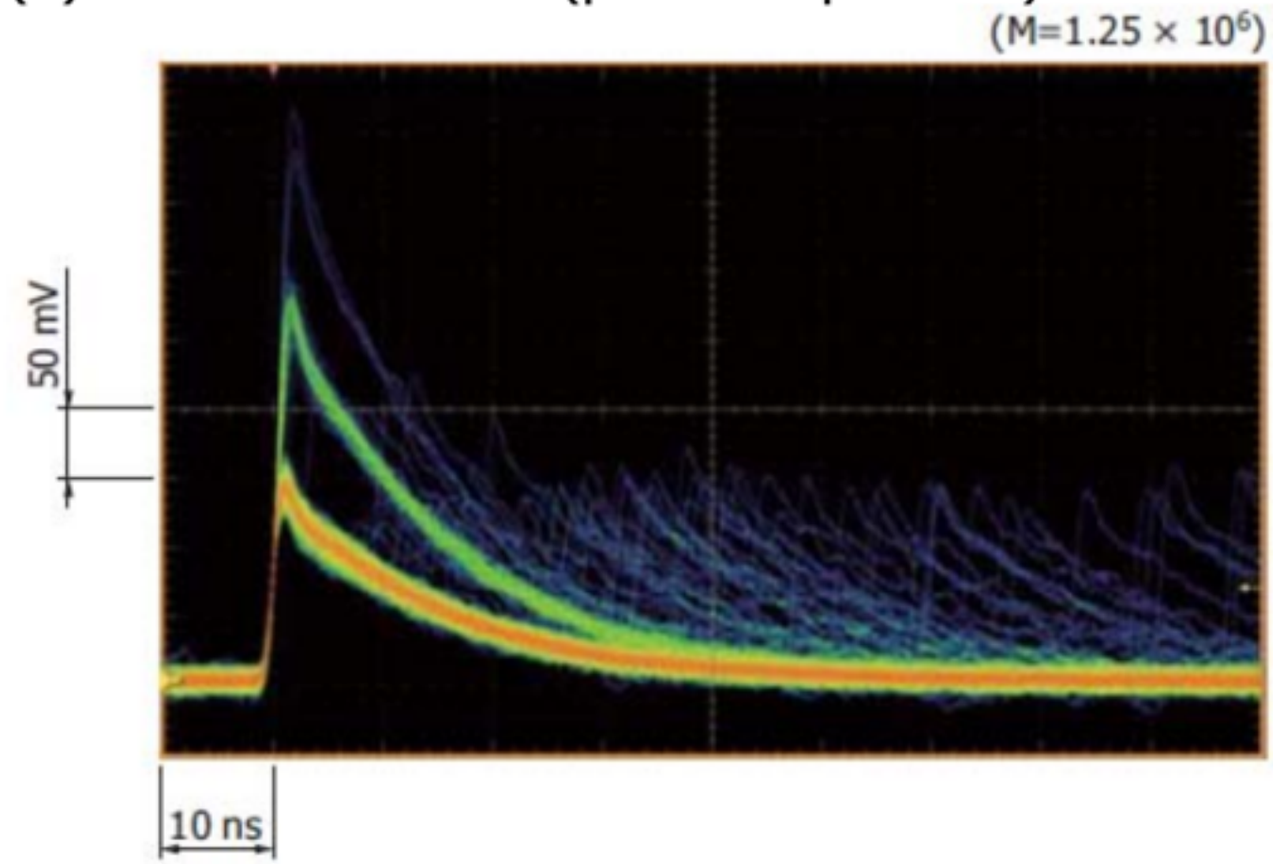
- problem for stat properties of pulses
  e.g. mean over sigma squared proxy
  for number of pixels fired

- optical trenches

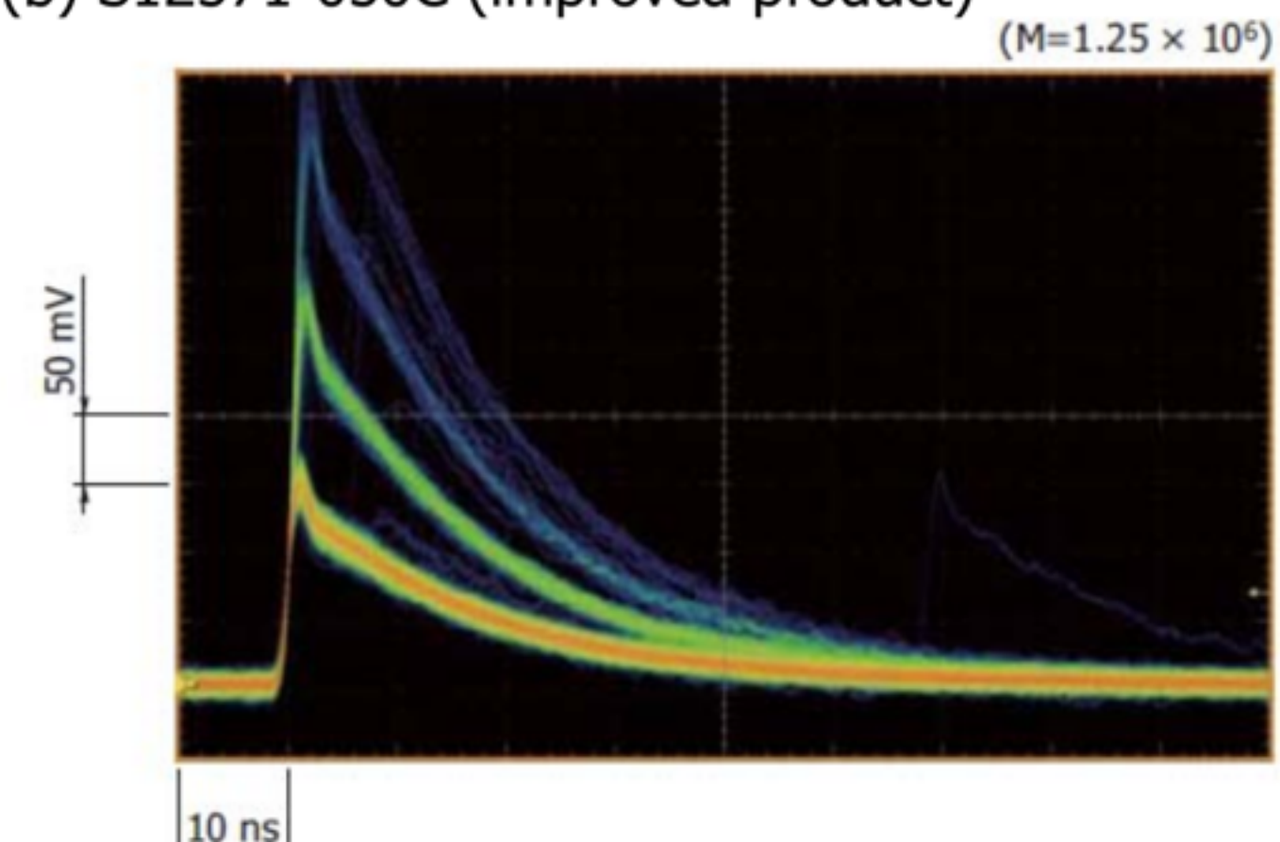
after-pulsing

- incomplete discharge
- part trapped
- delayed release

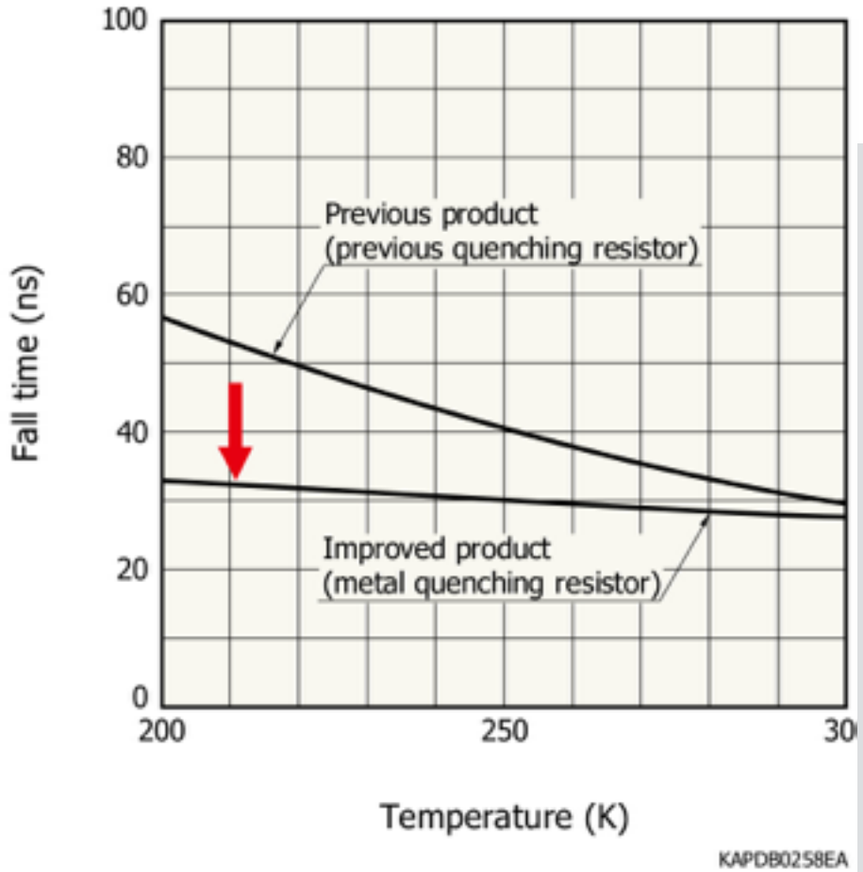
(a) S10362-11-050C (previous product)

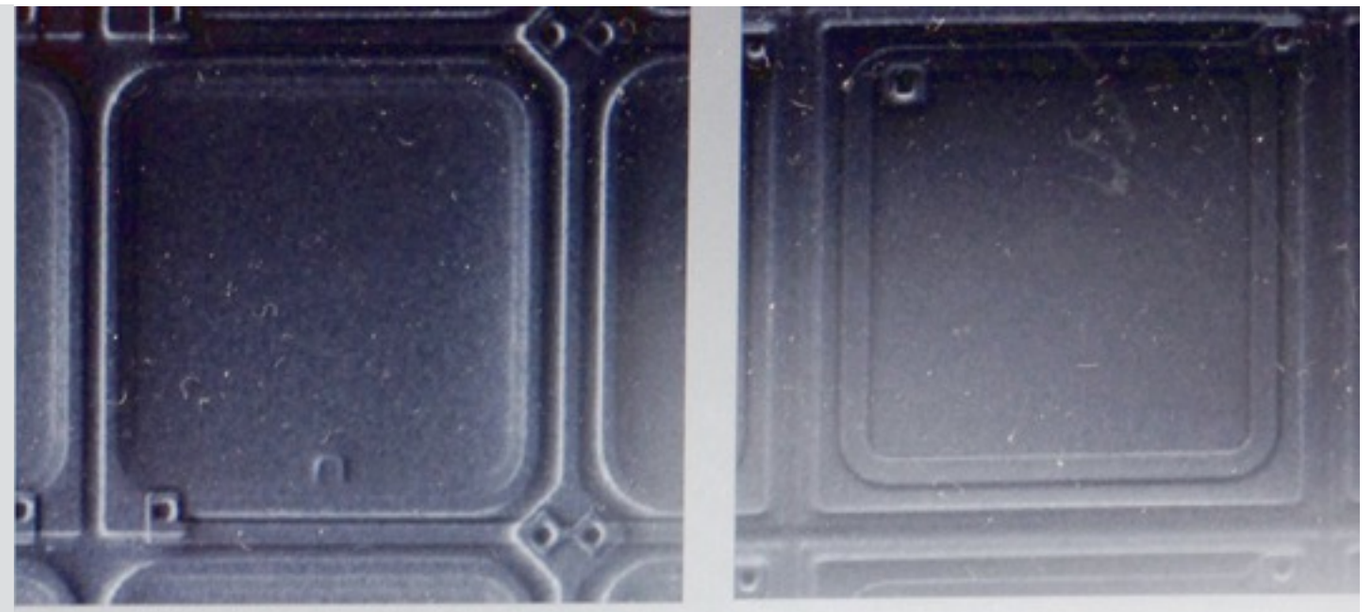


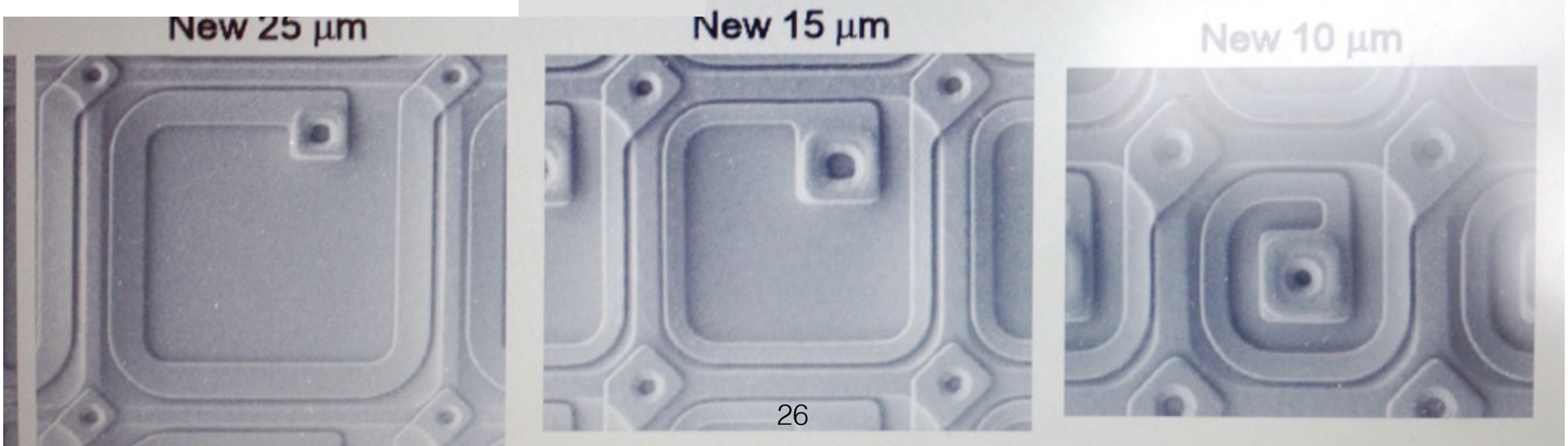
(b) S12571-050C (improved product)



Ni based quench resistor





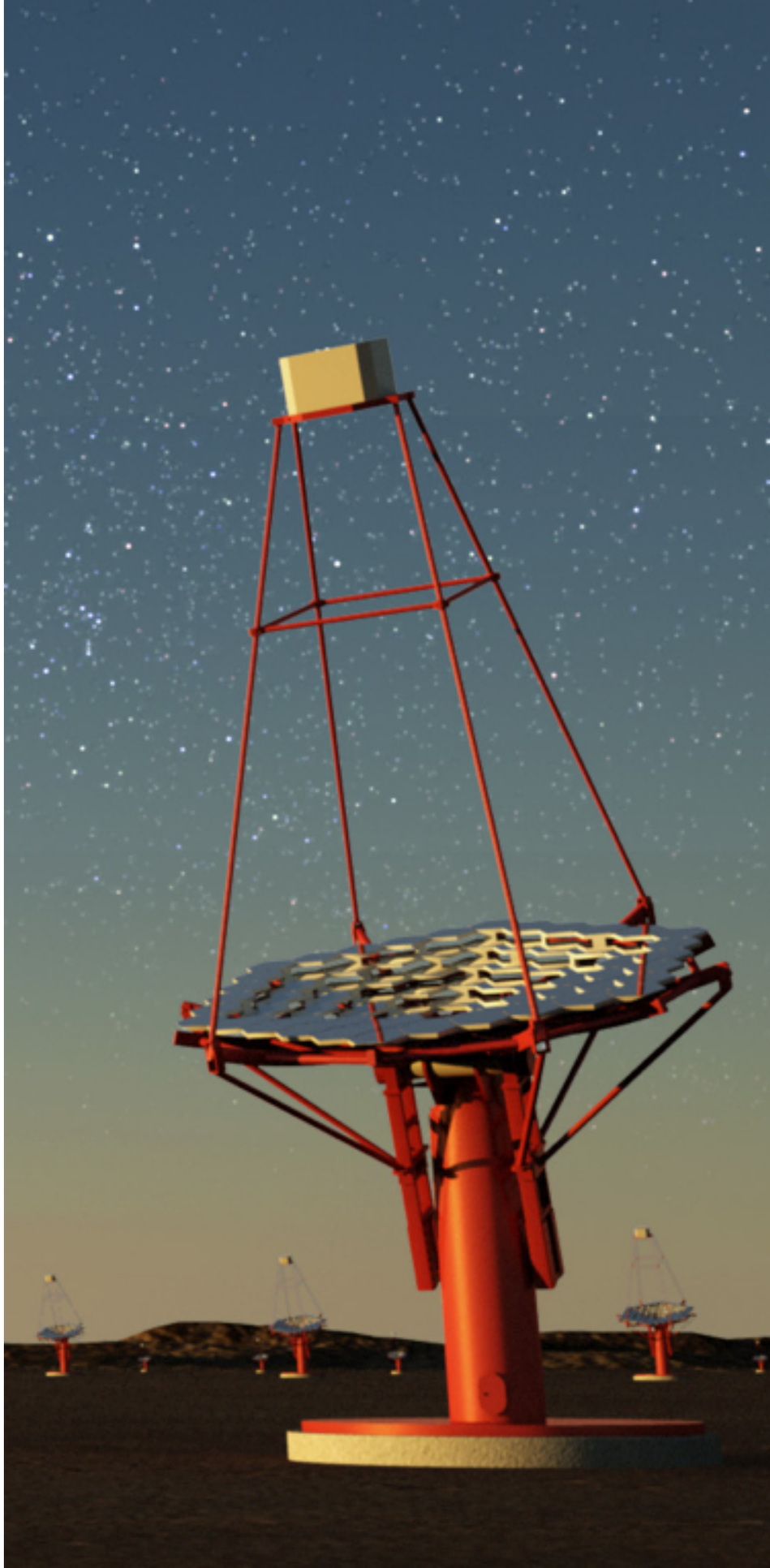


examples of use

- Cerenkov telescopes (CTA)
  single photons, shaping, clipping, pole-zero correction

- hadron calorimeters
  ~1000 photons
  Cerenkov, fast scint, or both

- positron emission tomography
  TOF



pre-amplifier

batteries not included (like a PMT without a base)

3 possible designs:

- voltage amplifier with a shunt resistor
  pulse shapes ~40 nsec

- discrete trans-impedance amplifier
  pulse shapes ~10 – 20 nsec

- *integrated trans-imp. amplifier*
  pulse shapes ~5 nsec

SiPM board design goals

- energy scale (gain) stability
  comes from pulse amplitude
  0.1 % (short time stability)

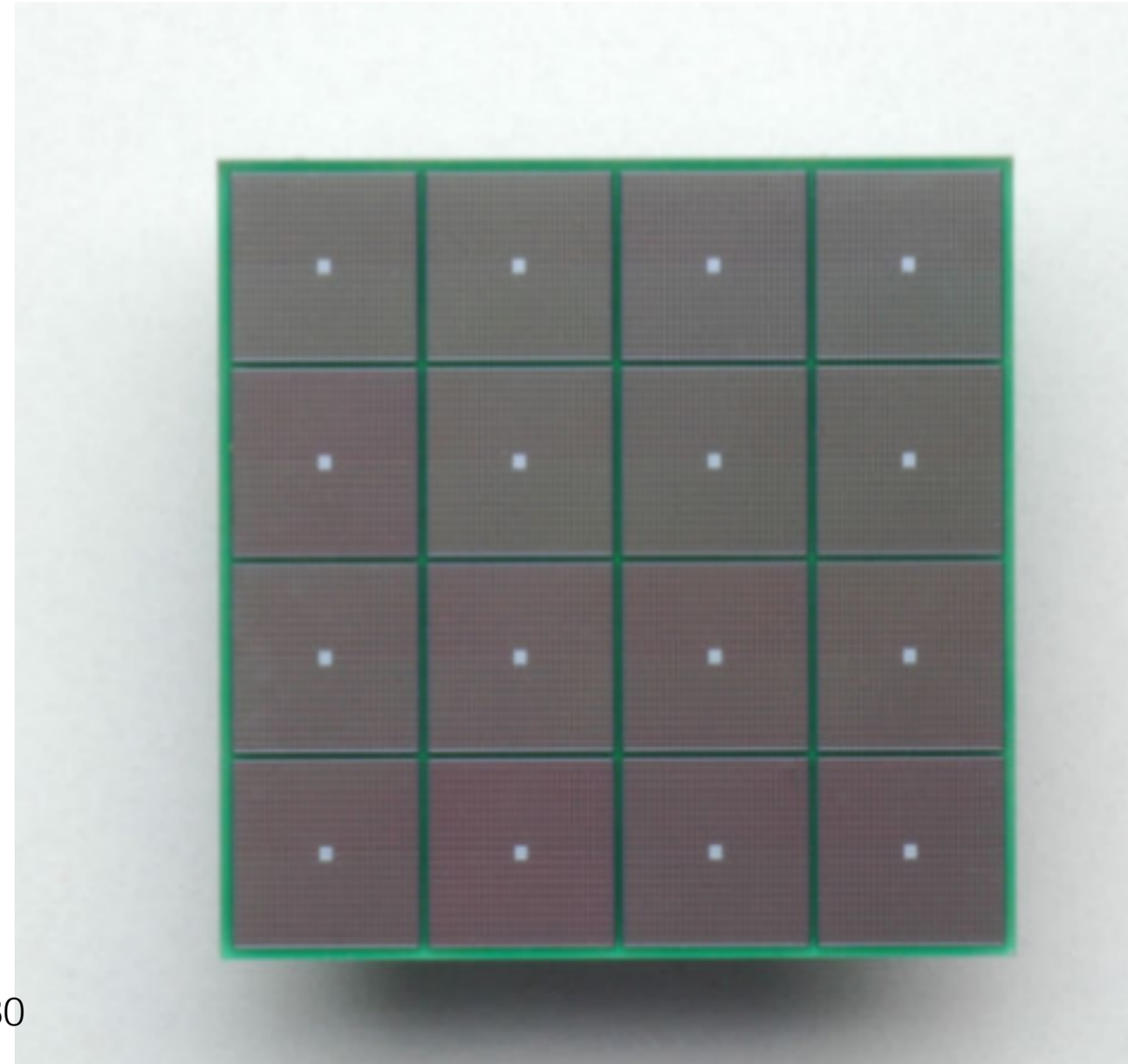
- timing resolution, time scale accuracy
  comes from the leading edge
  ~30 ps (different crystals), ~50 ps (pile-up)

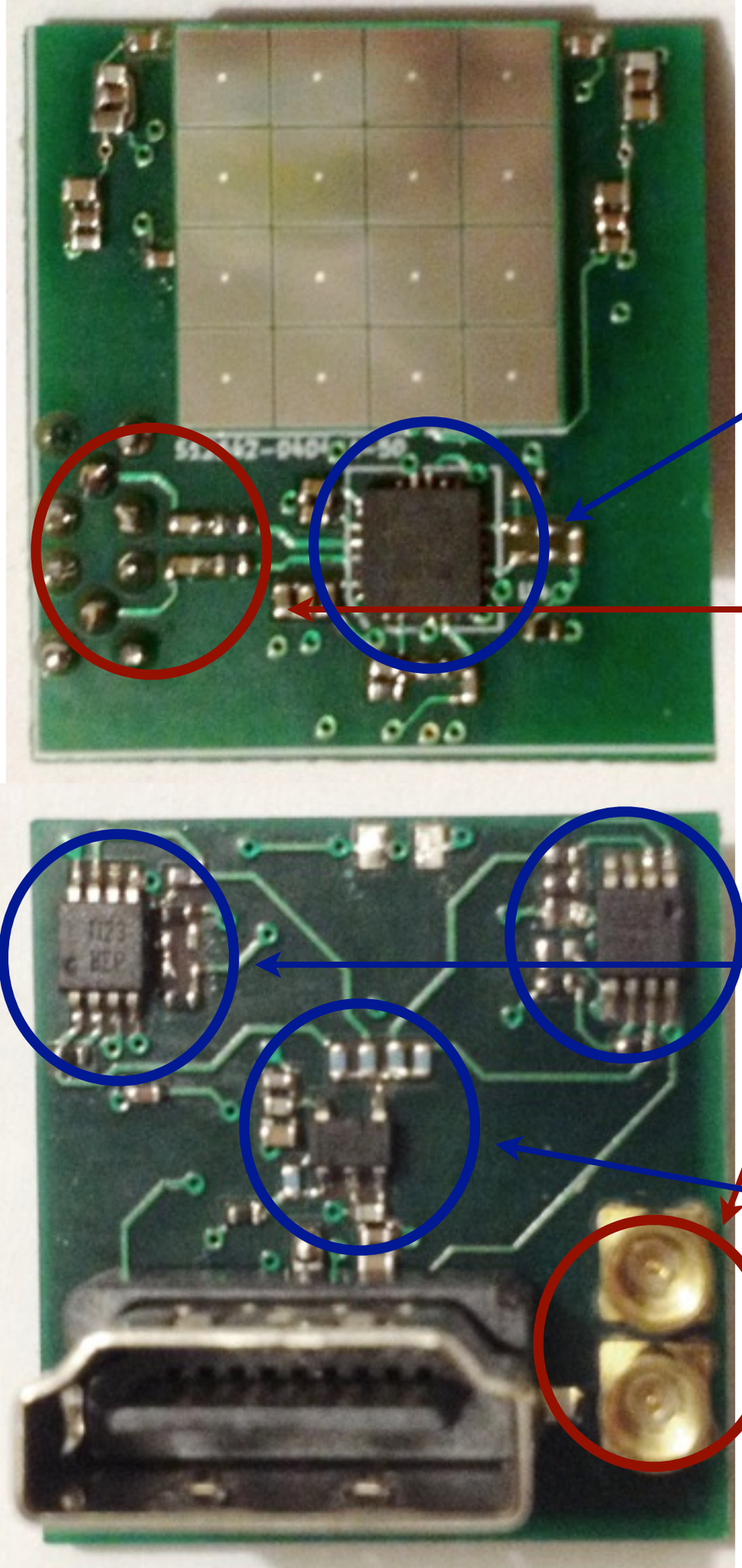
- pulse width
  leaked energy vs. direct hit, lost muon
  SiPM board should preserve light profile

Monolithic design

S12642-0404PA-50
16 channel array
12x12 mm^2 (active) area
50 μm pixels
Ni-based quench. resistor
through silicon vias
high purity Si wafer

25 – 4000 photons





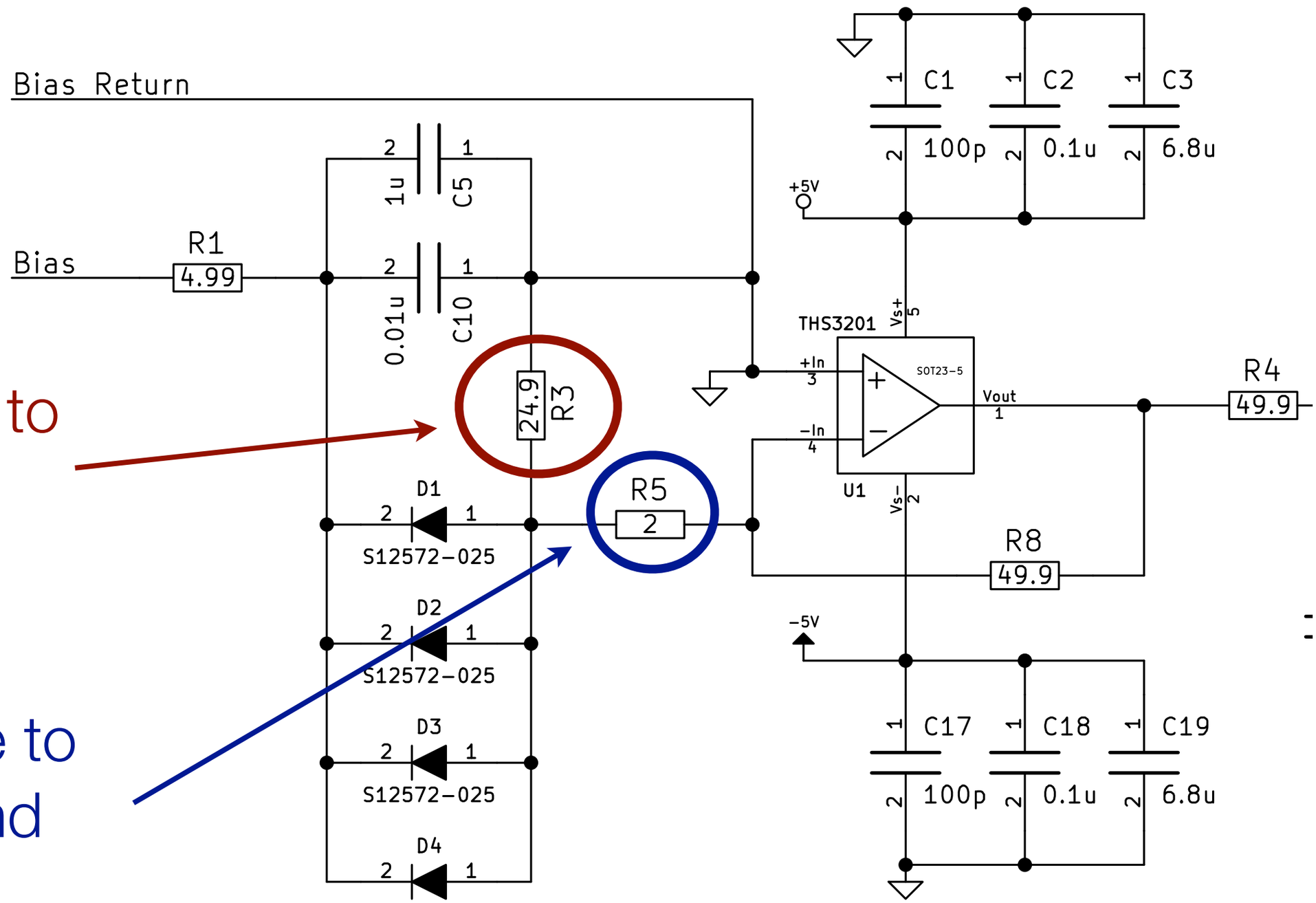
LMH6881 fully differential op-amp
variable gain (6–26dB), SPI
thermal coupling to crystal

DC coupled output
2 MMCX connectors feeding
twinax cable

2x THS3202 dual op-amp
each sums 4 SiPM channels

THS3201 at unity gain
sums four 4-sums

Knobs to turn



SiPM anode to ground

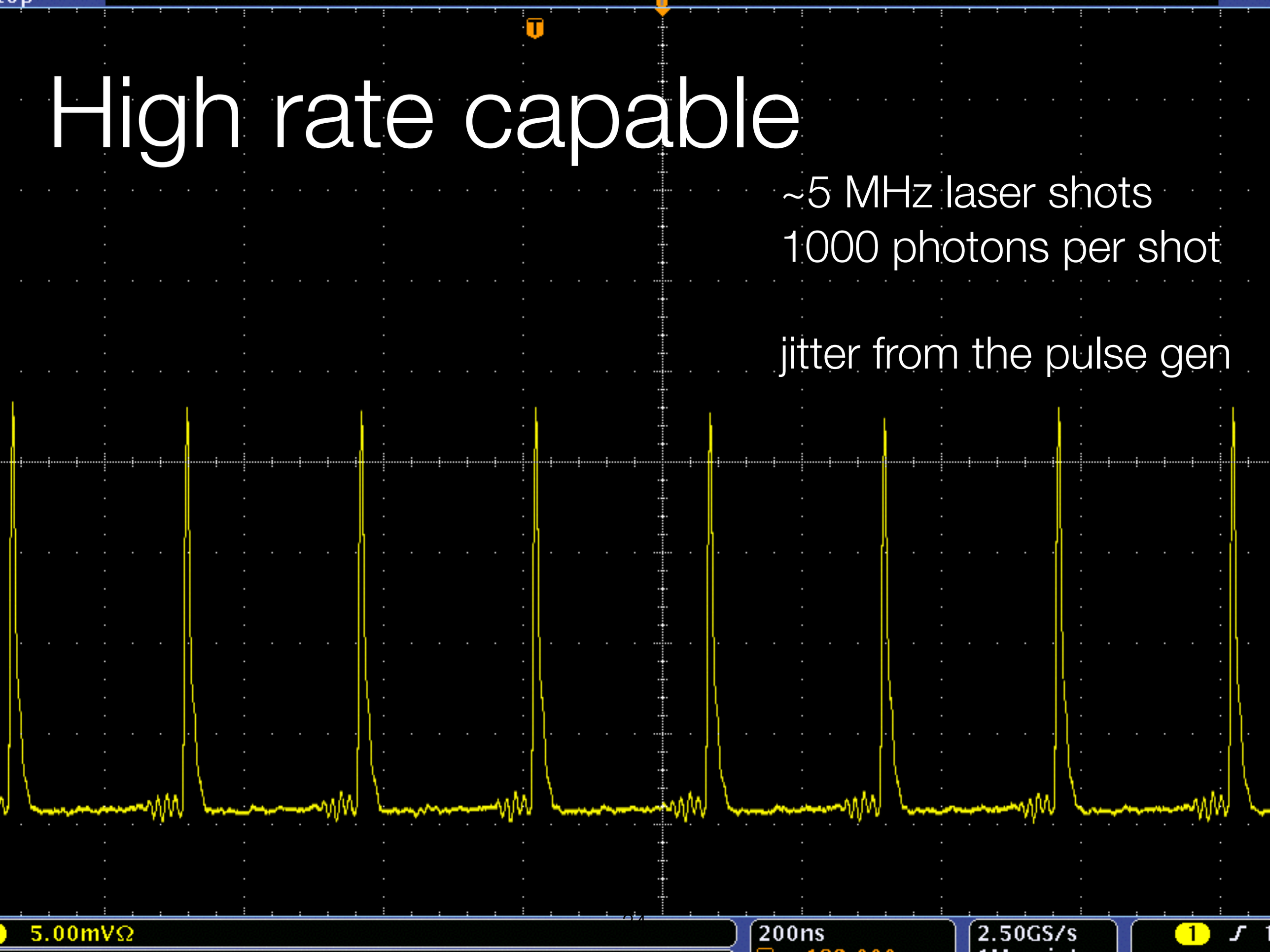
SiPM anode to virtual ground

pulse width ~8 nsec
timing resolution ~30ps (fit)
2 20.0mVΩ
4.00ns
945.240ns
2.50GS/s
10k points

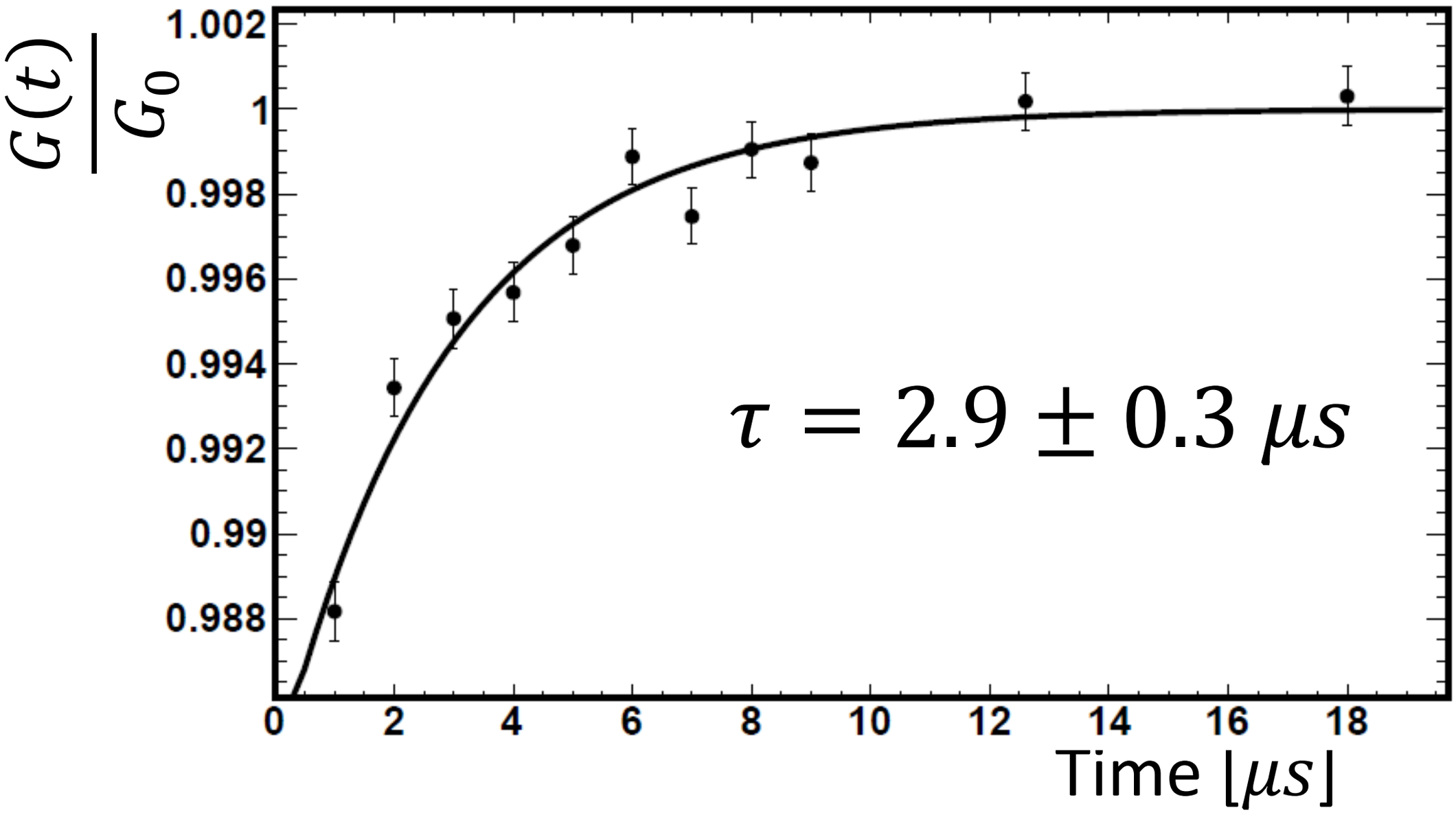
High rate capable

~5 MHz laser shots
1000 photons per shot

jitter from the pulse gen

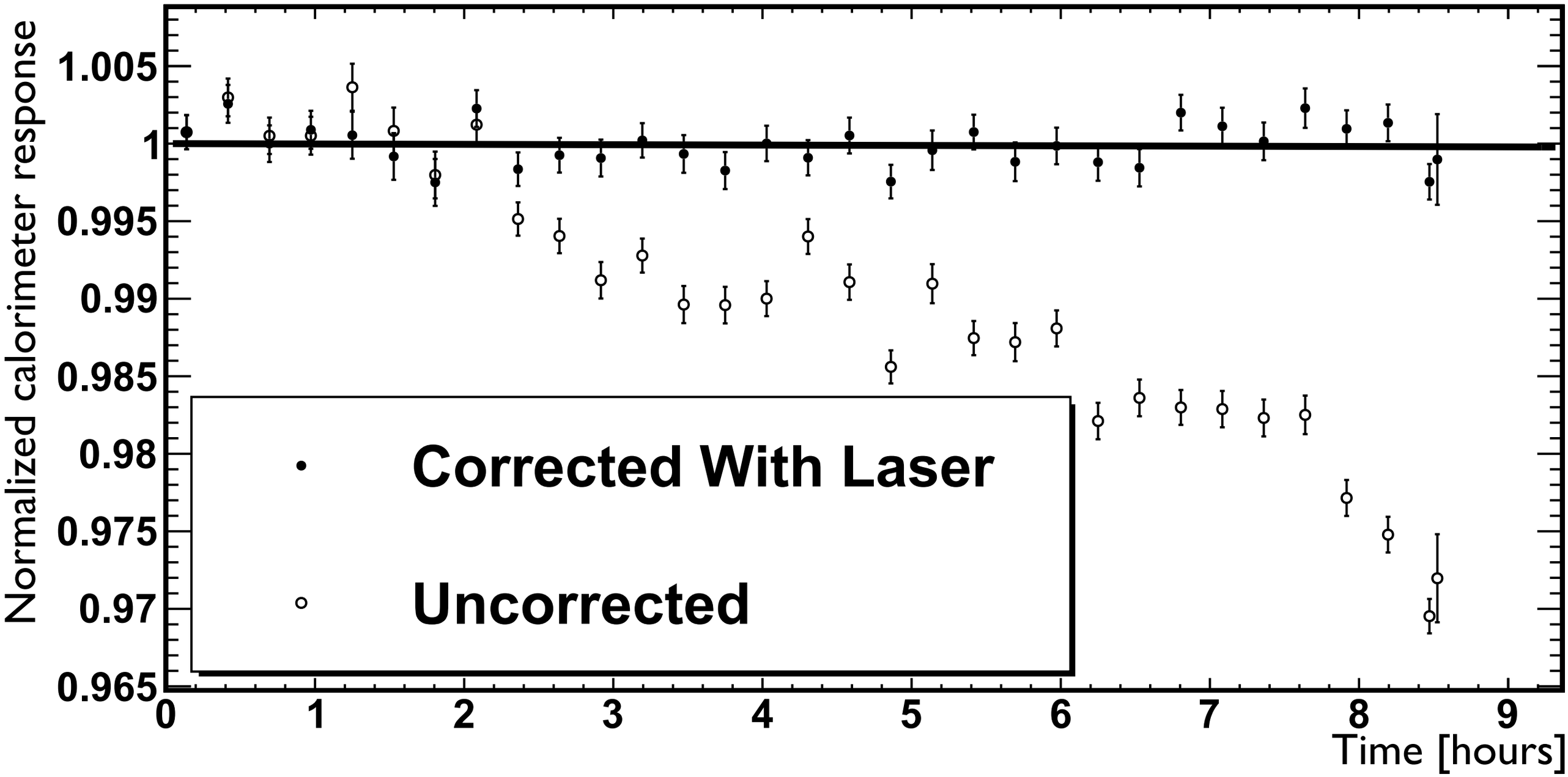


Flash Test Result



SiPM fully recovered from intense flash in $< 20\ \mu s$

long term gain stability ~1e-4/hour



A.Fienberg et al. NIM A 783, 12–21, (2015); arxiv://1412.5525

SiPM summary

- Geiger mode avalanche photodiodes
- **fast, compact, cheap, low-voltage devices, high detection efficiency**
- much lower radioactivity than PMT, cryo friendly
- data analysis straight-forward, and bit more involved than PMT
- **requires custom readout board**
- gain is sensitive to temperature; must control environment