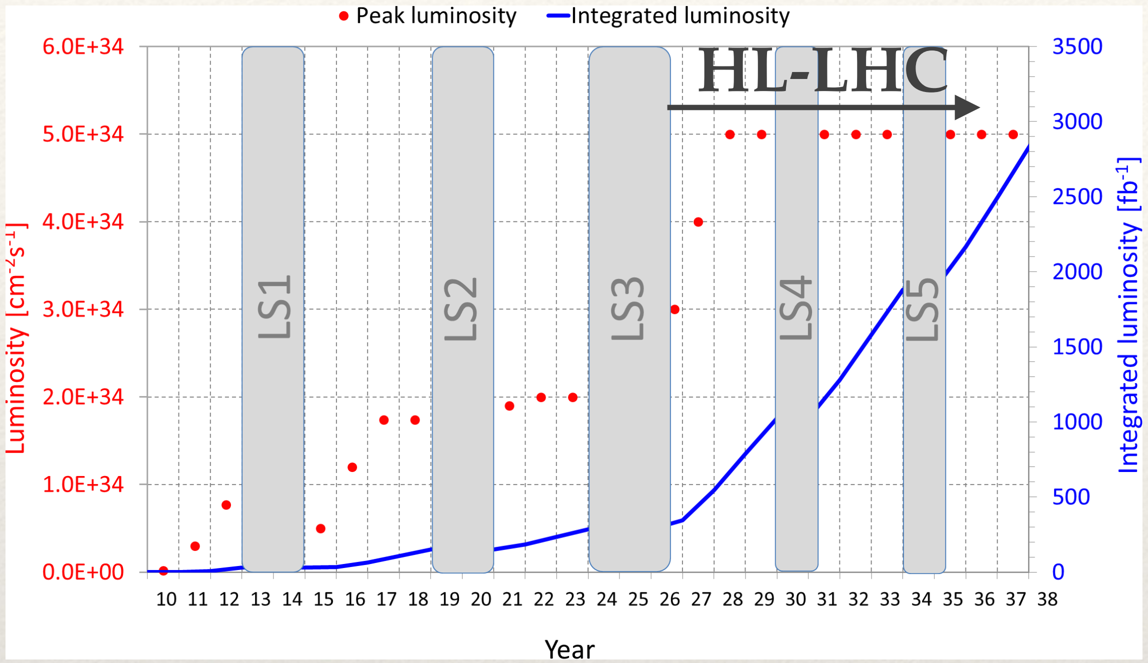
CHEF 2017 - Lyon

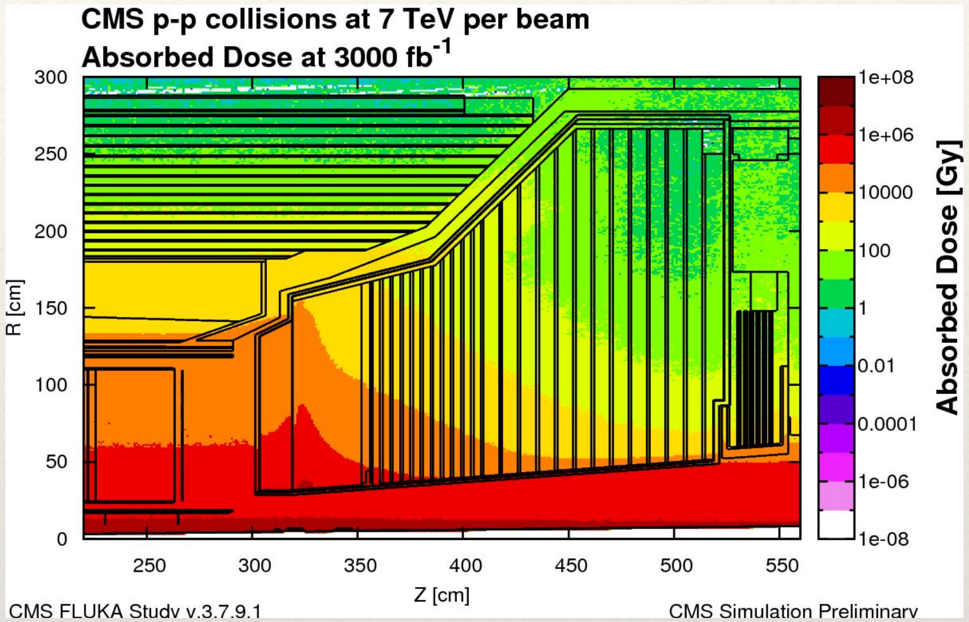
Scintillator performance at low dose rates and low temperatures for the CMS High Granularity Calorimeter for HL-LHC

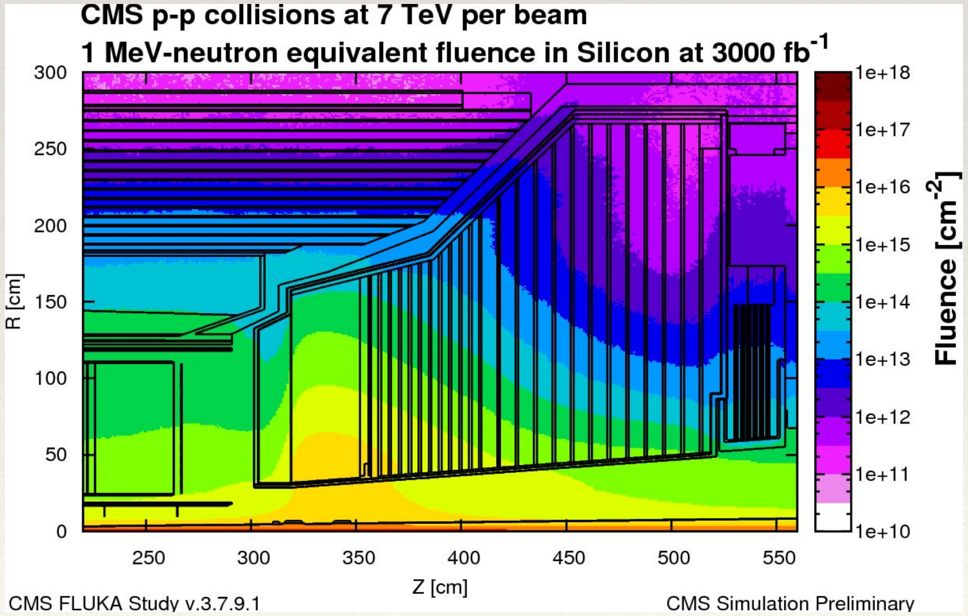
Francesca Ricci-Tam on behalf of the CMS collaboration

HL-LHC



10 kGy = 1 Mrad

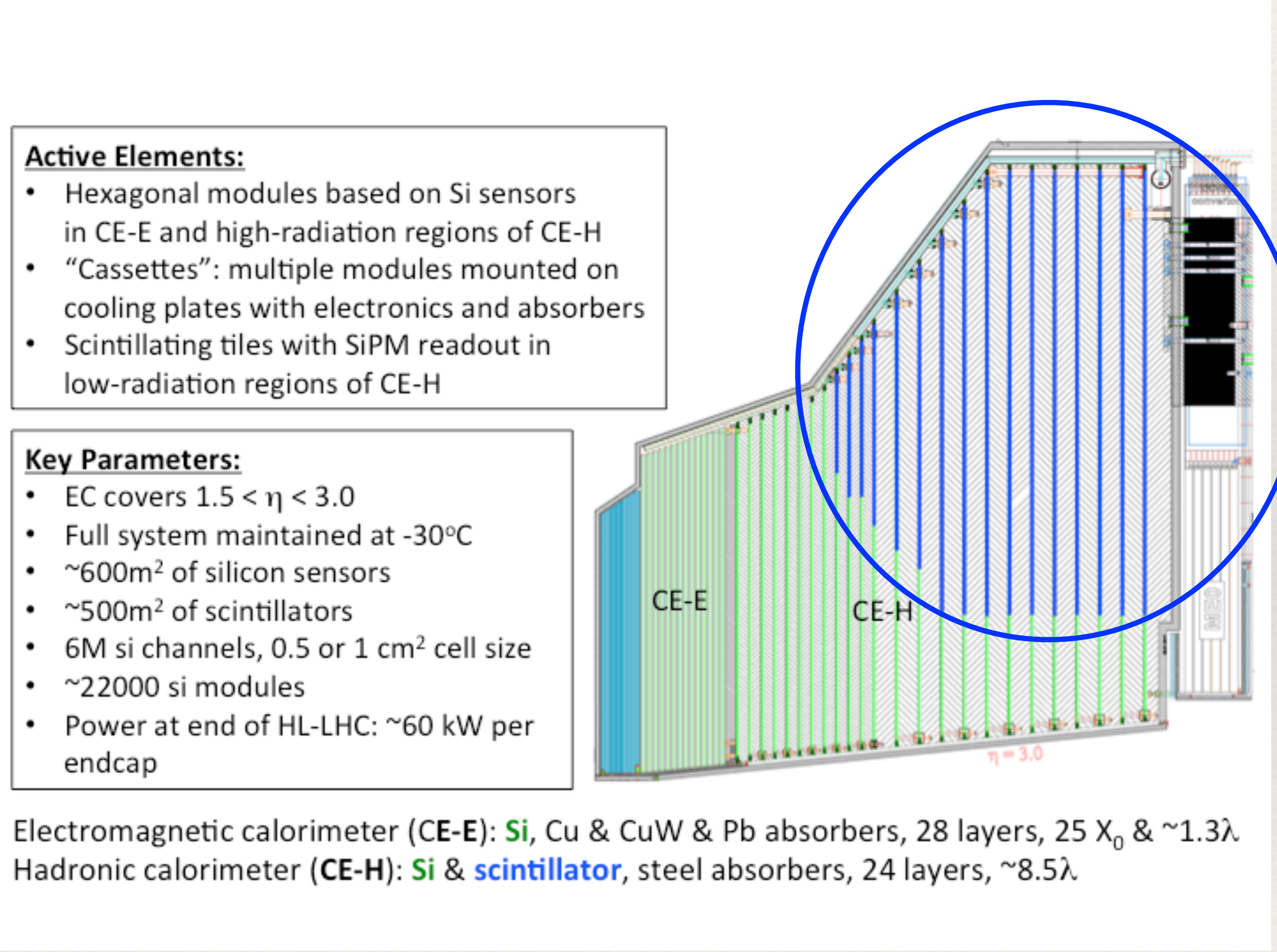




- Expected instantaneous luminosity of $2 \cdot 10^{34}$ cm^{-2} s^{-1} before the start of LS3
- Up to ~ $7.5 \cdot 10^{34}$ cm^{-2} s^{-1} during HL-LHC
- <PU> ~ 200 per bunch crossing
- Up to 30 Mrad integrated radiation dose in high-η region of calorimeter
- Required: complete revamp of ECAL and HCAL endcaps with high-granularity calorimeter (HGC) — electronics, active material, etc

Phase II Endcap Calorimeter

- Must minimize effects of radiation damage on the detector
- High-granularity calorimeter (HGC)
  - Si and plastic scintillator
  - Operates at -30°C
- After 3000 fb^{-1} (~10 years), projected doses and dose rates for HGC:
  - integrated dose 0.3 Mrad, dose rate ~O(10^{-4}-10^{-2} krad/hr) in scintillator region
  - integrated dose up to 30 Mrad, ~O(1 krad/hr) in Si region

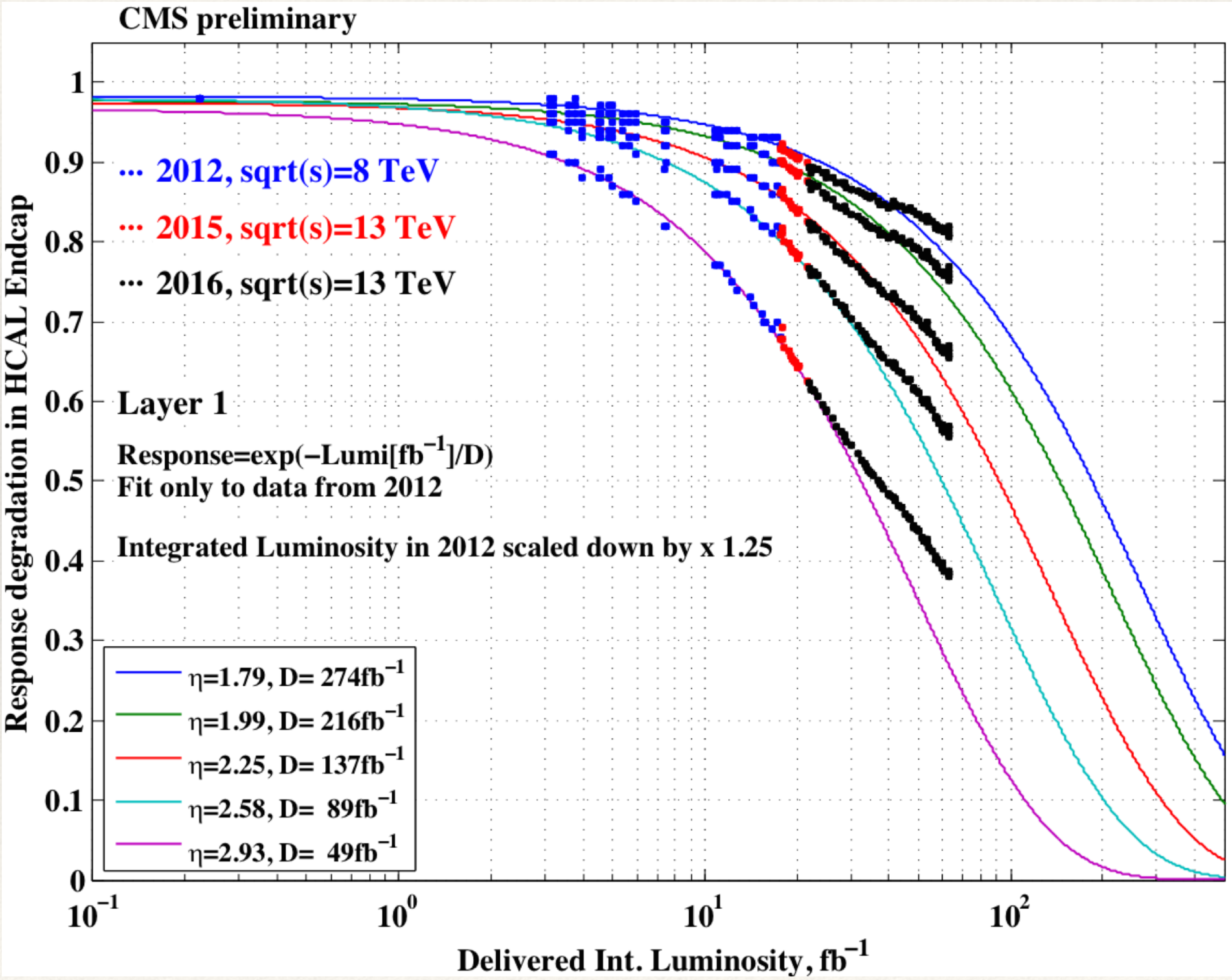


Radiation damage in plastic scintillators

- Exponential loss in light yield as a function of integrated dose d
- D = dose constant
  - smaller D ≡ less radiation tolerance
  - depends on a variety of factors: (e.g., base material, fluor, O_2 concentration, dose rate)
  - typically ~O(0.1-1Mrad) for the dose rates expected in HGC

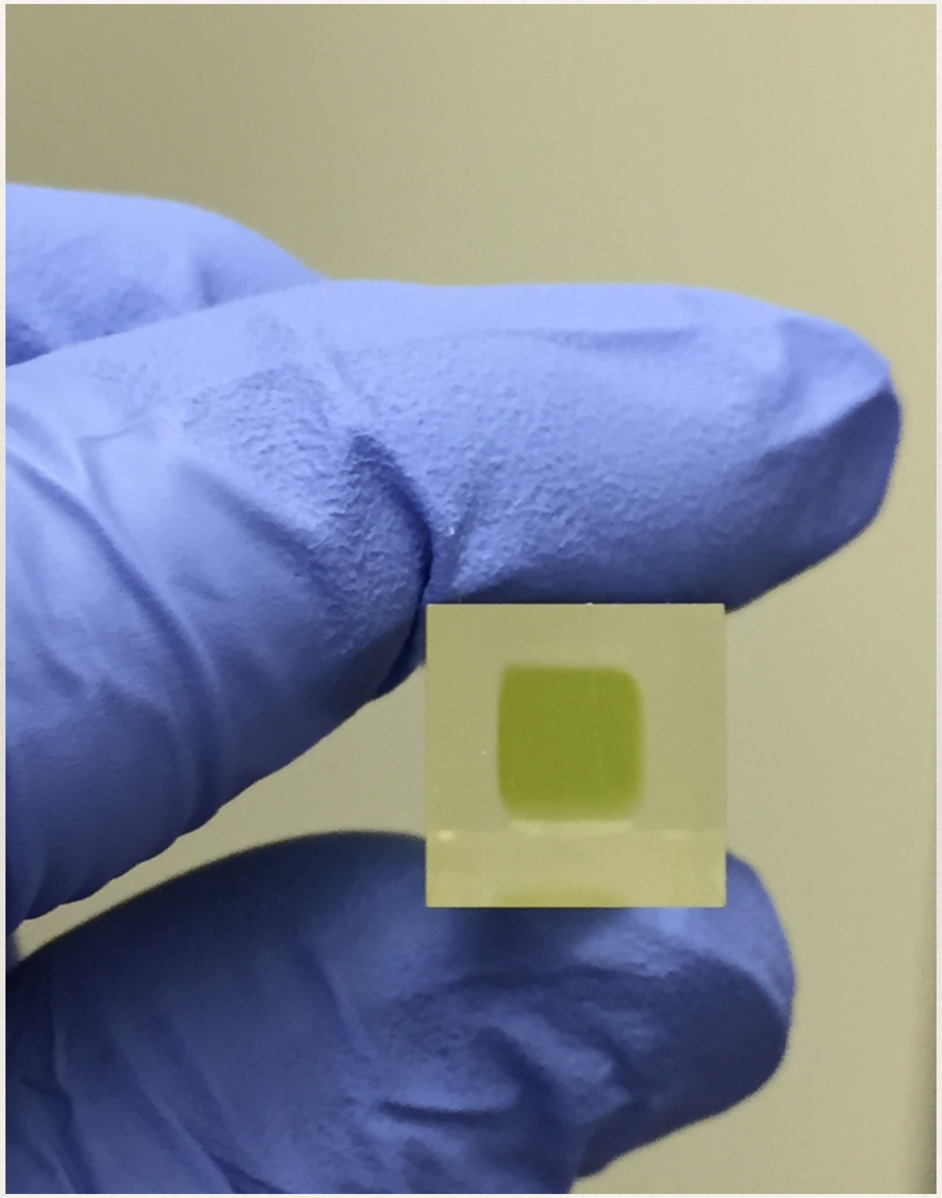
$$L(d)/L(0) = e^{-d/D}$$

dose d
dose constant D

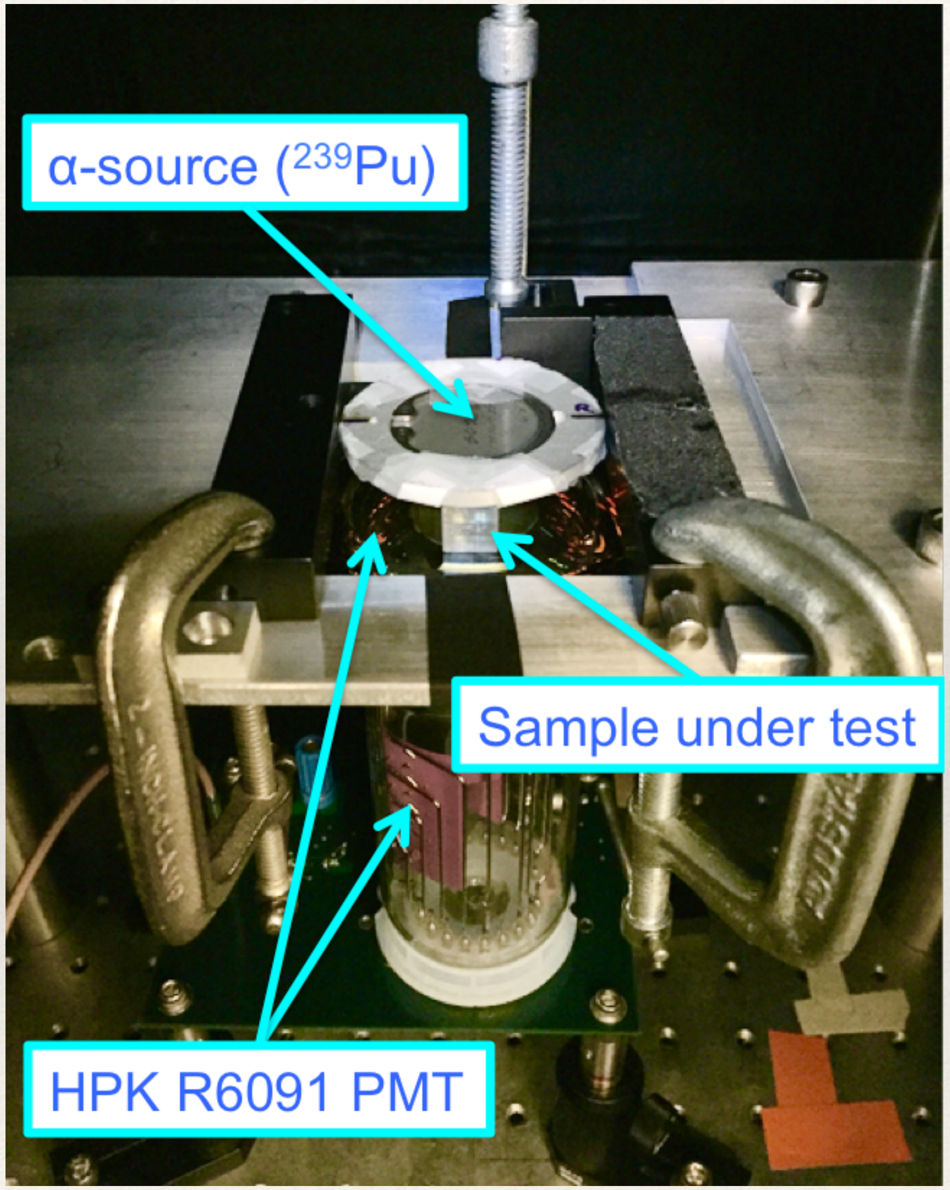


Types of radiation damage

- Loss of transmission and/or scintillation
- Temporary damage (e.g., color centers that eventually anneal)
- Permanent damage (e.g., damage to fluors, color centers that do not anneal)
- Effects of oxygen
  - increases rate of annealing (less temporary damage)
  - increases rate of permanent damage via reactions with free radicals and fluors
  - lower dose rates permit more diffusion of O_2 into scintillator material



Outline

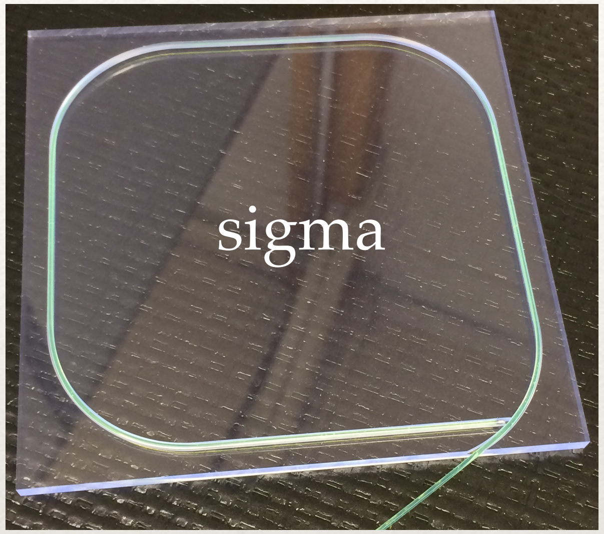


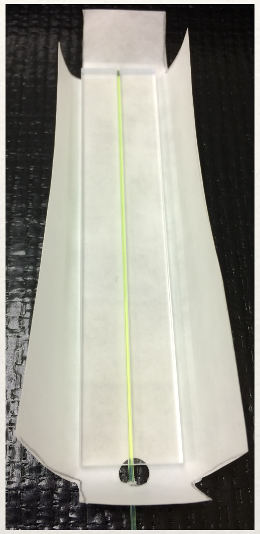
α source irradiation setup

- Presentation of results:
  - performance of plastic scintillators irradiated in cold vs warm temperatures (lab irradiation) at high and low dose rates
  - measurements of dose constant vs dose rate for different scintillators (LHC environment irradiation)

Properties of scintillator samples

- Tile geometries
  - sigma tiles (10 cm x 10 cm x 0.4 cm), WLS fiber
  - finger tiles (10 cm x 2 cm x 0.4 cm), WLS fiber
  - rods (5 cm x 1 cm x 1 cm)
- Plastic scintillator materials
  - SCSN81 (blue), BC408 (blue): used in current CMS hadronic calorimeter
  - EJ200 (blue), EJ260 (green): candidates for HGC, provided by Eljen Technology
    - 1X1P: standard concentrations of primary (P) and secondary (X) fluors
    - 1X2P: double concentration of primary fluor
    - 2X1P: double concentration of secondary fluor

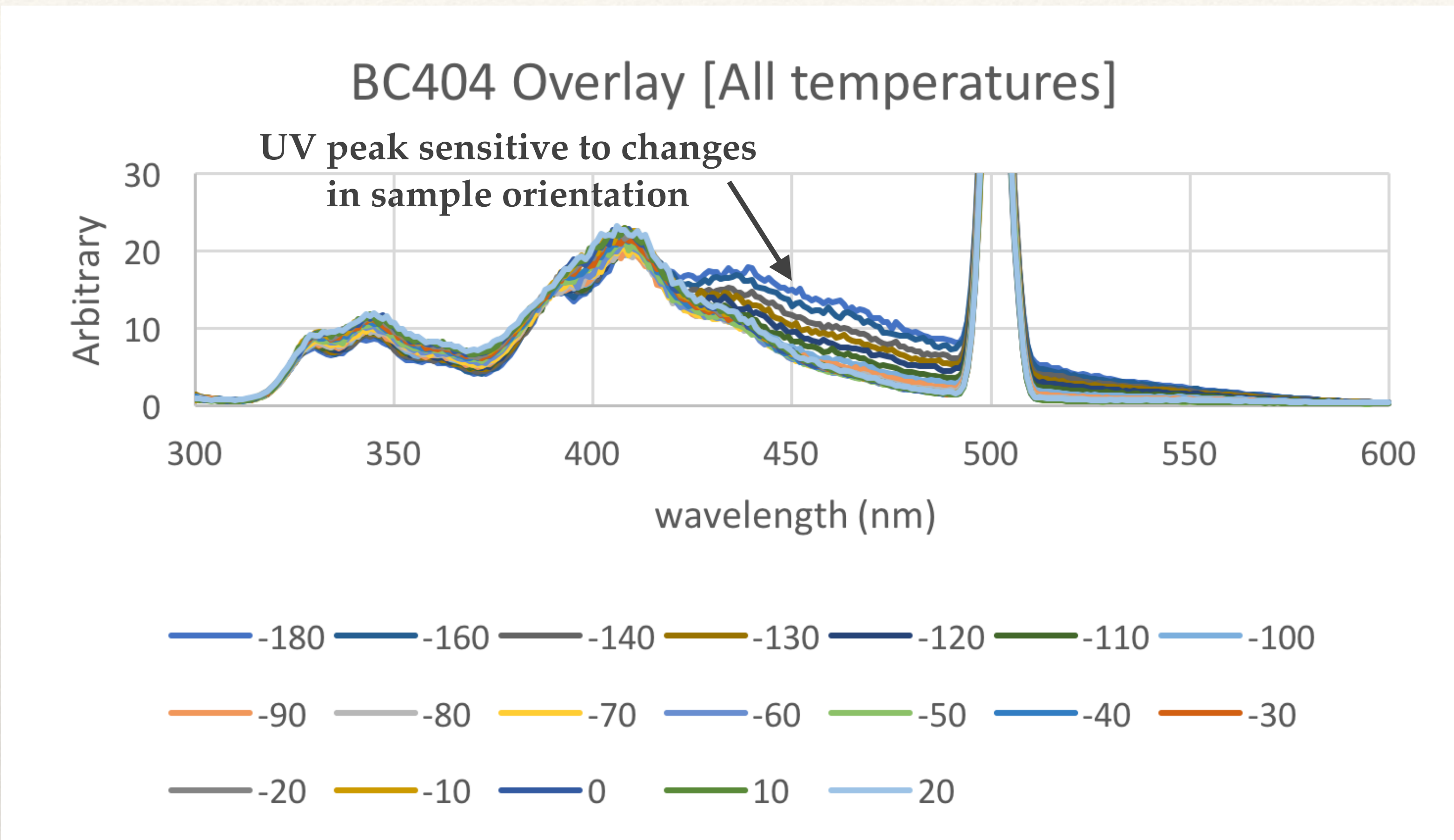


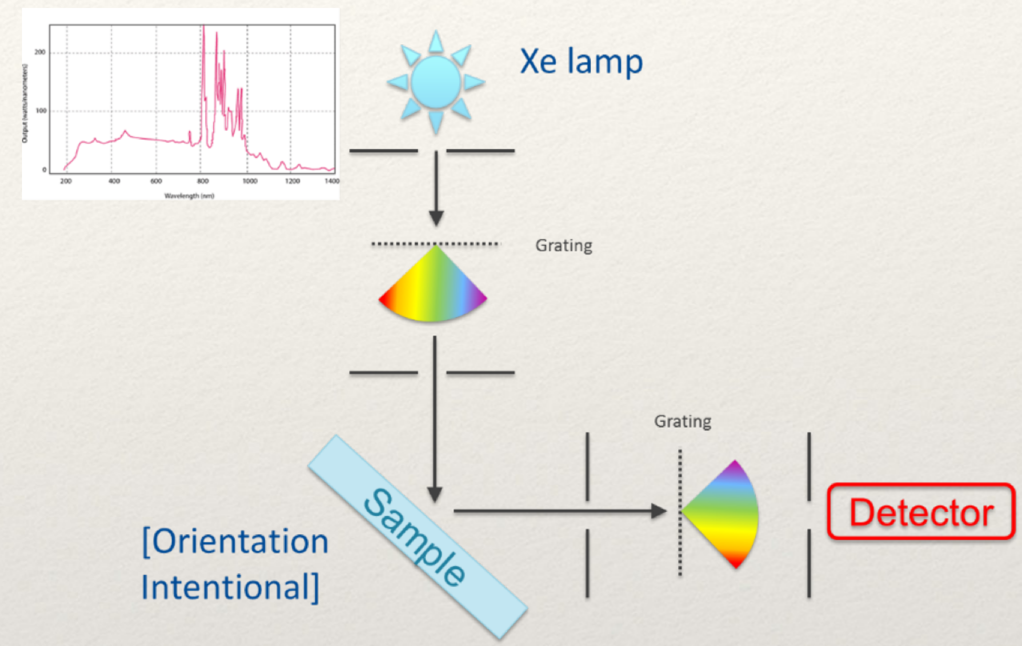


finger

rods

Emission spectrum independent of temperature





- D. Lincoln et al. (FNAL): effect of temperature on plastic scintillator emission spectrum
- Fluorescence spectra measured at temperatures ranging from -192°C to 20°C (samples cooled with liquid nitrogen)
- Scintillators: BC404, BC408, SCSN81, EJ260
- No substantial change in spectra as temperature changed

* National Institute of Standards and Technology

Samples irradiated at NIST*

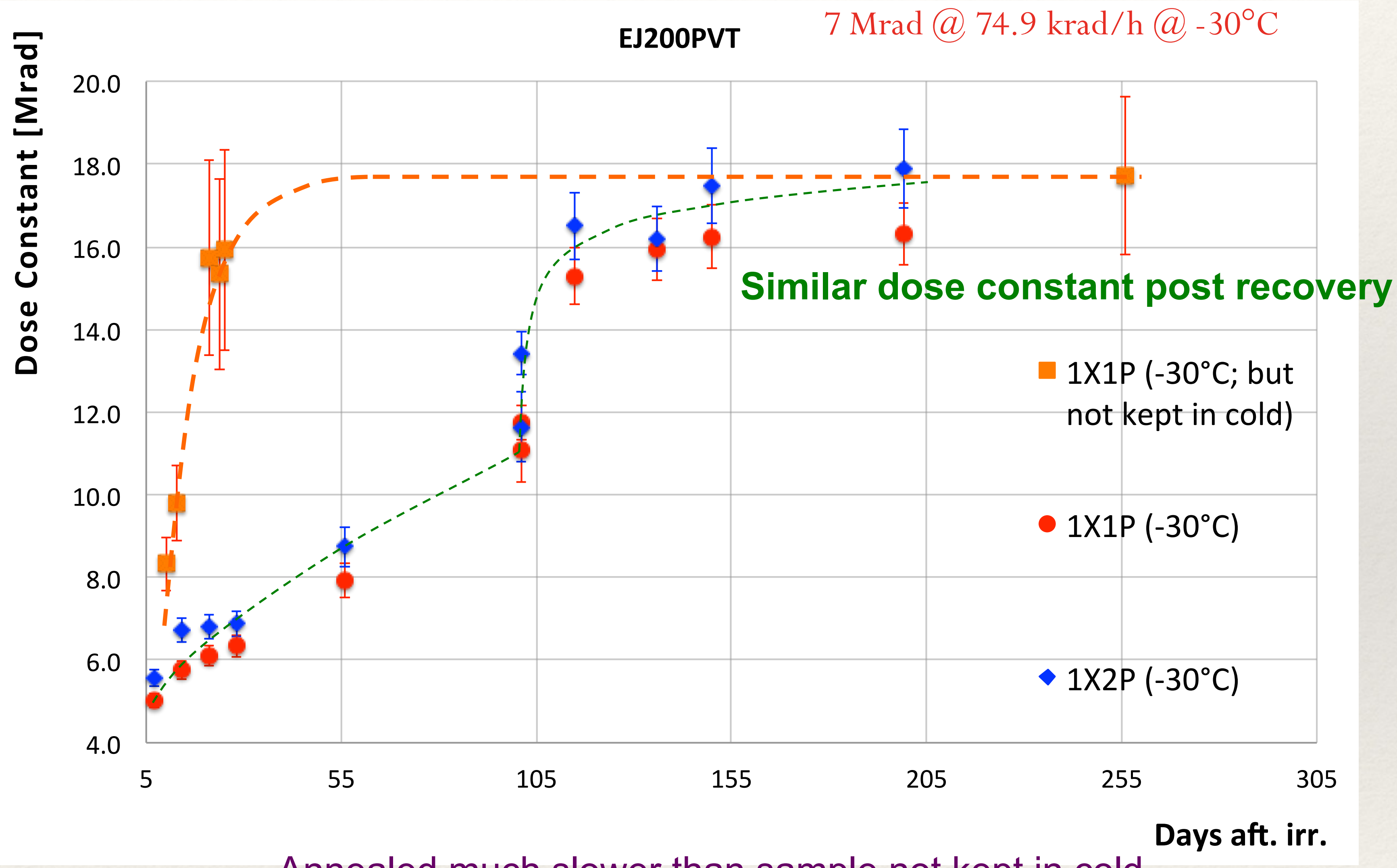
Special thanks to Chuck Hurlbut (Eljen), Lonnie Cumberland (NIST), Geng-Yuan Jeng (UMD)

- Geometry: 5 cm x 1 cm x 1 cm rods
- Base materials: PVT vs PS
- Scintillators: EJ200 vs EJ260, 1X1P vs 1X2P
- Gamma irradiation from Co^{60} source
- Temperatures: 23°C vs -30°C
- Received doses (**N.B.: high dose rate, ~10^4x higher than highest expected levels for HB and HGC**)
  - 5.82 Mrad at 80.4 krad/hr (cold samples warmed up immediately after irradiation)
  - 7 Mrad at 74.4 krad/hr (cold samples kept cold for 101 days after irradiation)

NIST: annealing rate increases with T

- Recovery curves for EJ200 PVT samples irradiated at -30°C
- Annealing occurs more slowly at cold temperatures
- Same level of recovery, whether warmed up immediately after irradiation or not

5.82 Mrad @ 80.4 krad/h @ -30°C
7 Mrad @ 74.9 krad/h @ -30°C
7 Mrad @ 74.9 krad/h @ -30°C

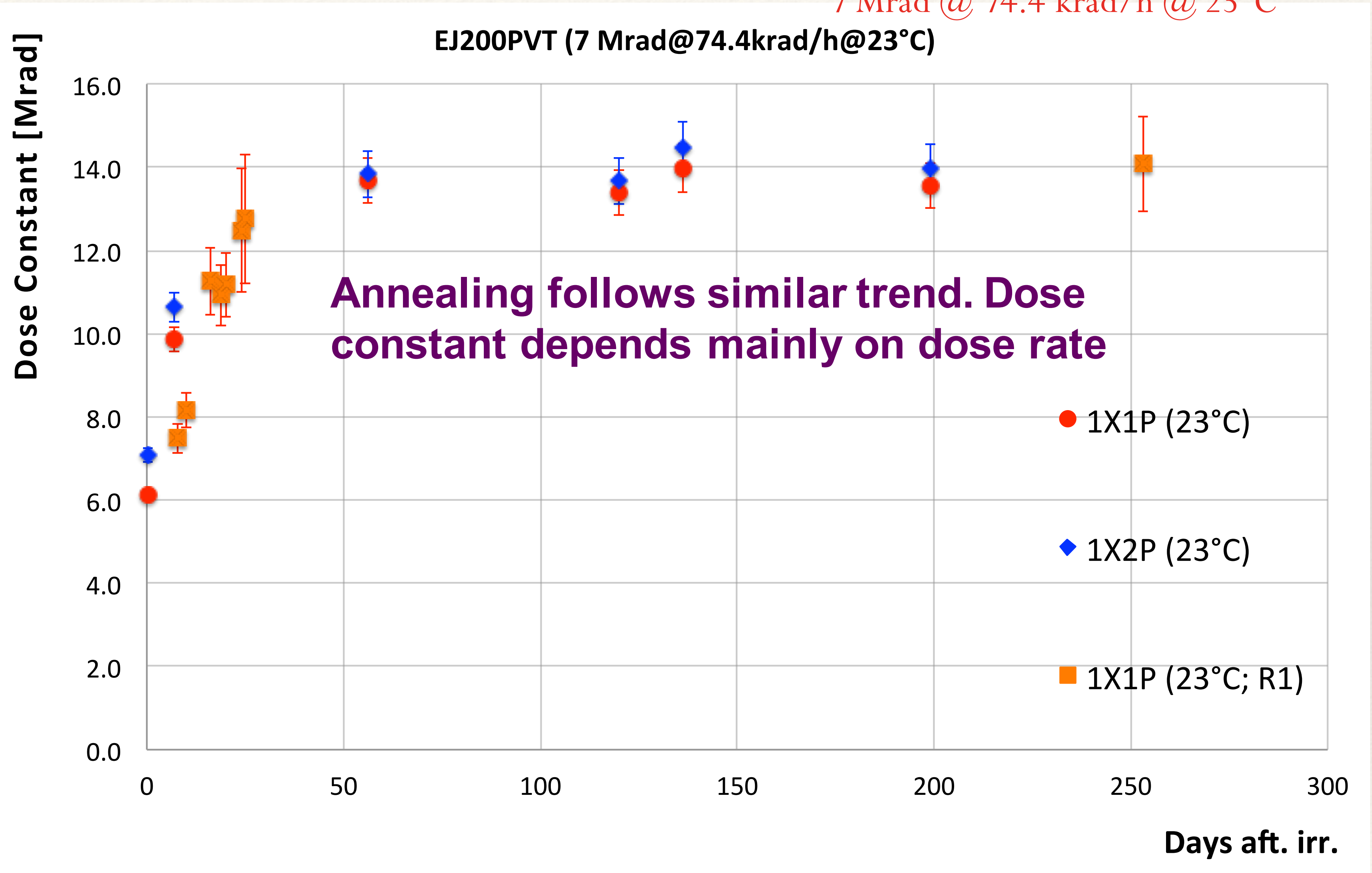


Annealed much slower than sample not kept in cold.
Sped up after warmed up to room temperature

NIST: annealing trend unaffected by previous low T

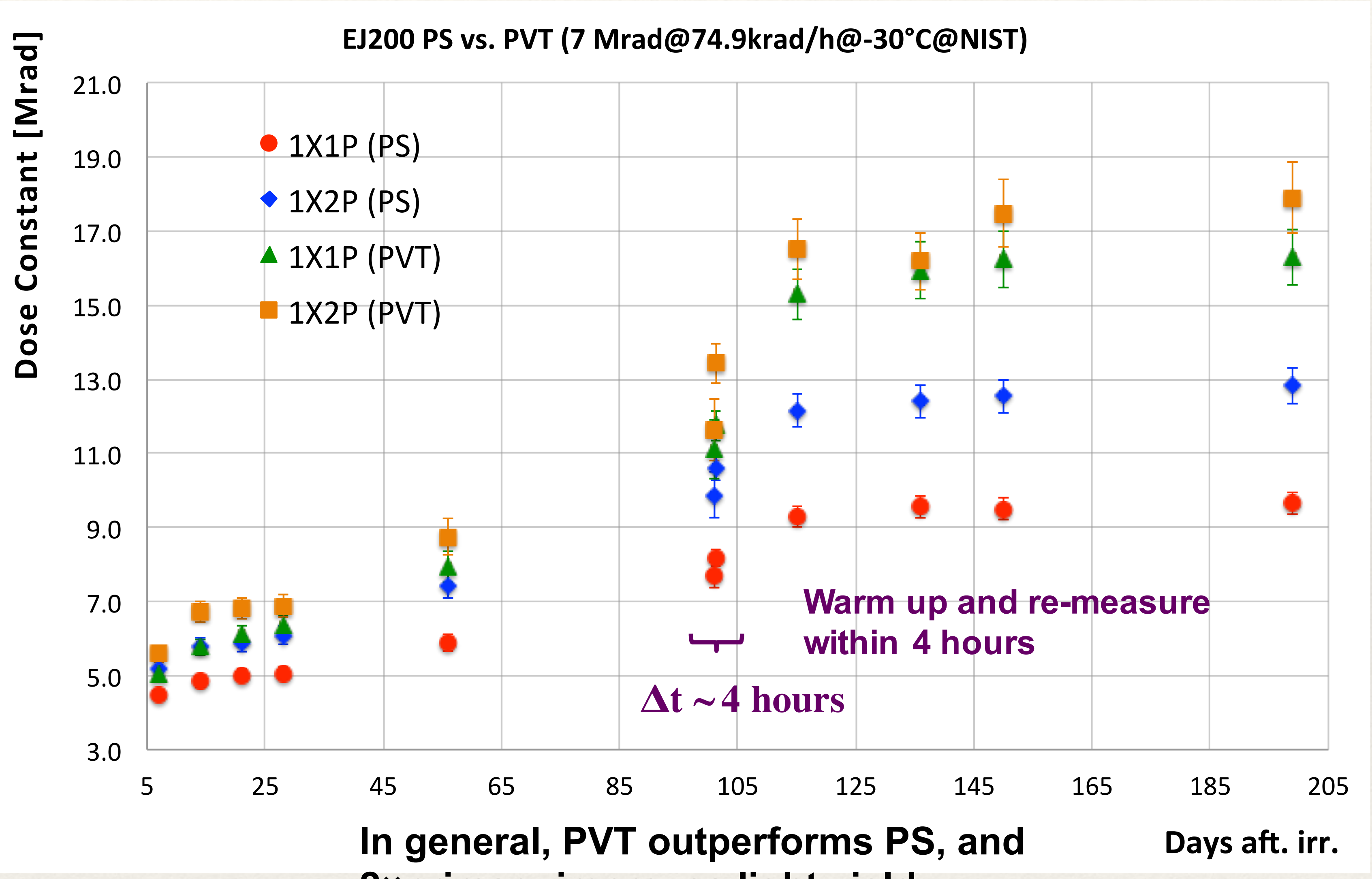
- Analogous recovery curves for samples irradiated at 23°C
- Annealing trend is similar for warm and cold samples

5.82 Mrad @ 80.4 krad/h @ 23°C
7 Mrad @ 74.4 krad/h @ 23°C
7 Mrad @ 74.4 krad/h @ 23°C



NIST: comparing PVT and PS

- EJ200: comparison of PS vs PVT at -30°C
- Doubling primary fluor concentration improves light yield
- PVT shows better performance post-recovery (higher dose constant), but more studies are needed to see how that trend is affected by dose rate and temperature

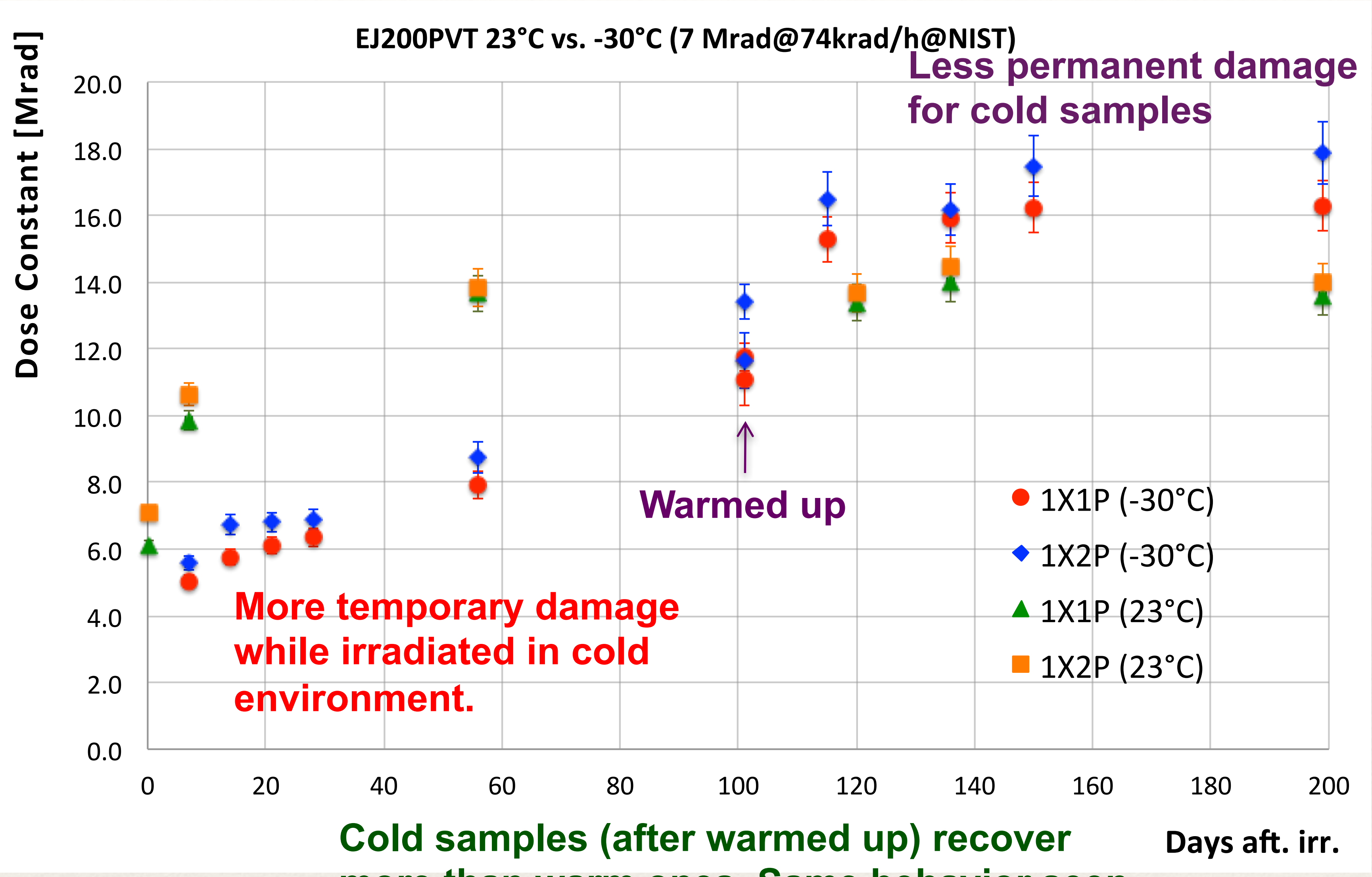


In general, PVT outperforms PS, and 2×primary improves light yield (larger difference for PS)

NIST: cold reduces permanent damage

7 Mrad @ 74.9 krad/h @ -30°C
7 Mrad @ 74.4 krad/h @ 23°C

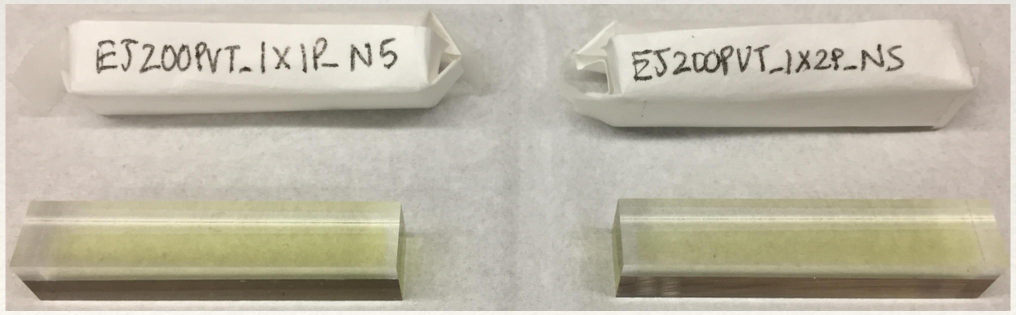
- EJ200 PVT samples: comparing warm and cold irradiation
- More temporary damage in cold samples (lower dose constant)
- More recovery in cold samples than in warm ⇒ less permanent damage



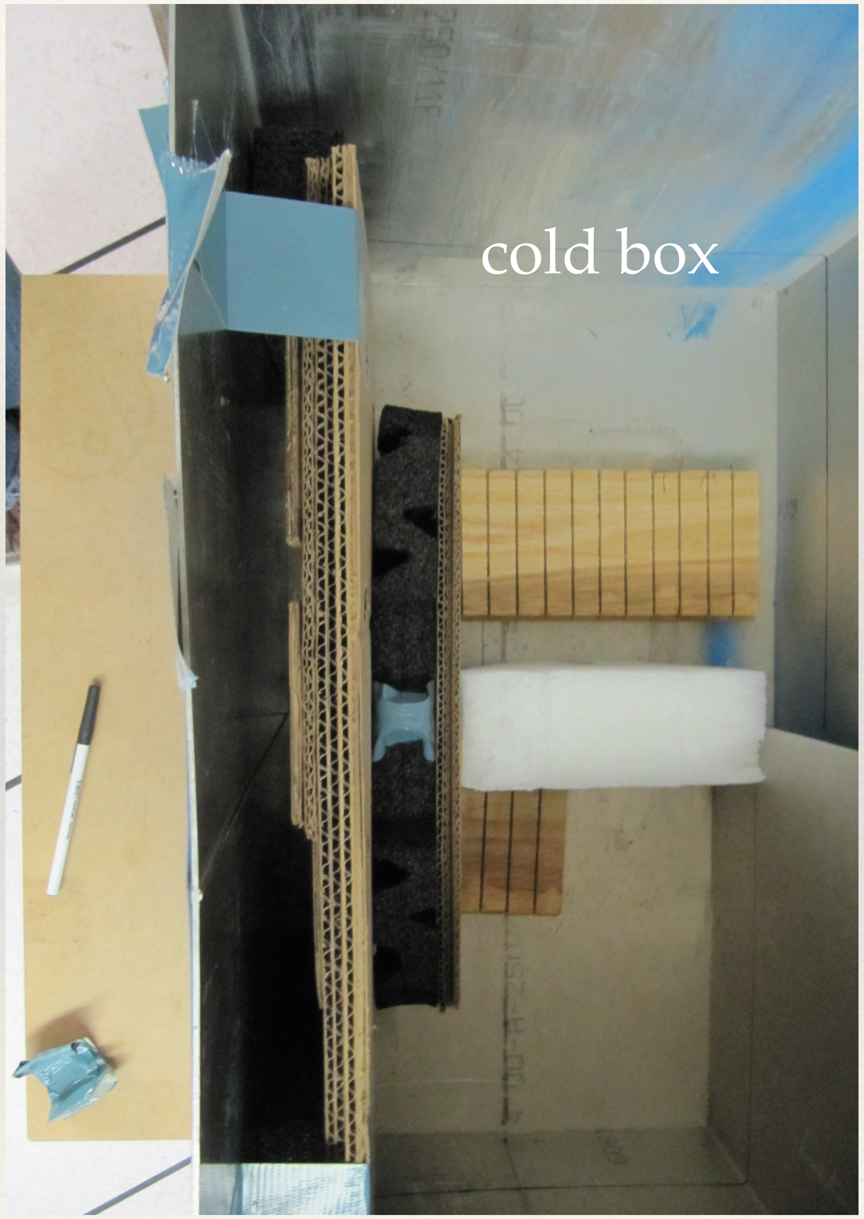
Cold samples (after warmed up) recover more than warm ones. Same behavior seen in previous NIST run

Samples irradiated at Goddard

- Geometry: both tiles and rods
- Base materials: PVT vs PS
- Scintillator materials: EJ200 vs EJ260, 1X1P vs 1X2P
- Gamma irradiation from Co^{60} source
- Received dose: 0.38 Mrad at 0.3 krad/hr (**N.B.: low dose rate, ~10x higher than highest expected levels for HB and HGC**)
- Temperatures: 23°C vs -20°C (cold samples kept cold for 84 days after irradiation)

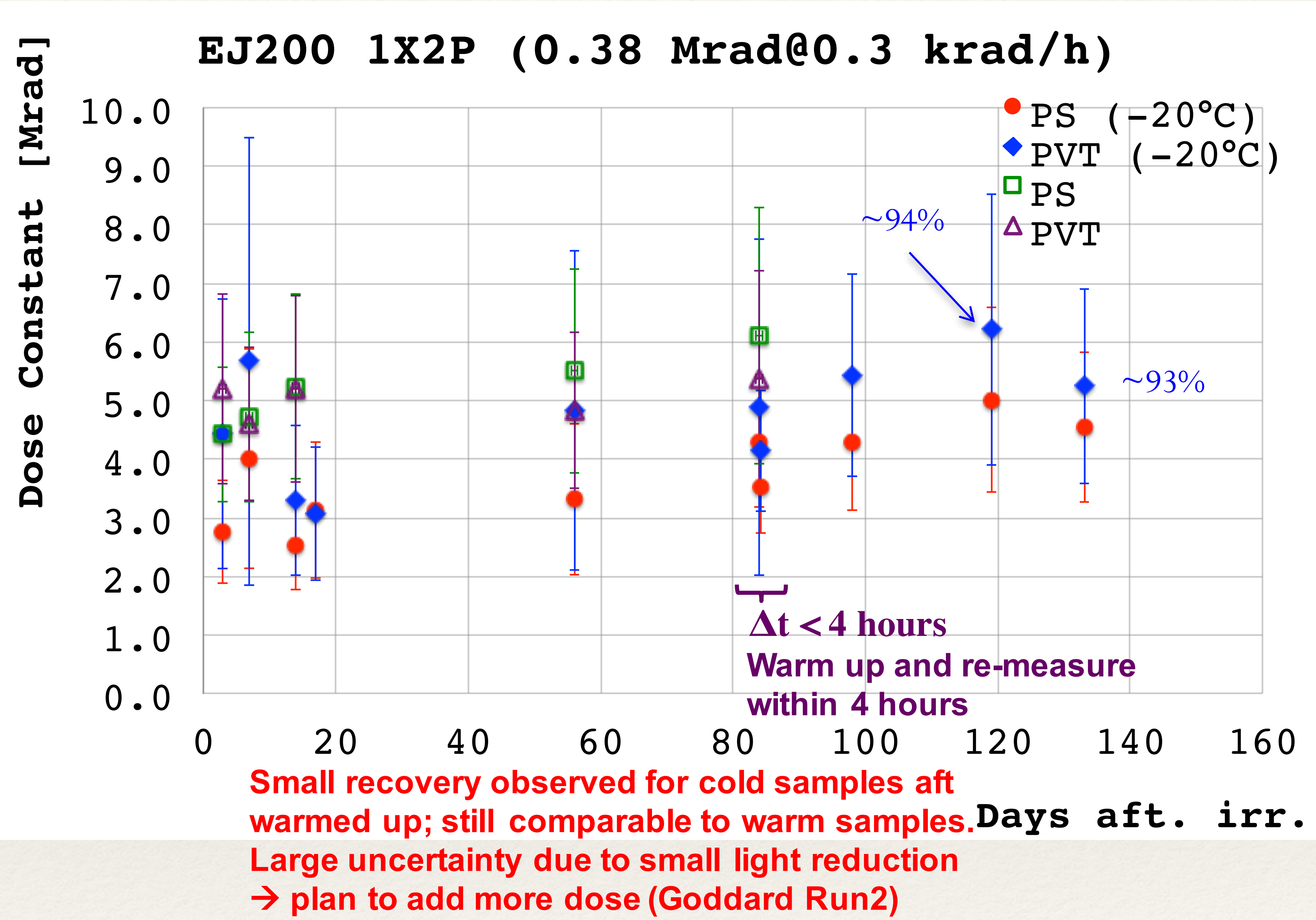


Thanks to Martin Carts (Goddard), Geng-Yuan Jeng (UMD)



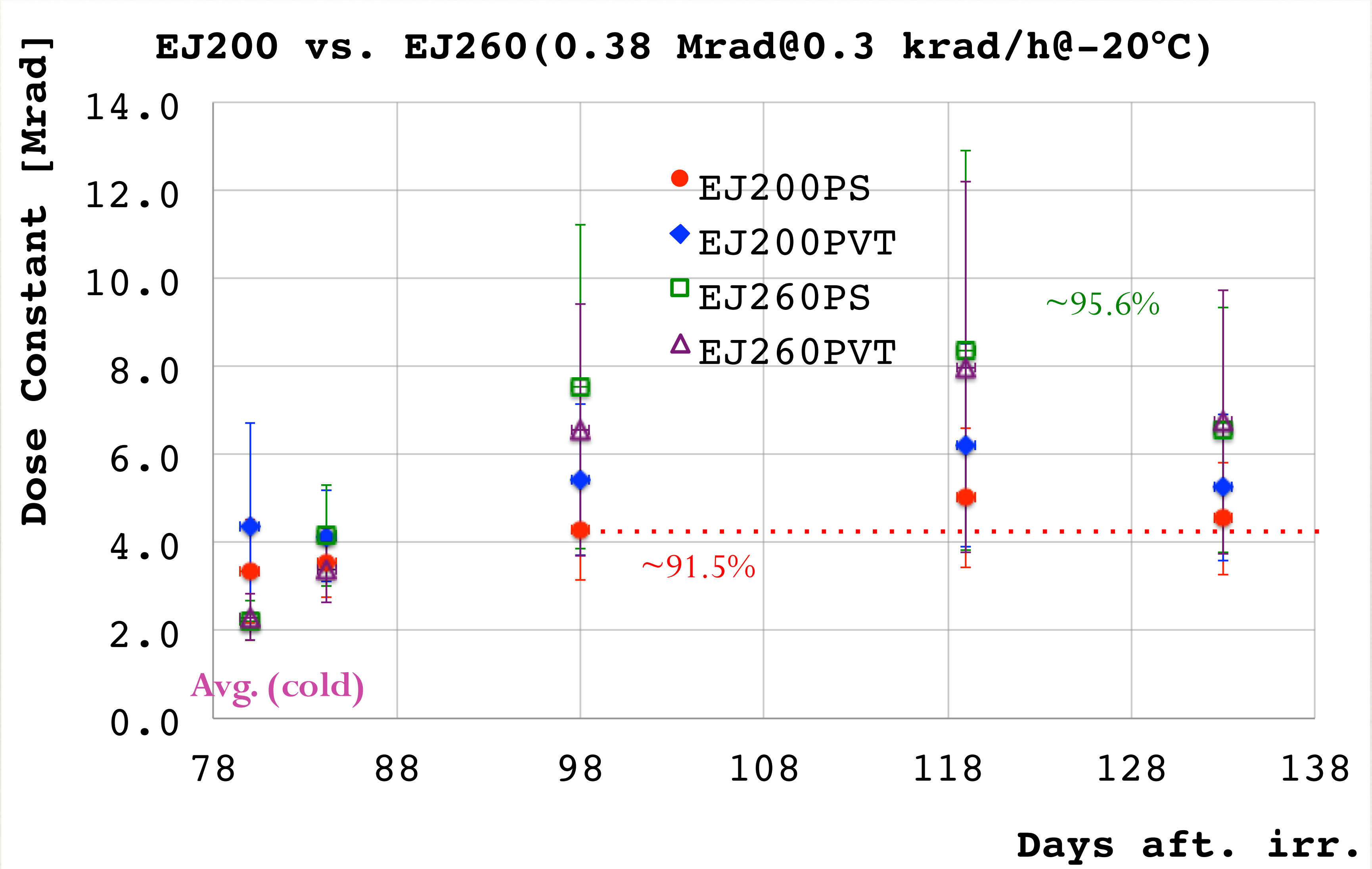
Goddard: little temporary damage at low dose rates

- EJ200 1X2P recovery curves: comparing PS and PVT, warm vs cold
- Large uncertainty due to small loss in light yield (not much temporary damage), for both warm and cold samples



Goddard: EJ200 vs EJ260

- EJ200 vs EJ260, PS vs PVT
- Large uncertainty due to small loss in light yield (not much temporary damage), for both warm and cold samples
- Slightly more temporary damage (and recovery) in EJ260 than EJ200



Dose constant vs dose rate: latest CMS fit

- Laser data from CMS
  - radiation damage from LHC environment (gamma + hadrons)
- Parametrization: $D = a \cdot R^{b}$
- D ~ 0.2-0.4 Mrad at dose rate of 10^{-2} krad/hr
- We want to characterize the performance of different scintillator candidate materials at the dose rate range expected for HGC scintillator region during HL-LHC

CMS-TDR-2017-002

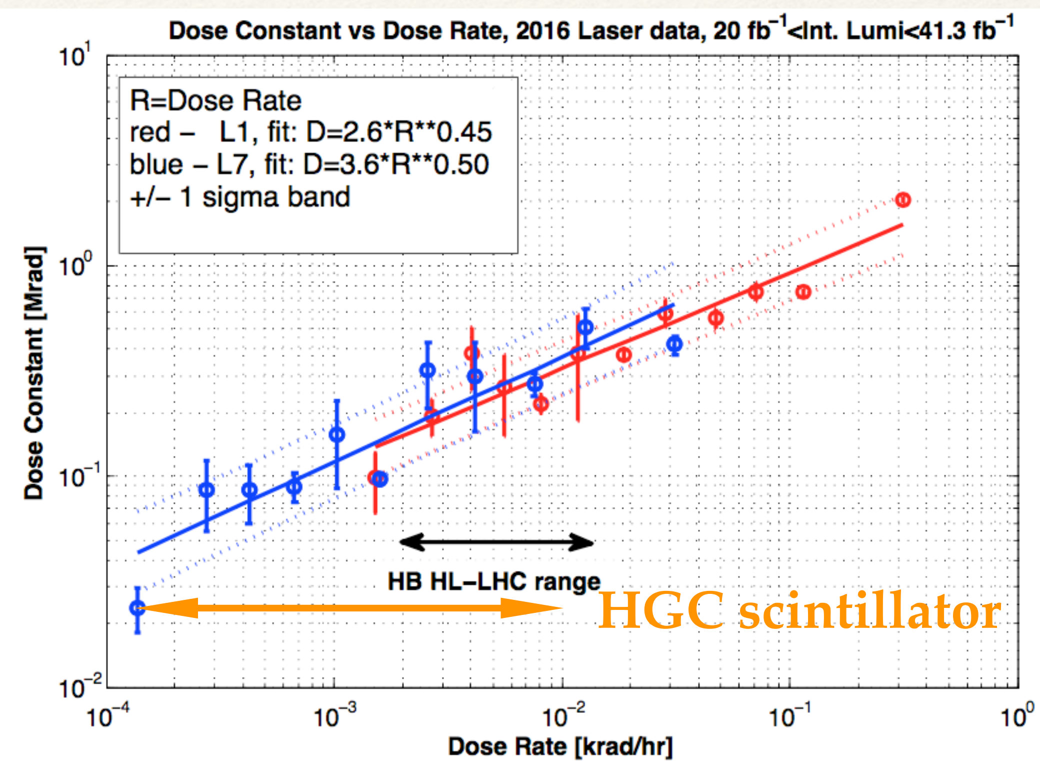
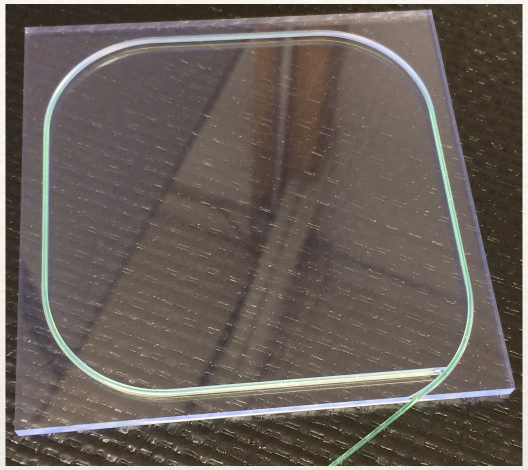


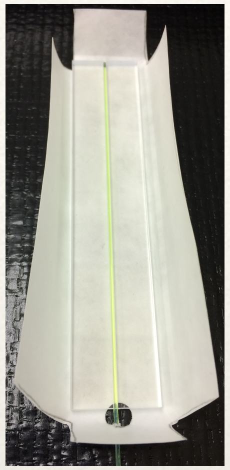
Figure 2.24: Dose constant D as a function of dose rate R using HE data from 2016. The points show the average over the ten best HPDs, with red (blue) points corresponding to L1 (L7) data. Error bars are calculated using RMS of the variation in D extracted from the response loss vs. dose of individual scintillator tiles. Solid lines correspond to fits using the parametrization $D = a \times R^{b}$. Dashed lines indicate the error band associated with the fits.

CASTOR Radiation Facility (CRF)

- SCSN81
- EJ200
- EJ260

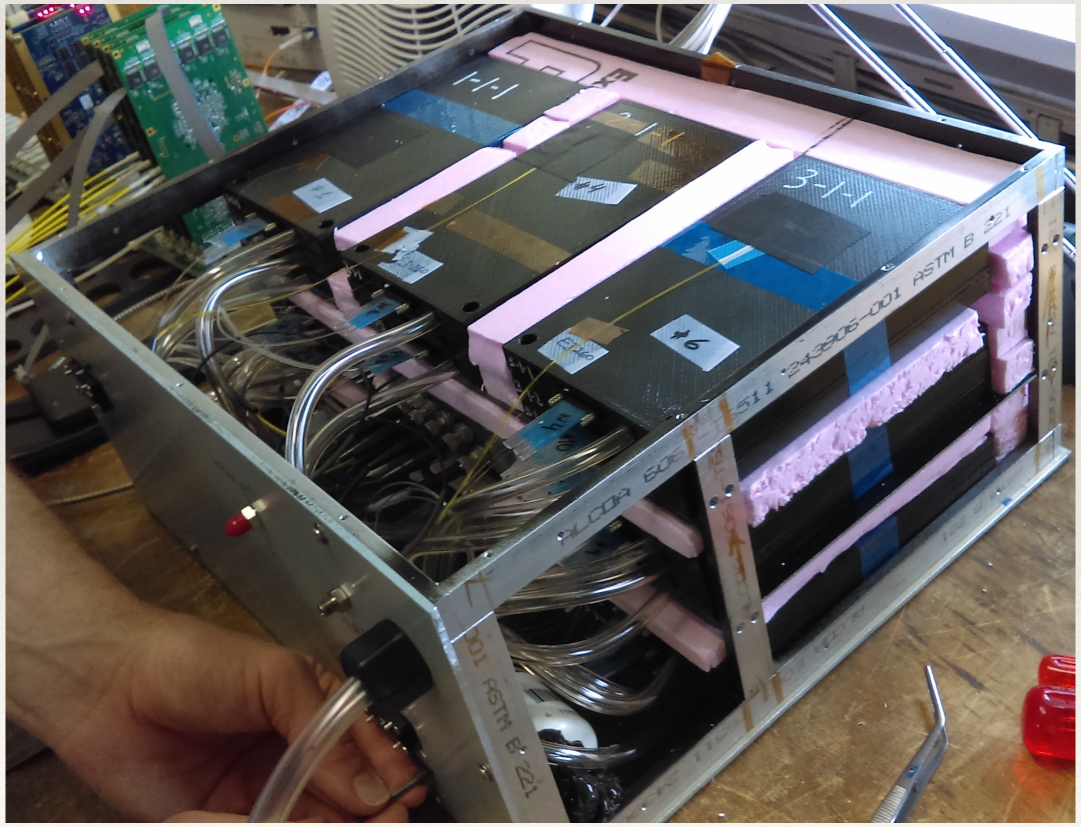
sigma tile

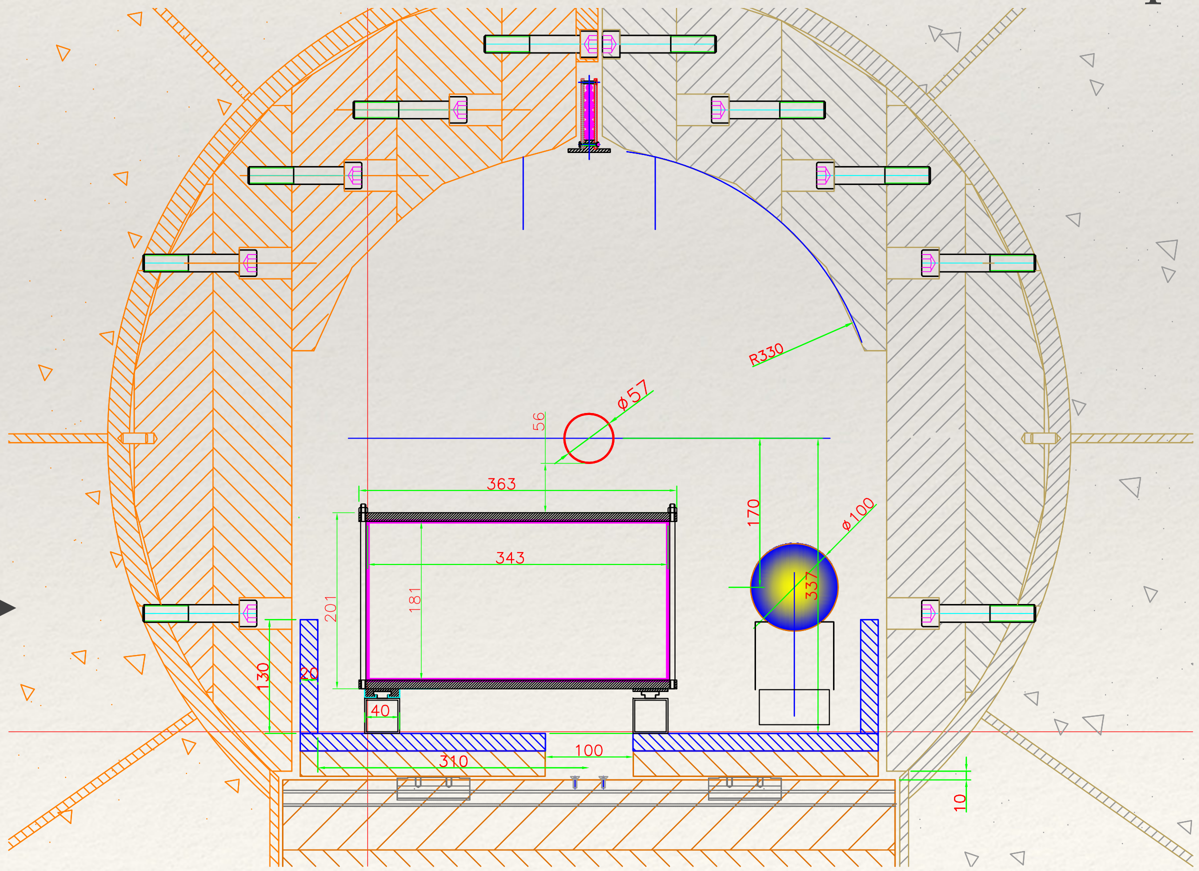




finger tile

CASTOR table setup

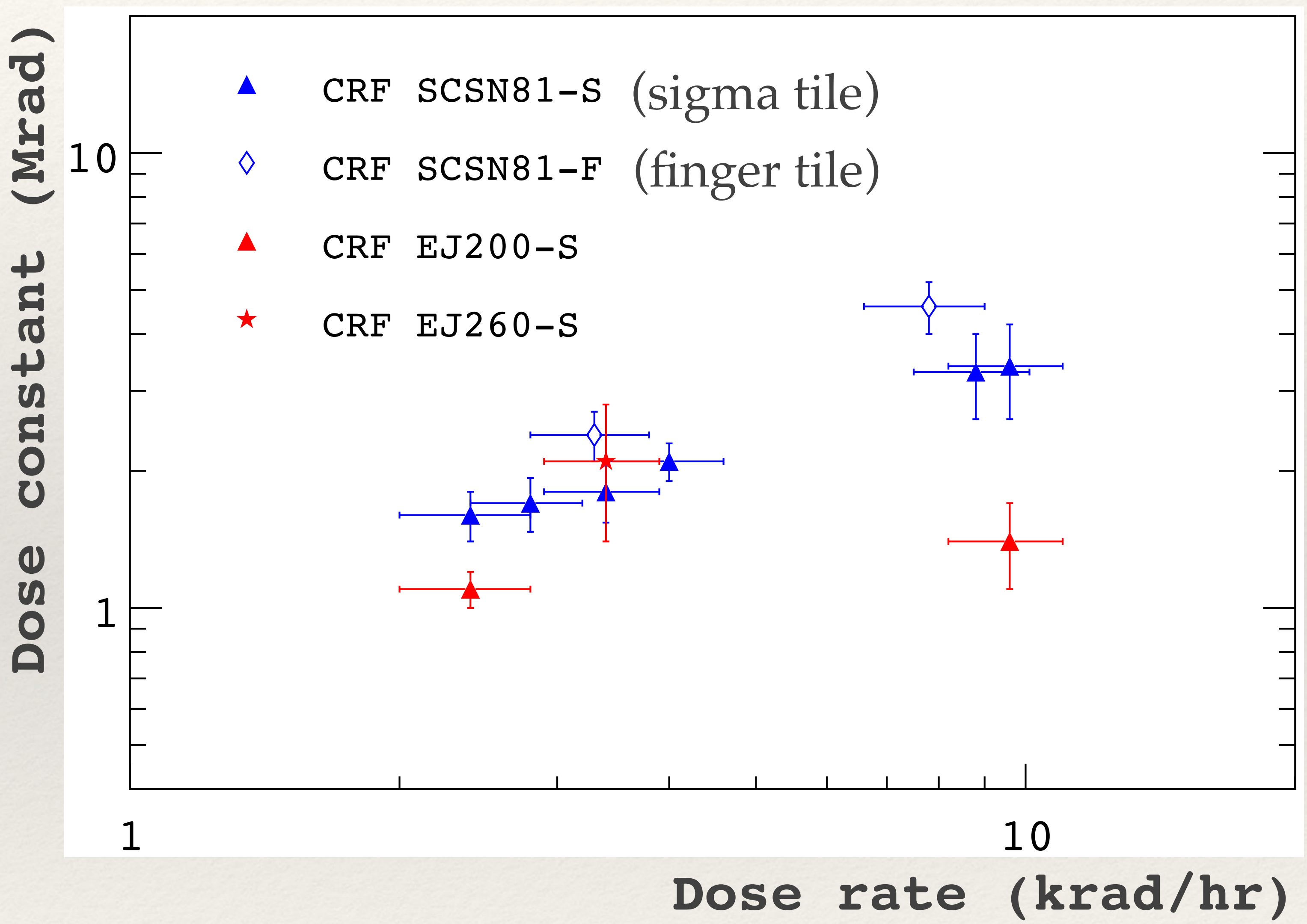




Dark box

CRF dose constant measurements

- Successful irradiation of SCSN81, EJ200, and EJ260 tiles (sigmas and fingers) on CMS CASTOR table (CRF) in 2016
  - see previous slide for setup
  - performed at ambient temperature, no cooling
  - Phase I HE readout of samples
- Ongoing second iteration of this study
  - now with Peltier cooling of tiles
  - new design of box to hold samples farther from beampipe where dose rates are more like those of HGC environment



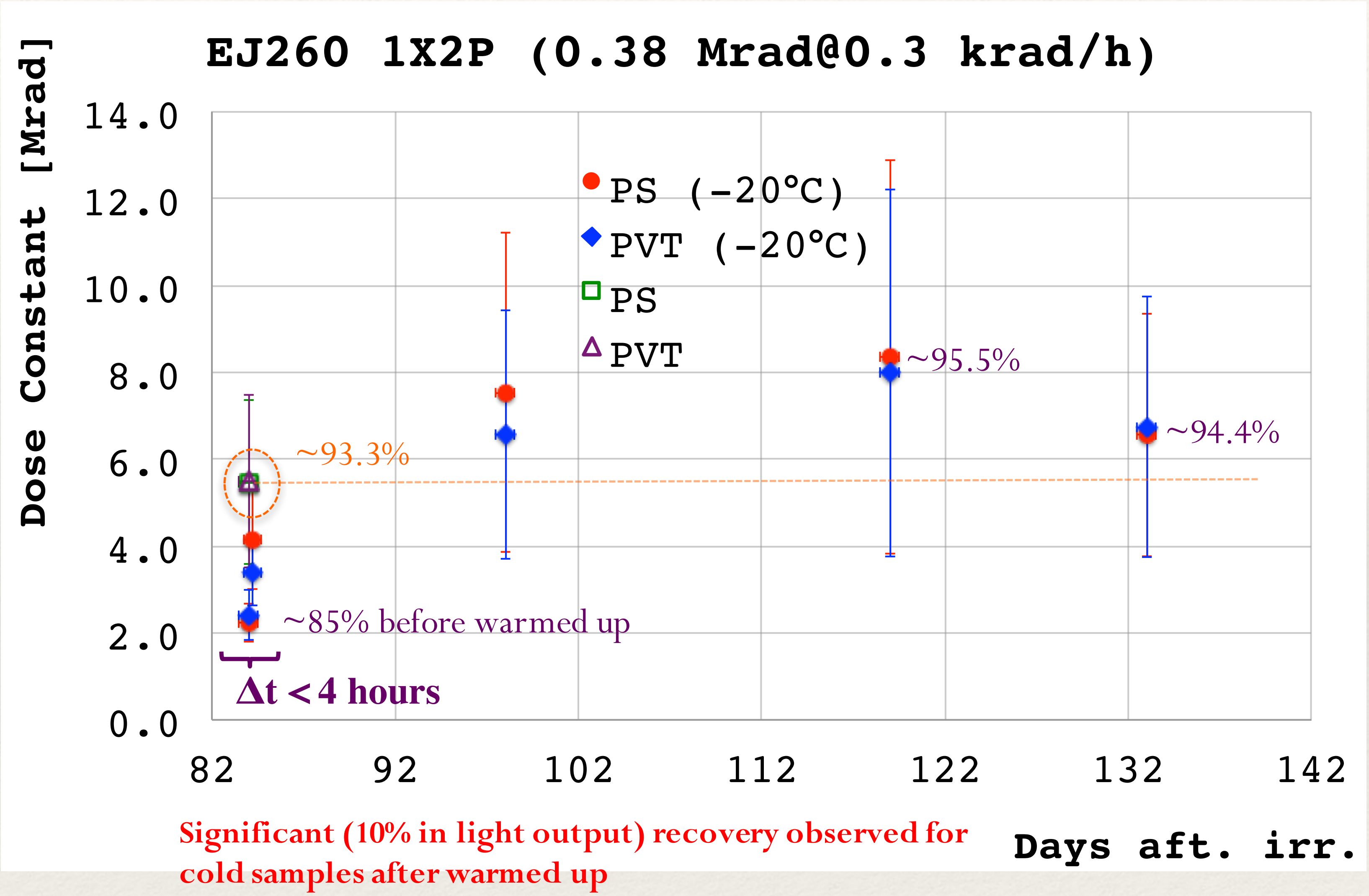
Summary and conclusions

- Operating at low temperatures (-30°C)
  - does not affect emission spectrum
  - leads to more accumulation of temporary damage (can recover) but reduces permanent damage
  - once warm, recovery is unaffected by previous low T
- Low dose rates
  - cause less temporary damage, as expected
  - further studies are needed at dose rates closer to projected HGC levels
- Dose constant measurement vs dose rate
  - studies ongoing to measure D for Phase II scintillator candidates
  - characterize their performance in HGC-like temperatures and radiation environment
  - will inform choice of scintillators for Phase II

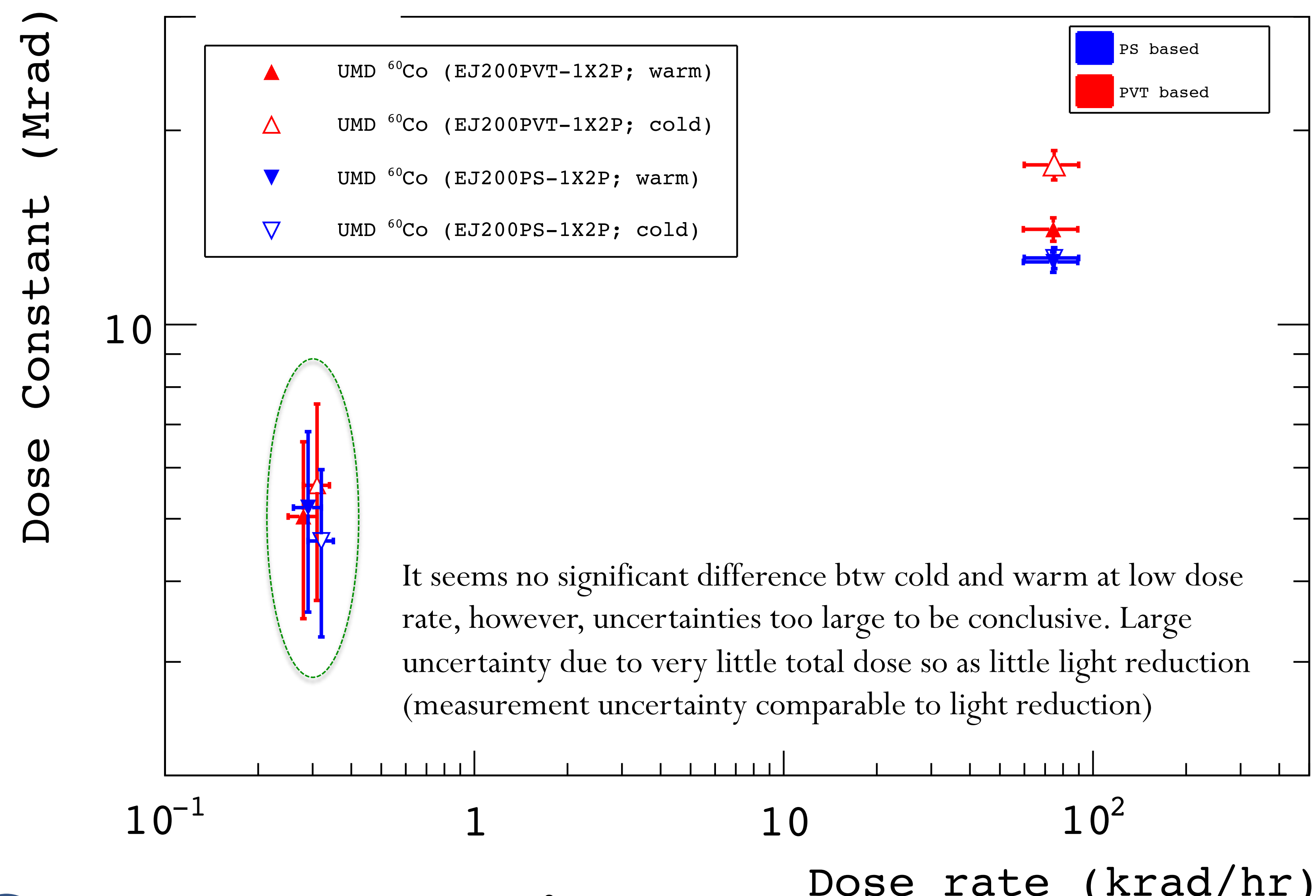
BACKUP

Goddard: more temporary damage (and recovery) in EJ260

- EJ260 1X2P recovery curve: comparing PS and PVT
- Large uncertainty due to small loss in light yield (not much temporary damage), for both warm and cold samples
- 10% recovery observed in cold samples



Example 5: cold vs. warm

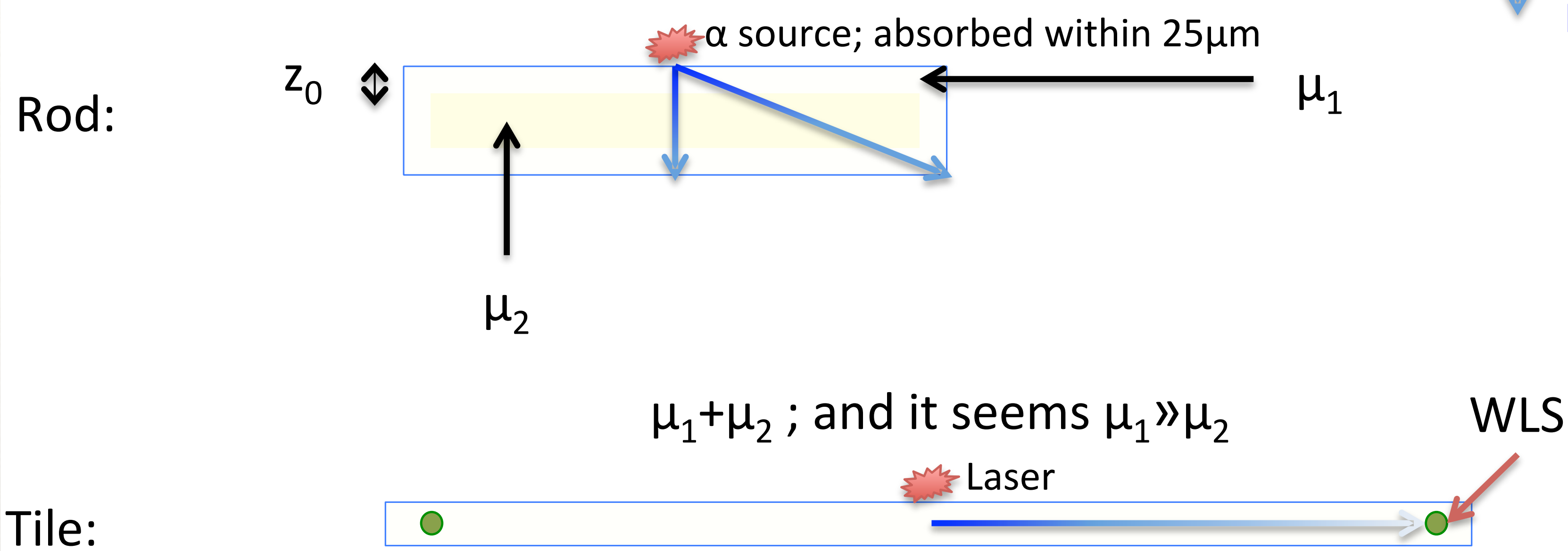


$5{\times}1{\times}1$ cm^3 samples

Effect of tile geometry on light yield

$$L = L_0 \times e^{-\mu_1 (2z_0) - \mu_2 t}$$ t=1 cm

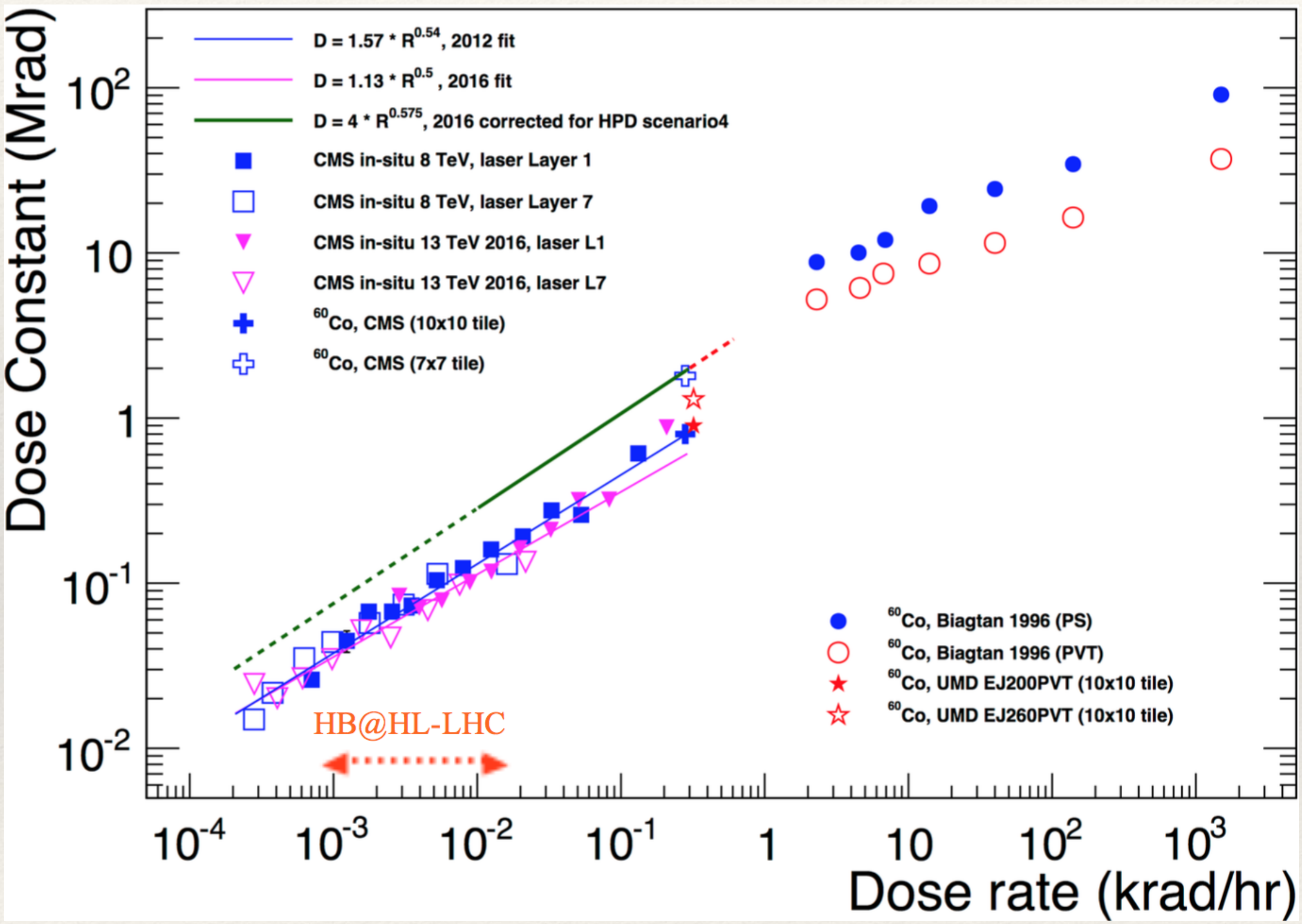
Signal light initiated by alpha particle or laser



$$L = L_0 \times e^{-(\mu_1 + \mu_2)T}$$ T≈5 cm

- Rudimentary first order estimation and ignoring attenuation of matrix itself
- z_0 > 2 mm for R ≤ 10 krad/h (next slide)
- μ_1 is the region where more damage to matrix and less temporary color centers due to oxygen; μ_2 is the region independent of oxygen concentration

Dose constant vs dose rate



- Many measurements of D
- Laser data from CMS
- Gamma irradiations from Biagtan
- Tiles irradiated near CMS beampipe ("CASTOR Radiation Facility" or CRF) and by alpha sources
- Green line: correction for effect of HPD damage in HCAL

Caveat for CMS dose constants

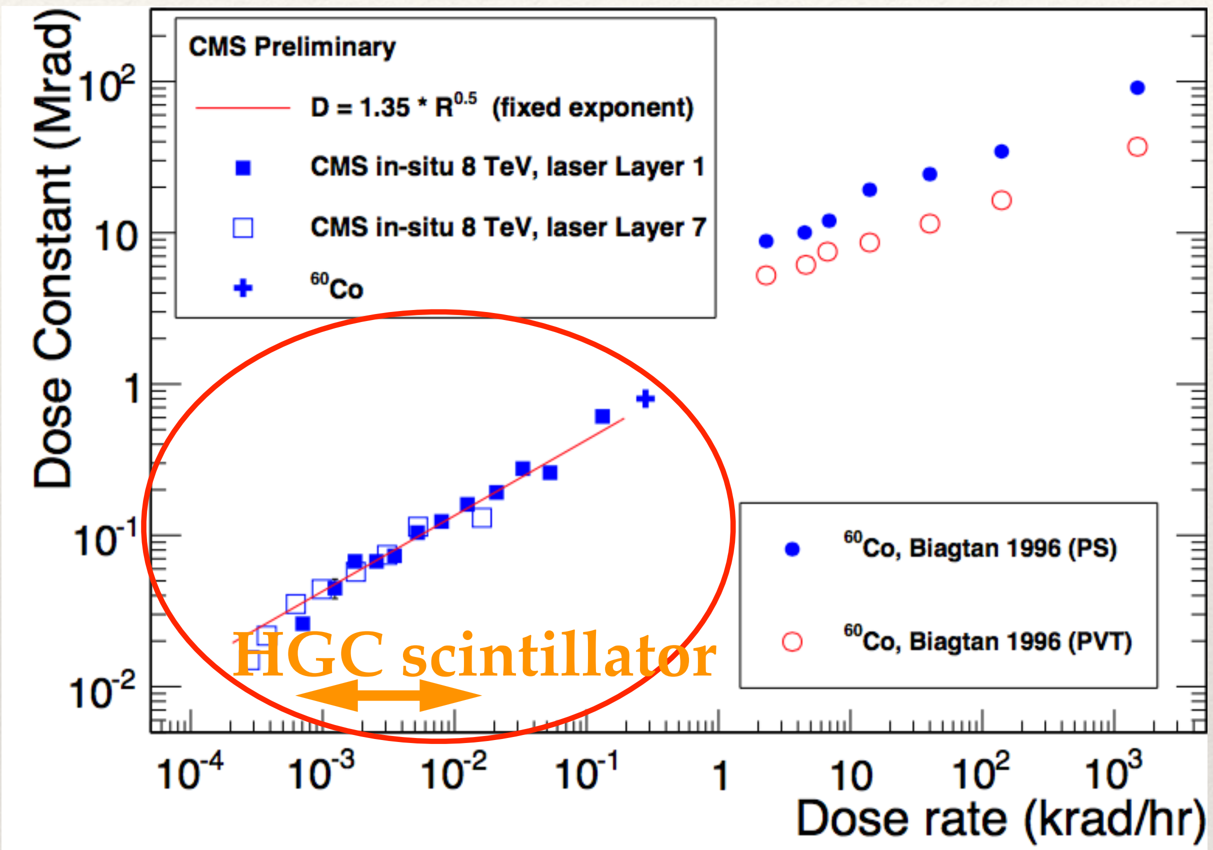


Fig. 5. Dose constant D [Mrad] as a function of dose rate R [krad/hr]. Results from scintillators based on PS (blue data points) and PVT (red data points). CMS in-situ 8 TeV data from 2012 run is shown in blue squares, with scintillators read out by HPDs. Solid line corresponds to a fit using the parametrization $D = a \times R^{0.5}$.

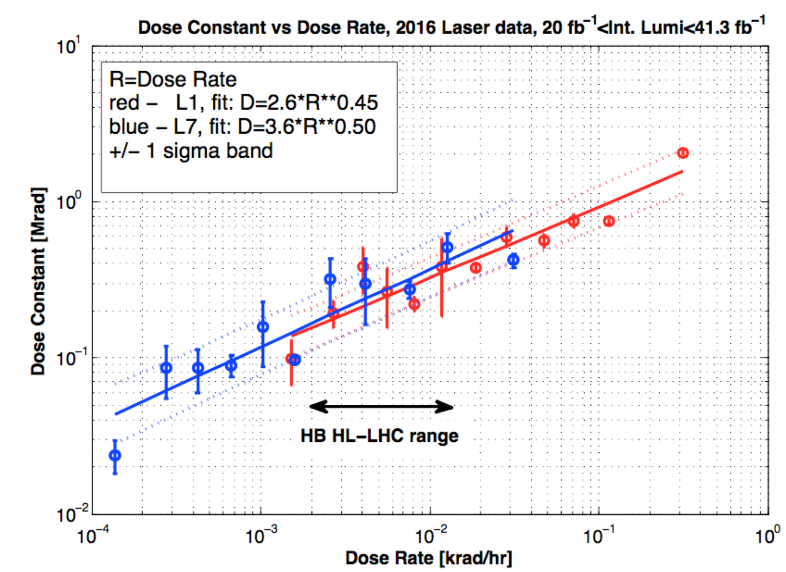


Figure 2.24: Dose constant D as a function of dose rate R using HE data from 2016. The points show the average over the ten best HPDs, with red (blue) points corresponding to L1 (L7) data. Error bars are calculated using RMS of the variation in D extracted from the response loss vs. dose of individual scintillator tiles. Solid lines correspond to fits using the parametrization $D = a \times R^b$. Dashed lines indicate the error band associated with the fits.