Scintillators for high energy x-ray detection

NIF diagnostics workshop, Los Alamos

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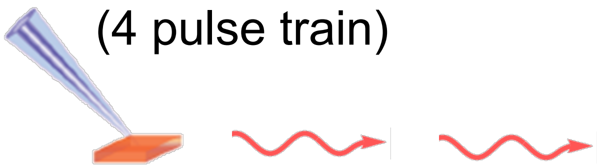
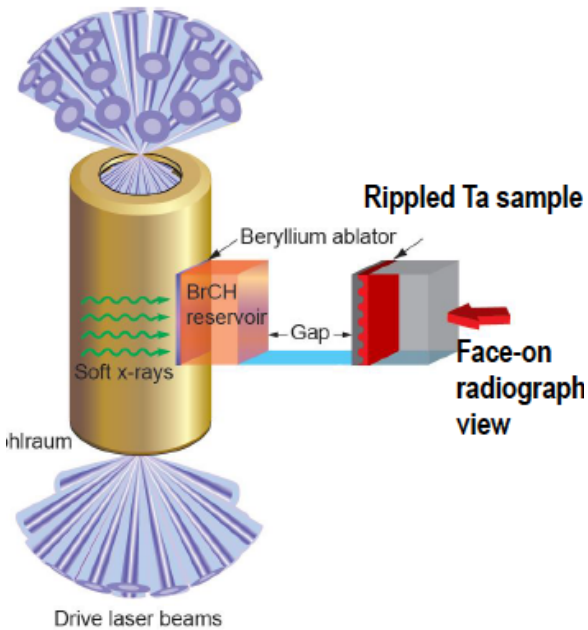
Face-on point-projection radiography for material strength experiments on NIF require 20-60keV gated detectors

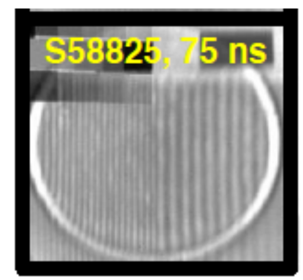
ARC backlighter
(4 pulse train)



X-rays

22keV Ag Kα
58keV W Kα



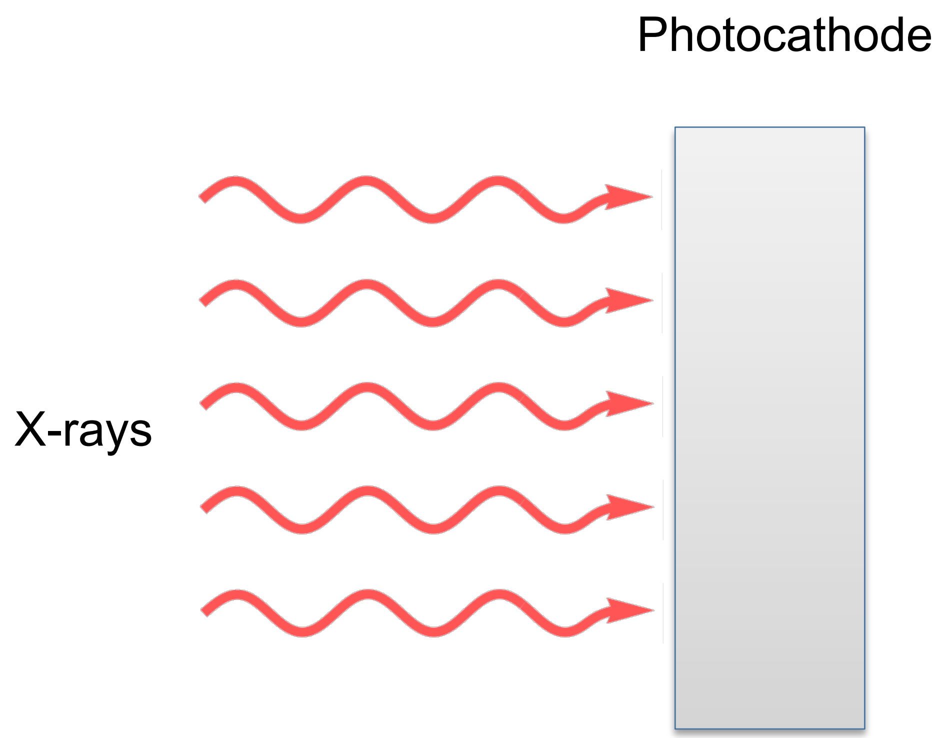


Face-on x-ray radiograph

Use the Sandia gated CMOS camera to either directly gate the x-rays, or gate the optical from a fast scintillator. For this talk I'm going to concentrate on gated scintillators

Ideally we would like 1ns gate, 4 frames, over 10s of ns, 25μm spatial resolution over a few cm, 100% efficiency and 10^3 dynamic range. But this is asking a bit much so what can we reasonably expect?

Why scintillators? Photocathodes are not sensitive enough (~% level at best, need 10s of %)



Only electrons generated within a few escape depths of the exit face contribute to the signal

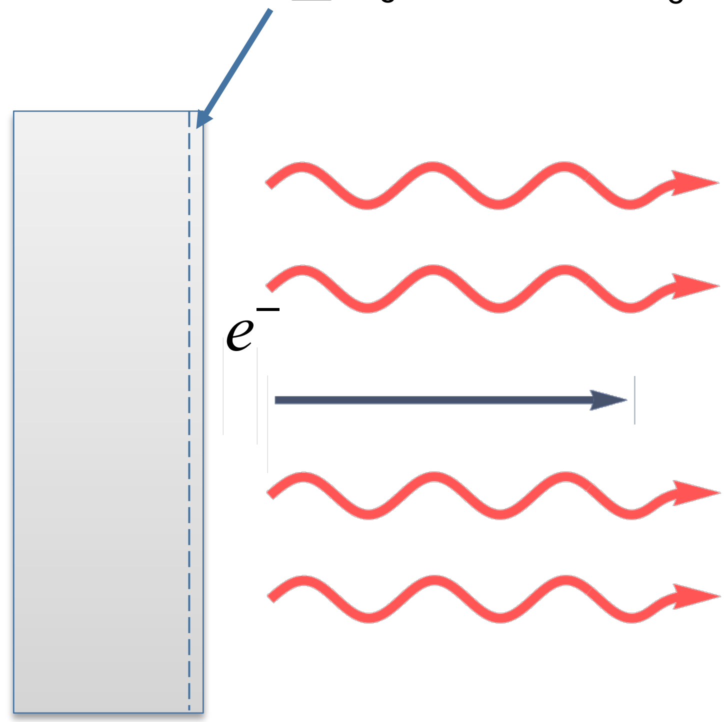
The useful bit:
a few [illegible] λ_e

λ_e CsI ~ 10 x $e_E^{1.5}$ nm
λ_e Au ~ 2.8 x $e_E^{1.5}$ nm

Optimum thickness*

$$t_{opt} = \lambda_e \ln(\lambda_x / \lambda_e)$$

λ_x x-ray attenuation length
λ_e electron escape depth



Expect Q.E. ~ λ_e/λ_x

Making the photocathode thicker doesn't increase efficiency
just attenuates the incoming signal

*Henke, B.L., Knauer, J.P., Premaratne, K., J. Appl. Phys. **52** 1509 (1981)

Useful thicknesses for 20-60 keV X-rays are only a few % of the X-ray mfp

$\lambda_e \approx 10$(h[illegible] - IP)$^{1.5}$ nm (CsI)

$\lambda_e \approx 2.8$(h[illegible] - IP)$^{1.5}$ nm (Au)

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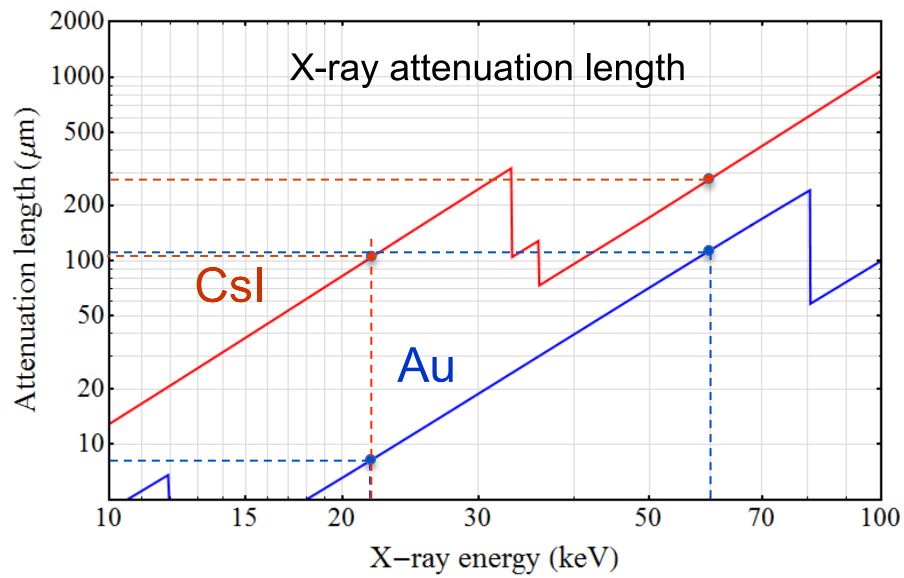
CsI $$t_{opt} = \lambda_e \sinh^{-1}(\lambda_x / \lambda_e)$$

Au $$t_{opt} = \lambda_e \ln(\lambda_x / \lambda_e)$$



	e^- escape depth (μm)		X-ray attenuation length (μm)		Optimum thickness: t_{opt} (μm)		Ratio t_{opt}/λ_x	
	22keV	60keV	22keV	60keV	22keV	60keV	22keV	60keV
Au	0.09	0.9	8.4	114	0.4	4.4	0.05	0.04
CsI	0.9	1.3	107	280	4.9	7.9	0.04	0.03

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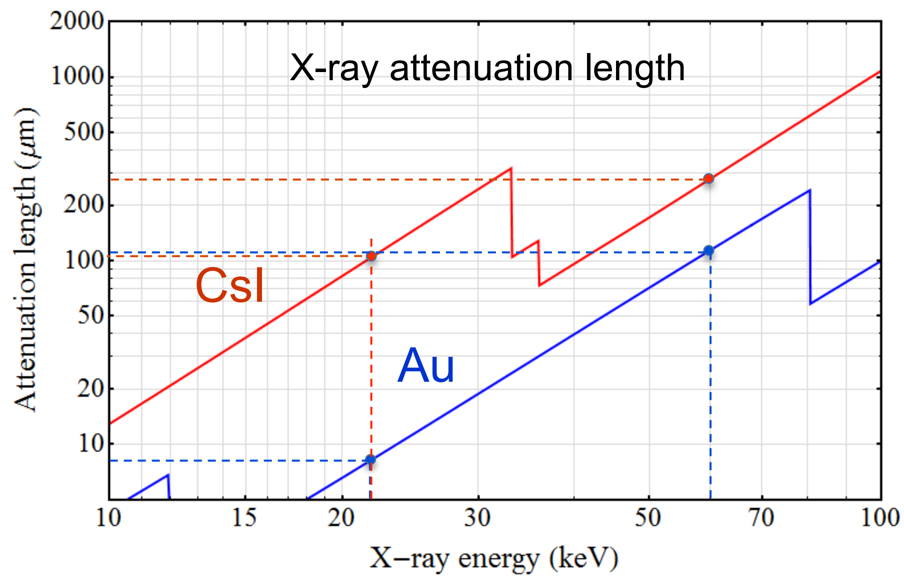

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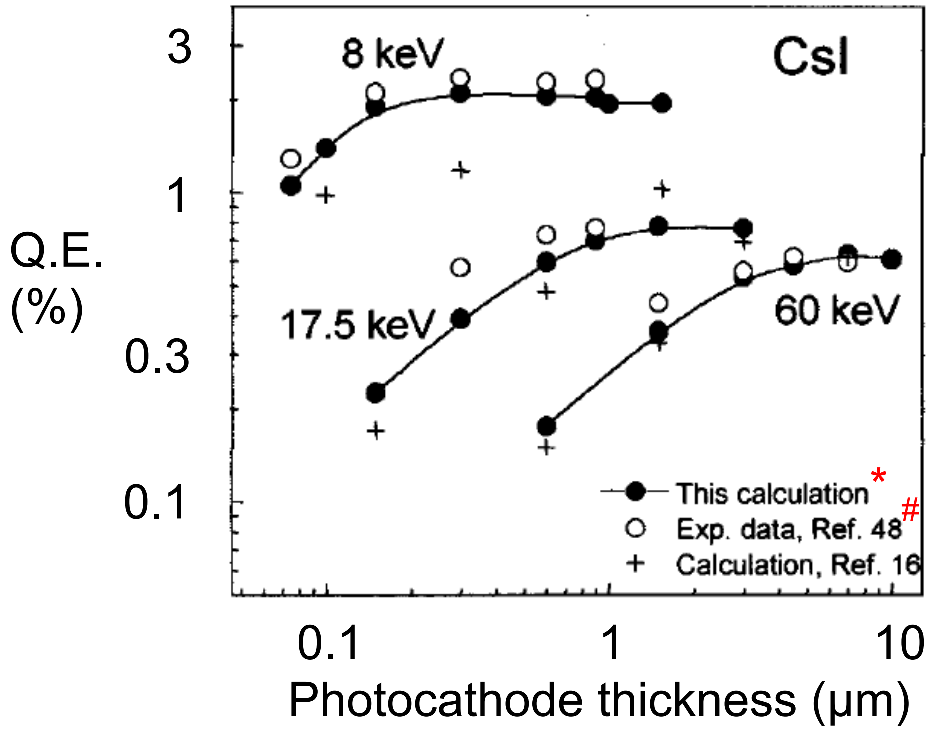
Consistent with < 1% quantum efficiency observed and modelled for CsI @ > 15 keV even few µm thick



*T. Boutboul, *et al.,* J.Appl.Phys., **86** (10) 5841 (1999)
#I. Frumkin, *el al.,* NIM A **329**, 337 (1993)

So for efficiency in the 10s of % or more at > 20 keV X-ray energy, in the absence of direct detection we probably need to start with a thick transparent scintillator

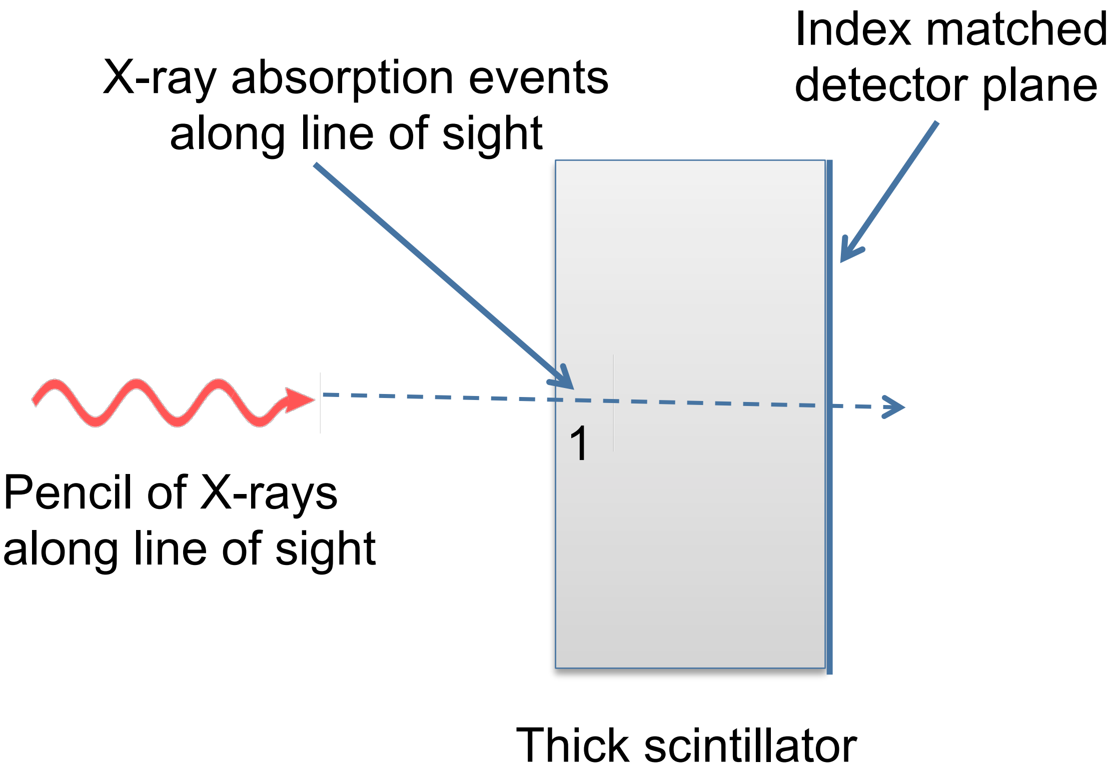
UHV negative electron affinity semiconductor photocathodes (i.e GaAs activated with pure cesium) get higher efficiency but with reduced temporal and spatial resolution and need to be refreshed in-situ every few hours. Grazing incidence cathodes increase sensitivity for certain applications (see Kathy's talk)

Fast scintillators for 22keV (Ag Kα) and 58keV (W Kα)

The detector (scintillator + optical detector + digitizer) needs to:

- Stop the required fraction of incoming photons
- Collect enough light from each x-ray photon absorption event to unambiguously detect it
- Maintain required spatial resolution
- Decay to nothing before the next frame, or decay in a way that can be properly subtracted (places extra headroom requirement on optical detector) whilst maintaining required signal to noise and dynamic range

A pencil of rays is absorbed throughout the depth of a thick scintillator



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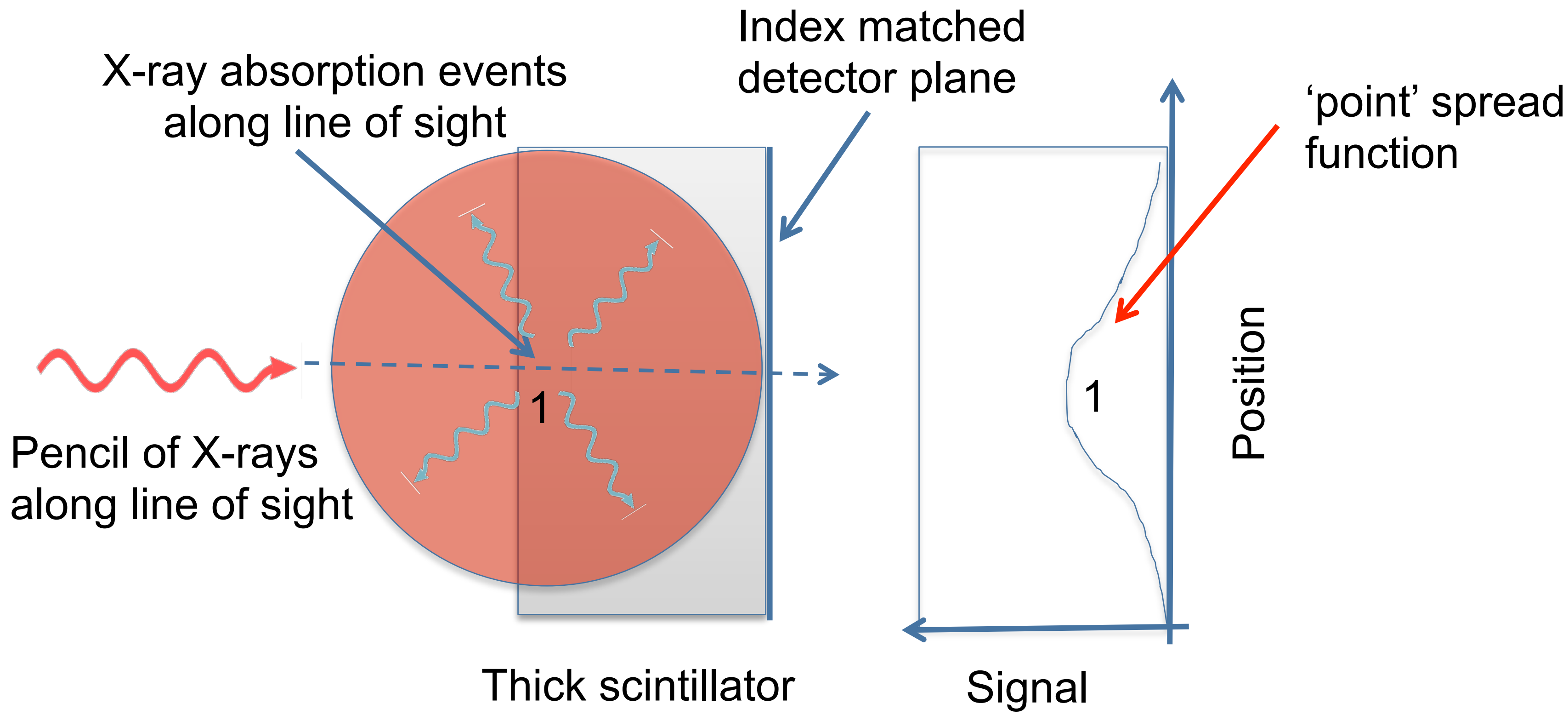

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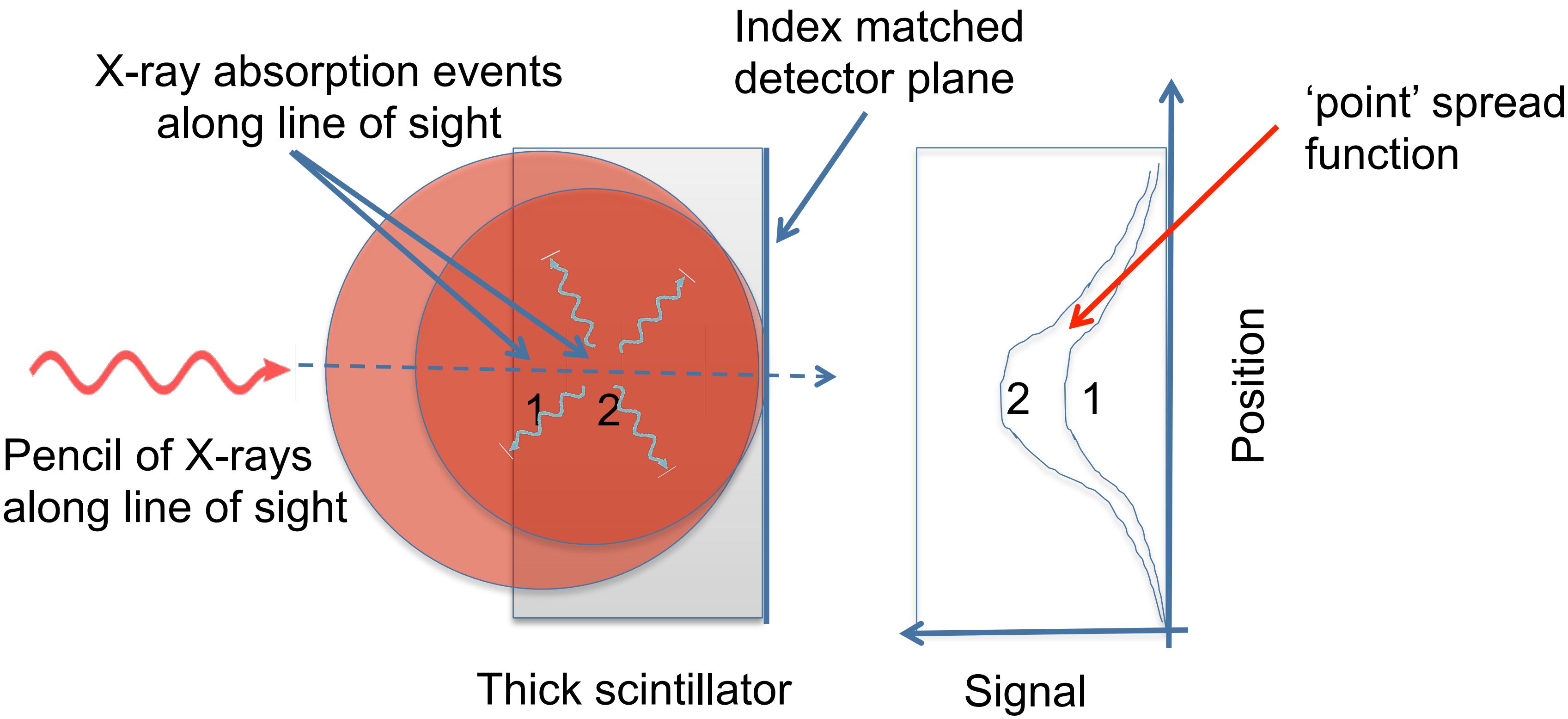

X-rays absorbed closer to the detector contribute narrower components to the point spread function

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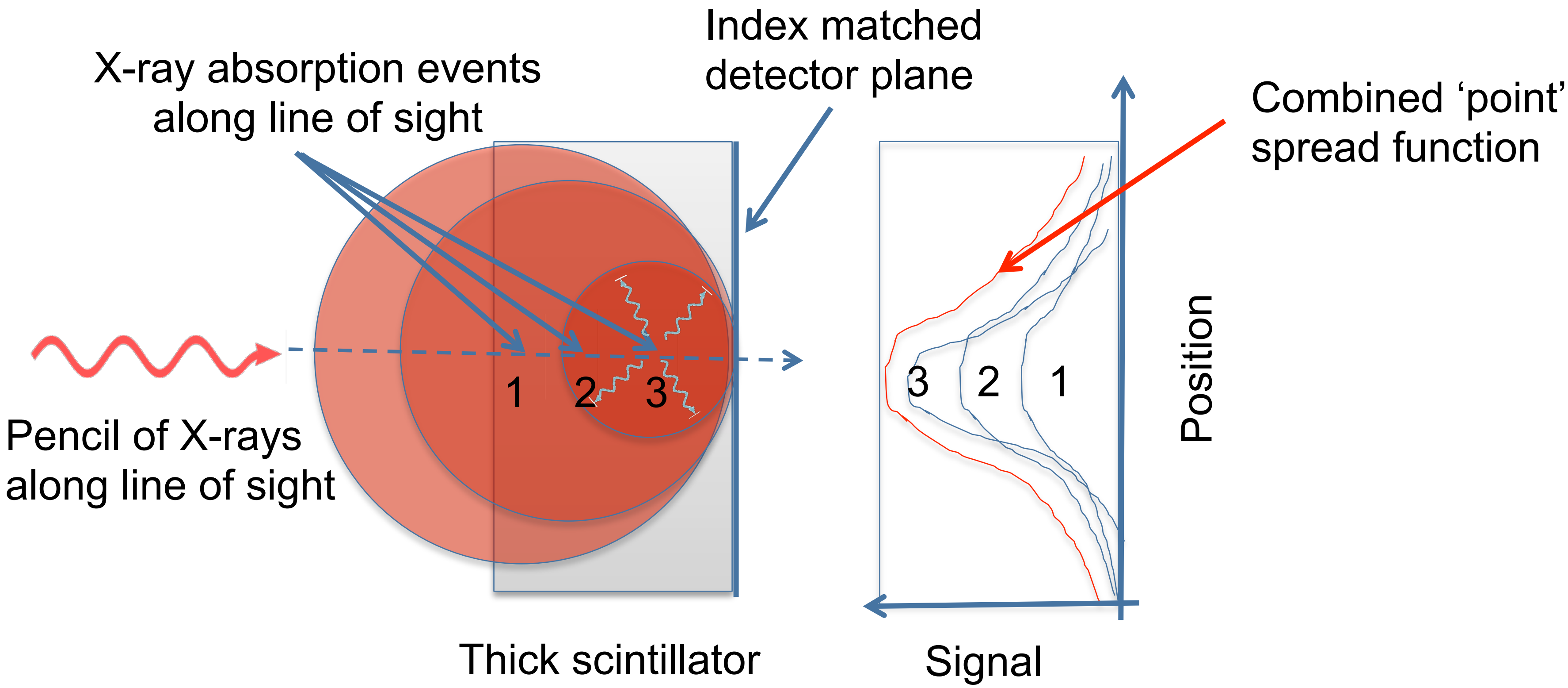
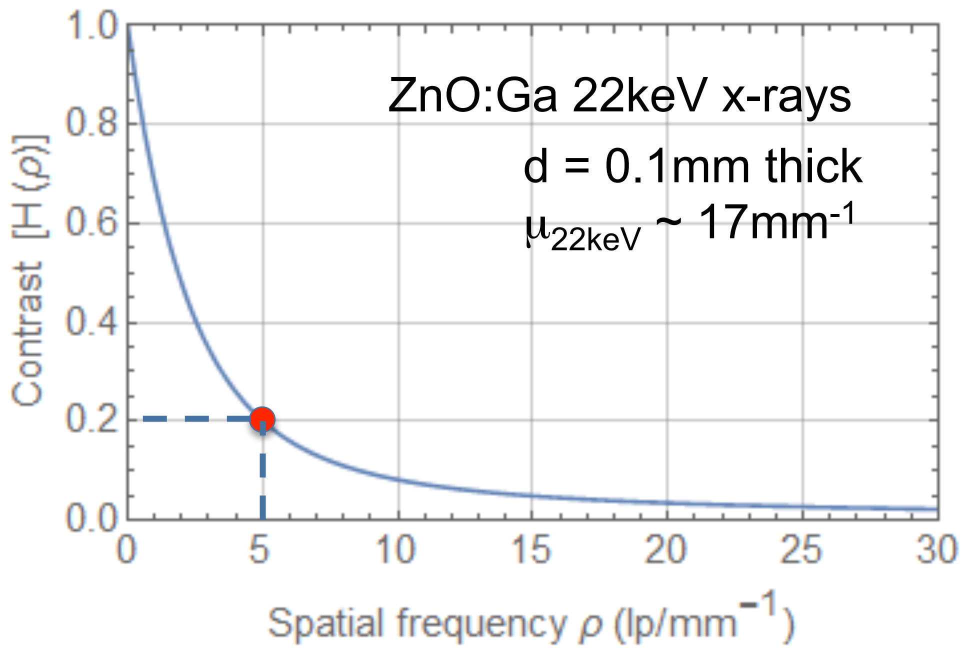


X-rays absorbed closer to the detector contribute narrower components to the point spread function

In the absence of total internal reflection this will considerably limit spatial resolution

The transfer function for a thick, index-matched scintillator screen suggests we need to limit the NA



$$H_{\rho,d,\mu} = \frac{\mu\left(e^{d\,(\mu-2\pi\rho)}-1\right)}{\left(e^{d\mu}-1\right)\,(\mu-2\pi\rho)}$$

H(ρ) = contrast at ρ (lp/mm)
(max-min)/(max+min)

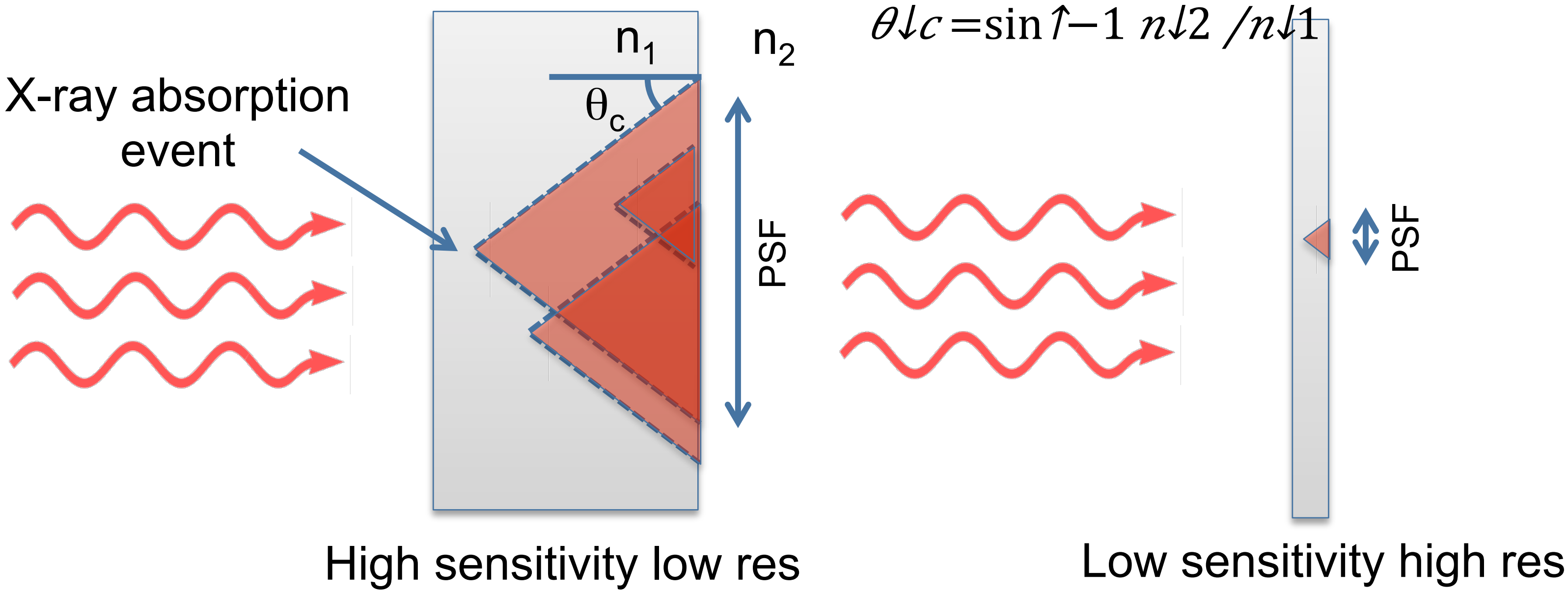
d = thickness
μ = absorption coefficient
ρ = spatial frequency

For example, using 100μm thick ZnO:Ga scintillator at 22keV x-ray energy gives only ~20% contrast at 5 lp/mm

Total internal reflection limits the cone of rays that can be collected

Intentionally not index matching the scintillator reduces the numerical aperture of the detector with half angle θ_{crit} but reduces overall sensitivity

$$\theta_c = \sin^{-1} n_2 / n_1$$

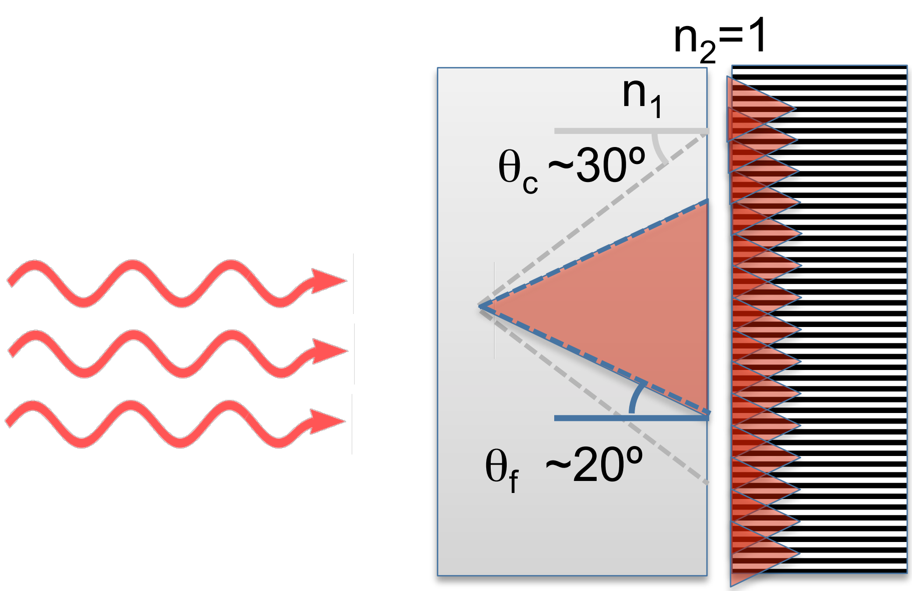


Spatial resolution is governed by scintillator thickness and refractive index

A fiber faceplate with lower numerical aperture increases resolution but decreases signal further

For example, ZnO:Ga has refractive index n_1 ~2.1 at it's peak emission of 385 nm

giving critical angle $\theta_c = \sin^{-1} n_2/n_1$ ~30°



A fiber optic with numerical aperture NA accepts light within a half cone angle in the scintillator:

$$\theta_f = \sin^{-1} NA/n_1$$

For numerical aperture 0.66 , θ_f ~18°

So for this abs event the width of the point spread function is reduced by:

$$\frac{\tan \theta_f}{\tan \theta_c} = \frac{\tan 18^\circ}{\tan 30^\circ} \sim 0.6$$

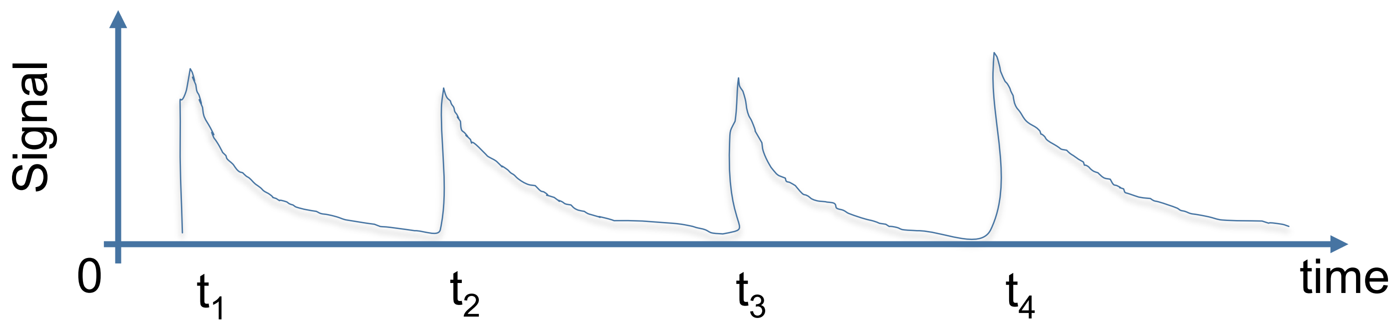
So ***given enough signal*** there's useful information to be retrieved at higher spatial frequencies so we should look at the photon statistics for reduced NA

Which scintillators are suitable for this?

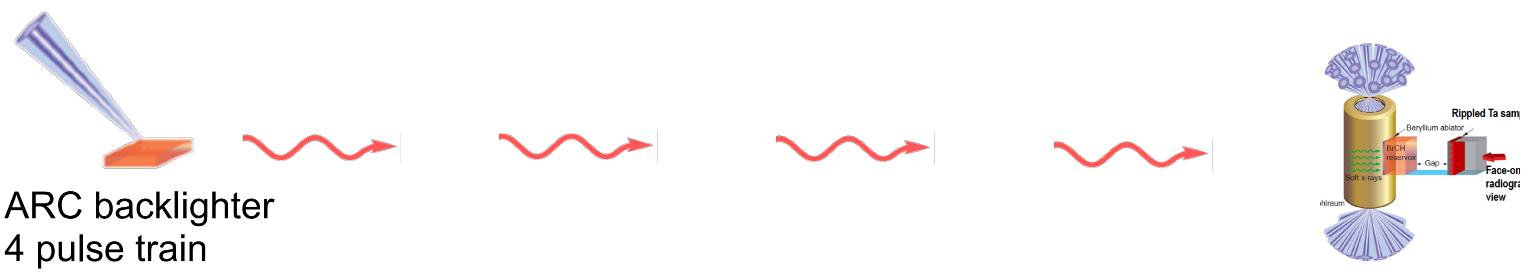
	1/e decay	Peak nm	n	r g/cc	hv/keV	Non-powder
NaI (pure)	60 ns	303	1.78	3.67	80	Yes
N104 (organic)	1.8 ns	405	1.58	1.03	24	Yes
LSO:Ce	40 ns	420	1.82	7.4	30	Yes
Cs_2ZnCl_4	1.6-3 (30% 21ns)	360	?	2.93	0.6	Yes
BaF2	0.6 ns	220	1.53	4.9	2	Yes
ZnO:Ga #	0.8 ns	385	2.1	5.7	9	Yes
New LBL *	<0.2 ns	~540	~2	~5	0.2*	Yes

#difficult to dope uniformly; we need several cm^2 ~0.1-1mm thick
*new scintillator from Derenzo group at LBL (will be published next month)
Readily doped and can be drawn into fibers. Dopant needs to be optimized, scope for factor of 10-100 improvement in optical yield while maintaining <0.2ns

Ideally the scintillator is fast and bright enough to get the required contrast by simply gating it



Faster scintillator



ARC backlighter
4 pulse train

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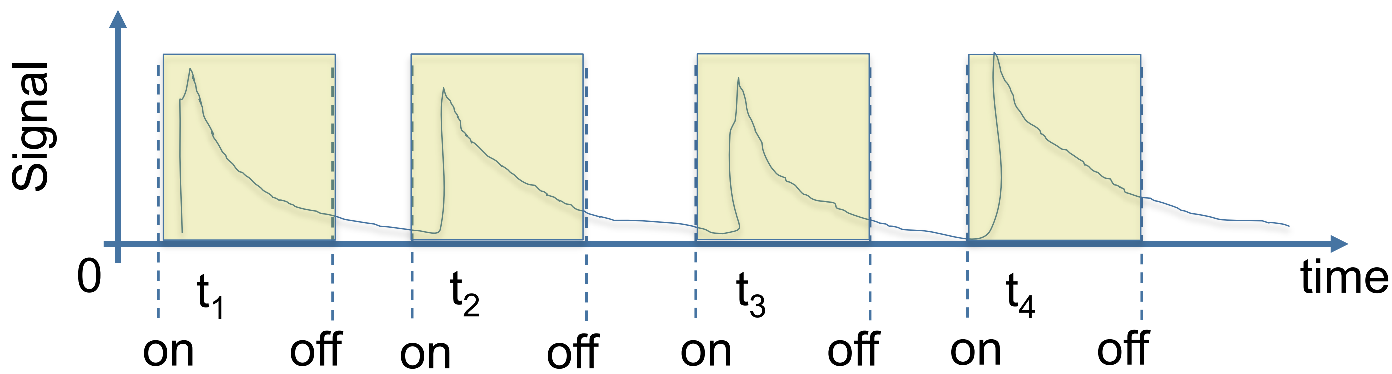
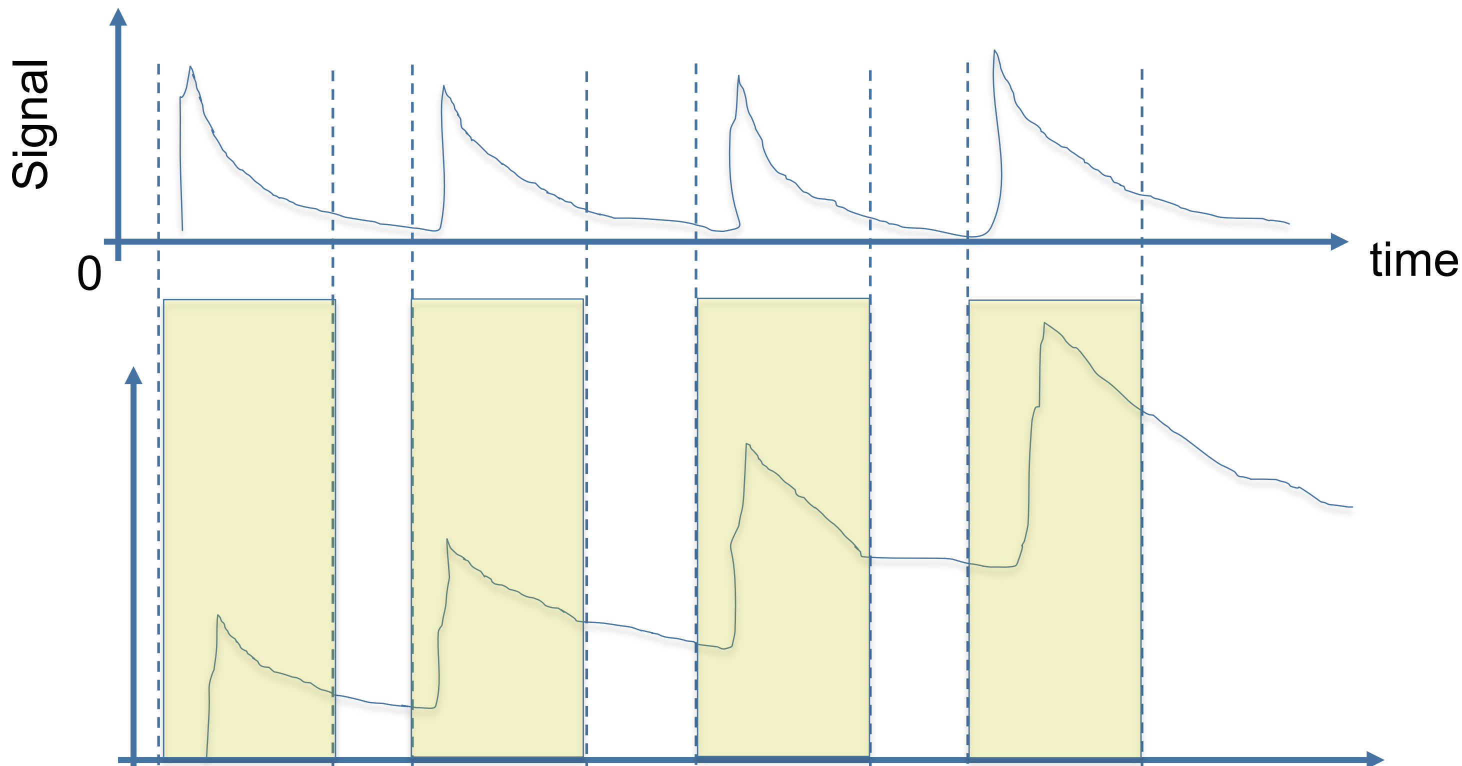
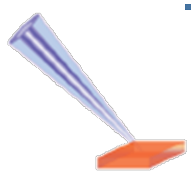


Faster scintillator

If scintillator decay is slow compared to the gate, estimate afterglow from last frame and subtract





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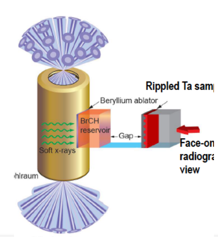
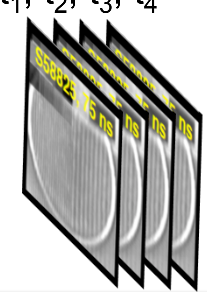
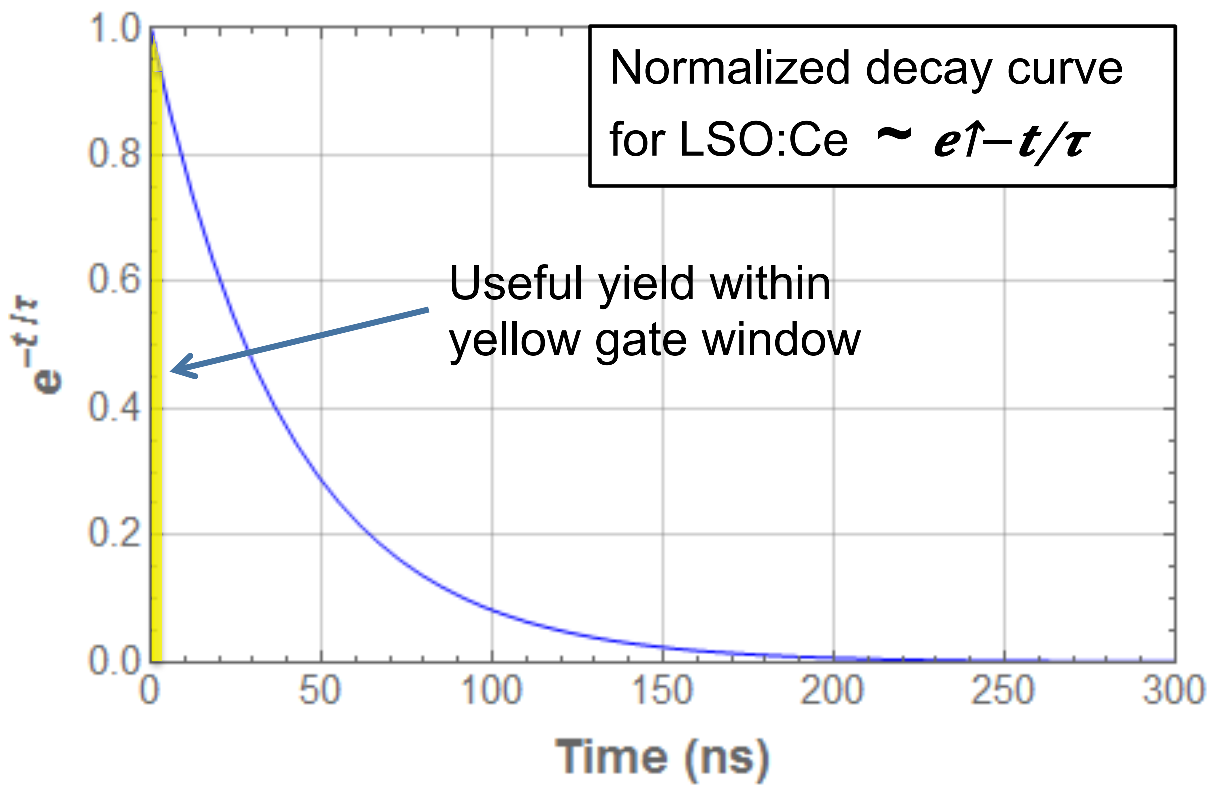




For a slow scintillator to be more effective it must provide greater signal to noise ***within the gate***

e.g. Cerium doped LSO (Lu2SiO5:Ce) assuming ~exponential decay
1/e decay time: τ **~40ns,** Yield: **Y ~30 optical photons / keV**



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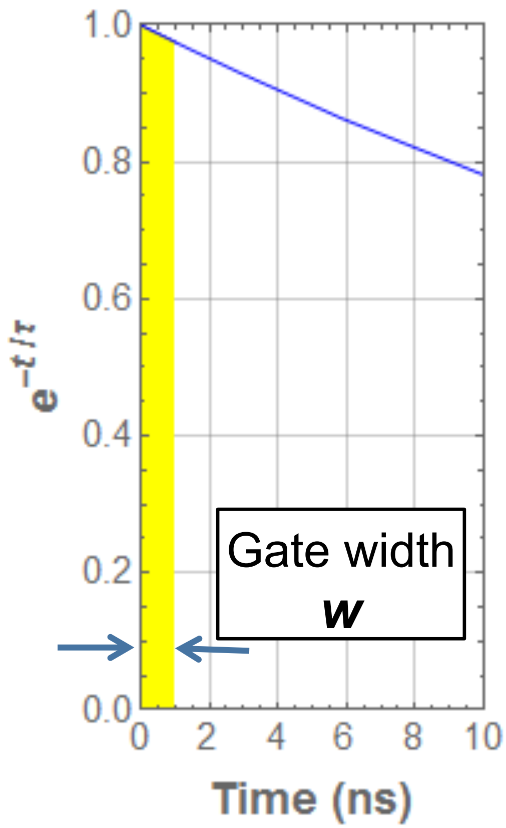


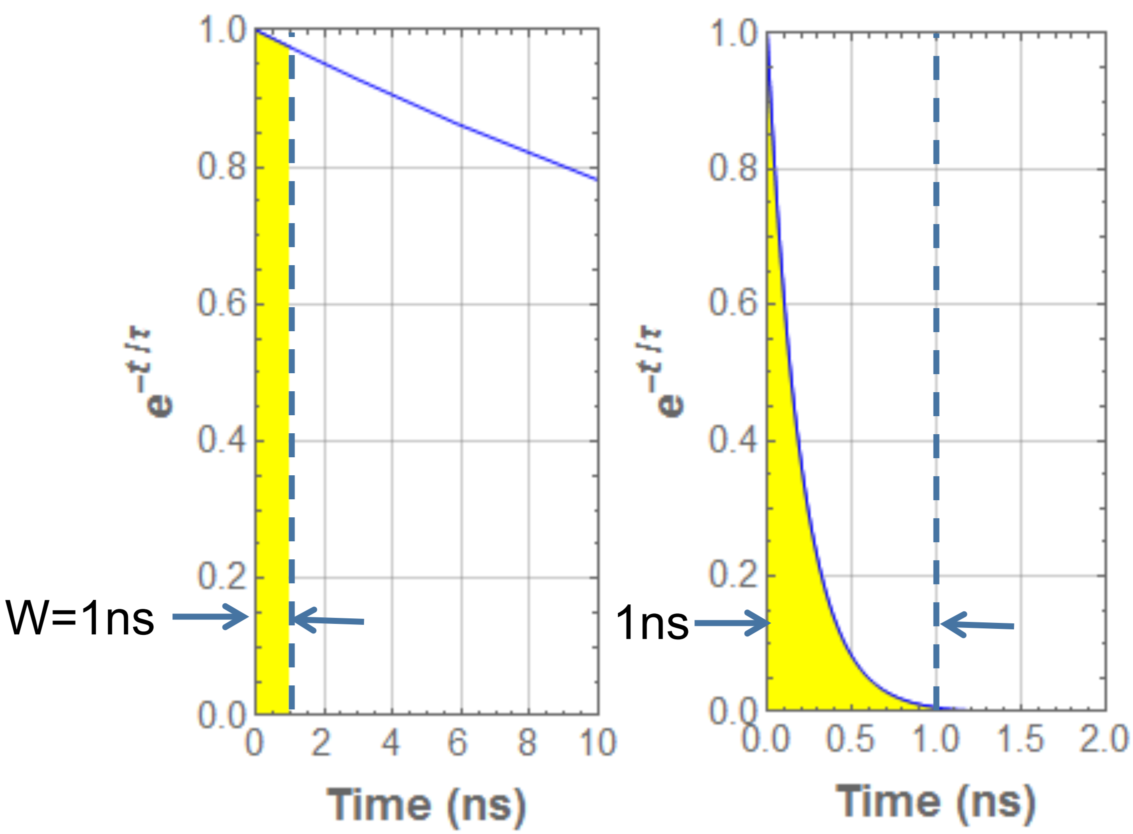
Useful yield (optical photons / keV):

$Y \int_0^{w} e^{t/\tau}\, dt \,/ \int_0^{\infty} e^{t/\tau}\, dt = Y(1-e^{w,}$

Compared to the fast LBL scintillator in its current form, LSO:Ce has ~4x the useful light yield

LSO:Ce τ **~40ns,** Yield: **Y ~30 optical photons / keV**
Fast LBL: τ **~0.2ns,** Yield: **Y ~0.2 optical photons / keV**

W = 1ns gate



$Y_{useful} = Y(1-e\uparrow w/\tau\ )$

Scintillator	Y_{useful}
Fast LBL	0.2
LSO:Ce	0.74

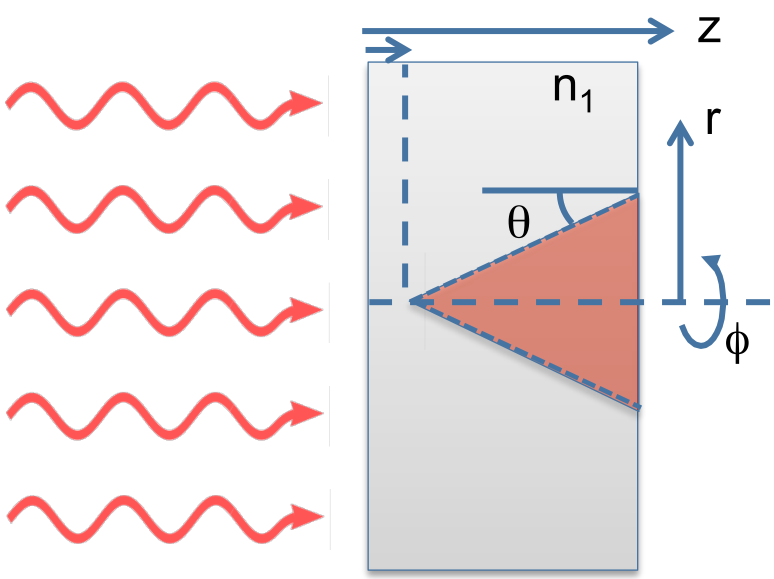
ZnO:Ga has ~30x the useful light yield and decays to 1% in ~3.7ns

Material	Yield	1/e	Y_{useful}	$Y_{remaining}$	$t_{1\%}$	$t_{0.1\%}$
LSO:Ce	30	40ns	0.74	~97.5%	185 ns	276 ns
NaI (pure)	80	60ns	1.32	~98.4%	276ns	414ns
ZnO:Ga	**9**	**0.8ns**	**6.4**	**~30%**	**3.7ns**	**5.5ns**
Fast LBL	**0.2**	**0.2ns**	**0.2**	**~0%**	**0.92ns**	**1.4ns**

So for a ~5ns gate separation ZnO:Ga can operate in "fast" mode with no need to subtract prior signal

Model point spread function and efficiency as a function of absorption, thickness and NA

Use the absorption coefficient to calculate the energy dumped in the scintillator as a function of depth, multiply by internal QE, then integrate the signal at the detector over z and ϕ, as a function of r



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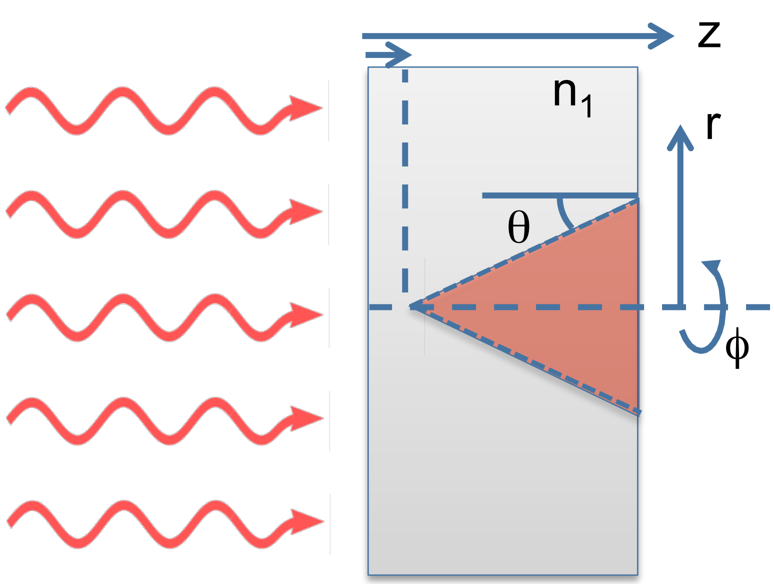


Limit r using a maximum value for θ, with either:

θ_f (limited by fiber NA)

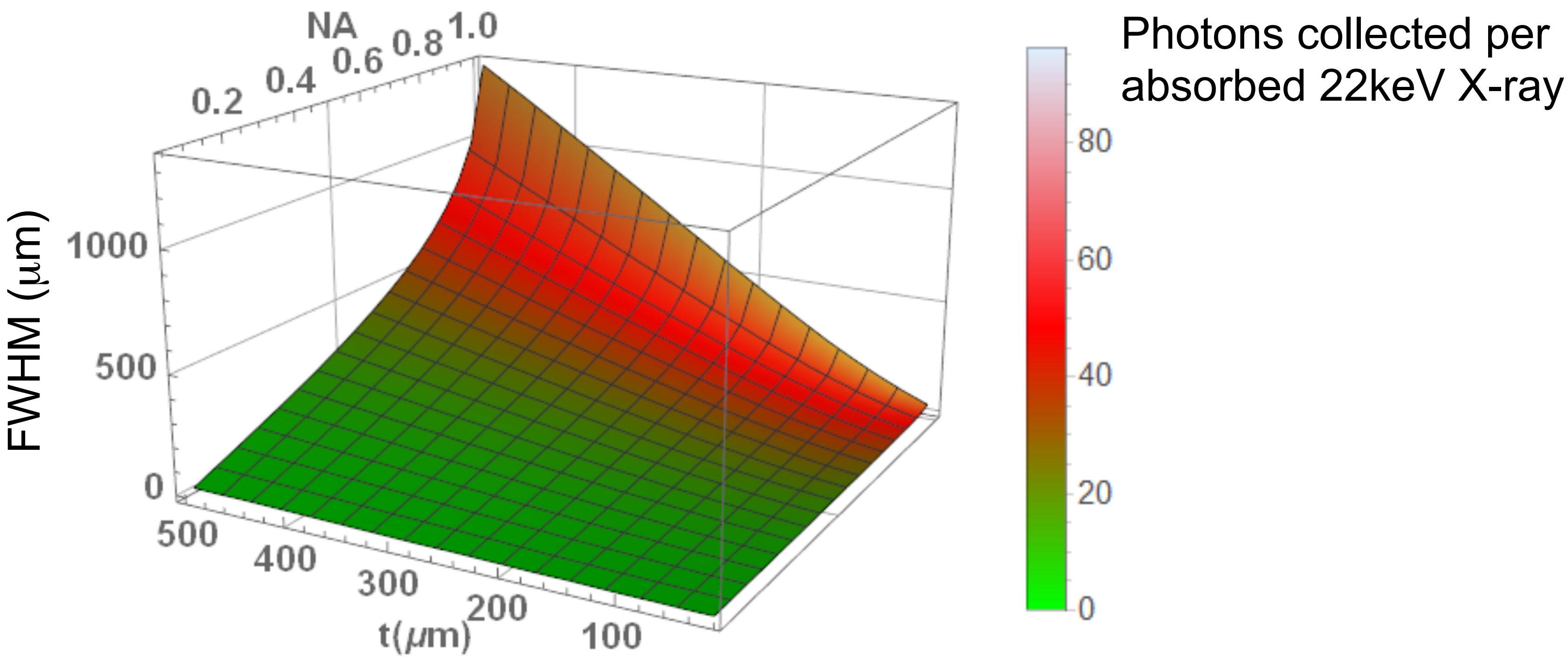
or

θ_c (scintillator refractive index)

Plot both optical collected per x-ray and PSF FWHM, as a function of thickness and NA.

absorption coefficient μ and internal quantum efficiency Y are the input parameters

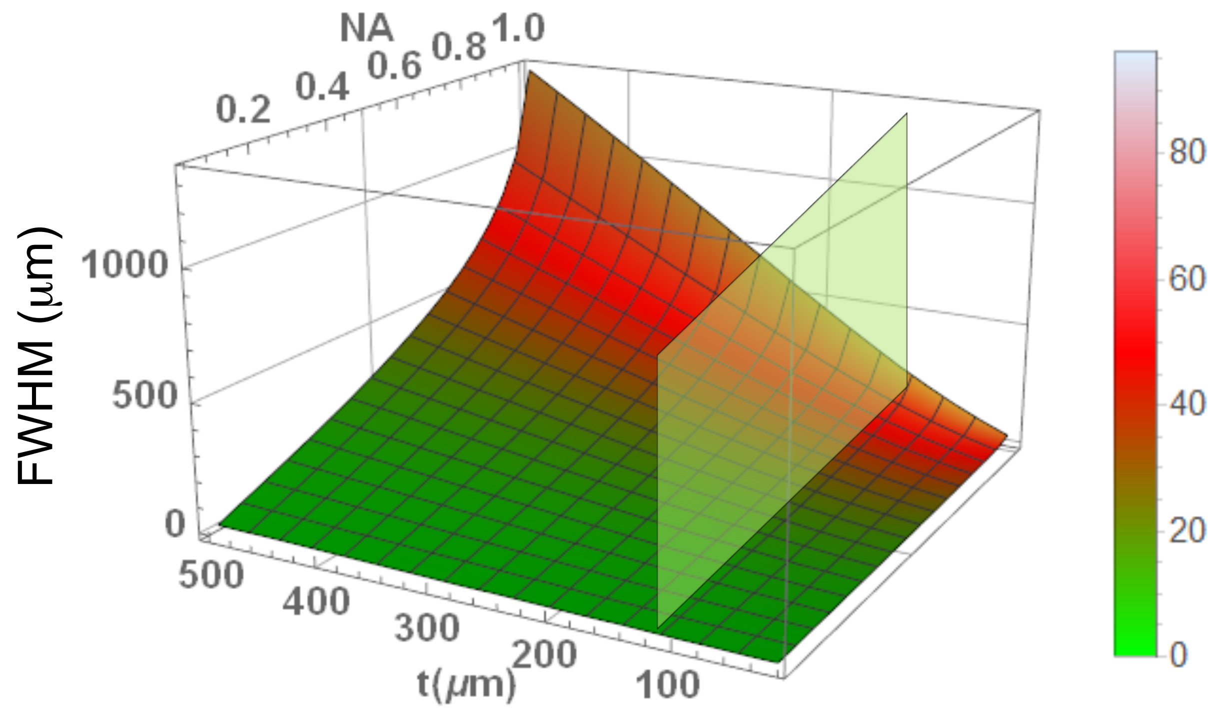
For ZnO:Ga at 22keV, using:
μ ~171cm^{-1} and Y ~9 optical photons per keV



Take a slice through the surface at t = 100μm

9 optical photons / keV (Derenzo)

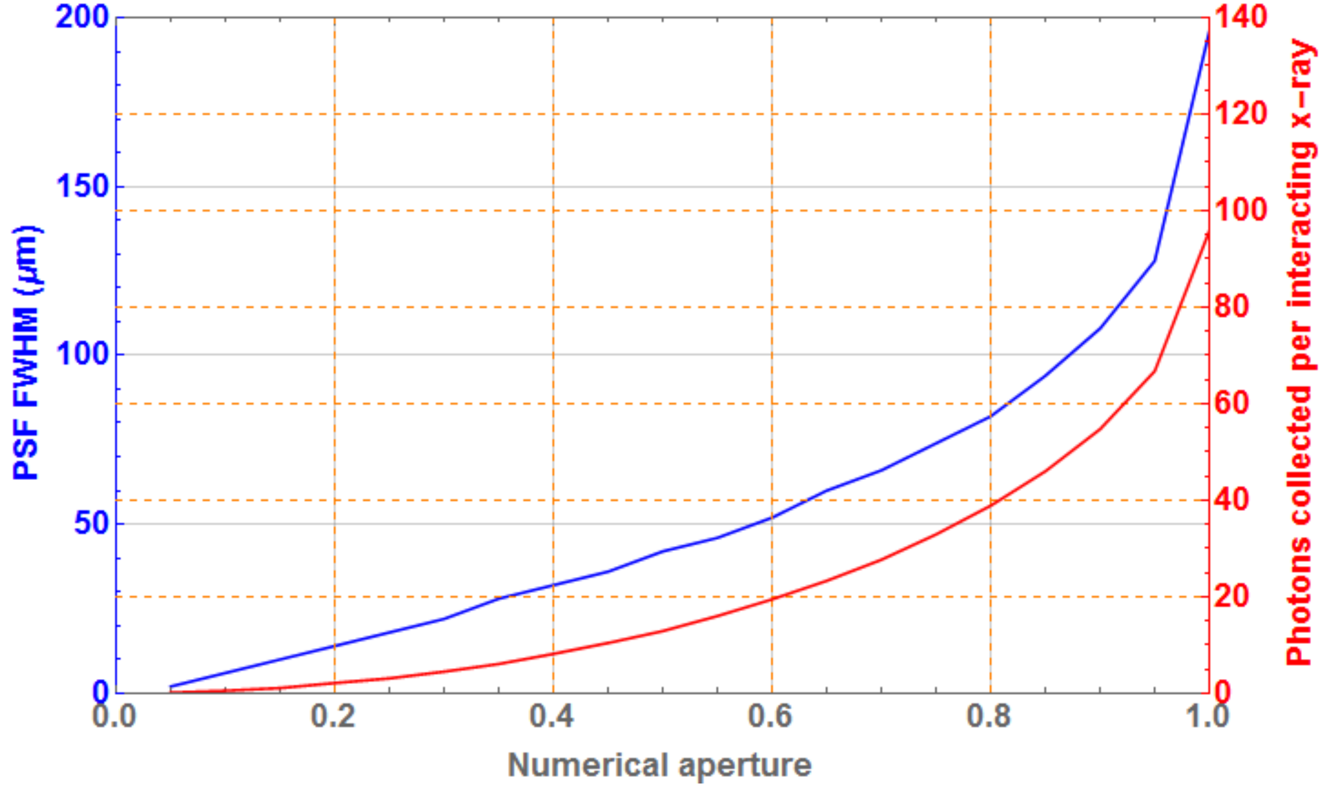
For ZnO:Ga at 22keV, using: μ ~171cm^{-1} and Y ~9 optical photons per keV



Photons collected per absorbed 22keV X-ray

plot FWHM vs numerical aperture
and photons collected per 22keV X-ray vs numerical aperture

Resolution and efficiency of a 100μm thick ZnO:Ga scintillator screen at 22keV vs NA



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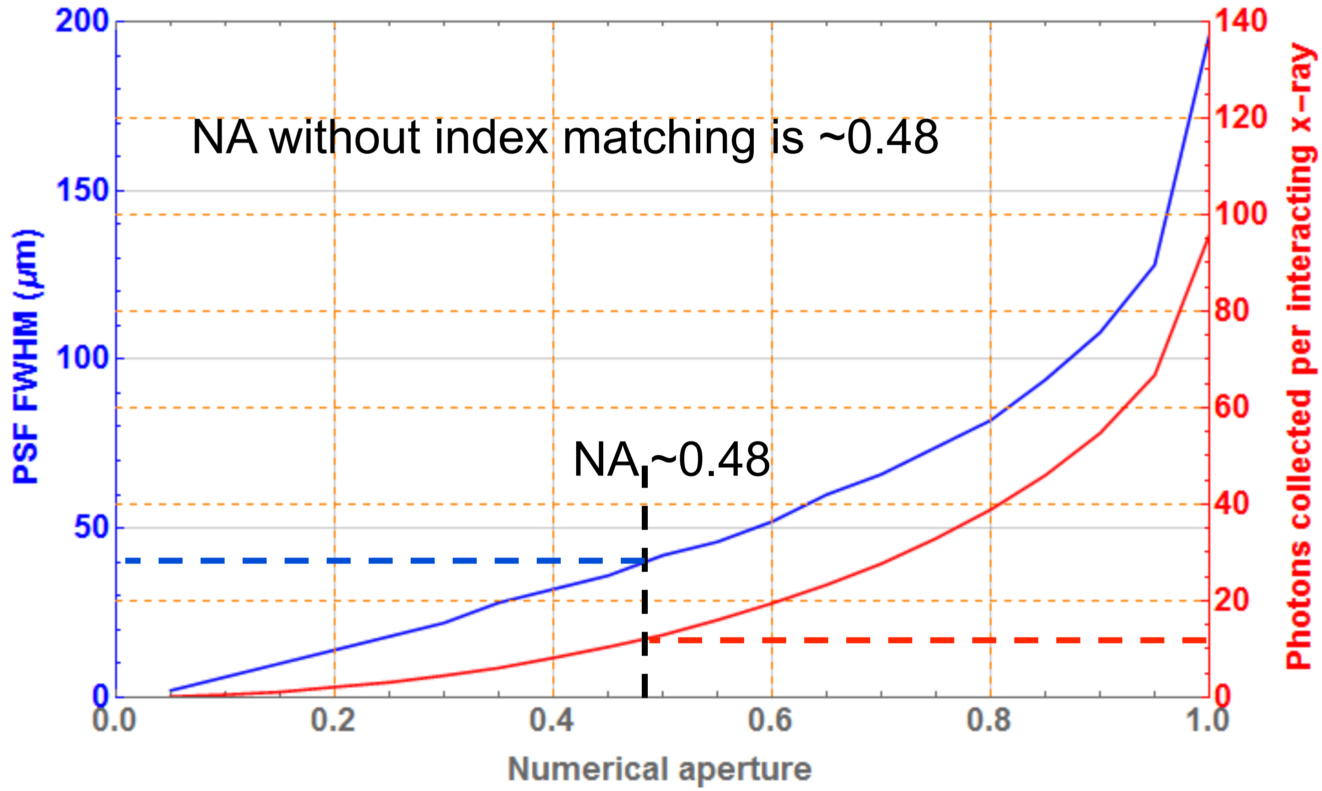
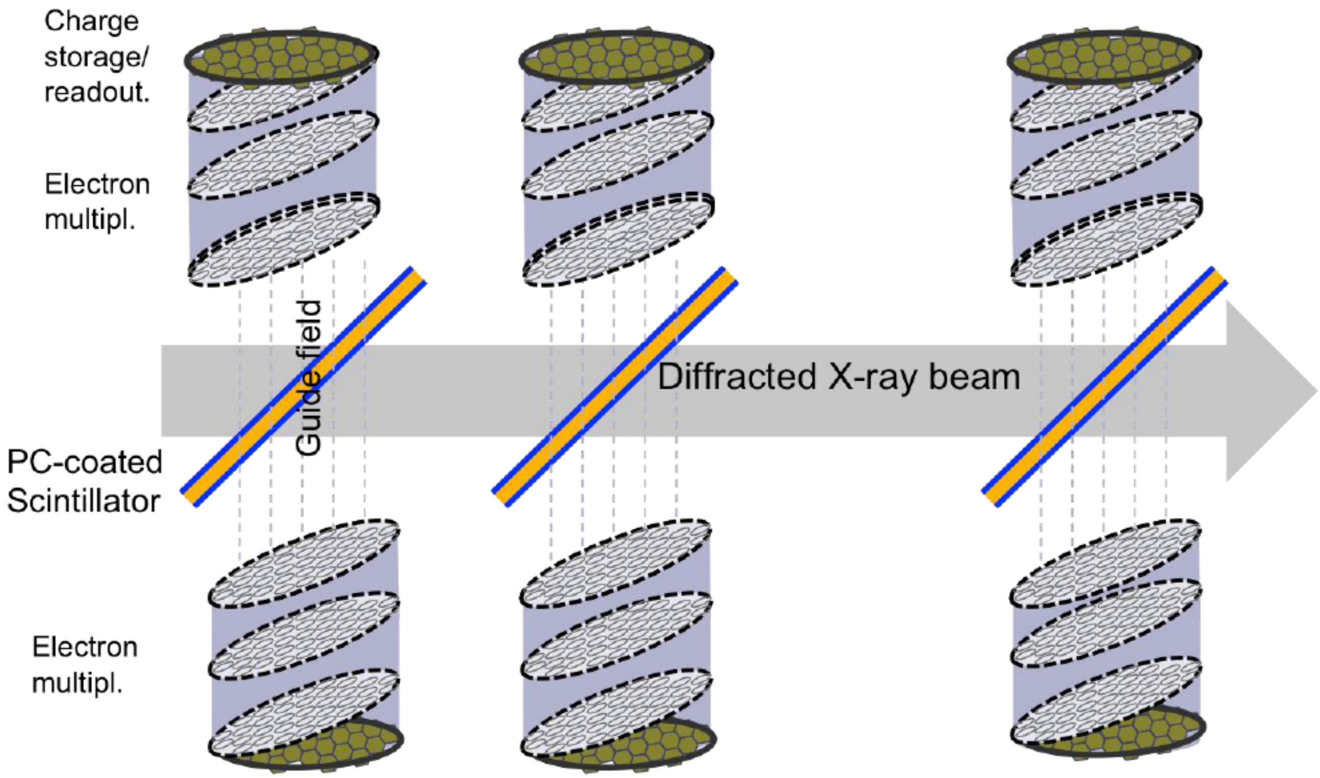


~12 optical photons are collected per interacting 22keV x-ray
82% of incident 22keV photons interact in a 100μm screen
And the point spread function has ~40μm FWHM

Conclusion

- Currently there is no identified scintillator solution for SLOS
  - Noise floor corresponds to ~600 optical photons, we can get ~12 / x-ray
- Way forward:
  - reduced noise floor for gated CMOS camera ~30x from 600 -> 20e$^-$ combined with:
  - i) ZnO:Ga scintillator (if it can be made large and uniform enough)
  - ii) Optimized dopant for the new LBL scintillator (~40x)
- To maximize efficiency whilst maintaining spatial resolution at higher energy ~60keV the scintillator should be in the form of a fiber optic faceplate
- The scintillator material needs to be drawable into fibers, fused and polished (new LBL can), or growable in an MCP like structure
- ZnO:Ga cannot be drawn, but maybe can grown or annealed in an MCP?

Zhehui Wang *et al*. (LANL), "Thin scintillators for ultrafast hard X-ray imaging" Proc. SPIE Vol. 9504 (2015)



X-ray -> optical -> electrons -> gain -> detection

Promising route for gated hard x-ray detection. Sensitivity and resolution still governed by scintillator thickness, but here the low optical signal can be boosted