Scintillating GaAs for the Detection of Electron Recoils from Dark Matter in the MeV Mass Range

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New Directions in the Search for Light Dark Matter Particles
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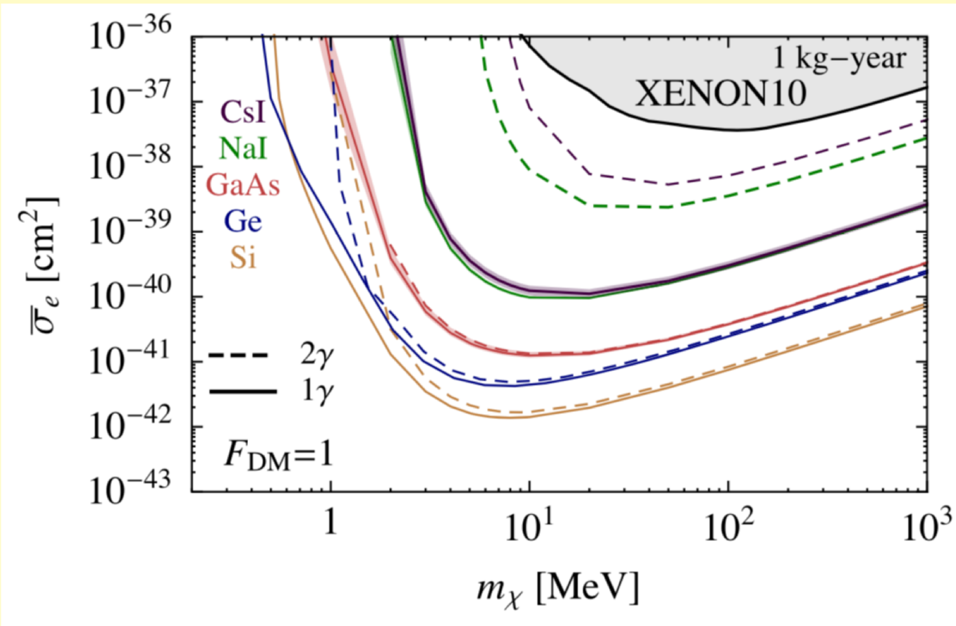
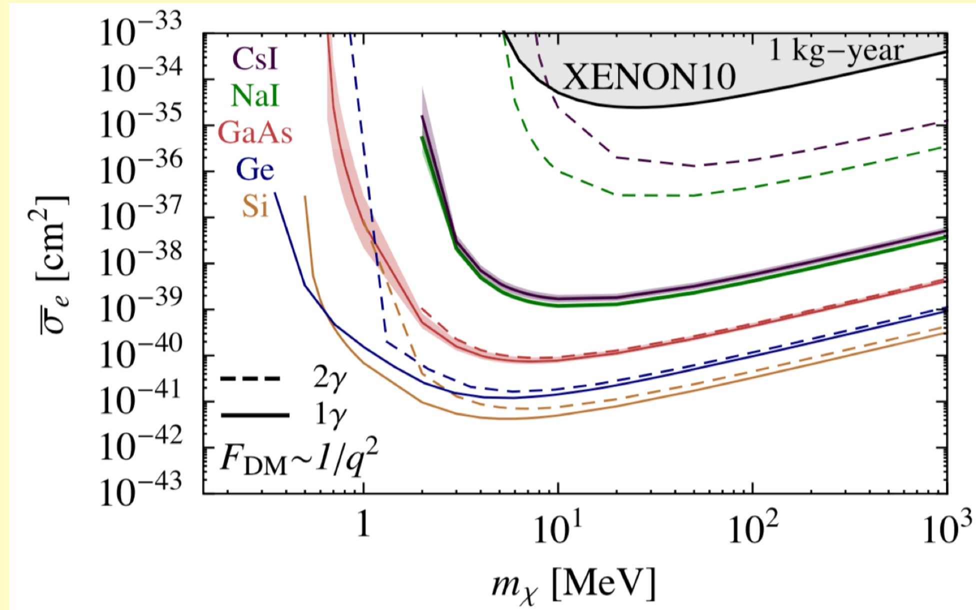
Outline

- DM direct search mass reach
- Electron recoil spectrum (GaAs vs. CsI)
- GaAs scintillation mechanism and threshold
- X-ray emission spectrum
- X-ray emission decay time
- X-ray excited afterglow
- Property summary table
- Commercially grown 10 cm crystal
- Si/TES readout
- Future plans

Experimental Mass Reach
(calculations by Essig et al.)



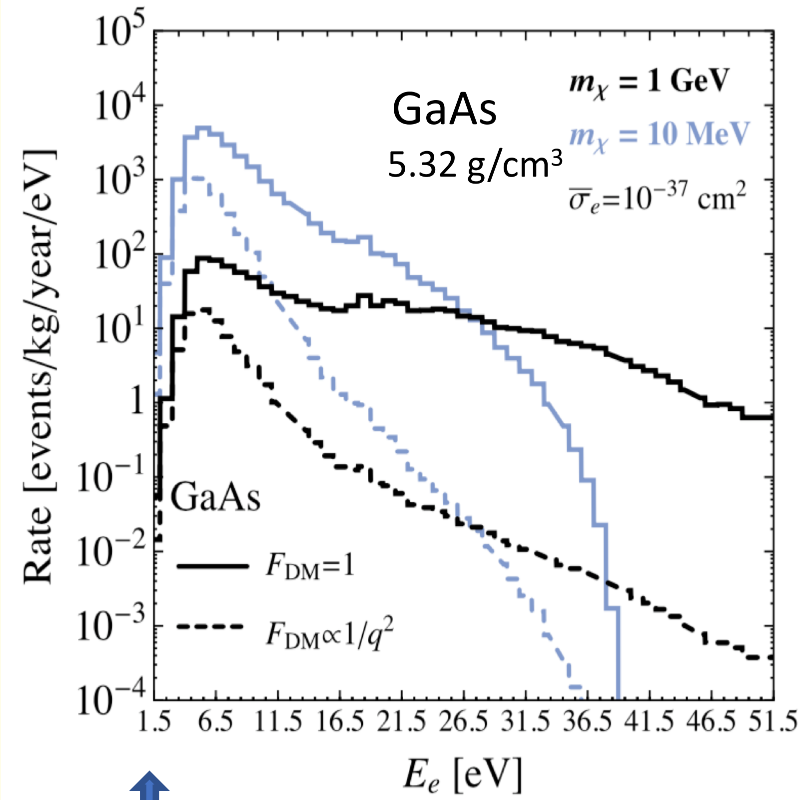


Lowest three are semiconductors

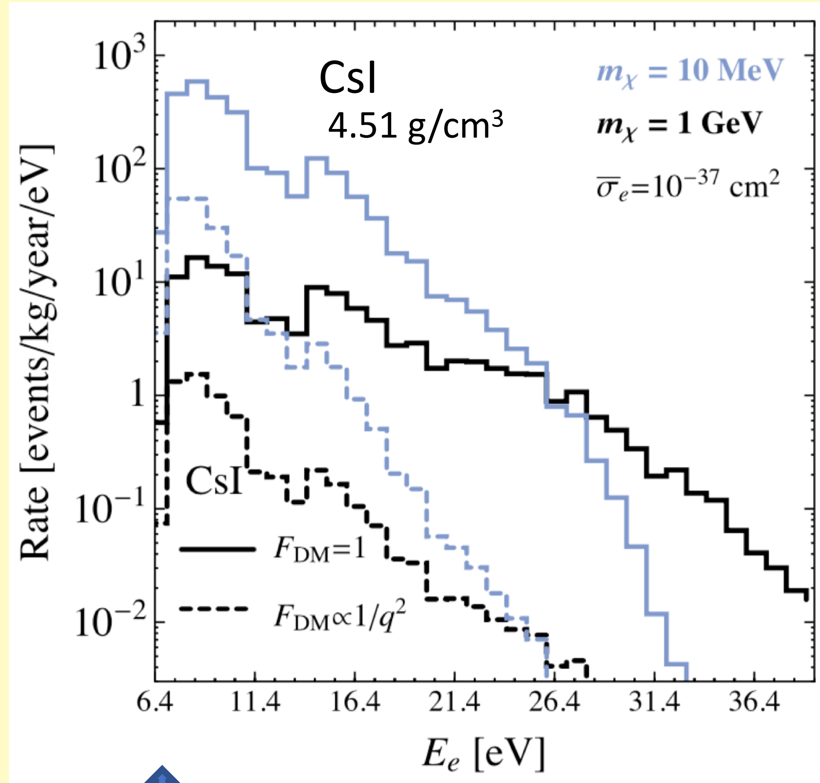
Low band gap => low electron recoil threshold

From “Direct detection of sub-GeV dark matter with scintillating targets”
Derenzo, Essig, Massari, Soto, and Tien-Tien Yu, PHYSICAL REVIEW D 96, 016026 (2017)

Electron Recoil Energy Spectra for GaAs and CsI
(calculations by Essig et al.)



Threshold 1.5 eV



Threshold 6.4 eV

GaAs rate per kg year about 10x CsI rate
Signal is one or a few photons
Very low afterglow essential

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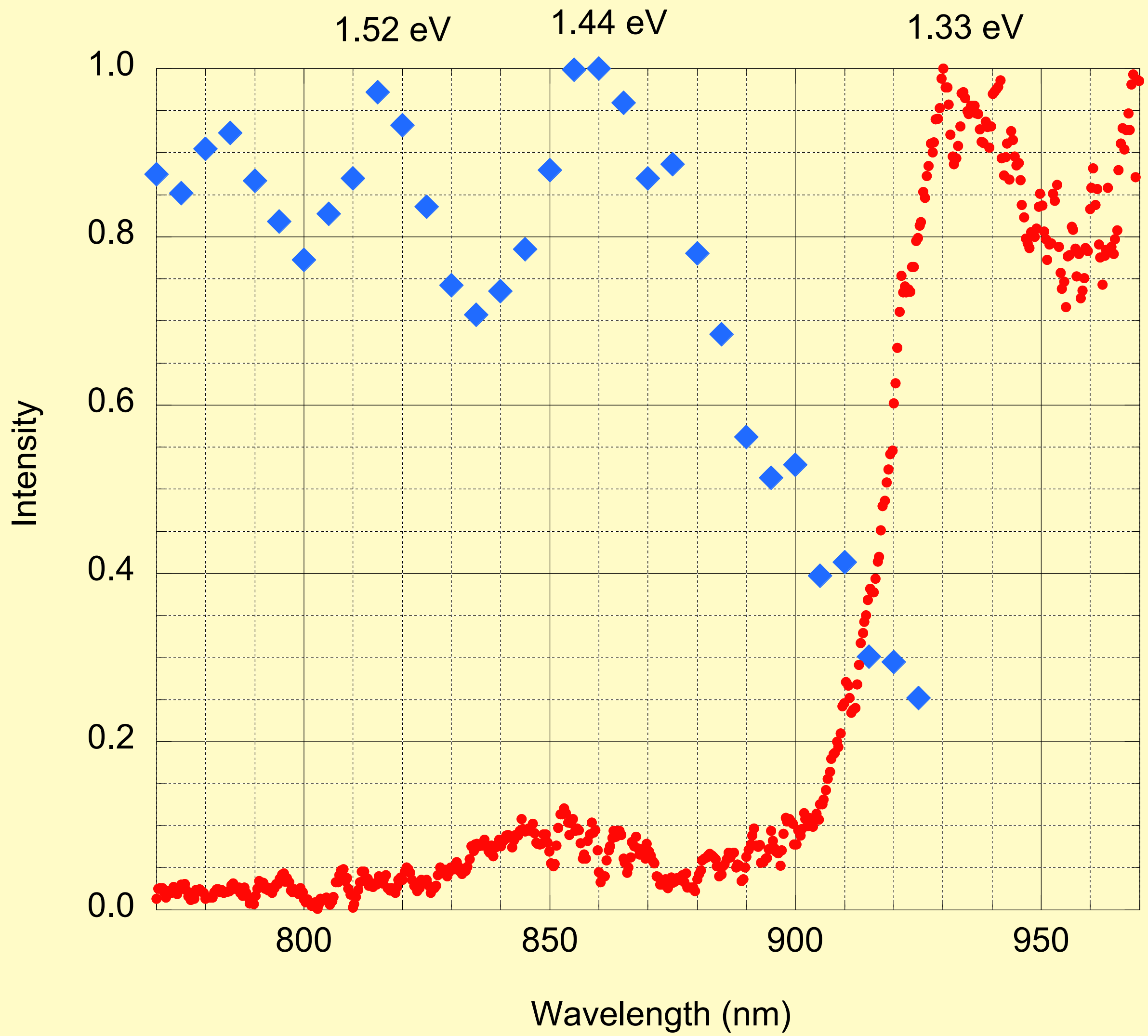
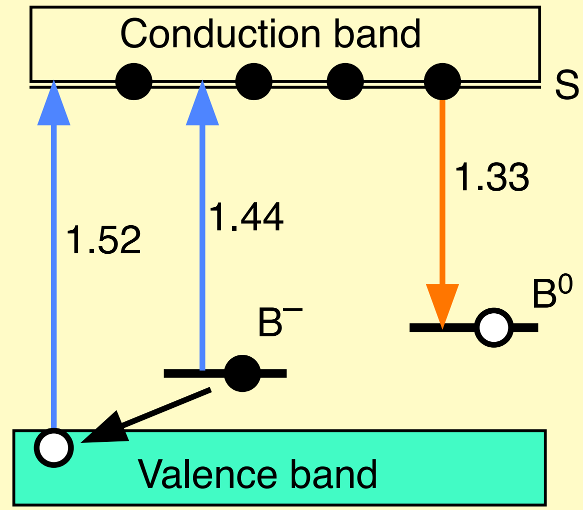
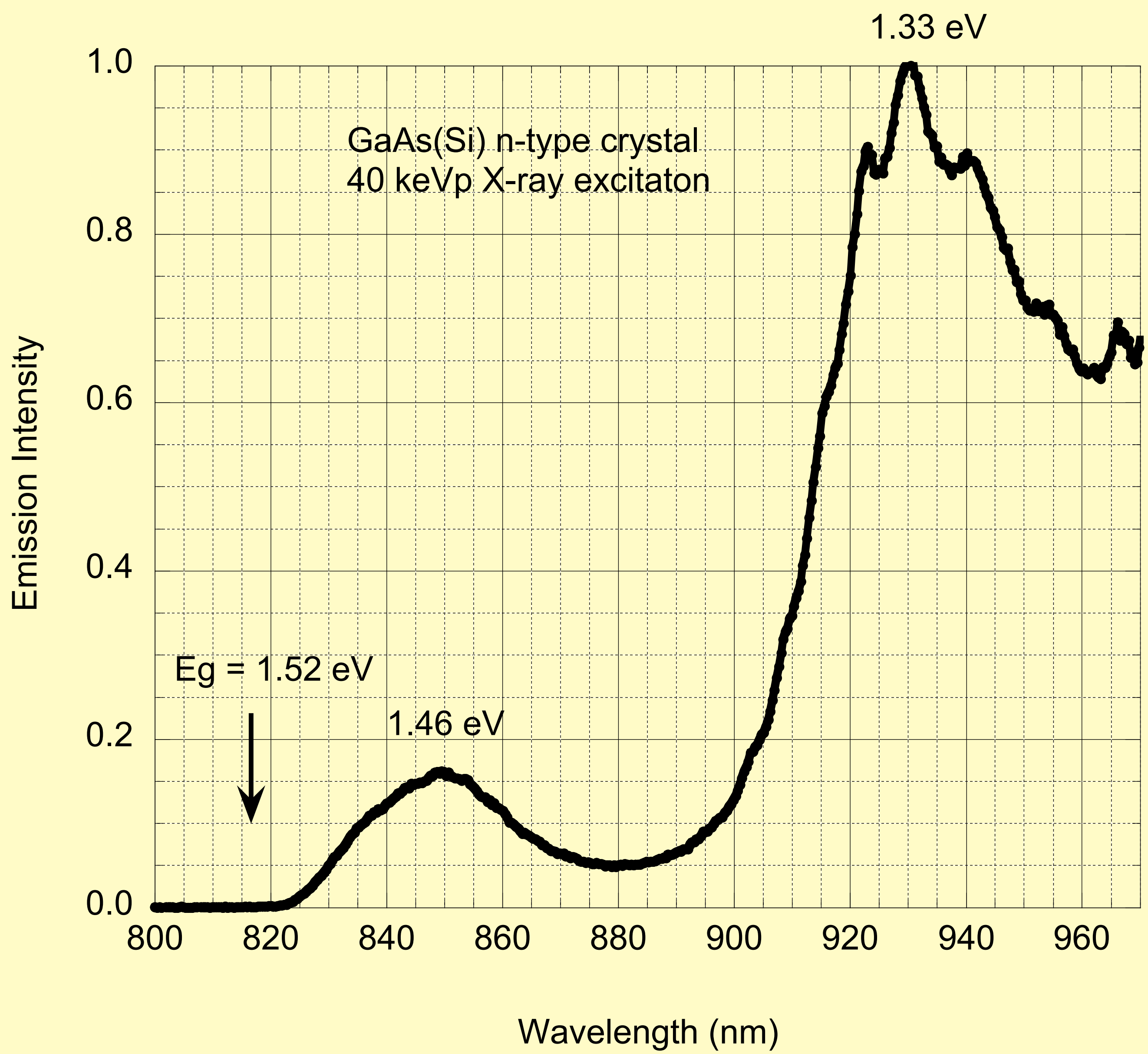
GaAs Optical Excitation/Emission Spectra at 10K



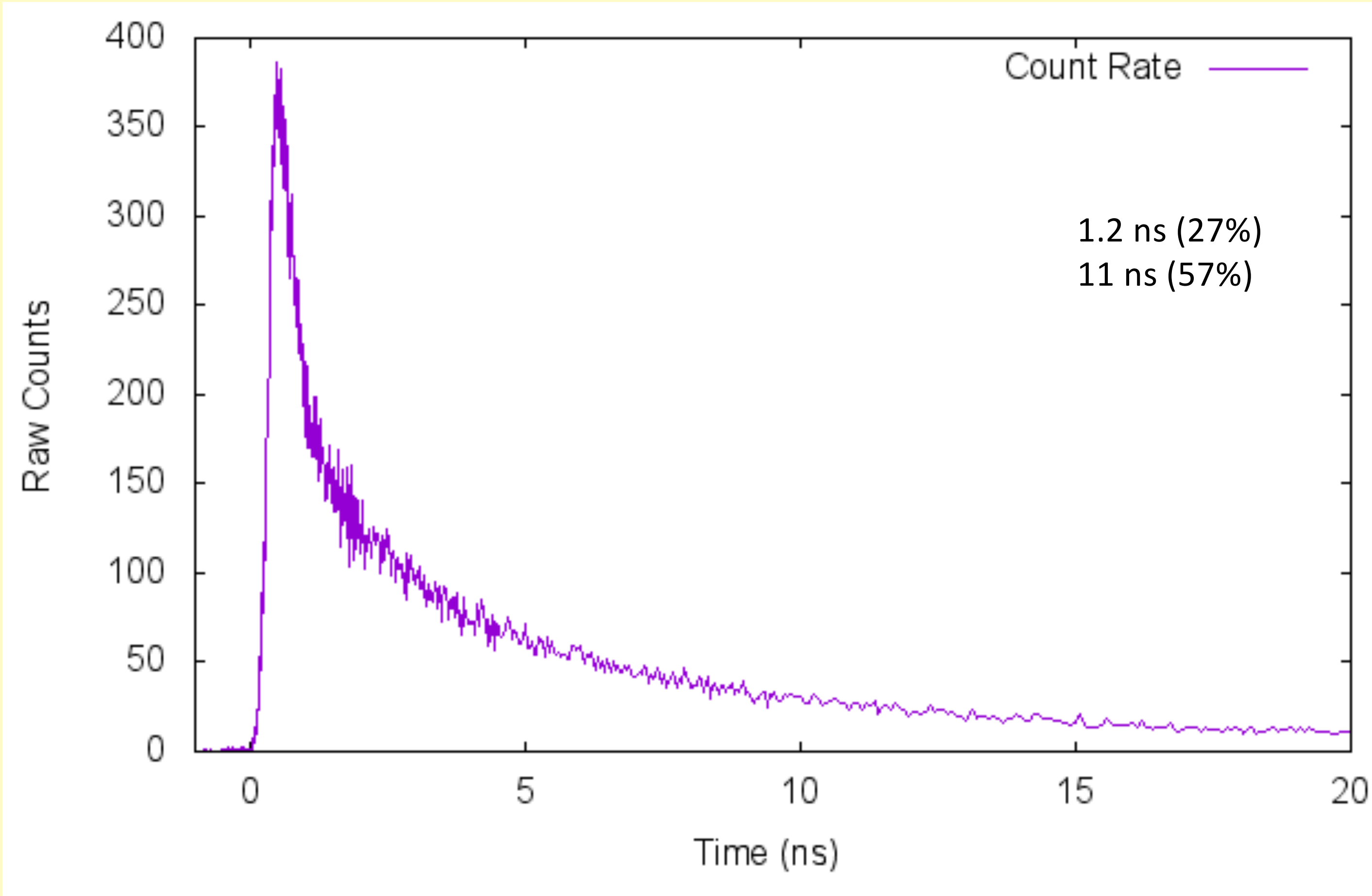


- Shallow silicon donors => CB e⁻ (even near 0 K)
- Boron acceptors are hole traps and radiative centers
- Stokes shift 0.11 eV
- Low self-absorption

GaAs X-ray Excited Emission Spectrum at 10K



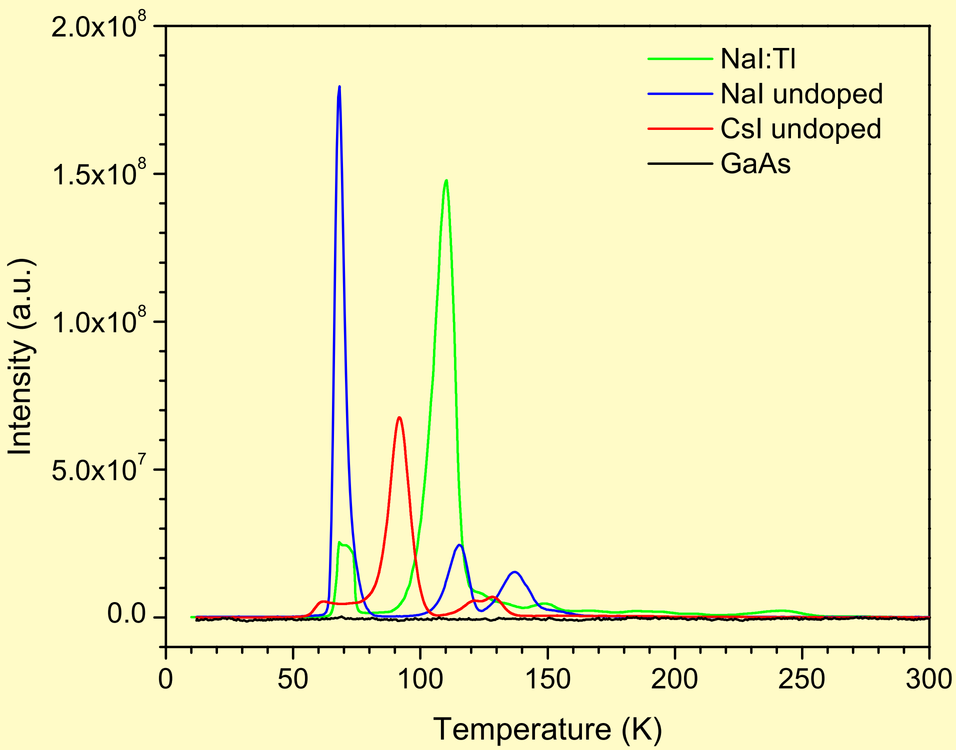
Pulsed X-ray 850 nm Emission

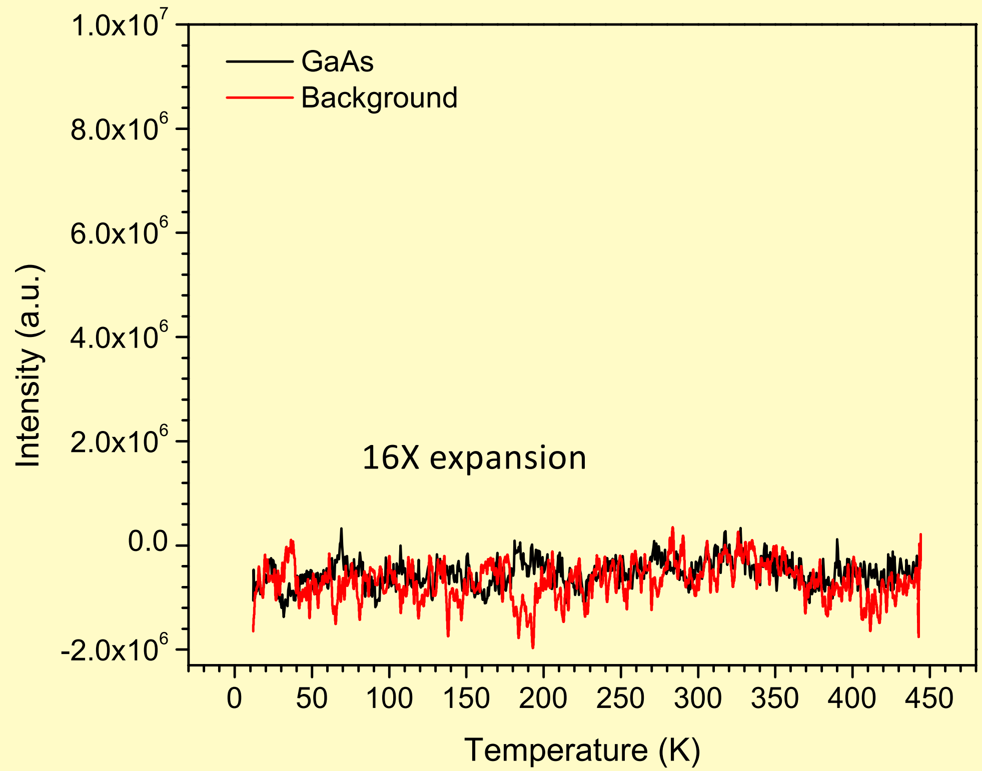


Prompt escape cone + scatter?

Afterglow: Thermally Stimulated Luminescence

1) 50 keVp X-ray bombardment 10K for 30 minutes
   Saturate metastable radiative states
2) Record stimulated emission T => 450 C





Any metastable radiative states in n-type GaAs annihilated by conduction band electrons => no afterglow

Properties of Scintillating GaAs for Direct Dark Matter Detection

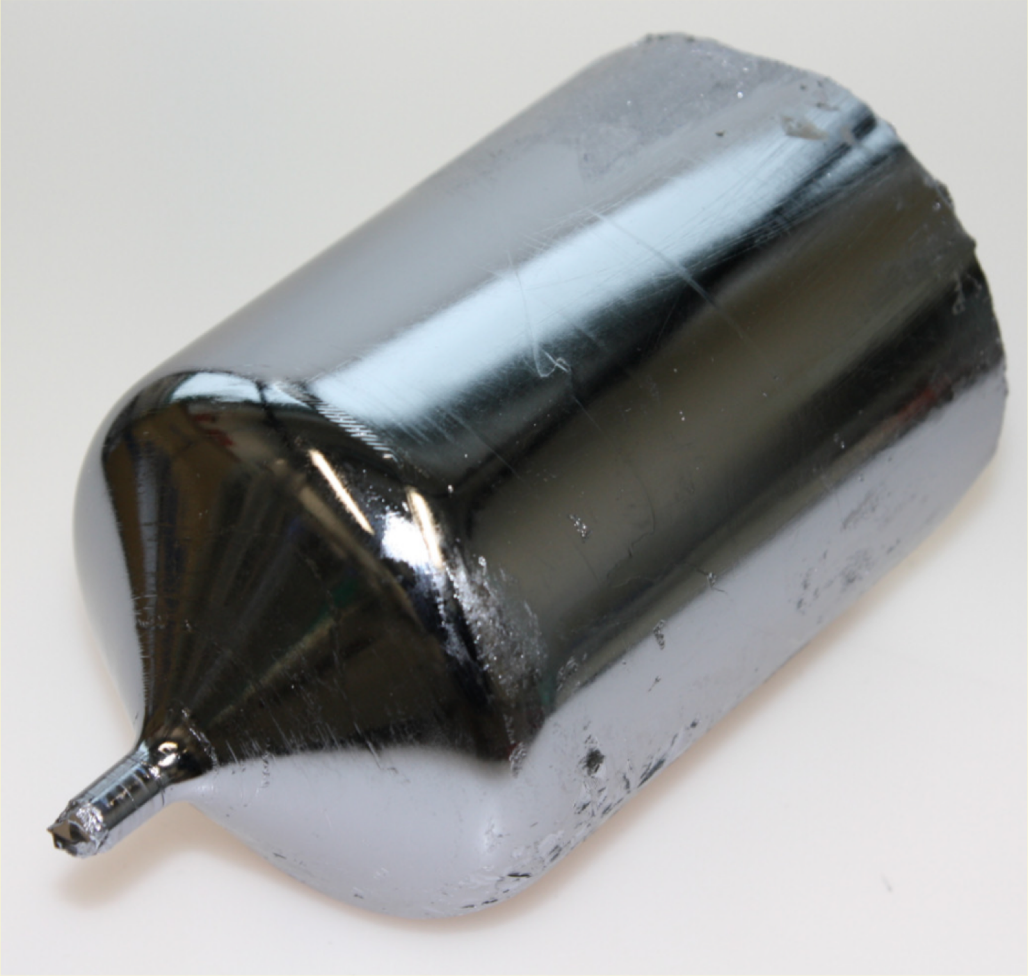
Property	Value	Comment
Band gap	1.52 eV (cryogenic)	Threshold for recoil electron detection
Scintillation mechanism	Donor band to acceptor emission	Silicon (0.002 eV donor) Boron (0.2 eV acceptor)
Luminosity	> 100 photons/keV [1,2]	Theoretical limit 300 photons/keV
Operating temperature	< 100K [1]	Silicon donor free electrons above $8\times10^{15}/cm^3$ do not freeze out [1]
Afterglow	None detected [1]	n-type e^- annihilate metastable radiative states
Stokes shift	0.11 eV [1]	Overlap between emission and absorption bands is small
Anti-reflective coatings	Apparently not essential, even with polished faces, despite 3.5 refractive index [1,2]	Apparent internal scattering from n-type free electrons
Narrow-beam absorption length	20 cm at 10^{16} carriers/cm^3 [3]	Ratio between loss and scattering not known
Typical size	5 kg	Large-scale production for electronic circuits

[1] Derenzo et al. arXiv1802.09171, 2018 Cryogenic Scintillation Properties of n-Type GaAs for the Direct Detection of MeV/c2 Dark Matter

[2] Vasiukov et al. arXiv 1904.09362 2019 GaAs as a bright cryogenic scintillator for the direct dark matter detection

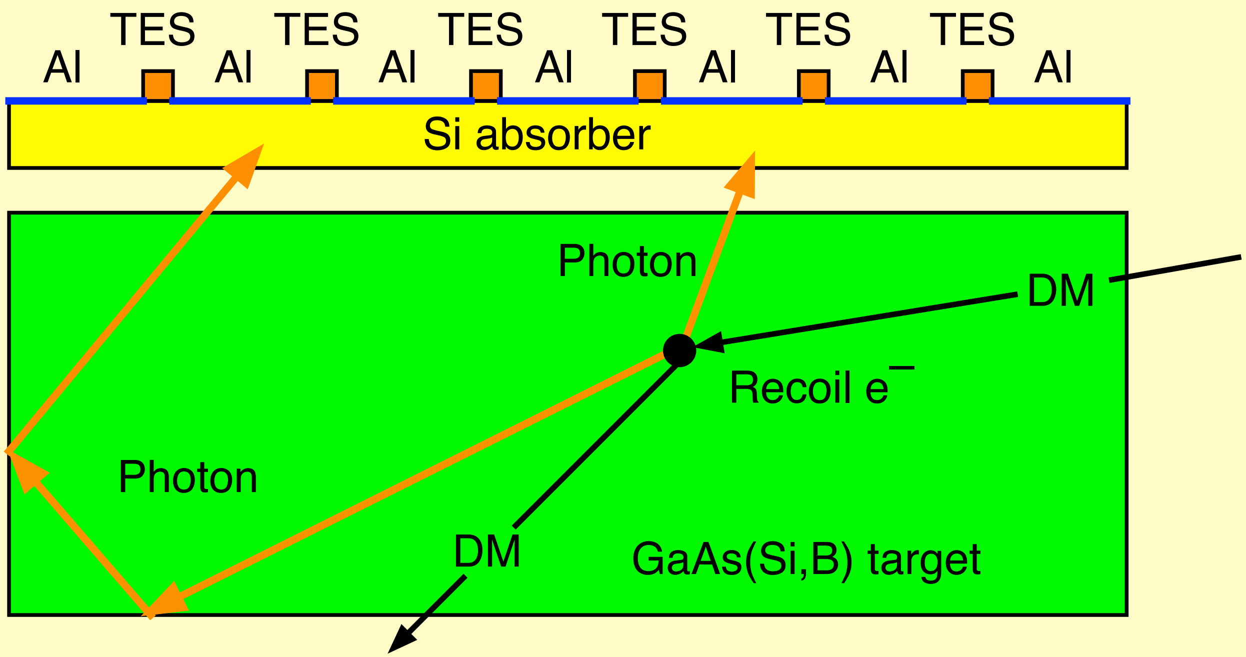
[3] Spitzer et al. Phys Rev 114 59-63, 1959 Infrared Absorption and Electron Effective Mass in n-Type Gallium Arsenide

Large Crystals of High Purity Commercially Grown



10 cm GaAs crystal (~5 kg) grown at the Leibniz-Institut für Kristallzüchtung (IKZ), Berlin, Germany

Si/TES Readout



- e^- recoils produce scintillation photons
- Si converts the photons into athermal phonons
- Phonon detection using Al/TES CDMS technology

Future Plans

Near term:

1) Test 1 cm^3 cubes with cryogenic InGaAs PMT
   Optimize silicon and boron doping
2) Test 1 cm^3 cubes with Si/Al/TES readout

Scale-up: Arrays of 8 cm (2 kg) cylinders

Thanks to

- Rouven Essig (Stony Brook) asking me to find a low band gap scintillator for low-energy electron recoils
- Edith Bourret (LBNL) for providing the first successful GaAs samples
- Matt Pyle (UC Berkeley) for raising the issues of afterglow and optical absorption
- Maurice Garcia-Sciveres, Dan Mckinsey (LBNL) for support and encouragement

Thank You for Your Attention

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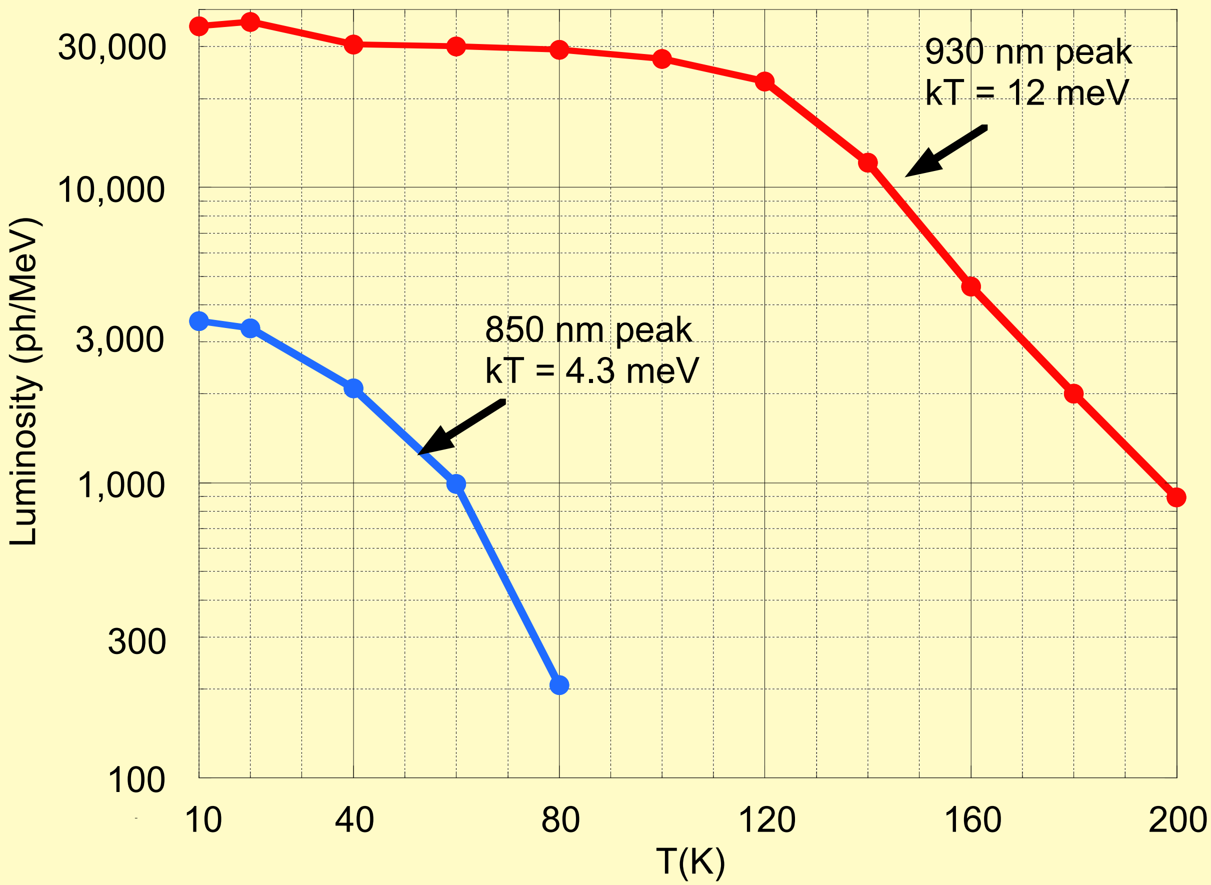
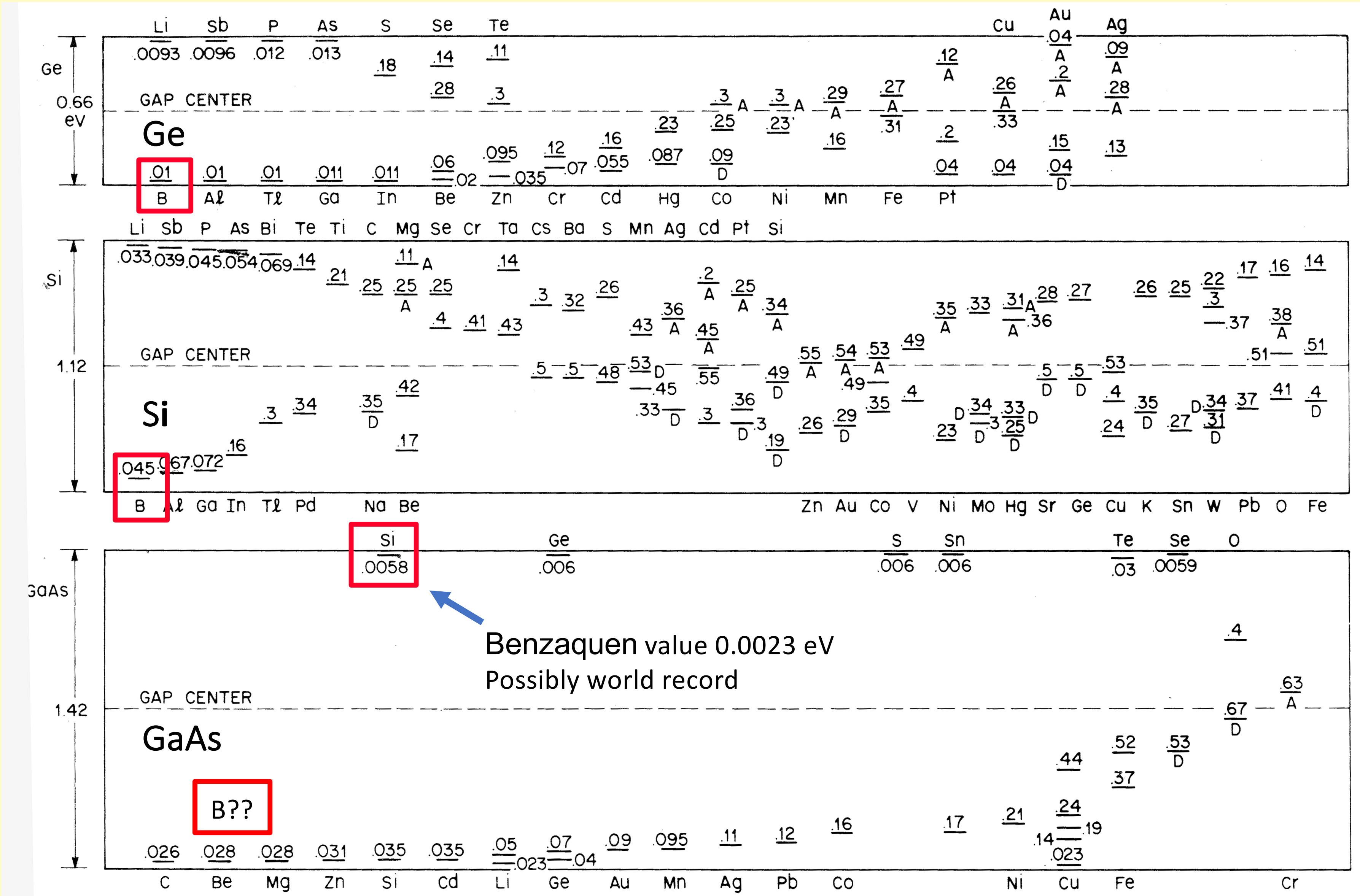
X-ray Excited Luminosity vs. Temperature
50 keVp X-ray excitation



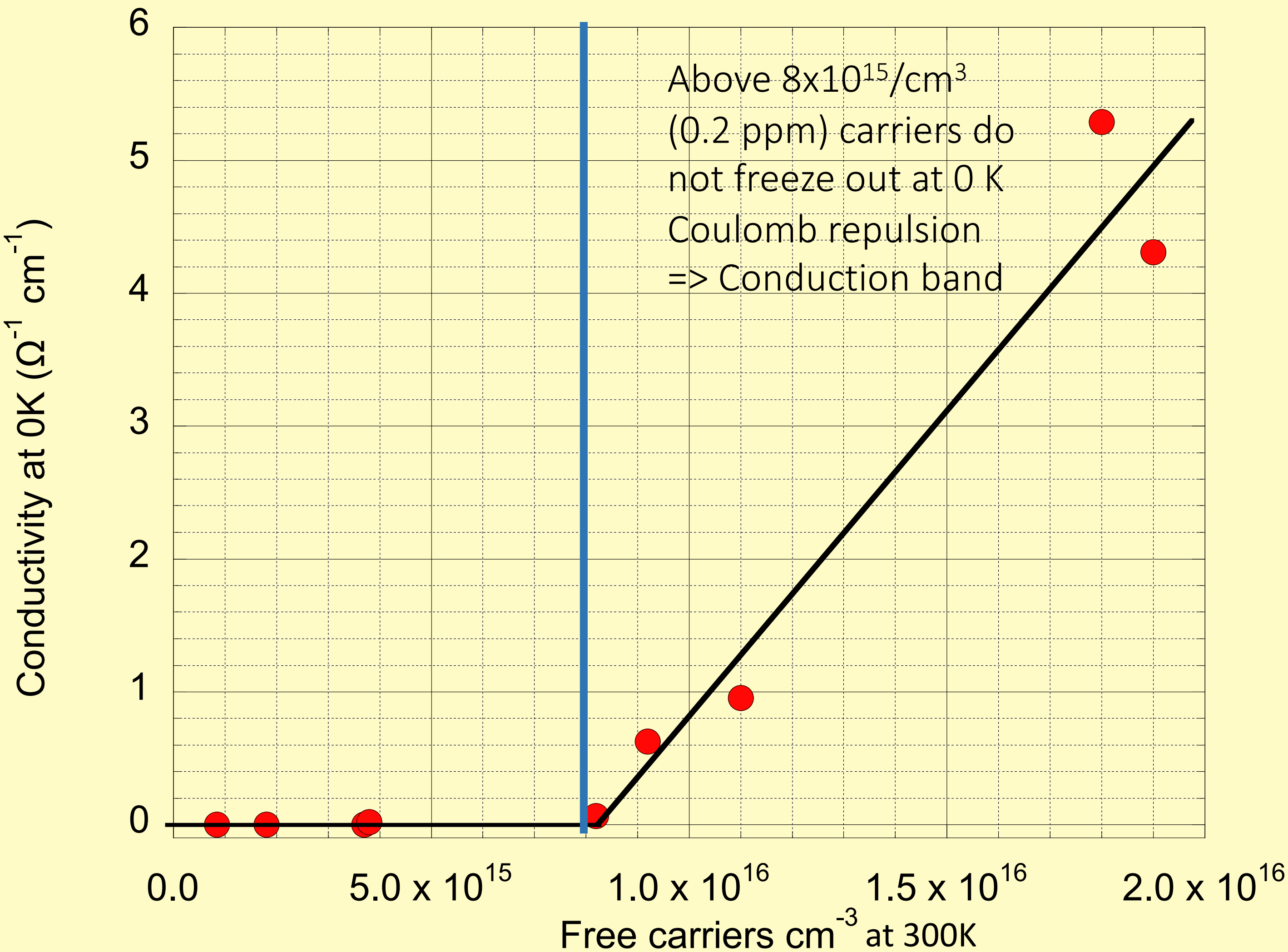
- Holes on B stable up to 120K
- Above 120K => 12 meV barrier for trapping by deeper traps (e.g. EL2)

- Luminosity calibrated against LSO and BGO crystals
- >40,000 ph/MeV (underestimate)
  - Miss >970 nm
  - No anti-reflection coating
  - Doping not optimized

Donor and Acceptor Ionization Energies in Si, Ge, GaAs

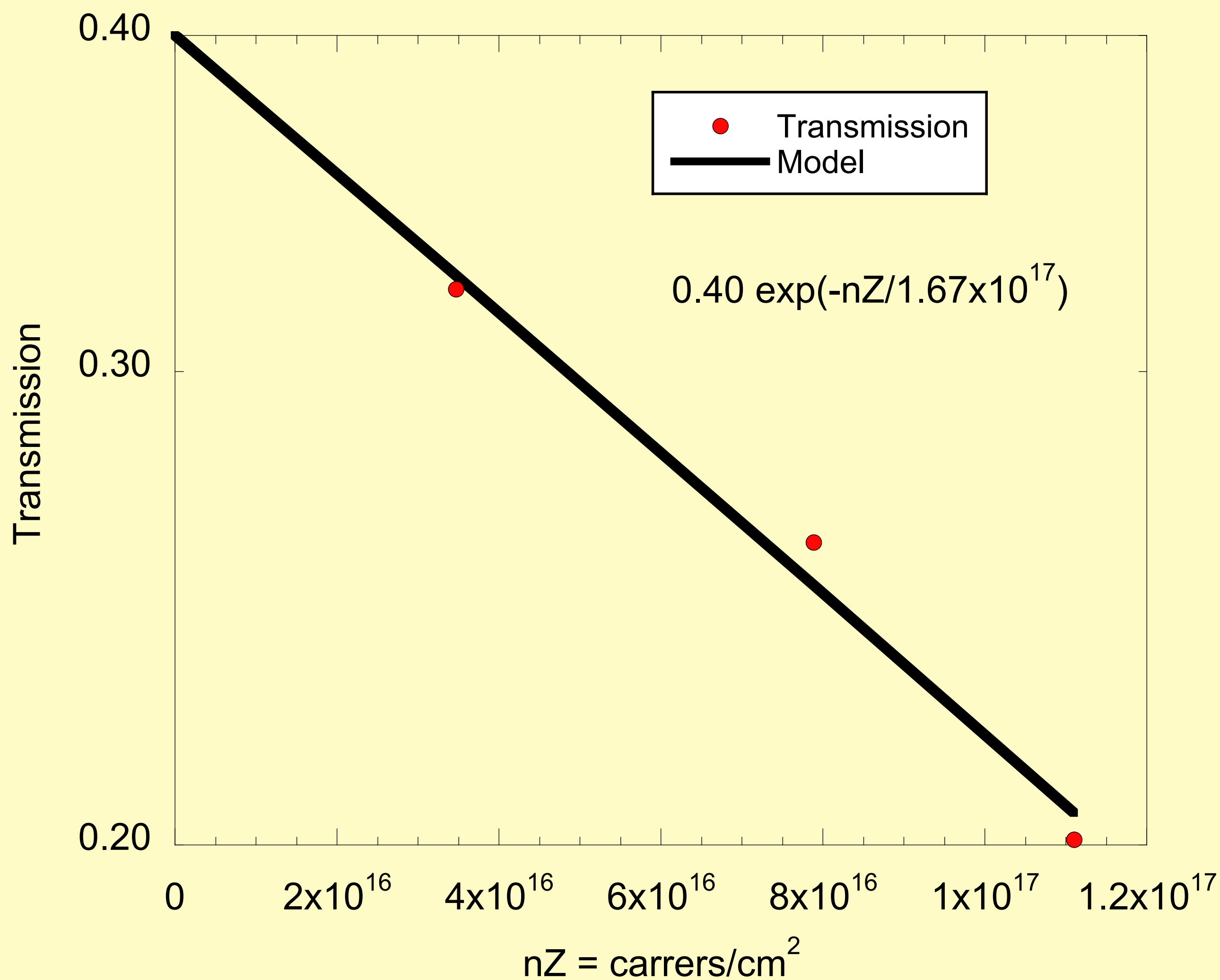


Mott Metal-Insulator Transition in *n*-type GaAs(Si)



Data from Benzaquen et al. "Conductivity of n-type GaAs near the Mott transition" Phys Rev B 36 (1987)

Scattering by n-Type Electrons



Photon scattering is proportional to the product of n (carriers/cm^3) and path length Z (cm)

At $n = 2\times10^{16}/cm^3$ narrow-beam attenuation length is 8 cm

Same as ref

GaAs Si B Concentration vs. Luminosity

Sample No.	Ne (cm^{-3})	Si (cm^{-3})	B (cm^{-3})	C (cm^{-3})	Lum (ph/keV)
13323*	0				<0.01
13357**	3.83×10^{10}				2.4
50075	3.0×10^{17}	3.0×10^{17}	1.5×10^{18}	1.2×10^{16}	19
13360	5.3×10^{16}	2.0×10^{17}	8.6×10^{18}	3.7×10^{16}	35
13365	2.2×10^{17}	3.8×10^{17}	2.5×10^{18}	3.6×10^{15}	49
13363	4.2×10^{17}	7.0×10^{17}	3.5×10^{18}	6.0×10^{15}	57
13359	1.9×10^{17}	2×10^{17}	8.0×10^{18}	1.0×10^{17}	150***

* Semi-insulating (excess As on Ga anti-sites)
** Intrinsic
*** Scattering on n-type electrons reduces internal trapping??

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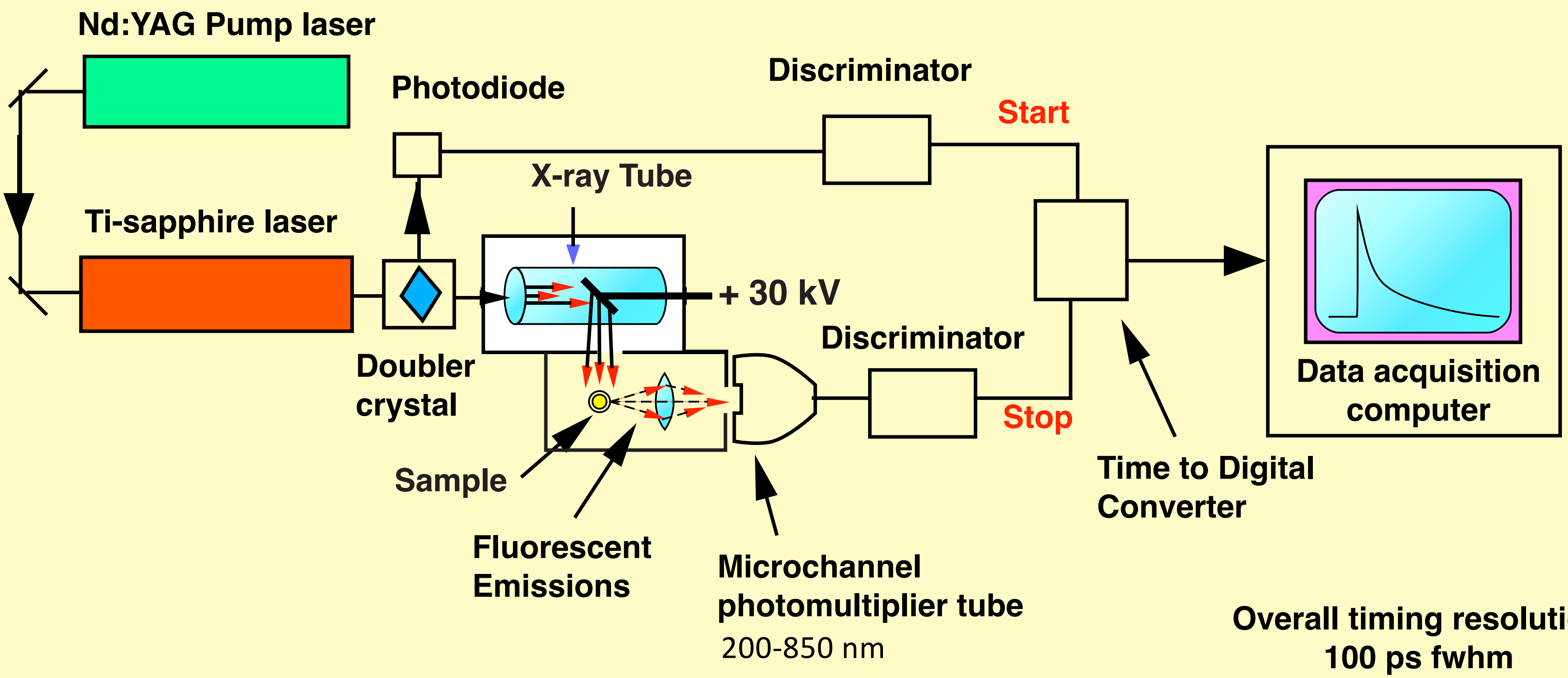
Pulsed X-ray Facility
(LBNL Scintillator Research Group, Bldg 55)



Overall timing resolution
100 ps fwhm