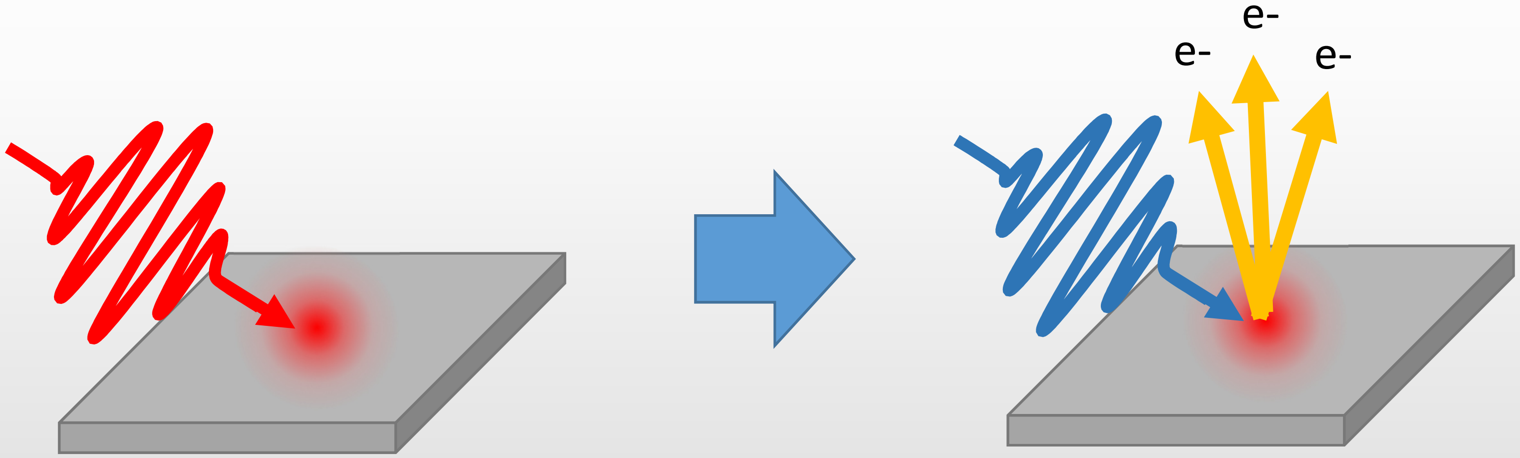
# Measuring the Mean Transverse Energy of Pump Probe Photoemitted Electrons

"Hunt for the Narrow Cone"




Christopher M. Pierce

# Acknowledgements


I would like to thank everyone who helped make this experiment possible

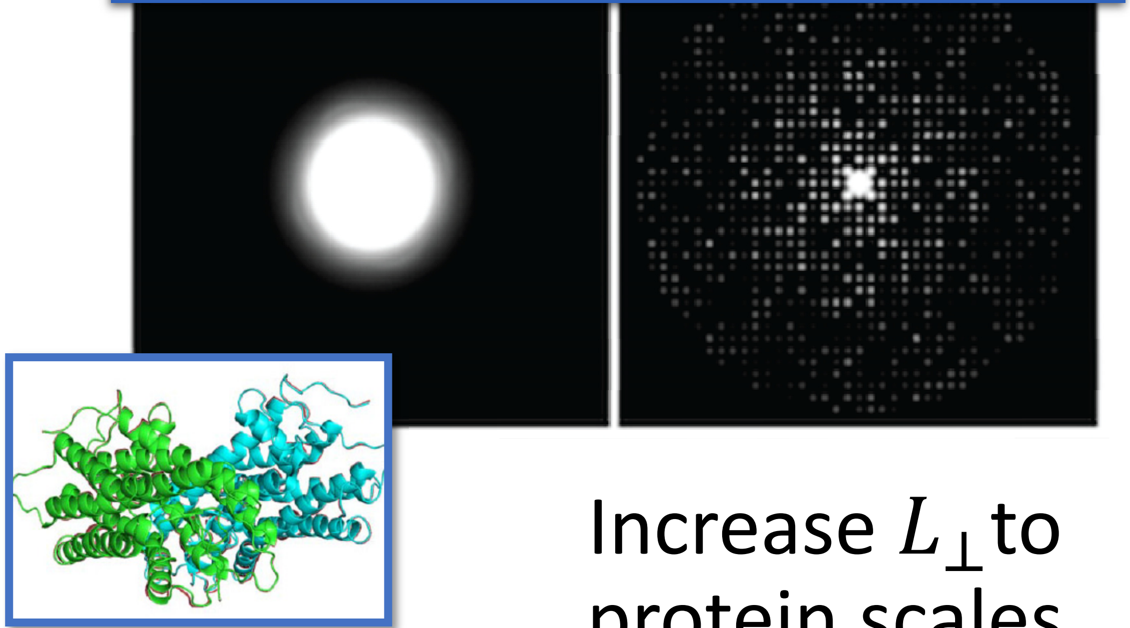
- Ivan Bazarov
- Jared Maxson
- Luca Cultrera
- Tomás Arias
- J. Kevin Nangoi
- Simon Rothman

This work was supported by the U.S. National Science Foundation under Award PHY-1549132, the Center for Bright Beams

# Introduction – Brightness

## Modern applications need brighter beams

### Ultrafast Electron Diffraction

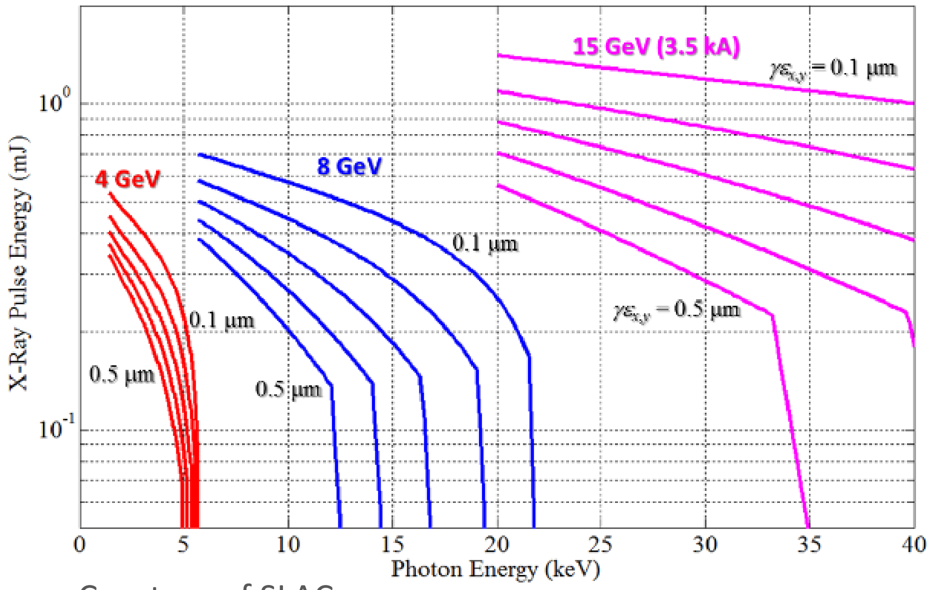


Increase $L_\perp$ to protein scales

### Free Electron Lasers

Shorter linac for same pulse energy

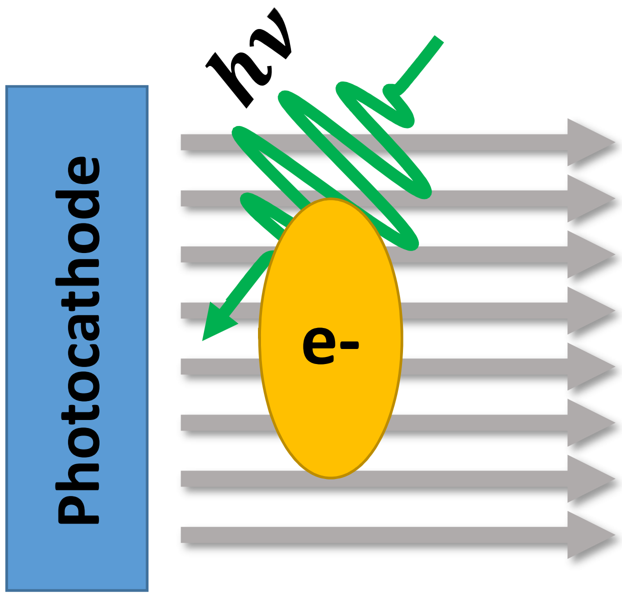
HXR ($\lambda_u$ = 26 mm) with SCRF Linac (red, blue) and Cu-Linac (magenta) and emittance of 0.1, 0.2, 0.3, 0.4, and 0.5 μm




Courtesy of SLAC

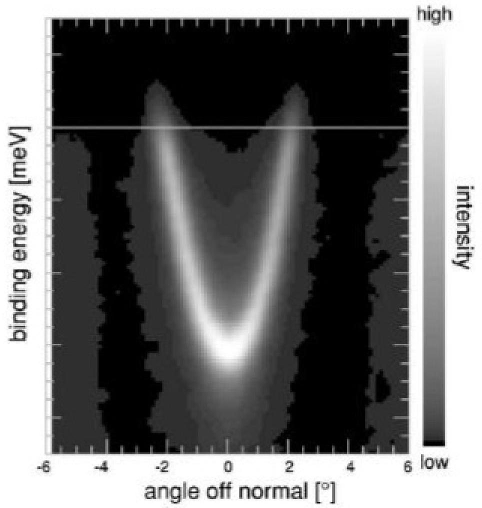
# Introduction – Brightness

## Spatial Density




Limit due to space charge

## Angular Density




PRB, 63, 115415 (2001)

MTE = Mean Transverse Energy

$$B_{4\mathrm{D}} \propto \frac{E_z}{\mathrm{MTE}}$$

**Pancake Regime**

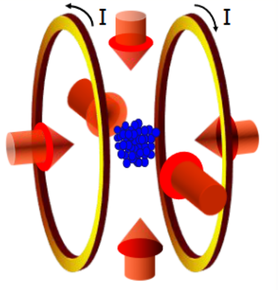
Bazarov et al., PRL 102, 104801 (2009)

$$B_{4\mathrm{D}} \propto \frac{E_z^{3/2}}{\mathrm{MTE}} \frac{\sigma_t}{\sqrt{\sigma_x}}$$

**Cigar Regime**

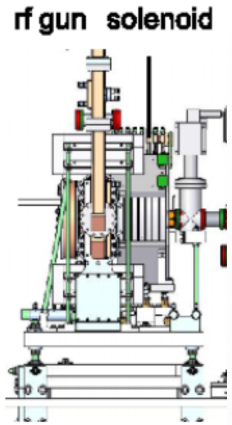
Filippetto et al., PRAB 17, 024201 (2014)

# Introduction – MTE Landscape




Magneto Optical Trap

At Threshold Metals




SLAC MeV UED Gun

CORNELL-BNL ERL TEST ACCELERATOR
CBETA

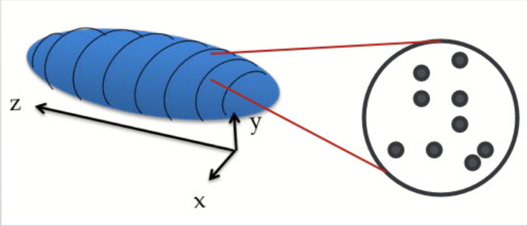
CBETA (ERL) Gun


LCLS Photoinjector

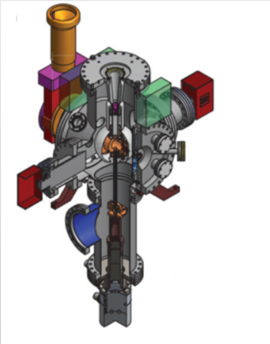
**MTE ->**
**Emittance ->**

| 1 meV | 10 meV | 300K | 100 meV | 1000 meV |
|---|---|---|---|---|
| 0.04 um/mm | 0.14 um/mm | | 0.44 um/mm | 1.4 um/mm |

Limit from Disorder Induced Heating



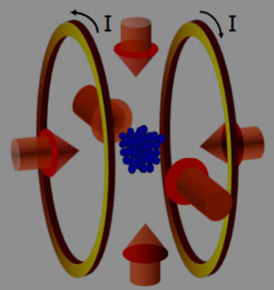

Cryocooled Photocathodes

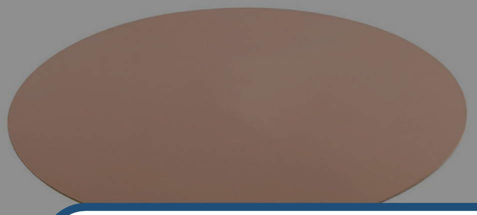


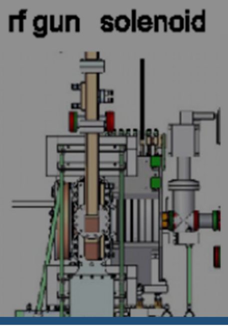
At Threshold Semiconductors

Thermionic Sources

# Introduction – MTE Landscape








Magneto Optical Trap

**Talking about GaAs**

LCLS Photoinjector

**MTE ->** 1 meV | 10 meV | 300K | 100 meV | 1000 meV

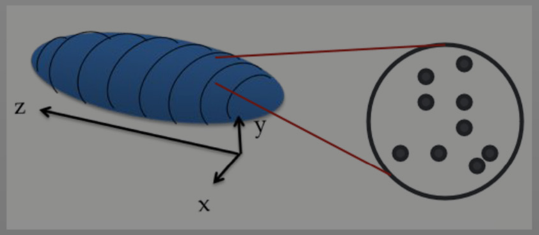
**Emittance ->** 0.04 um/mm | 0.14 um/mm | 0.44 um/mm | 1.4 um/mm

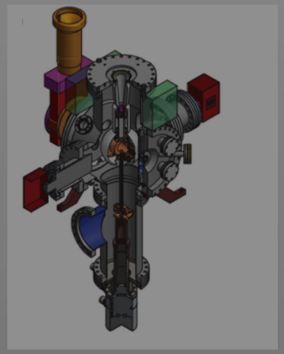
Limit from Disorder Induced Heating

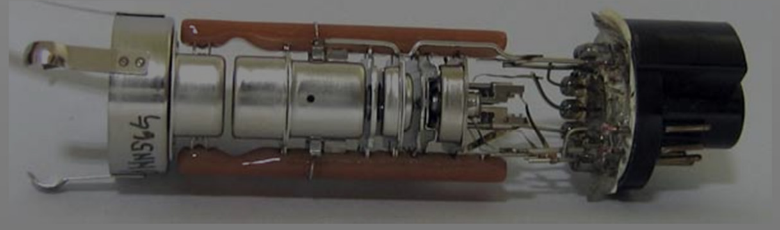
Cryocooled Photocathodes

At Threshold Semiconductors

Thermionic Sources



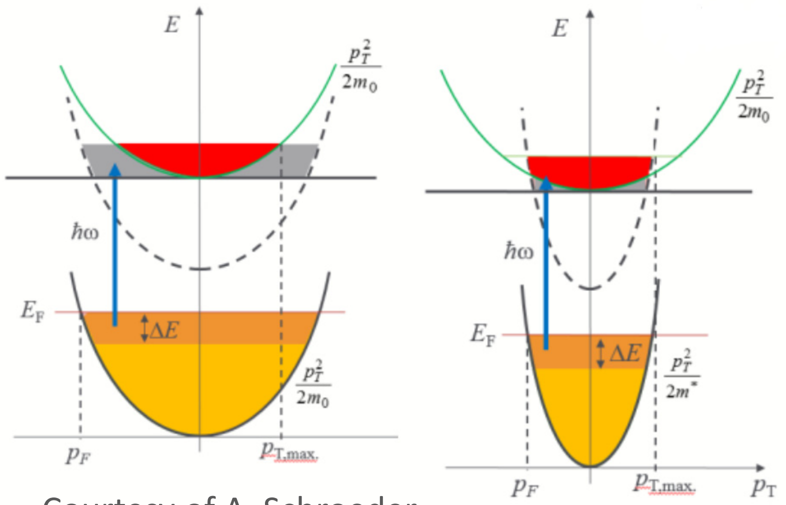





# Introduction – Narrow Cone

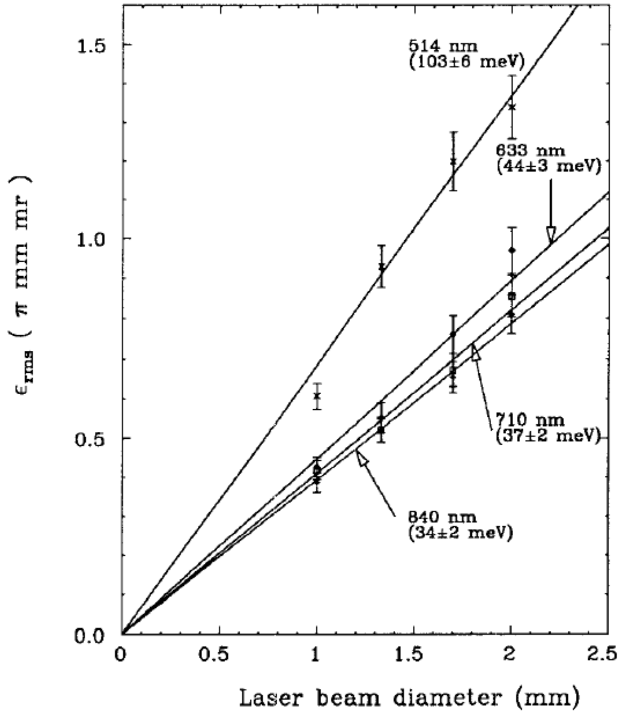
## Mystery of NEA GaAs MTE
## **"The Narrow Cone"**

**Should be 2 meV from m***



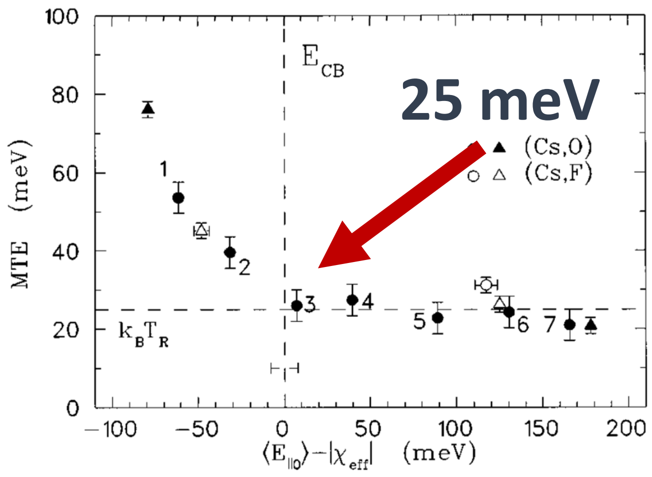
Courtesy of A. Schroeder

**Measured at > 25 meV**



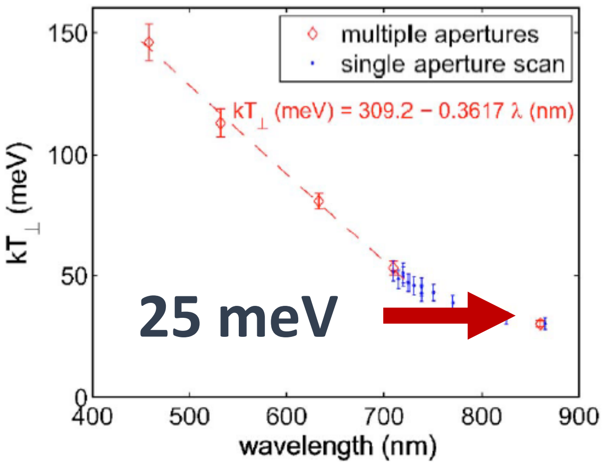


IEEE, 2, 1030–1032 vol.2 1995.





APL, 71(20), 2967–2969. (1997)



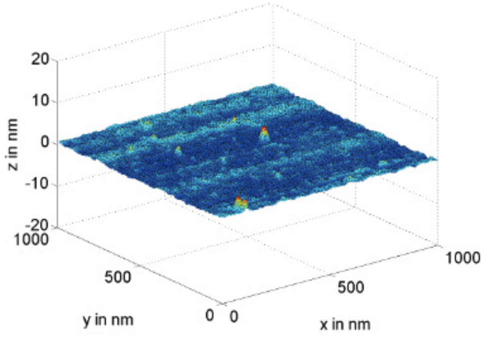


JAP, 103(5), 054901. (2008)

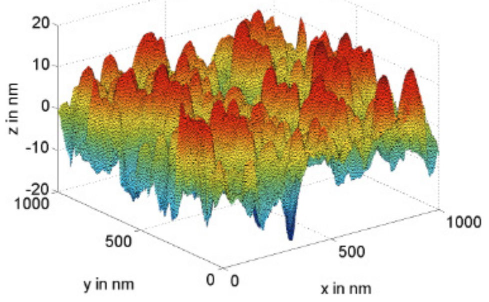
# Introduction – Narrow Cone

## Active area of research – No resolution

### Physical Roughness



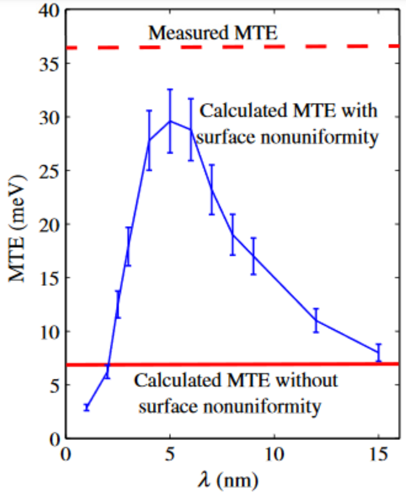

(a) Surface of atomically polished GaAs crystal before heat cleaning (smooth surface)

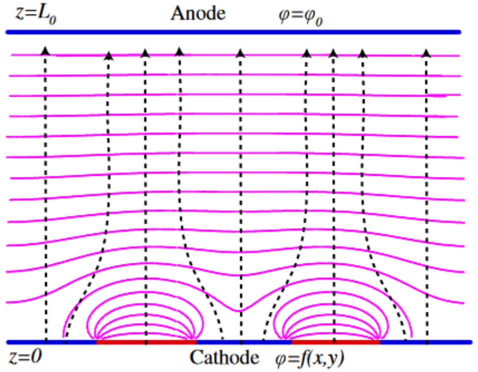



(b) Surface of heat cleaned and activated GaAs crystal used in the Cornell dc photoemission gun (rough surface)

*Applied Physics Letters, 98(9), 094104.*

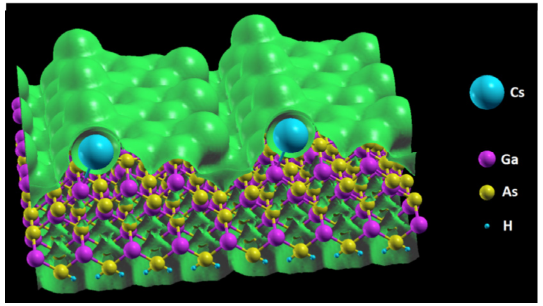
### Chemical Roughness

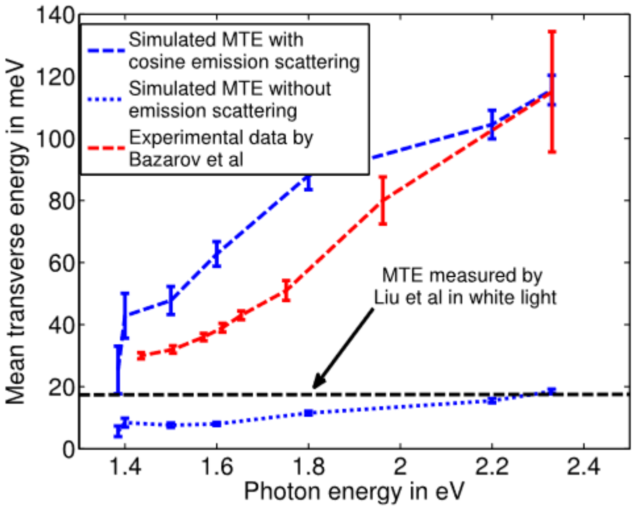



*Karkare, S., 2015 Physical Review Applied, 4(2).*

### Scattering in Cs



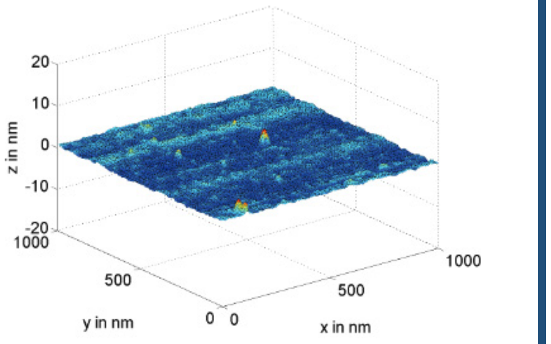




*Journal of Applied Physics, 113(10), 104904*

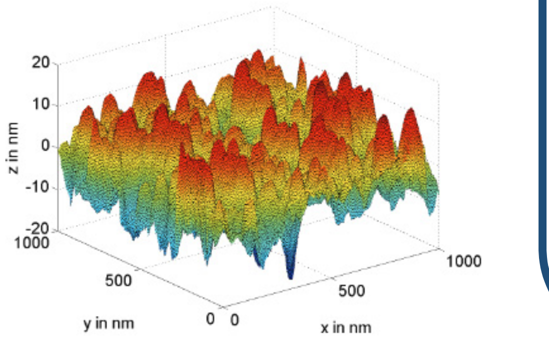
# Introduction – Narrow Cone

Acti … lution

## Physical Roughness



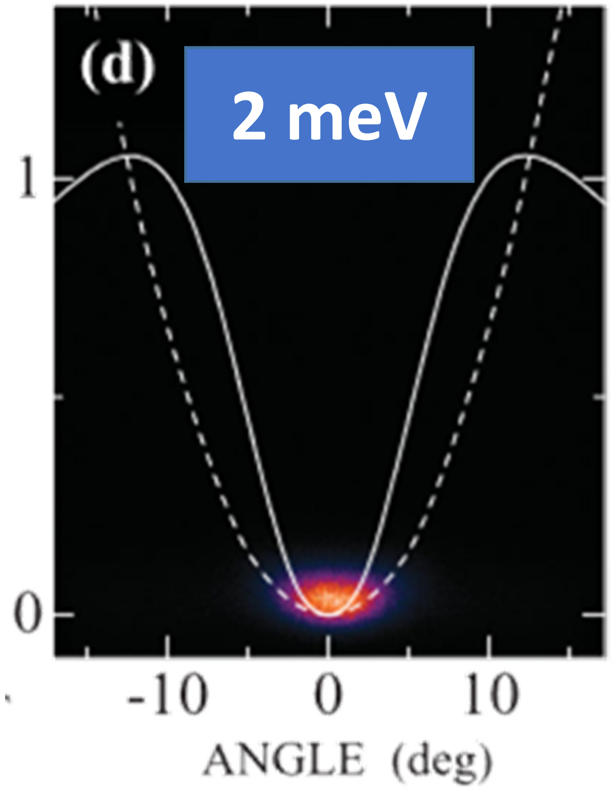

(a) Surface of atomically polished GaAs crystal before heat cleaning (smooth surface)

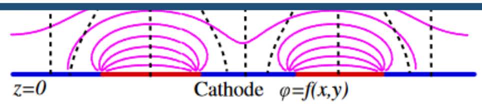



(b) Surface of heat cleaned and activated GaAs crystal used in the Cornell dc photoemission gun (rough surface)

4104.

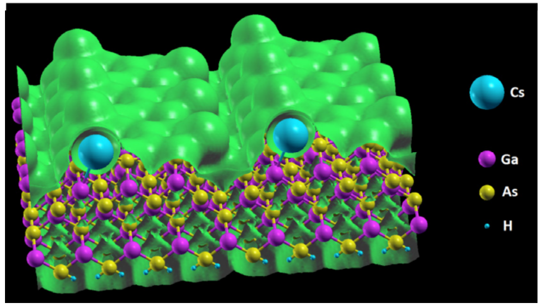
## Looks like small MTE?

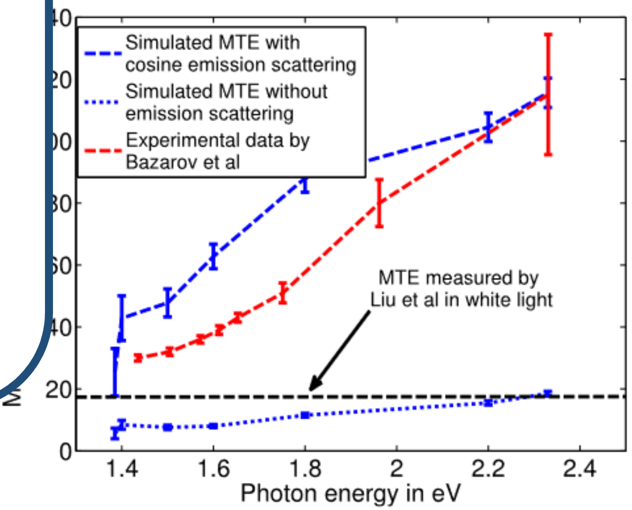



2).

## Scattering in Cs



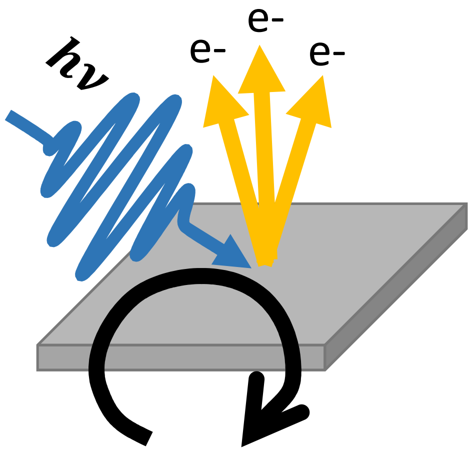




*Journal of Applied Physics, 113*(10), 104904

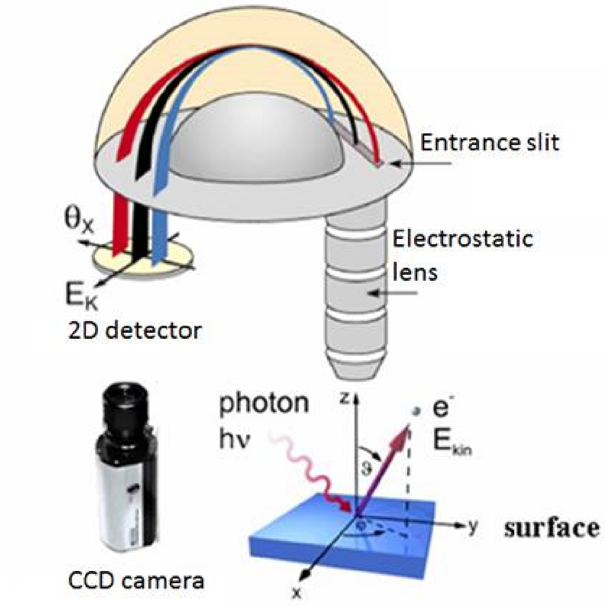
# Introduction – Narrow Cone

## What is ARPES?

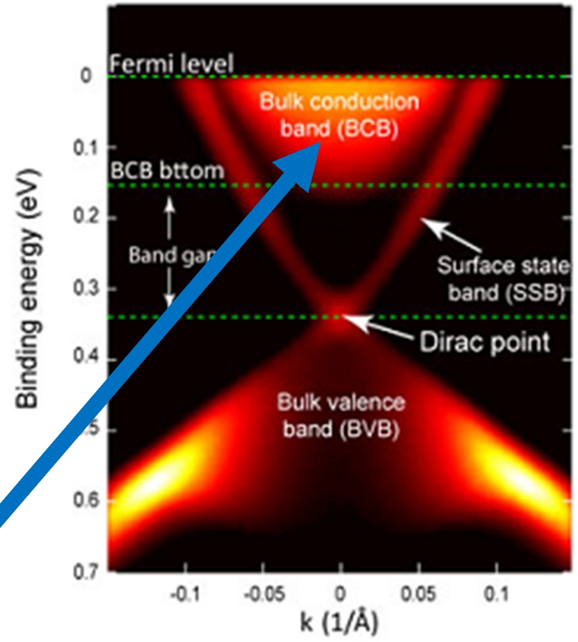
Eject Electrons




Filter E and $\theta$




Electronic Structure

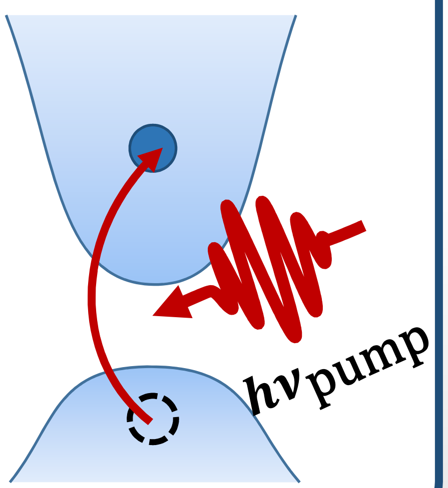



Can only measure occupied states

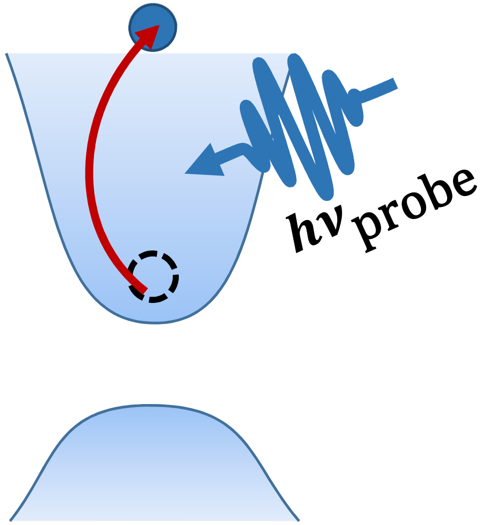
# Introduction – Narrow Cone

## Occupy empty states

### Populate States



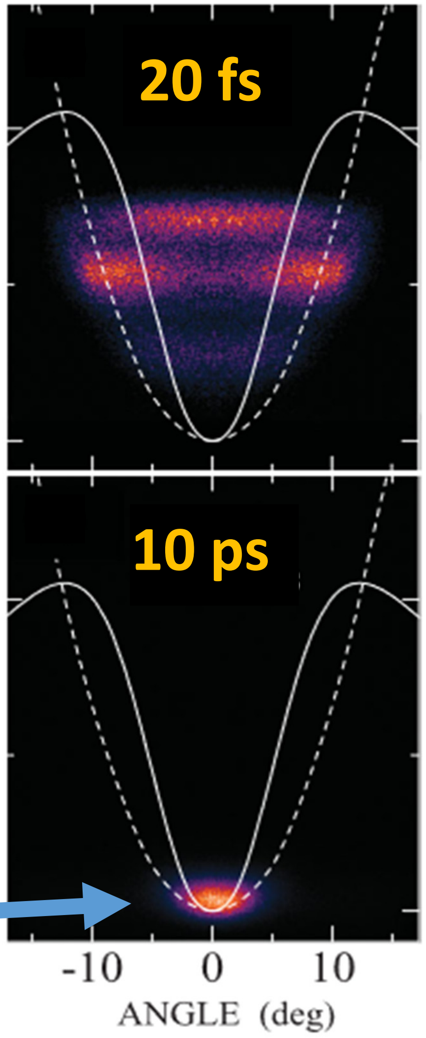

### Eject Them




New Parameter
**TIME**

Misses Electrons

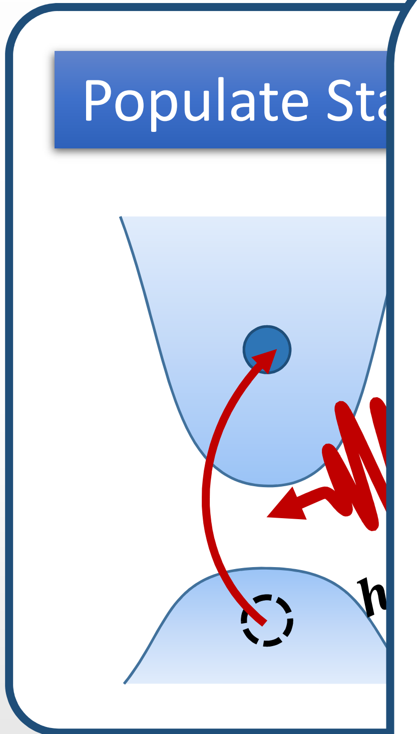
### GaAs (110) CBM




Kanasaki, Jun'ichi, et. al. PRL 113.23 (2014): 237401.

# Introduction – Narrow Cone

Occupy empty states



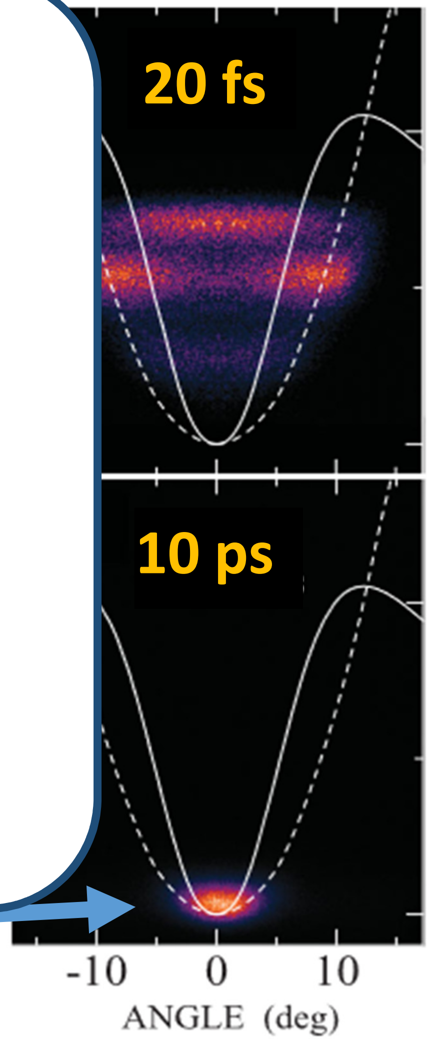

## Several Challenges

- Photoemission needs ultra clean **surface**
- Intricate **engineering of laser** for using those states
- Can we even **measure** single meV MTEs?

TIME

Electrons

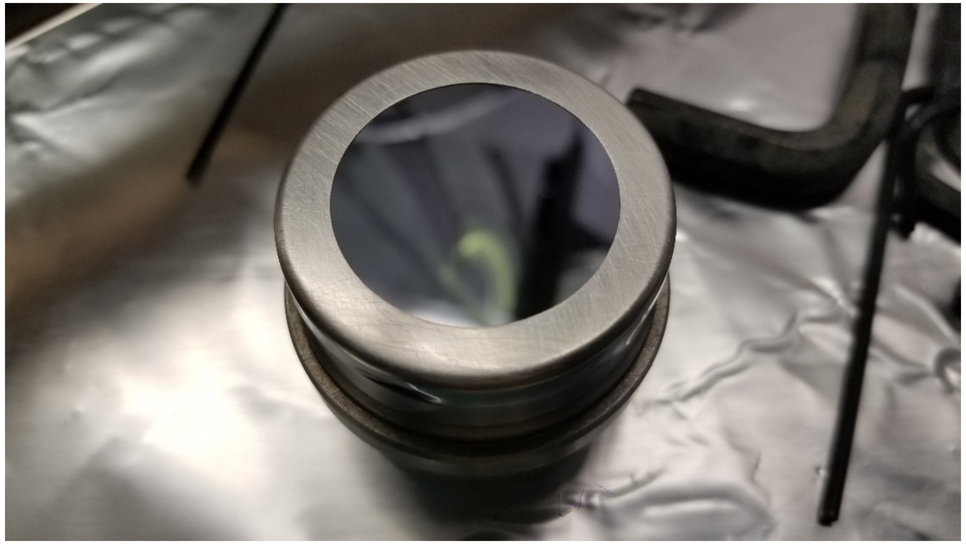
GaAs (110) CBM




Kanasaki, Jun'ichi, et. al. PRL 113.23 (2014): 237401.

# Experimental Setup

## Surface Prep



From NEA GaAs experience
**Etch and Anneal**

## Optics

OPA and Ultrafast Yb Fiber Laser

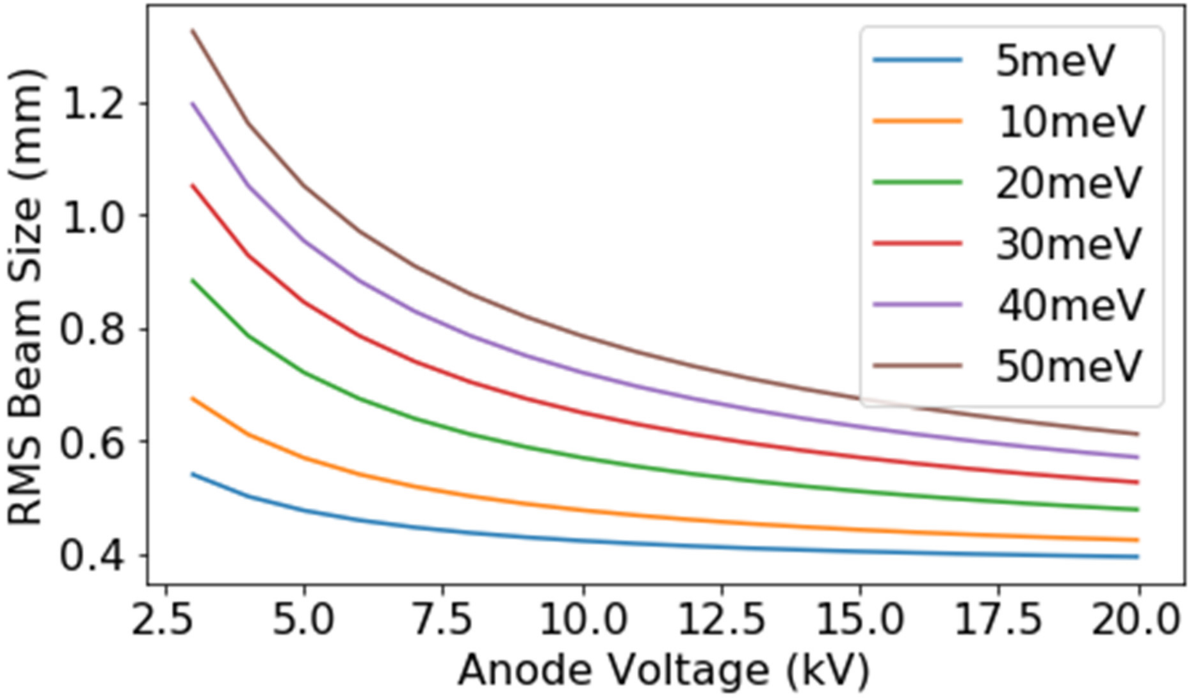
**Pump** – 750 nm
**Probe** – 343 nm

# Experimental Setup

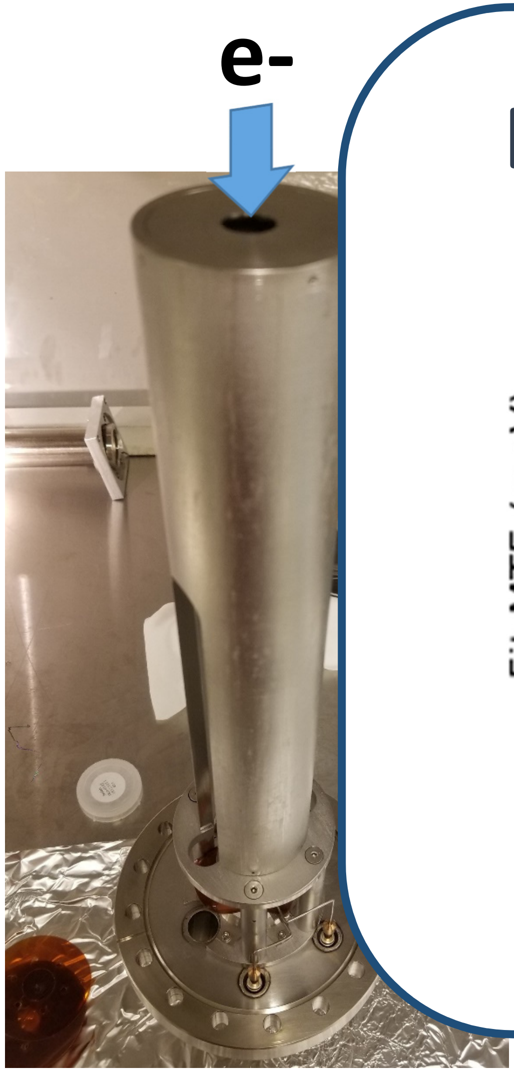
e-

Voltage Scan

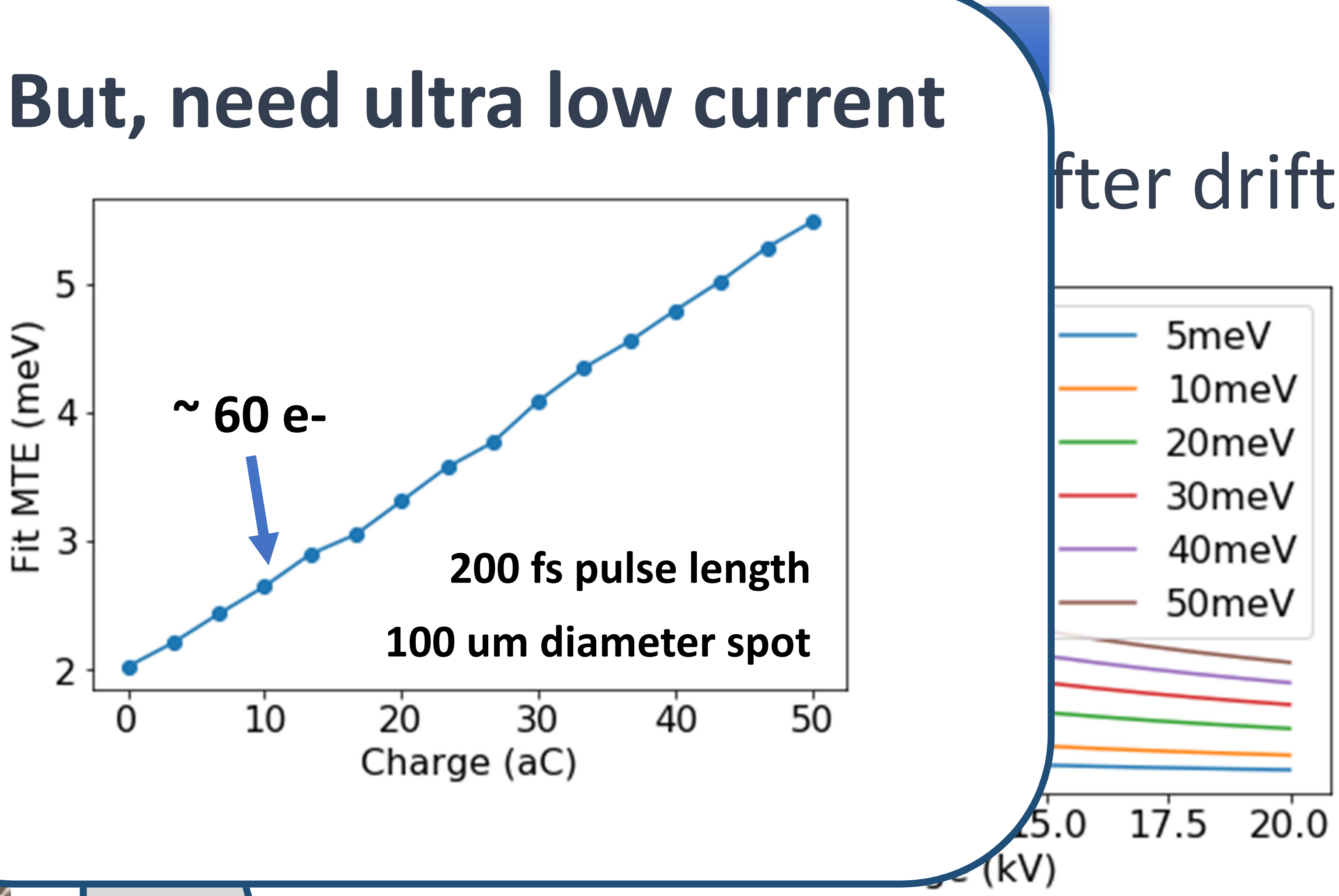
Measure $\sigma_x$ vs E after drift



# Experimental Setup

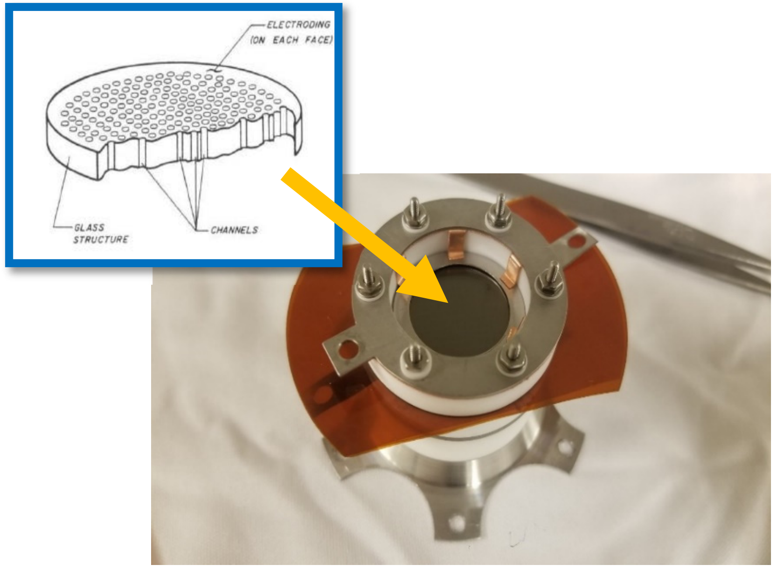



## But, need ultra low current

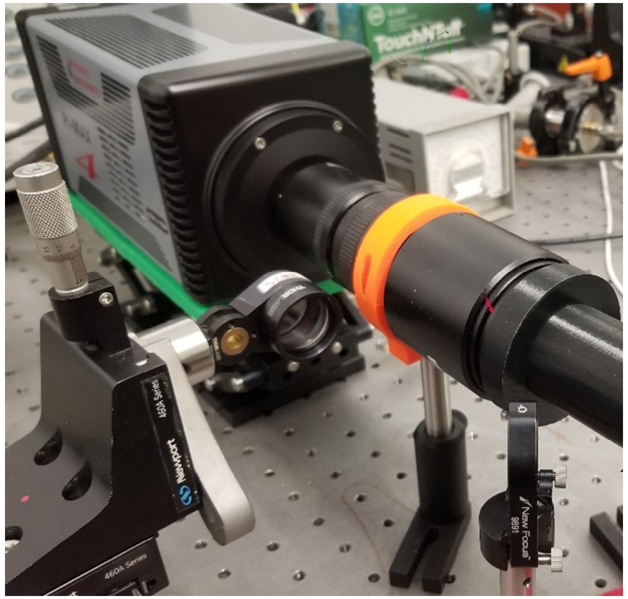


# Experimental Setup

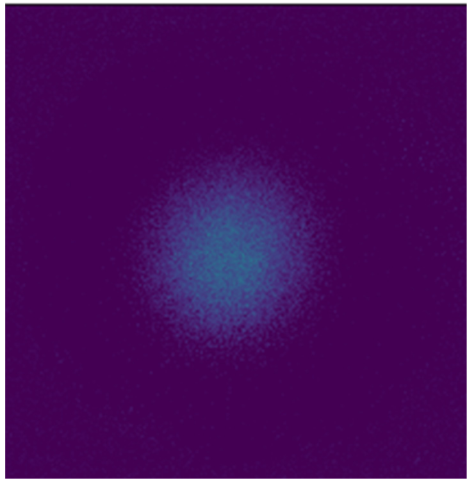
## Design an Amplifier




## Use ICCD Camera



## Testing

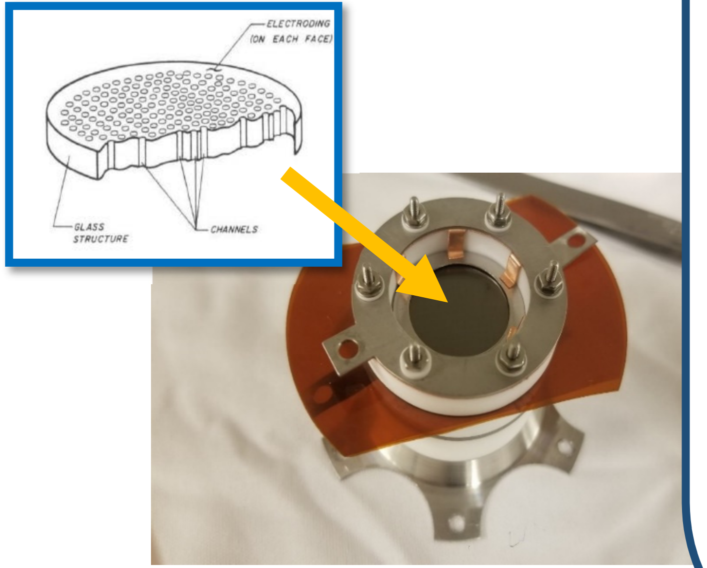


**~10 e- per pulse**

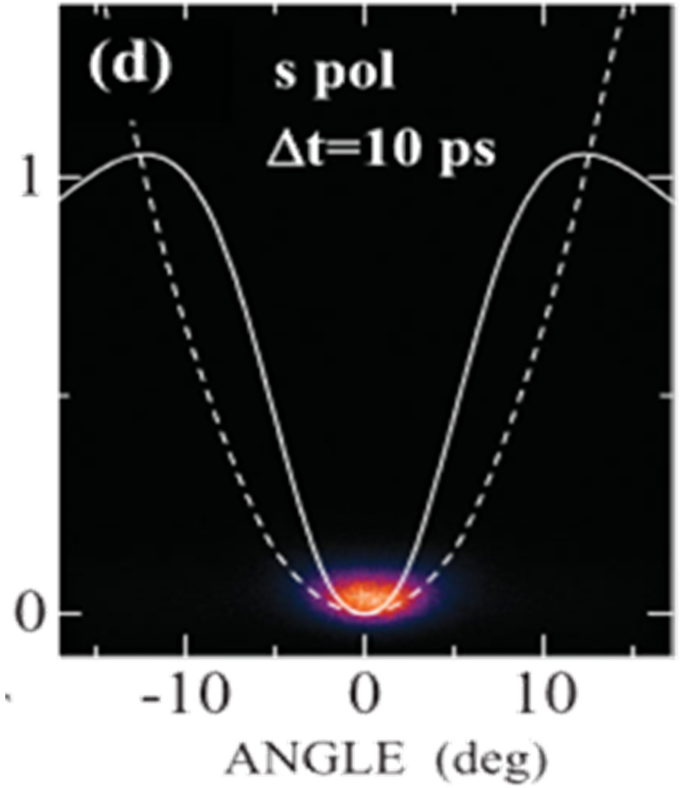
250 kHz rep rate

# Experimental Setup

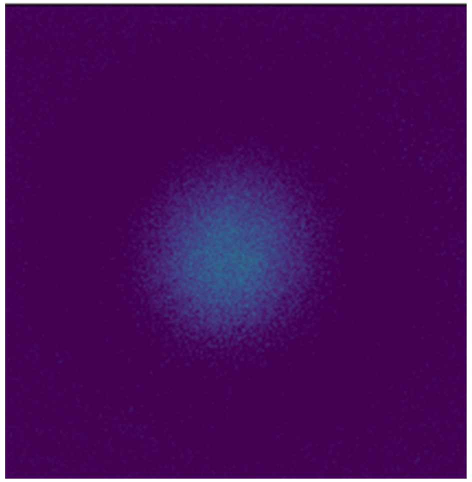
## Design an Amplifier




## Ready to measure 2 meV!

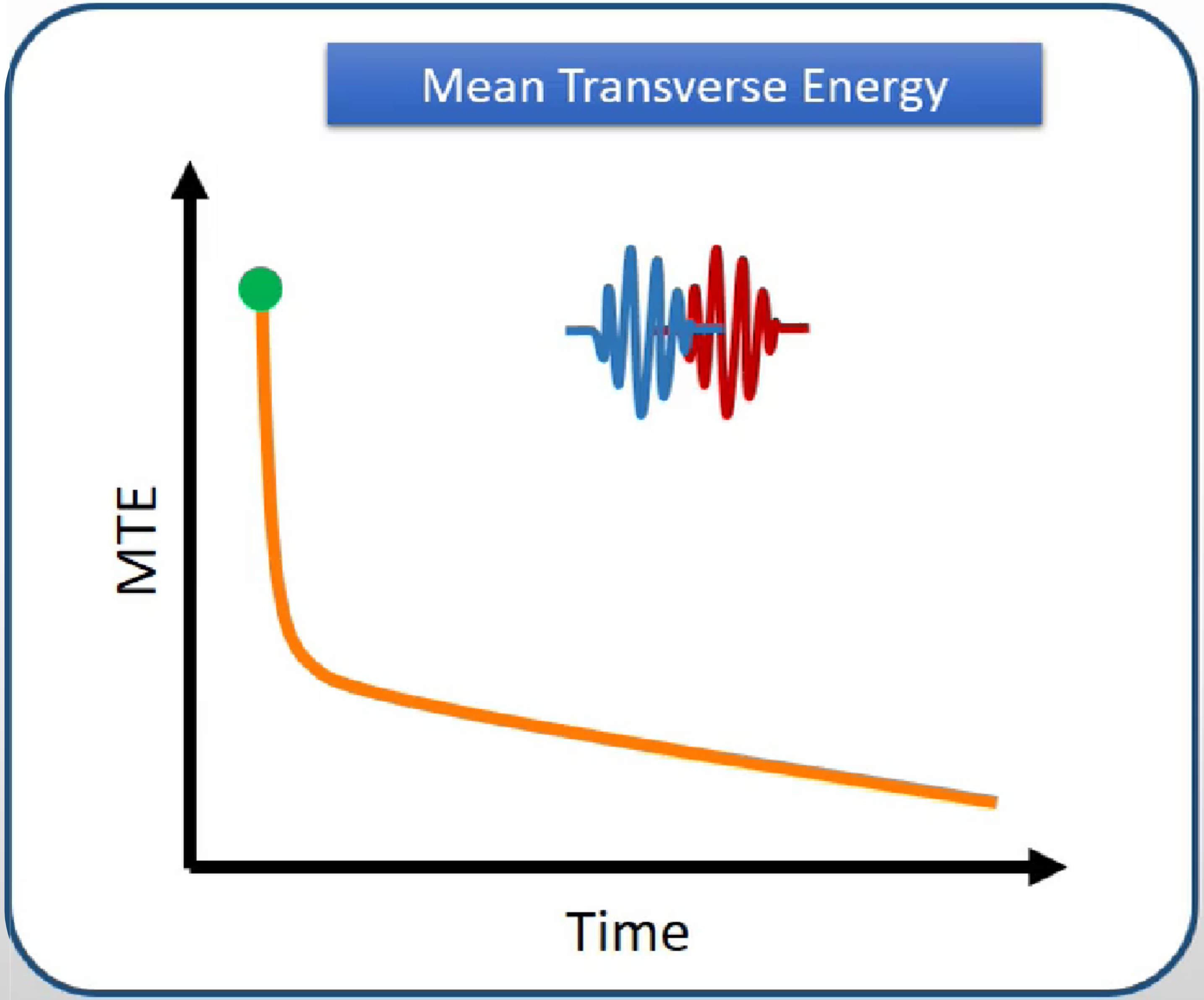


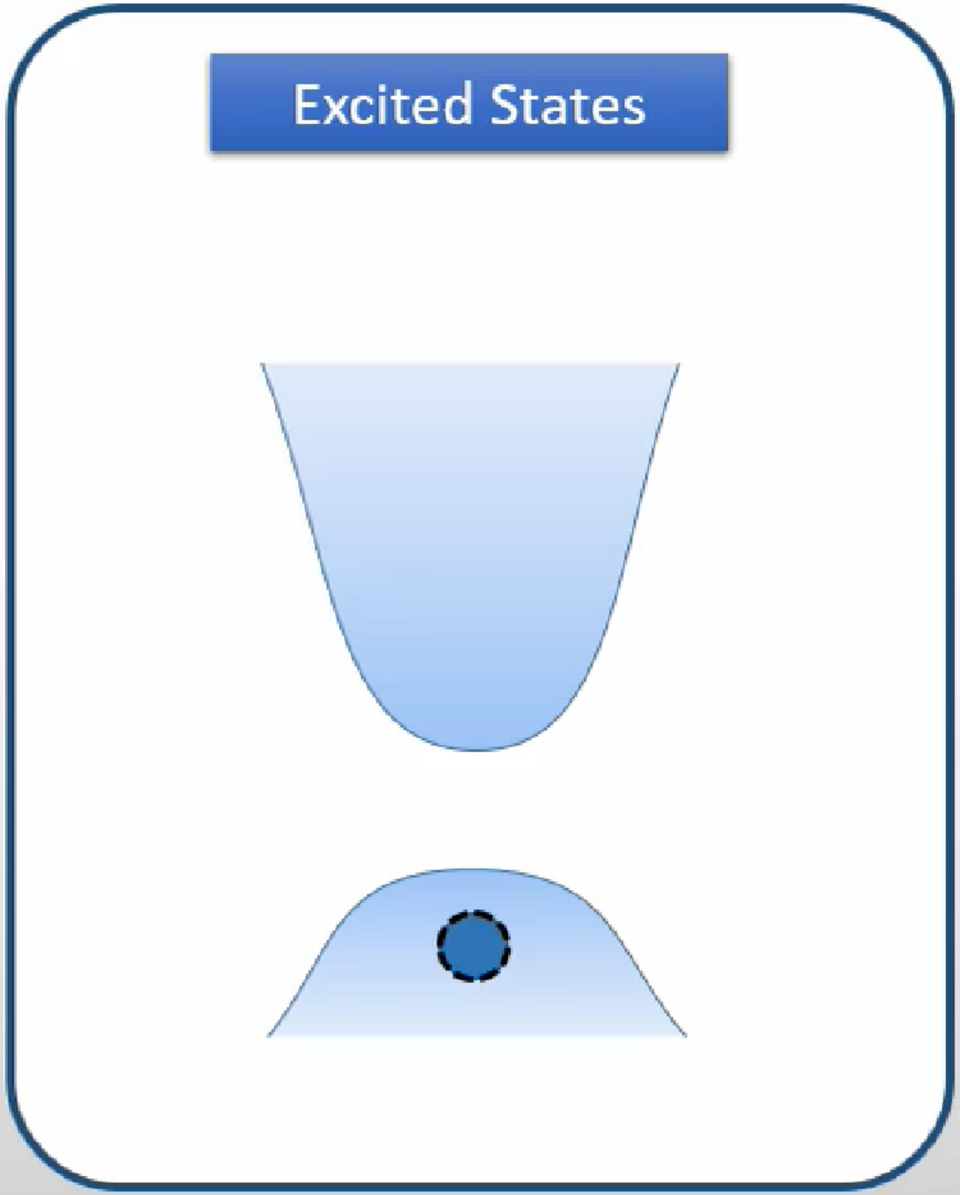

## Testing



**~10 e- per pulse**
250 kHz rep rate

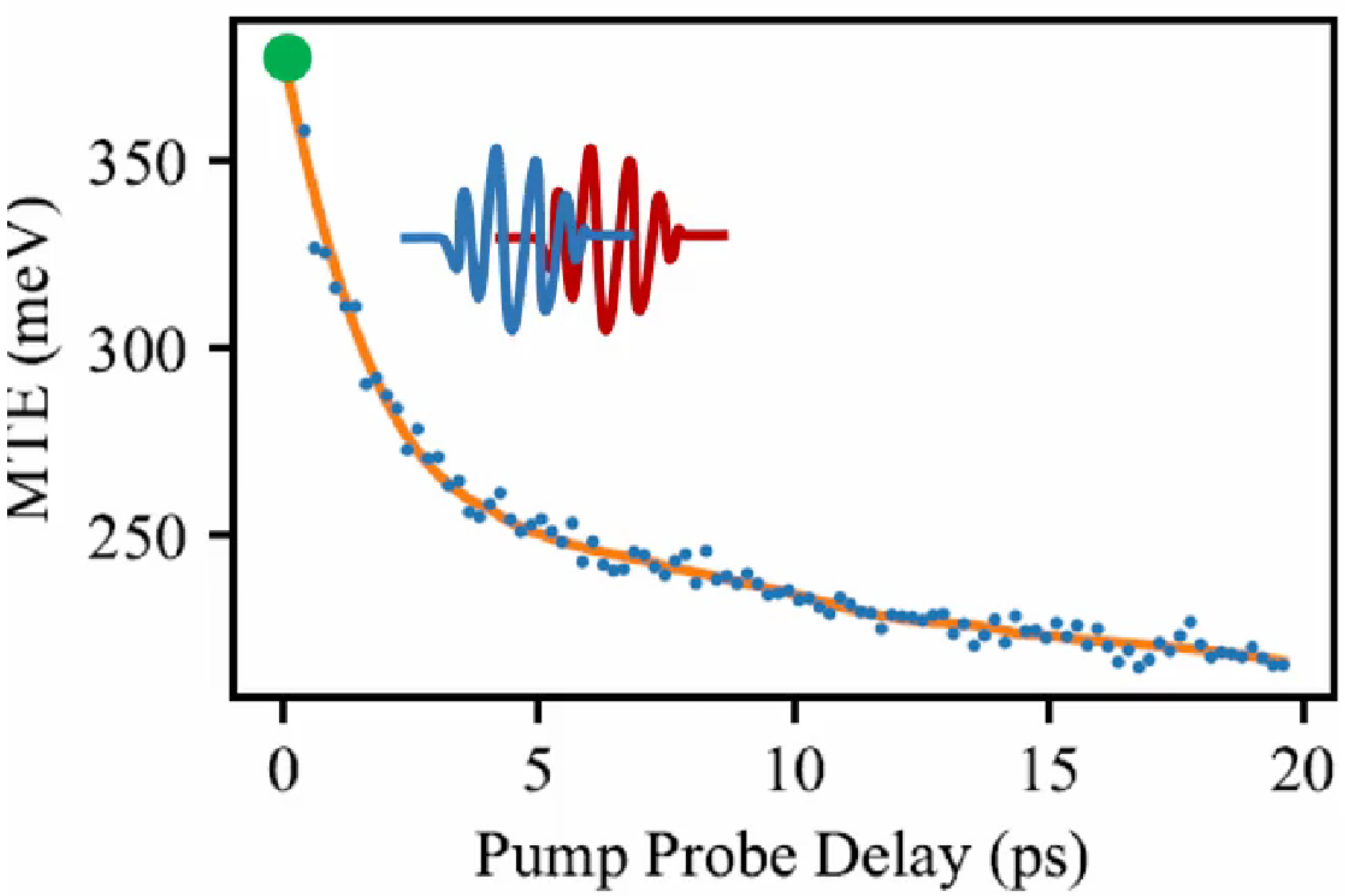
# MTE Measurements



# MTE Measurements

We measured 200 meV

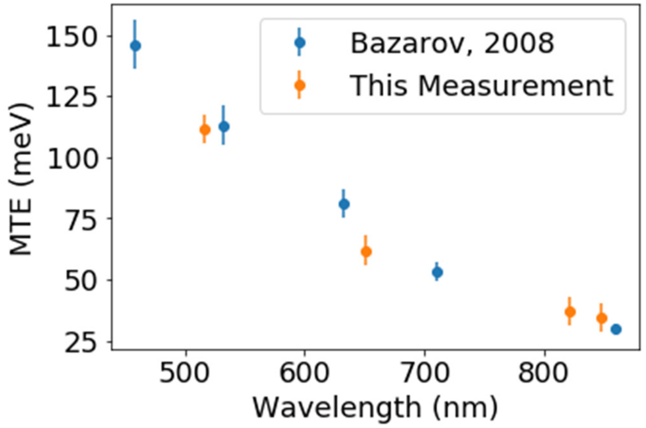


# Sanity Checks

## Is our measurement wrong? Probably not.

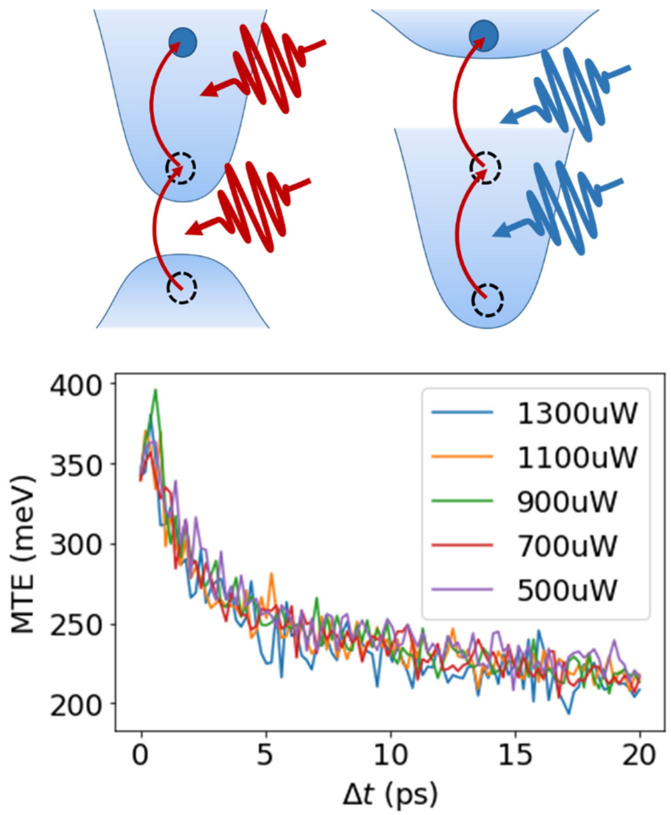
### The Instrument

Prepare Cs:GaAs



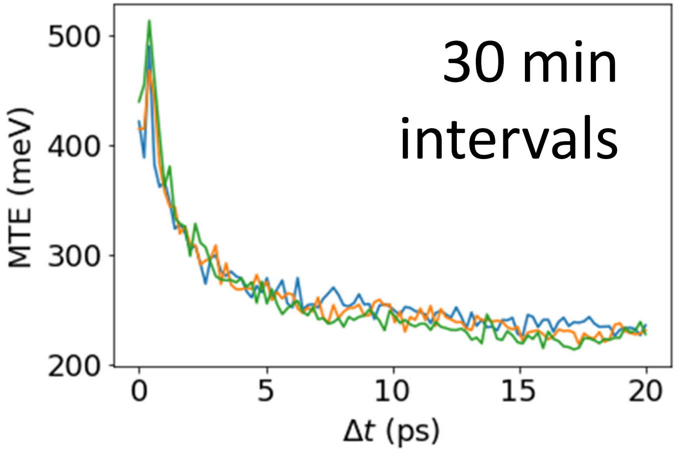

**Saw MTE = ~25meV**

### Multiphoton




### Adsorbates

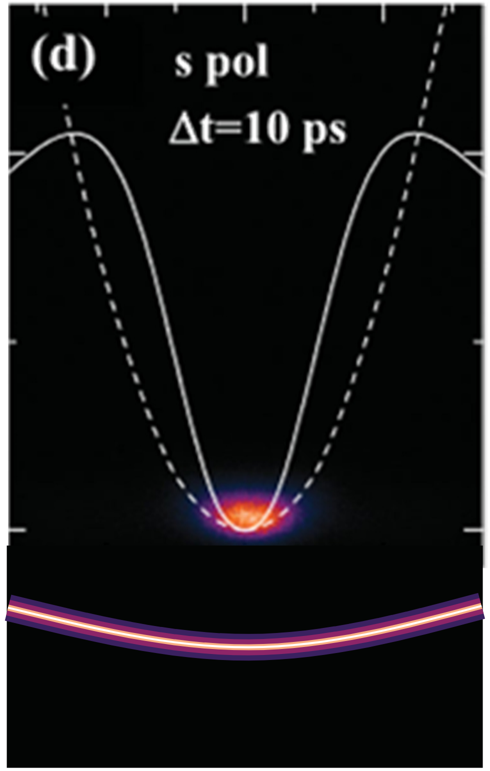
Annealing didn’t help




**MTE is Uniform**

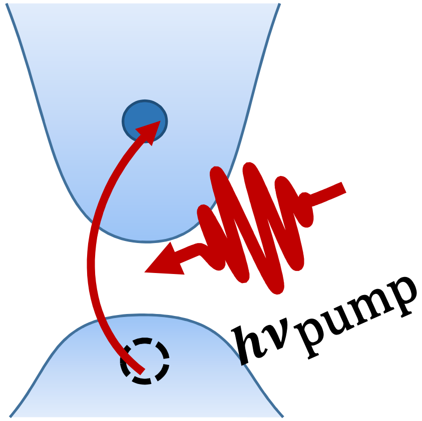
# Outlook

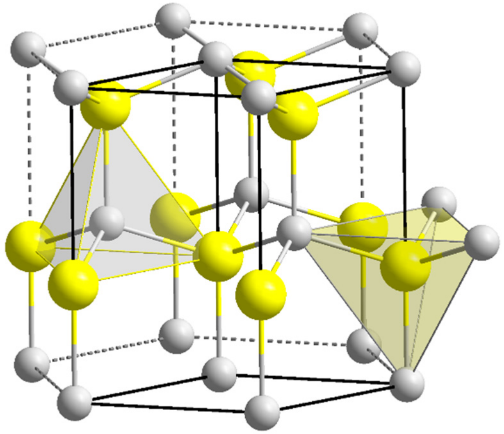
## Surface State




## New Paradigm for Photocathodes

Engineered carrier distribution for photocathodes



Excited to try other materials

## Slide 21

**WU16** Add more positive "lessons learned"
Windows User, 8/30/2019

**WU17** We have a new paradigm of emission
Windows User, 8/30/2019

**WU18** Add positive slide w/ "engineering the distribution" or new time resolved
Windows User, 8/30/2019

# Thanks for Listening!

Questions?