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2018 TeV Particle Astrophysics

Development of Next Generation sub-MeV and MeV Gamma-ray Detector

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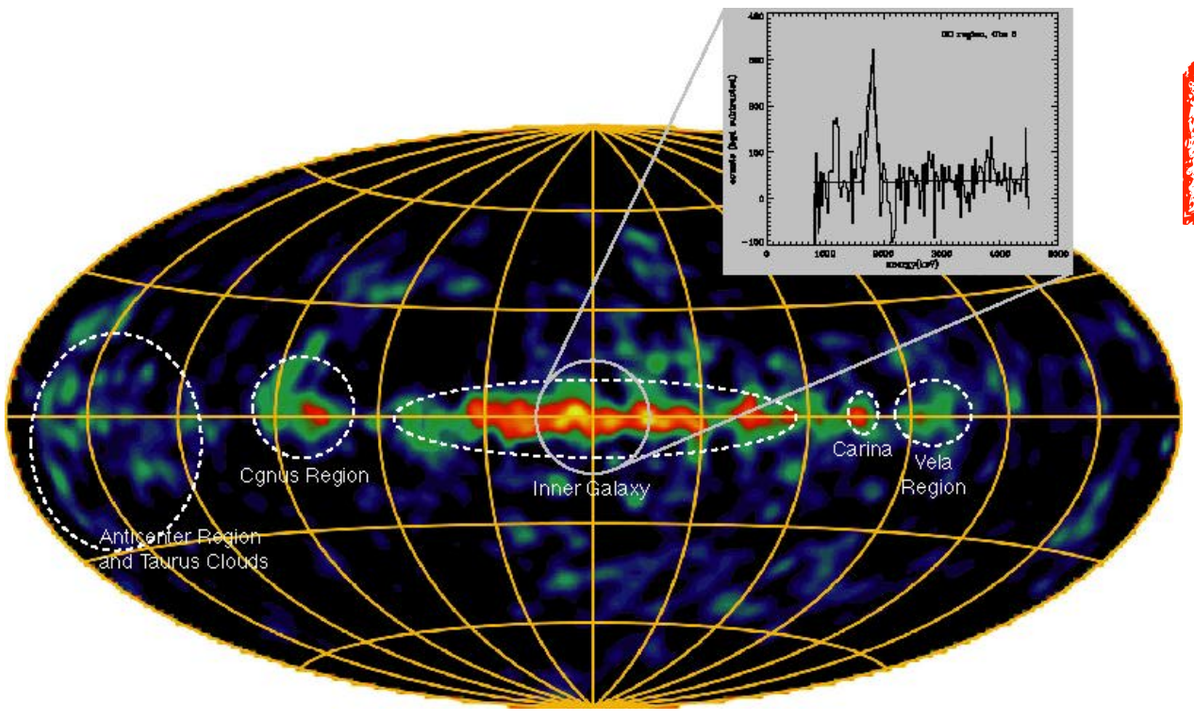
Sub-MeV & MeV astronomy



Nuclear Gamma-ray Line

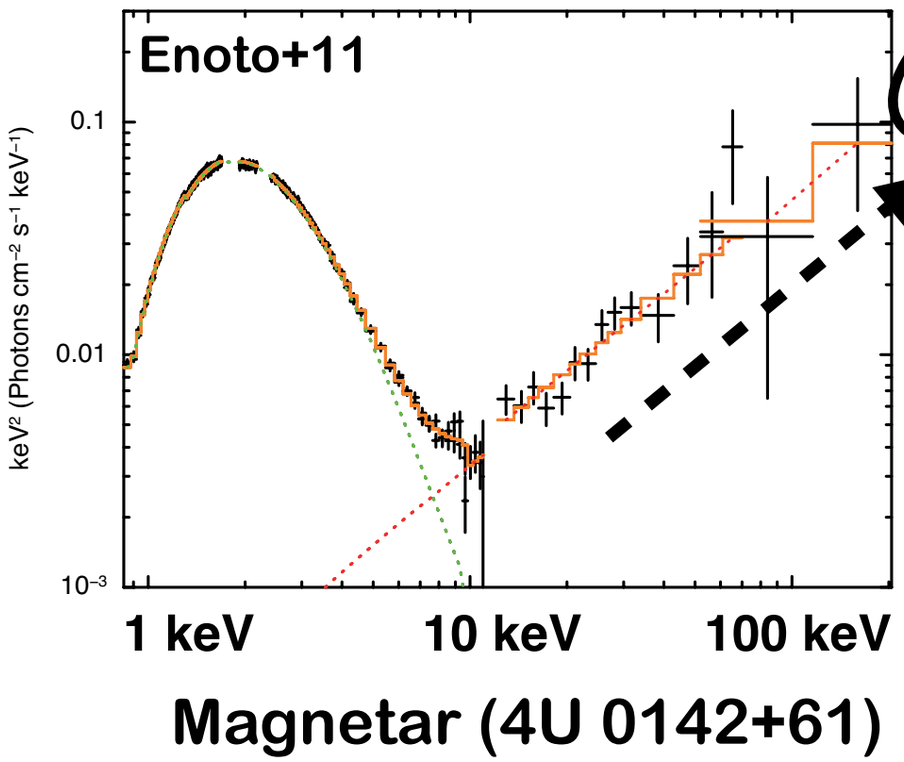
Nuclear gamma-ray line (few MeV)

→ **History of nucleosynthesis**

e^+e^- annihilation line (511 keV)

→ **Probe for positrons**

COMPTEL ^{26}Al (1.8 MeV) All-Sky Map



Magnetar (4U 0142+61)

Non-Thermal Emission

Joint between synchrotron and inverse Compton scattering

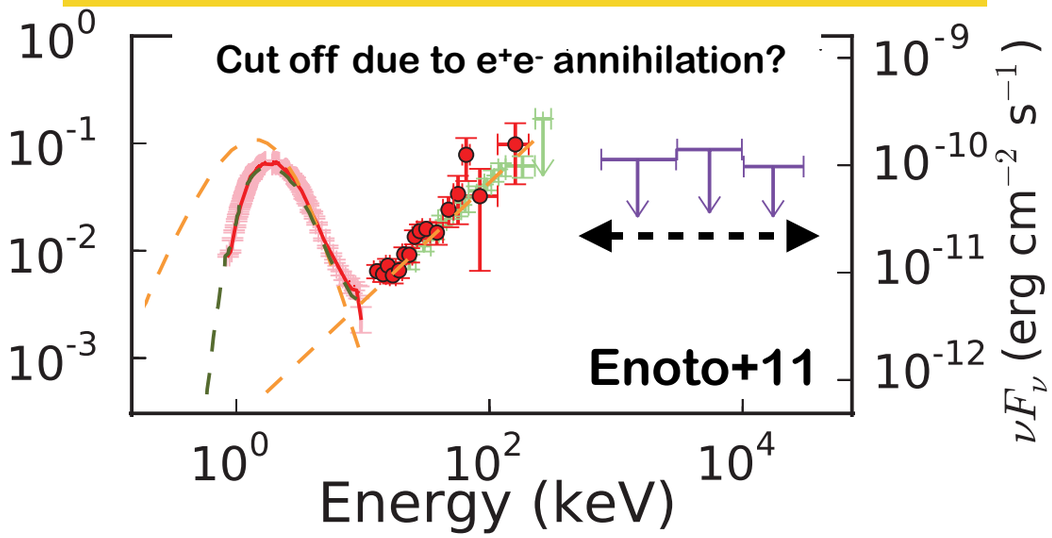
→ **Blazars, Pulsar wind nebulae**

Hard component from magnetars

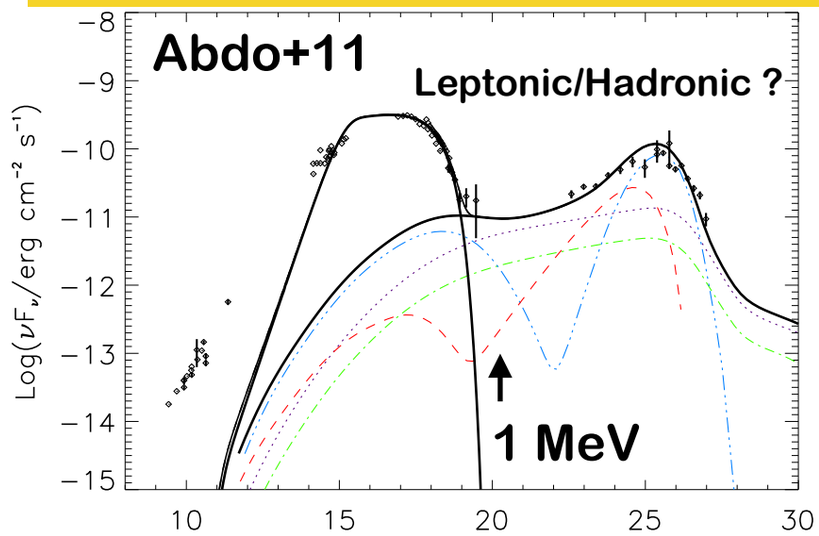
→ **Strong magnetic field science**

MeV Science v.s. Flux

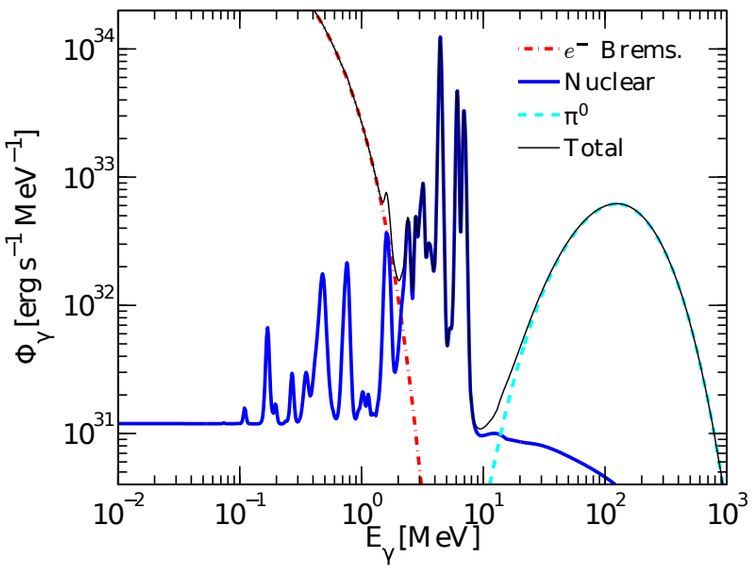
Magnetar (4U 0142+61) → ~10^{-11} erg cm^{-2} s^{-1}



Blazar (Mrk 421) → ~$10^{-12\sim-11}$ erg cm^{-2} s^{-1}

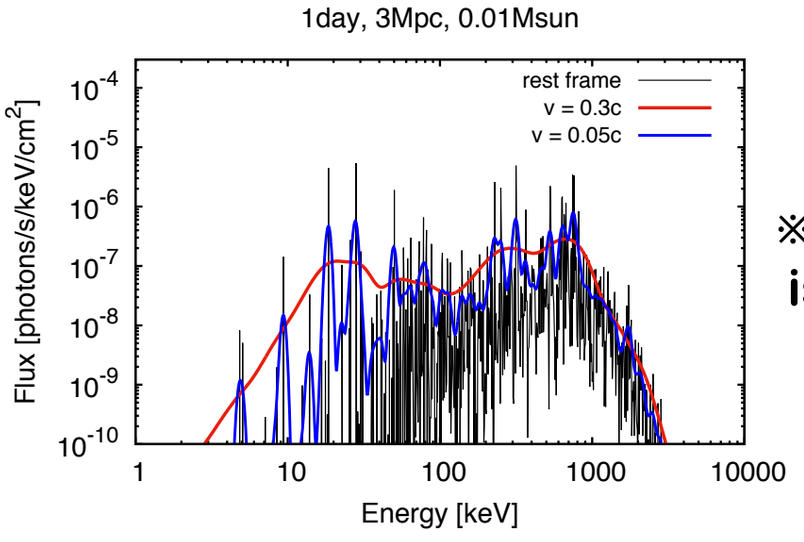


MeV gamma ray from ADAF → ~$10^{-13\sim-12}$ erg cm^{-2} s^{-1} @2kpc



Kafexhiu+18

MeV gamma ray from NS-NS merger → ~10^{-13} erg cm^{-2} s^{-1} @40 Mpc



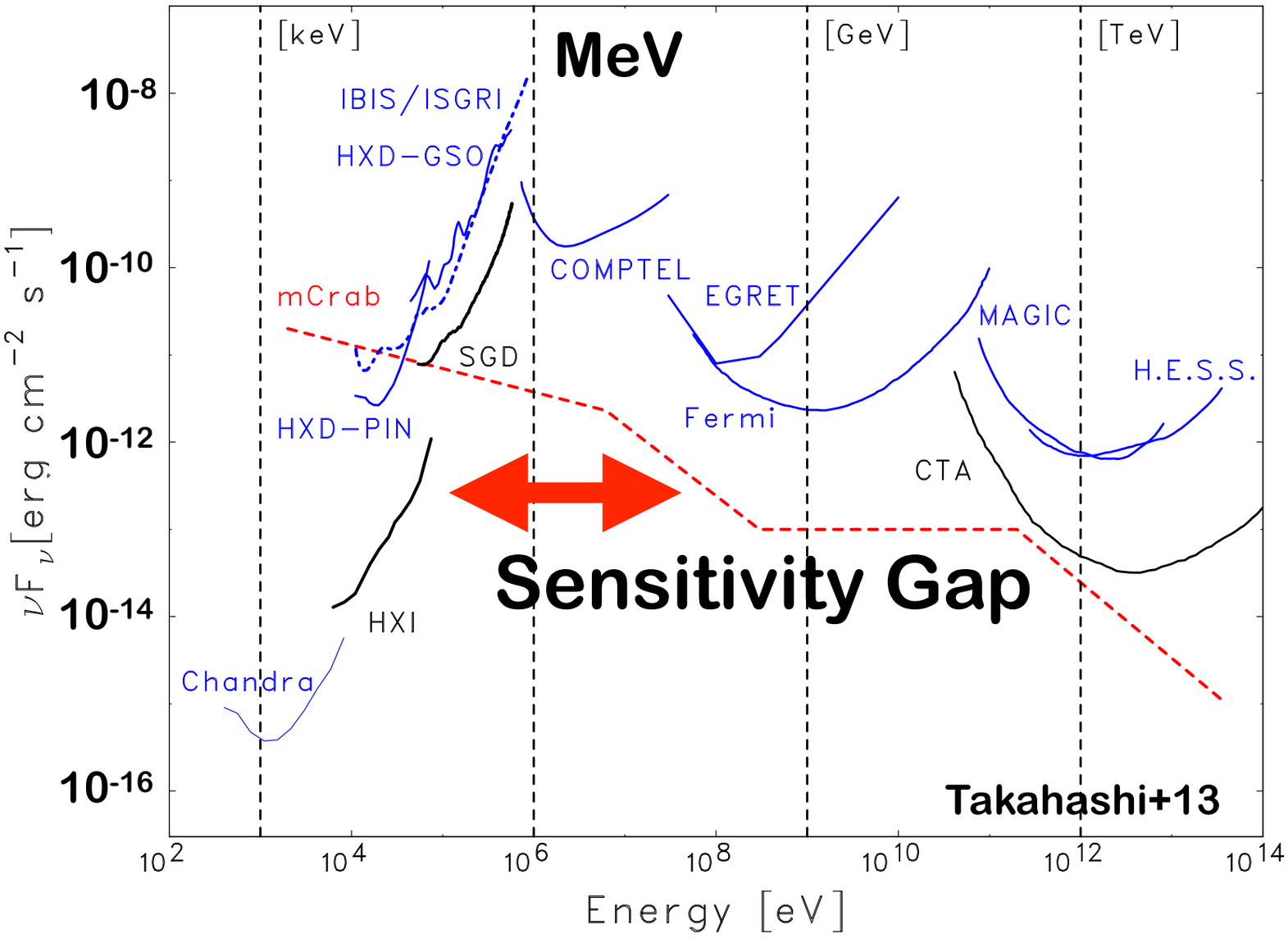
※The observation time is limited to ~10 days.

Hotokezaka+15

At least, we need the sensitivity of 10^{-11} erg cm^{-2} s^{-1}

Current Status

Sensitivities for a point source



The number of detected sources

MeV
=> 32 sources
(COMPTEL, Schoenfelder+10)

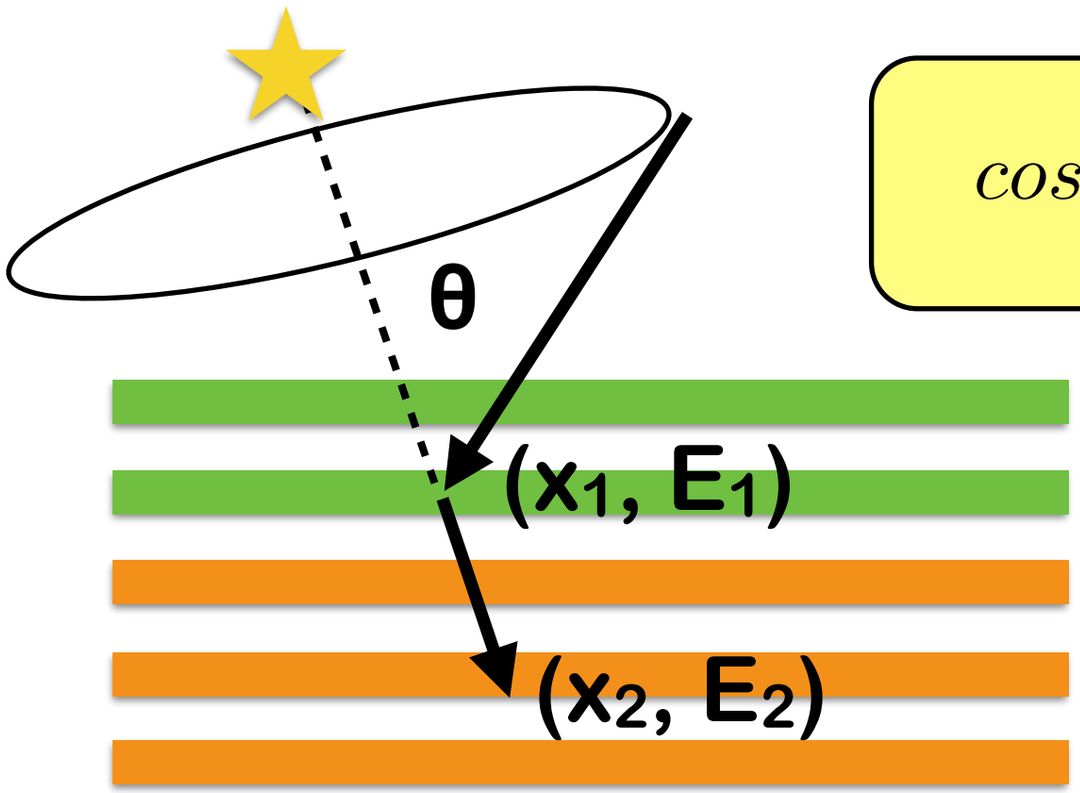
X-ray
=> ~300000
(Chandra, Evans+18)

GeV
=> ~3000
(Fermi-LAT Collaboration 2015)

Low sensitivity is the most critical issue

Compton Camera

Most powerful method to detect MeV gamma rays



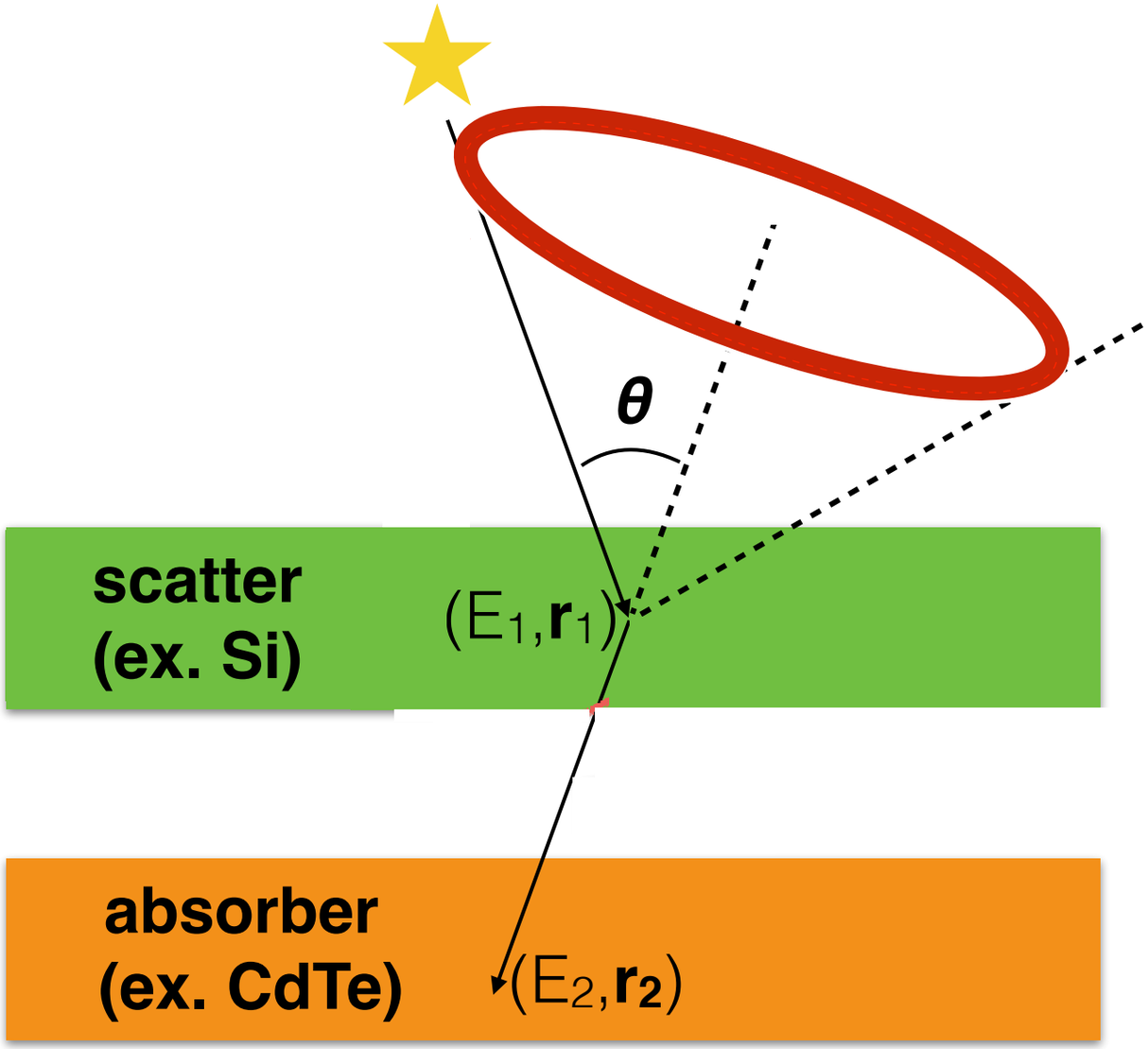
$$cos\theta = 1 - m_e c^2 \left(\frac{1}{E_2} - \frac{1}{E_1 + E_2} \right)$$

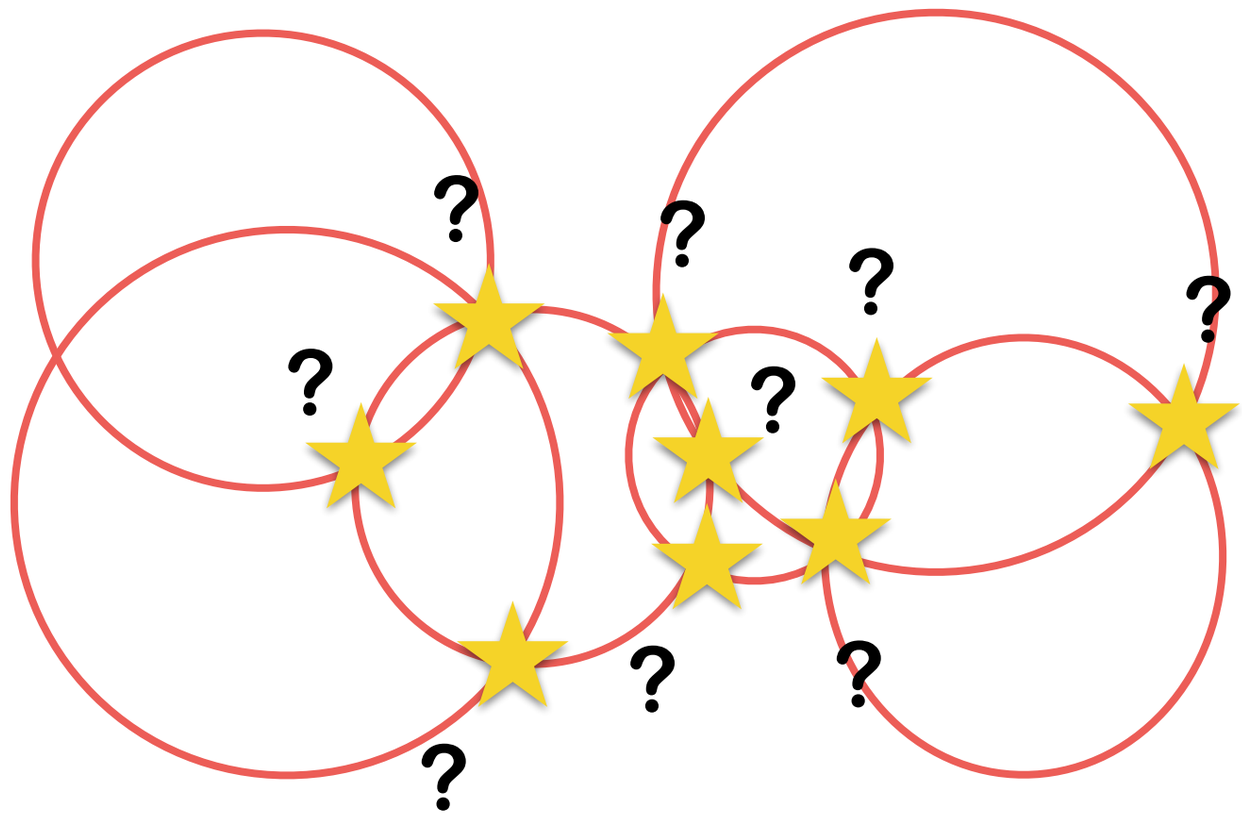
In MeV band,
Compton scattering
is dominant.

Matuura+14

Toward Higher Sensitivity

KEYPOINT = Track the Electron Trajectory





Electron Tracking Compton Camera (e.g. Vetter+11, Tanimori+15)

High energy resolution w/ semiconductor detector → Precise Line measurement

Toward Higher Sensitivity

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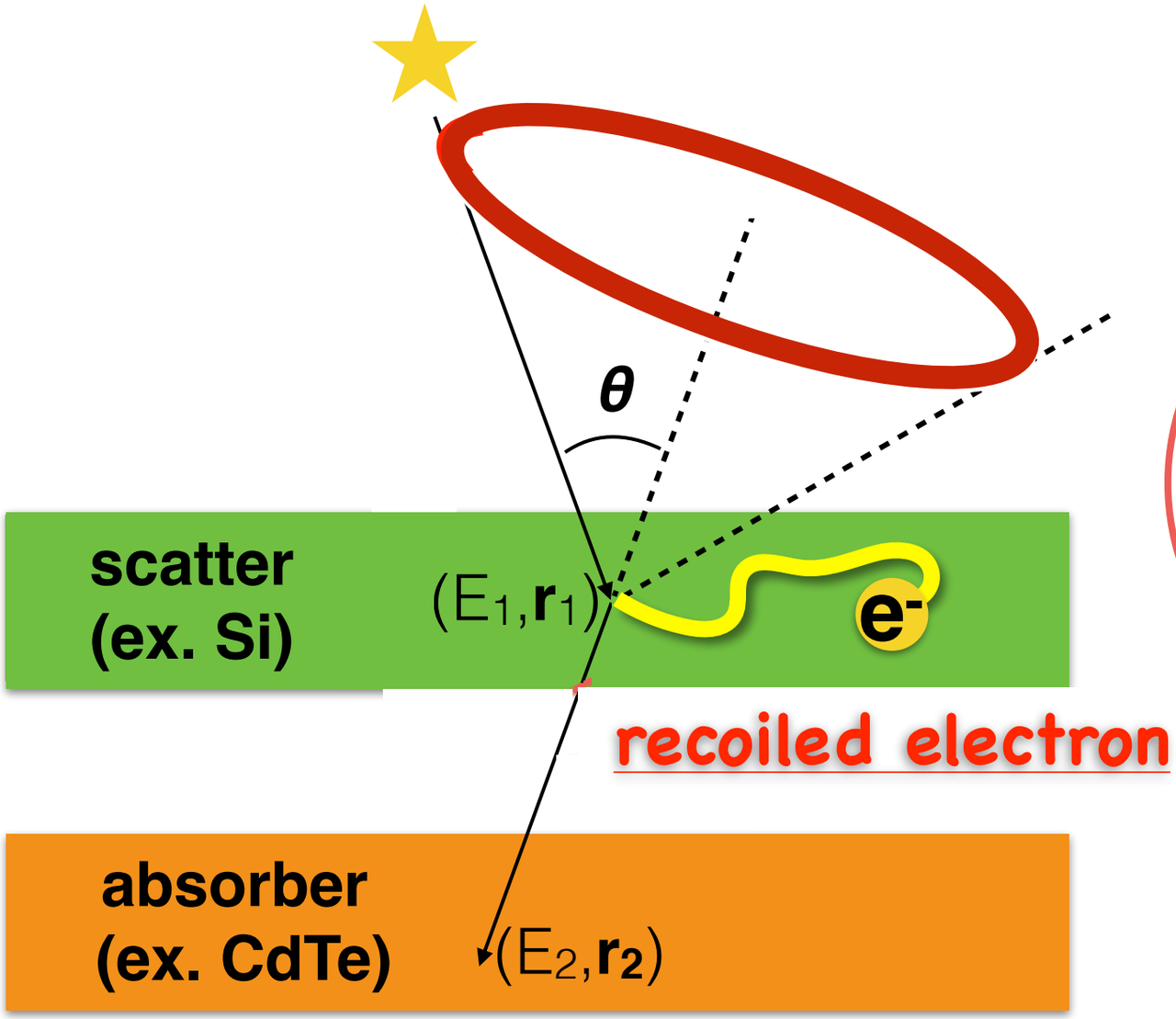

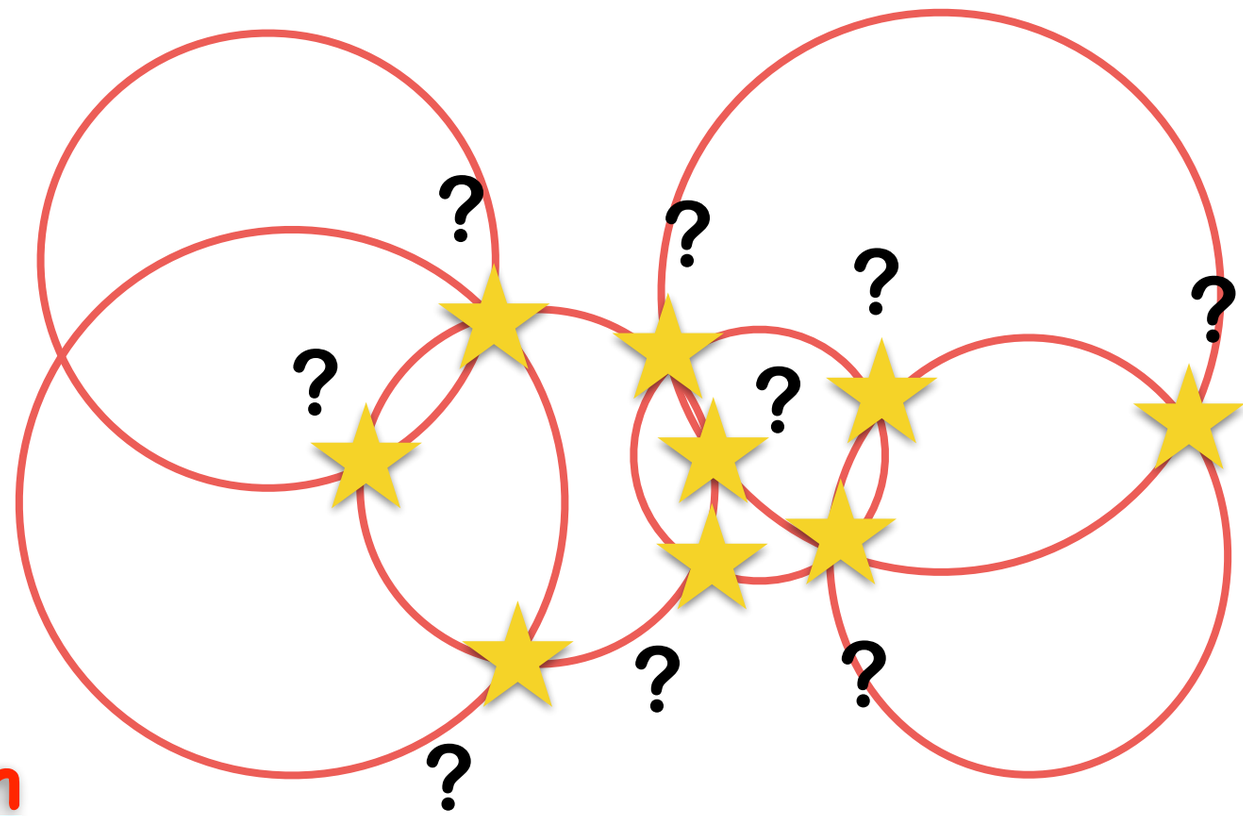

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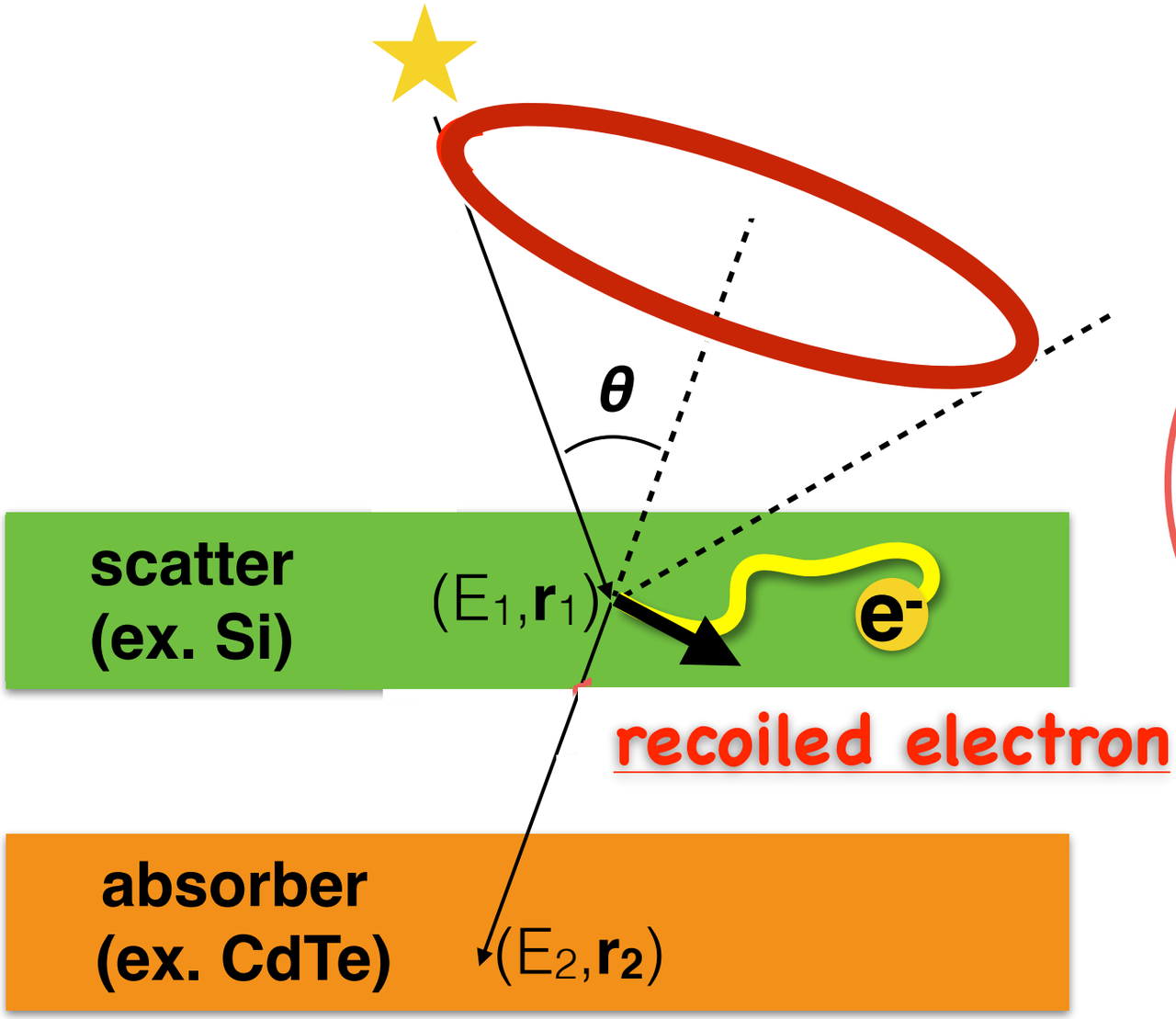

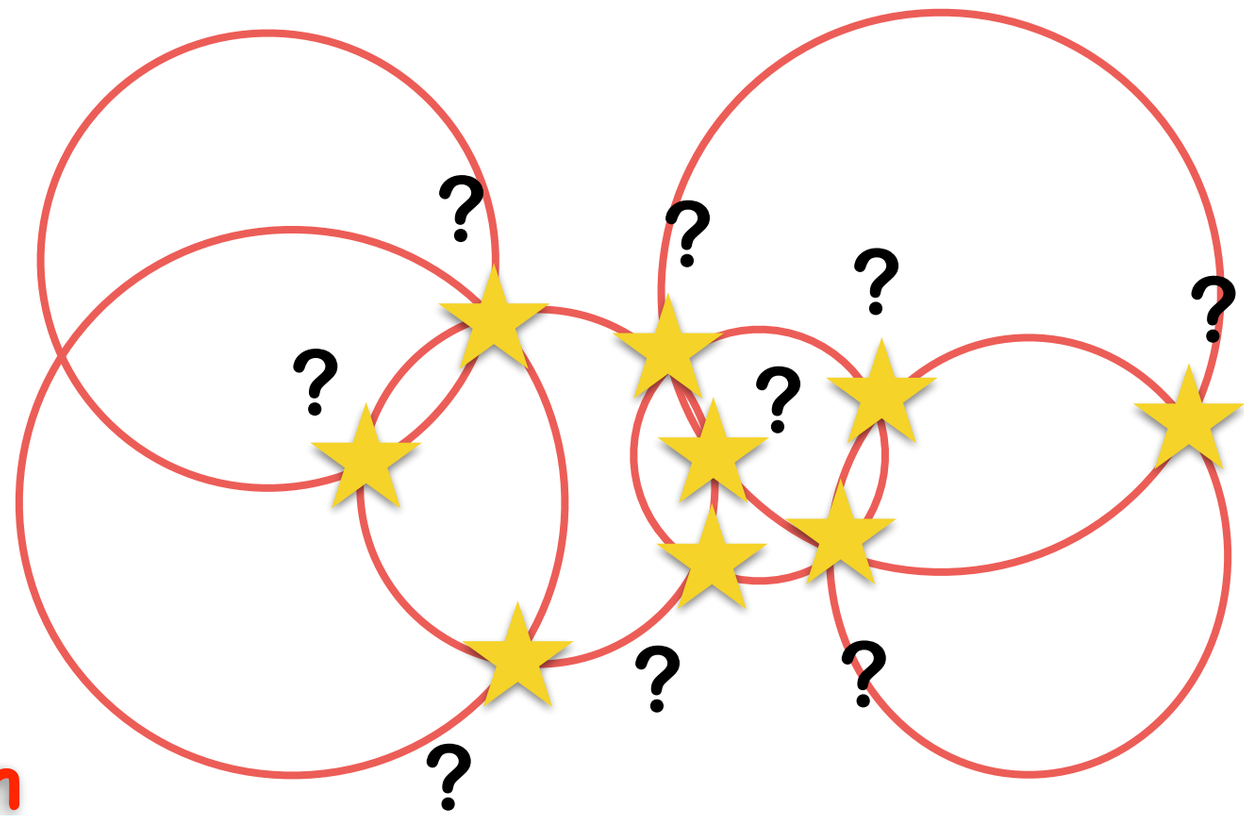

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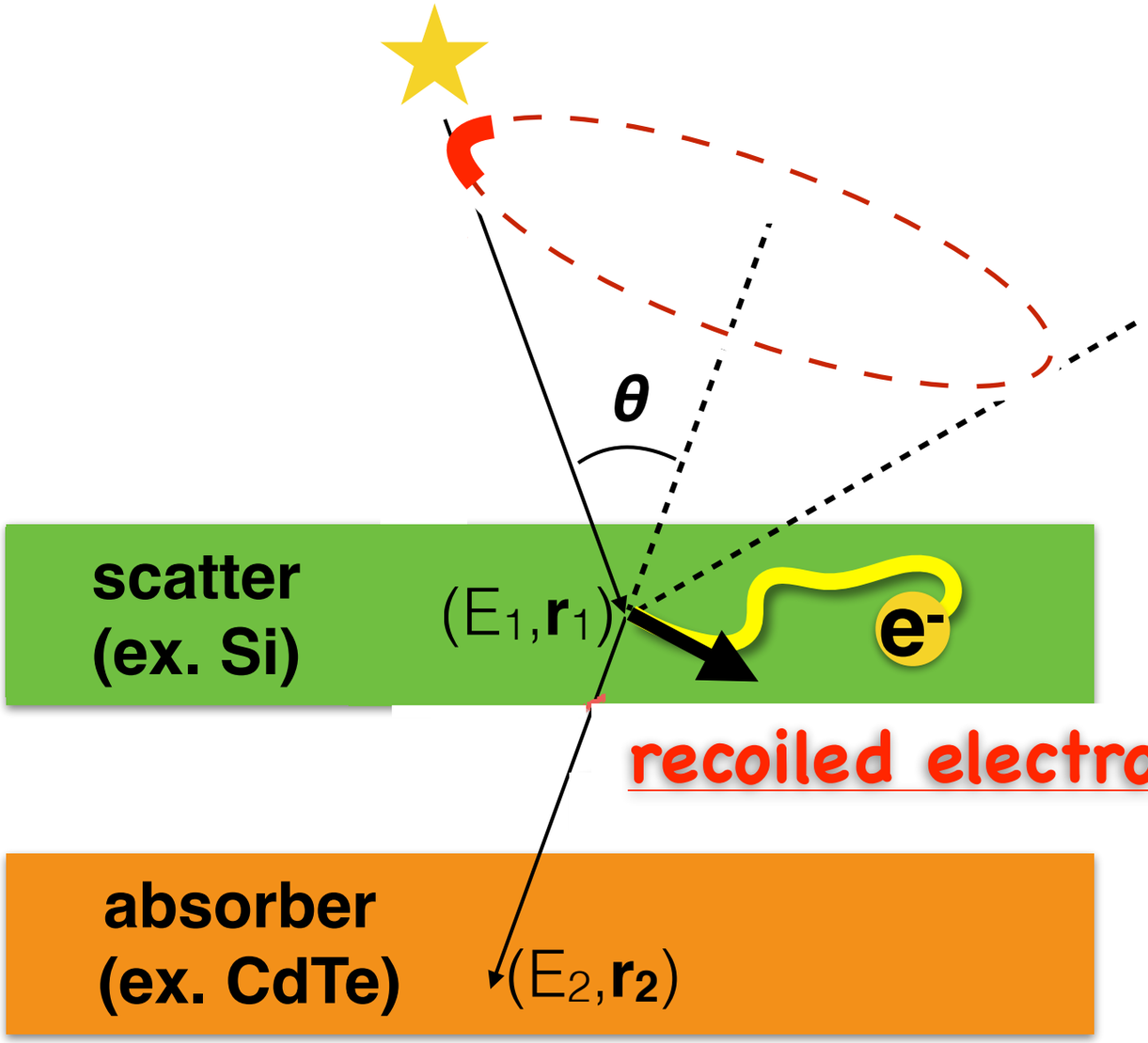

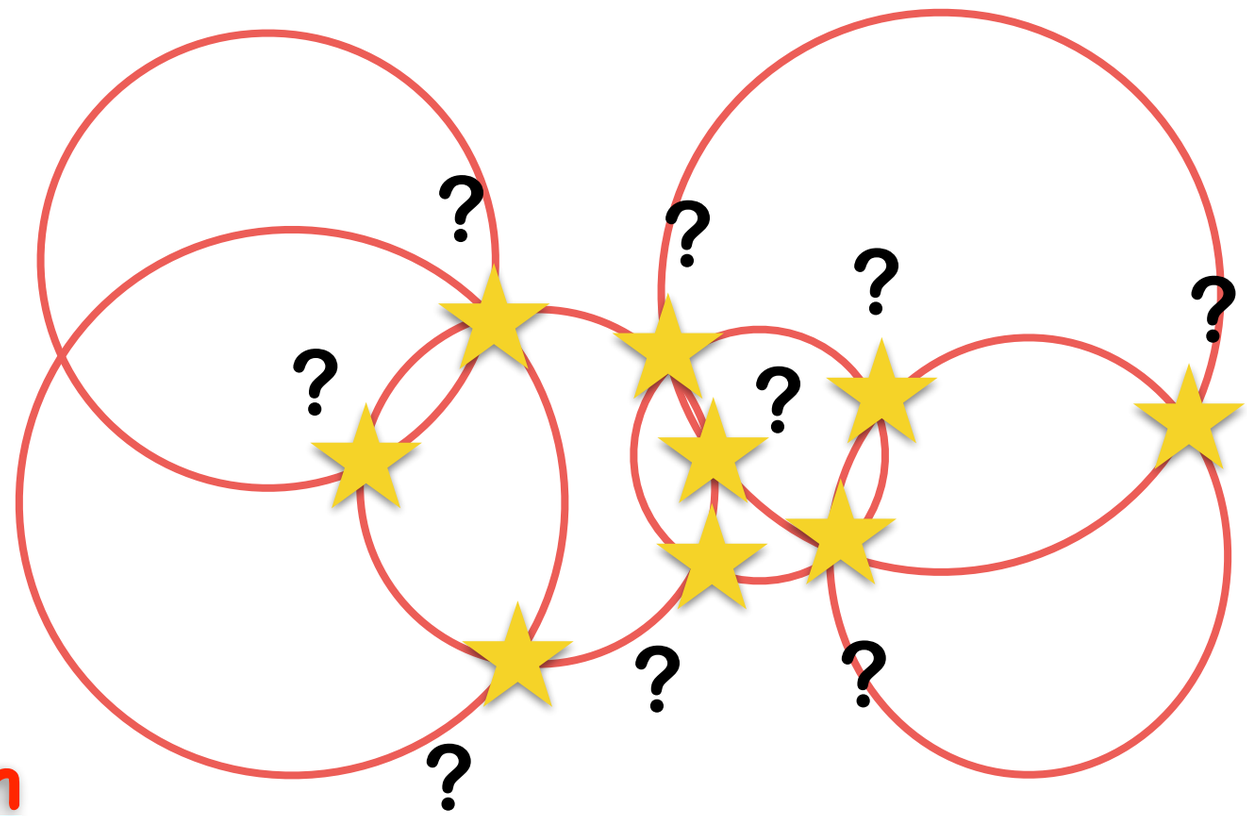

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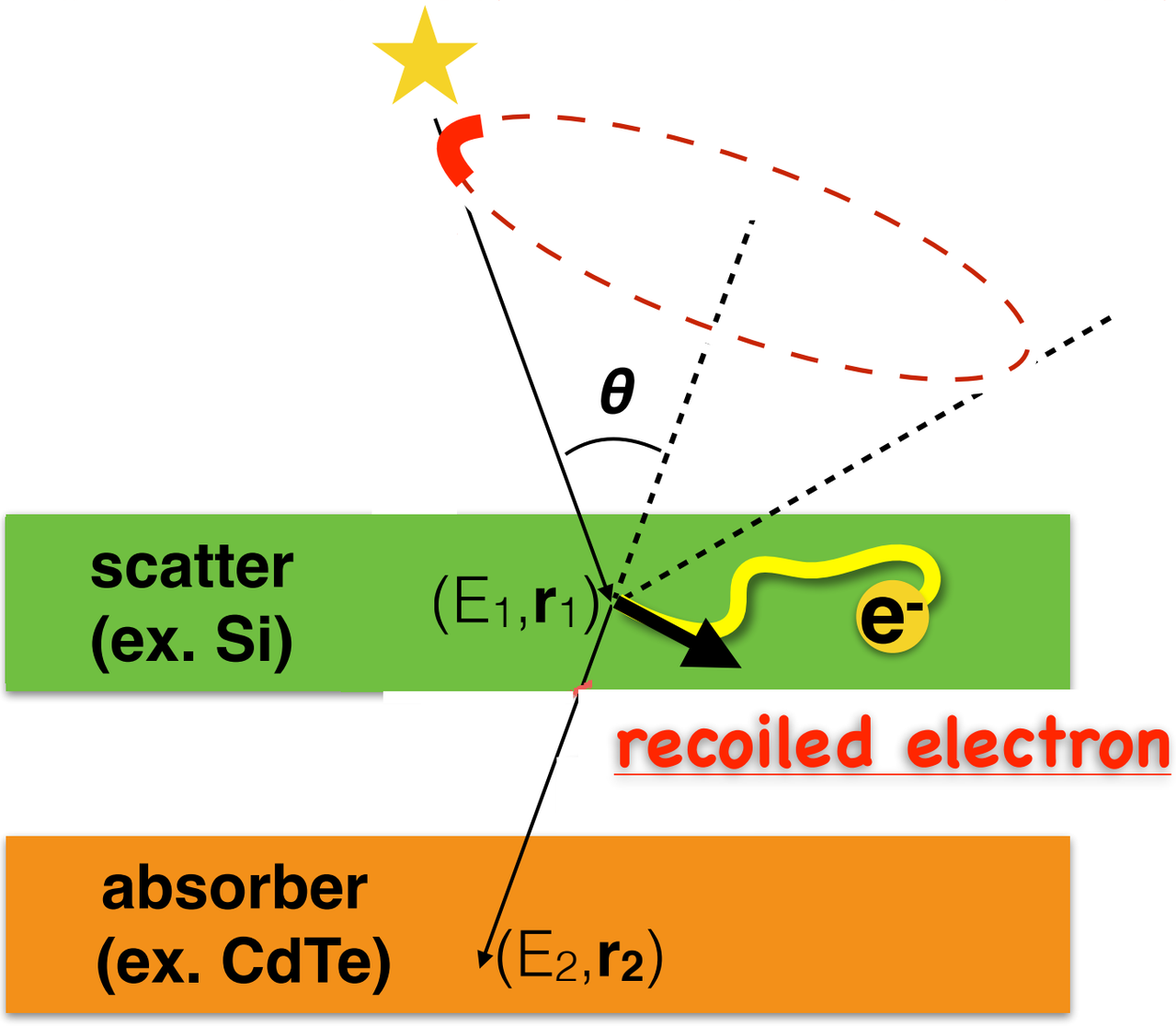
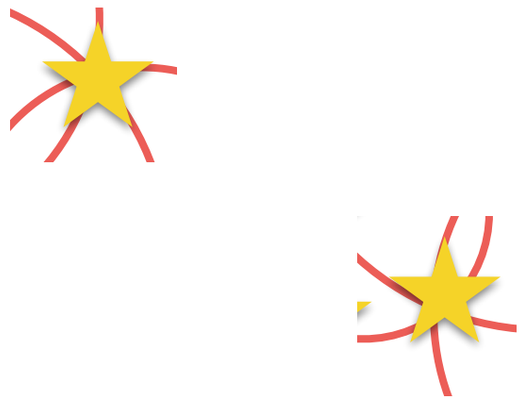




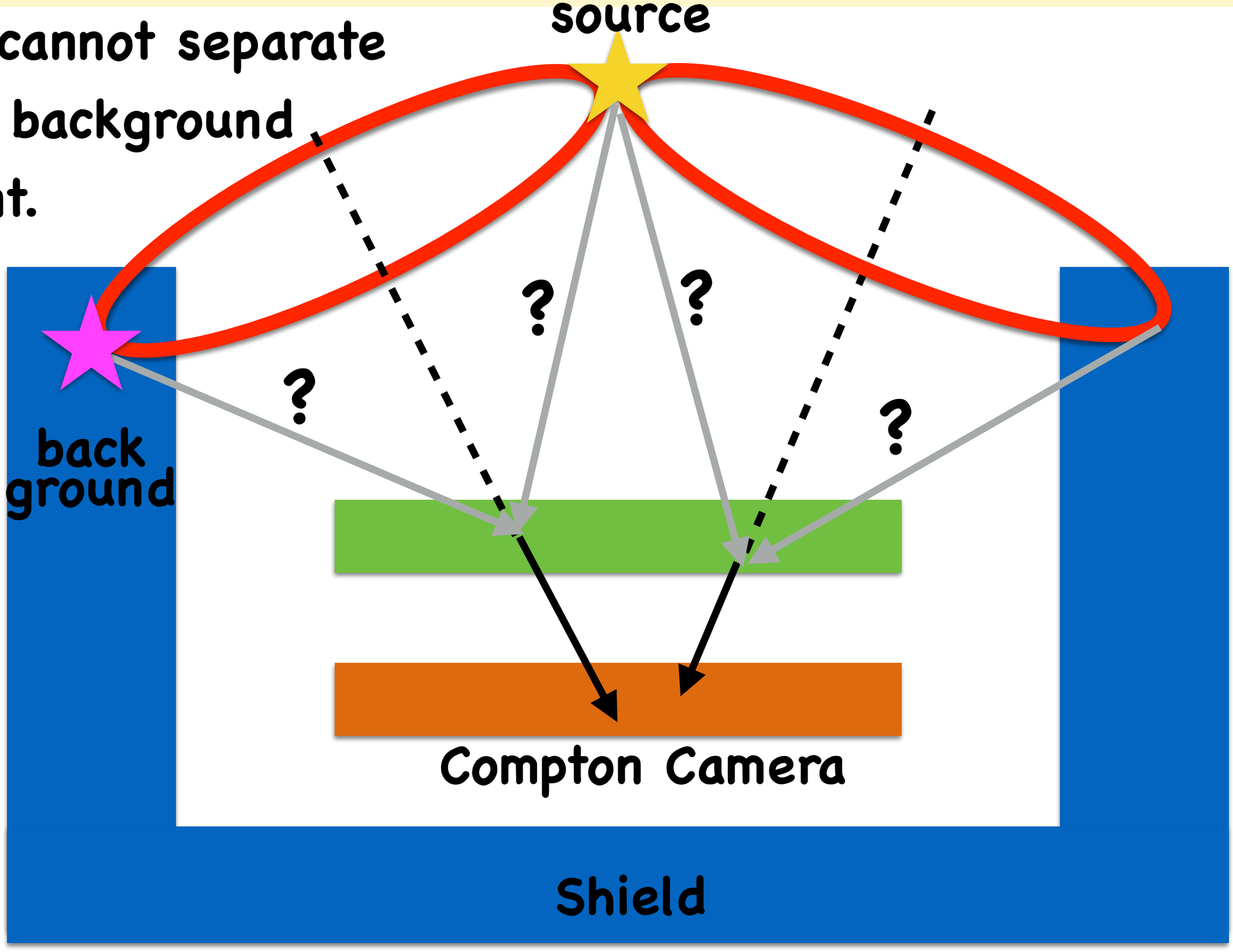
We can know a gamma-ray direction with less events.

Electron Tracking Compton Camera (e.g. Vetter+11, Tanimori+15)

High energy resolution w/ semiconductor detector → Precise Line measurement

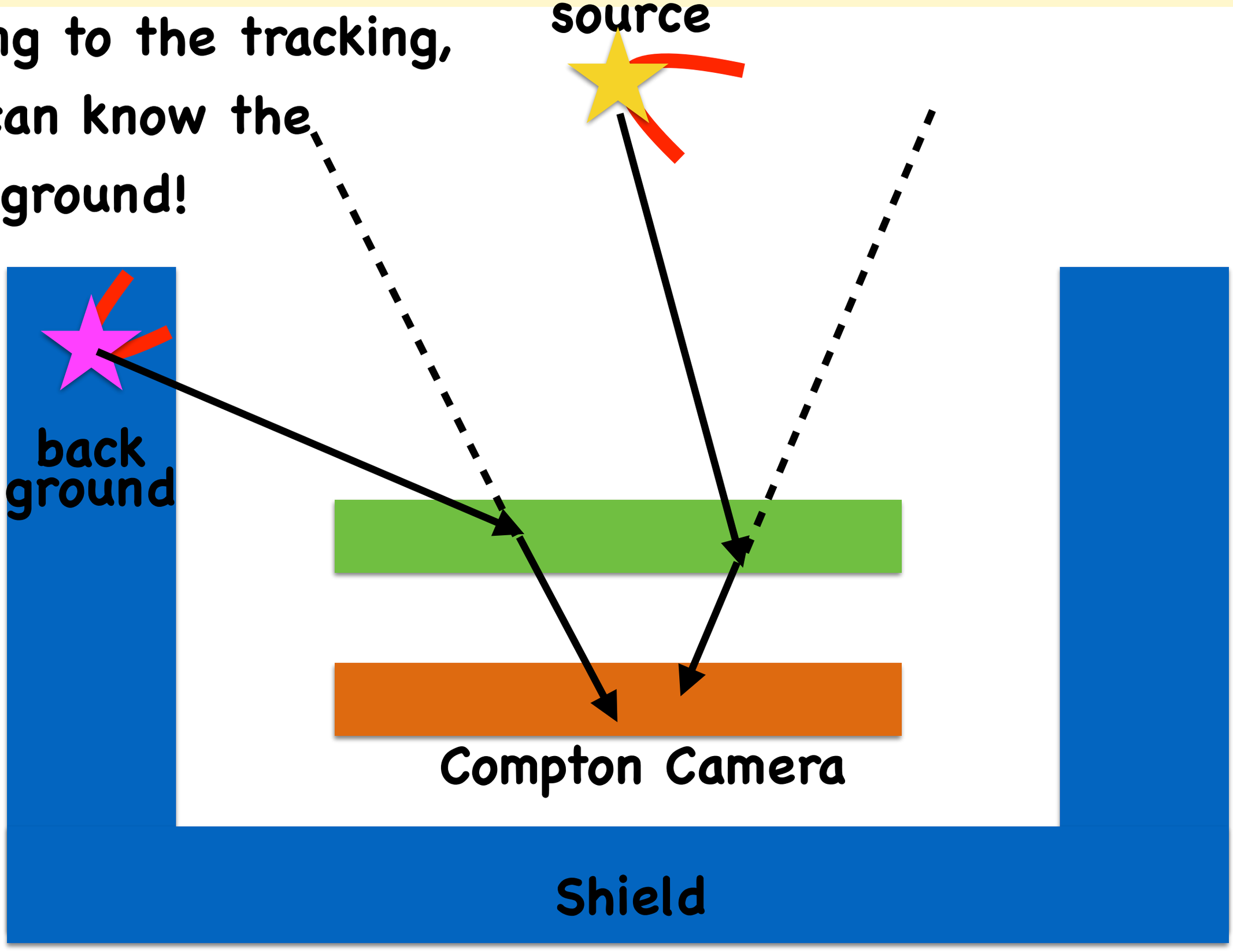
Toward Higher Sensitivity

We cannot separate this background event.



Toward Higher Sensitivity

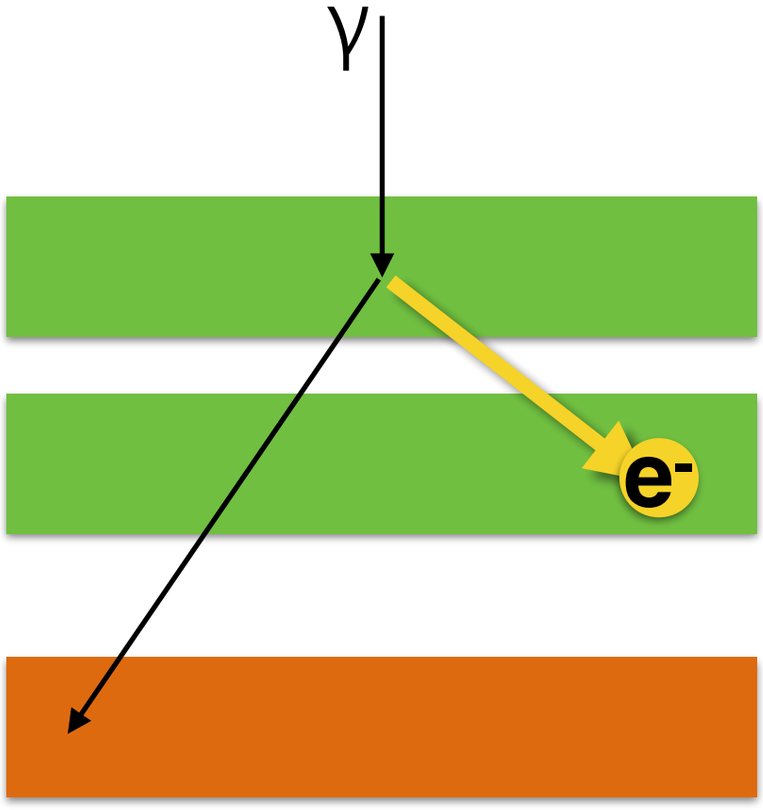
Owing to the tracking, we can know the background!



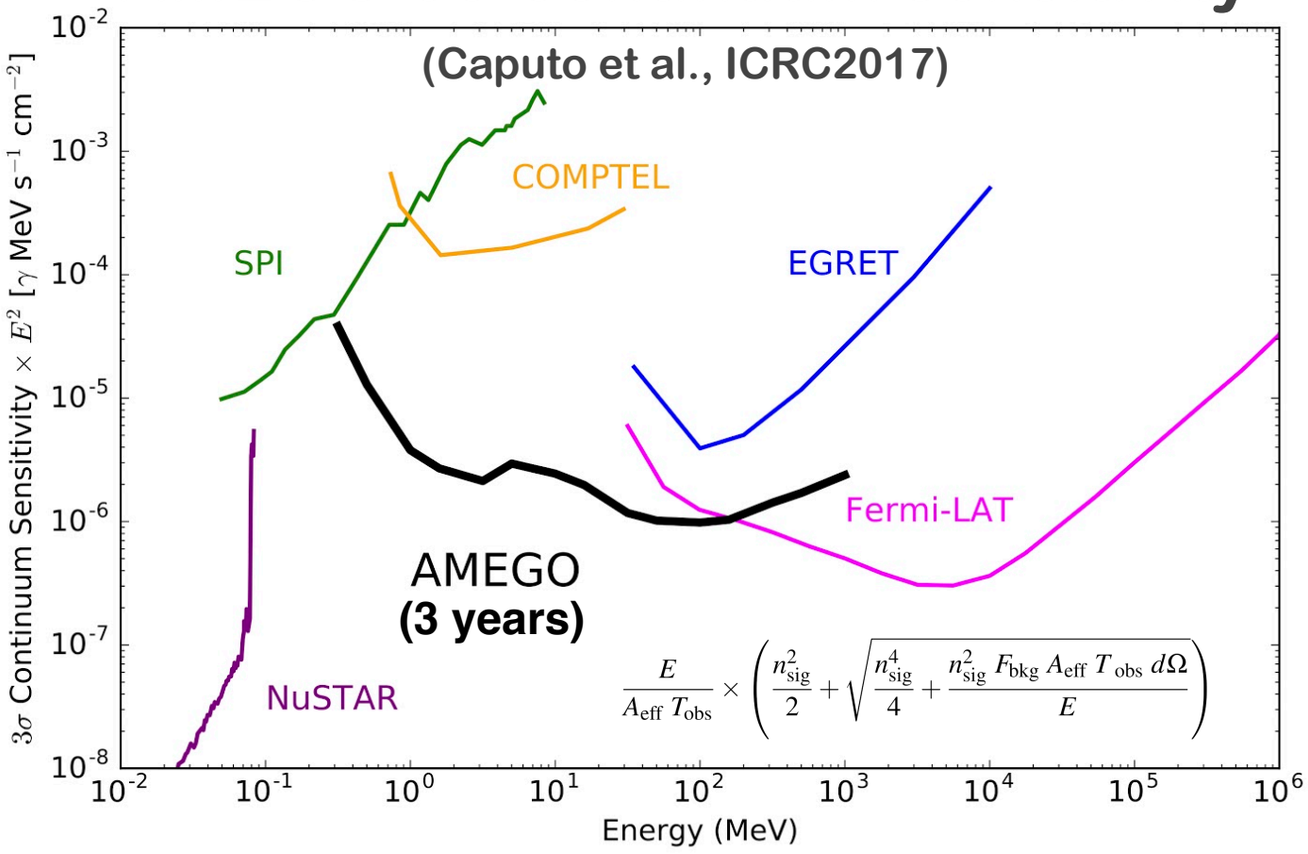
Need for Small Pixel Detector

Future missions are proposed
e.g. AMIGO, e-ASTROGAM

Electron tracking with 2 layers
(AMIGO/e-ASTROGAM)



AMEGO 3σ continuum sensitivity



Eγ = 1 MeV, scattering angle = 60 deg.

=> Ee = 500 keV

The path range of 500 keV e⁻ = ~600 μm

To improve the sensitivity < few MeV, we have to measure the electron trajectory in a single layer.

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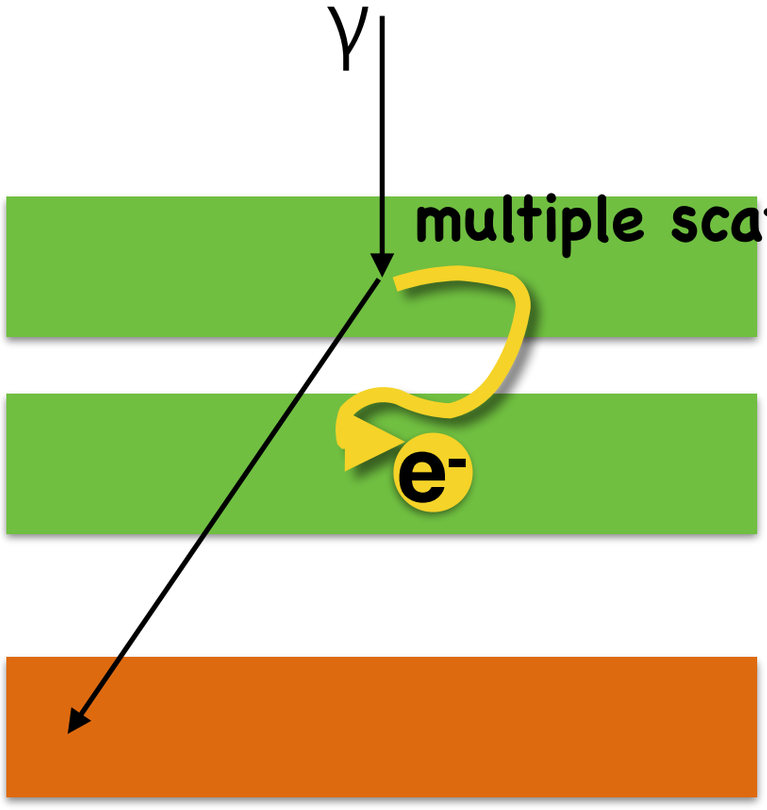

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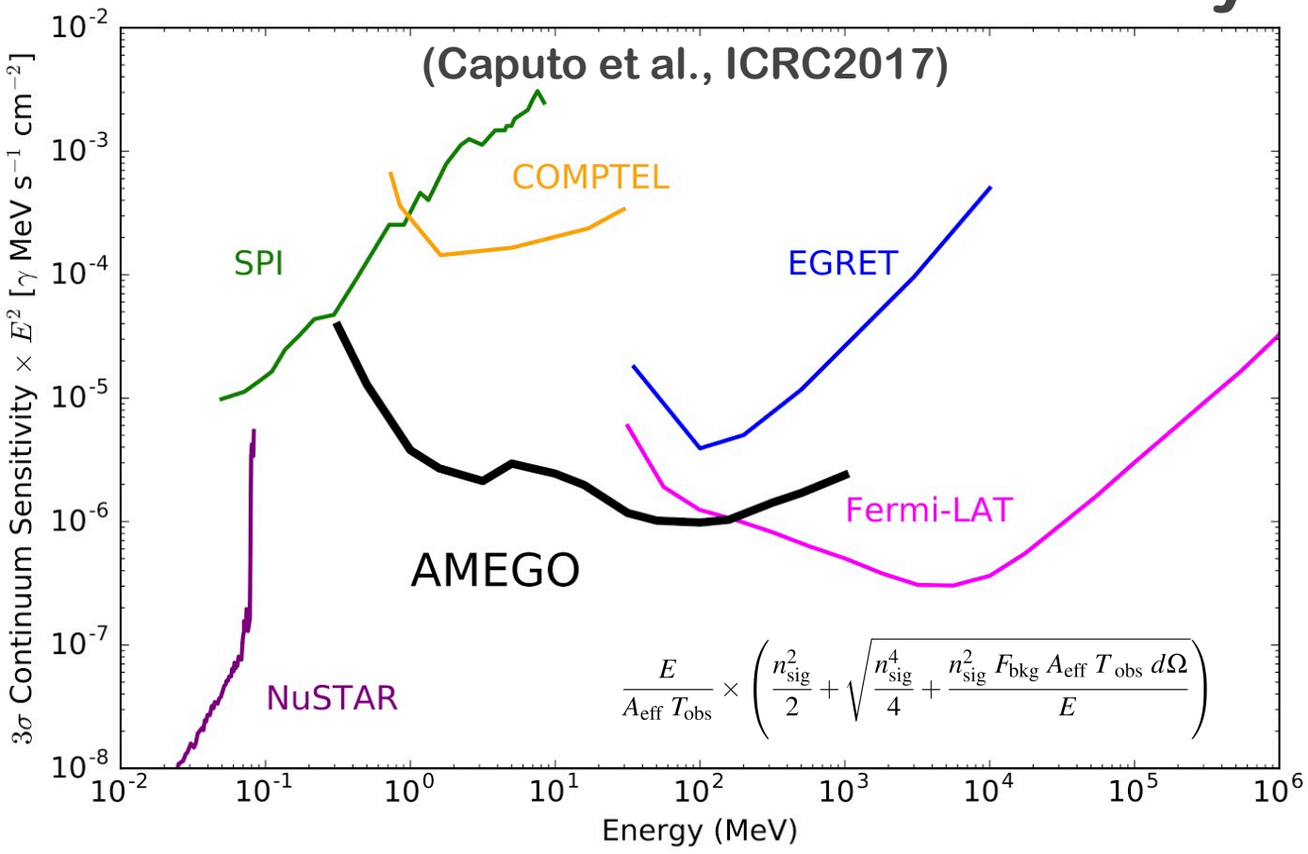

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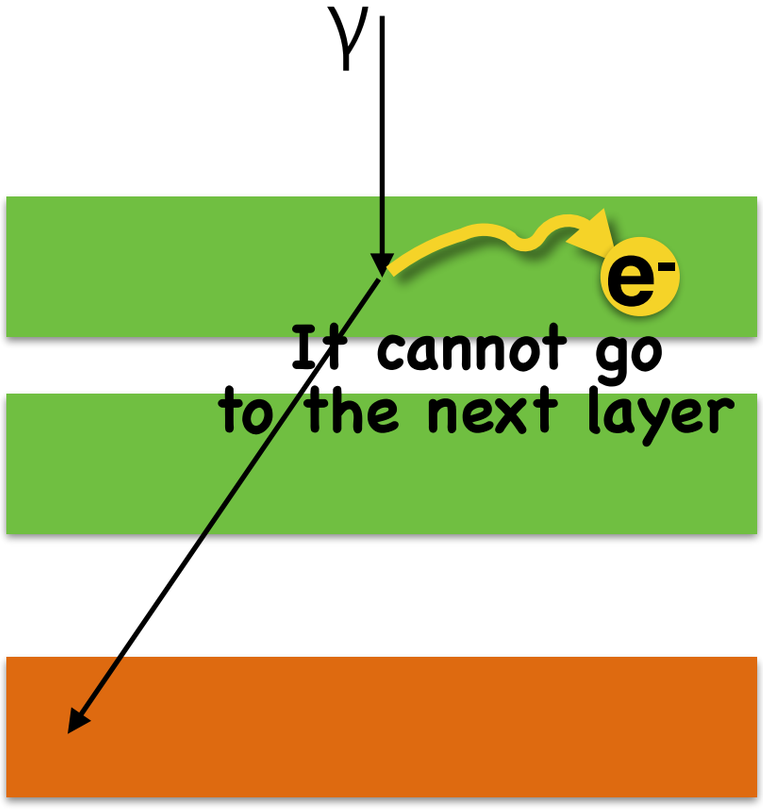

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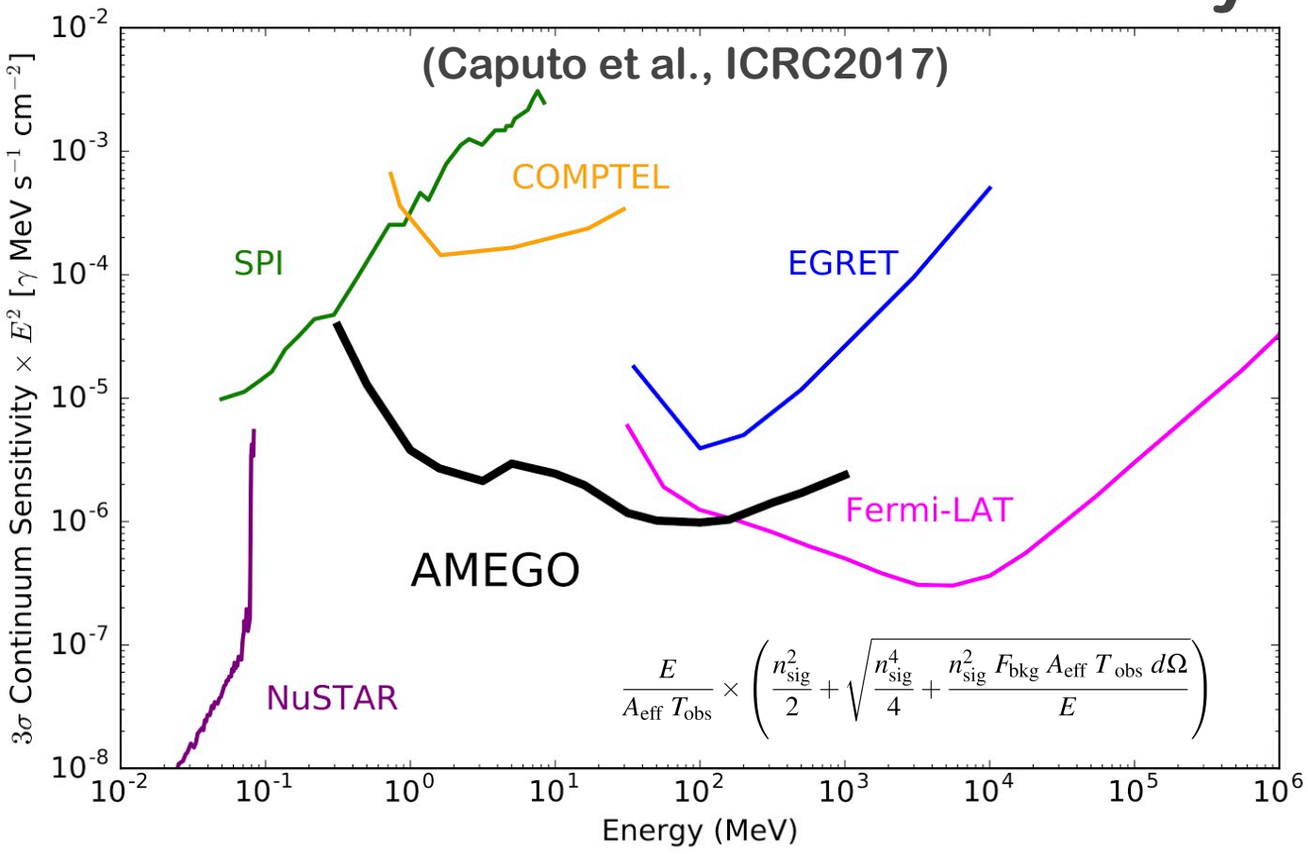

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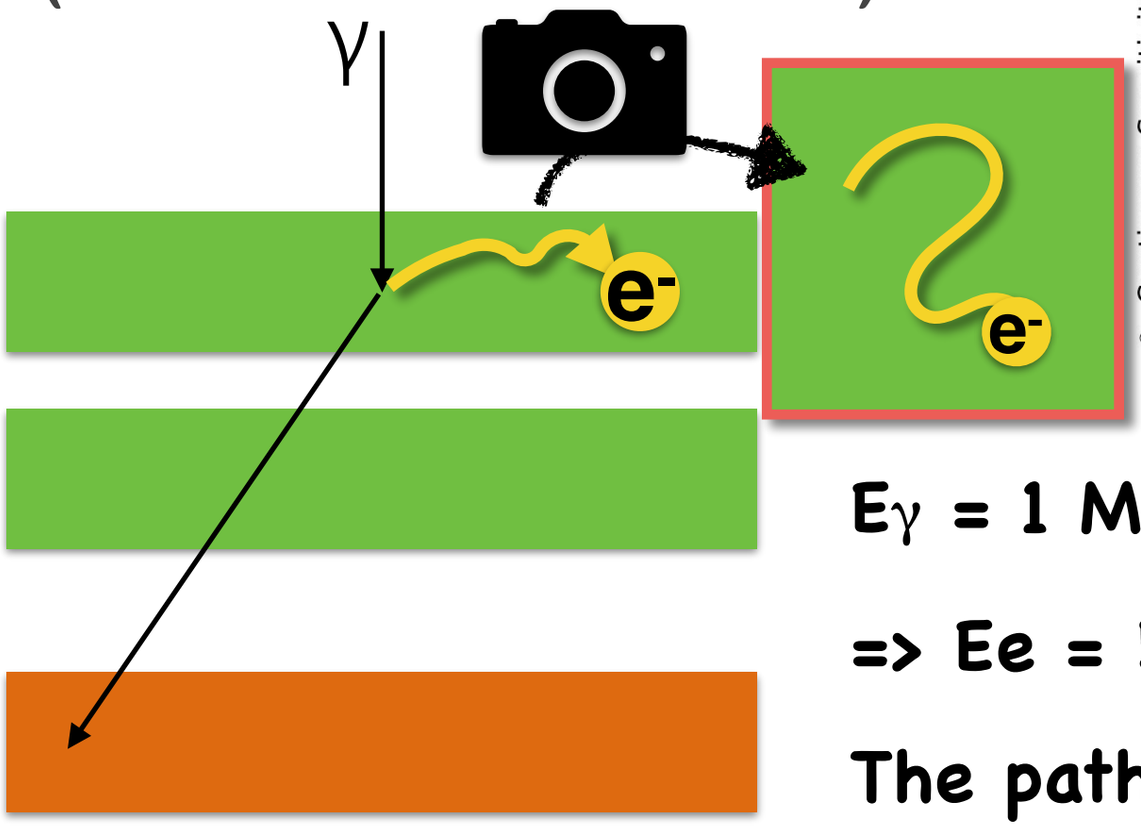

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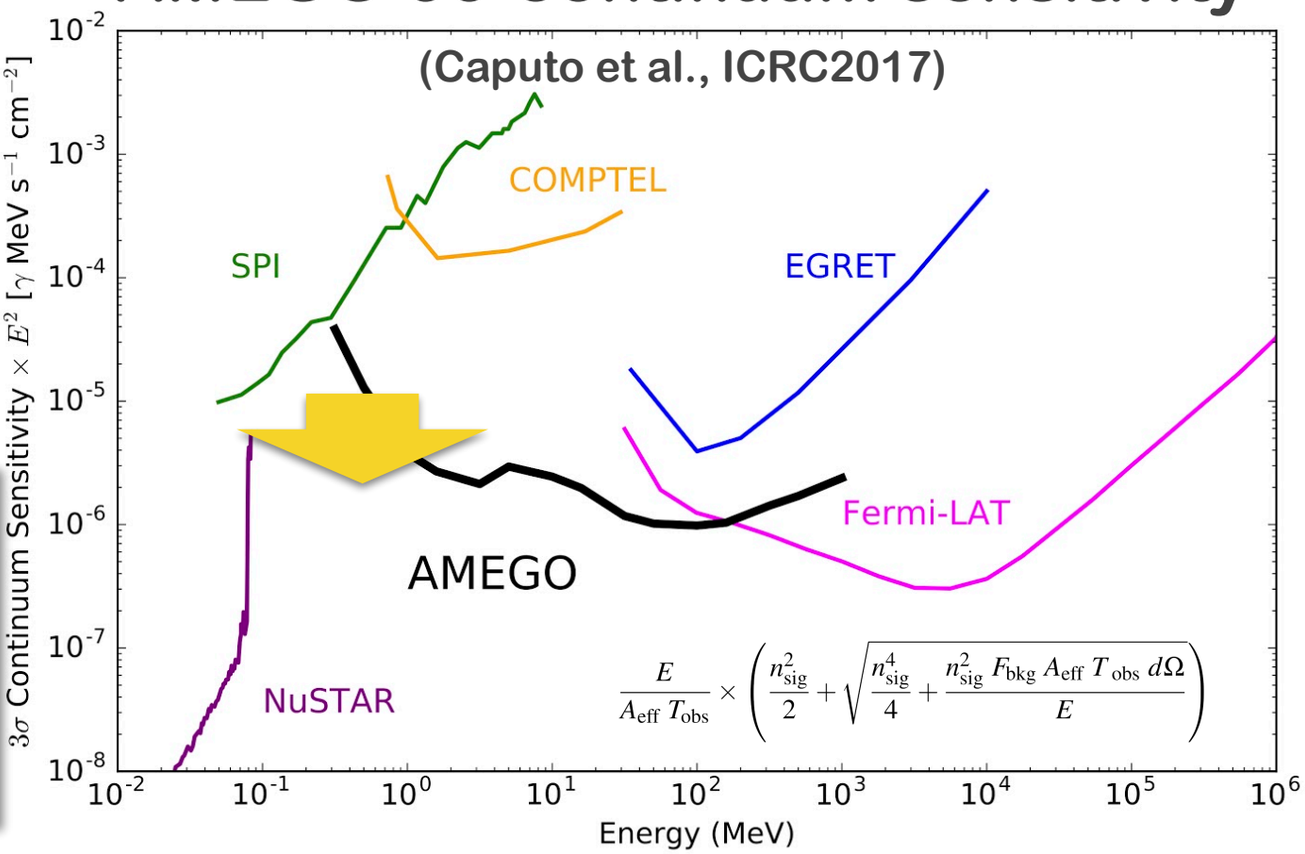

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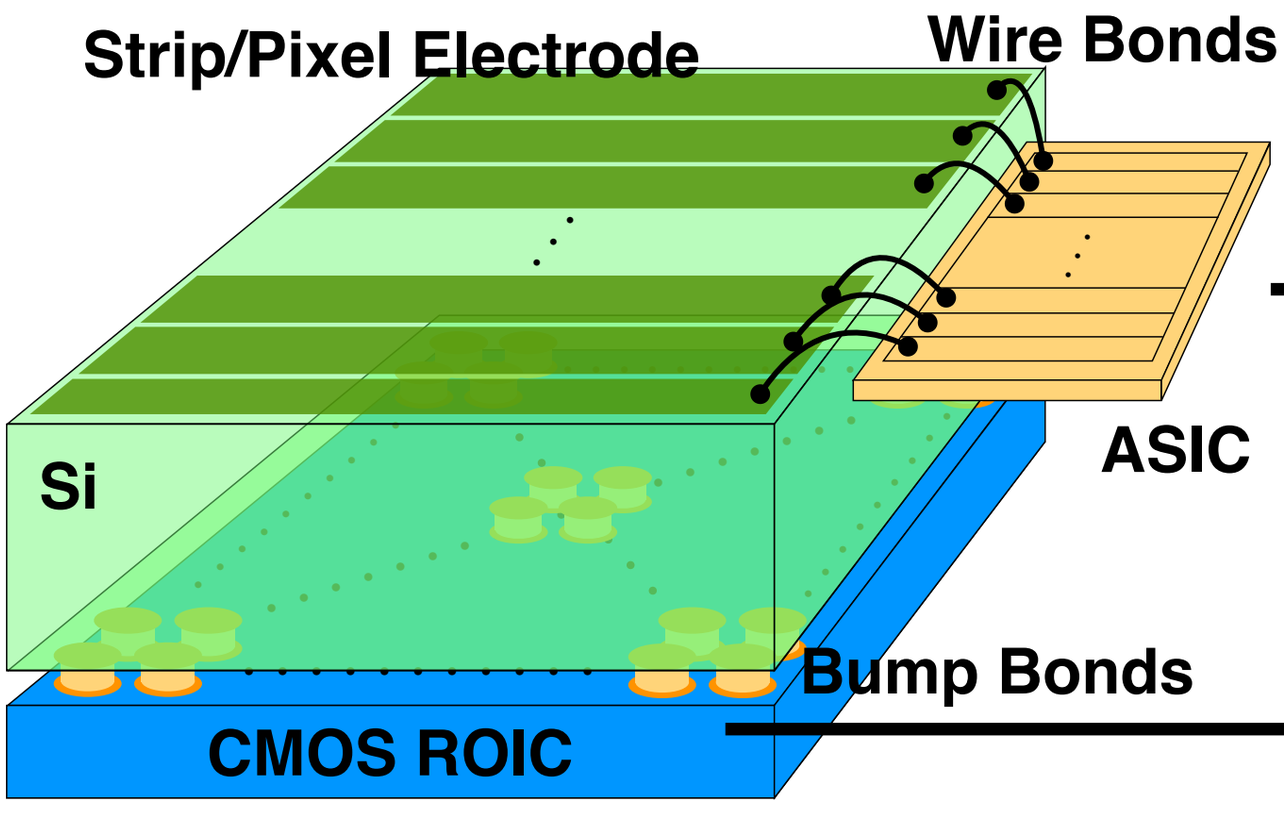
New Detector for Electron Tracking

Requirement

- **Few percents energy resolution**
- **Few us timing resolution** to determine coincident events
- **~500 um thickness of Si** (same as our previous Si detector)
- **Few 10 μm spatial resolution**

(The path range of 300 keV electron in Si is ~300 μm)

Si-CMOS hybrid detector in collaboration with **Hamamatsu Photonics** **(Yoneda et al. 2017)**

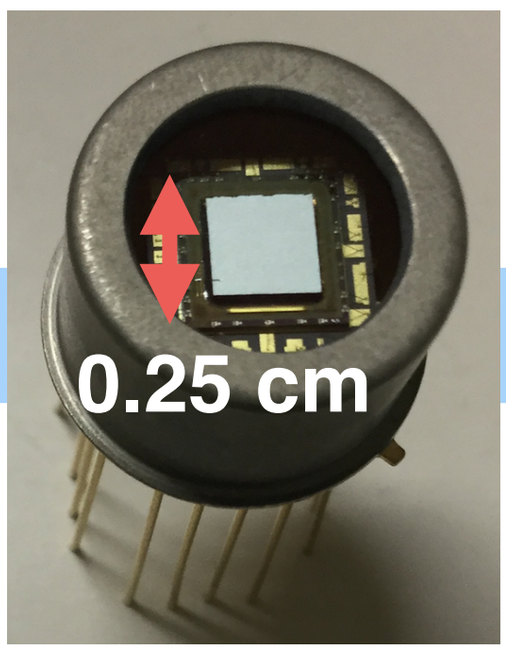


Timing Trigger & Energy

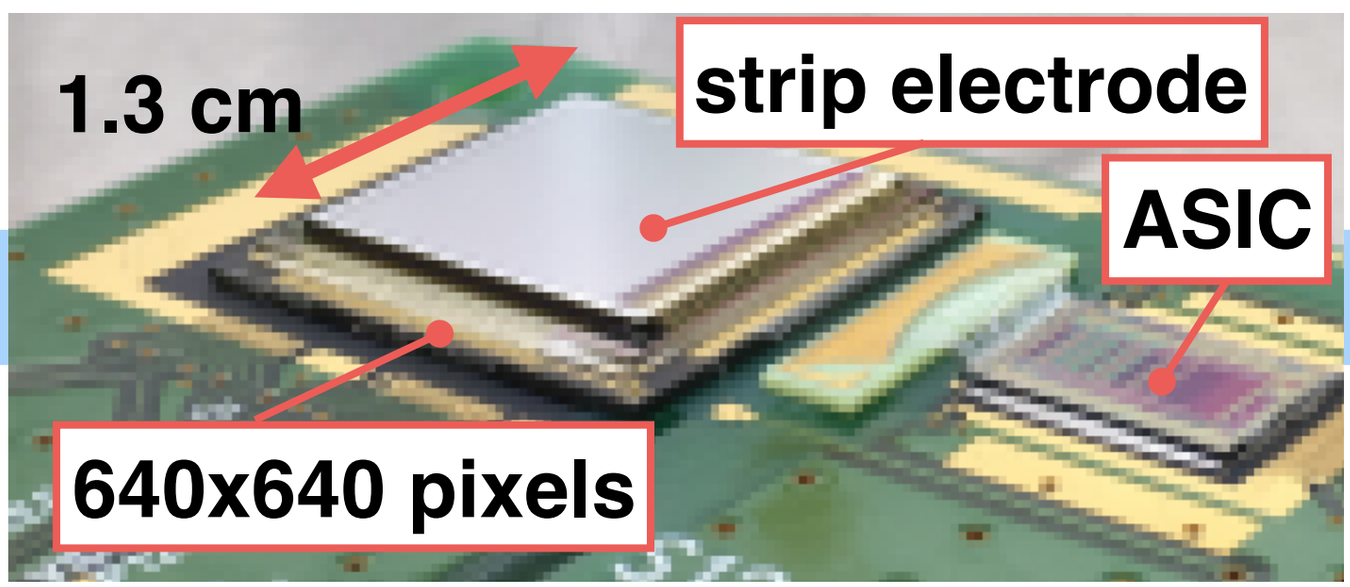
High spatial resolution Image (20x20 um pixel)

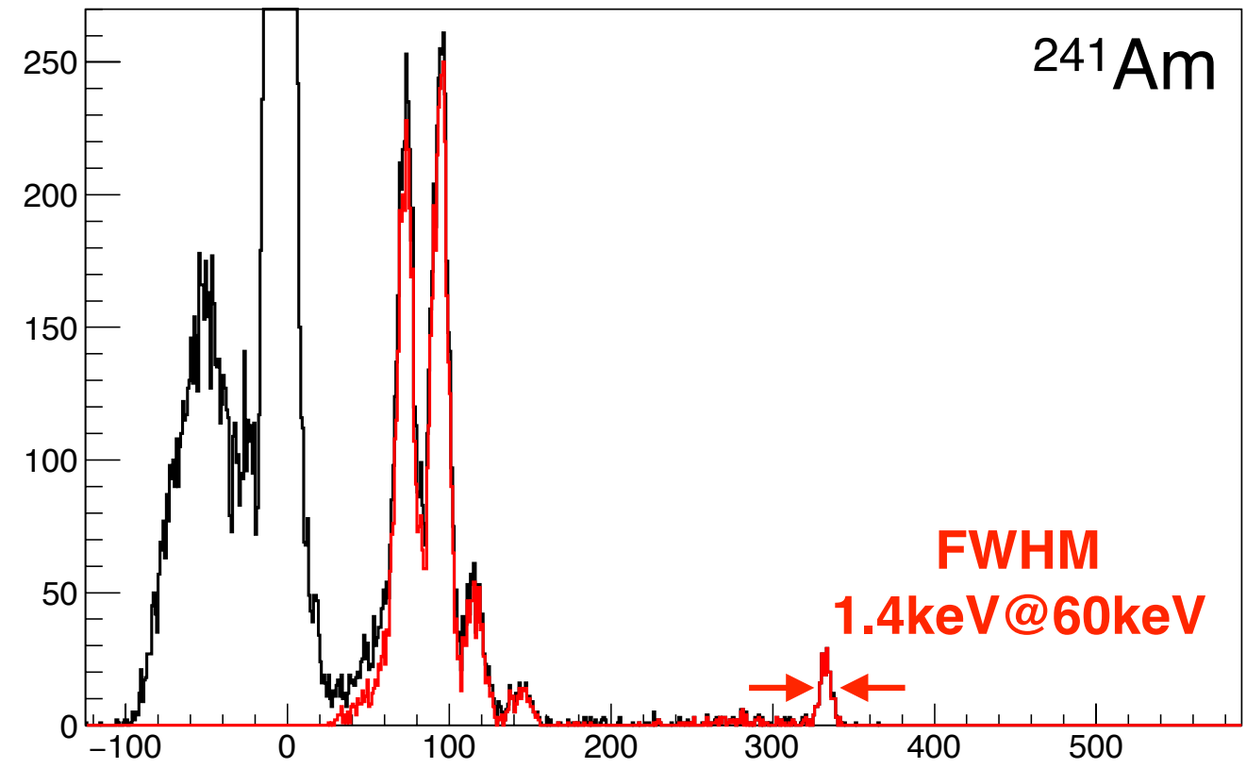
Performance of Si-CMOS detector

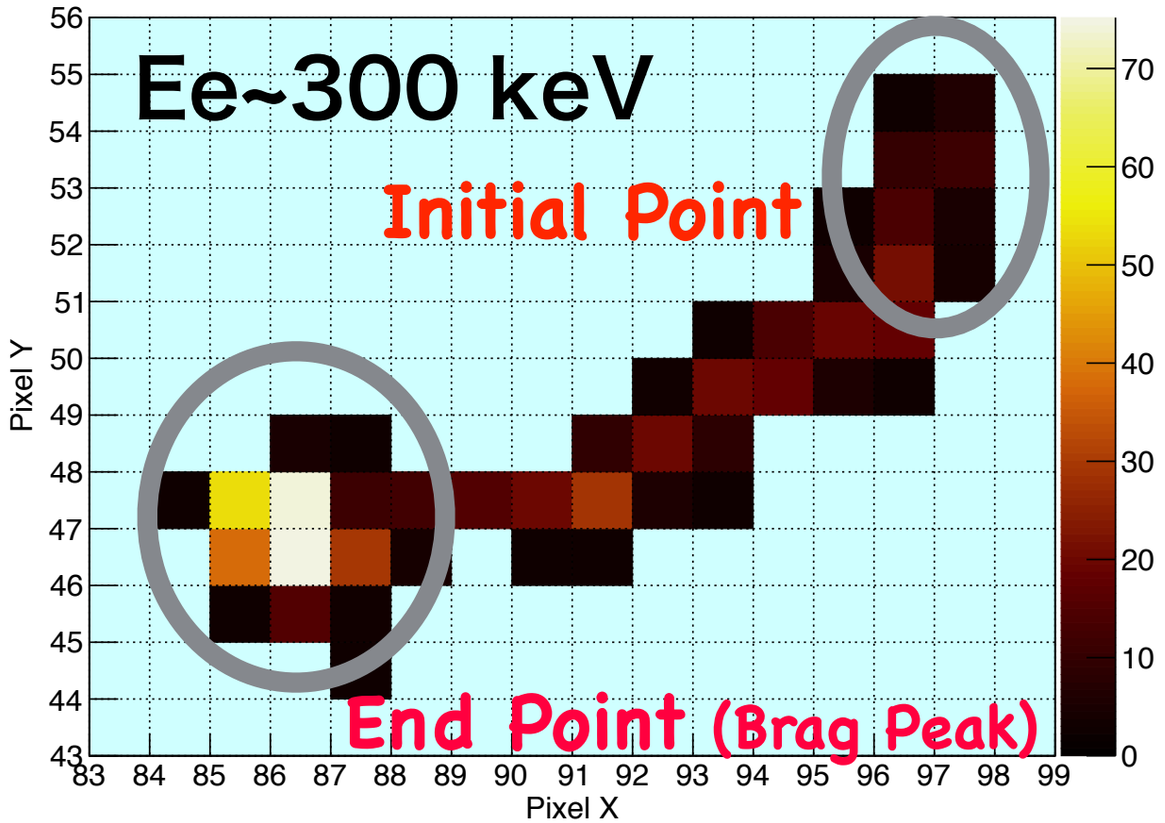
First Prototype (2014)



Second Prototype (2016)

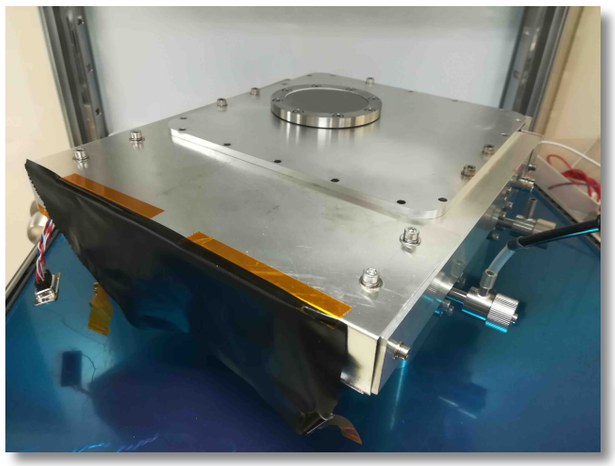


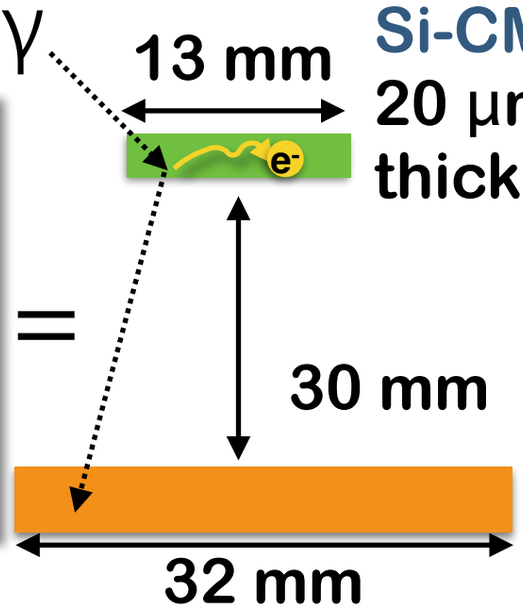




Demonstration of the concept of Si-CMOS Compton Camera

The first prototype using Si-CMOS/CdTe detector

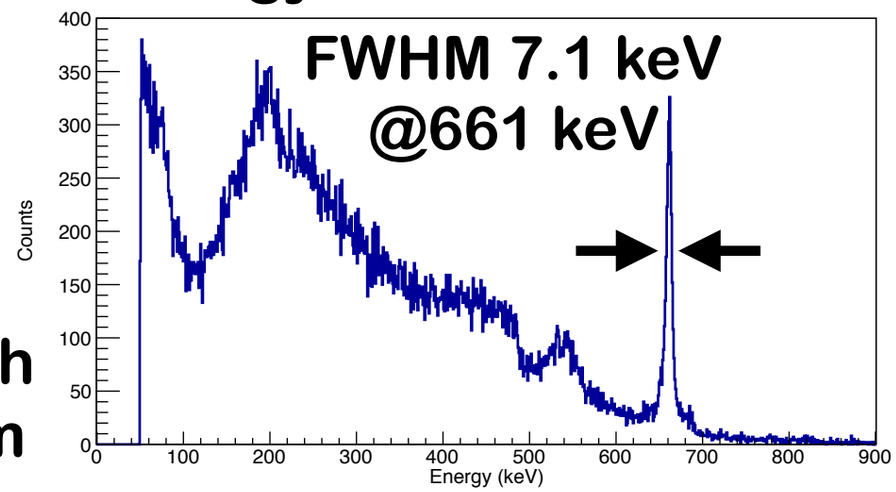




Si-CMOS detector
20 μm x 20 μm pixel
thickness of 0.5mm

CdTe-DSD
250 μm strip pitch
thickness of 2mm

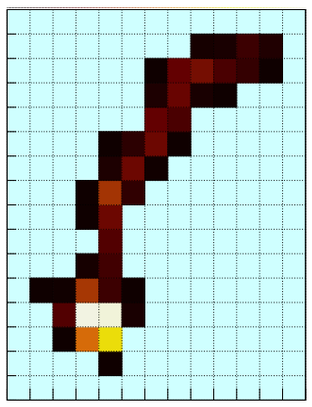
^{137}Cs spectrum
energy resolution of ~1%



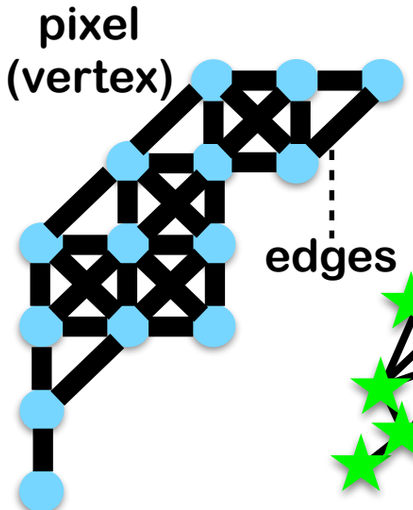
Electron Trajectory Reconstruction Algorithm

based on the graph theory approach (Yoneda et al. 2017)

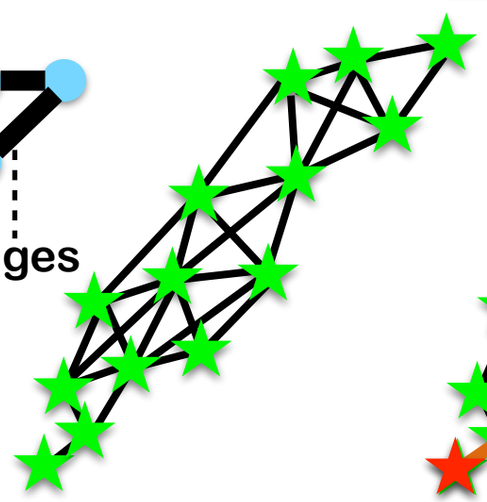
Data



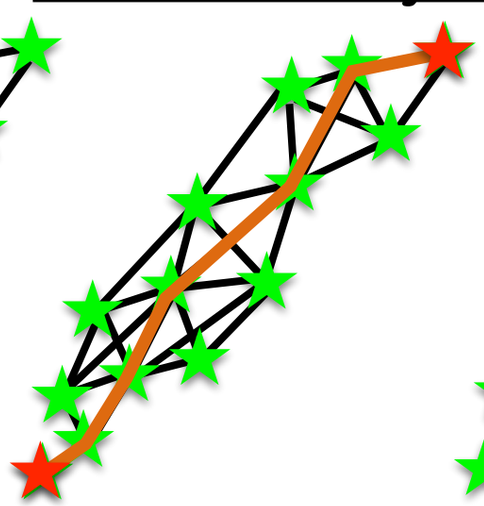
Make a Graph



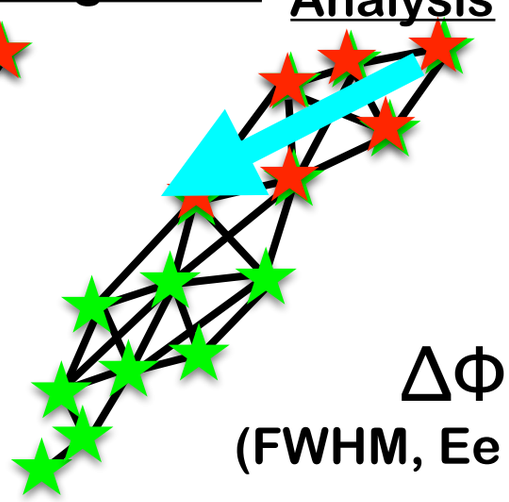
Smooth

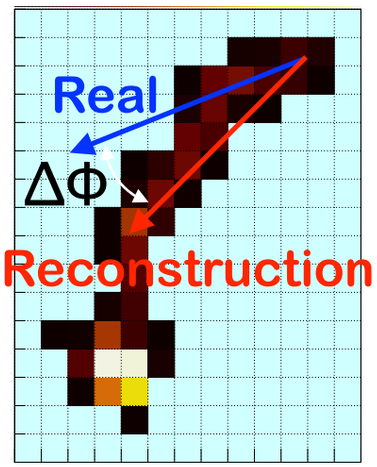


Find a longest path
w/ Warshall-Floyd algorithm



Principle Component Analysis

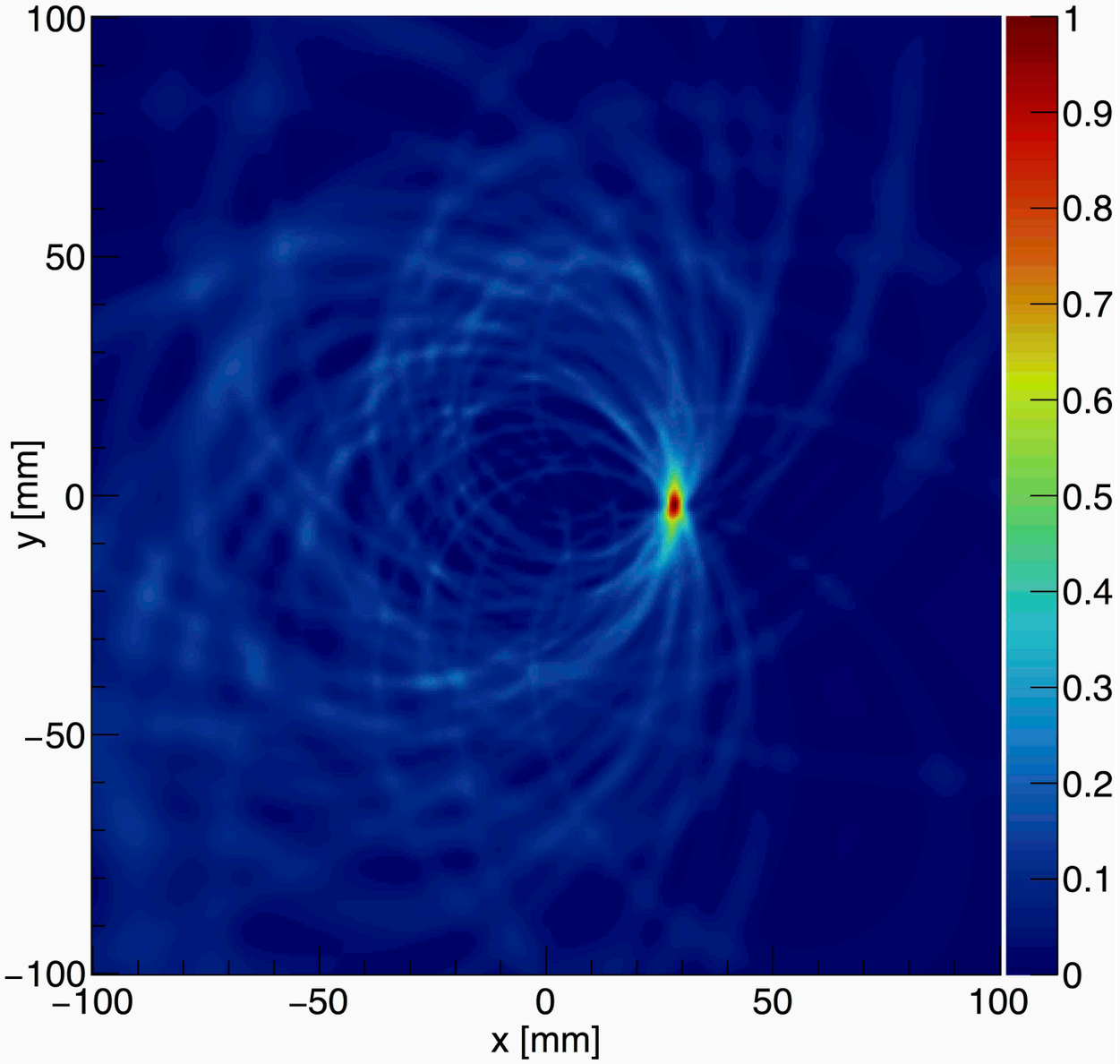




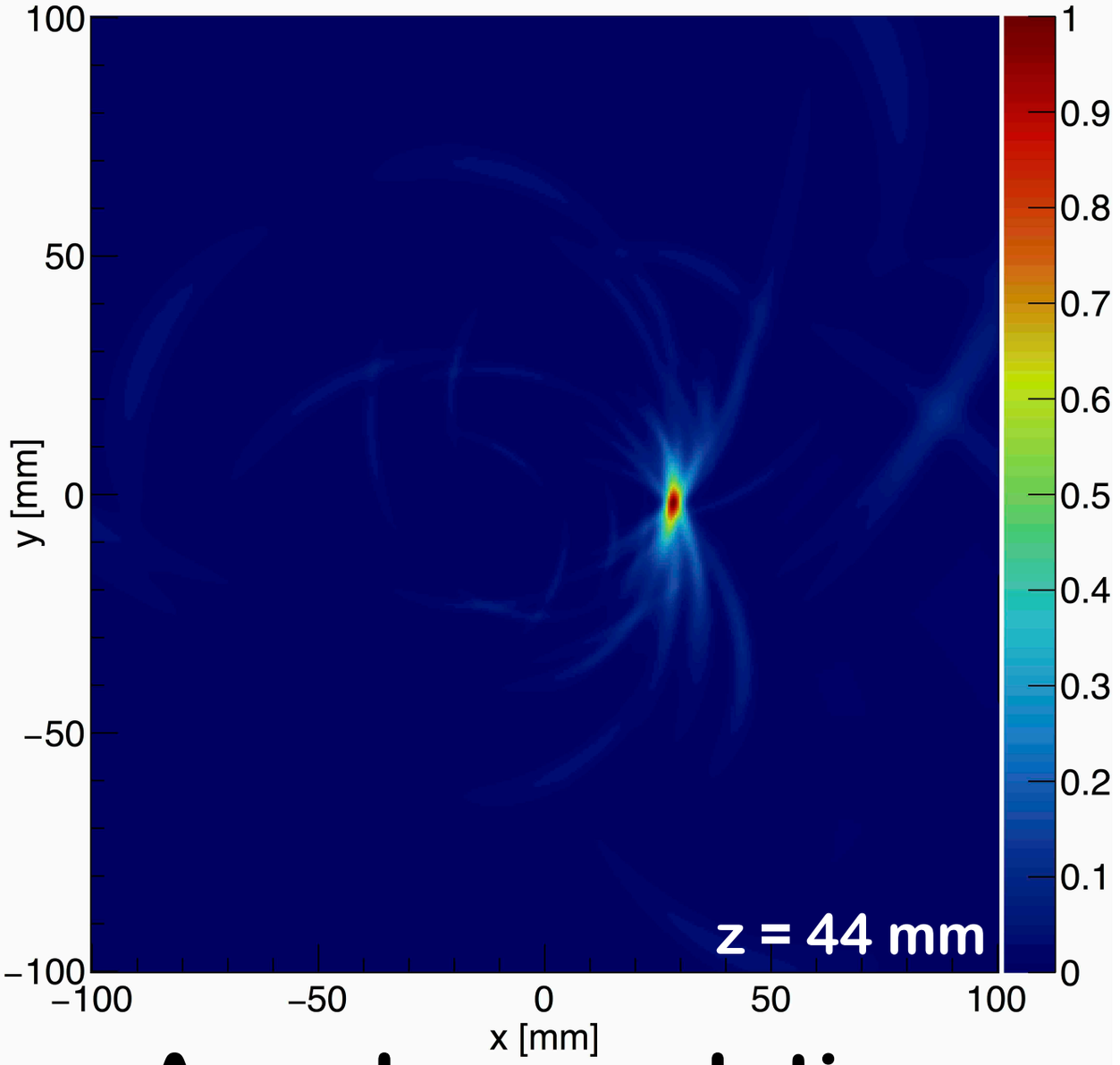
ΔΦ = 43 deg.
(FWHM, Ee = 300 ~ 500 keV, exp.)

Gamma-ray Image（1.3 MeV）

wo/ Electron Trajectory



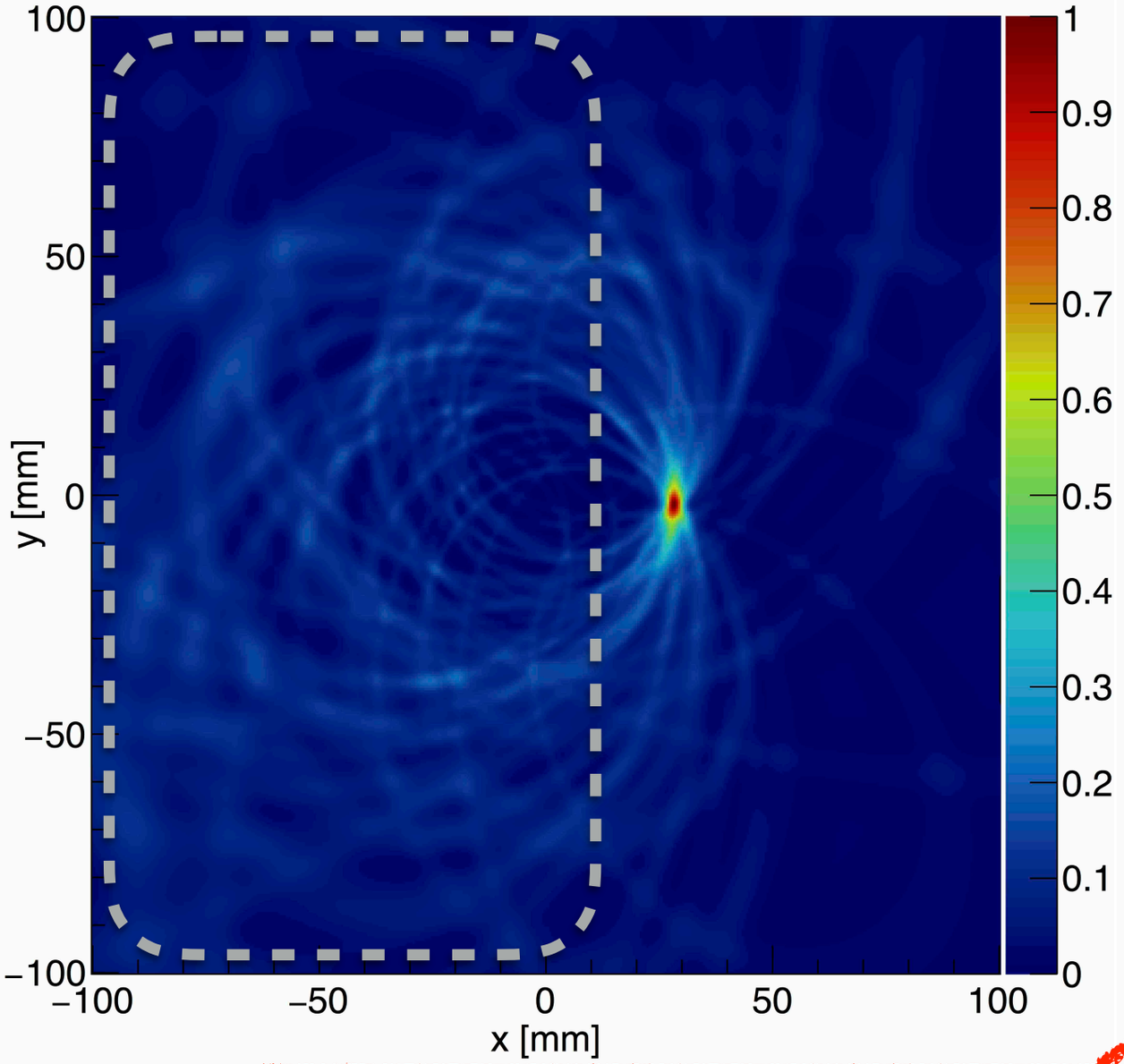
w/ Electron Trajectory



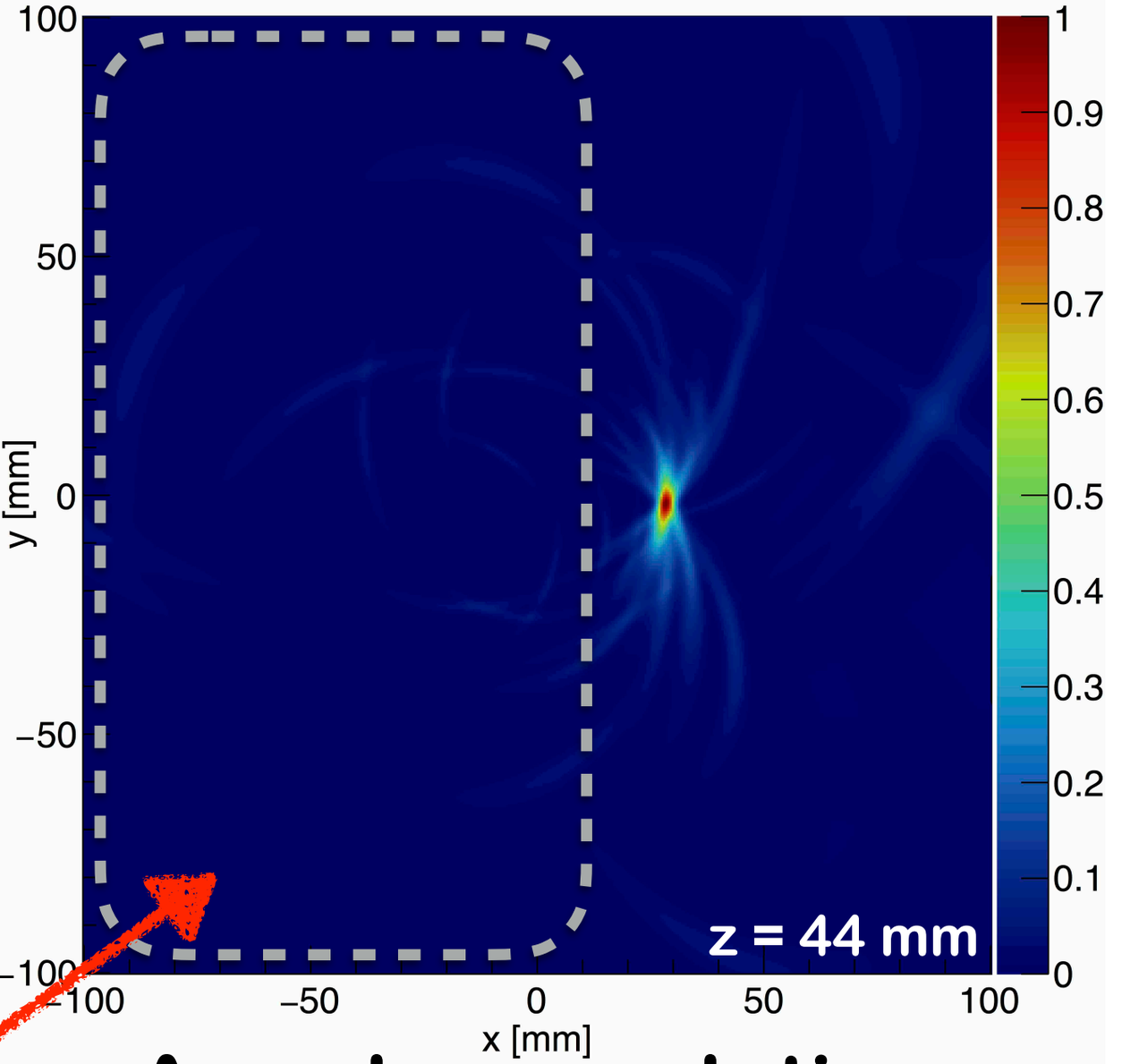
Angular resolution
= 1.75 deg. (ARM)

Gamma-ray Image（1.3 MeV）

wo/ Electron Trajectory



w/ Electron Trajectory



Offset Component is removed!

Angular resolution = 1.75 deg. (ARM)

Conclusion

- Gamma rays between 100 keV to a few tens of MeV have fruitful information i.e. nuclear gamma ray lines.
- To improve the sensitivity of the low MeV range, to “Track the Electron Trajectory” is the key technique.
- Si-CMOS hybrid detector is developed to measure the electron trajectory in a single layer.
- We showed the improved Compton image with the prototype Compton camera and the algorithm to reconstruct electron trajectories.
- The resulting angular resolution and energy resolution are 1.75 degrees and the order of 1%, respectively, for 1.3 MeV.

Future Works

- **Improve Si-CMOS hybrid detectors**
  larger size, data size reduction, smaller pixel size, lower noise
- **Develop a better electron trajectory reconstruction algorithm**
  deep learning (Geant4 + tensorflow)
- **Science Projects???**
  A balloon experiment? A small satellite?