New Mission Concept:
Investigation of the Galactic Center with
Galactic**Cen**ter**Ex**plorer **(GalCenEx)**

Alexander Moiseev
NASA/GSFC and University of Maryland, College Park

With thanks to Isabelle Grenier, David Thompson, Eugenio Bottacini , Igor Moskalenko, Elena Orlando, Aleksey Bolotnikov and AMEGO team for suggestions, interest and support

I am very excited to be here. Your comments will be critical for the fate of this project

I am very excited to be here. Your comments will be critical for the fate of this project

It is Prince Hamlet of Denmark, not Alex

It is Yorick, not GalCenEx

I am very excited to be here. Your comments will be critical for the fate of this project

TO BE OR NOT TO BE …

Motivation for the mission

- Several long-standing problems in high-energy astrophysics such as a fine structure of inner Galaxy in γ-rays, including Galactic Center and other heavy populated sky regions, nature of 511 keV γ-radiation are limited by angular (wanted to be a fraction of a degree and better) and energy resolution of the instrument.

Motivation for the mission

- Several long-standing problems in high-energy astrophysics such as a fine structure of inner Galaxy in γ-rays, including Galactic Center and other heavy populated sky regions, nature of 511 keV γ-radiation are limited by angular (wanted to be a fraction of a degree and better) and energy resolution of the instrument.
- **Angular resolution in photon energy range in 0.1-100 MeV is much complicated by competing processes of photon interaction, Compton scattering and pair production. Reconstruction of both kind of events is difficult due to several factors such as tracking of Compton electron, large multiple scattering at low energy, etc. Even if an event pattern is accurately reconstructed, angular resolution is limited by Doppler widening for Compton events or by a momentum of recoil nucleus for pair production. So, even 1 degree of angular resolution is extremely difficult to achieve in direct photon detection.**

Motivation for the mission

- Several long-standing problems in high-energy astrophysics such as a fine structure of inner Galaxy in γ-rays, including Galactic Center and other heavy populated sky regions, nature of 511 keV γ-radiation are limited by angular (wanted to be a fraction of a degree and better) and energy resolution of the instrument.
- Angular resolution in photon energy range in 0.1-100 MeV is much complicated by competing processes of photon interaction, Compton scattering and pair production. Reconstruction of both kind of events is difficult due to several factors such as tracking of Compton electron, large multiple scattering at low energy, etc. Even if an event pattern is accurately reconstructed, angular resolution is limited by Doppler widening for Compton events or by a momentum of recoil nucleus for pair production. So, even 1 degree of angular resolution is extremely difficult to achieve in direct photon detection.
- **Usage of Coded Aperture Mask (with its known downsides) is probably the only feasible way to provide an arcmin-level of position resolution in this energy range of photons. I wish Gerry Skinner were here with us!**

Motivation for the mission

- Several long-standing problems in high-energy astrophysics such as a fine structure of inner Galaxy in γ-rays, including Galactic Center and other heavy populated sky regions, nature of 511 keV γ-radiation are limited by angular (wanted to be a fraction of a degree and better) and energy resolution of the instrument.
- Angular resolution in photon energy range in 0.1-100 MeV is much complicated by competing processes of photon interaction, Compton scattering and pair production. Reconstruction of both kind of events is difficult due to several factors such as tracking of Compton electron, large multiple scattering at low energy, etc. Even if an event pattern is accurately reconstructed, angular resolution is limited by Doppler widening for Compton events or by a momentum of recoil nucleus for pair production. So, even 1 degree of angular resolution is extremely difficult to achieve in direct photon detection.
- Usage of Coded Aperture Mask (with its known downsides) is probably the only feasible way to provide an arcmin-level of position resolution in this energy range of photons. I wish Gerry Skinner were with us!
- **Currently being developed CZT calorimeter (to be used in AMEGO), based on the novel Frisch-grid bar CZT detectors (A. Bolotnikov et al.), represents a unique opportunity to develop a feasible instrument capable to conduct all these measurements in combination with Coded Aperture Mask. This detector provides a fraction of mm position resolution along with <1% energy resolution at 1 MeV.**

Science Objectives and Scientific Deliverables for the Mission

- **Understanding of the nature of the Galactic Center and other heavily populated sky regions such as Cygnus and Carina, including a structure of 511 keV positron annihilation line, by creating the high-resolution spectral (dE/E<1%) and intensity (angular resolution <10’) map of the surrounding regions for the photon energy 0.1 – 10 MeV**

Science Objectives and Scientific Deliverables for the Mission

- Understanding of the nature of the Galactic Center and other heavily populated sky regions such as Cygnus and Carina, including a structure of 511 keV positron annihilation line, by creating the high-resolution spectral (dE/E<1%) and intensity (angular resolution <10’) map of the surrounding regions for the photon energy 0.1 – 10 MeV

- **Explore Galactic chemical evolution and sites of explosive element synthesis by conducting high-sensitivity measurements of nuclear lines from Super-novae 1A and from other objects ($<10^{-5}$ ph cm^{-2} s^{-1})**

Science Objectives and Scientific Deliverables for the Mission

- Understanding of the nature of the Galactic Center and other heavily populated sky regions such as Cygnus and Carina, including a structure of 511 keV positron annihilation line, by creating the high-resolution spectral (dE/E<1%) and intensity (angular resolution <10’) map of the surrounding regions for the photon energy 0.1 – 10 MeV
- Explore Galactic chemical evolution and sites of explosive element synthesis by conducting high-sensitivity measurements of nuclear lines from Super-novae 1A and from other objects ($<10^{-5}$ ph cm^{-2} s^{-1})
- **Provide measurement of polarization**

Science Objectives and Scientific Deliverables for the Mission

- Understanding of the nature of the Galactic Center and other heavily populated sky regions such as Cygnus and Carina, including a structure of 511 keV positron annihilation line, by creating the high-resolution spectral (dE/E<1%) and intensity (angular resolution <10’) map of the surrounding regions for the photon energy 0.1 – 10 MeV

- Explore Galactic chemical evolution and sites of explosive element synthesis by conducting high-sensitivity measurements of nuclear lines from Super-novae 1A and from other objects ($<10^{-5}$ ph cm^{-2} s^{-1})

- Provide measurement of polarization

- **Precise localization and measurement of the spectrum for GRB (including that associated with GW events); measurement of polarization for the bright bursts**

Instrument design constrains:

- **High sensitivity**
- **High angular resolution**

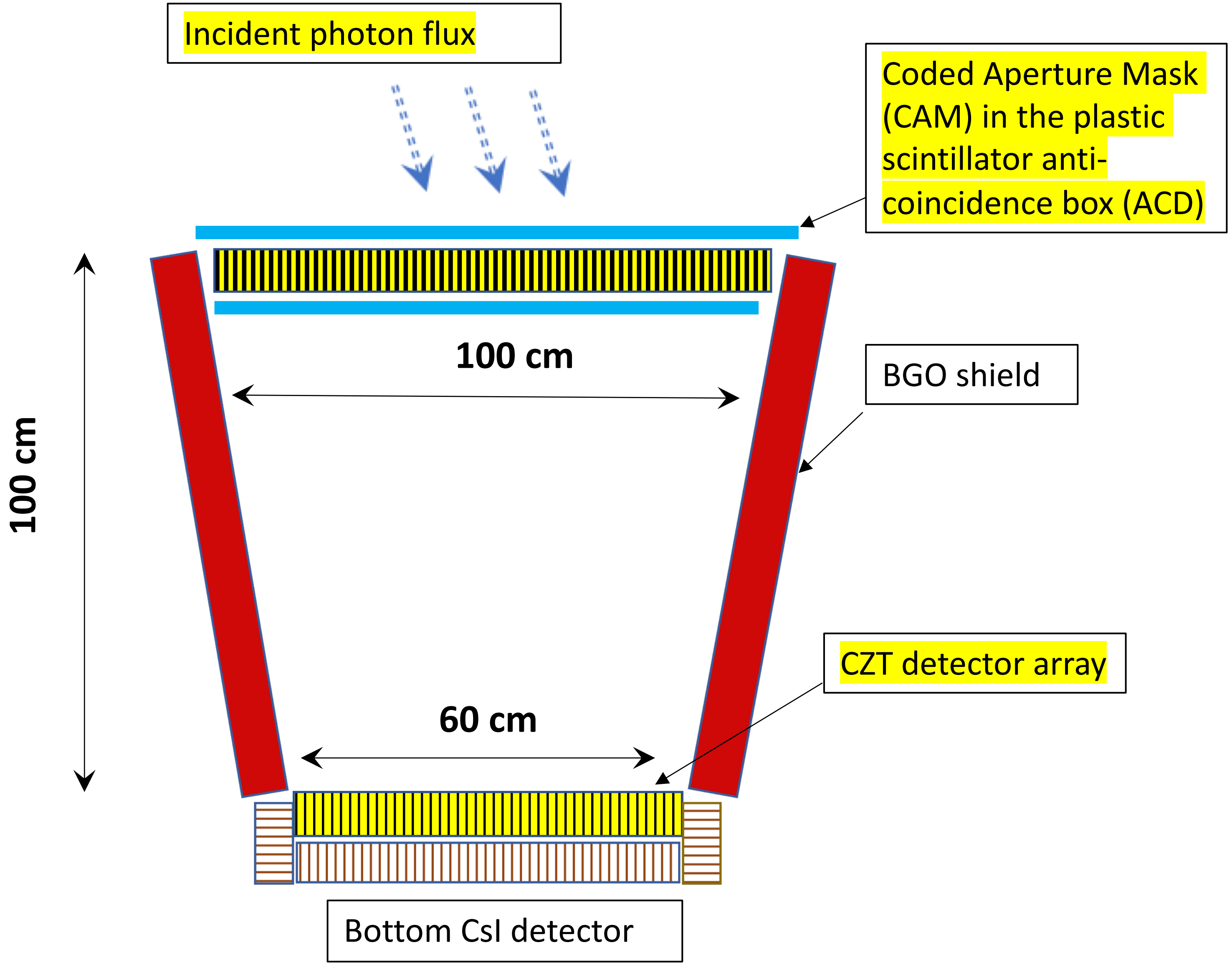
Source sensitivity

$$I_{src} = \frac{1}{A \times T} \times \left[\frac{n_\sigma^2}{2} + \sqrt{\frac{n_\sigma^4}{4} + \frac{n_\sigma^2 \times B_{bckg} \times A \times T \times \Delta\Omega}{E}} \right]$$

We will be designing the instrument with:

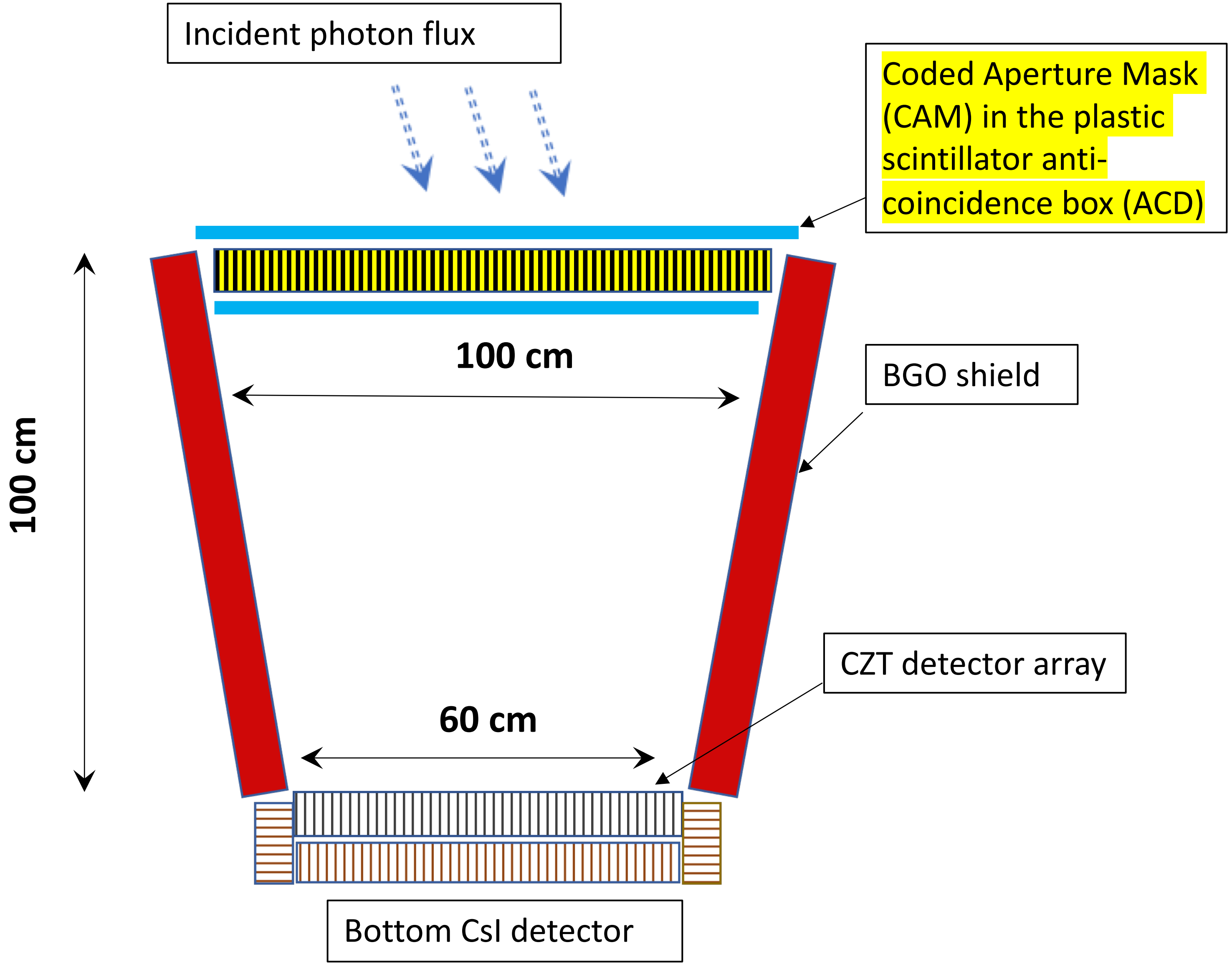
- **assessing and minimizing the effect of all known backgrounds → to increase a sensitivity**
- **Improving angular resolution → to increase a sensitivity and to provide source localization and resolution**

GalCenEx: Baseline Instrument Concept



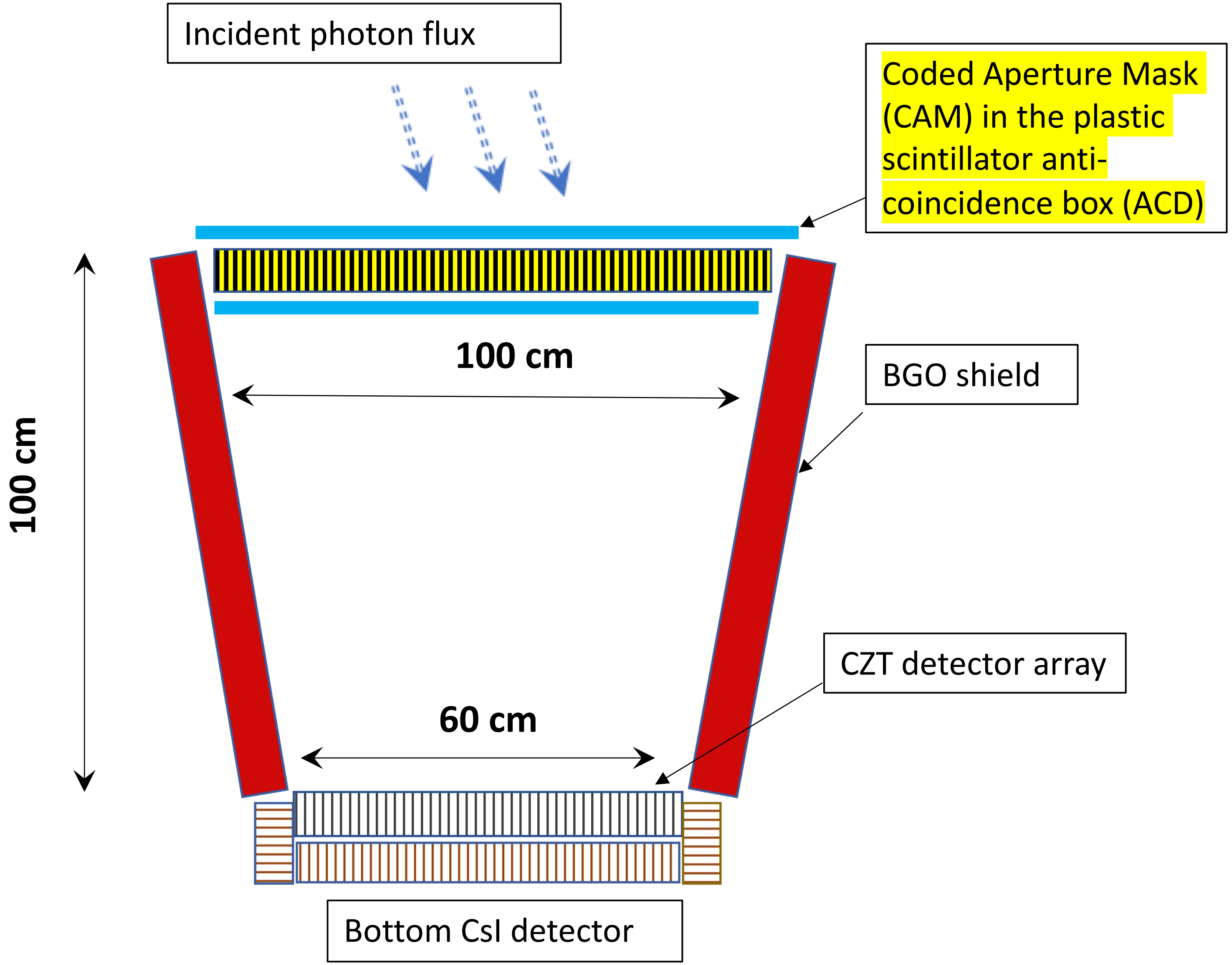
- **GOAL: "Background-free" instrument**
- **Incident photon flux is modulated while passing through the CAM and creates an image on the CdZnTe detector plane. The image is then reconstructed**

GalCenEx: Baseline Instrument Concept



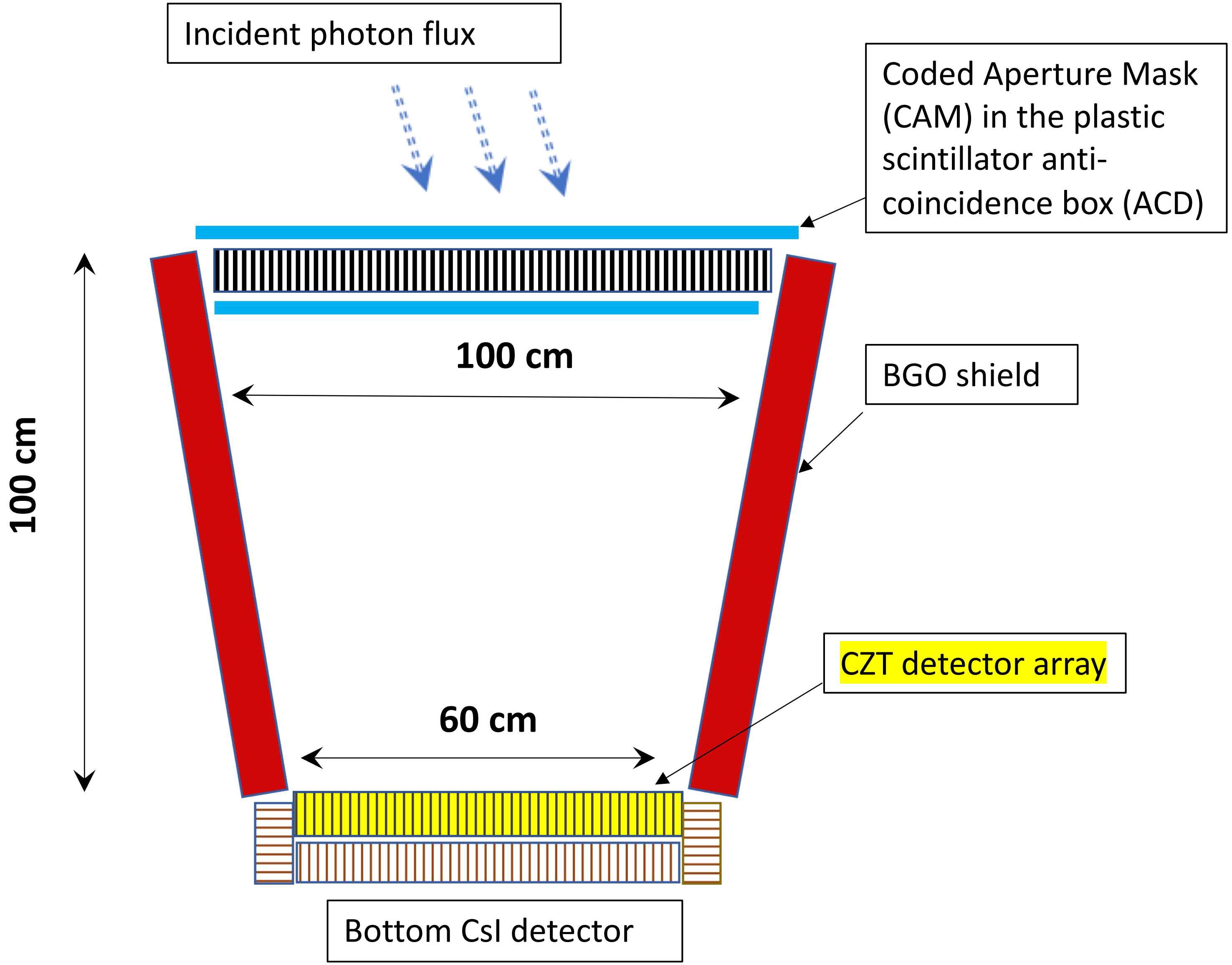
- **GOAL: "Background-free" instrument**
- Incident photon flux is modulated while passing through the CAM and creates an image on the CdZnTe detector plane. The image is then reconstructed
- **CAM also works as ~20^0 (0.1 sr) FoV passive collimator**

GalCenEx: Baseline Instrument Concept



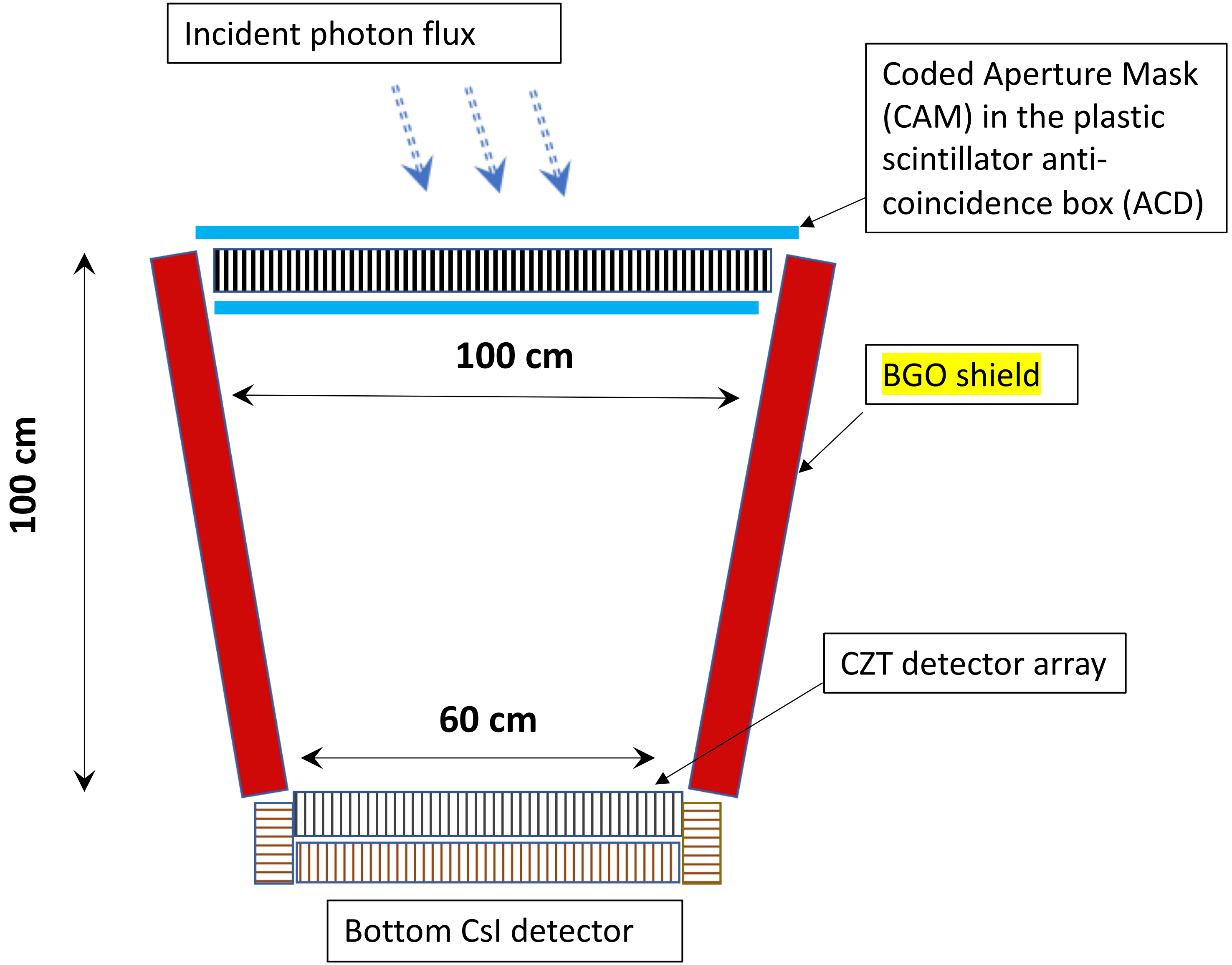
- **GOAL: "Background-free" instrument**
- Incident photon flux is modulated while passing through the CAM and creates an image on the CdZnTe detector plane. The image is then reconstructed
- CAM also works as ~20^0 (0.1 sr) FoV passive collimator
- **CAM is surrounded by ACD to veto the background photons produced in CAM by cosmic rays**

GalCenEx: Baseline Instrument Concept



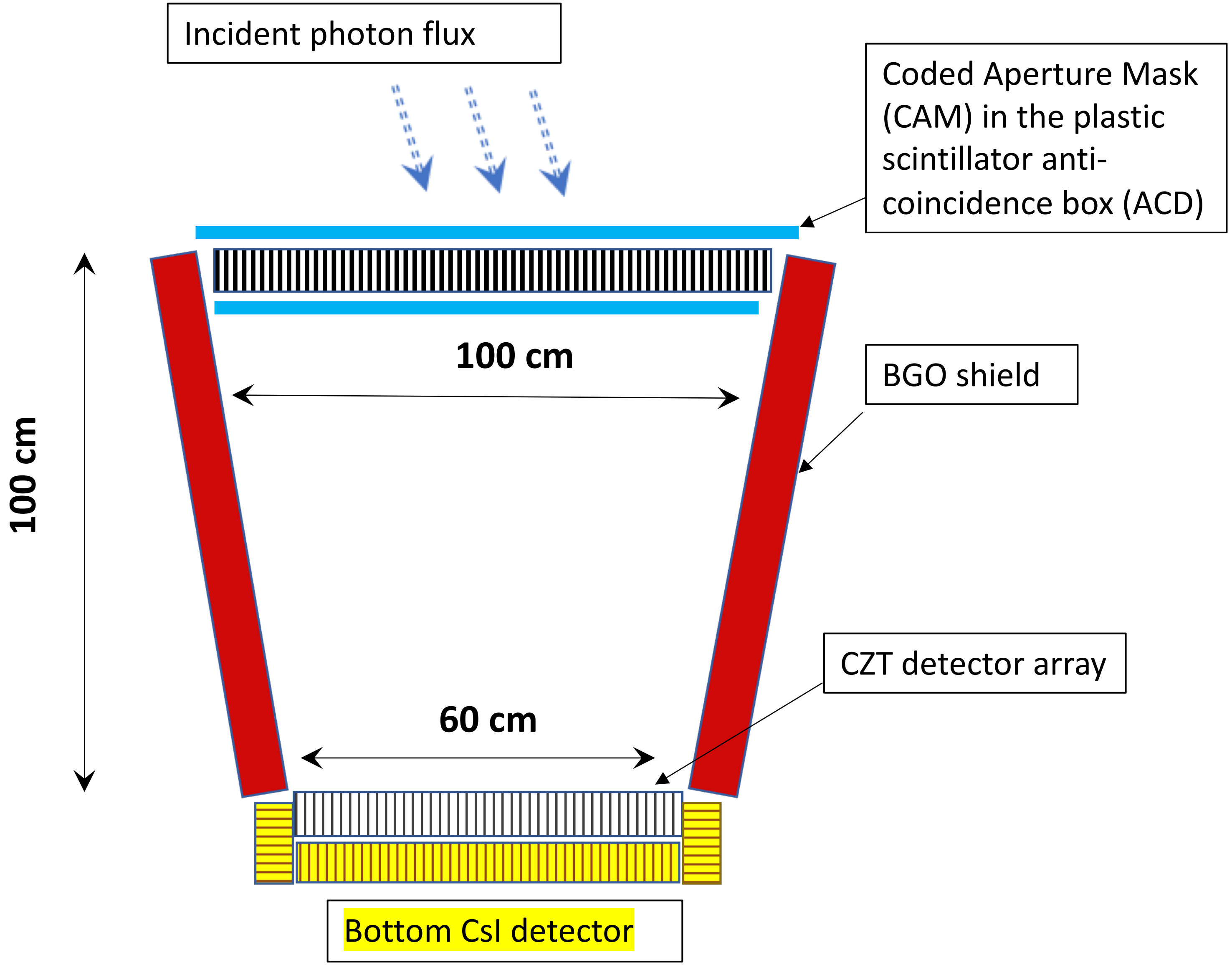
- **GOAL: “Background-free” instrument**
- Incident photon flux is modulated while passing through the CAM and creates an image on the CdZnTe detector plane. The image is then reconstructed
- CAM also works as ~20^0 (0.1 sr) FoV passive collimator
- CAM is surrounded by ACD to veto the background photons produced in CAM by cosmic rays
- **The CZT array provides detection of incident photons with a position resolution of <1mm and with energy resolution of ~1% at 1 MeV.**

GalCenEx: Baseline Instrument Concept



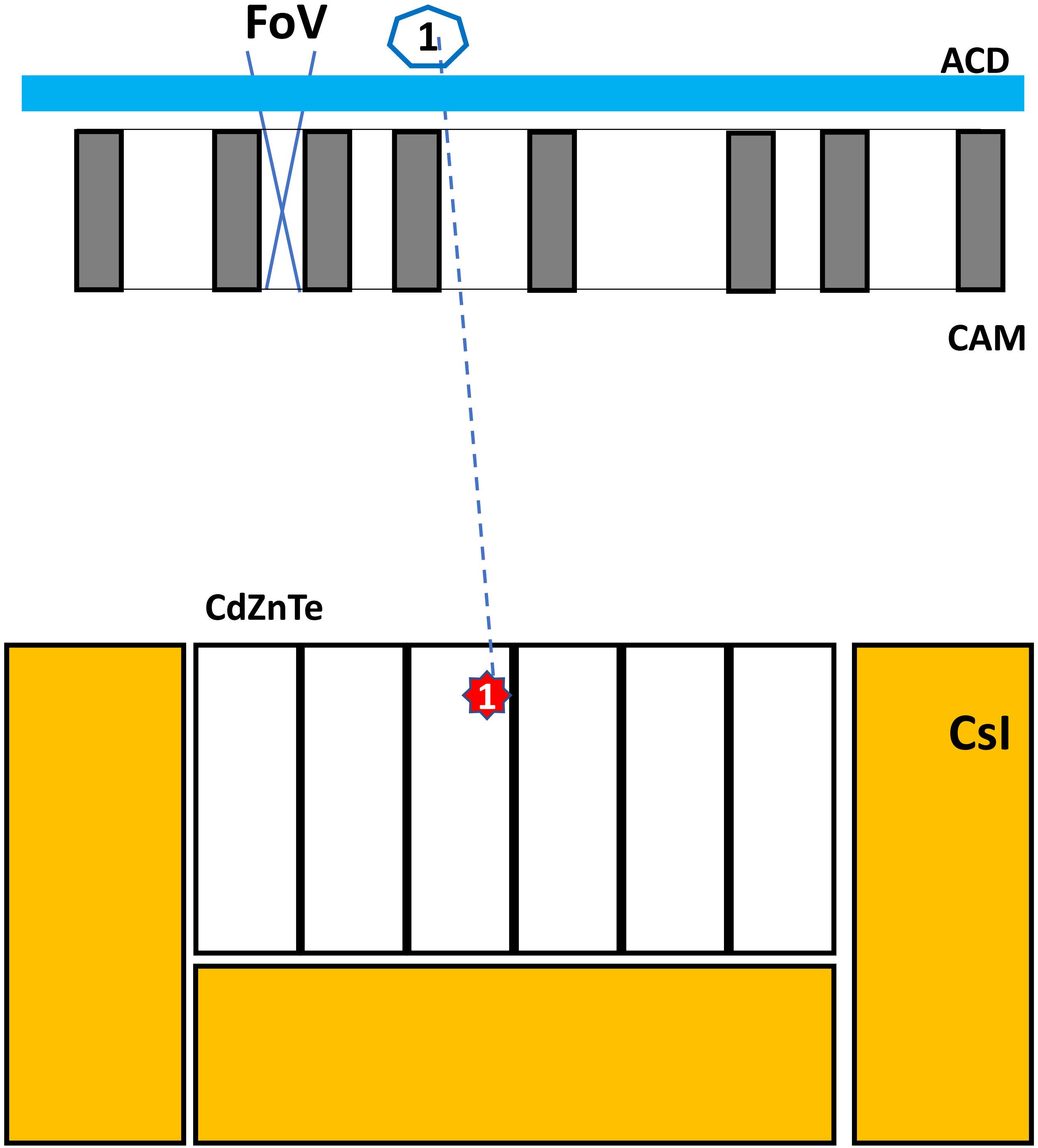
- **GOAL: "Background-free" instrument**
- Incident photon flux is modulated while passing through the CAM and creates an image on the CdZnTe detector plane. The image is then reconstructed
- CAM also works as ~20^0 (0.1 sr) FoV passive collimator
- CAM is surrounded by ACD to veto the background photons produced in CAM by cosmic rays
- The CZT array provides detection of incident photons with a position resolution of <1mm and with energy resolution of ~1% at 1 MeV.
- **BGO shield a) provides absorption of side-entering photons and b) defines the FoV**

GalCenEx: Baseline Instrument Concept



- **GOAL: "Background-free" instrument**
- Incident photon flux is modulated while passing through the CAM and creates an image on the CdZnTe detector plane. The image is then reconstructed
- CAM also works as ~20^0 (0.1 sr) FoV passive collimator
- CAM is surrounded by ACD to veto the background photons produced in CAM by cosmic rays
- The CZT array provides detection of incident photons with a position resolution of <1mm and with energy resolution of ~1% at 1 MeV.
- BGO shield a) provides absorption of side-entering photons and b) defines the FoV
- **Bottom 5-cm thick pixelated CsI detector a) absorbs albedo photons, b) increases instrument sensitivity by adding additional detecting media with position resolution**

Principle of operation (dual mode)

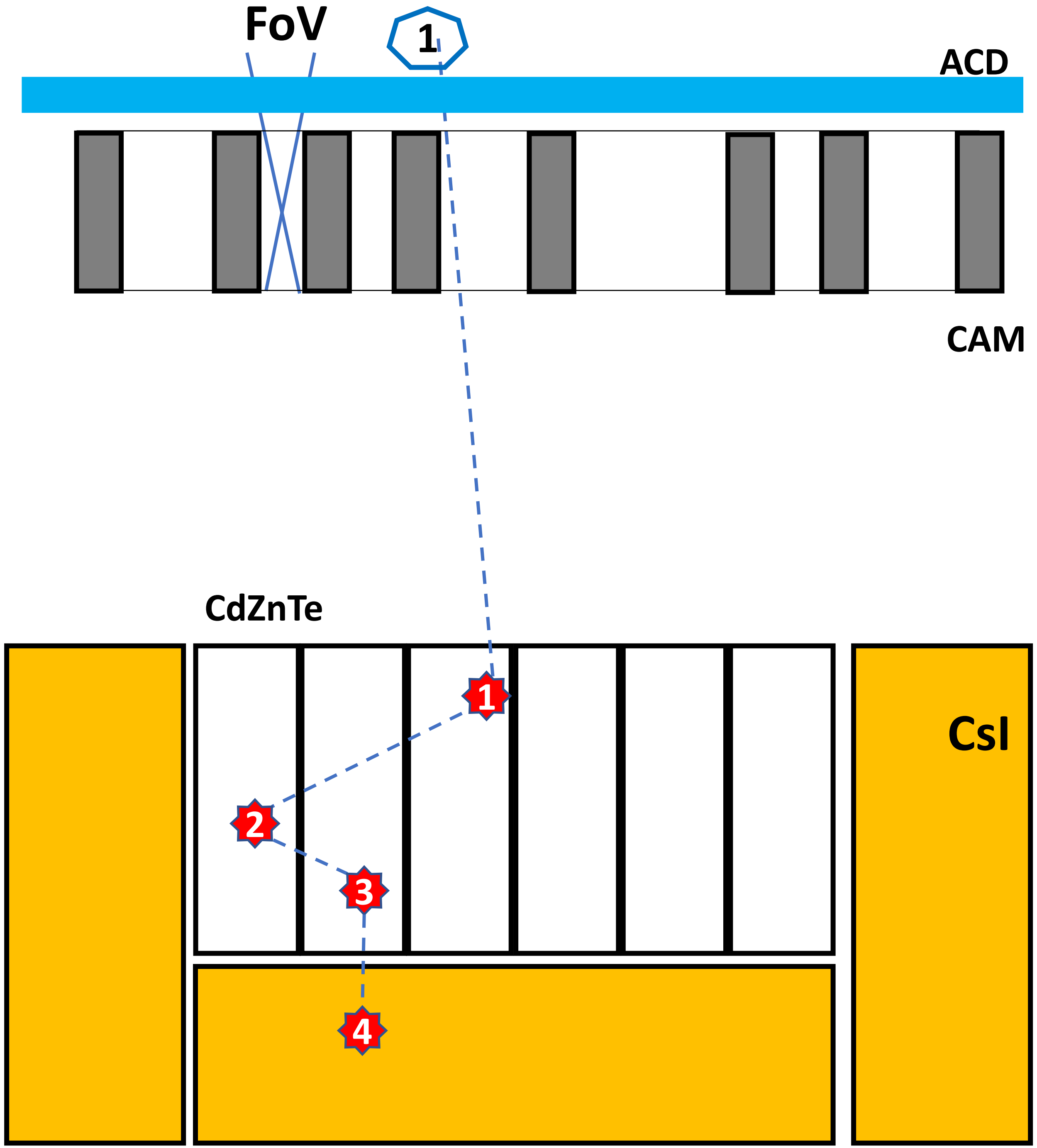


- interaction with energy deposition

1 - good photon detected in aperture

1 - event to be used in **Mask mode**

Principle of operation (dual mode)



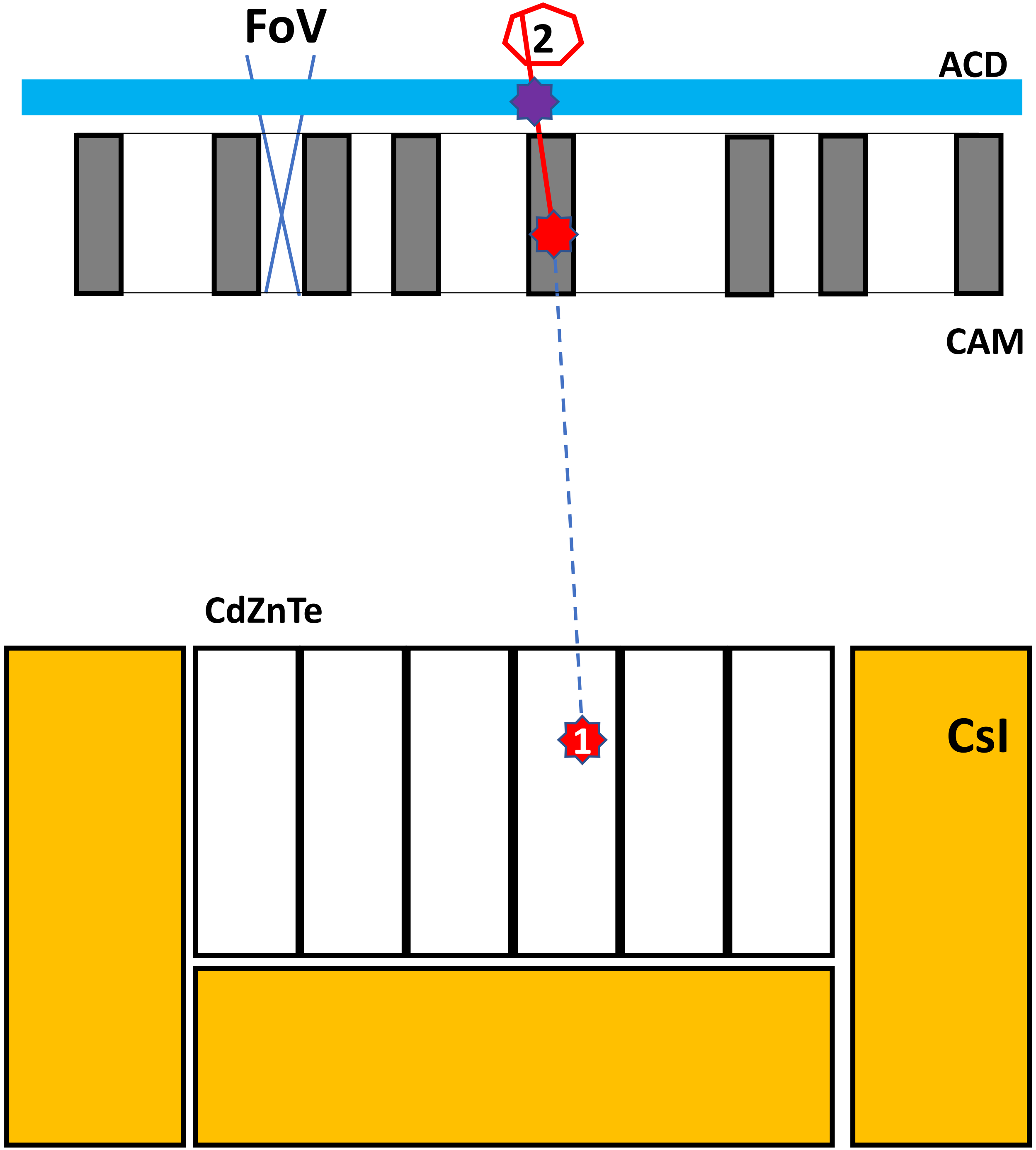
- interaction with energy deposition

1 - good photon detected in aperture

1 - event to be used in **Mask mode**

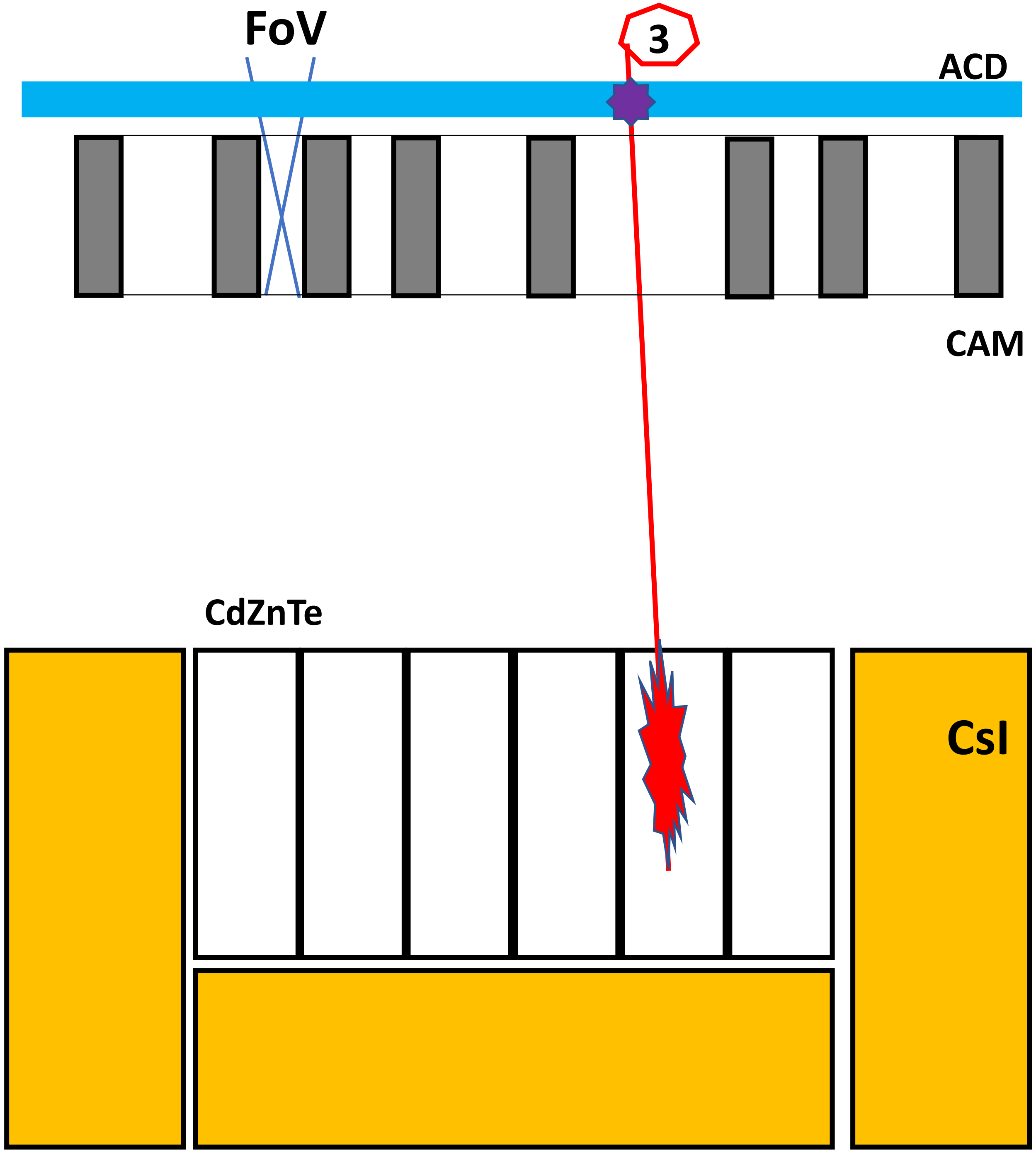
1 + 2 + … event to be used **also in Compton and Polarization modes**

Principle of operation (dual mode)



- event vetoed by a signal in ACD
- interaction with energy deposition
- 2 - charged CR creates photon – VETOed

Principle of operation (dual mode)

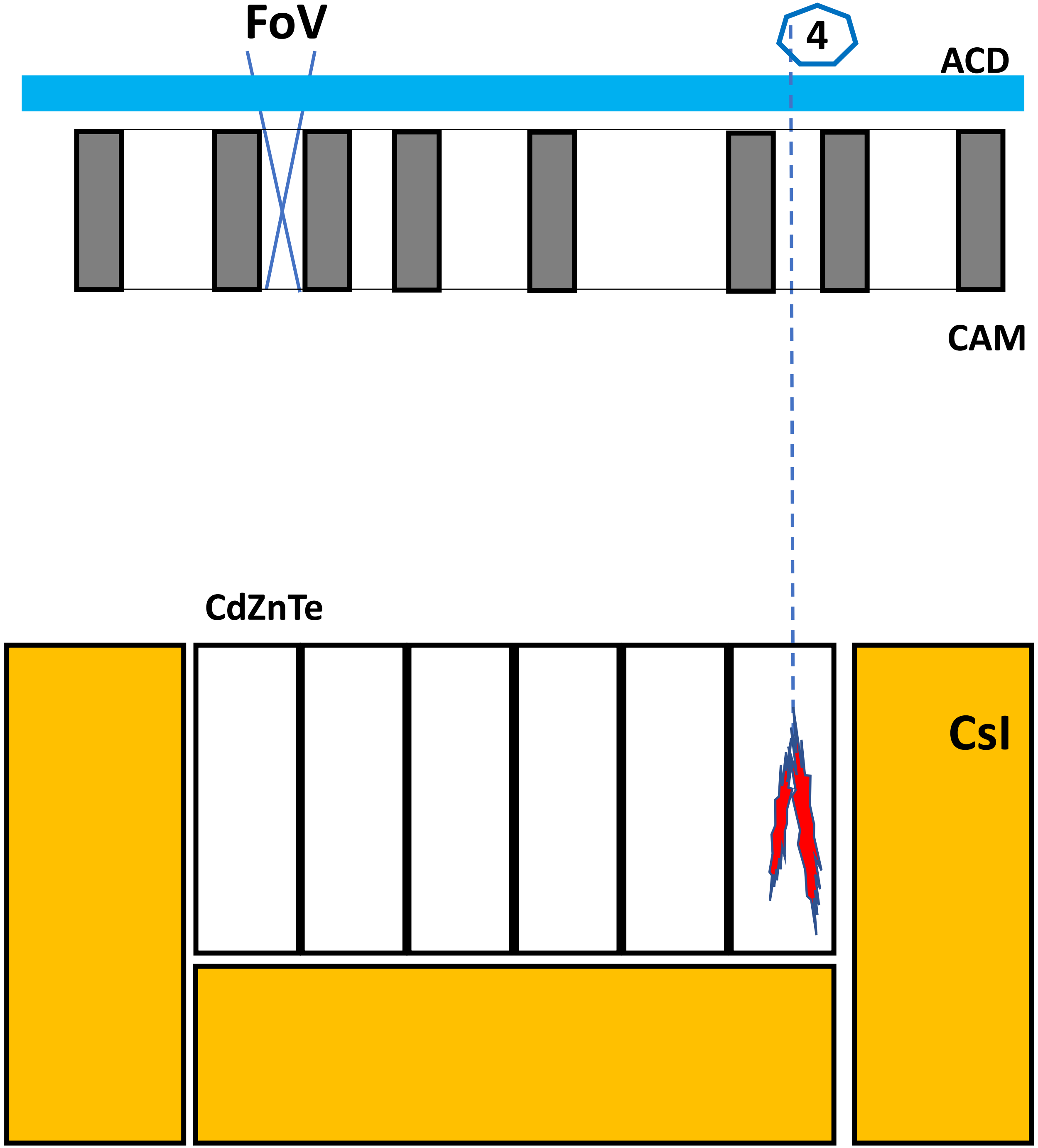


- event vetoed by a signal in ACD

- interaction with energy deposition

3 - charged CR, vetoed

Principle of operation (dual mode)

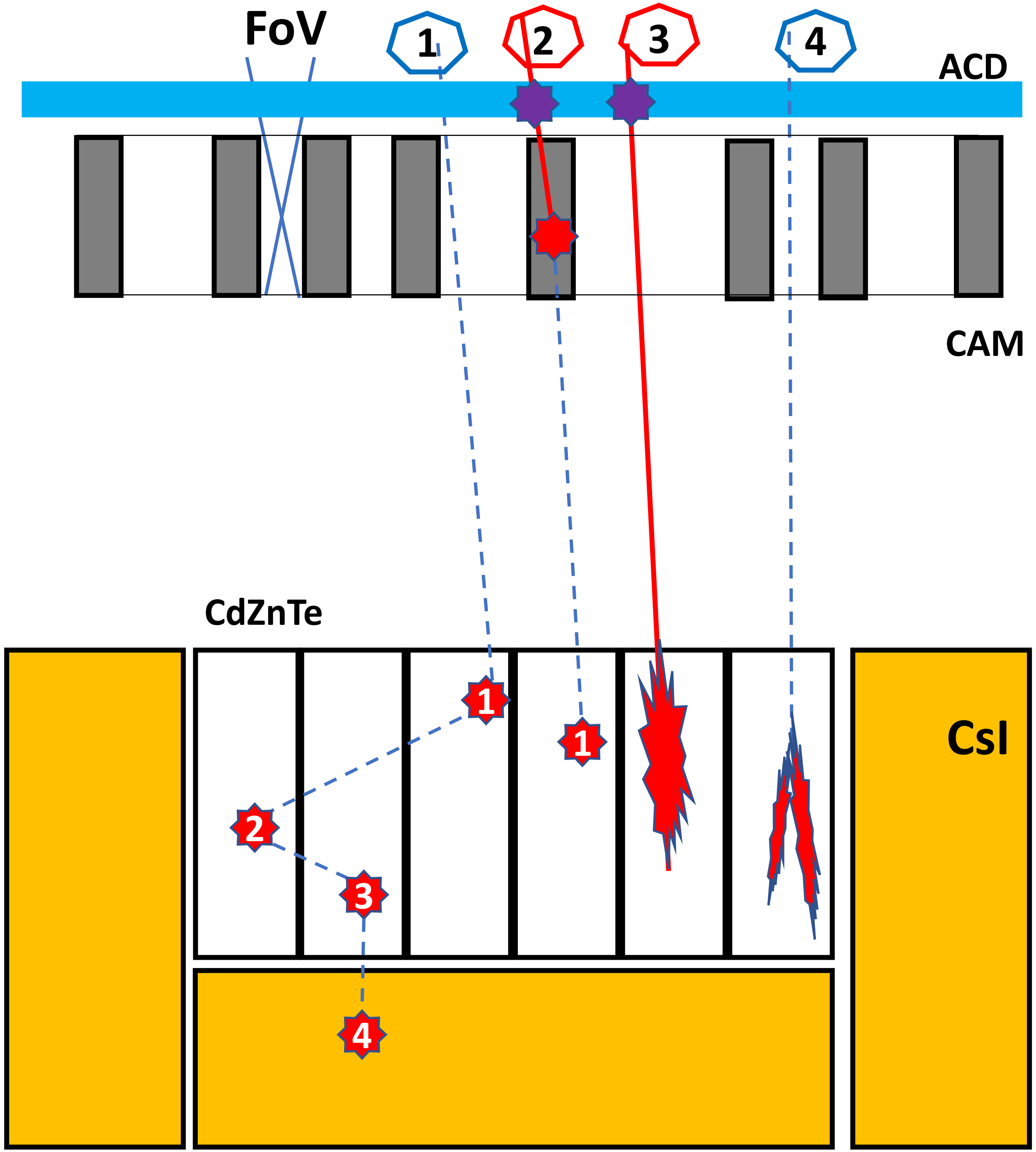


- event vetoed by a signal in ACD

- interaction with energy deposition

4 - high-energy photon: TBD

Principle of operation (dual mode)



- event vetoed by a signal in ACD

- interaction with energy deposition

1 - good photon detected in aperture

1 - event to be used in **Mask mode**

1 + 2 + … event to be used **also in Compton and Polarization modes**

2 - charged CR creates photon – VETOed

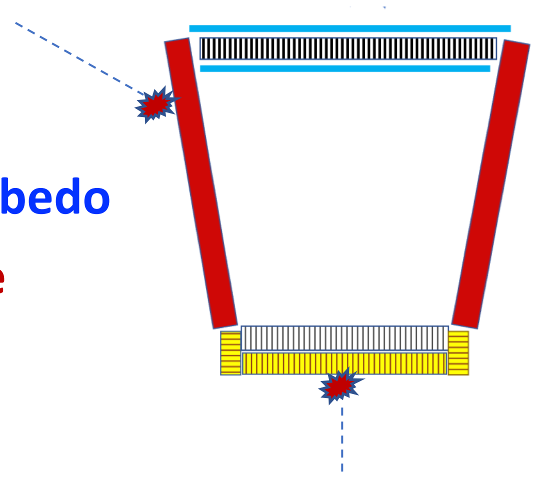
3 - charged CR, vetoed

4 - high-energy photon: TBD

Design approach to fight backgrounds

Known backgrounds and their suppression:

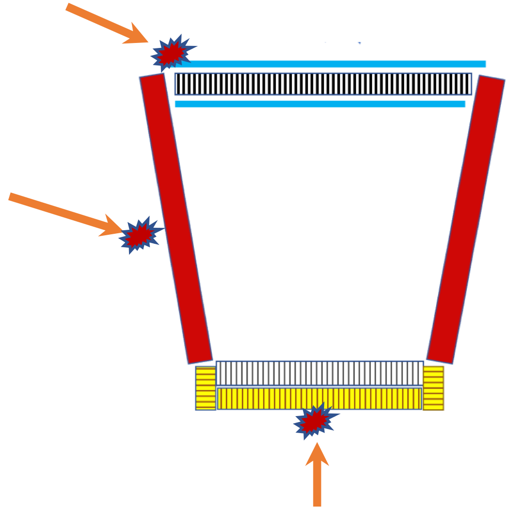
1. External gamma- radiation, both astrophysical (diffuse, sources) and Earth albedo
   - Reduced by sealing the aperture and bottom of the instrument by active detectors

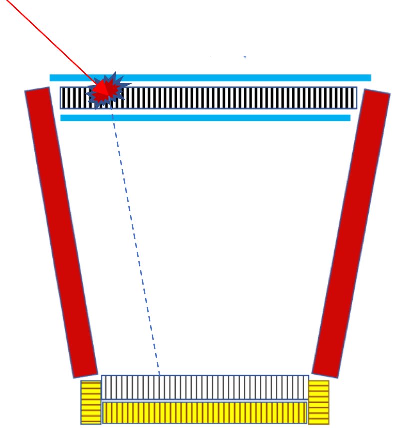


Design approach to fight backgrounds

Known backgrounds and their suppression:

1. External gamma- radiation, both astrophysical (diffuse, sources) and Earth albedo
    - Reduced by sealing the aperture and bottom of the instrument by active detectors
2. **External charged cosmic rays**
    - **Suppressed by high-efficiency plastic ACD (top) and BGO (sides)**



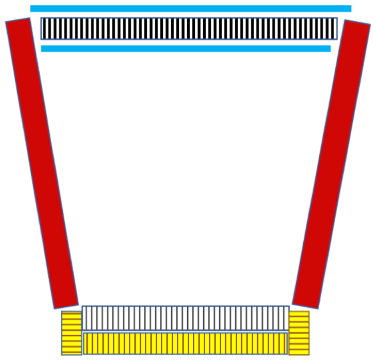


Design approach to fight backgrounds

Known backgrounds and their suppression:

1. External gamma- radiation, both astrophysical (diffuse, sources) and Earth albedo
   - Reduced by sealing the aperture and bottom of the instrument by active detectors
2. External charged cosmic rays
   - Suppressed by high-efficiency plastic ACD (top) and BGO (sides)
3. **Secondary photons directly produced in the instrument by cosmic rays (including that produced in the Coded Mask)**
   - **Suppressed by ACD**

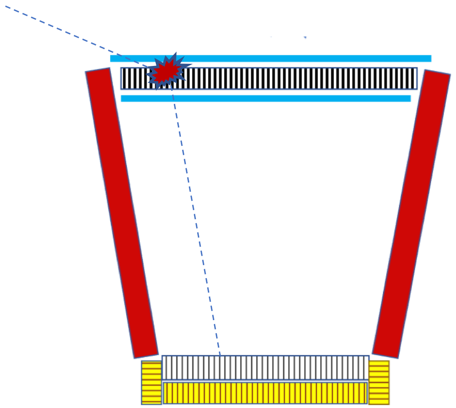
Design approach to fight backgrounds



Known backgrounds and their suppression:

1. External gamma- radiation, both astrophysical (diffuse, sources) and Earth albedo
   - Reduced by sealing the aperture and bottom of the instrument by active detectors
2. External charged cosmic rays
   - Suppressed by high-efficiency plastic ACD (top) and BGO (sides)
3. Secondary photons directly produced in the instrument by cosmic rays (including that produced in the Coded Mask)
   - Suppressed by ACD
4. **Instrument material activation**
   - **Use of equatorial LEO to reduce activation in SAA**
   - **Carefully select the materials used in the instrument. We will minimize the usage of any metals, replacing them by the composites (rapidly developing technology), targeting to have only unavoidable copper and Si in electronics.**

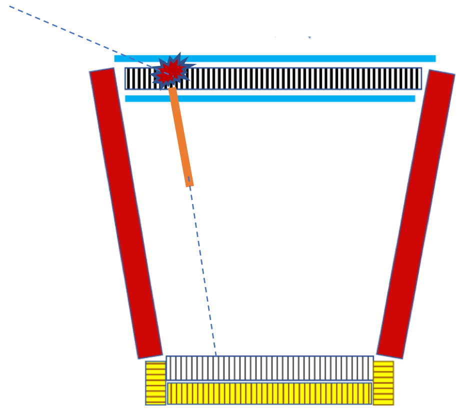
Design approach to fight backgrounds



Known backgrounds and their suppression:

1. External gamma- radiation, both astrophysical (diffuse, sources) and Earth albedo
   - Reduced by sealing the aperture and bottom of the instrument by active detectors
2. External charged cosmic rays
   - Suppressed by high-efficiency plastic ACD (top) and BGO (sides)
3. Secondary photons directly produced in the instrument by cosmic rays (including that produced in the Coded Mask)
   - Suppressed by ACD
4. Instrument material activation
   - Use of equatorial LEO to reduce activation in SAA
   - Carefully select the materials used in the instrument. We will minimize the usage of any metals, replacing them by the composites (rapidly developing technology), targeting to have only unavoidable copper and Si in electronics.
5. **Secondary photons produced as a result of Compton scattering of primary photons in the absorbing elements of the Mask**
   - **Make absorbing elements to be active (e.g. BGO) – TBD. However will have to reduce FoV**

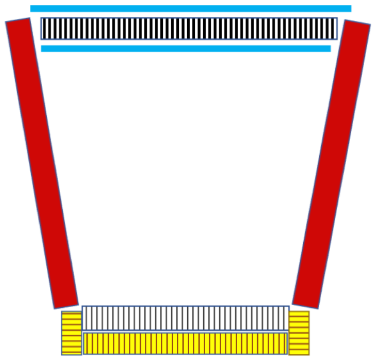
Design approach to fight backgrounds



Known backgrounds and their suppression:

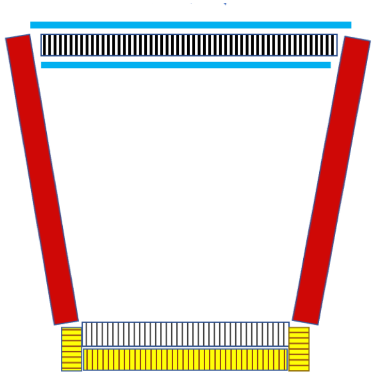
1. External gamma- radiation, both astrophysical (diffuse, sources) and Earth albedo
   - Reduced by sealing the aperture and bottom of the instrument by active detectors
2. External charged cosmic rays
   - Suppressed by high-efficiency plastic ACD (top) and BGO (sides)
3. Secondary photons directly produced in the instrument by cosmic rays (including that produced in the Coded Mask)
   - Suppressed by ACD
4. Instrument material activation
   - Use of equatorial LEO to reduce activation in SAA
   - Carefully select the materials used in the instrument. We will minimize the usage of any metals, replacing them by the composites (rapidly developing technology), targeting to have only unavoidable copper and Si in electronics.
5. Secondary photons produced as a result of Compton scattering of primary photons in the absorbing elements of the Mask (especially 511 keV)
   - Make absorbing elements to be active (e.g. BGO) – TBD. However will have to reduce FoV
6. **Charged particles (electrons and positrons) resulting from pair-production by primary photons in the Mask – TBD if they are bad**
   - **ACD under the Mask**

Design approach to fight backgrounds



Known backgrounds and their suppression:

1. External gamma- radiation, both astrophysical (diffuse, sources) and Earth albedo
    - Reduced by sealing the aperture and bottom of the instrument by active detectors
2. External charged cosmic rays
    - Suppressed by high-efficiency plastic ACD (top) and BGO (sides)
3. Secondary photons directly produced in the instrument by cosmic rays (including that produced in the Coded Mask)
    - Suppressed by ACD
4. Instrument material activation
    - Use of equatorial LEO to reduce activation in SAA
    - Carefully select the materials used in the instrument. We will minimize the usage of any metals, replacing them by the composites (rapidly developing technology), targeting to have only unavoidable copper and Si in electronics.
5. Secondary photons produced as a result of Compton scattering of primary photons in the absorbing elements of the Mask (especially 511 keV)
    - Make absorbing elements to be active (e.g. BGO) – TBD. However will have to reduce FoV
6. Charged particles (electrons and positrons) resulting from pair-production by primary photons in the Mask – TBD if they are bad
    - ACD under the Mask
7. **Neutrons: lessons learned from INTEGRAL, optimal orbit**

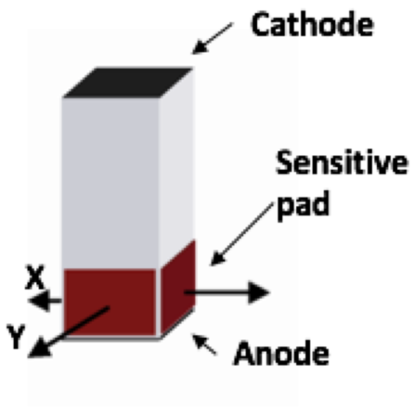


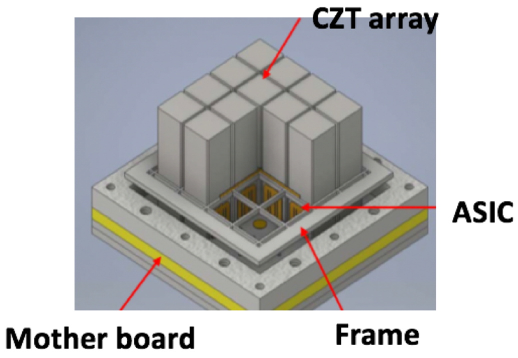
Design approach to fight backgrounds

Known backgrounds and their suppression:

1. External gamma- radiation, both astrophysical (diffuse, sources) and Earth albedo
    - Reduced by sealing the aperture and bottom of the instrument by active detectors
2. External charged cosmic rays
    - Suppressed by high-efficiency plastic ACD (top) and BGO (sides)
3. Secondary photons directly produced in the instrument by cosmic rays (including that produced in the Coded Mask)
    - Suppressed by ACD
4. Instrument material activation
    - Use of equatorial LEO to reduce activation in SAA
    - Carefully select the materials used in the instrument. We will minimize the usage of any metals, replacing them by the composites (rapidly developing technology), targeting to have only unavoidable copper and Si in electronics.
5. Secondary photons produced as a result of Compton scattering of primary photons in the absorbing elements of the Mask (especially 511 keV)
    - Make absorbing elements to be active (e.g. BGO) – TBD. However will have to reduce FoV
6. Charged particles (electrons and positrons) resulting from pair-production by primary photons in the Mask – TBD if they are bad
    - ACD under the Mask
7. Neutrons: lessons learned from INTEGRAL, optimal orbit
8. **Background due to misreconstructed Compton events**
    - **Optimize the analysis, improve detectors performance (energy and position resolution)**

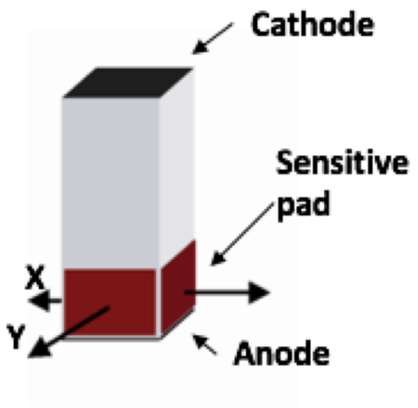
Virtual Frisch-grid bar CdZnTe Detector: a key detector, it ignited the project!

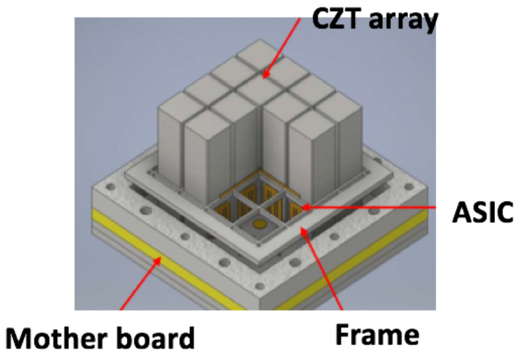




- CdZnTe bar is cut from 6-8 mm thick wafer with a length of 2-3 cm, can be up to 5cm
- 4 virtually-grounded copper pads are placed near anode to shield it, working as a Frisch-grid. Induced signals from them are converted into X-Y coordinates of the energy deposition in the detector. A Cathode/Anode signal ratio, along with drift time, provide Z coordinate
- The bars are assembled in 4x4 bar module, served by a single ASIC. A Calorimeter of any required area can be built by plugging the modules in the motherboard

Virtual Frisch-grid bar CdZnTe Detector: a key detector, it ignited the project!





- CdZnTe bar is cut from 6-8 mm thick wafer with a length of 2-3 cm, can be up to 5cm
- 4 virtually-grounded copper pads are placed near anode to shield it, working as a Frisch-grid. Induced signals from them are converted into X-Y coordinates of the energy deposition in the detector. A Cathode/Anode signal ratio, along with drift time, provide Z coordinate
- The bars are assembled in 4x4 bar module, served by a single ASIC. A Calorimeter of any required area can be built by plugging the modules in the motherboard

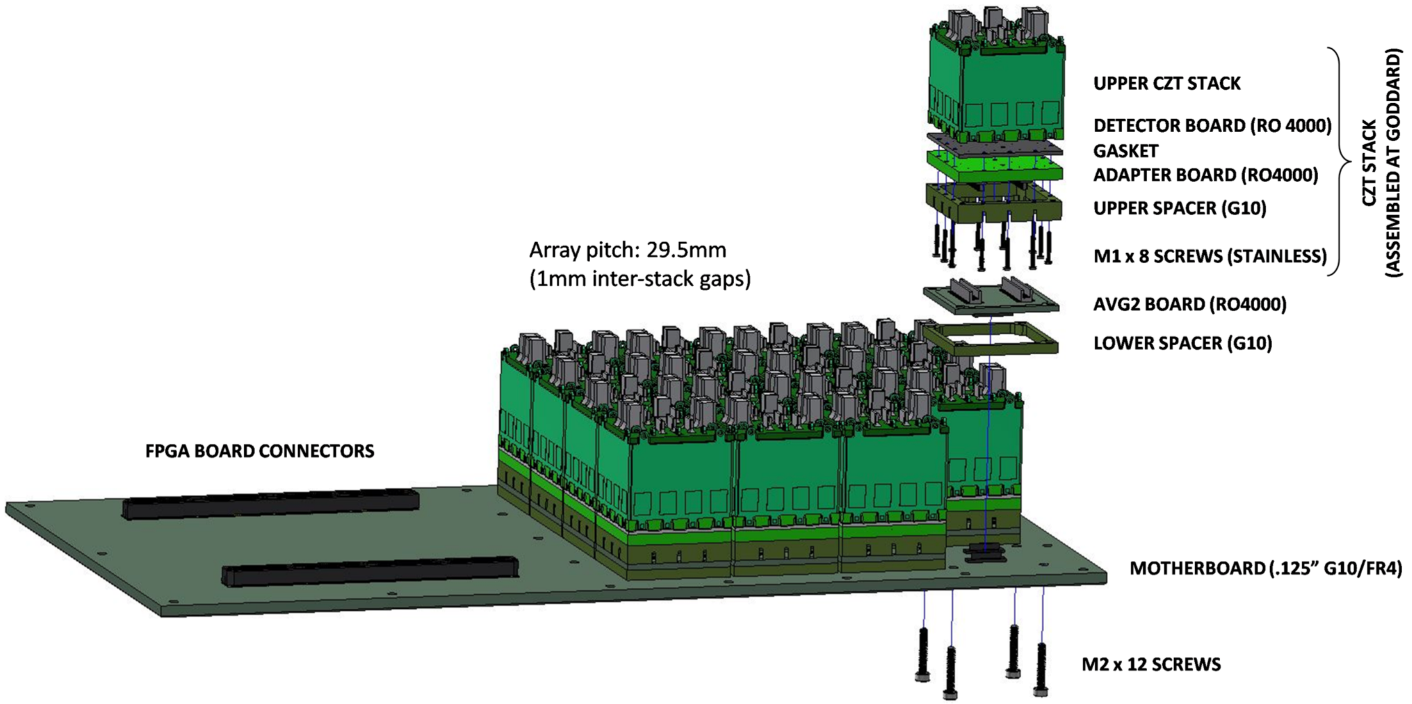
FEATURES:

- Placing a bar (bar array) vertically, up to 5 cm thick detector can be built
- Ability to correct response non-uniformity caused by crystal defects, which allows to use unselected (standard grade) crystals to reduce a cost and improve performance
- **3D position intrinsic resolution of <1mm**: huge saving in a number of FEE channels

- **Performance of the virtual Frisch-grid CdZnTe detector has been published in several papers by A.Bolotnikov et al.: dE/E < 1% at 1 MeV (FWHM)**
- **It ideally suites our needs, but have to be re-designed and tested for space applications**

Currently the CZT calorimeter containing 16 modules is being built at Goddard for the AMEGO/ComPair project to undergo comprehensive tests at the beam (2019), balloon flight (2020), as well as environmental tests

AS OF 12/10/18



Instrument parameters and performance

	IBIS	COSI	AMEGO	GalCenEx
Detector	Coded Aperture Mask 4x4x2 mm^3 CdTe 8.5x8.5x30 mm^3 CsI	3 layers of 8x8x1.5cm^3 Ge	60 layers of 0.5mm thick Si-strip DSD 8x8x30mm^3 CdZnTe bars	Coded Aperture Mask 8x8x30mm^3 CdZnTe bars
Detector area	3,000 cm^2 CdTe, CsI	256 cm^2, Ge	6,400 cm^2 Si-strip, CdZnTe	3,600 cm^2 CdZnTe
Detector thickness, g/cm^2	14.6 (1.7 X_0)	23.4 (1.9 X_0)	7 (0.32 X_0) (only Si)	17.5 (1.9 X_0)
Energy range	15 keV – 10 MeV	0.2 – 5 MeV	0.2MeV – 10 GeV	0.1 – 100 MeV (TBC)
Effective Area, cm^2 (at 1 MeV)		~20 cm^2	~200 cm^2	~200 cm^2 (Compton mode) ~1000 cm^2 (Mask mode)
Field-of-View, sr	0.02 (8^o) ?		2.4	0.1 (20^o)
dE/E, FWHM	6%	0.4%	1%	1%
Angular resolution, FWHM	12’ (with Mask)	4.5^o	4.5^o	10’ (with Mask) 4.5^o (Compton mode)

SUMMARY

1. Main science objectives have been identified, detailed work continues
2. Baseline instrument concept is developed, main detectors are identified
3. Much of work needs to be done on the instrument design optimization and individual subsystem development
    - Performance of CdZnTe detector at high energy (above 3 MeV) has to be investigated. Its ability to detect pair events and position accuracy will define the upper energy limit for GalCenEx
    - Compton event reconstruction and polarization measurement optimization have to be developed
    - Coded Aperture mask has to be optimized: Active or not? Rotating mask? Anti-mask?
    - Ability to measure “diffuse” radiation: remove CAM’s sources from “Compton” FoV?
    - Careful investigation of all known backgrounds and the tools to suppress them
    - Etc, etc
4. We are proposing to NASA to design, build and test a small prototype of GalCenEx to develop the subsystems and optimize the design
5. We will be considering next MIDEX AO as a potential opportunity to propose GalCenEx for the flight

SUMMARY

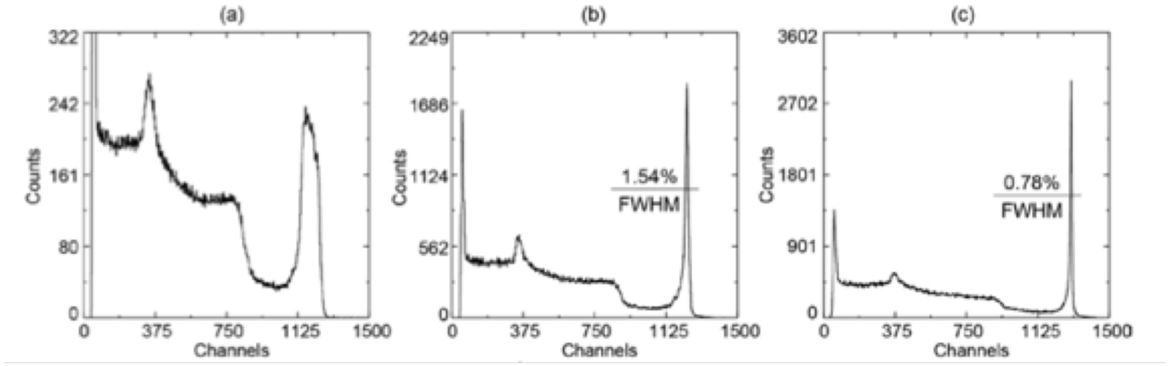
1. Main science objectives have been identified, detailed work continues
2. Baseline instrument concept is developed, main detectors are identified
3. Much of work needs to be done on the instrument design optimization and individual subsystem development
   - Performance of CdZnTe detector at high energy (above 3 MeV) has to be investigated. Its ability to detect pair events and position accuracy will define the upper energy limit for GalCenEx
   - Compton event reconstruction and polarization measurement optimization have to be developed
   - Coded Aperture mask has to be optimized: Active or not? Rotating mask? Anti-mask?
   - Ability to measure “diffuse” radiation: remove CAM’s sources from “Compton” FoV?
   - Careful investigation of all known backgrounds and the tools to suppress them
   - Etc, etc
4. We are proposing to NASA to design, build and test a small prototype of GalCenEx to develop the subsystems and optimize the design
5. We will be considering next MIDEX AO as a potential opportunity to propose GalCenEx for the flight

THANK YOU!

BACK-UPS

Performance of the virtual Frisch-grid bar detector

Energy measurement: 3D correction



Raw spectrum

After 1D (DOI) correction

After 3D correction

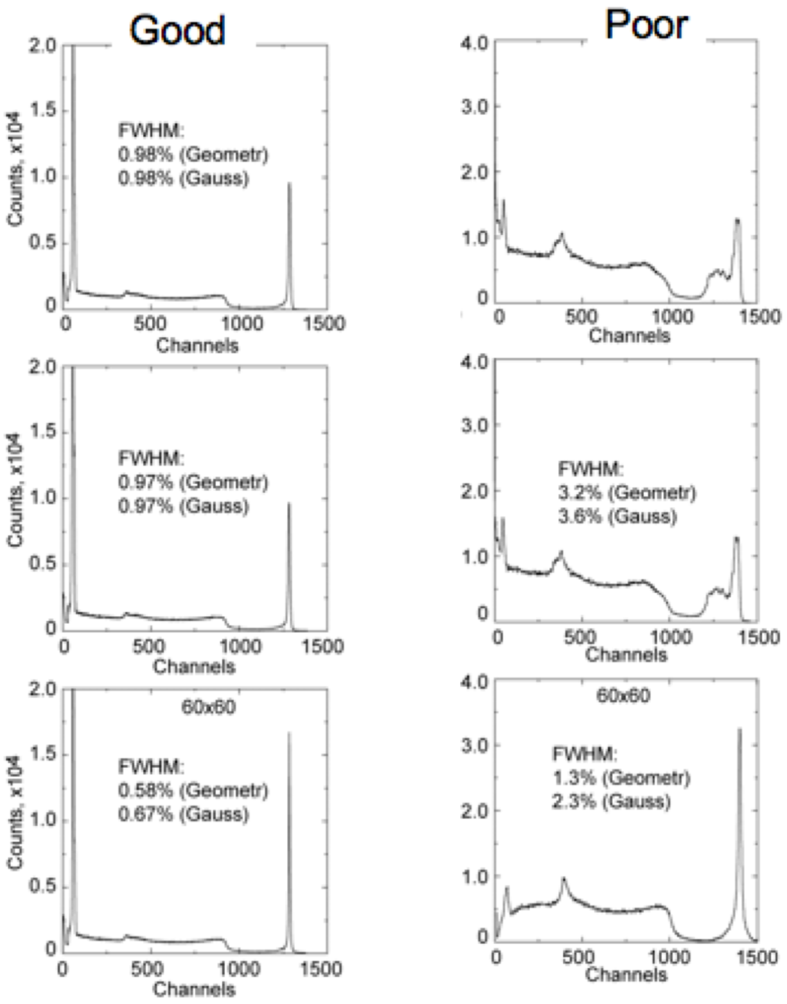
- **Energy resolution (662 keV): improves from ~3% to ~0.8% (all FWHM) with the use of 3D correction**
- **Poor quality detector performance can be recovered**

Recovery of poor quality detectors

Raw spectrum

After drift-time correction

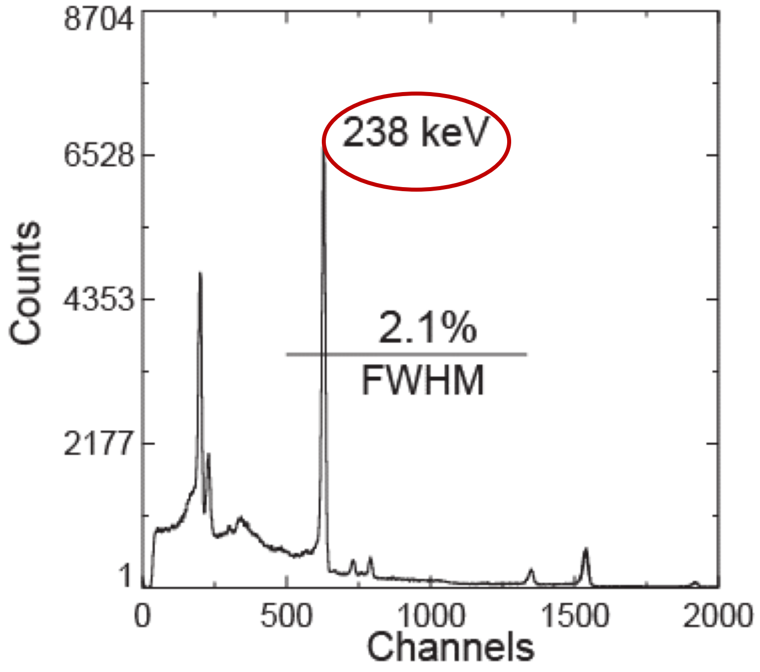
After segmenting the detectors into 60x60x30 voxels



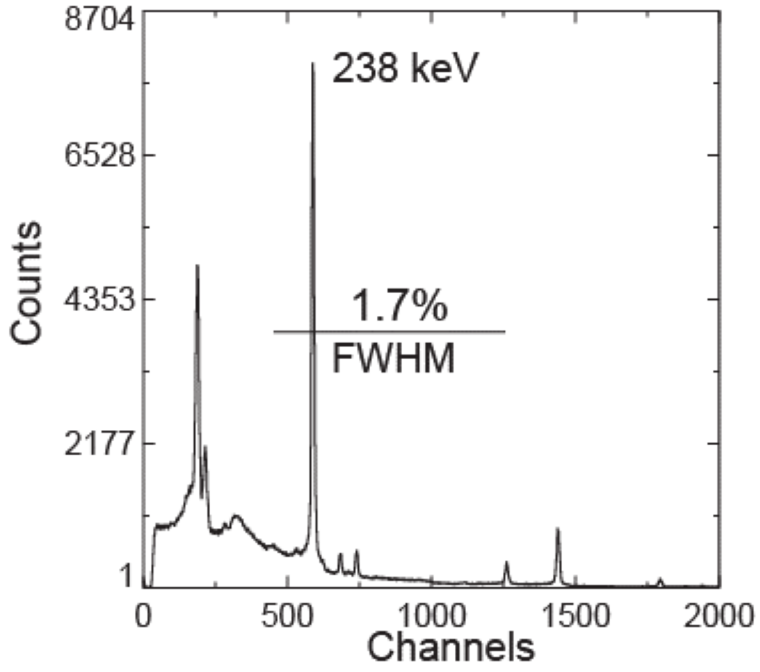
Measurements by A. Bolotnikov (BNL)

U-232

No corrections

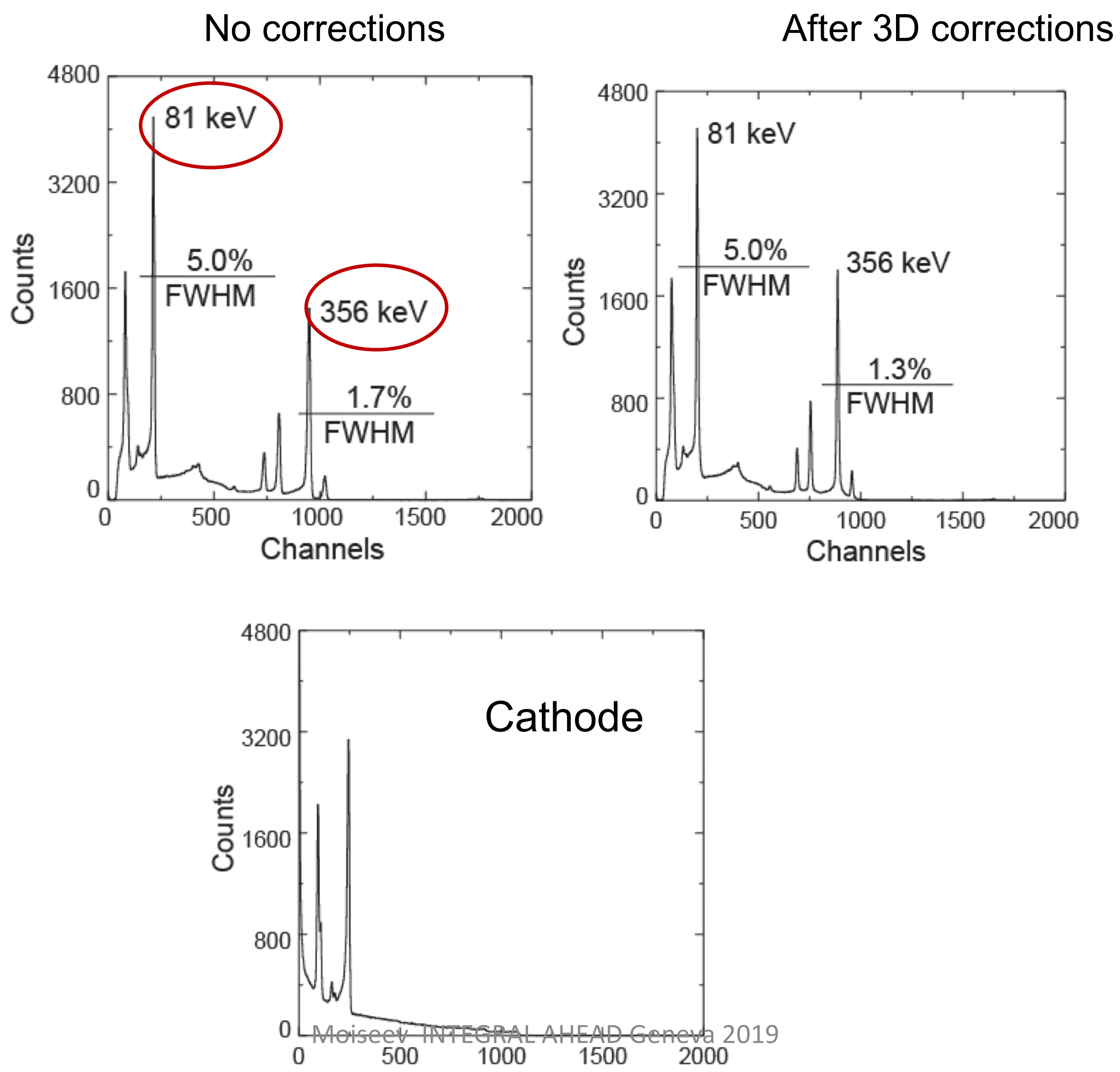


After 3D corrections



Measurements by A. Bolotnikov (BNL)

Ba-133

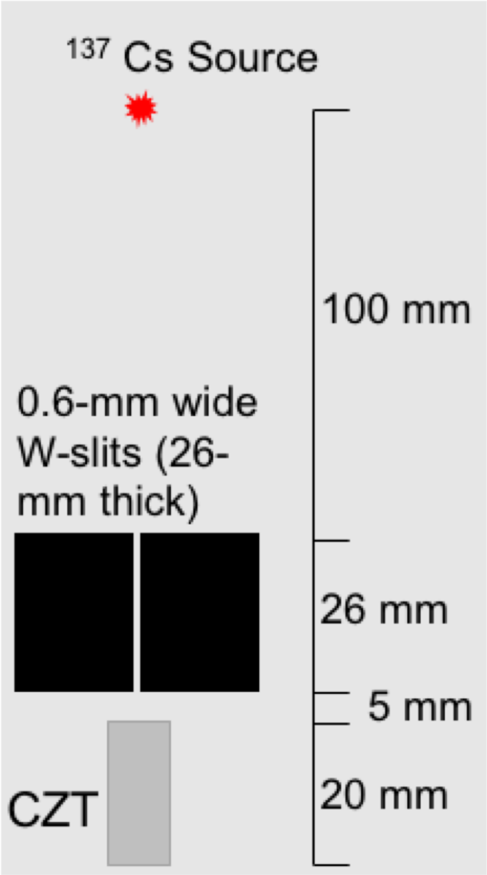


Measurements by A. Bolotnikov (BNL)

Position resolution

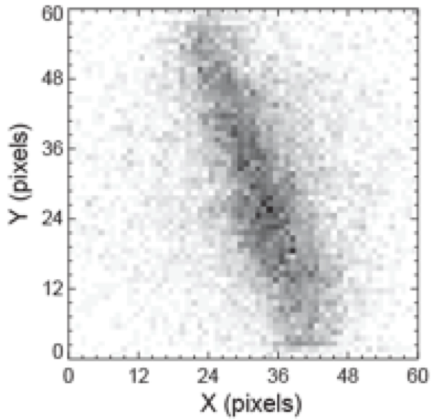
Measurement approach: Monte Carlo simulation of the exact experiment configuration (with a collimator) and apply and vary the detector intrinsic resolution in MC to find the best match to the experimental data

Geometry of the experiment

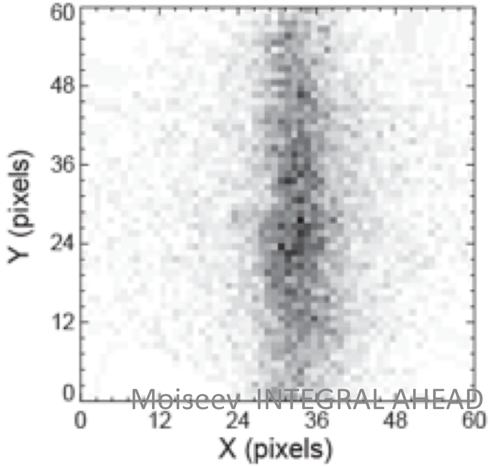


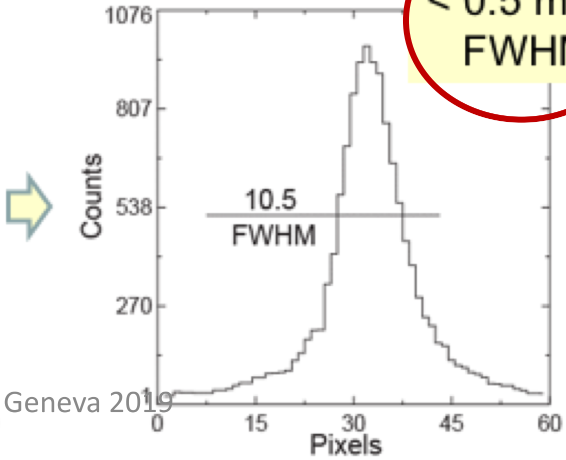
- Events distributions over a detector area (XY)
- All events within a detector length are included

6x6 mm²

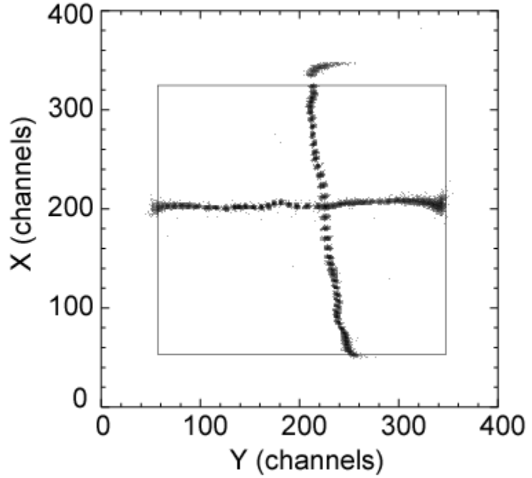


Rotated image





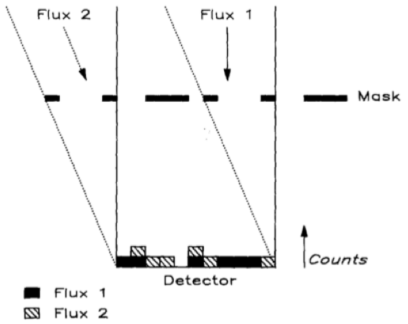
< 0.5 mm FWHM



Illumination by 500 keV laser beam: beam diameter 20 μm, step pitch 0.1mm

Measurements by A. Bolotnikov (BNL)

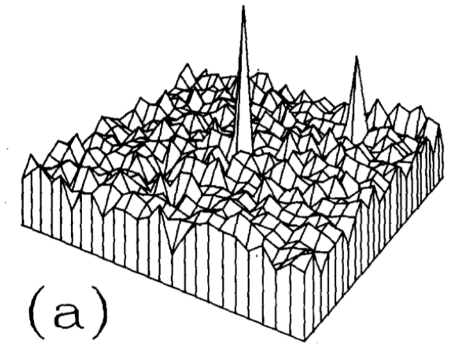
Coded Aperture Mask



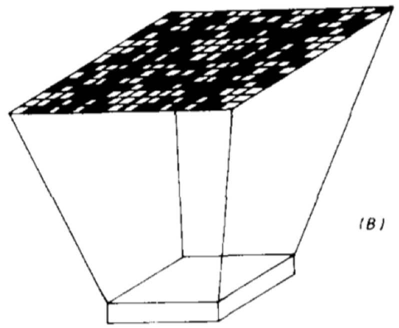
E. Caroli et al., 1987

CAM modulates incident photon flux and creates its shadow (image) on the detector

- System opening angle (or field-of-view) is ~***a/h*** and normally is of the order of 20 degrees (***a*** is a mask element size, ***h*** is its thickness)
- Anti-coincidence detector vetoes photons which are created in the mask opaque elements by incident cosmic ray



- Mask is a combination of randomly positioned opaque and transparent elements with size of ***a*** and thickness ***h***. Mask is placed on a distance ***l*** from the Detector
- Angular resolution of the system can be estimated as ***a/l***. If ***a***=2mm and ***l****=1m*, ***Δφ***~0.1 degree
- *Mask element size* ***a*** has to be 2-3 times smaller than the position resolution of the detector



CAM Concept for GalCenEx

- Mask size 100cm x 100cm, and it is spaced by 100 cm from the CZT Detector
- Mask element size 2mm x 2mm, opaque elements are made of 1cm thick W (FOW ~ 20 degrees), assuming the CZT position resolution of 0.5-1 mm
- Mask is boxed in ACD, which made of 1cm thick plastic scintillator, read out by SiPM's, and supported by the honey-comb structure