AdEPT

Advanced **E**nergetic **P**air **T**elescope

A Discovery Mission for Medium-Energy Gamma-Ray Polarimetry

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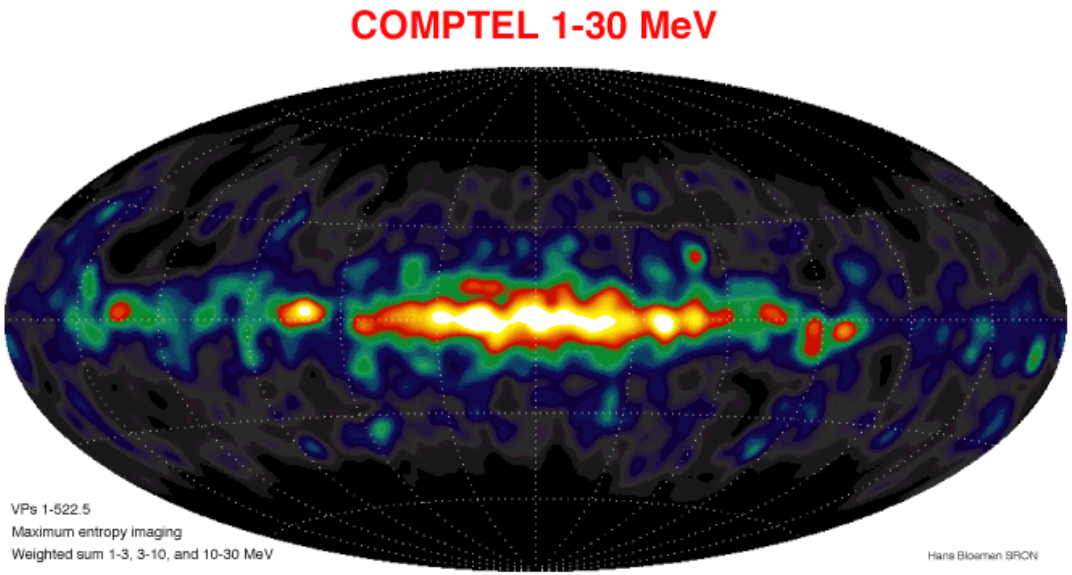
on behalf of AdEPT team

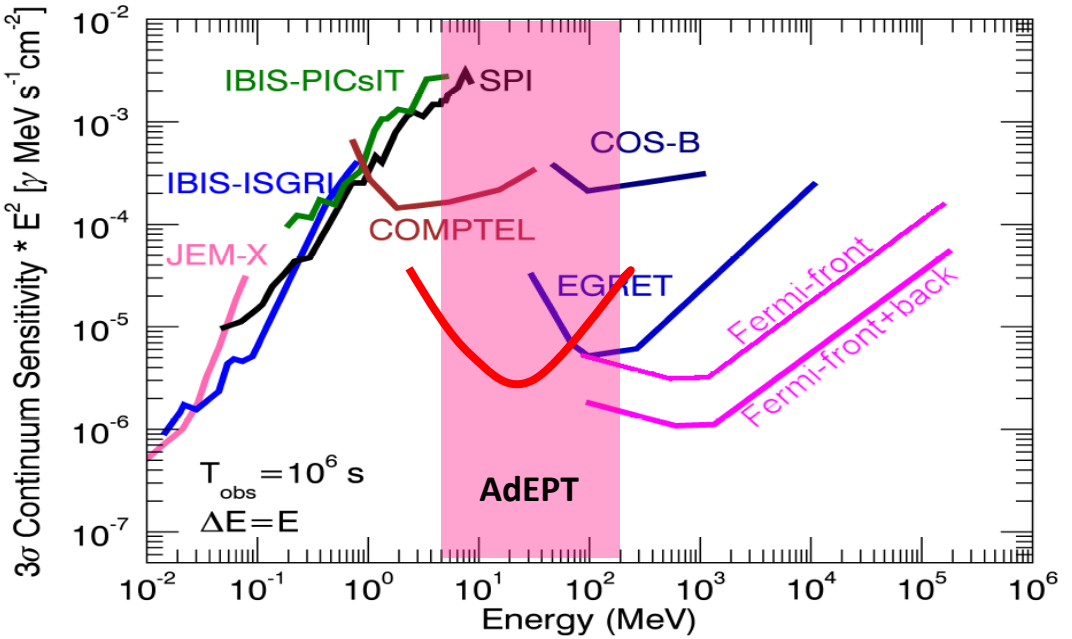
Future Space-based Gamma-ray Observatories

March 24, 2016

AdEPT Science: Why MeV?

- The MeV sky is largely unexplored:
  - new class of sources?
  - different emission regions
- Many Fermi sources indicate peaks in MeV range
- Optimal energy band for γ-ray polarimetry
- $\pi^0 \rightarrow \gamma\gamma$ @ E ~ 67.5 MeV





AdEPT Science: Survey with Polarimetry

Energy Range: 2-500 MeV

- Poorly explored domain
  - Detailed look at known accelerators
    PSRs, PWNs, SNR, AGN, GRBs
  - Yet unseen accelerators
    - Polar cap emission in PSRs
    - Magnetars
    - New classes of sources
- $\pi^0 \rightarrow \gamma\gamma$ @ E ~ 67.5 MeV

  π^0 - telltale signature of hadrons
  - Leptonic vs. Hadronic acceleration scenarios
  - Dark Matter photon mediators

Polarization: 0.1% MDP

- Polarization measurements:

  Geometry of accelerators

  no foreground propagation effects
- Strict limits on polarization:

  Distinguishes π^0 emission

  $\pi^0 \rightarrow \gamma\gamma$ is **unpolarized**
- Unique test of relativity

  vacuum birefringence effect

Angular Resolution: ~0.2°

- Excellent source localization
  down to ~1' ($0.2^o/\sqrt{N_{ph}}$)
- Resolving MeV background
- Dark Matter profiles

Polarization helps to discriminate between Emission Mechanisms

Synchrotron Radiation:
polarization up to 75%
$E \perp B$

Curvature Radiation:
polarization up to 100%
$E \| B$

Inverse Compton Scattering:
Scattering Polarized radiation (SSC)
polarization up to 50%

Scattering Unpolarized radiation –
low polarization < 1%

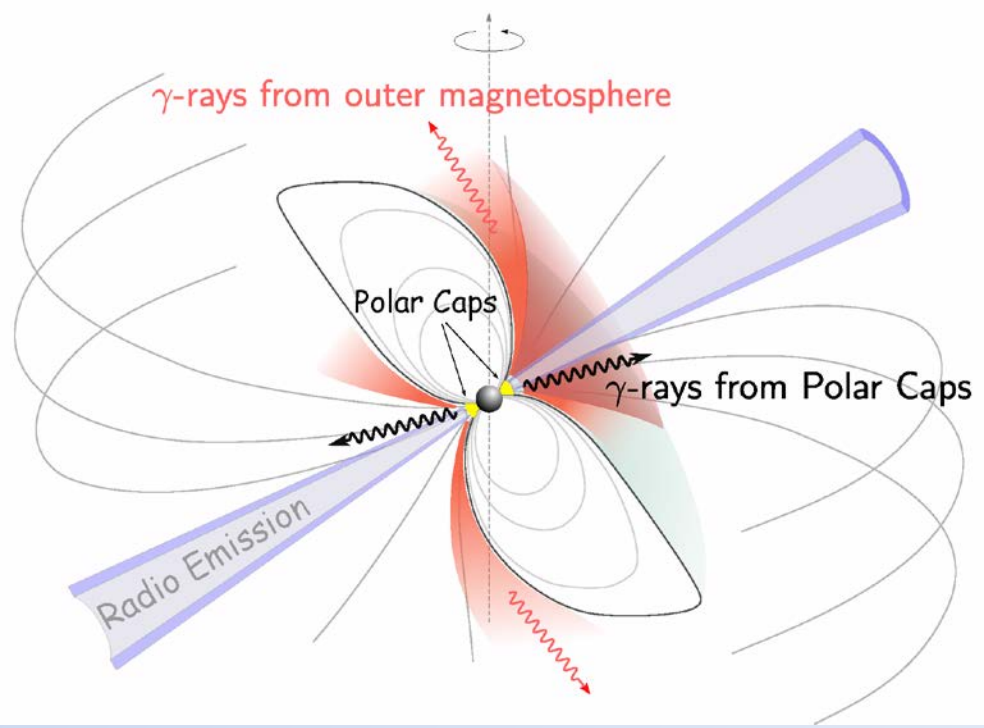
$\pi^o \rightarrow \gamma + \gamma$
completely unpolarized

Pulsar Physics

AdEPT will determine the structure of pulsar acceleration zones in the inner and outer magnetosphere by measuring the gamma-ray polarization.

GeV gamma-rays come from the outer magnetosphere. *Fermi* results suggest strong emission at MeV energies.

10 - 100 MeV gamma-rays from the inner magnetosphere (Polar Caps) are predicted in **all** pulsar theories

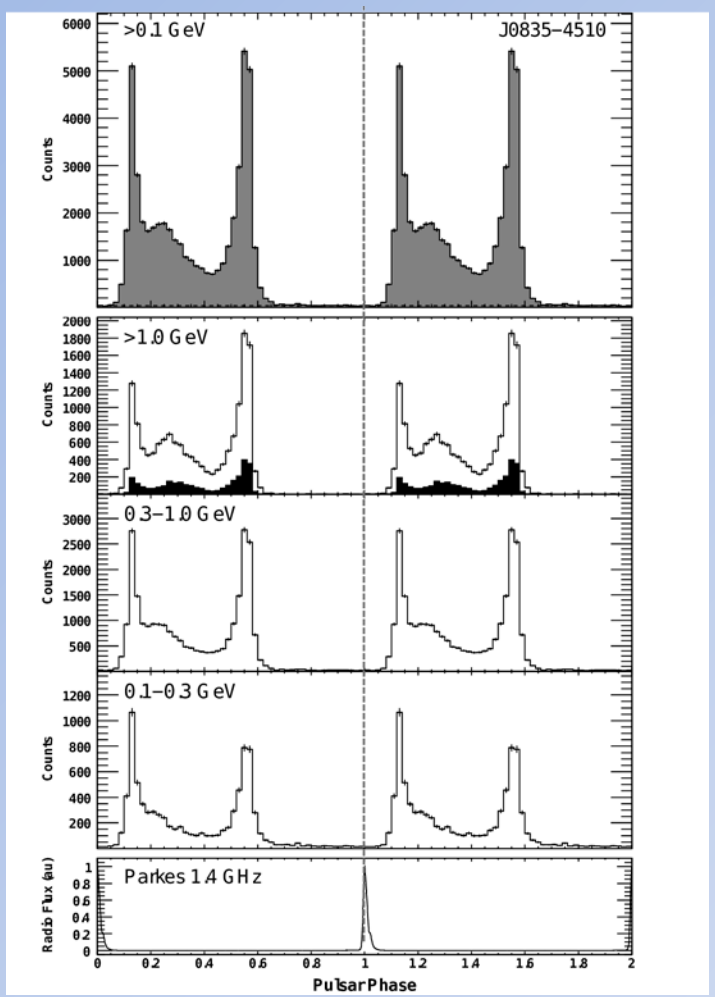


Instrument Requirements:

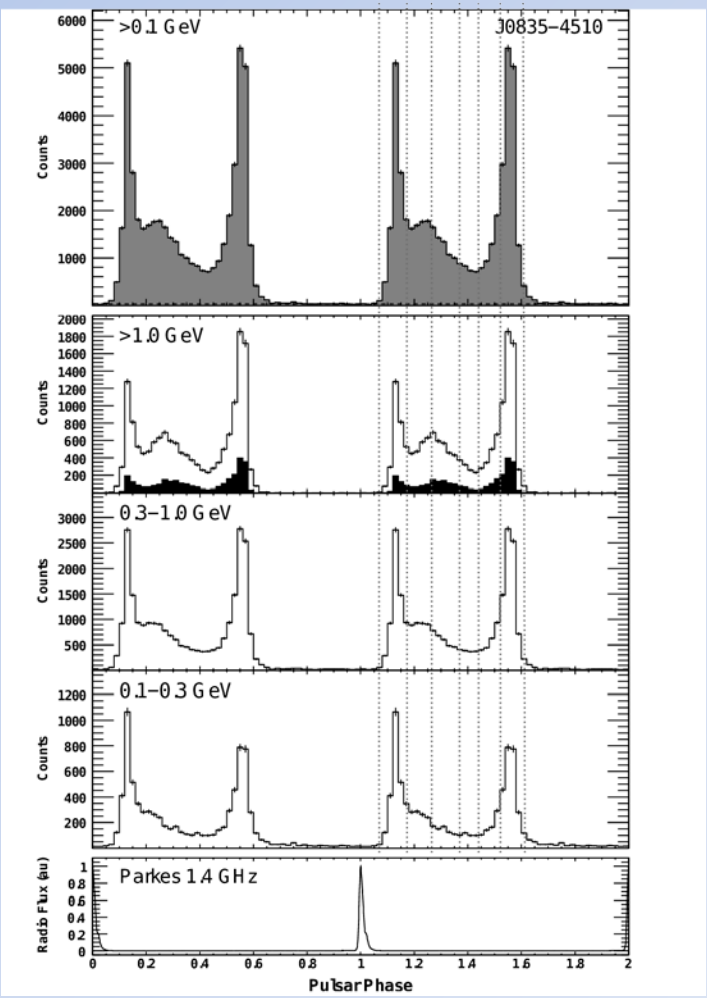
- MDP Polarization sensitivity ~1%
- Polarization angle accuracy ~10°
- Timing resolution ~1-10 msec
- Energy range 10-100 MeV
- Energy Resolution ~20%
- Angular resolution < 1 deg
- FOV ~2π sr

Pulsar Physics

Polar Cap emission



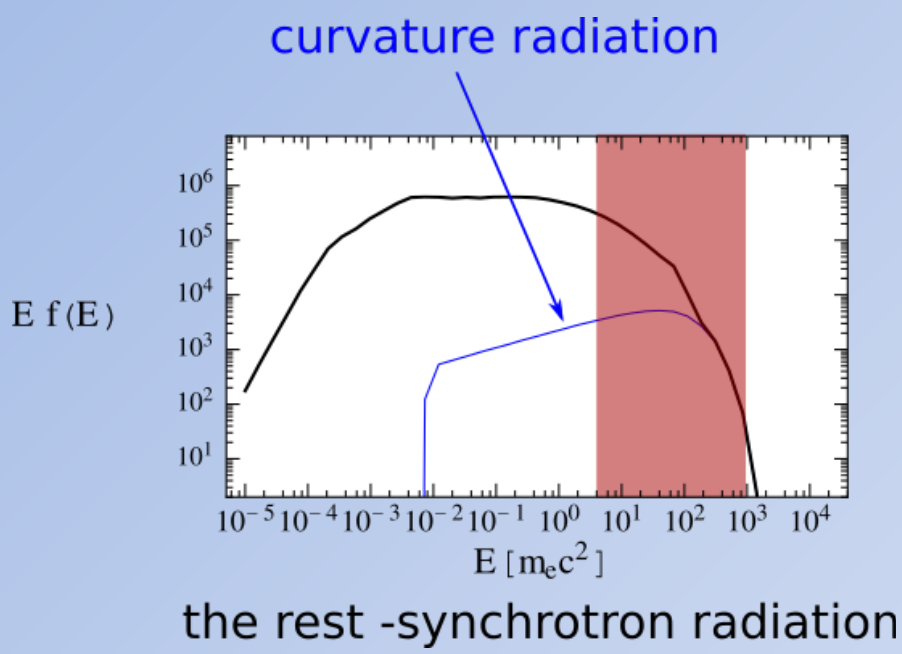
Phase-resolved polarization



Pulsar Physics

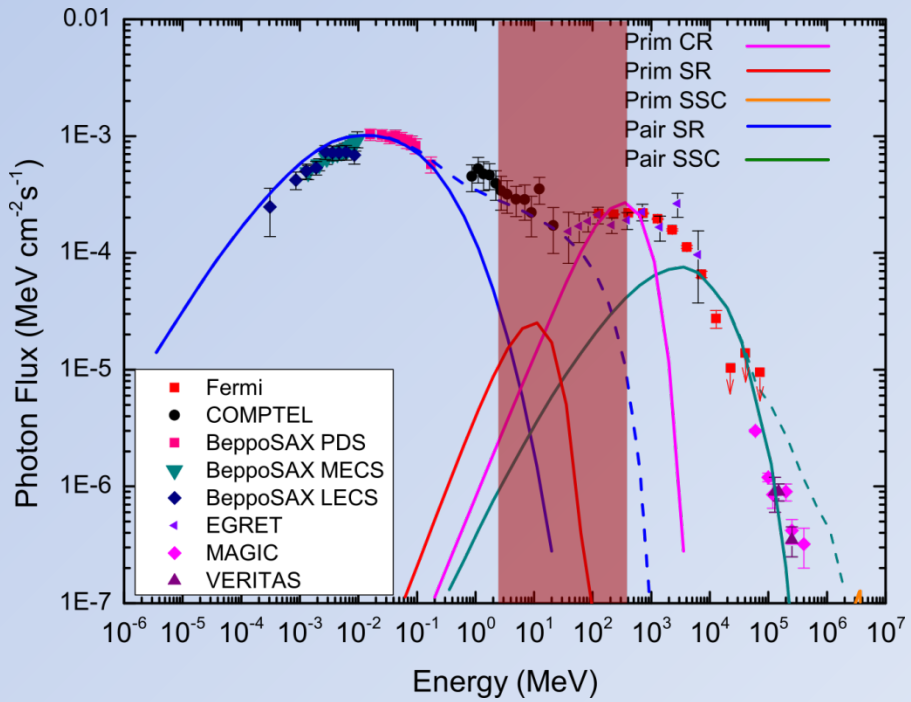
transition between emission mechanisms

Polar Cap emission



(Timokhin & Harding '15)

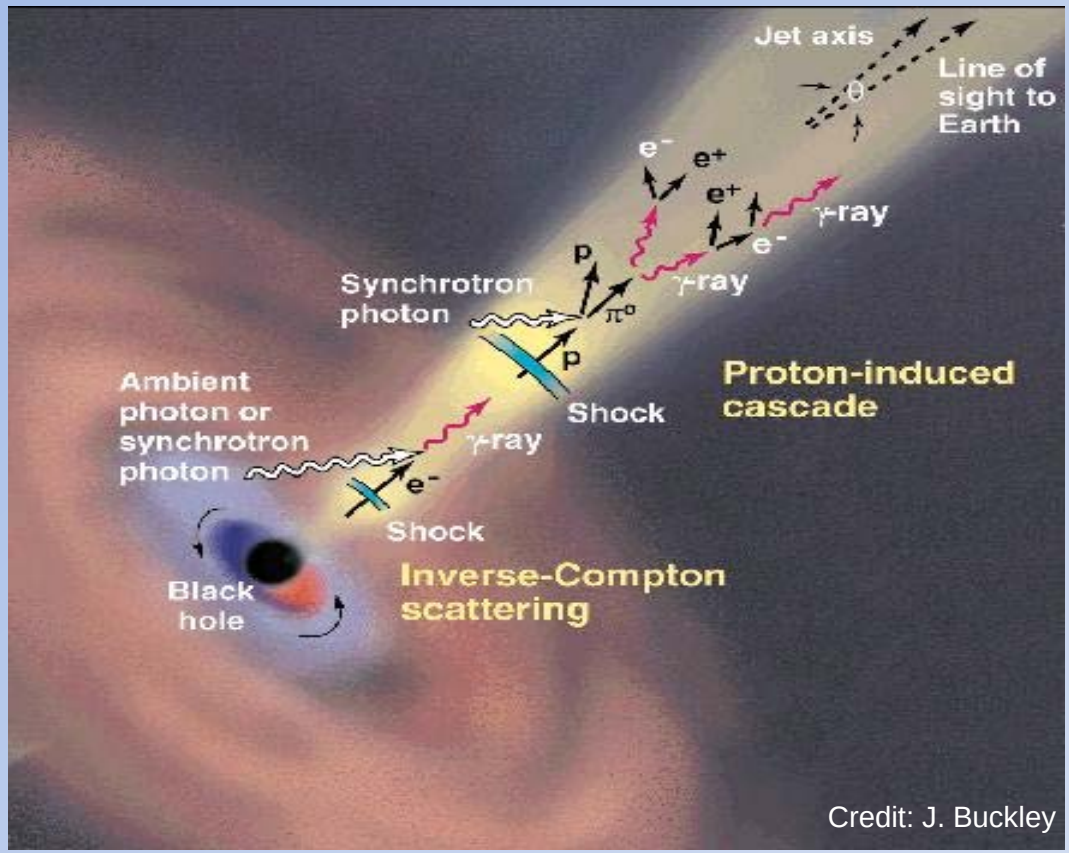
Outer magnetosphere emission

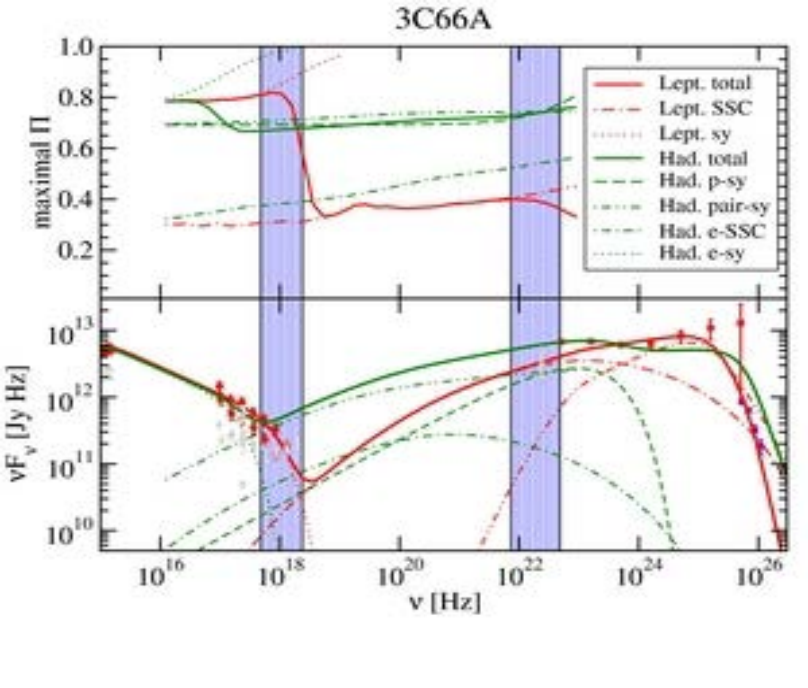


(Harding & Kalapotharakos '15)

AGN & GRB Physics

AdEPT will determine the cosmological evolution of AGNs and GRBs by mapping the magnetic fields and distinguishing between leptonic and hadronic processes

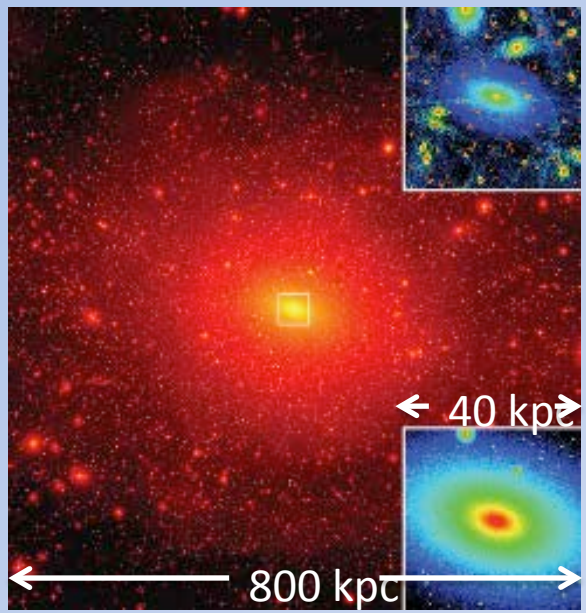




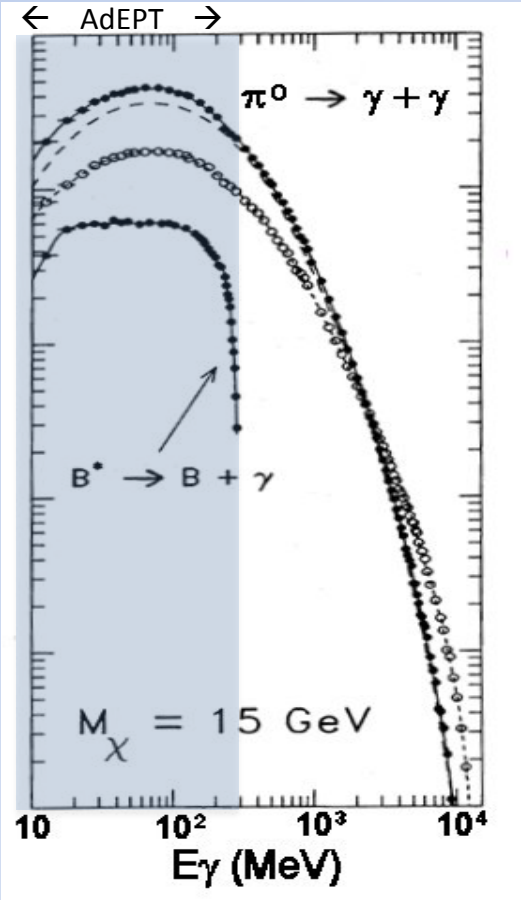
(Zhang & Boettcher '13)

Milky Way Dark Matter

AdEPT will search for Galactic dark matter in the Milky Way center and halo by looking for a MeV gamma-ray annihilation signature of dark photon mediators



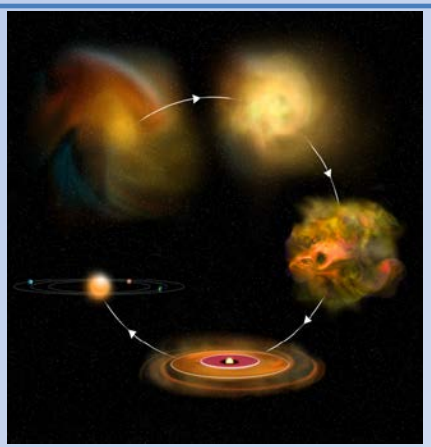
DM Sim (Diemand et al. Nature, 2004)

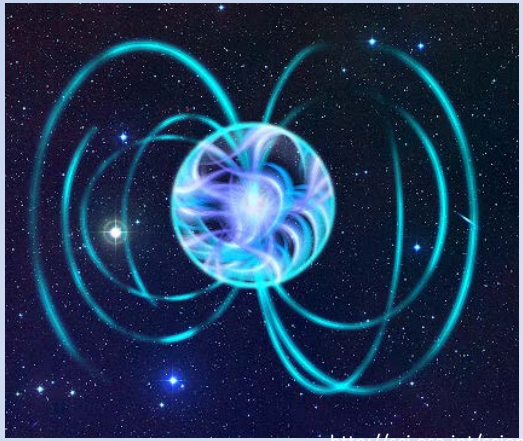


DM Annihilation g-ray spectra
(Stecker & Tylka 1989)

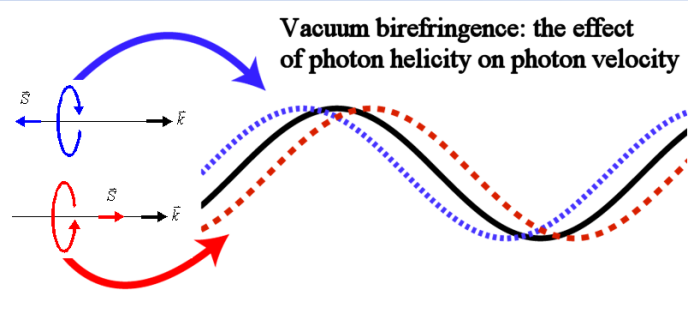
Other Science Goals

- <u>Galactic Diffuse Emission</u>
  - Study star formation and cycle of matter
  - Resolve source contribution to Galactic diffuse emission
  - Distinguish Galactic regions where leptonic vs. hadronic processes are dominant
- <u>Time Domain Astronomy</u>
  - Observe entire sky every orbit
  - Gamma Ray Bursts
- <u>Exotic Physics</u>
  - Test physics around neutron stars, magnetars, and black holes
  - Test limits of Relativity (Lorentz invariance)



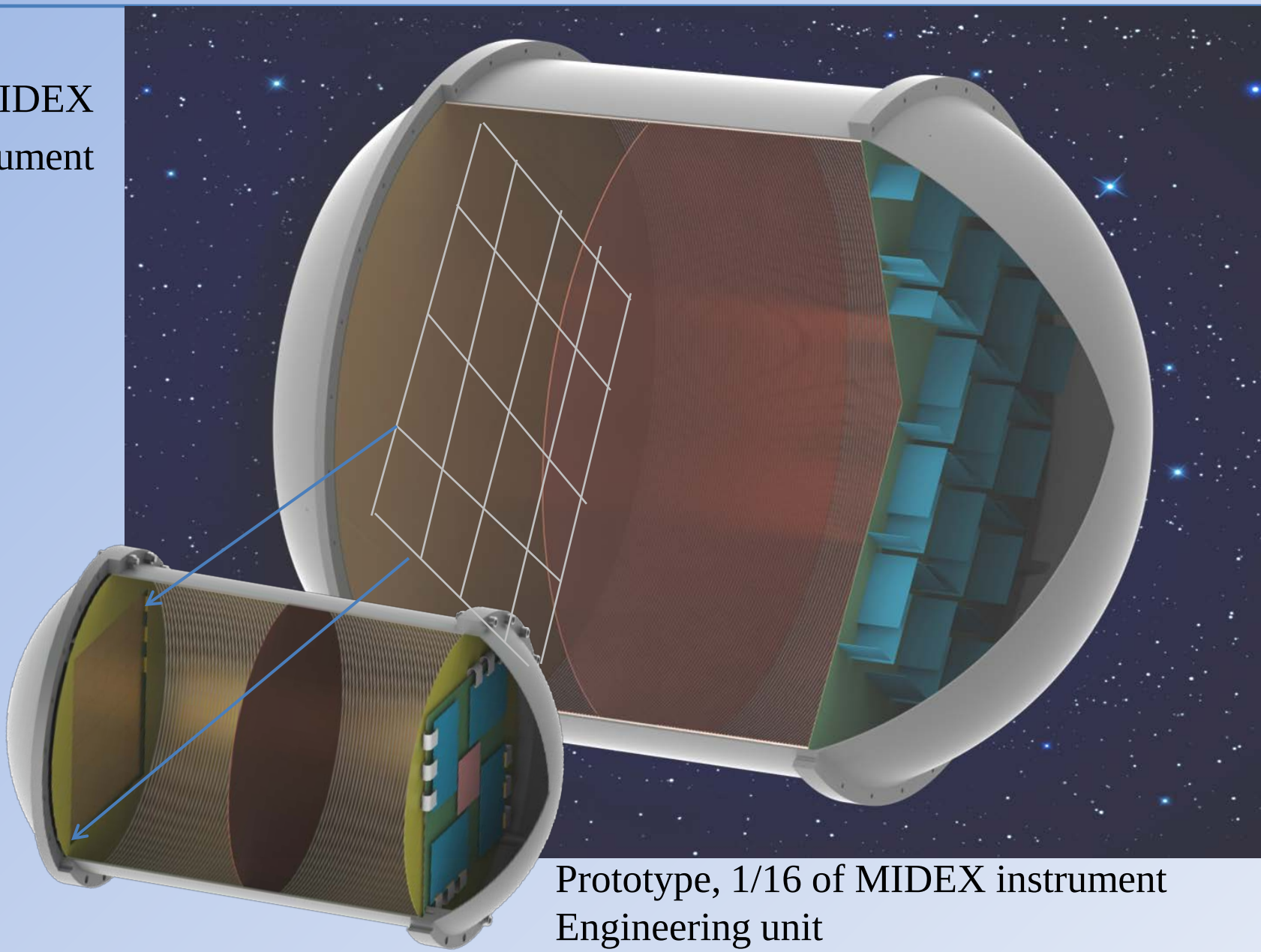


http://sci.esa.int/science-e/



AdEPT MIDEX and Prototype

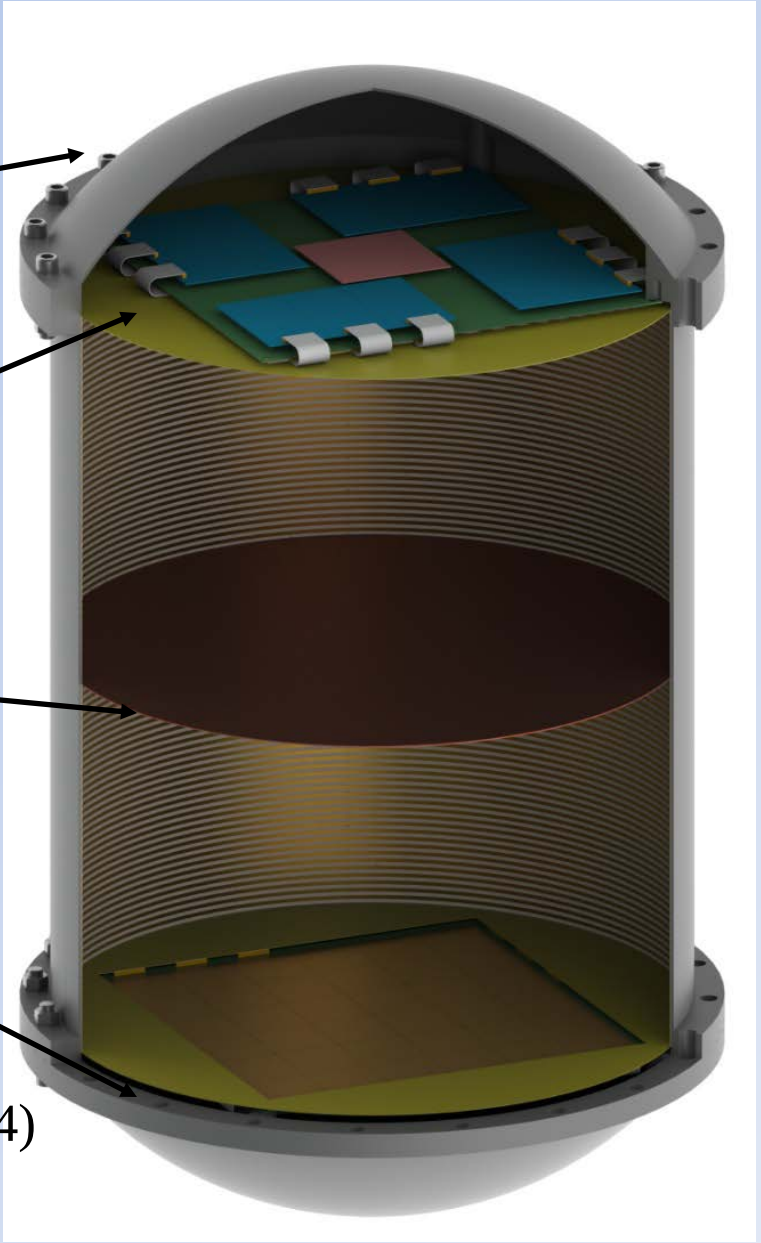
MIDEX
Instrument



Prototype, 1/16 of MIDEX instrument
Engineering unit

AdEPT Instrument

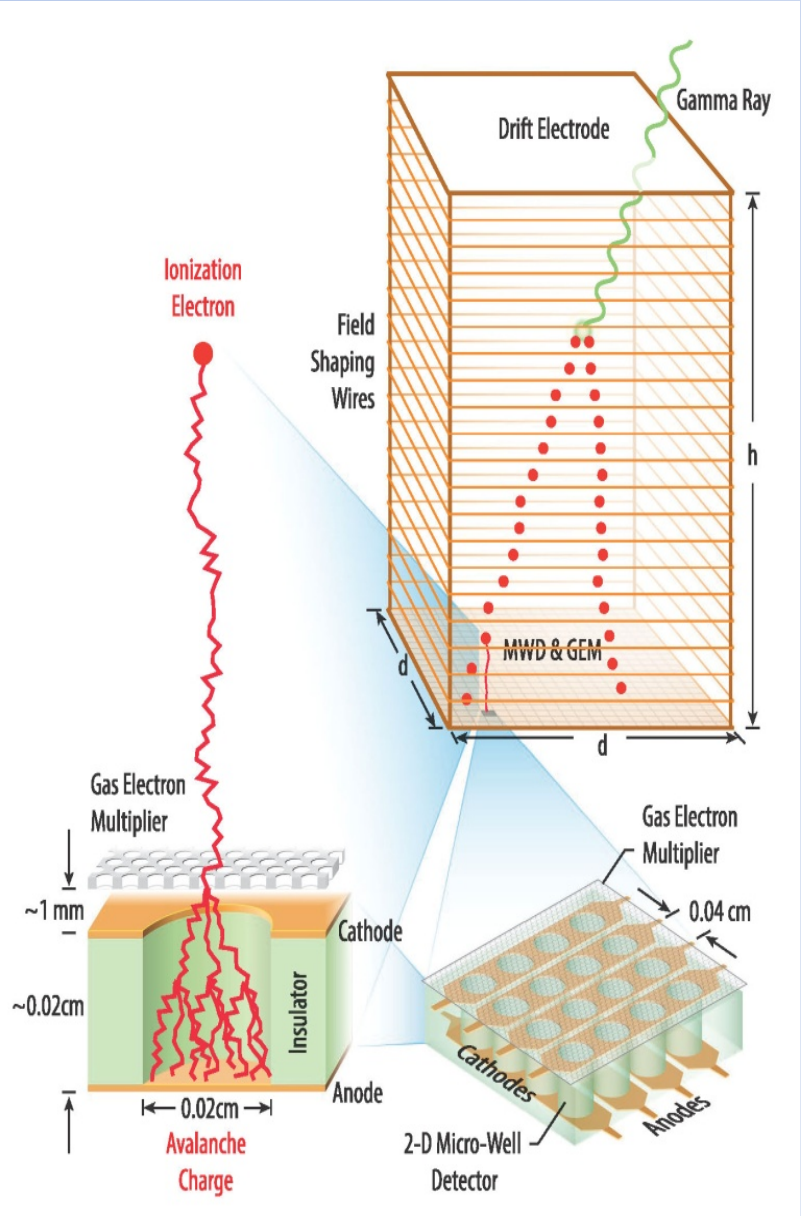
- AdEPT is a simple instrument, only 4 mechanical structures
  - Gas pressure vessel
    - Cylinder, Field shaping grid on internal surface
    - Upper and lower domes
  - Upper readout plane
  - Common high voltage plane
  - Lower readout plane
  - Electronics
  - On-board computer processing



- Hunter, et al., Astroparticle Physics 59, 18-28 (2014)

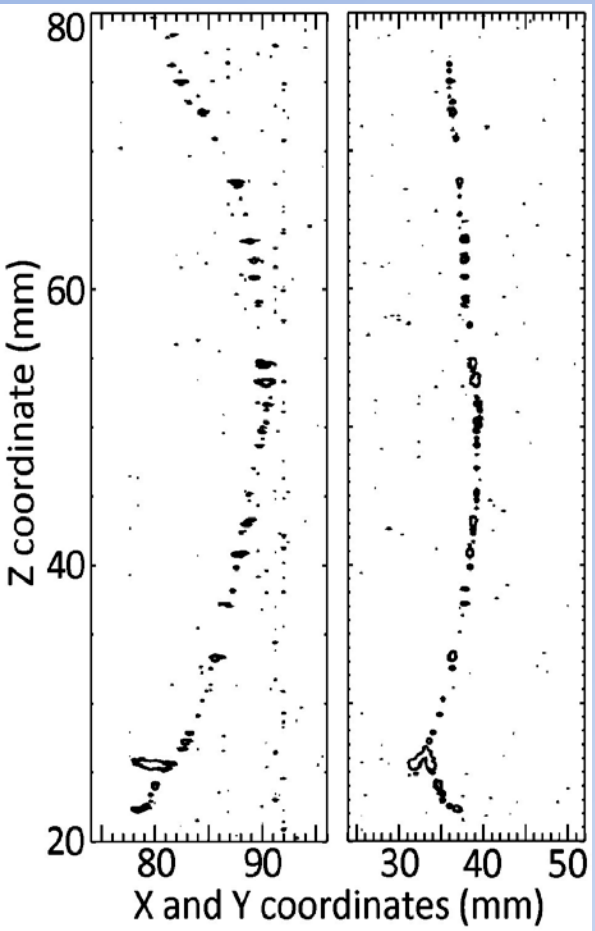
Instrument Detector Physics

- **Enabling technology** is 3-DTI, Three-Dimensional Track Imager
  - Large volume gaseous TPC
    - Ionization chamber
  - Micro-Well Detector (MWD) readout
    - 2-D Proportional counter (PC)
    - Z-coordinate from drift time
  - Ar + CS_2 at 1.5 atm
    - Ar – active detection medium
      - Chemically inert, no gas deterioration
    - CS_2 negative ion molecule
      - Dramatically reduces diffusion → increased detector volume



AdEPT Heritage

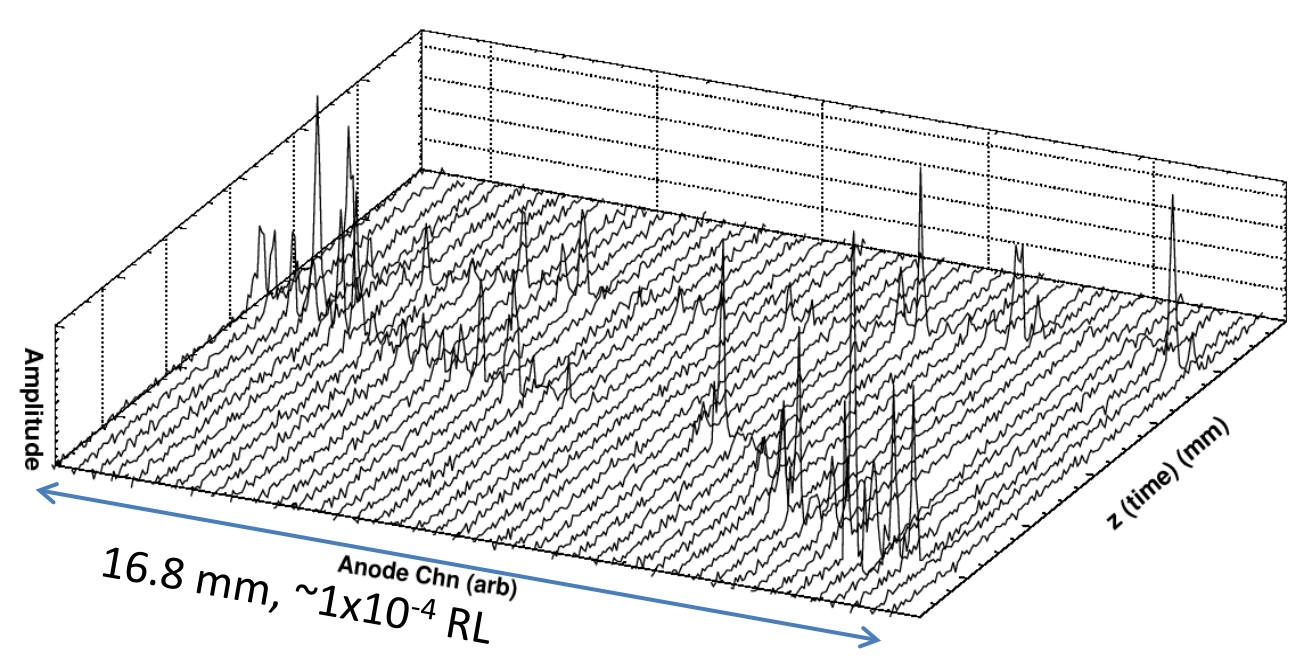
Demonstration of 3-DTI for neutron imaging - 2011



Electron Tracking in 3-DTI

X-Z, & Y-Z projections of single electrons from ^{90}Sr in Ar +CS_2 with 0.4 mm resolution

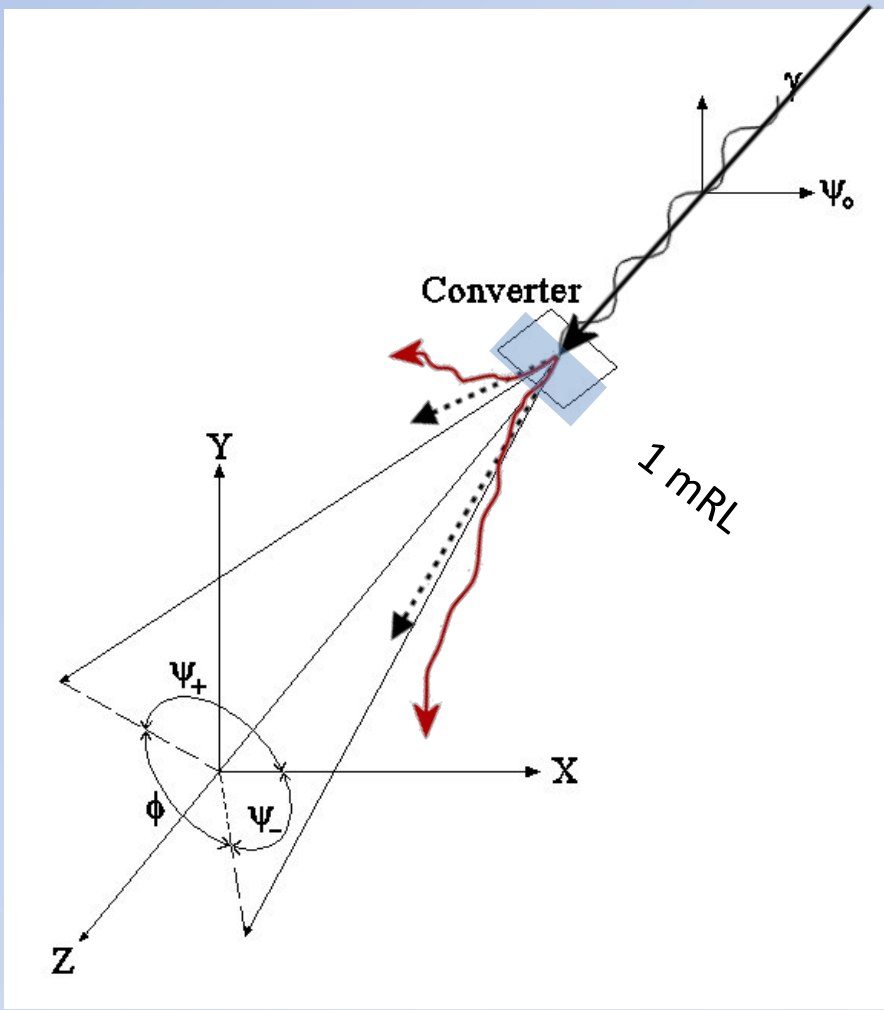
X-Z projection of 6.129 MeV gamma interaction in 80% P-10 + 20% CS_2



Principle of Polarization Measurement

- Polarization is encoded in the azimuthal angle of the pair

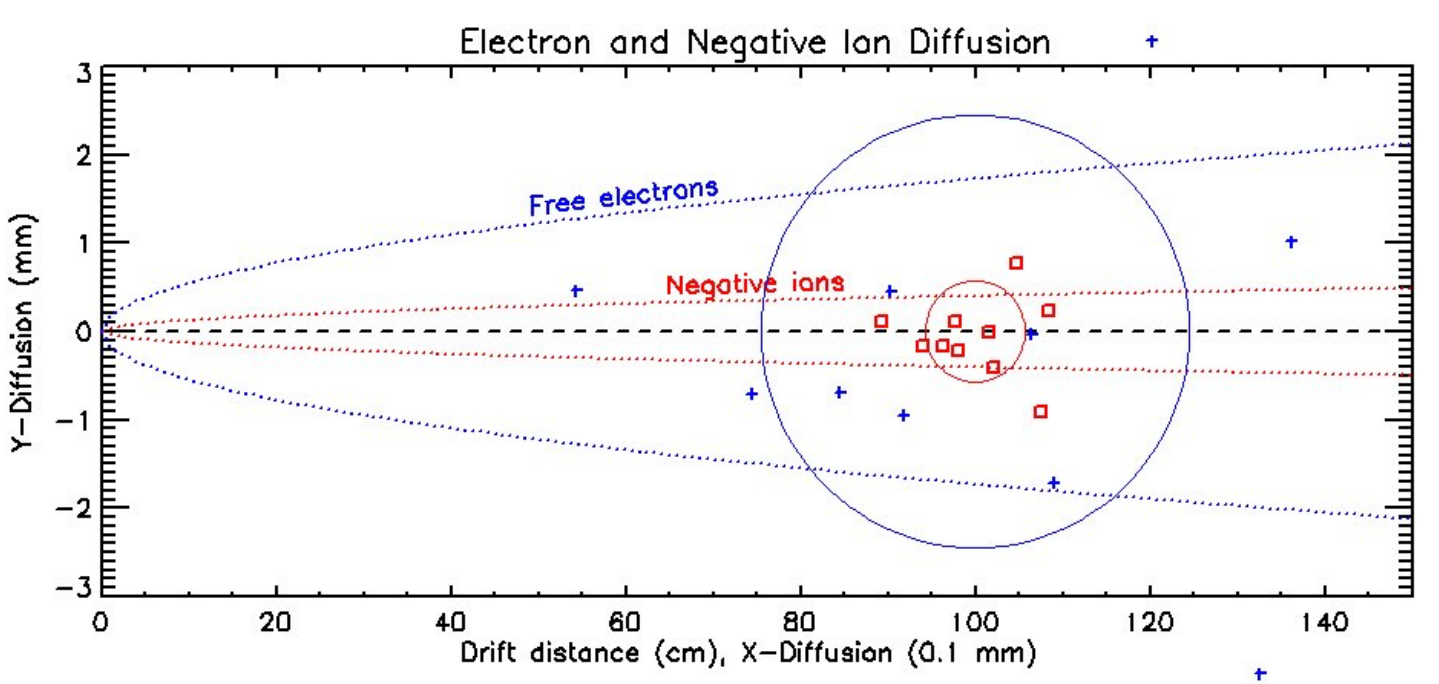
- **Direction of the pair must be measured before being confused by Coulomb scattering, in < 1 mRL**



1 mRL:
~100 μm of Si (< 1 track coordinate)
~80 mm of Ar at 1.5 atm (200 track coordinates)

Enabling Long Drift Distance

by adding an electronegative component to the gas

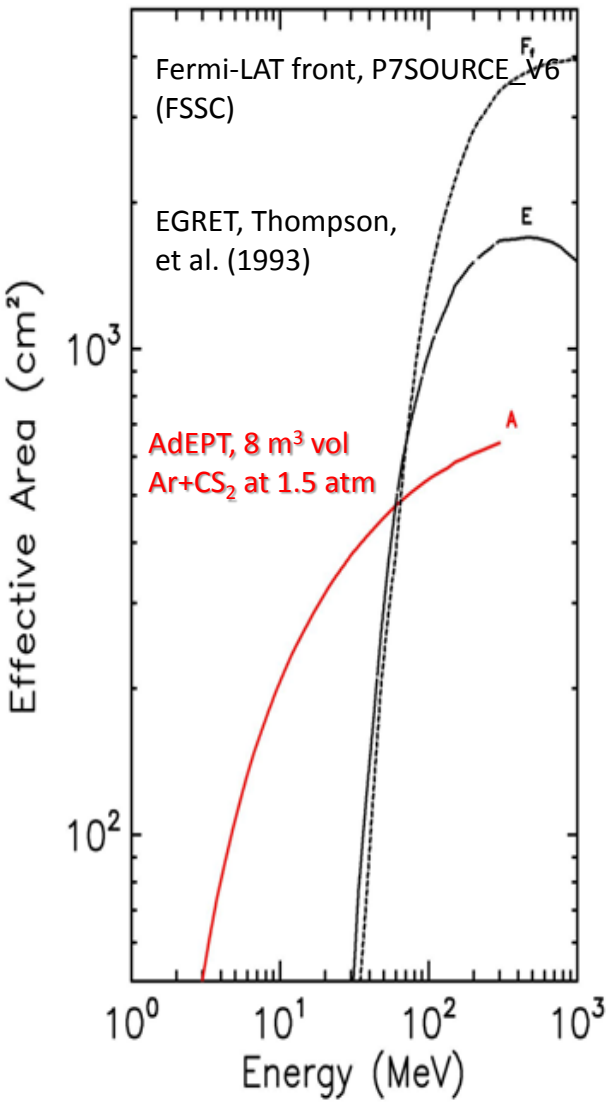


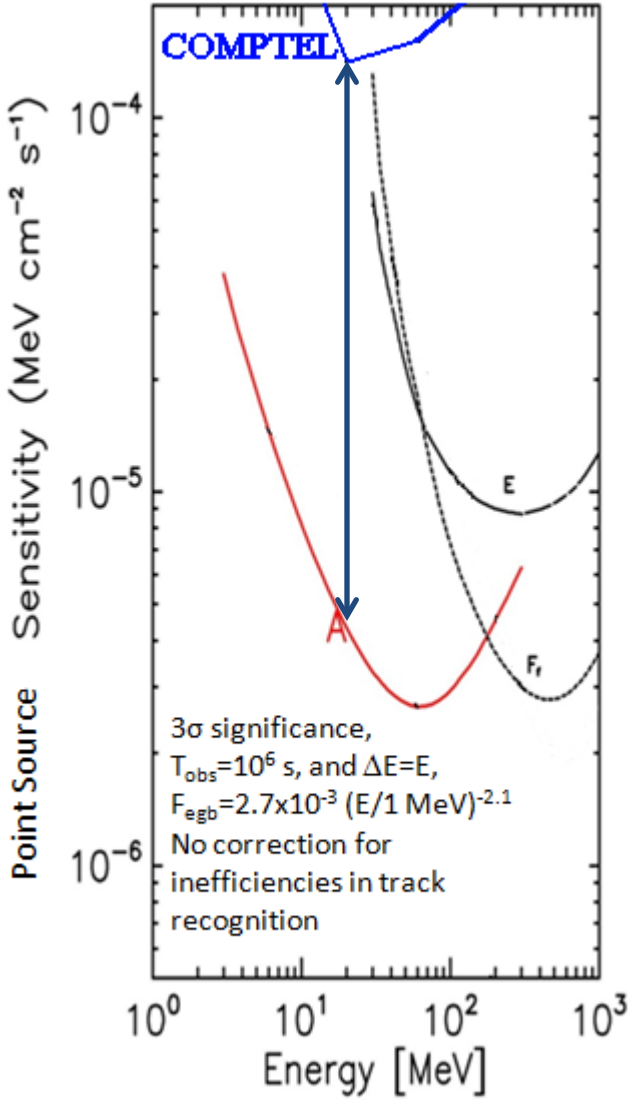
- CS_2 captures ionization electrons, forming negative ions, which drift in thermal equilibrium with the gas.
- Diffusion *decreases* with increasing drift field and is independent of gas mixture

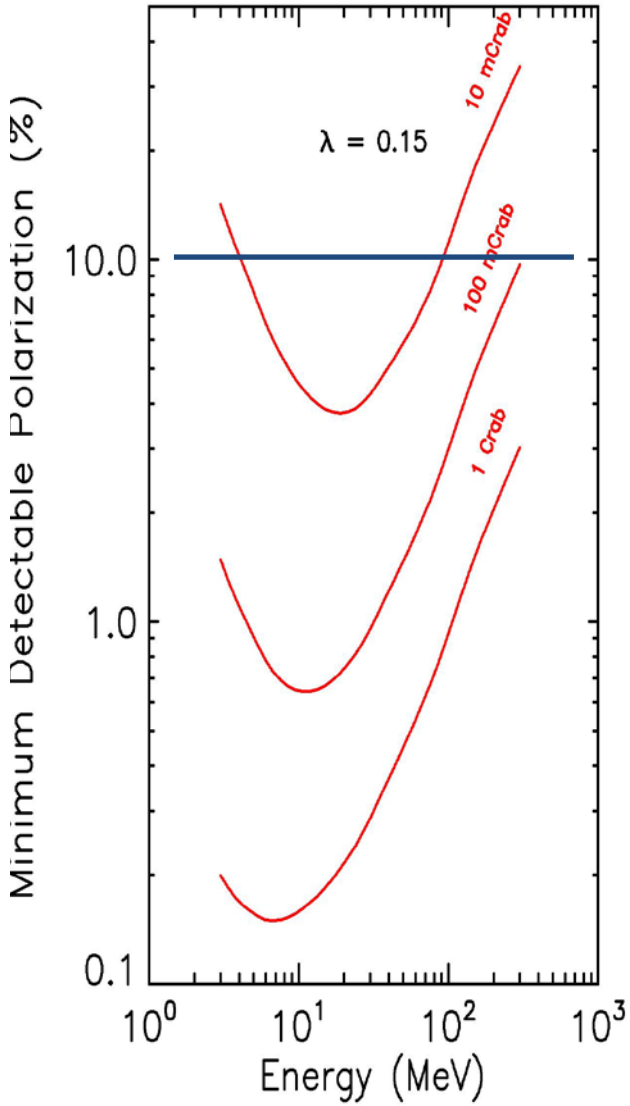
Baseline Gas Options

- Gas, Noble gas preferable
  - Chemically inert
    - He, Z=2, difficult to seal PV
    - Ne, Z=10, costly
    - **Ar, Z=18, cheap**
    - Kr, Z=36, radioactive, costly
    - Xe, Z=54, negative ion drift velocity too low (~2 m/s)
    - Rn, Z=86, radioactive, negative ion drift velocity way too low
- Negative ion additive
  - Gas or low vapor pressure
  - Low-ish electronegativity
    - CH_2NO_2
    - **CS_2, Z=40**
    - O_2, Z=8, appealing, untested

AdEPT Baseline Performance

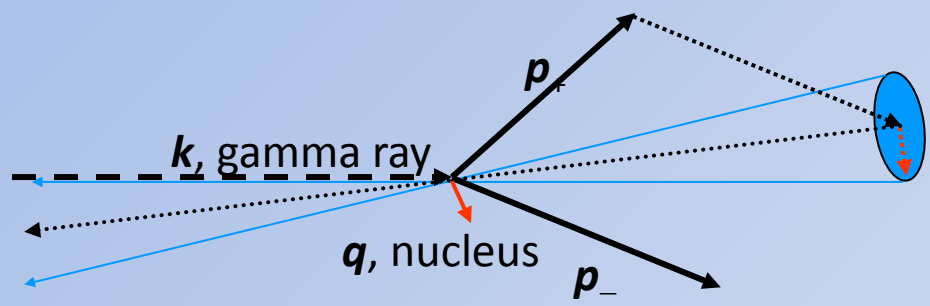




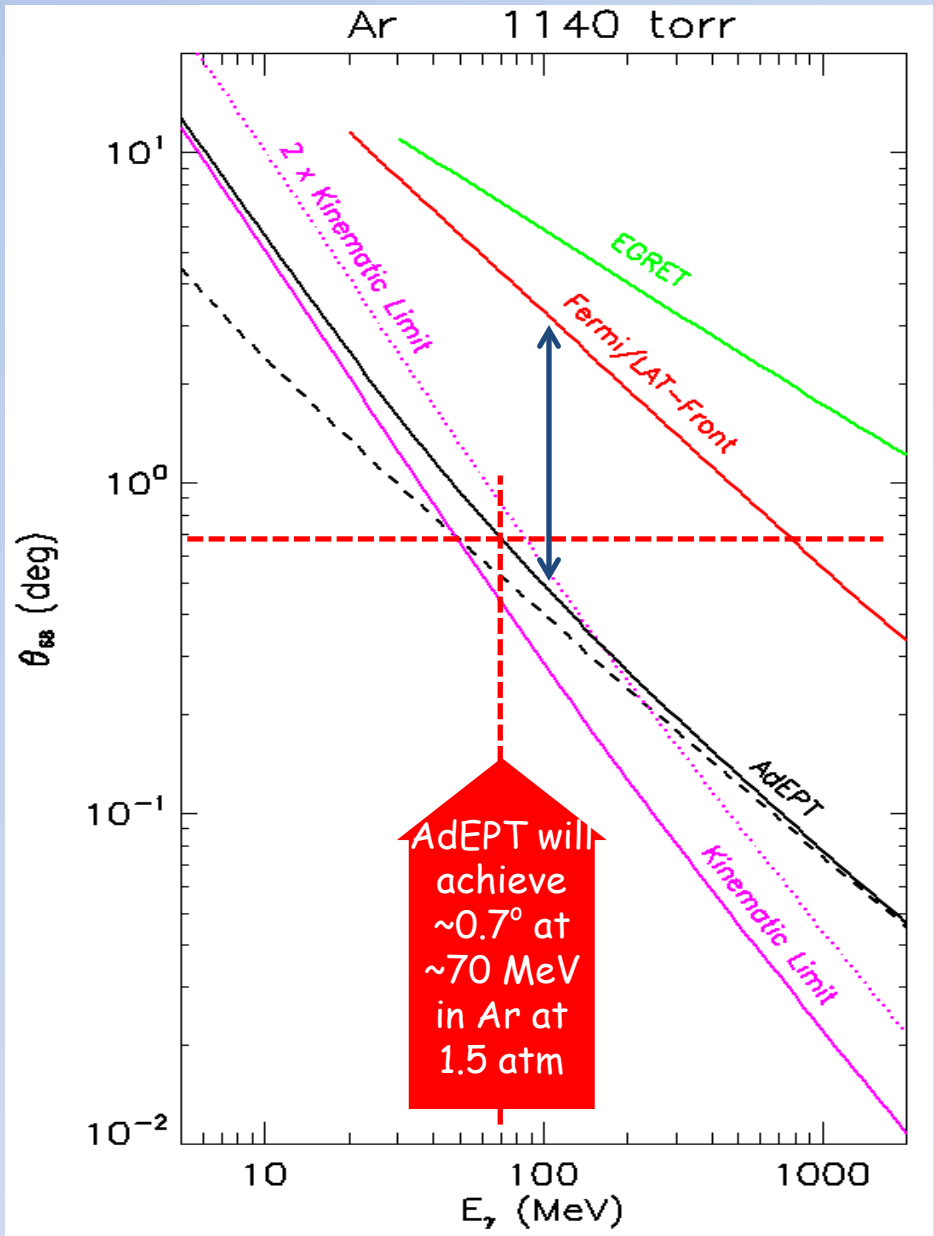


AdEPT Angular Resolution

- AdEPT will achieve **angular resolution** approaching the **kinematic limit**, the best allowed by the physics

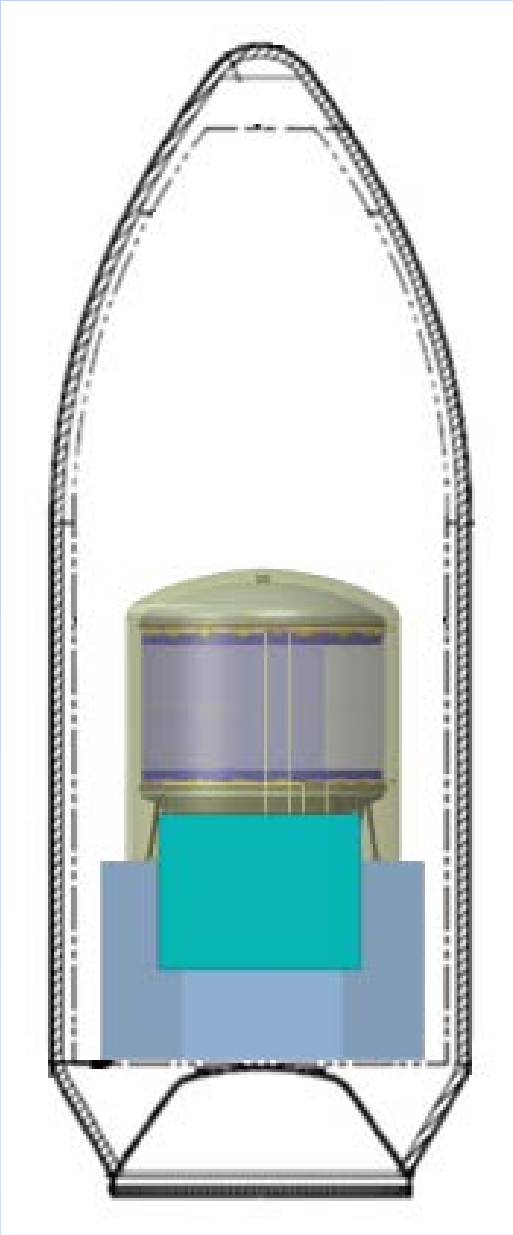


- Equivalent of "diffraction limited" optics!

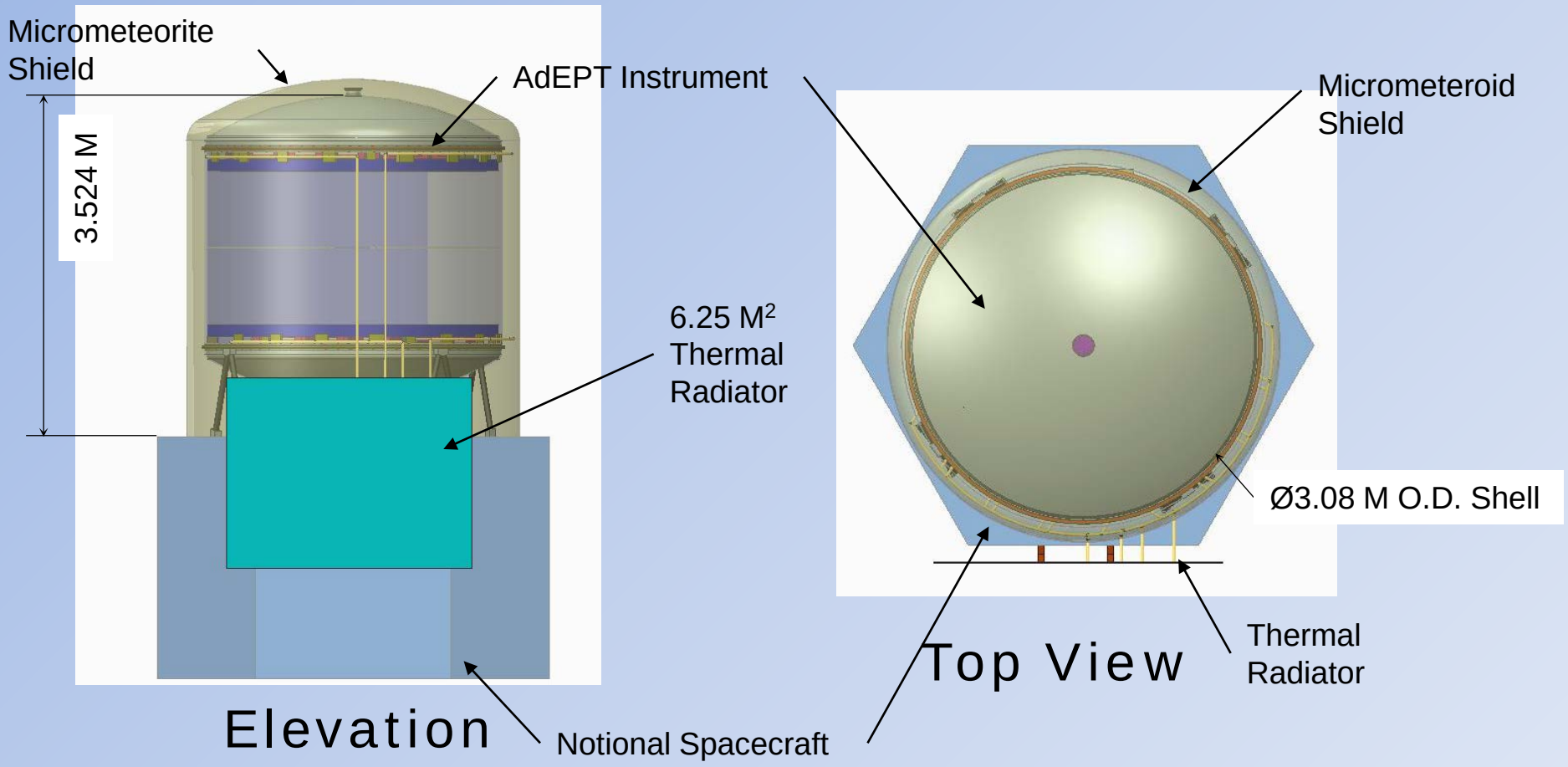


AdEPT Mission Realization

- Gas volume: 8 m^3
- Instrument: 995 kg
  Spacecraft: 445 kg
- 600 km circular LEO, 28° inclination
  zenith pointed, scanning mode operation
- Falcon-9 rocket
- Fits within MIDEX constraints



Instrument Design

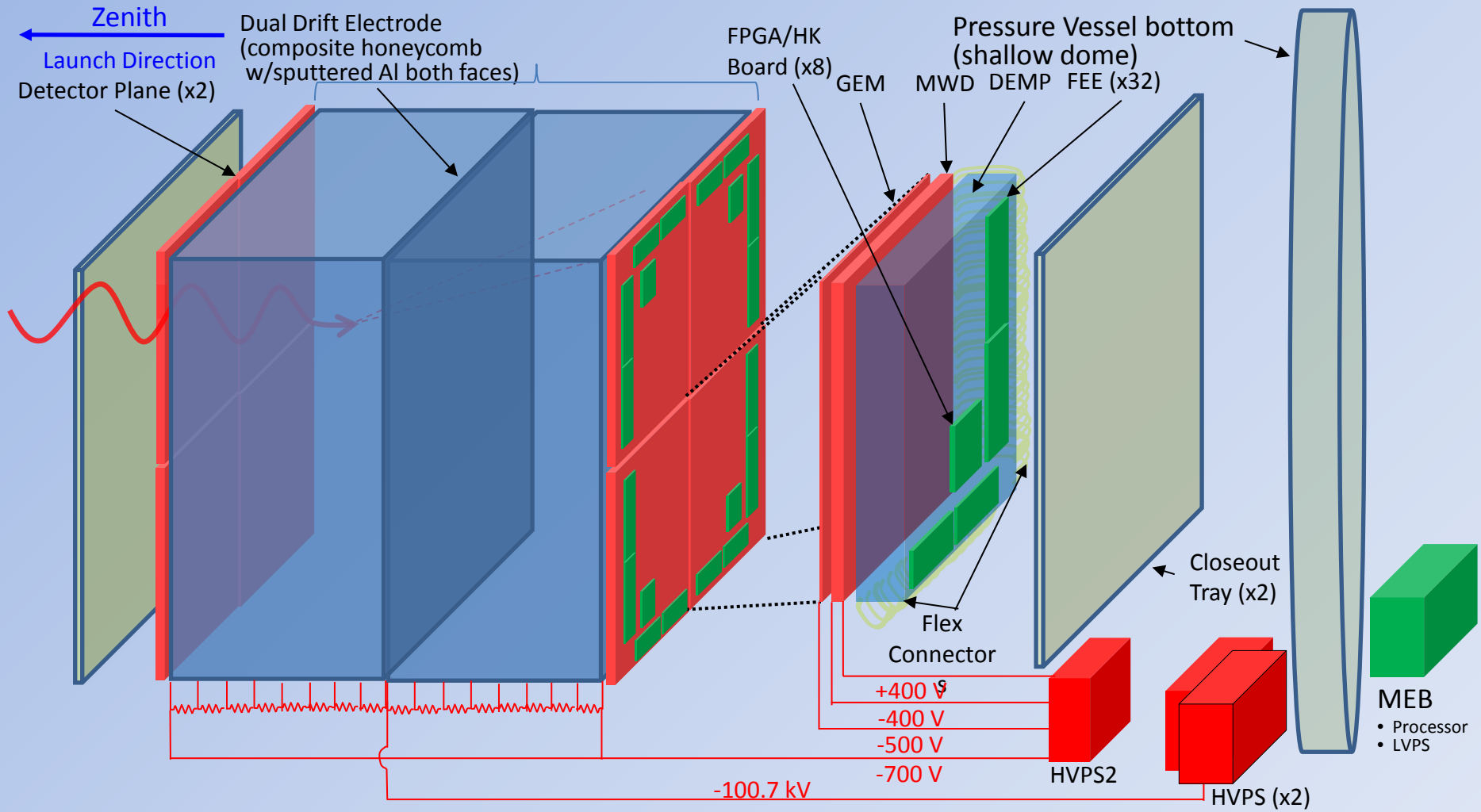


AdEPT Technologies

new science - new technology

1. Composite Pressure Vessel
2. Field Shaping Grid
3. **Micro-Well Detector**
4. ASIC and FPGA
5. **On-Board Processing**

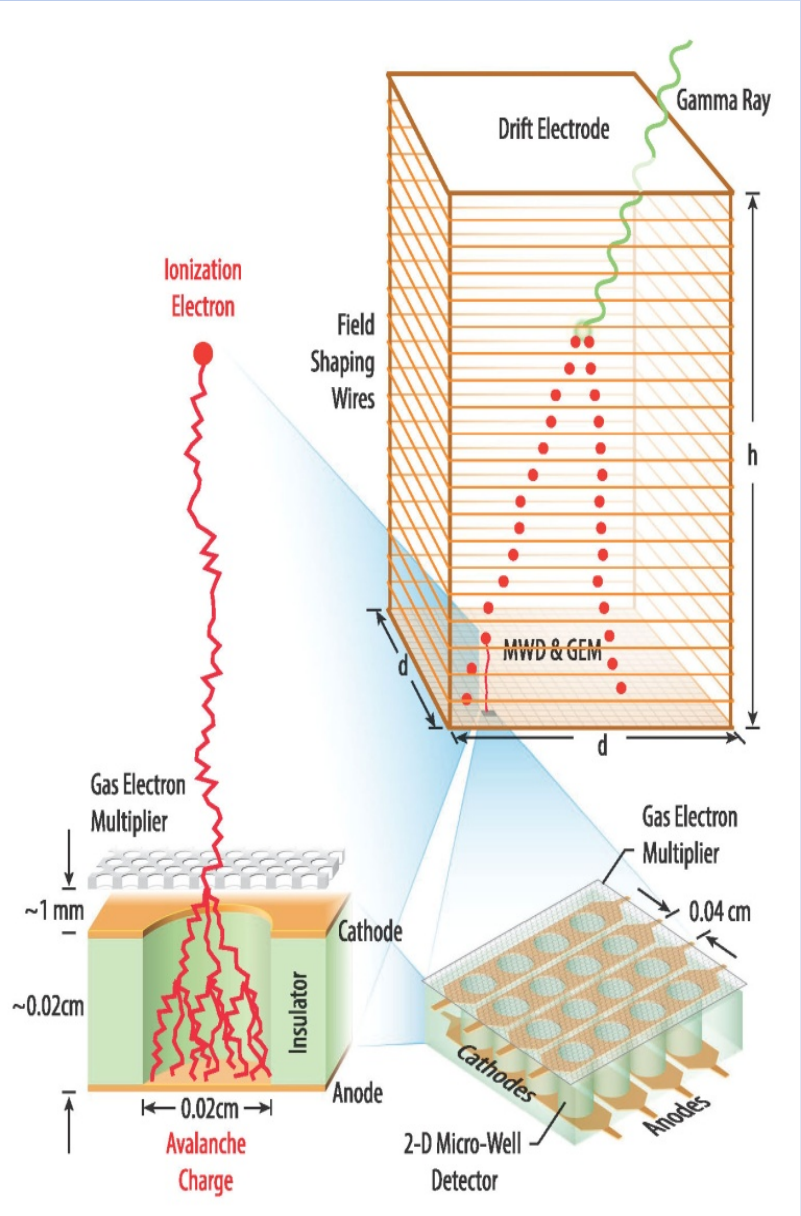
Instrument Block Diagram



Micro Well Detector Approach

- Ionization from charged particles drifts to detectors and must be "read out"

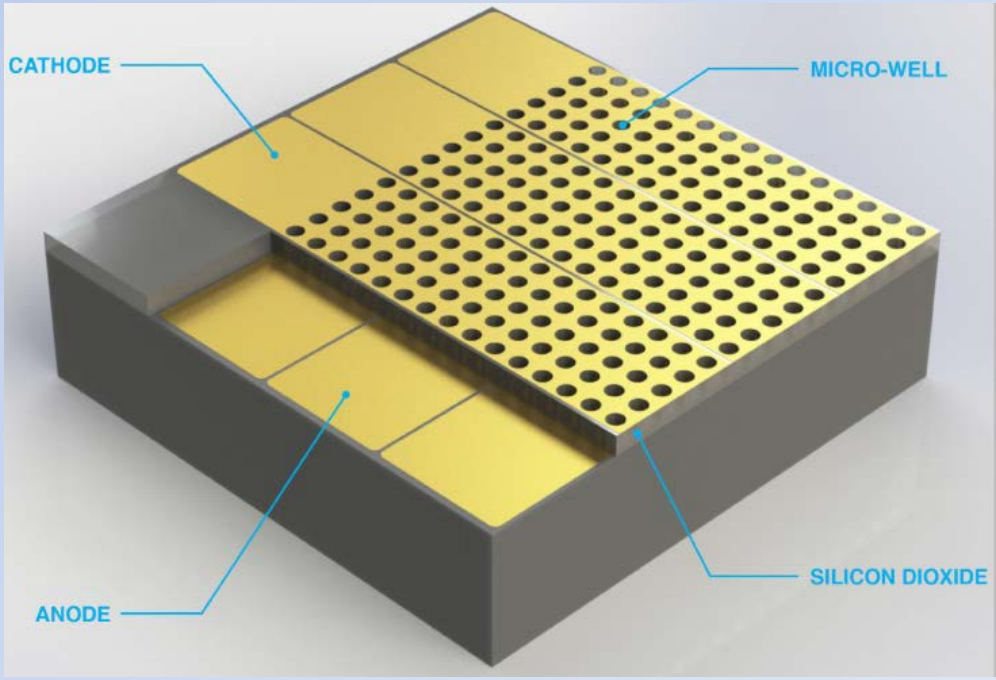
- Micro Well Detectors (MWD)
  - 2-D readout from single detector
  - Active detector, gain up to 10^6



Silicon Micro Well Detectors

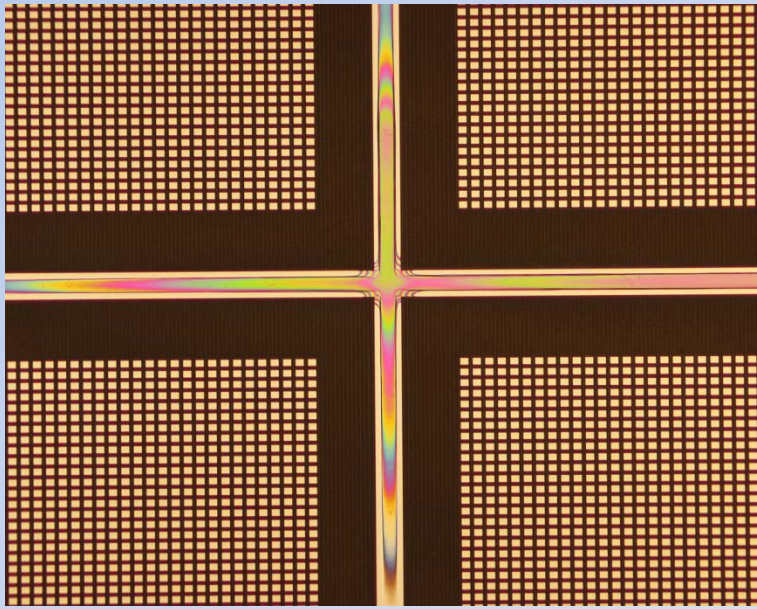
- Pixel size related to diffusion
  - Pitch: 400 μm ≈ 1/2 electron cloud diffusion over 100 cm drift
  - Well diameter: 1/4-1/8 of pitch,
  - Well depth (aspect ratio), ~1:1 empirically determined

- Inorganic SiMWD
  - Inorganic materials
  - Take advantage of commercial silicon wafer technology

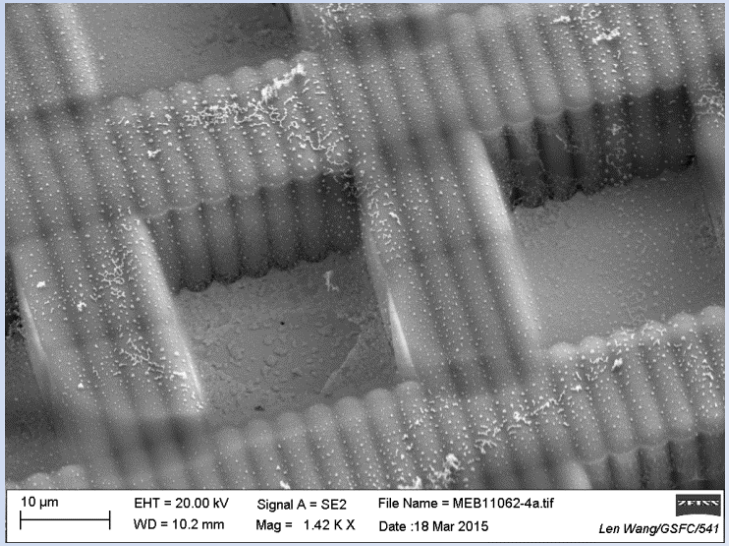


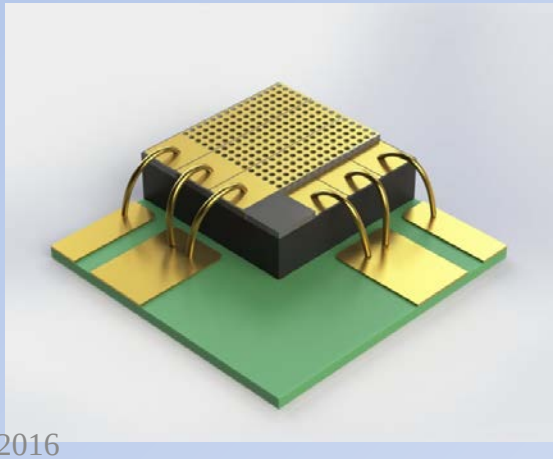
SiMWD Fabrication

- Use inorganic materials
  - SiO_2 insulator, surrounding Si posts
  - Au electrodes
  - Etch away Si posts to form wells
  - All electrodes accessible from top surface
- Packaging
  - Bonding SiMWDs to substrate
  - Wire bonds for electrode-electrode interconnect electrodes and electrode-PCB



First DDL engineering unit, Dec. 2014





On-Board Processing (OBP)

must discriminate γ-rays from cosmic rays to generate science data

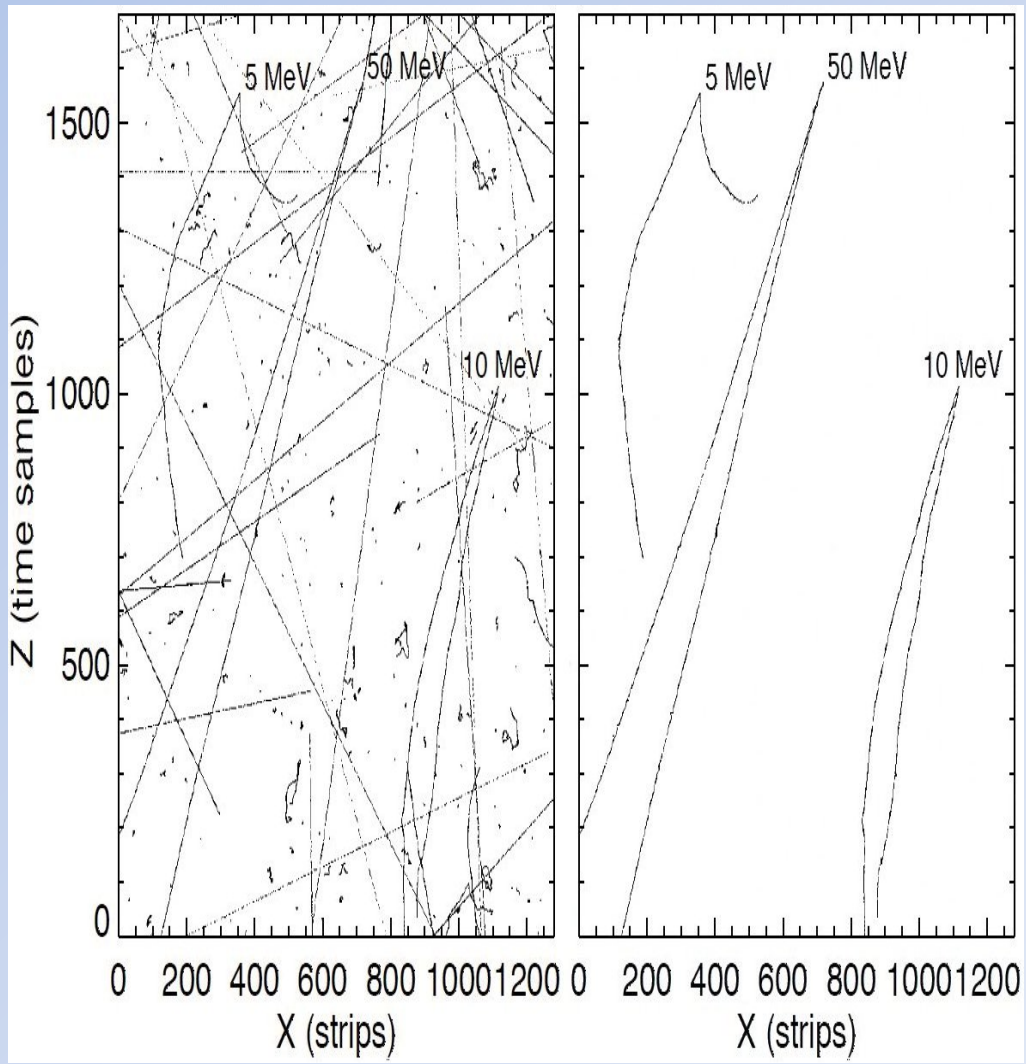
- Tracks drift to MWD and must be "read out"

  No trigger possible

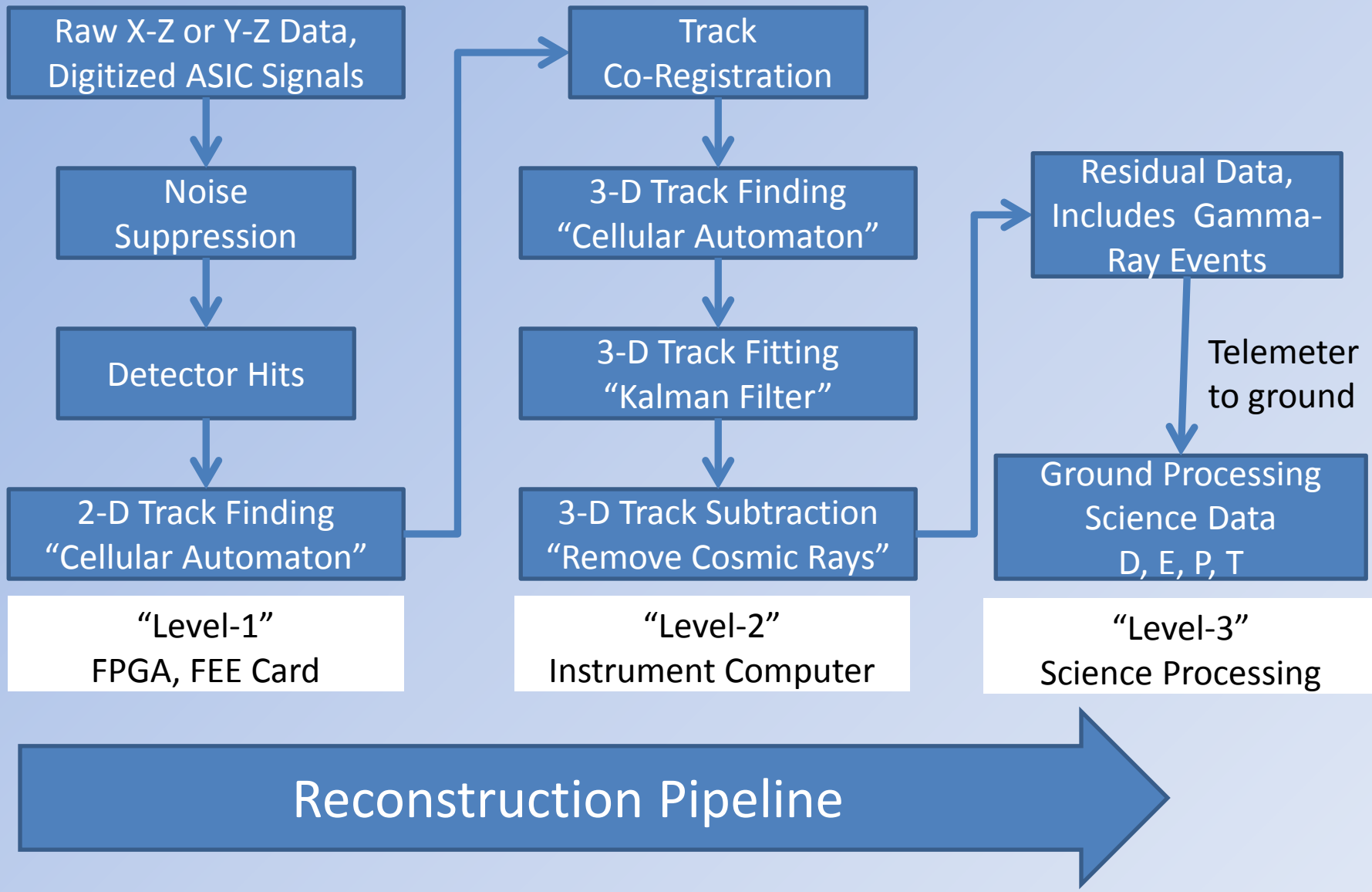
- Negative ion technique
  - Enables long drift distance ~1m
  - Reduces drift velocity $\times 10^3$, ~16 m/s
  - Total drift time is ~50 ms
  - Increases occupancy of CR tracks

  Anti-coincidence not viable

- Streaming Mode Operation
  - Gb/s raw data rate
  - No readout dead-time

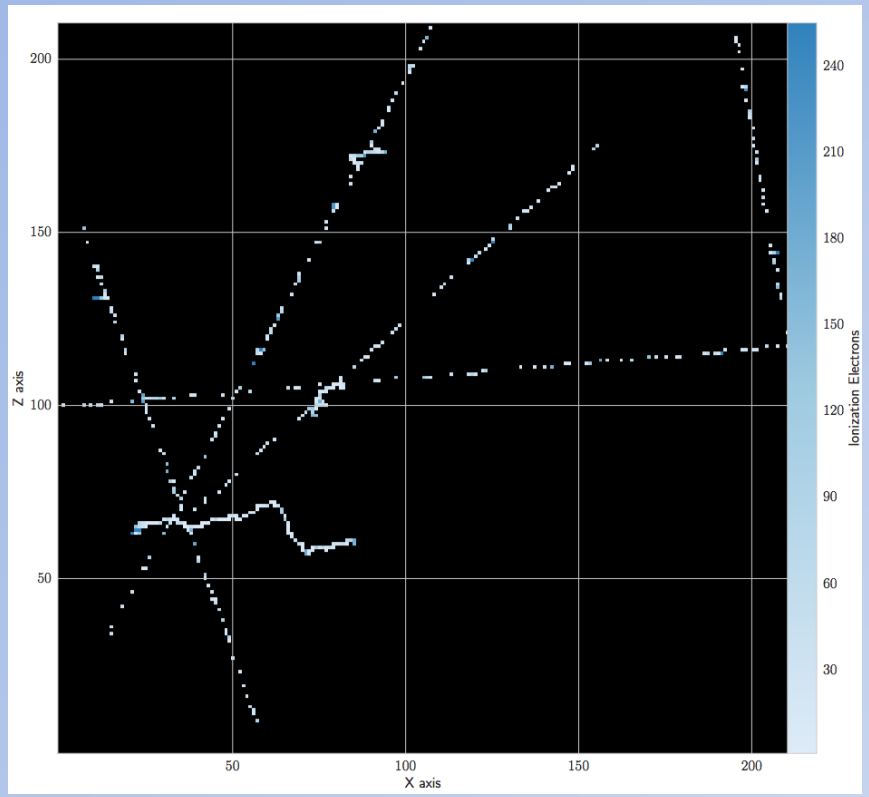


OBP, Approach

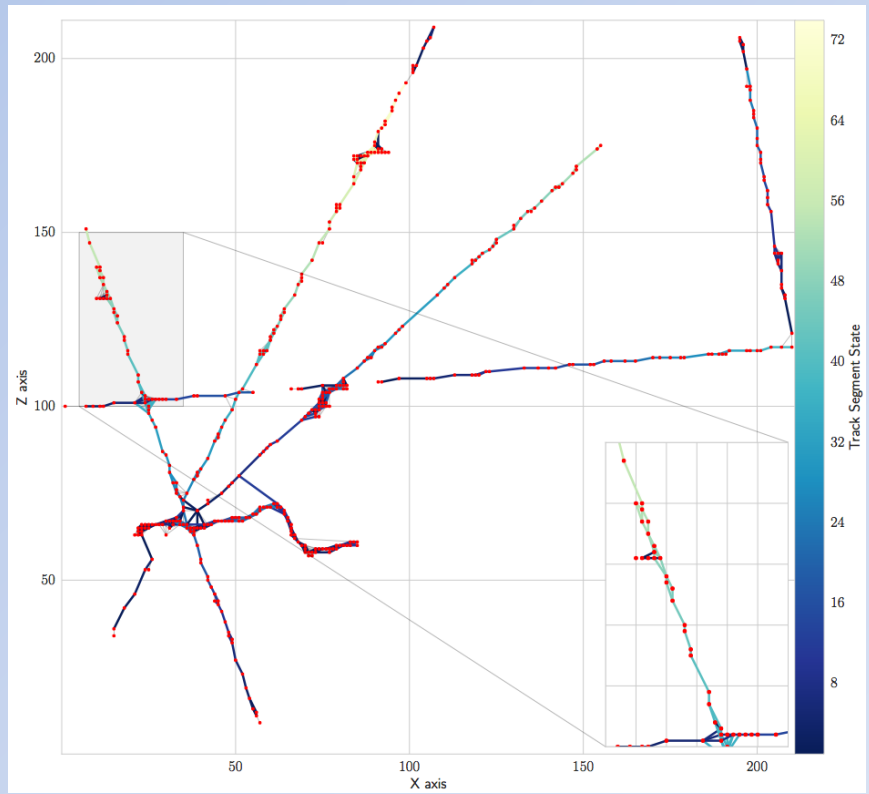


OBP, CAA Monte Carlo Results

Raw Data



CA Track Finding



Cellular Automaton Advantages

- Simple, Vector based (fast)
- Intrinsically parallel
- Performed locally on the FPGA of the FEE
- Useful for complicated event topologies

Instrument flow-down requirements

Science Requirement	**Physical parameter**	**Detector requirement**	**Instrument requirement**
Energy range 2-500 MeV	Pair production	3-D tracking of e-/e+ pair	3-D position of ionization electrons
Highest achievable polarization sensitivity	Measure pair azimuthal angle in < 1 mRL	Accurate tracking, high granularity	Minimize electron diffusion, low density medium
Best angular resolution	Limited by recoil momentum	Minimize Coulomb scattering	Low density interaction medium
Isotropic performance	No preferred tracking direction, 2π sr FOV	Isotropic interaction medium, omni-directional tracking	100 % active conversion medium, no passive material
Substantial improvement in continuum sensitivity	Large geometric area, large interaction volume, best angular resolution	Minimize distortion due to electron diffusion	Negative ion drift, large active volume
Energy resolution to resolve pi-zero feature	$\Delta E/E$ better than 30%	Measure Coulomb scattering of tracks over large distances	Energy $\propto$ Coulomb scattering, large active volume

The AdEPT is

A

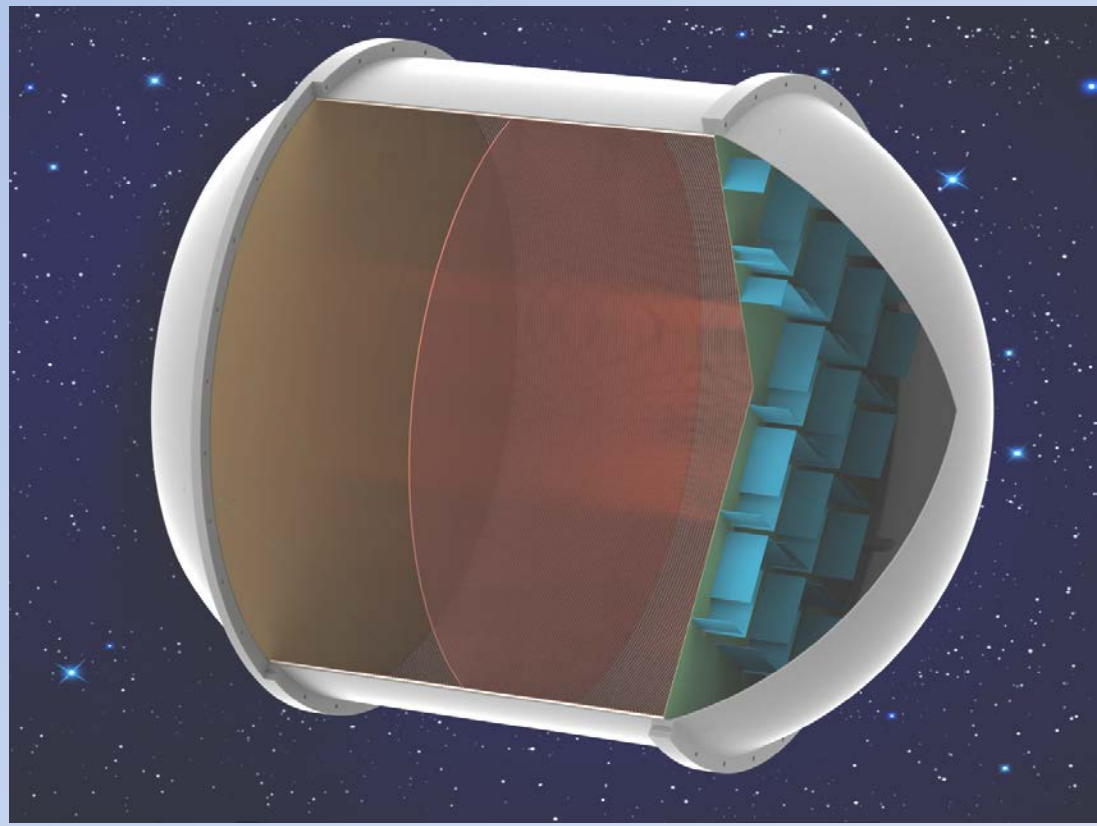
Direction

Energy

Polarization

Time

Mission



The complete photon signature