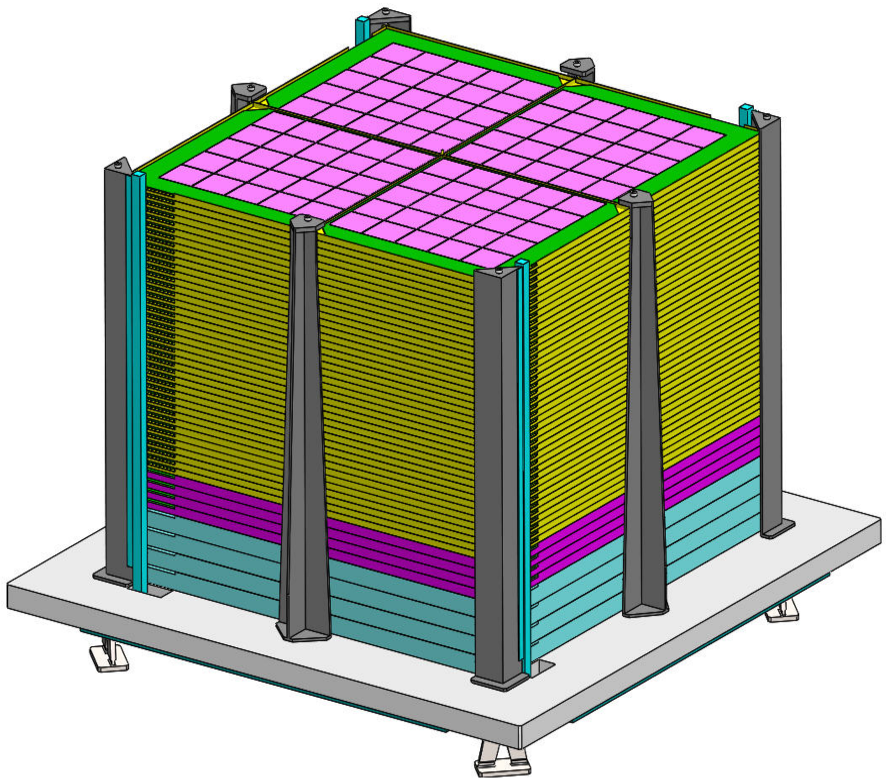
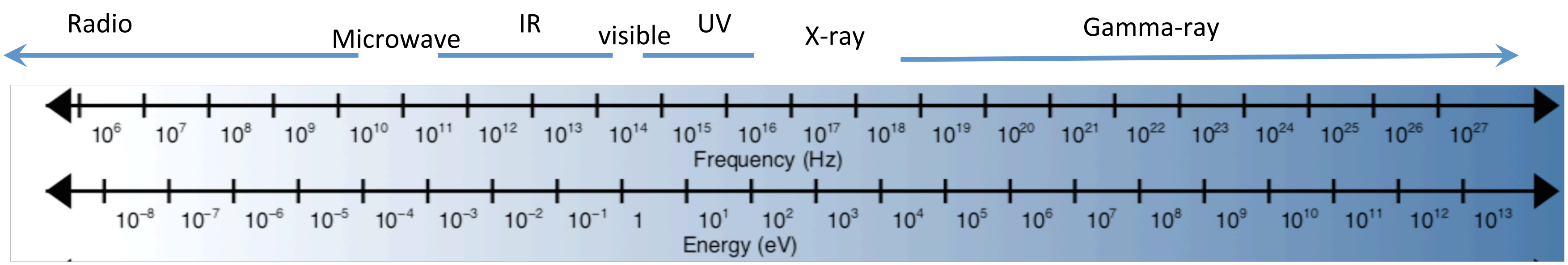
Exploring the MeV Universe

Julie McEnery (NASA/GSFC)



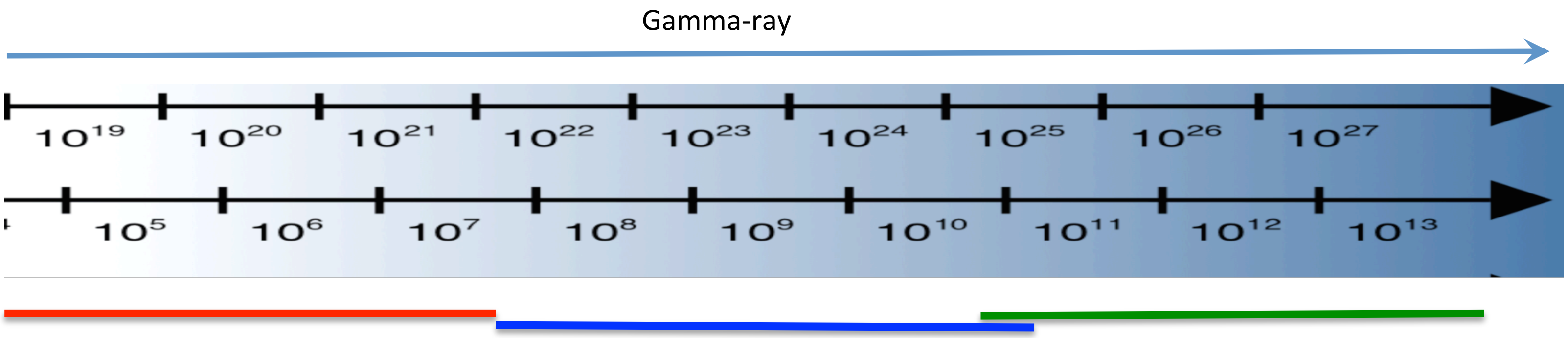
Gamma-ray Astrophysics



- Gamma-rays cover a huge swath of the electromagnetic spectrum
- High-energy gamma-rays probe the non-thermal universe
  - Explore extreme environments hosting powerful particle accelerators
- Huge advances in the past decade…

Gamma-ray Astrophysics

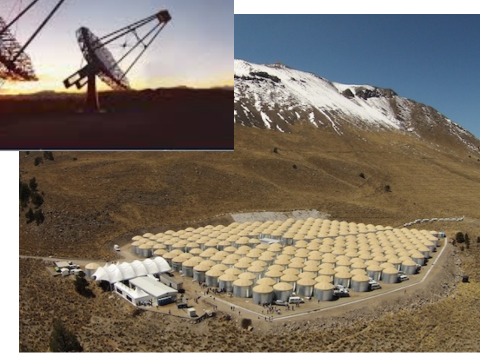
Freq (Hz)
Energy (ev)



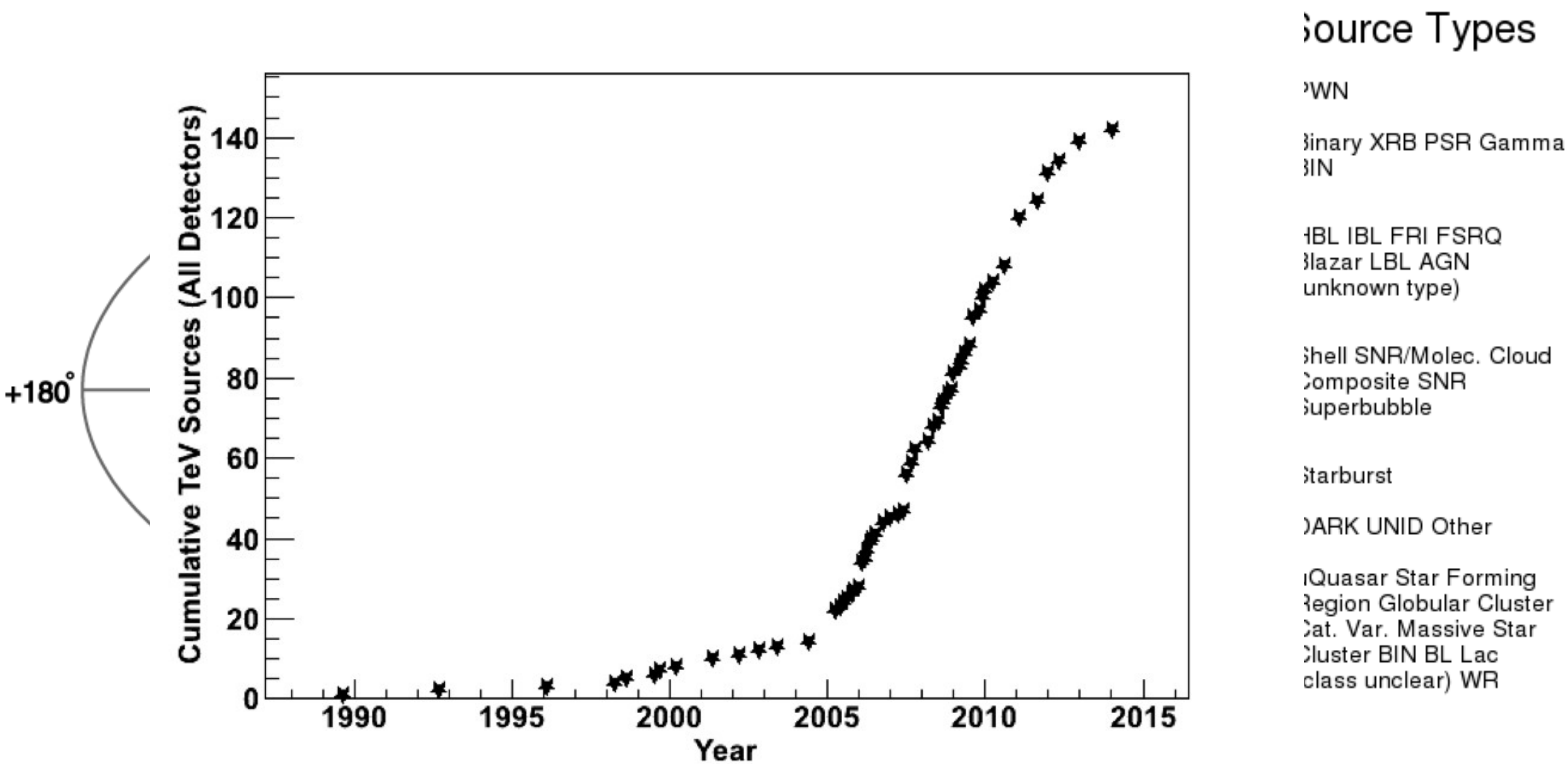
Medium Energy gamma-rays (aka MeV)

High Energy gamma-rays (aka GeV)

Very High Energy (VHE) gamma-rays (aka TeV)

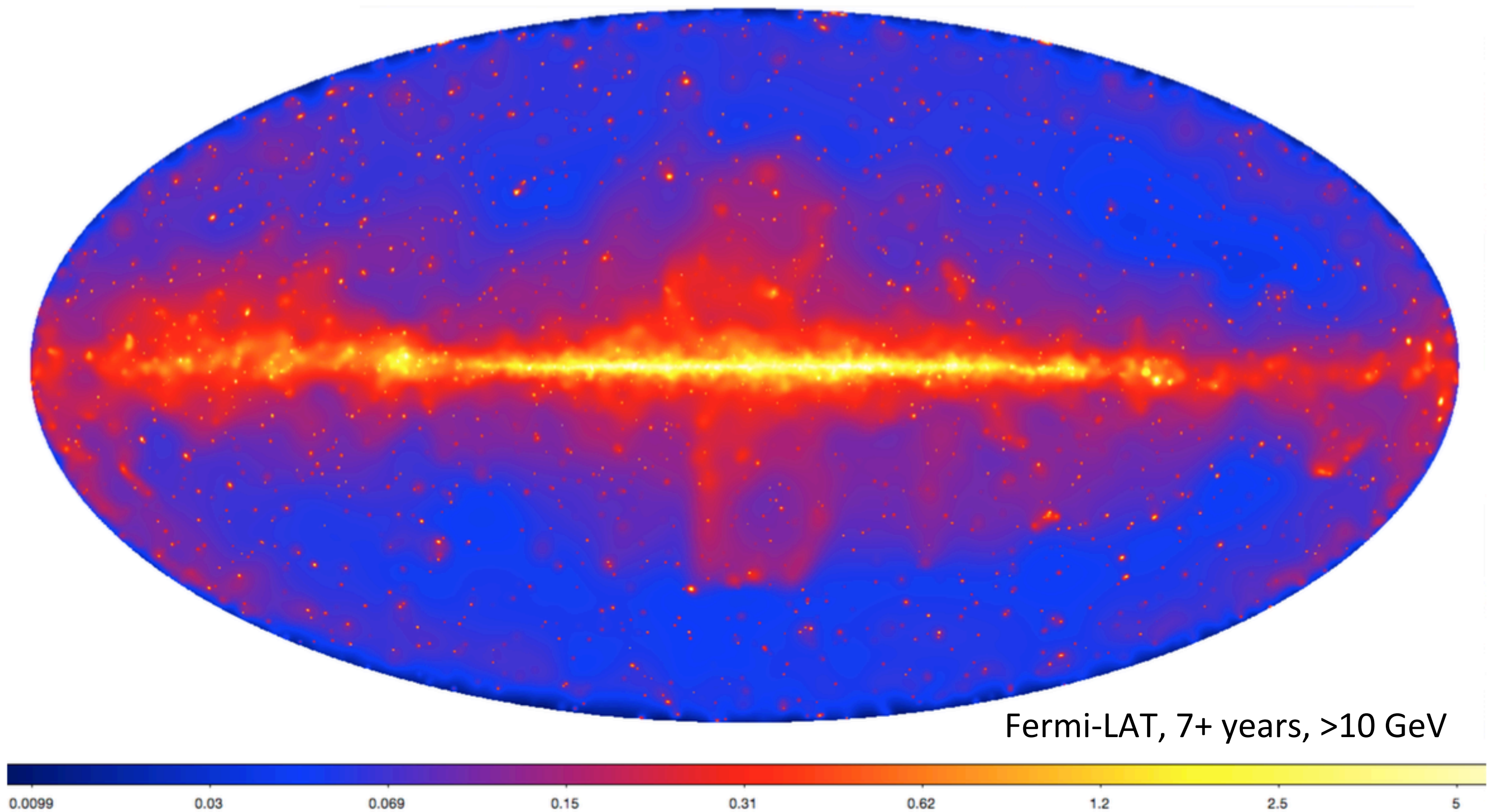


VHE Gamma-ray Astrophysics

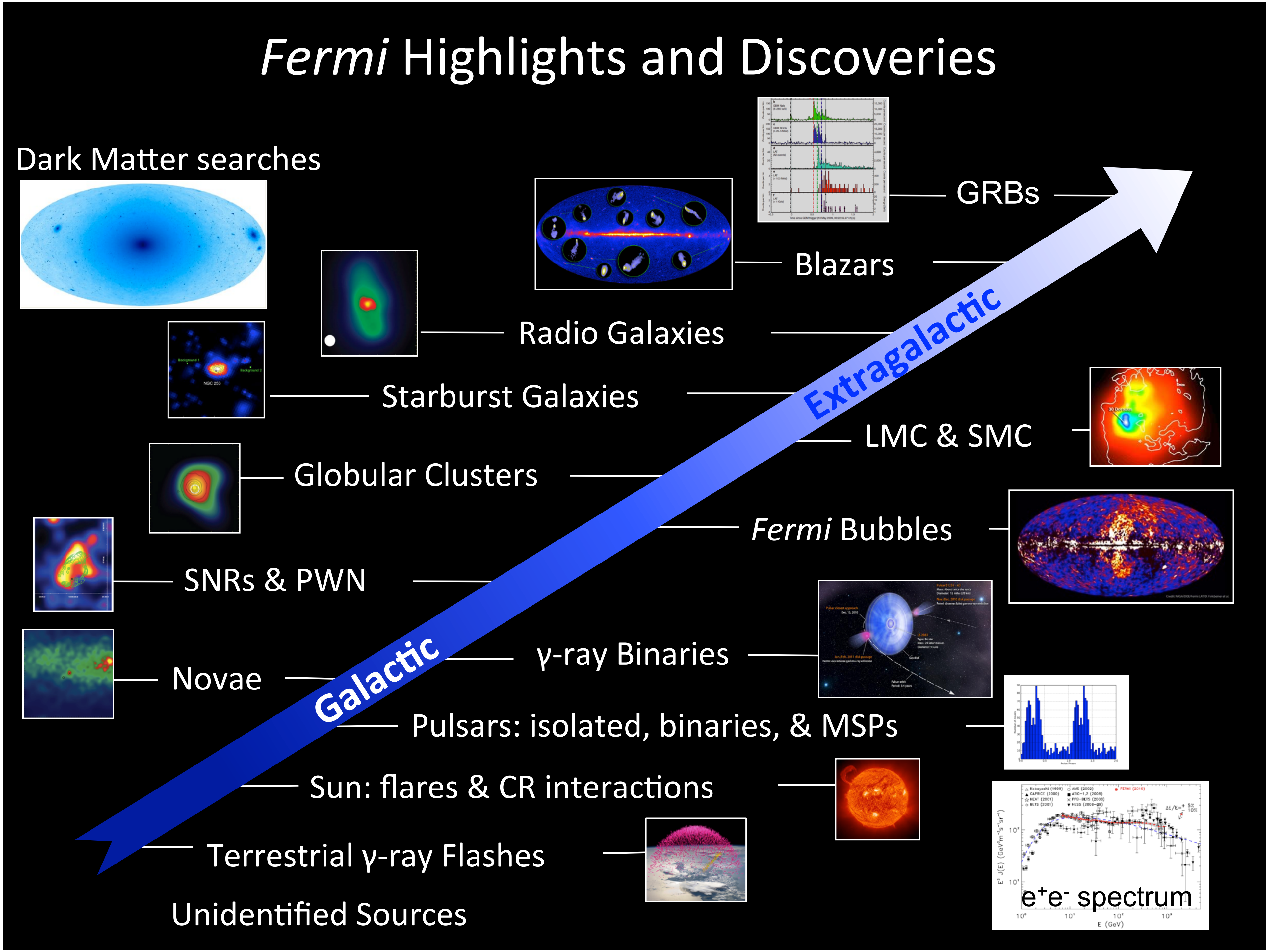


- 176 sources above ~200 GeV (c.f. ~5 sources in 1996)

High Energy Gamma-rays

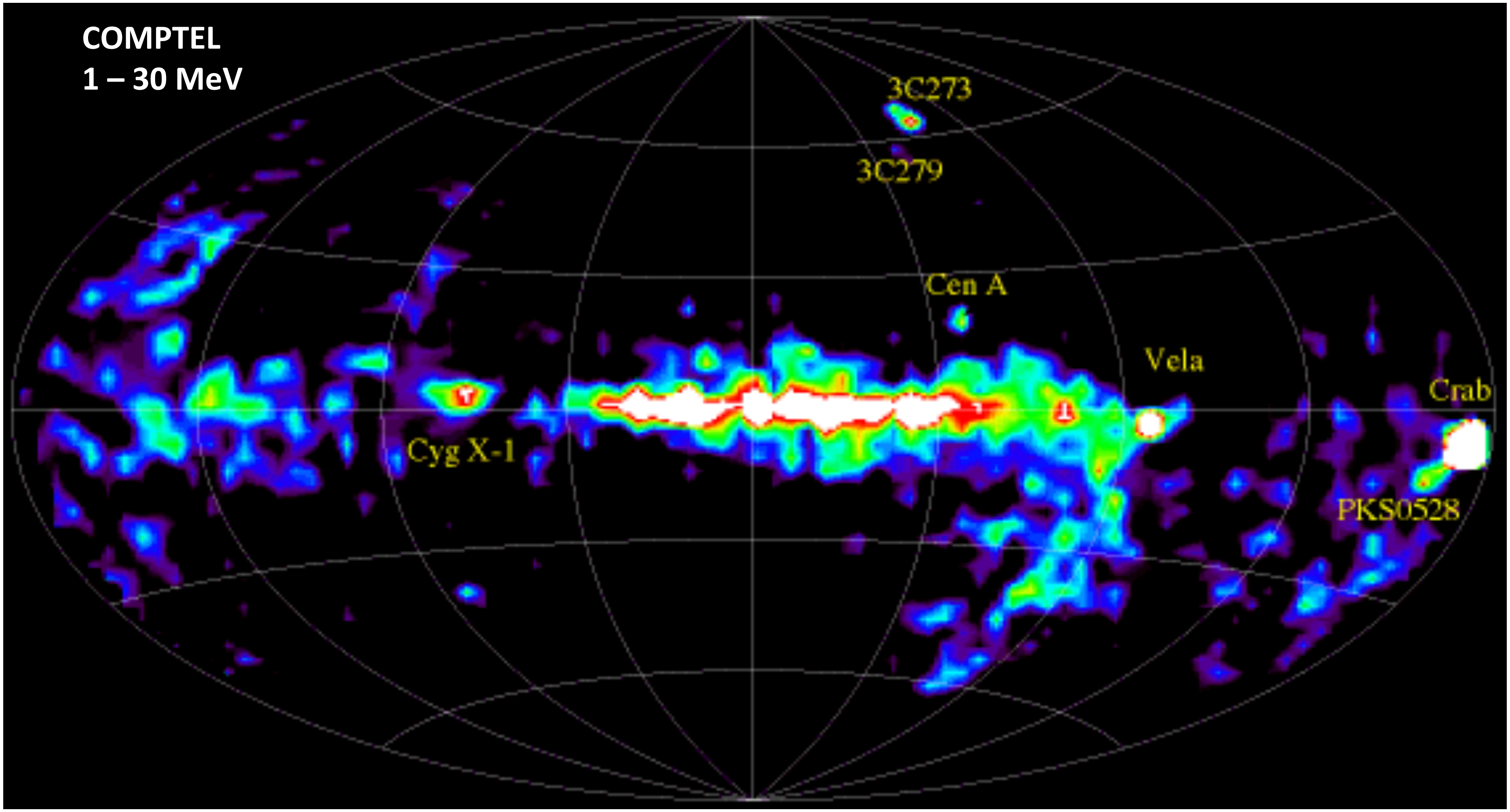


- >3000 sources above 100 MeV (c.f. ~300 in 1996)

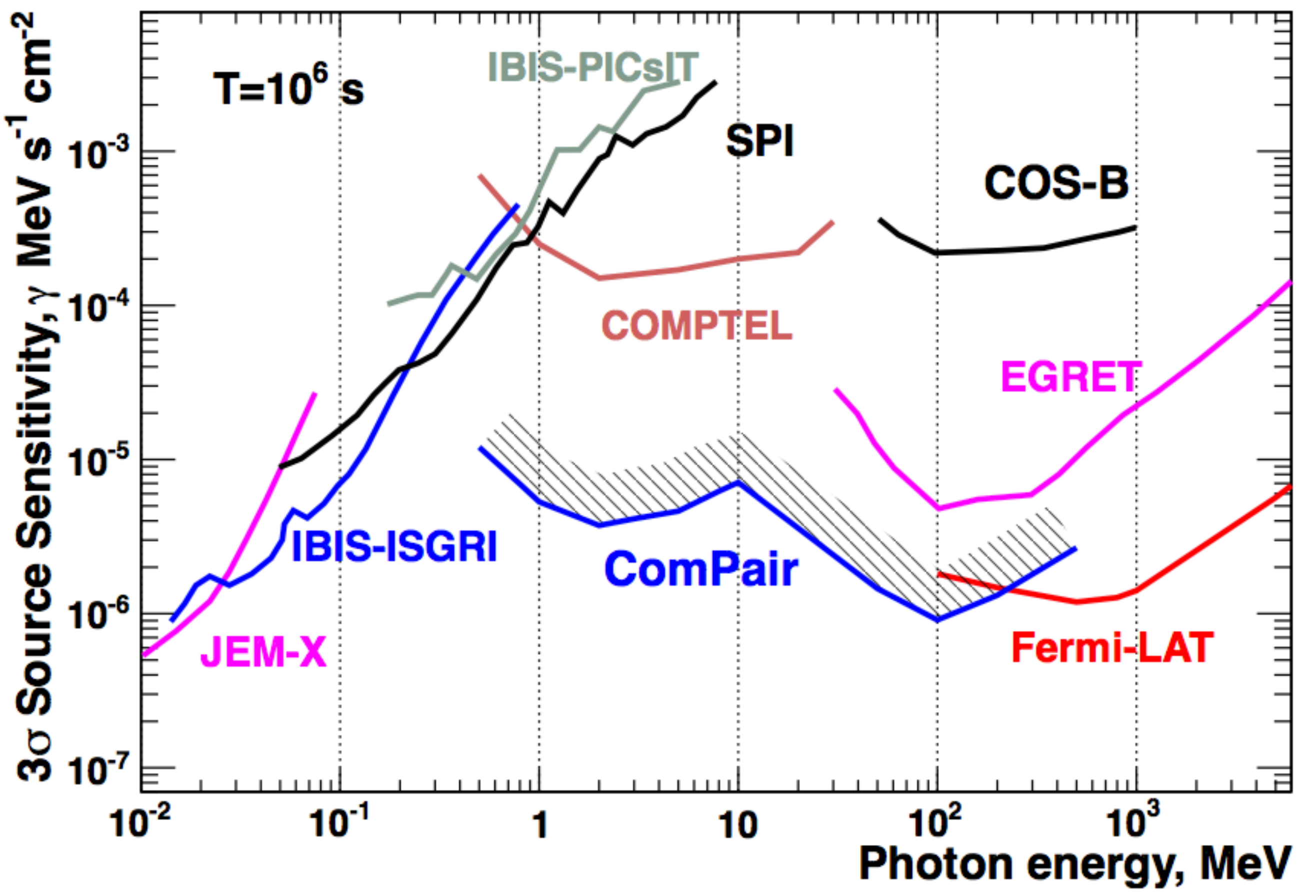

Fermi Highlights and Discoveries
Dark Matter searches
GRBs
Blazars
Radio Galaxies
Starburst Galaxies
Extragalactic
LMC & SMC
Globular Clusters
Fermi Bubbles
SNRs & PWN
γ-ray Binaries
Novae
Galactic
Pulsars: isolated, binaries, & MSPs
Sun: flares & CR interactions
Terrestrial γ-ray Flashes
Unidentified Sources
e⁺e⁻ spectrum
E (GeV)

The MeV Gamma-ray Sky

32+ steady sources and 31 GRBs (Schoenfelder et al. 2000)



An Underexplored Energy Band

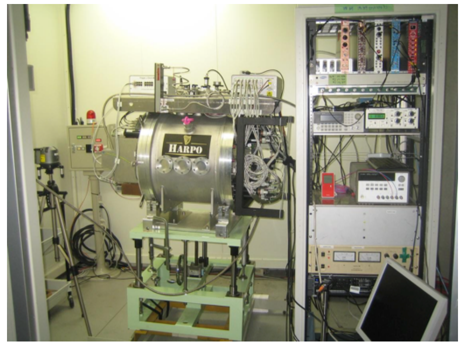


- No significant progress in the MeV band over the past 20 years

MeV Gamma-ray Instrument Landscape

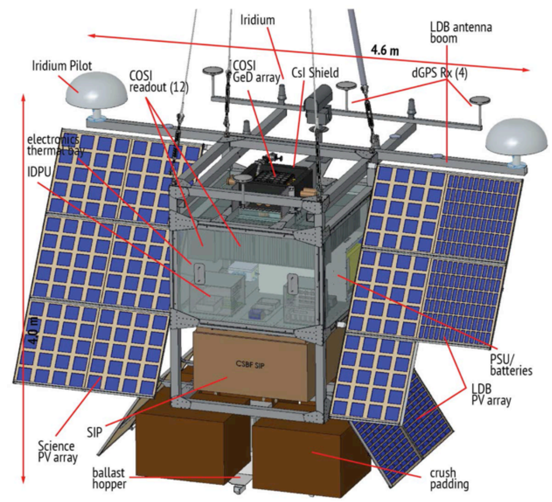
Understanding the MeV universe requires a *multi-instrument, multi-technique* approach.

Time Projection Chambers: (AdEPT, HARPO, LArGO) high angular resolution, good polarization capability



Spectrometers / mappers:

(COSI, GRX) high resolution spectroscopy, wide field of view, some polarization capability



Continuum / survey mappers: (ComPair, MEGA, AstroGAM) high flux sensitivity, wide field of view, broad energy coverage, some polarization capability

ComPair Science

Understanding Extreme Environments

Astrophysical Jets

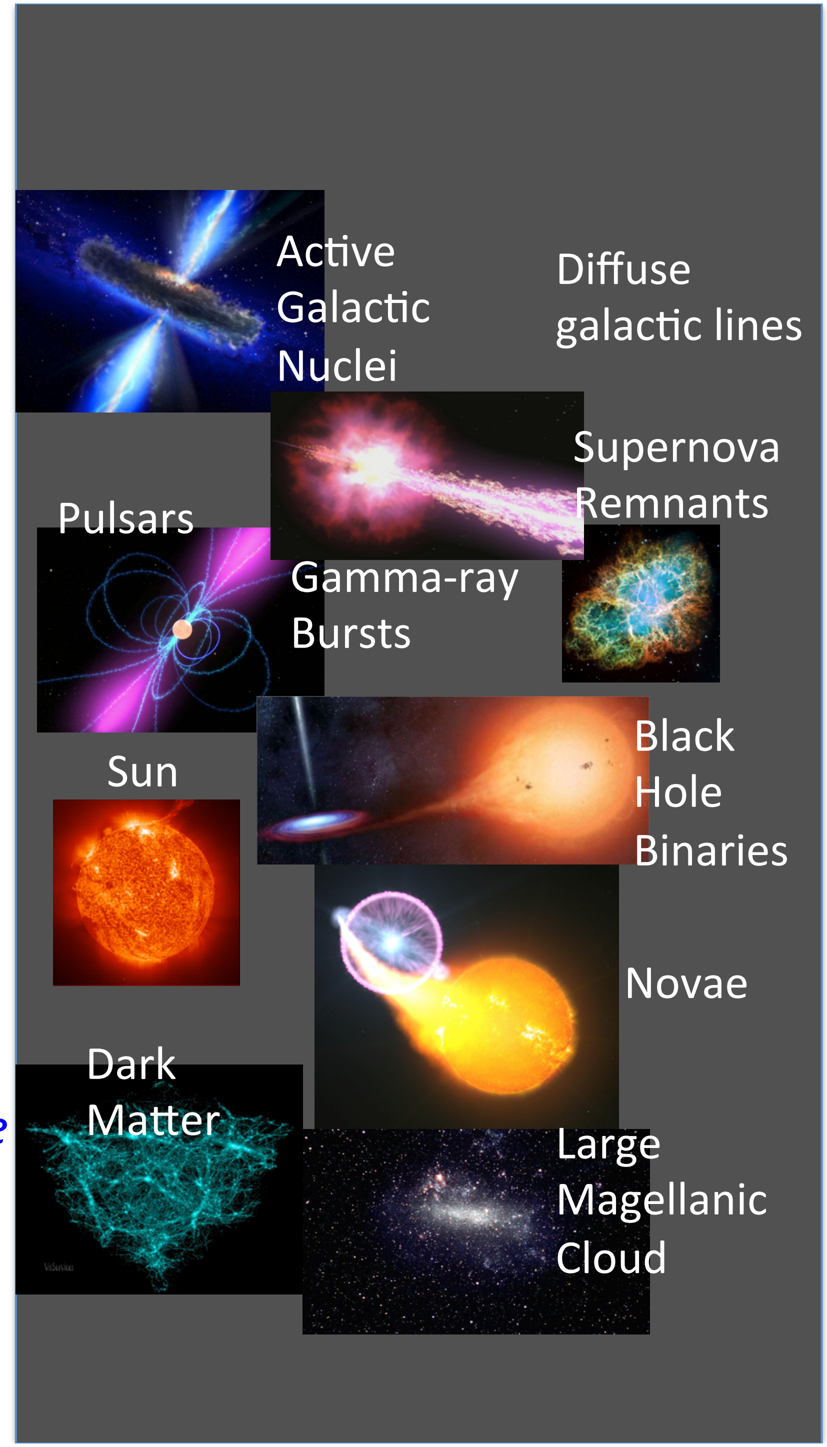
Enormous power from small regions

Compact Objects

Laboratories for extreme gravity & magnetism

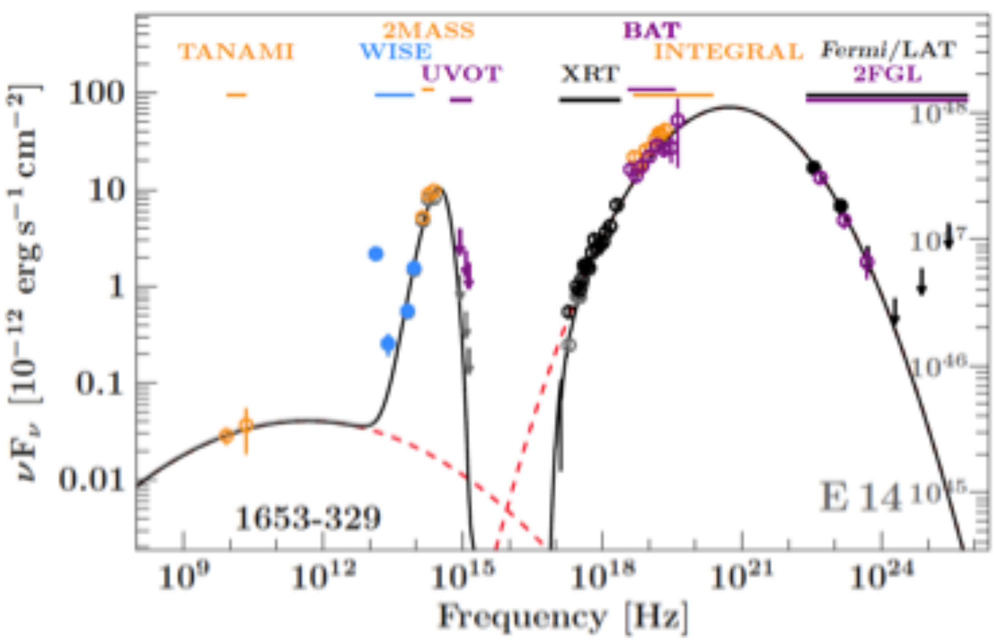
Unidentified GeV Sources

Guaranteed discovery space in determining the origin of these sources



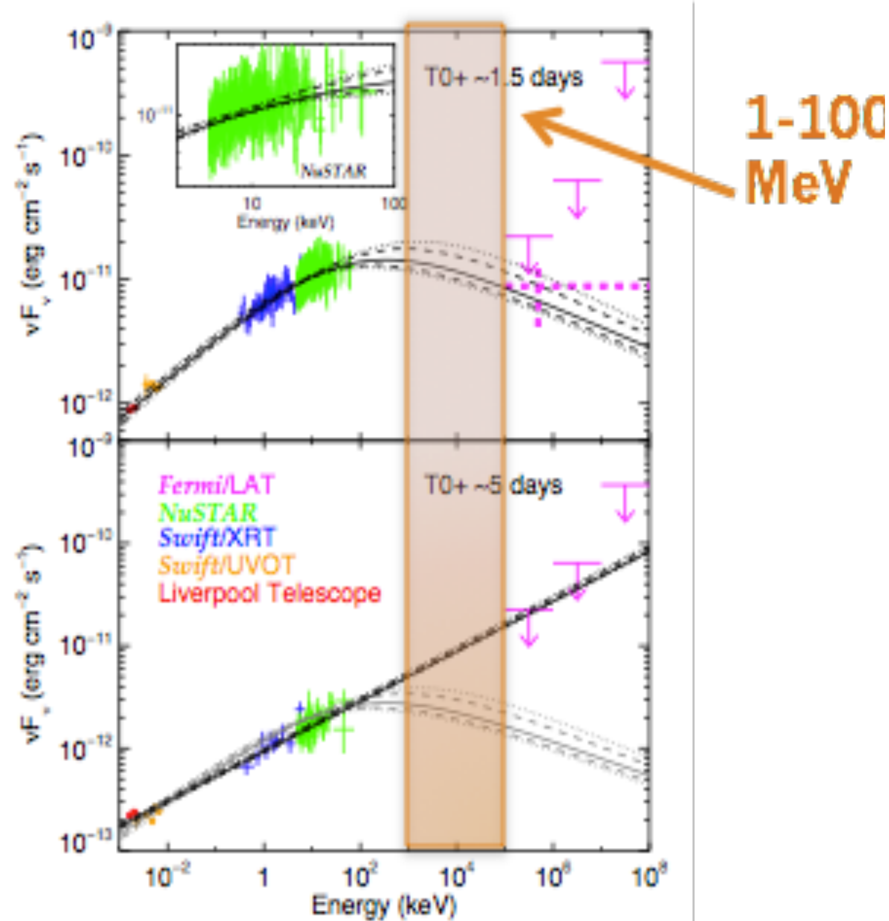
Ubiquity of Jets

- Jets are powerful accelerators, but we do not yet understand their emission mechanisms
- Measurement of their SEDs is vital for physical models of their radiation processes



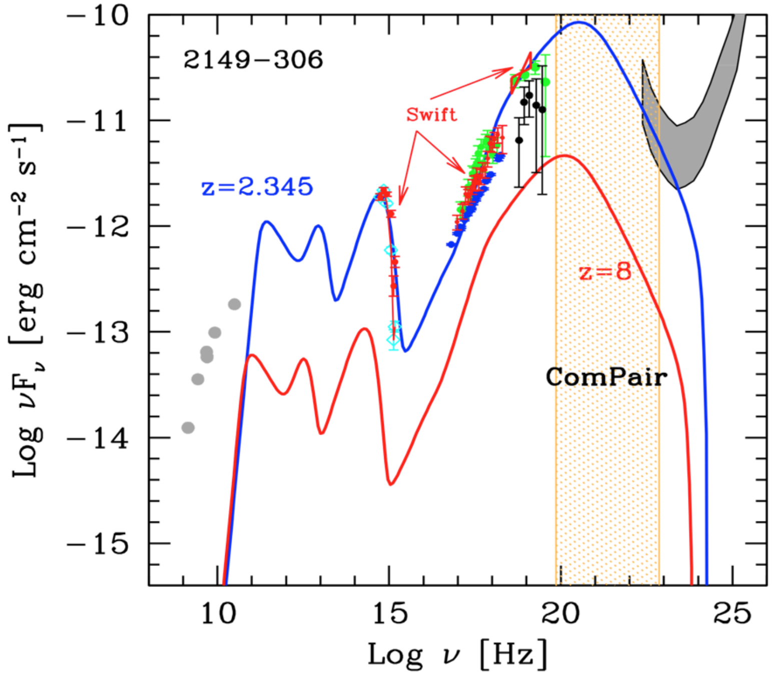
J1653-329 a candidate PeV neutrino emitter (Krauss et al 2014)

GRB 130427A

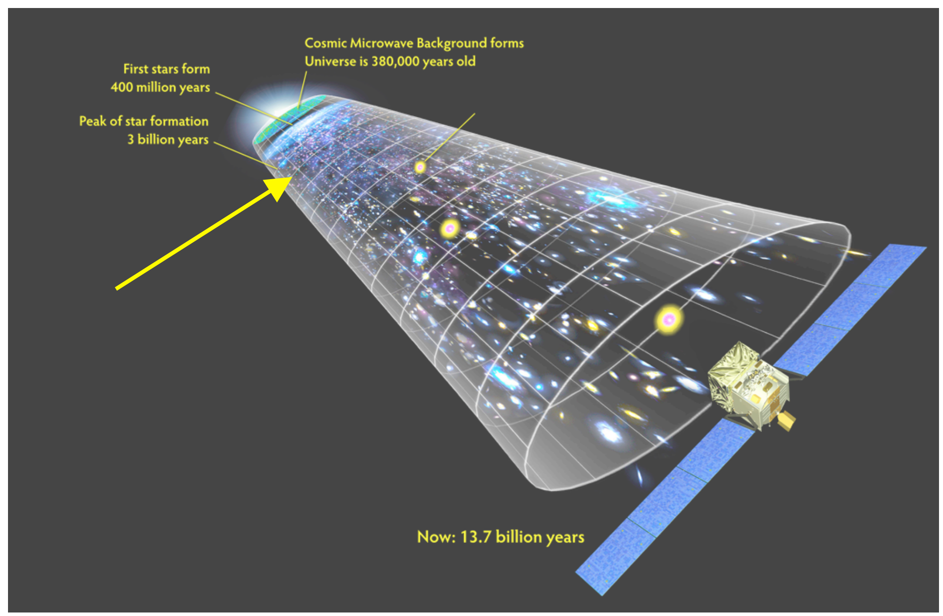


Kouveliotou et al. 2013

MeV Blazars: The Heaviest Black Holes



- Blazars whose power output peaks at ~1 MeV
  - are more luminous and have faster jets than all other active galactic nuclei
  - are known to harbor the heaviest black holes ($M_{\odot}>10^9$)
  - are the most distant persistent gamma-ray sources

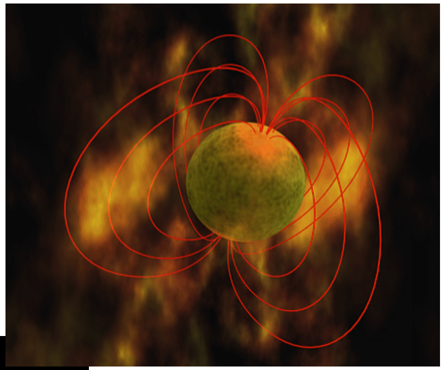


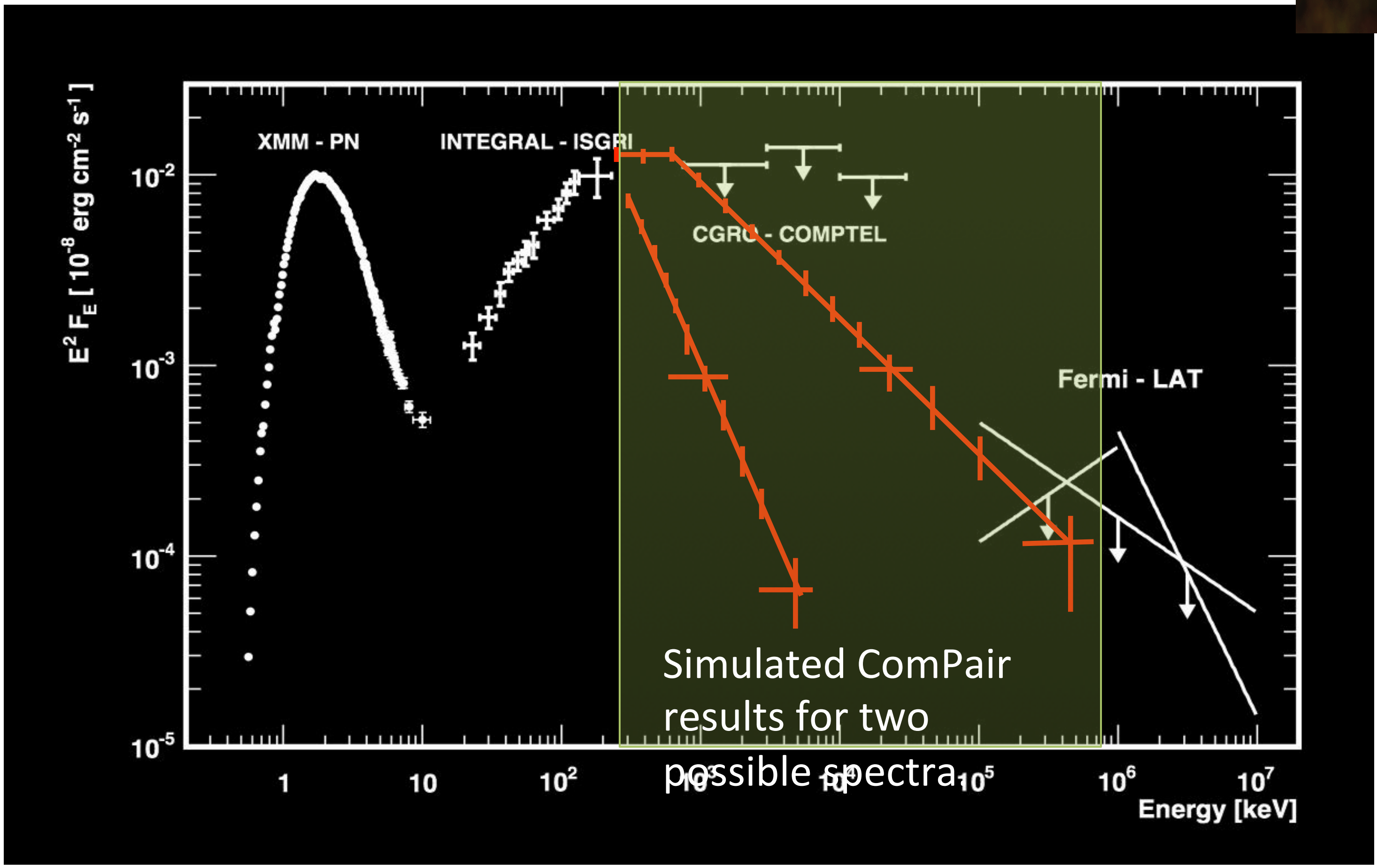
ComPair will detect >500 blazars out to z~6-8

- Discovery of MeV blazars at high redshift will show that massive black holes can grow via processes other than accretion

Magnetars

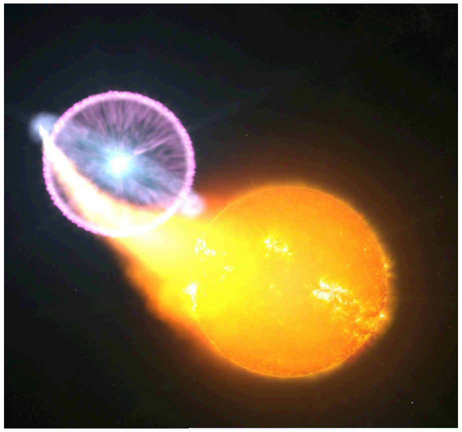
The Strongest Magnetic Fields in the Universe





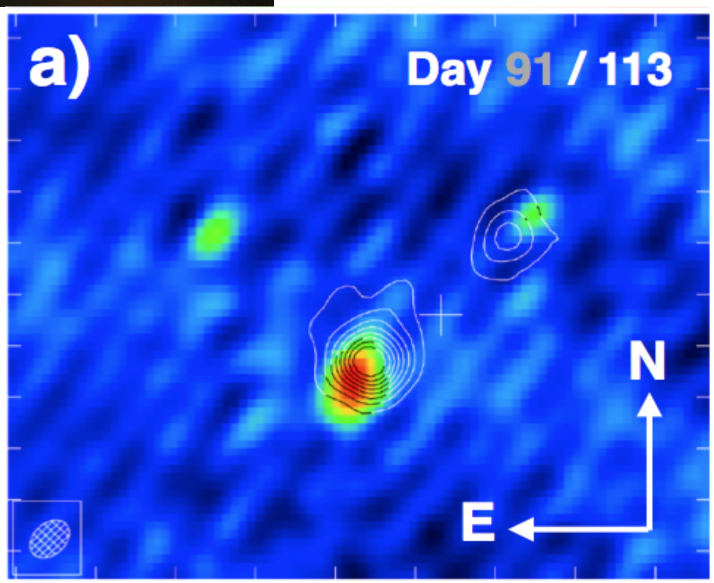
ComPair will reveal how these huge magnetic fields release energy by measuring the shape of the energy spectrum at and above the peak energy output.

Novae: A New Player

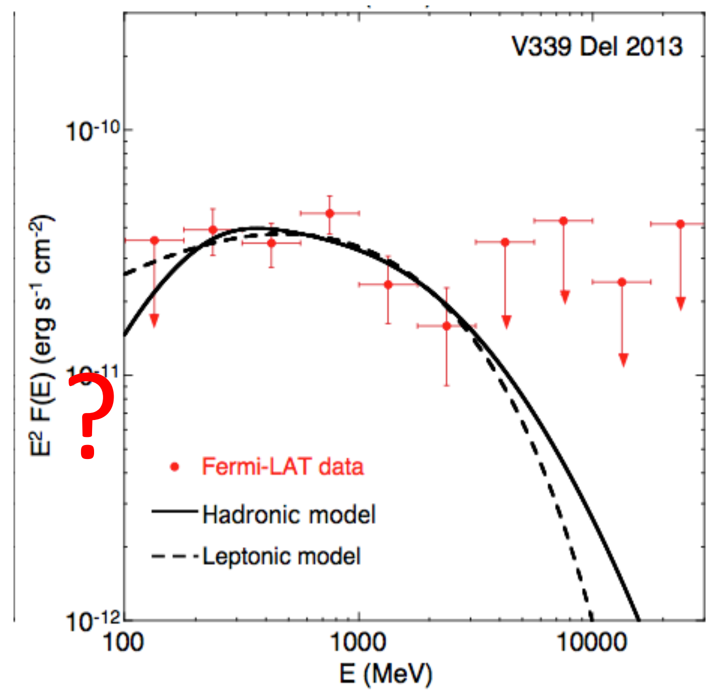


How do close binary star systems like classical novae eject mass during outbursts?

Shocks in the expanding nova envelope produce gamma rays. ComPair will measure the energy spectrum below 100 MeV to determine the shock properties and identify novae missed by optical observations.



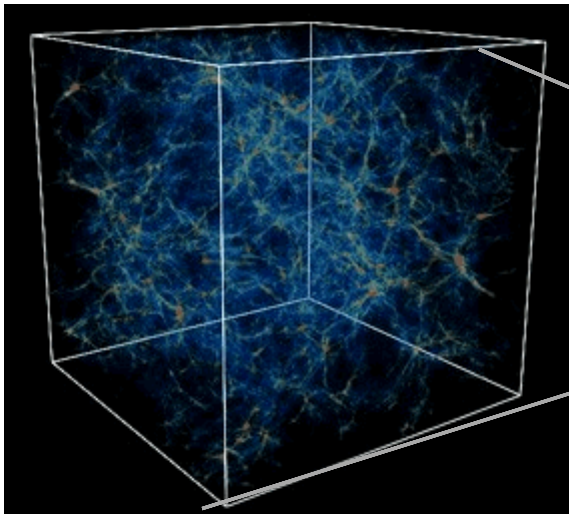
Synergy with radio observations that reveal shock sites - V959 Mon gamma-ray nova example.

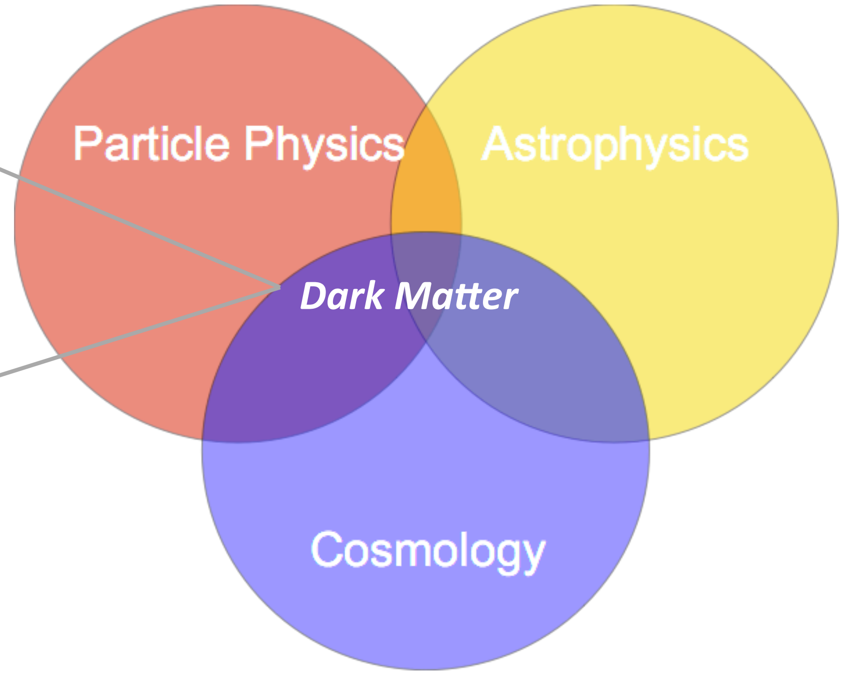


Fermi LAT - energy spectrum below 100 MeV is undetermined

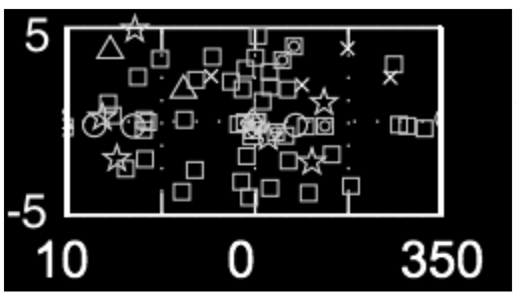
New/Fundamental Physics

Structure of the universe

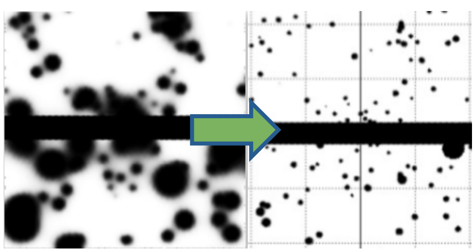




Discover Sources: the Galactic Center

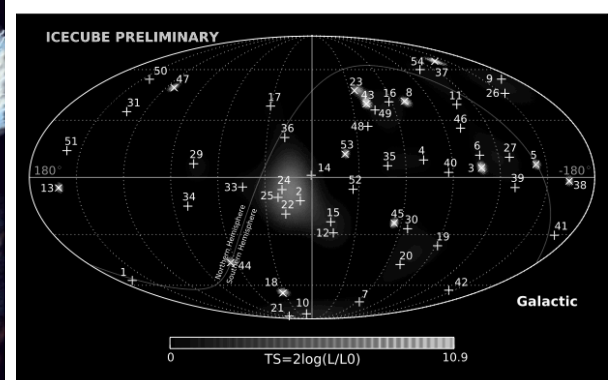


3FGL point sources at the GC



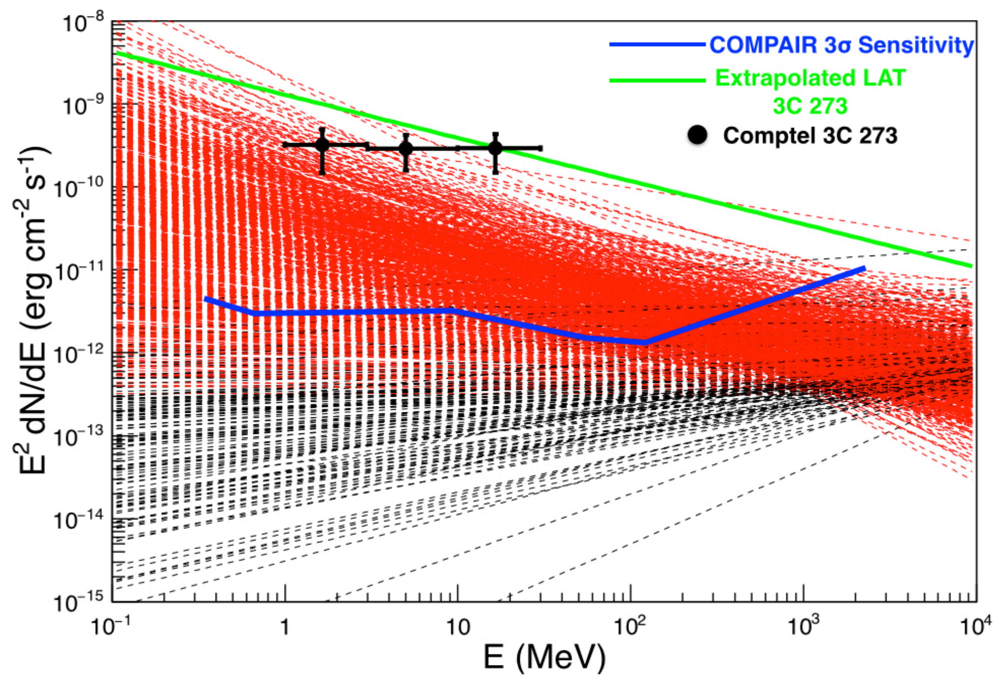
40x40 deg
10x improvement in PSF
@100 MeV

Multimessenger: gravitational waves and neutrinos



Discovery Space

- Previous instruments covering the 1-100 MeV range were COMPTEL/ OSSE on CGRO and Integral SPI
- ~⅓ of Fermi-LAT sources remain unidentified
  - ComPair will provide a bridge between high- energy gamma-ray and X-ray regimes, helping to identify and understand these objects
- Below 200 MeV, ComPair will dramatically improve sensitivity will open a new window in the EM spectrum leading to the discovery of many new sources and source classes



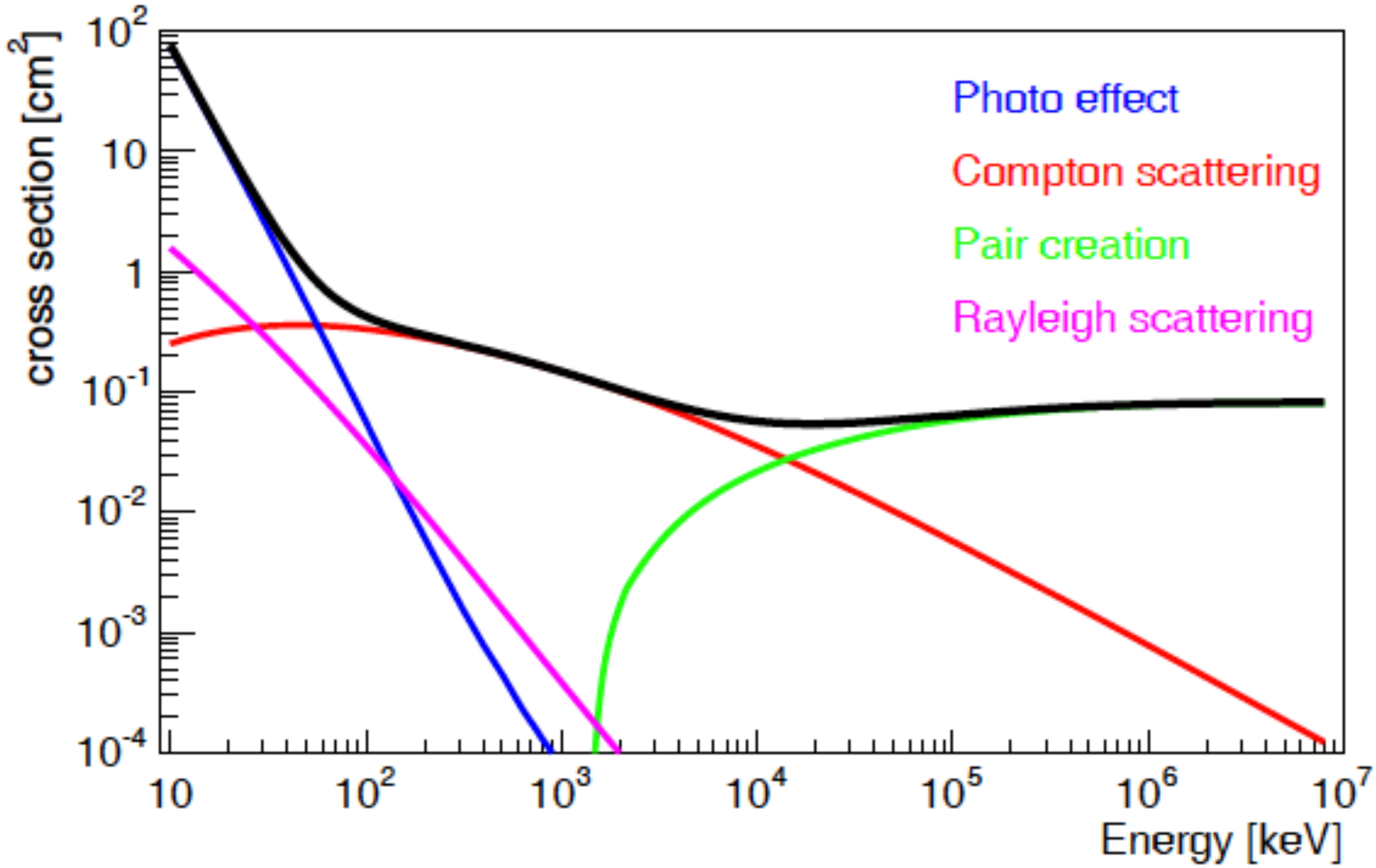
>50% of Fermi-LAT catalog sources have a peak below the Fermi-LAT band.

Detecting MeV Gamma-rays

Challenges for MeV telescopes

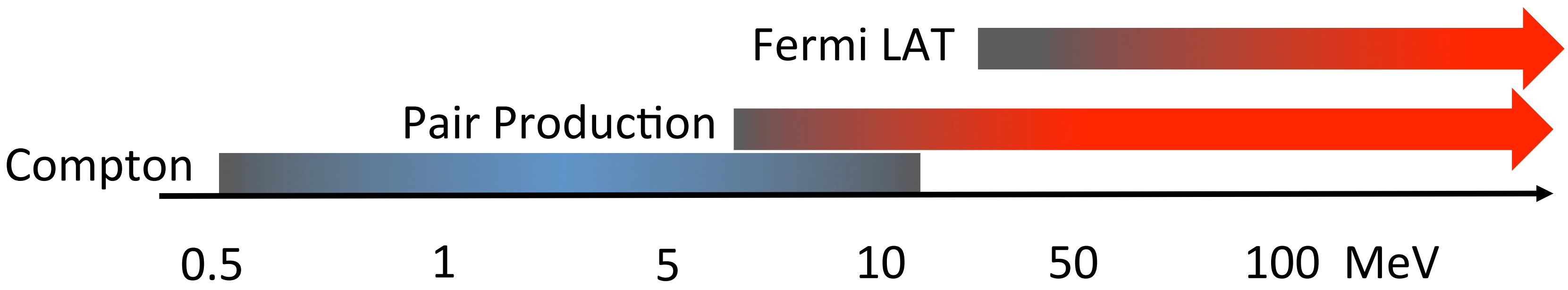
- Significant backgrounds
  - Charged particles/cosmic rays
  - Photons from the Earth
  - Local radiation
- Limited angular resolution/source confusion
- Balancing the need for resolution with constraints of space missions
  - Low mass, low power, minimal onboard processing, and low complexity

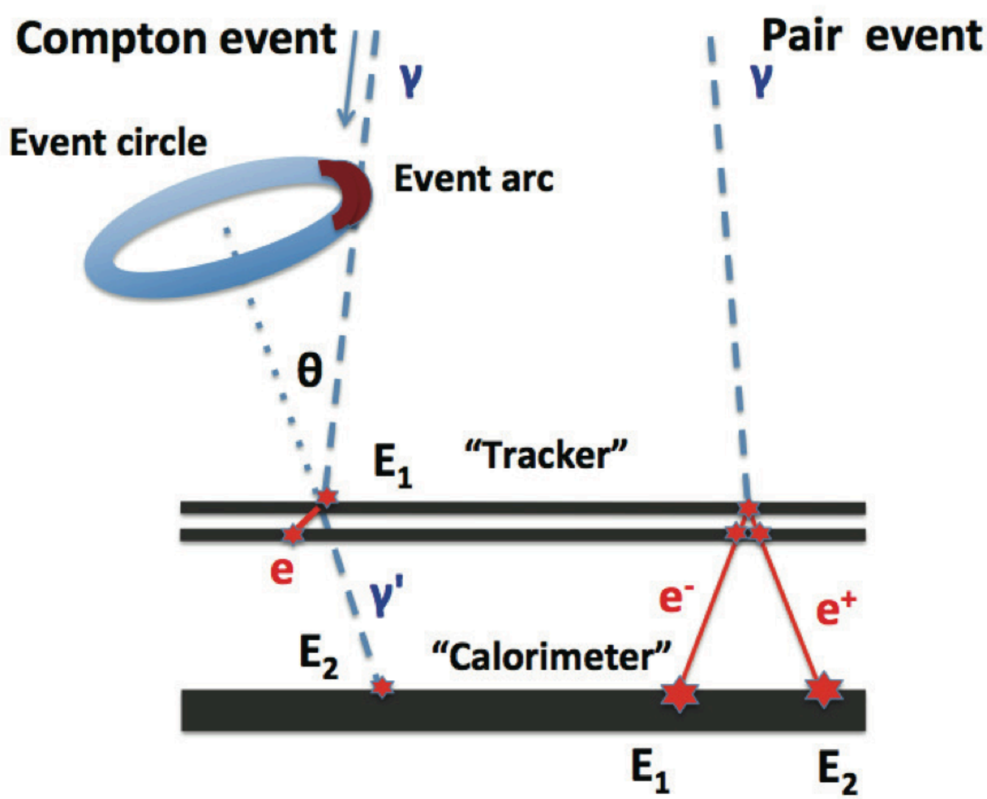
Gamma-ray Interactions in Matter



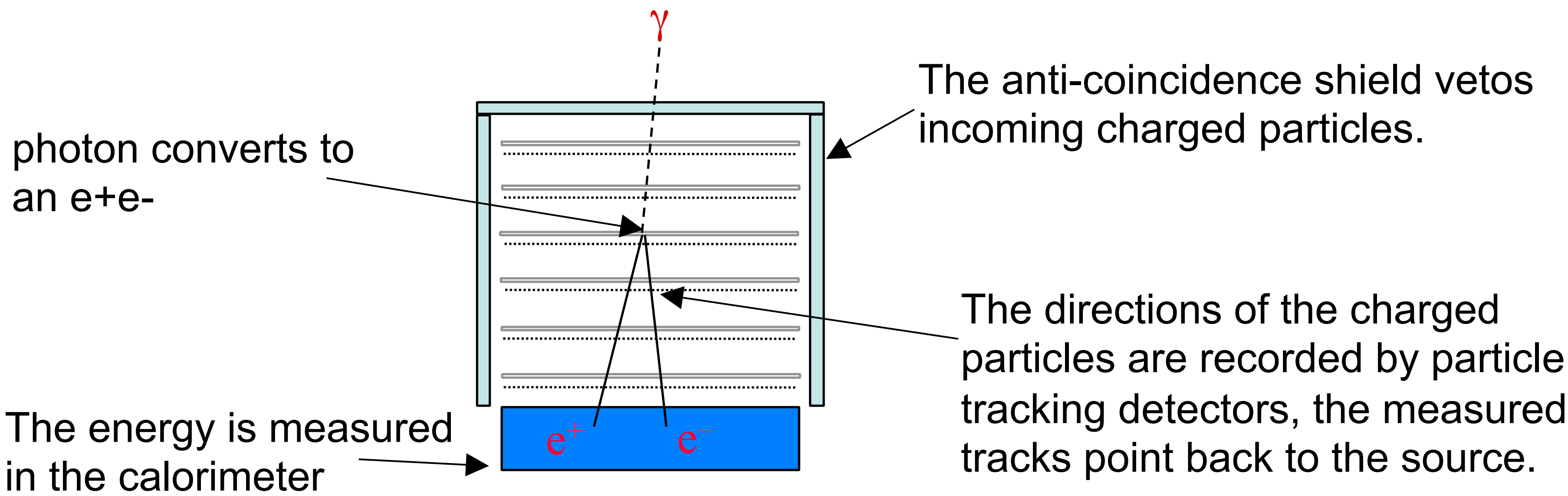
- To fill the "MeV Gap" need to consider both Compton Scattering and Pair Production

Compton + Pair Telescope Concept





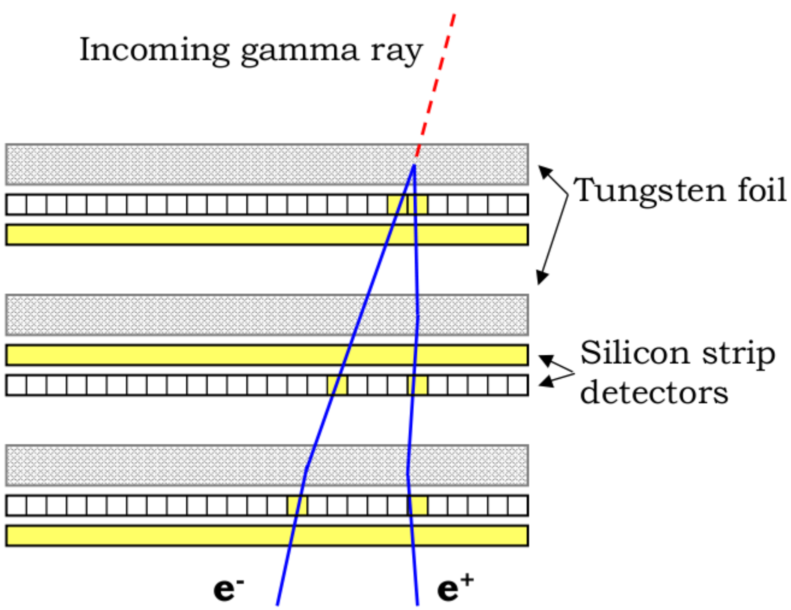
Pair Production

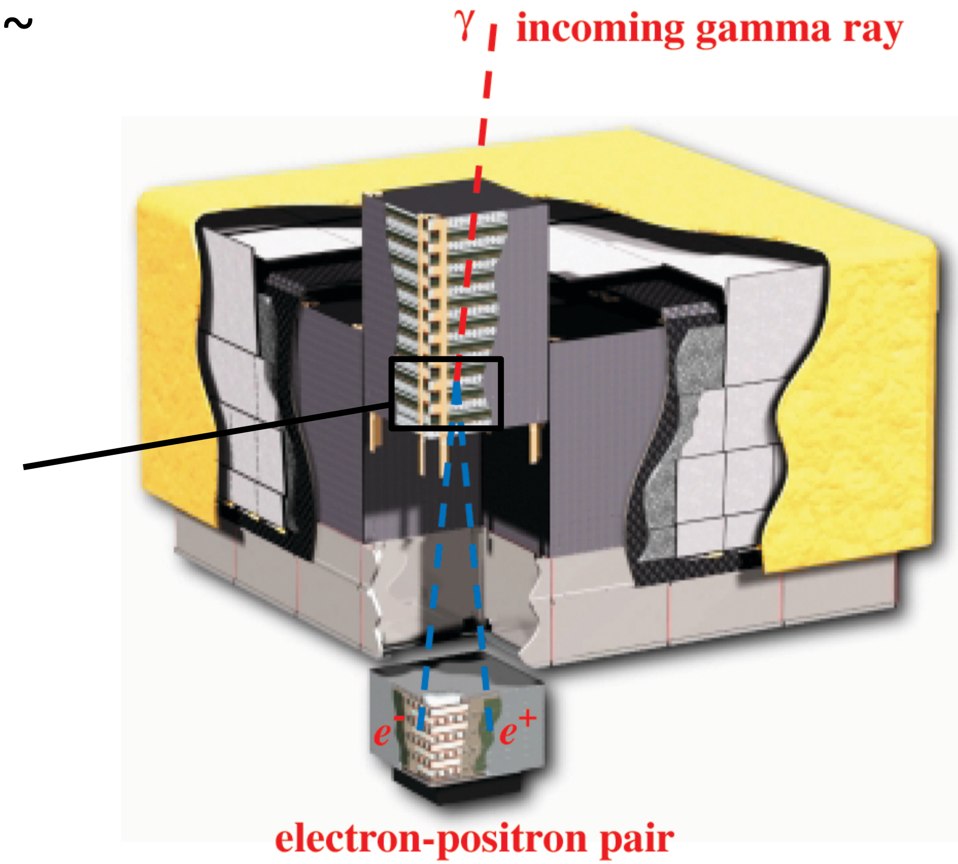


- Tracker: angular resolution is determined by:
  - multiple scattering (at low energies) => Minimize high-Z material
  - position resolution (at high energies) => fine pitch detectors
- Conversion efficiency -> More converter material
- Calorimeter: Enough X_0 to contain shower

A lower energy Fermi-LAT

LAT performance optimized at ~ 1 GeV

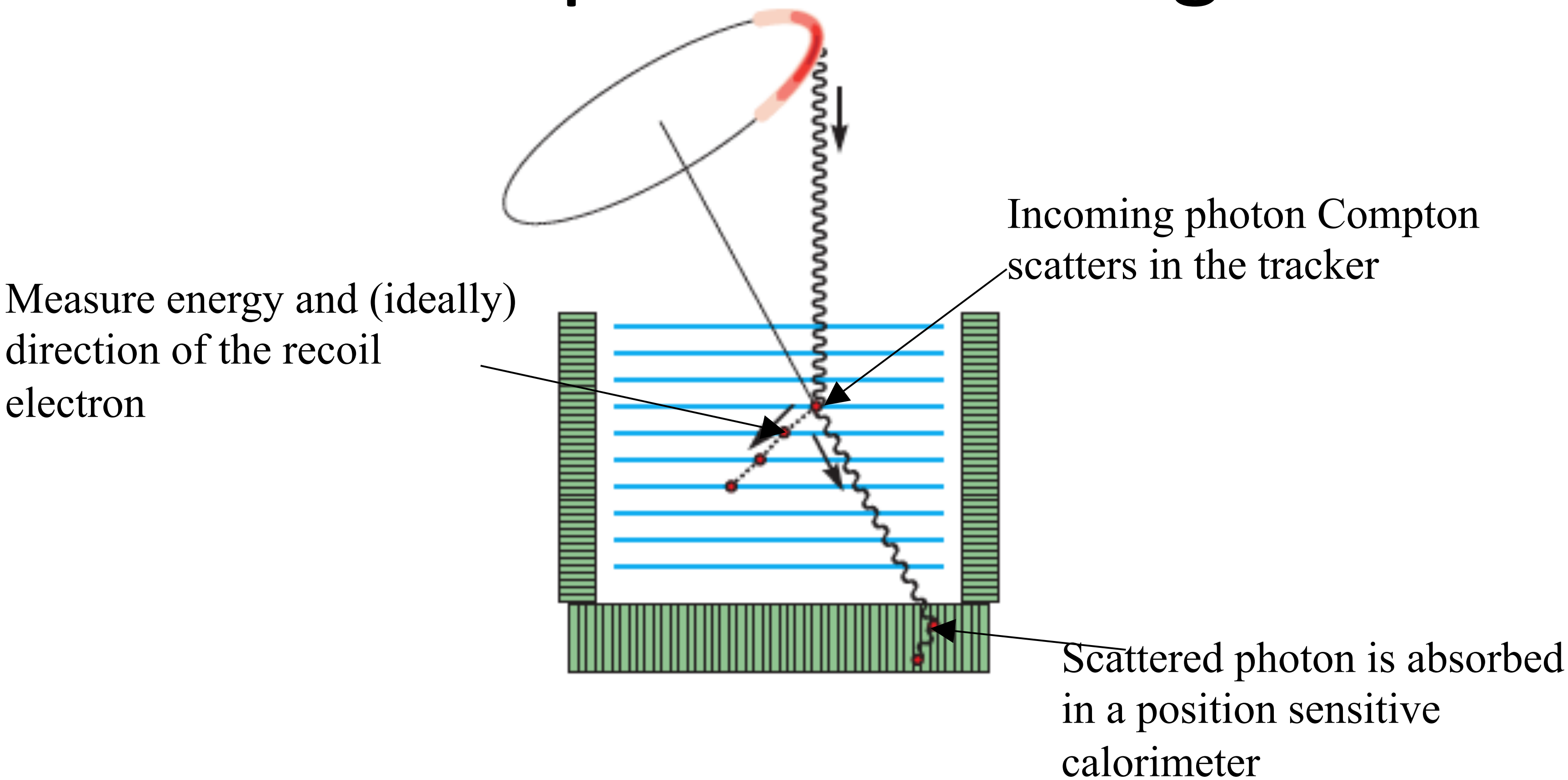




- Remove tungsten layers
    - Reduce absorption and Coulomb scattering of electron and positron
- Use double-sided Silicon-strip detectors
    - Improve spatial and energy resolution for electron/positron tracking

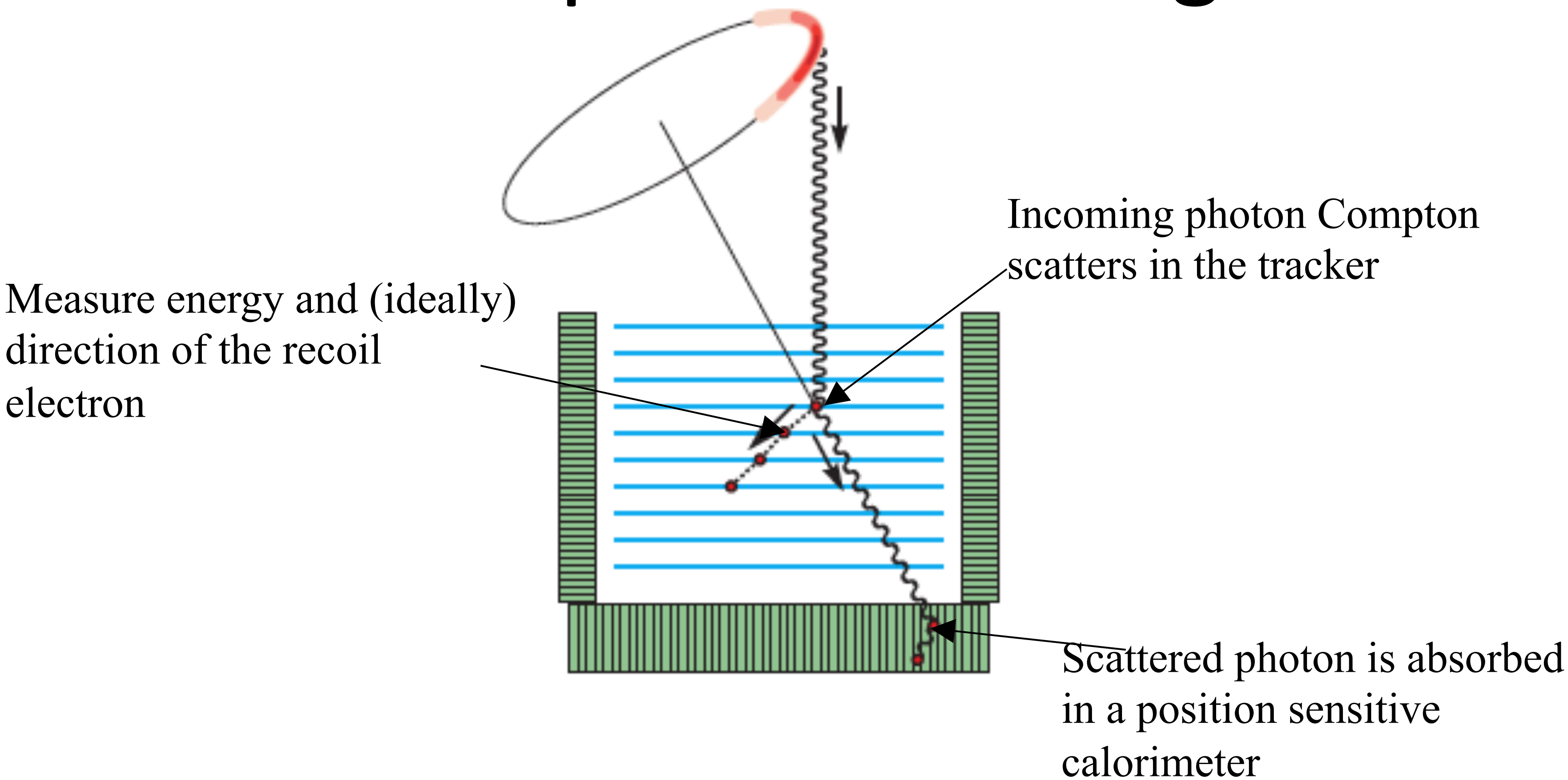
Similar concept to MEGA, GRIPS and AstroGAM

Compton Scattering



- Need to measure location of the Compton interaction and absorption of the scattered photon
- Energy of the recoil electron and scattered photon
- For best reconstruction, also want to measure direction of recoil electron
- Scattered photons tend to scatter at right angles to the polarization vector

Compton Scattering



Making a real detector:

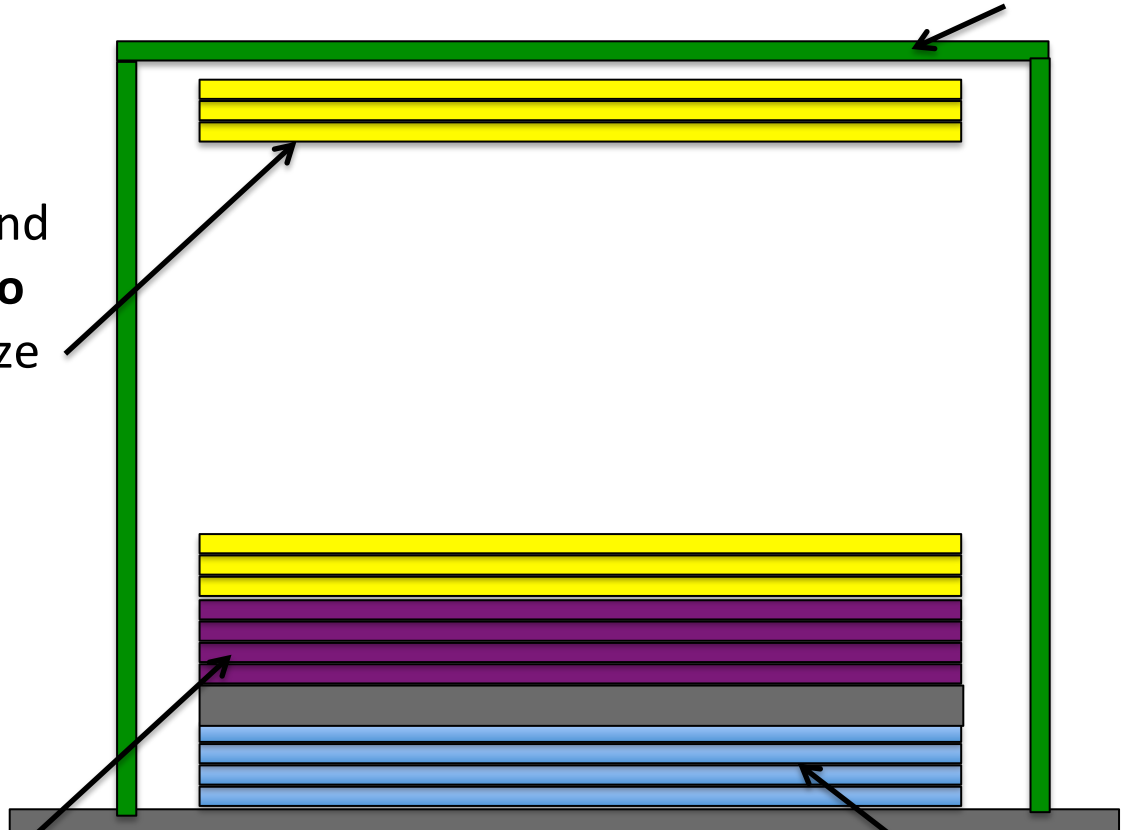
- Double sided silicon strip detector to measure energy and path of recoil electron
- CZT calorimeter to provide good energy and position resolution measurement of scattered photon
- Plastic scintillator anticoincidence detector (not shown in figure)

NASA/GSFC, UCSC,
Clemson University,
NRL, Washington
University

ComPair Instrument

Anticoincidence detector

Double-sided Si strip detector with analog readout – good spatial and energy resolution with **no conversion foil** – minimize multiple scattering (essential for low energy performance)

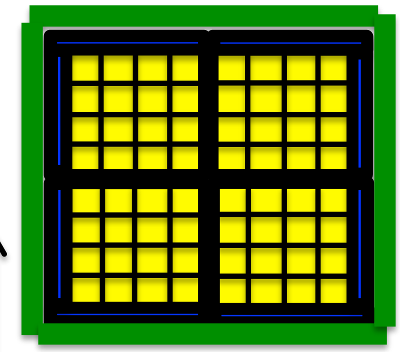


CZT calorimeter ,
good spatial and energy resolution needed for good Compton performance

CsI calorimeter,
add depth to contain higher energy showers from pair events

ComPair Instrument

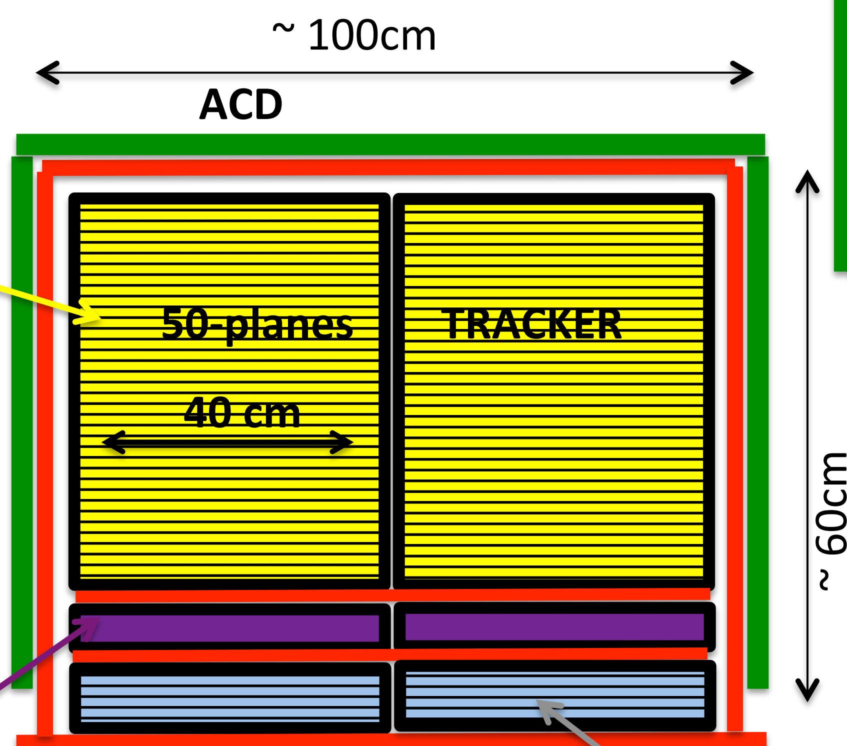
TOP VIEW



Tracker

Incoming photon undergoes pair production or Compton scattering. Measure energy and track of electrons and positrons

- 50 layers DSSD, spaced by 1 cm
- Strip pitch 0.5mm



CZT Calorimeter

Measure location and energy of Compton scattered photons

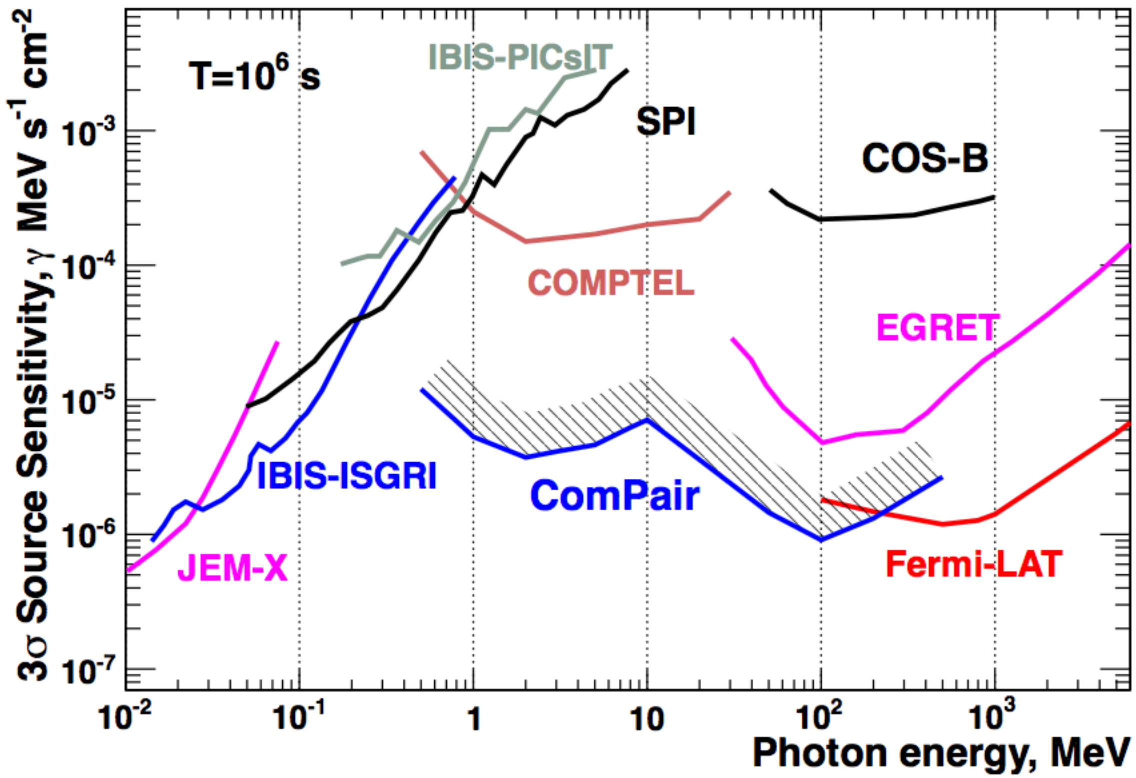
- 4 planes CZT strip detectors (0.5 cm thick)
- Orthogonal strips on opposite sides of each layer, 0.5 cm strip pitch

CsI Calorimeter

Measure energy from higher energy gamma-rays

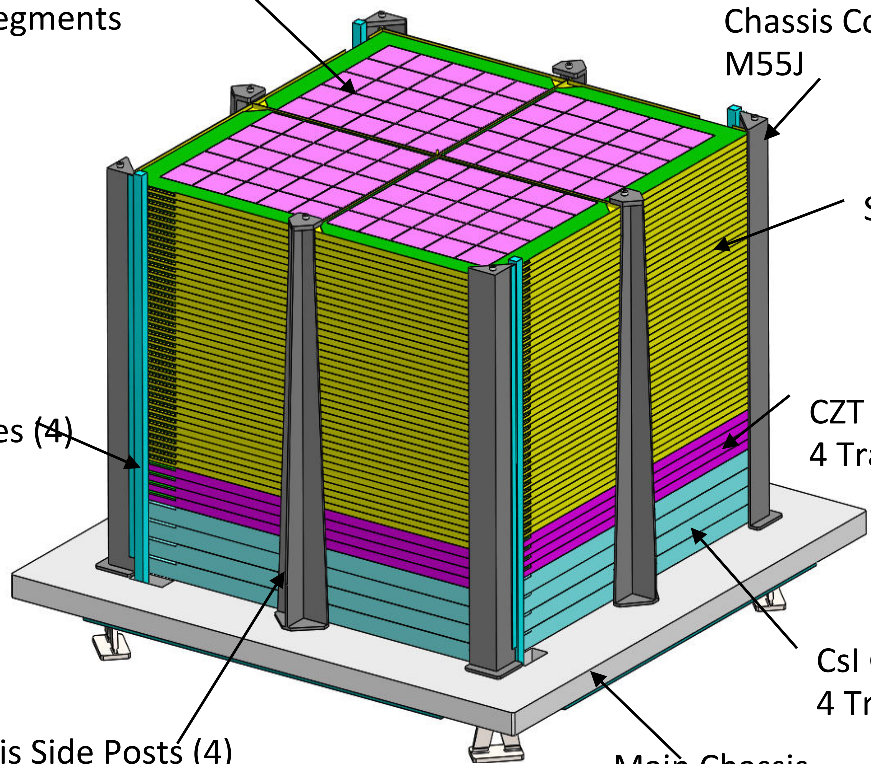
- 4 layers of CsI logs, each log is 1.2cm x 1.2 cm x 33 cm

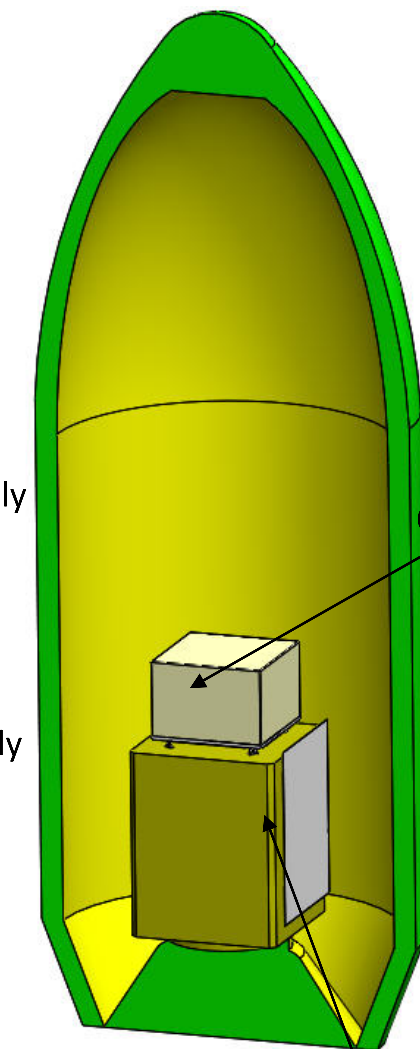
ComPair: *A wide aperture discovery mission for the MeV band*



- Energy range: 500 keV – 500 MeV
- Angular resolution: 3° (1 MeV), 10° (10 MeV), 1.5° (100 MeV)
- Field of View: ~2.5 sr
- Operate in survey mode, view 80% of the sky in one orbit
- Some sensitivity to polarization and nuclear lines

Observatory and Falcon 9 Fairing





Total Mass (including electronics, harness,
MMS and thermal system): 925k

What's happening now?

- Building a small prototype for beam tests and a balloon flight
  - Demonstrate that the system can be built and operated with required performance
- Ongoing work developing/improving the simulations, reconstruction and performance evaluation
  - Likely lead to further optimization of instrument configuration
- Sequence of future MeV mission workshops to build community support/involvement
  - You are at the second one now

ComPair Science: *Why now?*

Astrophysical context from *Fermi*, *INTEGRAL*, *Swift*, *NuSTAR*

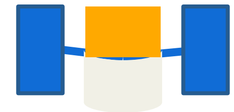
- *Important outstanding problems point towards the MeV range*

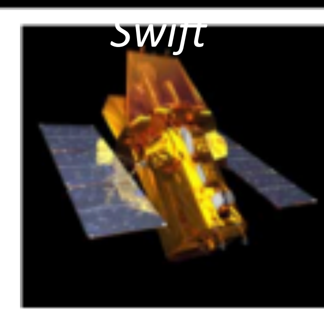
Synergies with upcoming wide-field surveys

- *LSST, LOFAR, LIGO/Virgo, HAWC …*

Fits well with recent community and NASA Science Planning Documents

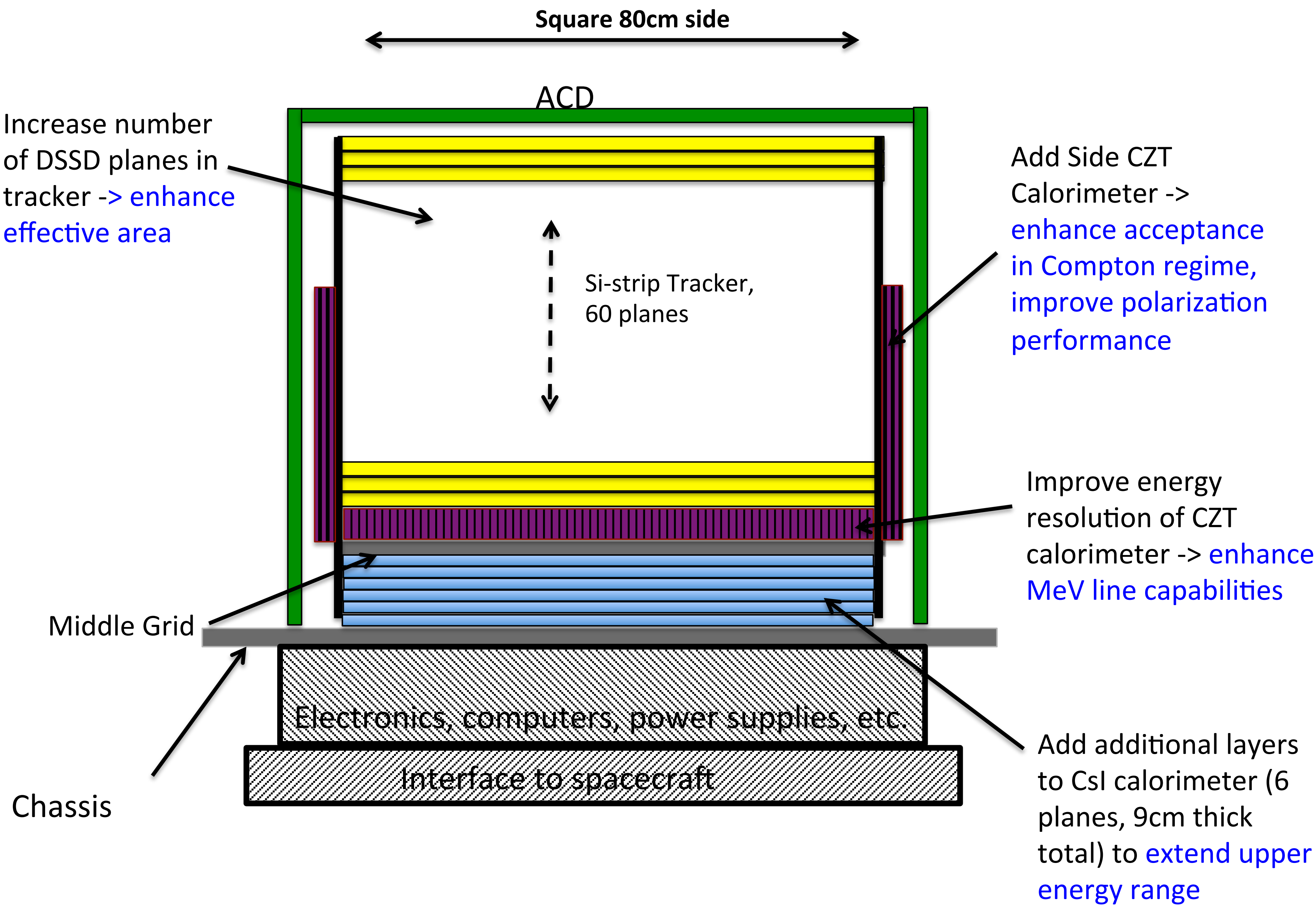
- *A natural fit to time domain astronomy key science topic in Astro2010*
- *2013 NASA Roadmap emphasized small and mid-size missions for its visionary plan - including monitoring energetic transients with Gamma-ray telescopes*





What would we do with more resources?

All-sky Medium Energy Gamma-ray Observatory



Summary

- The MeV gamma-ray band has enormous scientific potential
- ComPair, optimized for high flux sensitivity, broad energy range and a wide field of view will focus on astrophysical extremes
  - High matter densities
  - Strong magnetic fields
  - Powerful jets

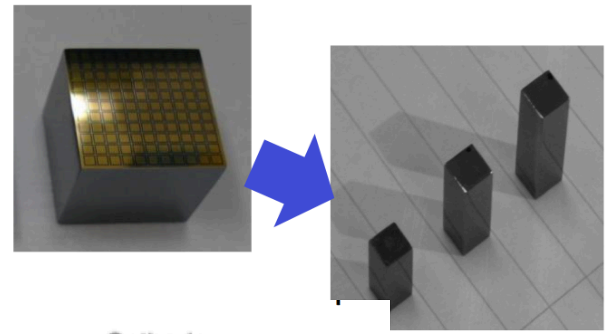
And will be sensitive to spectral features such as breaks, turnovers, cutoffs, and temporal behavior, which are critical to discriminate between competing physical models, occur within the MeV energy range.

Lots of cool science that I have not mentioned…

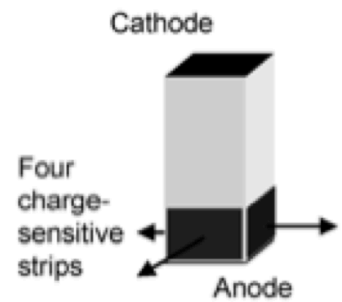
BACKUP

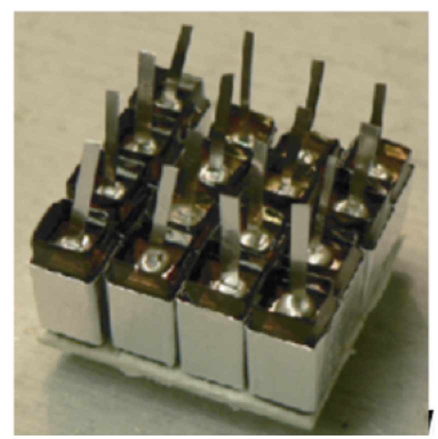
High Resolution CZT Calorimeter

20x20x15 mm^3



- Compton performance requires good spatial and energy resolution in the calorimeter
- Highest energy resolution for CZT comes from pixelated detectors (limit is ~0.5% at 662 keV)
  - BUT requires many channels, and area and depth of detectors limited by quality + cost
- **Alternative:** 3D segmented drift detector based on the Frisch-grid approach (A. Bolotnikov+ 2014)
  - Thick detectors. 1 layer = 4 cross-strip
  - Correct for lost charge by measuring X,Y,Z position within detector. Reaches ~1-2% dE/E for relaxed quality requirements
  - Significant performance and cost benefits for moderate increase in electronics complexity
    - Uses pulse shape and timing

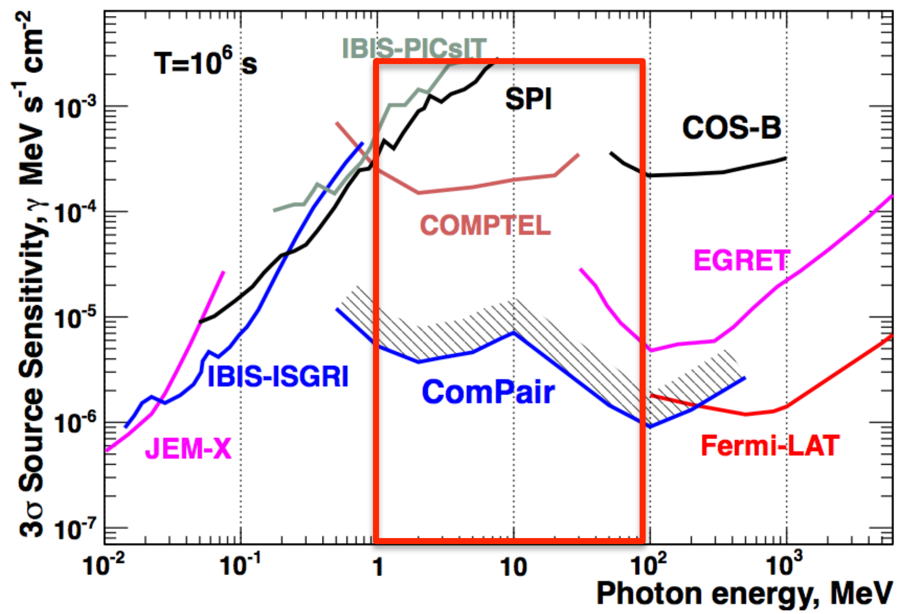




ComPair: *A wide aperture discovery mission for the MeV band*

- Exploring the most extreme regions in the Universe
  - *ComPair will provide a huge leap in sensitivity and breakthrough science capability*

  Builds on the success of NASA's *Fermi* Large Area Telescope



ComPair Team includes NASA Goddard, Clemson University, Naval Research Laboratory, University of California Santa Cruz, and Washington University

ComPair Performance

Simulations of the baseline ComPair concept (ICRC 2015) using the MEGALib package (Zoglauer)

Improved angular resolution compared to LAT for pair events

Retains effective area below 100 MeV for pair events