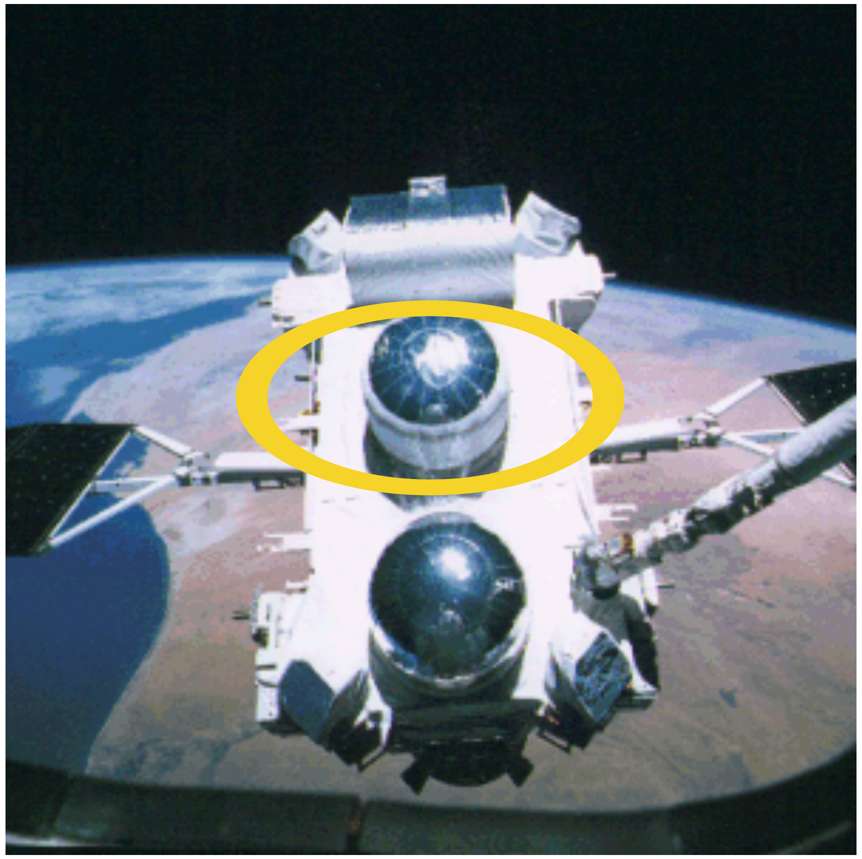
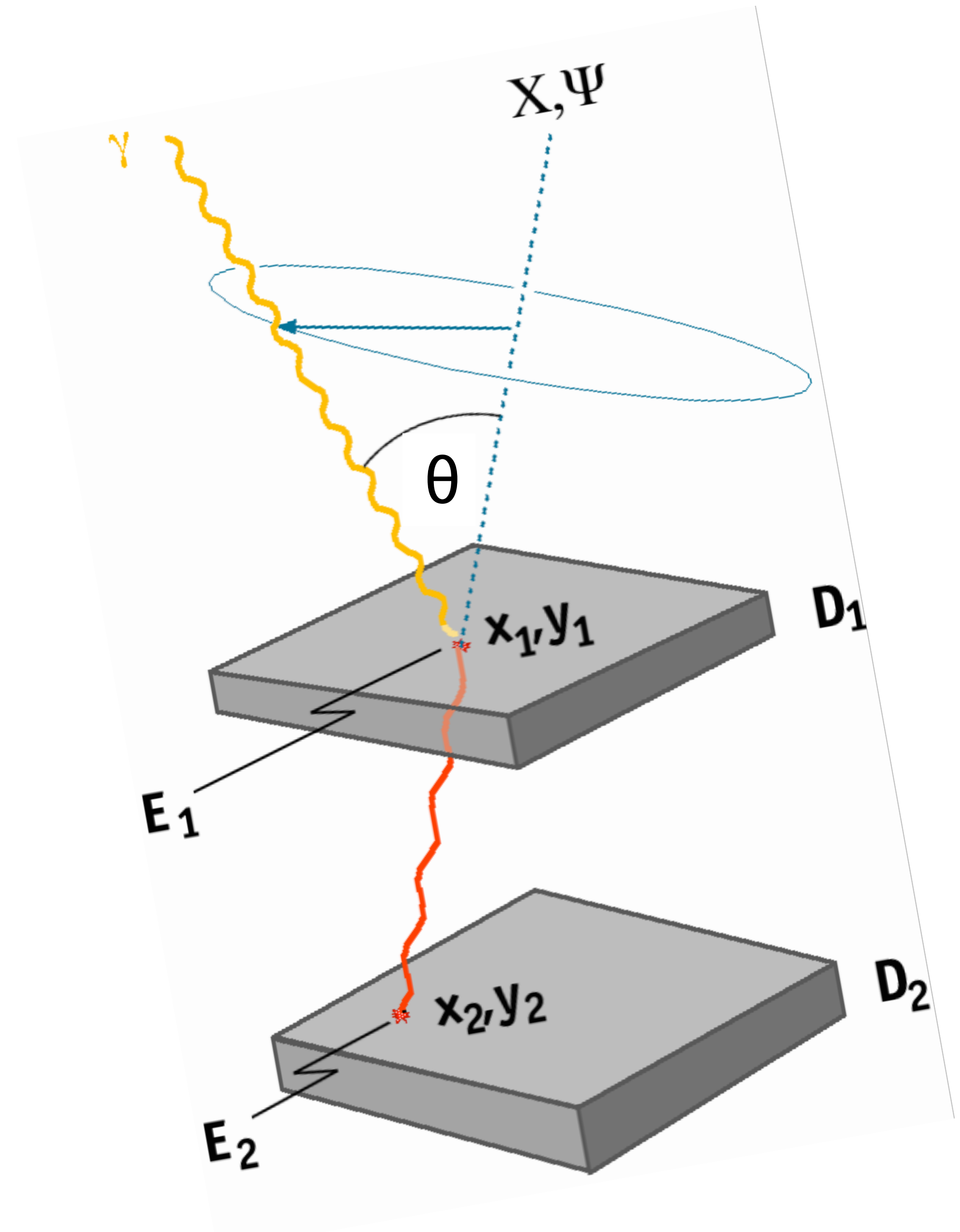
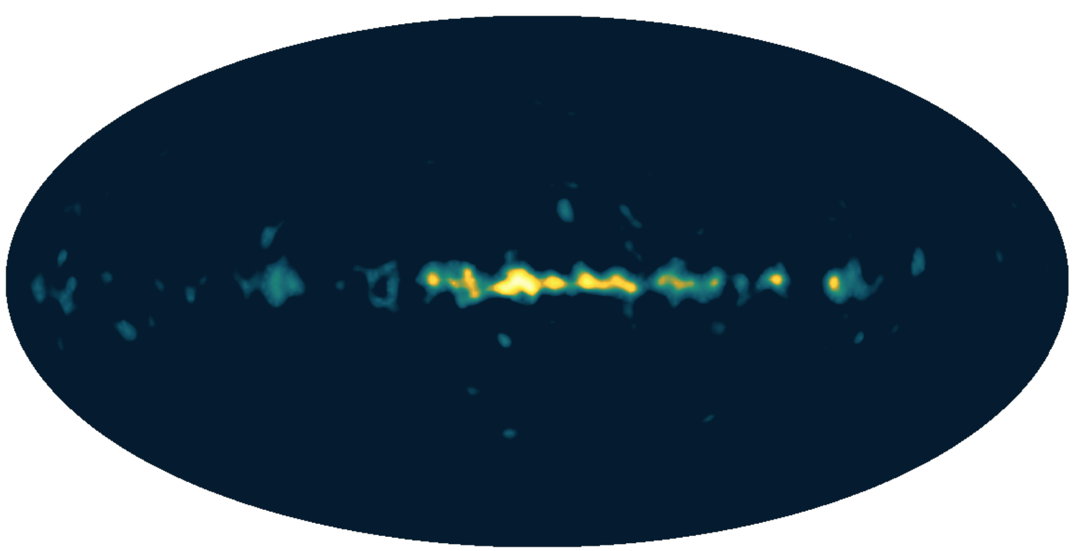


Compton telescopes: Design considerations, etc



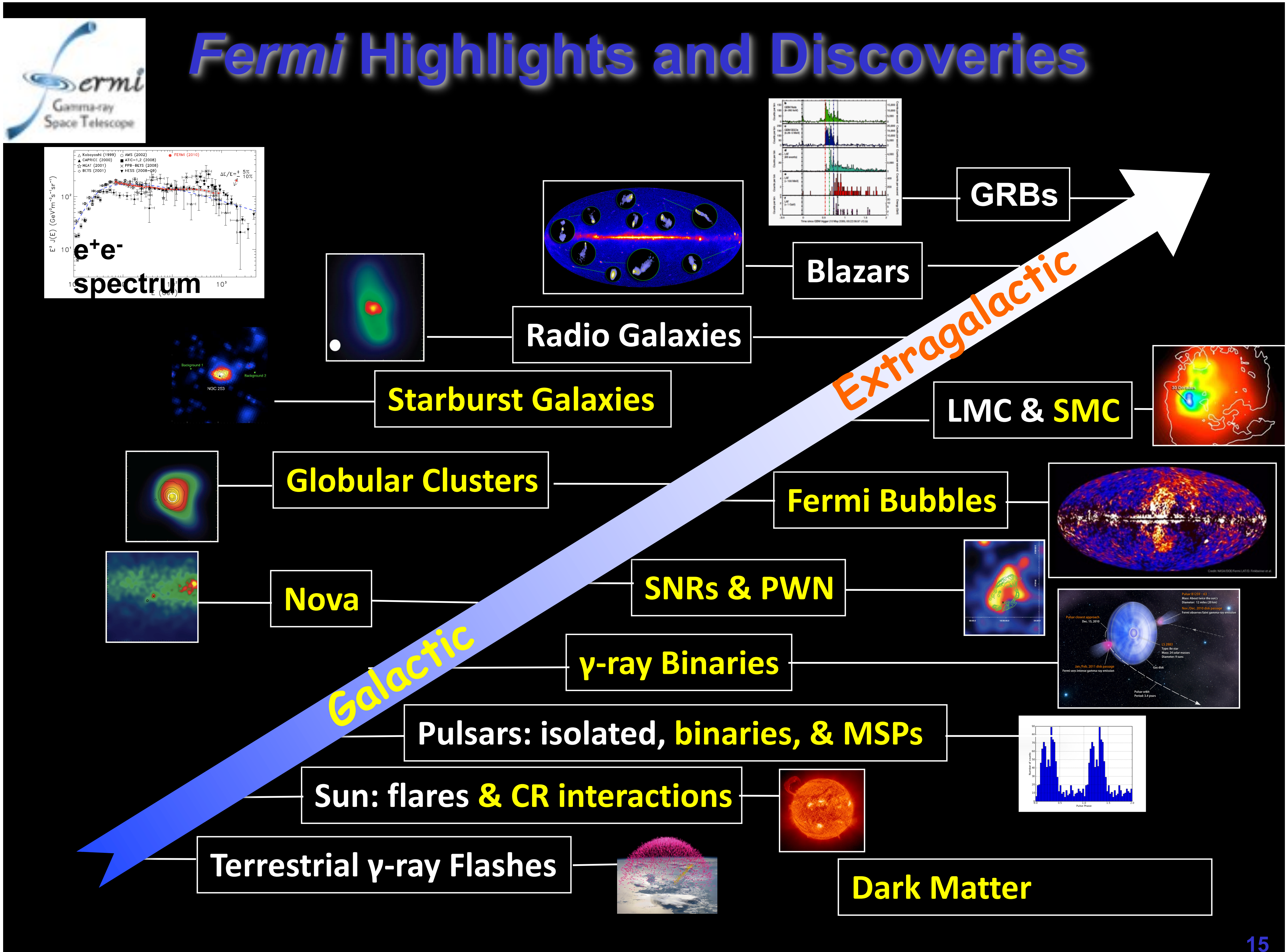
J. Eric Grove

U.S. Naval Research Laboratory

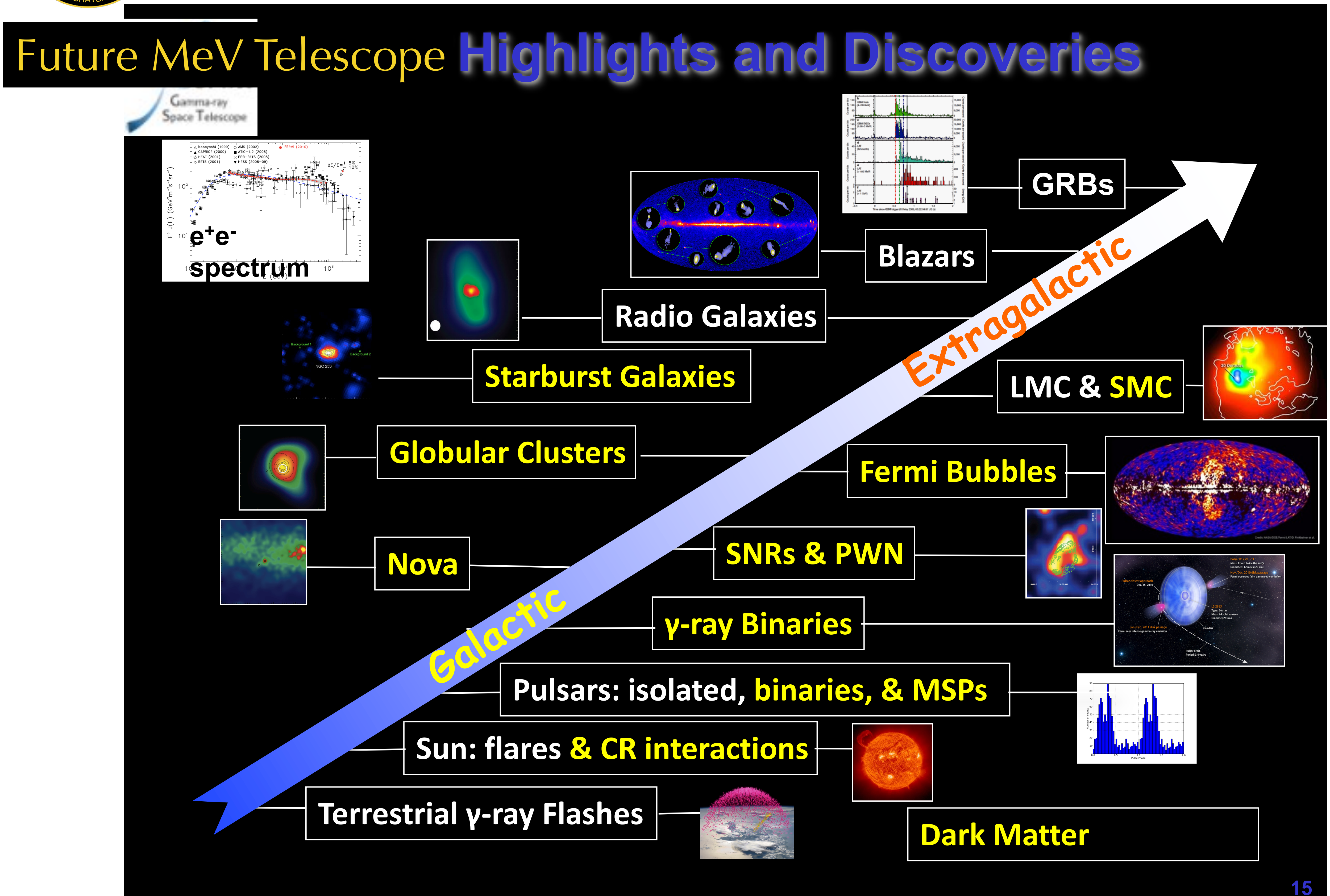


first ^{26}Al all-sky map

Why observe near 1 MeV?



Why observe near 1 MeV?



Why observe near 1 MeV?

Future MeV Telescope Highlights and Discoveries

All this, and nuclear astrophysics too!

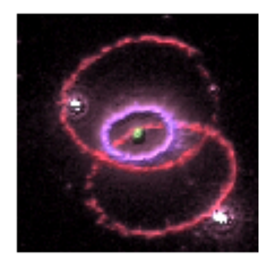
Studying the life cycle of matter, the synthesis and distribution of the elements

Supernovae (^{56}Ni, ^{57}Ni, ^{44}Ti)

- Understand the explosion mechanism
- Abundances of synthesized elements
- Structure & dynamics of ejecta

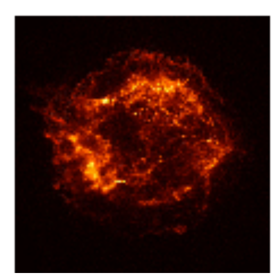
Giants (^{26}Al)

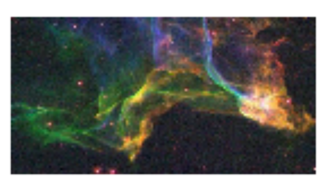
- Convective shell burning



Stars/Sun (many)

- Ion acceleration
- Ambient abundances
- Accelerated abundances





Remnants (^{44}Ti, ^{26}Al, ^{106}Sn)

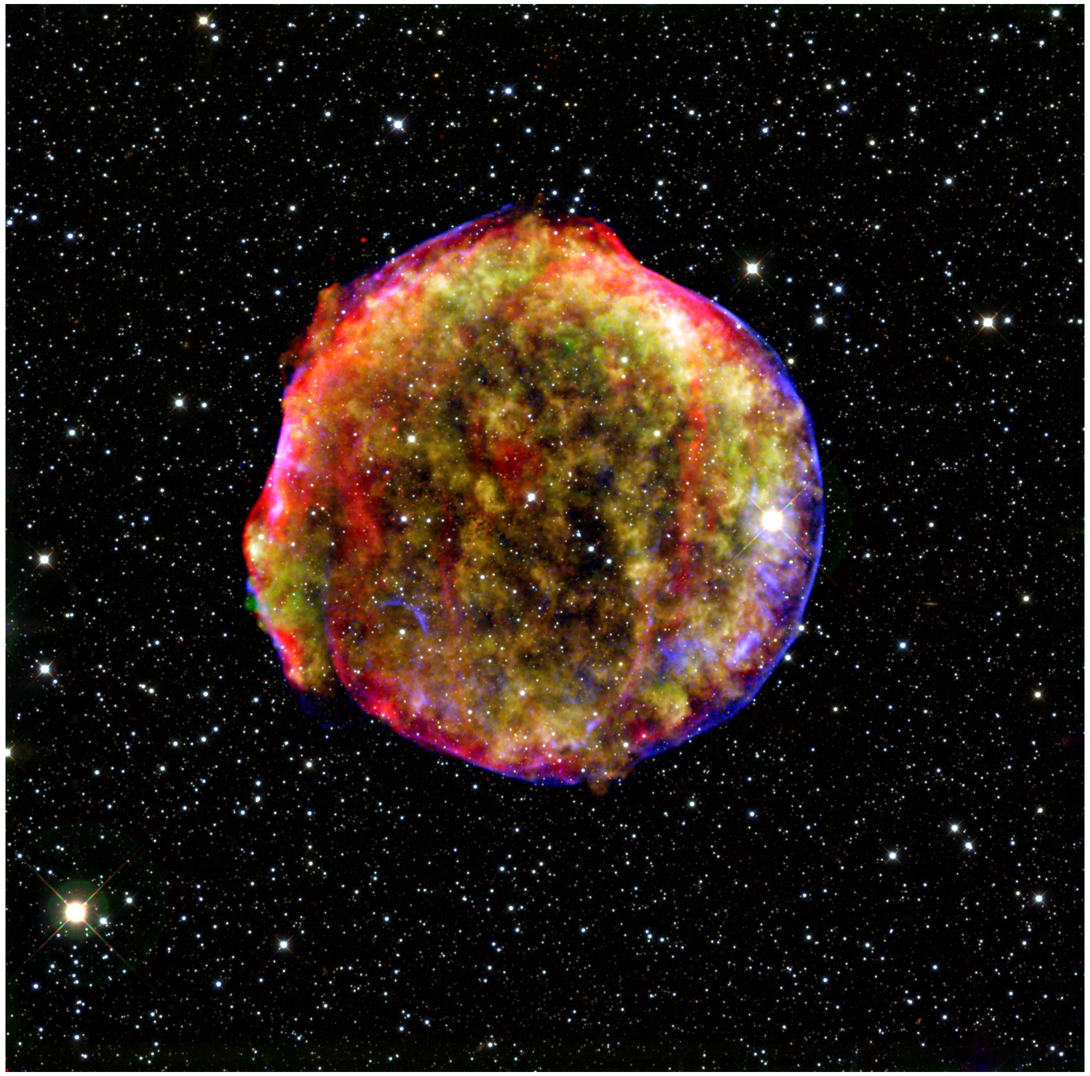
- Structure & dynamics
- Ejection of heavy elements
- Compact object formation
- Discovery of young remnants
- CR acceleration

Interstellar Medium (^{26}Al, ^{60}Fe,...)

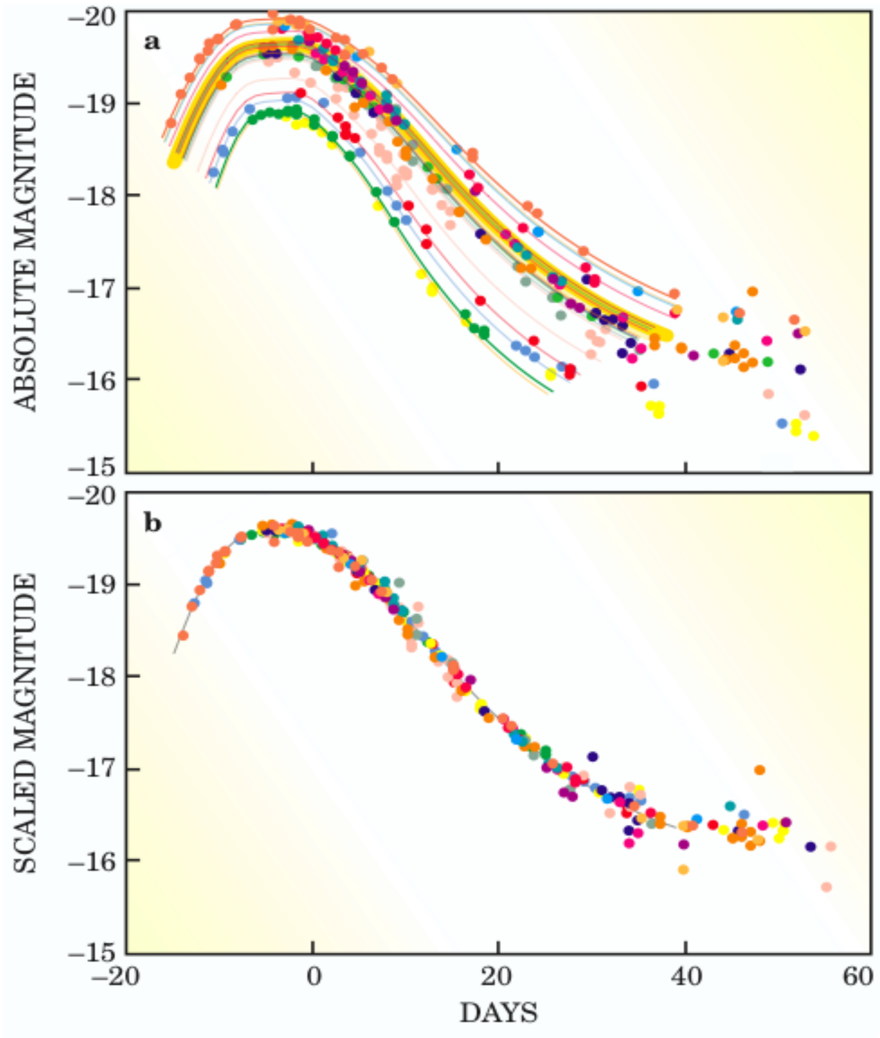
- Galactic history of nucleosynthesis
- Formation, evolution and death of massive stars
- CR interactions, chemical composition

Supernovae Type Ia and MeV astronomy

- SN Ia have been crucial in understanding the structure of the universe



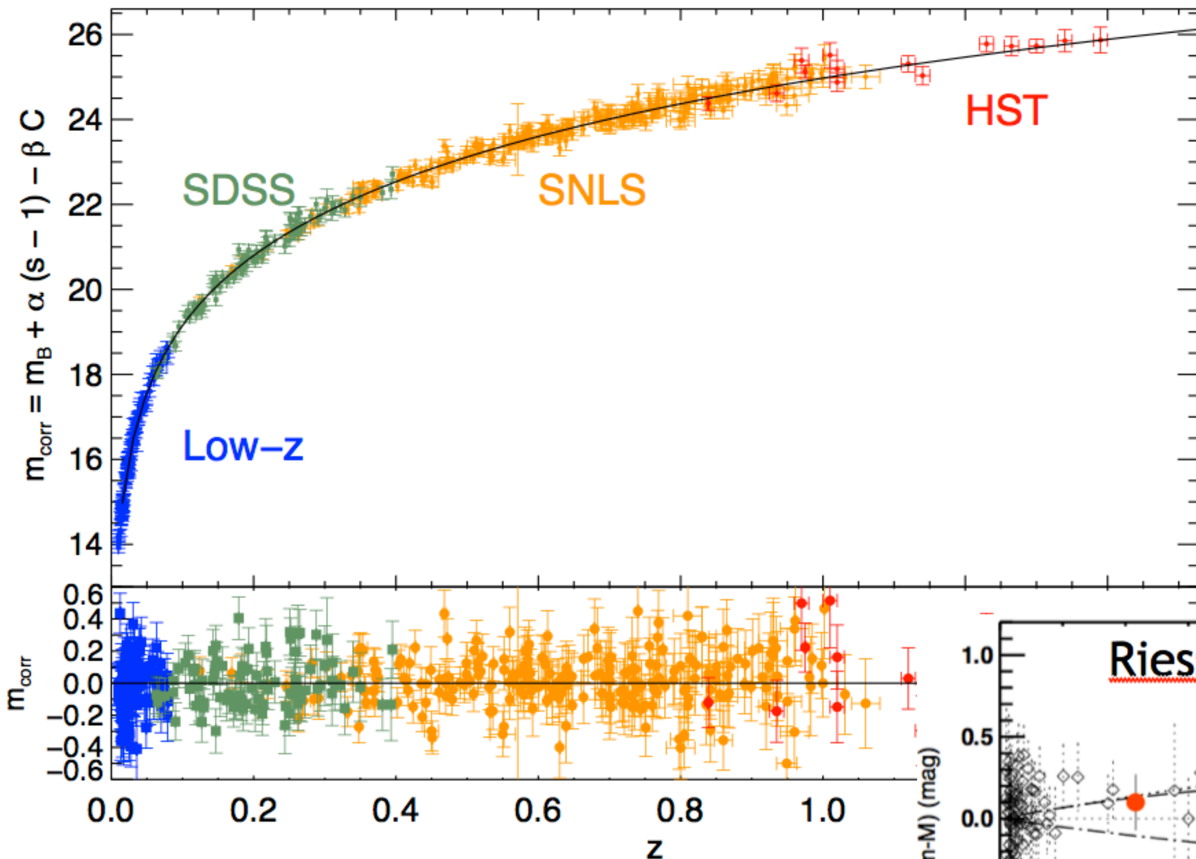
Tycho SNR (1572 CE)
Warren et al. 2005



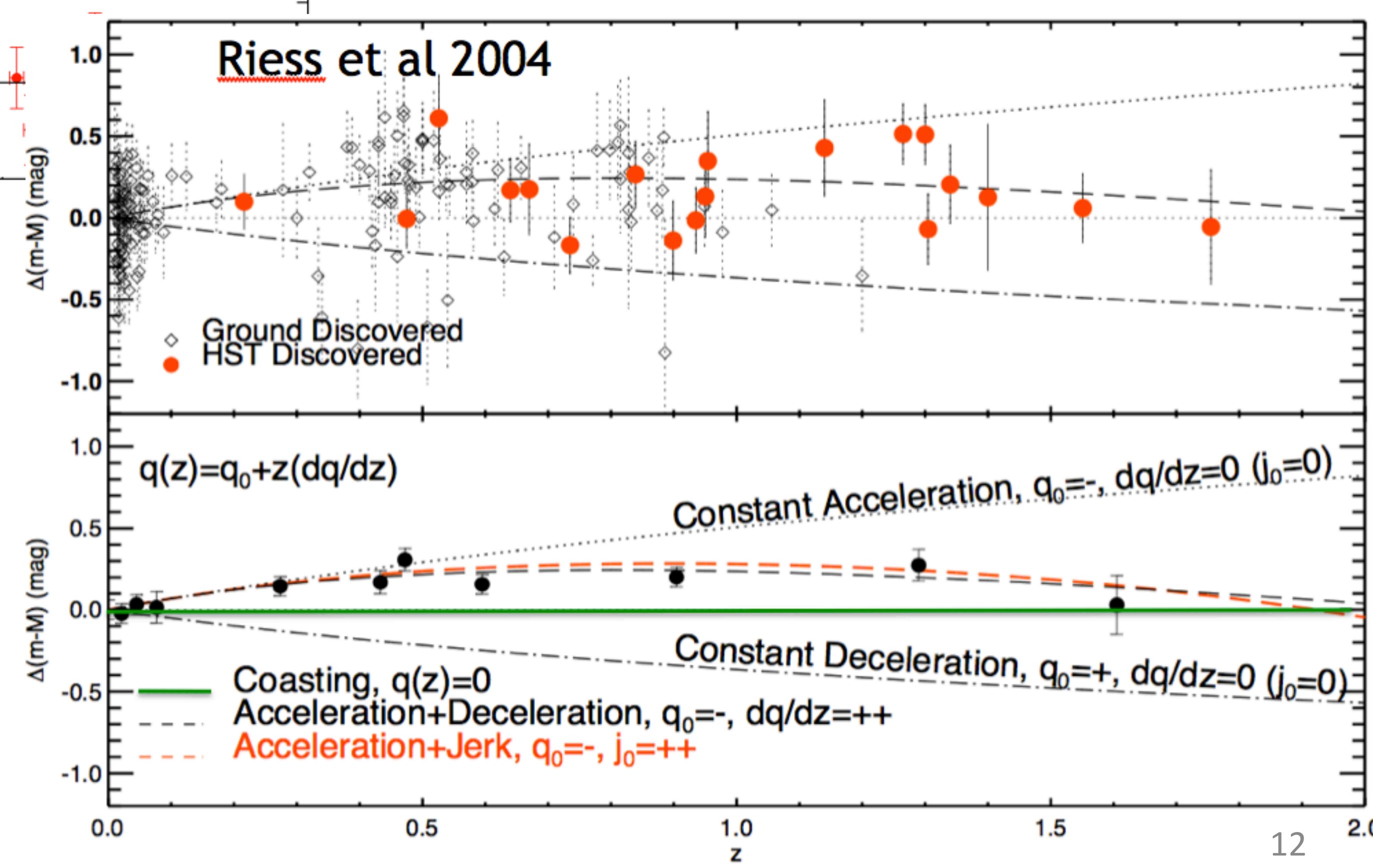
Perlmutter 1999 Physics Today

Supernova Type Ia cosmology

Conley et al. 2011



Assuming a one-parameter calibration of light curves, we use SN Ia with dramatic implications for Dark Energy. We have to understand absolute luminosities to ~0.1 mag to high z and low Z.



Grove - MeV Astronomy 12

… yet we do not understand the nearby SN Ia well

Type Ia supernova scenario

- Nuclear ignition in a White Dwarf (WD), with a large fraction of the mass burned to nuclear statistical equilibrium, centered around ^{56}Ni. The entire star is disrupted in the explosion.

Explains:

- Hydrogen deficiency
- Late-time Fe-group emission
- High velocities, ~10^4 km/s
- Presence in elliptical galaxies

Outstanding Issues:

- Nature of progenitor systems, composition & mass of WD
- Ignition location(s)/conditions
- Nuclear flame propagation
- Effect of rotation, **B** on explosion
- Nature of observed luminosity/duration correlations, and impact of metallicity (Timmes et al. 2003, Jackson et al. 2010)

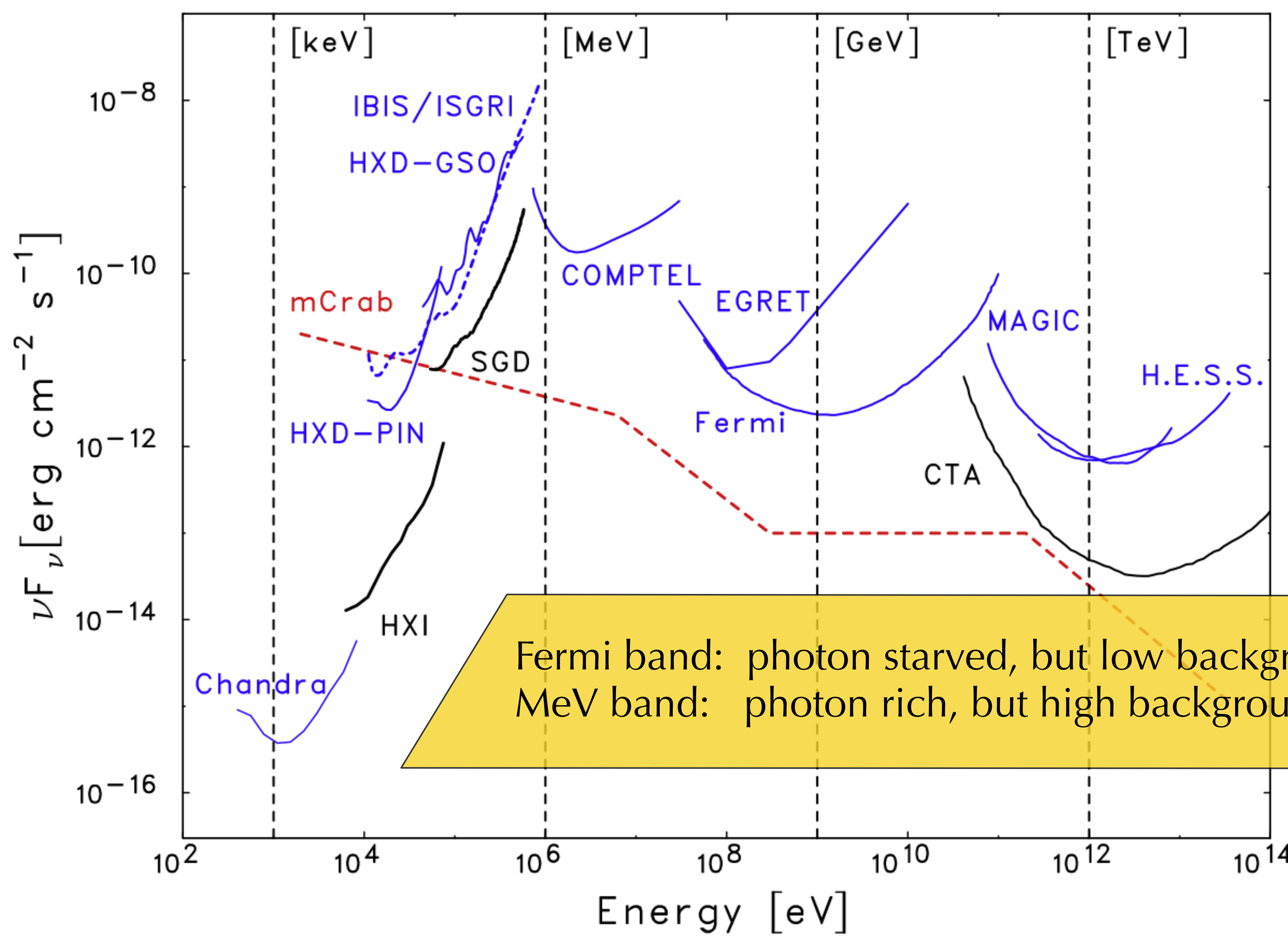
^{56}Ni is key to understanding these explosions….

$$^{56}Ni \xrightarrow{6\ d} {}^{56}Co \xrightarrow{77\ d} {}^{56}Fe$$

158 keV 812 keV etc.	847 keV 1238 keV etc.

Why hasn't this been done already?

Rich science at ~1 MeV is hampered, so far, by poor sensitivity

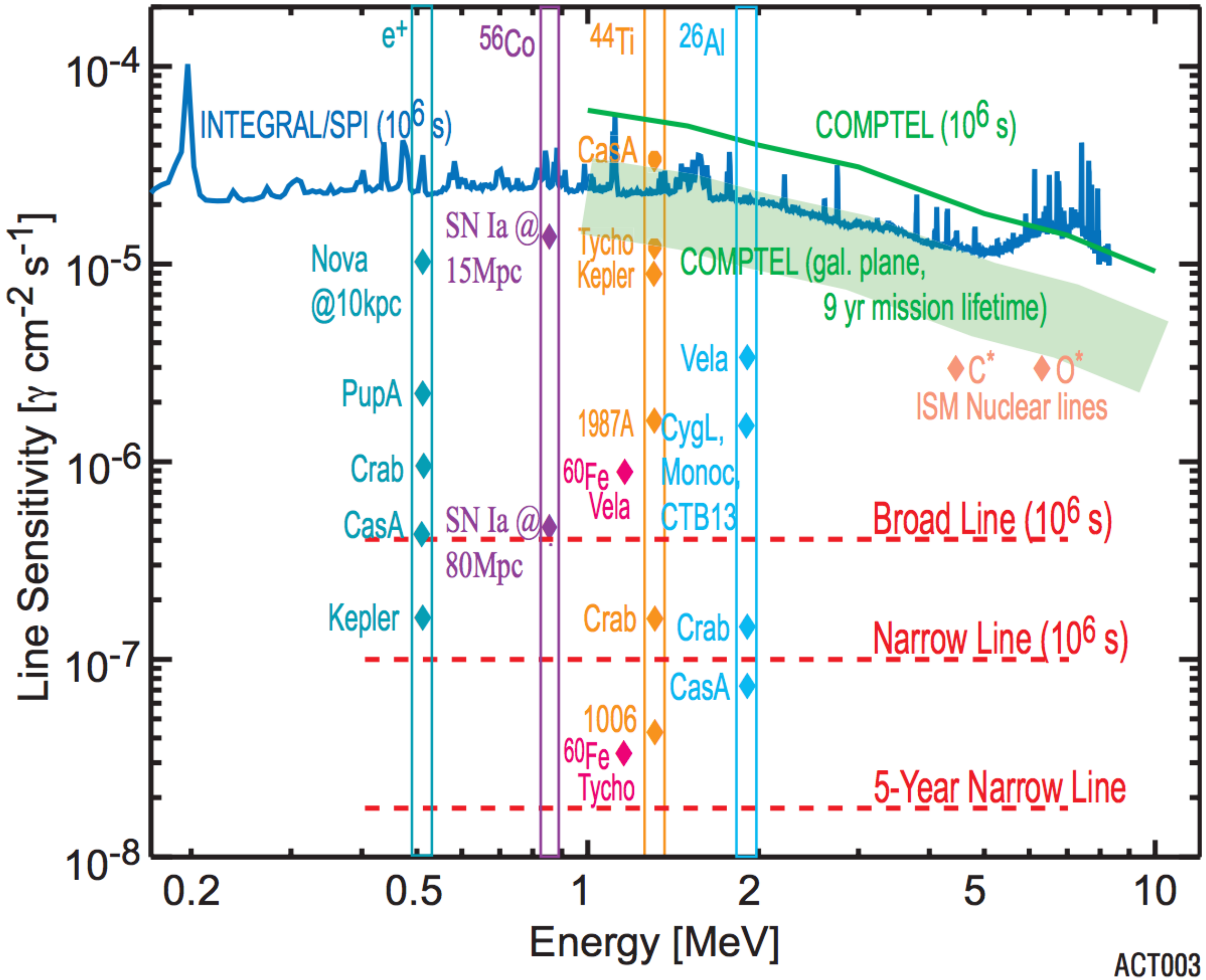


Fermi band: photon starved, but low background
MeV band: photon rich, but high background and imaging is hard

Why so difficult?

- No focusing; imaging difficult
- Small interaction probability
- High background

Differential continuum sensitivities of X-ray and γ-ray instruments for isolated point sources
Takahashi et al. 2013



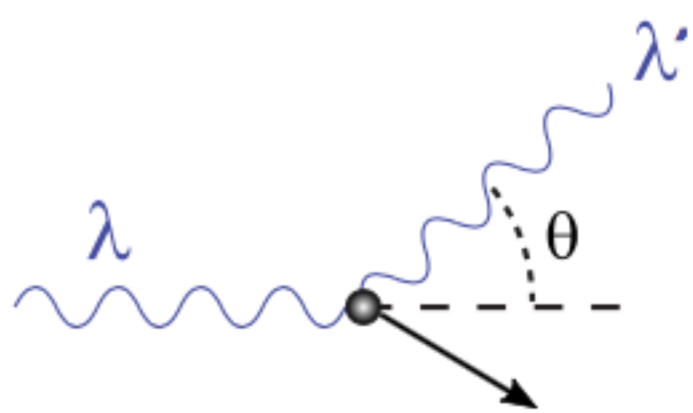
From Advanced Compton Telescope mission concept study (Boggs 2007)

- Narrow and broad line sensitivity needed for nuclear astrophysics
  - Compare current/historical mission sensitivities to theoretical predictions
    - COMPTEL and Integral/SPI: ~ few x 10^{-5} ph cm^{-2} s^{-1} in 10^6 sec
    - Want < few x 10^{-7} ph cm^{-2} s^{-1} in 10^6 sec
  - Goal
    - Time dependence and many sources

Interaction with matter

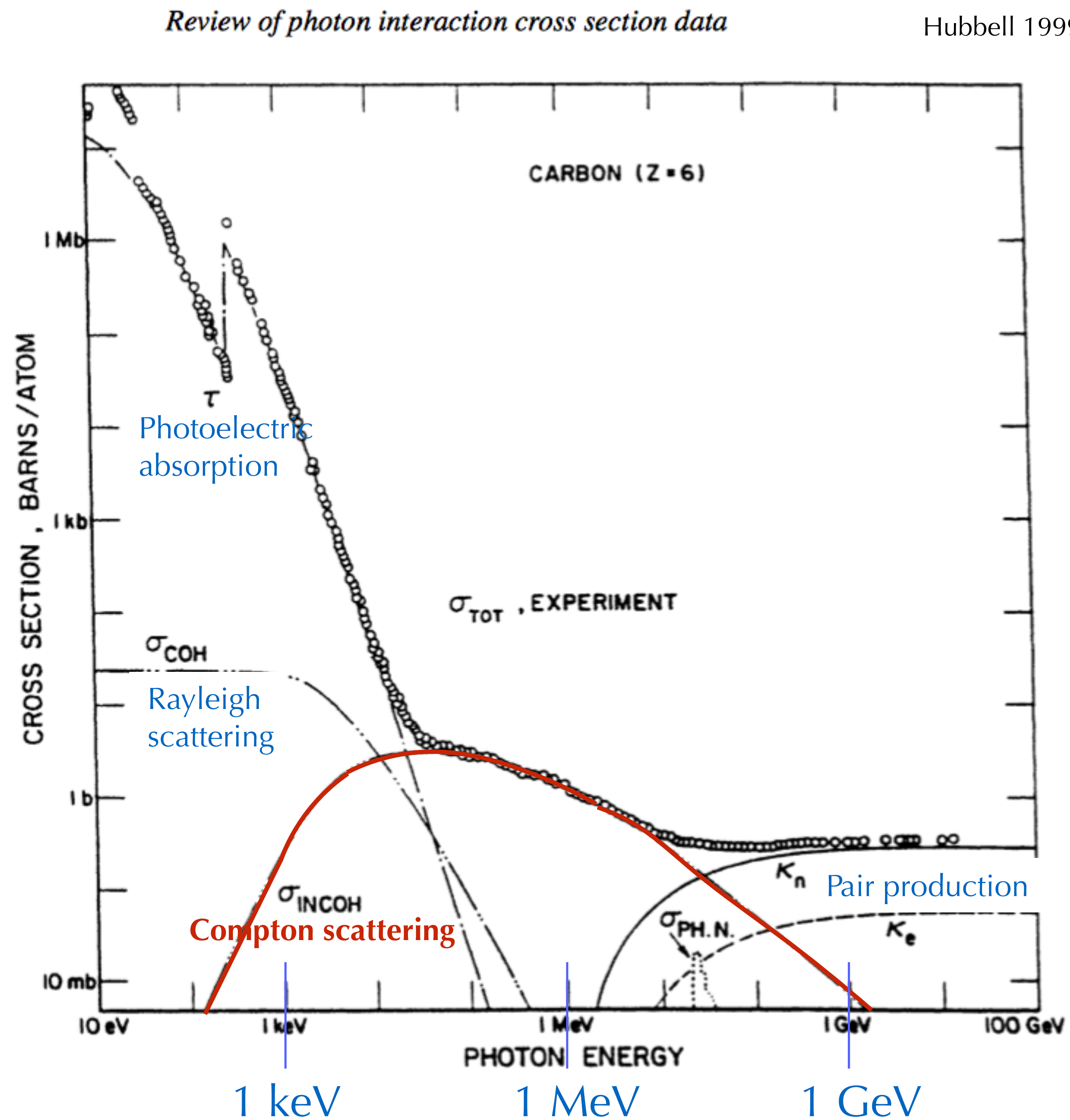
- Photon interaction cross section
  - Photoelectric absorption
  - Compton scattering
  - Pair production

- Compton scattering
  - Interaction with bound electrons



Credit: Wikipedia

$$\lambda' - \lambda = \frac{h}{m_e c}(1 - \cos\theta)$$

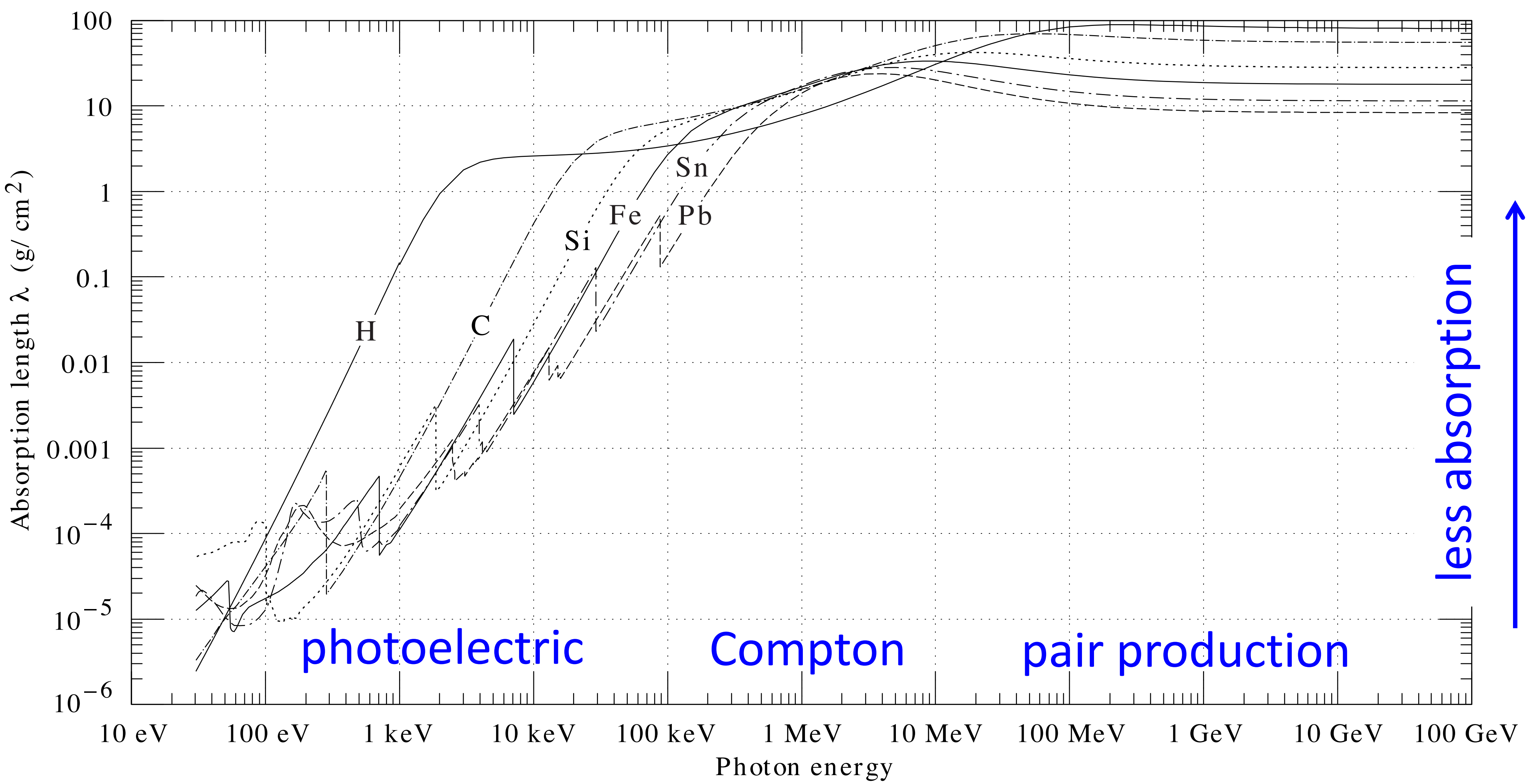


Hubbell 1999

- Scattering angle and photon energy loss are directly related

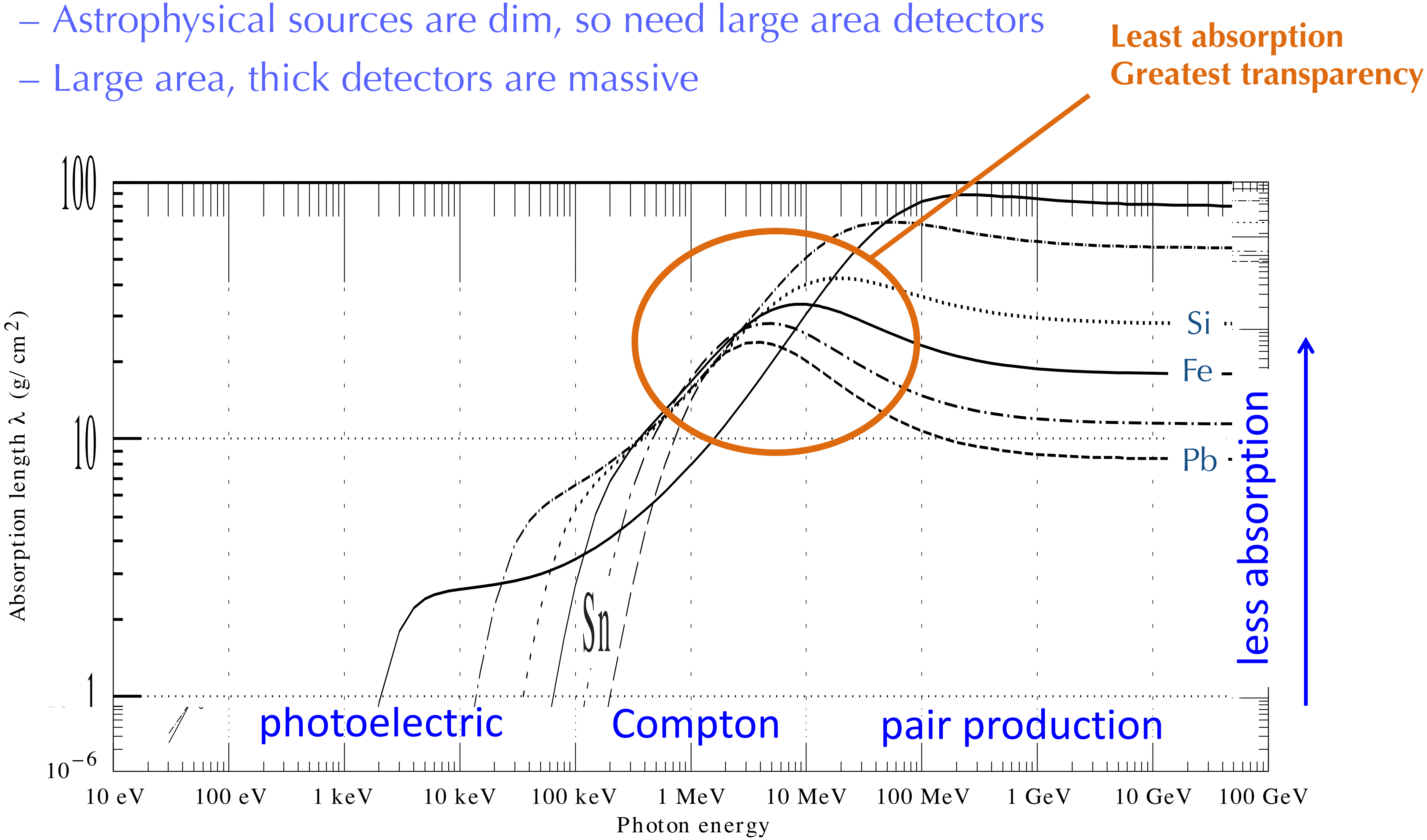
Interaction with matter

- Detector materials are most transparent in the MeV band!
  - Need thick detectors
  - Astrophysical sources are dim, so need large area detectors
  - Large area, thick detectors are massive



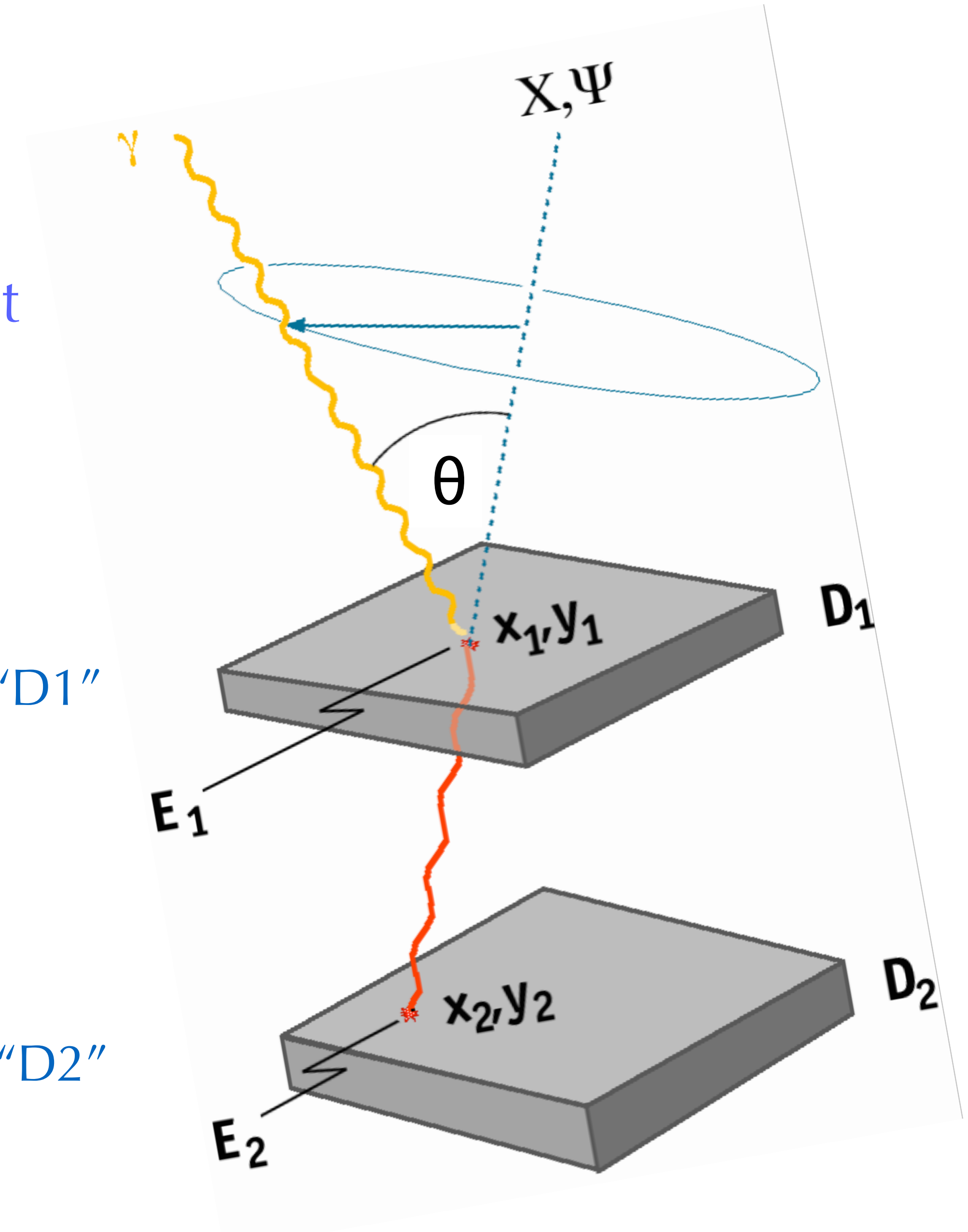
Interaction with matter

- Detector materials are most transparent in the MeV band!
  - Need thick detectors
  - Astrophysical sources are dim, so need large area detectors
  - Large area, thick detectors are massive



Basic Compton telescope

- Two components
  - One detector to scatter the γ ray
  - Another detector to absorb the scattered γ
  - Use Compton formula to reconstruct incident photon direction
    - Need to measure position and energy deposition in both detectors



Scattering detector: "D1"

Absorbing detector: "D2"

- What happens if scattered γ ray isn't fully absorbed? How would we know it's fully absorbed?

Compton telescope principles

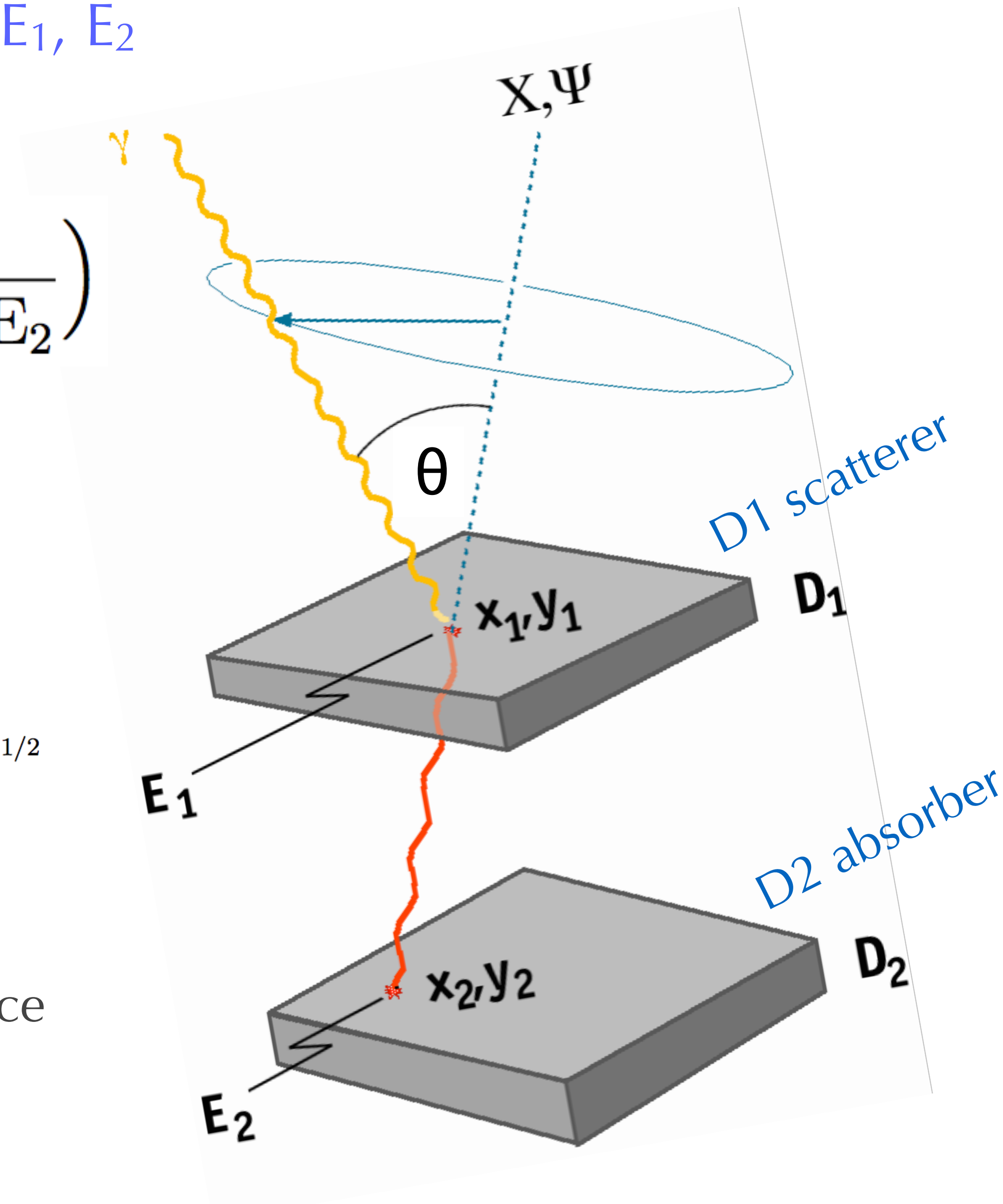
- Compton event reconstruction
  - Incident energy = sum of measured energies E_1, E_2
  - Incident direction from Compton formula

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

    - Incident direction reconstructs to cone
      - Annulus on sky
    - Width of cone ("angular response measure") is function of E and position resolution
      - dE term:

$$\Delta\theta = \frac{m_e c^2}{\sin\theta} \left[\frac{\Delta E_1^2}{(E_1 + E_2)^4} + \Delta E_2^2 \left(\frac{1}{E_2^2} - \frac{1}{(E_1 + E_2)^2} \right)^2 \right]^{1/2}$$

  - Must have good dE and good dx
    - Angular resolution depends on spectral performance
      - e.g. good dE: Si, Ge, $LaBr_3$, SrI_2



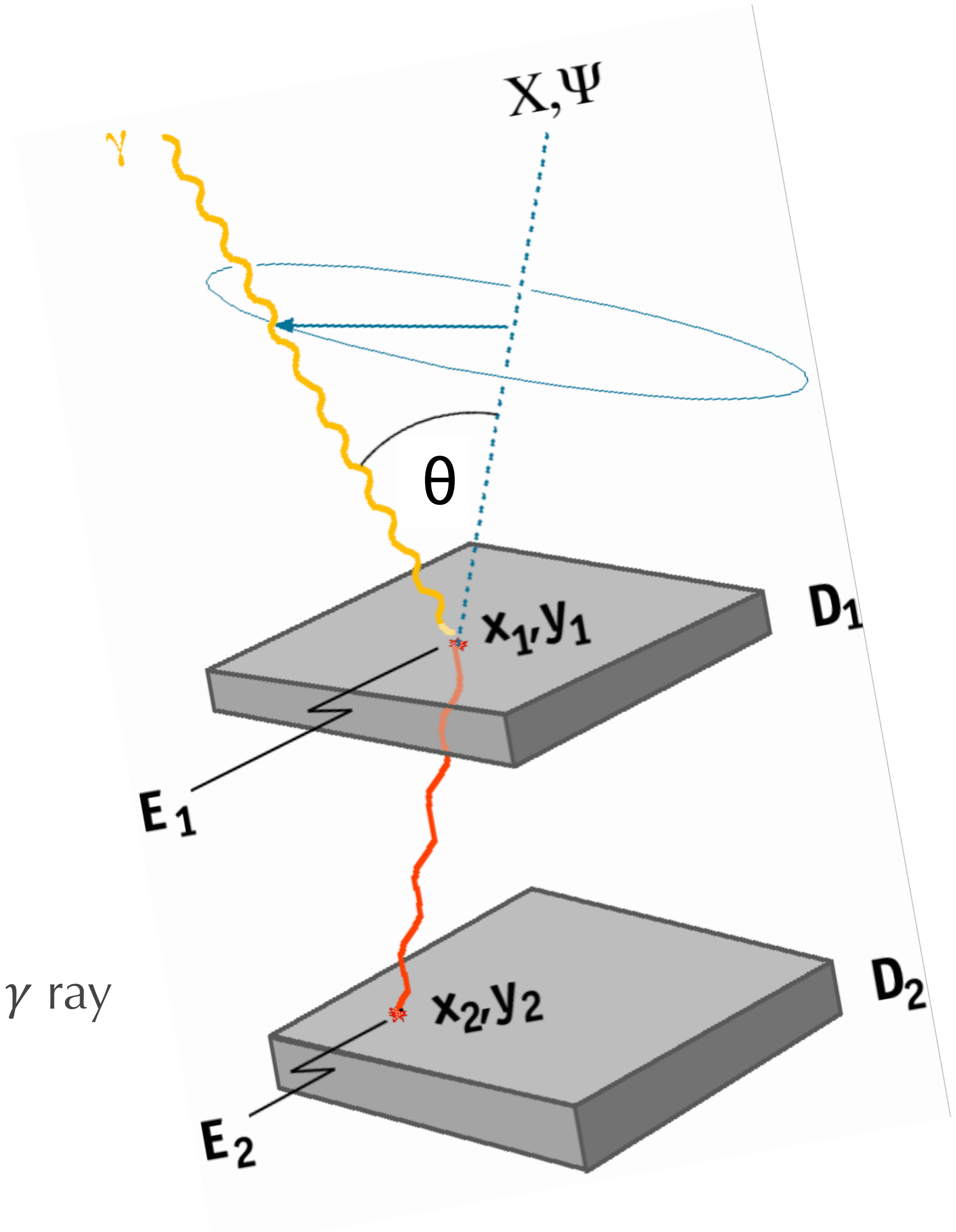
  - Must fully absorb in D2
    - Reconstructed E and direction will be wrong if energy escapes
    - (Not entirely trivial to find such a detector material; e.g. need lots of Si, Ge)

Compton telescope principles

- Compton event reconstruction
  - Width of cone ("angular response measure") is function of E and position resolution
    - dE term:

$$\Delta\theta = \frac{m_e c^2}{\sin\theta}\left[\frac{\Delta E_1^2}{(E_1+E_2)^4} + \Delta E_2^2\left(\frac{1}{E_2^2} - \frac{1}{(E_1+E_2)^2}\right)^2\right]^{1/2}$$

    - dx term:
      - » Separating D1 and D2 increases lever arm



– Design trade

- Separating D1 and D2
  - Improves angular resolution
  - Decreases effective area
    - » Decreases efficiency for detecting scattered γ ray

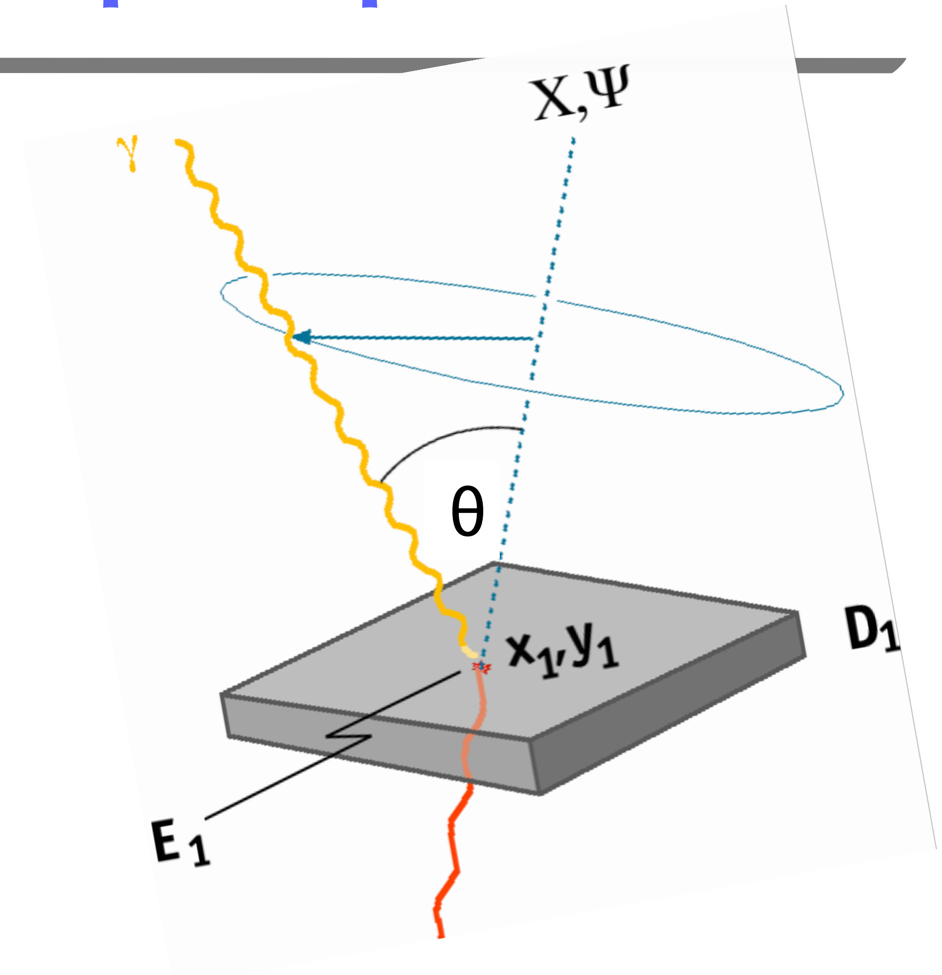
What's the right choice?

Compton telescope principles

- Compton event reconstruction
  - Width of cone ("angular response measure") is function of E and position resolution
    - dE term:

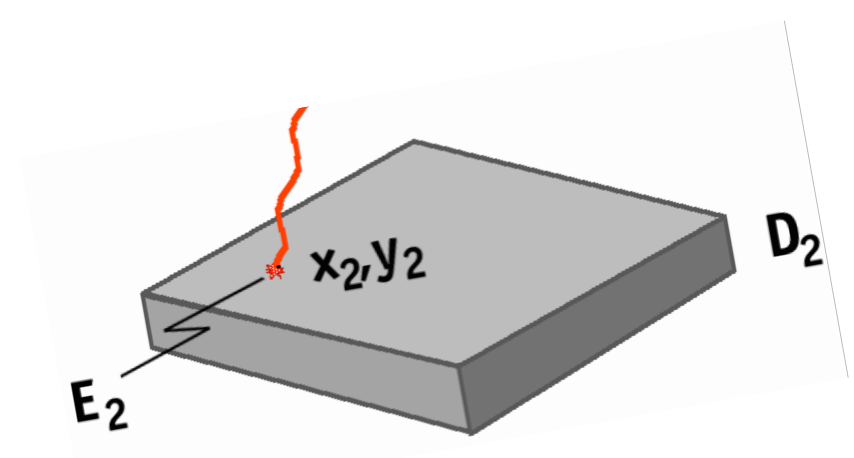
$$\Delta\theta = \frac{m_e c^2}{\sin\theta}\left[\frac{\Delta E_1^2}{(E_1+E_2)^4} + \Delta E_2^2\left(\frac{1}{E_2^2} - \frac{1}{(E_1+E_2)^2}\right)^2\right]^{1/2}$$

    - dx term:
      - » Separating D1 and D2 increases lever arm



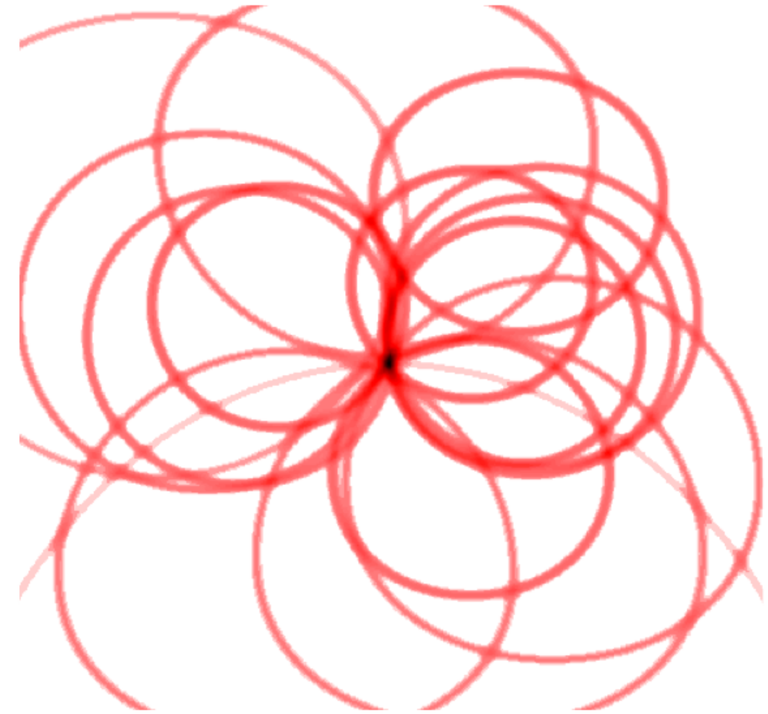
- Design trade
  - Separating D1 and D2
    - Improves angular resolution
    - Decreases effective area
      - » Decreases efficiency for detecting scattered γ ray

What's the right choice?



Compton imaging

- Image
  - Each photon = ring
  - Intersection of many rings
- Issue
  - Source confusion
  - Rejection of sky background
    - Especially the bright atmosphere of Earth
  - Complicated PSF

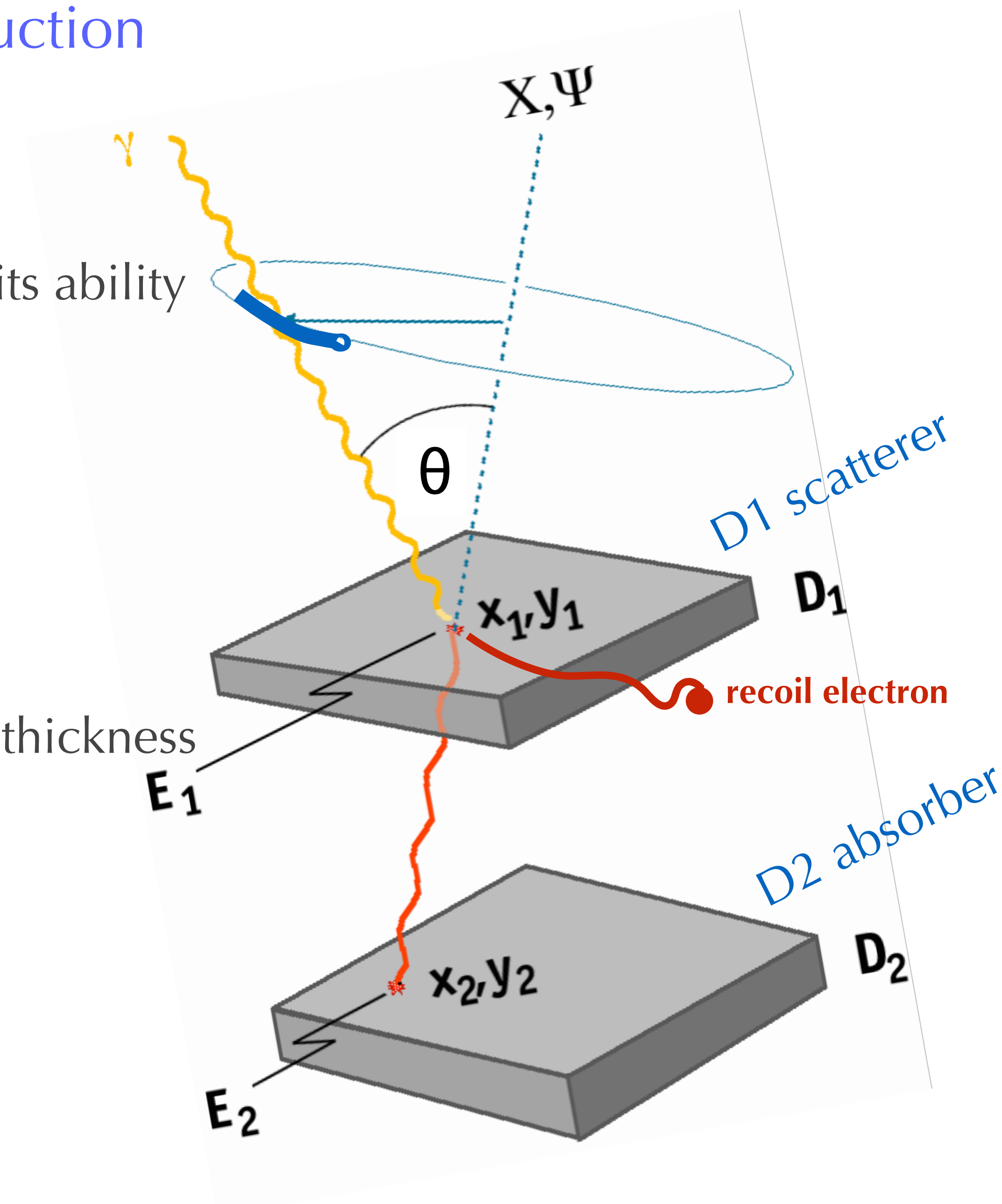


- ➢ The origin of a single not-tracked event can be restricted to the so called "event circle".
- ➢ The photon originated at the point of all overlap.

- Mitigation
  - Best possible E and position resolution
    - Keep them well matched
  - Get more information about the scatter in D1: track the recoil electron

Electron tracking

- Measuring recoil electron track
  - Allows almost complete interaction reconstruction
  - Reduces Compton ring to an arc
    - Multiple coulomb scattering of recoil electron limits ability to measure initial recoil direction
      - Want low-density D1 to minimize MCS
      - But that minimizes Compton probability
  - But it raises low E threshold for instrument
    - Recoil electron must travel through finite detector thickness
    - e.g. range(500 keV e) < 1 mm of Si



- Note: Doppler broadening
  - Momentum of bound electron is important
    - Significant contribution below ~1 MeV
    - Whether electron tracking or not
  - Sets fundamental limit on measurement uncertainty
  - Low-Z materials make better scatterers

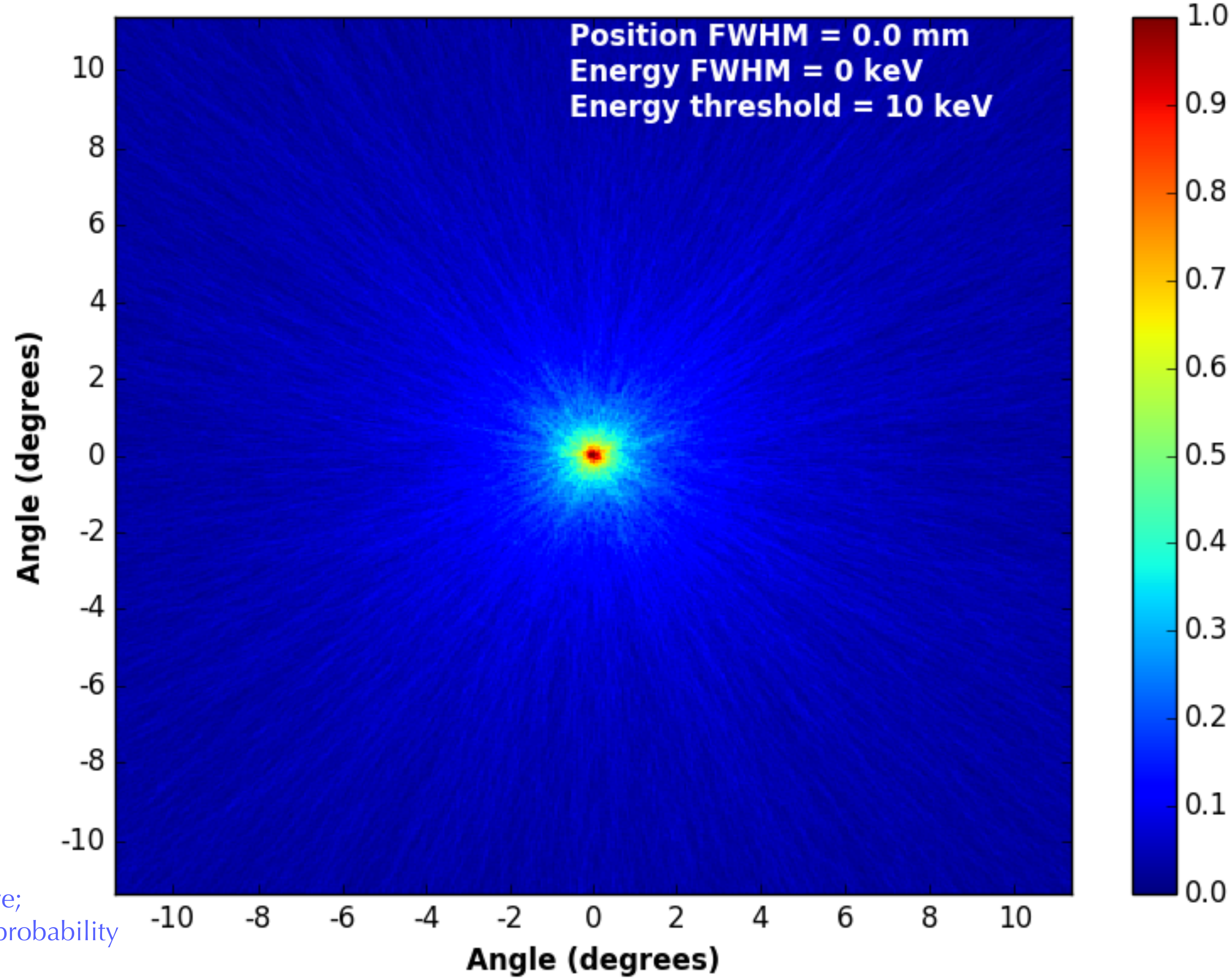
Monte Carlo example: cubic meter of Si

- Point source at 847 keV
  - 10^4 shots into 1x1x1 m Si cube: ~2 days observing SNIa at 15 Mpc
  - Require 2 interactions, no electron tracking: ~8500 reconstructed γ rays

Perfect detector, only Doppler broadening
- Individual rings (almost) visible

“Realistic” detector parameters
- Rings are wide
- Rings are blurred over large area

Note to Compton experts:
This looks worse than expected because solid Si puts interactions too close together (reduces lever arm). Vertical gaps between Si wafers are a Good Thing™



Color scale is relative; fraction of peak probability

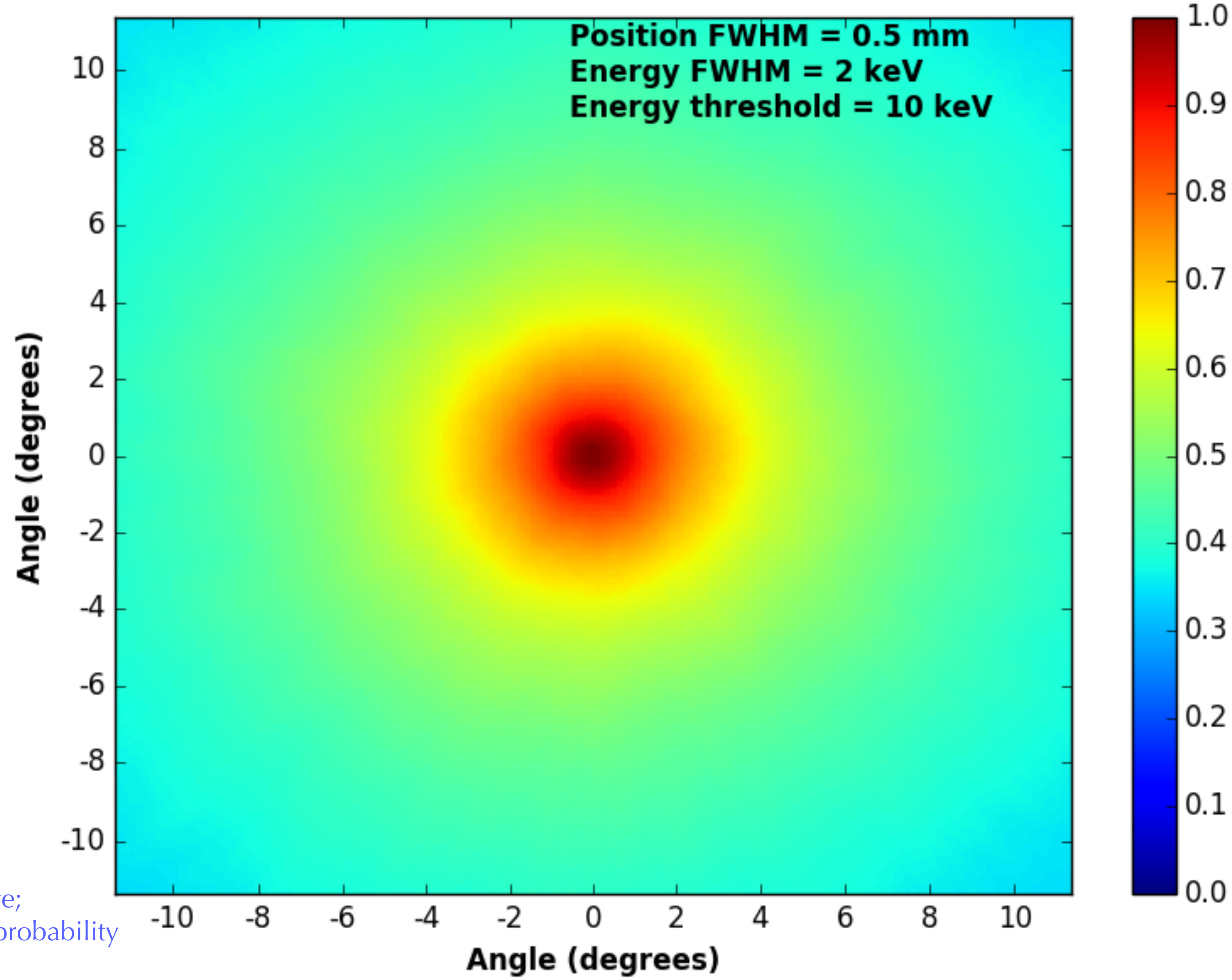
Monte Carlo example: cubic meter of Si

- Point source at 847 keV
  - 10^4 shots into 1x1x1 m Si cube: ~2 days observing SNIa at 15 Mpc
  - Require 2 interactions, no electron tracking: ~8500 reconstructed γ rays

Perfect detector, only Doppler broadening
- Individual rings (almost) visible

"Realistic" detector parameters
- Rings are wide
- Rings are blurred over large area

Note to Compton experts:
This looks worse than expected because solid Si puts interactions too close together (reduces lever arm). Vertical gaps between Si wafers are a Good Thing™



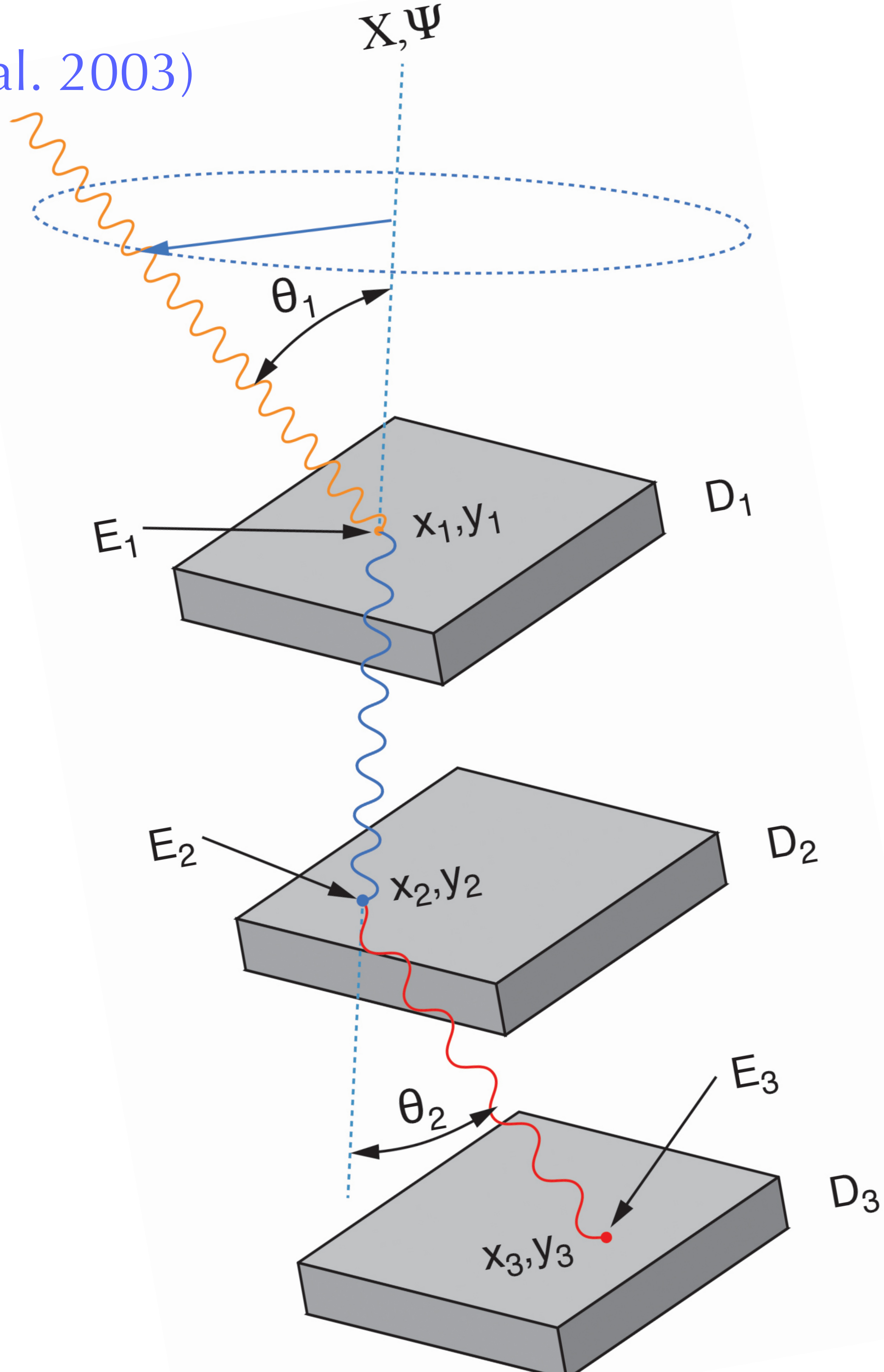
Color scale is relative;
fraction of peak probability

Multiple Compton scatters

- But wait… we can be more clever
  - No need for full absorption (patent: Kurfess et al. 2003)
  - If γ ray scatters at least twice (i.e. at least 3 interaction points in telescope), can measure incident energy without totally absorbing the incident photon

$$E_0 = E_1 + \frac{1}{2}E_2 + \frac{1}{2}\left[E_2^2 + \frac{4m_ec^2E_2}{1-\cos\theta_2}\right]^{1/2}$$

  - Thick, high-Z D2 absorber is not required!
    - Imagine a large array of Si detectors….
    - "Easy" to get excellent position and energy resolution



Multiple-Compton technique

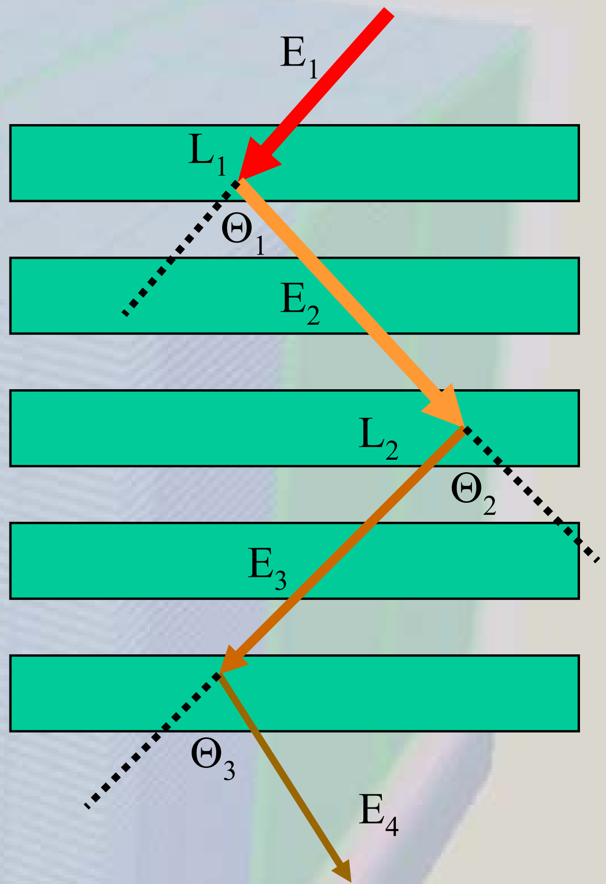
Three Gamma Interaction Technique

Θ_2 is computed from geometry;

$$E_1 = L_1 + \frac{L_2 + \left[L_2^2 + \dfrac{4 m_e c^2 L_2}{1 - \cos\Theta_2}\right]^{\frac{1}{2}}}{2}$$

above is derived from:

$$\begin{cases} \cos\Theta_2 = 1 - m_e c^2 \left(\dfrac{1}{E_3} - \dfrac{1}{E_2}\right) \\ L_2 = E_2 - E_3 \end{cases}$$



- **Unknown source: 3 interactions required to determine energy, *E_1***
- **Known source: 2 interactions required to determine energy, *E_1***
- **Does *not* require total energy absorption**
- **Efficient Compton telescope, even if using *silicon* detectors**
- **Ordering algorithm is essential**

See N1-1: Wulf et al. for prototype results

Novikova (NRL) et al. 2005 – Si ACT

Multiple-Compton technique

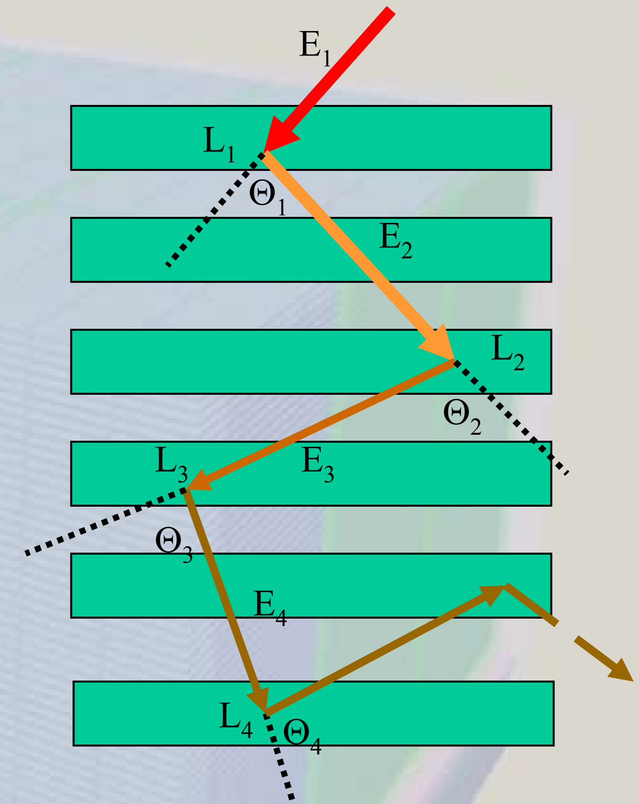
- Warning: order of scatters is essential, and number of scatters can be large

Multiple Estimates of Incident Gamma Ray Energy

$$E_1 = L_1 + \frac{L_2 + \left[L_2^2 + \frac{4m_e c^2 L_2}{1-\cos\Theta_2}\right]^{\frac{1}{2}}}{2};$$

$$E_1 = L_1 + L_2 + \frac{L_3 + \left[L_3^2 + \frac{4m_e c^2 L_3}{1-\cos\Theta_3}\right]^{\frac{1}{2}}}{2}$$

$$E_1 = L_1 + L_2 + L_3 \frac{L_4 + \left[L_4^2 + \frac{4m_e c^2 L_4}{1-\cos\Theta_4}\right]^{\frac{1}{2}}}{2}$$



- **Ordering algorithm is essential**
- **N hits result in N! possible sequences**
- **N interactions provide N-2 estimates of E_1**
- **Sequence with the most consistent estimates of E_1 is accepted**
- **Currently accept only events with 4 to 8 hits, and fully absorbed events with 3 hits**
- **In the future: check Klein-Nishina and absorption probabilities; electron tracking**

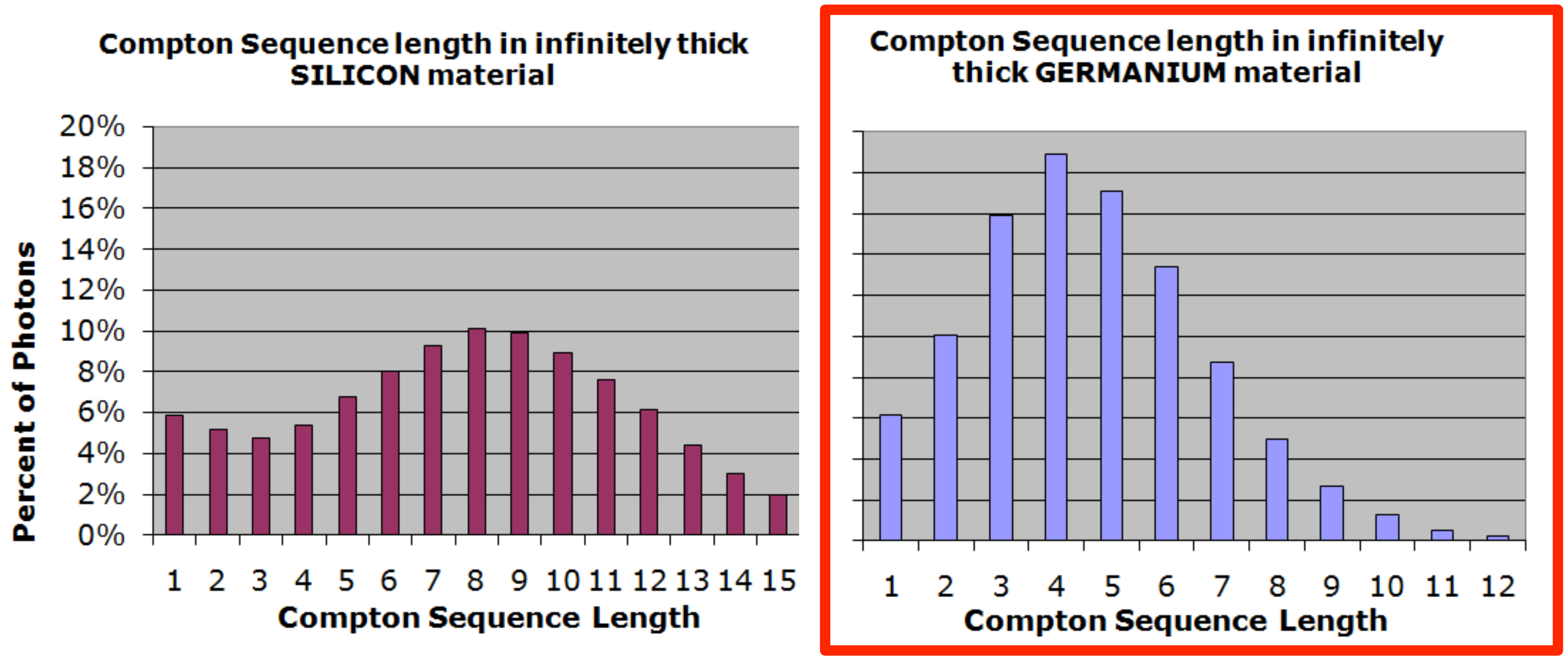
October 26, 2005 IEEE NSS N19-5 Puerto Rico 8

Novikova (NRL) et al. 2005 – Si ACT

How common are multiple Comptons?

- Very, so don't throw them out
  - Maybe Si-only Compton telescope isn't optimal, but needs higher Z somewhere

asCi design considerations - material



Ge : 4±2 interactions needed to transform full energy (75% of photons)
Si : 8+3-2 interactions needed to transform full energy (75% of photons)

Ge : provides sufficient number of interactions (algorithms require ≥ 2) while providing enough stopping power to prevent too many interactions (makes reconstruction impossible, since they increase with *n*!) and increase the chance of the full photon energy being deposited.

from von Ballmoos, Nov 2013, All Sky Compton Imager

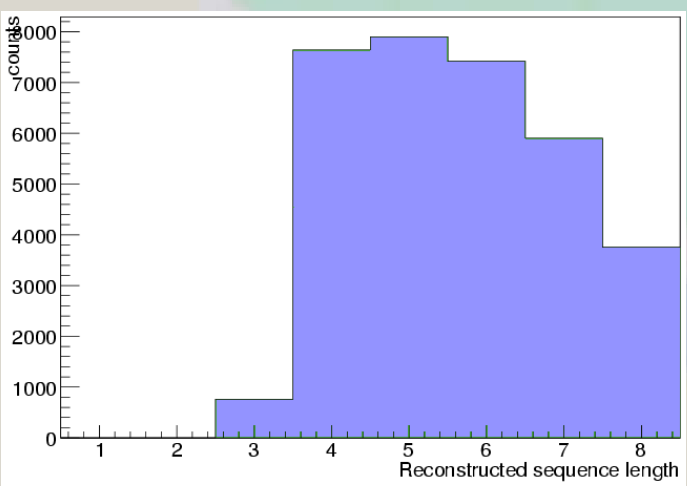
Si ACT (and variants)

Mass model modifications

Compton sequence length for: Horizon cut 92.5^0; E = 847 +/- 22.75 keV; 1 mil events

Main Model
64 x 3mm Si

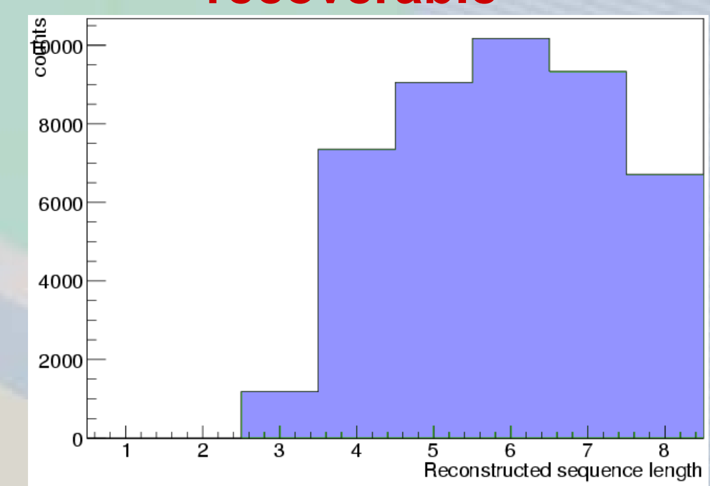
Baseline



Eff. Area 860 cm^2
FWHM Ang.Res: 1.44^0

Thicker Si (Wafer Bonding*)
25 x 7.5mm Si

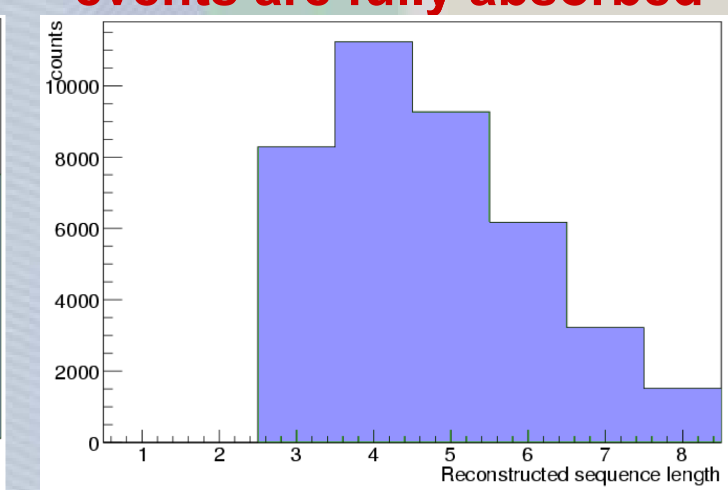
Less dead material:
longer sequences are recoverable



Eff. Area 1266 cm^2
FWHM Ang.Res: 1.9^0

Si interleaved with CZT
(5mm CZT + 12 x 3mm Si) x 4

High-Z material interleaved:
no need for longer sequences, because more events are fully absorbed



Eff. Area 1073 cm^2
FWHM Ang.Res: 1.78^0

***see N35-62: Phlips et al. for wafer bonding**

Novikova (NRL) et al. 2005 – Si ACT

Si ACT (and variants)

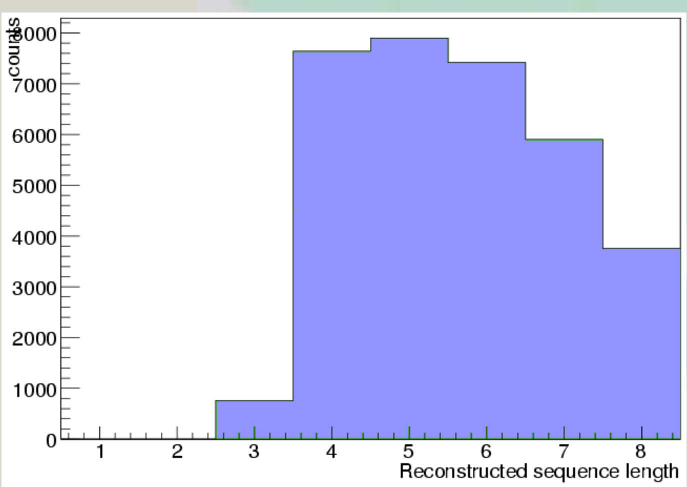
Mass model modifications

Insert high Z, high resolution det
Truncates scatter sequence
Preserves dE, ARM

Compton sequence length for: Horizon cut 92.5^0; E = 847 +/- 22.75 keV

Main Model
64 x 3mm Si

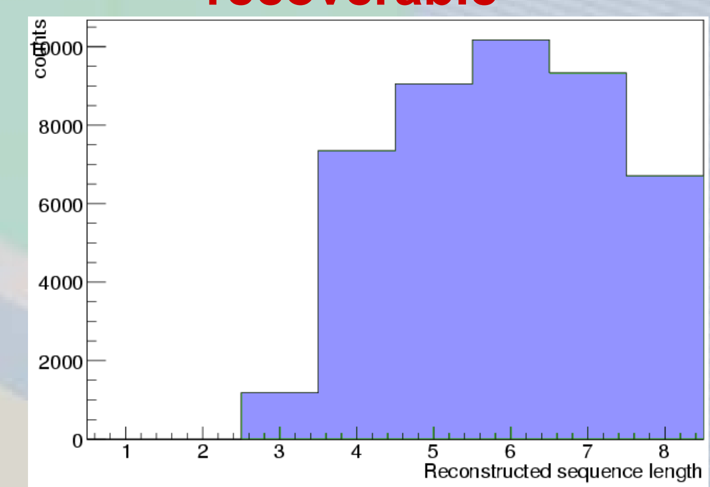
Baseline



Eff. Area 860 cm^2
FWHM Ang.Res: 1.44^0

Thicker Si (Wafer Bonding*)
25 x 7.5mm Si

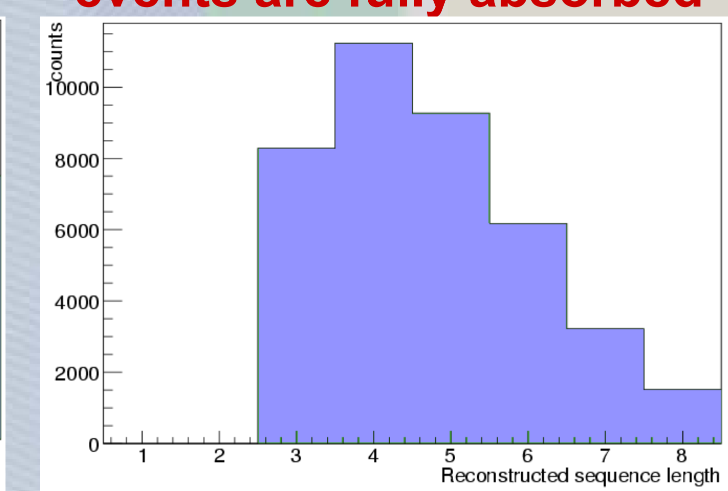
Less dead material: longer sequences are recoverable



Eff. Area 1266 cm^2
FWHM Ang.Res: 1.9^0

Si interleaved with CZT
(5mm CZT + 12 x 3mm Si) x 4

High-Z material interleaved: no need for longer sequences, because more events are fully absorbed



Eff. Area 1073 cm^2
FWHM Ang.Res: 1.78^0

***see N35-62: Phlips et al. for wafer bonding**

October 26, 2005 IEEE NSS N19-5 Puerto Rico 12

Novikova (NRL) et al. 2005 – Si ACT

"Requirements" for high-res Compton tele

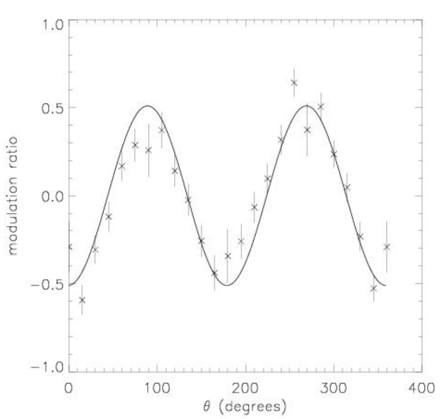
- Low Z scatterer
  - Minimizes Doppler broadening (most important below MeV)
  - Minimizes MCS of recoil electron, if tracking
- High Z absorber
  - Good stopping power to absorb scattered gamma (and minimize multi-Compton)
- High efficiency
  - Proper scatterer and absorber to give highest possible efficiency
  - Compact (as possible) to maximize geometric cross section for interaction
- Excellent energy resolution
  - Well matched with d^3x
- Fine position resolution
  - Well matched with dE
    - Thumb: ~1 mm and ~few keV are commensurate
- Low-power electronics
  - Preserve intrinsic dE, d^3x of detectors while staying within power budget
- Minimal passive mass within detection volume
  - Interactions can be missed in passive material, and kill Compton performance
  - Minimize structural supports, co-located electronics
  - Minimize detector guard rings

Polarimetry

- Compton telescope is good polarimeter
  - Compton scatter preferentially in direction perpendicular to polarization vector
  - Measure intrinsic polarization of γ-ray source by measuring modulation in scatter angles in detector

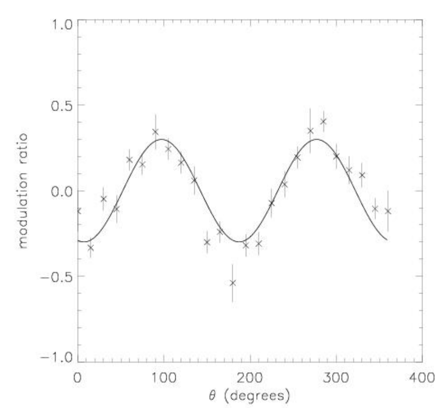
Modulation ratios for 2-layer instrument

In-plane



•High polarization ratio.
•Short lever arm.
•High geometric efficiency for thick detectors (strip pitch < thickness).
•Data more difficult to process.

Out-of-plane



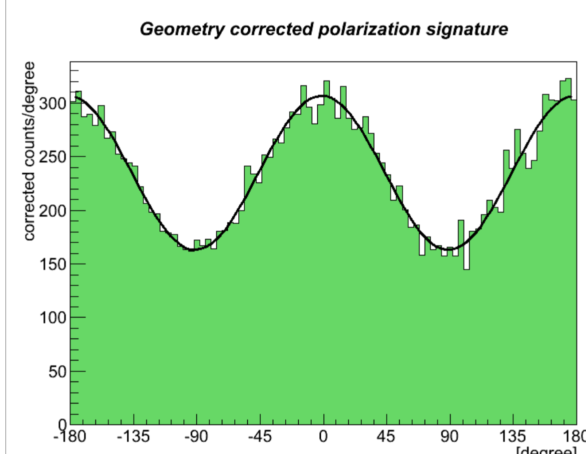
•Lower polarization ratio.
•Longer lever arm.
•Efficiency rises as ~N2.
•Data simpler to process.

Polarization response

Crab-like source (ref: Jourdain & Roques 2009)

Energy range (MeV)	Selections	Modulation μ_{100}	Source (s^{-1})	Atmosph. bgd (s^{-1})	CGB (s^{-1})	Cosmic-ray induced bgd (s^{-1})	$MDP_{3\sigma}$ (c)
0.2 – 2	2+ events without e- tracking θ_{EHC}=20°, θ_{ARM}=3.5°	0.305	28.3	15.0	61.4	7.0 (a)	0.37%
3 – 10	3+ events with e- tracking θ_{EHC}=20°, θ_{ARM}=1.5°	0.124	0.13	0.36	0.10	0.37 (b)	19.2%

(a) Activation from both primary and secondary (i.e. semi-trapped) protons; (b) Activation from primary and secondary protons + prompt reactions from primary protons, and secondary protons and leptons; (c) 3σ minimum detectable polarization for $T_{obs} = 10^6$ s



Polarigramme for a Crab-like source on axis in the range 0.2 – 2 MeV, yielding a modulation μ_{100} = 0.305

- Minimum detectable polarization:

$$MDP_{3\sigma} = \frac{3\sqrt{C_S + B}}{\mu_{100} C_S \sqrt{T_{obs}}}$$

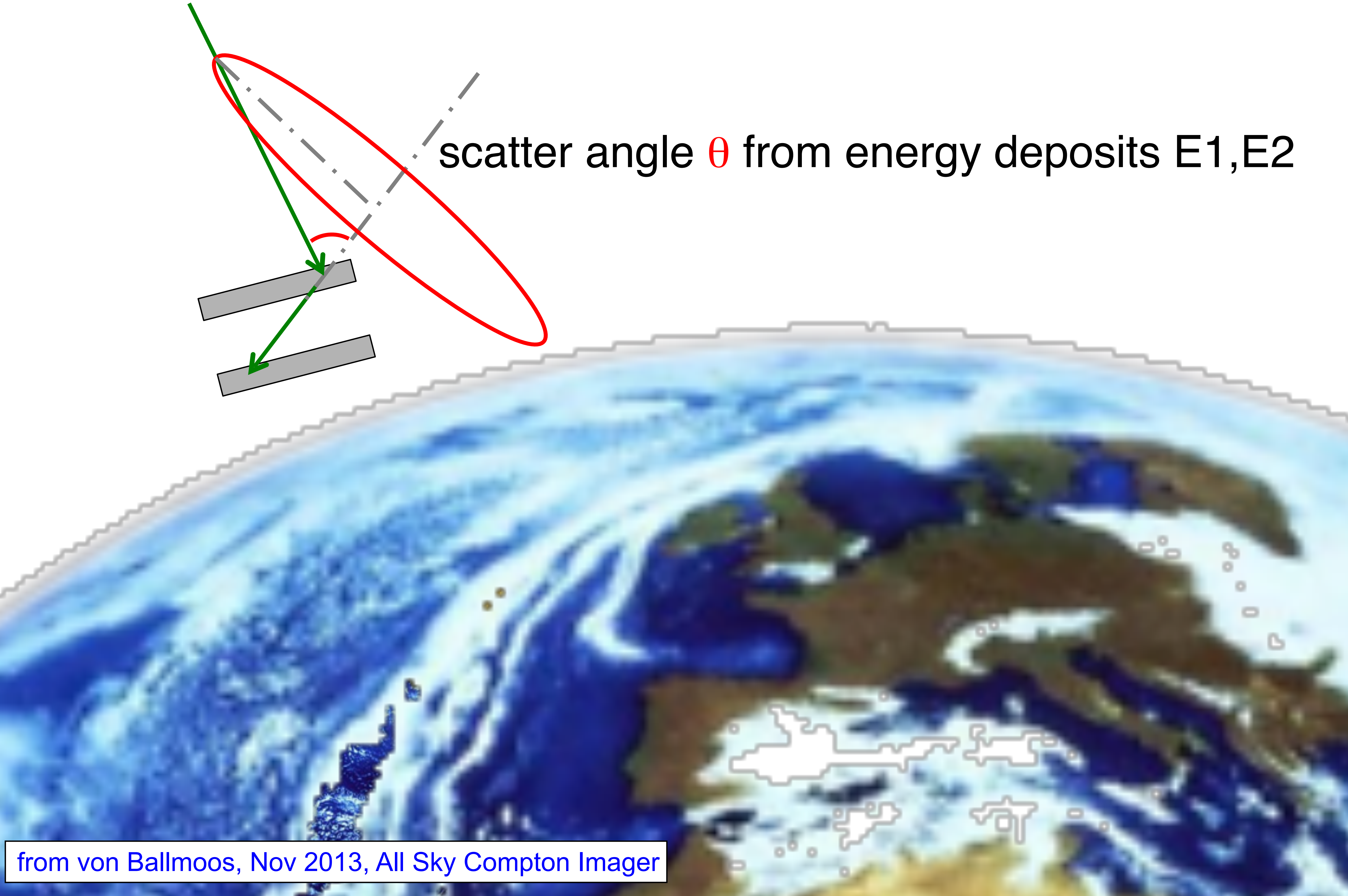
where B and C_S are the background and source count rates and μ_{100} the modulation

Compton telescopes have wide fields

detection of a coincidence event

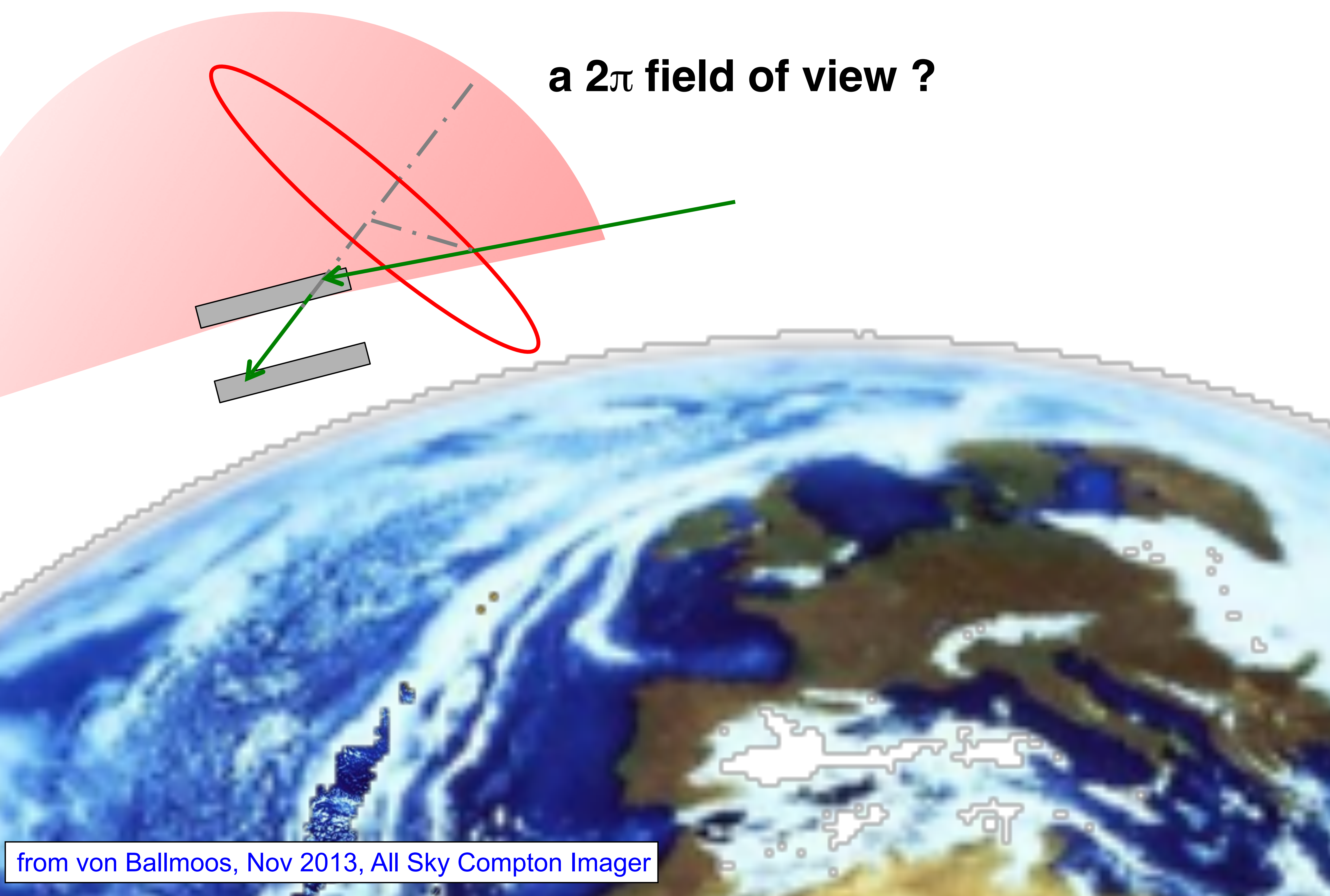
from von Ballmoos, Nov 2013, All Sky Compton Imager

Compton telescopes have wide fields



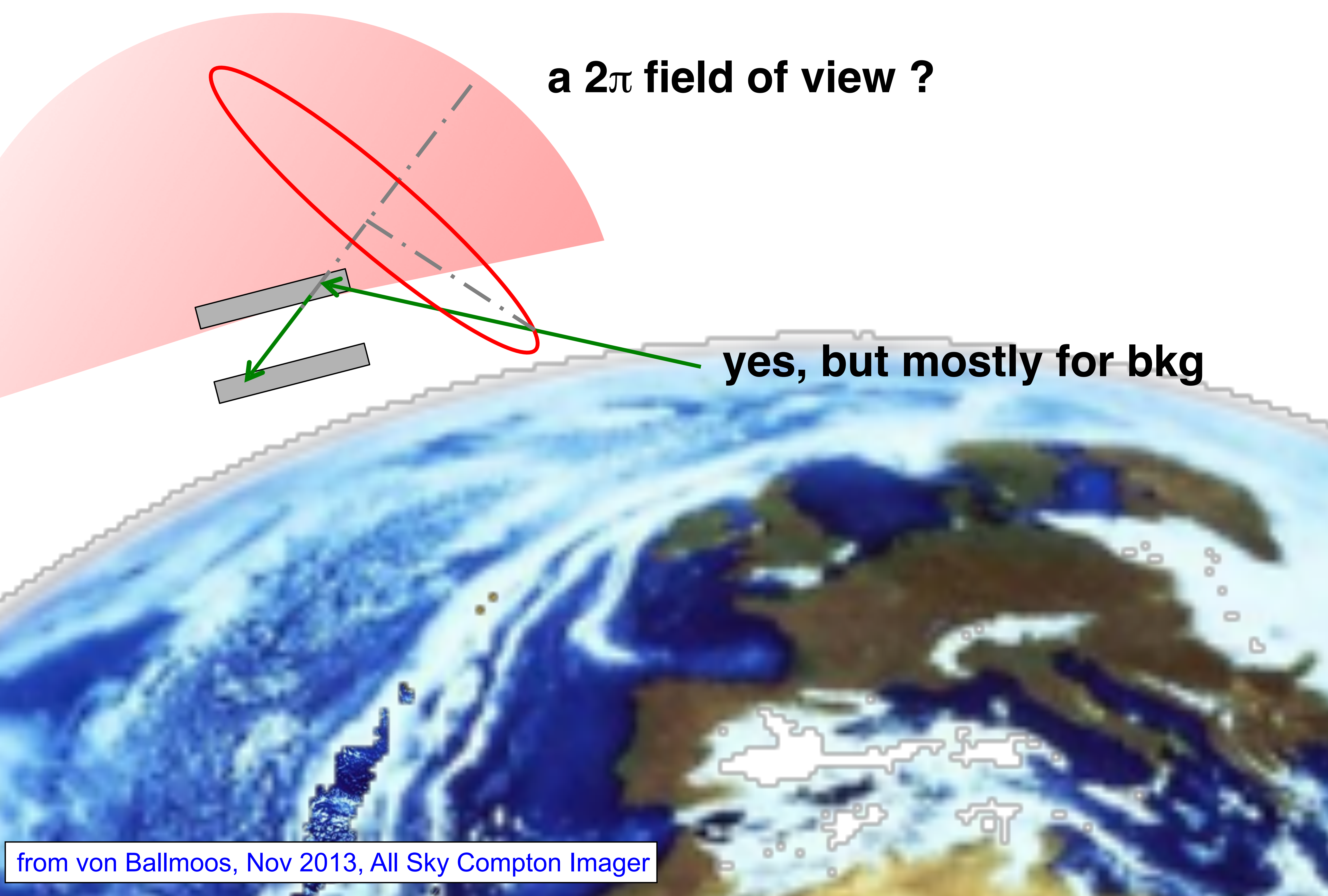
from von Ballmoos, Nov 2013, All Sky Compton Imager

Compton telescopes have wide fields



from von Ballmoos, Nov 2013, All Sky Compton Imager

Compton telescopes have wide fields



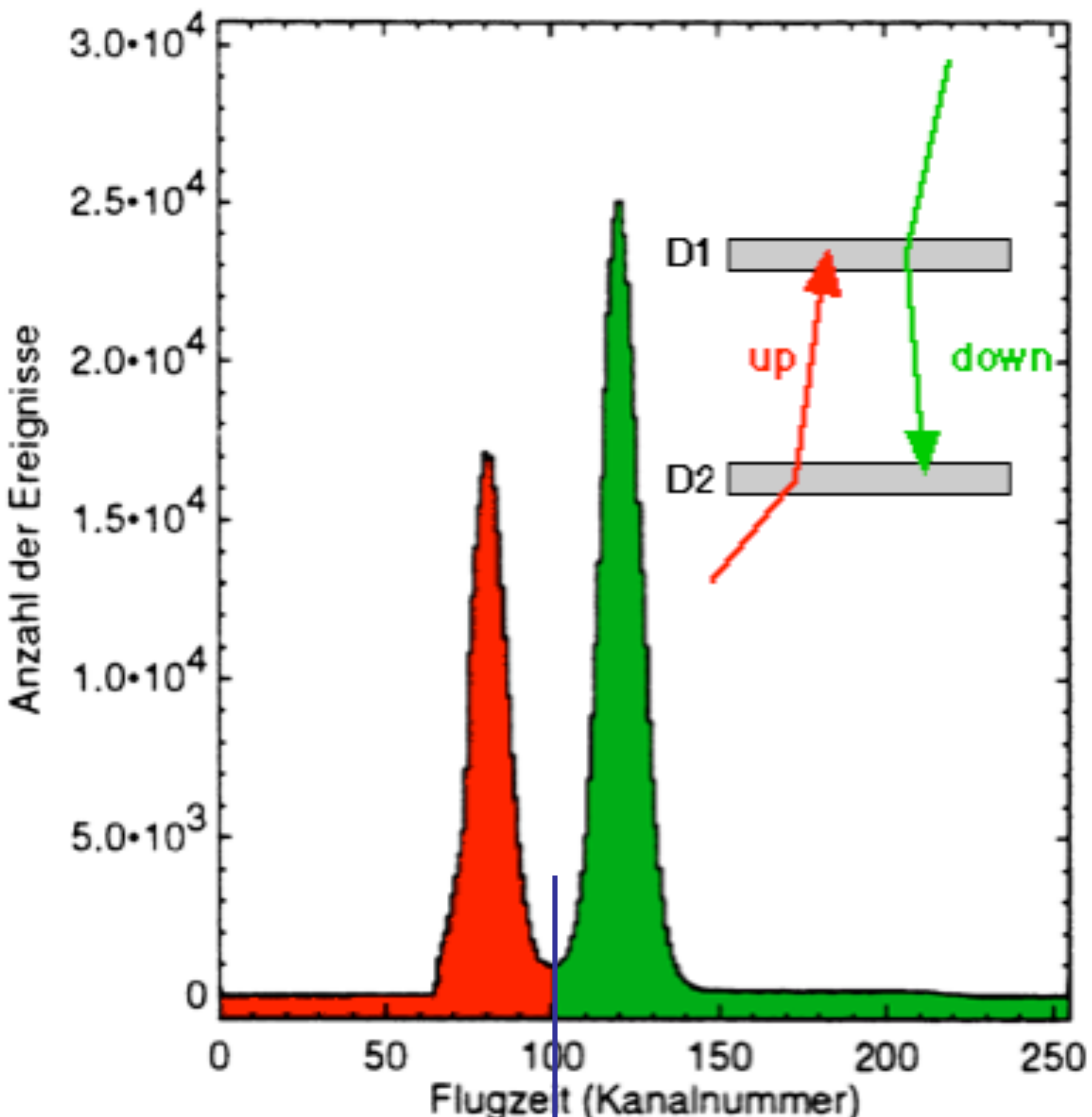
from von Ballmoos, Nov 2013, All Sky Compton Imager

Backgrounds

- Sources of background
  - Same as LAT
    - CR primaries, trapped particles, particle albedo
    - Prompt CR secondaries
      - Atmo gammas and local gammas
        - » Atmosphere is brightest source
        - » Beware your spacecraft, the pressure vessel on your gas TPC, etc
  - And below 10 MeV, beware radioactivities
    - Self-activity and CR-induced activation

- Mitigating the backgrounds
  - Fight the bkg
    - Shielding
      - Passive
      - Active anti-coincidence shielding
    - Bkg discrimination
      - Pattern recognition
      - Pulse shape discrimination
      - Time-of-flight
  - Avoid the bkg
    - Optimal orbit
    - Minimize passive material
    - Choose low-bkg materials

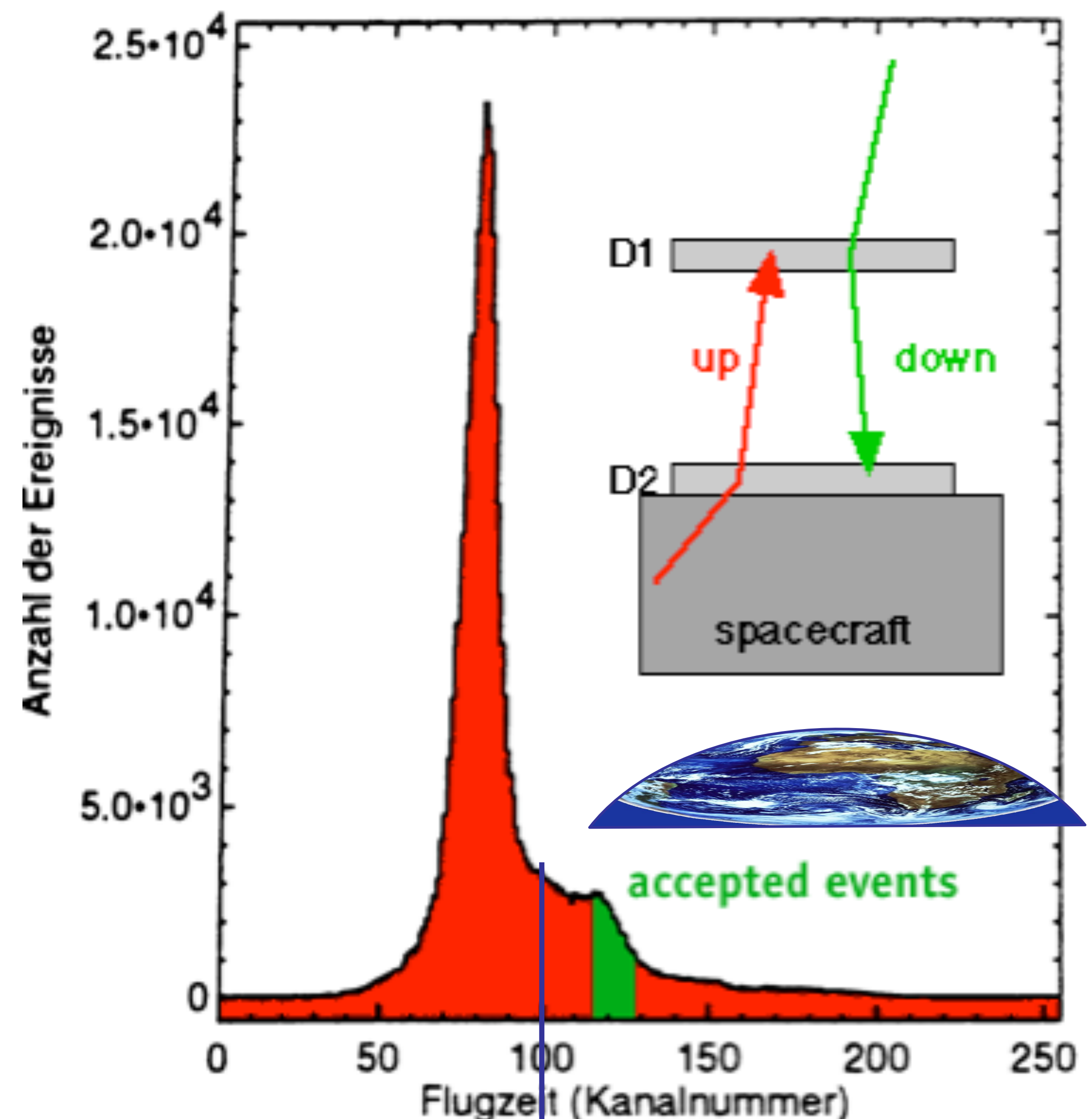
Time of Flight coincidence - COMPTEL data



<- upward | downward ->

COMPTEL calibration data

channel width : 0.25 ns
distance D1-D2 : 1.5 m ≈> 5 ns)

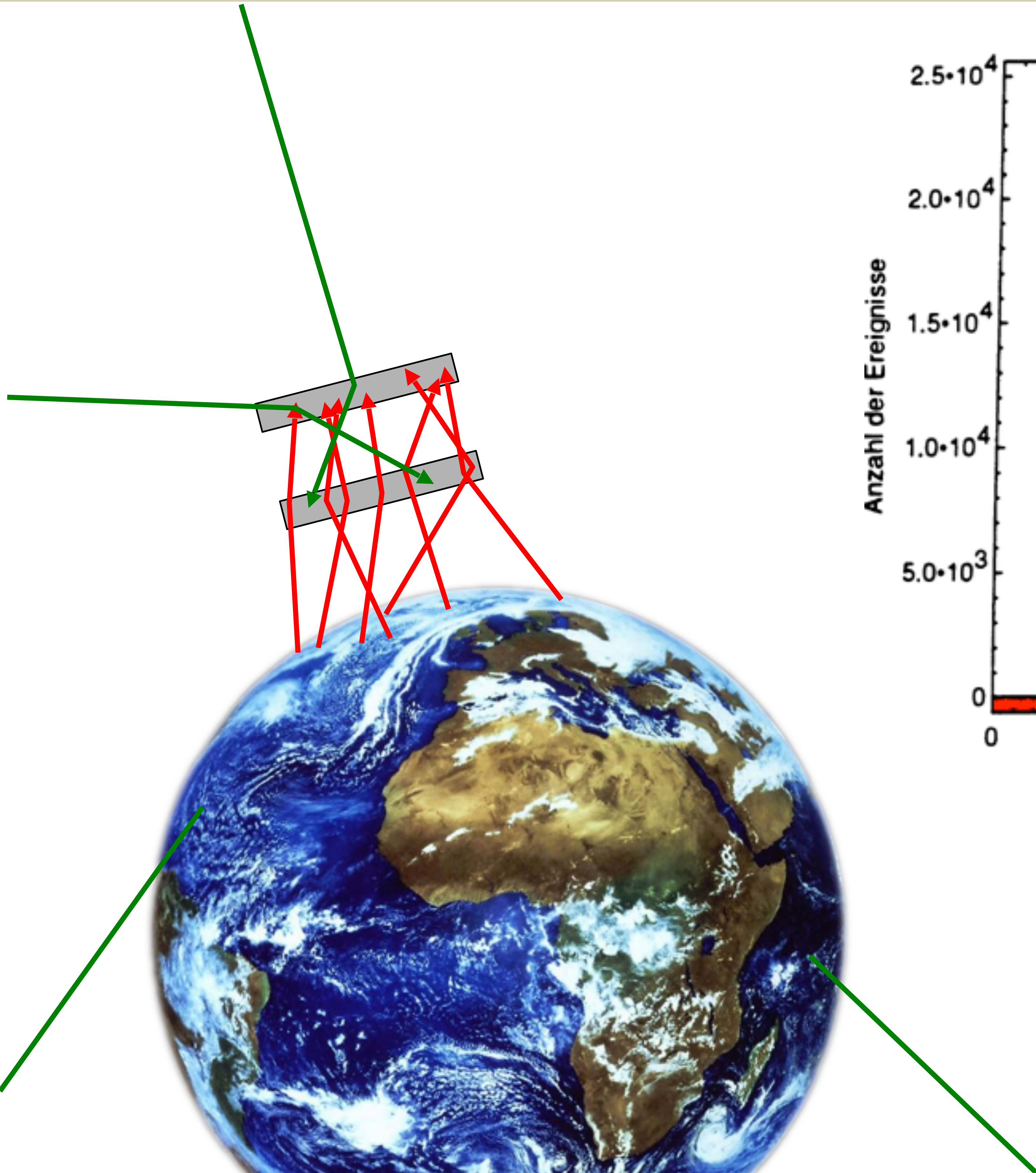


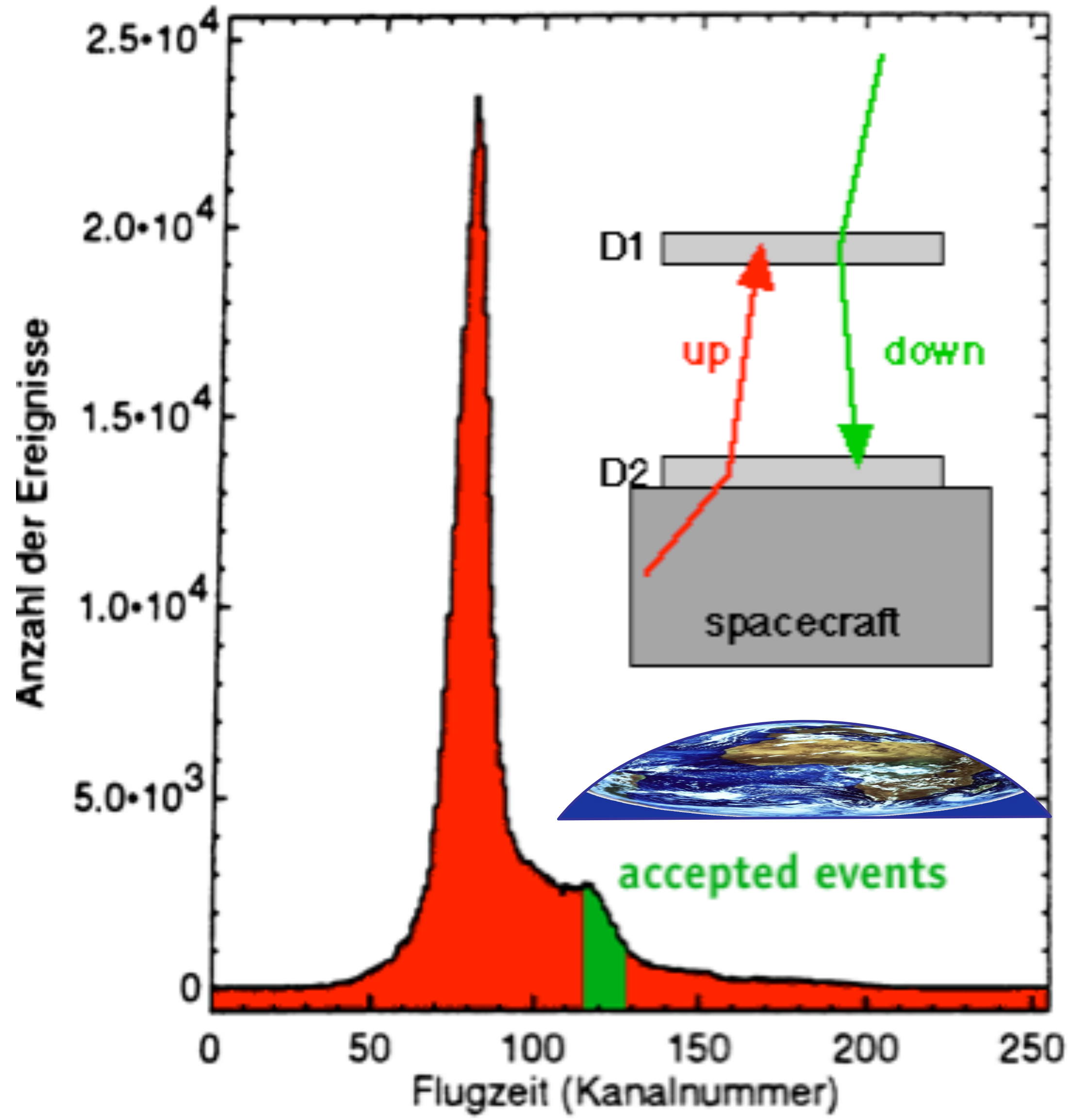
<- upward | downward ->

COMPTEL flight data

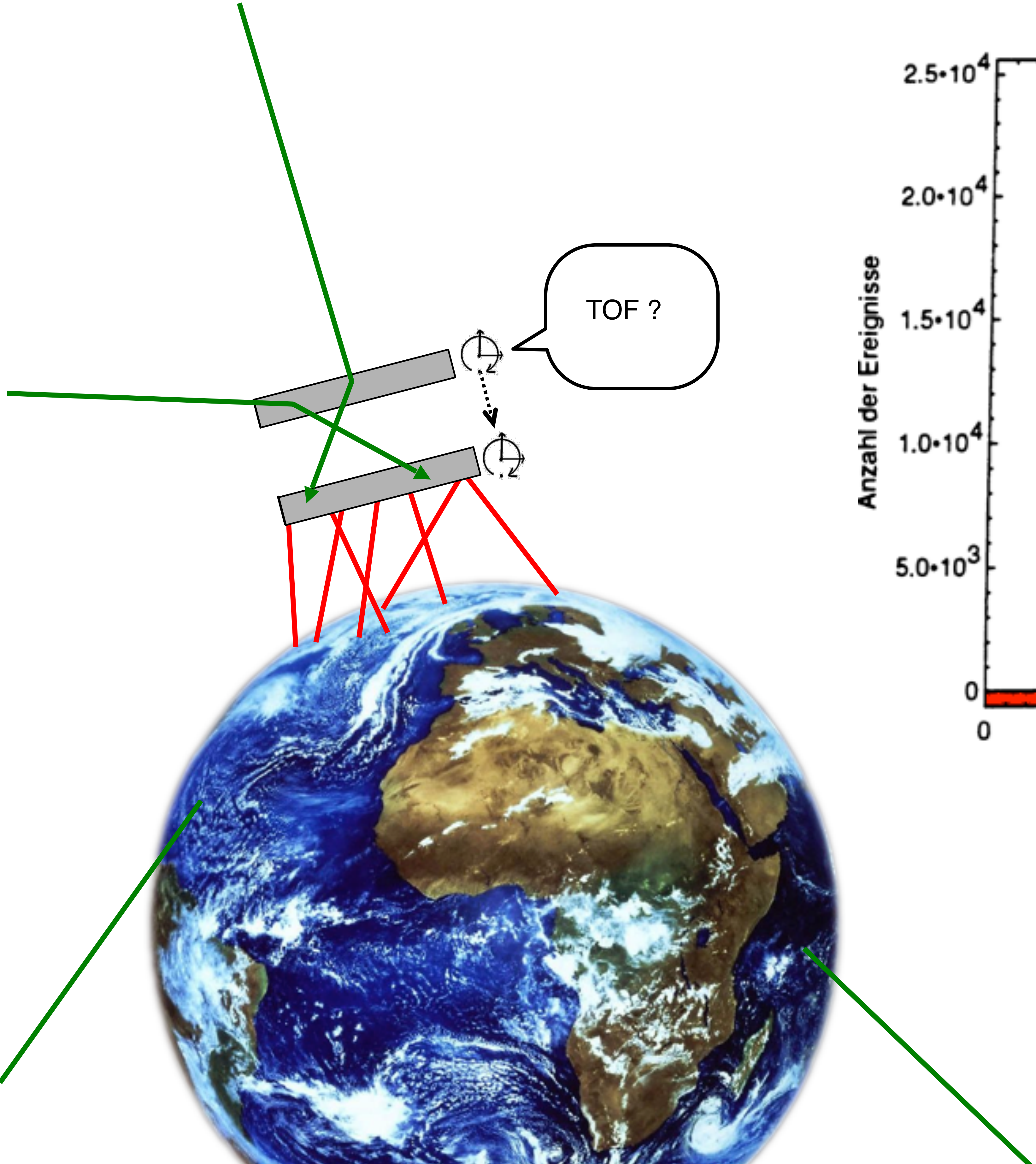
channel width : 0.25 ns
"upward bkg" from spacecraft and Earth

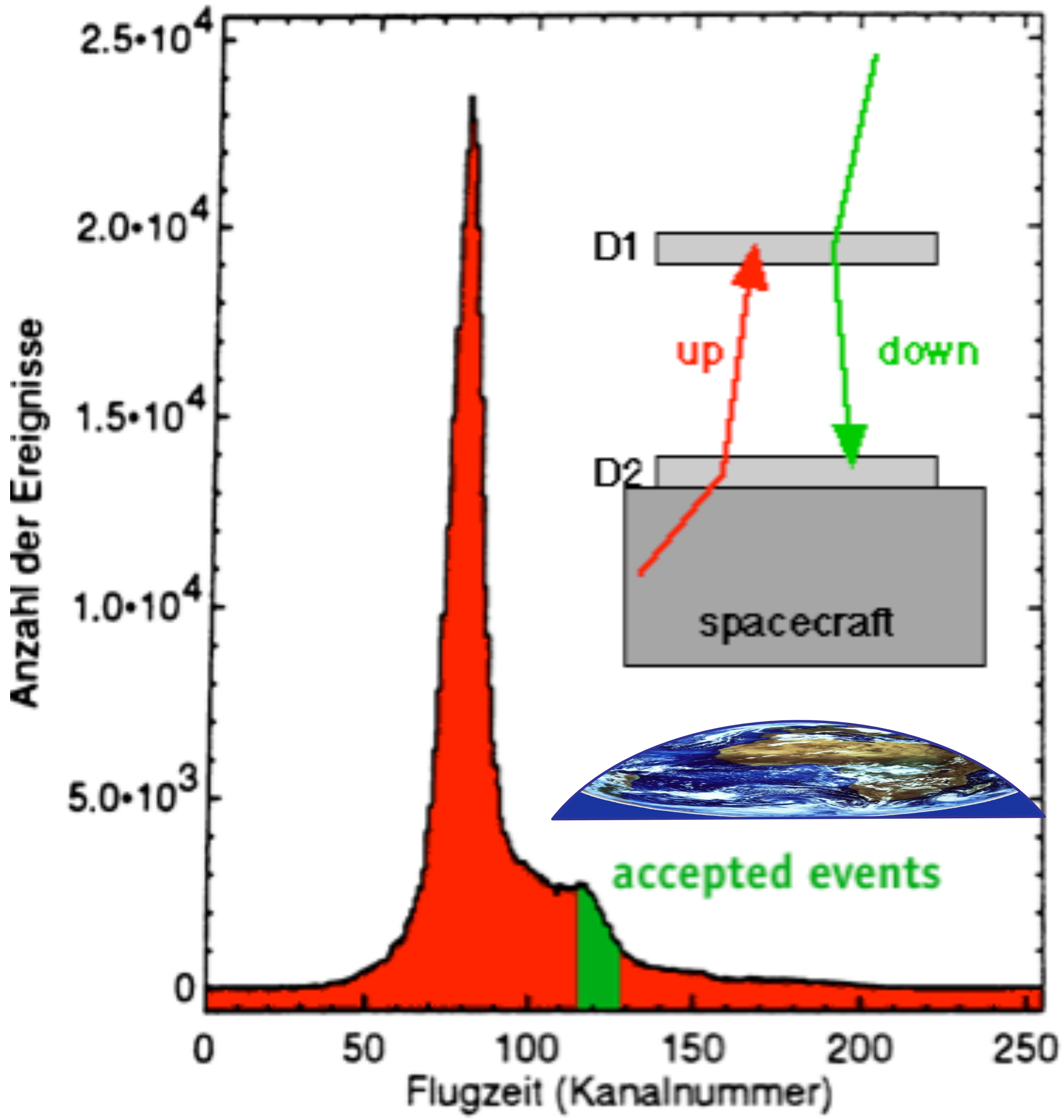
option A : time-of-flight electronics



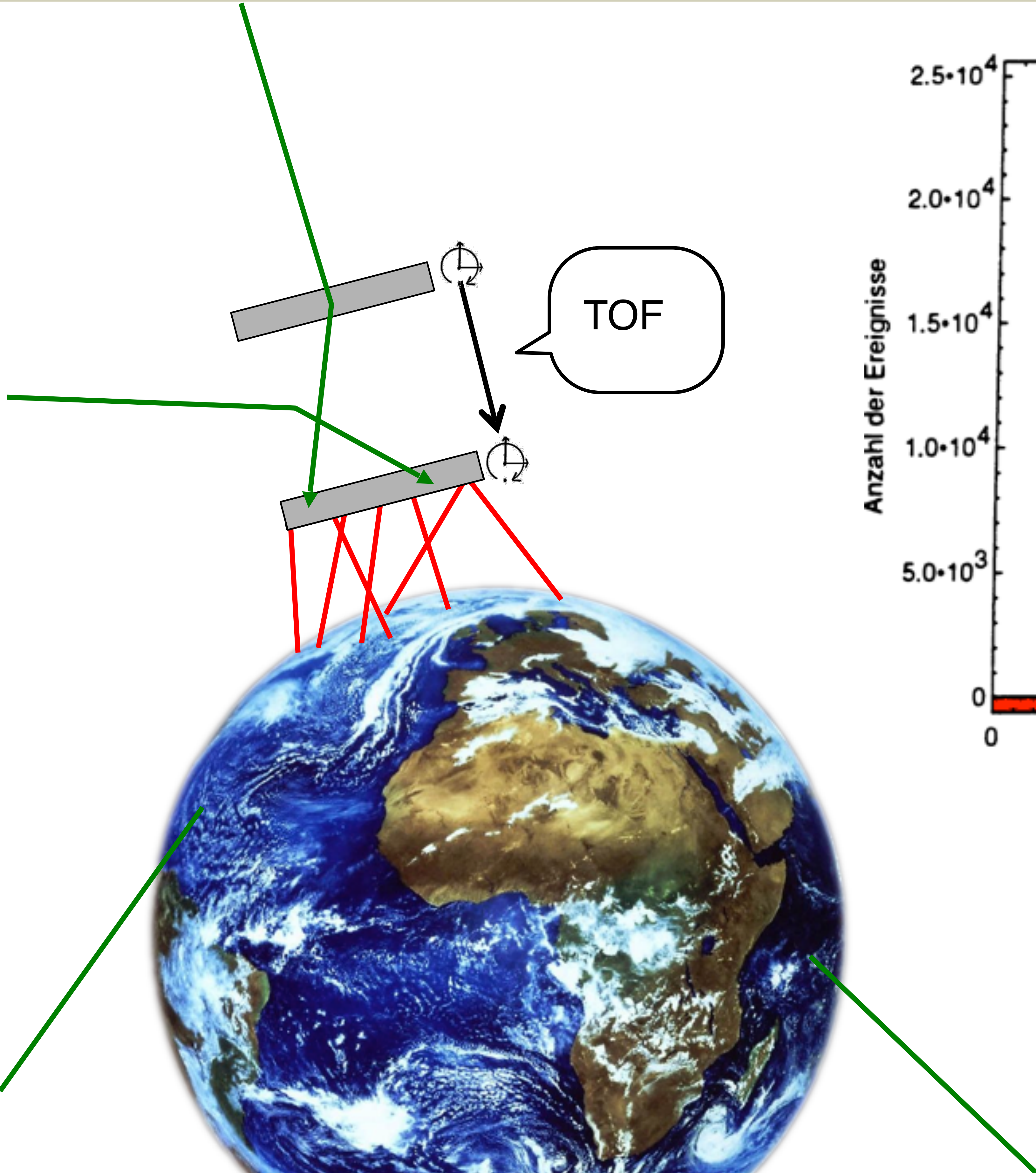


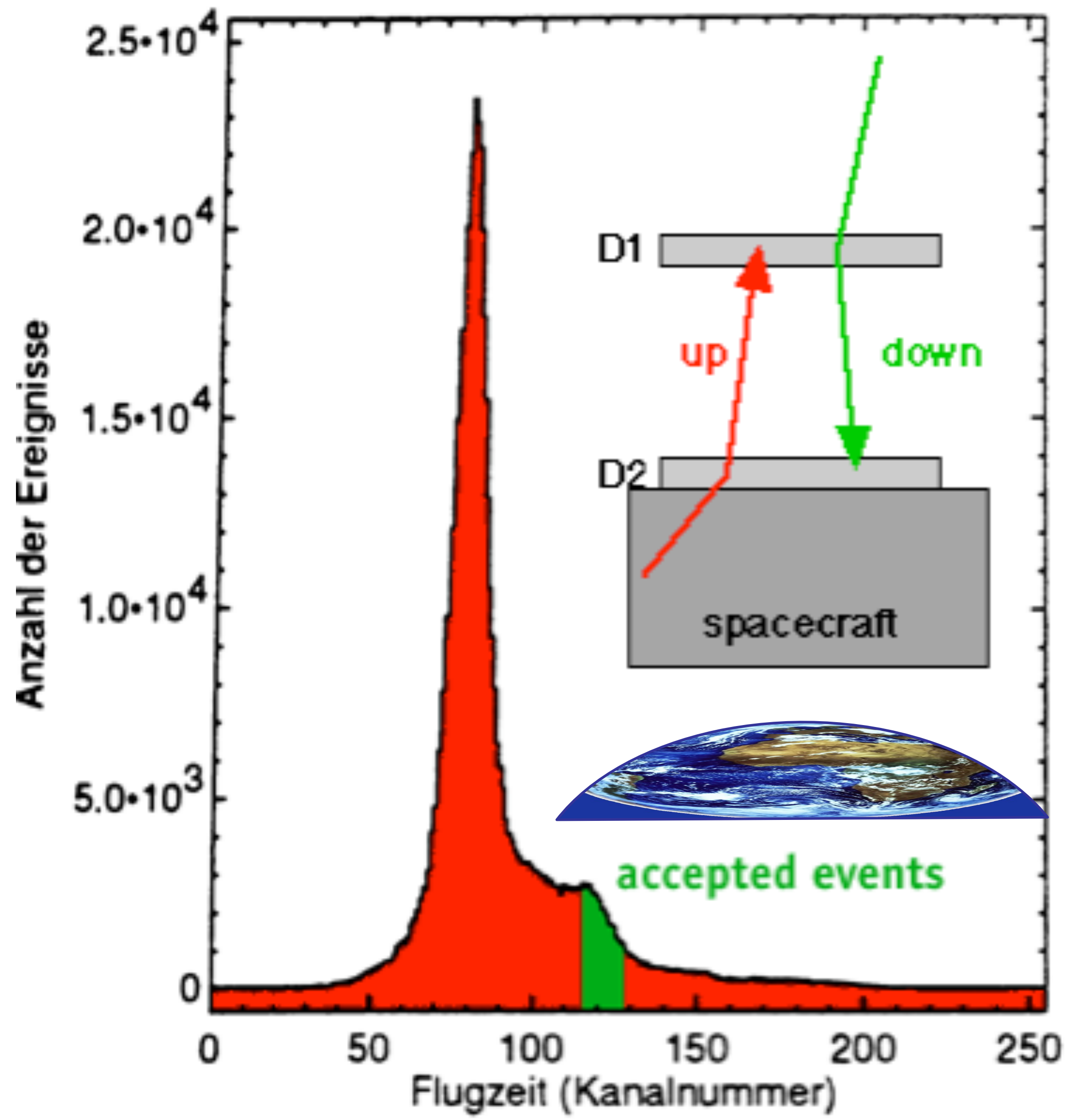
option A : time-of-flight electronics



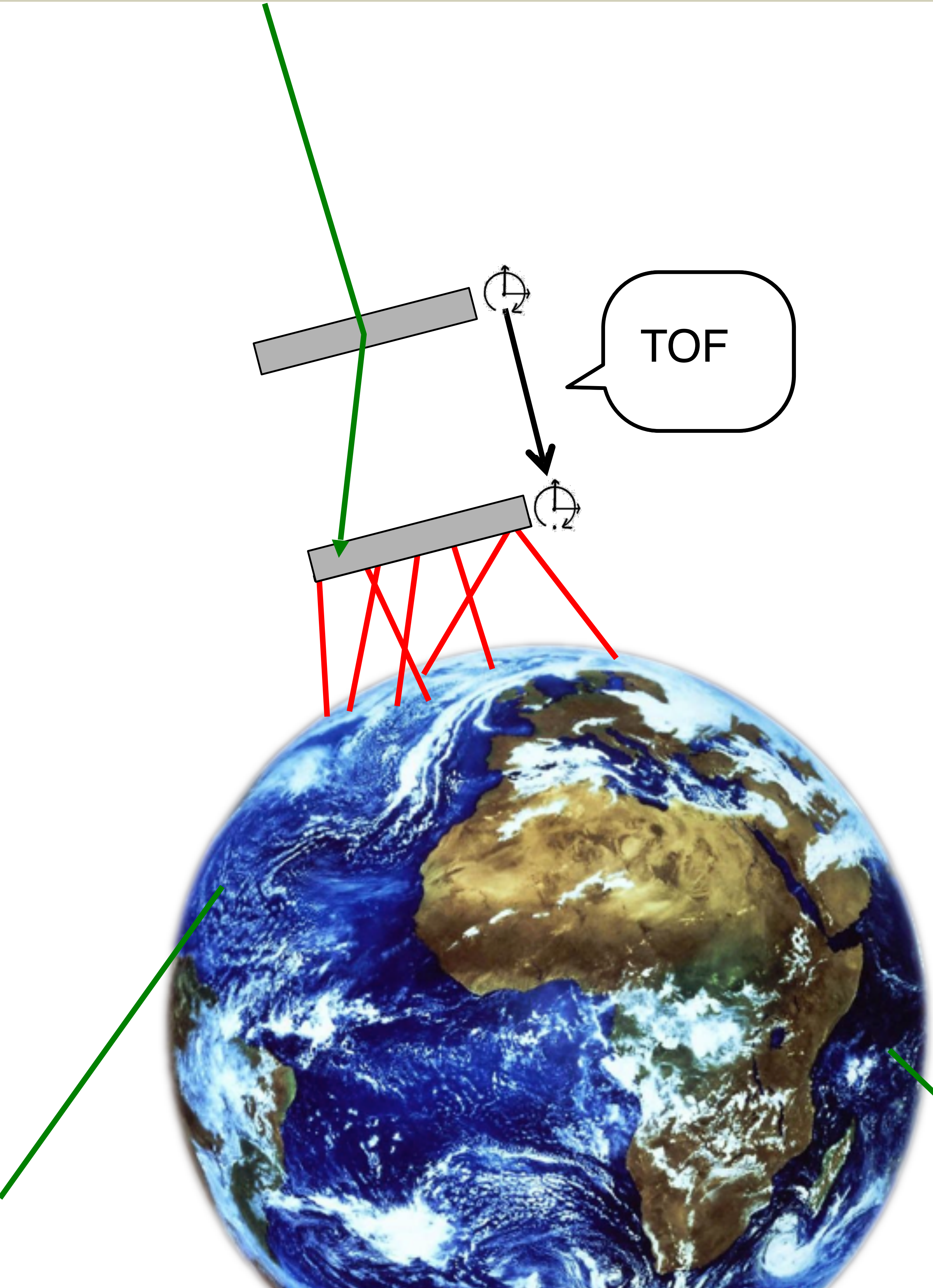


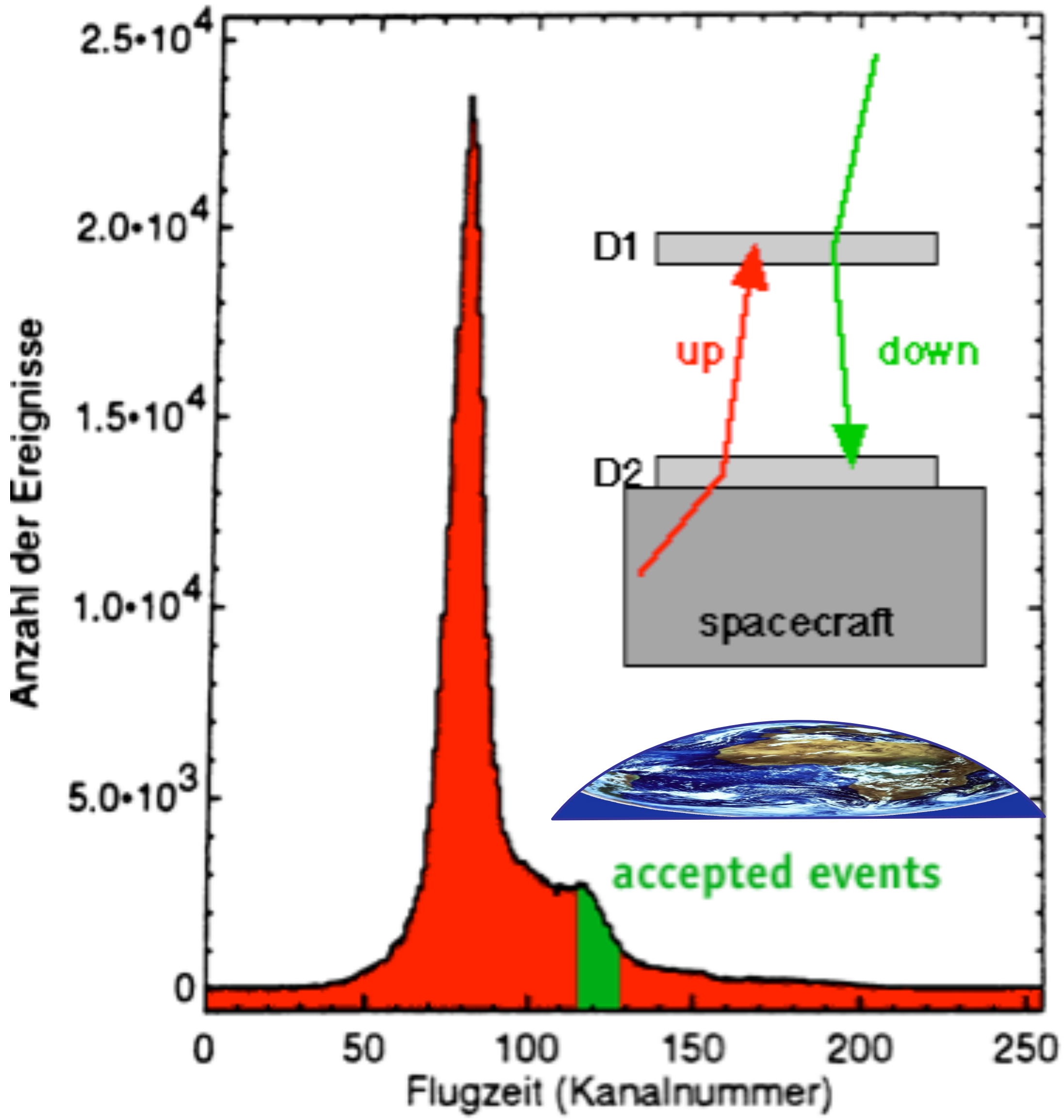
option A : time-of-flight electronics





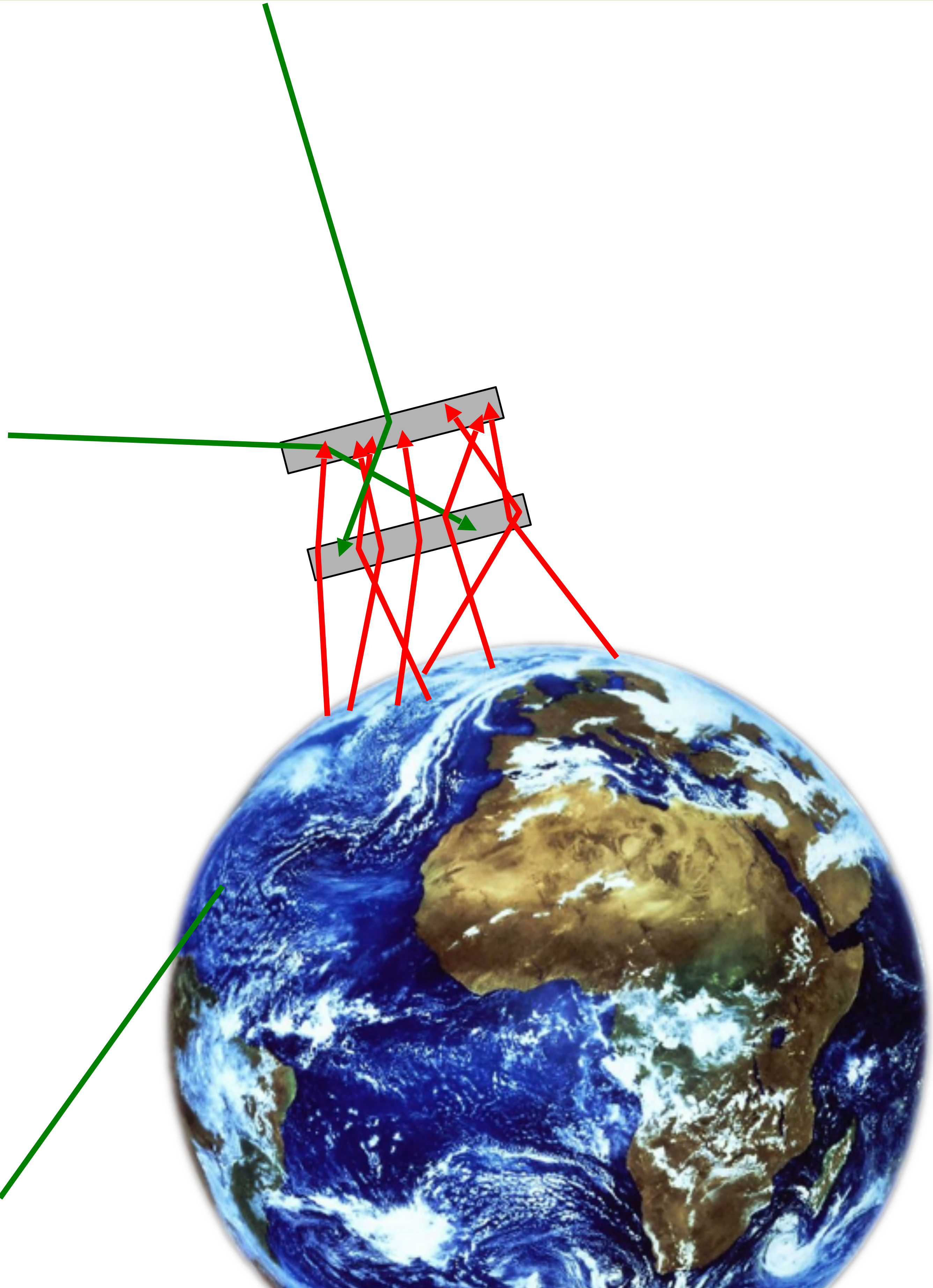
option A : time-of-flight electronics

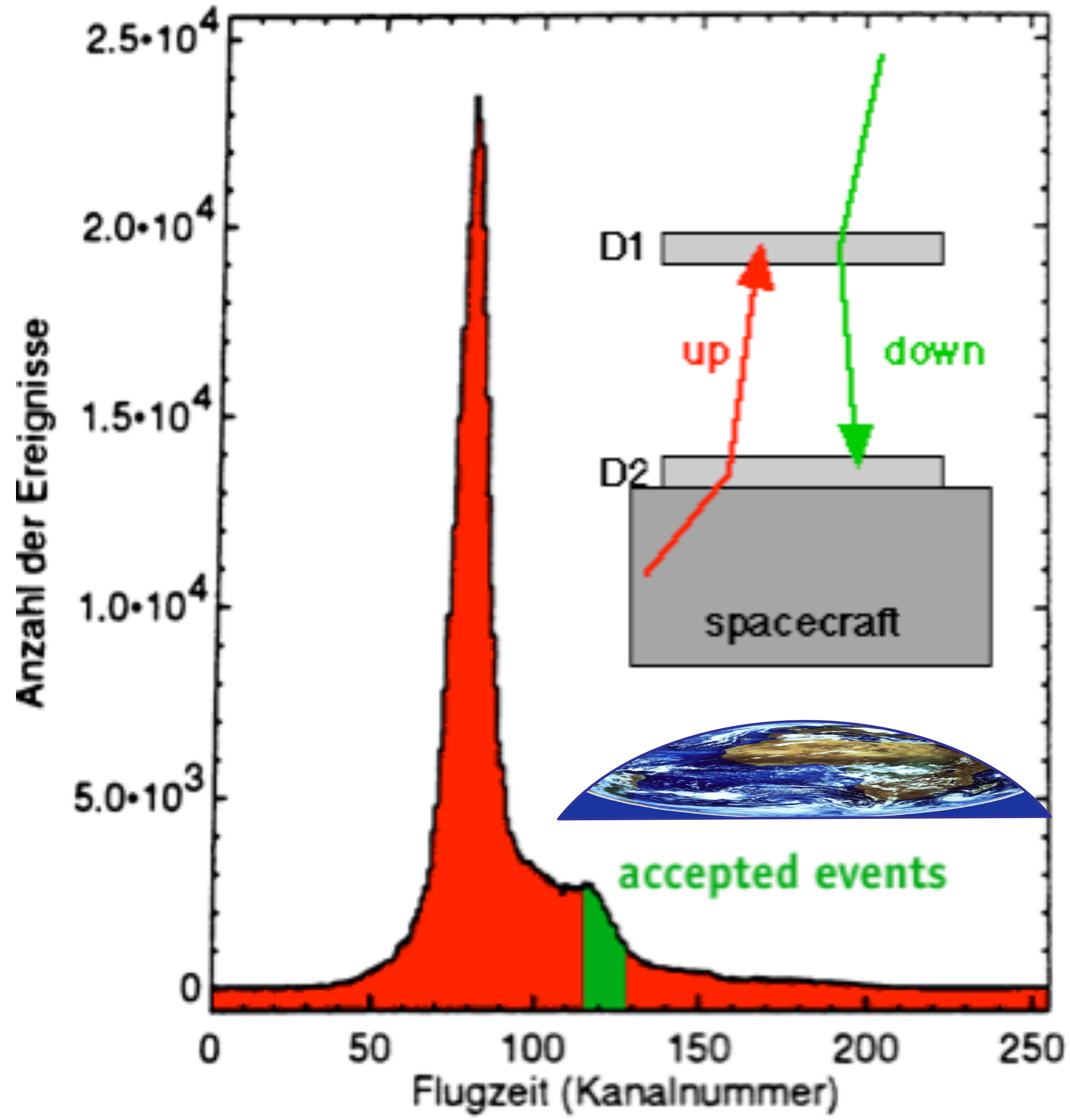




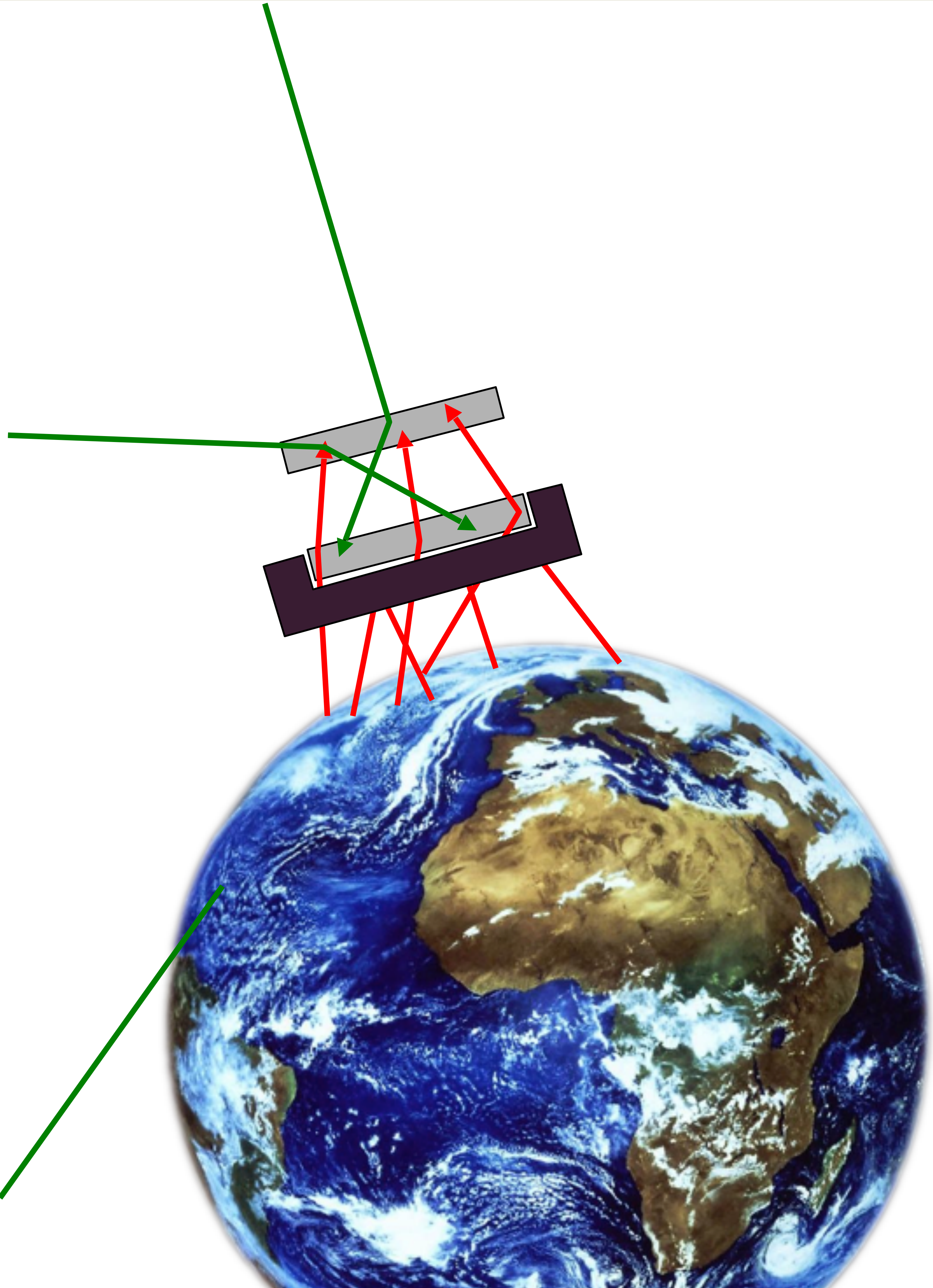
measuring TOFs requires
long baselines between D1 and D2
=> low probability for coincidence
=> **low efficiencies** (few % at most)

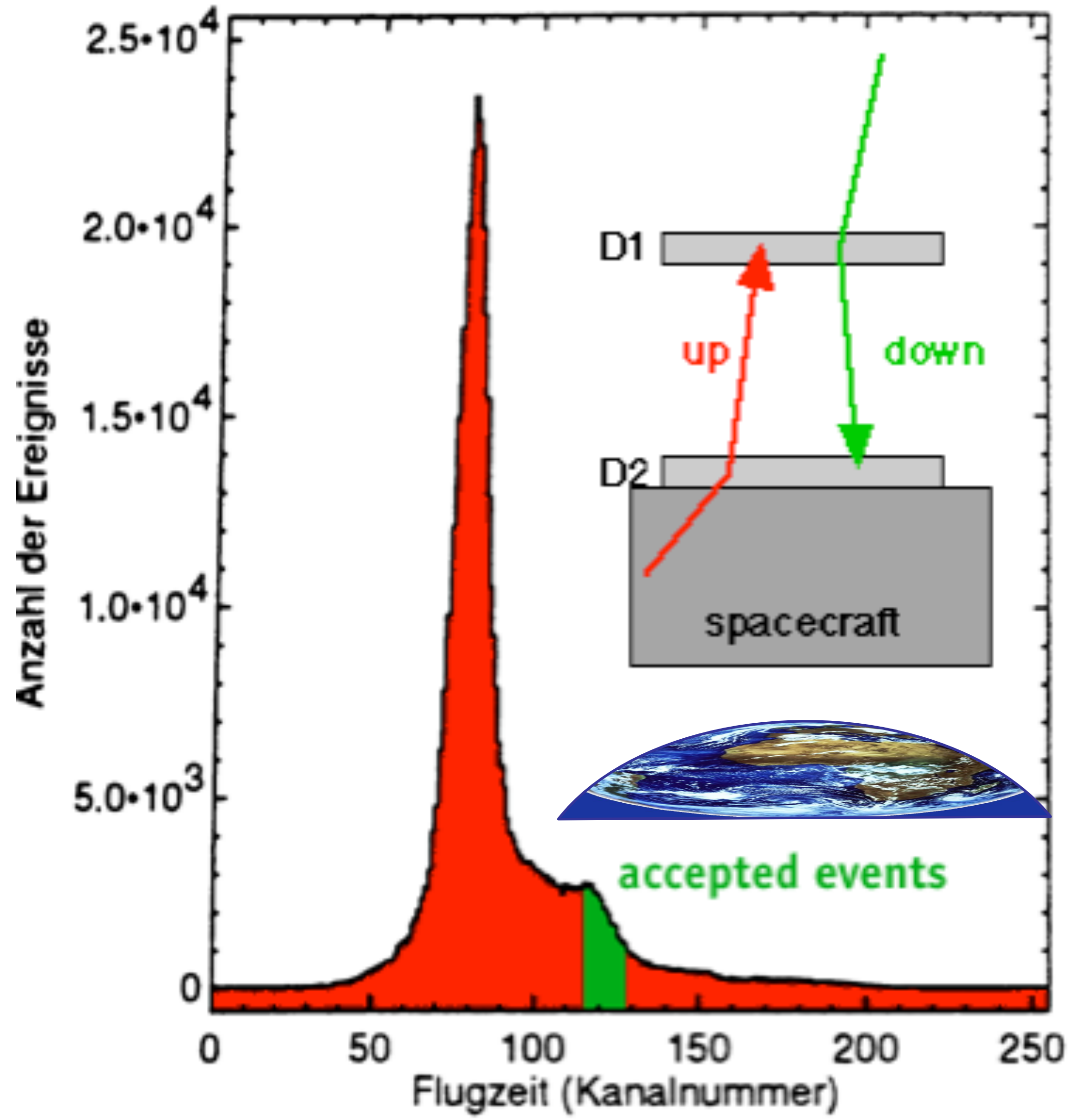
option B : anticoincidence shield





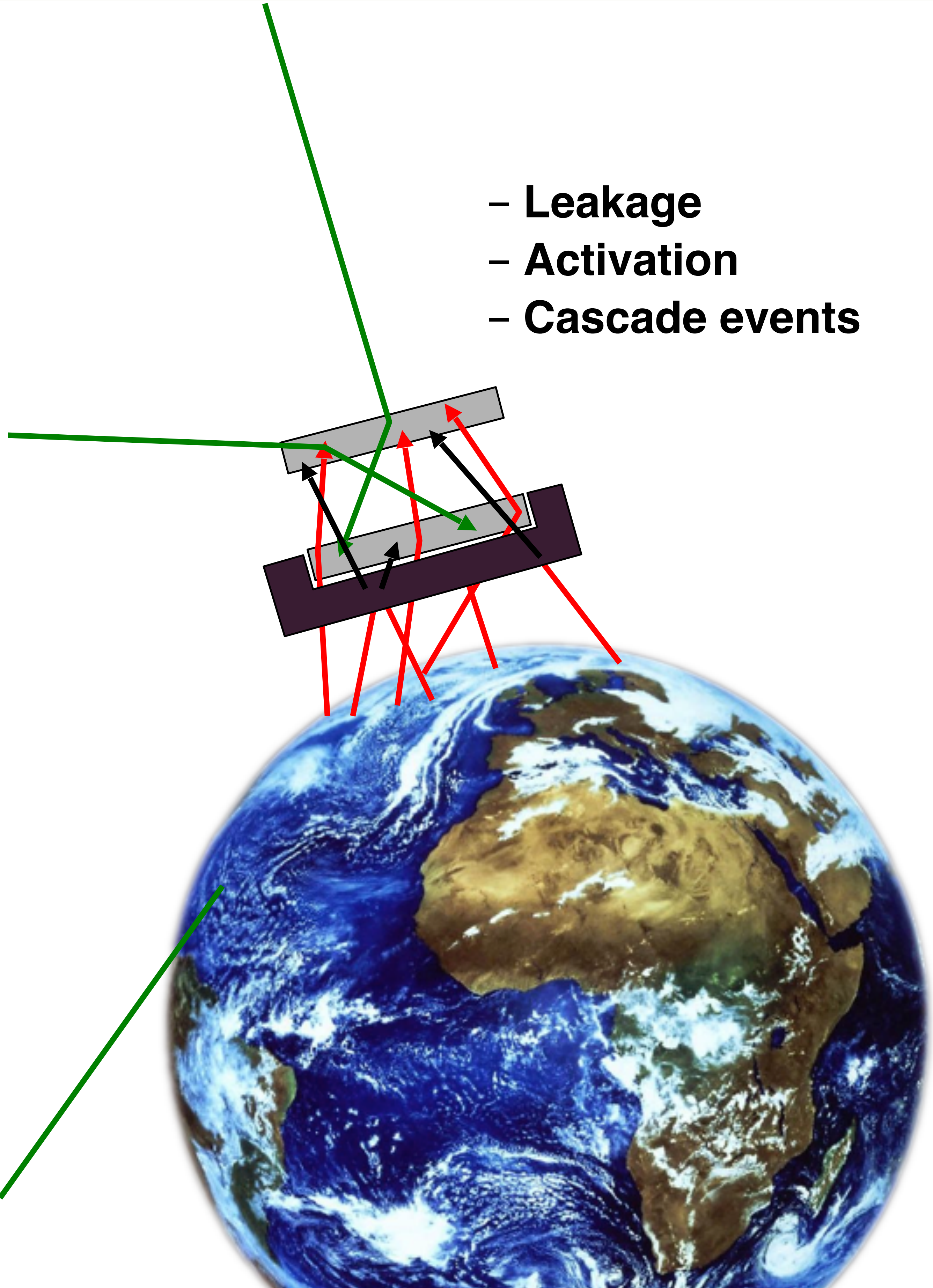
option B : anticoincidence shield

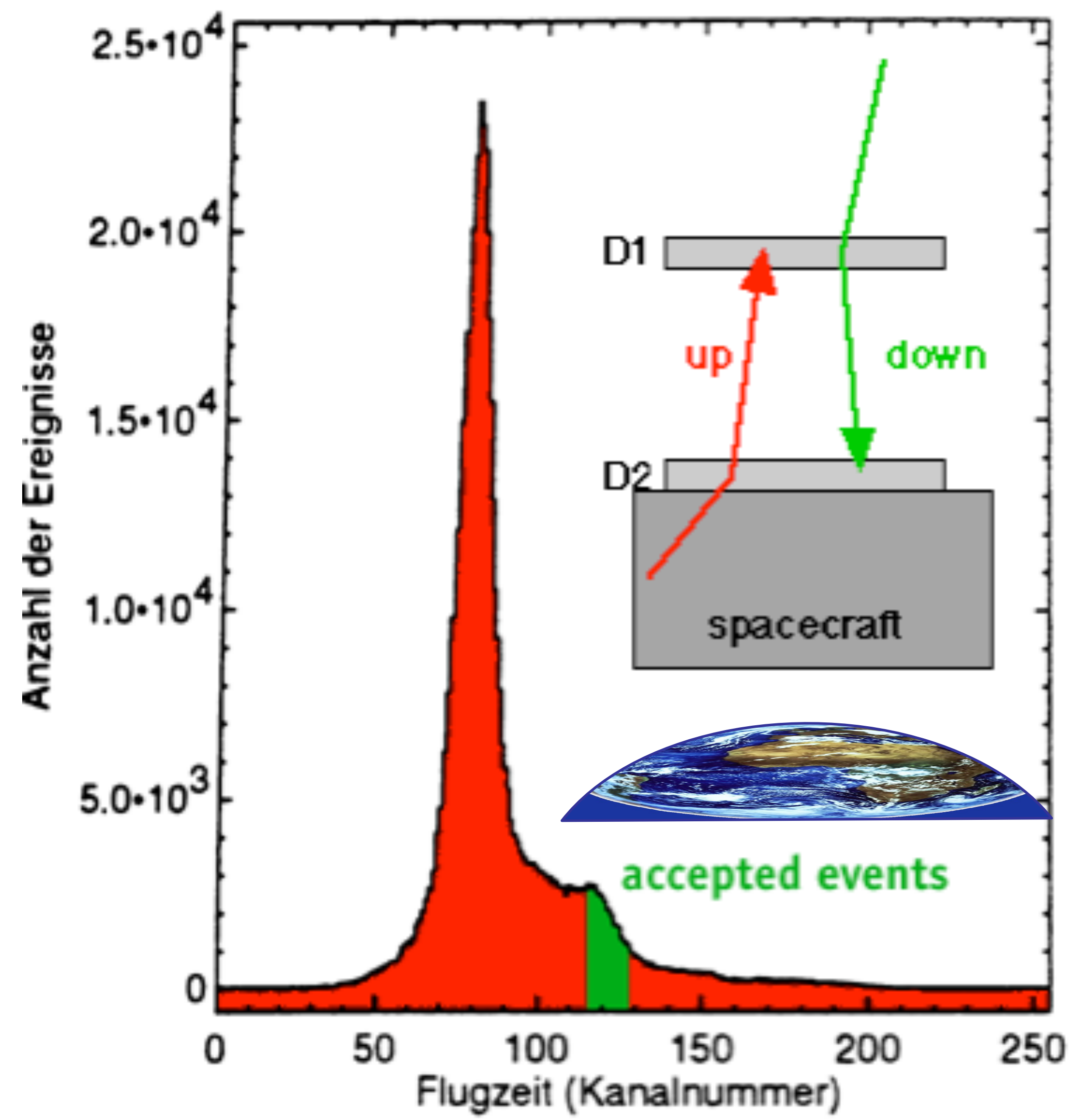




option B : anticoincidence shield

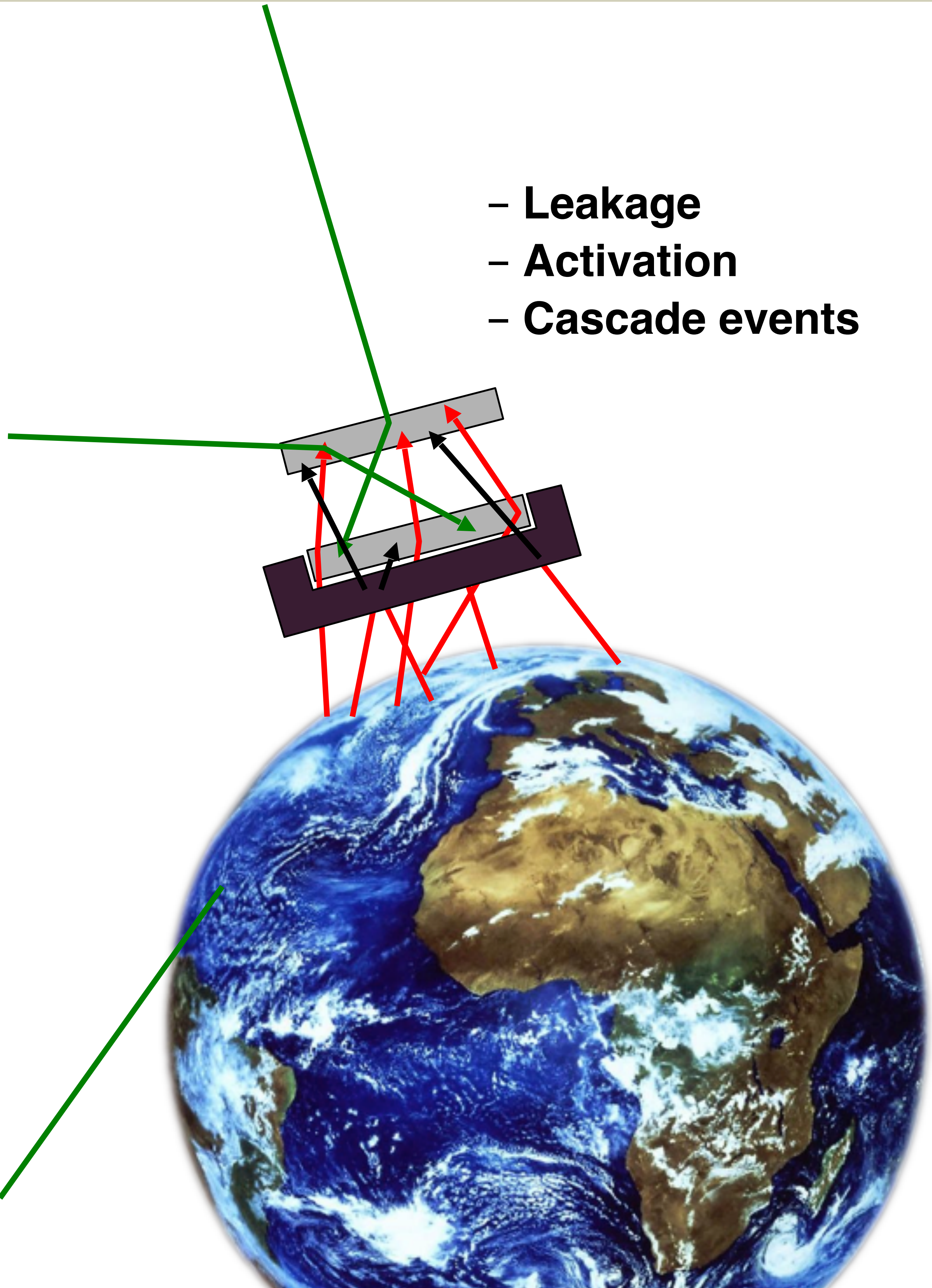
- **Leakage**
- **Activation**
- **Cascade events**

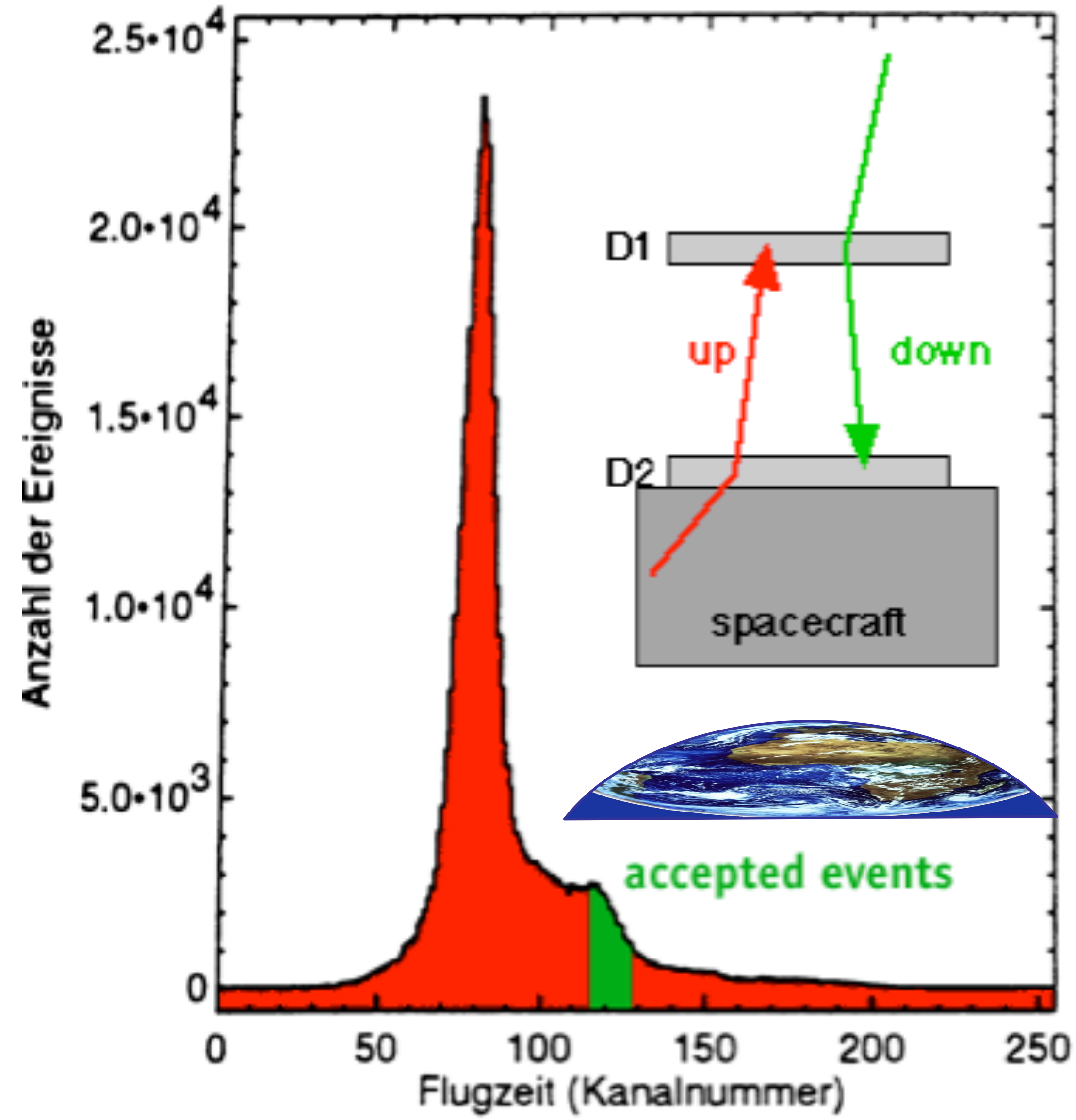




option B : anticoincidence shield

- **Leakage**
- **Activation**
- **Cascade events**

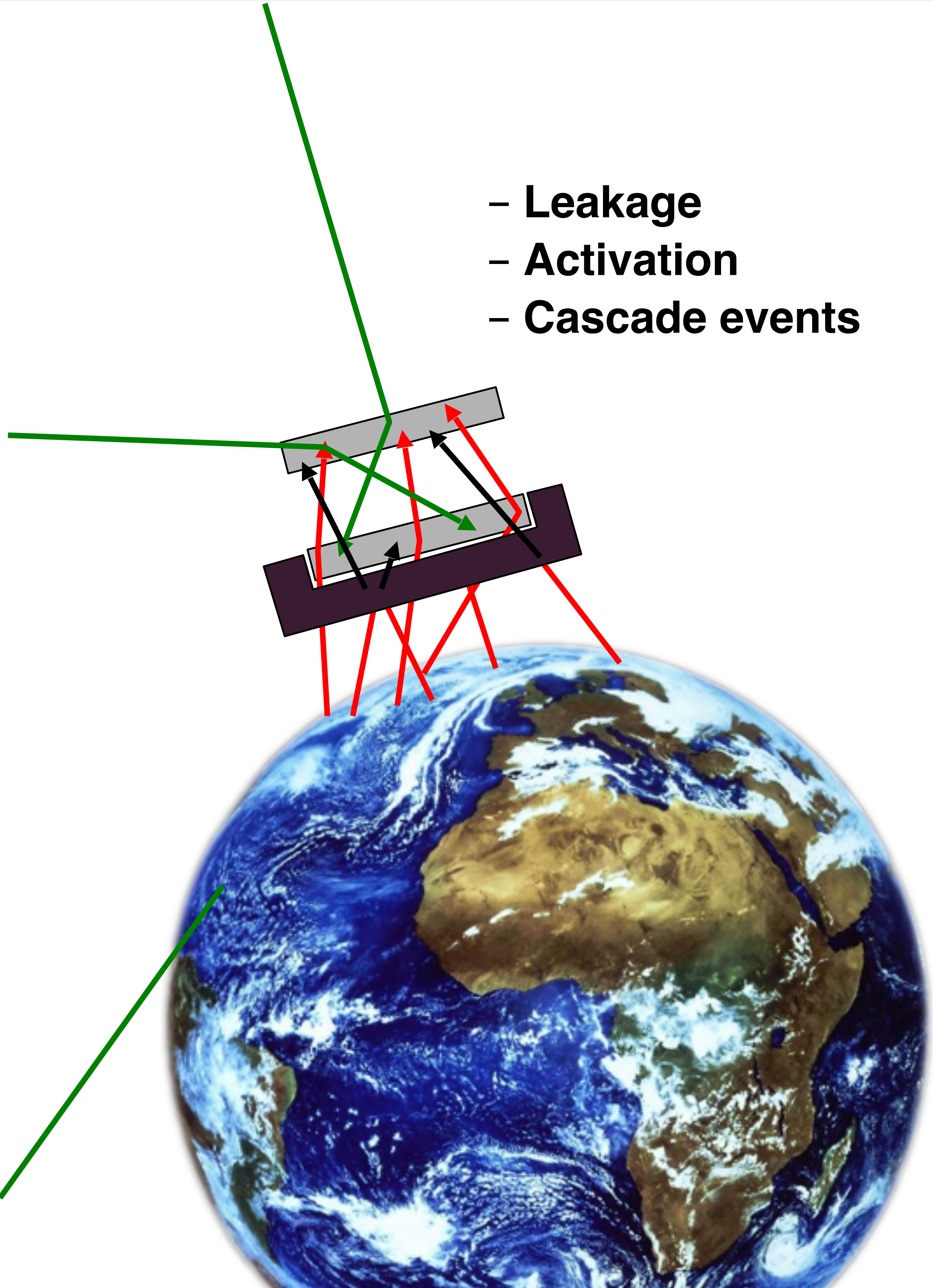


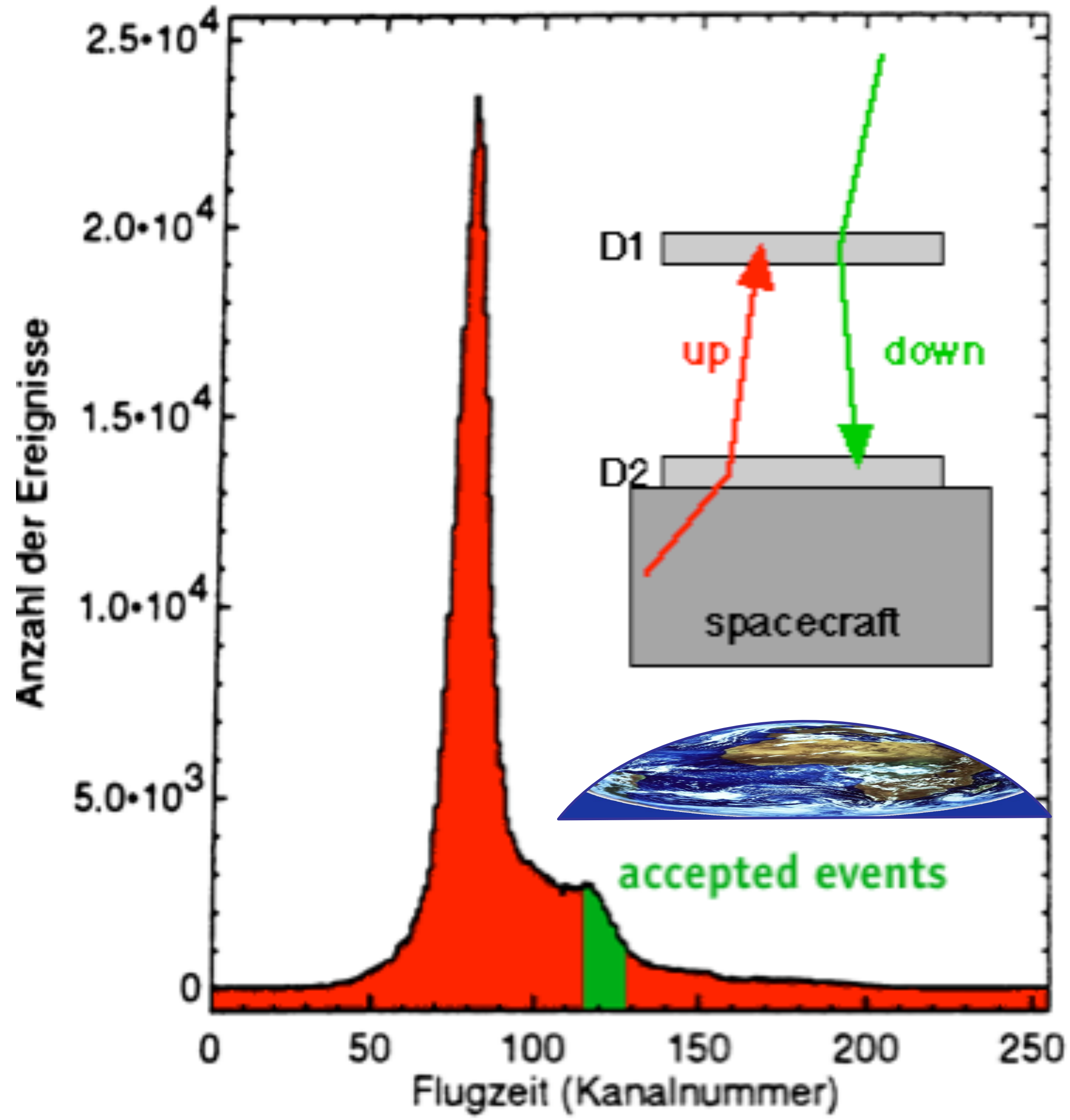


Compact solid state CTs

option B : anticoincidence shield

- **Leakage**
- **Activation**
- **Cascade events**

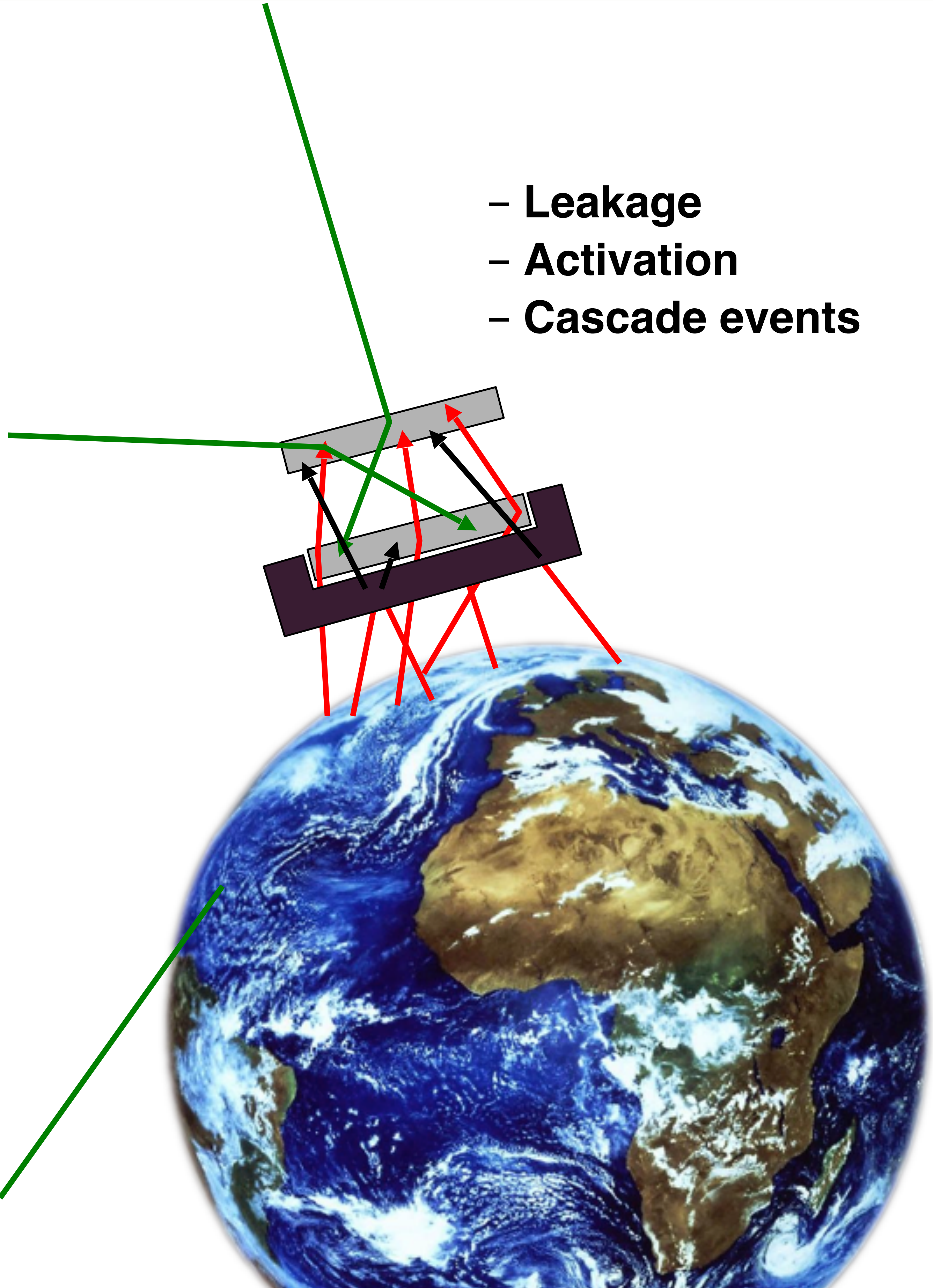




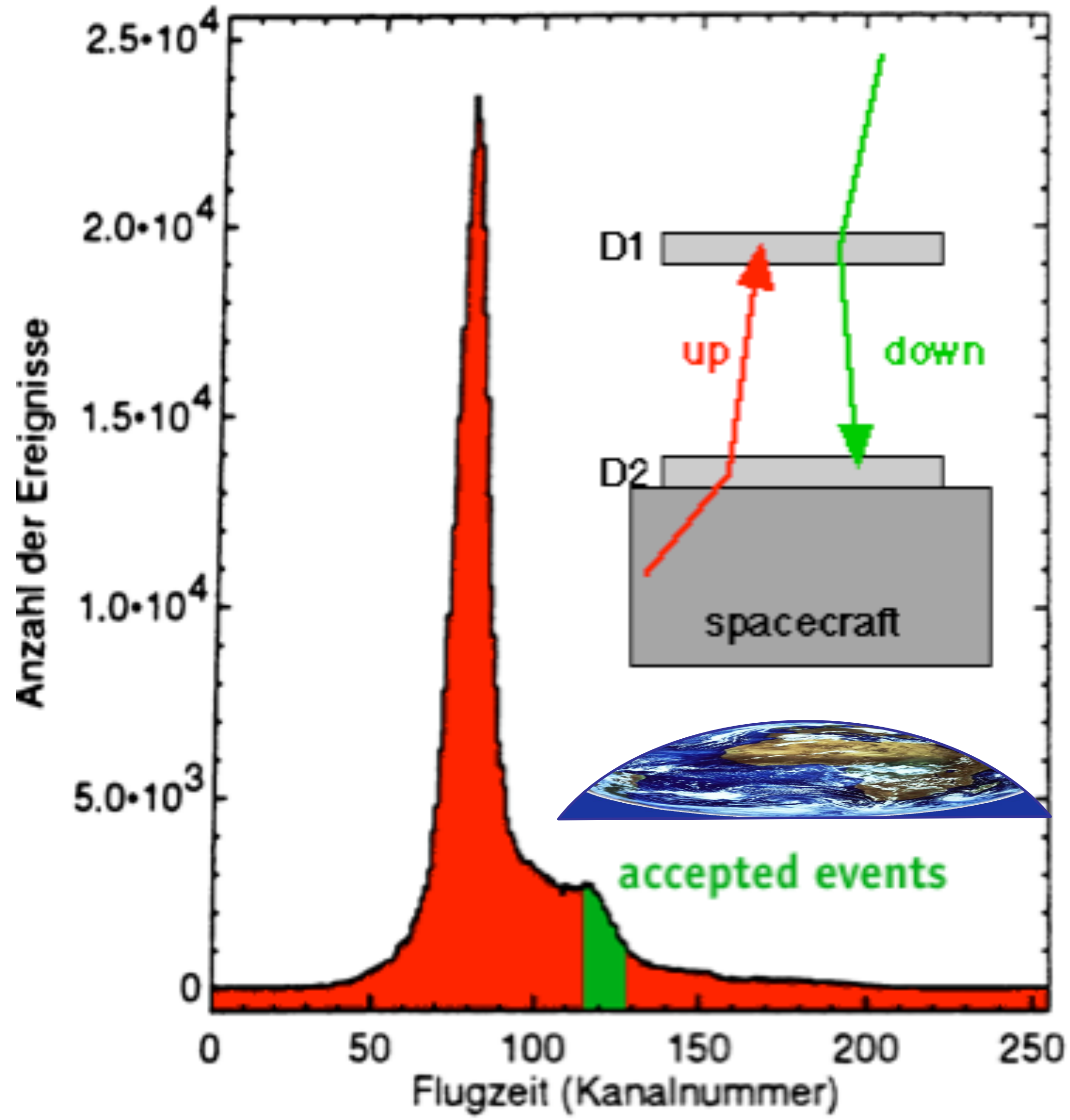
Compact solid state CTs

Higher Compton efficiency

option B : anticoincidence shield



- **Leakage**
- **Activation**
- **Cascade events**

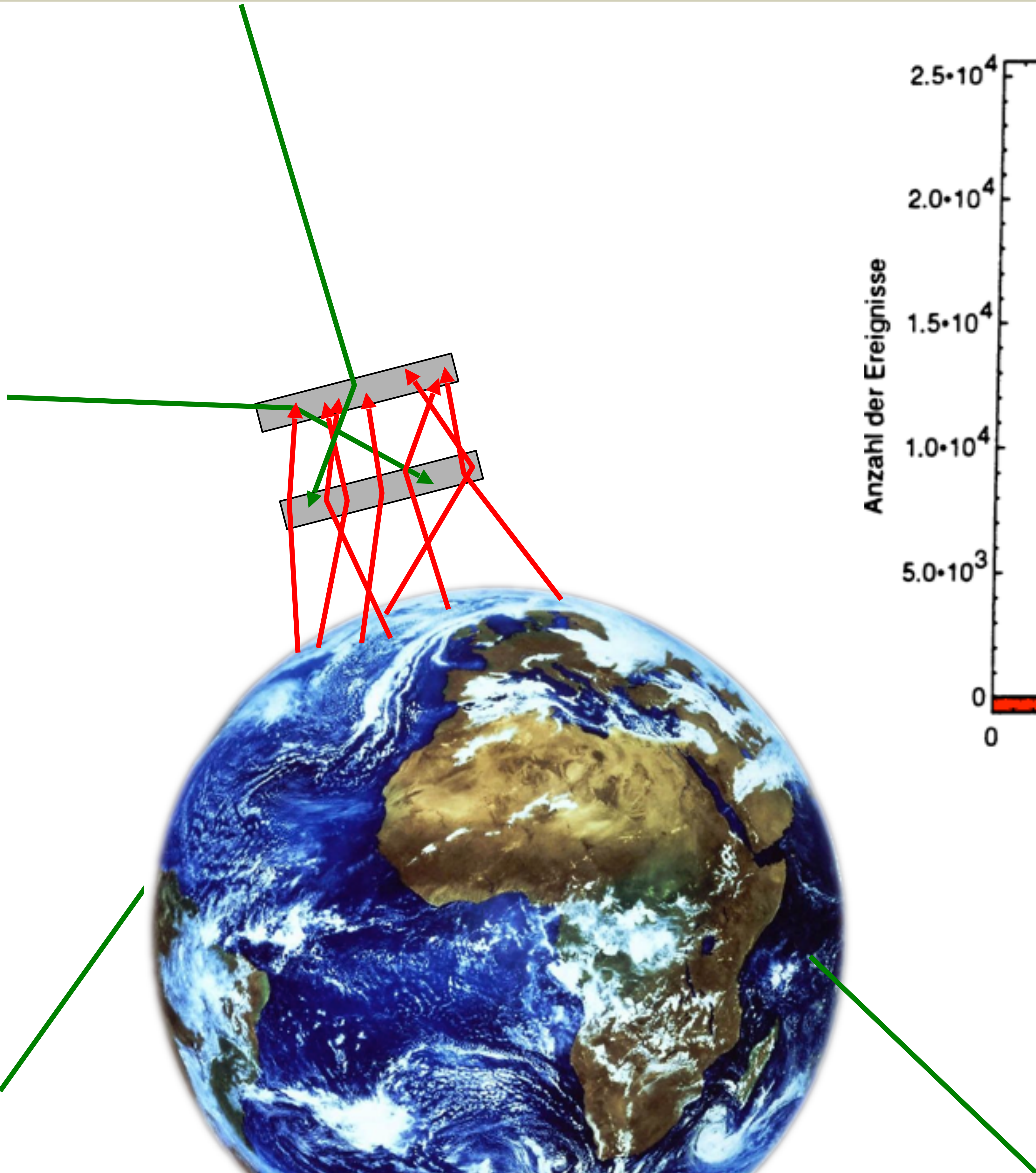


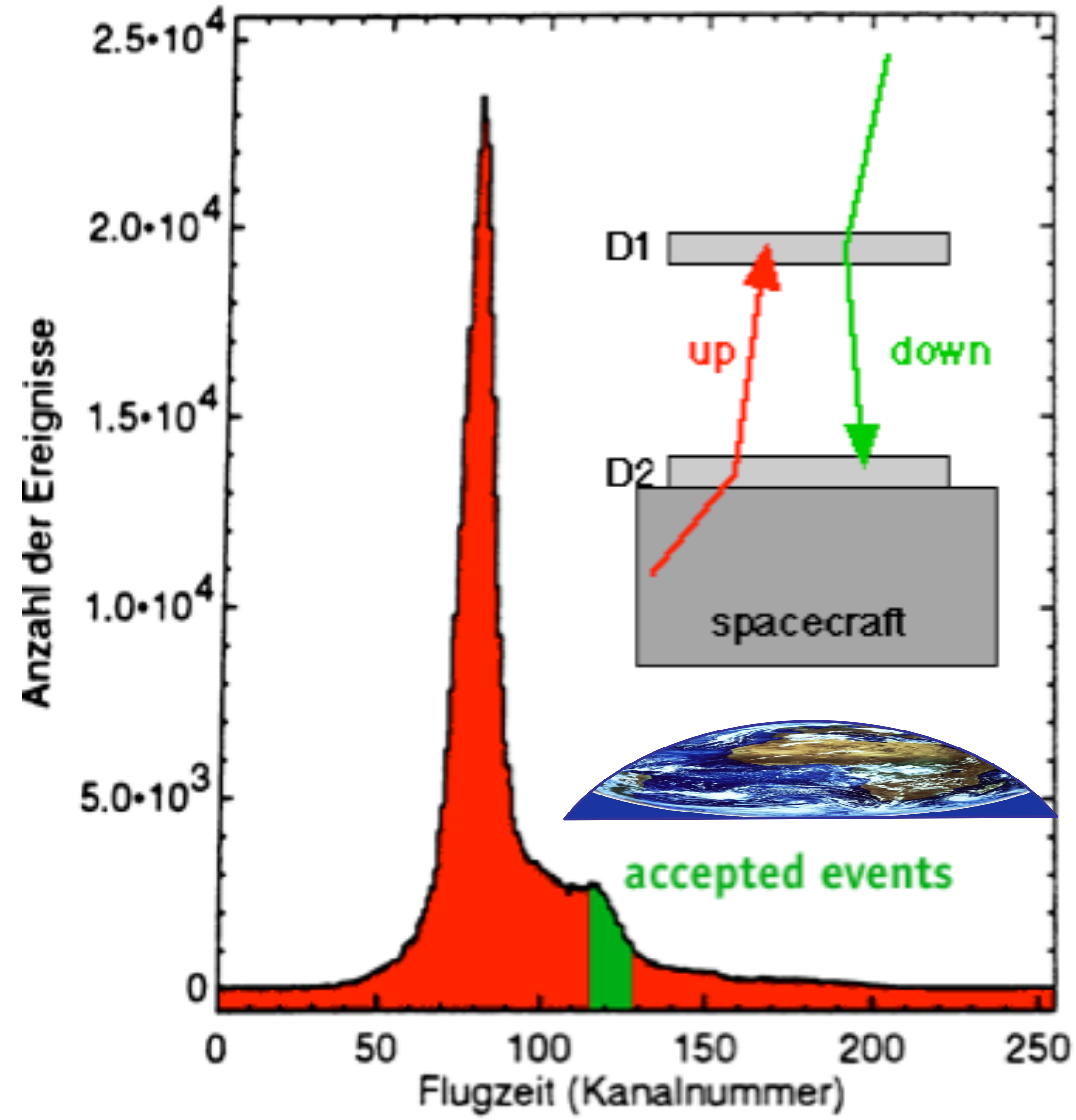
Compact solid state CTs

Higher Compton efficiency

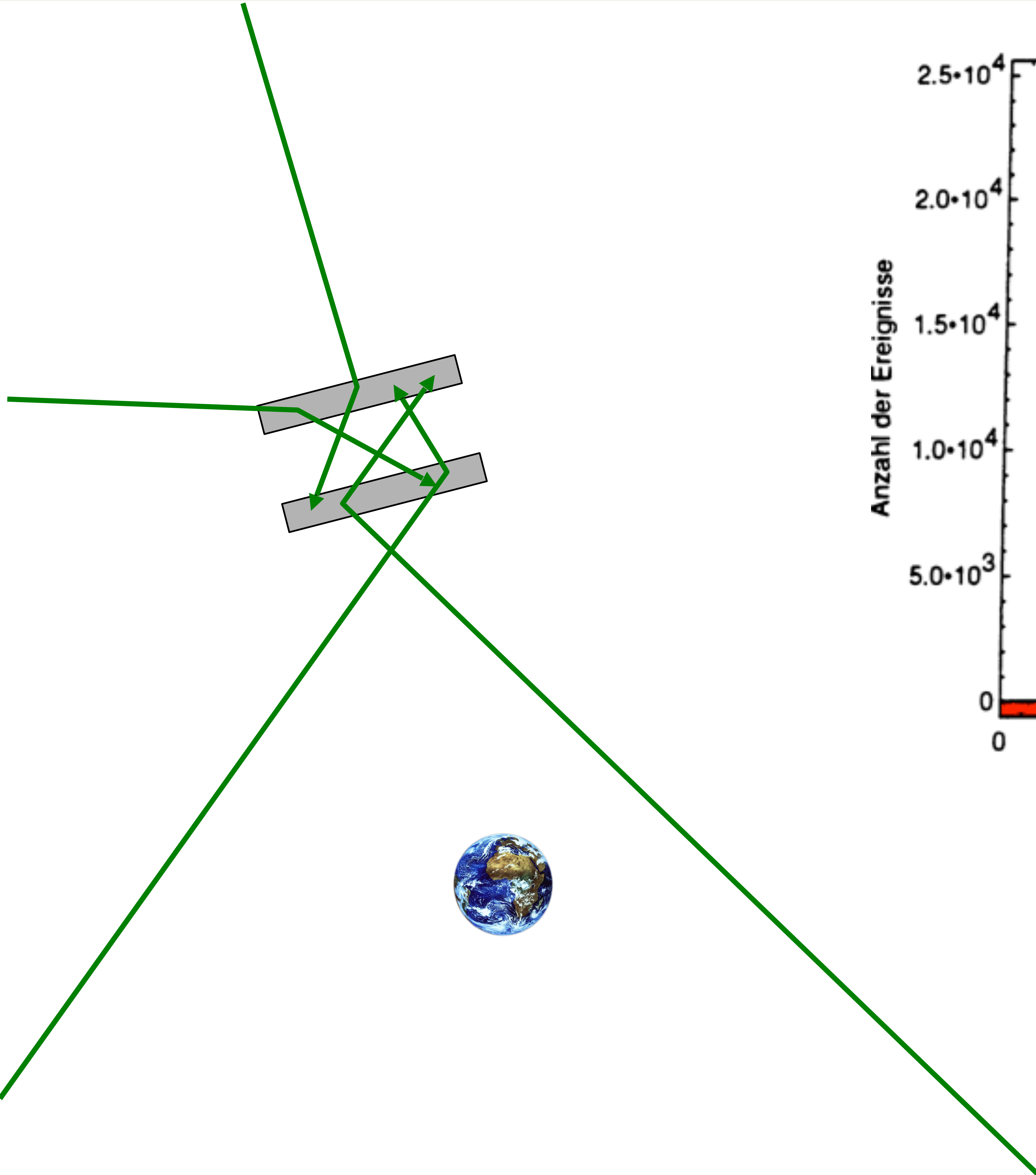
They require **AC shields** often **more massive than the instrument** itself

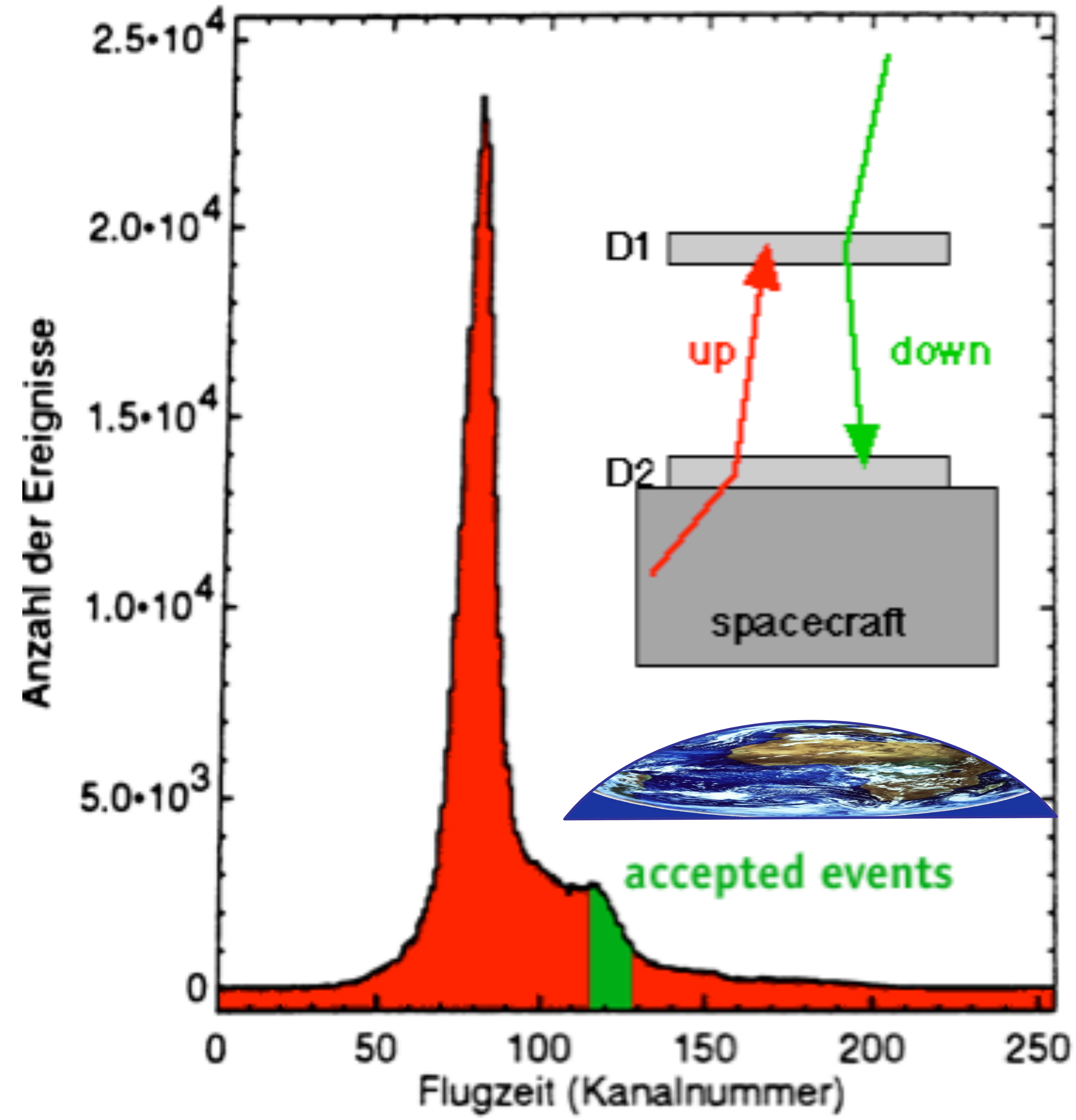
option C : no bkg from external passive mass



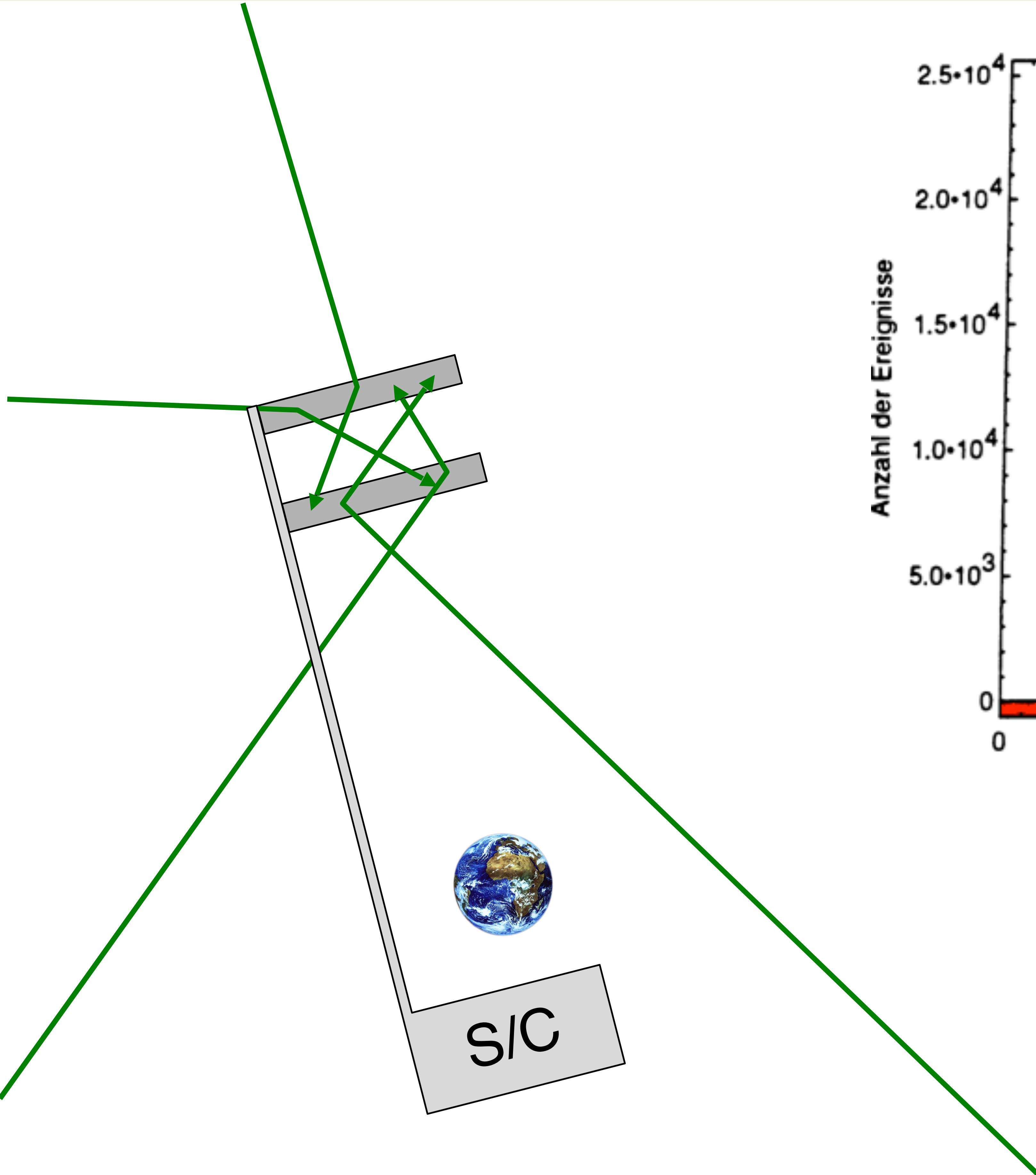


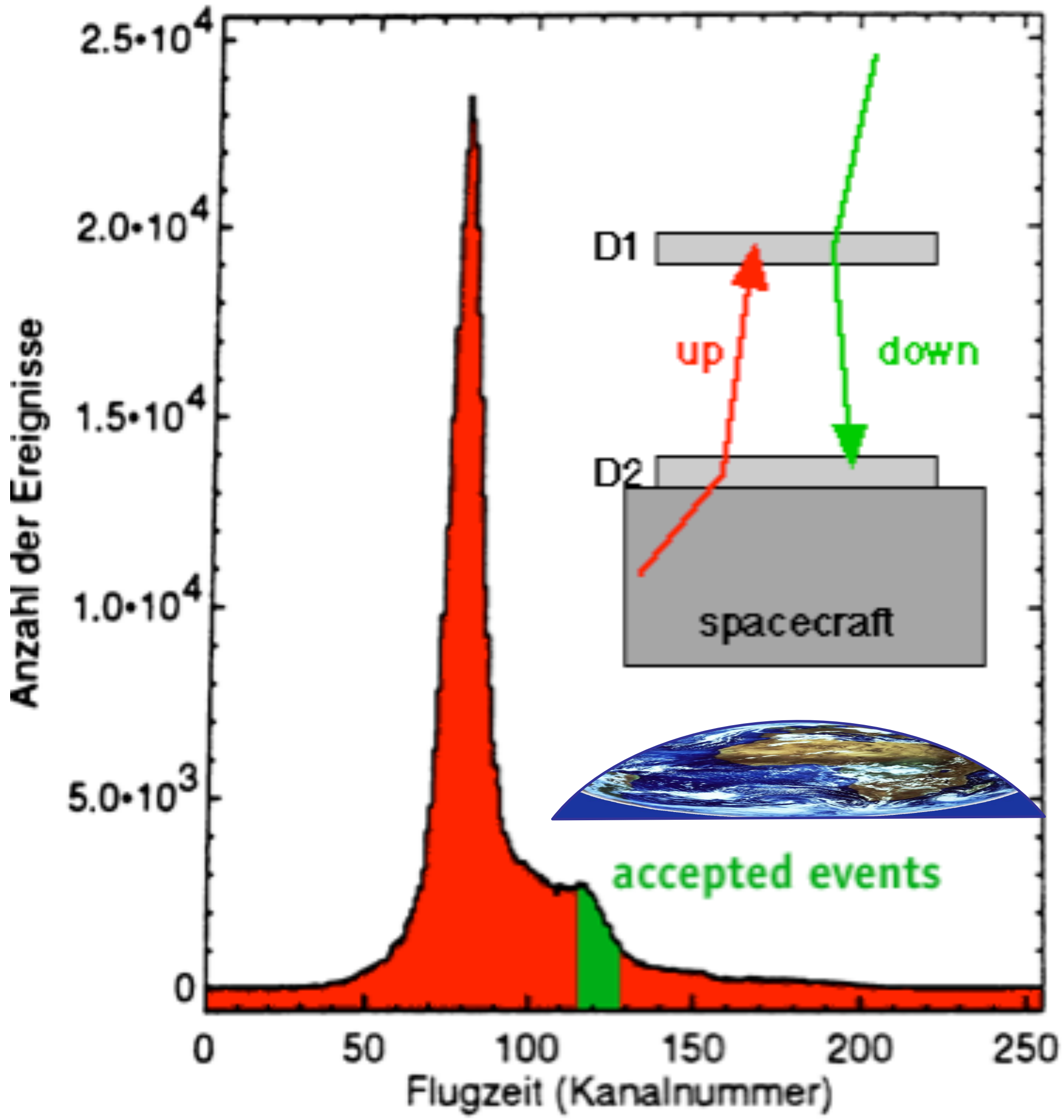
option C : no bkg from external passive mass



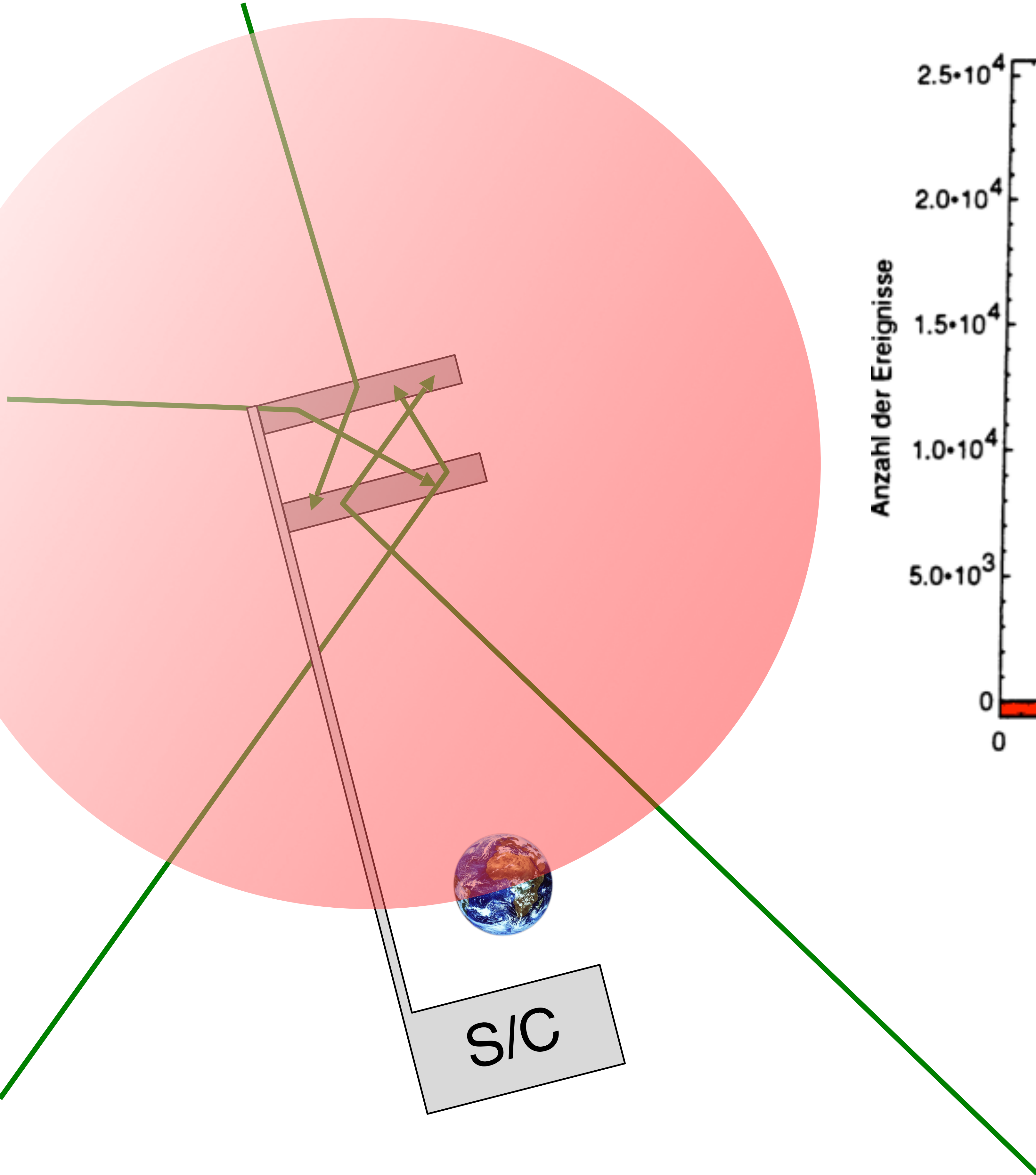


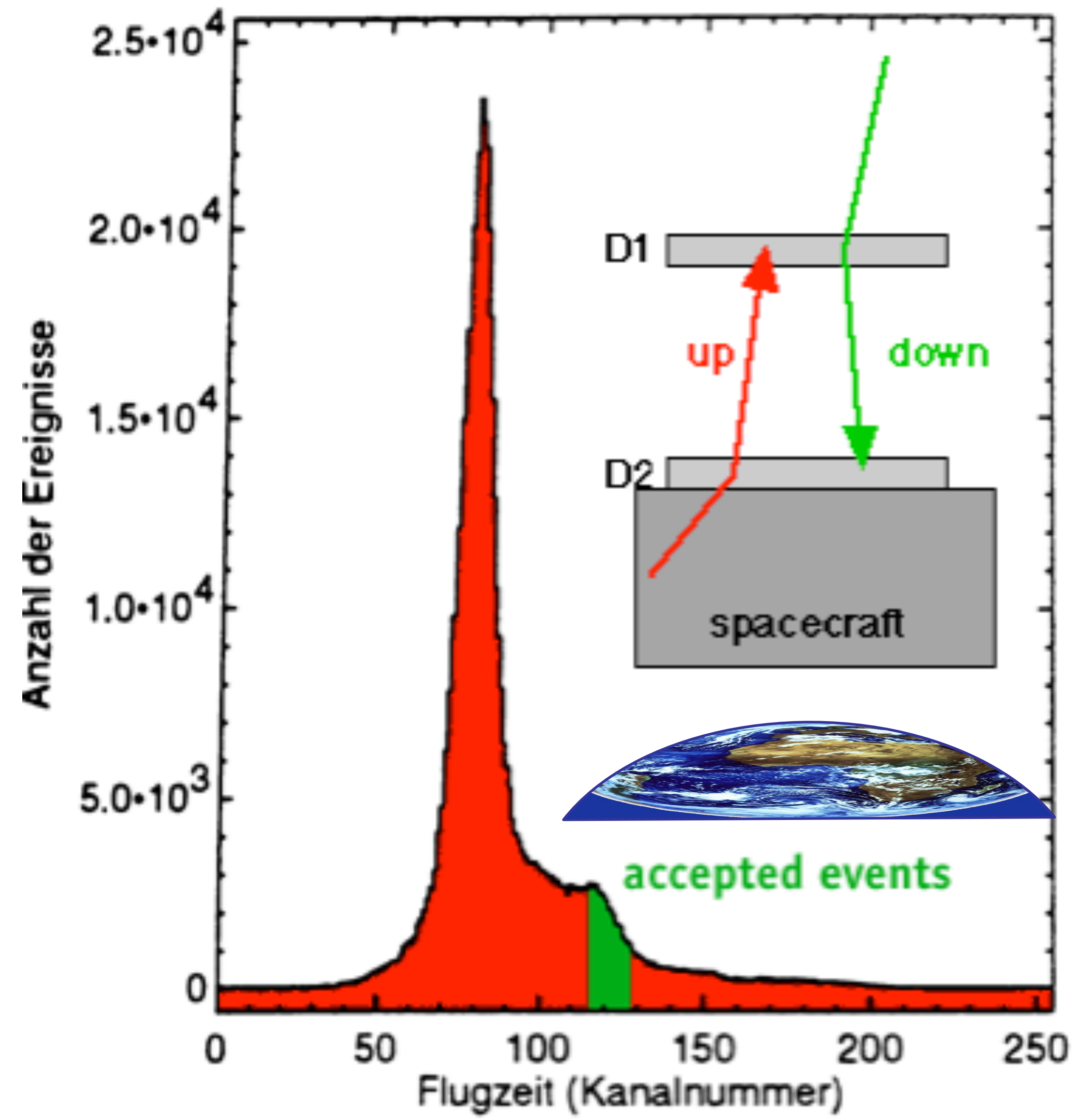
option C : no bkg from external passive mass





option C : no bkg from external passive mass





Which orbit? LEO or HEO?

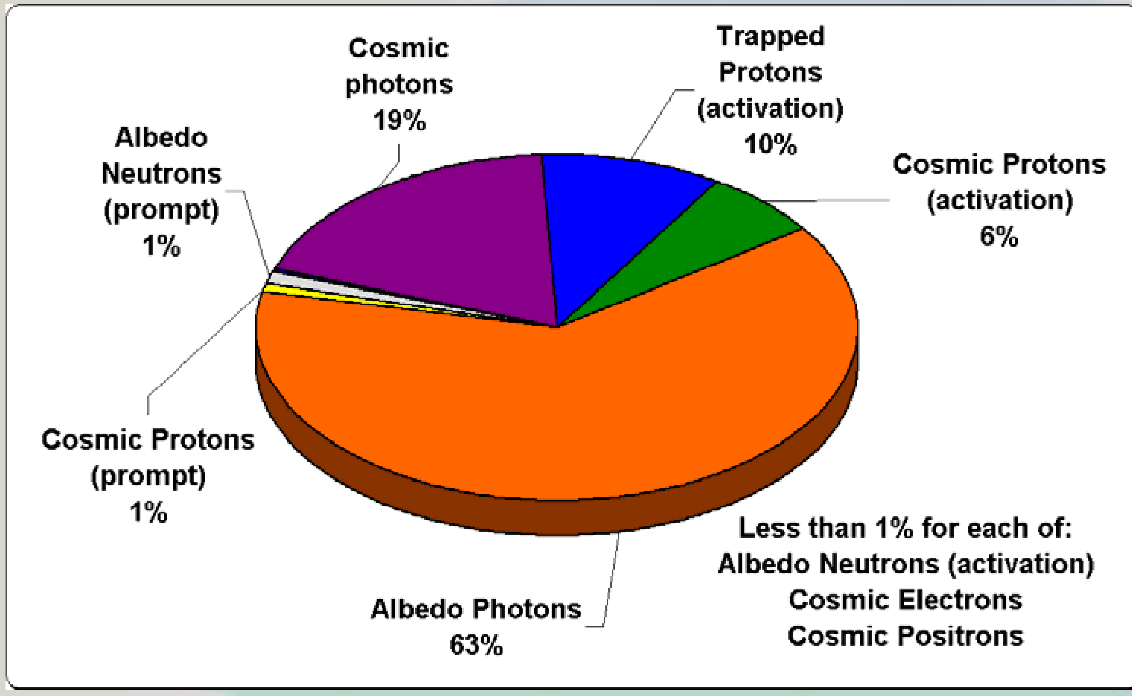
- Low Earth Orbit
  - Advantages
    - Reduced CR background from geomagnetic shielding
      - Reduced prompt CR contamination
      - Reduced instrument and s/c activation
      - Note: want low inclination (i.e. near 0 deg)
        - » Maximizes geomagnetic screening, i.e. minimizes CR-induced background
        - » Improves livetime by avoiding SAA
    - Increased payload mass at lower launch cost
  - Disadvantages
    - Strong atmospheric γ-ray background
    - Earth occults ~1/3 of the sky

- High Earth Orbit
  - Advantages
    - Reduced atmospheric γ-ray background
    - Increased FOV (nearly 4π possible)
  - Disadvantages
    - Increased CR background
      - Increased prompt CR contamination
        - » High trigger rate, data volume
        - » More CRs to identify and reject
      - Increased instrument and s/c activation
    - Decreased payload mass and/or higher launch cost

What's the right choice?

Example trade study for Si ACT

Low Earth Orbit vs. High Earth Orbit Background

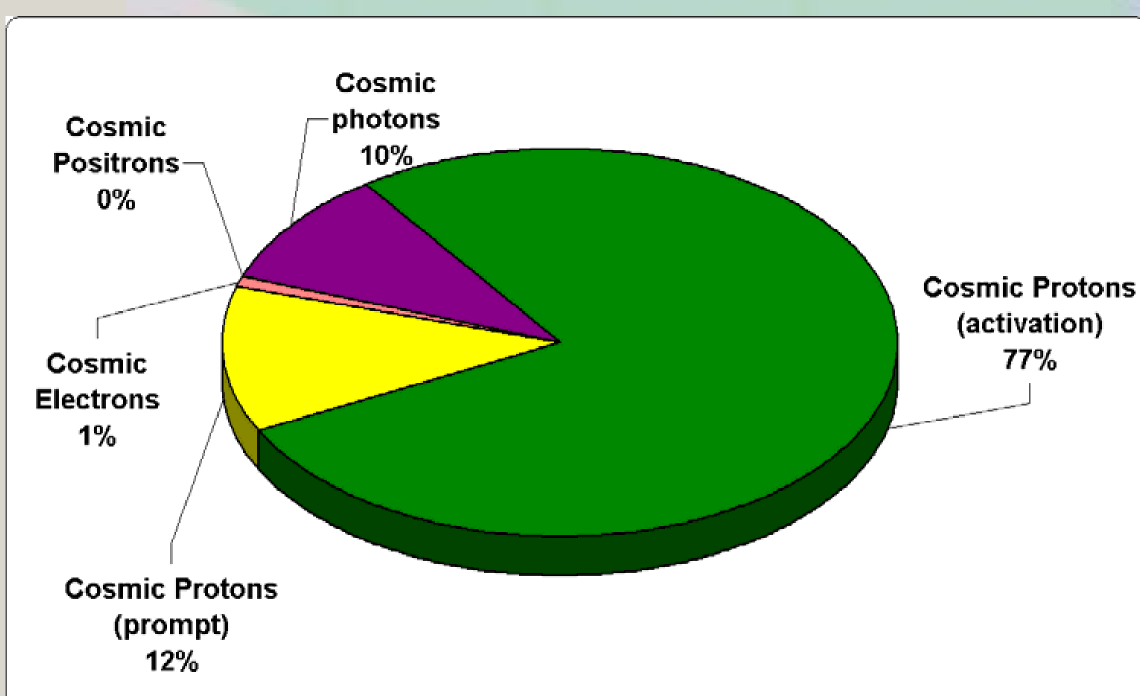


LEO: 550 km, 8^0 inclination

Contributions for: Horizon cut 92.5^0; E = 847 +/- 22.75 keV; ARM radius 1^0

3σ sensitivity over 10^6 sec, at 3% FWHM brdn. 847keV line, on-axis plain wave:

$2.37 * 10^{-6}\ \gamma * cm^{-2} * s^{-1}$



HEO: 40,000 km

Contributions for: Horizon cut 10^0; E = 847 +/- 22.75 keV; ARM radius 1^0

3σ sensitivity over 10^6 sec, at 3% FWHM brdn. 847keV line, on-axis plain wave:

$2.97 * 10^{-6}\ \gamma * cm^{-2} * s^{-1}$

Novikova (NRL) et al. 2005 – Si ACT

Backgrounds

- Beware of self-activity
  - Are lanthanum halides good choices for Compton calorimeter?
  - $LaBr_3$, $LaCl_3$
    - Fast scintillator, good energy resolution (~4% at 1 MeV), high stopping power
    - Hot
  - Study performed for ACT, GRIPS

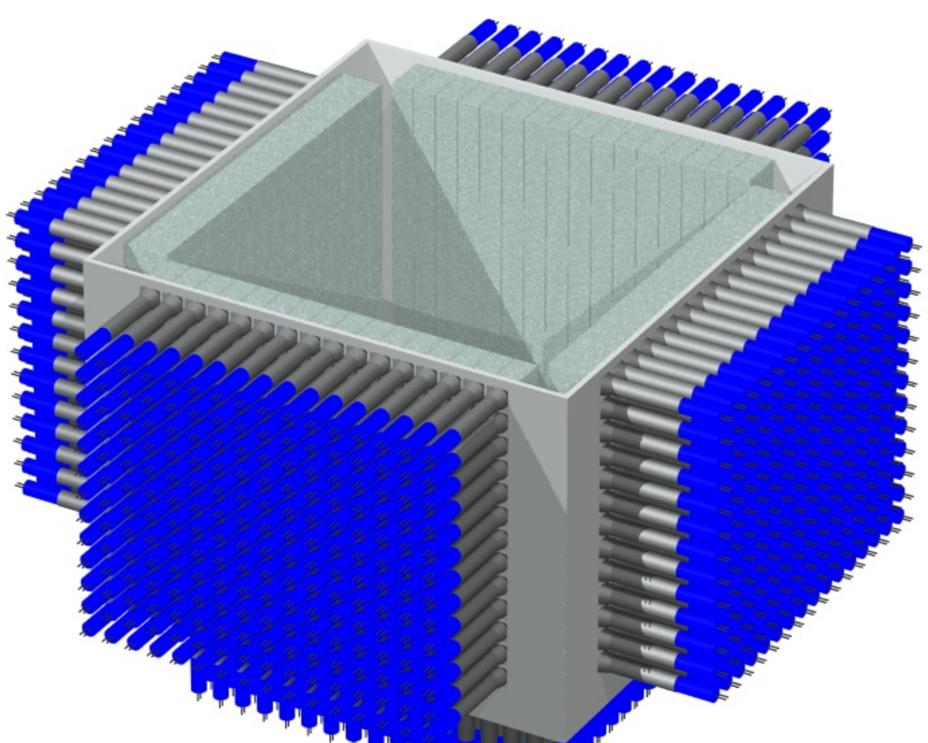
NaI vs LaBr Compton Calorimeter

Bernard Phlips

Code 7654

Naval Research Laboratory

Calorimeter



- NaI crystals are standard parts
- Frame will also support stack of silicon
- Need slots for cables from/to silicon detectors
- Area inside calorimeter ~ 45 cm x 45 cm

Note size

Self activity or induced activation

- Beta-gamma decays look just like signal
  - e.g. La self-activity for large instrument creates many kHz of nasty bkg

Lanthanum Activation

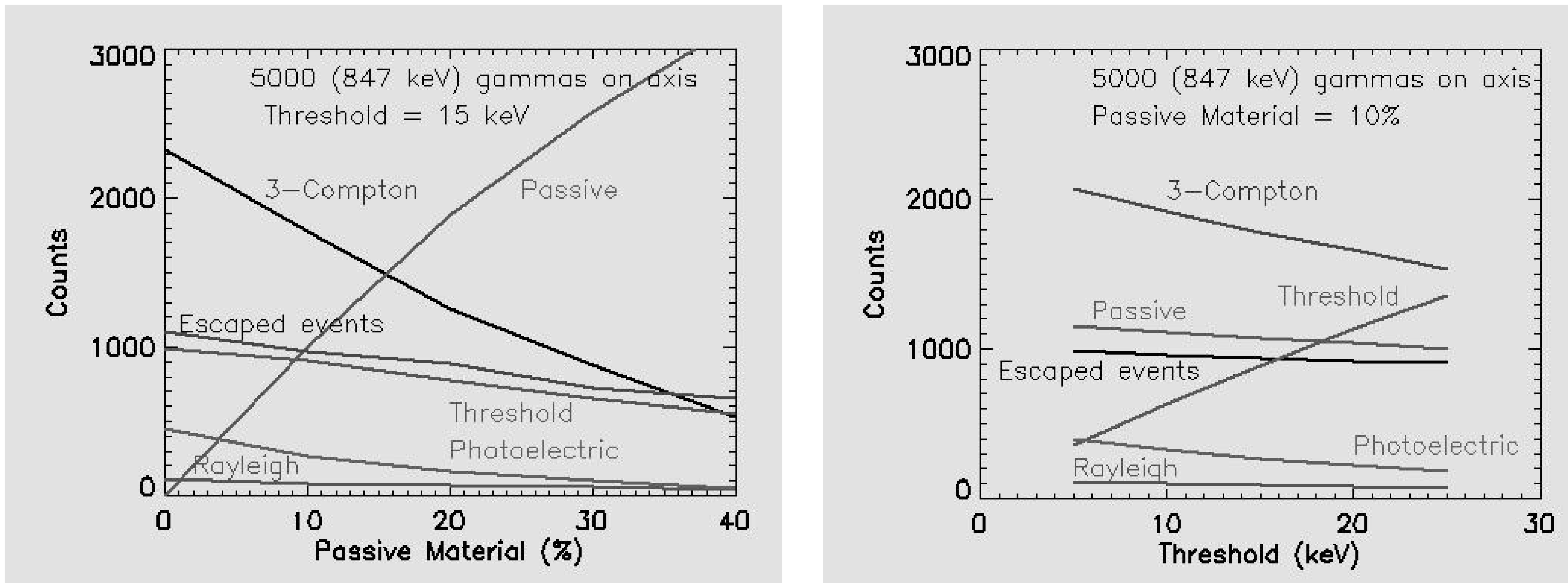
- Lanthanum is 99.91% ^{139}La, and 0.09% ^{138}La
- ^{138}La decays with 2 different decay schemes:- 788.7 keV gamma
  - 1438.8 keV gamma and a beta with 205 keV endpoint
- The activity is 1.8 Bq/cm^3 for $LaCl_3$ and 1.62 Bq/cm^3 for $LaBr_3$
- For 5 cm thickness, have ~30 000 cm^3 calorimeter.
- ~50 000 Bq of activity within the instrument for LaBr3!

		Hits in Silicon								
		0	1	2	3	4	5	6	7	8
Hits in scintillator	0	16187	331	114	38	18	8	3	1	0
	1	27814	782	324	124	43	10	5	1	1
	2	22573	911	303	107	30	6	1	0	0
	3	9801	462	124	27	6	3	0	0	0
	4	2500	118	24	8	1	0	0	0	0
	5	442	21	4	1	0	0	0	0	0
	6	53	4	1	0	0	0	0	0	0
	7	5	1	0	0	0	0	0	0	0
	8	1	0	0	0	0	0	0	0	0

- We modeled the activity and logged the different types of events
- There are ~3500 coincidences/second between silicon and calorimeter from self activity!
- Lanthanum halides probably not the way to go for large instruments

Passive material is bad

Sensitivity Improvement with New Technologies



- Current simulations result in about 2-4% effective area
- This is ≤ 10% of the potential events that could be used
- Clearly worth effort to substantially improve this performance

Reduce passive material
Reduce thresholds

18 August 2005 ACT Team Meeting

- Recall Fermi LAT TKR passive material
  - Even after deleting W, trays are ~50% Si and ~50% passive Al-composite
    - Don’t forget also that not all of Si is active

“Requirements” for high-res Compton tele

- Low Z scatterer
  - Minimizes Doppler broadening (most important below MeV)
  - Minimizes MCS of recoil electron, if tracking
- High Z absorber
  - Good stopping power to absorb scattered gamma (and minimize multi-Compton)
- High efficiency
  - Proper scatterer and absorber to give highest possible efficiency
  - Compact (as possible) to maximize geometric cross section for interaction
- Excellent energy resolution
  - Well matched with d^3x
- Fine position resolution
  - Well matched with dE
    - Thumb: ~1 mm and ~few keV are commensurate
- Low-power electronics
  - Preserve intrinsic dE, d^3x of detectors while staying within power budget
- Minimal passive mass within detection volume
  - Interactions can be missed in passive material, and kill Compton performance
  - Minimize structural supports, co-located electronics
  - Minimize detector guard rings

Backup material

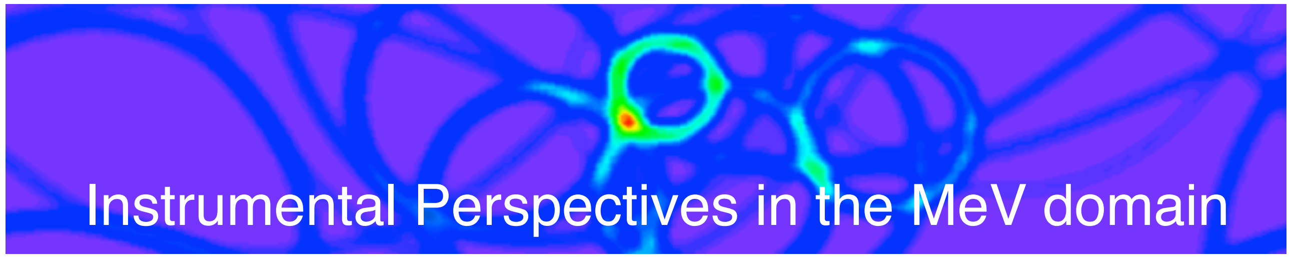
Scaling with target material

Dependence of photon interaction (mass attenuation coefficient) on material composition

- **Photoelectric effect** (photons see atomic shells)
  - Increases strongly with Z
  - Absorption edges (especially at K shell)
- **Compton scattering** (photons see individual electrons)
  - Scales with electron density (number of electrons per gram)
    - High in hydrogen due to lack of neutrons
    - Only varies by 20% in other elements
- **Pair production** (photons see nucleus)
  - Increases strongly with Z (approximately as Z^2)
  - High energy limit (>> $m_e c^2$):

$$\sigma = \frac{7}{9} 4\alpha r_0^2 Z_{nucl} (Z_{nucl} + 1) \ln \left(\frac{183}{3\sqrt{Z_{nucl}}} \right)$$

Slides borrowed from … etc.



Instrument Options in the MeV range

What made progress so slow ?

Recent R&D projects towards a future MeV mission

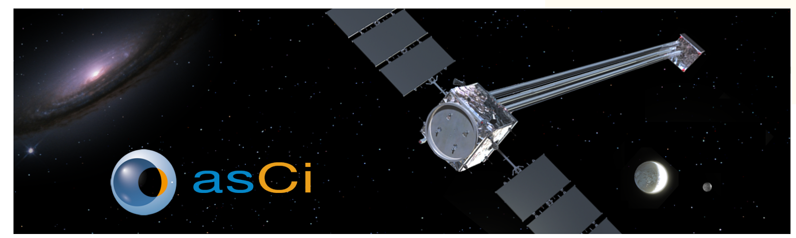
Peter von Ballmoos, IRAP Toulouse

GAMMA CUBE

(LE – GLAST)

A scintillation tracker

R. Chipaux, P. Laurent, F. Lebrun, R. Terrier



all sky Compton imager

design considerations for Compton Telescopes
the asCi choice - detector and mission concept
performance estimates
one more thing

Peter von Ballmoos, IRAP Toulouse

NCT

The Nuclear Compton Telescope

A balloon-borne gamma-ray spectrometer, polarimeter, and imager

Steve Boggs

for the NCT collaboration

Thick Silicon Compton Imager for ACT

Bernard Phlips
Jim Kurfess
Eric Wulf
Elena Novikova
Neil Johnson

18 August 2005

18 August 2005 ACT Team Meeting

Simulations of a Si-based Advanced Compton Telescope (ACT)

Elena I. Novikova[1], Eric A. Wulf[1], Bernard F. Phlips[1], James D. Kurfess[1], Andreas Zoglauer[2], Georg Weidenspointner[3], R.Marc Kippen[4]

[1]NRL, Washington, DC, USA
[2]UC Berkeley, CA, USA
[3]CESR, Toulouse, France
[4]LANL, Los Alamos, NM, USA

October 26, 2005 IEEE NSS N19-5 Puerto Rico 1