

# *Performance of the MeV gamma-ray telescopes and polarimeters of the future.*

$\gamma \rightarrow e^+e^-$  in silicon-detector active targets

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**12th INTEGRAL conference and 1st AHEAD gamma-ray workshop, 11 - 15 Feb. 2019, Geneva**



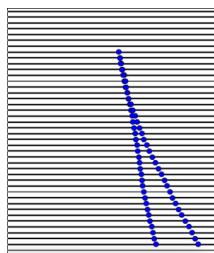
# *MeV telescopes and polarimeters. Science case: a short extract*

- $\gamma$ -ray astronomy: monster **sensitivity gap** 0.1 - 30 MeV
- No  $\gamma$ -ray polarimetry of cosmic source(s) above 1 MeV to date. Would enable:
  - Astrophysics:
    - **Blazars**: decipher leptonic synchrotron self-Compton (SSC) against hadronic (proton-synchrotron) models,  
[Zhang and Böttcher, \*Astrophys.J.\* 774, 18 \(2013\)](#)
    - **Young pulsars**: tag the transition between curvature radiation and synchrotron radiation, [Harding and Kalapotharakos, \*Astrophys. J.\* 840 73 \(2017\)](#)
  - Fundamental physics:
    - Search for Lorentz Invariance Violation, **LIV**, higher energy  $\Rightarrow$  higher sensitivity.
    - Search for **axion**, [Rubbia and Sakharov, \*Astropart. Phys.\* 29, 20 \(2008\)](#)

# 3 technologies

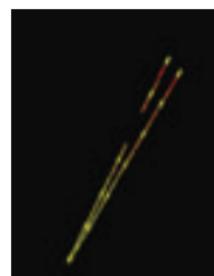
W-less, Si-stack detectors  
AMEGO, e-ASTROGAM  
 $1.3^\circ$  @ 100 MeV

De Angelis *et al.*, Exp. Astr. 44 (2017) 25



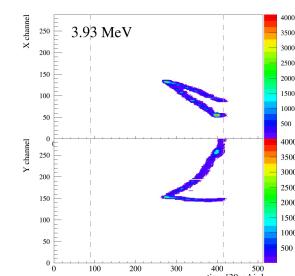
Emulsions  
GRAINE  
 $1^\circ$  @ 100 MeV

Takahashi *et al.*, PTEP 2015 (2015) 043H01



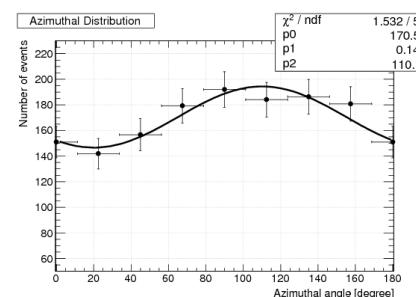
Gas TPC  
HARPO  
 $0.4^\circ$  @ 100 MeV

Bernard, Nucl. Instrum. Meth. A 701 (2013) 225



Polarimetry with  $\gamma \rightarrow e^+e^-$ :

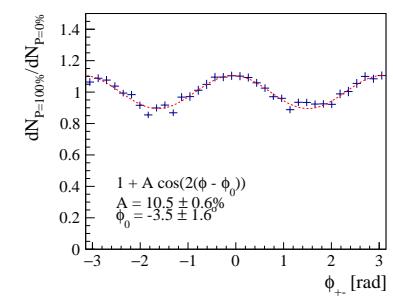
Ozaki *et al.*, Nucl. Instrum. Meth. A 833 (2016) 165



?

2.4 GeV (50 MeV threshold ?)

Gros *et al.*, Astroparticle Physics 97 (2018) 10



11.8 MeV

Combined Compton / pair ?

Yes

?

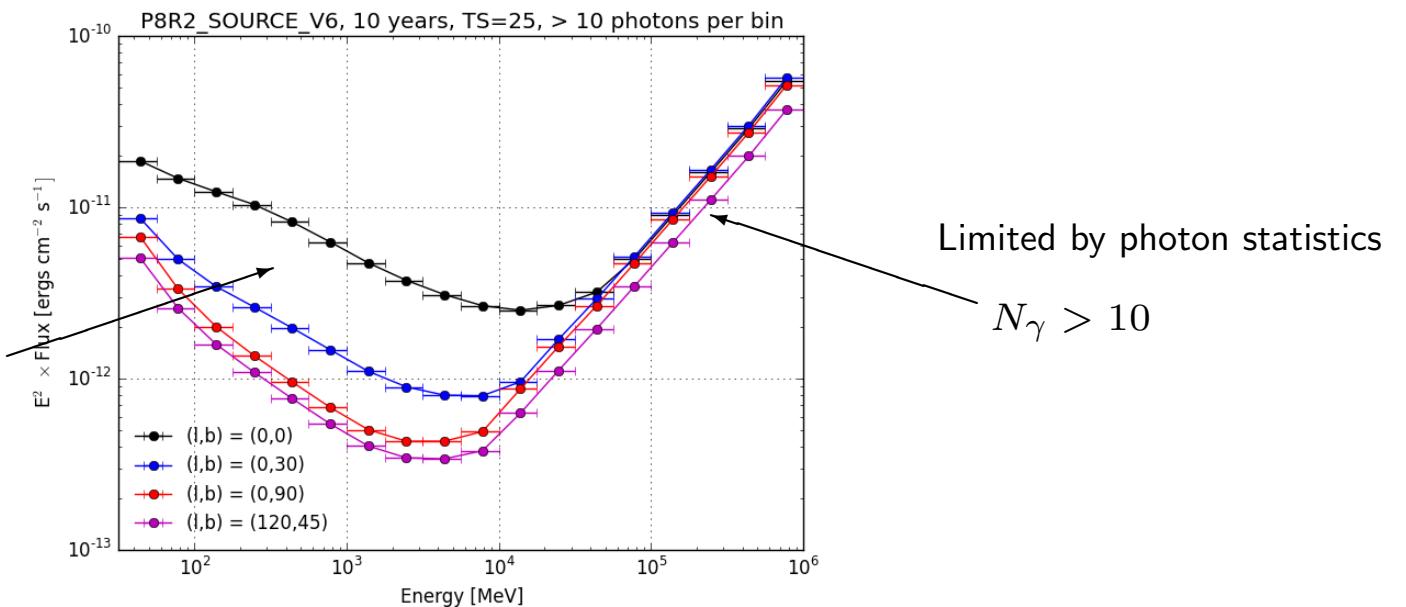
Yes

Tanimori *et al.*, Astrophys.J. 810 (2015) 28

# Differential flux sensitivity and angular resolution

Limited by background rejection

$$s \approx \frac{n \sigma_\theta E^2}{\Delta E} \sqrt{\frac{\pi \int B(E) dE}{T \eta A_{\text{eff}}}}$$

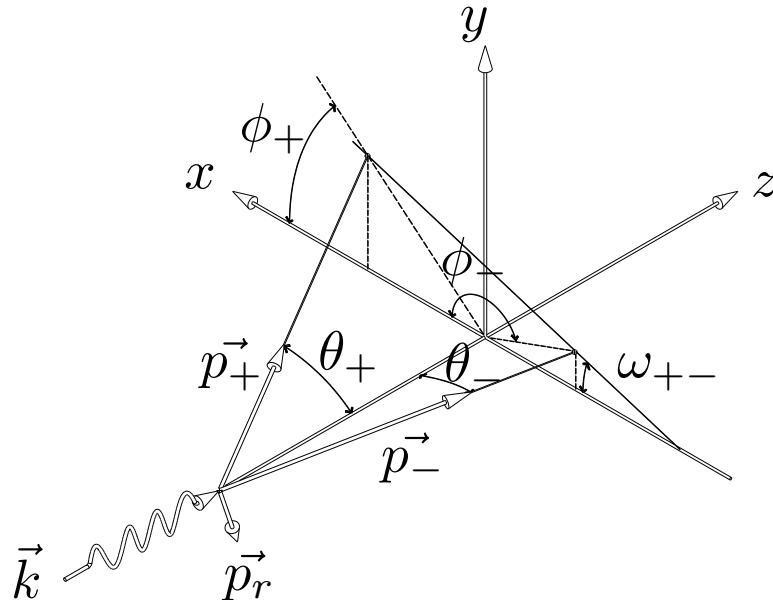


[Fermi LAT performance.html](#)

- In this talk I focus on the angular resolution,  $\sigma_\theta$ .

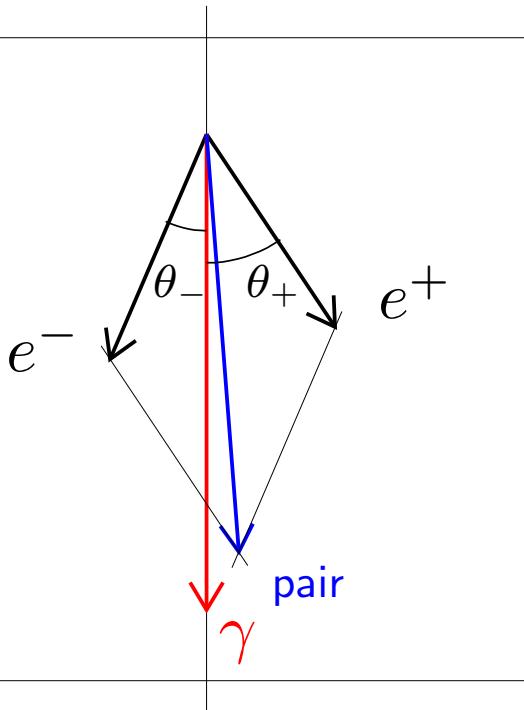
## $\gamma$ -ray conversion differential cross-section

- Five dimensional (5D),
- Variables: azimuthal ( $\phi_+$ ,  $\phi_-$ ) and polar ( $\theta_+$ ,  $\theta_-$ ) angles of  $e^+$  and  $e^-$ , and  $x_+ \equiv E_+/E$



- Analytical “Bethe and Heitler” expressions:
  - $P = 0$ , [Bethe and Heitler, Proc.Roy.Soc.Lond. A146 \(1934\) 83](#)
  - $P = 1$ , [Berlin and Madansky, Phys. Rev. 78 \(1950\) 623](#) and [May, Phys. Rev. 84 \(1951\) 265.](#)  
(misprint corrected in [The theory of photons and electrons](#), Jauch and Rohrlich, (Springer Verlag, 1976).)
- Only linear polarization relevant to first Born order.

## Pre-existing event generators

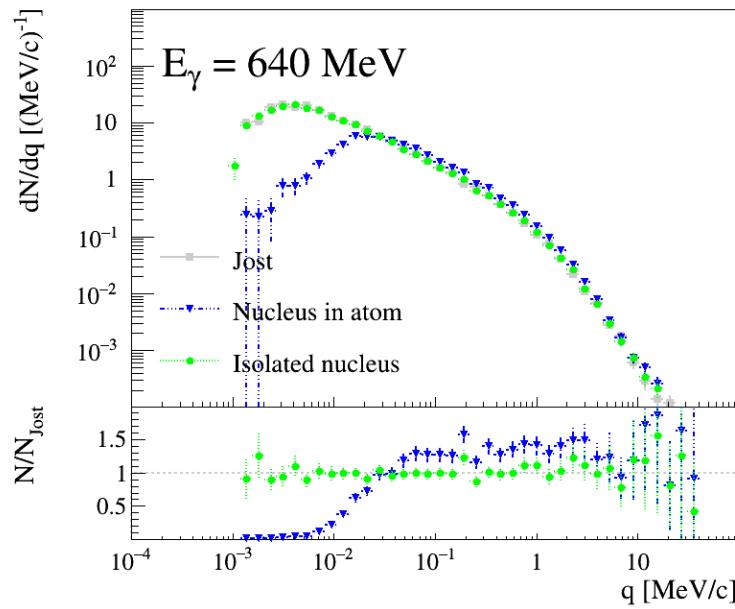


- pdf = product of 1D pdf's
- No recoil explicitly generated ( $E_+ + E_- = E$ )
  - $\Rightarrow$  conversion wrongly generated in a plane that contains  $\vec{k}_\gamma$ 
    - $\Rightarrow$  no kick transverse to the plane
- $e^+$  and  $e^-$  polar angles generated independently
  - $\Rightarrow$  energy-momentum not conserved !
    - $\Rightarrow$  artificial kick in the plane (and wrong distribution)
- Attempts to verify polarized models failed

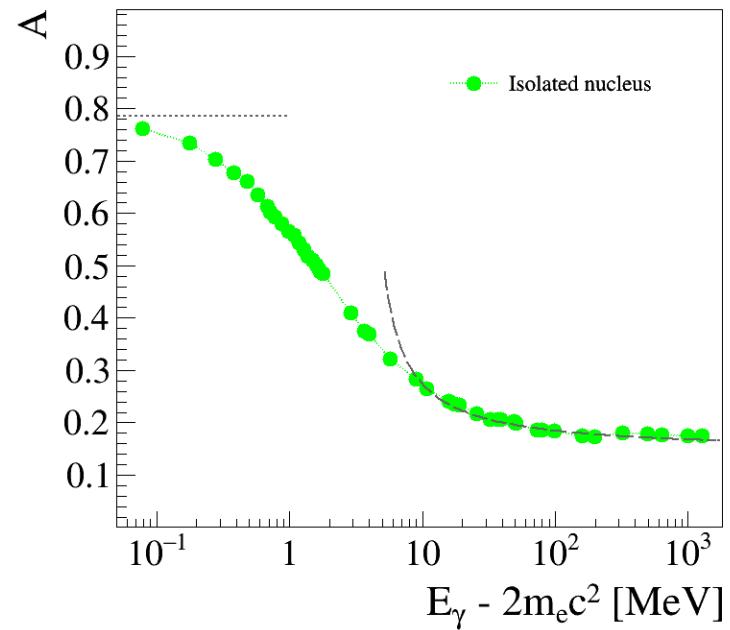
Gros and Bernard, Astroparticle Physics 88 (2017) 60

# G4BetheHeitler5DModel Physics Model in Geant4 Release 10.5

- Exact (5D) Bethe-Heitler differential cross section with strict energy-momentum conservation
- Conversion of (polarized or non-polarized)  $\gamma$ 's on (isolated or atomic) (nuclei or electrons) targets
- Ancestor version [Bernard, Nucl. Instrum. Meth. A 729 \(2013\) 765](#)



Recoil momentum distribution compared to the analytical high-energy expression from [Jost et al., Phys. Rev. 80, 189 \(1950\)](#). The ratio plot is relative to Jost.



Polarisation asymmetry as a function of available energy, compared to published asymptotic expressions (exact expression of event azimuthal angle  $(\phi_+ + \phi_-)/2$ , [Gros and Bernard, Astroparticle Physics 88 \(2017\) 30](#))

- Characterization of Geant4-compatible sampling method [Bernard, Nucl. Instrum. Meth. A 899 \(2018\) 85](#)
- **Geant4 10.5 released Dec. 2018**

## *Photon angular resolution*

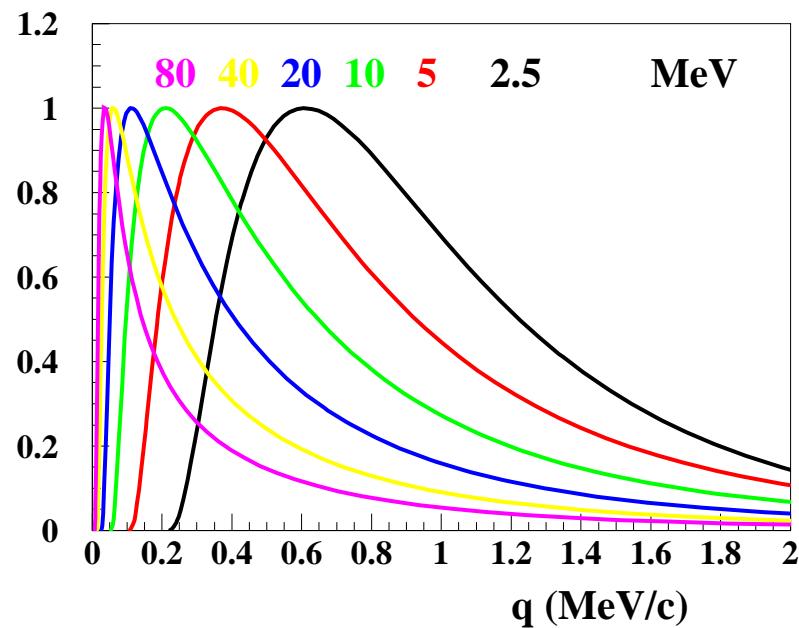
$$\gamma \ Z \rightarrow e^+ \ e^- \ Z$$

$$\vec{k} = \vec{p}_{e^+} + \vec{p}_{e^-} + \vec{p}_r$$

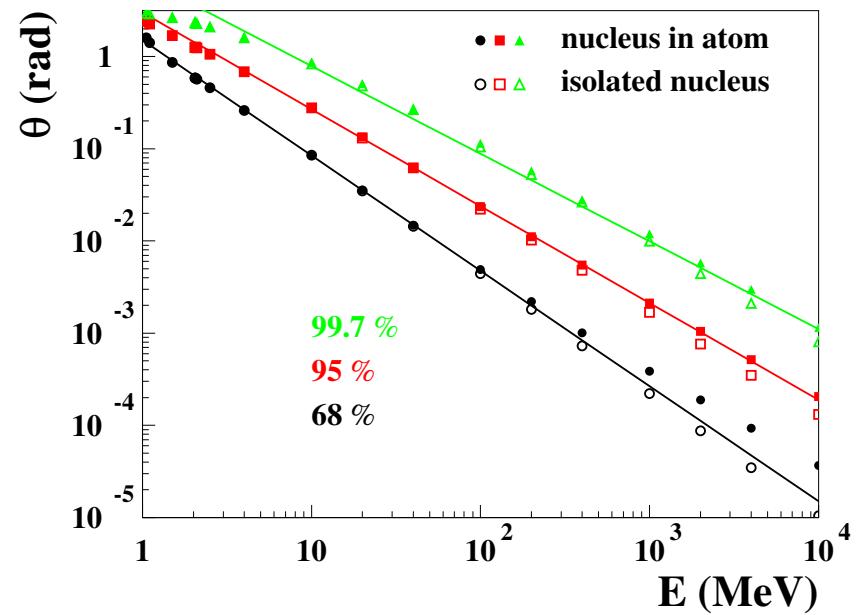
### Contributions:

- Un-measured nucleus recoil momentum,
- Single-track angular resolution,
- Single-track momentum resolution Not addressed in this talk

# Angular resolution: Un-measured nucleus recoil momentum



Recoil momentum distribution  
for various photon energies  
(no screening of atomic  $e^-$  field)



68, 95 and 99.7 % containment angles

- $\theta_{68\%} \approx 1.5 \text{ rad } (E/\text{MeV})^{-5/4}$
- $\theta_{95\%} \approx 3.0 \text{ rad } (E/\text{MeV})^{-1.05}$
- $\theta_{99.7\%} \approx 7.0 \text{ rad } (E/\text{MeV})^{-0.95}$

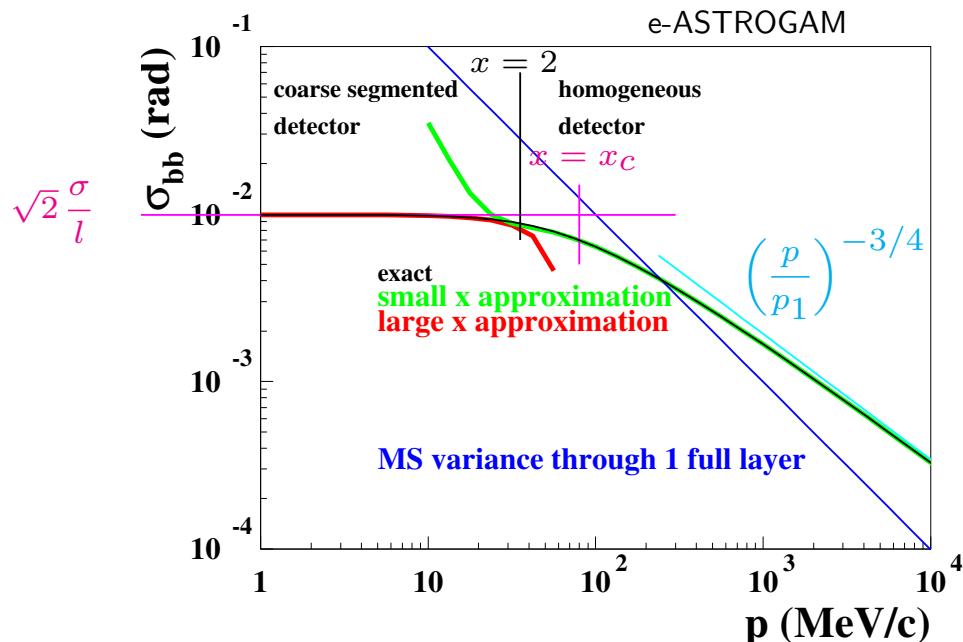
Bernard, Nucl. Instrum. Meth. A 701 (2013) 225

Gros and Bernard, Astroparticle Physics 88 (2017) 60

# Segmented active targets: single-track angular resolution

- Thick detector assumed ( $N$  large)
- $x$  distance between wafers, normalized to detector “scattering length”

$$p_0 = 13.6 \text{ MeV}/c$$



$$p_1 = p_0 \left( \frac{4\sigma^2 l^4}{X_0^3 \Delta x^3} \right)^{1/6}$$

Bernard, Nucl. Instrum. Meth. A 729 (2013) 765

- $x < 2$  ( $p > 35 \text{ MeV}/c$  for e-ASTROGAM), homogeneous detector
- $x > 2$  ( $p < 35 \text{ MeV}/c$  e-ASTROGAM), segmented detector

$$x \equiv \frac{l}{\lambda} \approx \sqrt{\frac{l}{\sigma}} \frac{p_0}{p} \sqrt{\frac{\Delta x}{X_0}}, \quad p = p_0 \sqrt{\frac{\Delta x}{X_0}} \frac{l}{\sigma x^2}$$

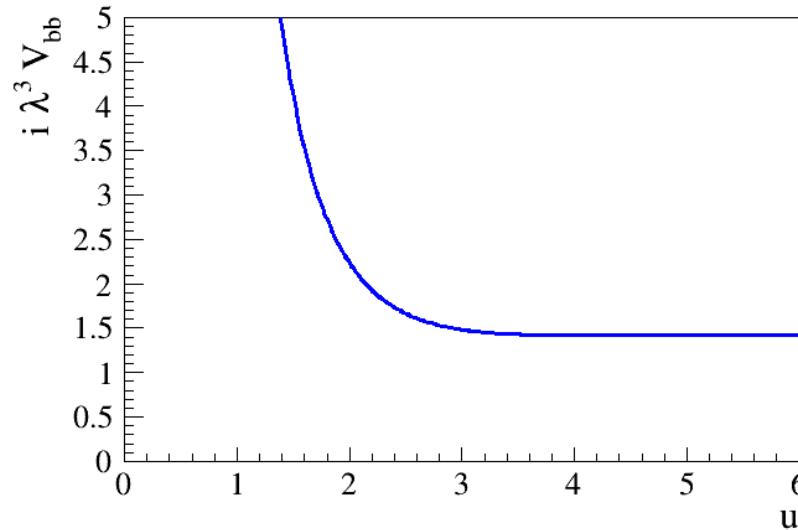
- $x < x_c$  ( $p > 80 \text{ MeV}/c$  for e-ASTROGAM), Kalman filter useful,  $\left(\frac{p}{p_1}\right)^{-3/4}$ ,  $p_1 = p_0 \left( \frac{4\sigma^2 l^4}{X_0^3 \Delta x^3} \right)^{1/6}$
- $x > x_c$  ( $p < 80 \text{ MeV}/c$  for e-ASTROGAM), measure from two first wafers,  $\sqrt{2} \frac{\sigma}{l}$ , Kalman filter useless
- In case conversion took place inside the 1st wafer, in addition, MS

Frosini and Bernard, Nucl. Instrum. Meth. A 867 (2017) 182

see back-up slides 26-27

## *Homogeneous detectors: when thick ?*

- Only the begining of a track contributes to the measurement of the incident angle
- All the rest is ruined by multiple scattering



Variance of angle measurement normalized to  $1/(\imath\lambda^3)$ , as a function of  $u$ , detector total thickness normalized to the detector scattering length at momentum  $p$

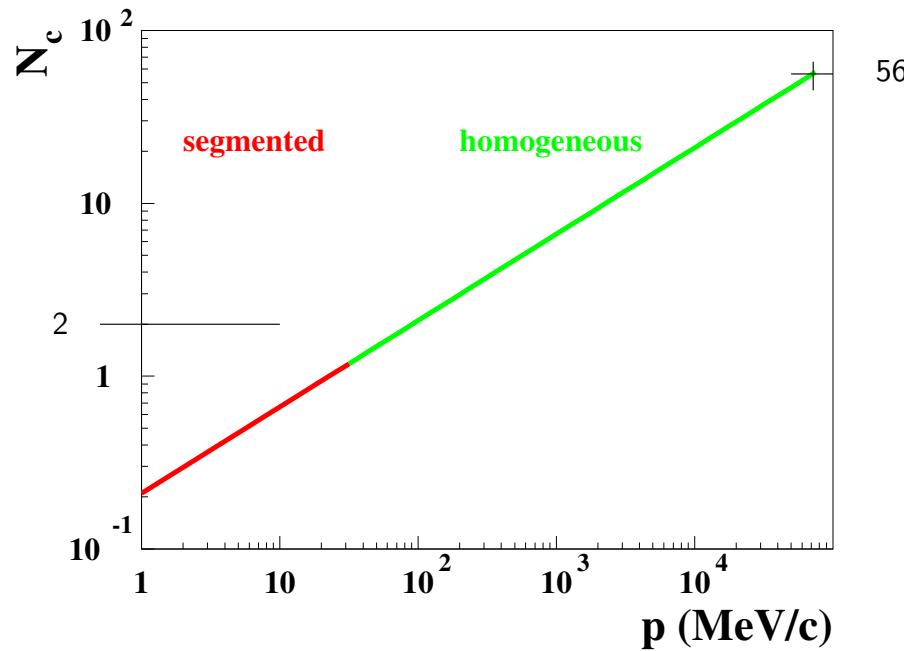
$$u \equiv \frac{Nl}{\lambda} \approx N \sqrt{\frac{l}{\sigma} \frac{p_0}{p} \sqrt{\frac{\Delta x}{X_0}}} , \quad u = Nx , \quad p = p_0 \sqrt{\frac{\Delta x}{X_0}} l N^2 \frac{1}{\sigma u^2}$$

- Say detector thick for  $u > u_c = 2.5$

Frosini and Bernard, Nucl. Instrum. Meth. A 867 (2017) 182

## *When thick ?*

- e-ASTROGAM is a thick detector up to  $72 \text{ GeV}/c$ .

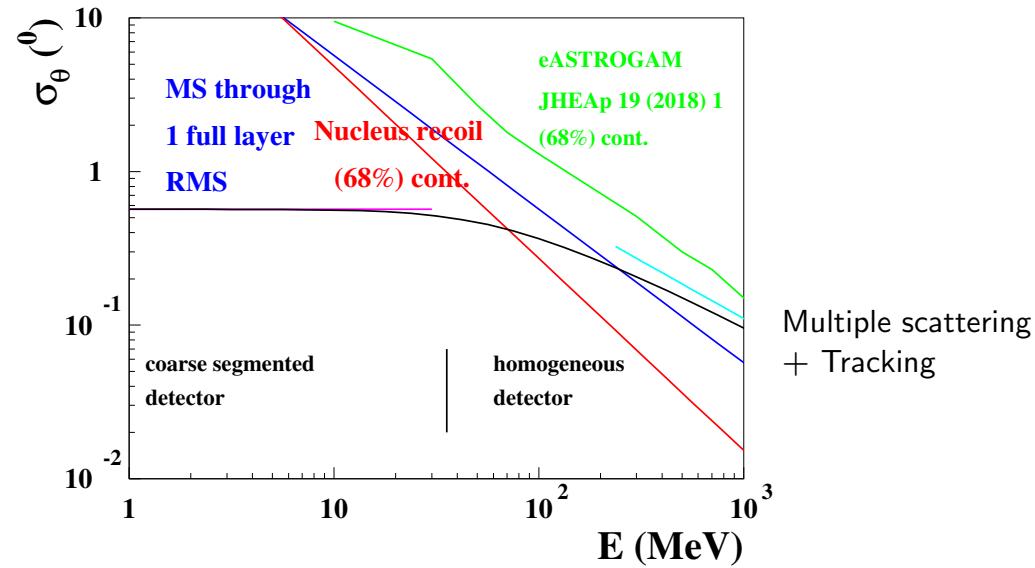


Number of layers,  $N_C$ , for which  $u = u_c = 2.5$  as a function of track momentum  $p$

- $N_c$  small on most of the momentum range
  - For most of the spectrum, the angular resolution independent of conversion layer position
  - Kalman filter-based tracking of the full track feeds the fit with noise, not signal  
⇒ Non optimal tracking due to non-Gaussian statistics (e.g. Bremsstrahlung)

# Single-photon angular resolution

- Assuming direct transfer from track  $p$  to photon  $E$  (see [Nucl. Instrum. Meth. A 701 \(2013\) 225, Fig. 1](#))
- e-ASTROGAM detector parameters



Contributions to the single-photon angular resolution as a function of photon energy, compared to e-ASTROGAM's [JHEAp 19 \(2018\) 1](#)

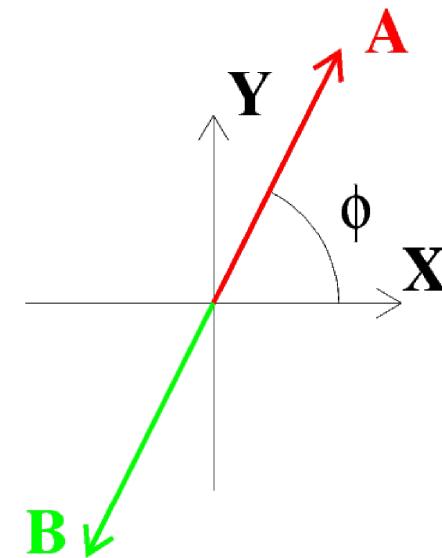
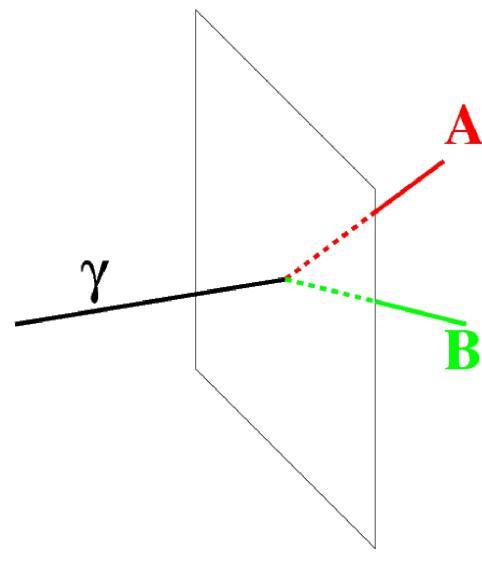
- Beware [JHEAp 19 \(2018\) 1](#) used a **pre-10.5 Geant4 release** (not the exact differential cross section).
- (Unmeasured recoil) + (multiple scattering in conversion wafer) dominant at low energy
- (Tracking) + (multiple scattering in conversion wafer) dominant at high energy

# Polarimetry

- Modulation of azimuthal angle distribution

$$\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A}P \cos [2(\phi - \phi_0)]),$$

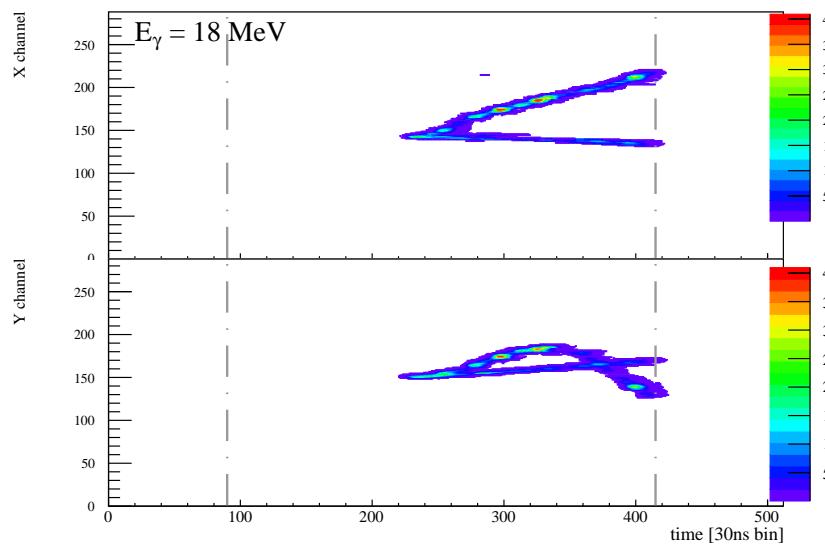
$$\sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}},$$



- $P$  source linear polarisation fraction
- $\mathcal{A}$   $\gamma$ -ray conversion polarization asymmetry
- $\phi$  event azimuthal angle
- $\phi_0$  source polarization angle.

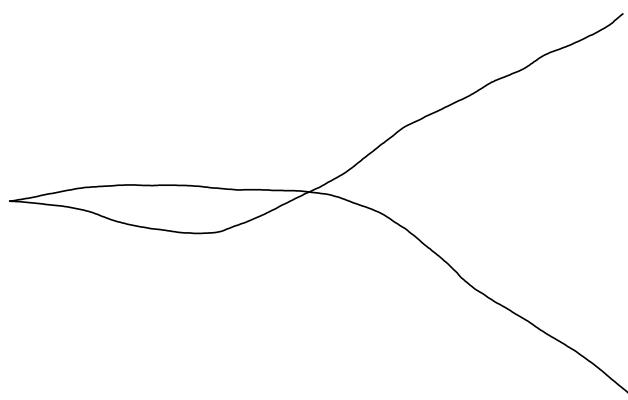
# Polarimetry with $\gamma \rightarrow e^+e^-$ : The enemy is multiple scattering

- Data



$(x, t)$  and  $(y, t)$  views of a 18 MeV  $\gamma$ -ray from the BL01 beam line at NewSUBARU (LASTI, Hyôgo U., Japan) converting to  $e^+e^-$  in the 2.1 bar Ar:Isobutane 95:5 gas of the HARPO TPC prototype

- MC simulation

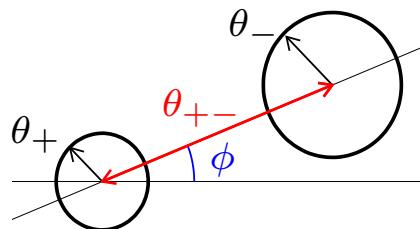


$\gamma$ -ray conversion in argon

# Conversion in a Slab and Multiple Scattering: Dilution of the Polarisation Asymmetry

- $(1 + \mathcal{A}P \cos[2(\phi)]) \otimes e^{-\phi^2/2\sigma_\phi^2} = (1 + \mathcal{A} e^{-2\sigma_\phi^2} P \cos[2(\phi)])$

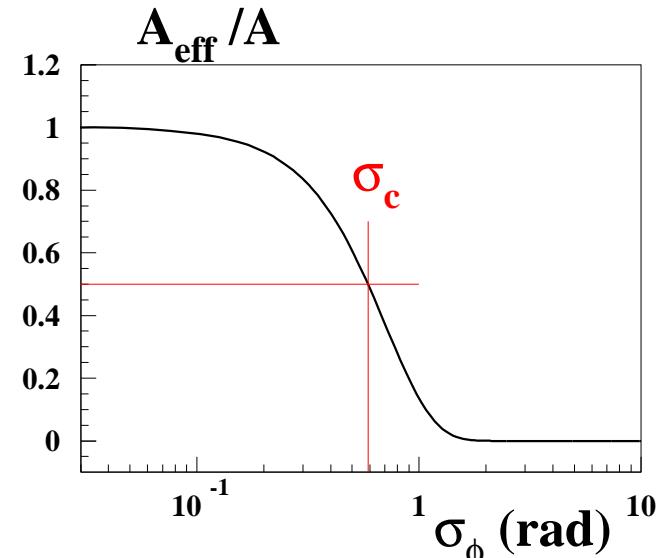
$$\Rightarrow \mathcal{A}_{\text{eff}} = \mathcal{A} e^{-2\sigma_\phi^2}, \quad D = \mathcal{A}_{\text{eff}}/\mathcal{A} = e^{-2\sigma_\phi^2}$$



- azimuthal angle RMS  $\sigma_\phi = \frac{\theta_{0,e^+} \oplus \theta_{0,e^-}}{\hat{\theta}_{+-}}$ ,

$$\bullet \theta_0 \approx \frac{13.6 \text{ MeV}/c}{\beta p} \sqrt{\frac{x}{X_0}},$$

$$\bullet \text{most probable opening angle } \hat{\theta}_{+-} = 1.6 \text{ MeV}/E$$



Olsen, Phys.Rev. 131 (1963) 406

$$\Rightarrow \sigma_\phi \approx 24 \text{ rad} \sqrt{x/X_0},$$

$$\mathcal{A}_{\text{eff}}/\mathcal{A} = 1/2 \text{ for } x \approx 10^{-3} X_0$$

(100 μm of Si, 4 μm of W)

- This dilution is energy-independent.

Conventional wisdom:  $\gamma$  polarimetry impossible with nuclear conversions  $\gamma Z \rightarrow e^+e^-$

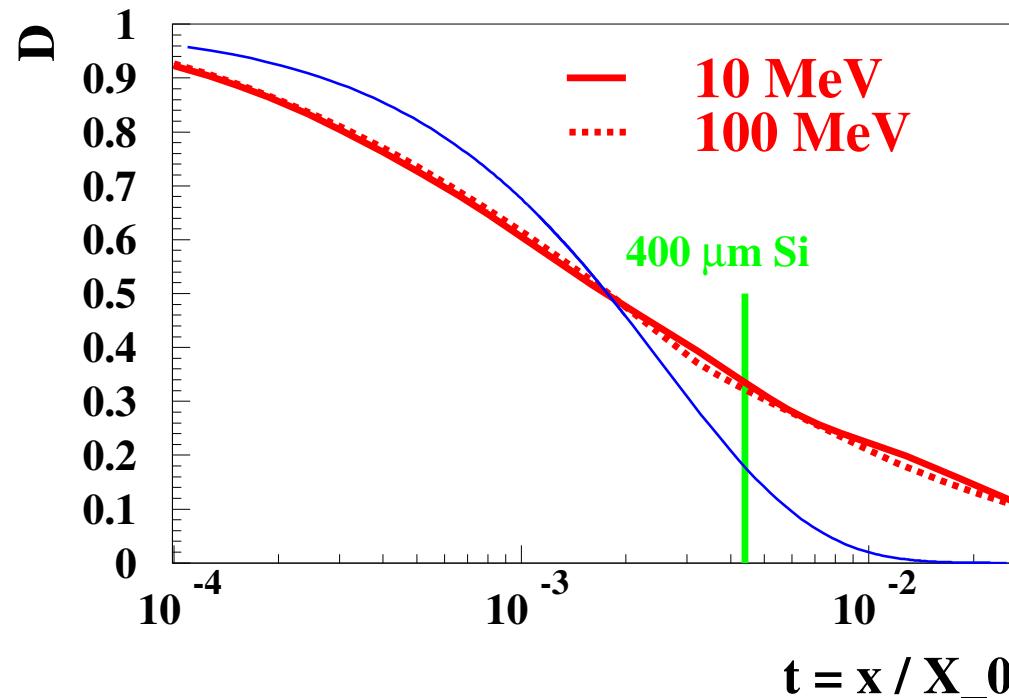
Kotov, Space Science Reviews 49 (1988) 185,

Mattox, Astrophys. J. 363 (1990) 270

## Polarimetry with pairs: dilution in the conversion wafer

- Multiple scattering in the conversion wafer only, full thickness.

Thin line is Kotov's  $E$ -independent,  $\hat{\theta}_{+-}$ -based approximation.



Full (5D) simulation of the dilution of the polarization asymmetry as a function of wafer thickness normalized to radiation length

- Updated from [Bernard, Nucl. Instrum. Meth. A 729 \(2013\) 765](#) with exact definition of event azimuthal angle  $\phi = (\phi_+ + \phi_-)/2$ , [Gros and Bernard, Astroparticle Physics 88 \(2017\) 30](#)
- Averaging on the conversion depth provides even larger results,  $D \approx 0.5$  for 400μm Si

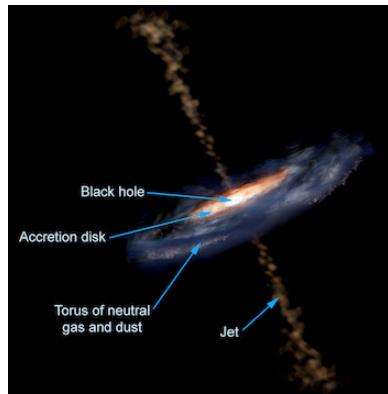
## Conclusion

- Analytical models of SSD  $\gamma$ -ray telescopes angular resolution available
  - Unmeasured nucleus recoil dominates at low energy
    - Use G4BetheHeitler5DModel in Geant4 Release  $\geq 10.5$
  - Tracking with multiple scattering dominates at high energy
    - Homogeneous-detector approximation valid there.
  - Event-dependent angular resolution from conversion depth estimate ?
  - SSD telescopes are thick active targets
    - Angular resolution independent of conversion depth
  - Optimal number of wafers for tracking,  $N_c$ , low
    - For  $N \gg N_c$ , Bremsstrahlung radiation just adds non Gaussian noise.
- Dilution of polarization asymmetry in conversion wafer much better than Kotov's approximation
  - Use G4BetheHeitler5DModel in Geant4 Release  $\geq 10.5$
  - Use correct definition of event azimuthal angle
  - Dilution found to be photon-energy independent

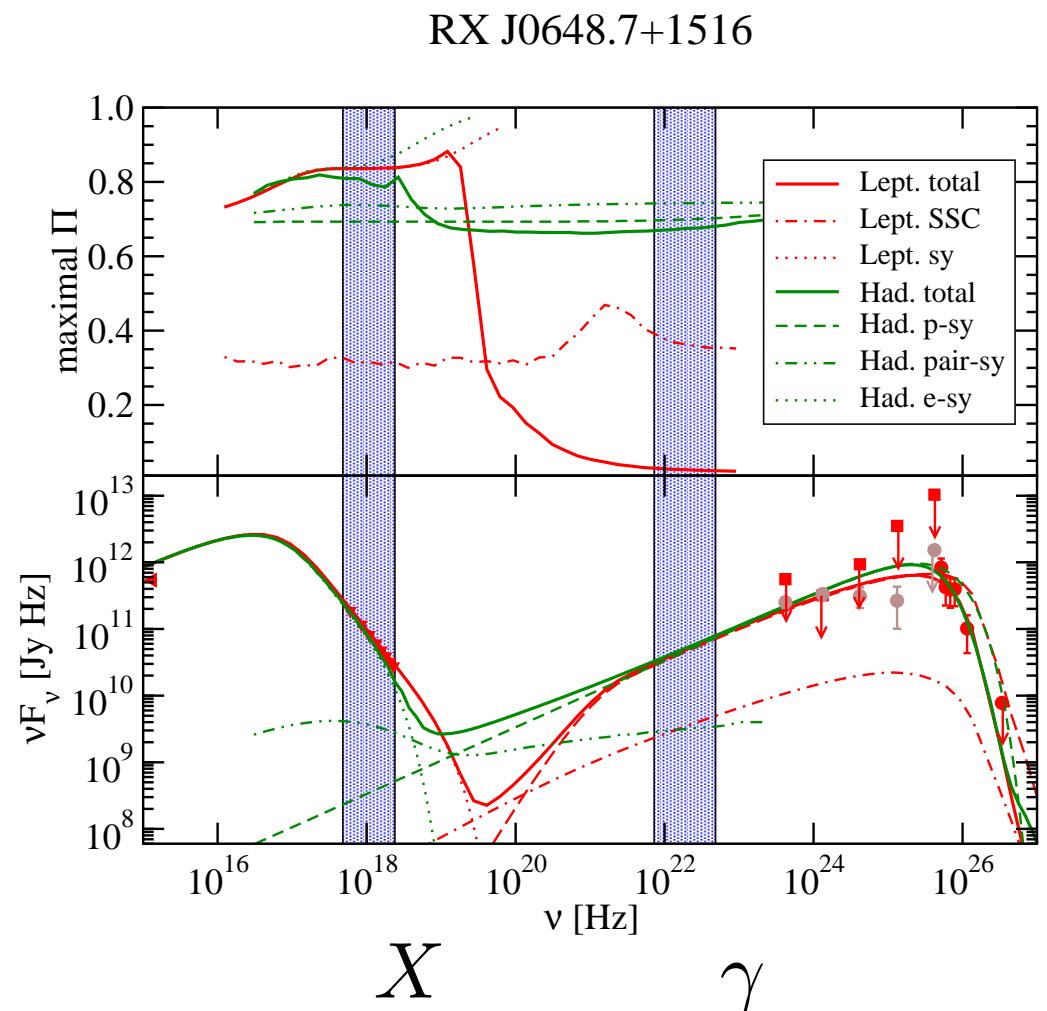
## *Back-up Slides*

# Deciphering emission mechanism in Blazars with $\gamma$ -ray polarimetry

- Blazars: active galactic nuclei (AGN) with one jet pointing (almost) to us  
**leptonic** synchrotron self-Compton (SSC)    or    **hadronic** (proton-synchrotron) ?

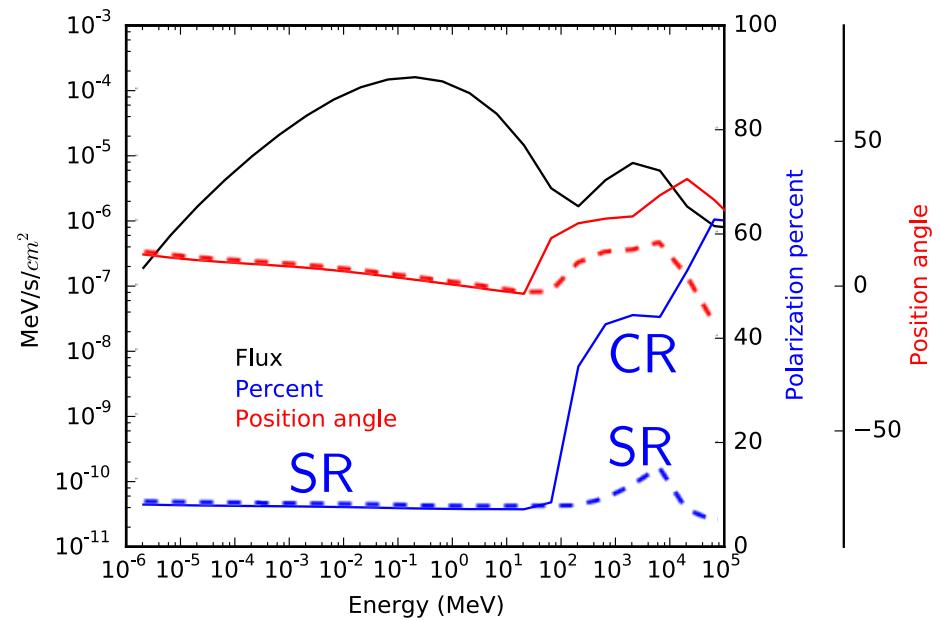
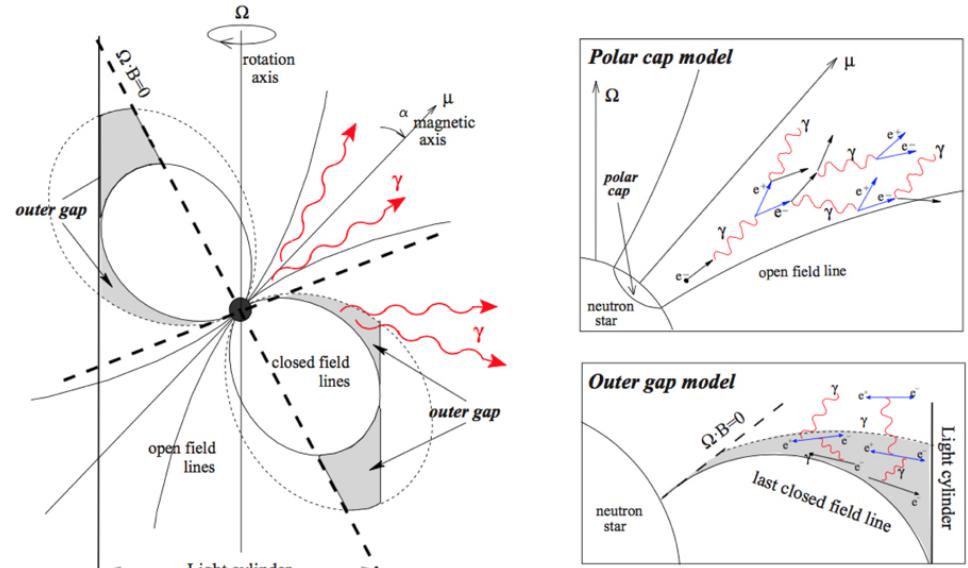


- high-frequency-peaked BL Lac
- X band: 2 -10 keV
- $\gamma$  band: 30 - 200 MeV
- SED's indistinguishable, but
  - X-ray:  $P_{\text{lept}} \approx P_{\text{hadr}}$
  - $\gamma$ -ray:  $P_{\text{lept}} \ll P_{\text{hadr}}$



Zhang and Böttcher, *Astrophys.J.* 774, 18 (2013)

# Tagging the (curvature radiation CR – synchrotron radiation SR) transition in pulsars



## Polar-cap model of Crab-like pulsar

- MeV component is SR from pairs  
GeV component is either CR (solid line) or SR (dashed line)
- “Polarization of MeV and GeV emission is a powerful, independent diagnostic, capable of constraining both the location and mechanism of the radiation” .

Harding and Kalapotharakos, *Astrophys. J.* 840 73 (2017)

# Search for Axions

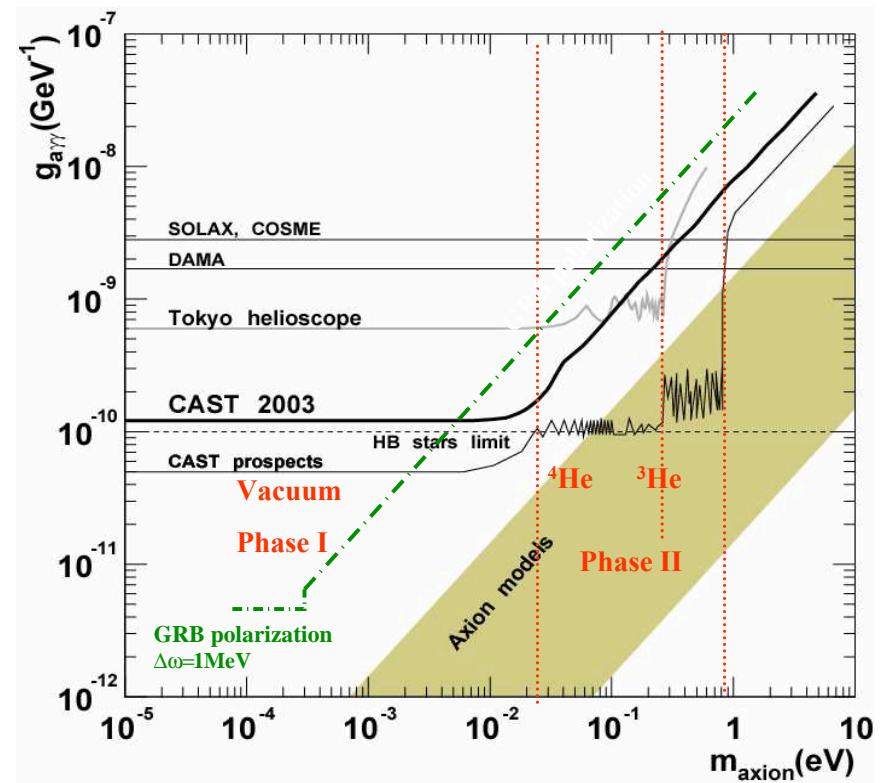
- Scalar field associated with  $U(1)$  symmetry devised to solve the strong CP problem.
- Couples to  $2 \gamma$  through triangle anomaly.
- $\gamma$  propagation through  $B \Rightarrow$  Dichroism  $\Rightarrow E$  dependant rotation of linear polarization  $\Rightarrow$  linear polarization dilution.

$$g_{a\gamma\gamma} \leq \pi \frac{m_a}{B \sqrt{\Delta\omega L_{GRB}}}$$

- Saturation over  $L = 2\pi\omega/m_a^2 > L_{GRB}$  for  $m_a \leq \sqrt{\frac{2\pi\omega}{L_{GRB}}}$

and the limit  $g_{a\gamma\gamma}$  reaches a  $\omega$ -independent constant.

Rubbia and Sakharov, Astropart. Phys. 29, 20 (2008)

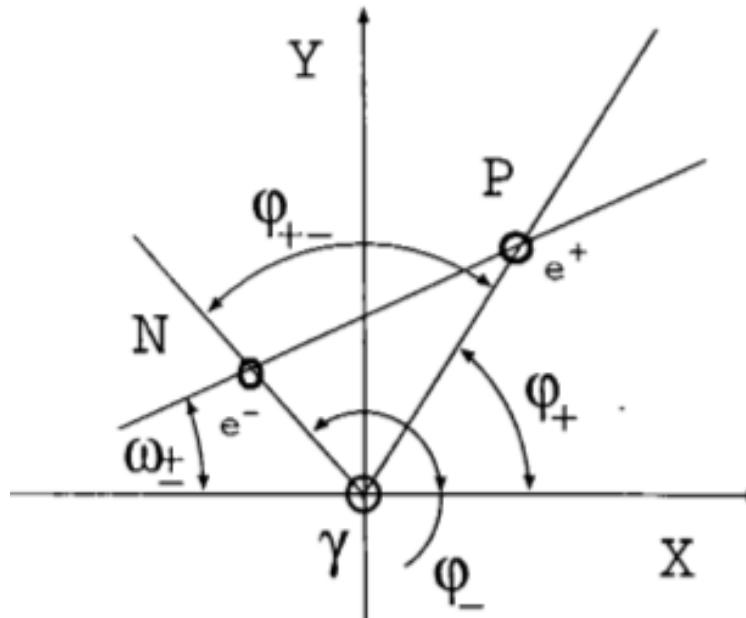


## *LIV: Search for Lorentz Invariance Violation*

- Particle (photon) dispersion relations modified in LIV effective field theories (EFT)
- Additional term to the QED Lagrangian parametrized by  $\xi/M$ ,  $M$  Planck mass.
- $\xi$  bounds:
  - time of flight from the Crab:  $\Delta t = \xi(k_2 - k_1)D/M$ ,  $\xi \leq \mathcal{O}(100)$ .
  - birefringence  $\Delta\theta = \xi(k_2^2 - k_1^2)D/2M$   
LIV induced birefringence would blurr the linear polarization of GRB emission.  
 $\xi \leq 3.4 \times 10^{-16}$  with IBIS on Integral (250 – 800 keV)  
Götz *et al.*, MNRAS 431 (2013) 3550
- Bound  $\propto 1/k^2$  !

# Polarimetry: Defining the Azimuthal Angle ?

- $\omega$ , most often used in publications since 2000's

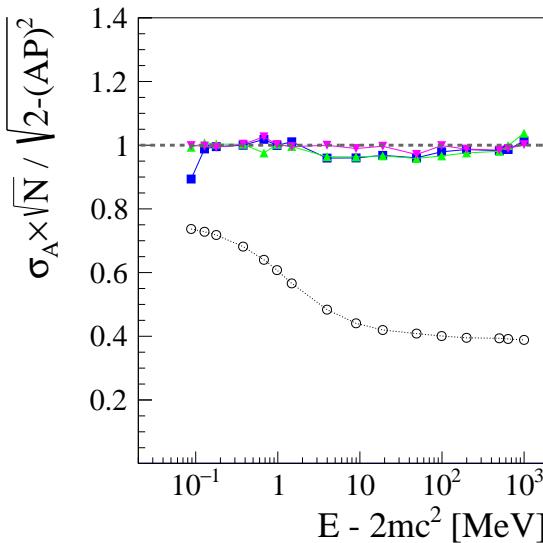
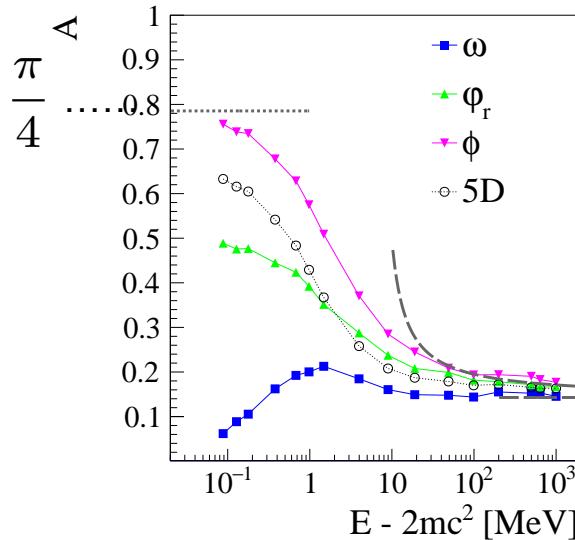


"Pair-Polarimeter for High Energy Protons", B. Wojtsekhowski (2000), pdf

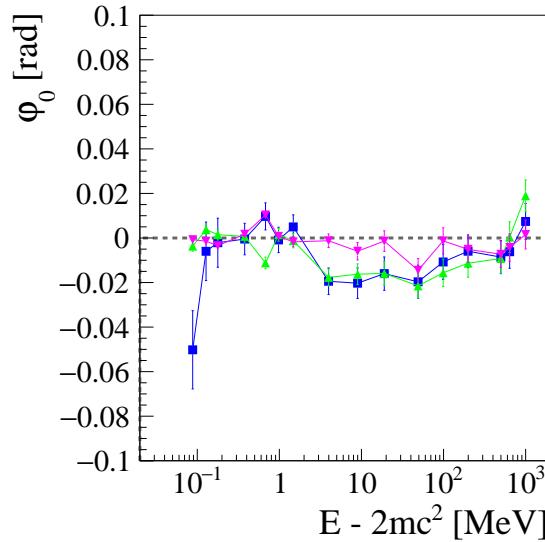
- $\varphi_r$  recoil angle,  $\varphi_r = \varphi_{\text{pair}} \pm \pi$
- $\phi = (\varphi_+ + \varphi_-)/2$ , bisector of  $e^+$  and  $e^-$  direction

# Polarimetry: Defining the Azimuthal Angle ? Bisector Optimal !

polarization asymmetry

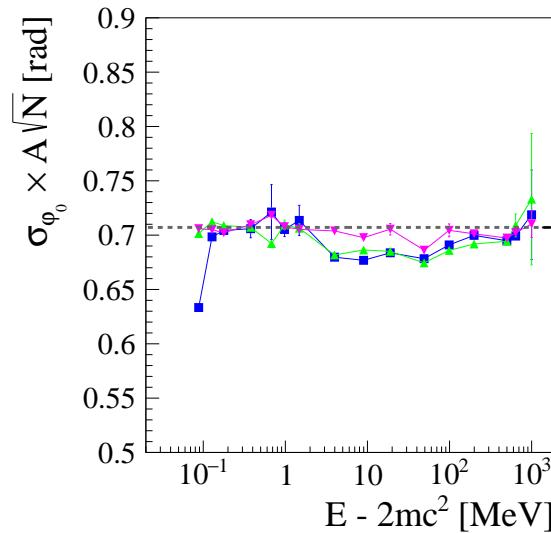


polarization angle



$\omega$

- $\omega$
- $\phi_r$  recoil angle,  $\phi_r = \phi_{\text{pair}} \pm \pi$
- $\phi = (\phi_+ + \phi_-)/2$ , bisector of  $e^+$  and  $e^-$  direction



$E$ (MeV)	loss factor wrt $\phi$	
	$\omega$	$\phi_r$ or $\phi_{\text{pair}}$
10	0.56	0.67
100	0.74	0.94

Gros & Bernard,  
Astropart. Phys. 88 (2017) 30

We checked that on a  $P = 0$  MC sample, the measured value is found to be  $\mathcal{A} \times P \approx 0$

# Segmented active targets: Optimal tracking with multiple scattering (à la Kalman)

$l$	cm	longitudinal sampling (layer spacing).
$\sigma$	cm	single track, single layer spatial precision
$p$	MeV/c	track momentum
$p_0$	13.6	MeV/c
$\Delta x$	cm	scatterer (wafer or converter) thickness
$X_0$	cm	scatterer radiation length
$\imath \equiv$	$\frac{1}{l\sigma^2}$	cm $^{-3}$
$s \equiv$	$\left(\frac{p_0}{p}\right)^2 \frac{1}{X_0} \frac{\Delta x}{l}$	average multiple-scattering angle variance per unit track length
$\lambda \equiv$	$\frac{1}{\sqrt[4]{\imath s}}$	detector scattering length at momentum $p$
$x \equiv$	$\frac{l}{\lambda}$	detector longitudinal sampling normalized to $\lambda$
$u \equiv$	$\frac{L}{\lambda}$	detector thickness normalized to $\lambda$

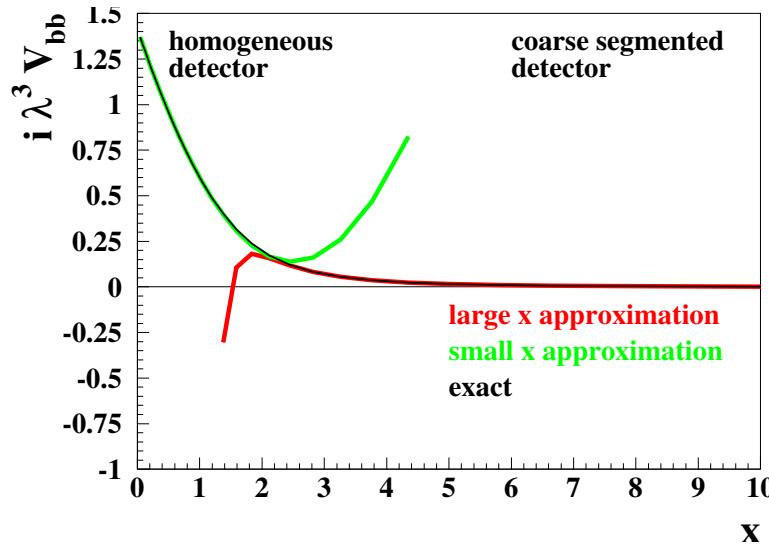
- small  $x$  (large  $p$ ), homogeneous detector (continuous equation),
- large  $x$  (small  $p$ ), segmented detector (discrete equation)

and

- small  $u$  (large  $p$ ), thin detector,
- large  $u$  (small  $p$ ), thick detector.

Frosini & Bernard, Nucl. Instrum. Meth. A 867 (2017) 182

# Variance of angle measurement for segmented active targets



Variance of angle measurement normalized to  $1/(\imath\lambda^3)$ , as a function of

$x$ , detector longitudinal sampling normalized to the detector scattering length at momentum  $p$

$j$  imaginary unit

exact expression

$$\frac{2 l s \left( \sqrt{-x^2(x^2-4j)} + \sqrt{-x^2(x^2+4j)} \right)}{\left( jx^2 + \sqrt{-x^2(x^2-4j)} \right) \left( -jx^2 + \sqrt{-x^2(x^2+4j)} \right)}$$

misprint correction

(20)

coarse detector (large  $x$ )

$$V_{bb} = \frac{1}{\imath l^3} \left[ 2 - \frac{10}{x^4} + O\left(\frac{1}{x^8}\right) \right]$$

1/x → 0:  $V_{bb} = 2 \left(\frac{\sigma}{l}\right)^2$  (25)

homogeneous detector (small  $x$ )

$$V_{bb} = \frac{\sqrt{2}}{\imath \lambda^3} \left[ 1 - \frac{x}{\sqrt{2}} + \frac{1}{8}x^2 + \frac{x^3}{128} - \frac{1}{1024}x^4 + O[x^5] \right].$$

(22)

Frosini & Bernard, Nucl. Instrum. Meth. A 867 (2017) 182

## Polarimetry: Optimal Measurement with Moments

- Remember, fit of  $\frac{d\Gamma}{d\phi} \propto (1 + \mathcal{A}P \cos [2(\phi)])$  yields  $\sigma_P \approx \frac{1}{\mathcal{A}} \sqrt{\frac{2}{N}}$ ,
- Optimal measurement;  $\Omega$ 
  - let's define  $p(\Omega)$  the pdf of set of (here 5) variables  $\Omega$
  - search for weight  $w(\Omega)$ ,  $E(w)$  function of  $P$ , and variance  $\sigma_P^2$  minimal;
  - a solution is  $w_{\text{opt}} = \frac{\partial \ln p(\Omega)}{\partial P}$  e.g.: Tkachov, Part. Nucl. Lett. 111 (2002) 28
  - polarimetry:  $p(\Omega) \equiv f(\Omega) + P \times g(\Omega)$ ,  $w_{\text{opt}} = \frac{g(\Omega)}{f(\Omega) + P \times g(\Omega)}$ .
    - If  $\mathcal{A} \ll 1$ ,  $w_0 \equiv 2 \frac{g(\Omega)}{f(\Omega)}$ , and
    - for the 1D “projection”  $p(\Omega) = (1 + \mathcal{A}P \cos [2(\phi)])$ :
$$w_1 = 2 \cos 2\phi, \quad E(w_1) = \mathcal{A}P, \quad \sigma_P = \frac{1}{\mathcal{A}\sqrt{N}} \sqrt{2 - (\mathcal{A}P)^2},$$

Bernard, Nucl. Instrum. Meth. A 729 (2013) 765

# *Polarimetry: Optimal Measurement with Moments*

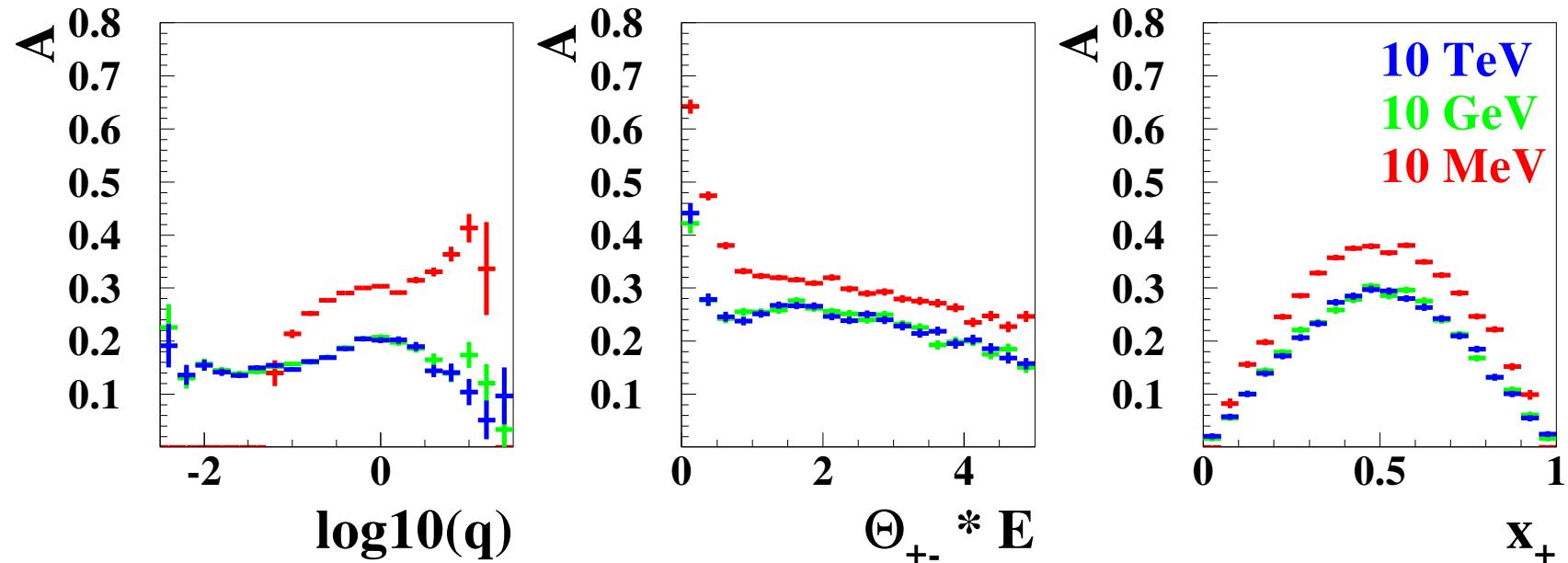
## *Unknown polarization angle*

$$A = 2\sqrt{\langle \cos 2\varphi \rangle^2 + \langle \sin 2\varphi \rangle^2}, \quad (1)$$

$$\varphi_0 = \frac{1}{2} \arctan \left( \frac{\langle \sin 2\varphi \rangle}{\langle \cos 2\varphi \rangle} \right), \quad (2)$$

Gros & Bernard, Astropart. Phys. 88 (2017) 30

# Polarimetry: Variation of polarization asymmetry with event kinetic variables



Variation of polarization asymmetry with:

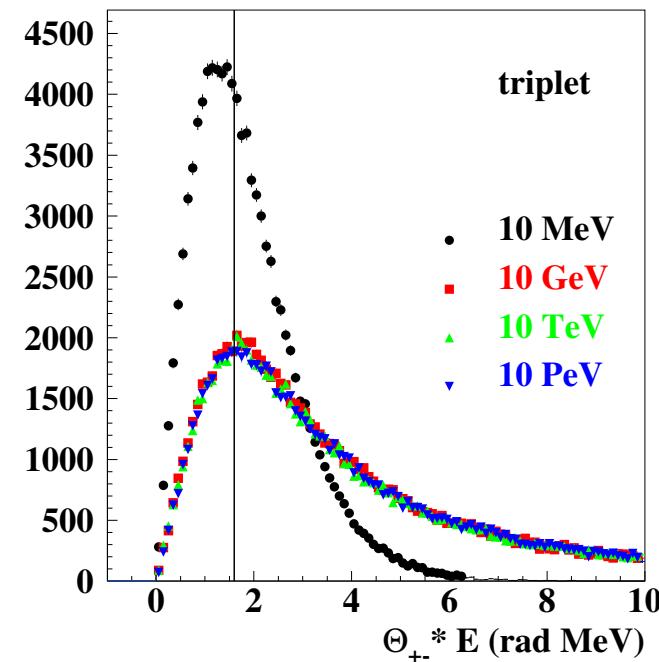
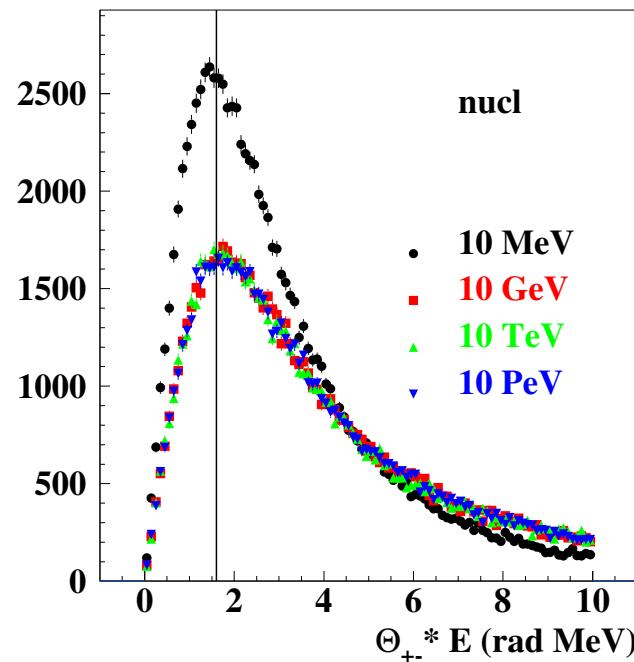
- $\log_{10}$ (recoil momentum)
- pair opening angle (normalized to inverse of incident photon energy)
- fraction of energy carried away by the positron

Contrary to (experimentalist) hope, the polarization asymmetry is larger at lower opening angle.

Updated from [Bernard, Nucl. Instrum. Meth. A 729 \(2013\) 765](#) with exact expression of event azimuthal angle

$$\phi = (\phi_+ + \phi_-)/2, \text{ Gros and Bernard, Astroparticle Physics 88 (2017) 30}$$

## Pair opening angle distribution



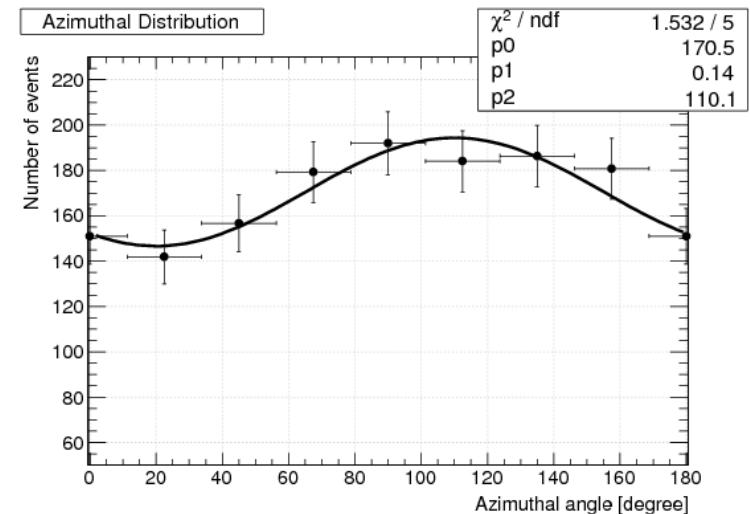
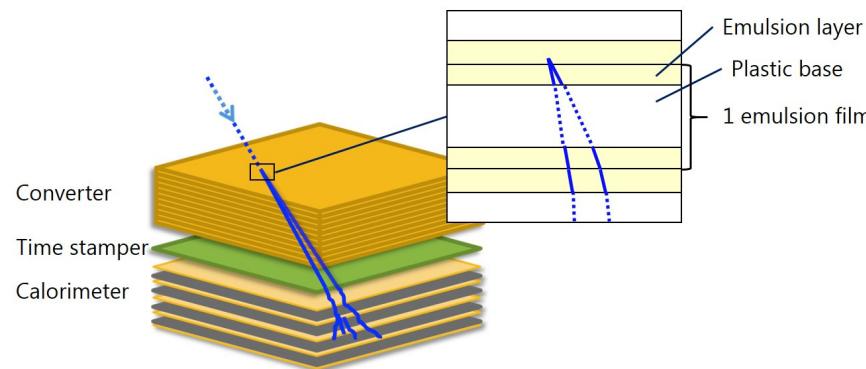
- Distributions of the product of the pair opening angle and of the photon energy,  $\theta_{+-} \times E$ .
- Left: nuclear conversion. Right: triplet conversion.
- The vertical value shows the most probable value of 1.6 rad MeV, high-energy approximation, [Olsen, Phys.Rev. 131 \(1963\) 406](#)

Bernard, Nucl. Instrum. Meth. A 899 (2018) 85

# Emulsions: GRAINE project

## (Gamma-Ray Astro-Imager with Nuclear Emulsion)

- Kôbe University - Nagoya University Collaboration



- 2.4 GeV SPring-8/LEPS gamma-ray beam
- Emulsion thickness 200 – 300 $\mu\text{m}$ , bromide crystal size 200 nm; single grain position accuracy 60 nm;
- $\mathcal{A}_{\text{eff}} \times P = 0.14^{+0.07}_{-0.06}$  measured
- beam  $P = 0.66$  estimated
- $\mathcal{A}_{\text{eff}} = 0.21^{+0.11}_{-0.09}$  calculated, a  $3.06\sigma$  non-zero polarization observation

Takahashi *et al.*, PTEP 2015 (2015) 043H01

Ozaki *et al.*, Nucl. Instrum. Meth. A 833 (2016)165

# *GRAINE balloon test flight*

- Goal: see the Vela pulsar gamma-ray emission
- JAXA balloon flight on 26 April 2018, altitude 38 km
- 7 hours of data taken within the Vela pulsar window

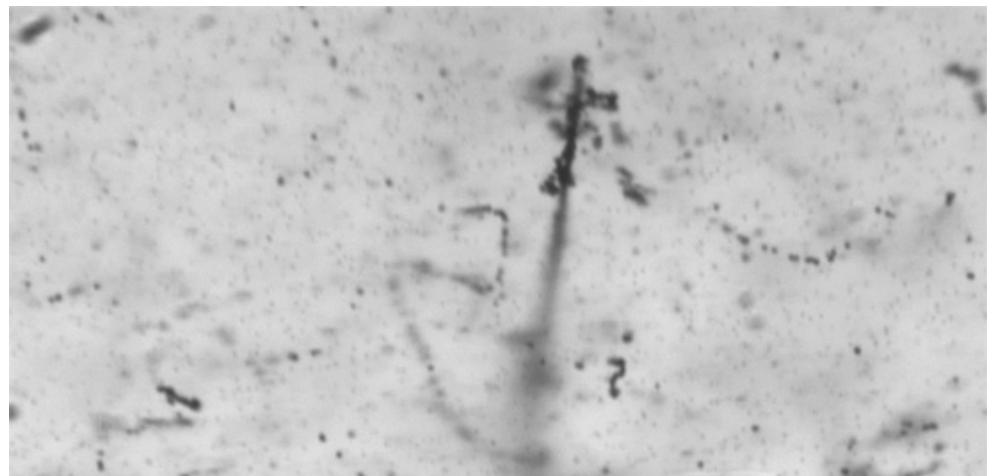
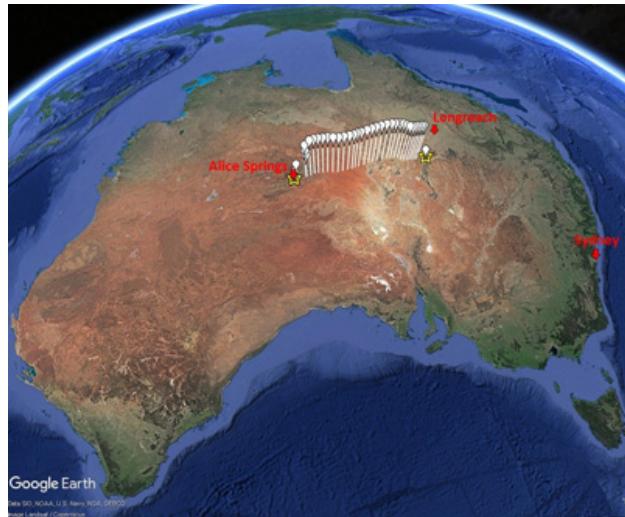


image width  $\approx 100 \mu\text{m}$

- Stay tuned ..

“Balloon-borne telescope looks for cosmic gamma rays”, [kobe-u.ac.jp](http://kobe-u.ac.jp/), August 8, 2018