Polarimetry of high-energy photons (X, gamma) for astrophysics

With a special focus on gaseous detectors

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Special Workshop on Photon Detection with MPGDs
RD51 Academia-Industry Matching Event
CERN 10 – 11 June 2015

Talk Lay out

- Polarisation: what is it ?

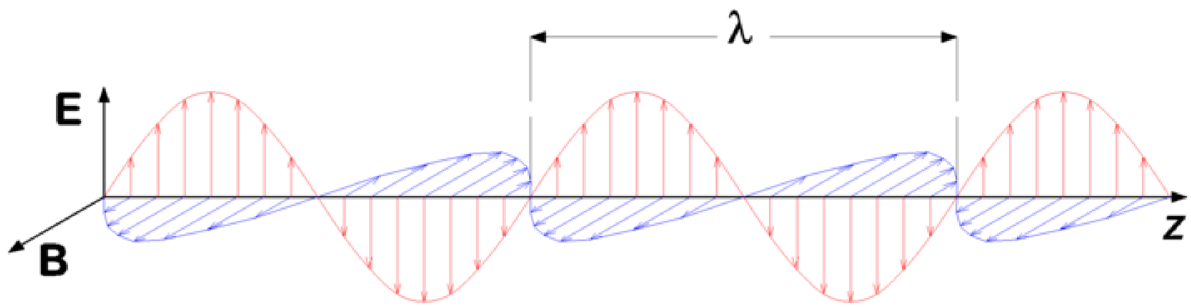
- Polarimetry: what is it useful for (in astrophysics) ?

- Polarisation: how measure it ?

Electromagnetic waves

- wave vector $\vec{k}$ along propagation axis $\vec{z}$, electric field $\vec{E}$, magnetic field $\vec{B}$.

  orthogonal 2 by 2: $\vec{E} \perp \vec{k}$, $\vec{B} \perp \vec{k}$, $\vec{E} \perp \vec{B}$.



Source: Wikipedia

- polarisation describes the orientation of the (say) electric field, and its evolution upon propagation; above plot: “linear” polarization.

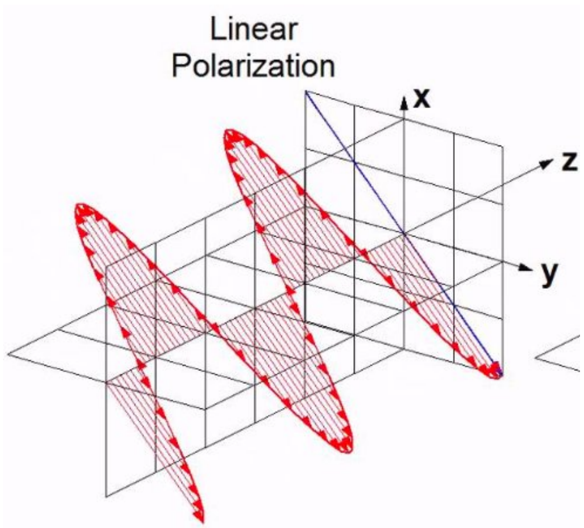
- in a photon beam: description of orientation statistics. P polarisation “fraction”.

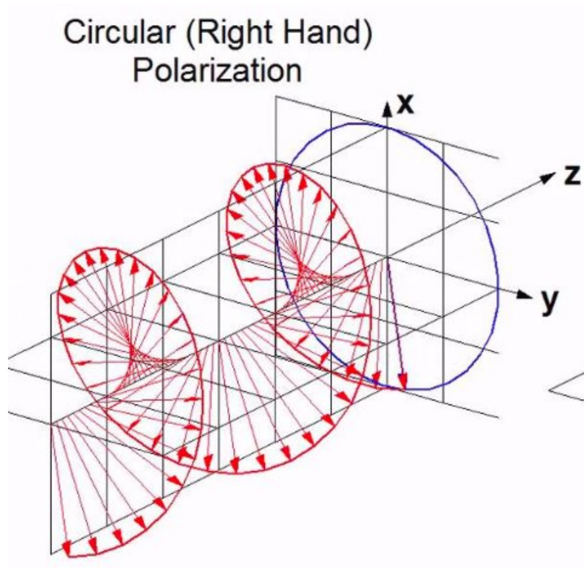
- $P = 0$: “random” polarisation: $\vec{E}$ isotropic (but still $\vec{E} \perp \vec{z}$!) orientation of a given photon.

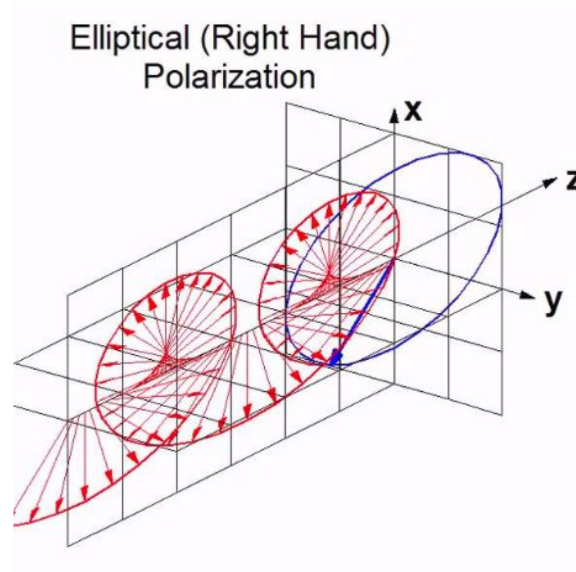
Linear / Circular Polarisation

Red: Electric field $\vec{E}$

Source: Wikipedia







$\vec{E}$ direction:	constant	rotates with EM wave ω	
$\lvert\vec{E}\rvert$	sinusoidal	constant	elliptic

Polarimetry in astrophysics

- Radiation in the Universe non-polarized to first order (accretion disks, stars, cosmic microwave background (CMB) ..
- Synchrotron radiation linearly polarized up to $P = 0.8$
  - provides $\vec{B}$ direction, possibly $\vec{B}$ mapping $\Rightarrow \vec{B}$ turbulence
  - if isotropic electrons with power law energy distribution, index Γ:
    - $P = \dfrac{\Gamma + 1}{\Gamma + 7/3}$, $P = 0.60$ for $\Gamma = 1$, (optically thin plasma)
    - $P = \dfrac{1}{2\Gamma + 13/3}$, $P = 0.16$ for $\Gamma = 1$, (optically thick plasma)
- Zeeman effect ($\vec{B}$ // line of sight) circular polarization
  - molecules with net magnetic moment (HI, OH, CN, H_2O ...)
- Faraday rotation due to birefringence of magnetised plasma for circularly polarised radiation.
- Tiny cosmic microwave background (CMB) polarization: dust, lensing, primordial signal (from inflation era) ? (Planck, BICEP2, *et al.*

Magnetic Field in M51

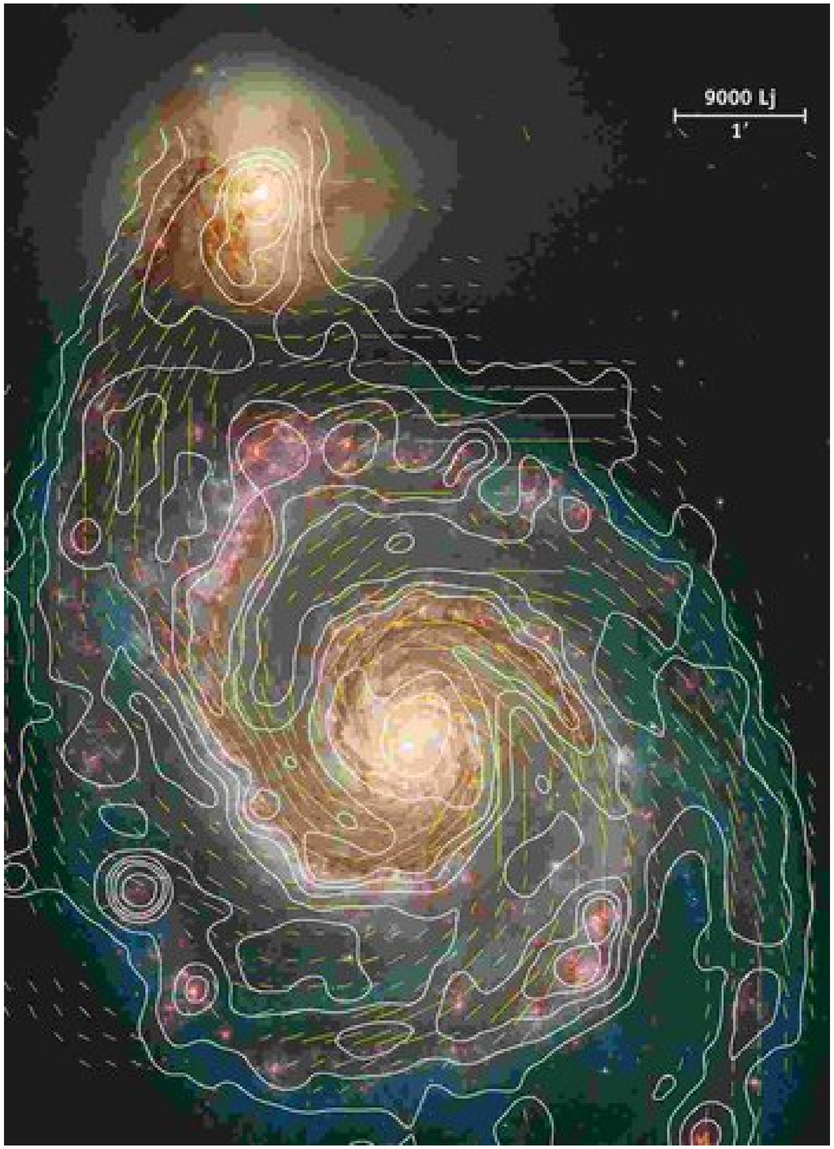
- Optical image of the spiral galaxy M51 obtained with the Hubble Space Telescope (from Hubble Heritage), overlaid by contours of the total radio intensity and polarization vectors at 6cm wavelength, combined from radio observations with the Effelsberg and VLA radio telescopes

- Synchrotron radiation emitted by relativistic e^- that spiral around interstellar magnetic field lines

  $P \leq 0.40$

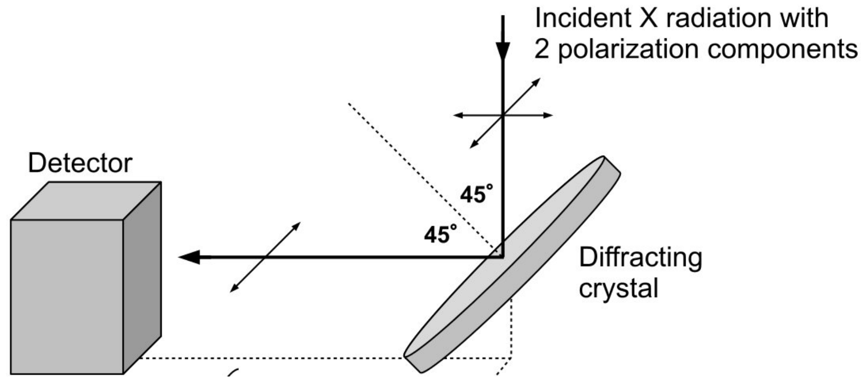
  $B \approx 15\mu\text{G}$

  Fletcher *et al.* MNRAS 412, 2396 (2011)



3 Detection Schemes

energy range	Radio waves	Optical (IR - vis - UV)	soft X	X-gamma
observable	Electric Field E	light intensity $I \propto E^2$		single photon reconstruction
measure P	$\frac{\langle E_x^2 \rangle - \langle E_y^2 \rangle}{\langle E_x^2 \rangle + \langle E_y^2 \rangle}$	$\frac{I_{0^\circ} - I_{90^\circ}}{I_{0^\circ} + I_{90^\circ}}$		azimutal angle fit
tool	x, y antennas	polarizer	Bragg crystal	This talk
		+ photon detector		

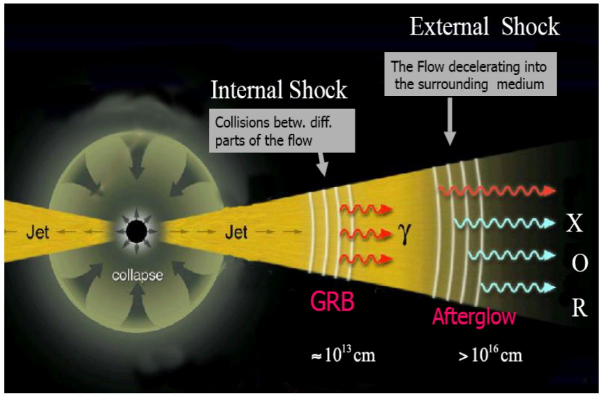


Bragg diffraction polarimetry
Trippe, JKAS 47 (2014) 15.

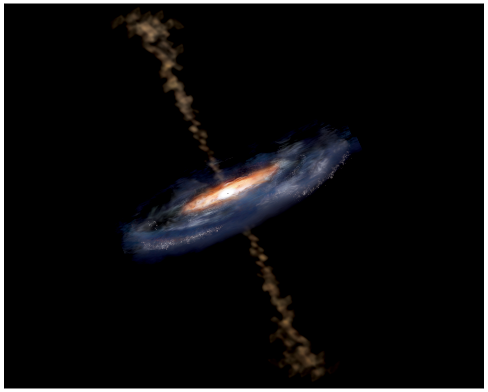
One X-gamma significant cosmic source polarisation measurement OSO-8 (2.6 – 5.2 keV, Bragg, 1975): Crab nebula $P = 19 \pm 1\%$

High-energy specific science case : one example only: Understanding cosmic objects "with jets"

	GRB gamma ray burst	AGN Active galactic nuclei	
core size (cm)	10^6	$10^{11} - 10^{14}$	(Schwarzschild Radius)
core B (G)	10^{14}	$10^4 - 10^5$	
jet size (cm)	10^{14}	$10^{20} - 10^{23}$	
jet B (G)	10^6	10^{-4}	
mass ($M_\odot$)	10	$10^6 - 10^9$	
jet Lorentz γ	100 - 1000	20	



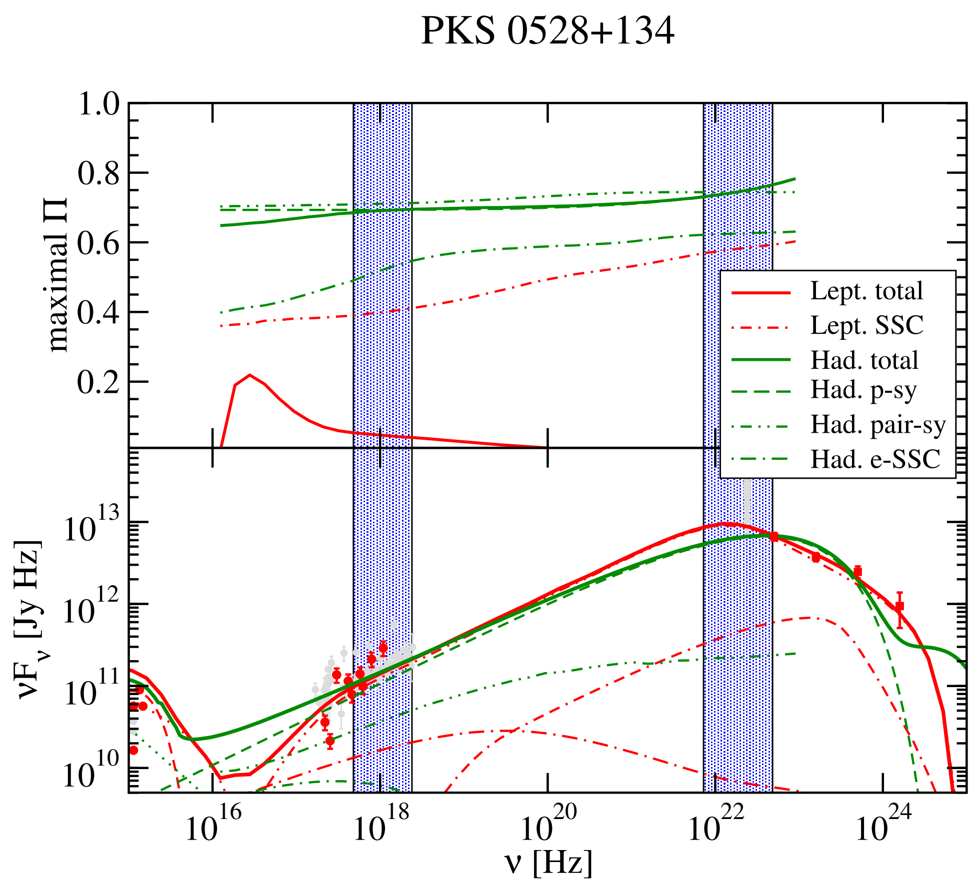
Brightest objects in Universe



Brightest permanent objects in Universe

One example: AGN: decipher leptonic synchrotron self-Compton (SSC) against hadronic (proton-synchrotron) models

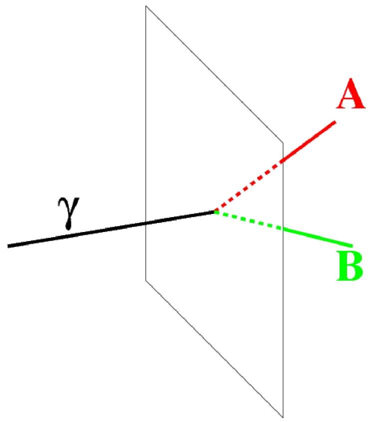
- Blazars: AGN with jet pointing (almost) to us.
- PKS 0528+134 is a flat-spectrum radio quasar [FSRQs]
- SSC is γ "up-shift" by inverse Compton scattering on same (e^- or p^+) beam that synchrotron-produced them.
  - X band: 2 -10 keV
  - γ band: 30 - 200 MeV

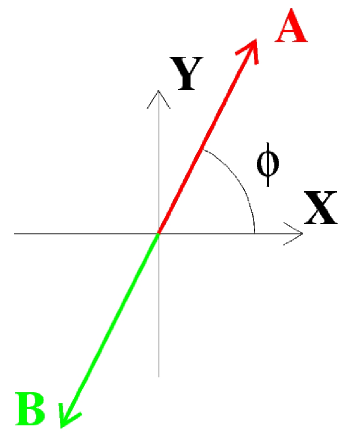


Zhang and Boettcher, A.P. J. 774, 18 (2013)

Polarimetry of high-energy photons (X, gamma)

- 1 photon converts by interaction with detector atom.



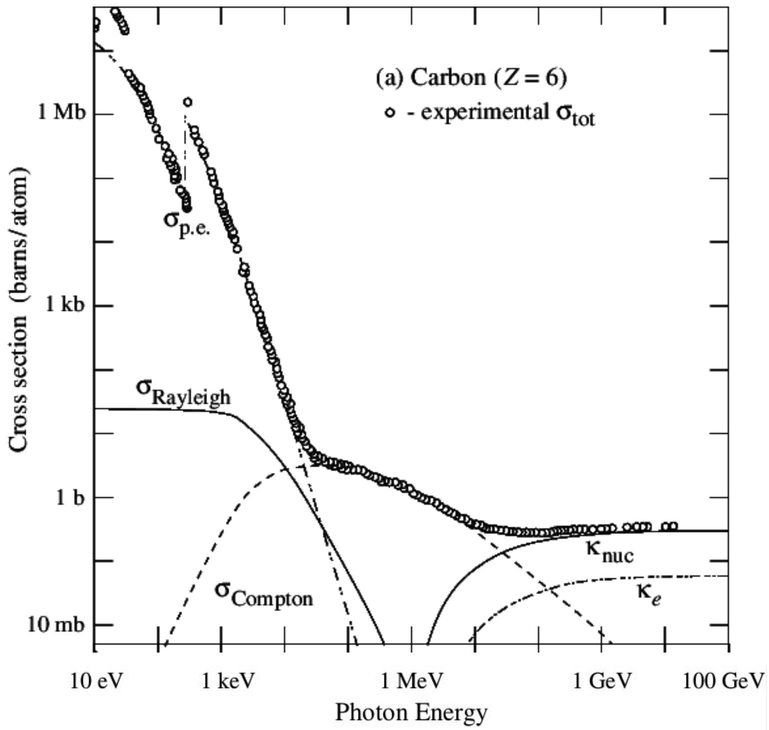


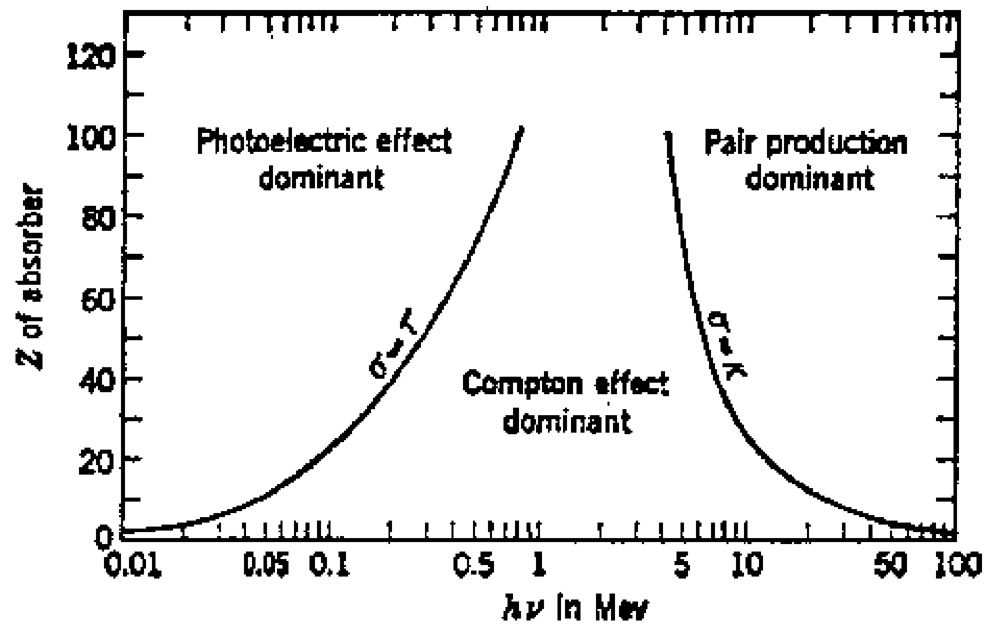
- "Azimutal" angle ϕ recorded

- differential cross-section $\frac{\mathrm{d}\Gamma}{\mathrm{d}\phi} \propto (1 + \mathcal{A}P\cos[2(\phi - \phi_0)])$,
  - $\mathcal{A}$ Polarization asymmetry
  - P: source linear polarisation fraction

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

Conversion of high-energy photons (X, gamma)

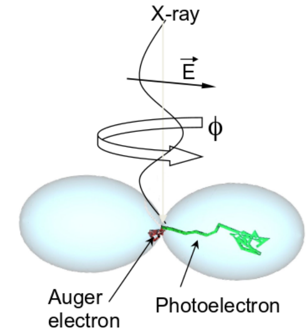




Source: NIST / PDG

Photoelectric effect	Compton scattering	Pair conversion
$\gamma A \to e^- A^+$	$\gamma e^- \to \gamma e^-$	$\gamma Z^+ \to e^+ e^- Z^+$ $\gamma e^- \to e^+ e^- e^-$
No polarimeter ever flown to space	IBIS (100 keV - 1 MeV) Crab nebula $P = 46 \pm 10\%$	No polarimeter ever flown to space

X-ray polarimetry: photo-electric effect: $\gamma A \rightarrow e^- A^+$

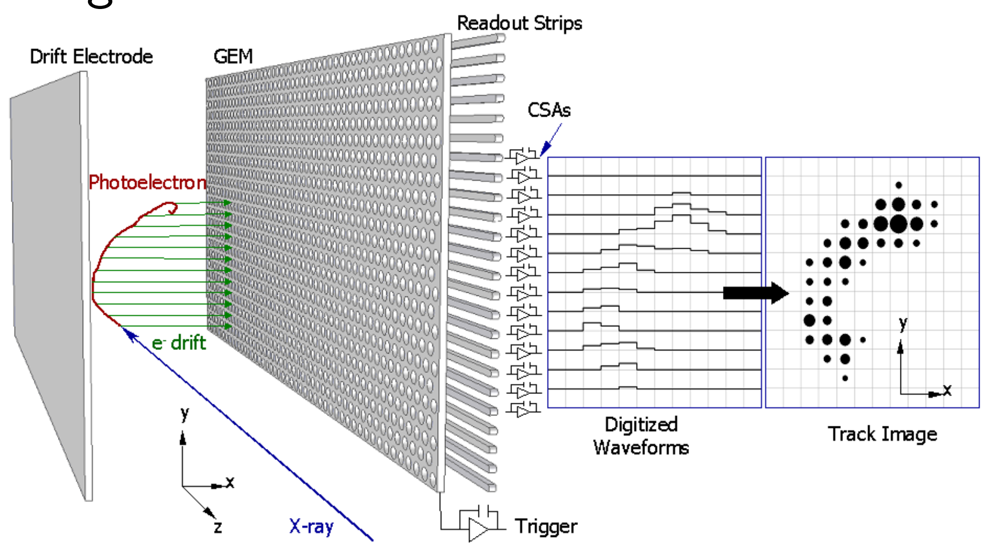


- polarization asymmetry $\mathcal{A} = 1$ maximal !

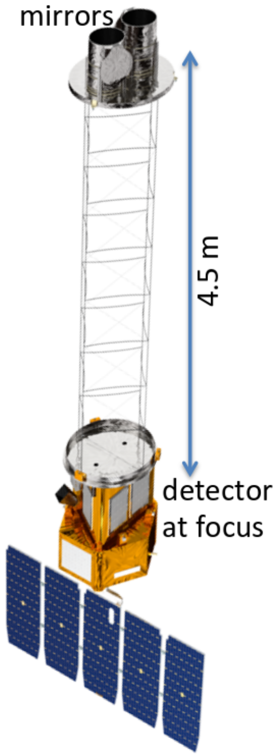
$$\frac{d\sigma}{d\Omega} \propto \cos^2\phi \propto (1 + \cos 2\phi) \quad \Rightarrow \quad \mathcal{A} = 1$$

- here ϕ electron azimutal angle.
- astronomy (photon $\leftrightarrow$ source assignment): collimation / masking / focussing
- low density (gas) needed and fine tracking needed: 10 keV e^- CSDA range in 1 bar argon is 0.2 cm.
- example of reading scheme "side" TPC:

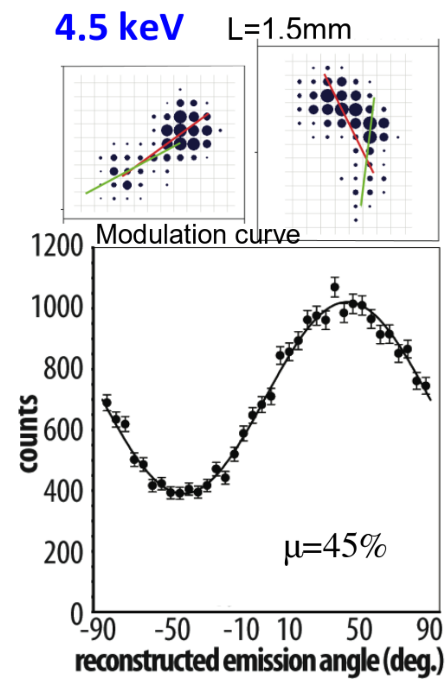
Black 2007 J. Phys.: Conf. Ser. 65 012005



X-ray Polarimetry: Photo-electric Effect: The Gravity and Extreme Magnetism Explorer (GEMS) project



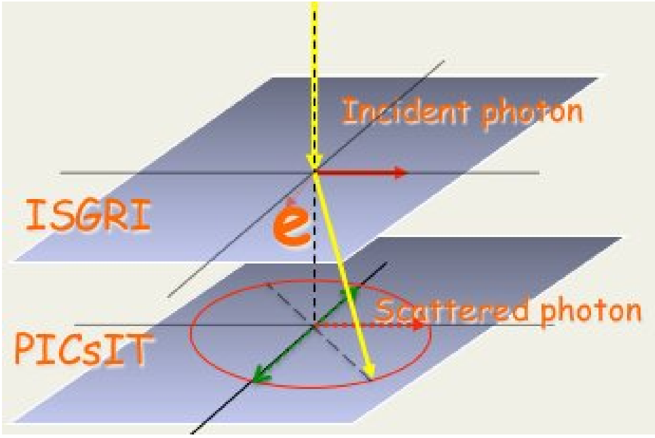
- Selected by NASA in 2009 for launch in 2014 but cancelled (funding issues)
- energy band 2 - 10 keV
- 190 Torr pure DME (250 mbar C_2H_6O)
- 128 strips, pitch $120\mu m$, width $60\mu m$, length 7.8 cm, sampling 20 MHz.
- Liquid Crystal Polymer LPC-GEM amplification pitch $140\mu m$, ϕ $70\mu m$, thickness $100\mu m$



Tamagawa MPGD2013 Zaragoza

Hard-X-ray / soft-γ-ray Polarimetry: Compton scattering

- Compton scattering event reconstruction based on multiscatters
- Need dense detector (200 keV γ Compton attenuation in Si is only $0.12\mathrm{cm}^2/\mathrm{g}$
- Simple polarimeters have been flown to space, e.g. IBIS onboard INTEGRAL
  - Imager 15 keV – 10 MeV, ESA, Launched 2002
  - Collection area $A \approx 3000\mathrm{cm}^2$
  - 2 layer detector, at distance 10 cm
    - 2 mm thick CdTe (ISGRI)
    - 30 mm thick CsI (PICsIT)
  - Coded mask located 3.2 m above detector
  - Polarimeter
    Crab nebula $P = 46 \pm 10\%$, 200 – 800 keV



Compton Scattering Polarimetry: Projects

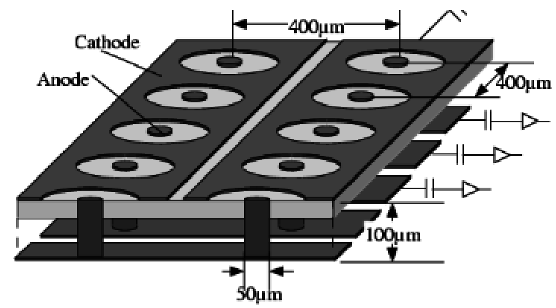
- Several projects, past, passed or under development

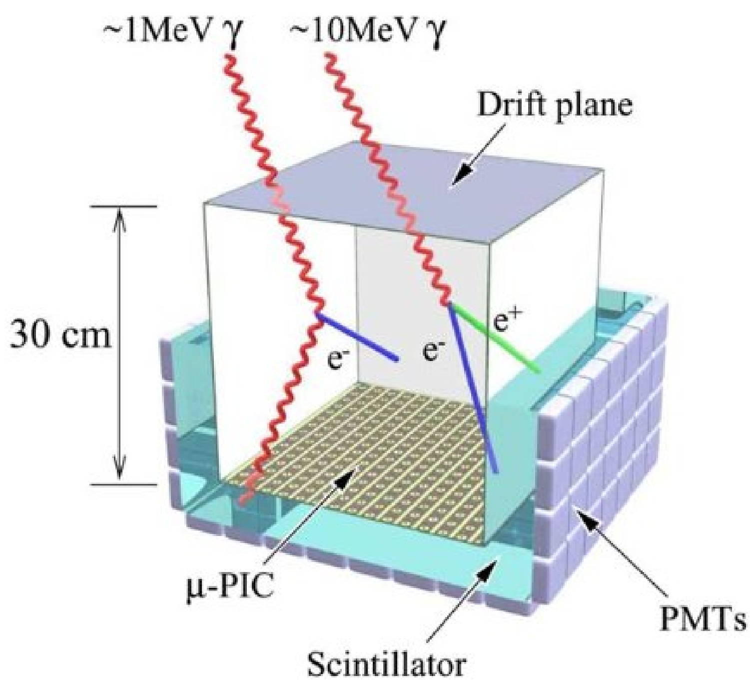
	GRIPS	ASTROGAM	GRAPE	X-Calibur
tracker / converter	Si stack	Si stack	1 scintillator	1 scintillator
calorimeter	$LaBr_3$	Tl:CsI	high-Z crystal scintillator	CZT
Astronomy E range	200 keV – 50 MeV	300 keV – 100 MeV	10 – 70 keV	
Polarimetry E range	200 – 1000 keV	200 keV – 2 MeV	50 – 300 keV	10 – 70 keV

- No claim to exhaustivity !

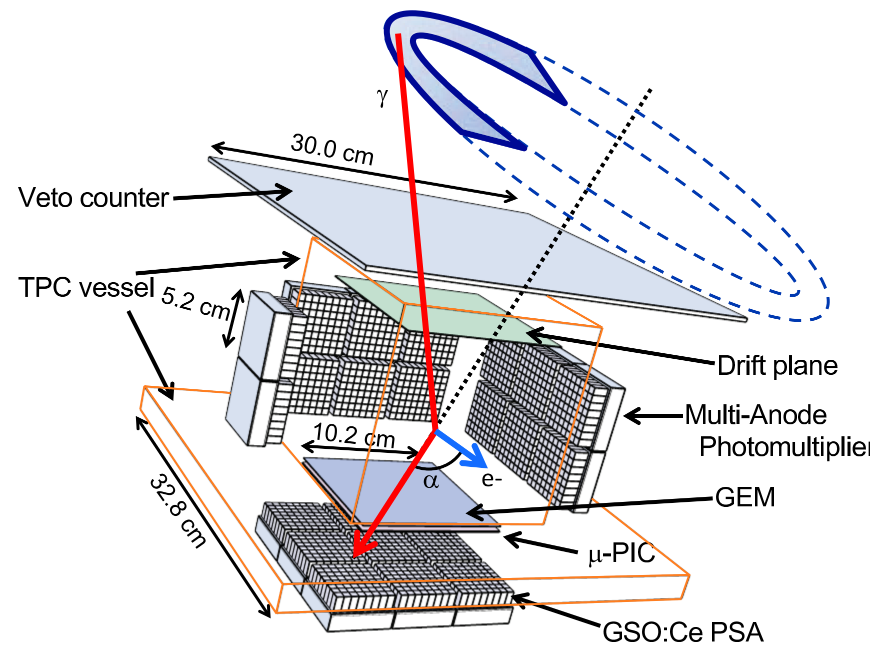
TPC for a better Compton telescope (and polarimeter): The electron-tracking Compton camera (ETCC)

- Tracking (measure of direction) of the 1rst electron determines the kinematics in a 2-blob event.
- Development by Kyôto group





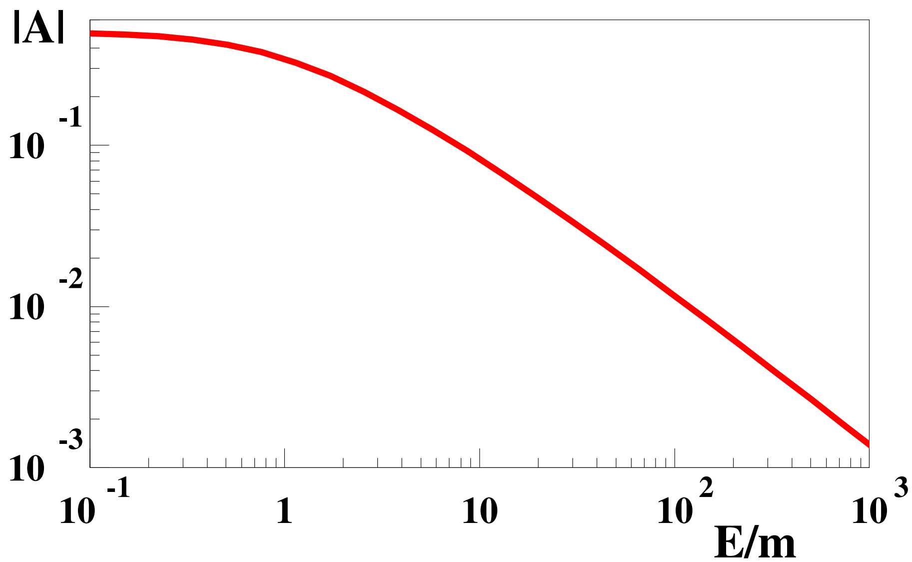
Tanimori, New Astronomy Reviews 48 (2004) 263



Takada, Ap.J. 733 (2011) 13

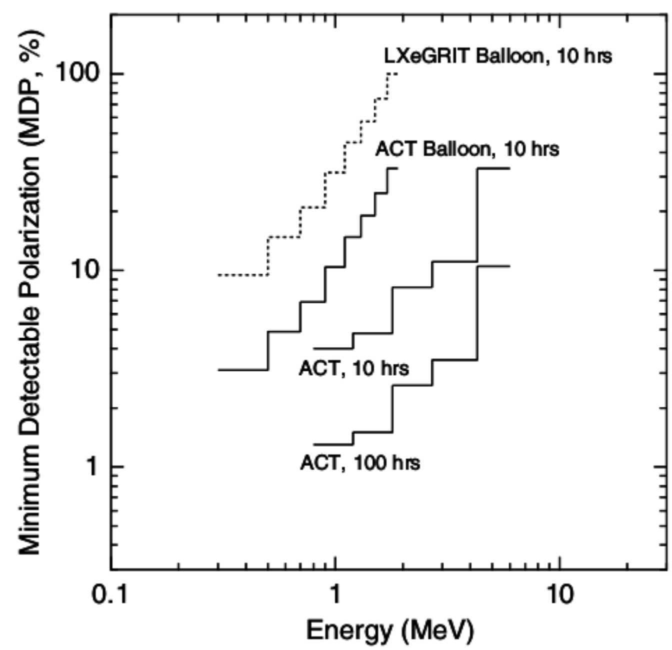
γ-ray Polarimetry: why Compton scattering is having hard time at high energy

- Not only the Compton cross section is decreasing above 0.1 MeV,
- and cosmic sources fluxes are decreasing with E ...
- but the polarization asymmetry is decreasing too, $\mathcal{A} \propto 2m/E$, asymptotically:



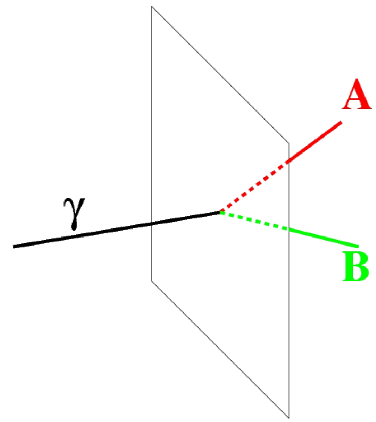
Bernard, SPIE (2014) 91441M

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

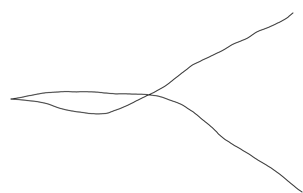


McConnell & Ryan, New Astronomy Reviews 48 (2004) 215

γ-ray Polarimetry: using pair creation, $\gamma Z^+ \rightarrow e^+e^-Z^+$



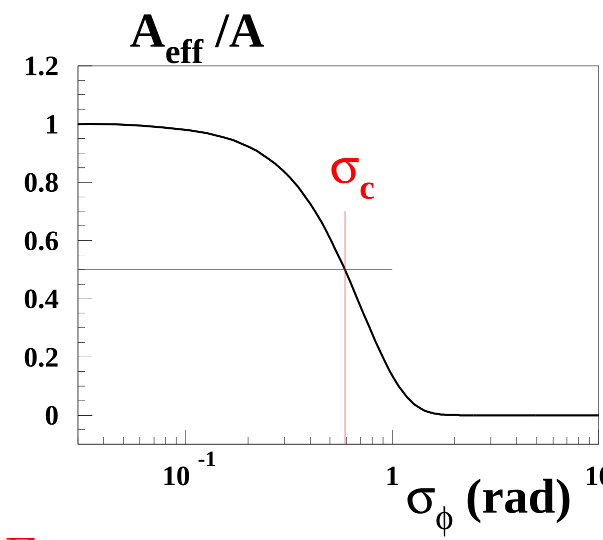
- Here ϕ azimutal angle of conversion plane.
- Threshold
  - $2mc^2$ (nuclear, $\gamma Z^+ \rightarrow e^+e^-Z^+$)
  - $4mc^2$ (triplet, $\gamma e^- \rightarrow e^+e^-e^-$)
- In principle full evt reconstruction from e^+, e^- tracks
- In practice no pair polarimeter flown to space, ever.
  - tracks lose initial direction before ϕ measured : multiple scattering



Conversion in a slab and multiple scattering : Dilution of the polarisation asymmetry

- γ conversion in a slab of thickness x. Assume pathlength = full thickness
- $(1 + \mathcal{A}P\cos[2(\phi)]) \otimes e^{-\phi^2/2\sigma_\phi^2} = (1 + \mathcal{A}\ e^{-2\sigma_\phi^2}\ P\ \cos[2(\phi)])$

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



- azimuthal angle RMS $\sigma_\phi = \dfrac{\theta_{0,e+} \oplus \theta_{0,e-}}{\hat{\theta}_{+-}}$,
  - $\theta_0 \approx \dfrac{13.6\,\text{MeV}/c}{\beta p}\sqrt{\dfrac{x}{X_0}}$,
  - most probable opening angle $\hat{\theta}_{+-} = 1.6\,\text{MeV}/E$ Olsen, PR. 131, 406 (1963).

$\Rightarrow \sigma_\phi \approx 24\,\text{rad}\sqrt{x/X_0}$ (e.g. $\mathcal{A}_{\text{eff}}/\mathcal{A} = 1/2$ for $110\,\mu\text{m}$ of Si, $4\,\mu\text{m}$ of W)

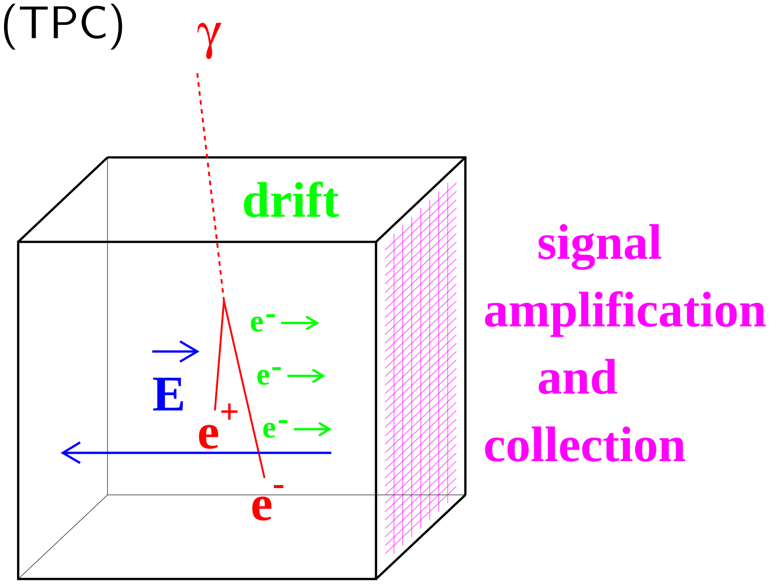
- This dilution is energy-independent.

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

e.g. Mattox J. R.Astrophys. J. 363 (1990) 270, and refs therein

Homogeneous detector, continuous tracking, optimal track fit (Kalman)

- Time Projection Chamber (TPC)



- single measurement resolution $\sigma = 1\mathrm{mm}$, track sampling $l = 1\mathrm{mm}$

- $\sigma_{\theta,\mathrm{track}} = (p/p_1)^{-3/4}$,

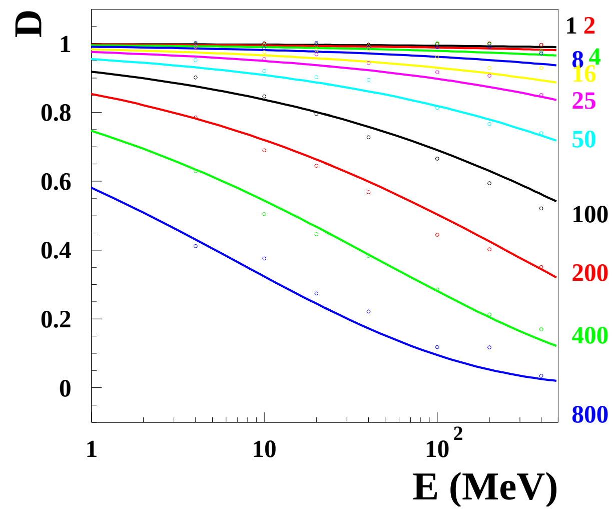
- $p_1 = 13.6\,\mathrm{MeV}/c \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6}$,

Argon : $p_1 = 50\,\mathrm{keV}/c$ (gas, 1 bar) $p_1 = 1.45\,\mathrm{MeV}/c$ (liquid, solid).

Dilution of polarization asymmetry due to multiple scattering : Optimal fits and full MC

- track angular resolution $(p/p_1)^{-3/4}$, $p_1 = 13.6\,\mathrm{MeV}/c \left(\frac{4\sigma^2 l}{X_0^3}\right)^{1/6}$

- $D \equiv \frac{\mathcal{A}_{\mathrm{eff}}(p_1)}{\mathcal{A}(p_1 = 0)}$



Energy variation of D for various values of $p_1(\mathrm{keV}/c)$

- Points are from full MC.

- Curves are $D(E, p_1) = \exp\left[-2(a\, p_1^b\, E^c)^2\right]$ parametrizations, a, b, c constants

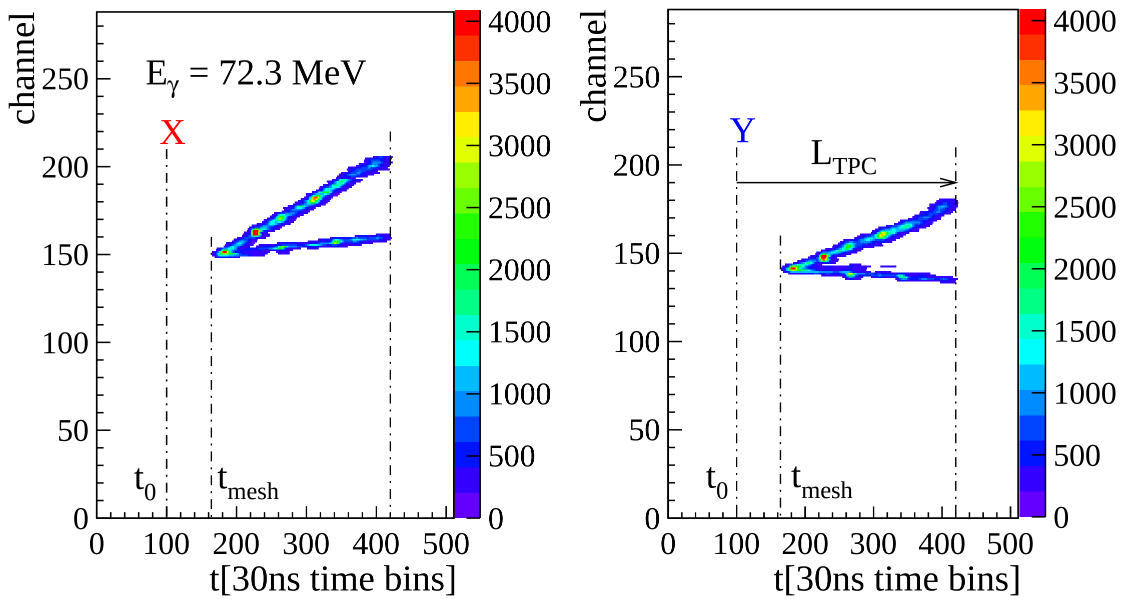
- Liquid : nope (Ar, $p_1 = 1.45\,\mathrm{MeV}/c$); gas : Possible ! (1 bar, $p_1 = 50\,\mathrm{keV}/c$)

Bernard NIM A 729 (2013) 765

HARPO project

- Characterization of a TPC based γ telescope and polarimeter

- Data taking on NewSUBARU beam line (Hyôgo U., Japan), 2014.



74 MeV γ conversion to e^+e^- in a 2 bar Ar:iso-C4H10, 30 cm cubic TPC

Wang, 7th conference on Large TPCs for Low Energy Rare Events, 2014 Paris, arXiv:1503.03772 [astro-ph.IM]

- Don't miss Philippe Gros'talk tomorrow !

Polarimetry of high-energy photons (X, gamma) for astrophysics: Conclusion

- Full coverage of (X, gamma) energy range involves
  - photoelectric effect,
  - Compton scattering,
  - pair creation,

  based detectors.

- TPC with MPGD amplification central in all schemes.