# Non-thermal emission from pulsars – experimental status and prospects


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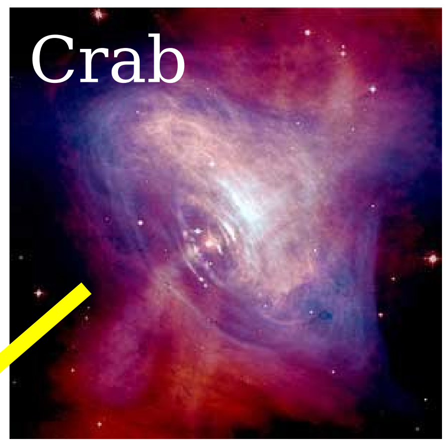


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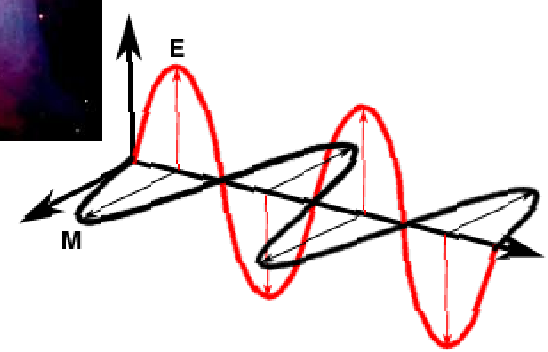


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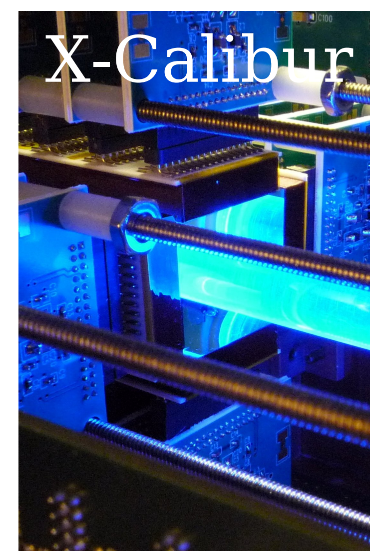
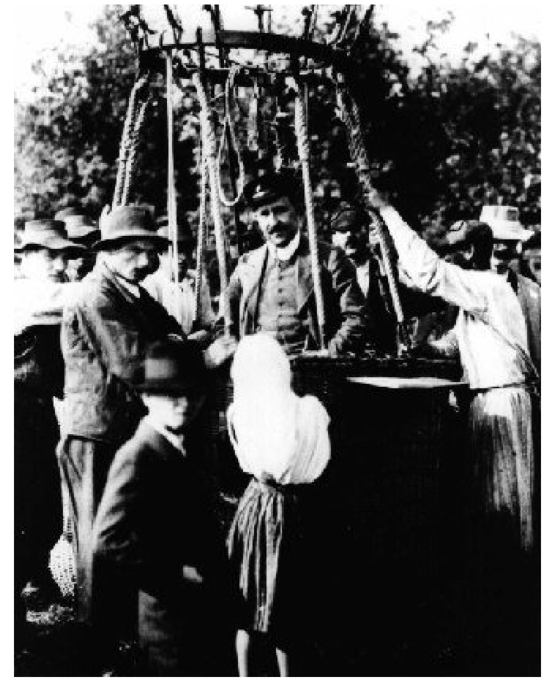
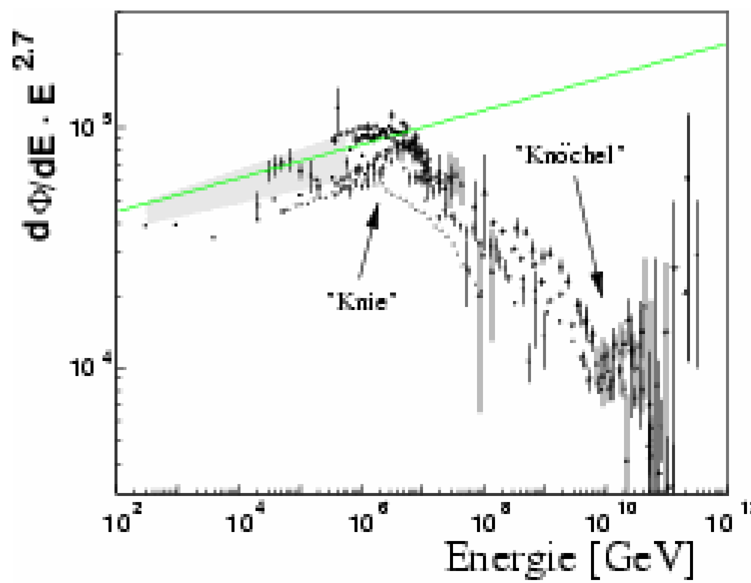


# TeV γ-ray astrophysics with VERITAS

# The charged cosmic radiation -
## how it all began...

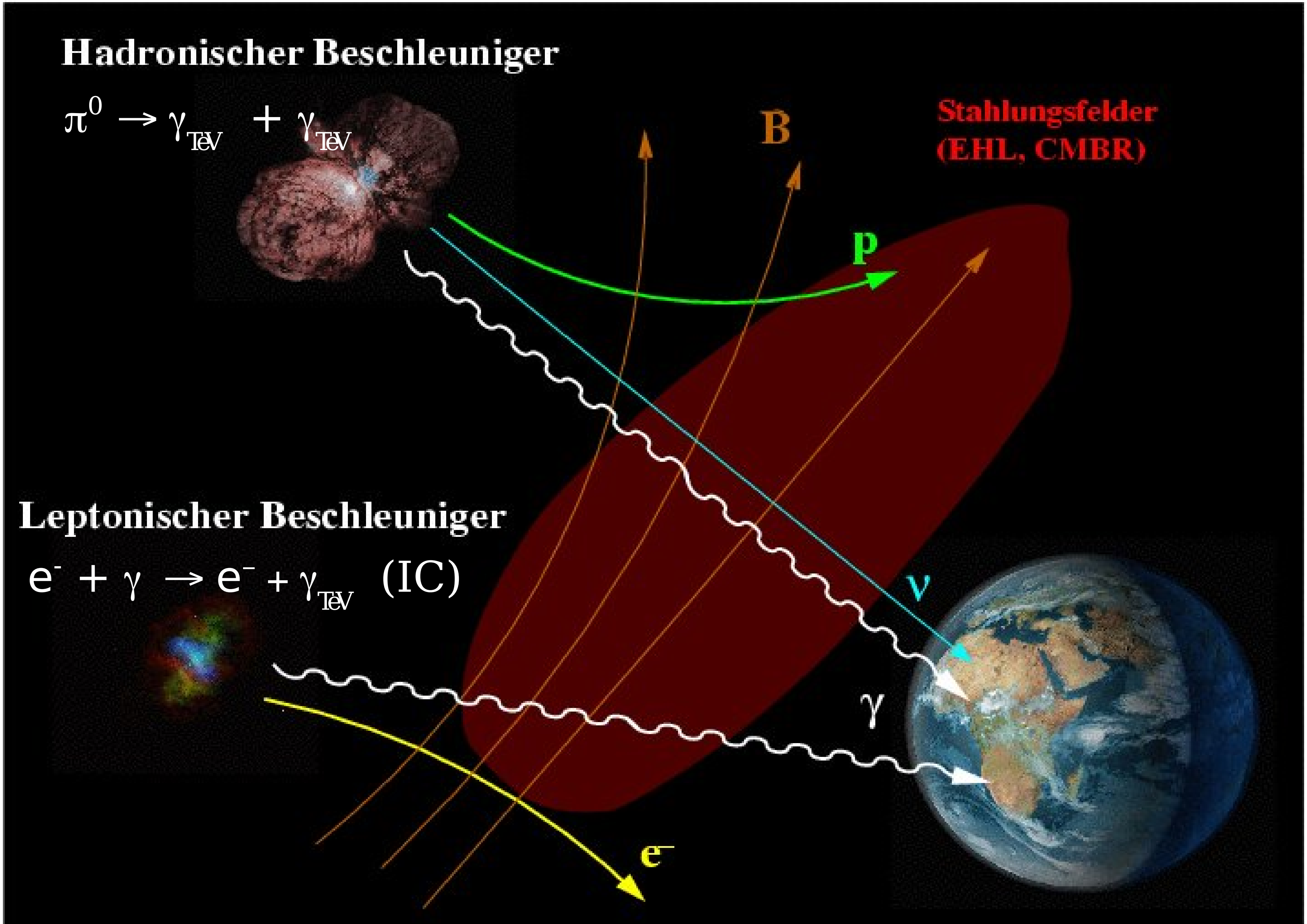
- **Discovery:** Victor Hess (1912)
- **Characteristics**
  - Isotropic in-fall
  - Nucleons (~98%), electrons (~2%) (composition energy dependent)
  - Energy spectrum: power-law
- **Origin:** not finally understood (shock acceleration, Fermi 1&2)
- **Problem:** Direction of charged particles lost in magnetic fields





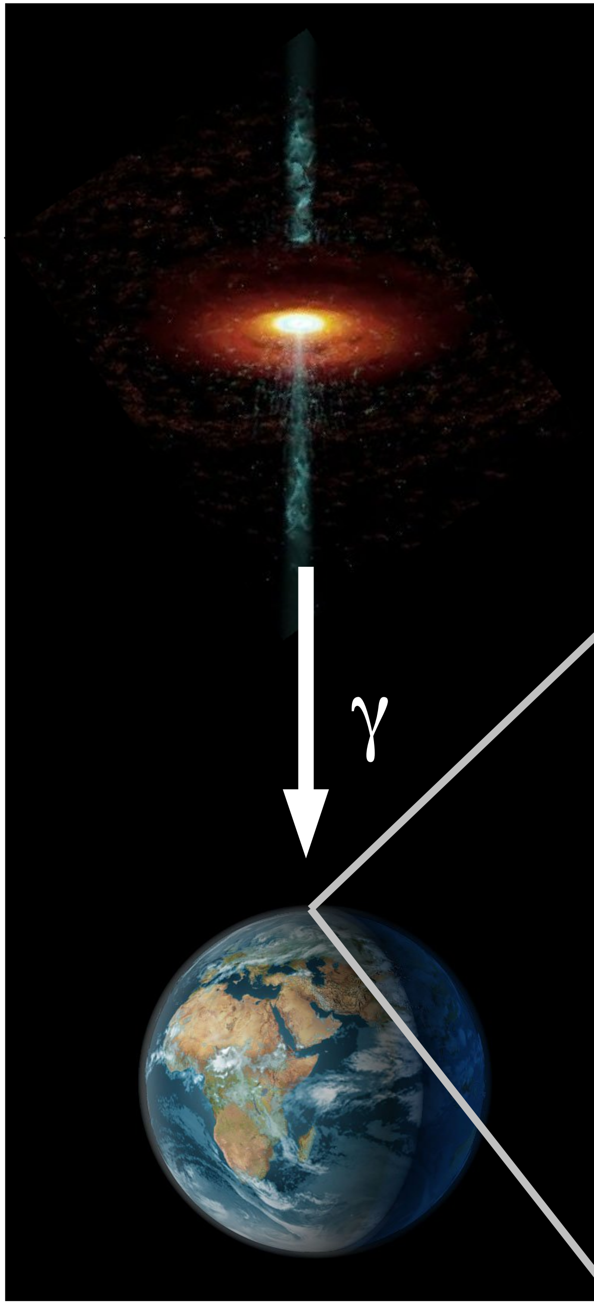

⇒ High energy γ astrophysics:
Probe sources/mechanisms of charged cosmic rays

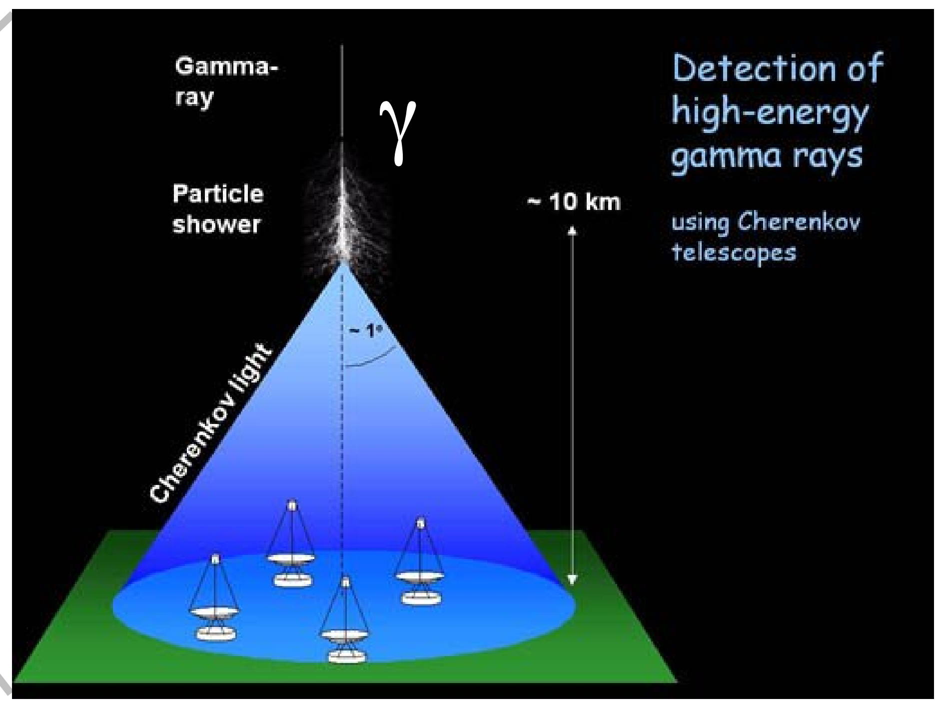
# TeV γ-ray astrophysics:
## Study hadronic/leptonic particle accelerators



# TeV γ-ray astrophysics with Cherenkov telescopes

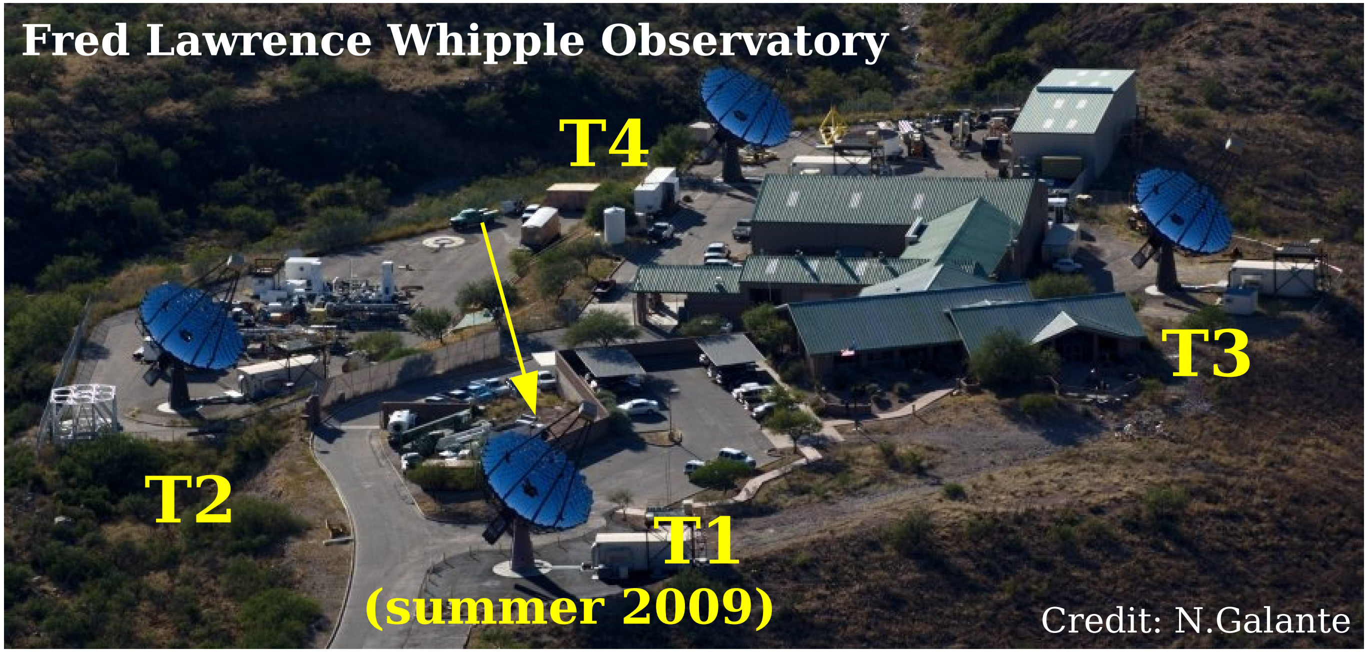
- **Gammas enter earth's atmosphere** and produce air showers & Cherenkov light
- **Imaging** of Cherenkov light with telescopes: reconstruct direction & energy
- **Reject CR background:** image properties



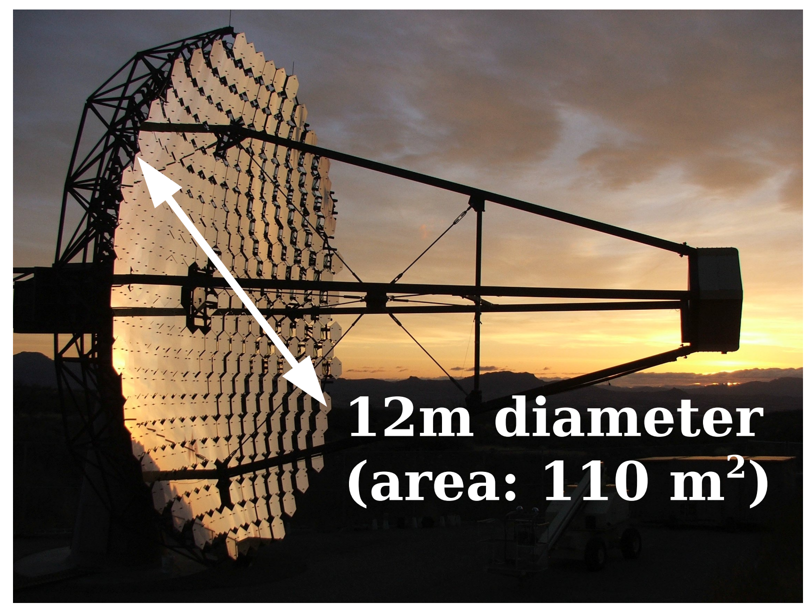

W.Hofmann

# The VERITAS Cherenkov Telescope Array
## (Very Energetic Radiation Imaging Telescope Array System)



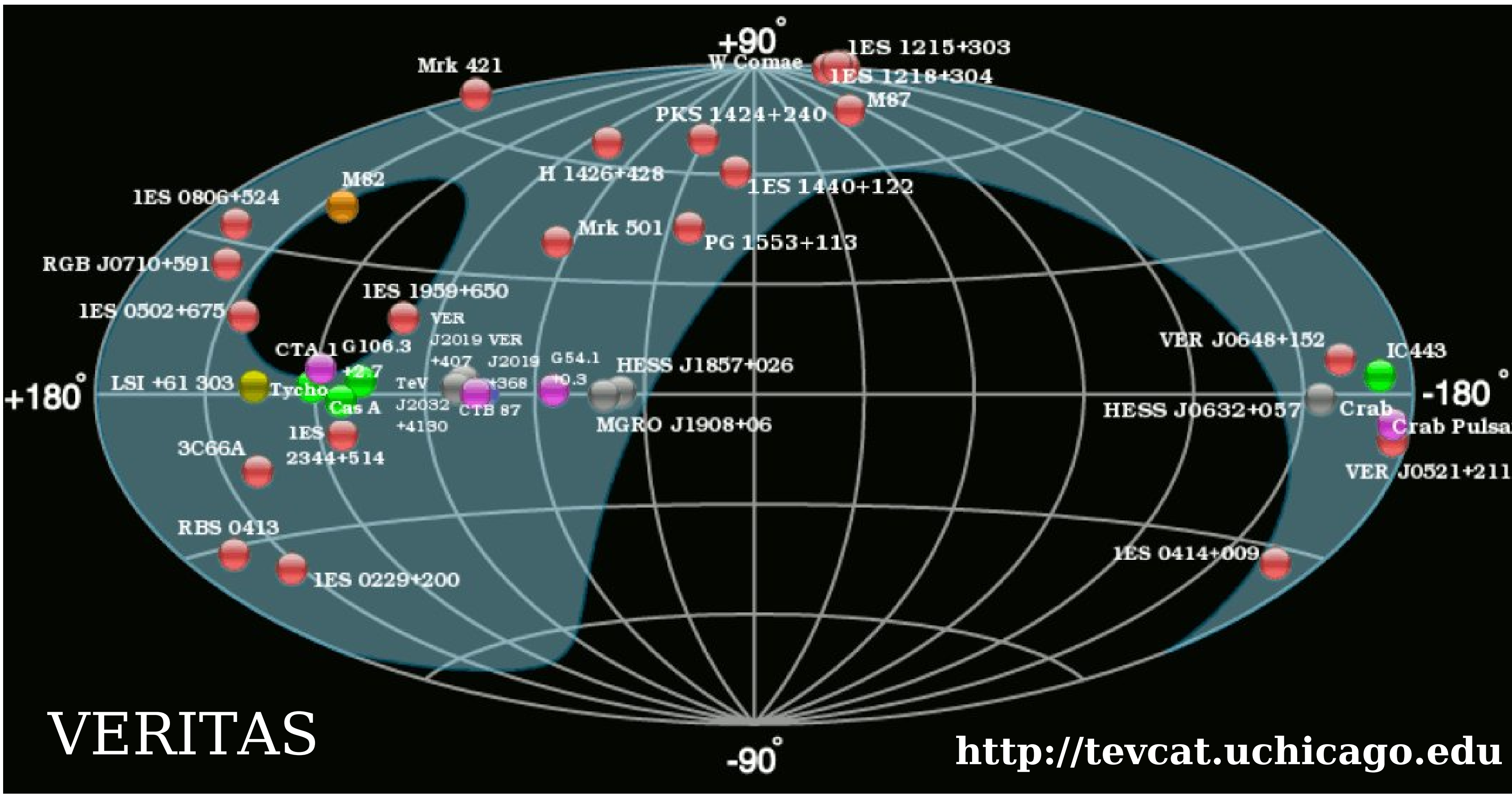

Supported by:
DOE
NSF
SAO (U.S.)
STFC (U.K.)
NSERC (Canada)
SFI (Ireland)

- Each camera: 499 PMT pixels
- Energy range: 0.1 - 30 TeV ($\Delta E/E$ <20%)
- Sensitivity: 0.1(0.01) Crab in 0.5h (26h)



# Introduction: TeV γ-ray astrophysics

- **Probe non-thermal universe**
- **Observations per year:** 700-800h (+200h moon data)
- **Dynamical field:** 2000: handful of sources, 2011: **>100 sources**



# Galactic TeV sources

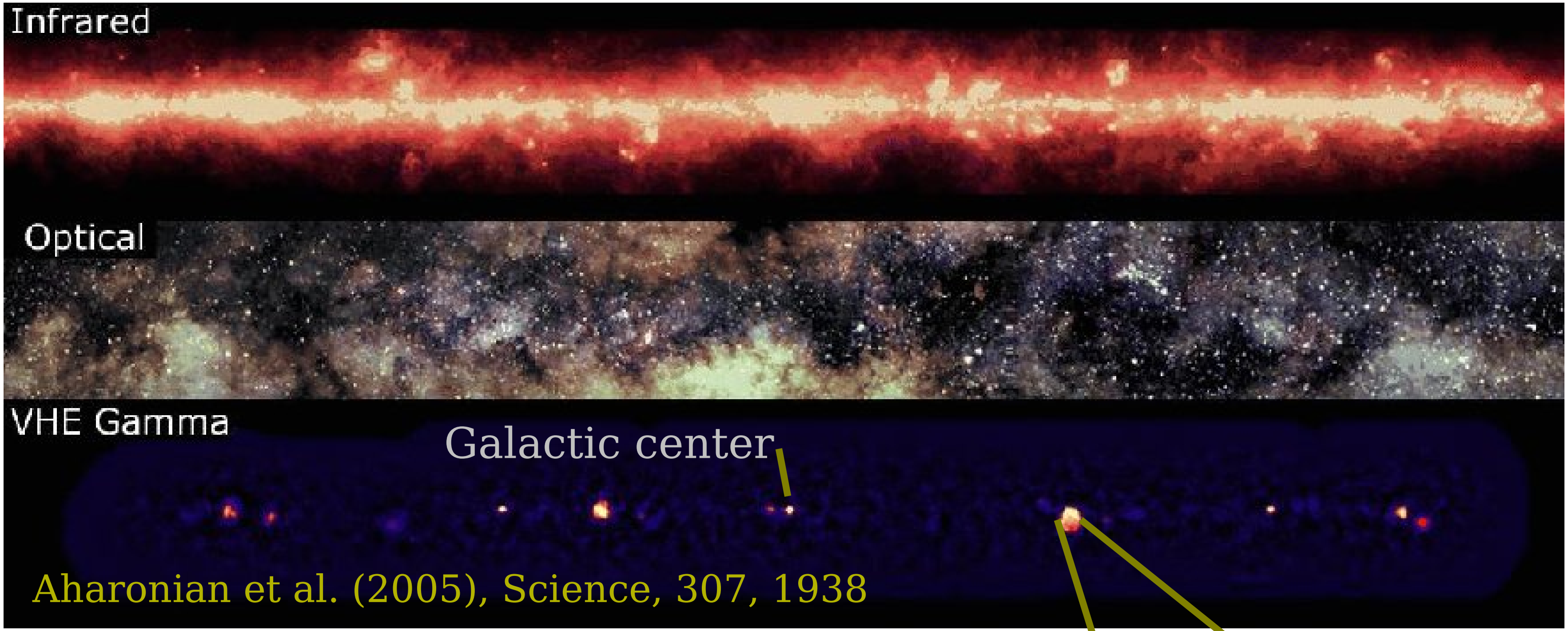
Galactic
TeV sources

# The galactic plane at TeV energies

IR

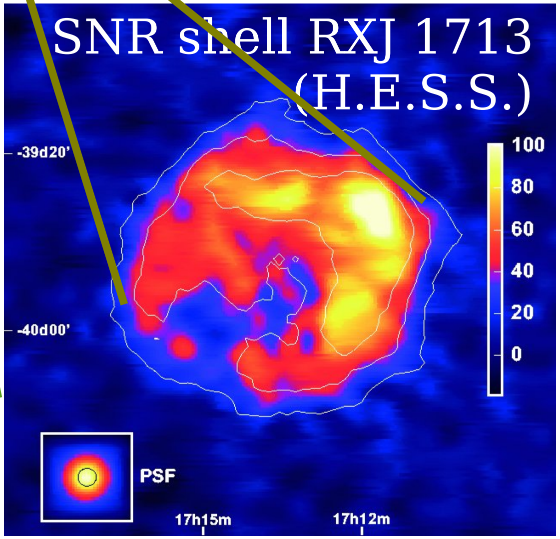
Opt

TeV




NASA

H.E.S.S.



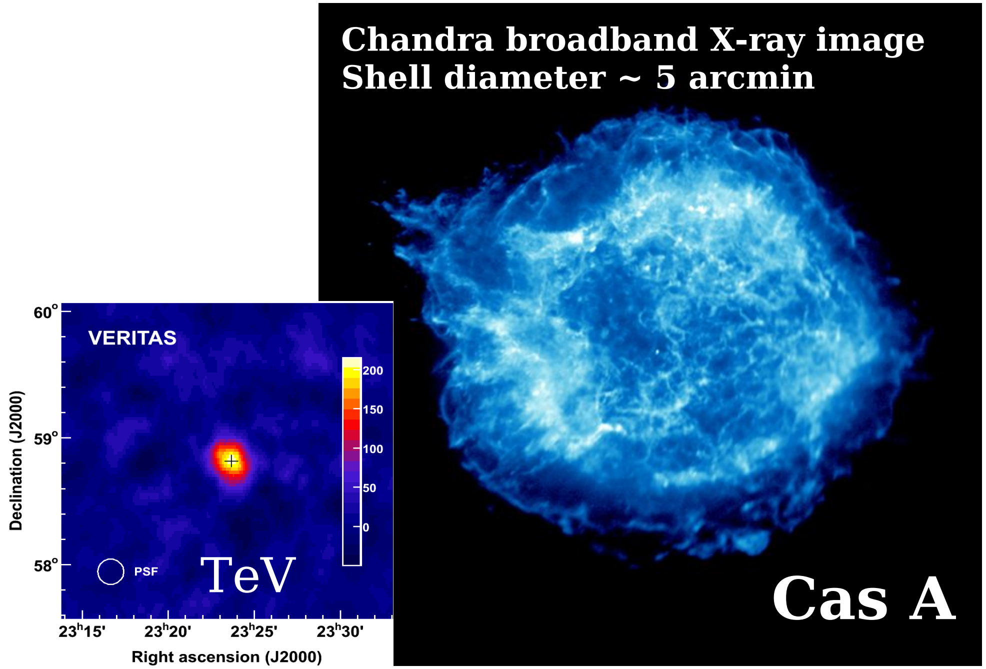

First direct evidence:
SNR shell accelerates
particles to E > 100 TeV

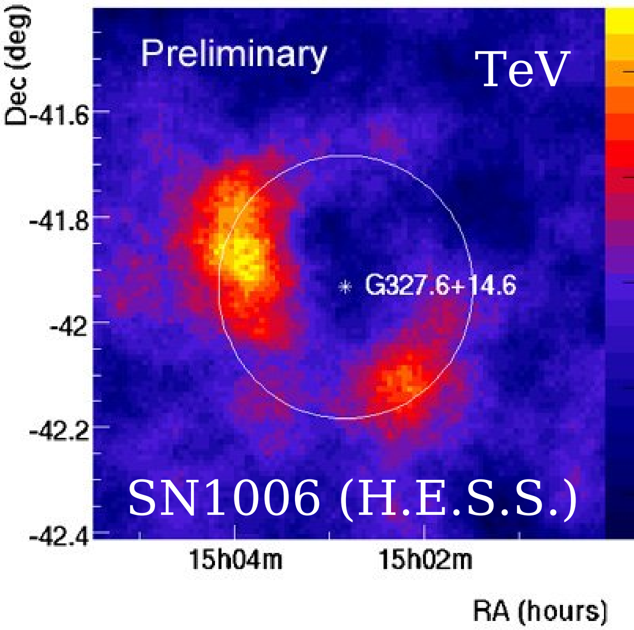
Aharonian et al.(2004),Nature,432,75

# Class1: Supernova Remnants (SNRs)

- **TeV emission from SNR:**
  - SN ejecta expand into interstellar medium
  - shock acceleration (charged particles)
  - TeV γ-rays (secondary reactions)
- **Open question:** hadronic or leptonic?
- **MWL (morphology and SED):**
  particle population & emission mechanisms


NASA, ESA, Zolt Levay (STScI)



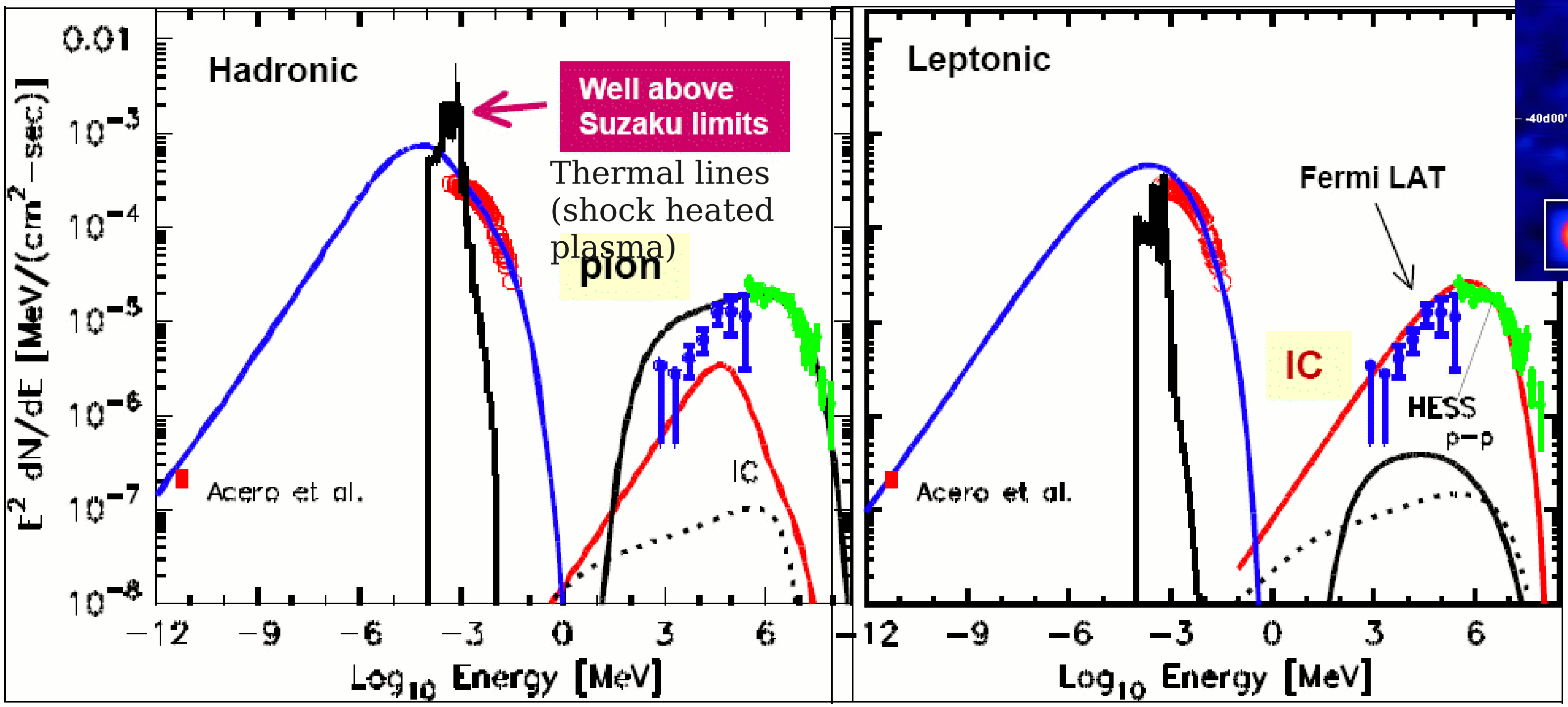



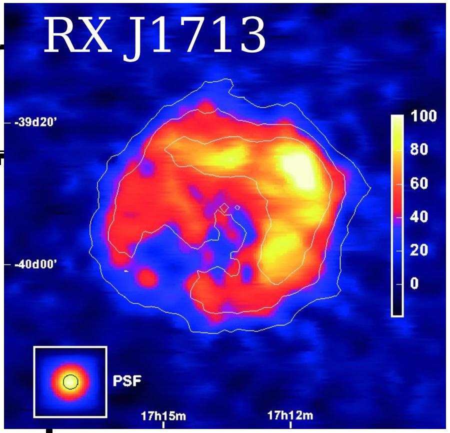

http://www.mpi-hd.mpg.de/hfm/HESS/pages/home/som/2008/08/

# Class1: Supernova Remnants (SNRs): RX J 1713

**indications for lepton domination (Ellison, Fermi Symposium 20111)**

When X-rays are calculated self-consistently, force lower density and higher $K_{ep}$ = 0.02, eliminates pion-decay fit




**Hadron model parameters:**
$n_p$ = 0.2 $cm^{-3}$
$e/p = K_{ep}$ = 5 $10^{-4}$
$B_2$ = 45 μG

**Lepton model parameters:**
$n_p$ = 0.05 $cm^{-3}$
$e/p = K_{ep}$ = 0.02
$B_2$ = 10 μG

Here, use only CMB photons for IC emission

Ellison, Patnaude, Slane & Raymond ApJ 2010

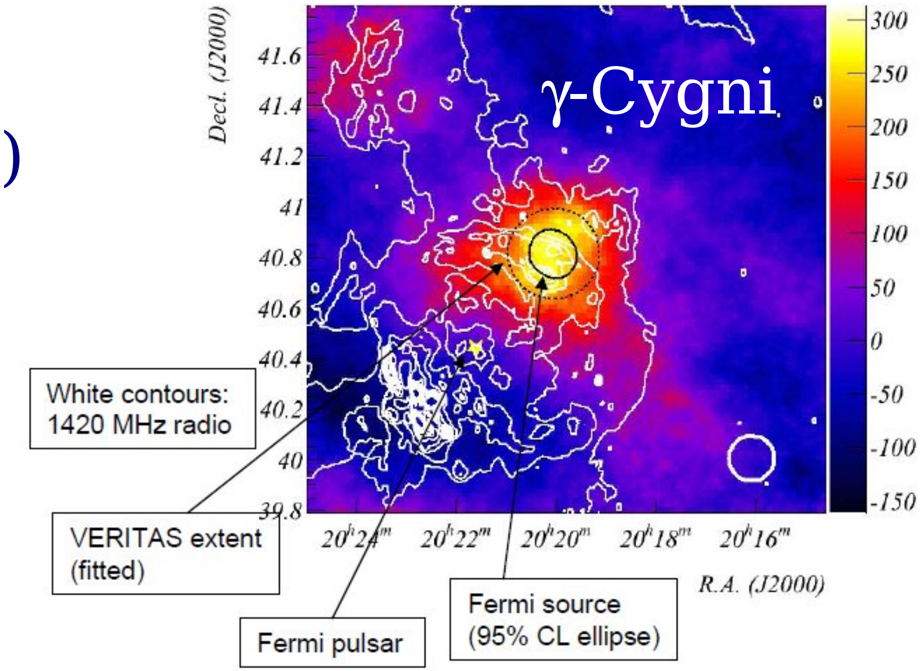
But: e- radiate ore efficiently in low density environments

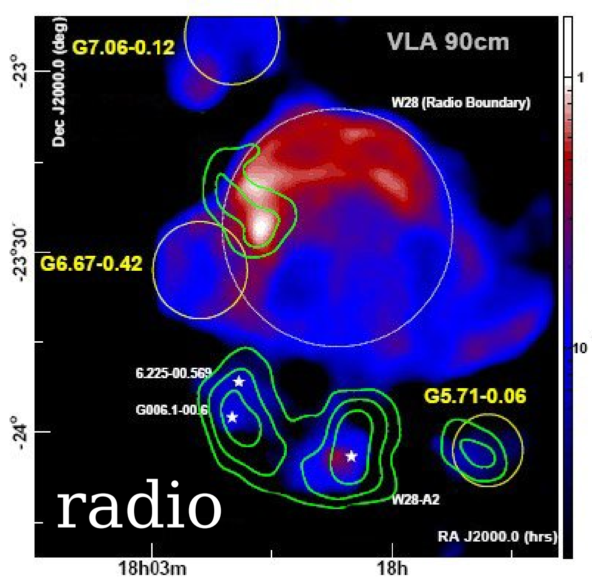
Recent Fermi LAT data consistent with leptonic model

# Class1b: SNR + molecular clouds

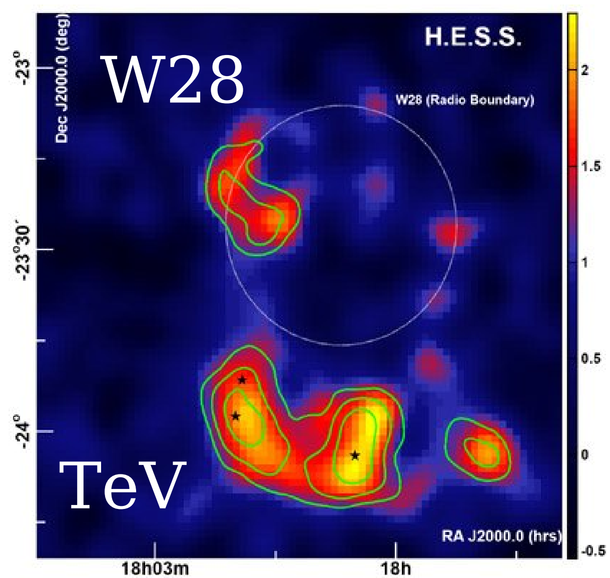
SN ejecta interacting
with molecular cloud (hadronic)

**Hadronic indication:**
**so far only from SNR+MC**




Brogan et al. (2006)

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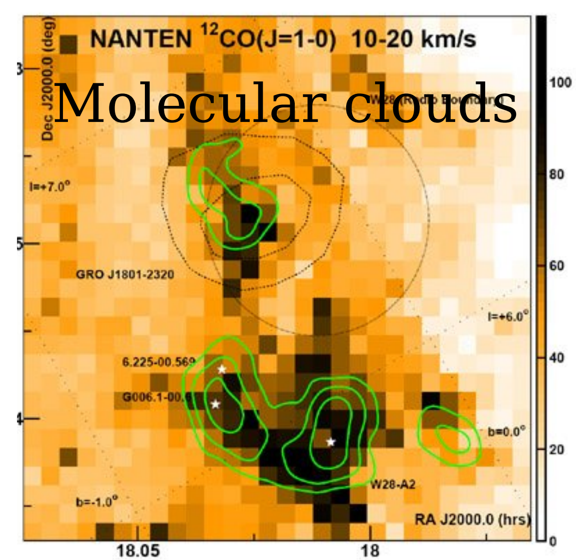
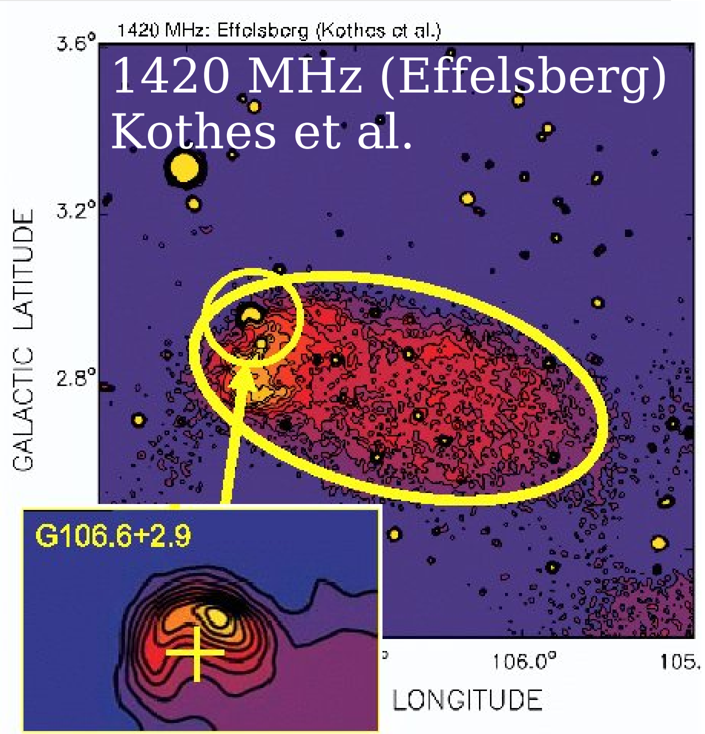
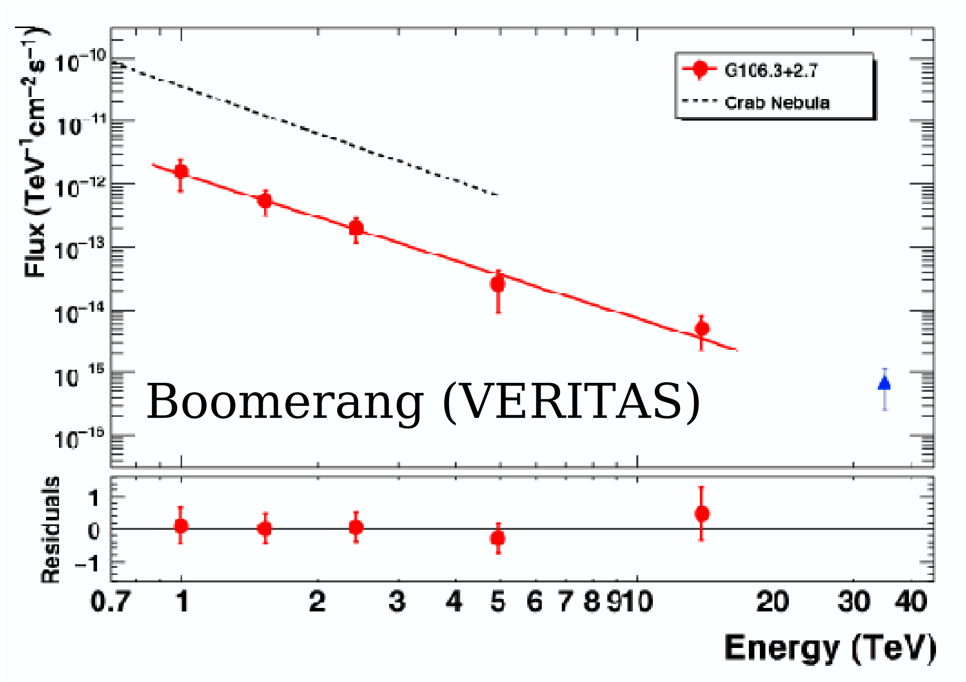


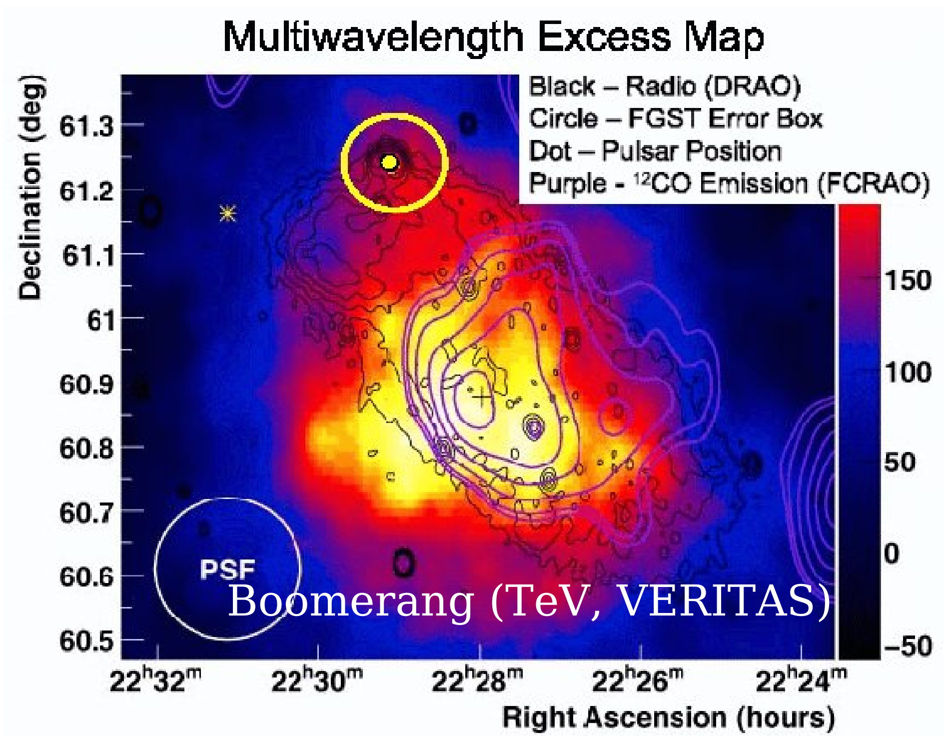

Nanteen radio telescope

# Class2:
# Pulsar wind nebulae (PWN)

- **TeV emission from PWN:**
  - pulsar driven bubble of relativistic particles
  - shock acceleration (SNR or ISM interaction)
  - TeV γ-rays emission: inverse-Compton
- **Example 'Boomerang':**
  age: 10,000 years, dE/dt = 2.2 x $10^{37}$ erg/s

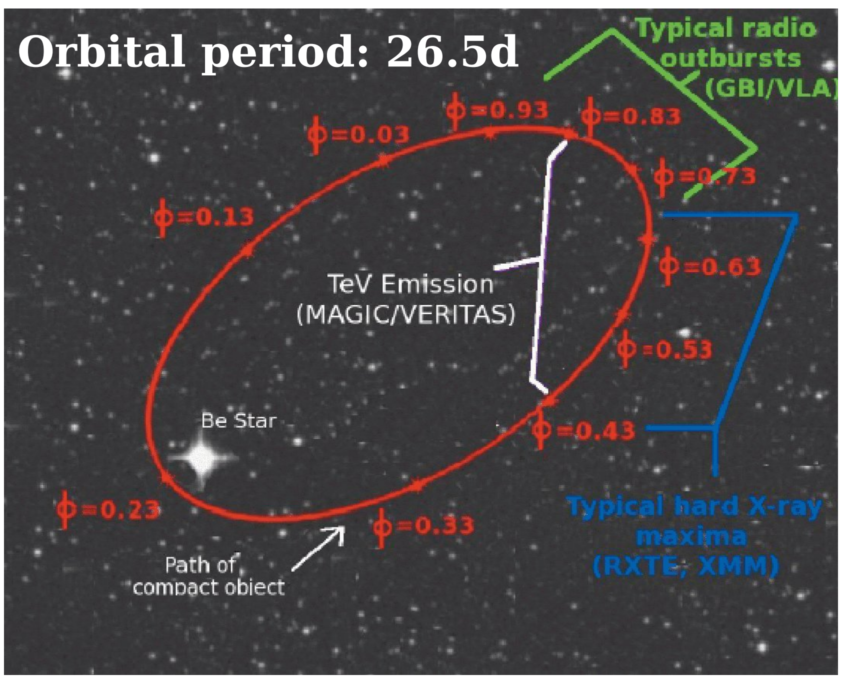


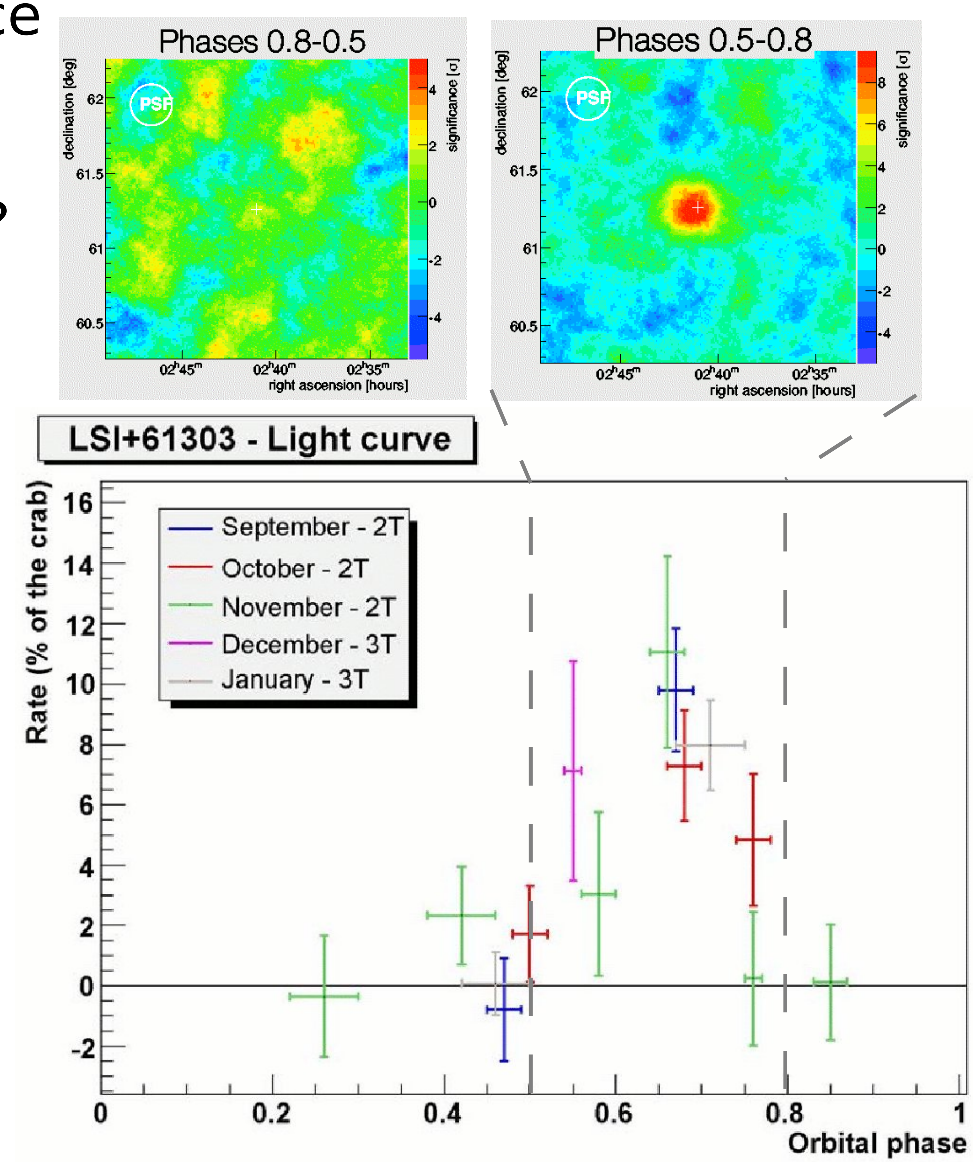



# Class3: High mass X-ray binaries (LSI +61 303)

- LSI+61: Variable TeV γ-ray source (seen by MAGIC/VERITAS)
- Emission mechanism unknown: Microquasar or interacting PWN? (+strong propagation/absorption effects)

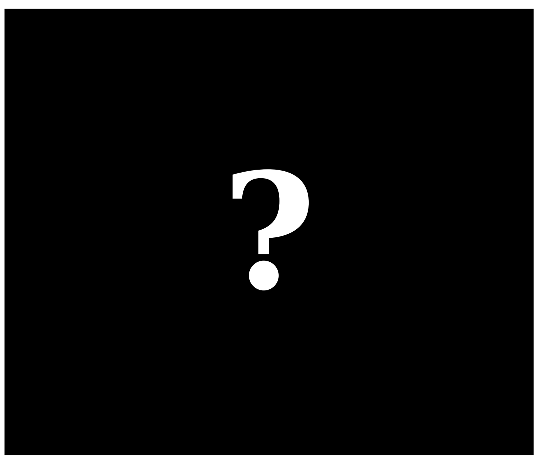



Acciari et al., ApJ, 679, 1427 (2008)

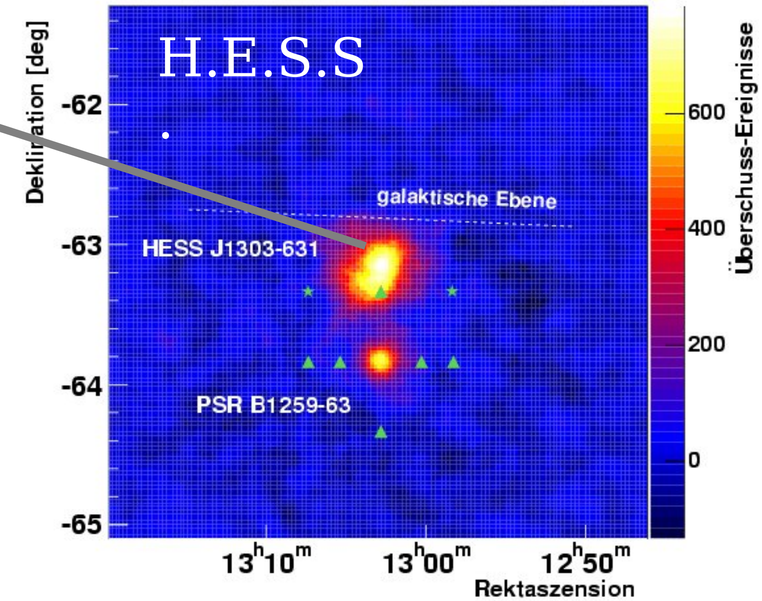
# Class4:
# Unidentified TeV γ-ray sources

- **Unidentified TeV γ-ray sources:**
  - no counterpart at other wavelengths
  - mostly extended
  - emission mechanism unknown

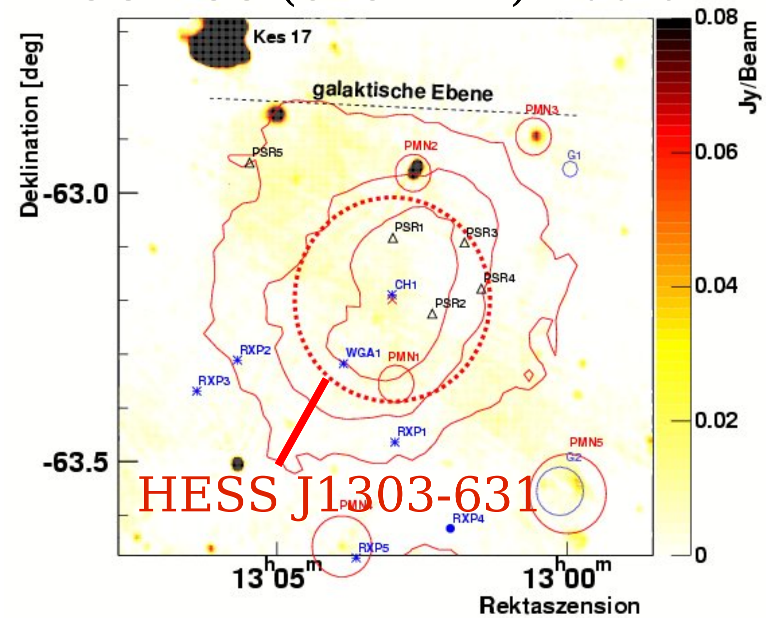



Strategies to identify:
MWL counterparts, variability

Aharonian et al.(2005),A&A,439,1013



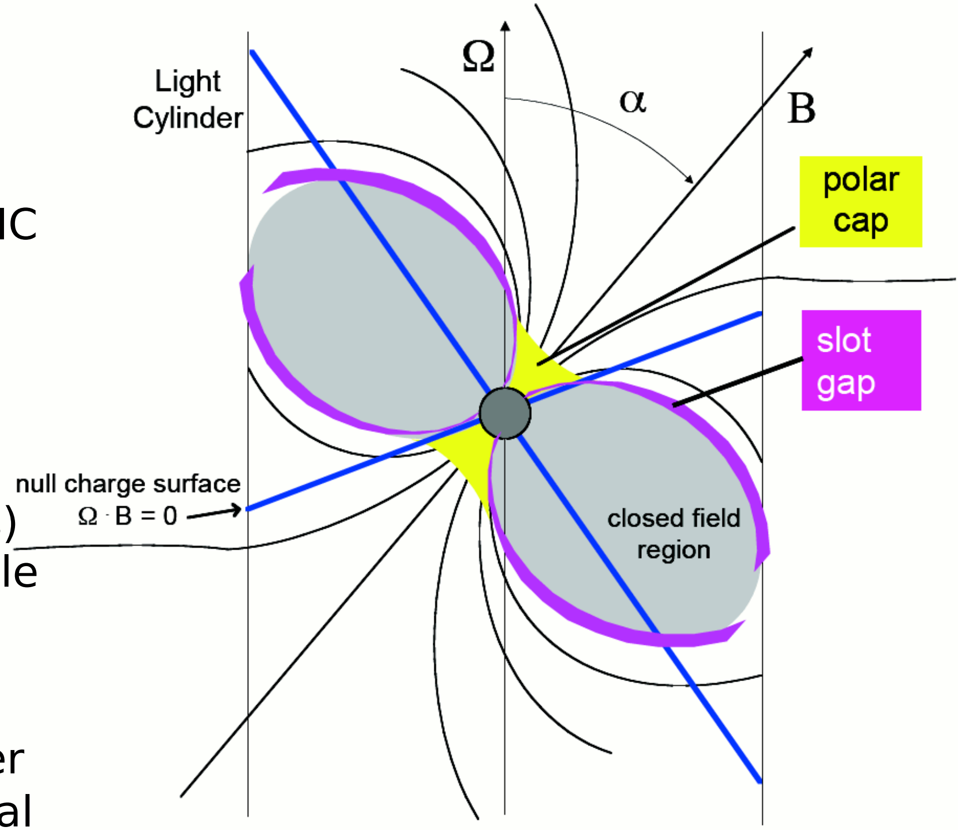

SUMSS (843 Mhz) Radio



# Can we see a pulsar at 0.1 TeV energies?

# High-energy emission from pulsars:
## polar cap vs. outer gap models

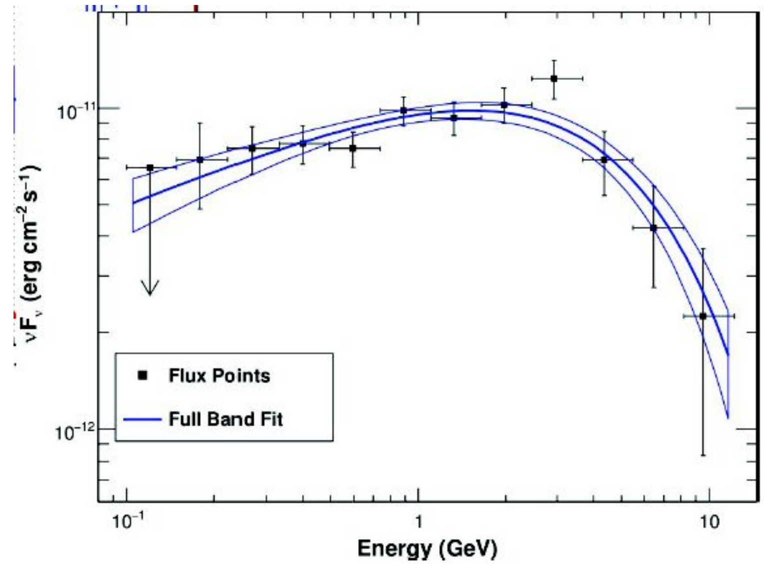
- Polar cap model (yellow):
  - strong **B** field extracts surface particles
  - particles stream out along open field lines
  - acceleration potential (few stellar radii)
  - particles: curvature radiation (exp cutoff) & IC
  - if sufficient angle to **B**: magnetic pair production => $e^+/e^-$ pair absorption => exponential cutoff at O(10 GeV)
  - $e^+/e^-$ pair/radiation cascades ($10^4$ particles)
  - final spectrum: curvature/IC continuum with cutoff at ~GeV + synchrotron (lower energies)
  - problem: small beamsize vs wide pulse profile
  - believed to dominate radio emission
- Outer gap model (magenta):
  - Outer gap: null surface (**B**⊥**Ω**) & light cylinder
  - further out: weaker **B** but $10^{15}$ volt **E** potential
  - accelerated electrons: curvature radiation
  - photon photon pair production with thermal X-rays from polar cap or SSC (as in Crab)
  - believed to dominate gamma-ray emission

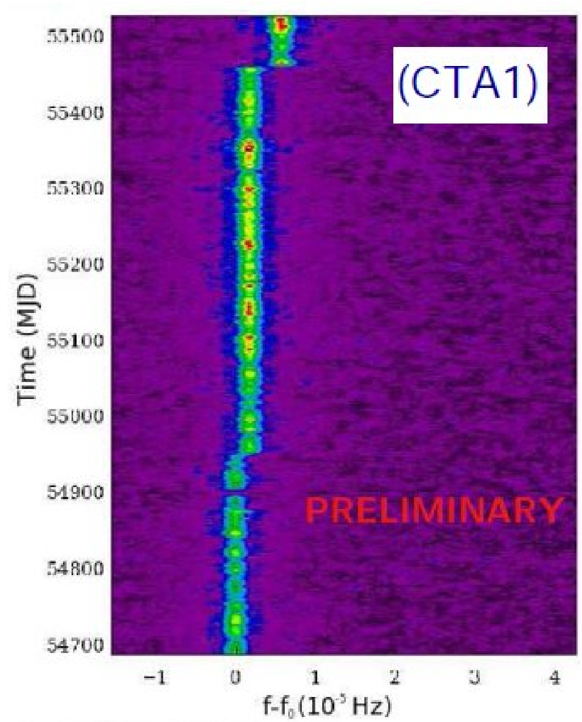



Polar cap vs. outer gap:
many model parameters
=> difficult to distinguish experimentally

# What can be observed?

- We can observe...
  - flux/spectrum
  - polarization (angle & fraction)
- ... as a function of...
  - time
  - ~~location~~
- ... to derive...
  - period P (phase), dP/dt, $d^2P/dt^2$
  - bursts (magnetars)
- ... re-iteration (using P) and derive...
  - spectrum vs. phase
  - polarization vs. phase
  - pulse width & MWL pulse correlations
  - energy loss dE/dt (need radius & mass)
  - glitches
  - etc
- ... model fits to data can constrain...
  - **B** field (strength/geometry)
  - angle between **Ω** and **B**
  - inclination angle

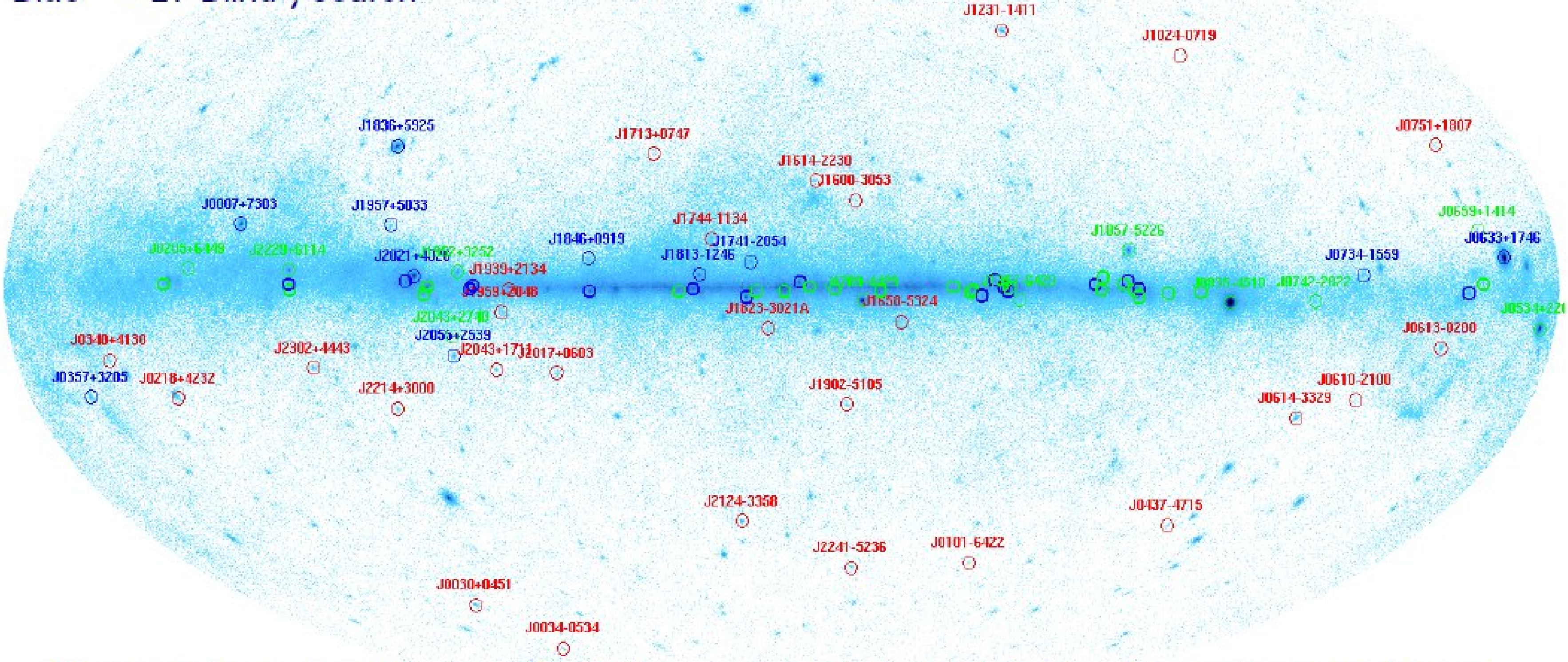


# 88 Gamma-ray pulsars

*One for every musical note on a piano. One for every constellation.*

*Green -- 34 radio ephemeris (young, and not-so-young)*
*Red – 27 radio MSP*
*Blue – 27 Blind $\gamma$ search*



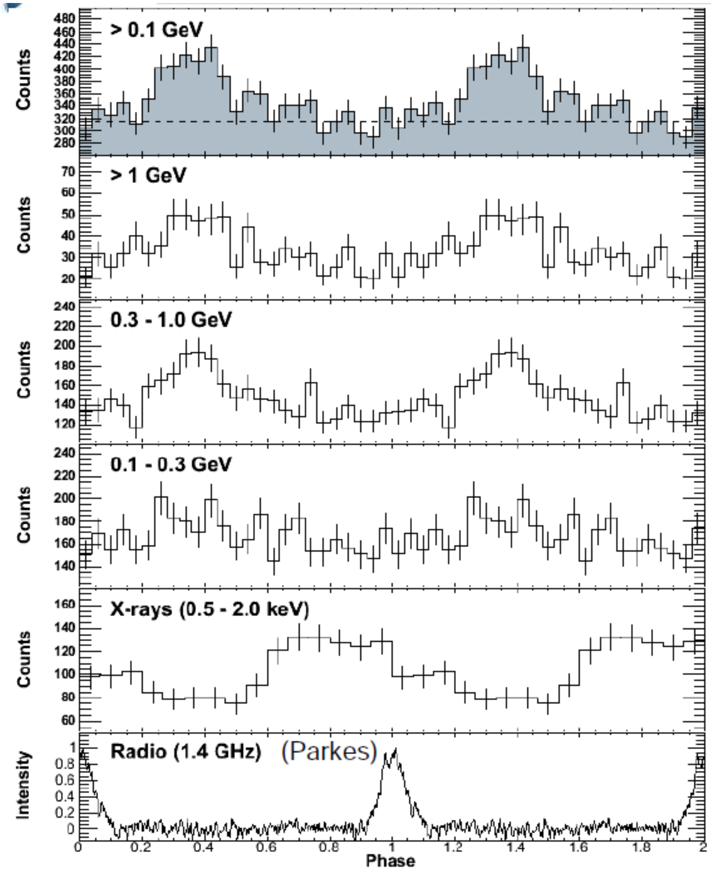

We require >5$\sigma$ pulsations using e.g. H-test, and ≥2 independent analyses.

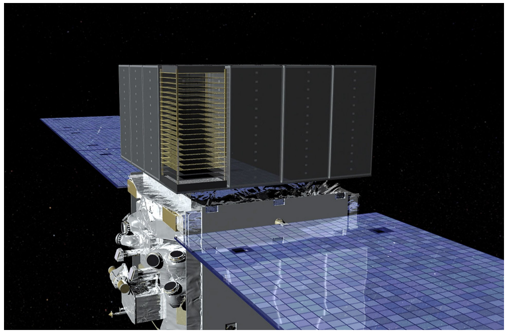
*~10 more with >4$\sigma$. Also awaiting ephemerides for ~20 MSPs found in Unld sources.*

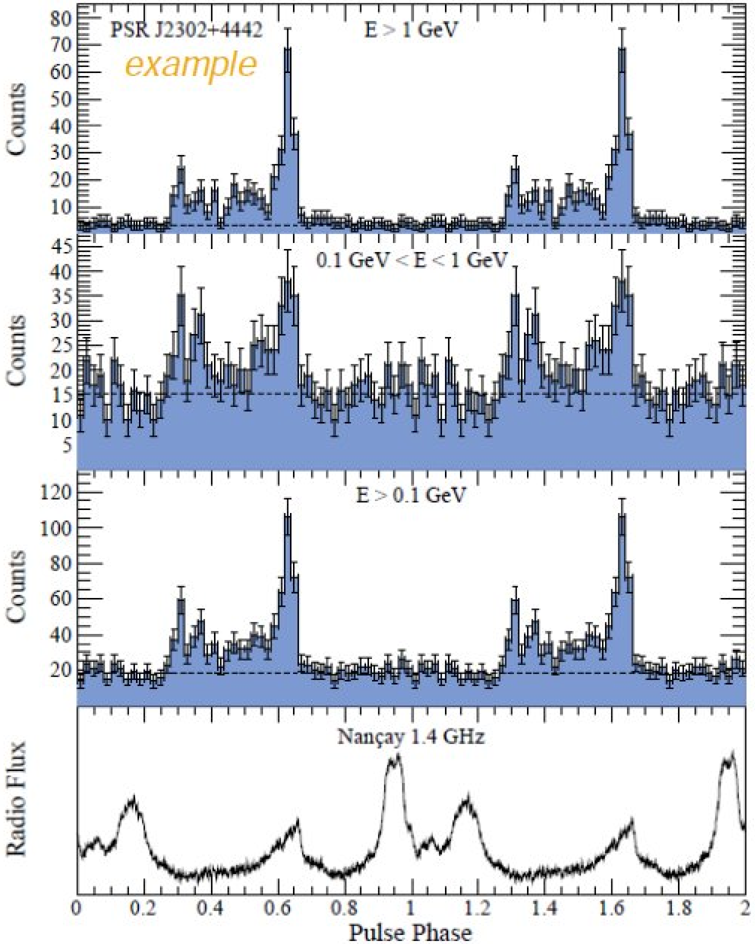
*There were 46 in the "1st Fermi Pulsar Catalog",* Abdo et al. ApJS 187, 460 (2010)

Slide by David A. Smith (Fermi Symposium, Rome 2011)

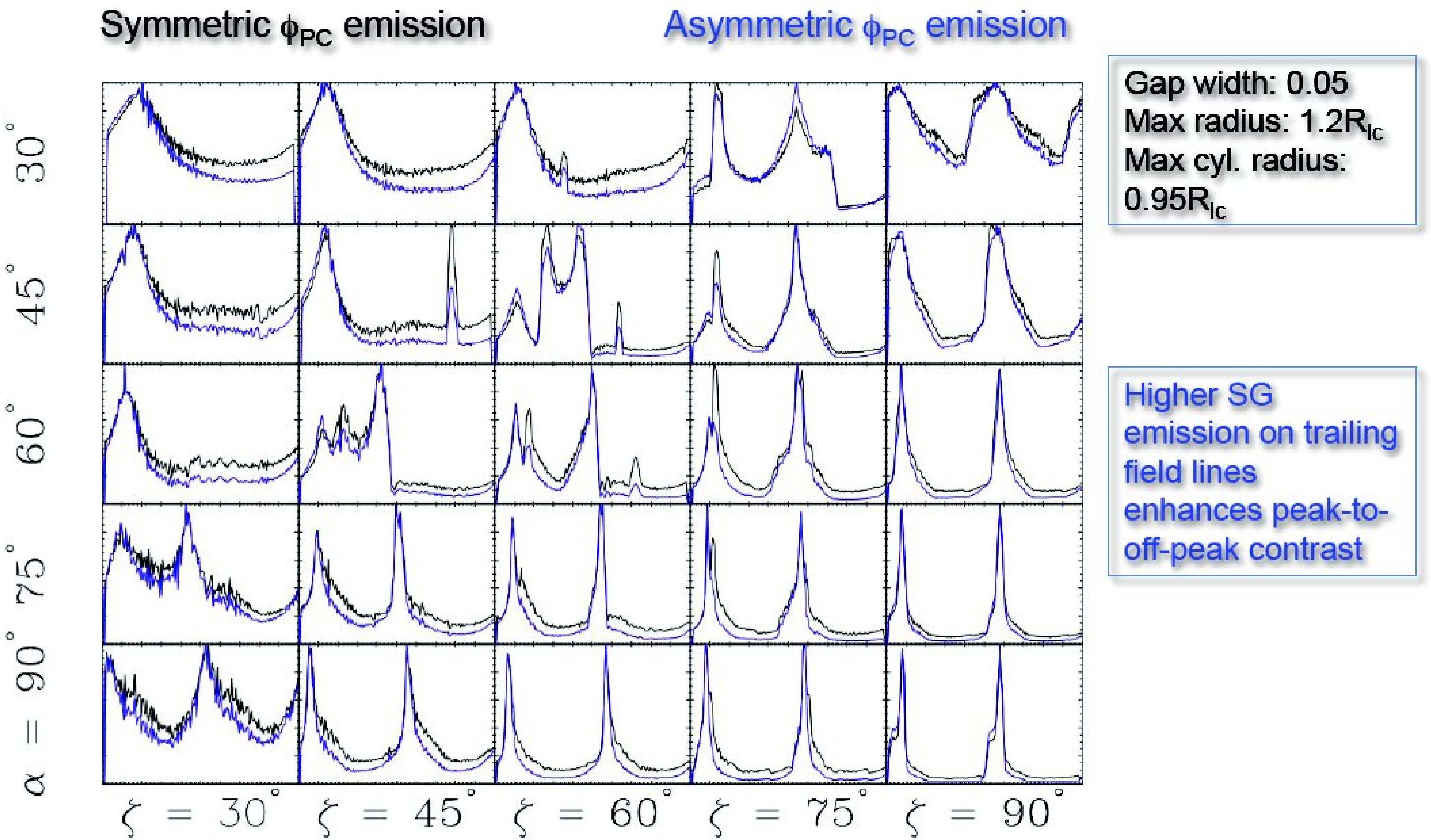
# Pulsar light curves measured at different energies





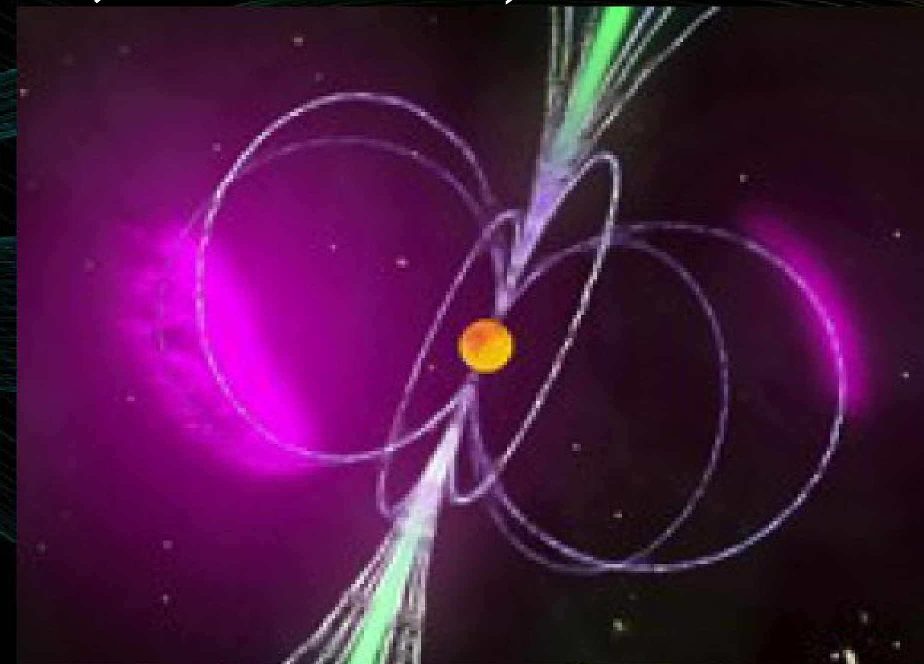
# Slot gap light curves for vacuum dipole geometry




Slide by A. Harding (Fermi Symposium, Rome 2011)

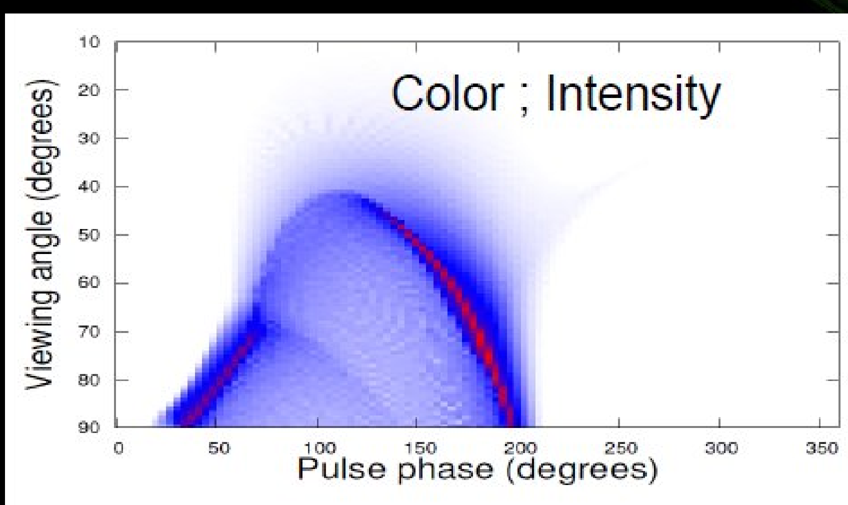
# γ-ray emissions

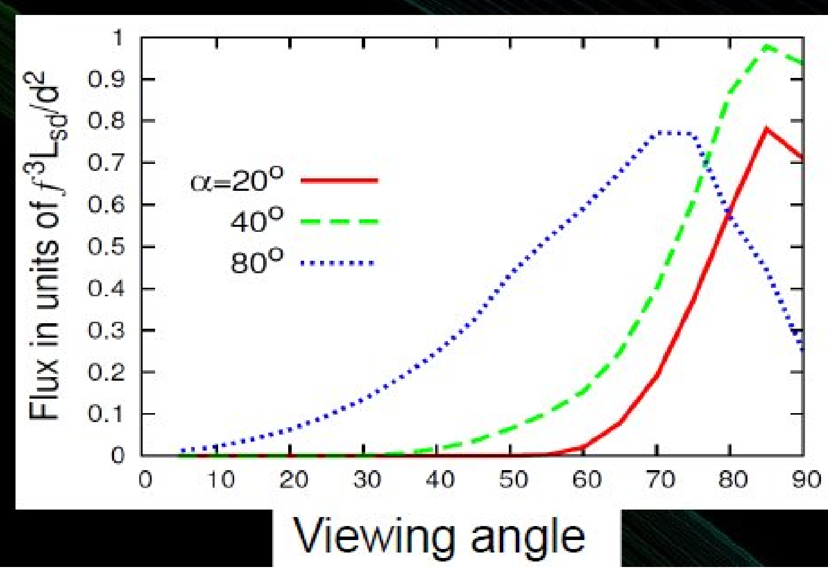
Slide by Takata (Fermi Symposium, Rome 2011)



- γ-ray emissions from outer gap
- Wang, Takata & Cheng (2010, 2011)
- 3-dimensional model

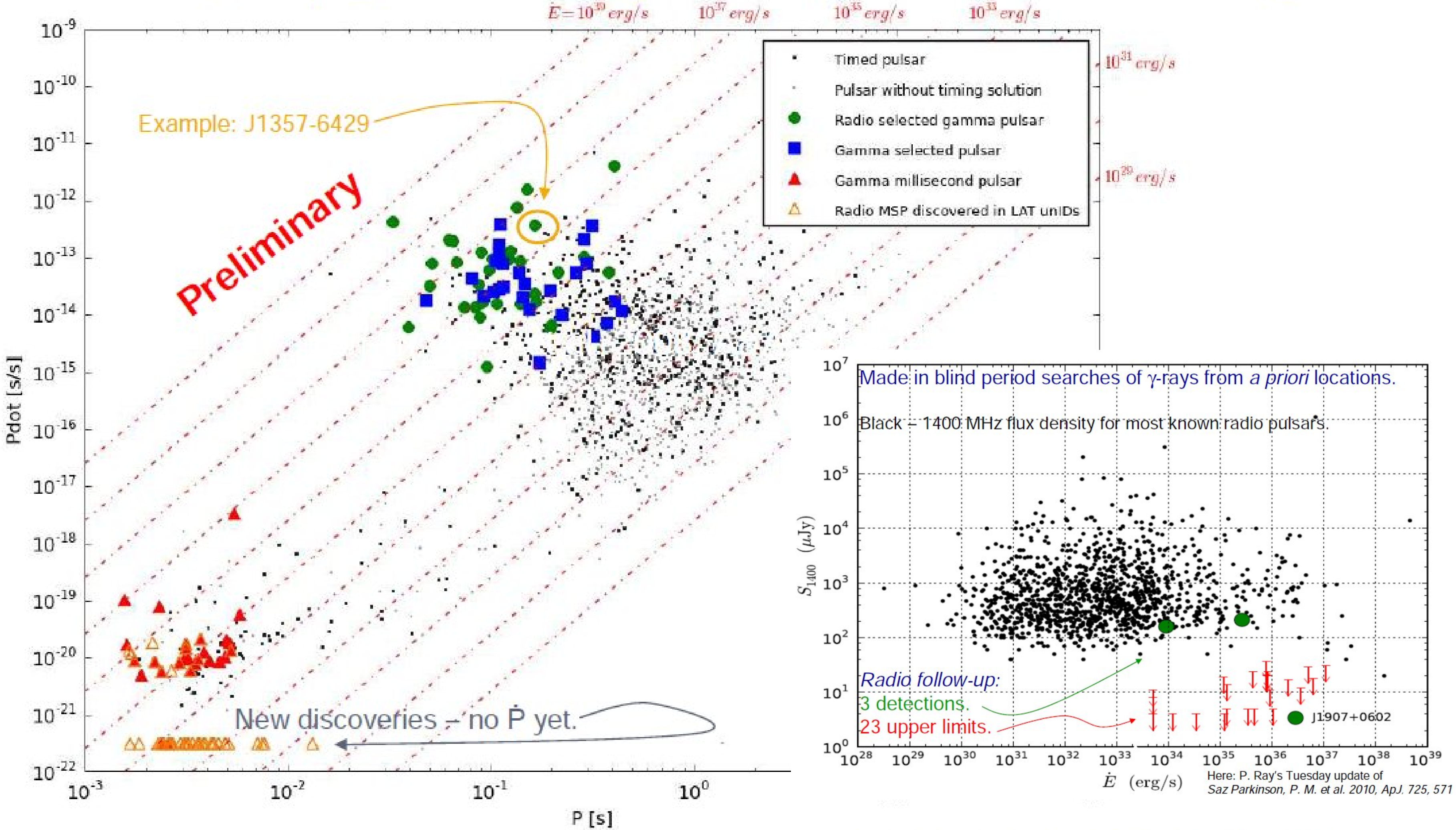
  -Dependency of the emission characteristics on the inclination angle and Earth viewing angle.



# P-Ṗ diagram

Pre-launch timing campaign*: Ė > 1E34 erg/s. We see pulsars down to Ė ~ 3E33 erg/s

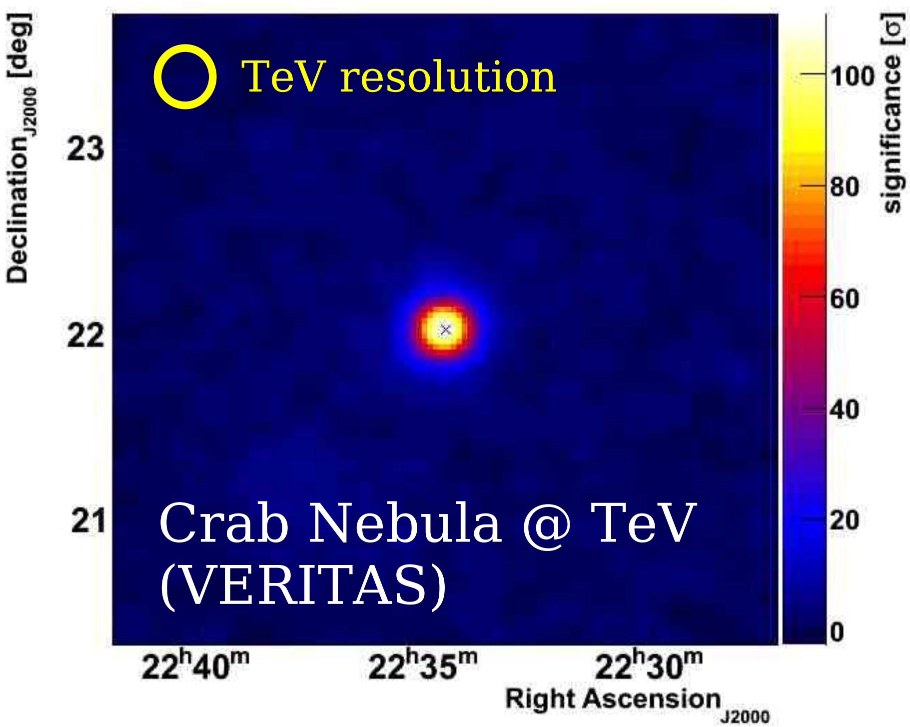


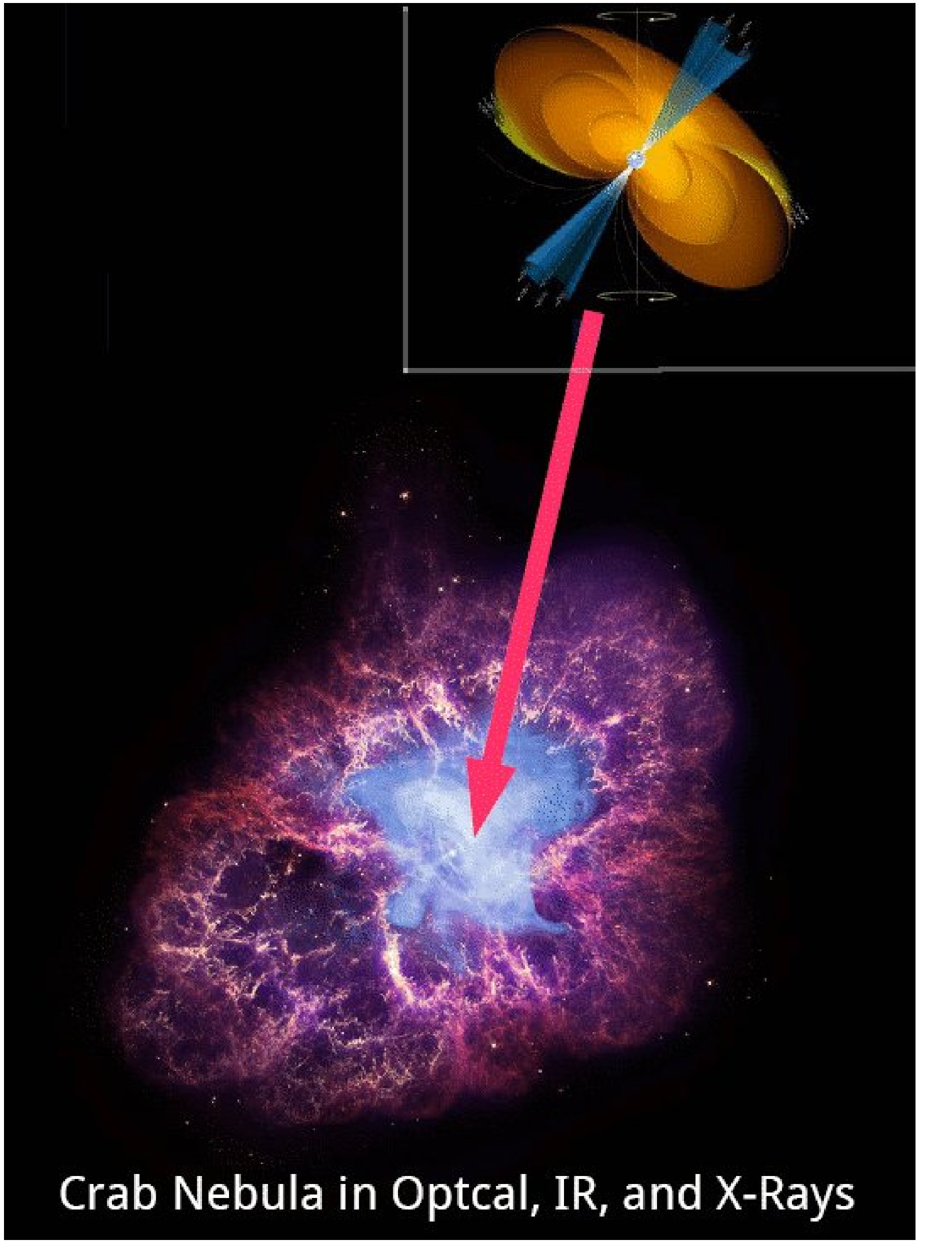

*Smith, Guillemot, et al. A&A, 492, 923 (2008)

Slide by David A. Smith (Fermi Symposium, Rome 2011)

# The Crab pulsar and nebula

- Supernova in 1054 a.d. (D = 2kpc)
- Most energetic pulsar:
  4.6 x $10^{38}$ ergs/s
  (one of the brightest MeV γ-ray pulsar)
- Powers the Crab nebula
  (one of the brightest TeV γ-ray source)
- Angular structure < TeV resolution



# The Crab pulsar and nebula

- Supernova in 1054 a.d. (D = 2kpc)
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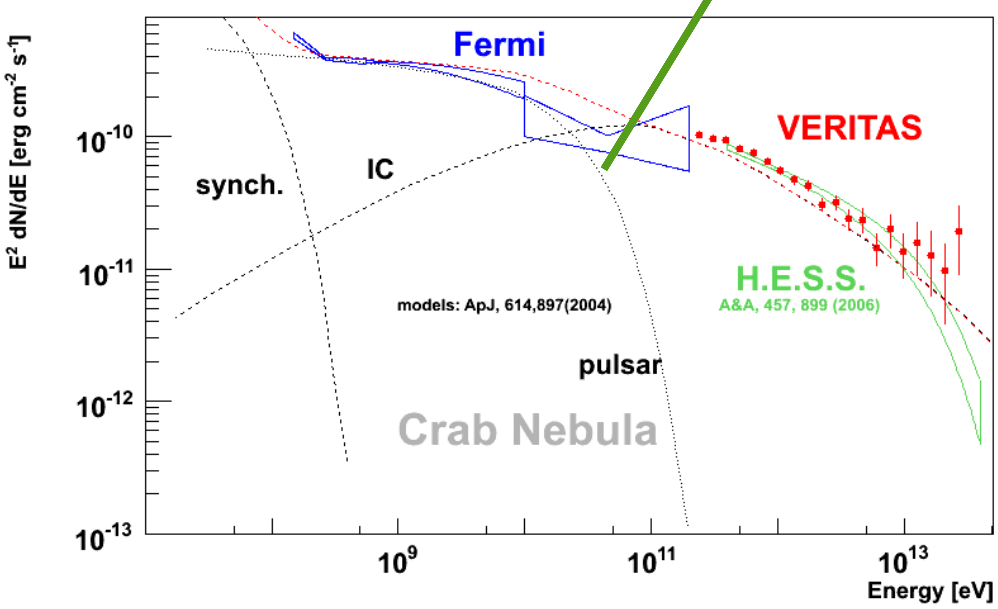
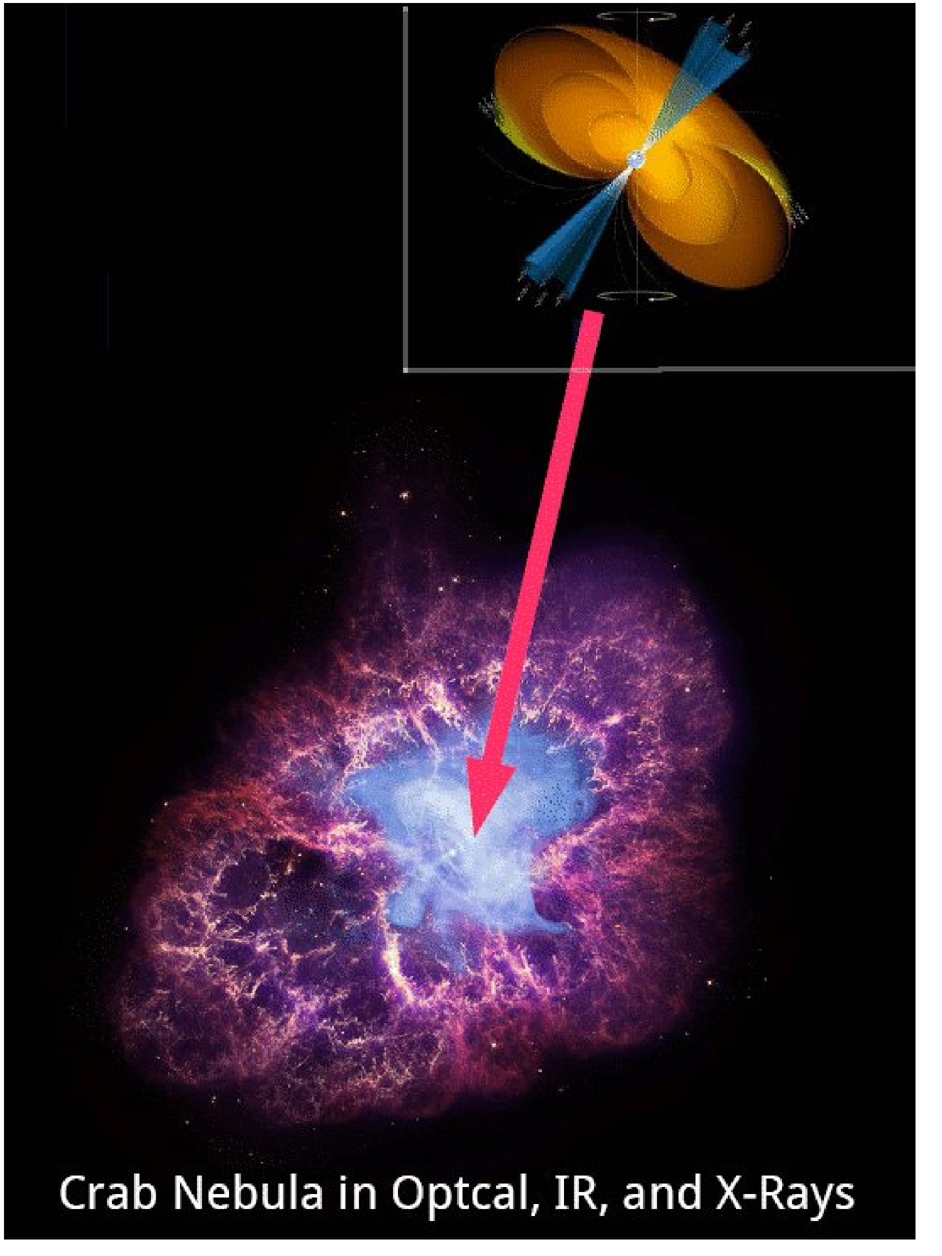
  $4.6 \times 10^{38}$ ergs/s
  (one of the brightest MeV $\gamma$-ray pulsar)
- Powers the Crab nebula
  (one of the brightest TeV $\gamma$-ray source)
- Angular structure < TeV resolution

Question:
high-energy end of pulsar spectrum



# The Crab pulsar: seen above 100GeV

**N.Otte, A.McCann, M.Schroedter**

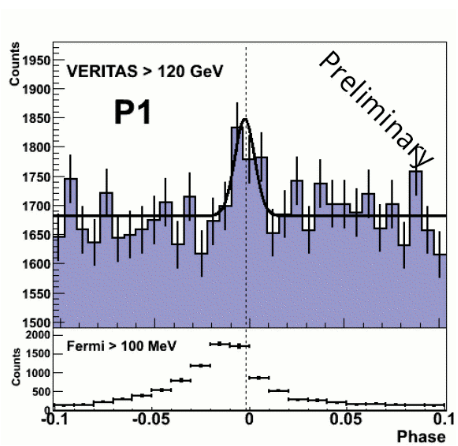
- Understanding so far:
  - spectral break in SED: between 0.1 - 5 GeV:
    Fermi/VERITAS fit: broken power-law favored
  - curvature radiation not favored (E>100GeV)
  - emission from >~~6~~ 10 stellar radii
    (favoring outer gap over polar cap)
- Very recently (paper submitted):
  VERITAS sees pulsar at E>120GeV

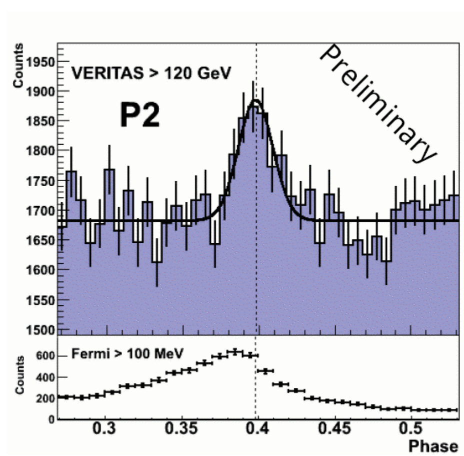
Please see publication

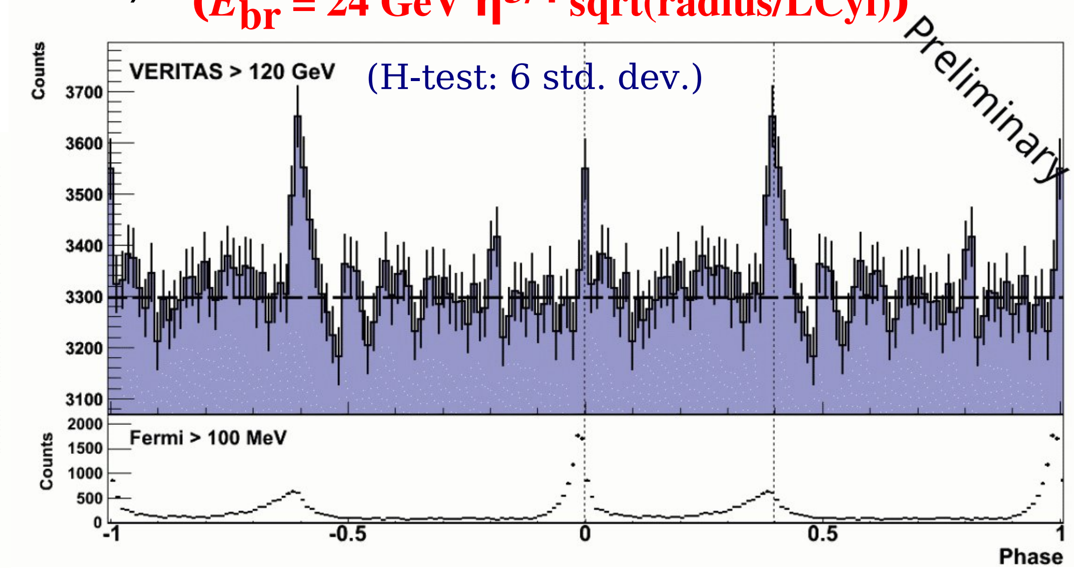
- E>120 GeV pulses:
  - aligned with radio pulses
  - shifted wrt to MeV (Fermi, analysis issue?)
  - 2-3 times narrower than MeV pulses
    (acceleration zone tapers assuming same **B**)
  - spectrum: 1% of nebula, dN/dE ~$E^{-3.8}$

**E>100GeV: curvature rad. unlikely**

**($E_{br}$ = 24 GeV $\eta^{3/4}$ sqrt(radius/LCyl))**

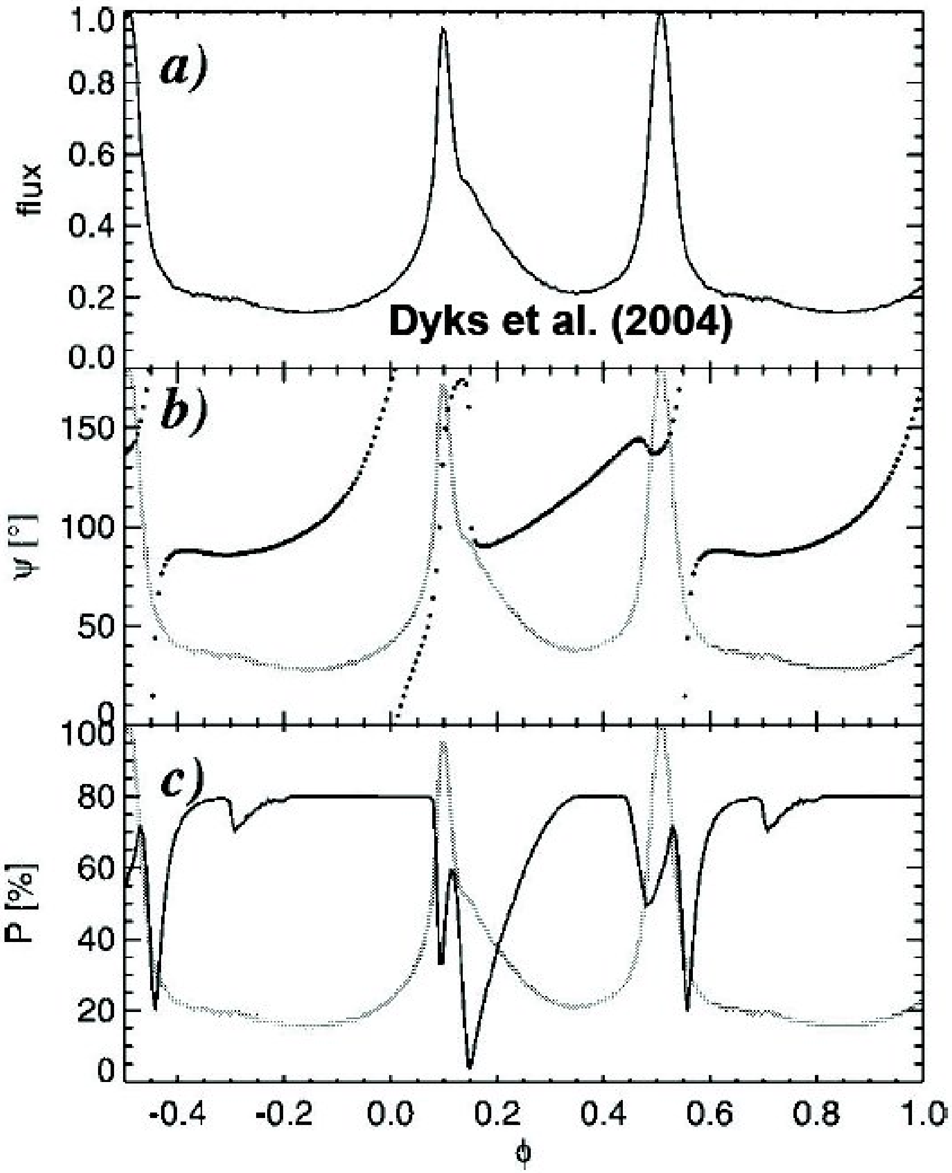


# X-ray Polarization: Future prospects

# Polarization Properties:




## Caustic Radio Emission

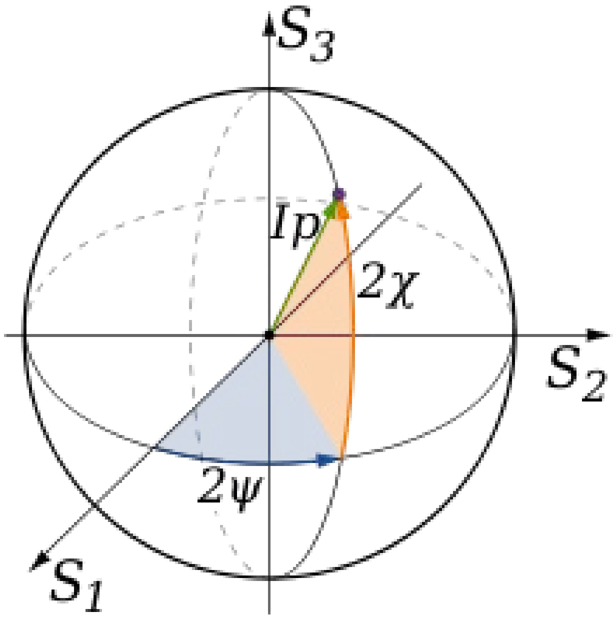
- RVM not really valid for MSPs
- Rapid PA swings
- "Mixing": accumulation of radiation from different positions in magnetosphere - depolarization
- Potential discriminator for caustic vs. non-caustic emission
- Polarization properties of J0034-0534 (0% linear, small circular), J1939+2134 (rapid PA changes / mode switching), & J1959+2048 (0% linear, 4% circular) fit with the caustic hypothesis.

Slide by Venter (Fermi Symposium, Rome 2011)

# Polarized X-rays: missions/status

## Stokes parameters:

- Describing linear ($S_1$,$S_2$) and circular ($S_3$) polarization
- Components of the electric field [unit: flux density].




## Processes resulting in polarized radiation:

- Synchrotron radiation (linear)
- Curvature radiation (circular)
- Thomson scattering & Bremsstrahlung
- Compton scattering off polarized photon field

## X-ray polarimetry: Status

→ Only one dedicated X-ray polarimetry mission so far: OSO-8:
2.6/5.2 keV polarization of the Crab (20%, 30° relative to jet) [ApJ, 220, L117, 1978]

→ INTEGRAL: Crab polarization (0.1-1MeV): ~46% [Science, 321, 1183, 2008]

→ Main difficulty: Need high statistics to determine Stokes parameters

## X-ray polarimetry: Future missions:

→ Gravity and Extreme Magnetism SMEX (GEMS): 2-10 keV (100 x OSO-8) [Swank]

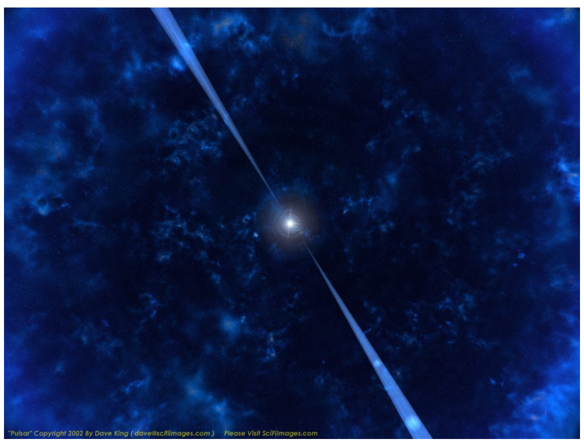
→ Astro-H: E>10 keV, Compton Polarimetry (systematics) [SPIE, 7732, 34, 2010]

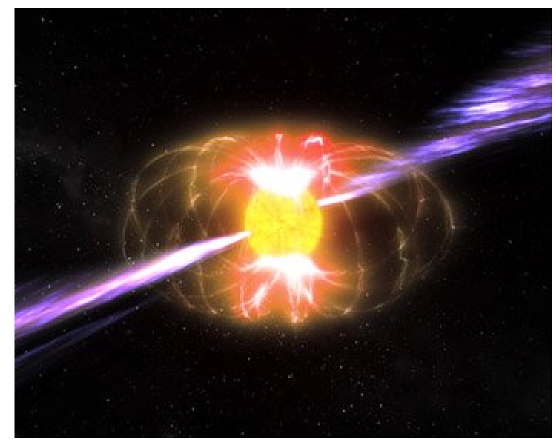
# Polarized X-rays: physics motivation (pulsars)

## Neutron stars, pulsars, PWN & Magnetars:

→ Radiation transfer in strongly magnetized plasmas:
polarization (curvature and/or synchrotron emission), phase & energy dependent.

→ Magnetars, strong magnetic fields (soft $\gamma$-ray repeaters): cyclotron features





**Constrain magnetic field and particle populations**

# X-Calibur: Design

## General idea:

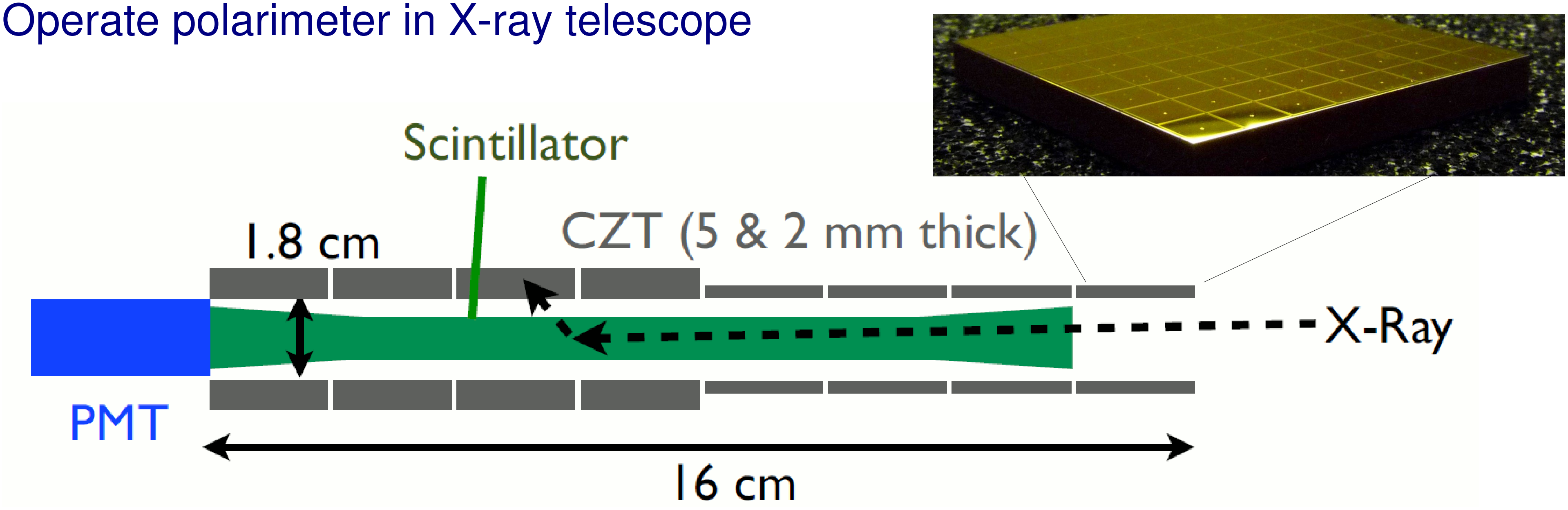
Compton scattering angle (linear polarized X-rays): more likely ⊥ to E field vector

**1:** low-Z Compton scatterer (Az dependence)
**2:** high-Z material to photo-absorb
**3:** Signature in distribution of scattering angles

**High fraction of unambiguously identified Compton scatter events**

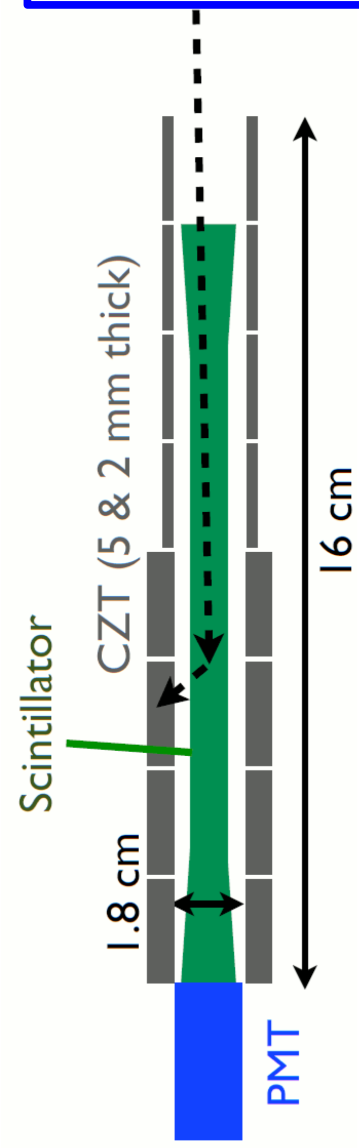
## X-Calibur polarimeter design:

→ Scintillator slab (low-Z Compton scatterer)
→ Detect scattered X-rays: high-Z CZT crystals
→ Operate polarimeter in X-ray telescope

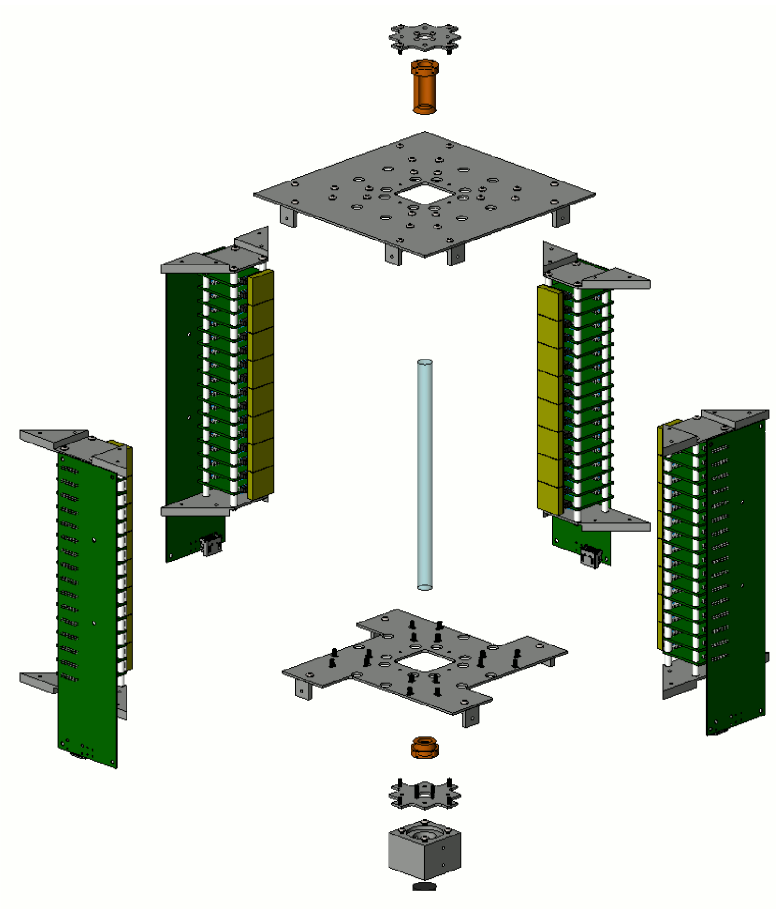


# X-Calibur: Design drawings

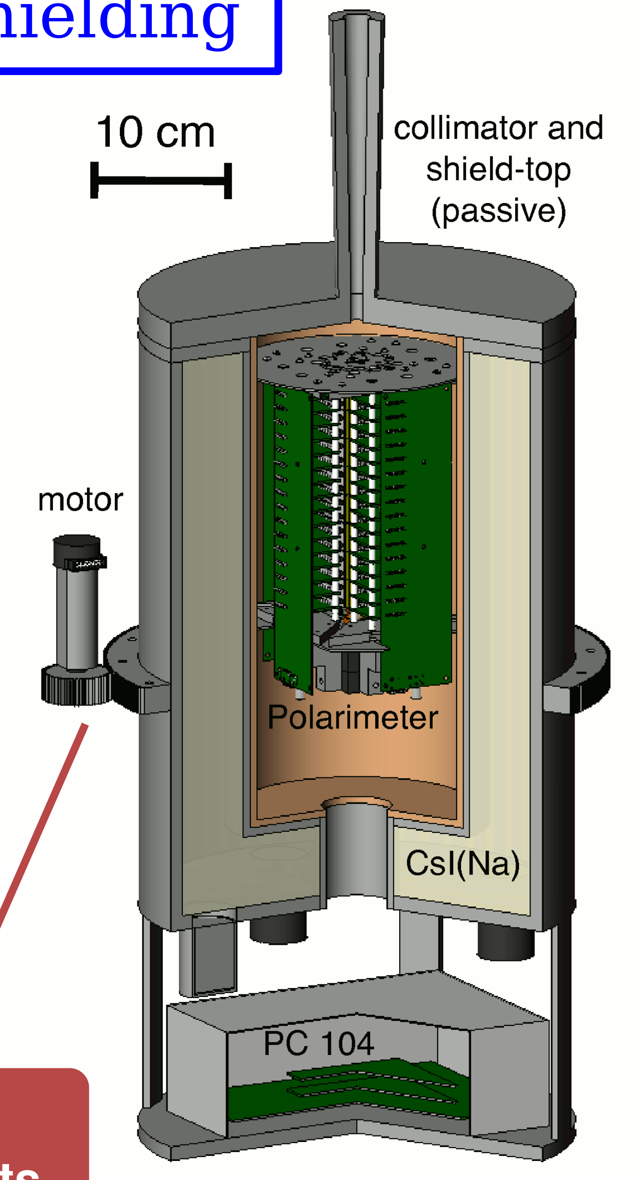
schematic




X-Calibur

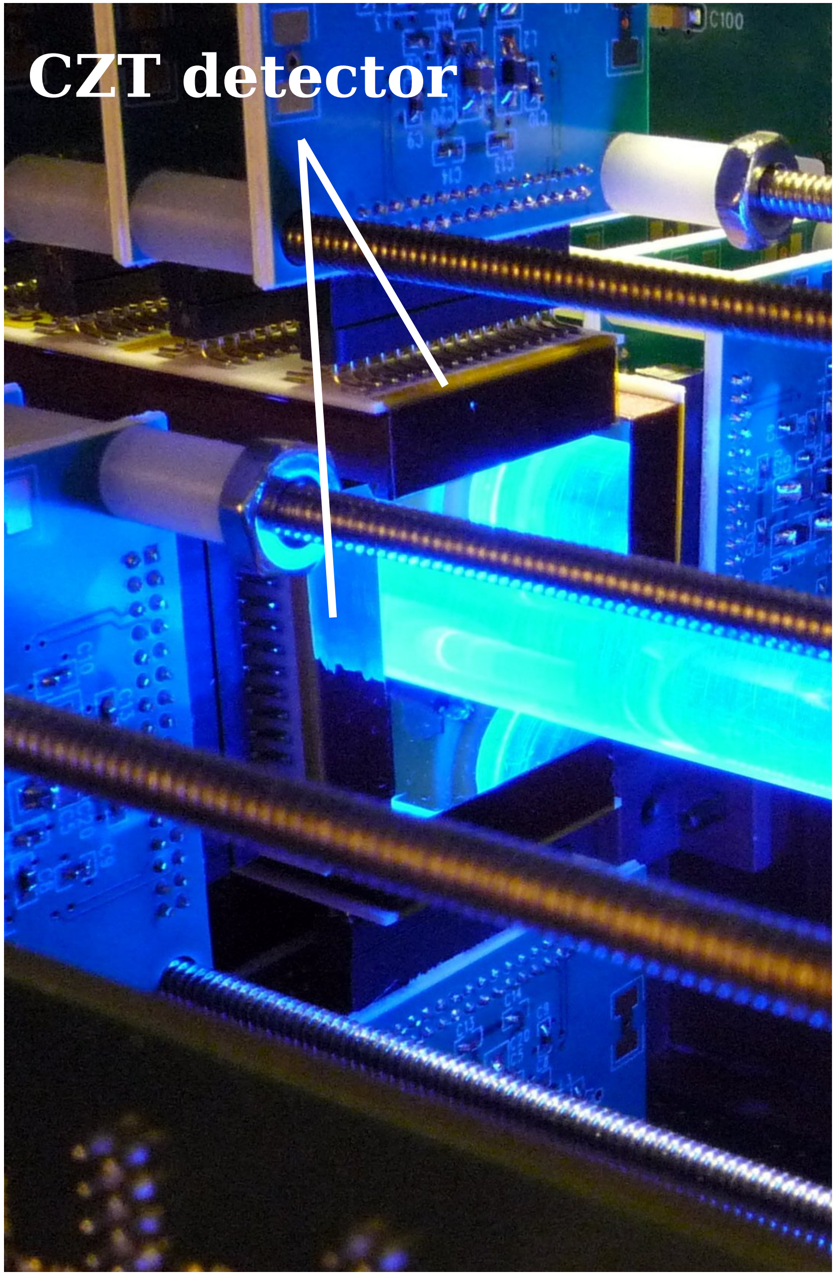


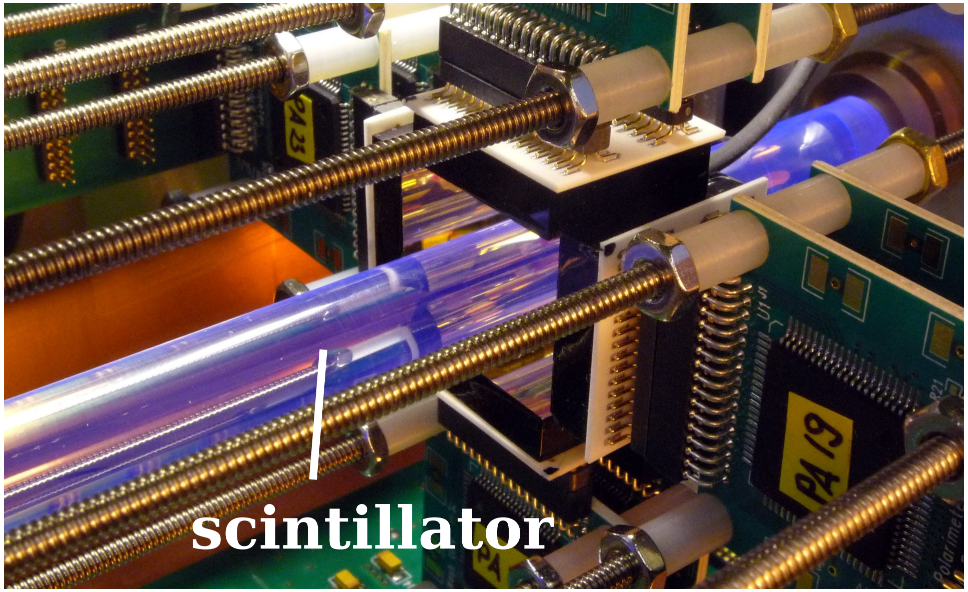
shielding

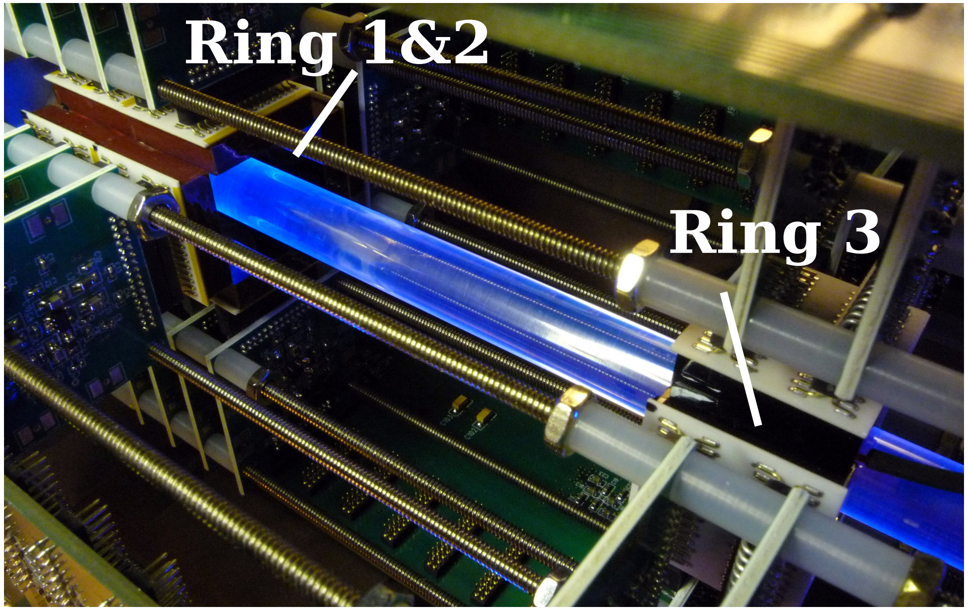



**Rotation mechanism: Reduce systematic effects**

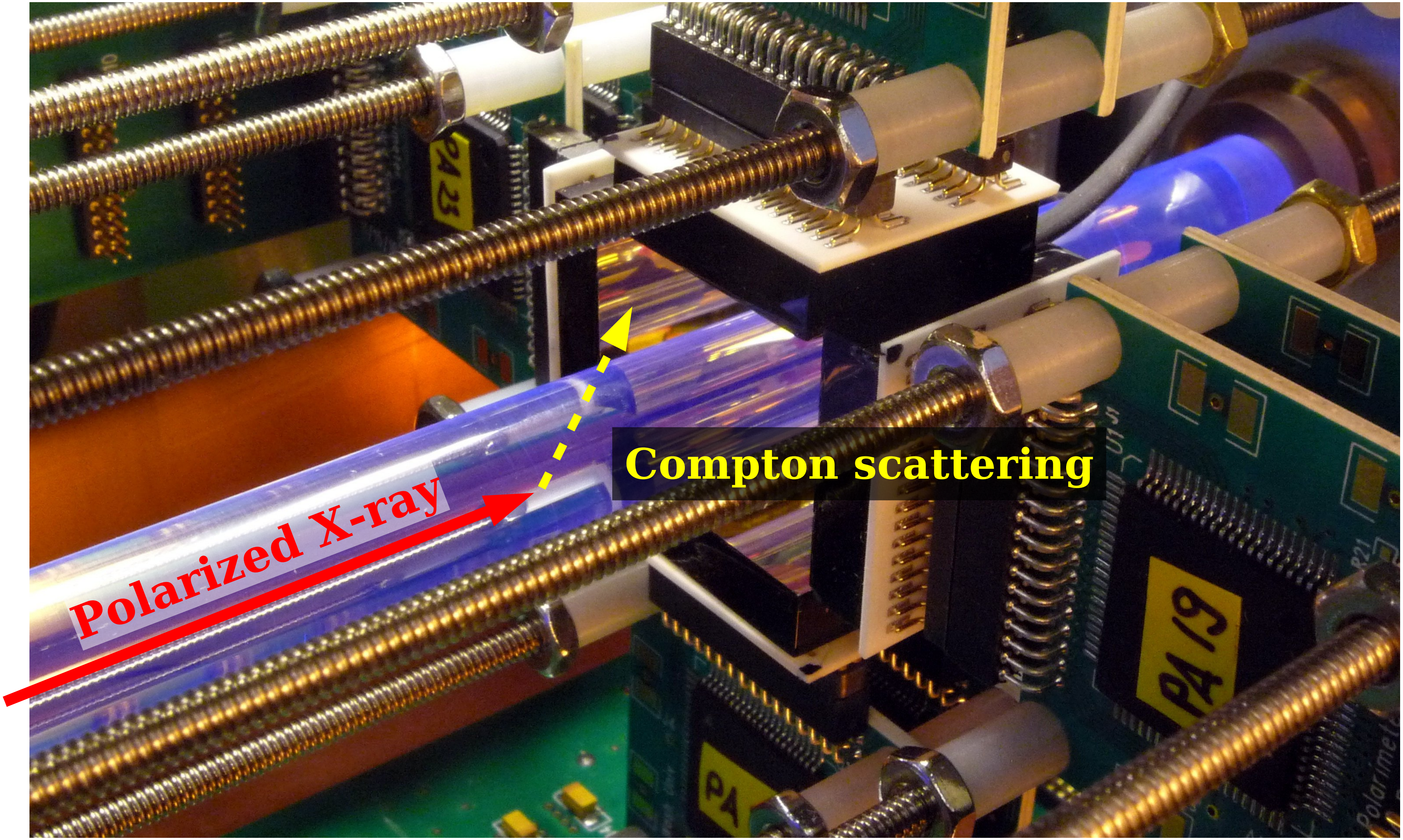
# X-Calibur: Design (prototype in the lab)



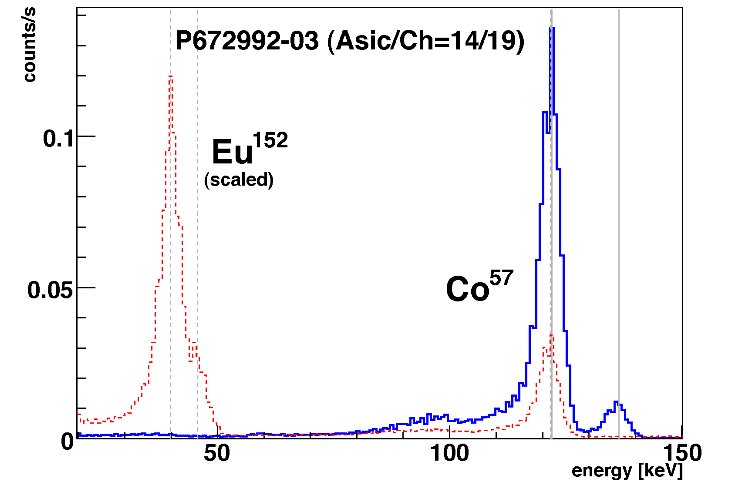
# X-Calibur: First measurement 1/3



# X-Calibur: First measurement 2/3

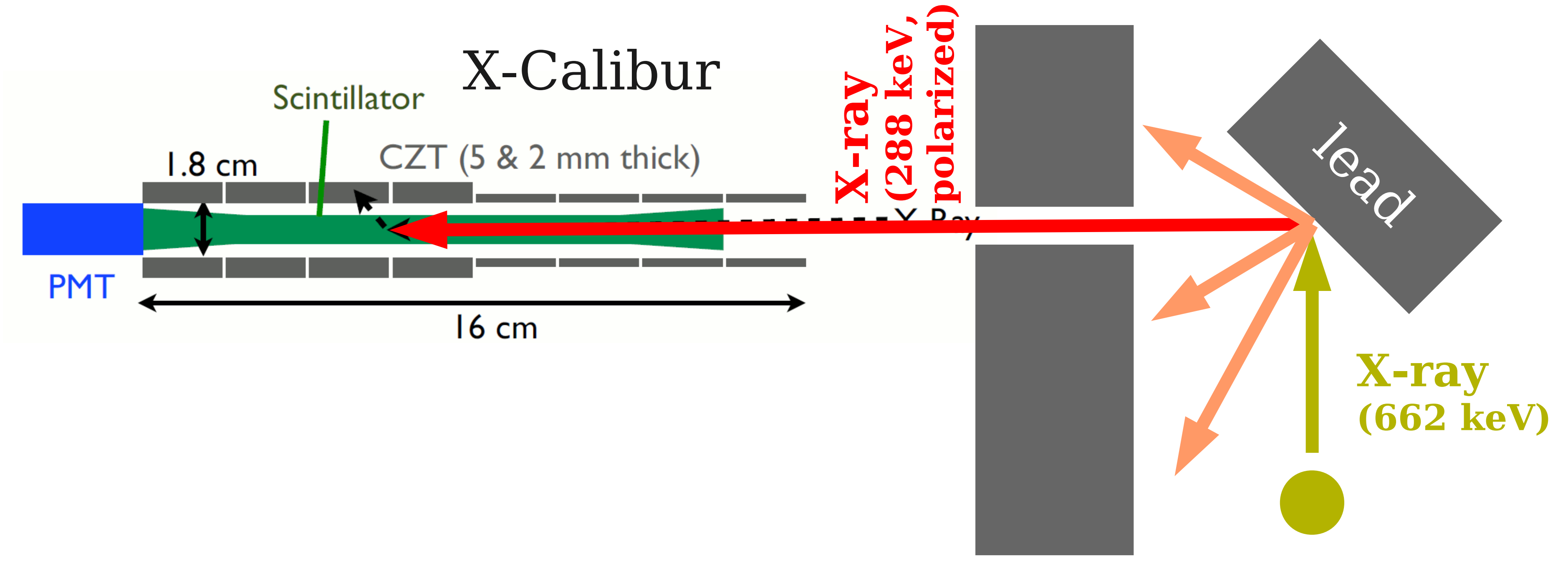
## Calibrate X-Calibur:

→ Calibrate CZT detectors with Eu[157] source
(4.1 keV FWHM @ 40keV and 5.0 keV FWHM @ 122keV)
→ Azimuthal acceptance: unpolarized Eu[157] beam




## Measure polarized beam:

→ Scatter Cs[137] source (662 keV) off lead brig
→ Collimator: only allow 90deg scattering angle
→ Entering X-Calibur: 288 keV polarized beam



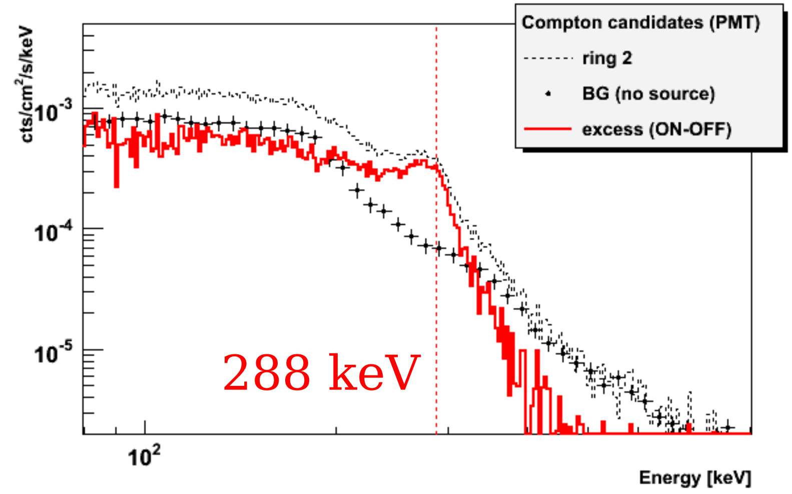
# X-Calibur: First measurement (results)

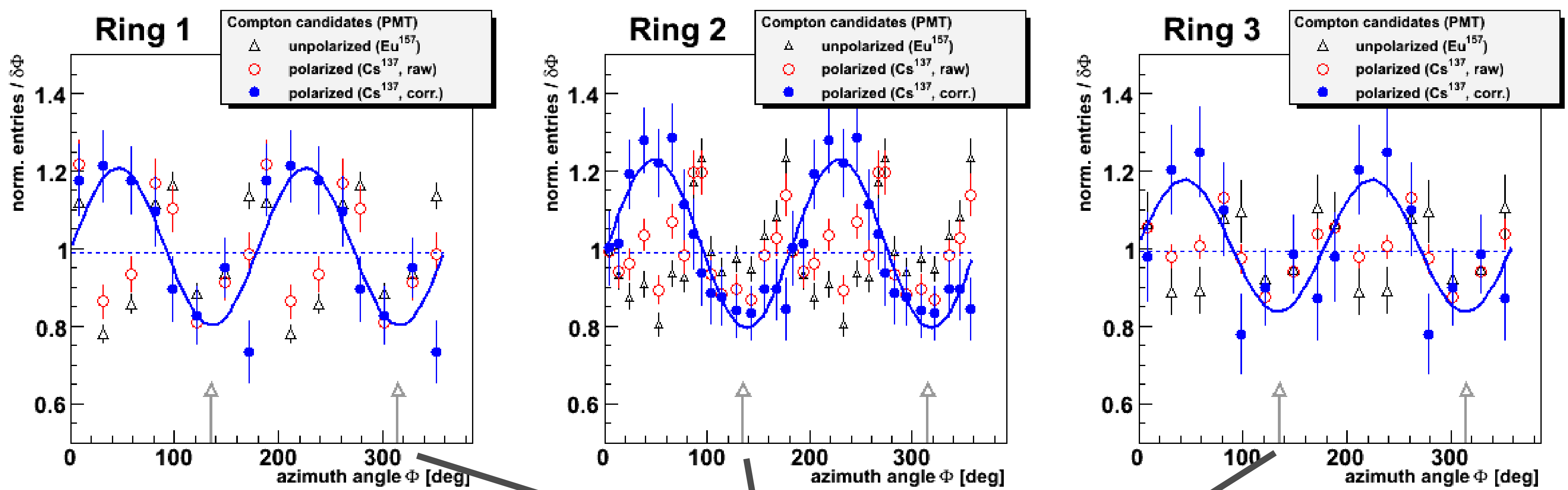
## Azimuthal scattering distribution:

→ Incoming beam: 288keV, 55% polarized, μ=0.4
→ Only PMT/CZT coincidence (Compton) events
→ Correct for azimuthal angle covered
→ Correct for azimuthal detector acceptance

**Measurements in agreement with expectations**

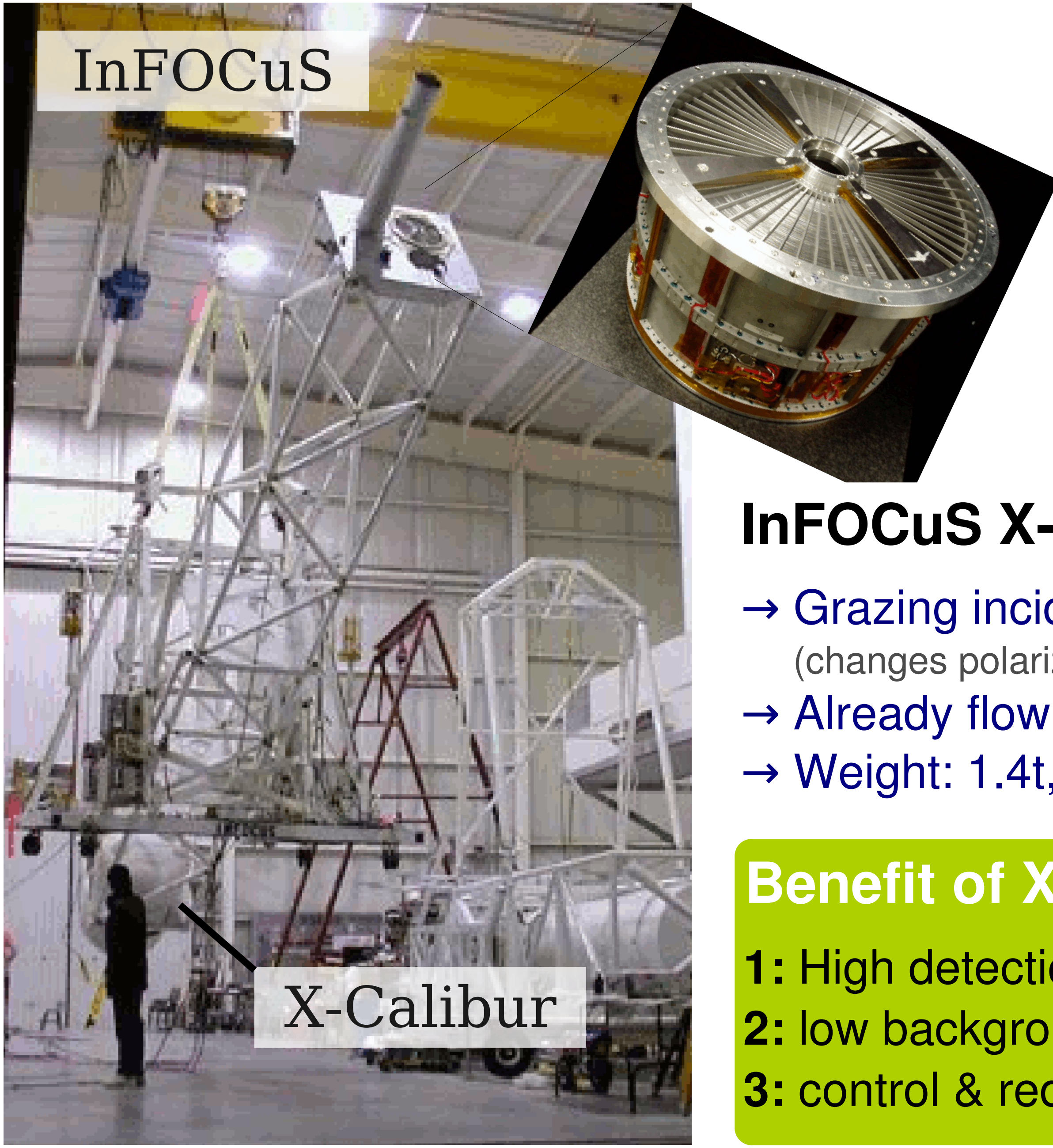
Compton-scatter spectrum

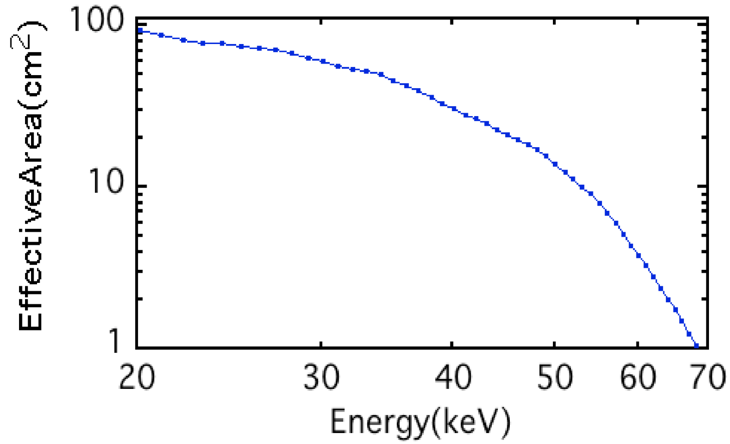



Plane of E field of polarized beam

# X-Calibur: Operate in InFOCuS X-ray telescope




## InFOCuS X-ray telescope:

→ Grazing incidence Wolter X-ray mirror
(changes polarization by <1%, Katsuta et al. 2009)

→ Already flown successfully (Tueller et al.)

→ Weight: 1.4t, focal length: ~8m

**Benefit of X-Calibur/InFOCuS:**

**1:** High detection efficiency (80% of photons)

**2:** low background (focusing, low CZT volume)

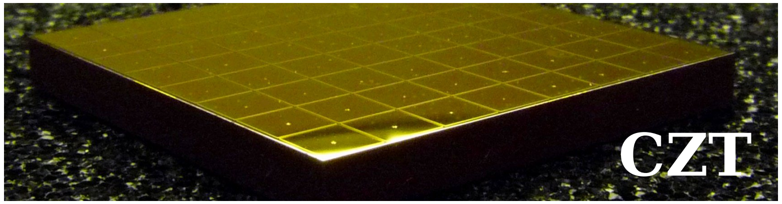
**3:** control & reduction of systematics (rotation)

# Backup slides

# X-Calibur: Design (scatterer and absorber)

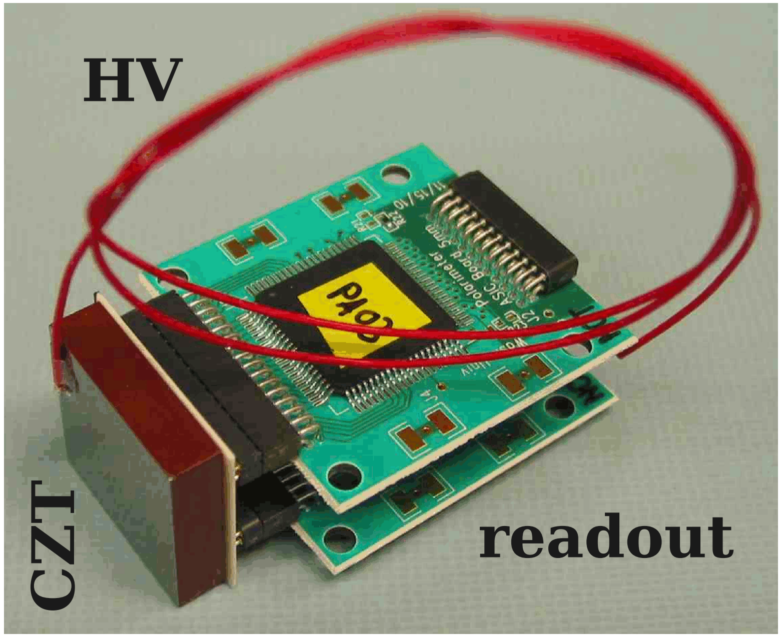
## Low-Z Compton scatterer:

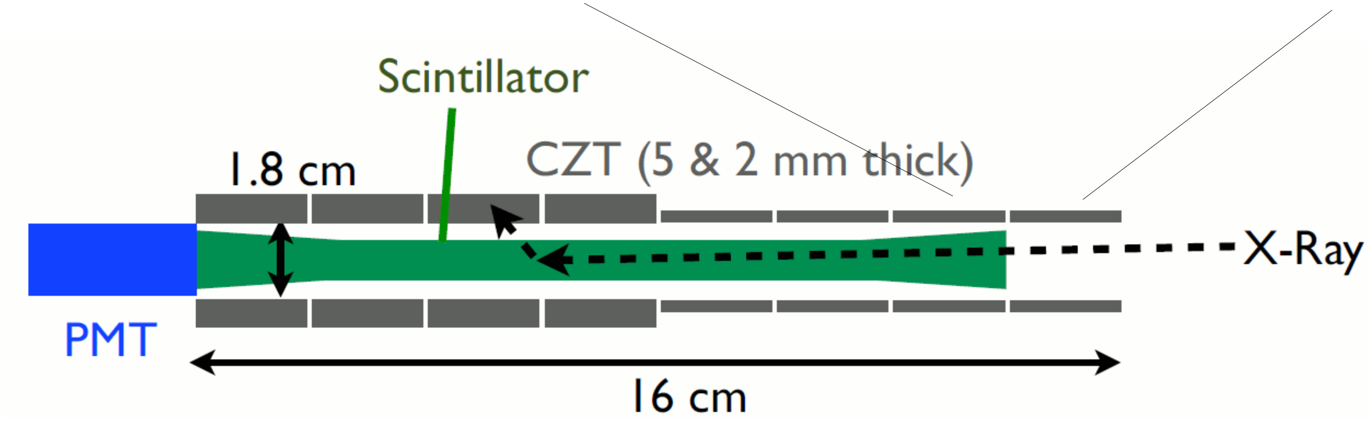
→ Scintillator rod (EJ-200, 16cm, $\rho \sim 1 g/cm^3$)
→ 80keV X-rays Compton-scatter (p>90%)
→ scintillator read by PMT (Hamamatsu R7600U)




## High-Z photo absorber:

→ $2x2\ cm^2$ CZT crystals (8x8 pixel anode)
Endicott Interconect, Quikpak/Redlen, Creative Electron
→ Bonded to ceramic chip carrier
→ Read by ASIC (G. DeGeronimo & E. Wulf)



# X-Calibur: Simulations

## Simulate X-Calibur performance:

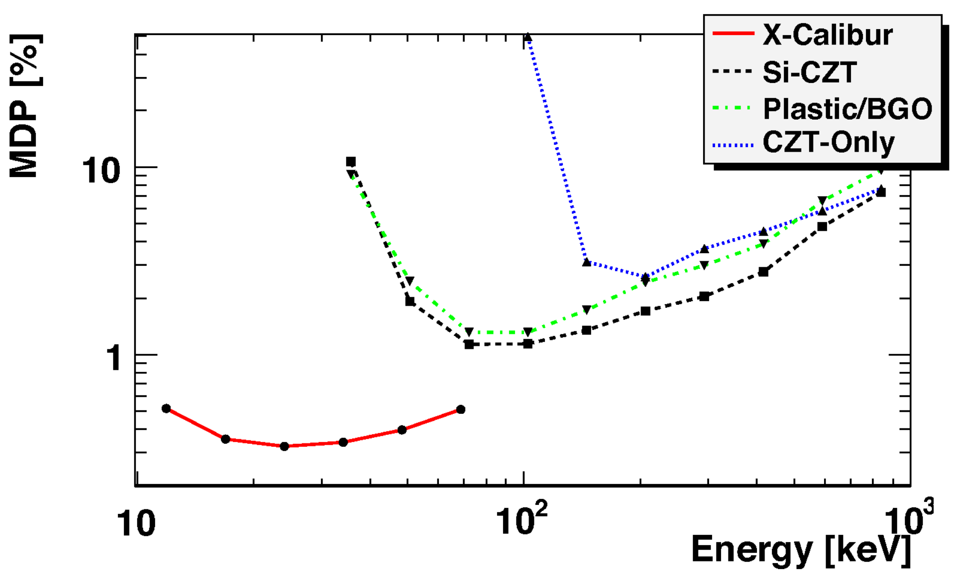
→ Use Geant4 package with Livermore model
(http://geant4.cern.ch)

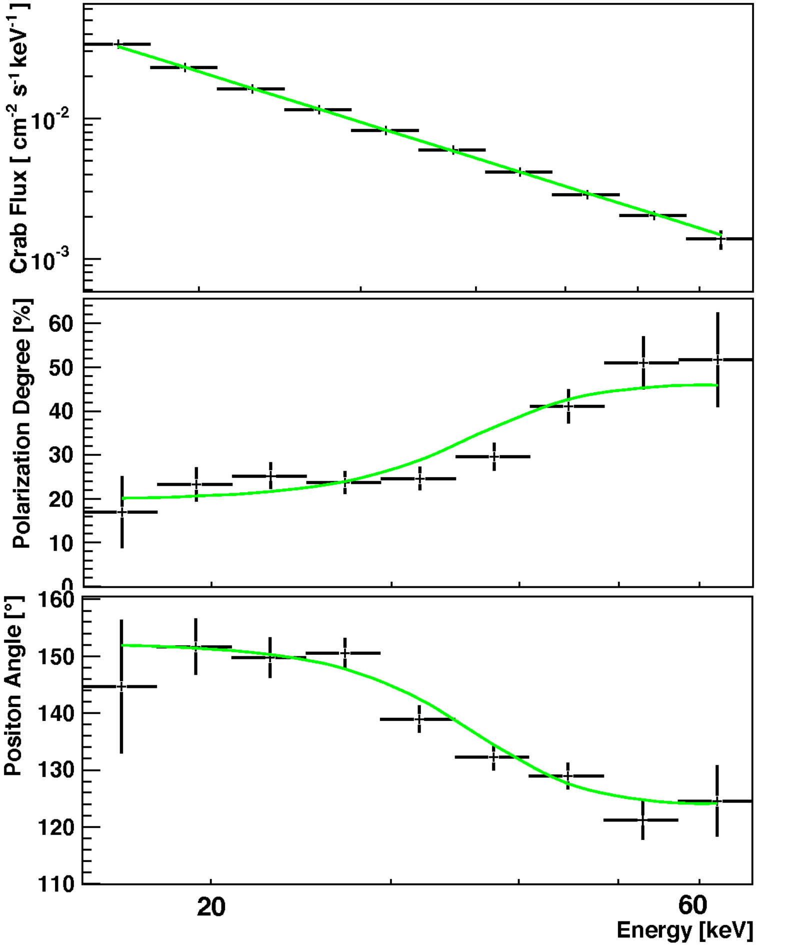
→ Assume X-Calibur/InFOCuS flight (5.6hrs)

→ Assume Crab-like source:
energy-dependent polarization degree and angle
ApJ, 220, L117 (1978) and Science, 321, 1183 (2008)

## Compare to competing designs:

→ See Guo et al: arXiv 1101.0595 (2010)




**X-Calibur:**
**detection efficiency > 80%**
**modulation factur μ~0.5**