Pushing the boundaries of Pulsar halo observations:

Geminga and LHAASO J0621+3755

Jooyun Woo (Columbia University) on behalf of
Silvia Manconi, Ruo-Yu Shang, Roman Krivonos, Claudia Tang, Mattia Di Mauro, Fiorenza Donato, Kaya Mori, Chuck Hailey (for Geminga)
VERITAS collaboration, Jon Kwong, Kaya Mori, Chuck Hailey, Samar Safi-Harb, Shuo Zhang, Naomi Tsuji, Silvia Manconi, Fiorenza Donato, Mattia Di Mauro (for LHAASO J0621+3755)

Nov 4, 2025 – TeVPA @ Valencia, Spain

Importance of observing pulsar halos, particularly in the VHE (with IACTs) and X-ray bands

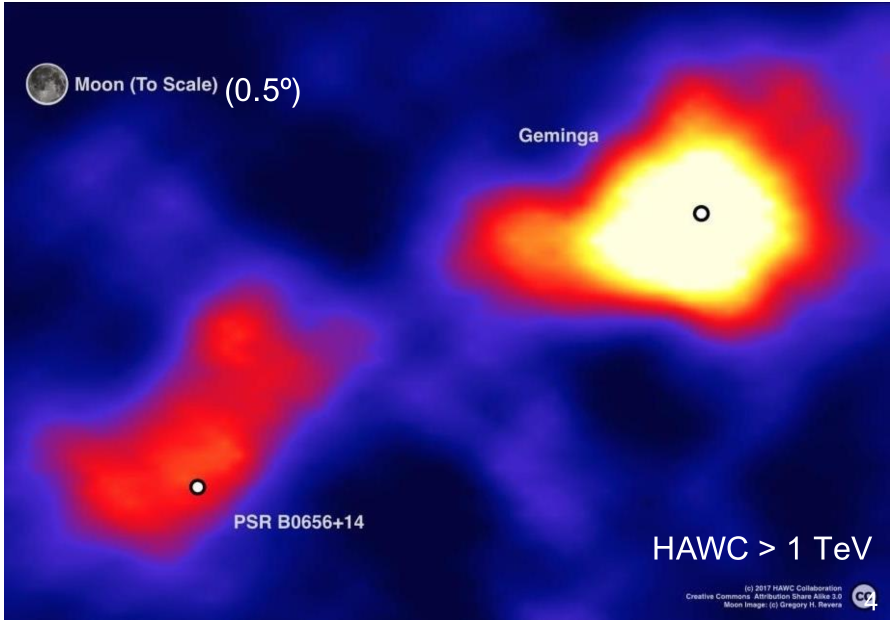
- **Inverse-Compton (TeV) halo around old (> 100 kyr) pulsars**
- Insights into **particle transport** around an accelerator
    - Function of (1) **particle energy** (2) **magnetic field** derived from observations of
      (1) Energy-dependent morphology (**VHE band with IACTs**)
      (2) Synchrotron halo (**X-ray band** – most compact & brightest)
- Emerging source class → population study to establish statistics

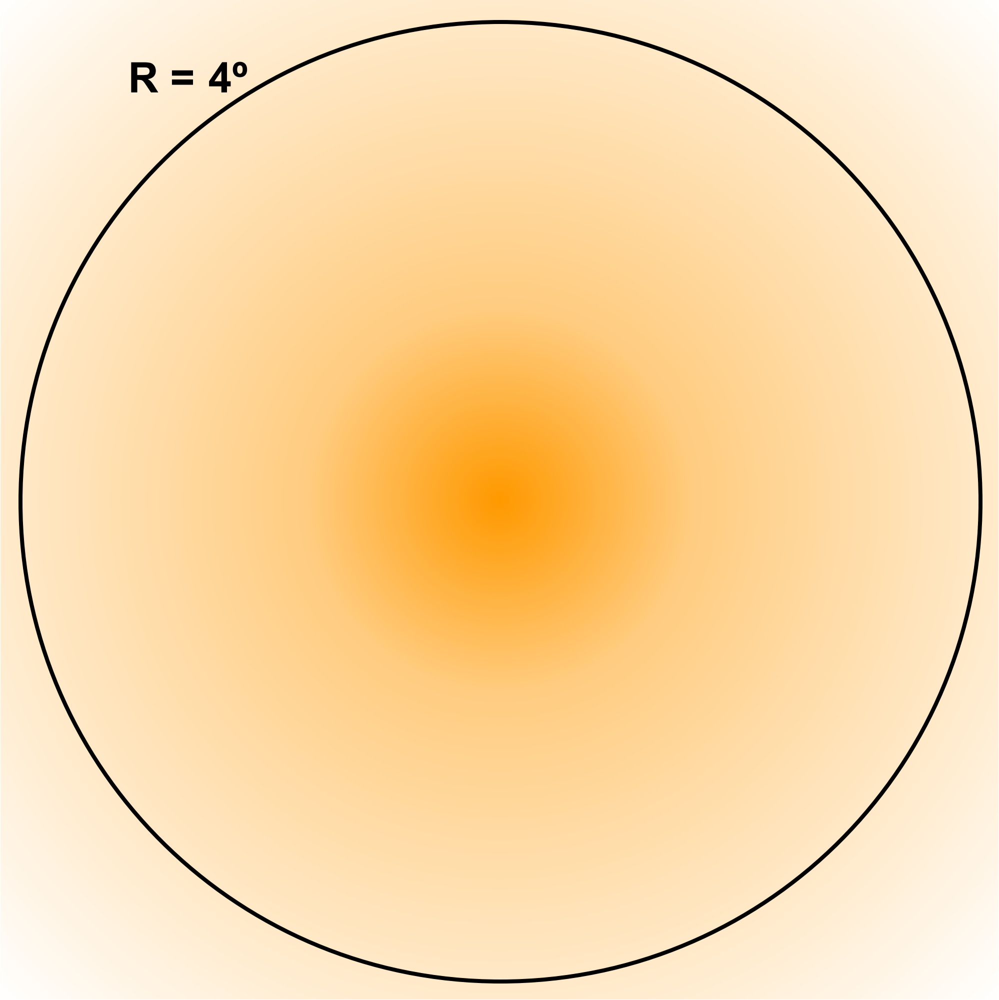
Challenges of observing pulsar halos with IACTs and X-ray telescopes

- Halo size (several degrees) vs. **limited telescope FoV**
  - VERITAS: R = 1.7º, NuSTAR: R = 7’
  - **Difficulties in background estimation**
- Overcome the challenges by
  - **Geminga**: utilize **NuSTAR stray lights** → expand **FoV to R = 4º**
  - **LHAASO J0621+3755**: accurate **VERITAS acceptance** modeling → background estimation using **minimal source-free region**
- $$\left.\begin{array}{r}\text{NuSTAR / VERITAS observation}\\ \textbf{Theoretical modeling (morphology, spectrum)}\end{array}\right\} \Rightarrow \left\{\begin{array}{l}\textbf{Diffusion coefficient}\\ \textbf{Magnetic field}\end{array}\right.$$

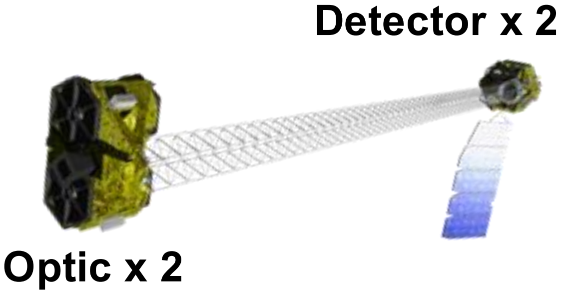
NuSTAR observation of the **Geminga halo**

- Geminga pulsar: τ = 342 kyr, $\dot{E} = 3.3 \times 10^{34}$ erg s^{-1}, d = 250 pc
- **Halo ~ several degrees in TeV** discovered with MGRO, detected with HAWC, Fermi-LAT, HESS, LHAASO
- X-ray non-detections with Chandra, XMM-Newton, eROSITA
  - Narrow energy & spatial coverage, shallow exposure
- **We utilized archival NuSTAR data from 2012 (total exposure 94 ks)**





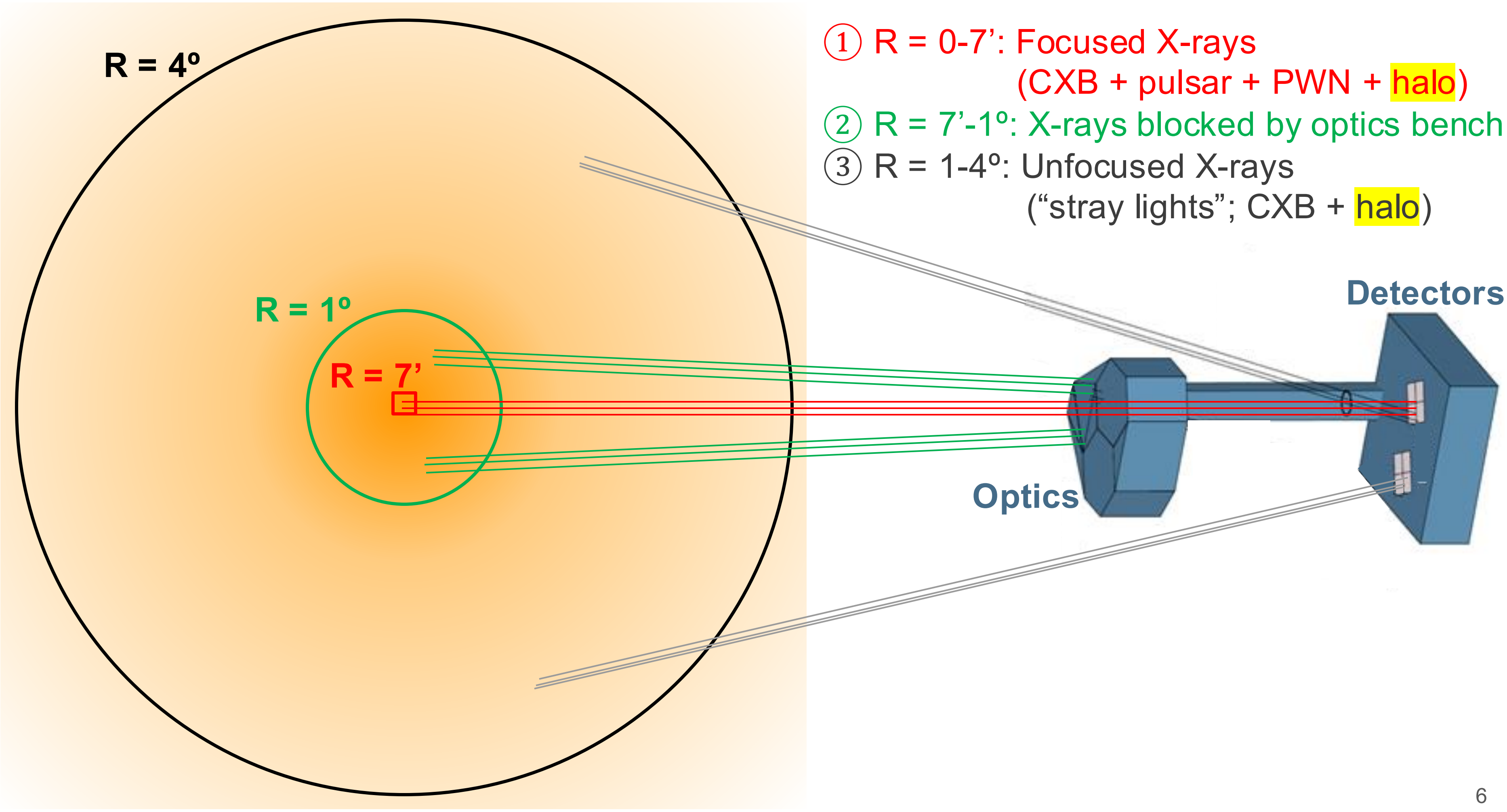
Observing synchrotron halo with NuSTAR

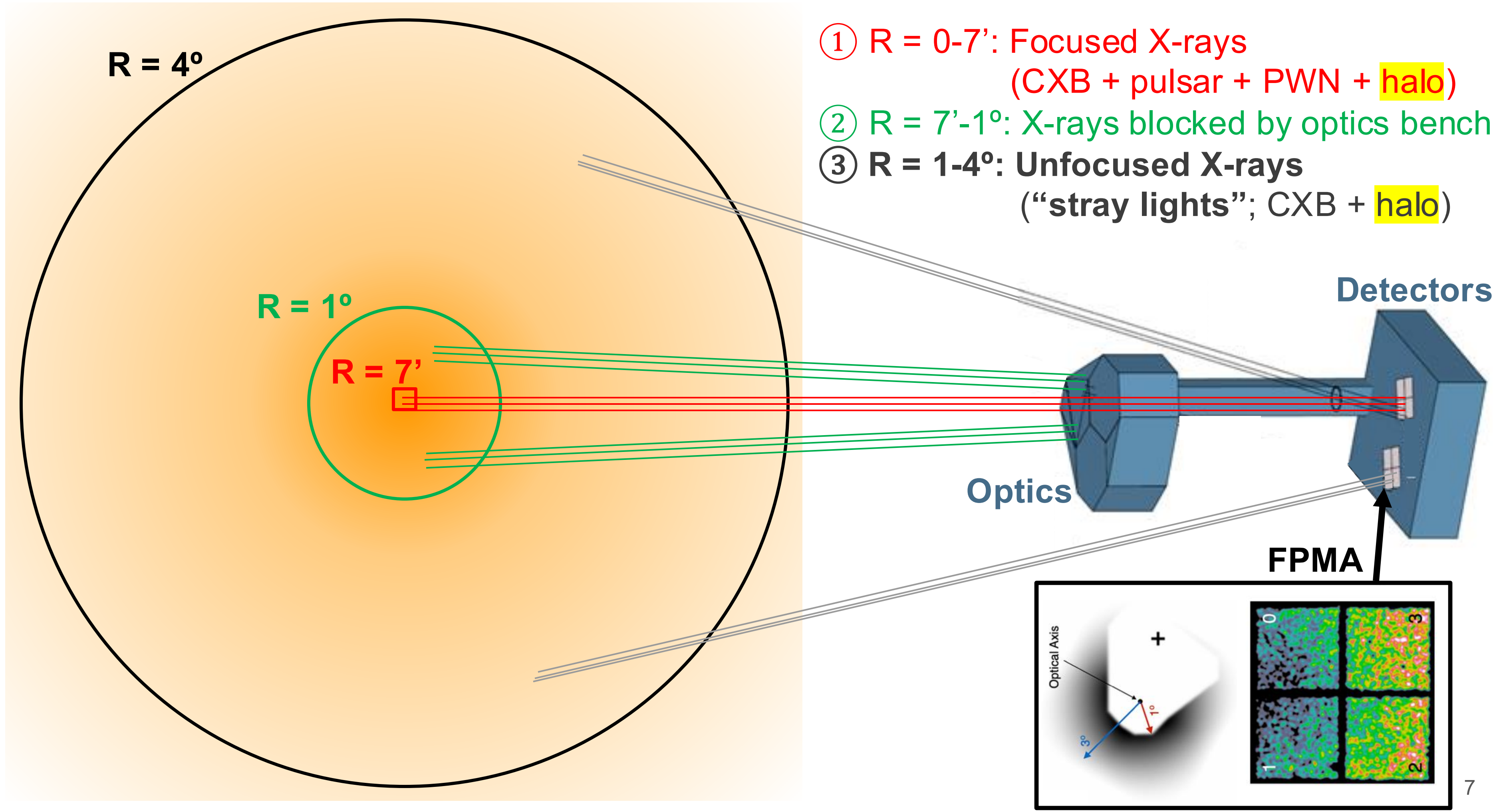


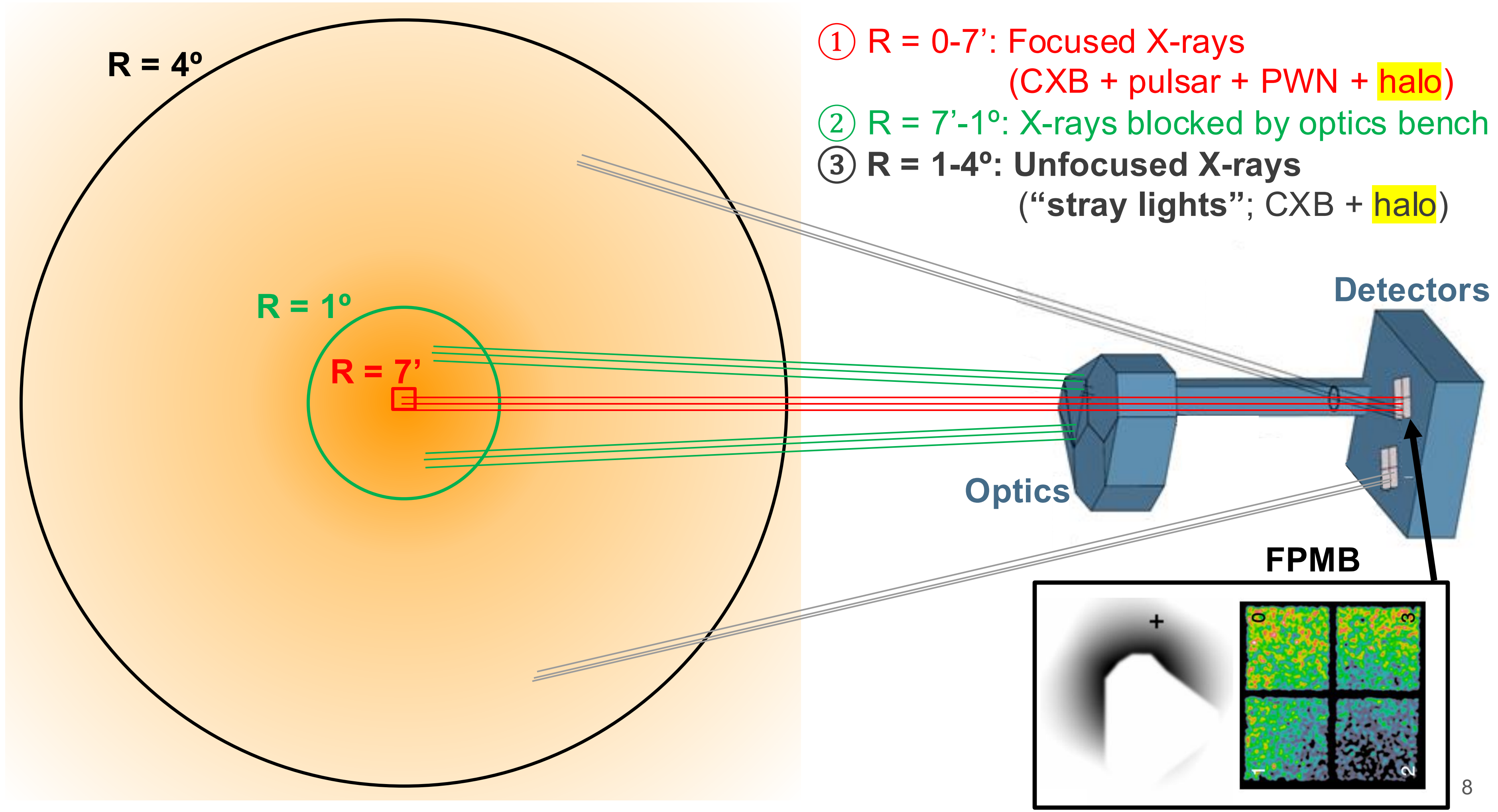
① R = 0-7’: Focused X-rays (CXB + pulsar + PWN + halo)

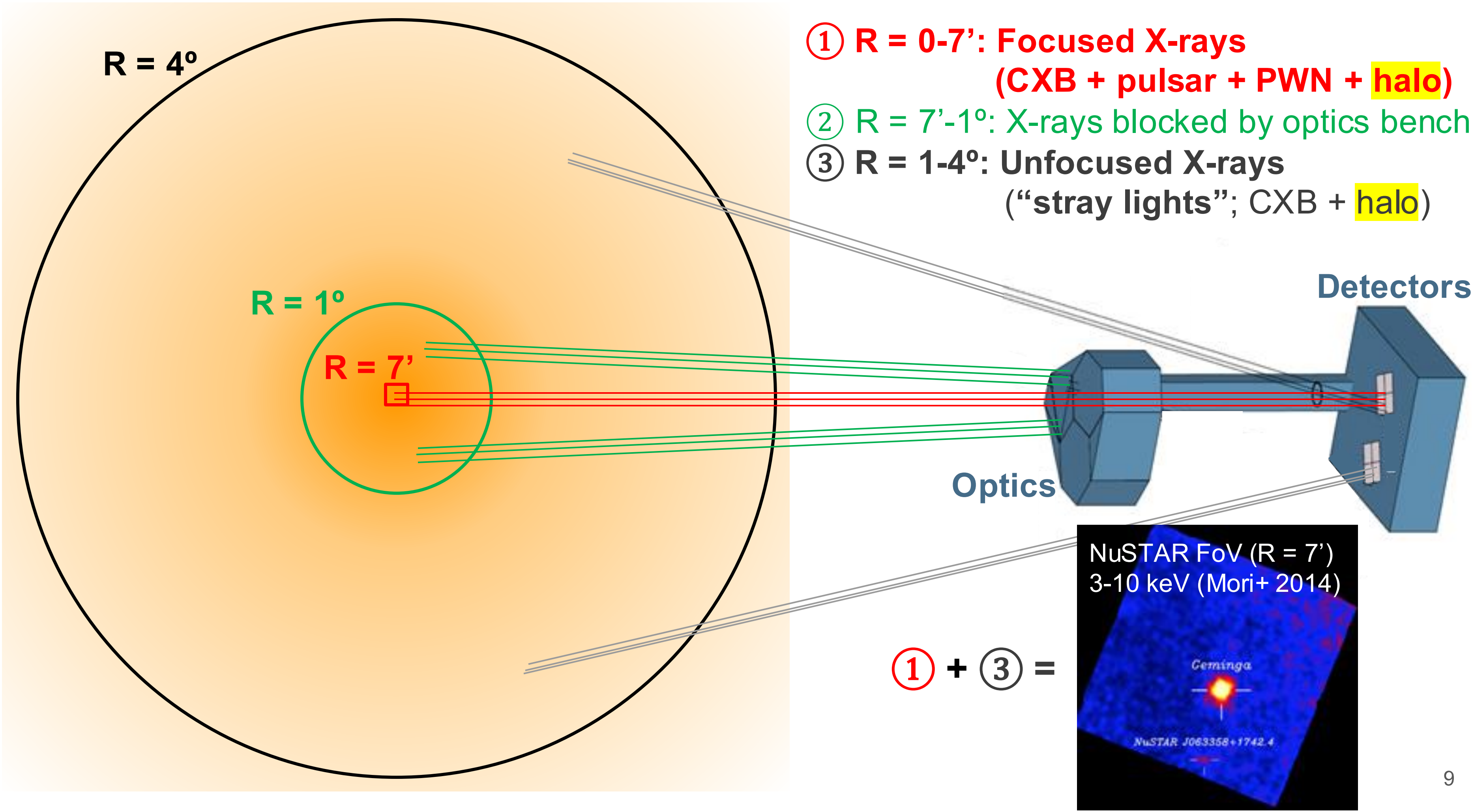
② R = 7’-1º: X-rays blocked by optics bench

③ R = 1-4º: Unfocused X-rays (“stray lights”; CXB + halo)



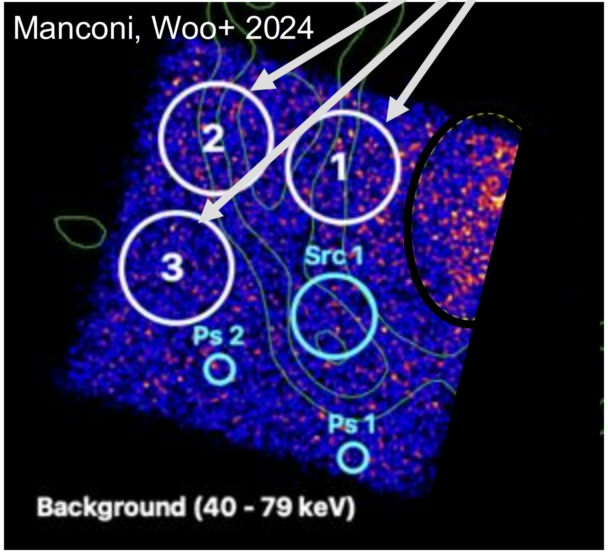

① R = 0-7’: Focused X-rays
(CXB + pulsar + PWN + halo)
② R = 7’-1º: X-rays blocked by optics bench
③ R = 1-4º: Unfocused X-rays
(“stray lights”; CXB + halo)
R = 4º
R = 1º
R = 7’
Detectors
Optics
FPMA
Optical Axis
1º
3º
0
1
2
3


① R = 0-7': Focused X-rays
(CXB + pulsar + PWN + halo)
② R = 7'-1°: X-rays blocked by optics bench
③ R = 1-4°: Unfocused X-rays
("stray lights"; CXB + halo)
R = 4°
R = 1°
R = 7'
Detectors
Optics
FPMB

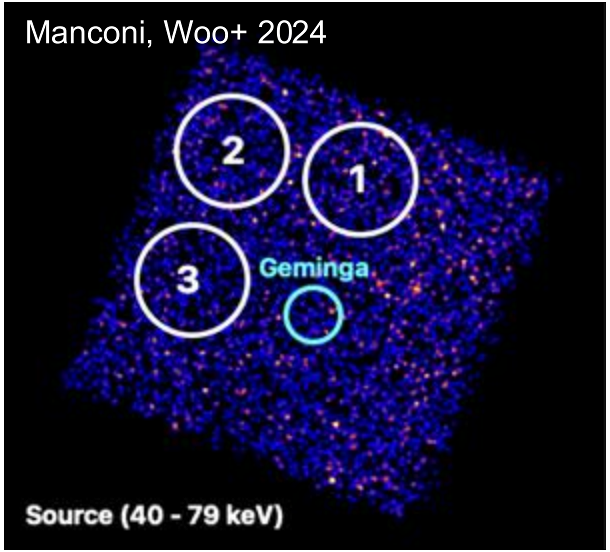

① R = 0-7': Focused X-rays
(CXB + pulsar + PWN + halo)
② R = 7'-1º: X-rays blocked by optics bench
③ R = 1-4º: Unfocused X-rays
("stray lights"; CXB + halo)
R = 4º
R = 1º
R = 7'
Detectors
Optics
NuSTAR FoV (R = 7')
3-10 keV (Mori+ 2014)
Geminga
① + ③ =

Modeling the mixture of focused (source+background) and unfocused (source + background) in NuSTAR FoV (R = 7')

① R = 0-7': Focused X-rays (CXB + pulsar + PWN + halo)
③ R = 1-4°: Unfocused X-rays ("stray lights"; CXB + halo)



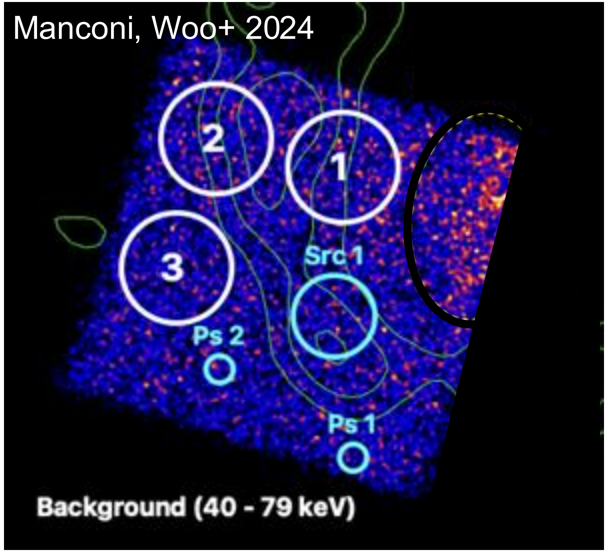
Nearby (6°) observation (IC 443)



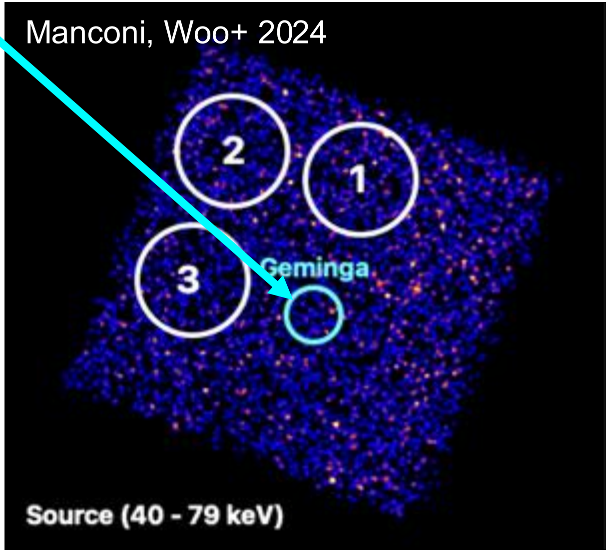
Geminga observation

Modeling the mixture of focused source+background and unfocused source + background in NuSTAR FoV (R = 7')

① R = 0-7': Focused X-rays (CXB + pulsar + PWN + halo)
③ R = 1-4º: Unfocused X-rays ("stray lights"; CXB + halo)



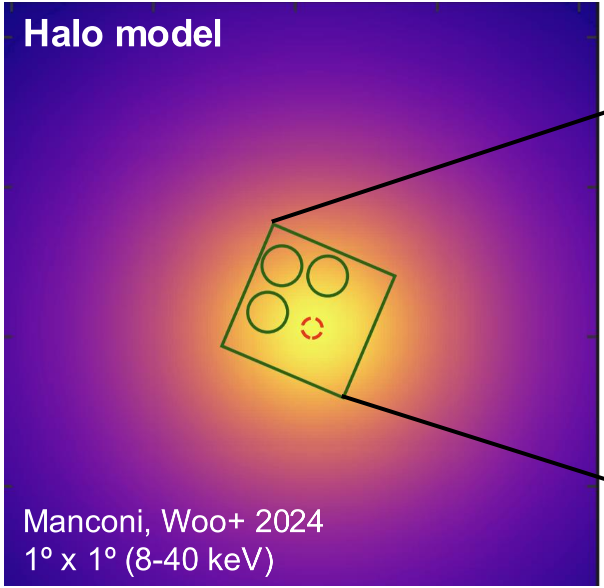
Nearby (6º) observation (IC 443)



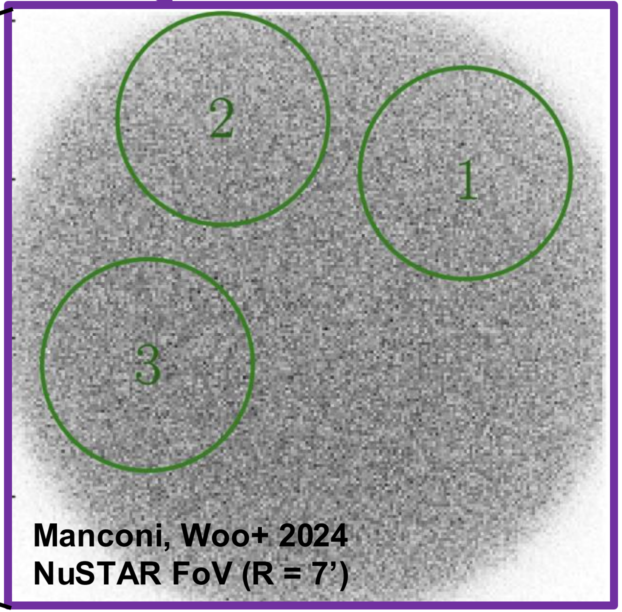
Geminga observation

Modeling the mixture of focused source+background and unfocused source + background in NuSTAR FoV (R = 7')

① R = 0-7': Focused X-rays (CXB + pulsar + PWN + halo)
③ R = 1-4º: Unfocused X-rays ("stray lights"; CXB + halo)



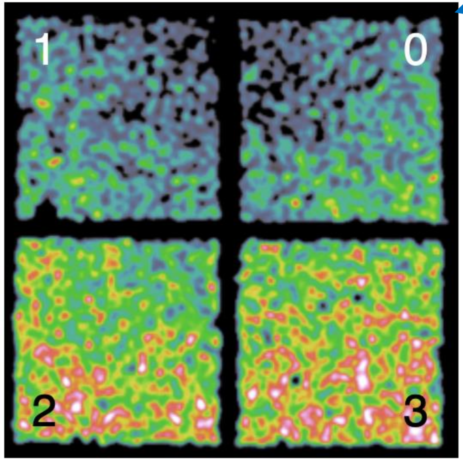
Ray tracing (SIXTE)



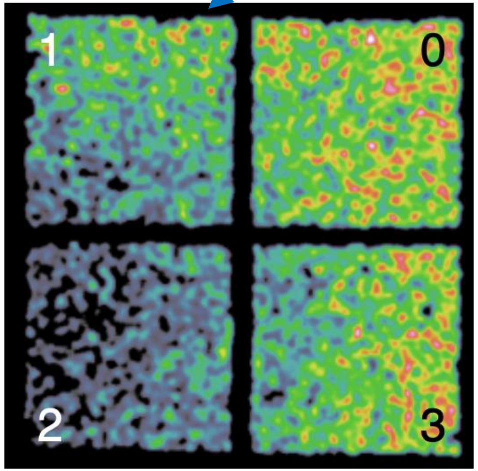
Modeling the mixture of focused source+background and unfocused source + background in NuSTAR FoV (R = 7’)

① R = 0-7’: Focused X-rays (CXB + pulsar + PWN + halo)
③ R = 1-4º: Unfocused X-rays (“stray lights”; CXB + halo)

Stray-light template ⊗ isotropic CXB



FPMA

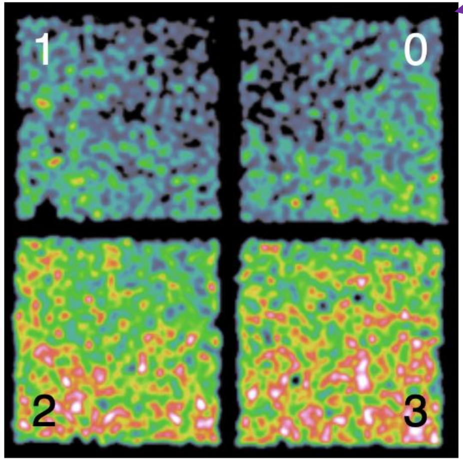


FPMB

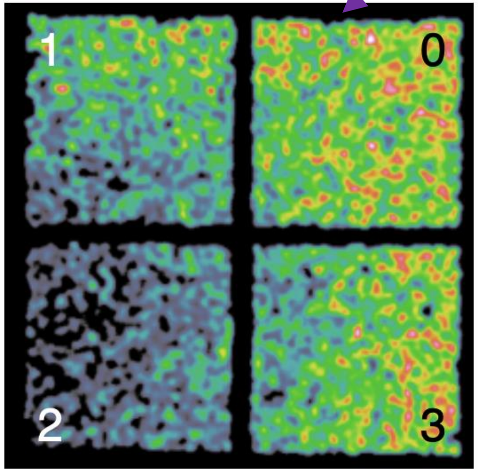
Modeling the mixture of focused source+background and unfocused source + background in NuSTAR FoV (R = 7’)

① R = 0-7’: Focused X-rays (CXB + pulsar + PWN + halo)
③ R = 1-4º: Unfocused X-rays (“stray lights”; CXB + halo)

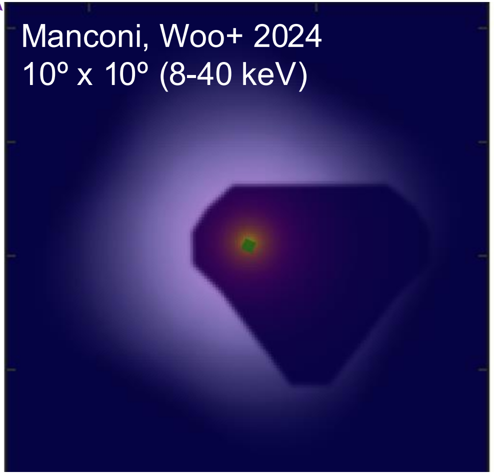
Stray-light template ⊗ halo model



FPMA

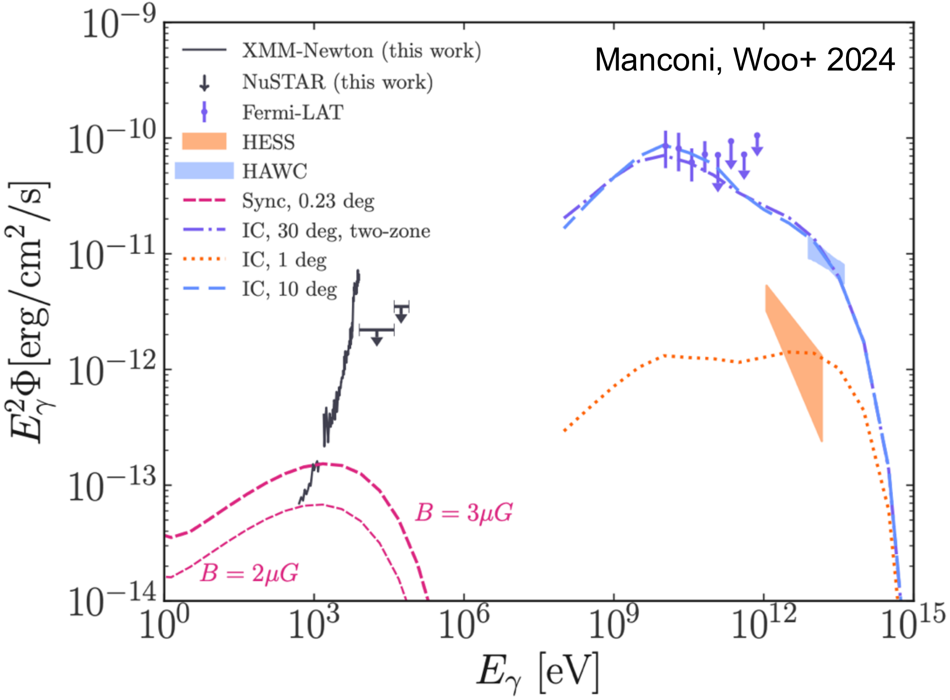


FPMB



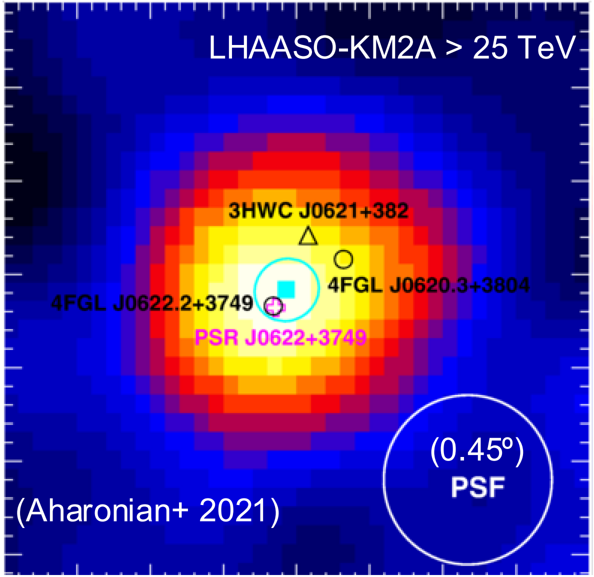
Diffusion coefficient = Galactic average / 100, Magnetic field < 2 μG

- **Iterative model fitting to the NuSTAR observations** by changing diffusion coefficient, magnetic field, electron spectrum
- **Suppressed diffusion, low magnetic field** consistent with previous works
- Electron exponential cutoff power law (α = 1.85, E_{cut} = 200 TeV)



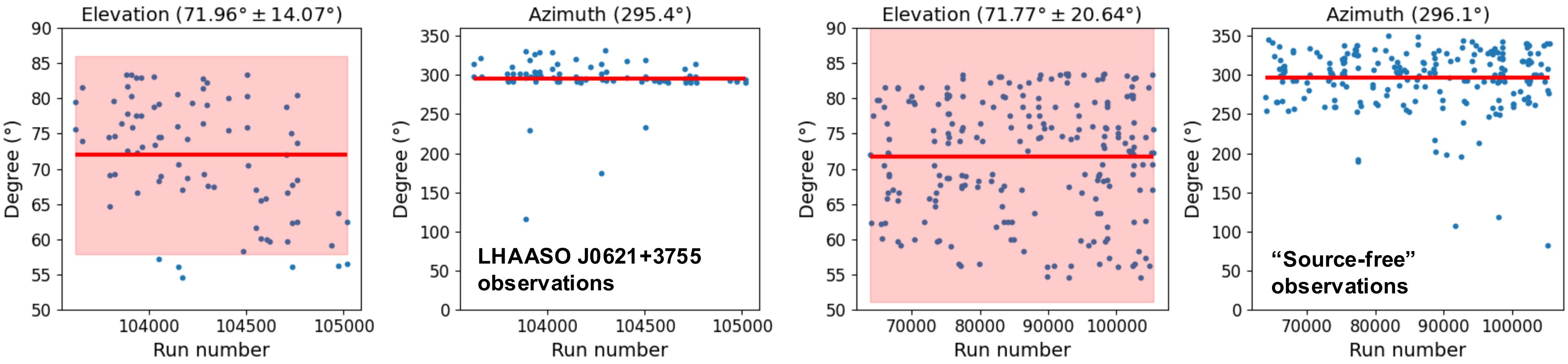
VERITAS observation of **LHAASO J0621+3755**

- PSR J0622+3749: τ = 208 kyr, $\dot{E} = 2.7 \times 10^{34}$ erg s^{-1}, d = 1.6 kpc?
- **Halo ~ 2º in TeV** discovered with LHAASO
- **VERITAS observation in 2022-2023 for 40 hr @ 72º elevation, 0.7º offset**
- VERITAS FoV = 3.5º → Minimal source-free region
  → Traditional background method not applicable
  (e.g. reflected region, ring background)



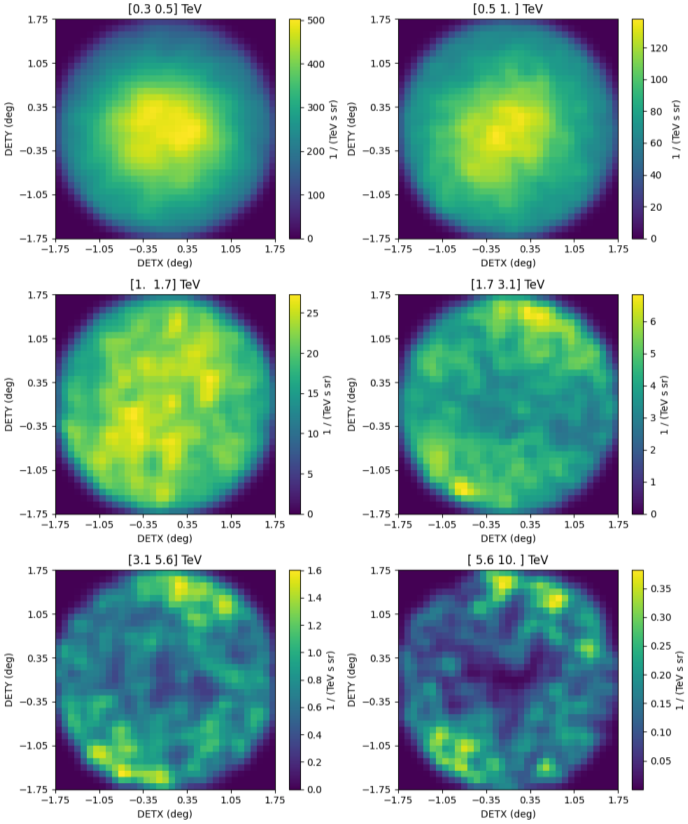
Accurate telescope acceptance + rescaling by minimal source-free region → FoV background technique

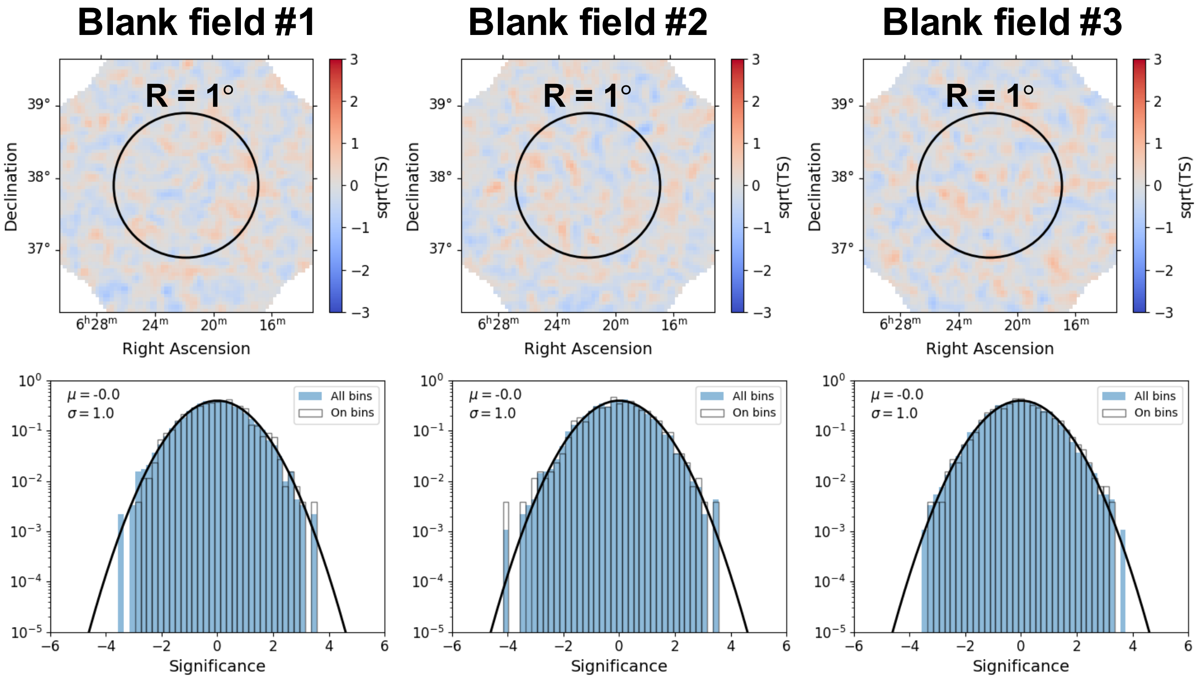
- Telescope acceptance depends on **observing conditions (elevation, azimuth)**
- **3D (energy, telescope X and Y) acceptance model** using source-free observations (100 hrs) with matching observing conditions



(Woo+ 2025)

3D acceptance model ⊗ **rescaling by (FoV – 2º) region**
→ reproduce blank fields with matching observing conditions

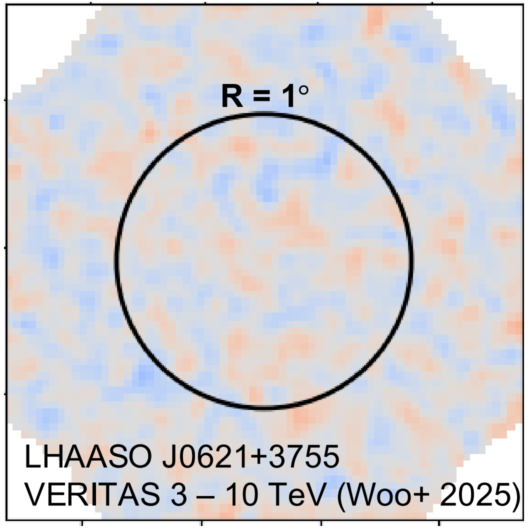


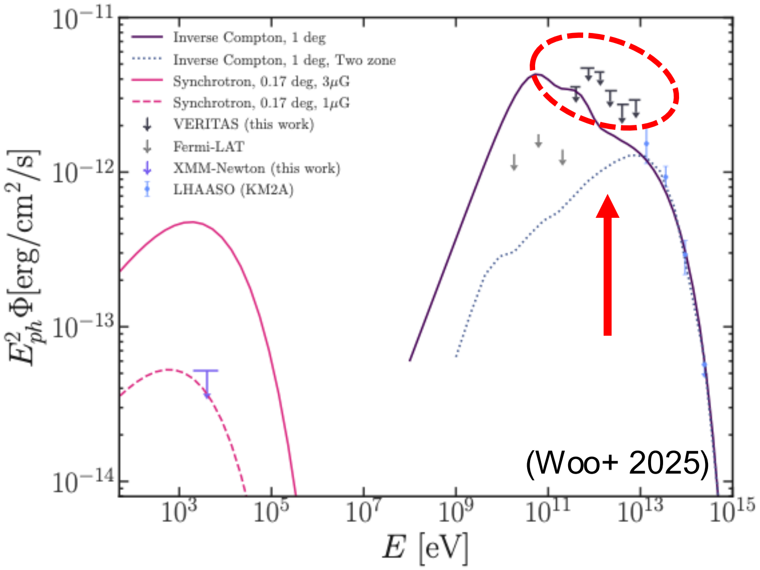


(Woo+ 2025)

Diffusion coefficient = Galactic average / 1000 **within 30 pc**, Magnetic field < 1 μG, **hard (α = 1.4) electron spectrum**

- Two-zone diffusion: **suppressed diffusion only within 30 pc of the pulsar**
- Low magnetic field (XMM-Newton analysis) consistent with the Geminga halo
- **Hard electron spectrum: α = 1.4**, E_{cut} = 200 TeV





Common traits of pulsar halos: suppressed diffusion, low magnetic field?

- Suppressed diffusion: CR-induced / SNR-shock-generated magnetic turbulence?
- Low (perpendicular component of) magnetic field → large-scale ordered field?

Geminga halo
(Manconi, Woo+ 2024)

LHAASO J0621+3755
(Woo+ 2025)