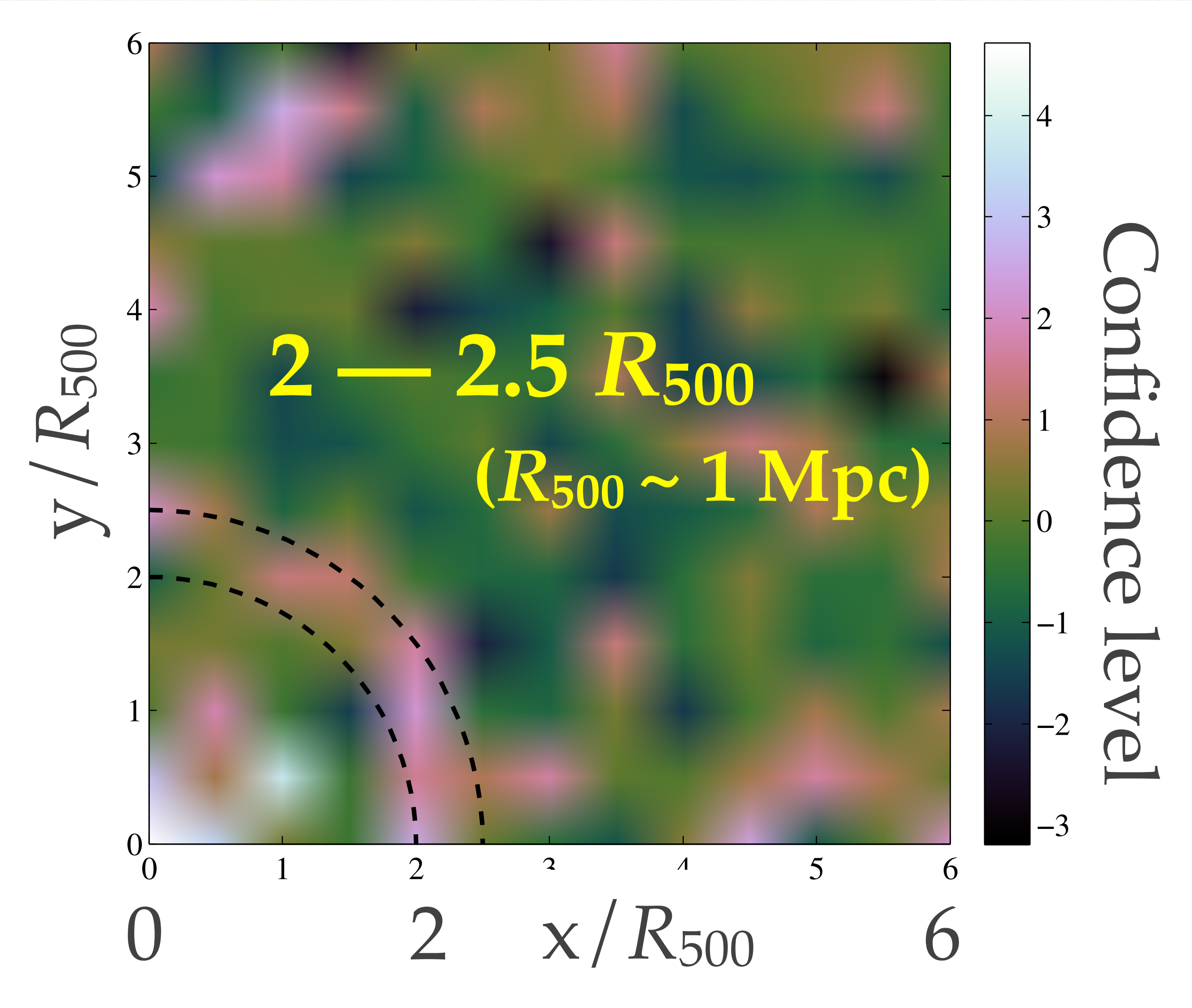
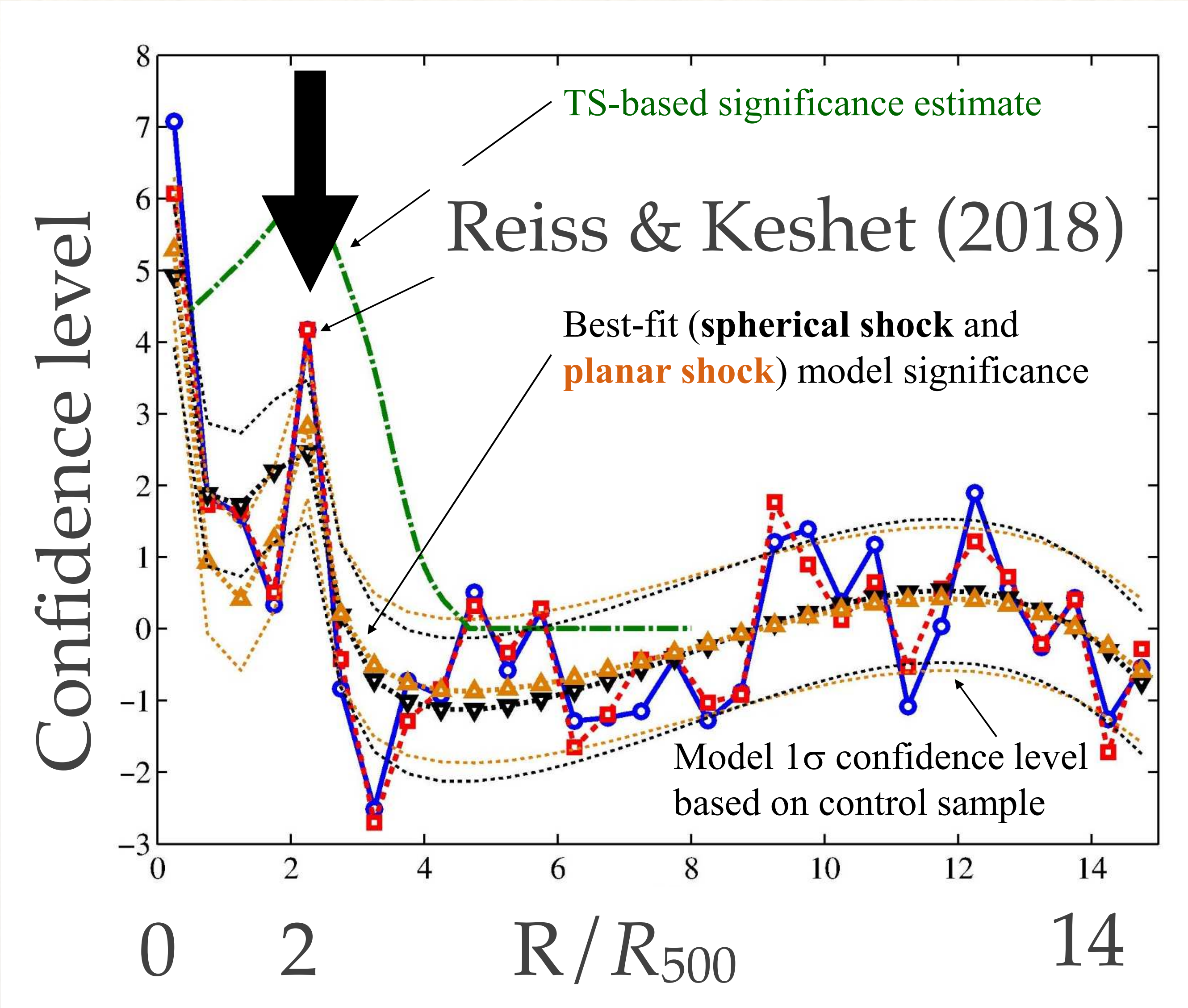
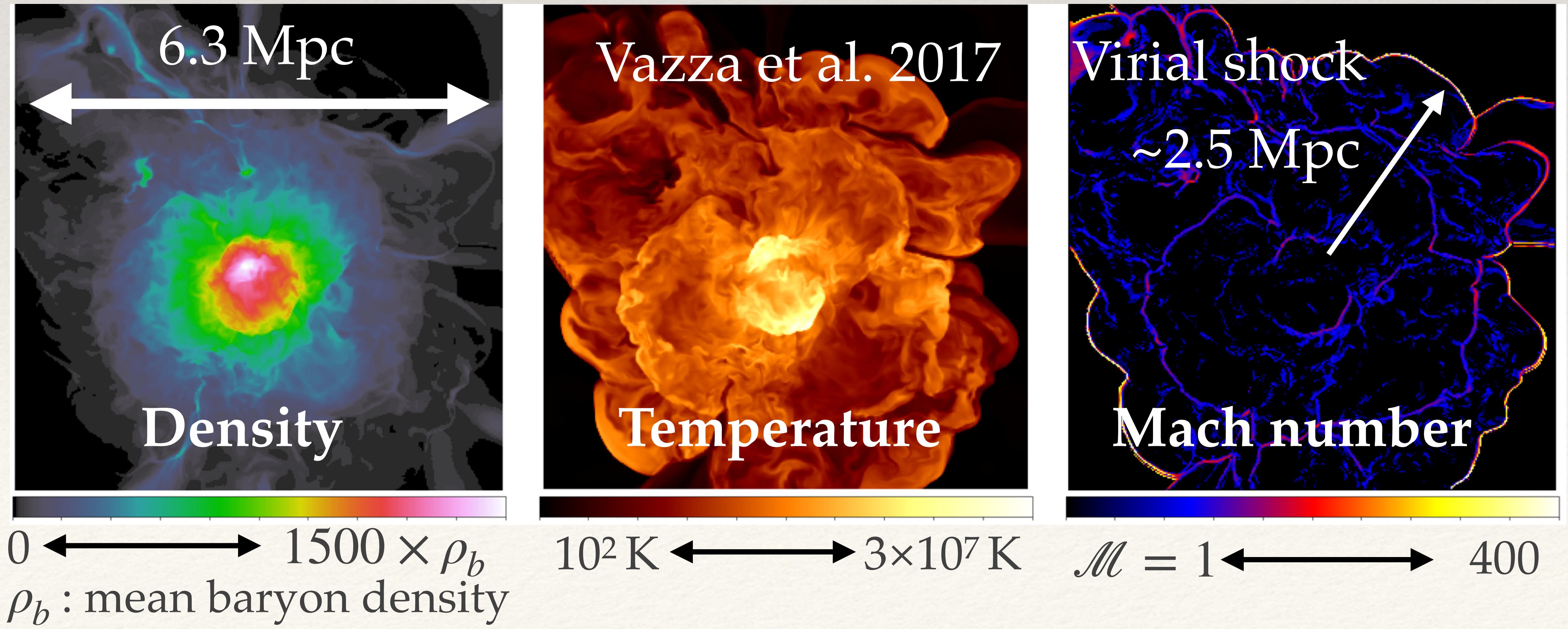
Virial shocks in galaxy clusters

(Structure formation shocks)

Ben-Gurion University of the Negev







Kuan-Chou Hou,

Ido Reiss and Uri Keshet

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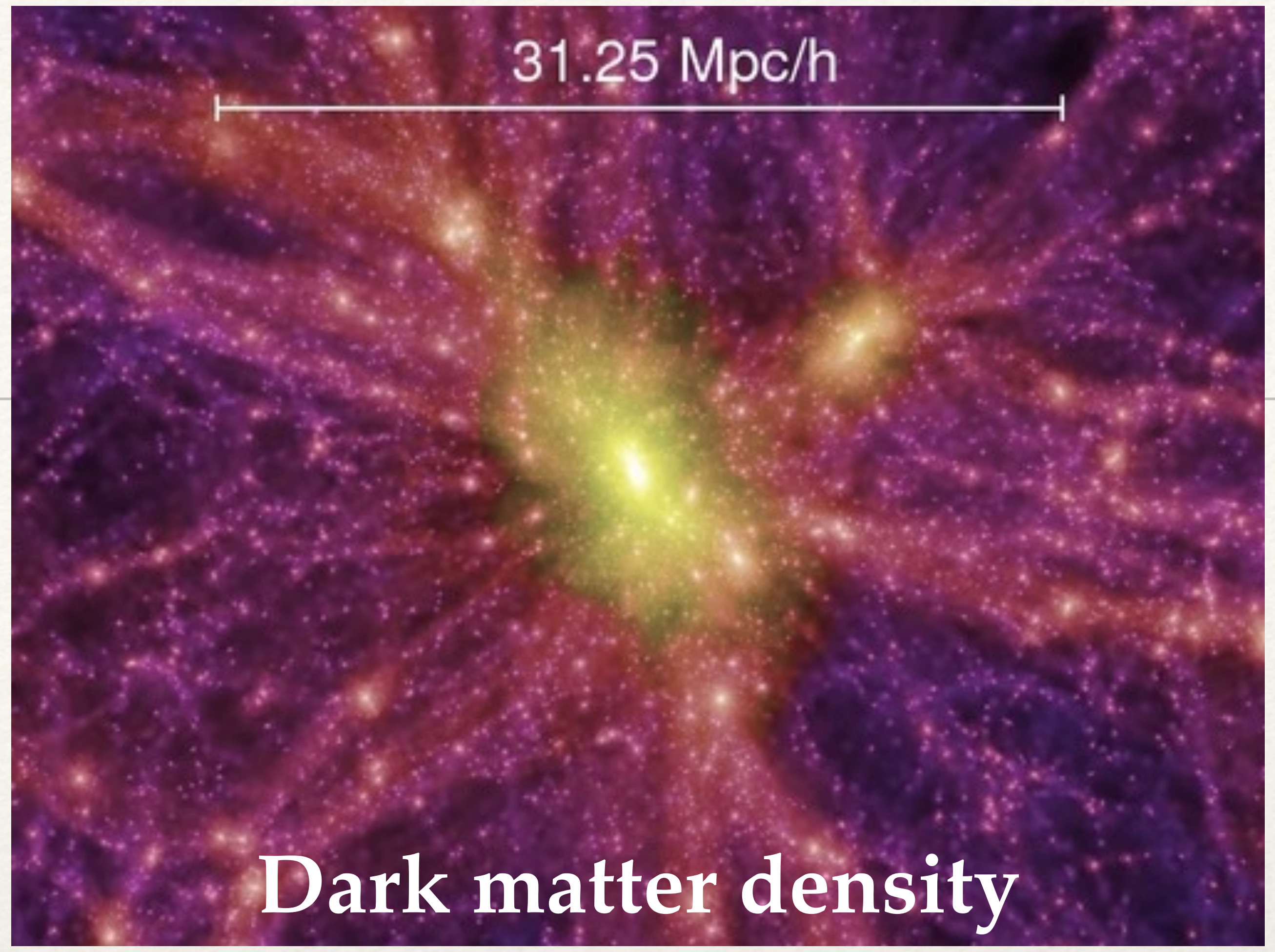
7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy

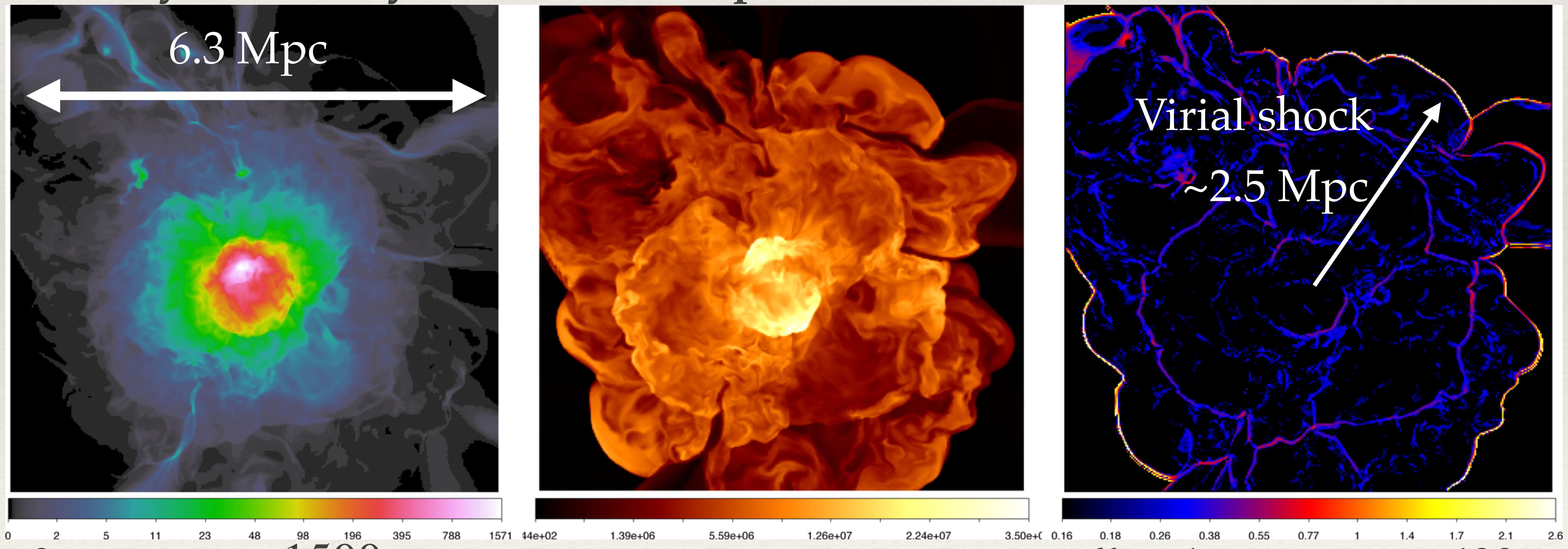
Shocks around galaxy clusters

- Galaxy clusters are thought to grow by accreting surrounding material
  → **strong, collisionless shocks**
- Virial shocks are expected to be at
  $2 < R/R_{500} < 3$ (R_{500} ~ 1 Mpc)
- These virial shocks **define the edges of clusters**
  - Useful information about the formation of large-scale structures, such as local accretion rate
  - A laboratory for studying collisionless shock physics (primordial, low magnetized < nG gas)

The Millennium Simulation



Baryon Density | Temperature | Mach number



$0 \longleftrightarrow 1500 \times \rho_b$ 10^2 K $\longleftrightarrow$ 3×10^7 K $\mathscr{M} = 1 \longleftrightarrow 400$

ρ_b : mean baryon density

Vazza et al. 2017

Detect virial shocks

- Virial shocks are thought to accelerate charged particles to highly relativistic, $\gtrsim$ 10 TeV energies
  - $dN_e/dE \propto E^{-p}$ ($p \sim 2$ from strong shocks, e.g. SNR observations)

    1. Optical to γ-ray emission from **Inverse Compton scattering** (Loeb & Waxman 2000; Totani & Kitayama 2000; Keshet et al. 2003)
    2. **Thermal SZ** in microwave (Kocsis et al. 2005)
    3. **Synchrotron radiation** in radio (Waxman & Loeb 2000; Keshet et al. 2004)

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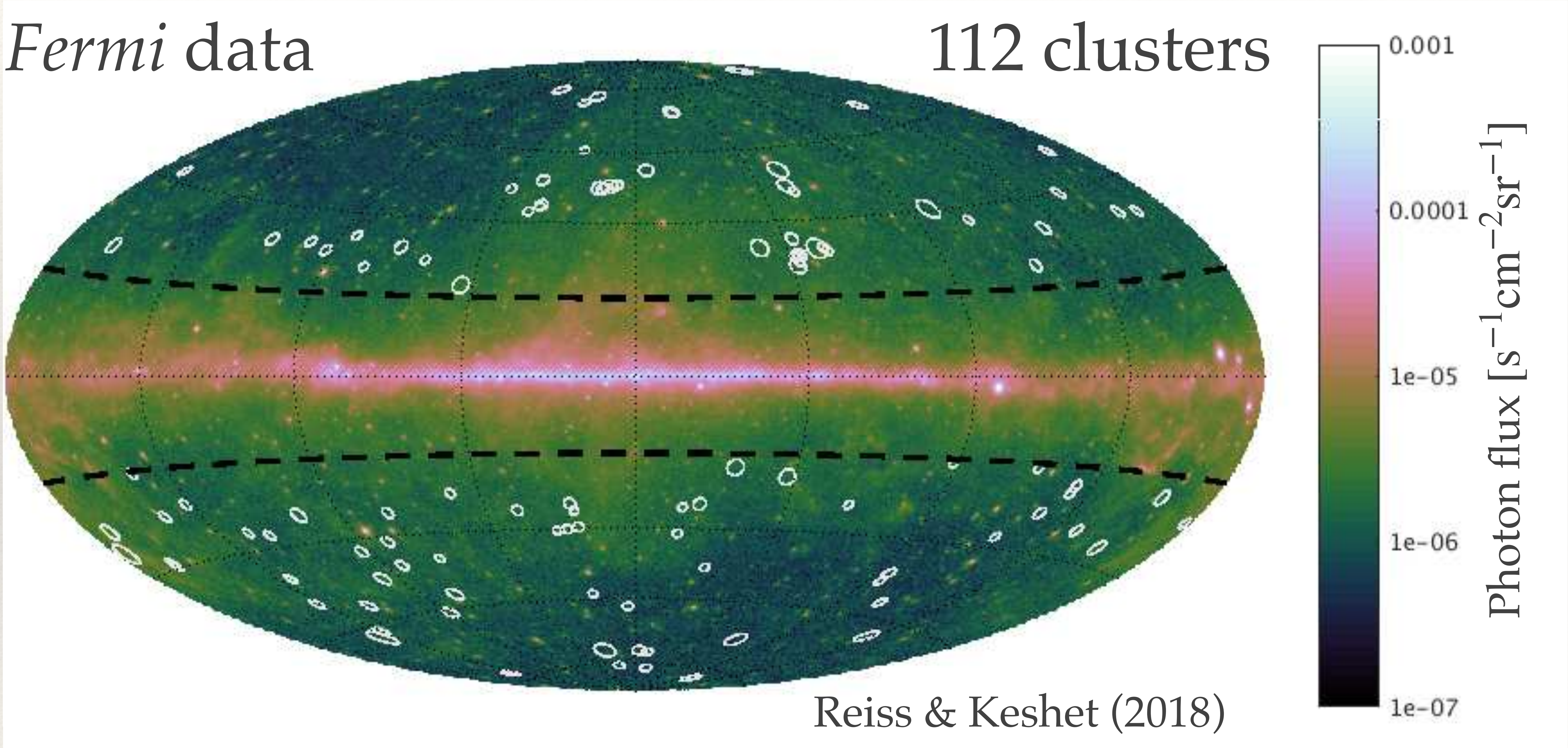
It is a challenge to detect virial shocks (weak signal, strong foreground)

Evidence of virial shock

- **Stacking *Fermi*-LAT data**
  - Properly scale cluster size with $R_{500} \rightarrow > 5\sigma$ ring signal
  - Follow-up → up-to-date *Fermi* data, clean cluster sample, and new 4FGL catalog
- **Select clusters**
  - A2319 → strong (8.6σ) SZ signal of shock
  - Coma → coincident SZ and γ-ray signal

Stacking *Fermi*-LAT data

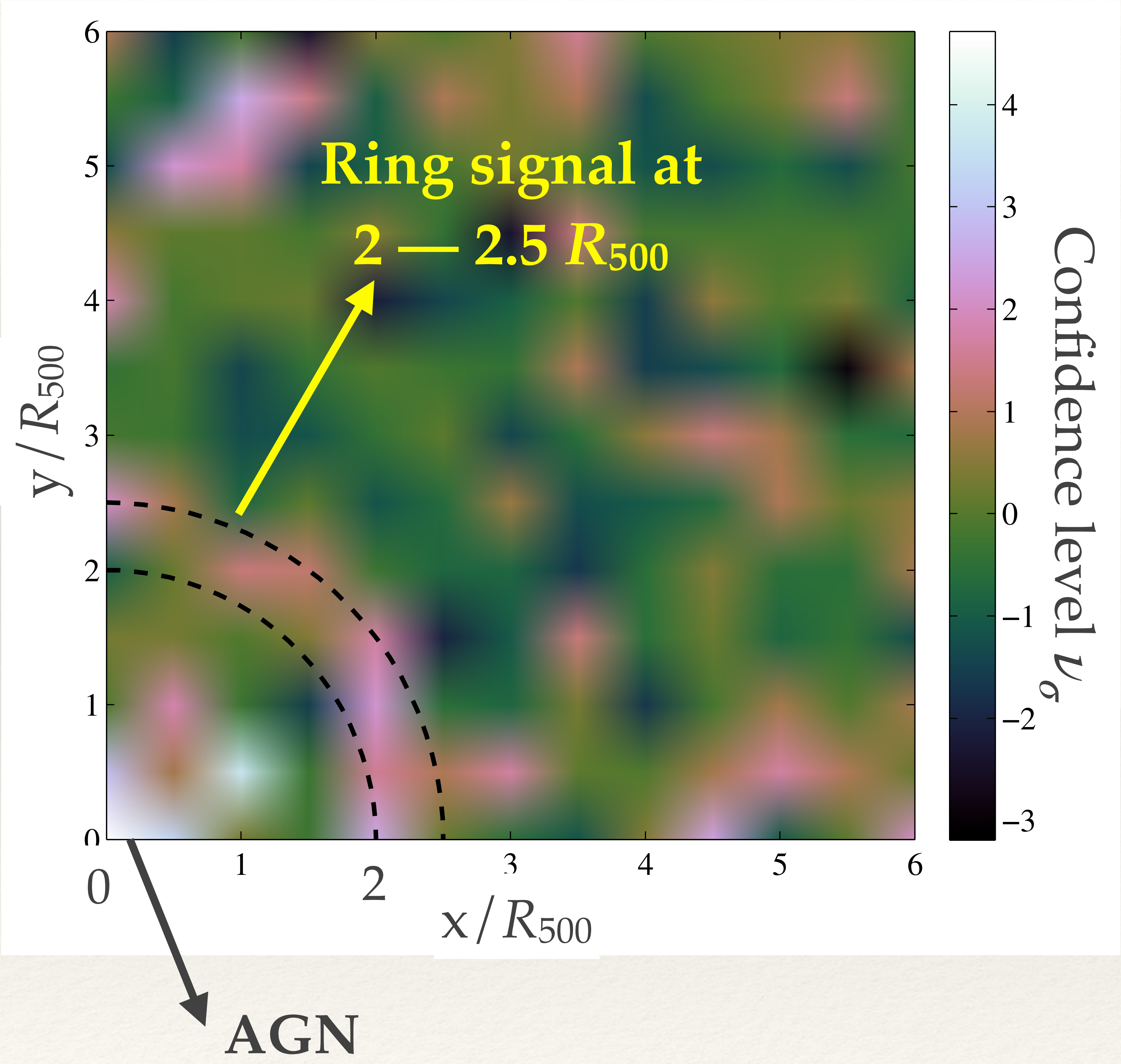
- 7.9 years data
- 1 — 100 GeV (4 logarithmic bins)
- Stack the data of each cluster normalized to its $R_{500} \sim 1$ Mpc
- Masking pixels within $1^{\circ}.8$ of each 3FGL point sources
- Meta-Catalog of X-ray Clusters (MCXC)
  - $M_{500} > 10^{13} M_{\odot}$
  - $0^{\circ}.2 < \theta_{500} < 0^{\circ}.5$
  - Latitude $|b| > 20^{\circ}$
  - $> 1^{\circ}.8$ from 3FGL point sources



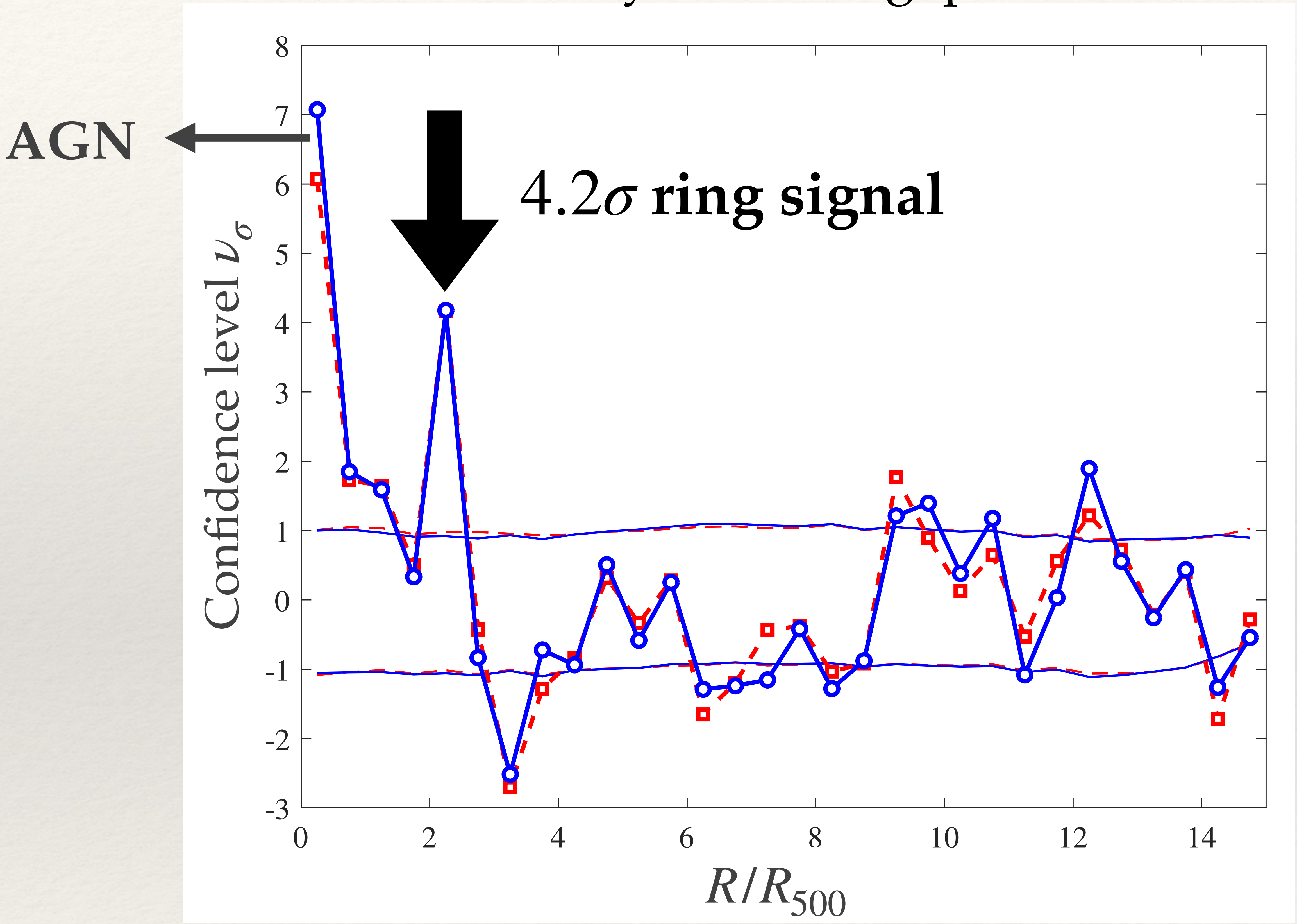
White circles have a $5R_{500}$ radius

Stacking *Fermi*-LAT data

2D significance map



Radially binned sig. profile

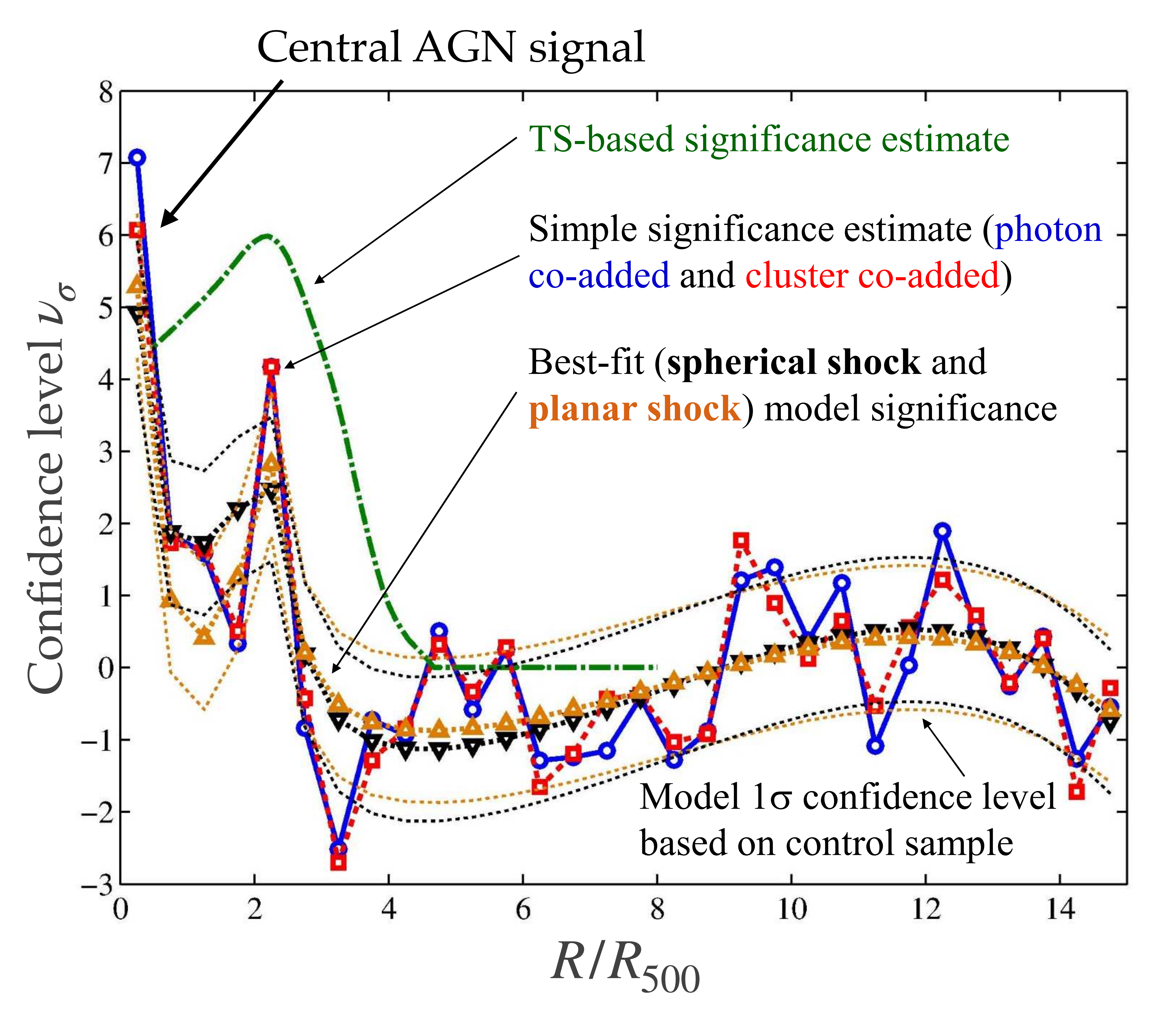


Equal weight per solid angle
Equal weight per cluster

Reiss & Keshet (2018)

Stacking *Fermi*-LAT data

- Model the shock signal
  - 5.8σ based on TS
  - Shock radius
    $\rho_s = 2.3 \pm 0.1 R_{500}$
  - CRE acceleration rate
    $\dot{m}\xi_e = (0.6 \pm 0.1)\ \%$
    (mass accretion rate $\dot{m} \simeq \dfrac{\dot{M}}{M \times H}$)
  - Spectral index
    $p = 2.1 \pm 0.2$



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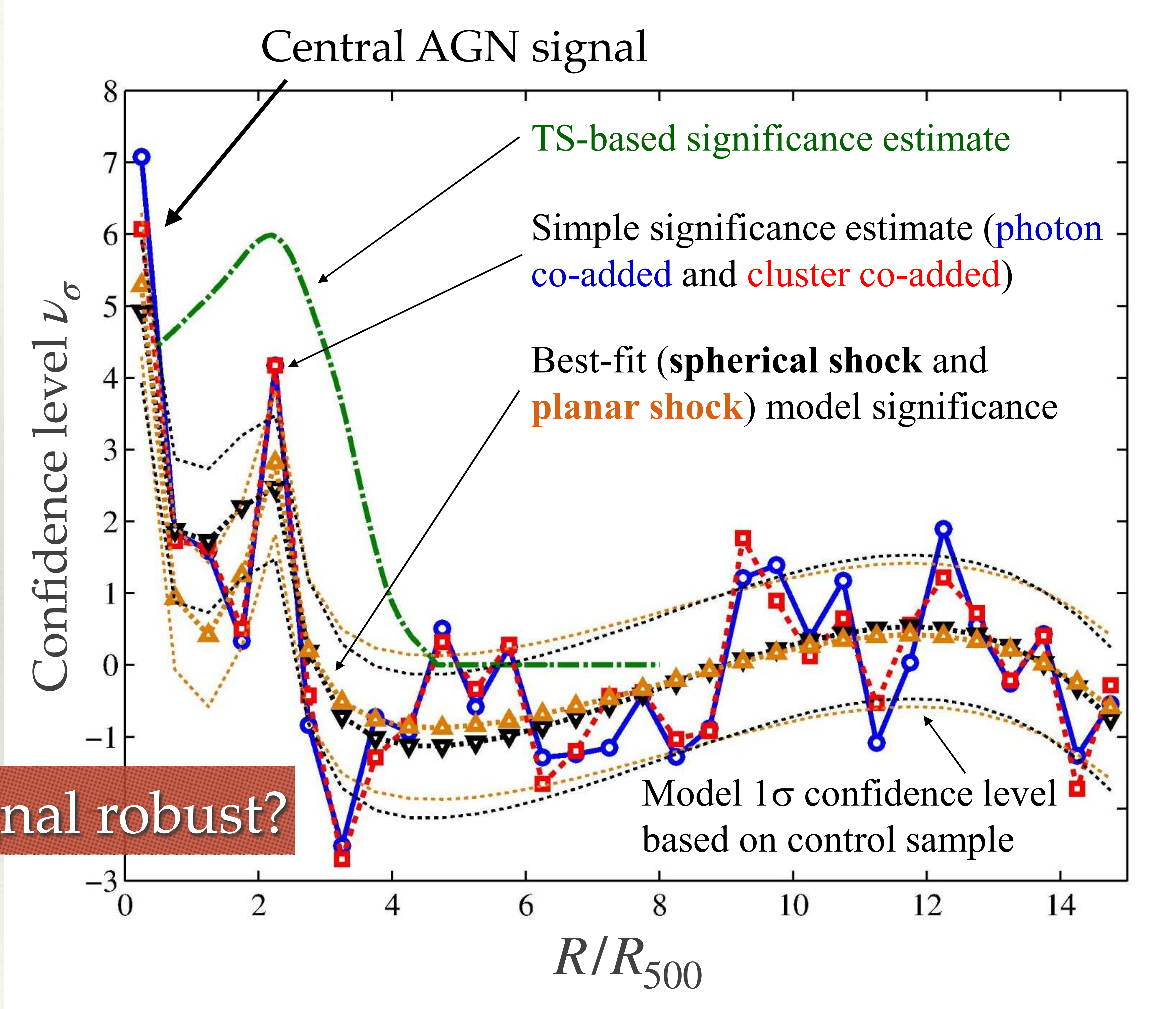
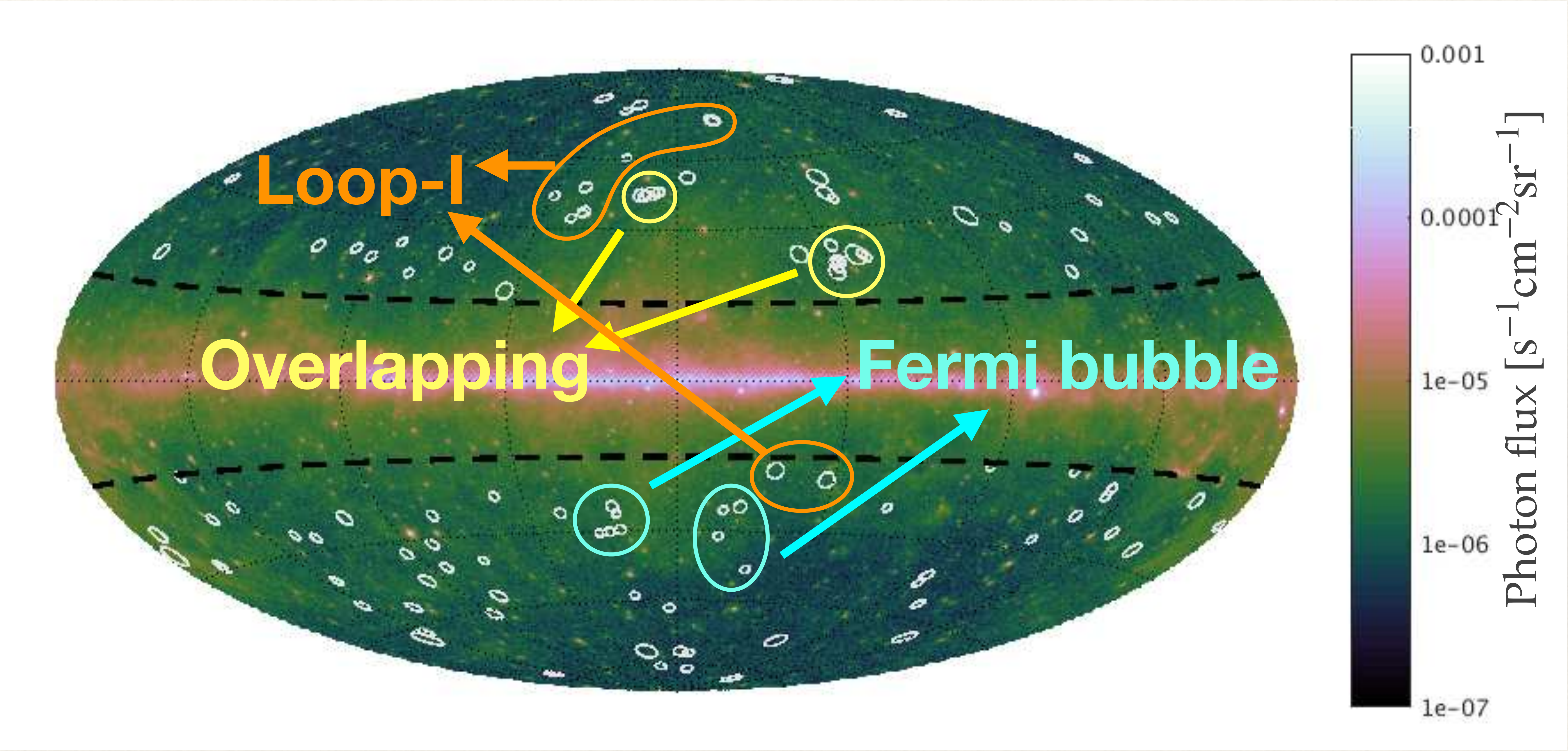


Is this ring signal robust?

Re-examination of the ring signal

- Increase data to 10.6 years (551 weeks)
- Remove clusters contaminated by the Loop-I, clusters overlapping, and Fermi bubble regions
  → 79 clusters remain
- Apply the same analysis and modeling



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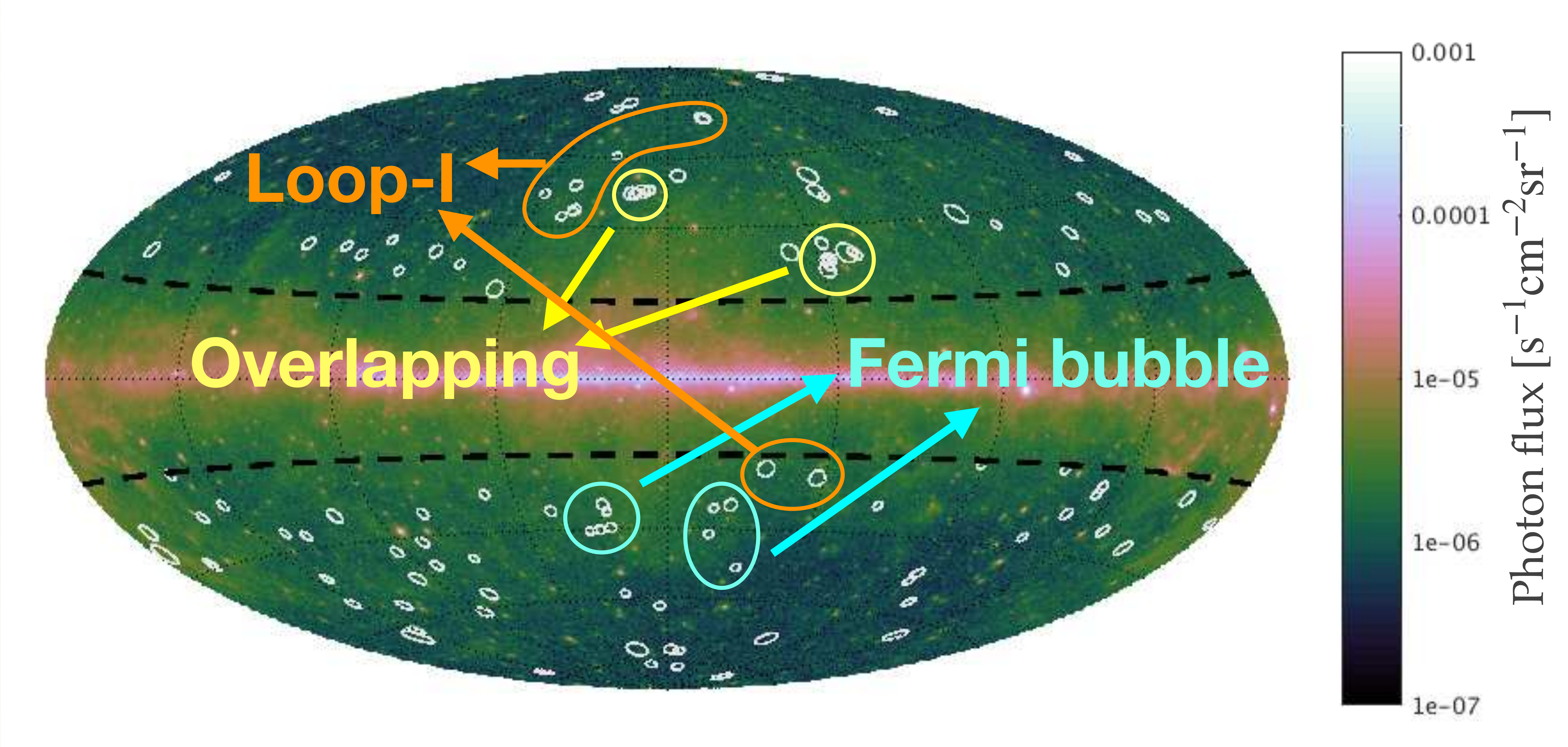
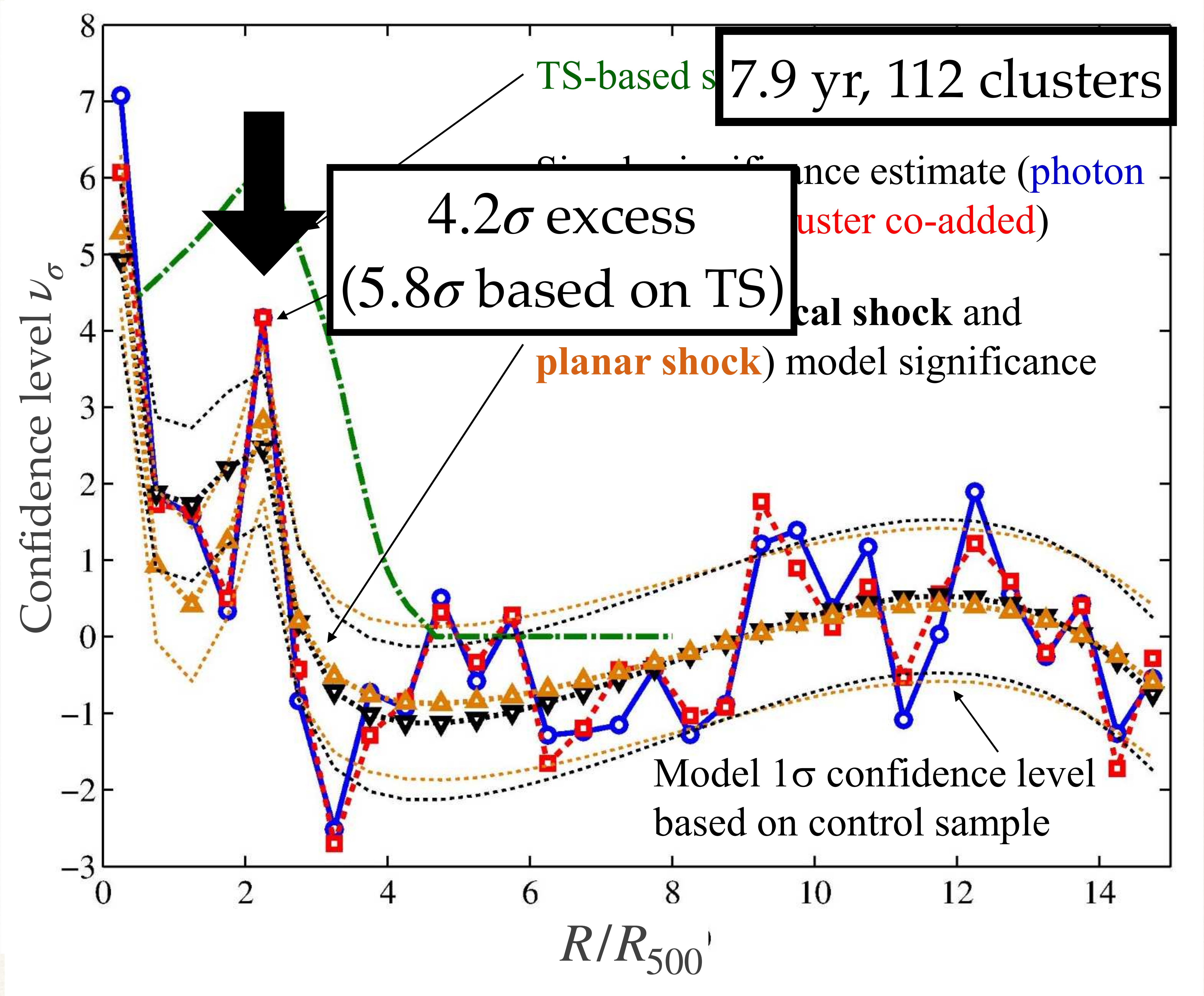
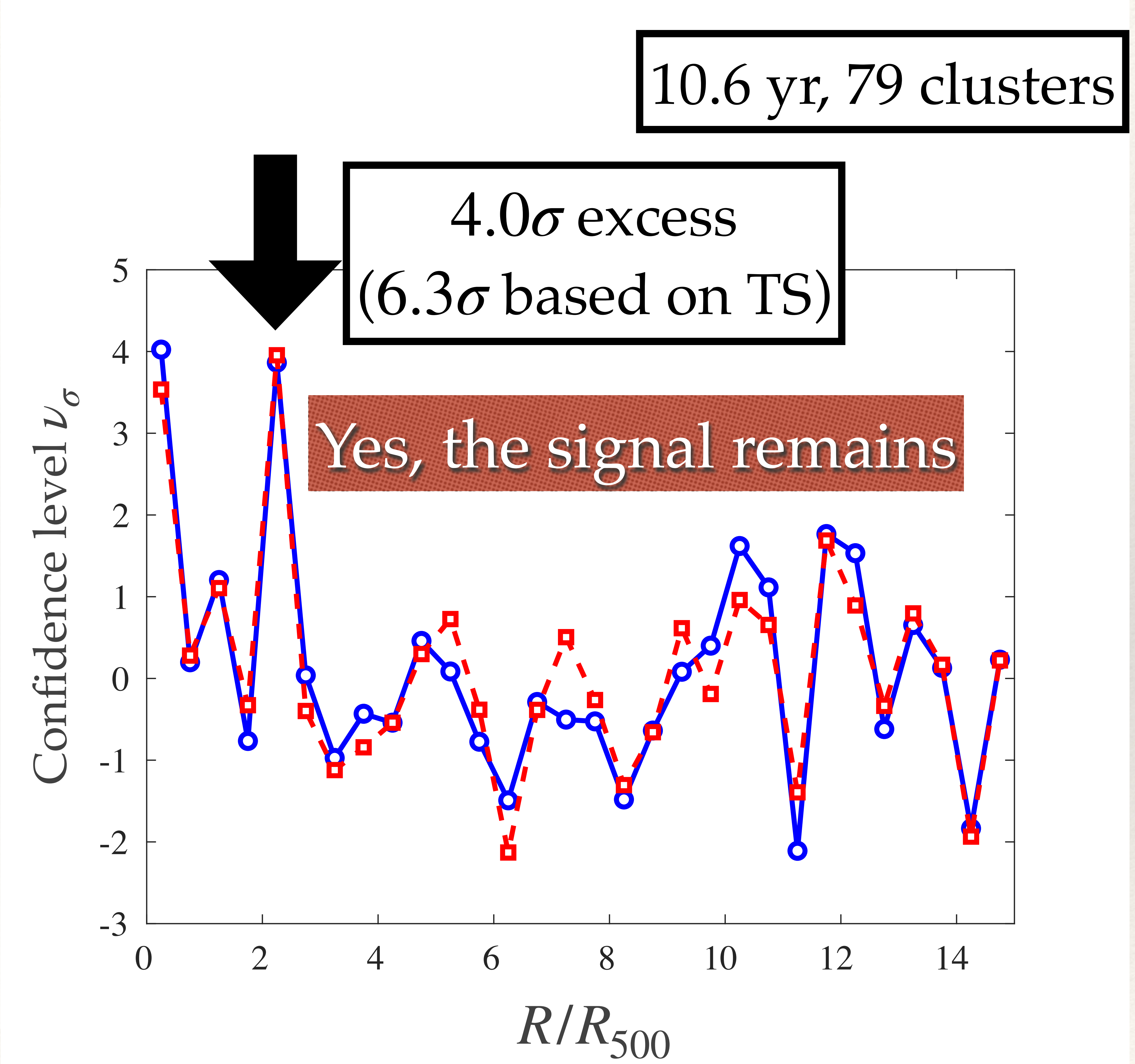


Does the virial shock signal remain?

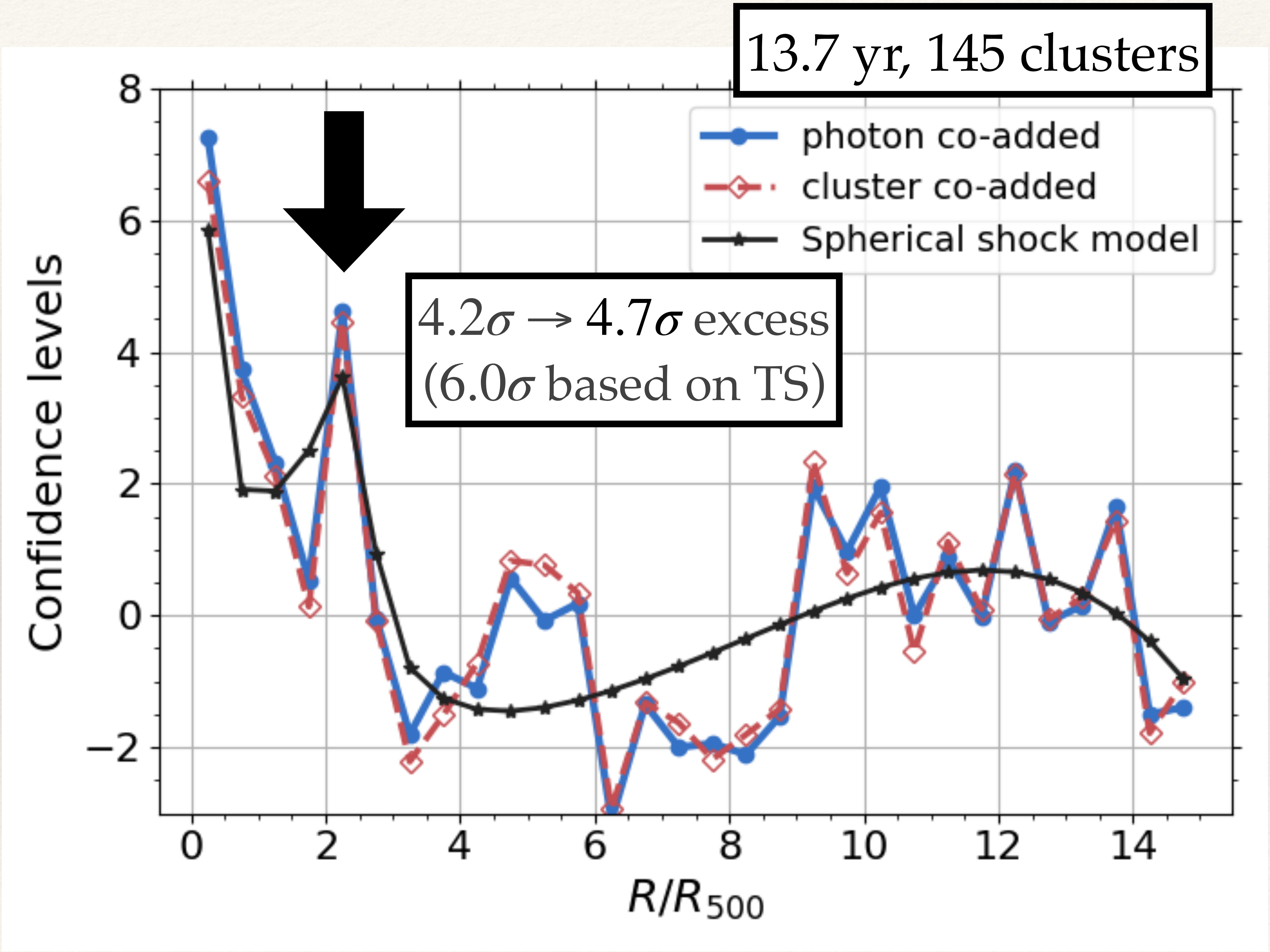
Re-examination of the ring signal





Re-examination of the ring signal

- Increase data to 13.7 years
- Include more clusters
    - Same cluster selections but with high-quality point sources from 4FGL-DR3 catalog ($> 1^\circ.8$ from SN>15 point sources)
    - 145 clusters
- Signal goes higher to 4.7σ



Hou+ in prep.

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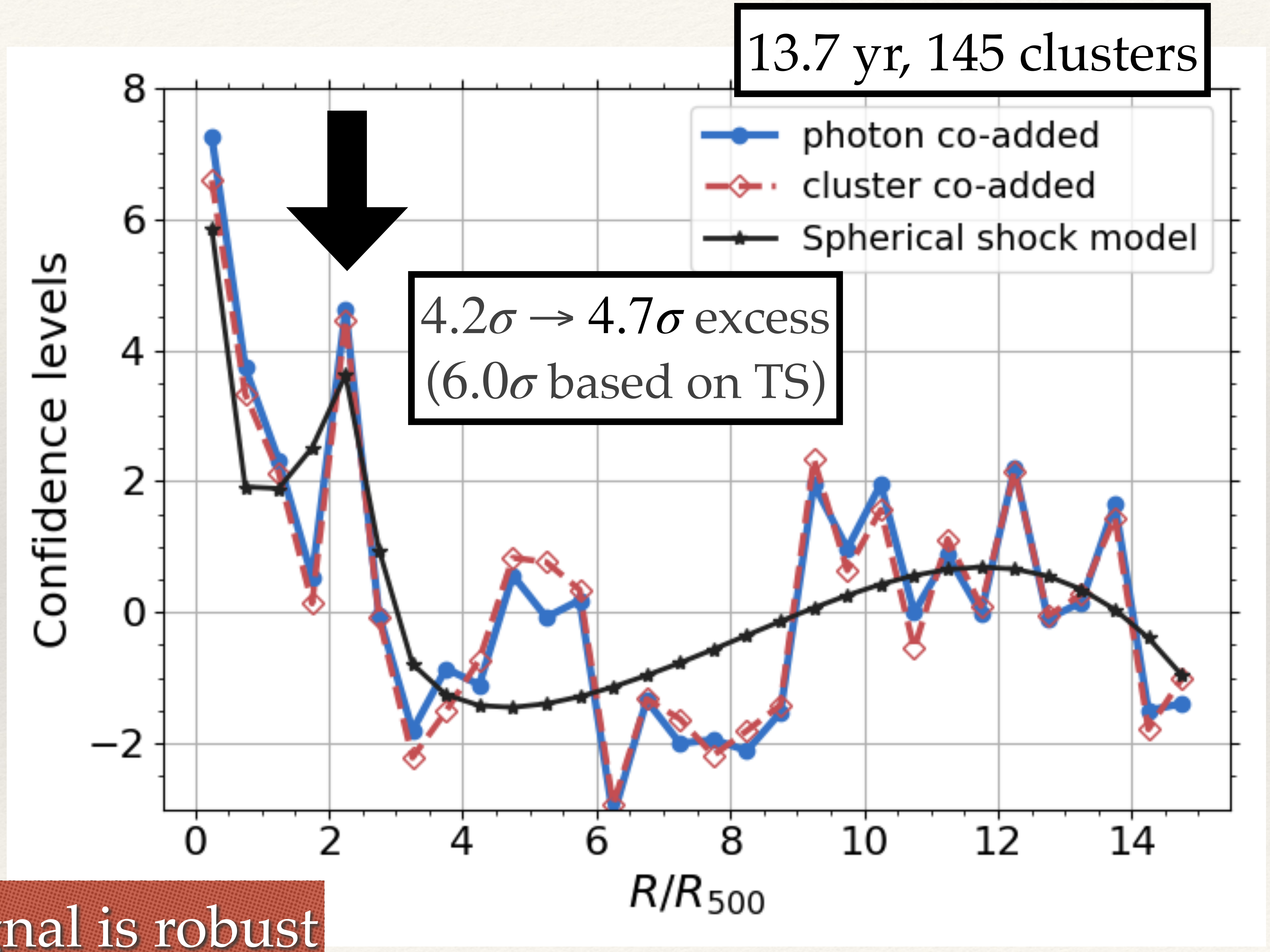
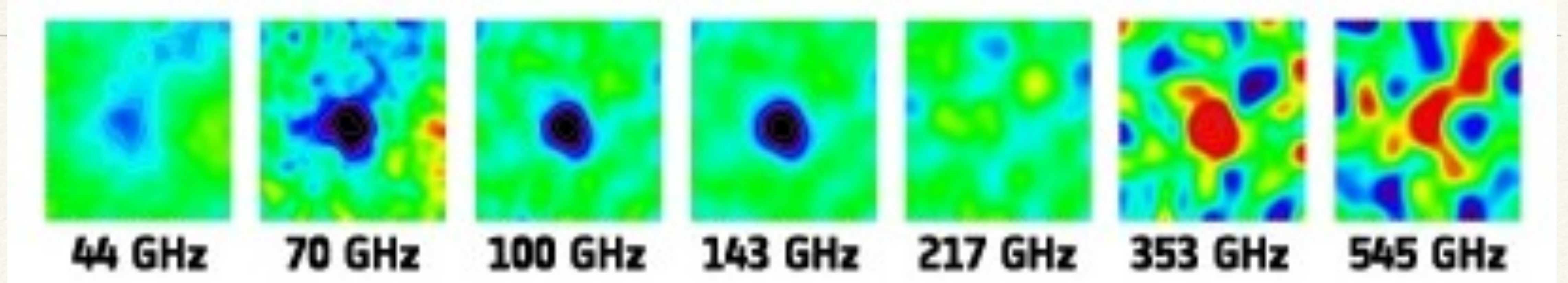


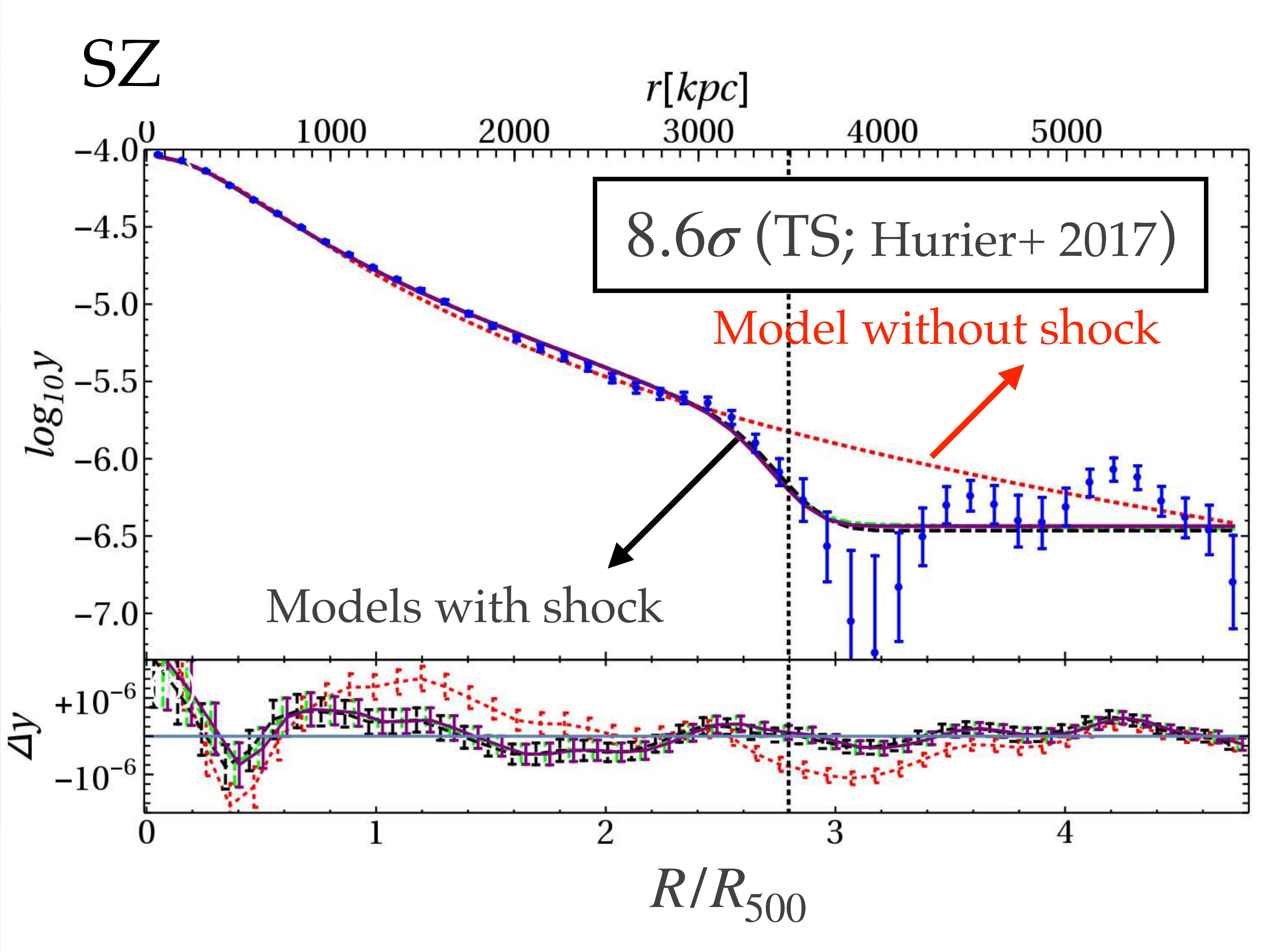
The ring signal is robust

Hou+ in prep.

Select clusters: A2319

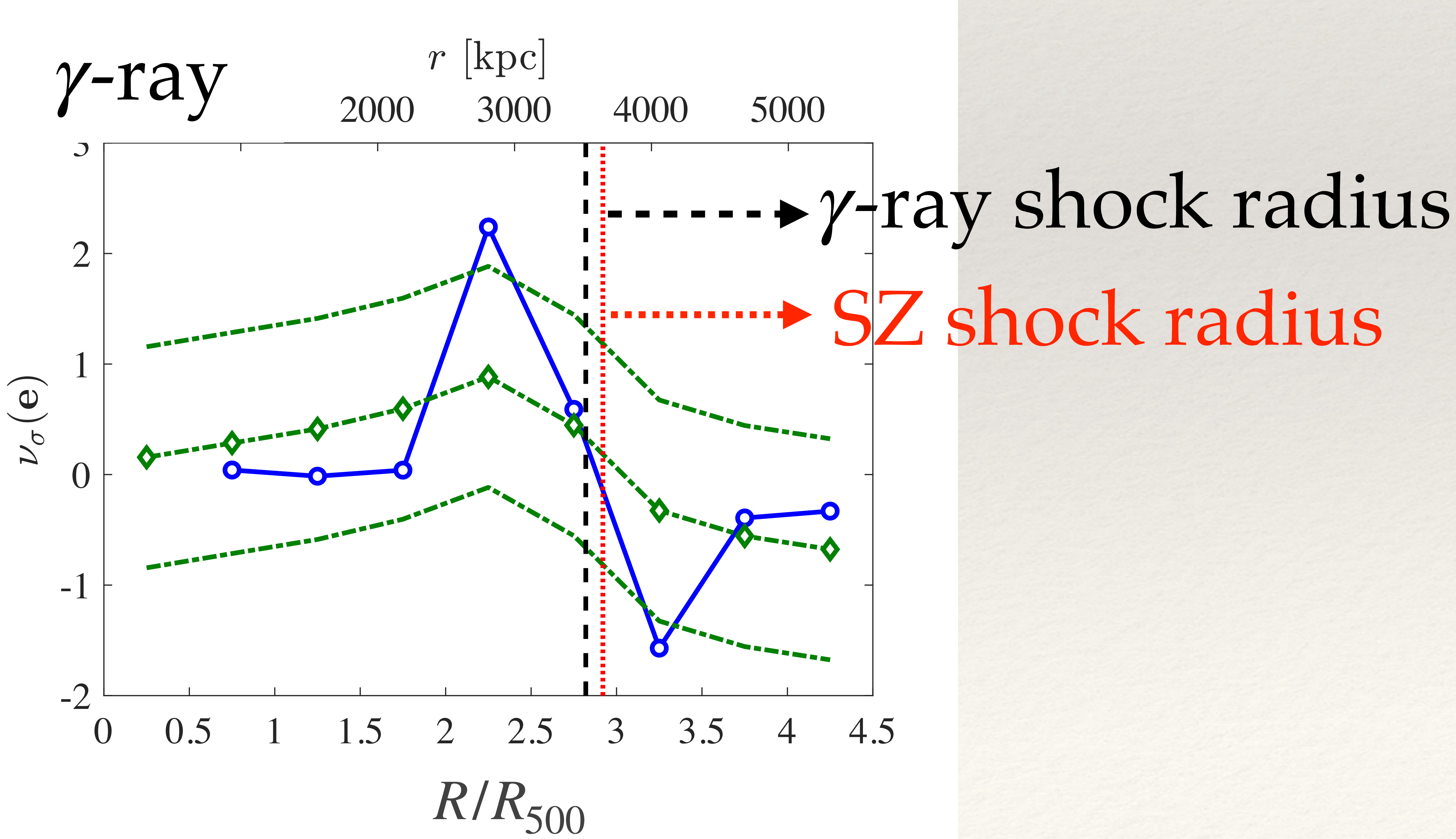


ESA / LFI & HFI Consortia

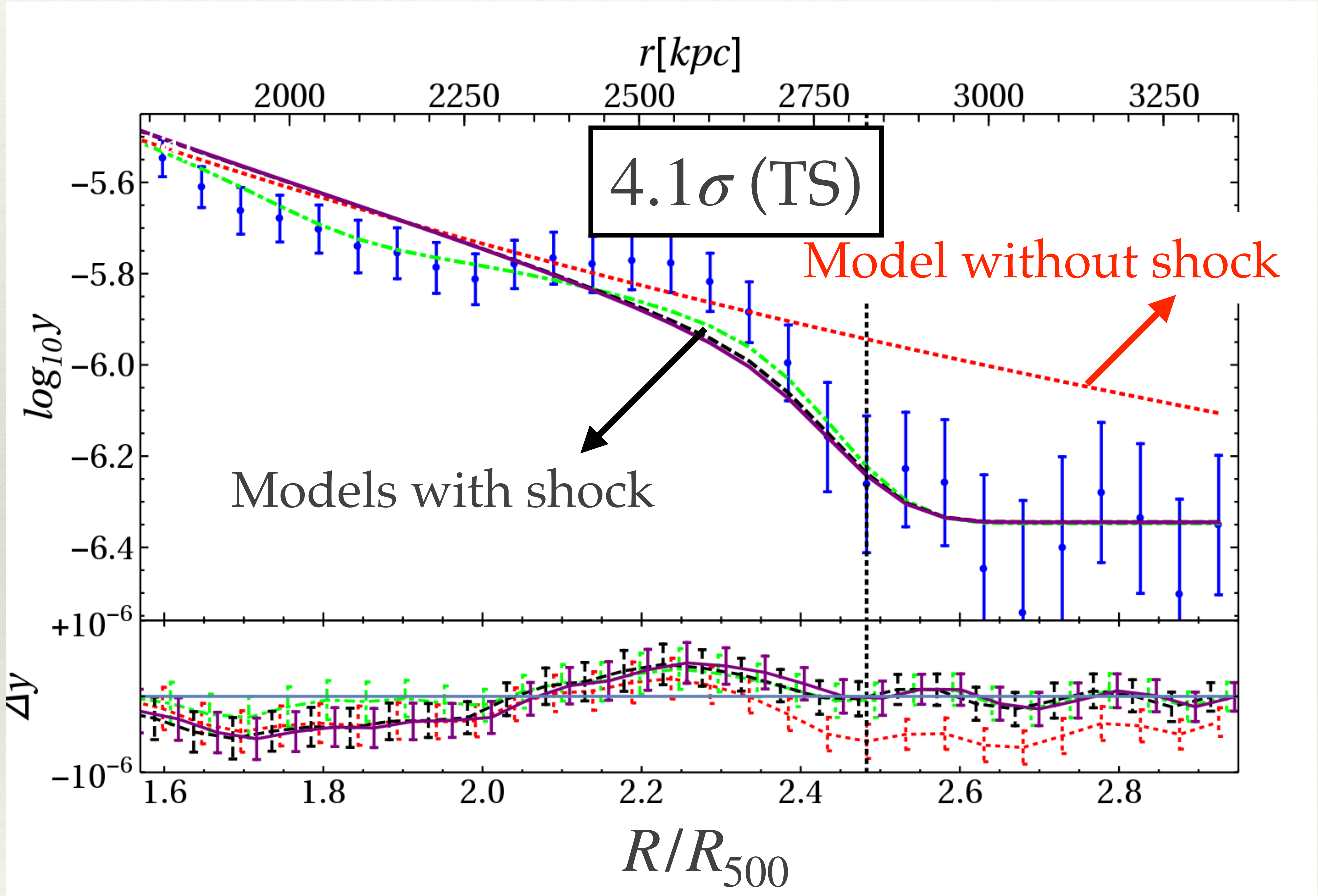


Keshet, Reiss, & Hurier (2017)

- *Planck* SZ
- The highest SN ratio in the *Planck* SZ catalogs
- Comptonization parameter $y = \dfrac{\sigma_T}{m_e c^2} \int P dl$
- Radially binned profile of y

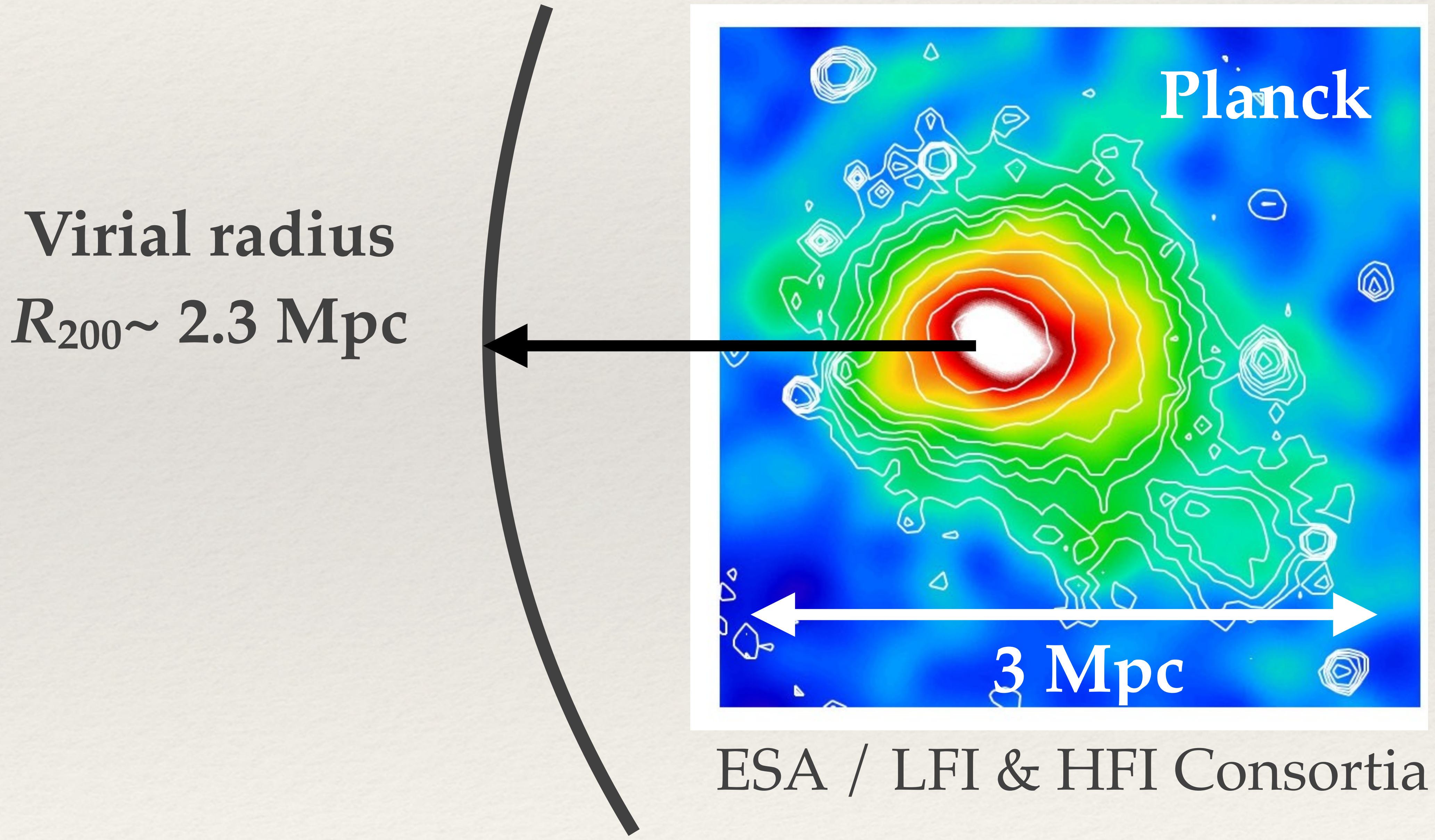


Select clusters: Coma



Keshet, Reiss, & Hurier (2017)

- *Planck* SZ
- Nearby massive cluster at the Galactic pole



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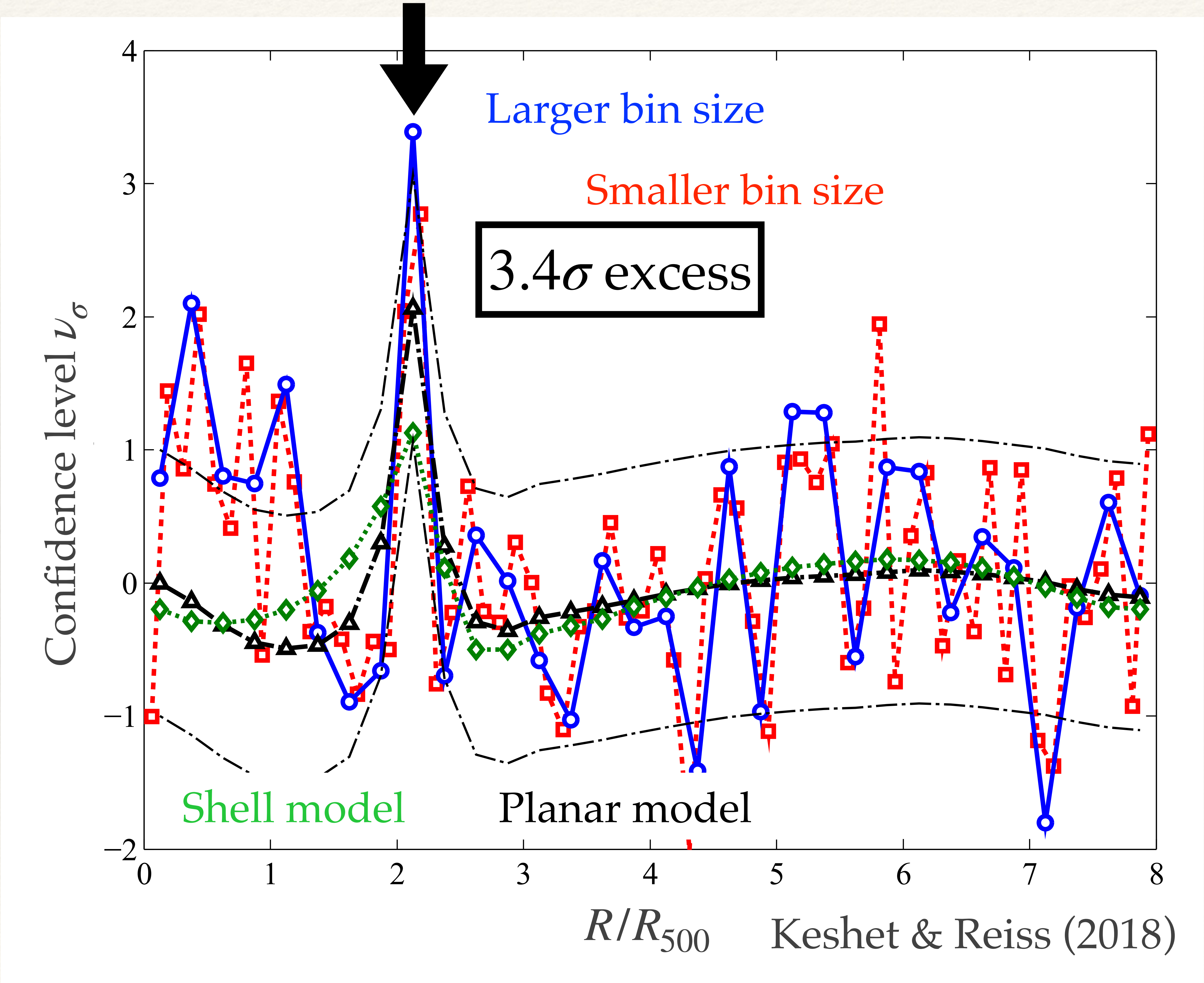
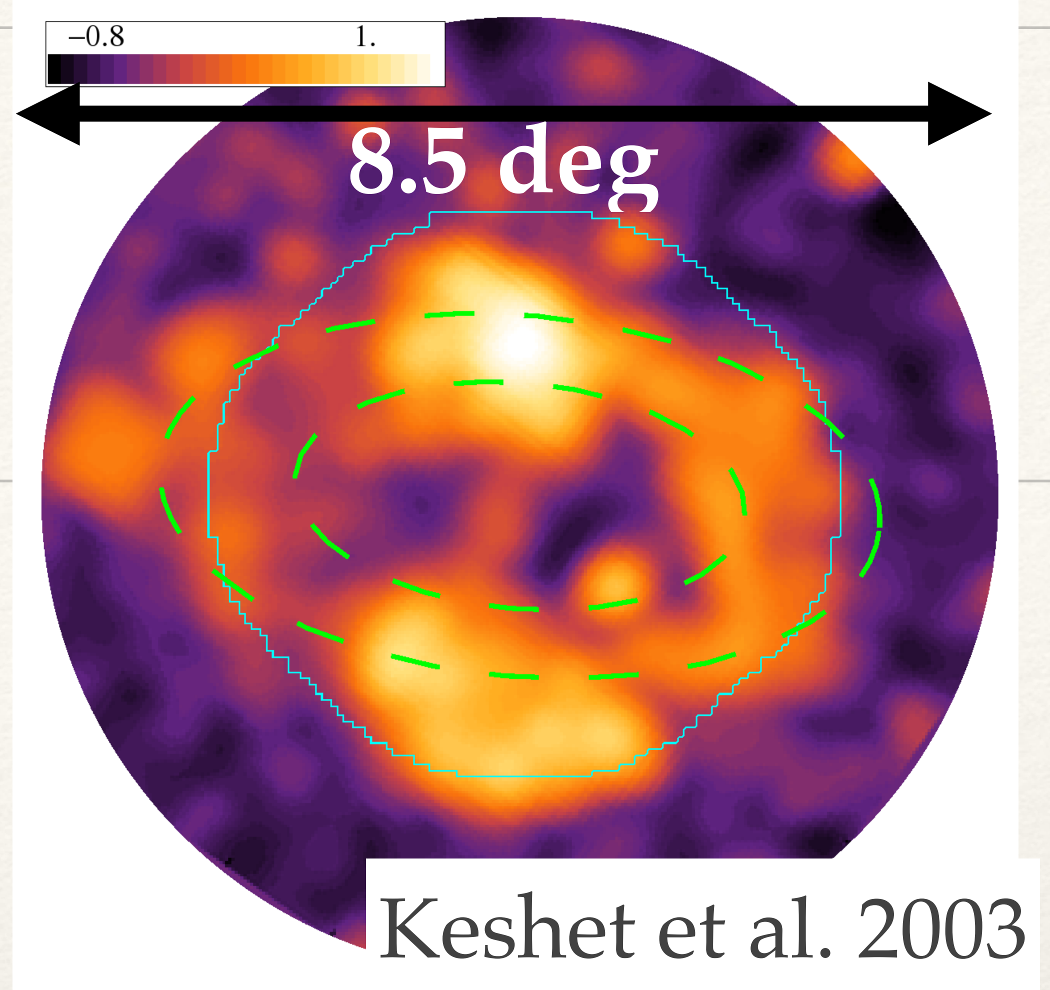


Simulated VERITAS flux map



- *Fermi*-LAT (1–100) GeV data (7.9yr)
- Masking pixels within 1°.8 of each point source
- Morphology taken from VERITAS flux map
  → Elongation $\zeta = 2.5$
- Model virial shock:
  - CRE acceleration rate $\dot{m}\xi_e \sim 0.3\,\%$
  - Shock radius $2.0 < R/R_{500} < 2.25$
  - Spectral index $p \simeq 2.0$ to 2.2

Summary

- There is a 4.2σ (5.8σ based on TS) excess at the expected virial shock position after stacking *Fermi* data around 112 clusters
- Follow-up examinations:
  - Removing possible contaminated clusters
    → the shock signal remains 4.0σ (6.3σ based on TS)
  - Up-to-date *Fermi* data and 4FGL-DR3
    → 4.7σ (6.0σ based on TS)
- Select clusters:
  - A2319 shows a 8.6σ virial shock SZ signal; the shock radius coincident with the *Fermi* signal
  - Coma shows a 4.1σ virial shock SZ signal; coincident the SZ and 3.4σ *Fermi* signal

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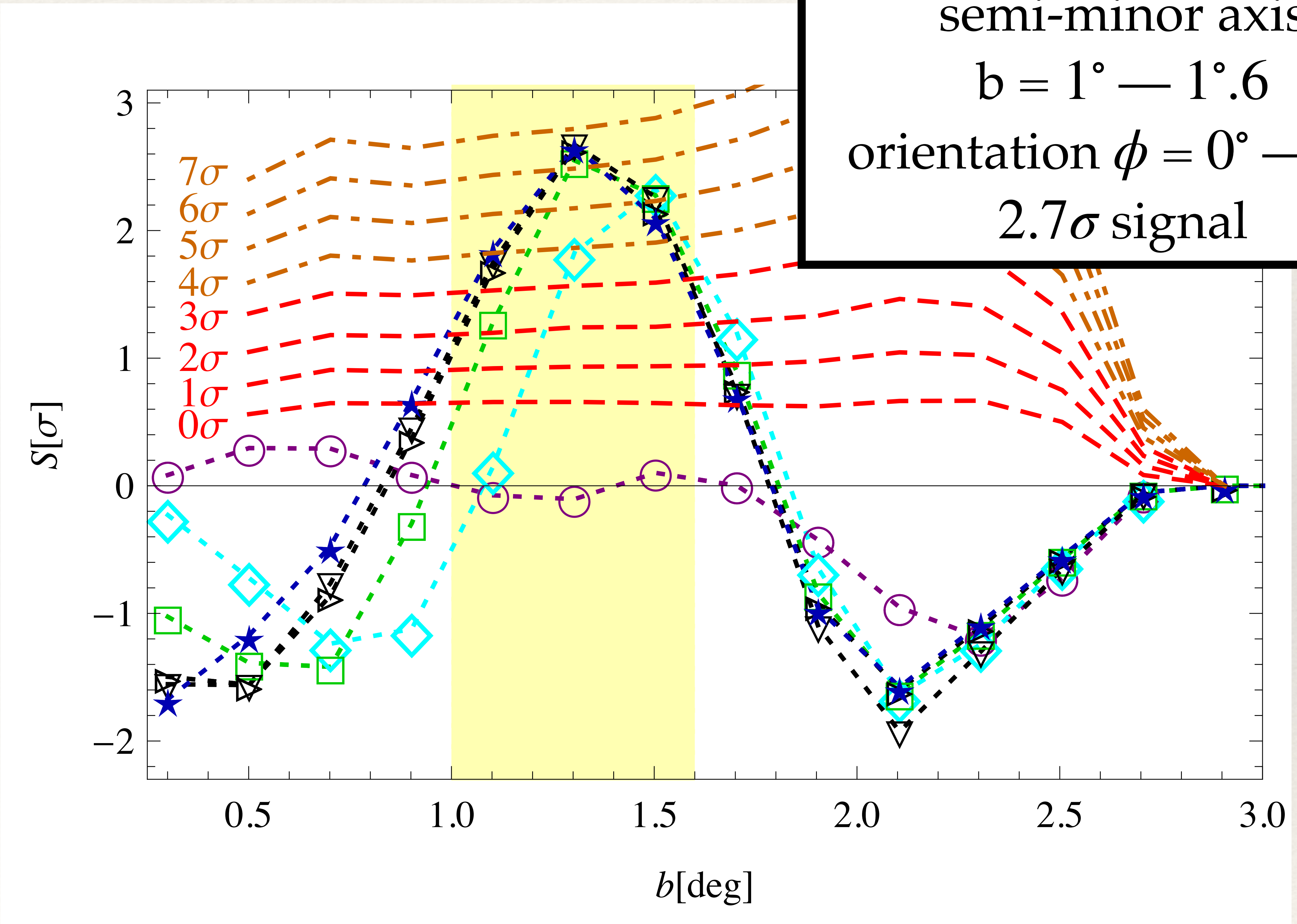
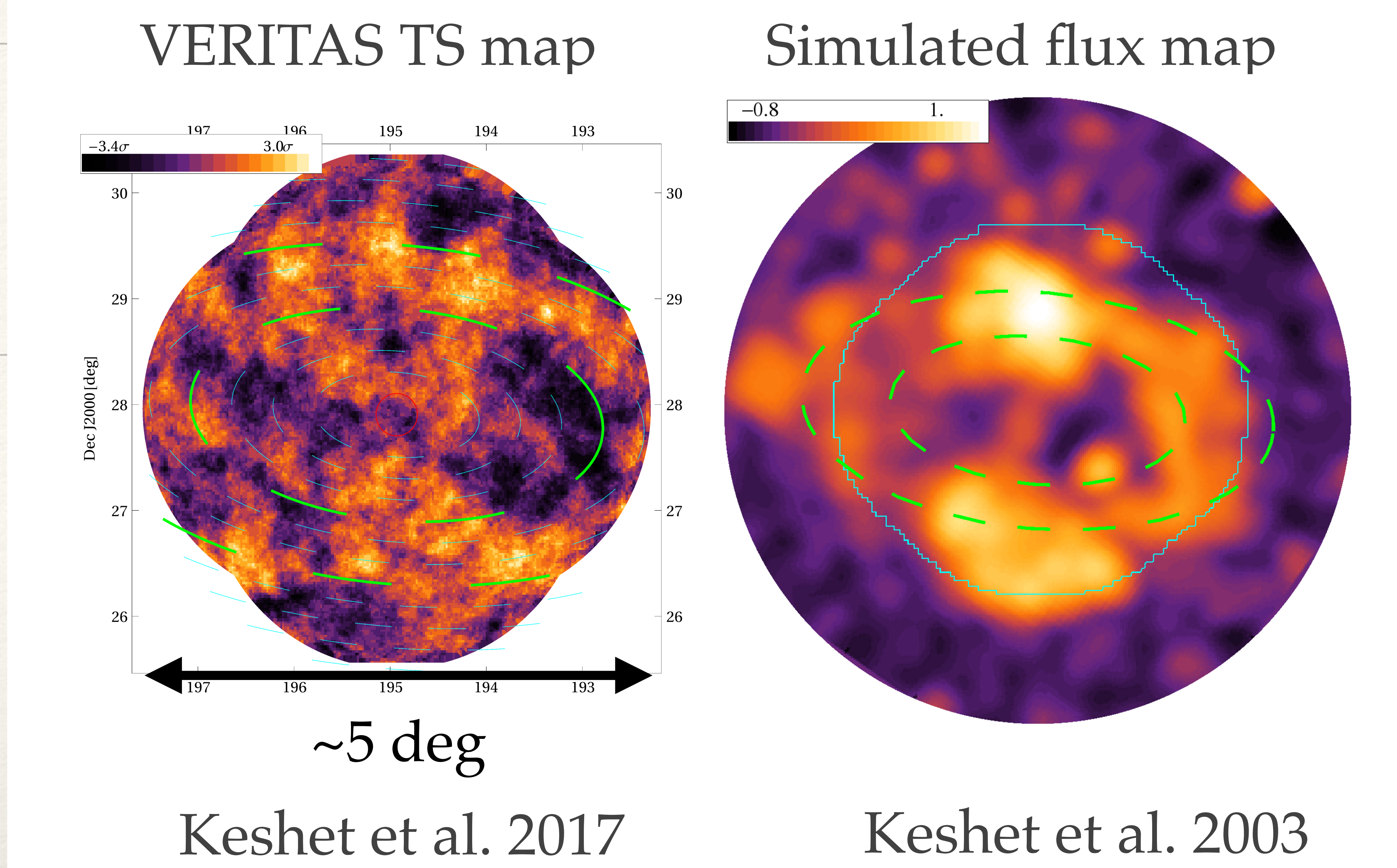
Thank you

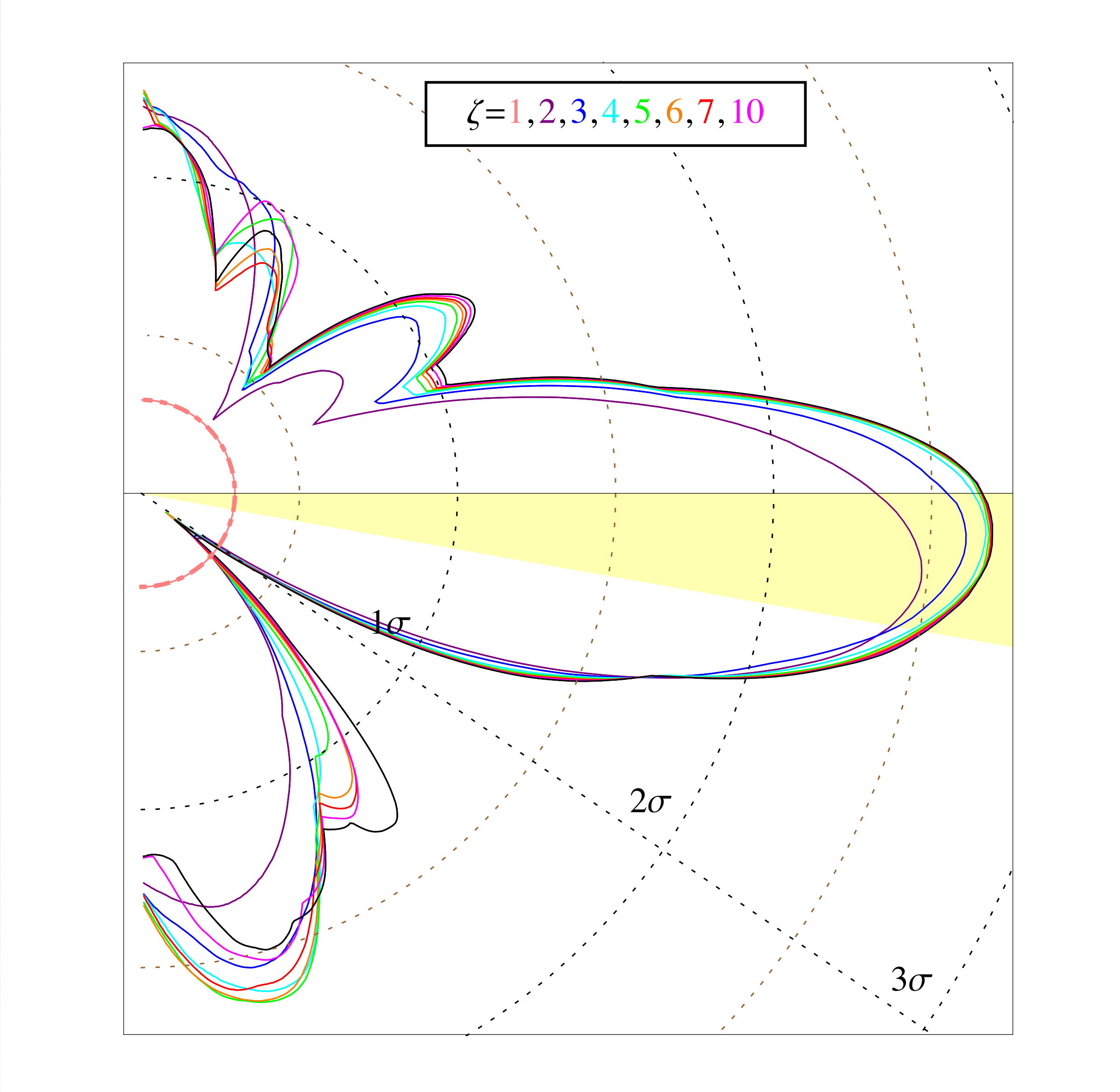
VERITAS signal: Coma



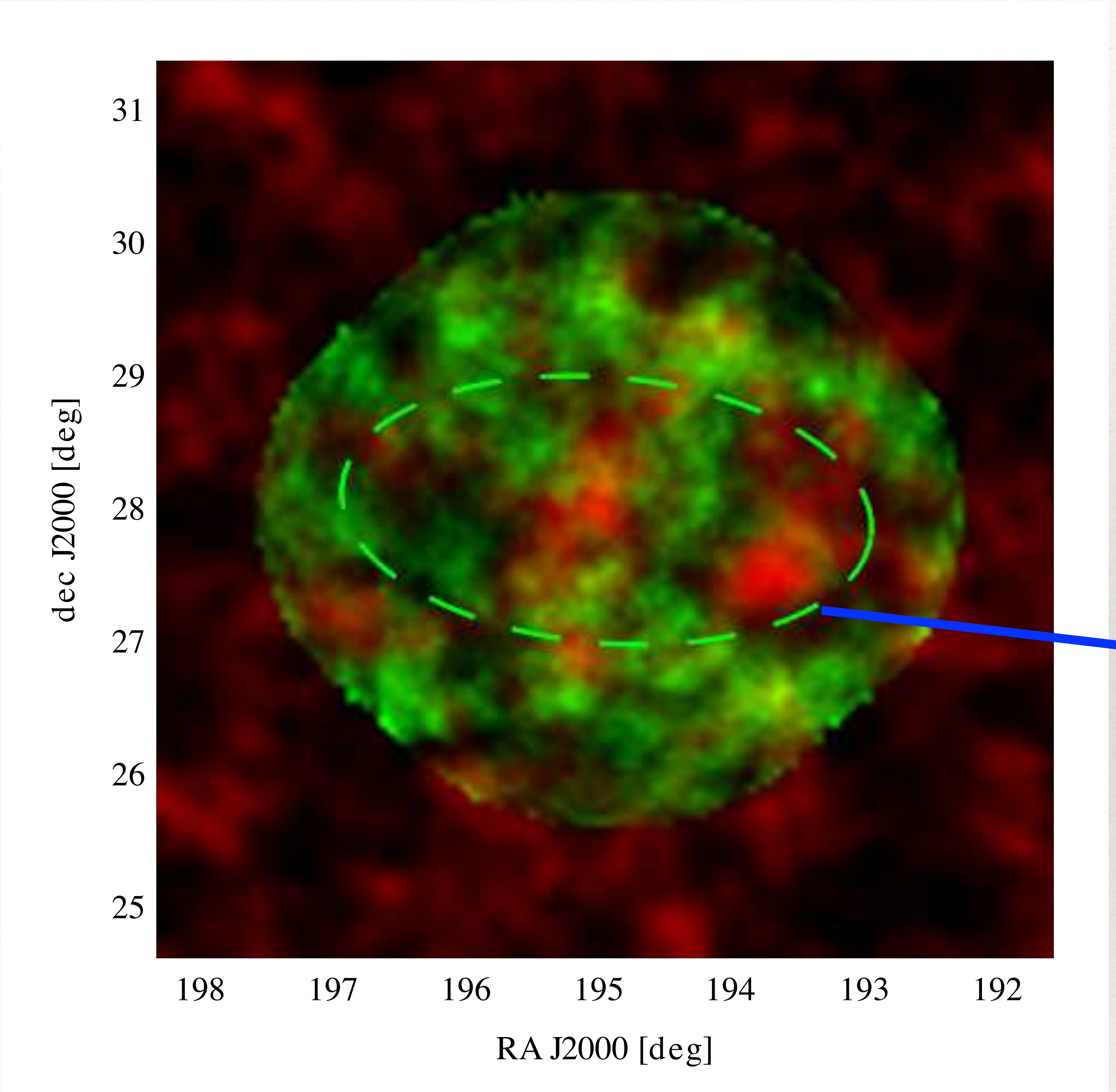
semi-minor axis
b = 1° — 1°.6
orientation ϕ = 0° — 10°
2.7σ signal

Ellipticity $\zeta \equiv a/b$





Synchrotron emission: Coma



Keshet et al. 2017

Green: VERITAS −3.4σ to +3.0σ

Red: −1.3 to $+5.4(\nu_0/\mathrm{GHz})^{3.2}$ K extracted from WMAP

Inner γ-ray $b = 1^\circ$ ring

Yellow: correlation between γ-ray and radio
→ outside the inner ring **+3.2σ** correlation