Detection of virial shocks in Fermi-LAT galaxy clusters

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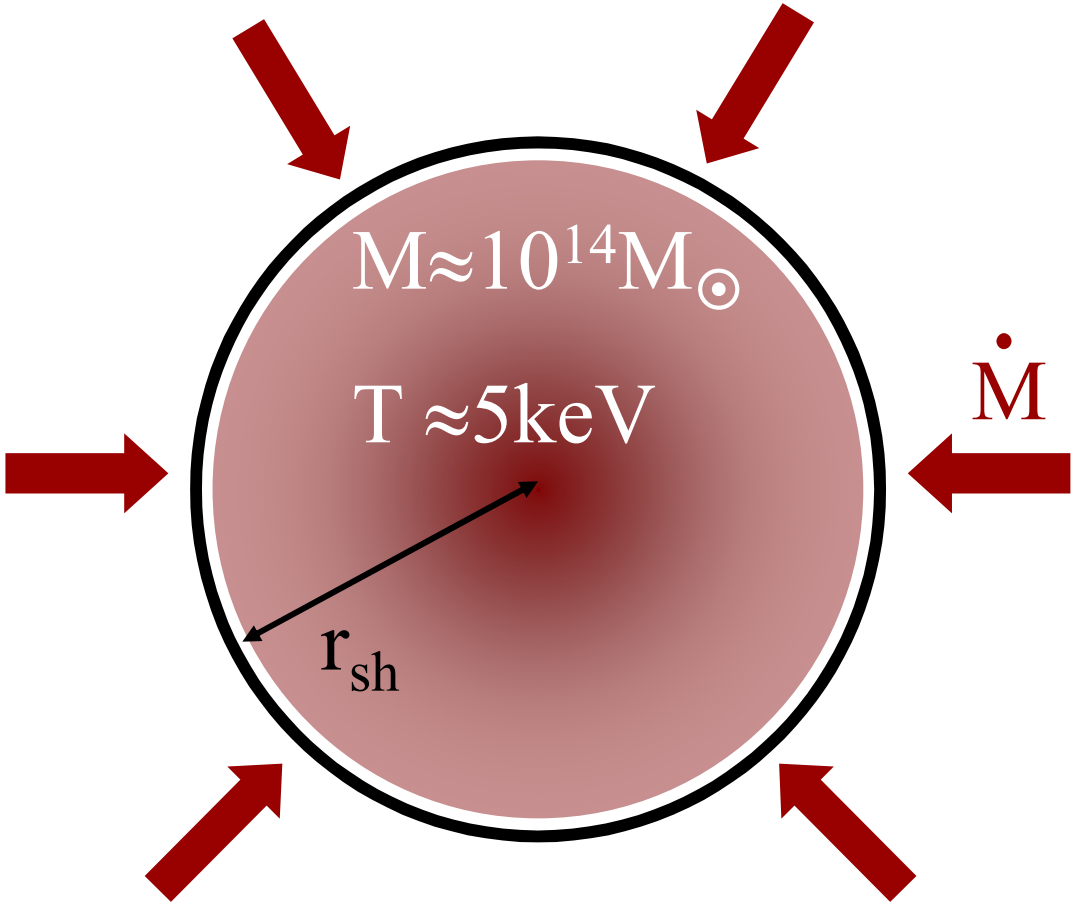
Outline

- Clusters and virial shocks
- Stacking analysis (IR&Keshet 1705.05376)
- X-ray to γ-ray view of Coma (Keshet&IR 1709.07442)
- Coincident SZ and γ-ray signals (Keshet, IR, Hurrier 1801.01494)
- Summary

We live in the age of galaxy clusters

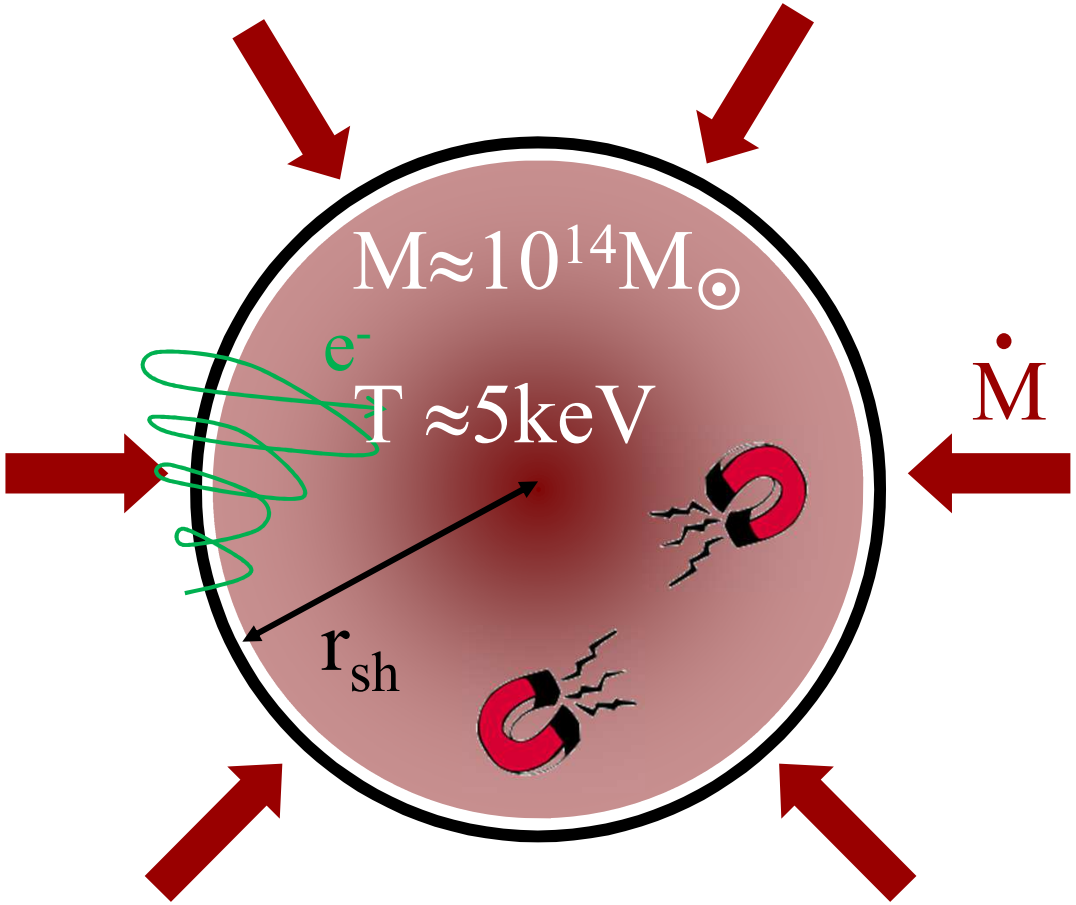
A2029



Galaxy clusters virial shock model

ξ_e

ξ_B

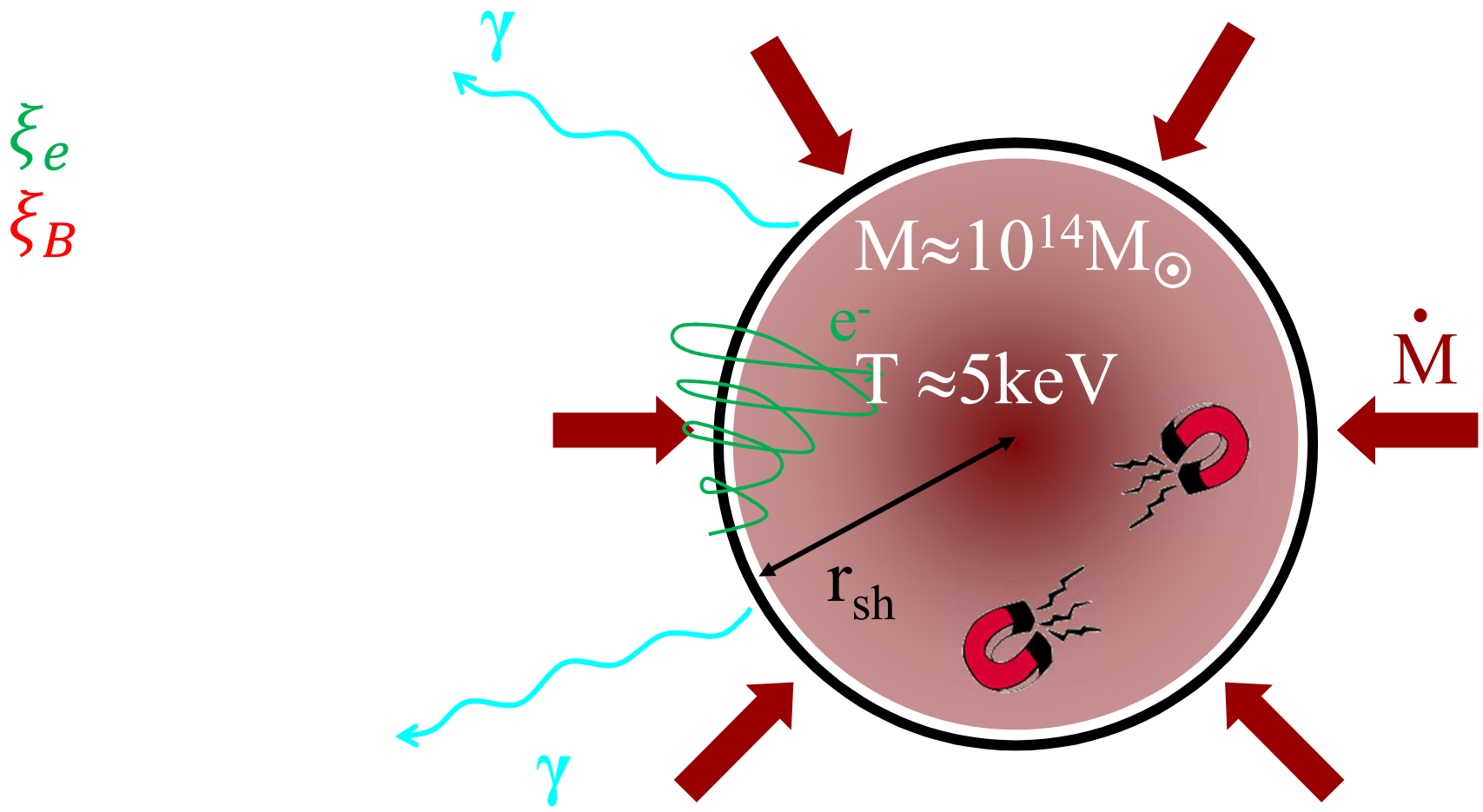


Upstream velocity ~ R/t_U ~ 1000 R_{20Mpc} km s^{-1}

This is similar to SNRs → similar physics

(after rescaling density and temperature, in the {Mach,β_B}>>1 limit)

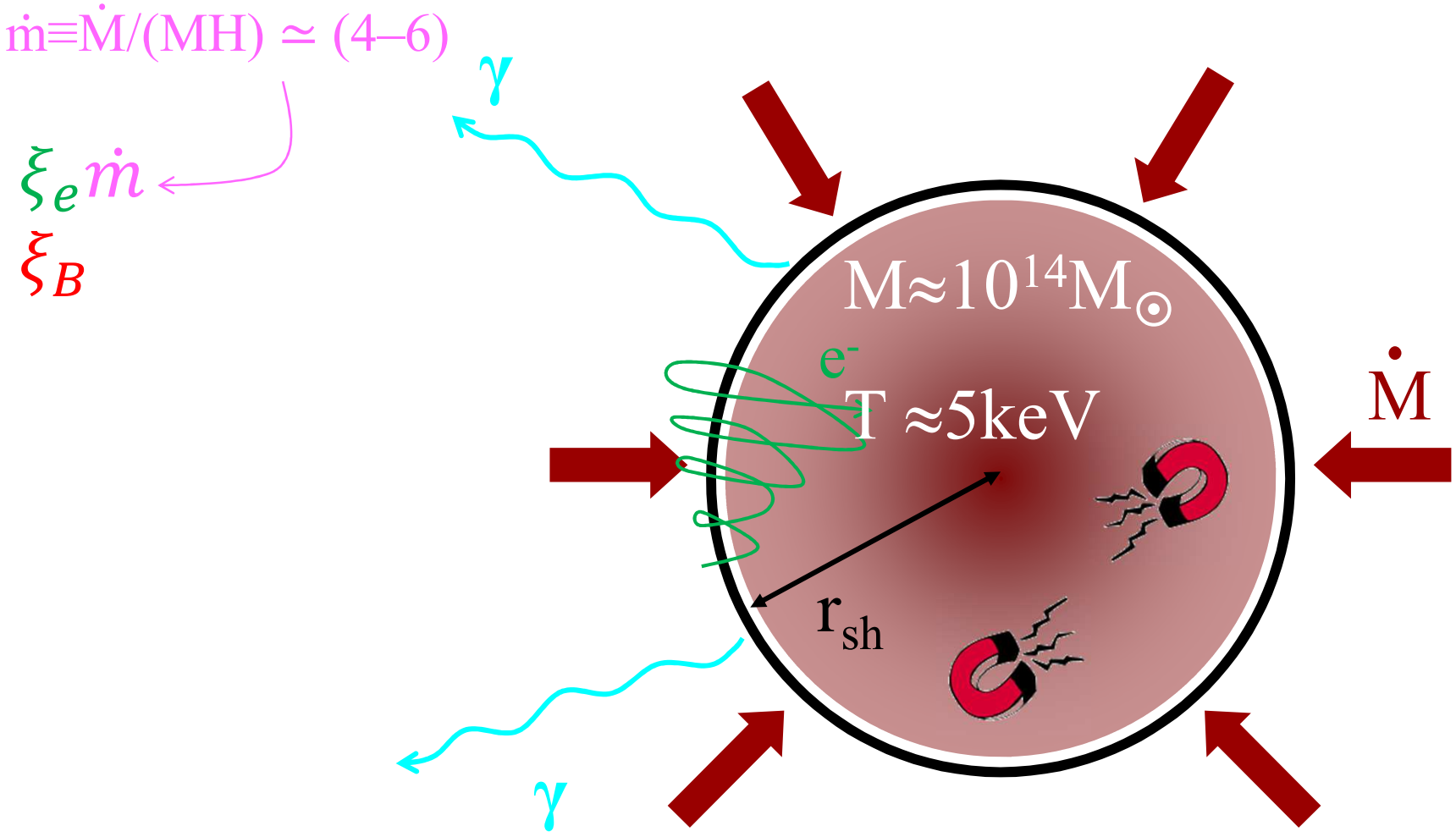
Galaxy clusters virial shock model



$$L_\nu \propto \xi_e \dot{M} T$$

Loeb+00, Nature

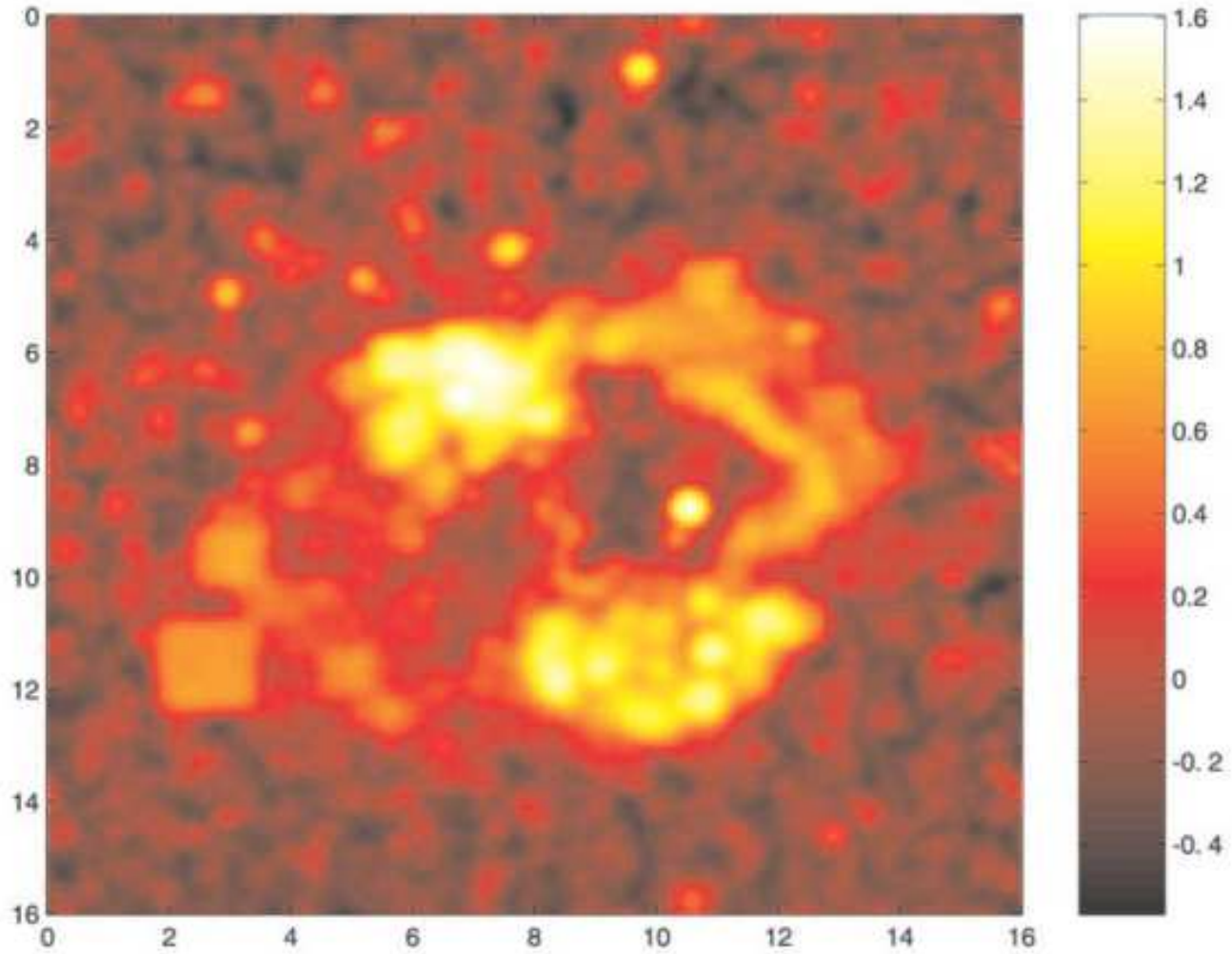
Galaxy clusters virial shock model



$$L_\nu \propto \xi_e \dot{M} T = \xi_e \dot{m} H M T \propto \xi_e \dot{m} M^{5/3}$$

Galaxy clusters virial shock model

This simple model was validated using simulations



Keshet+03 ApJ

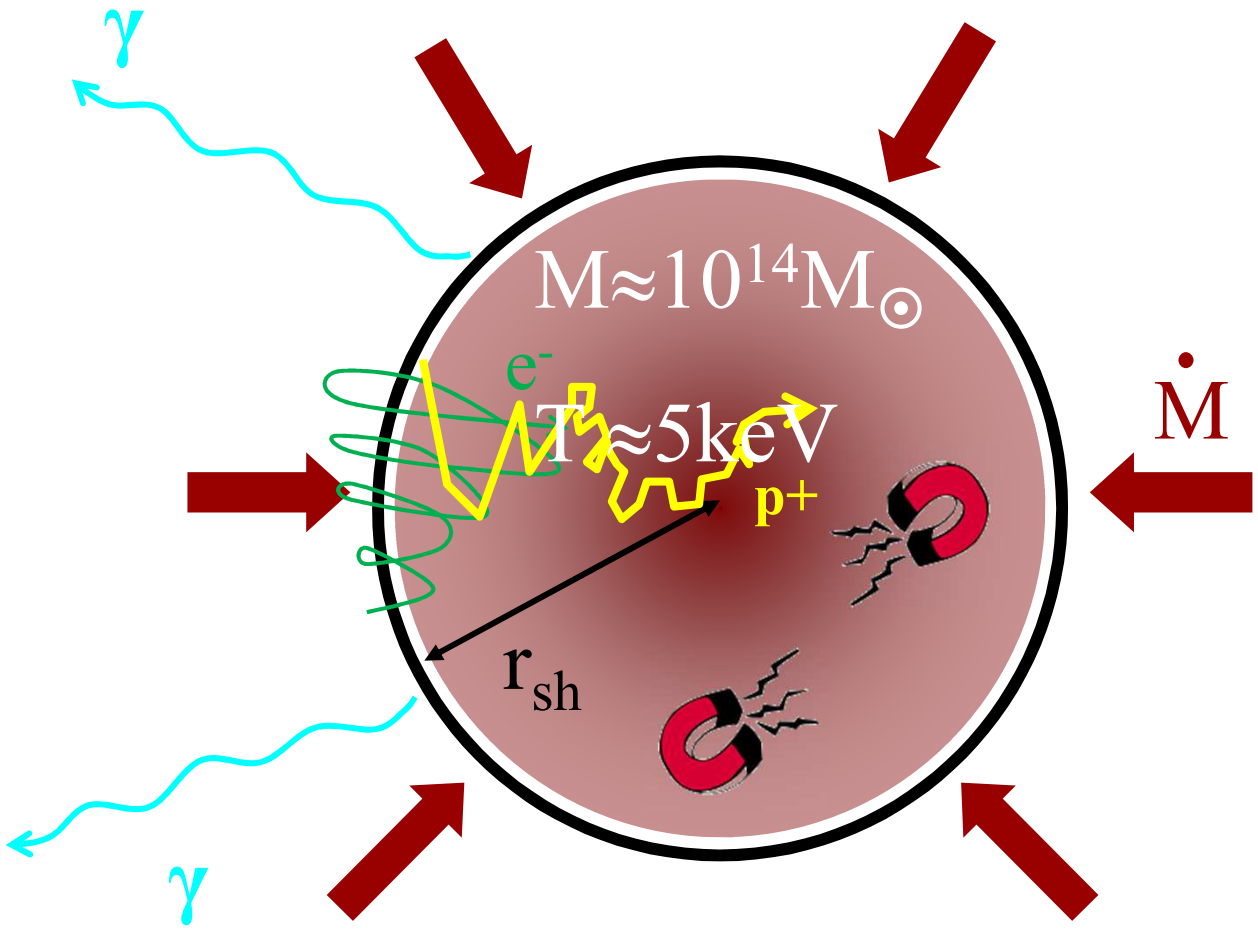
Also: Miniati+2002, Ryu+2003, Prfrommer+2006, Skillman+2008, Vazza+2009, …

Galaxy clusters virial shock model

$\xi_e \dot{m}$

ξ_B

ξ_p



Galaxy clusters virial shock model

$\xi_e \dot{m}$

ξ_B

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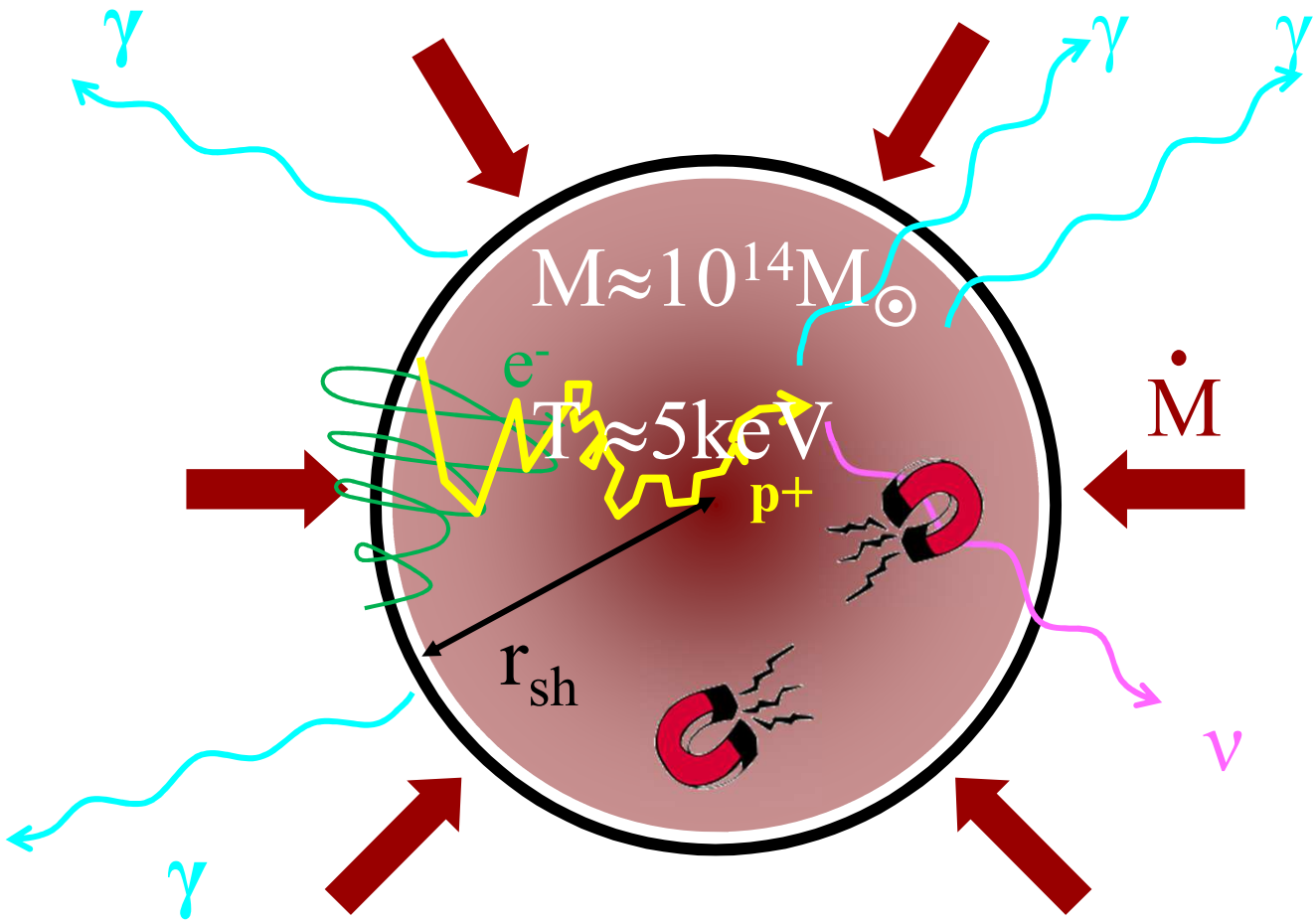
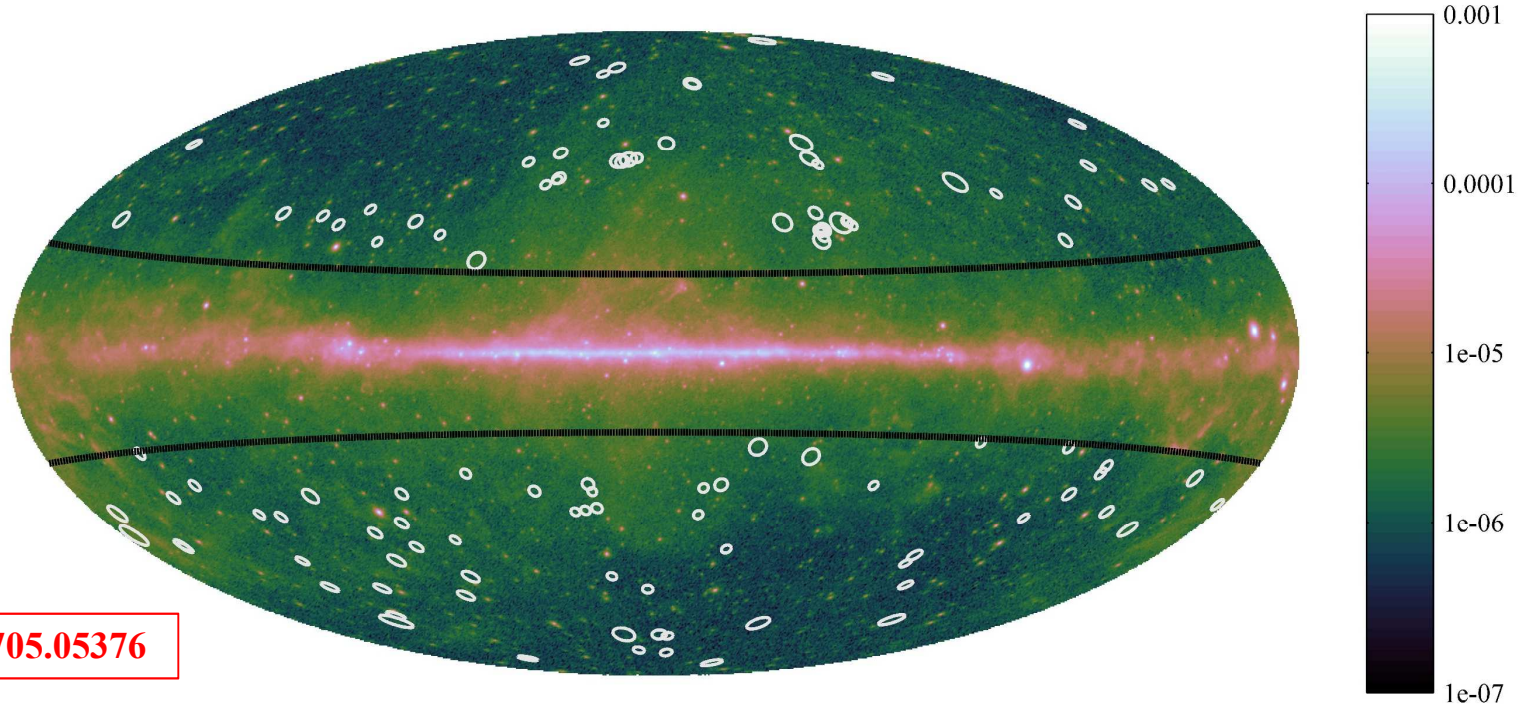


Stacking Analysis

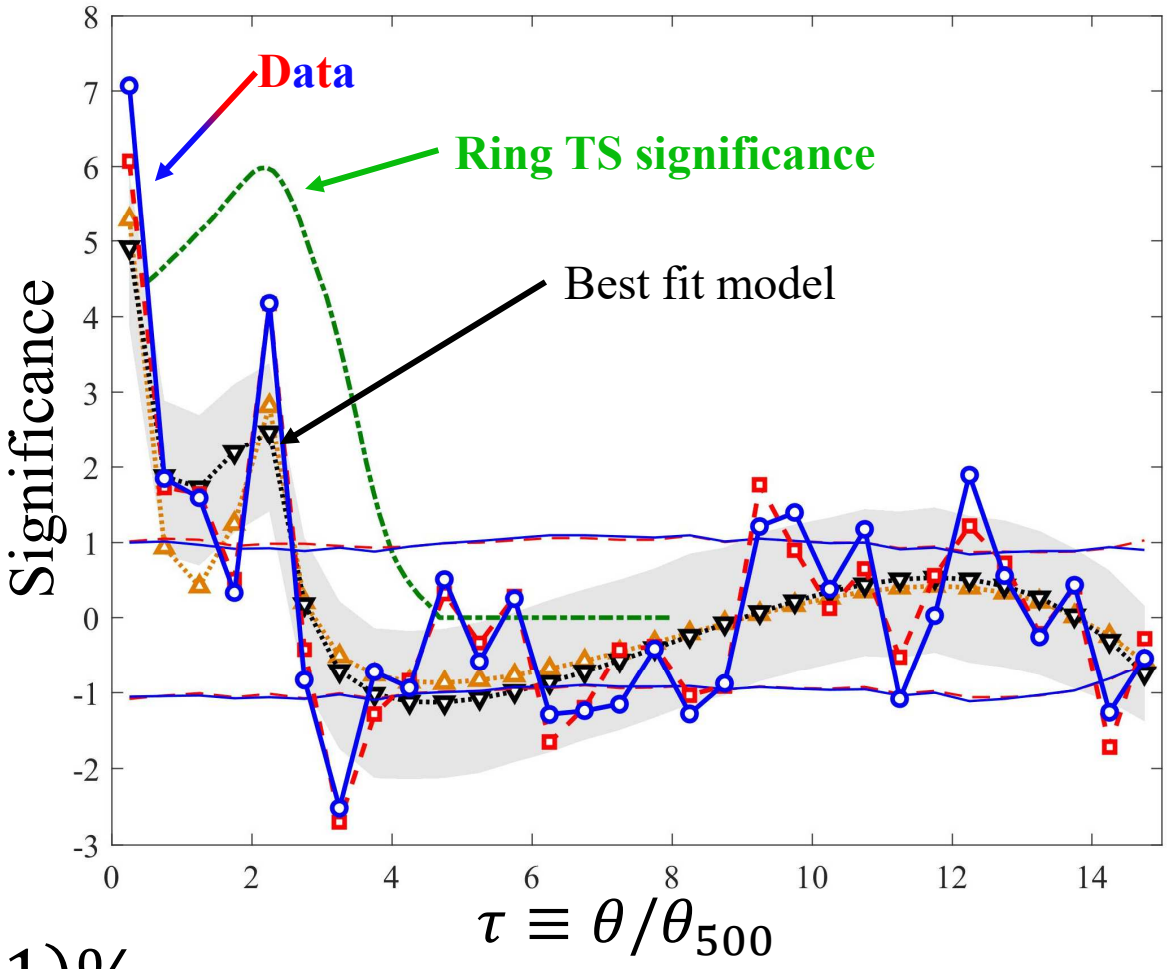
- 1-100 Gev ~8 years all sky data
  - 4 energy bands, HEALPix 10 discretization (0.057°)
- 112 clusters from MCXC
  - Massive ($M_{500}>10^{13}M_{\odot}$)
  - Extended ($0.2°<\theta_{500}<0.5°$)
  - Far from the galactic plane ($|b|>20°$)
  - Far (1.8°) from 3FGL point sources



IR&Keshet 1705.05376

Two signals – ring-like and point-like

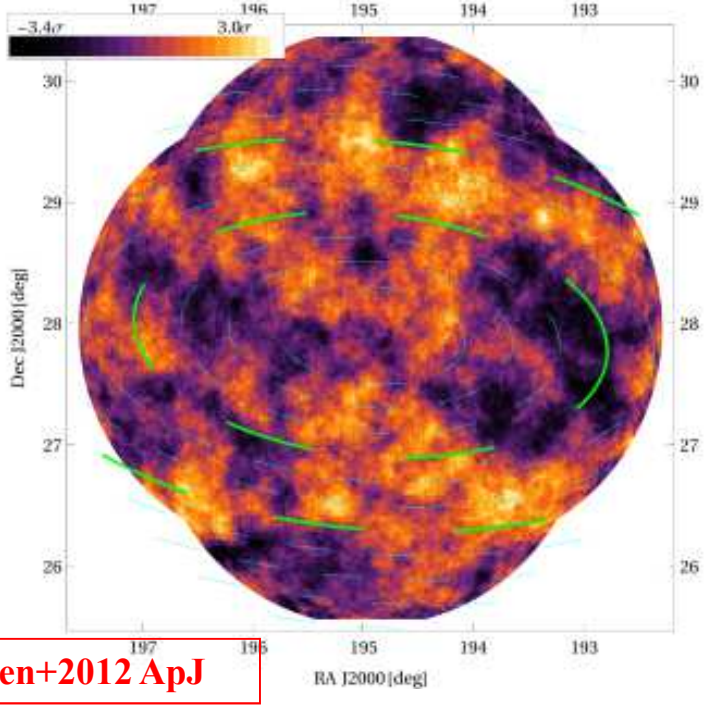
- Stack on the rescaled radius τ
- Fit foreground as a 4th order polynomial
- Masked point sources



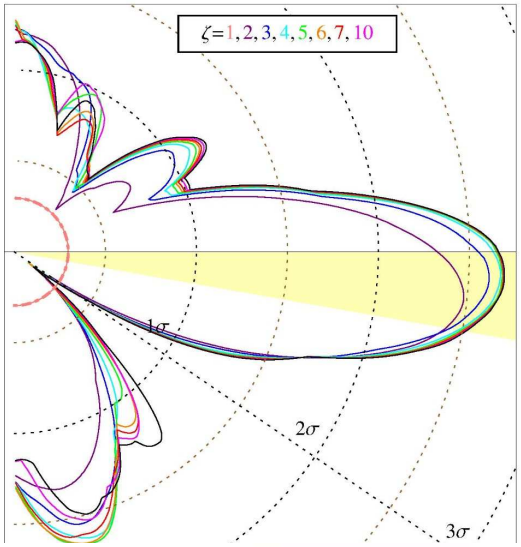
- TS_{ring}=37.9 (5.8σ)
- TS_{AGN}=38.1 (5.8σ)
- Ring parameters:
  - $\varrho_v = 2.4 \pm 0.1$,
  - $\xi_e \dot{m} = (0.65 \pm 0.11)\%$

IR&Keshet 1705.05376

VERITAS detects an elliptical ring around Coma

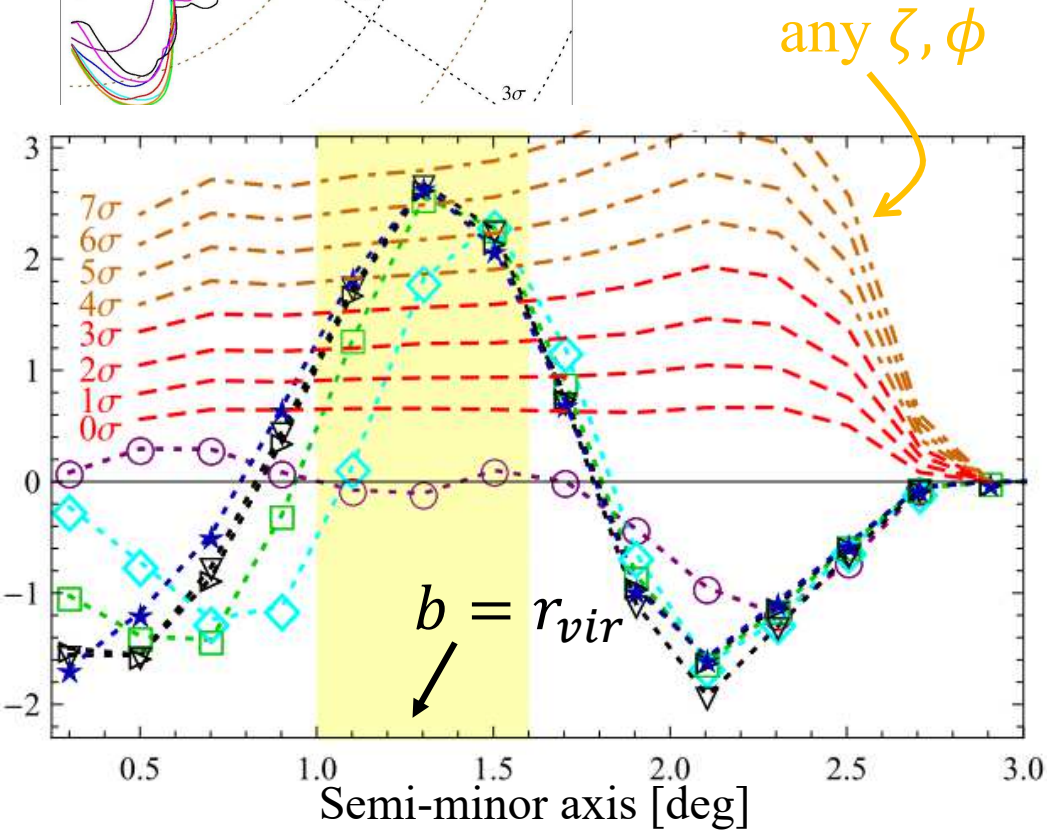


Arlen+2012 ApJ



Keshet +2017 ApJ

- East-west $\zeta \equiv \frac{a}{b} \gtrsim 2.5$ ring with $b = r_{vir}$: 2.7σ
- VERITAS-like pipeline for control sample of rings: 5.1σ (post-trial)
- Pixel histogram: better fit w/ diffuse source
- Gives $\xi_e \dot{m} \simeq 0.5\%$ (consistent w/ stacking)



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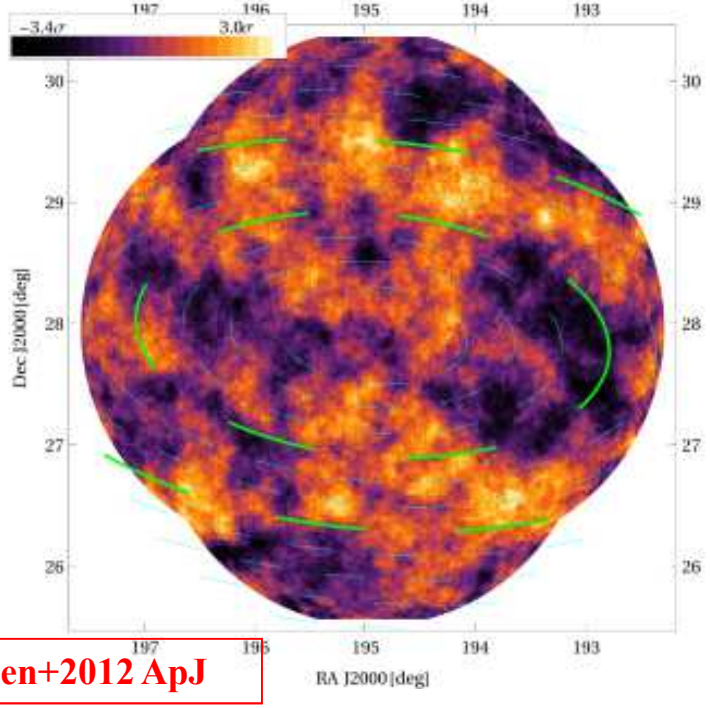

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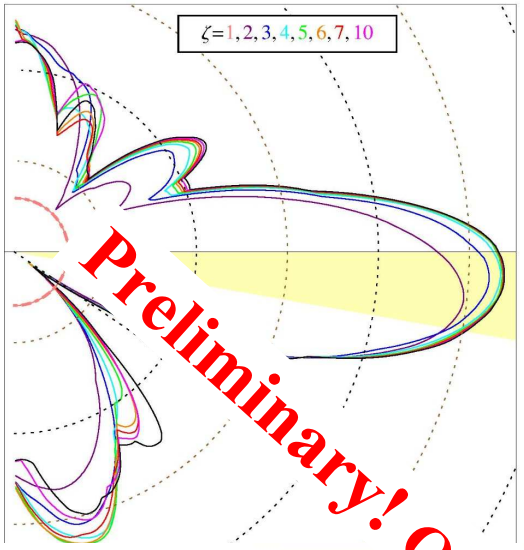
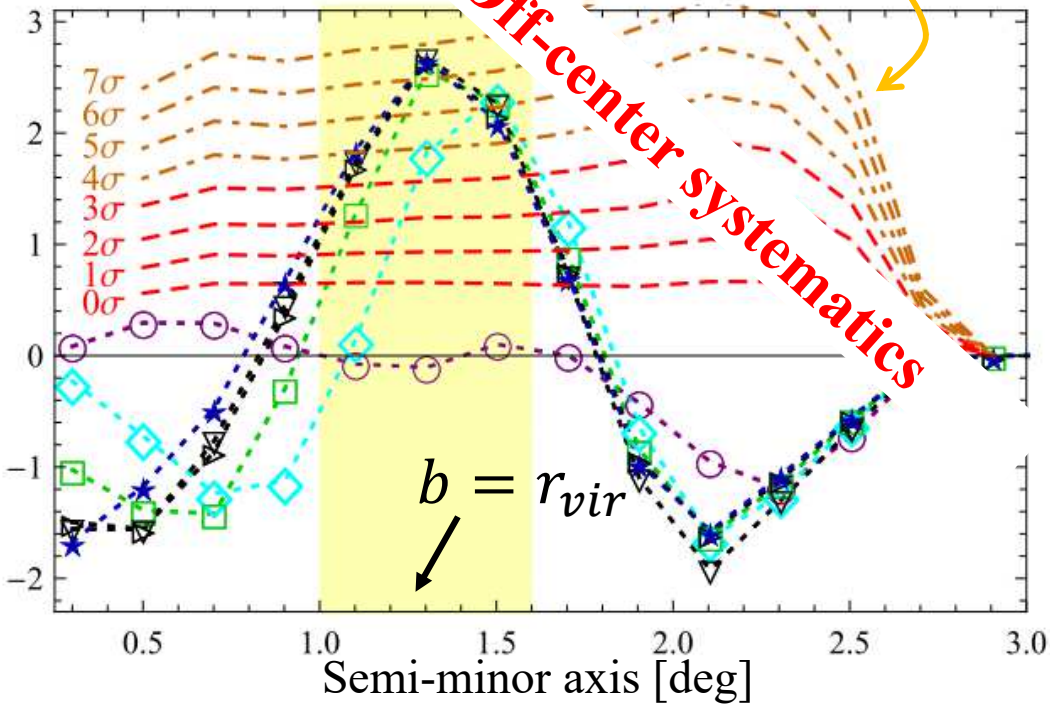


Keshet +2017 ApJ

Preliminary! Off-center systematics

any ζ, ϕ



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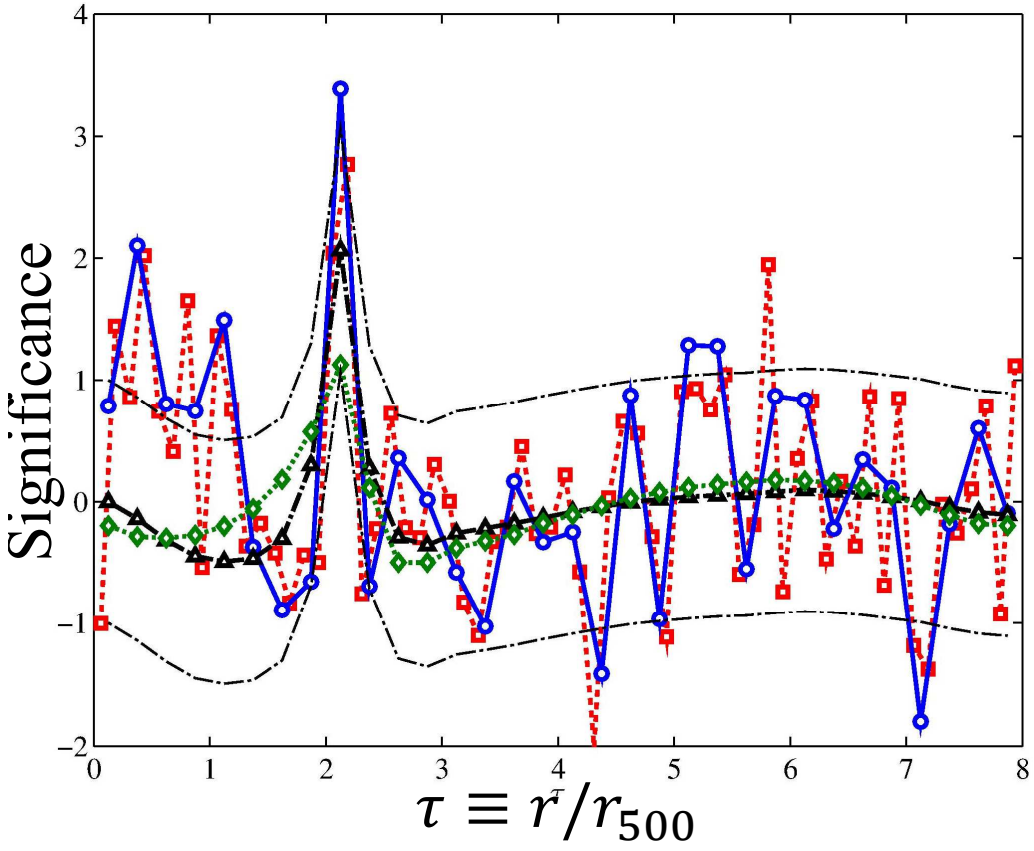
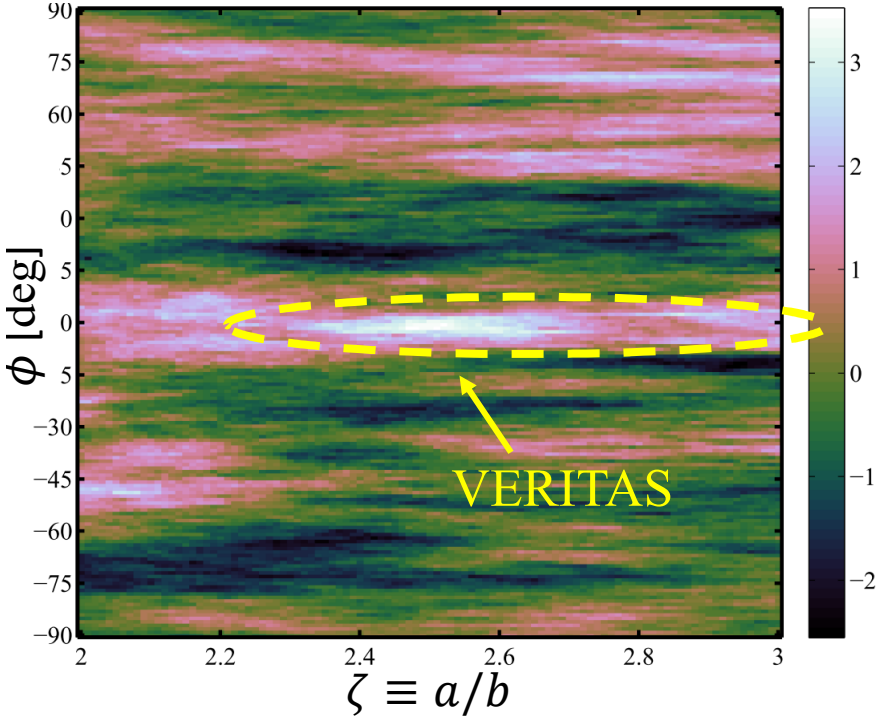
Fermi-LAT see a thin ring in Coma





Keshet&IR 1709.07442

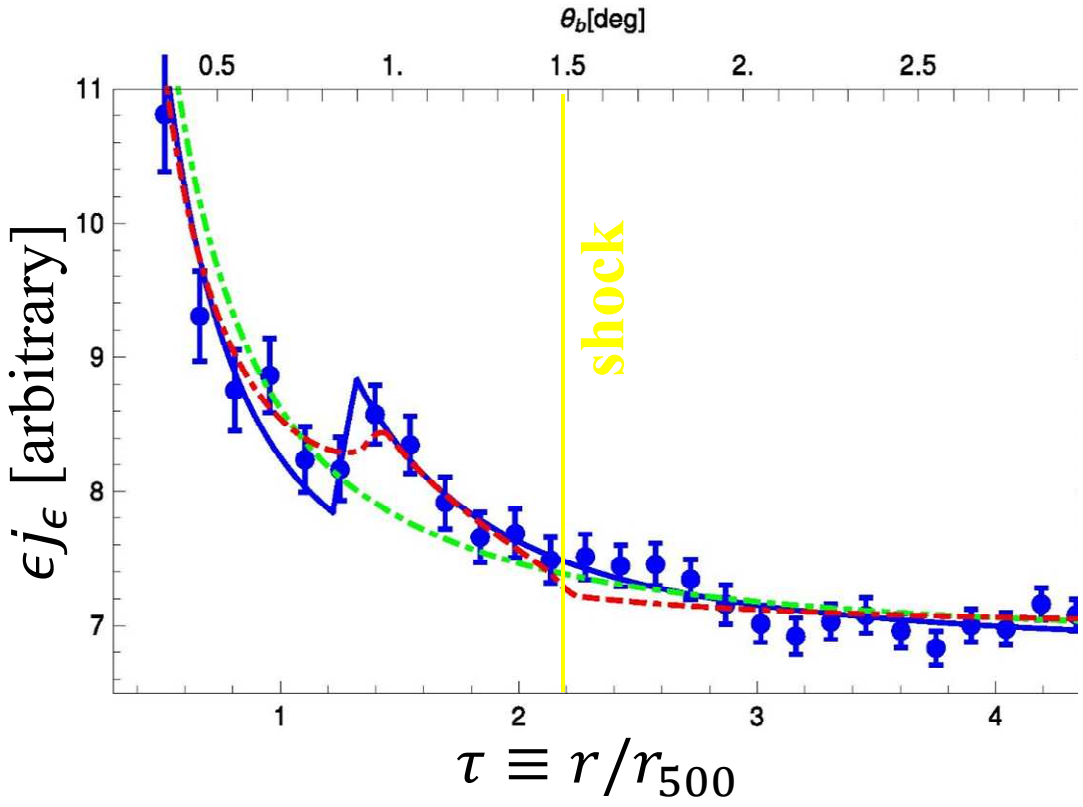
Peak 3.4σ TS 2.5σ

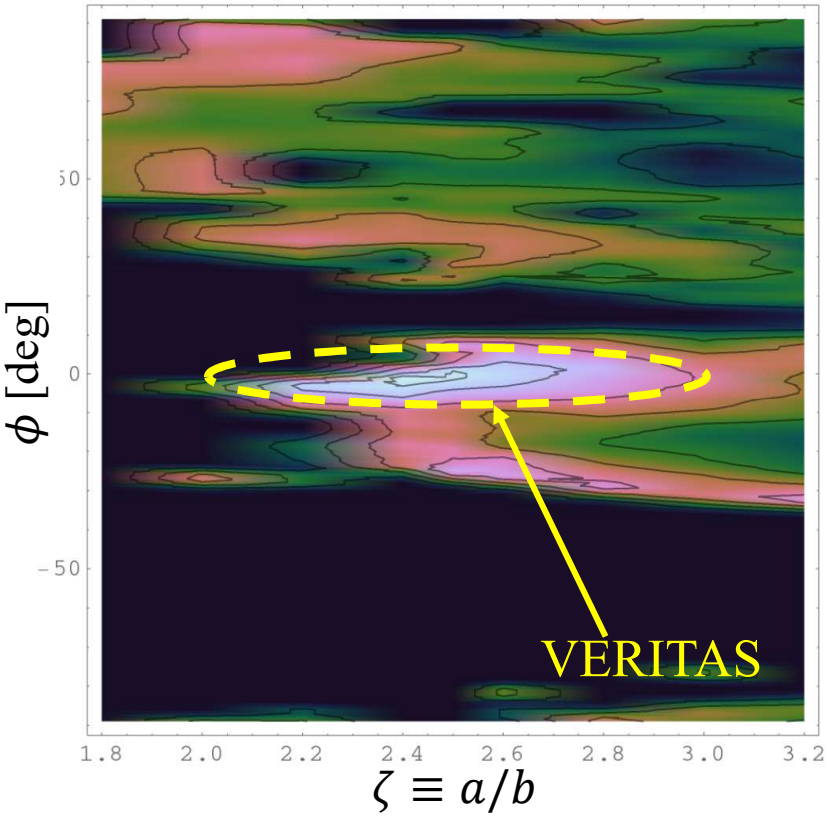
$\xi_e \dot{m} \simeq 0.19\% \pm 0.07\%$ (factor ~2 uncertainty)

$\tau = 2.14 \pm 0.07$

ROSAT show a virial signal downstream

Keshet&IR 1709.07442

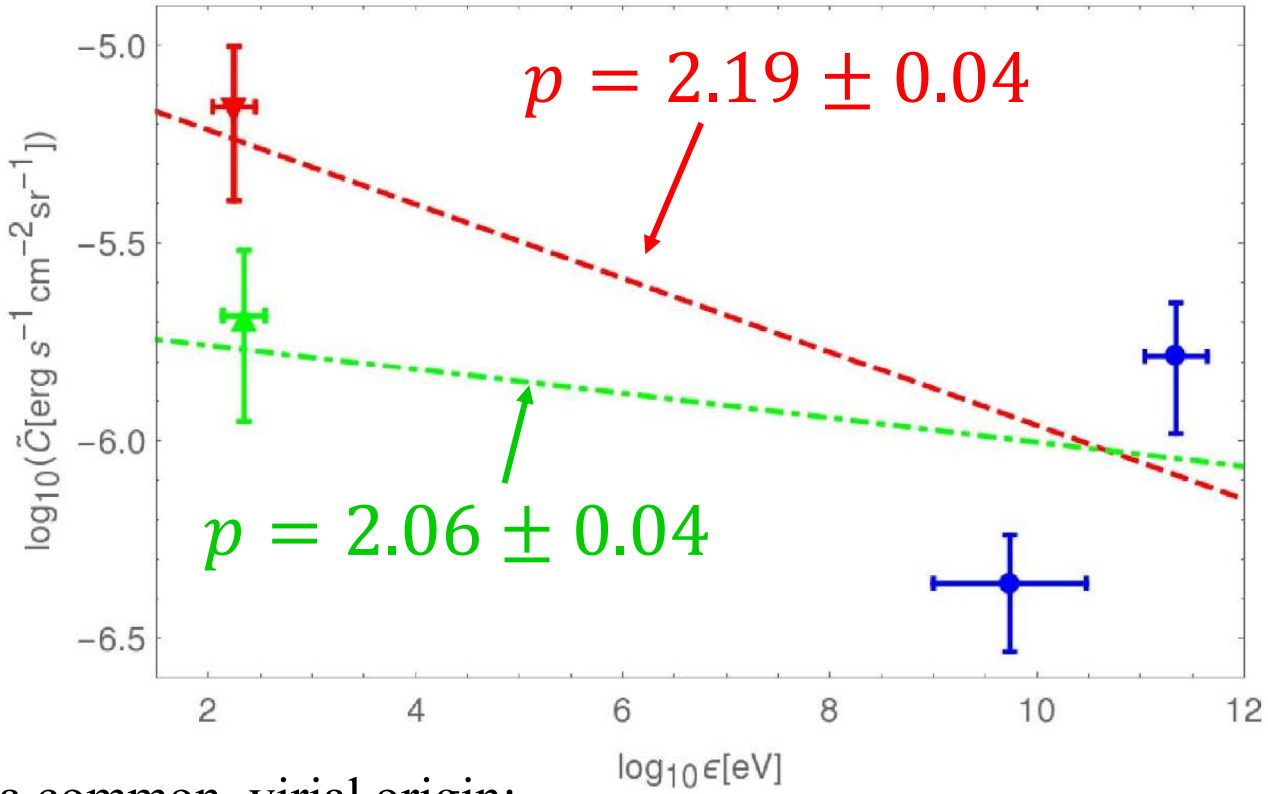




TS: 5.7σ (two free parameters: j_ϵ and $\tau_{cool} \simeq 1.4 \pm 0.2$)

Both @R1 and @R2 (0.1–0.3 keV) not at higher bands (>0.44 keV)

Signals agree over 9 orders of magnitude in Energy



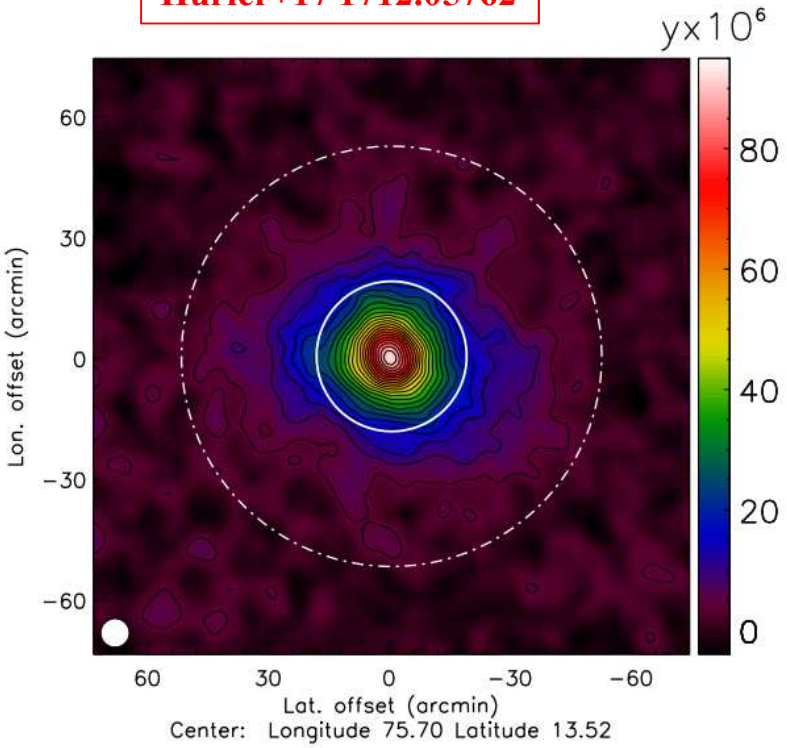
Indications of a common, virial origin:

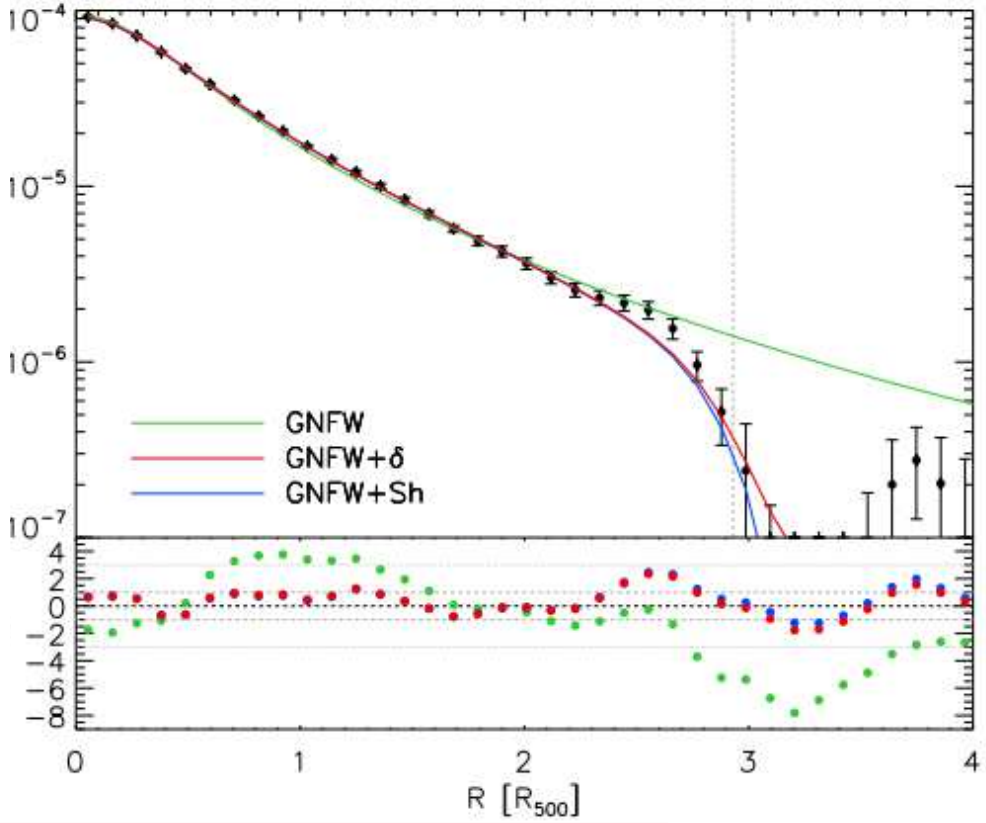
- fluxes agree for a flat (p~2) spectrum
- combined significance: very high
- reasonable virial parameters (τ, ξ_e, p)
- signals maximized at same morphology
- + at the expected τ, ϕ, and ballpark ζ
- all signals better match planar model
- anecdotal (e.g., all brighter @west)

Keshet&IR 1709.07442

Direct evidence for shock in A2319

Hurier+17 1712.05762





8.5σ detection

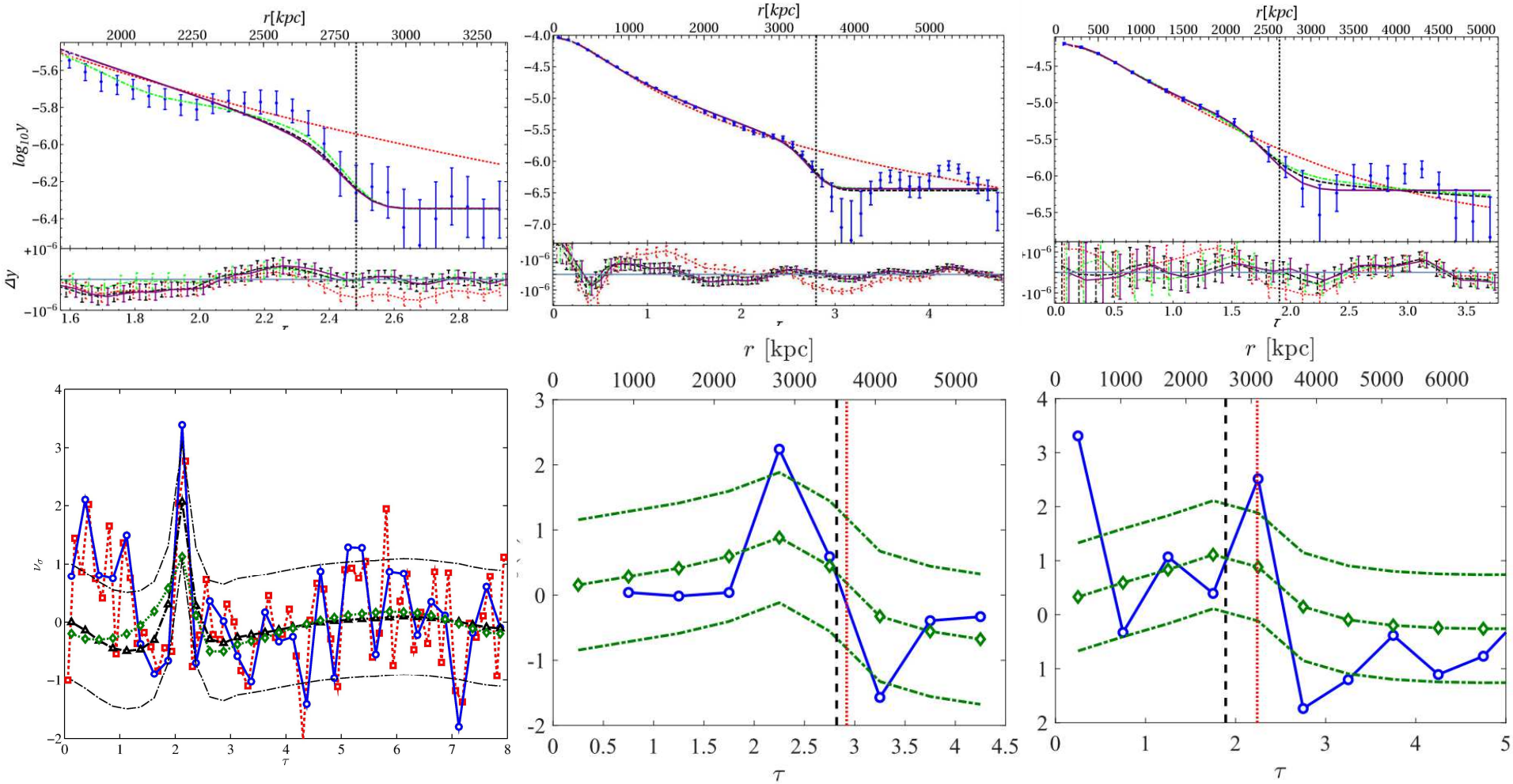
$\tau = 2.93 \pm 0.05$

$\mathcal{M} > 3.25$ (95% CL)

From 2MASS galaxy count, $\dot{m} = 2 \pm 0.6$

SZ shocks and γ-ray shocks coincide

Keshet, IR, Hurrier 1801.01494

	Coma	A2319	A2142
			
SZ	$\tau = 2.46 \pm 0.04\ (4.1\sigma),\ \mathcal{M} > 2.5$	$\tau = 2.82 \pm 0.05\ (14\sigma),\ \mathcal{M} > 1.6$	$\tau = 1.89 \pm 0.06\ (4.1\sigma),\ \mathcal{M} > 1.9$
LAT	$\tau = 2.14^{+0.07}_{-0.06}\ (2.5\sigma)$ $\xi_e \dot{m} = (0.19 \pm 0.07)\%$	$\tau = 2.9^{+0.3}_{-0.4}\ (1.2\sigma)$ $\xi_e \dot{m} = (0.4 \pm 0.2)\%$	$\tau = 2.2^{+0.2}_{-0.3}\ (2.2\sigma)$ $\xi_e \dot{m} = (0.7 \pm 0.3)\%$

SZ shocks and γ-ray shocks coincide

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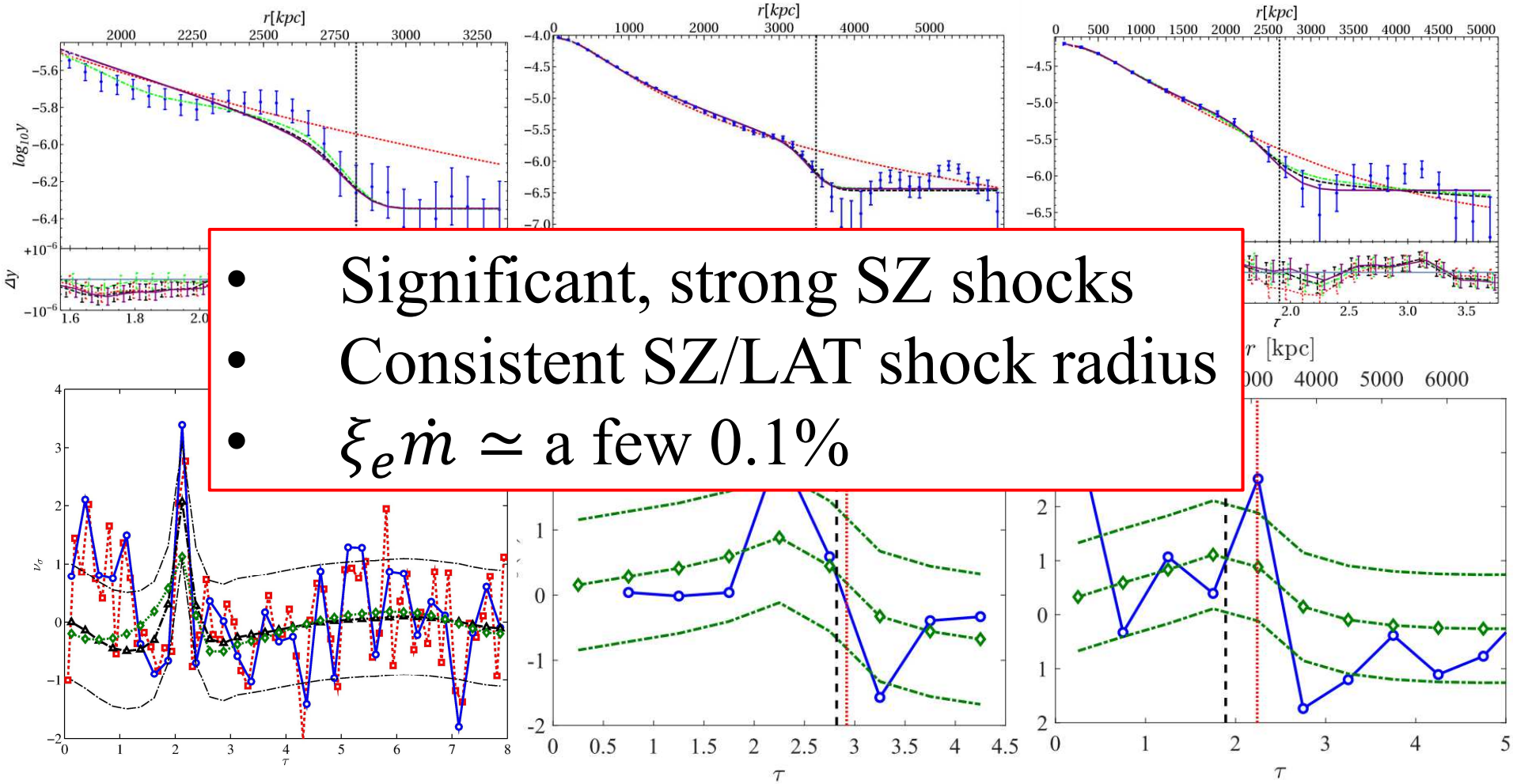
Coma **A2319** **A2142**



- Significant, strong SZ shocks
- Consistent SZ/LAT shock radius
- $\xi_e \dot{m} \simeq$ a few 0.1%

	Coma	A2319	A2142
SZ	$\tau = 2.46 \pm 0.04$ (4.1σ), $\mathcal{M} > 2.5$	$\tau = 2.82 \pm 0.05$ (14σ), $\mathcal{M} > 1.6$	$\tau = 1.89 \pm 0.06$ (4.1σ), $\mathcal{M} > 1.9$
LAT	$\tau = 2.14^{+0.07}_{-0.06}$ (2.5σ) $\xi_e \dot{m} = (0.19 \pm 0.07)\%$	$\tau = 2.9^{+0.3}_{-0.4}$ (1.2σ) $\xi_e \dot{m} = (0.4 \pm 0.2)\%$	$\tau = 2.2^{+0.2}_{-0.3}$ (2.2σ) $\xi_e \dot{m} = (0.7 \pm 0.3)\%$

Summary

- Stacking 112 clusters:
  - $> 5\sigma$ detection
  - $\xi_e \dot{m} \simeq 0.6\%$; flat (p~2) spectrum; $R_{sh} \simeq 2.4 R_{500} \simeq R_{90}$
  - Sky-averaged: $\epsilon^2 \frac{dJ}{d\epsilon} \simeq 20 \left(\frac{\xi_e \dot{m}}{0.5\%}\right) \mathrm{eV\ s^{-1} cm^{-2} sr^{-1}}$
- Coma:
  - Consistent signals over 9 orders of magnitude in energy
  - The combined signals indicate a virial signal at a high confidence
  - X-ray signal implies D(E $\simeq$ 300 MeV)$\lesssim 10^{32} \mathrm{cm^2 s^{-1}}$
- SZ:
  - SZ shocks coincide the LAT excess in Coma, A2319 and A2142
  - $\xi_e \dot{m} \simeq$ a few 0.1% in all three clusters
- Virial shocks useful in astrophysics + cosmology + plasma physics

Consistent with spherical collapse models ($\approx R_{100}$; Eke+96) and numerical simulations (Schaal&Springel 15)

15% of Fermi-LAT diffuse component at 100 GeV, (Ackermann+12)