Search for monochromatic gamma-ray emission

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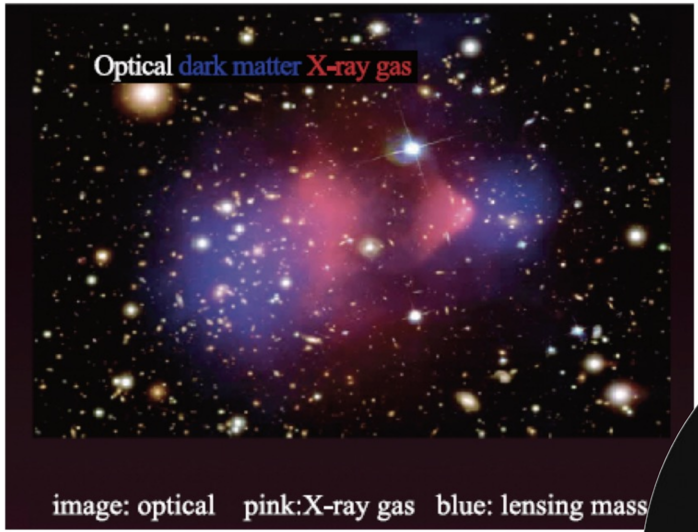
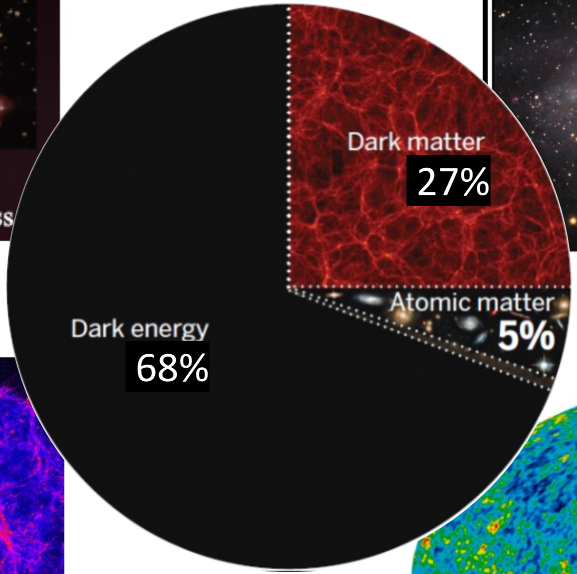
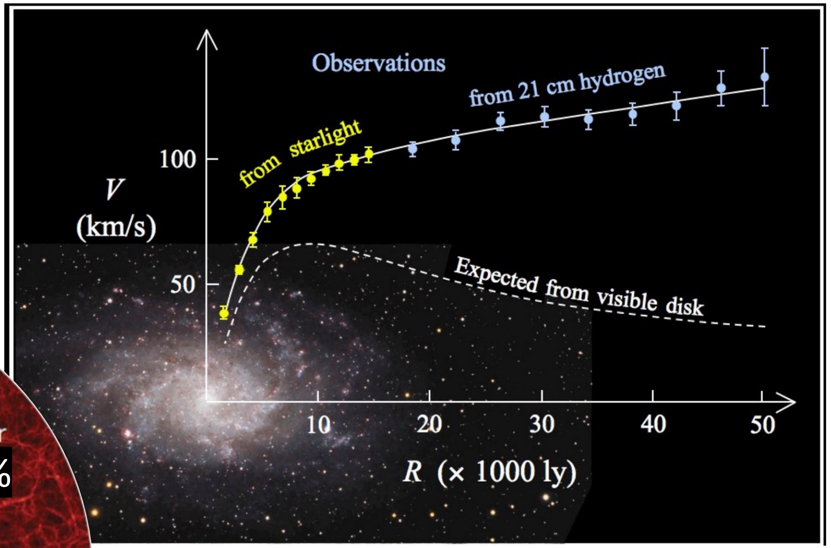
0. Ubiquity of dark matter (DM)

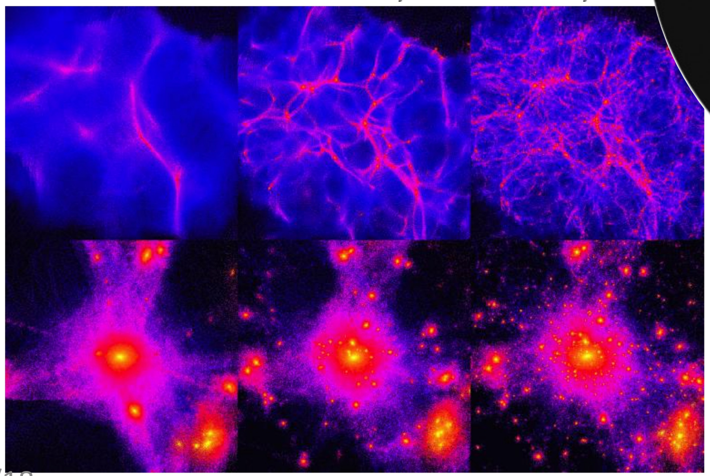


Collisions of galaxy clusters

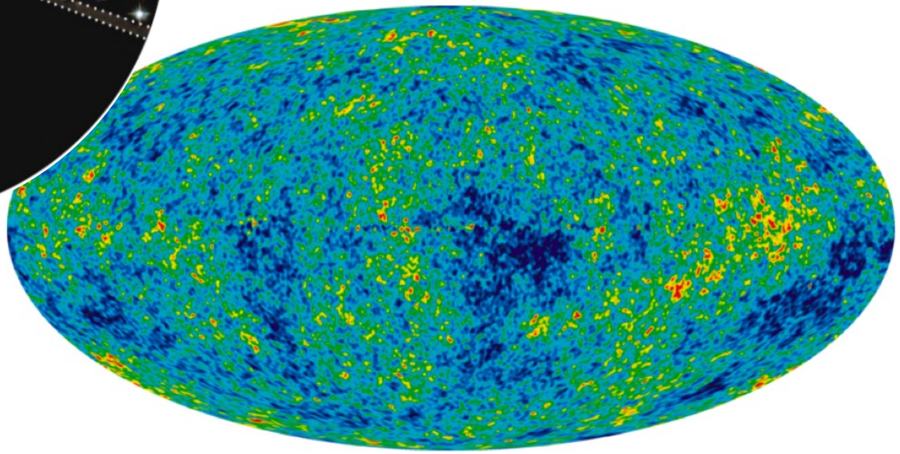




Rotation curves of galaxies

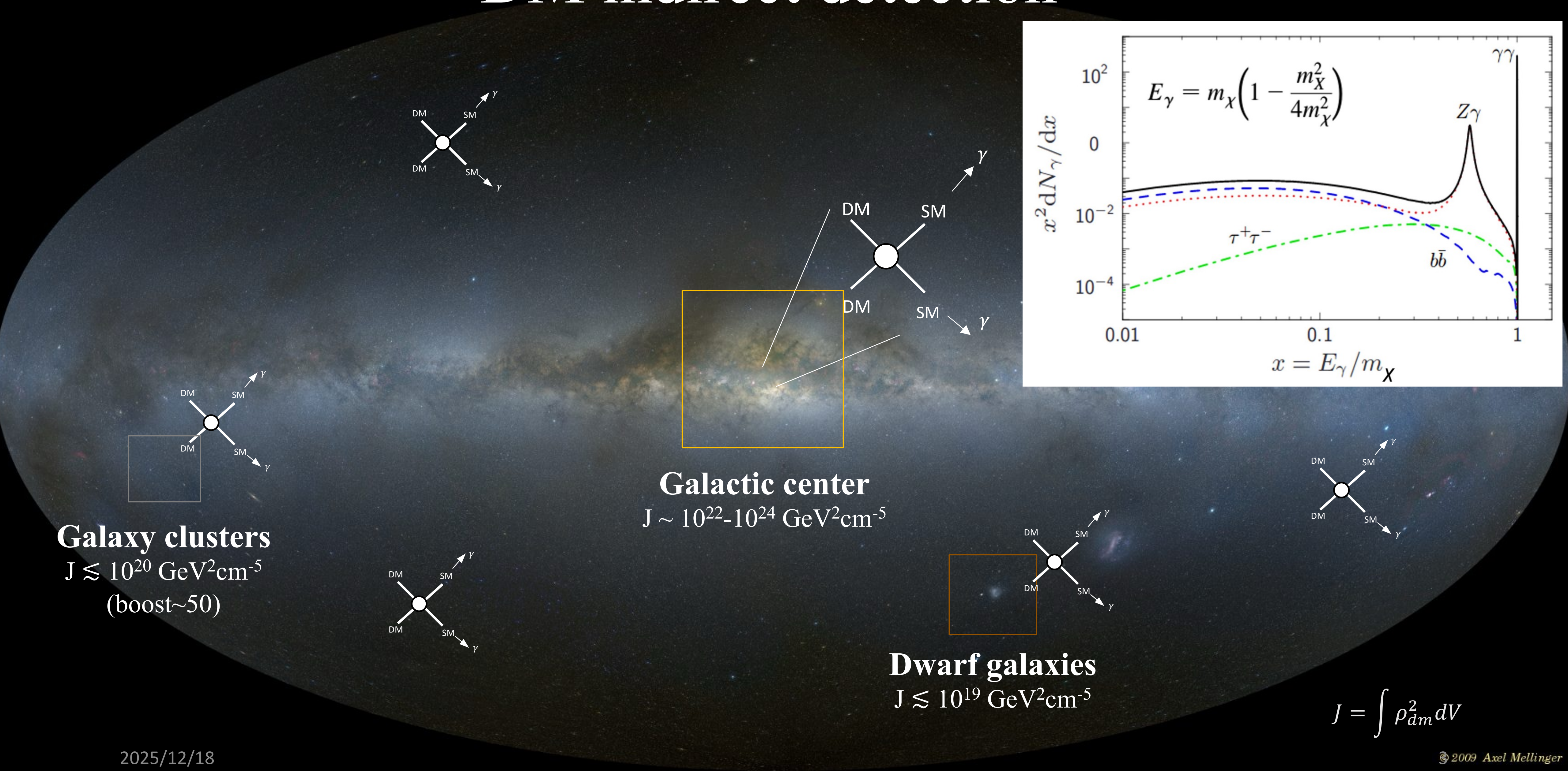


Large scale structure

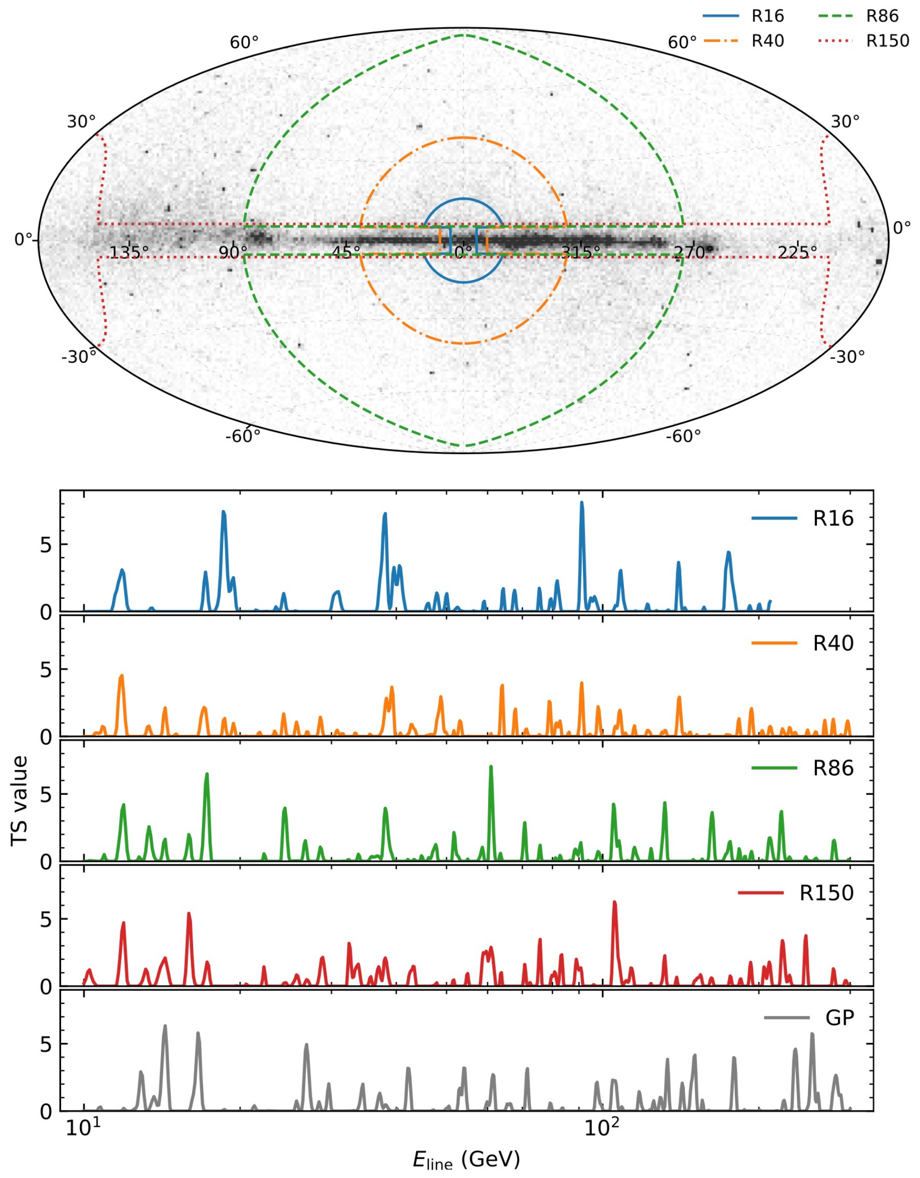


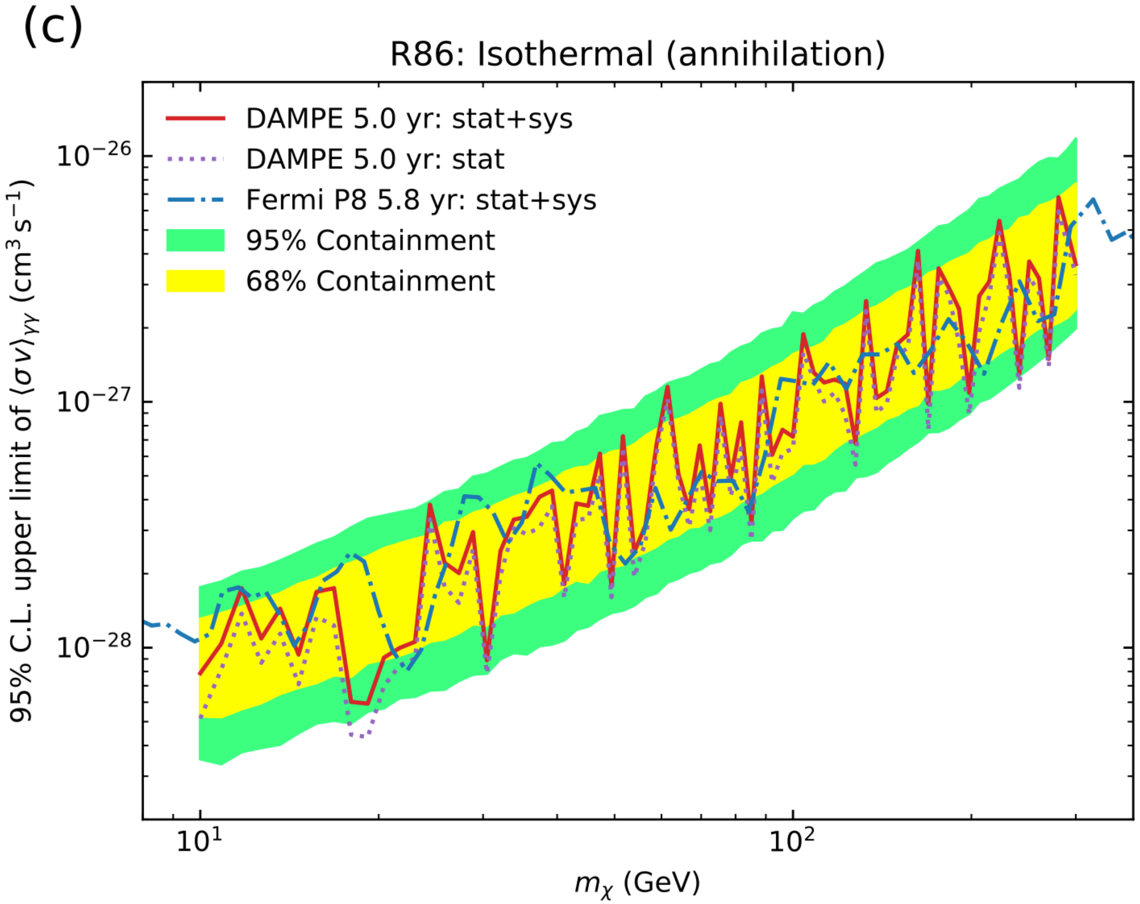
Cosmic microwave background

DM indirect detection



Line search in the Galaxy





No gamma-ray lines are detected in the observation of the Milky Way.

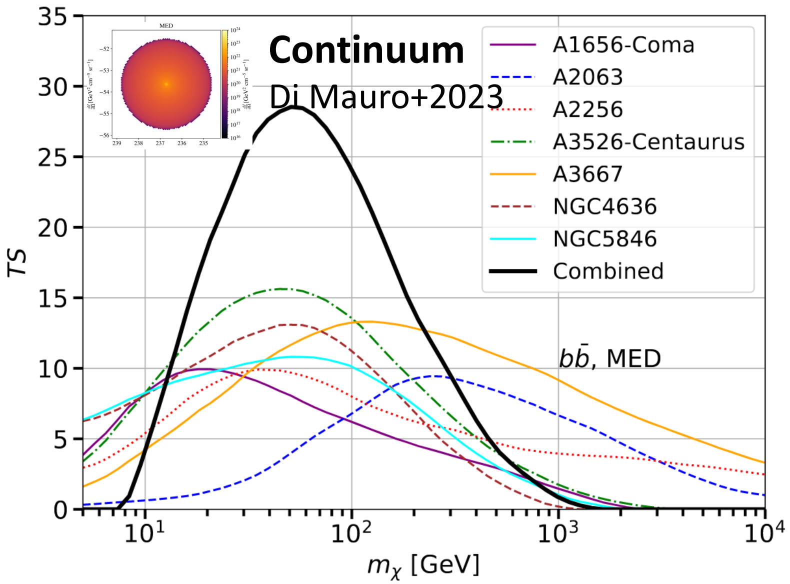
DAMPE 2022

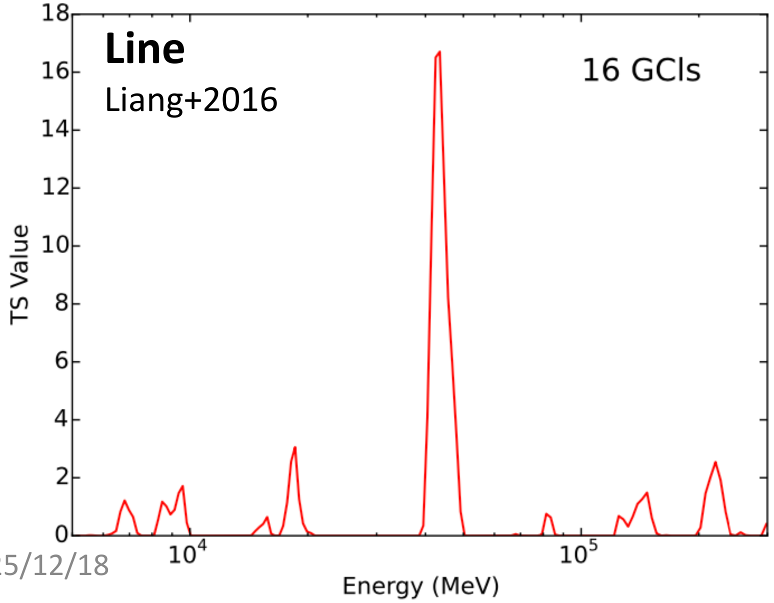
Galaxy clusters

Virgo cluster

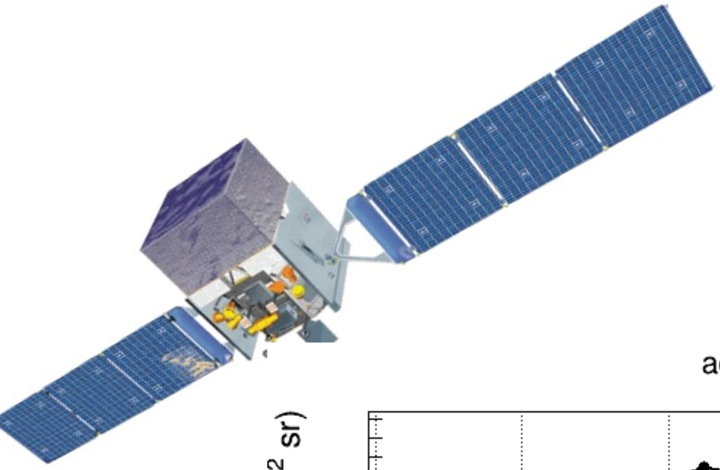
Mass: $M_{200} \sim 10^{14}\ M_\odot$
Mass-to-light ratio: $M/L \sim 500\ (M_\odot/L_\odot)$
J-factor$\sim 10^{20}\ \mathrm{GeV^2 cm^{-5}}$ (boost~50)

Previous DM searches in galaxy clusters

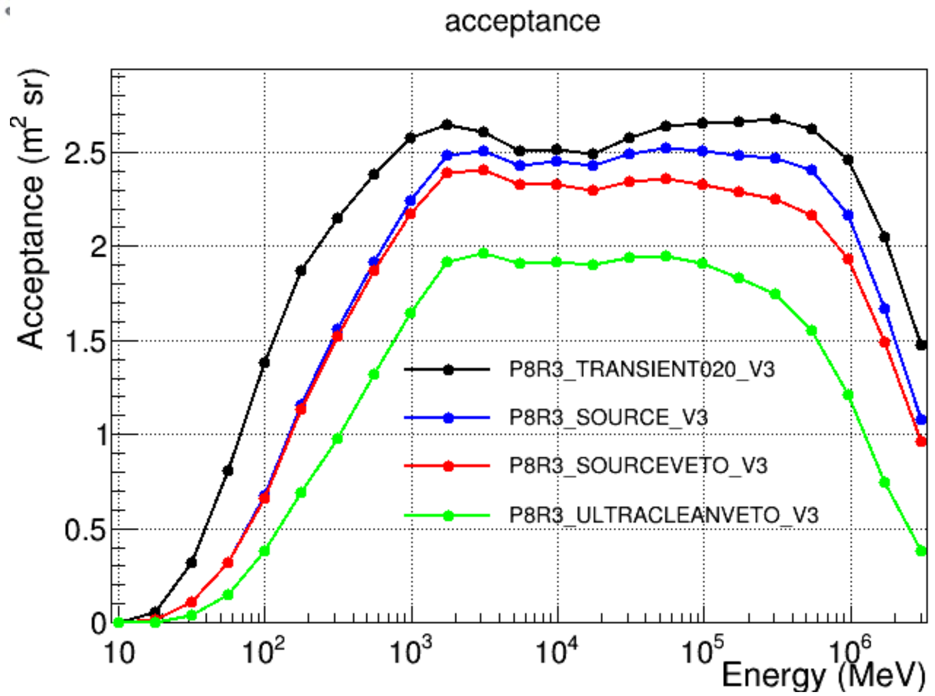


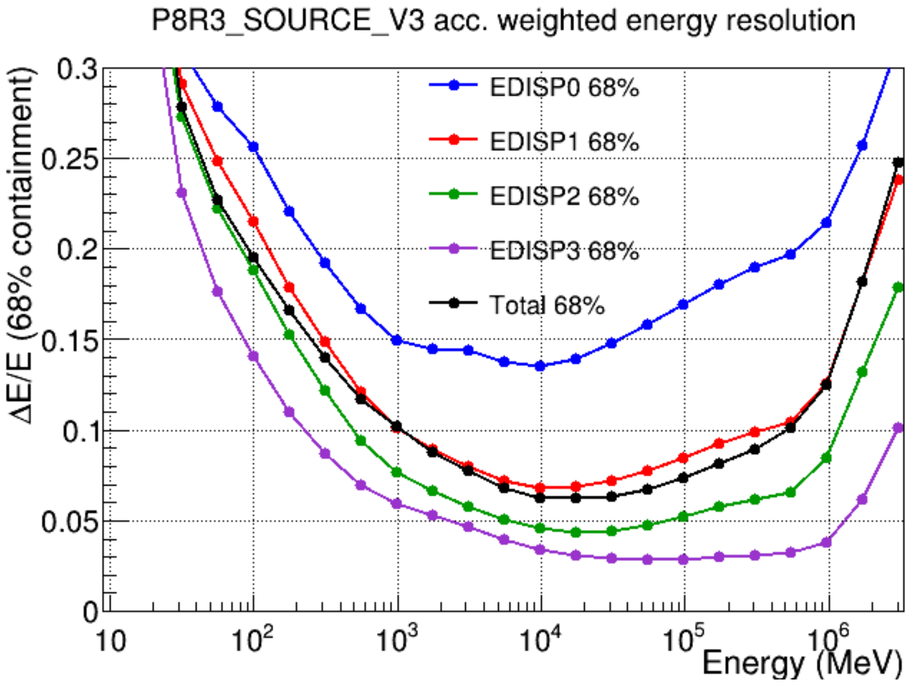


- Continuum excess:
  - ➢ No excess is found, and stringent constraints are set by many groups (Ackermann+2010, Huang+2012, Lisanti+2018, Thorpe-Morgan+2021).
  - ➢ A 2.5σ-3.0σ continuum excess is reported once the substructures are considered, suggesting 40-60 GeV annihilating DM (Di Mauro+2023).
  - ➢ The continuum excess can be affected by background point sources (Han+2012, Li+2025).
- Line-like excess:
  - ➢ 130 GeV line (Hektor+2013): later proved to be a systematic origin due to the same excess in the Earth limb data (Ackermann+2015).
  - ➢ 43 GeV line: suggested in the stacking data of galaxy clusters (Liang+2016, Shen+2021).



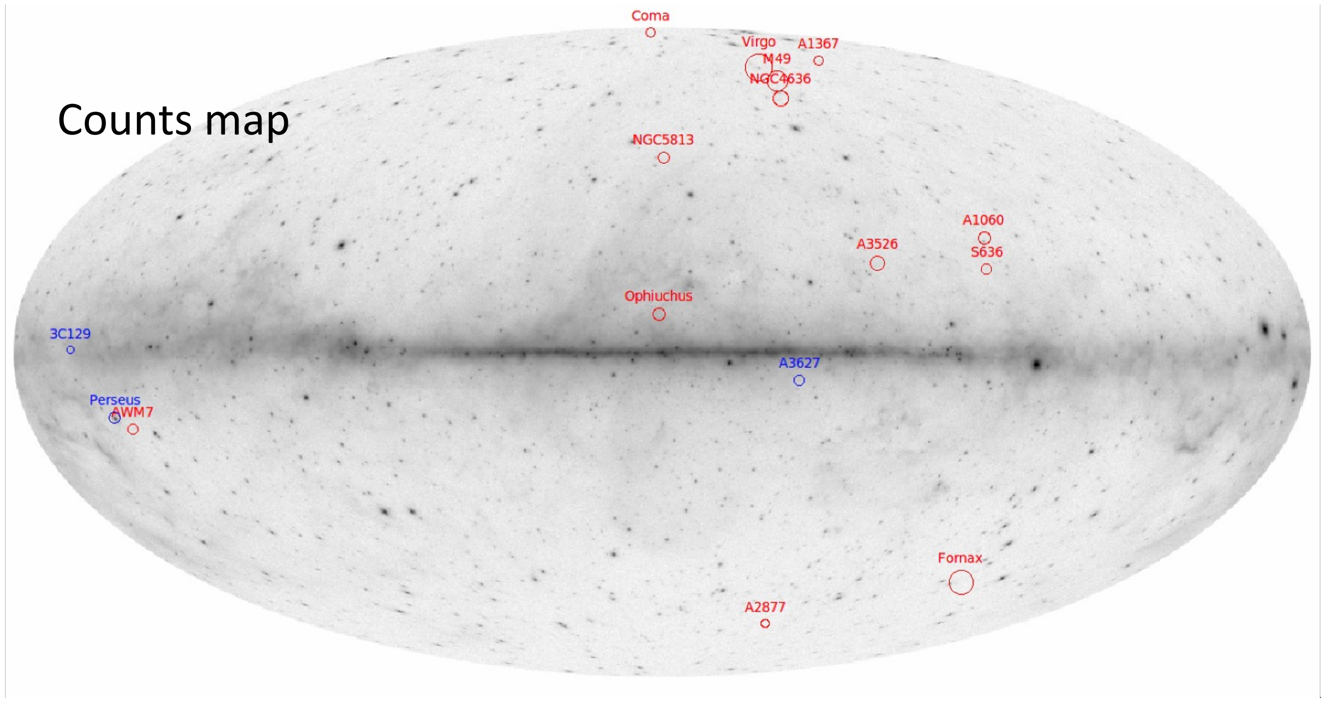
1. Fermi-LAT data





- Data: Fermi-LAT ULTRACLEAN data set with EDISP1+2+3 event type (good line sensitivity + low CR contamination).
- Observing time: 2008/10/27 – 2024/05/02.

Galaxy cluster sample



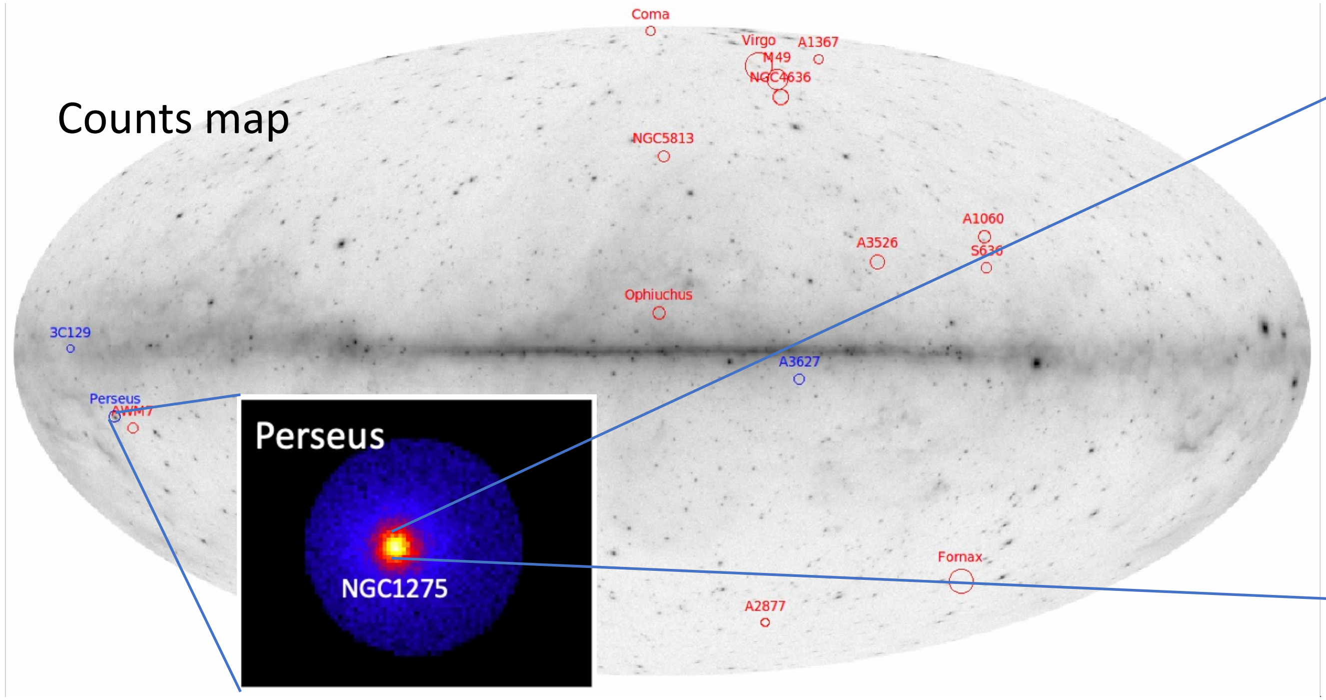
galaxy cluster	z	M_{200} ($10^{14} M_\odot$)	c_{200}	θ_{200} ($^\circ$)	$\log_{10}(J_{\rm NFW})$ ($\rm GeV^2\,cm^{-5}$)
Virgo	0.0038	$1.005^{+0.018}_{-0.018}$	$8.80^{+0.20}_{-0.20}$	$3.47^{+0.02}_{-0.02}$	$18.358^{+0.026}_{-0.026}$
Fornax	0.0046	$1.196^{+0.522}_{-0.540}$	$5.48^{+2.39}_{-1.59}$	$3.02^{+0.38}_{-0.55}$	$17.906^{+0.335}_{-0.407}$
Ophiuchus	0.0280	$34.691^{+22.619}_{-22.310}$	$4.98^{+1.94}_{-1.39}$	$1.56^{+0.28}_{-0.46}$	$17.769^{+0.404}_{-0.603}$
M49	0.0038	$0.441^{+0.020}_{-0.019}$	$5.86^{+2.26}_{-1.63}$	$2.62^{+0.04}_{-0.04}$	$17.685^{+0.258}_{-0.236}$
A3526	0.0103	$3.156^{+0.773}_{-1.329}$	$5.20^{+2.18}_{-1.47}$	$1.87^{+0.14}_{-0.31}$	$17.600^{+0.275}_{-0.385}$
A1060	0.0114	$2.309^{+0.756}_{-1.011}$	$5.28^{+2.25}_{-1.51}$	$1.53^{+0.15}_{-0.27}$	$17.388^{+0.302}_{-0.397}$
Coma	0.0232	$9.003^{+2.585}_{-3.042}$	$5.01^{+1.99}_{-1.40}$	$1.19^{+0.11}_{-0.15}$	$17.344^{+0.288}_{-0.331}$
NGC 4636	0.0037	$0.155^{+0.042}_{-0.062}$	$6.35^{+2.79}_{-1.83}$	$1.90^{+0.15}_{-0.30}$	$17.313^{+0.297}_{-0.382}$
AWM7	0.0172	$4.491^{+1.451}_{-2.167}$	$5.12^{+2.16}_{-1.45}$	$1.27^{+0.12}_{-0.25}$	$17.308^{+0.299}_{-0.431}$
A1367	0.0216	$6.733^{+1.519}_{-2.357}$	$5.05^{+2.03}_{-1.41}$	$1.16^{+0.08}_{-0.15}$	$17.283^{+0.267}_{-0.338}$
NGC 5813	0.0064	$0.385^{+0.464}_{-0.304}$	$5.92^{+3.33}_{-1.86}$	$1.49^{+0.45}_{-0.61}$	$17.184^{+0.502}_{-0.780}$
A2877	0.0241	$6.166^{+6.902}_{-3.521}$	$5.06^{+2.18}_{-1.45}$	$1.01^{+0.29}_{-0.25}$	$17.155^{+0.496}_{-0.508}$
S636	0.0093	$0.766^{+0.300}_{-0.136}$	$5.64^{+2.25}_{-1.64}$	$1.29^{+0.15}_{-0.08}$	$17.126^{+0.324}_{-0.250}$
A3627	0.0163	$4.487^{+0.903}_{-1.034}$	$5.12^{+2.03}_{-1.43}$	$1.34^{+0.08}_{-0.11}$	$17.353^{+0.260}_{-0.269}$
Perseus	0.0183	$5.477^{+1.804}_{-2.720}$	$5.08^{+2.14}_{-1.43}$	$1.28^{+0.12}_{-0.27}$	$17.337^{+0.301}_{-0.443}$
3C129	0.0223	$4.796^{+2.515}_{-2.219}$	$5.11^{+2.14}_{-1.46}$	$1.00^{+0.16}_{-0.18}$	$17.117^{+0.357}_{-0.416}$

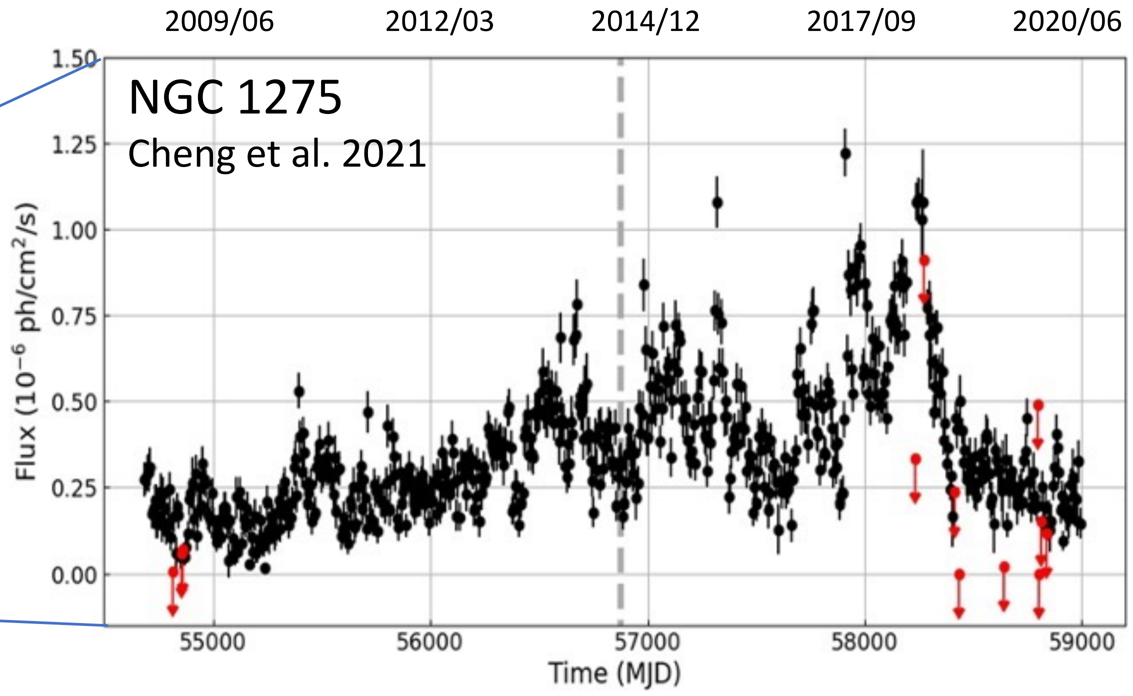
- Galaxy clusters from the HIghest X-ray FLUx Galaxy Cluster Sample (HIFLUGCS; Reiprich et al. 2002):
  - Virgo: mass and concentration from Simionescu et al. (2017);
  - M49: mass from Su et al. (2019).
  - Other clusters: mass from Chen et al. (2007).

  } Concentration relation (M_{200} -> c_{200}; Sanchez-Conde et al 2014)

- J-factor: $J = \int_0^{\theta_{200}} 2\pi\theta d\theta \int_{los} \rho_{NFW}^2(r(s,\theta))ds$, uncertainties from the mass and concentration are considered.

Galaxy cluster sample

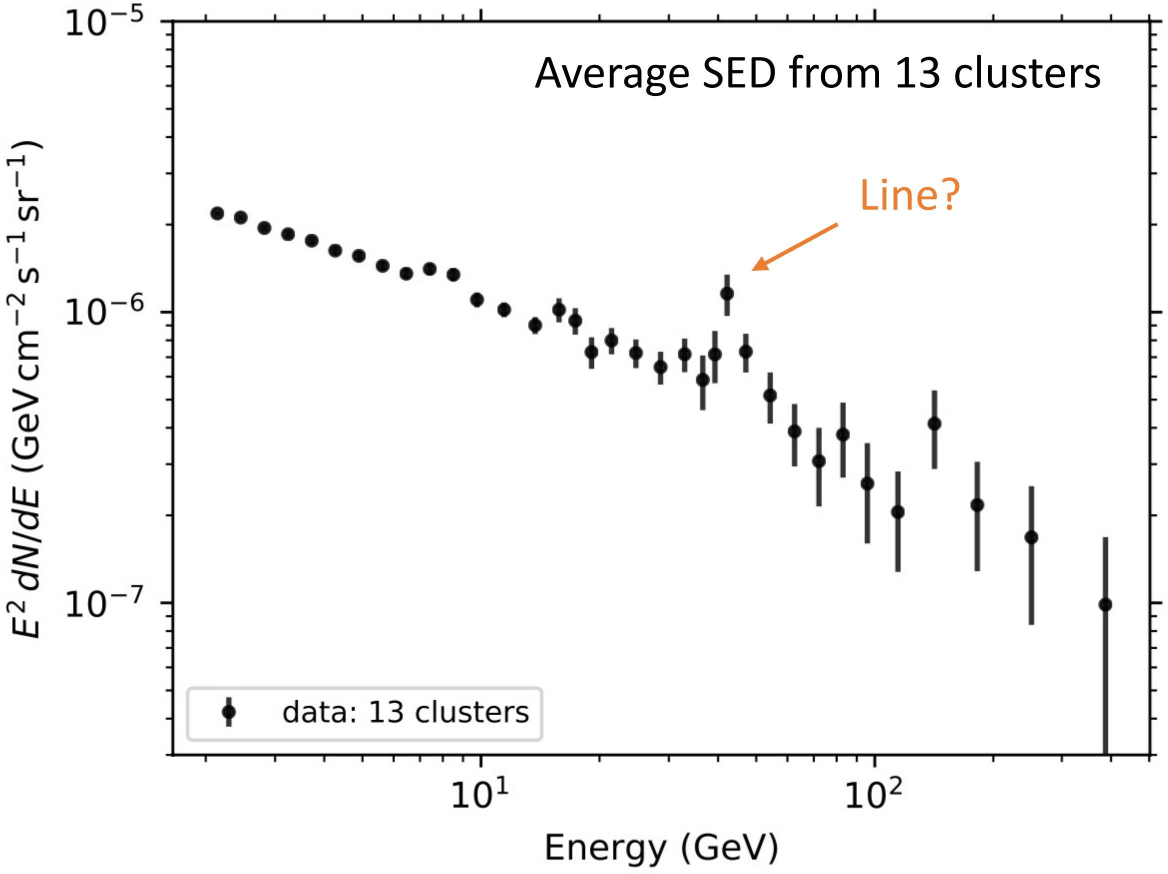




Some galaxy clusters are further excluded from our analysis:

- A3627, 3C129: low Galactic latitude;
- Perseus cluster: strong activity of NGC 1275, which will complicate the variability analysis of the line.

SED from the galaxy clusters

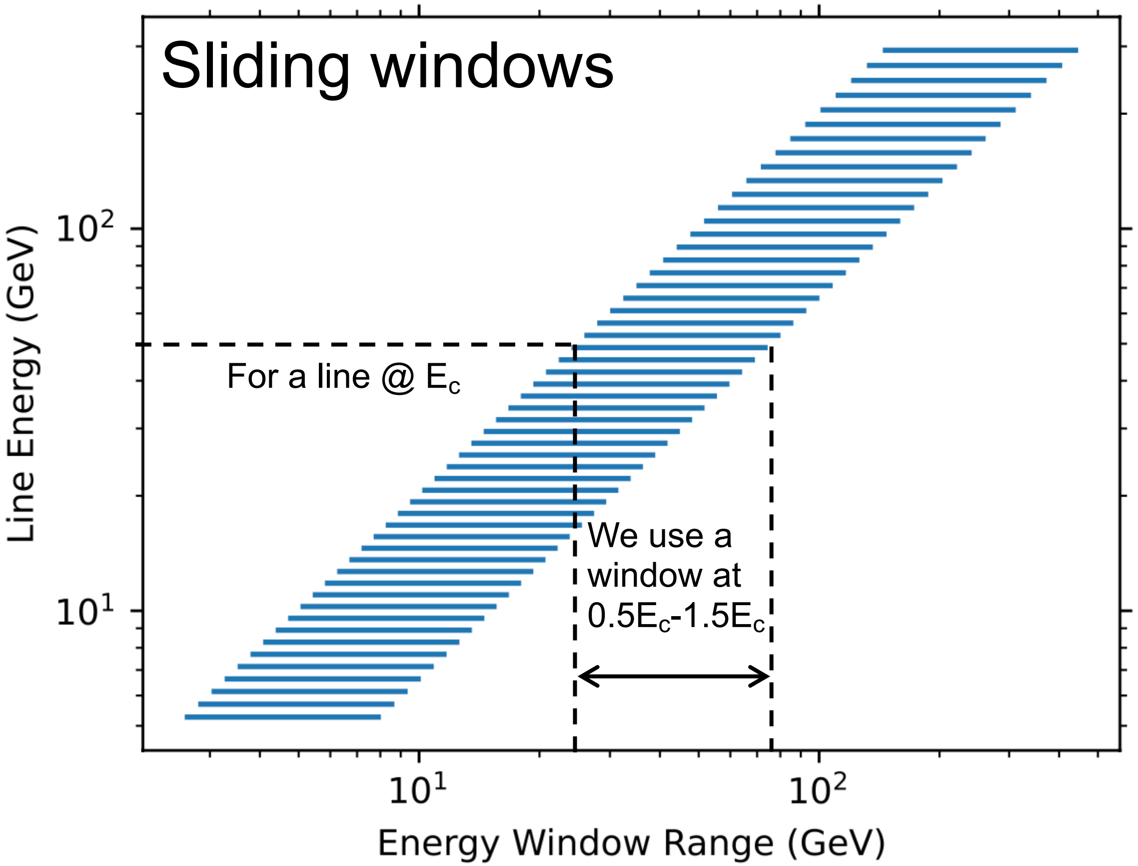


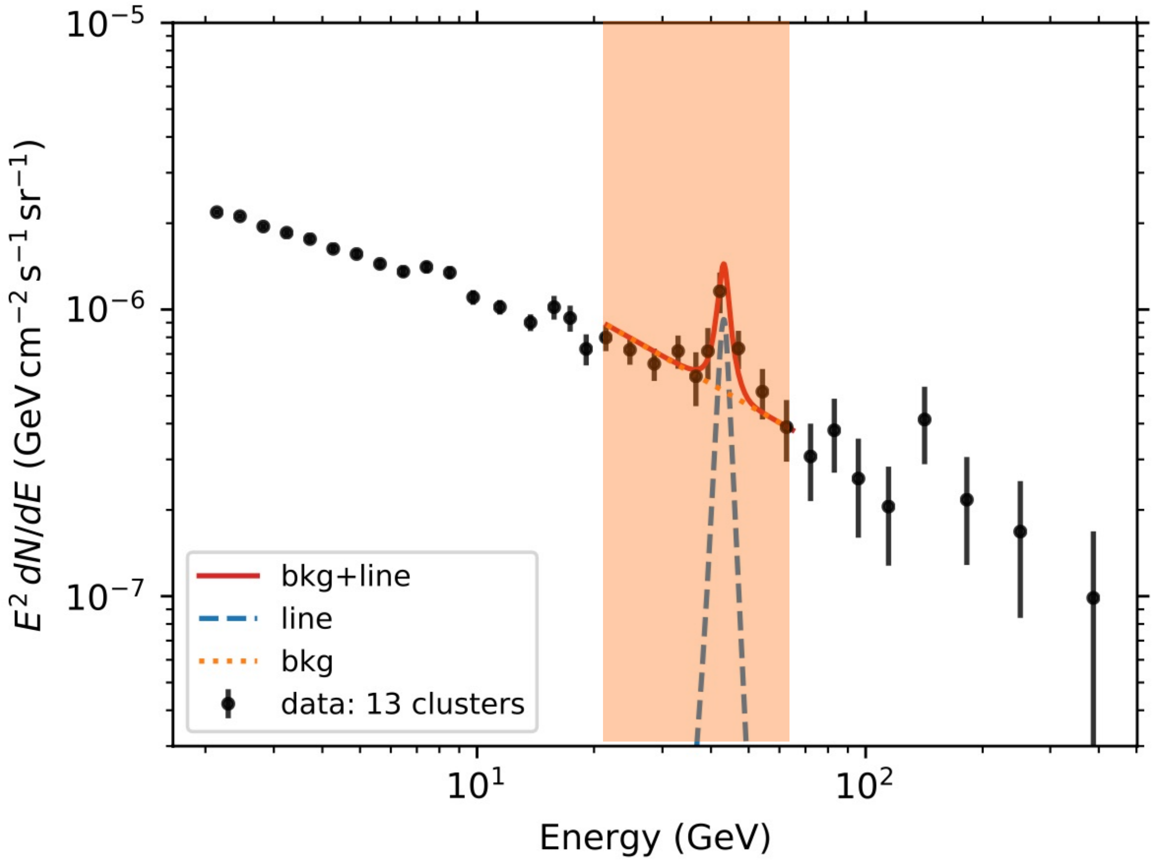
- Photons within the virial radii R_{200} of the clusters are collected.
- The average spectral energy distribution (SED) in *i*-th energy bin is derived with

$$\left(\frac{dN}{dE}\right)_i = \frac{\sum_{j=1}^{n_{\mathrm{gcl}}} N_{ij}}{\Delta E_i \sum_{j=1}^{n_{\mathrm{gcl}}} \epsilon_{ij}\Omega_j},$$

N_{ij}: the counts of the j-th cluster in i-th E bin;
ϵ_{ij}: the exposure;
Ω_j: the solid angle of the j-th cluster.

Sliding windows technique



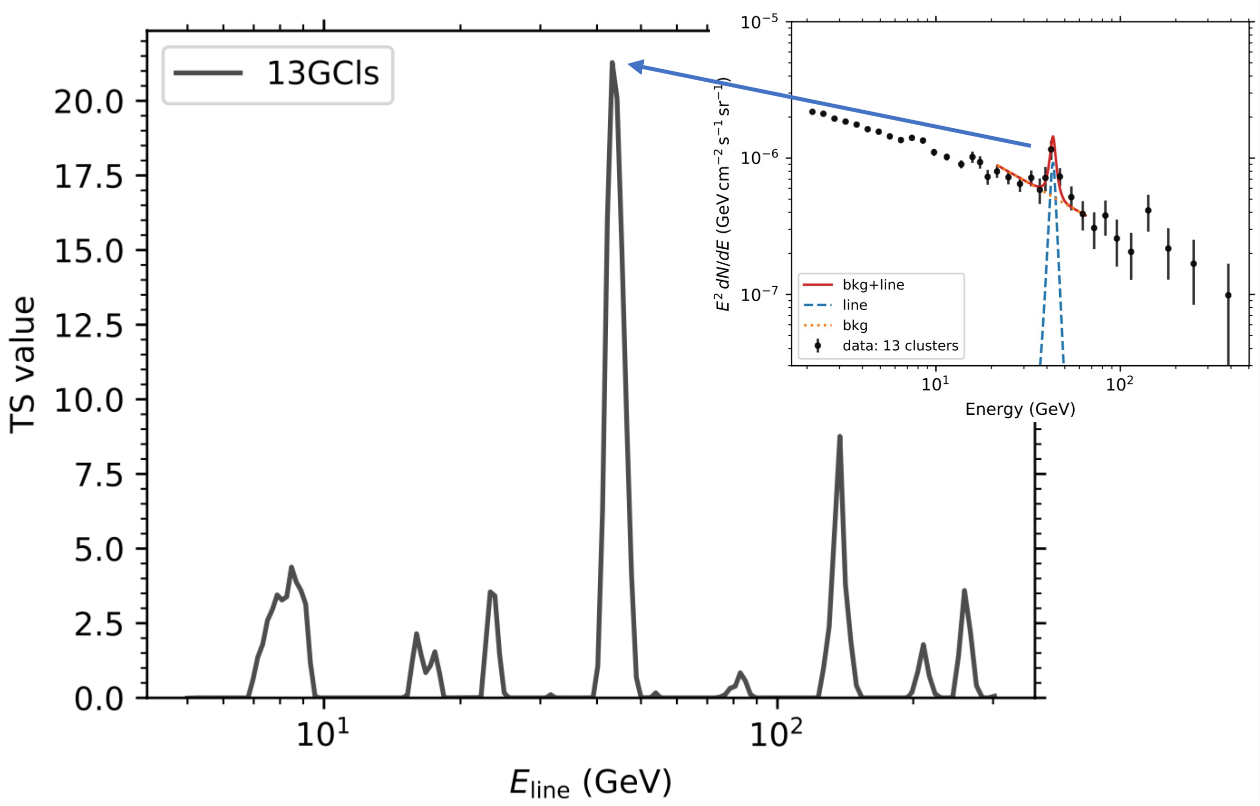


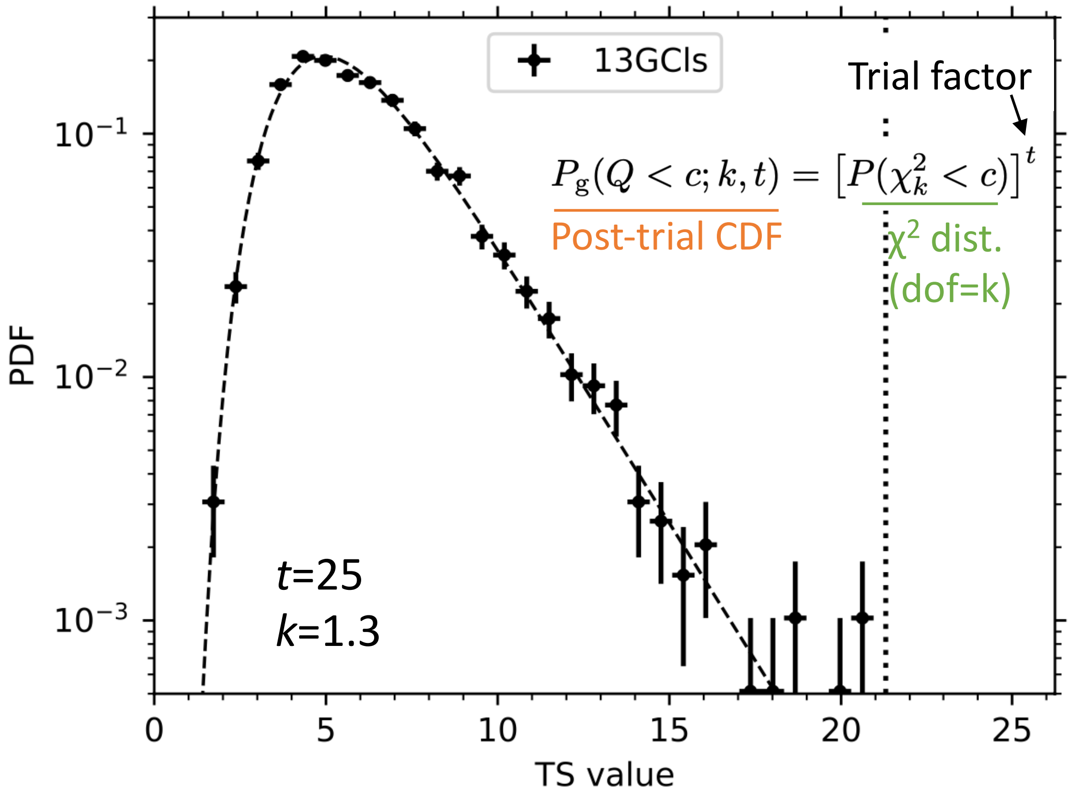
Null model: $\ln(\mathcal{L}_{\mathrm{null}}) = \sum_{i=1}^{N_{ph}}[\lambda_b(E_i;\Theta_b)] - \int \lambda_b(E;\Theta_b)dE$, where $\lambda_b = F_b(E)\epsilon(E)$.

Alternative model: $\ln(\mathcal{L}_{\mathrm{sig}}) = \sum_{i=1}^{N_{ph}}[\lambda_s(E_i;\Theta_b,\Theta_s)] - \int \lambda_s(E;\Theta_b,\Theta_s)dE$, where $\lambda_s = F_b(E)\epsilon(E) + F_s(E_{\mathrm{line}})\epsilon(E_{\mathrm{line}})$.

TS value: $\mathrm{TS} = -2\ln(\hat{\mathcal{L}}_{\mathrm{null}}/\hat{\mathcal{L}}_{\mathrm{sig}})$

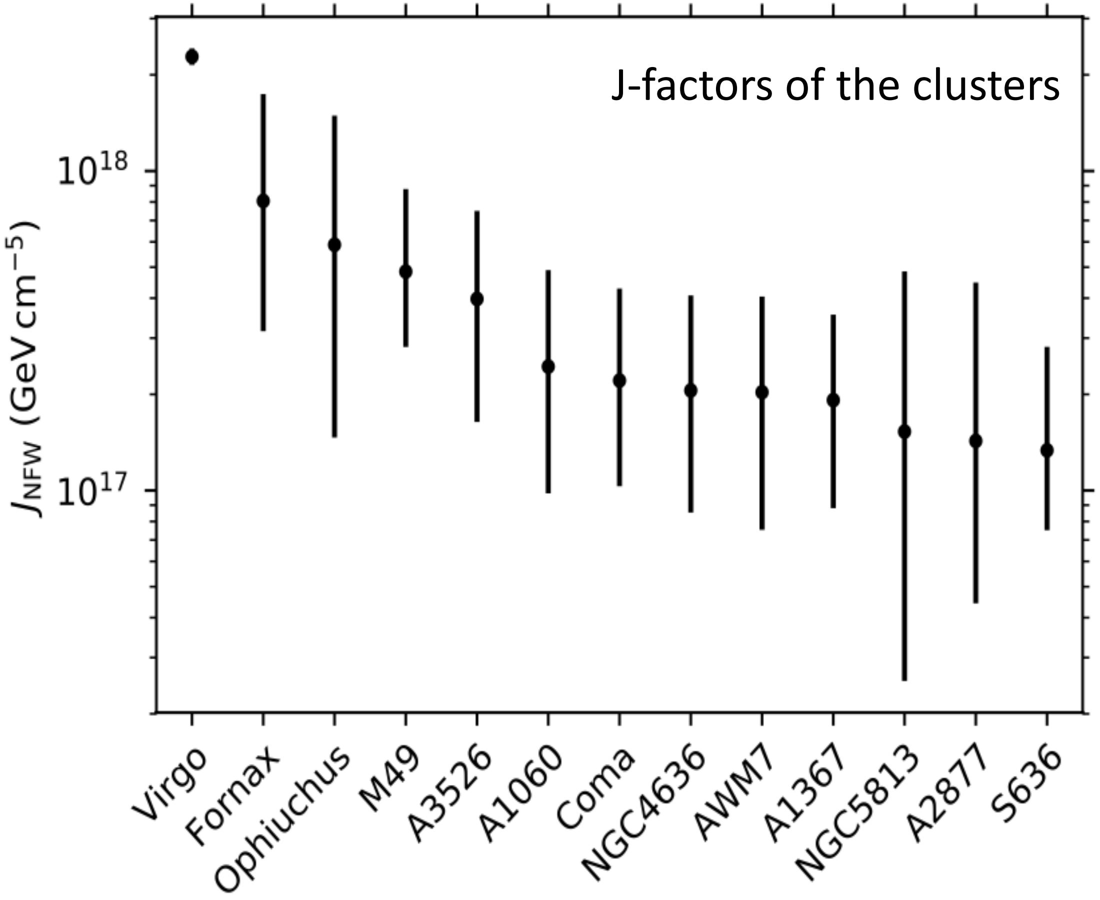
Significance of line from the total sample

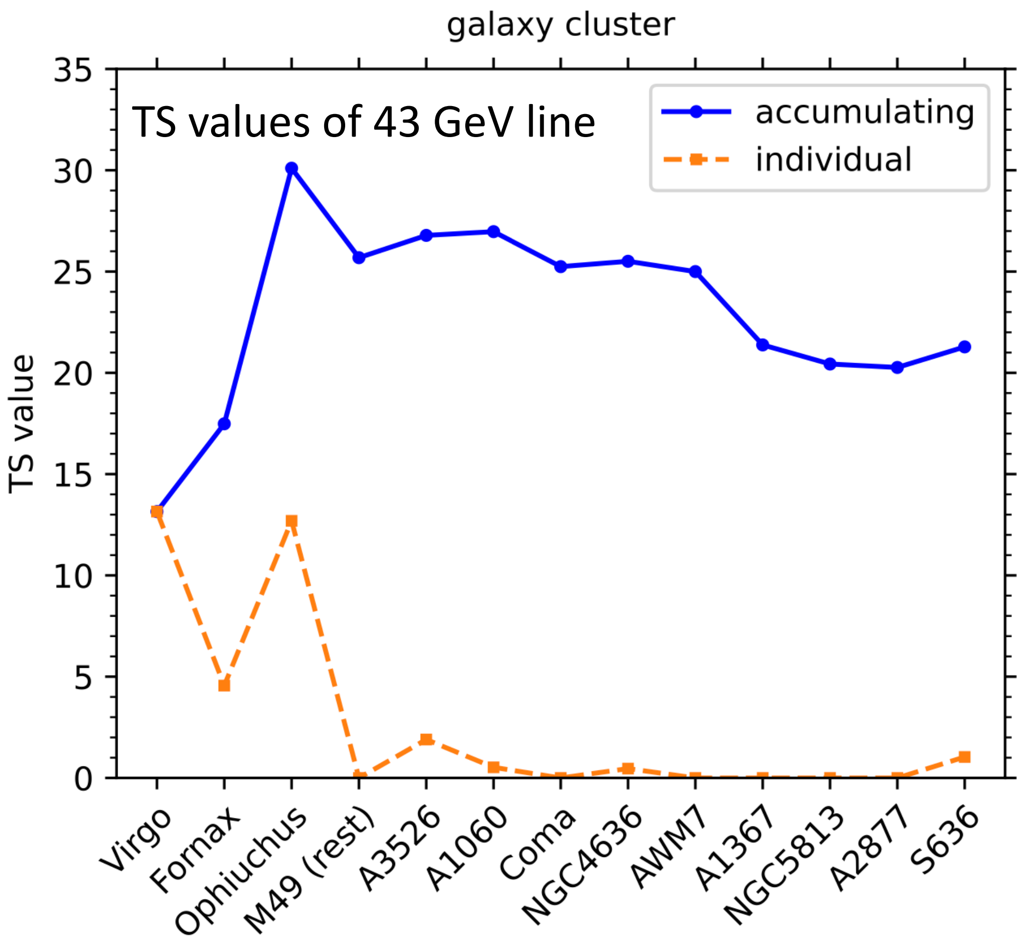




- The line-like excess is centered at 43.2 GeV. The TS value is 21.3.
- The Look elsewhere effect is corrected by repeating the same sliding window analysis in 3000 null simulation data sets. The post-trial significance is 3.7σ.

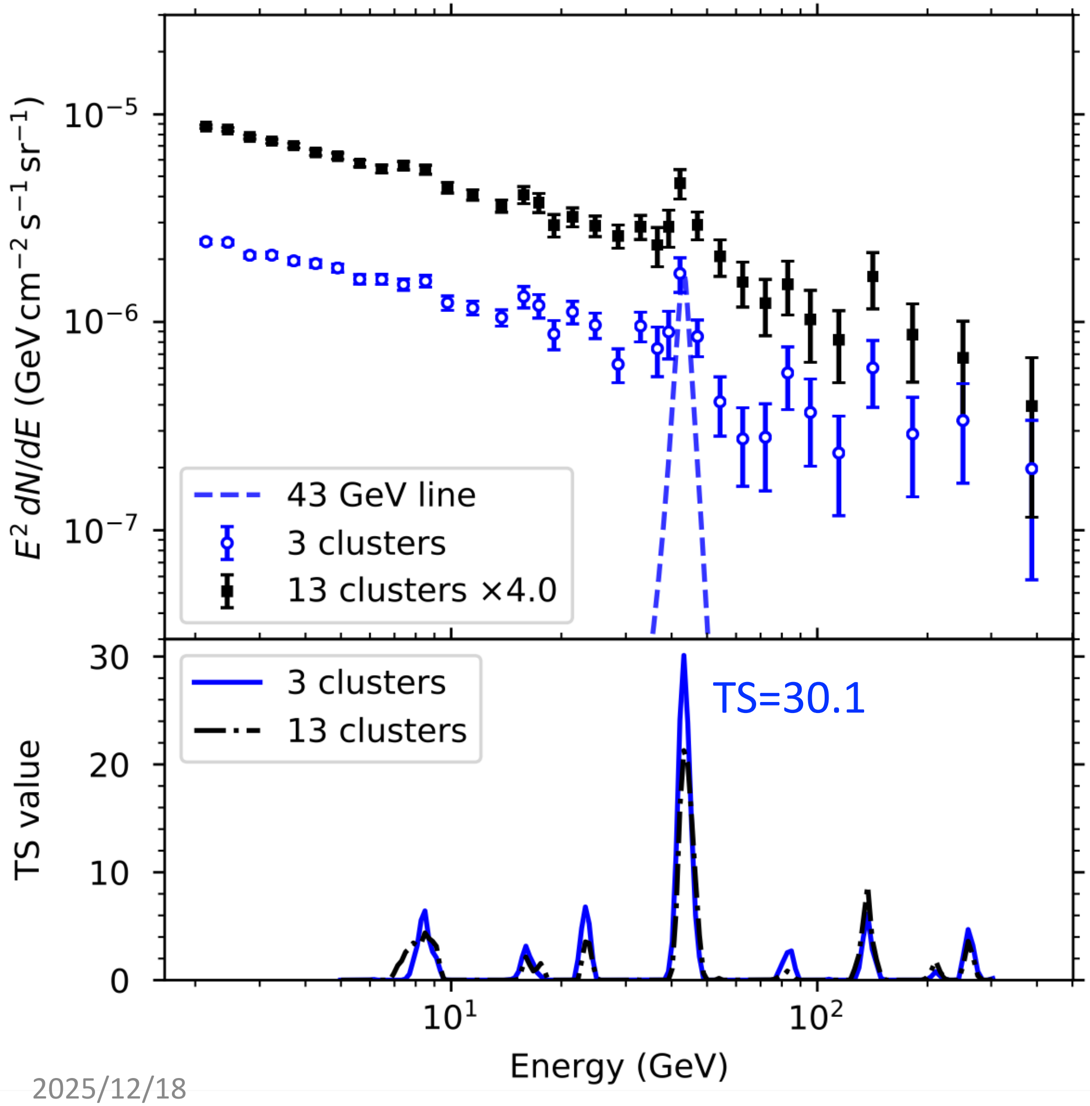
TS values for accumulating galaxy clusters

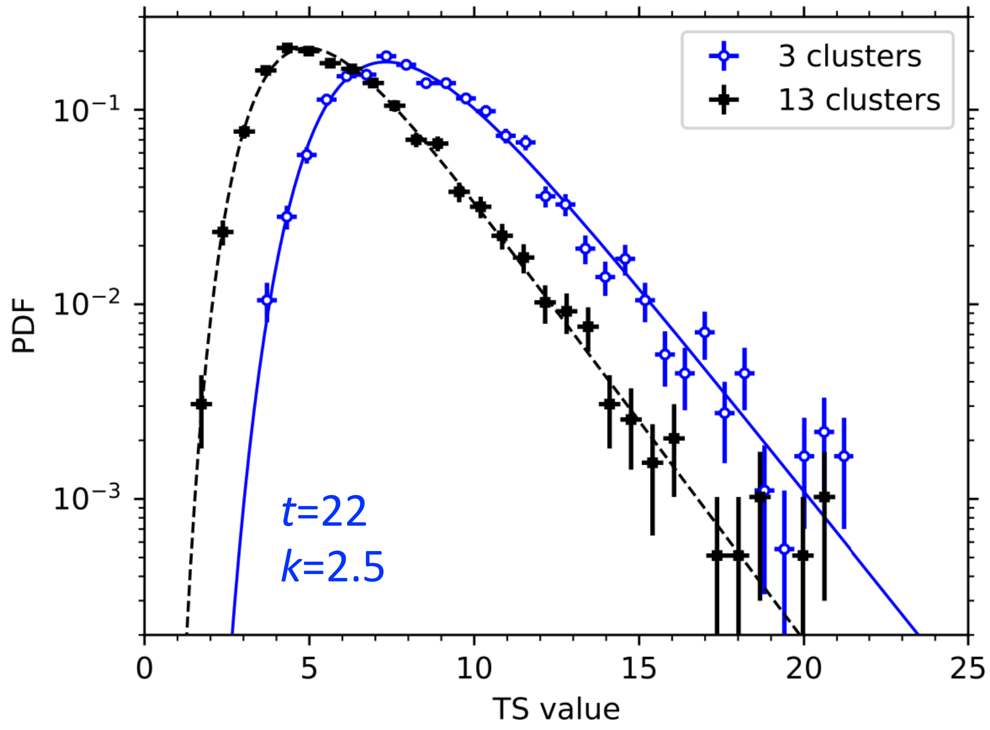




We sort the galaxy clusters according to the central values of the J-factors and gradually add the data into the line search analysis. The TS value of the 43 GeV line is peaked when the top 3 clusters are included.

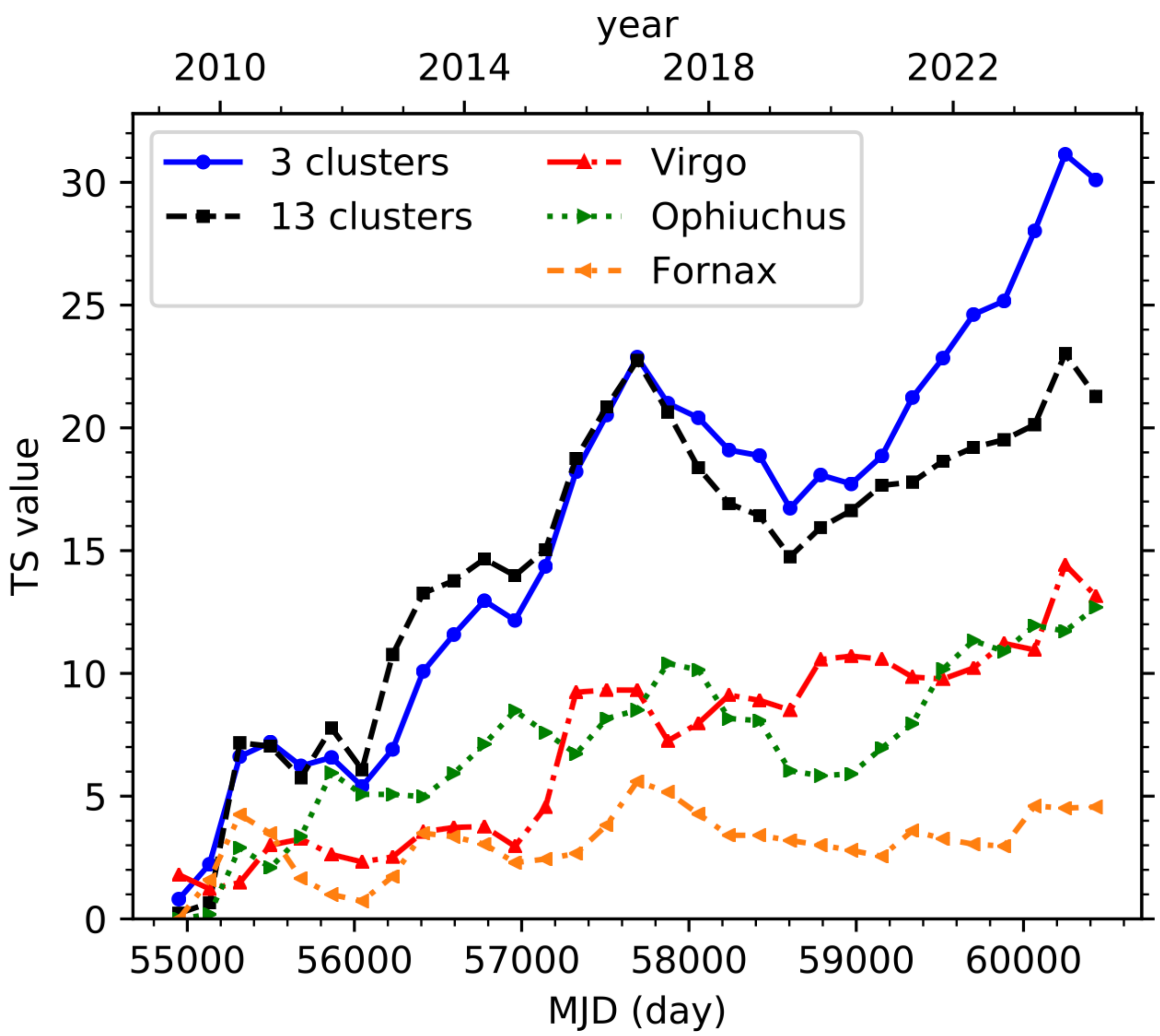
Line in top three galaxy clusters





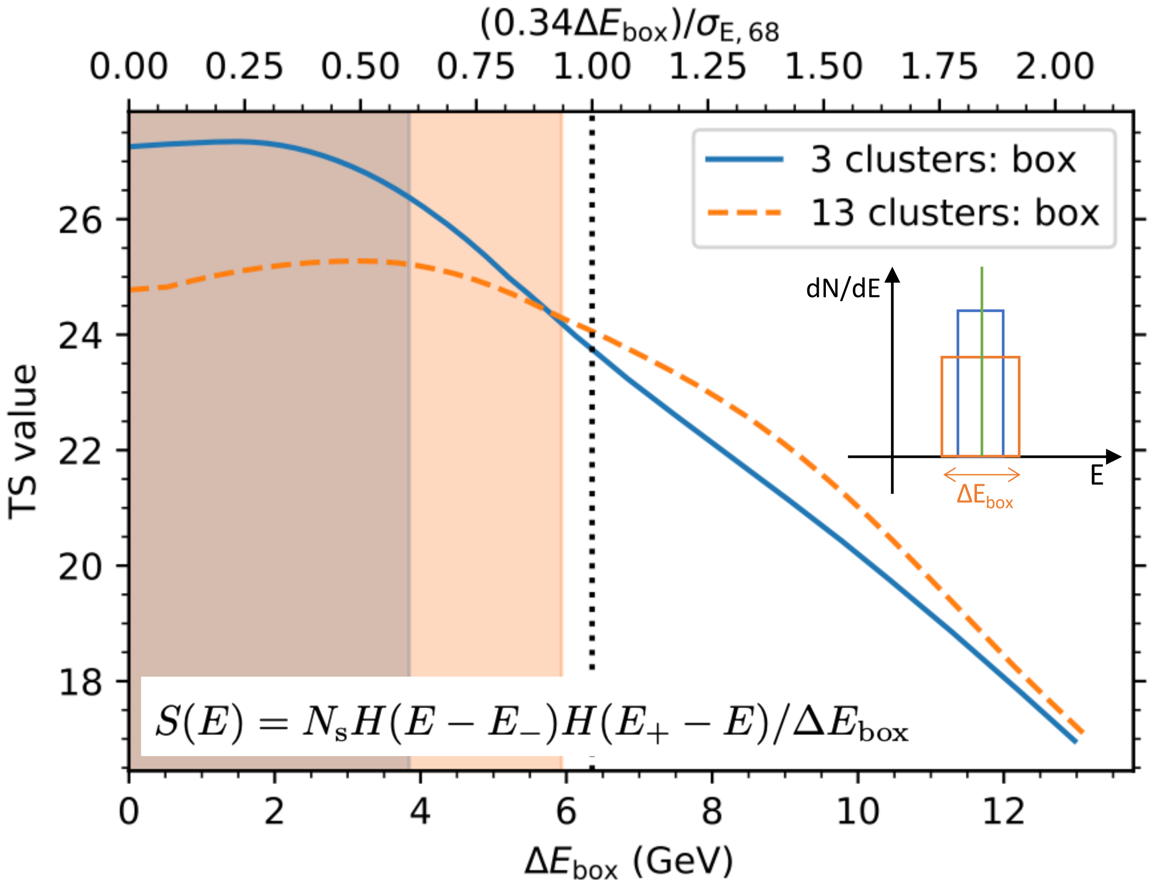
The TS value of the 43 GeV line in three clusters is 30.1, corresponding to a post-trial significance of 4.3σ.

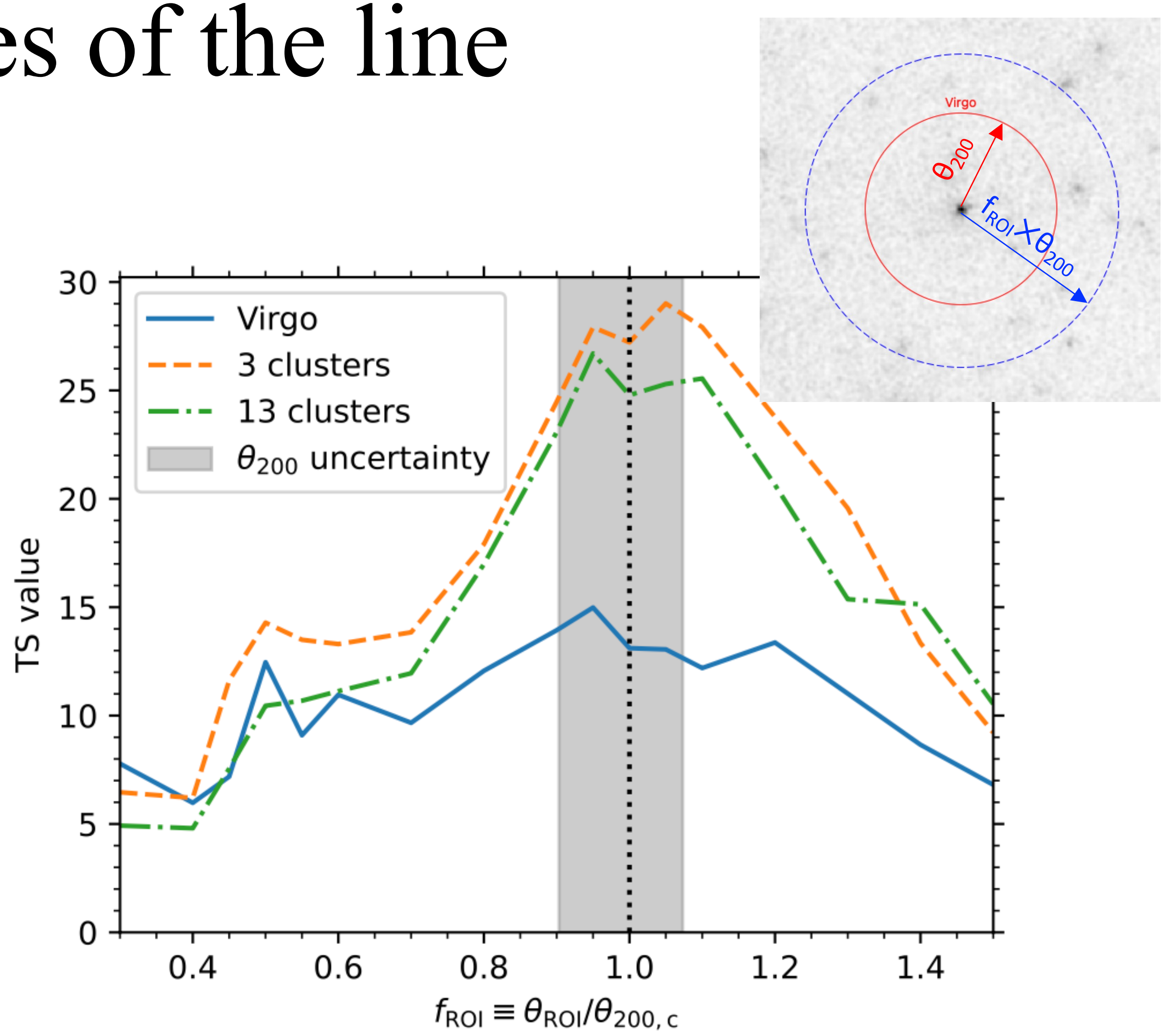
TS evolution of the 43 GeV line



The TS value roughly increases with time.

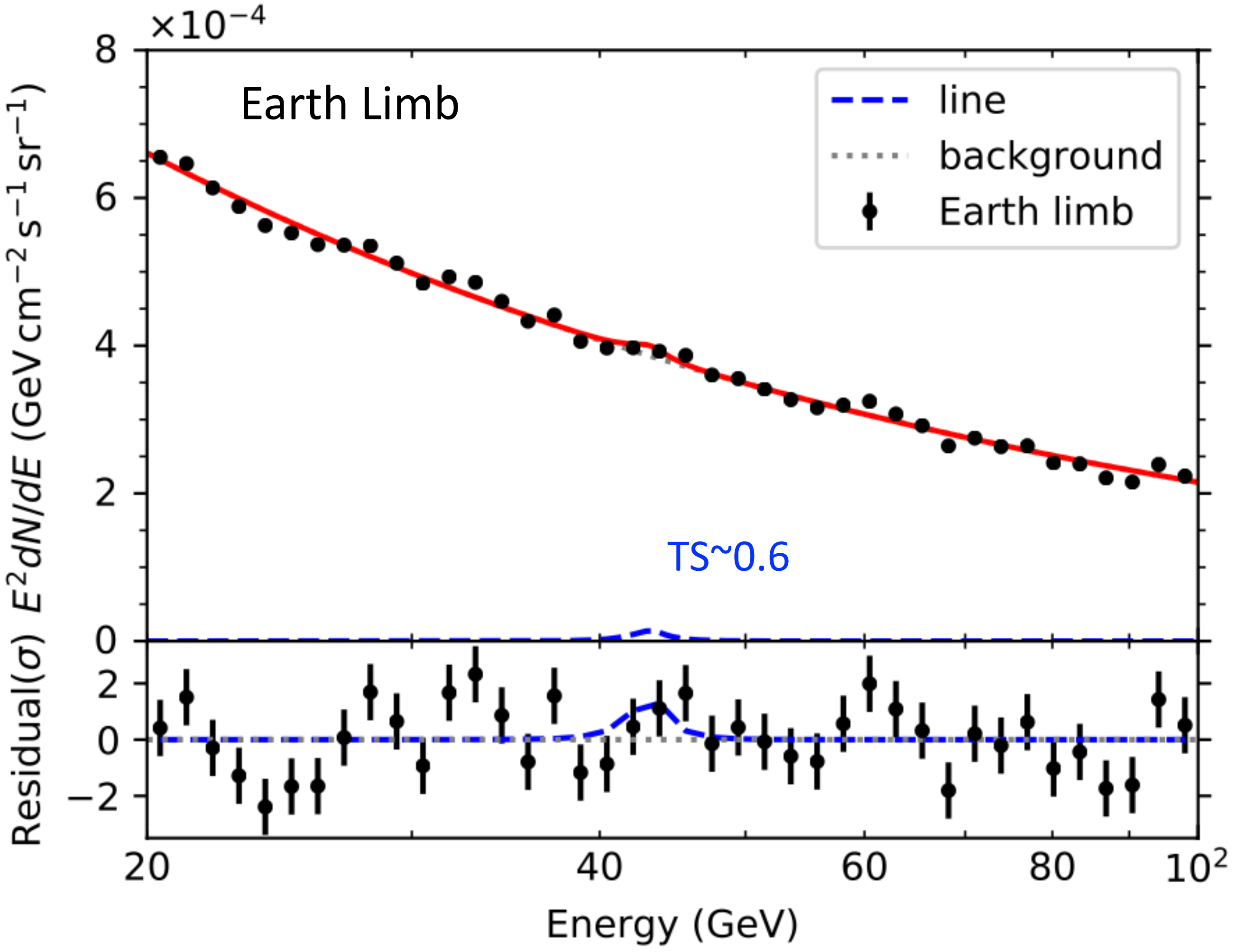
More properties of the line





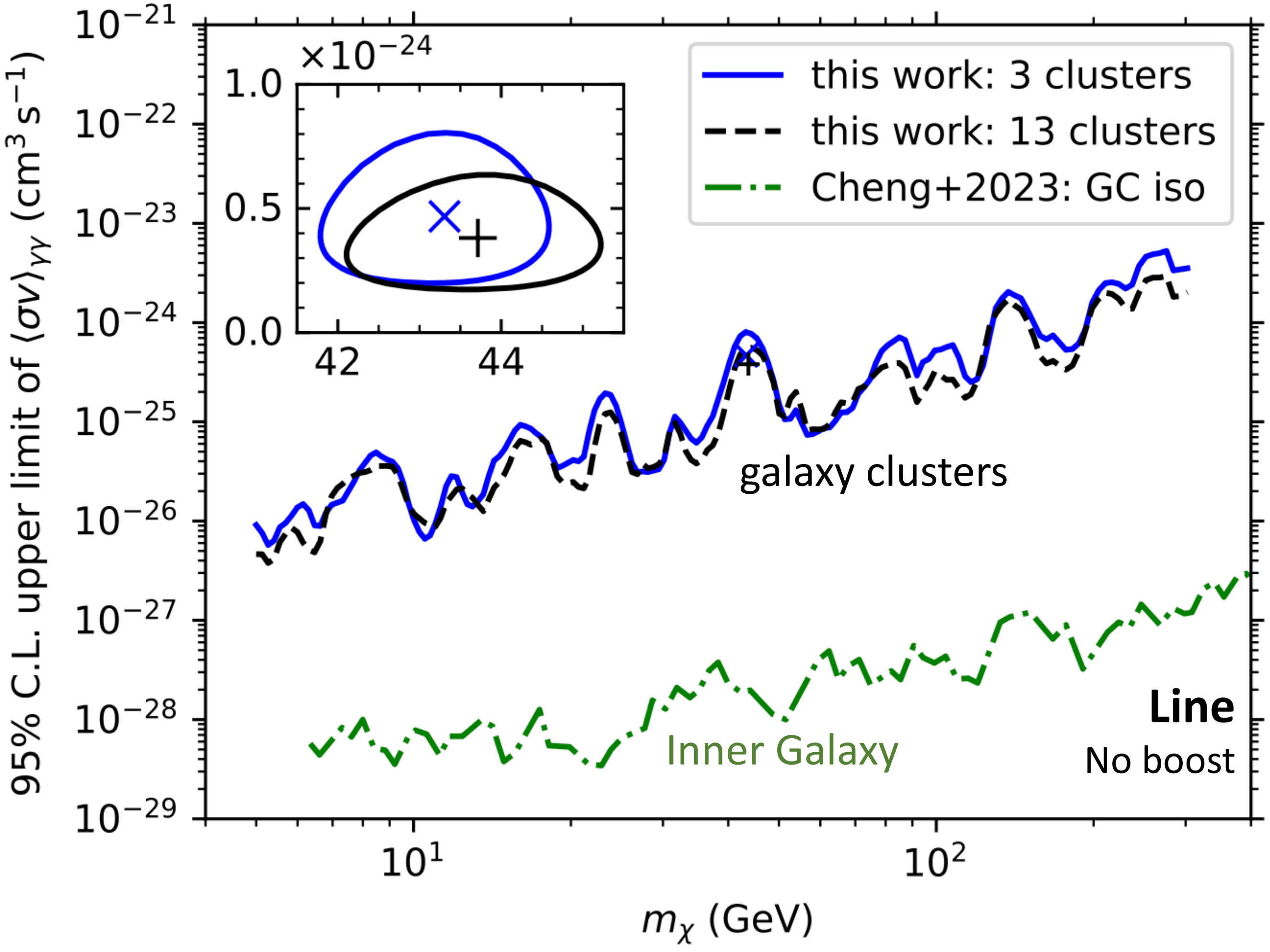
- The energy width of the excess is consistent with a monochromatic line.
- The radius of the excess is consistent with the virial radii of the clusters.

Test with Earth Limb data



- The spectrum of the Earth limb data lacks prominent features, so it can be used to test the smoothness of the instrumental responses.
- Earth Limb data: zenith angle $111° - 113°$ and rocking angle $> 52°$.
- The line TS value at ~ 43 GeV is only 0.6.

Constraints on DM parameters



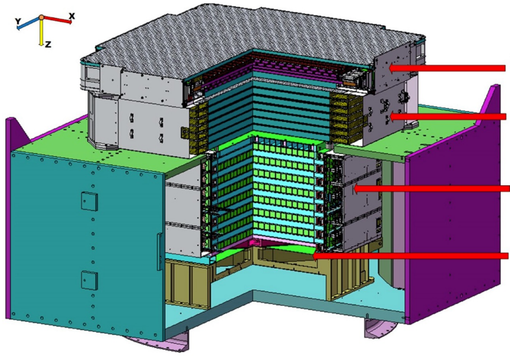
- The line candidate requires DM particles with $m_\chi \sim 43$ GeV and annihilation cross section $\langle \sigma v \rangle \sim 4 \times 10^{-25}\ \mathrm{cm^3\ s^{-1}}$.
- The cross section is excluded by the inner Galaxy. It may suggest a more sophisticated dark matter model or a peculiar astrophysical scenario.

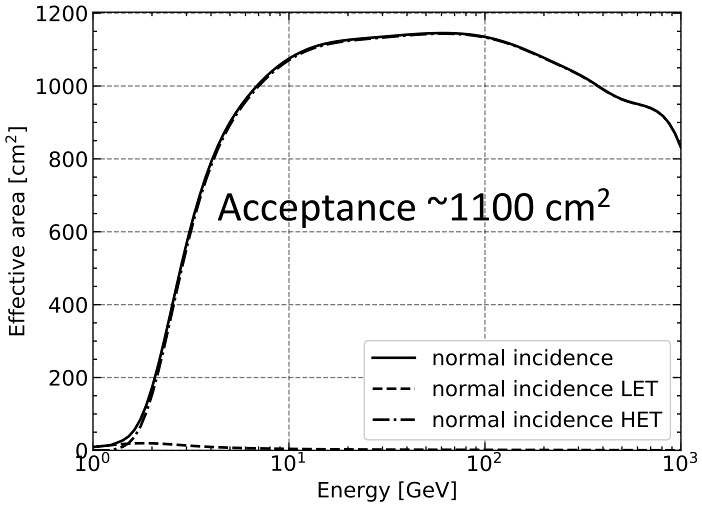
2. Current status of the 43 GeV line

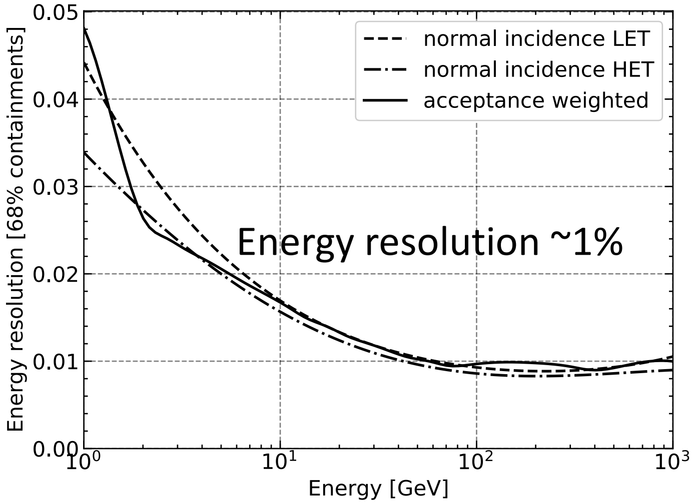
- Fermi-LAT:
  - ✓ 43 GeV line signal is detected with a relatively high significance (3.7σ-4.3σ)
  - ✓ Some clues support its reality
  - ✓ No similar signal is detected in the control region
  - ○ Double the data set may be required to detect the signal with >5σ significance
  - ○ Unknown intrumental artifacts may be presented and are triggered in a specific condition to create the signal

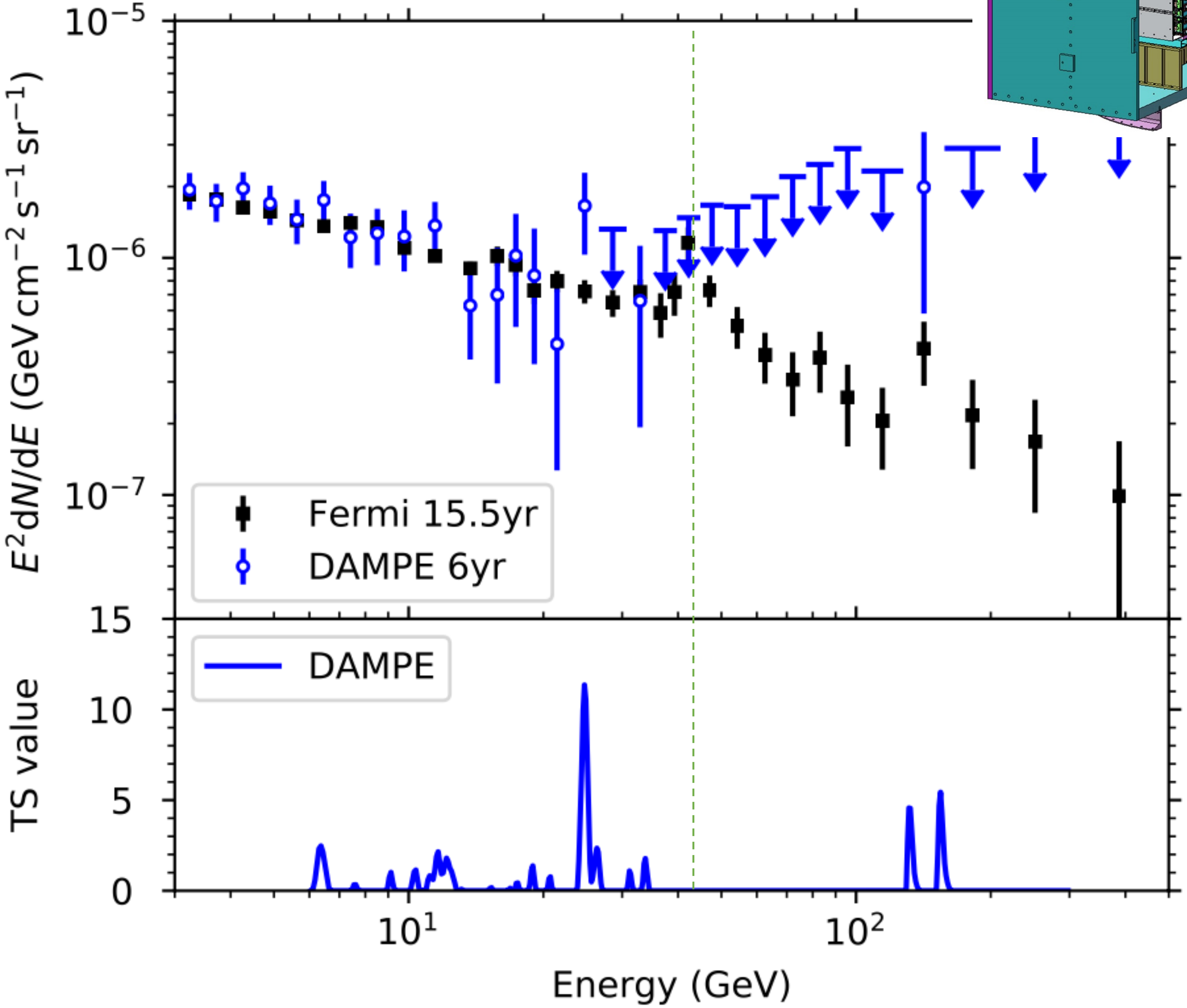
Crosschecks with independent telescopes are necessary!

Non-detection with DAMPE



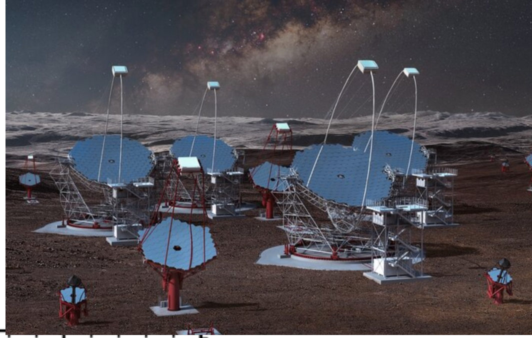


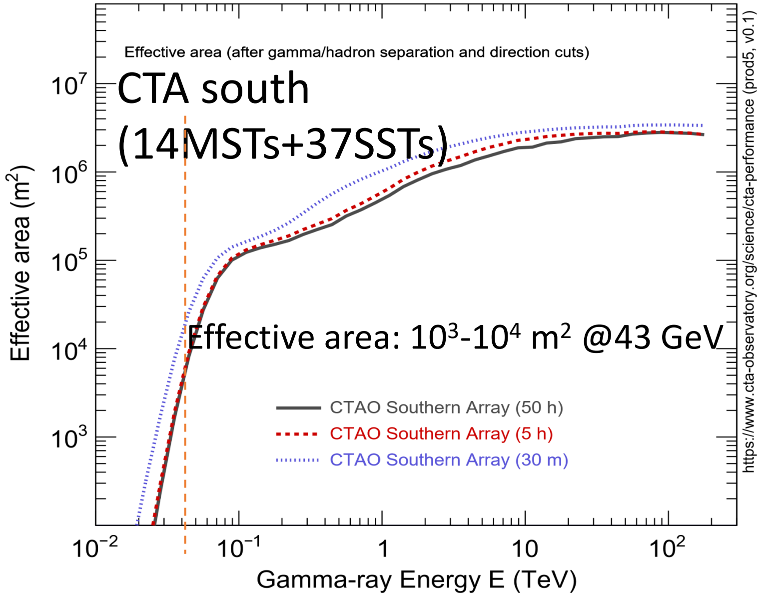


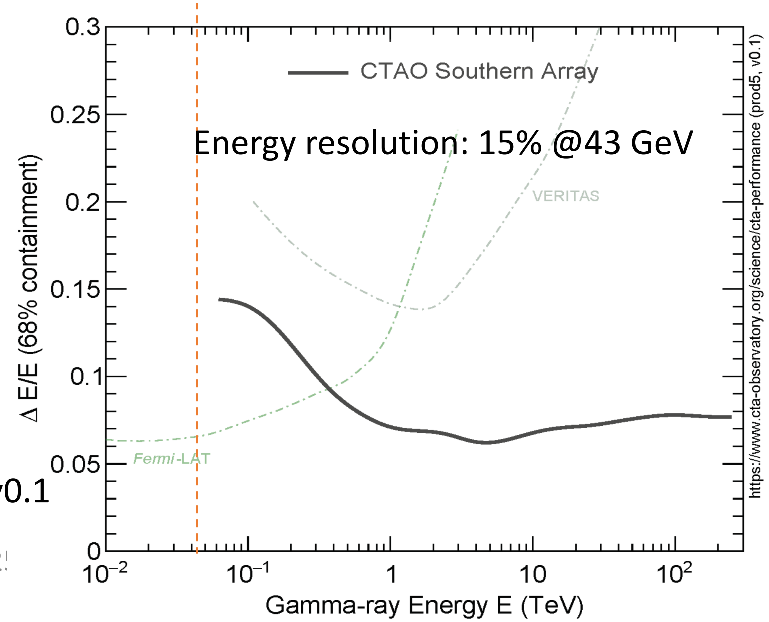


It is difficult to detect the signal with DAMPE because of the small acceptance of the telescope.

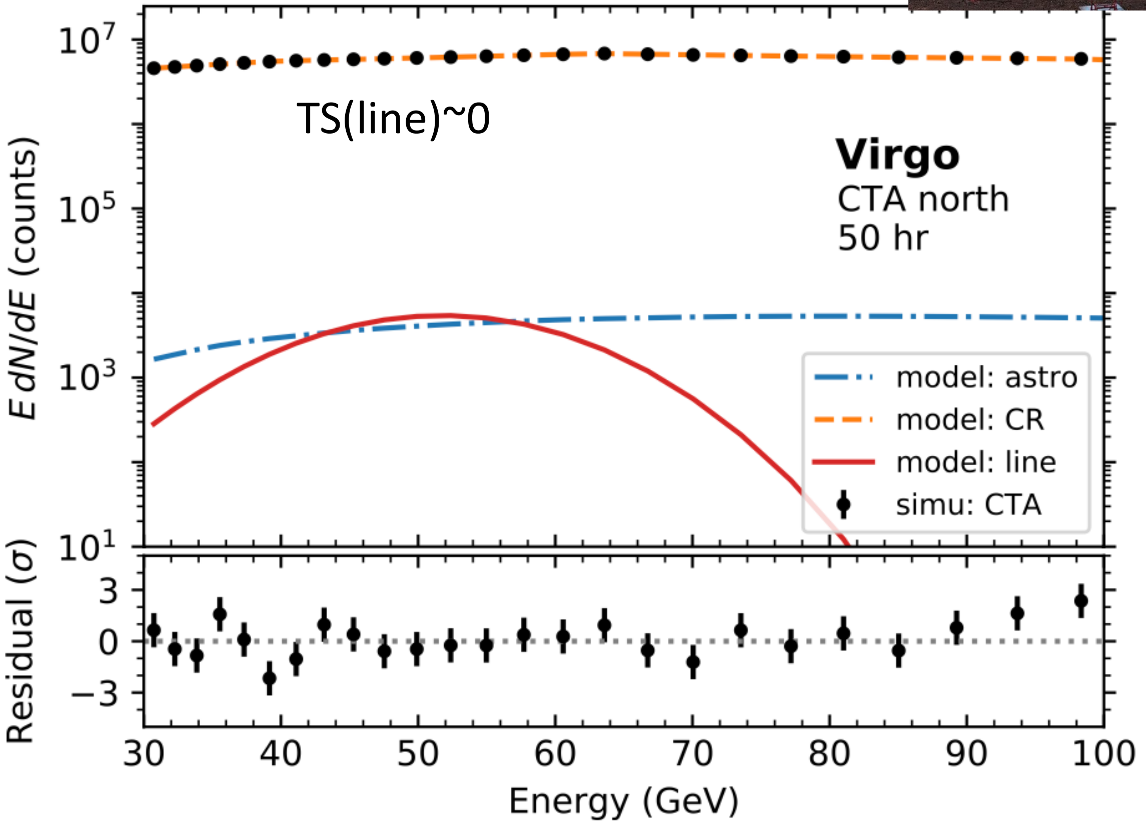
Hard to find 43 GeV line with CTAO





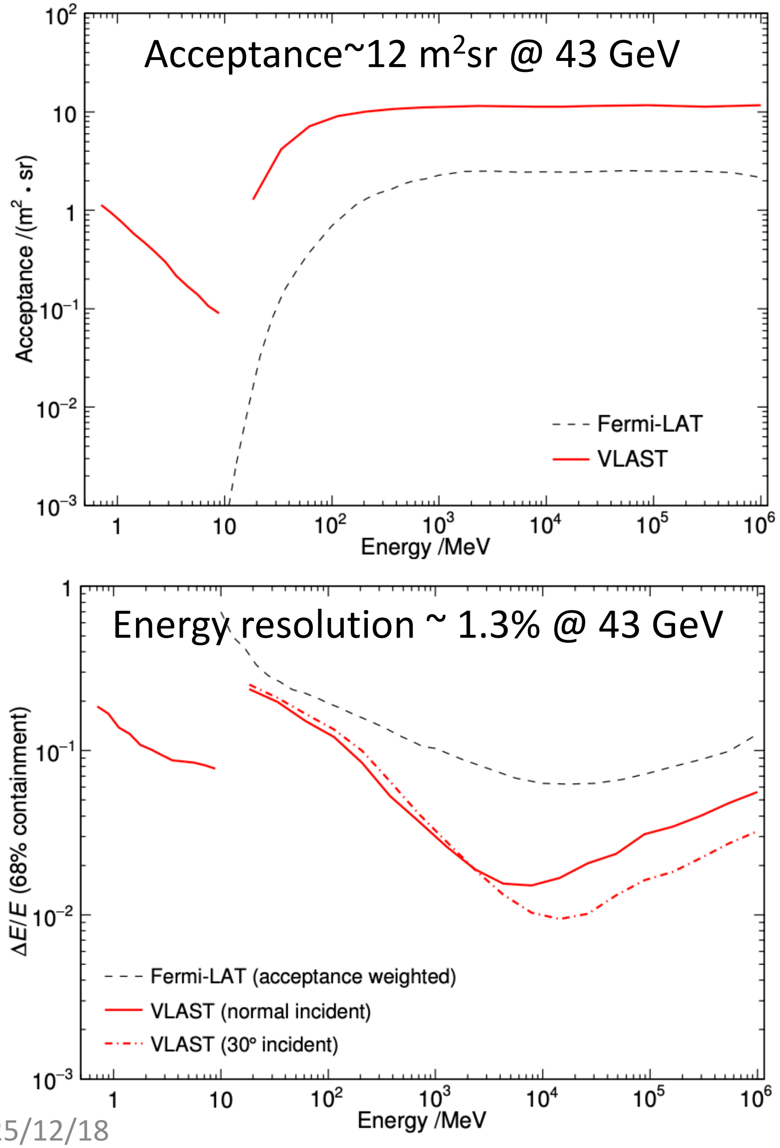


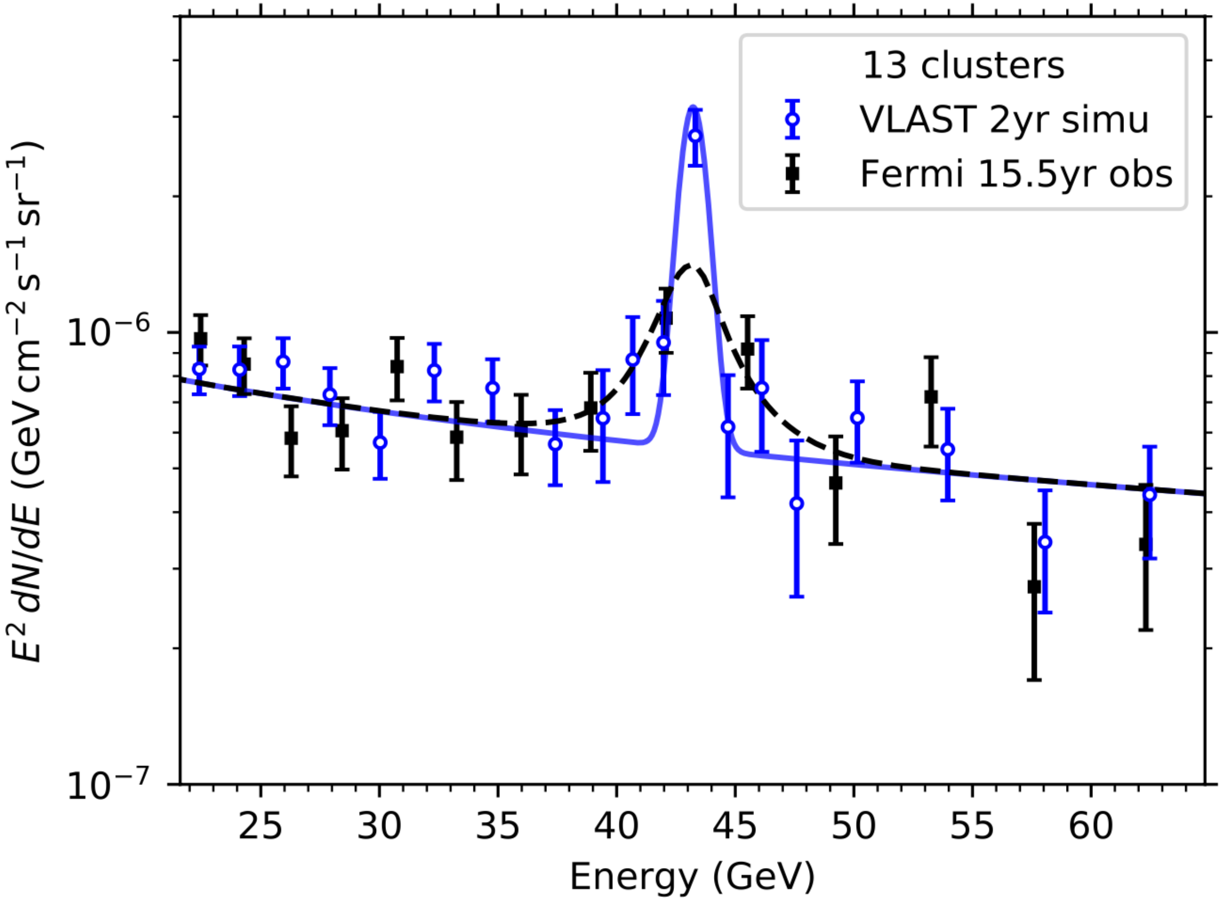
IRFs: prod5 v0.1



Due to the large CR background and relatively bad energy resolution, it is hard for the ground-based telescope such as CTAO to detect 43 GeV line.

Prospect of the line detection with VLAST





If the signal was true, with 2-yr VLAST observations of 13 galaxy clusters, the expected TS value would reach ~73.

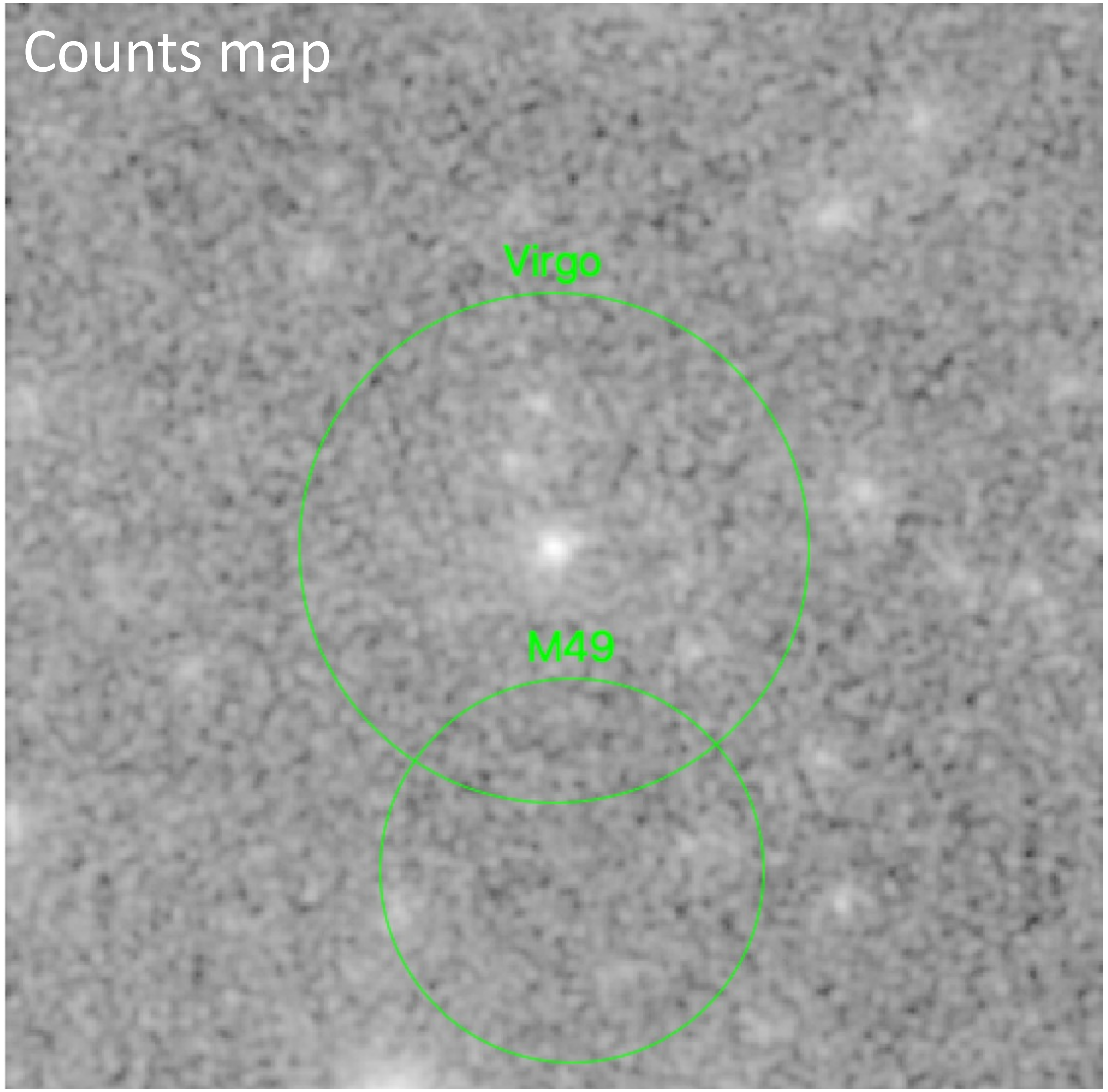
3. Summary

- There is probably a line in the nearby clusters, with central energy at 43 GeV:
  - Its post-trial significance is 3.7σ in 13 clusters, and 4.3σ in first 3 clusters.
- Some clues support the reality of the line signal:
  - Its TS value roughly increases with time;
  - The radial size of the signal region matches the virial radii of the galaxy clusters;
  - The energy width is consistent with a monochromatic line;
  - And no similar excess is detected in the Earth limb data.
- If the line is explained with DM annihilation into two photons, DM mass should be $m_\chi \sim 43\ \mathrm{GeV}$ and annihilation cross section should be $\langle \sigma v \rangle \sim 4 \times 10^{-25}\ \mathrm{cm^3\ s^{-1}}$.
- The signal can be quickly verified with large space telescopes such as VLAST in the future.

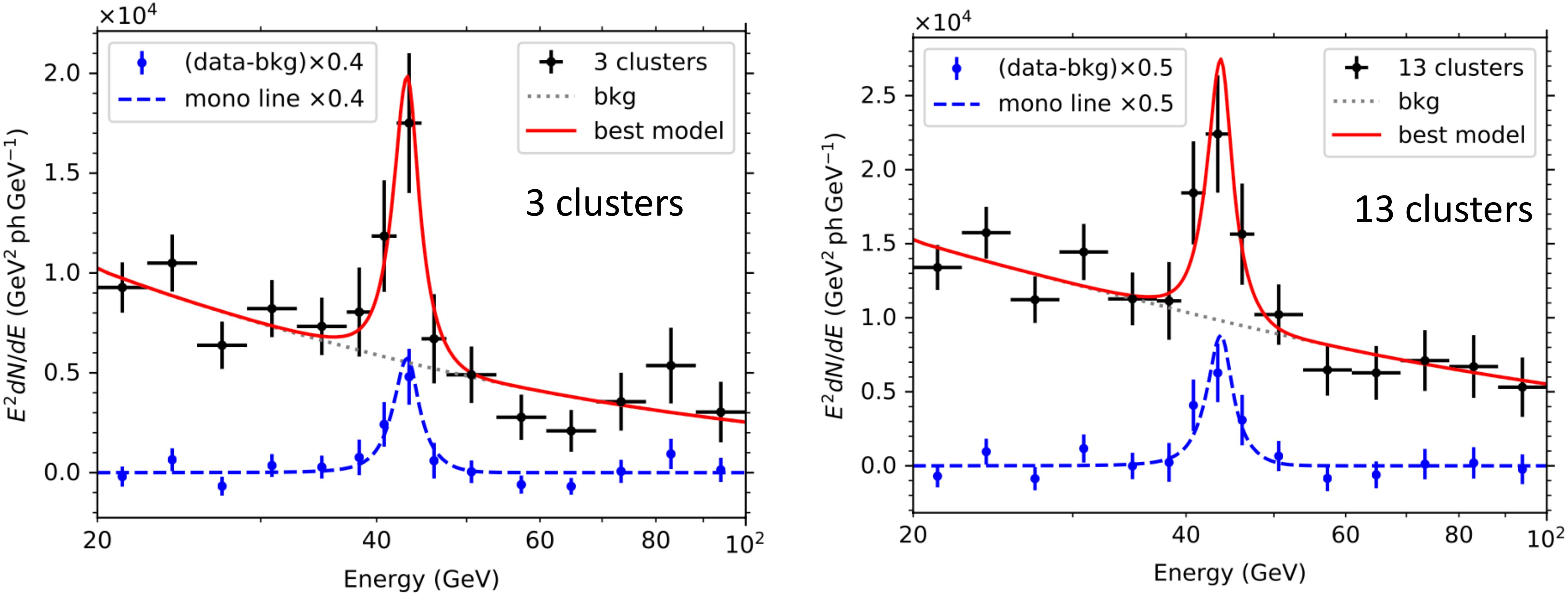
Thanks for your attention!

Backup slides

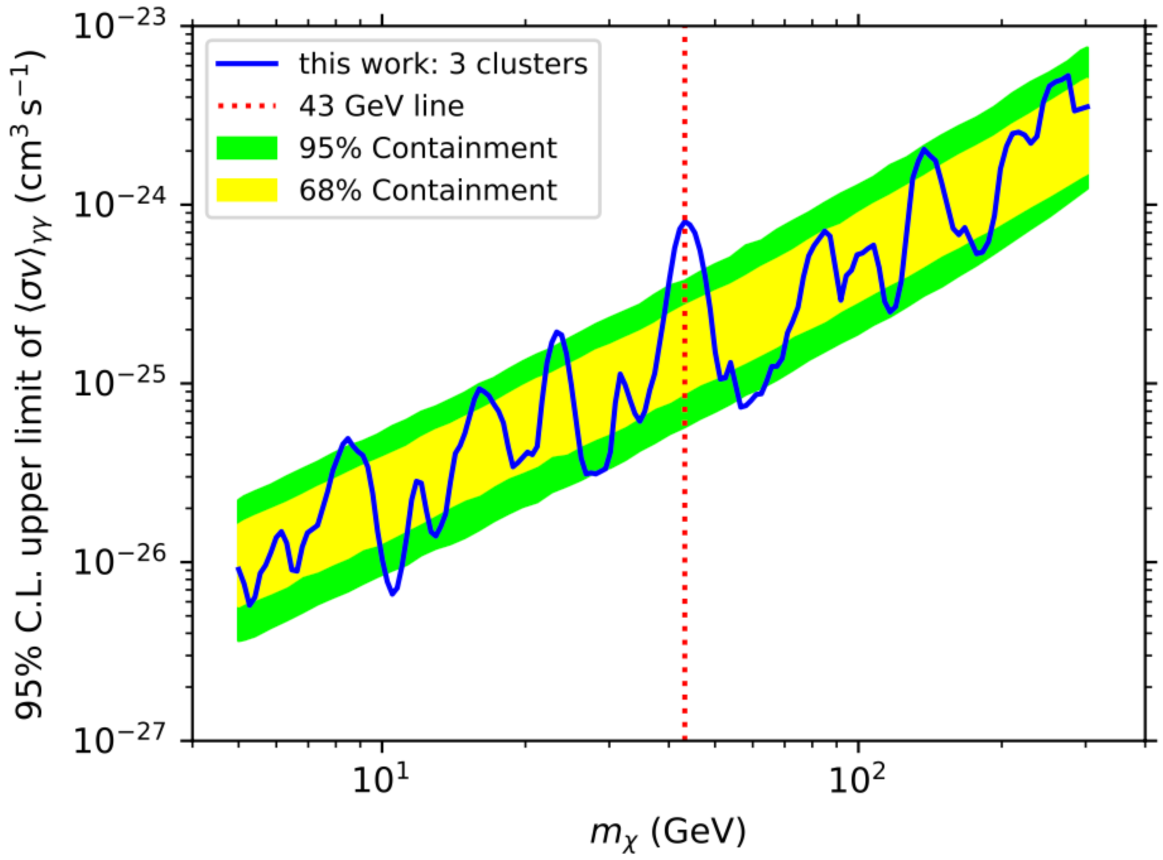
Virgo & M49

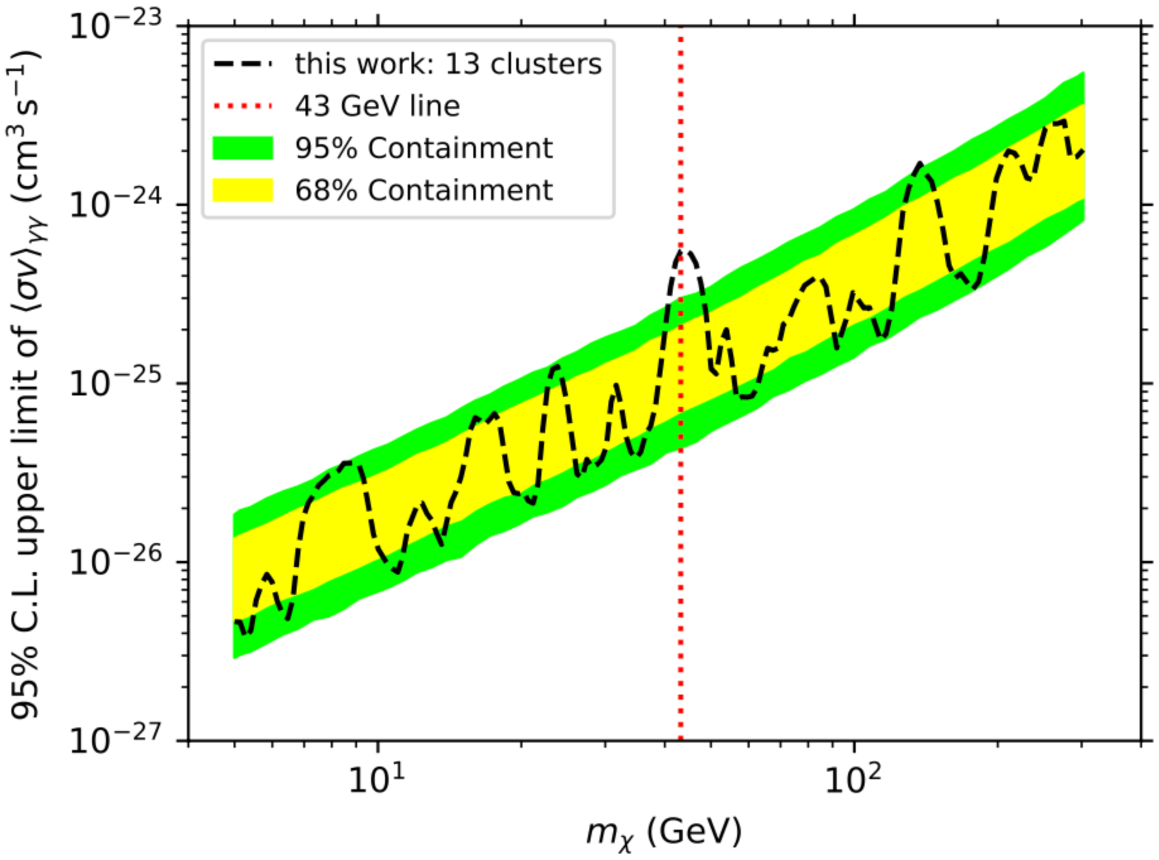


Counts spectra & residual

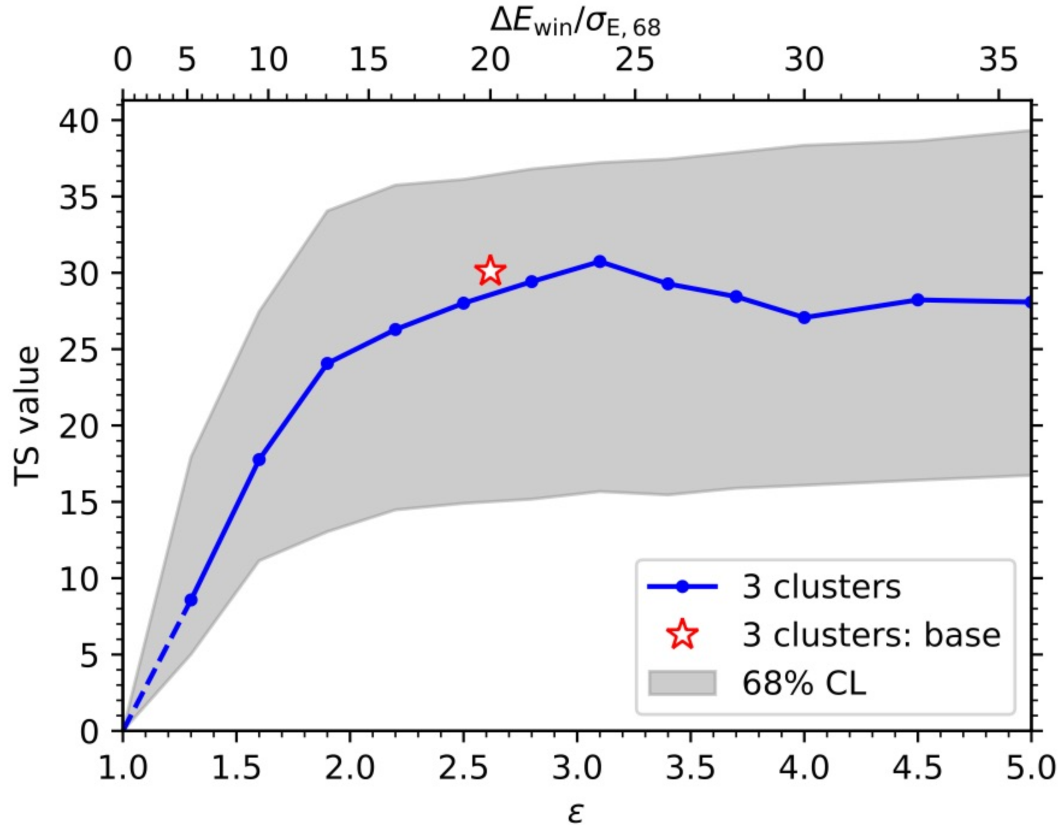


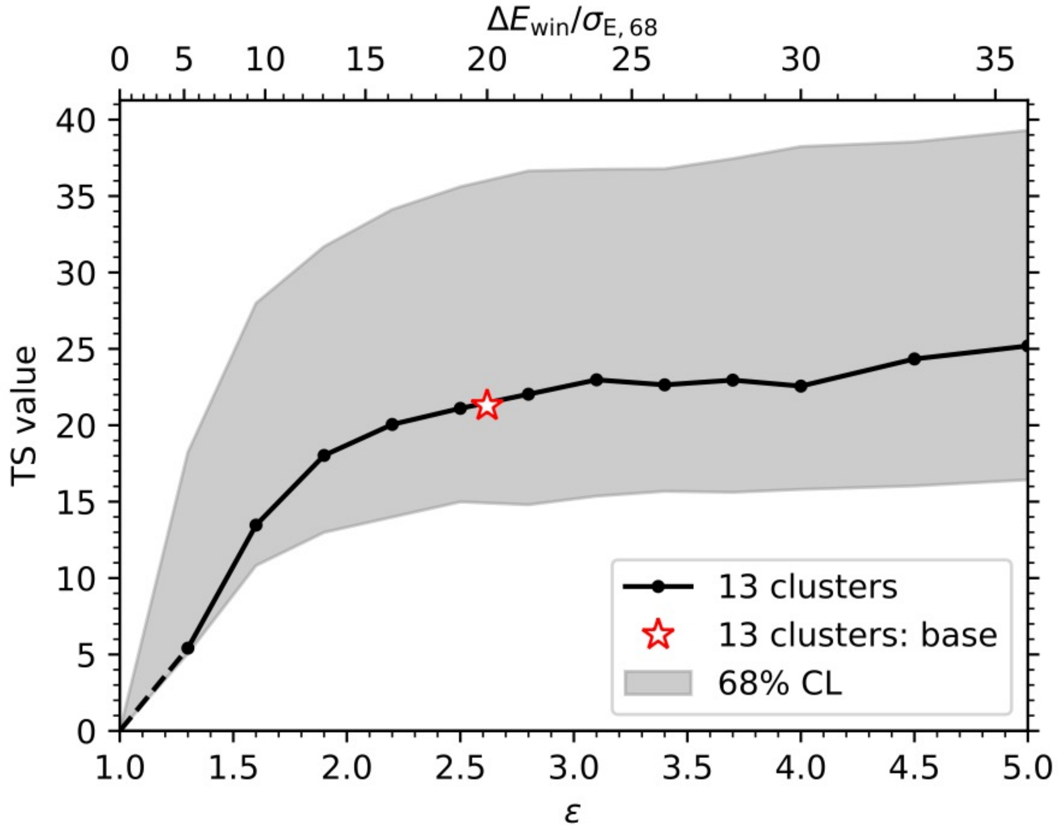
Containmnent bands





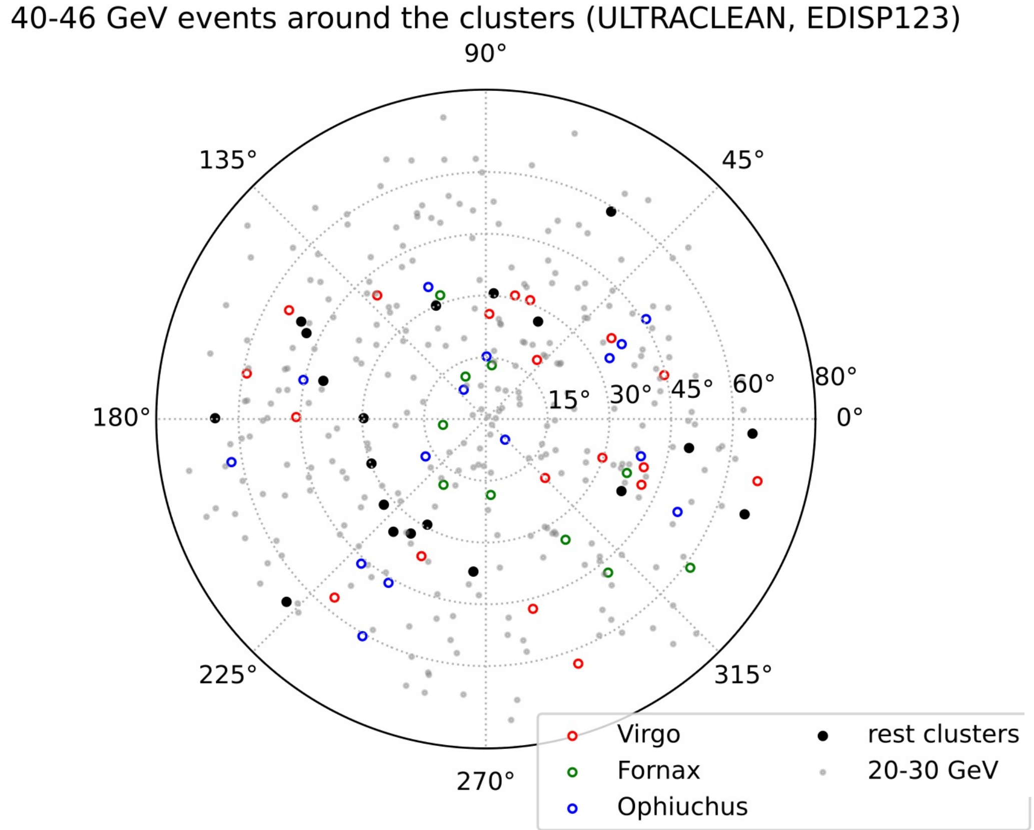
Systematic uncertainties: energy window size



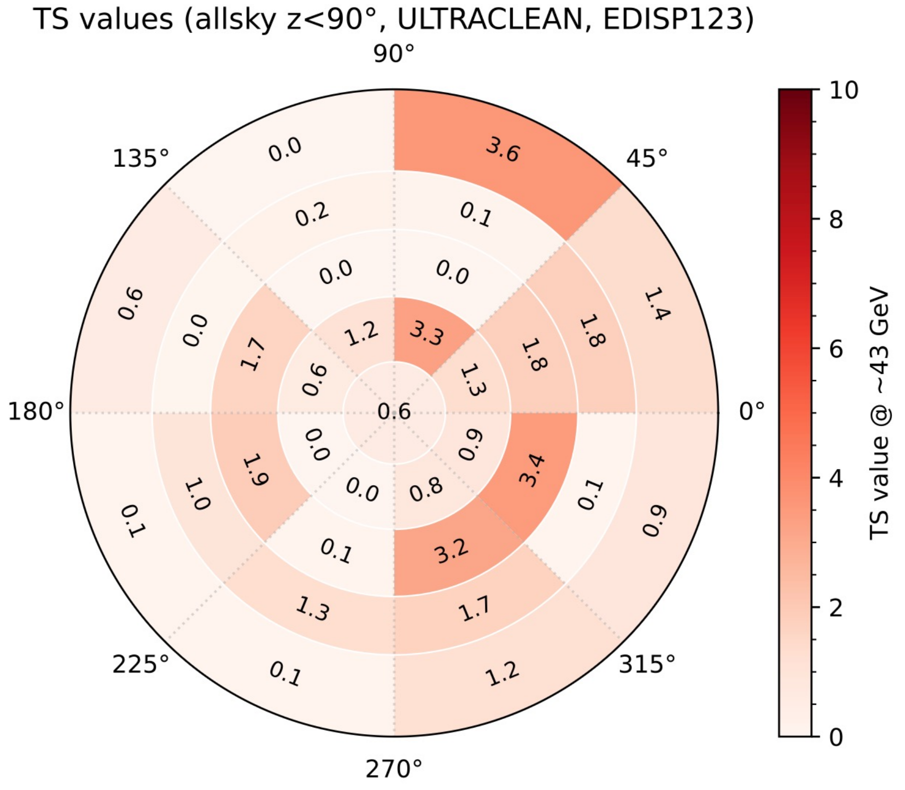


- We define the energy windows bounded by $[E_{\rm low}, E_{\rm upp}]$, where $E_{\rm low} = E_{\rm line}/\sqrt{\varepsilon}$ and $E_{\rm upp} = E_{\rm line}\sqrt{\varepsilon}$. The window width is controlled with the parameter ε.
- The TS values do not significantly derivate from the baseline ones when we change the E window.

Systematic uncertainties: incident angle

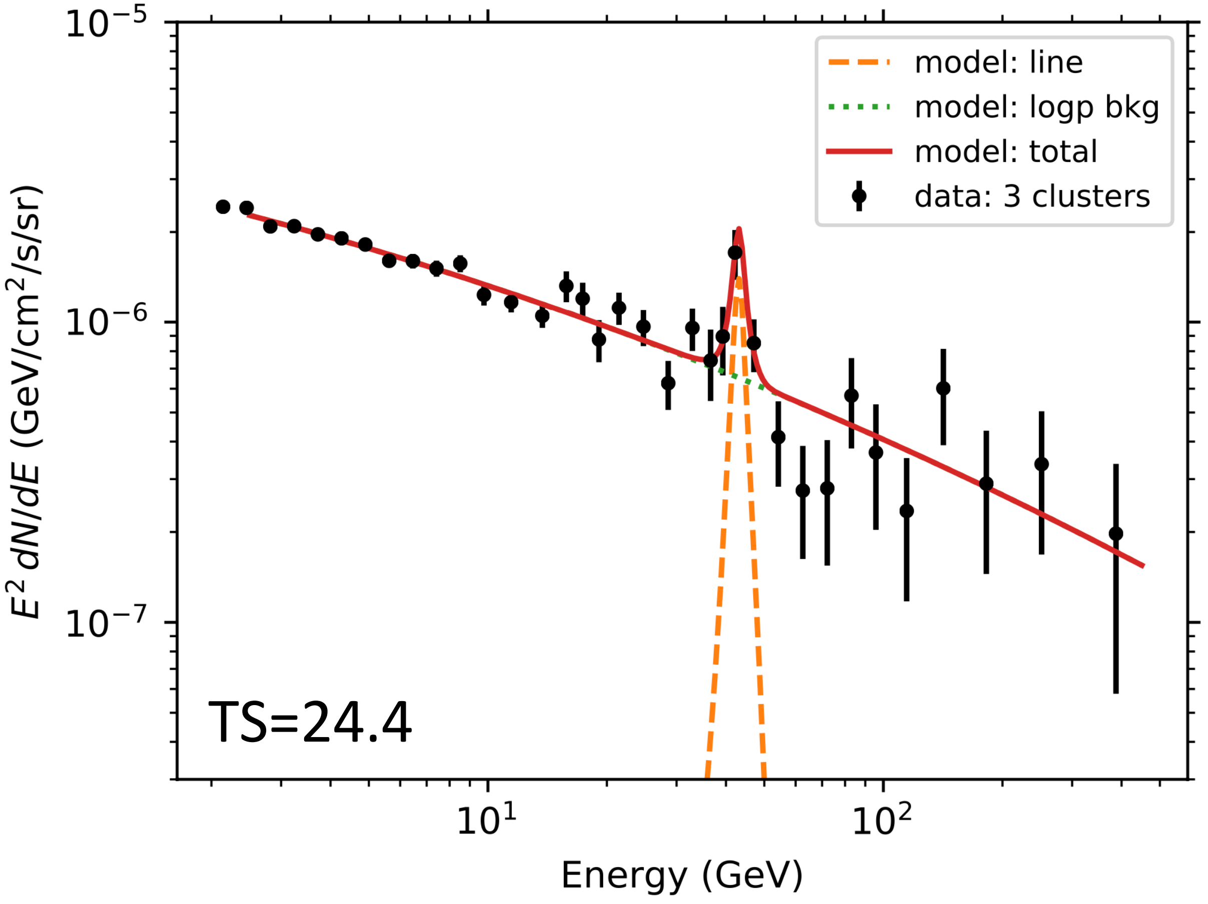


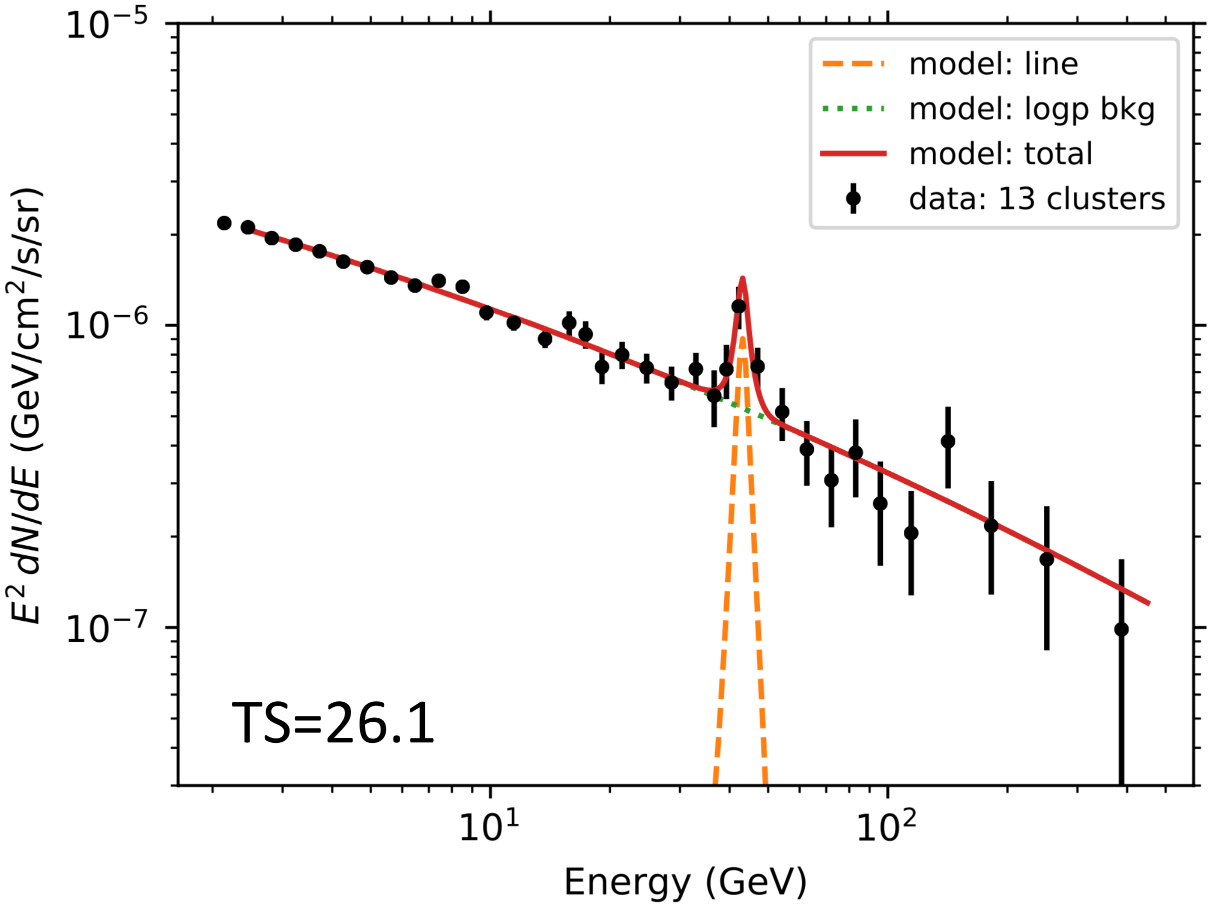
Events in source region



Analyses of control region

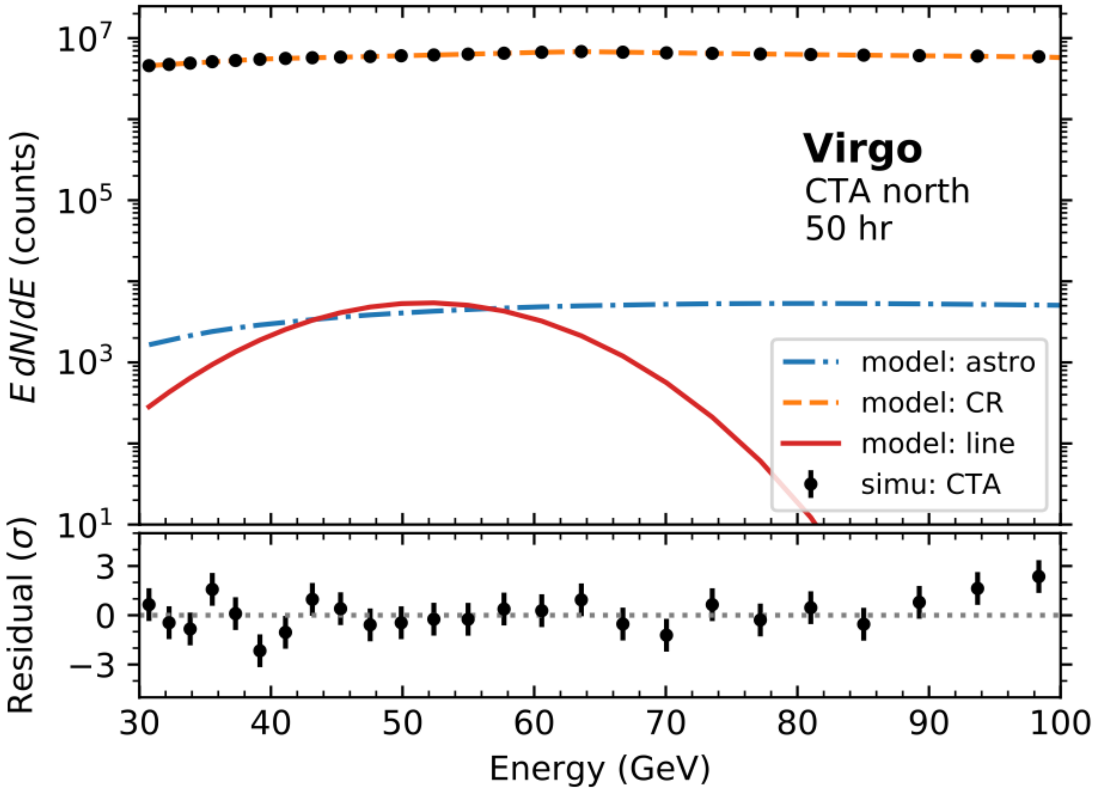
Systematic uncertainties: broadband fit

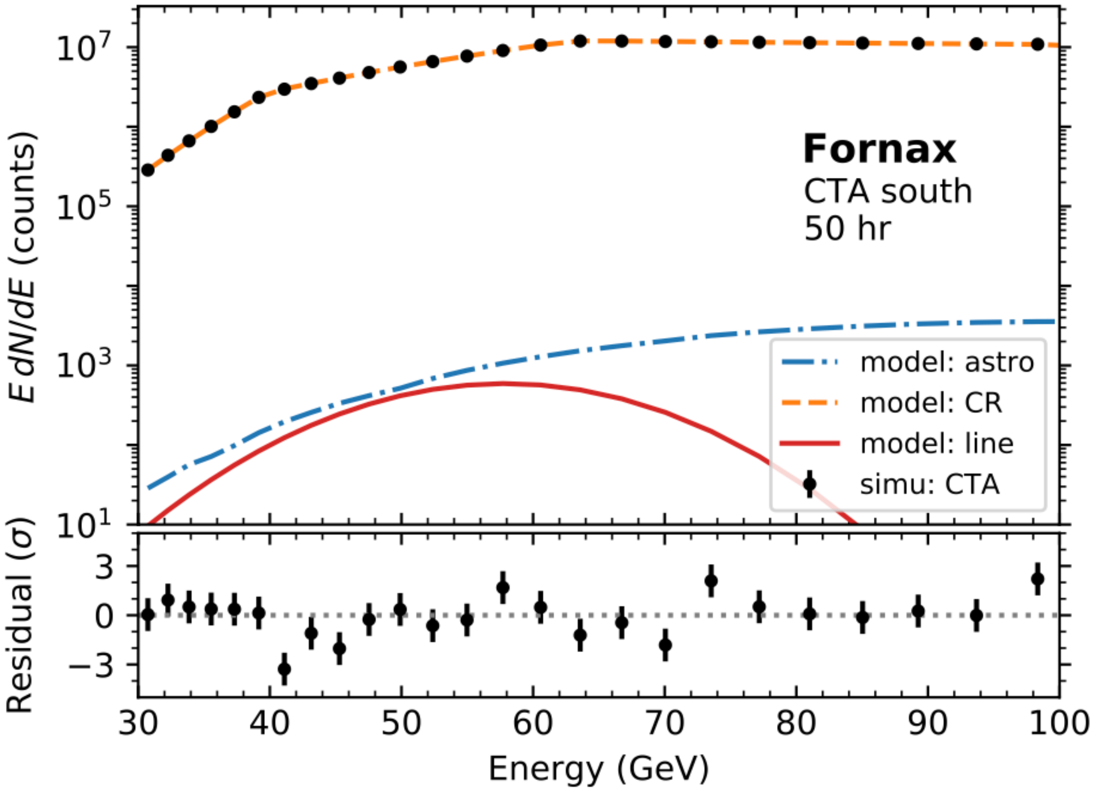




The LogParabola model has the best Akaike information criterion for both models, the TS values of the line are 24.4 and 26.1 for 3 and 13 clusters, respectively.

More details on the prospect of CTAO

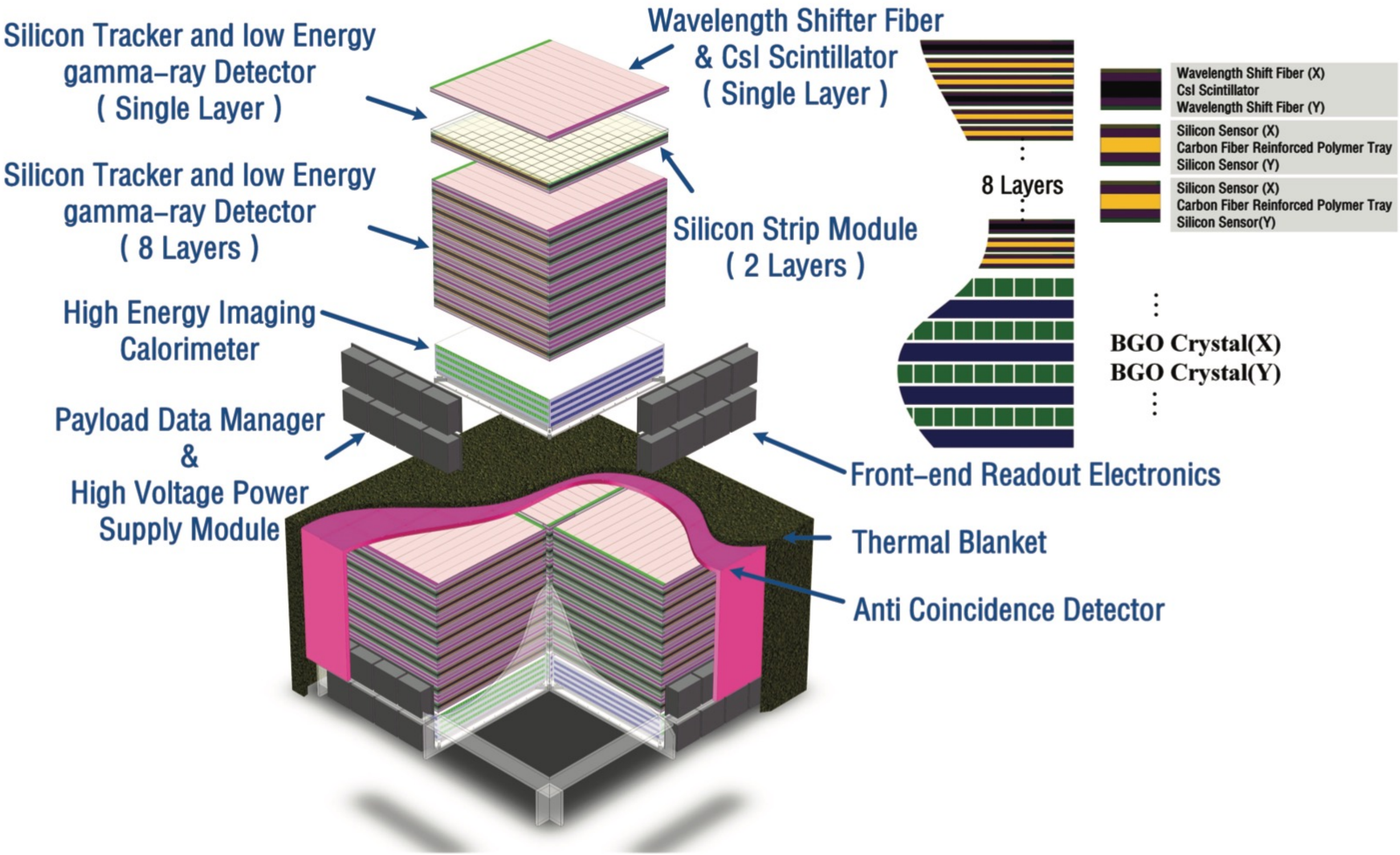




IRFs: prod5 v0.1
Energy resolution: 15% @43 GeV
Effective area: 10^3-10^4 m^2 @43 GeV

Astrophysical: gll_iem_v07 + IGRB_A + Fermi-LAT 4FGL-DR4
CR: CTAIrfBackground;
Line: optimal DM parameters from 13 galaxy clusters.

Very Large Area gamma-ray Space Telescope (VLAST)



Fan+2023; Pan+2024