Probing Dark Photon Dark Matter with the CTAO

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Overview

1. Theoretical framework
2. Astrophysical sources and DM density profiles
3. CTAO simulations and spectral analysis
4. Results and exclusion limits
5. Comparison with existing bounds and conclusions

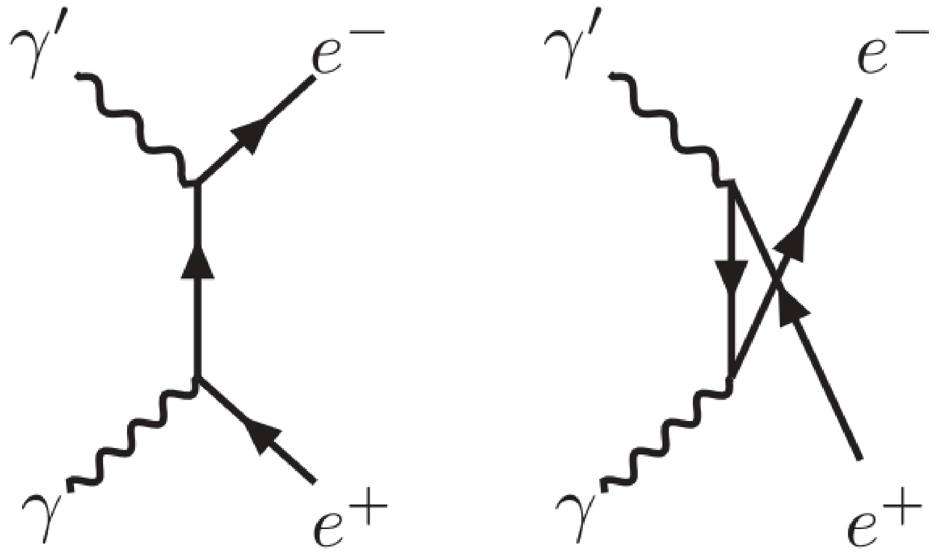
Introduction and motivation

1. Well-motivated non-WIMP dark matter scenario.
2. Kinetic mixing allows $\gamma\gamma' \to e^+e^-$
3. Goal: look for spectral attenuation in VHE gamma-ray sources
4. Compare CTAO constraints (for simulated observations) with current results from other experiments
   - Previous works: Bi et al. 2021 (Crab Nebula); Liu et al. 2024 (Blazars)

Theoretical framework

The Dark Photon is a new gauge boson arising in extensions of the Standard Model. It interacts with SM particles via kinetic mixing with the ordinary photon

$$\mathcal{L} \supset -\frac{e\varepsilon}{\sqrt{1-\varepsilon^2}} J_\mu A'^\mu \simeq -e\varepsilon J_\mu A'^\mu$$



Depending on how they're produced in the early Universe, dark photons could account for some or all of the dark matter

$$m_{A'} > 0$$

scattering occurs if

$$E > E'_{\mathrm{th}} = \frac{2m_e^2}{m_{A'}}$$

Theoretical framework

The scattering process can produce a detectable attenuation effect in the spectrum of VHE sources

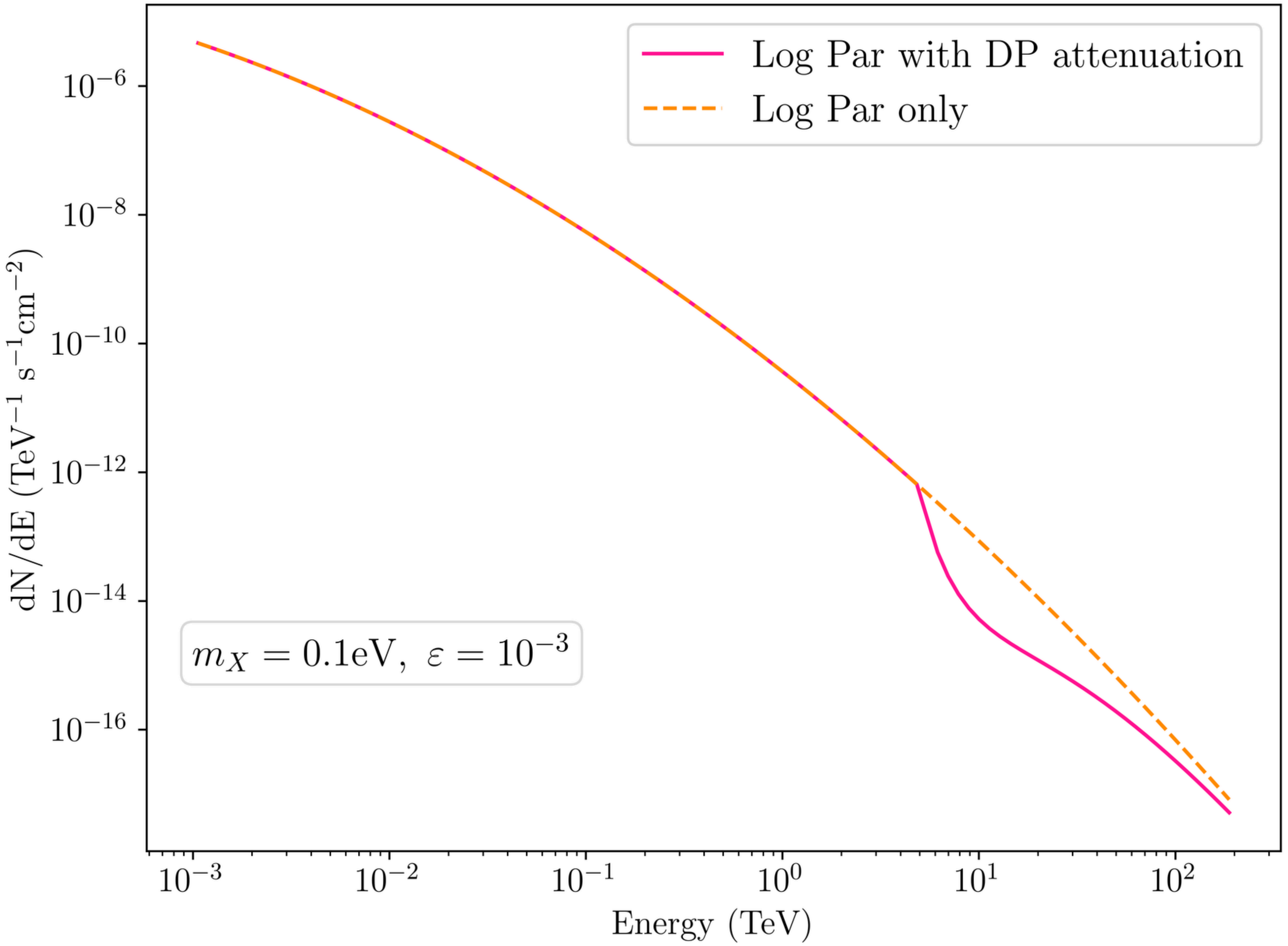
Survival probability $P_{\rm sur} = \mathrm{e}^{-\tau_{A'}}$ depends on:

- Scattering cross-section

$$\sigma_{A'} = \frac{8\pi e^2\alpha^2}{3(s-m_{A'}^2)^3}\Big[-\beta(s^2+4sm_e^2+m_{A'}^4) + \ln\left(\frac{1+\beta}{1-\beta}\right)\times\left(s^2+4sm_e^2+m_{A'}^4-4m_{A'}^2m_e^2-8m_e^4\right)$$

with $\beta = \sqrt{1-4m_e^2/s}$ and $s = 2Em_{A'} + m_{A'}^2$.

- DM Mass integral in the LOS $\tau_{A'} = \int_{\rm los} n_{A'}\sigma_{A'}\,dl.$



Astrophysical sources

- Crab Nebula: galactic source
- Mrk 421 & Mrk 501: extragalactic blazars with VHE gamma-ray emission
- Spectral models:
  - Crab: Log-parabola (as estimated by HAWC observations)

$$\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{-\alpha-\beta\log(E/E_0)}$$

  - Mrk 421/501: ECPL (HEGRA time-averaged observations)

$$\frac{dN}{dE} = N_0 \left(\frac{E}{1\,\mathrm{TeV}}\right)^{-\alpha} \exp\left(-\frac{E}{E_{\mathrm{cut}}}\right)$$

DM density profiles

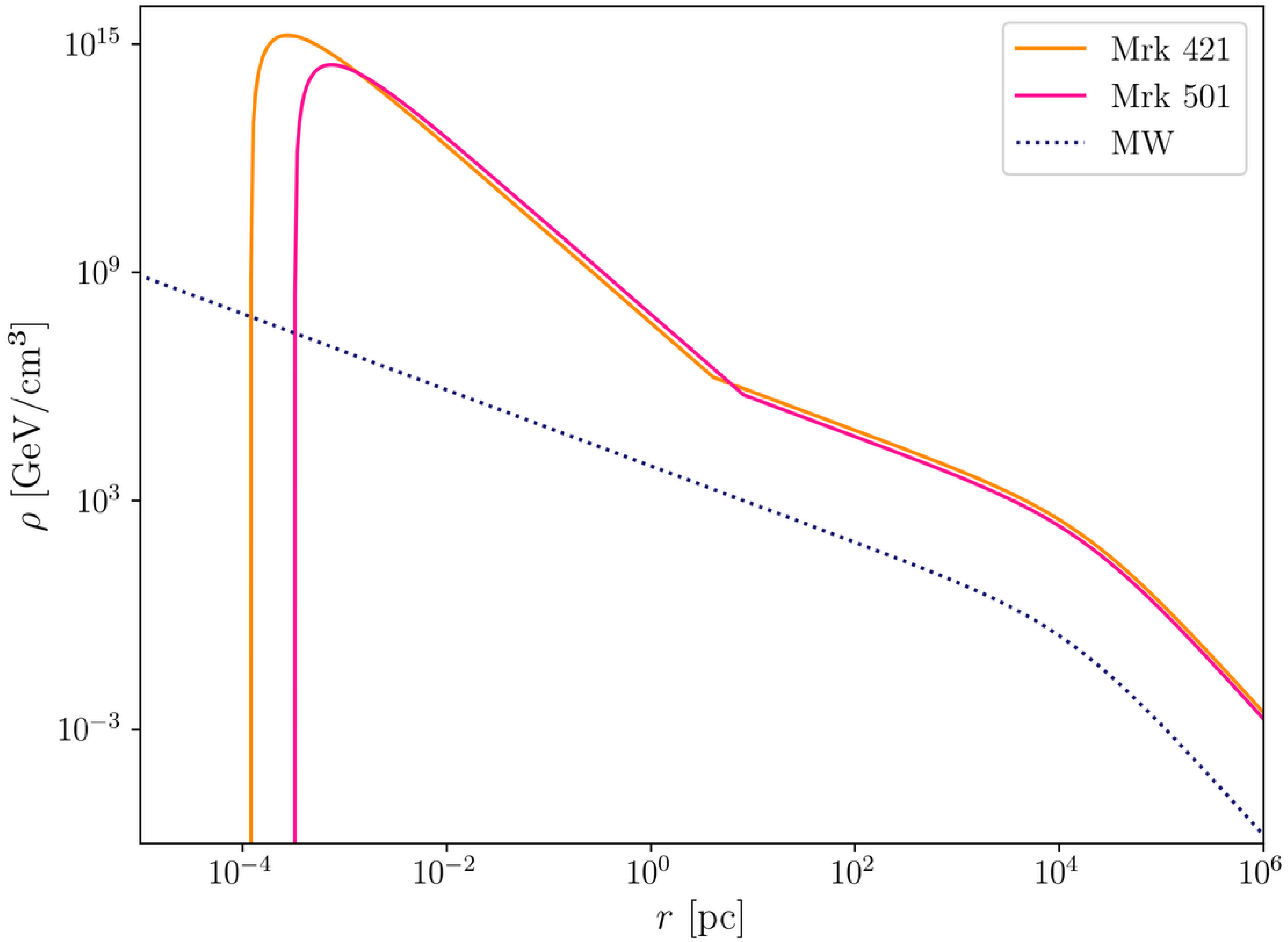
- For the Crab Nebula we used a canonical NFW profile:

$$\rho_{\rm NFW}(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}$$

- For the blazars Mrk 421 and Mrk 501, we accounted for a dark matter spike around the SMBHs:

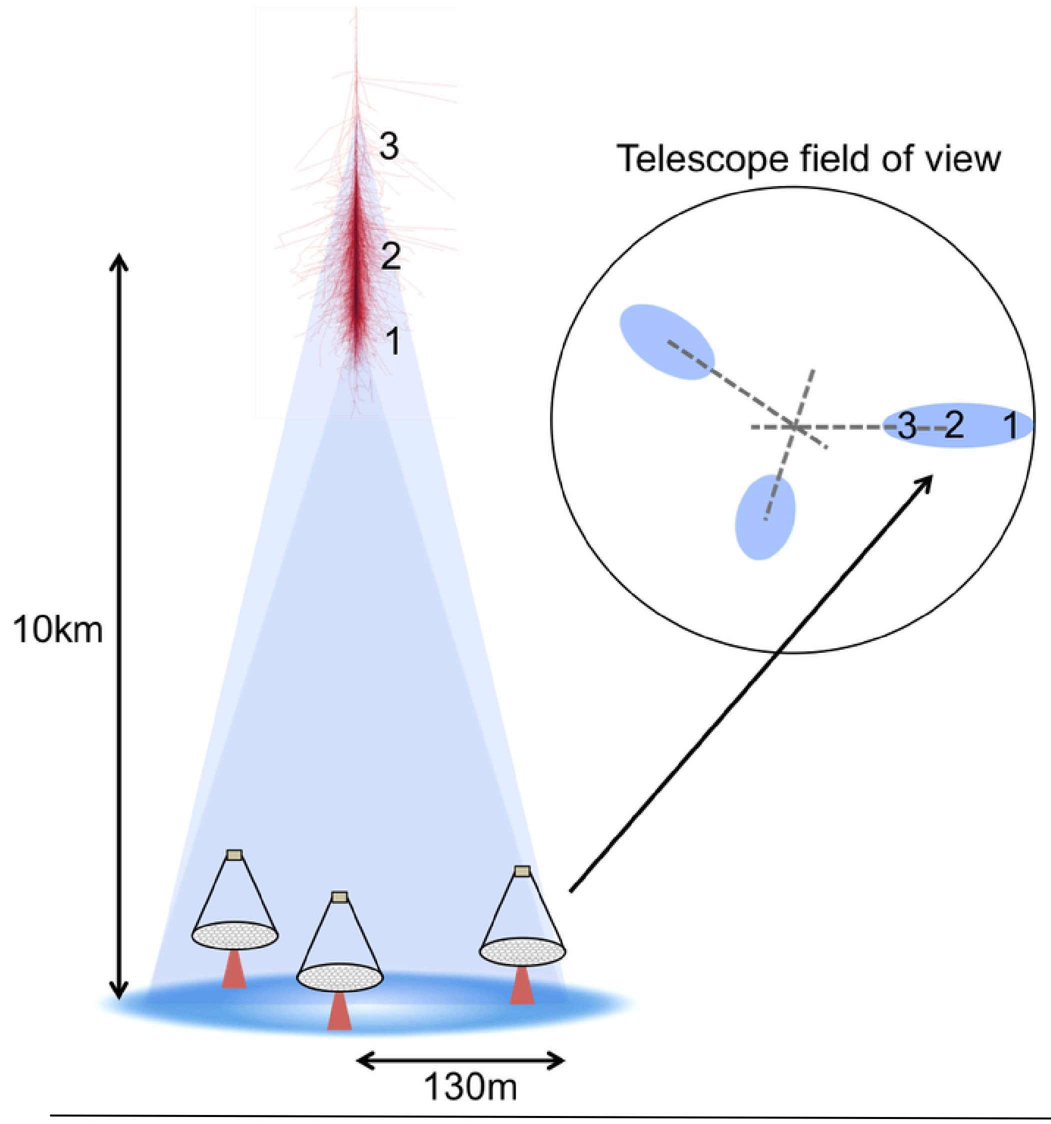
$$\rho_{\rm sp}(r) = \rho_R \, g_\gamma(r) \left(\frac{R_{\rm sp}}{r}\right)^{\gamma_{\rm sp}}$$

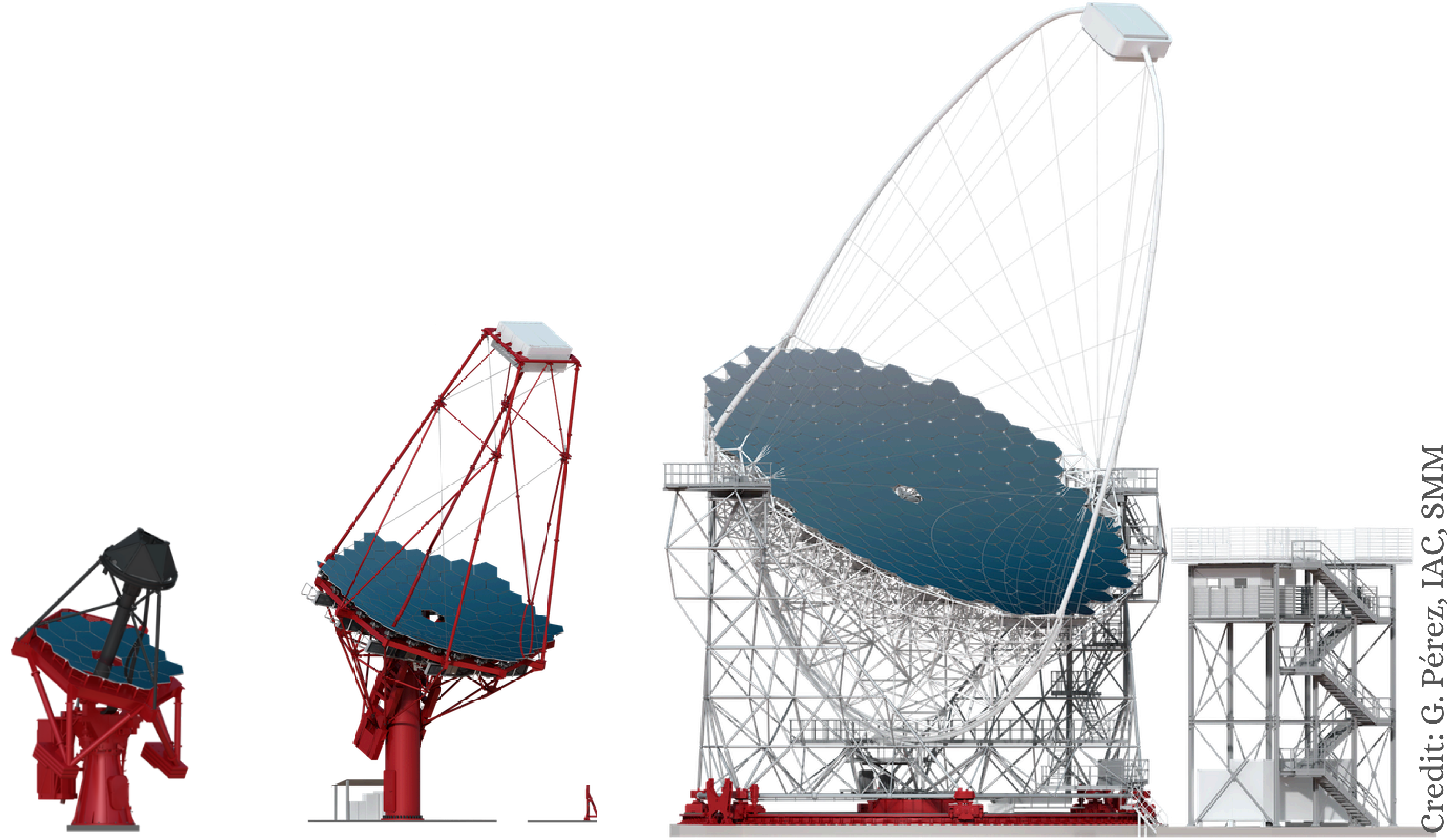
$$R_{\rm sp} = \alpha_\gamma r_s \left(\frac{M_{\rm BH}}{\rho_s r_s^3}\right)^{1/(3-\gamma)}$$



CTAO spectral simulations

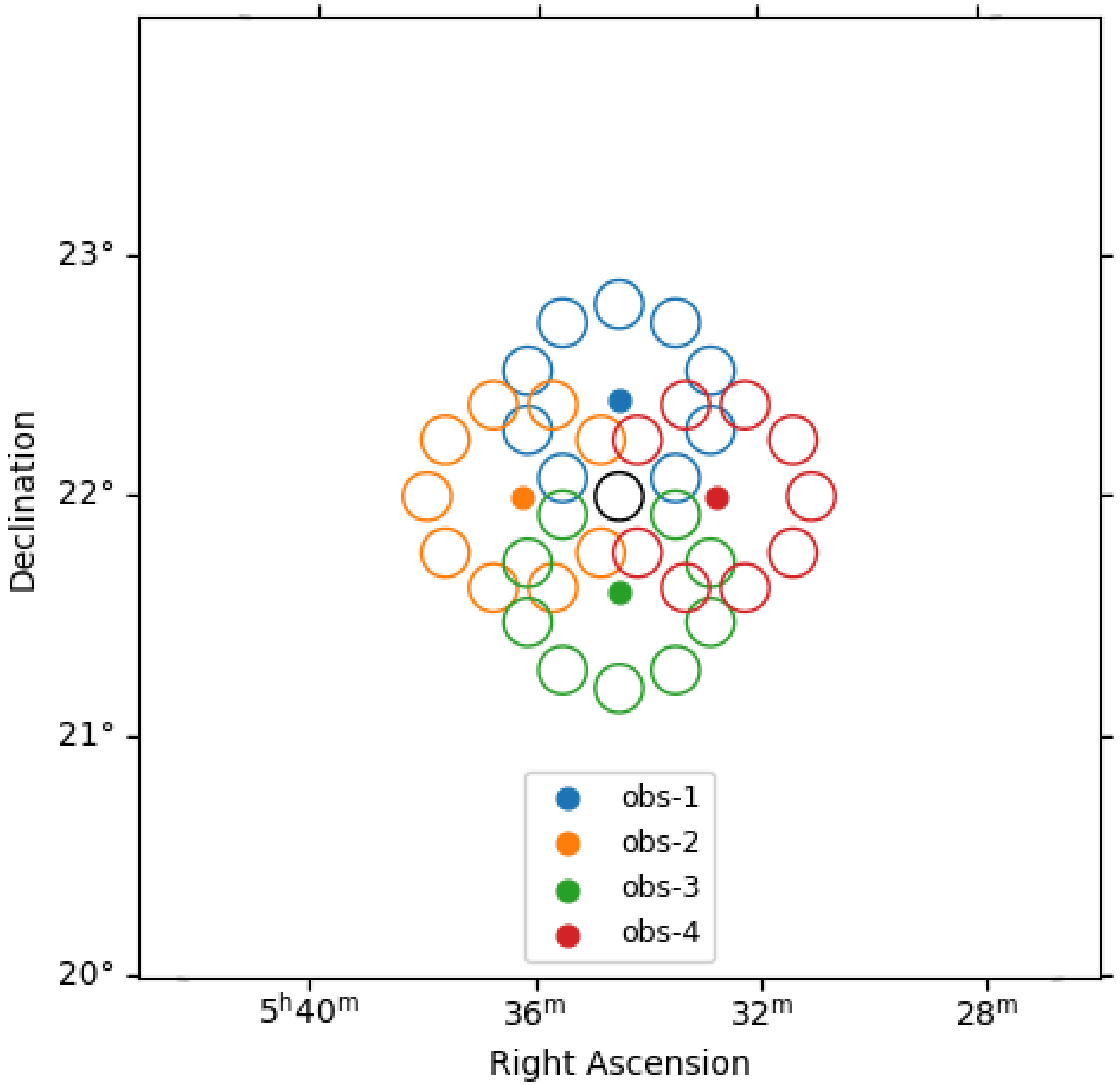
- The next-generation ground-based gamma-ray observatory.
- Two sites: CTAO-North in La Palma, Spain, and CTAO-South in Paranal, Chile.
- More than 60 telescopes: LSTs, MSTs and SSTs.
- Energy coverage from ~20 GeV to ~300 TeV.
- Uses the IACT technique





CTAO spectral simulations

- Crab Nebula: observed with CTAO South array
  - 14 MSTs + 37 SSTs
  - IRFs: South-20deg-AverageAz
  - Total livetime: 200 hours
  - Wobble strategy: 4 pointings at 0.4° offset
- Mrk 421 & Mrk 501: observed with CTAO North array
  - 4 LSTs + 9 MSTs
  - IRFs: North-20deg-AverageAz
  - Total livetime: 100 hours per source
  - Same wobble setup as Crab



*Background estimation via reflected regions; acceptance: α = 0.1 (10 reflected OFF regions)

Sensitivity calculations

- Likelihood ratio test with WStat:

$$W = 2\big(\mu_{\rm sig} + (1 + 1/\alpha)\mu_{\rm bkg} - n_{\rm on}\log\left(\mu_{\rm sig} + \mu_{\rm bkg}\right) - n_{\rm off}\log\left(\mu_{\rm bkg}/\alpha\right)\big)$$

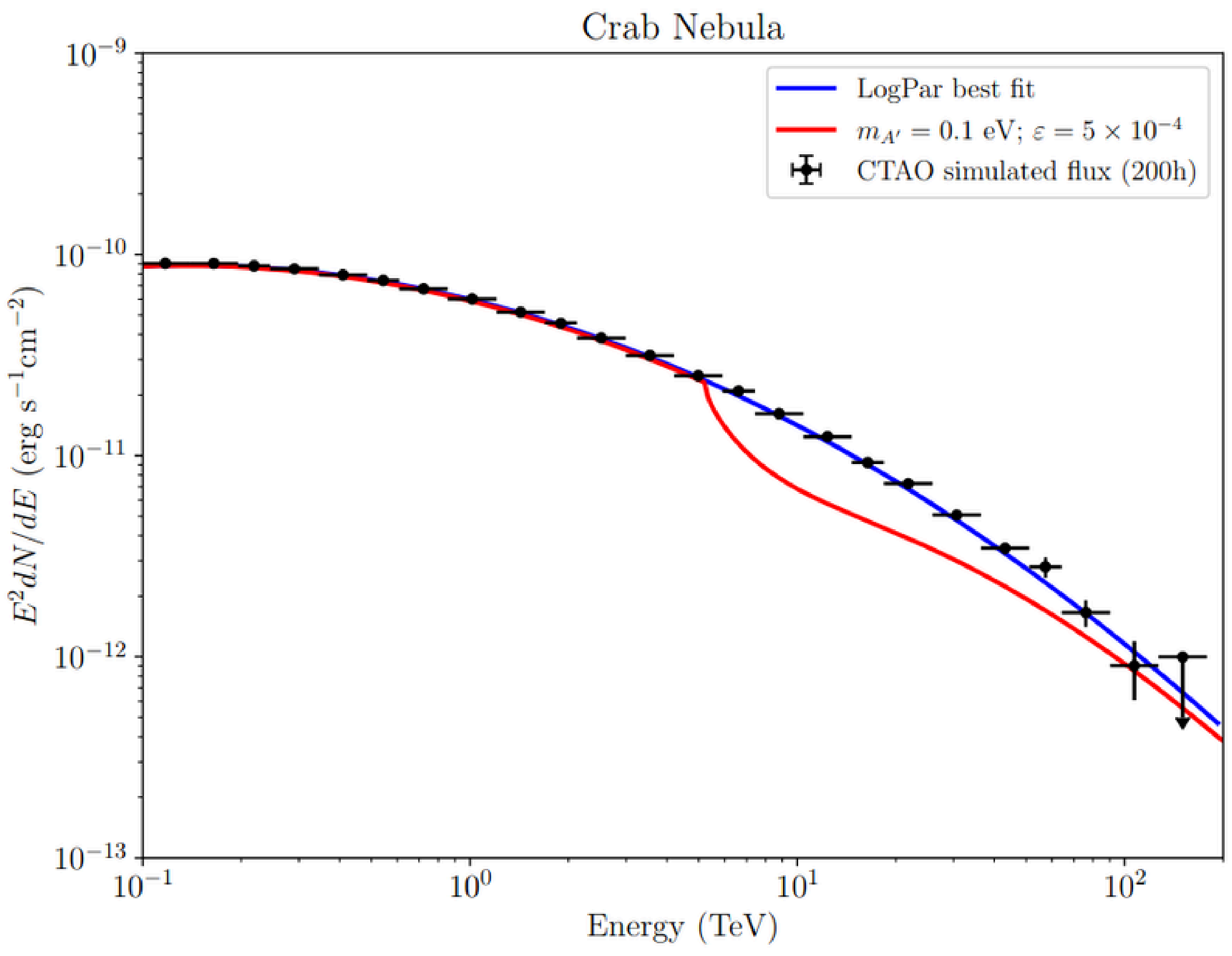
- H_0: no dark photon attenuation: $\left.\frac{dN}{dE}\right|_{H_0} = \left.\frac{dN}{dE}\right|_{\rm int} \times f_{\rm att}(E)$

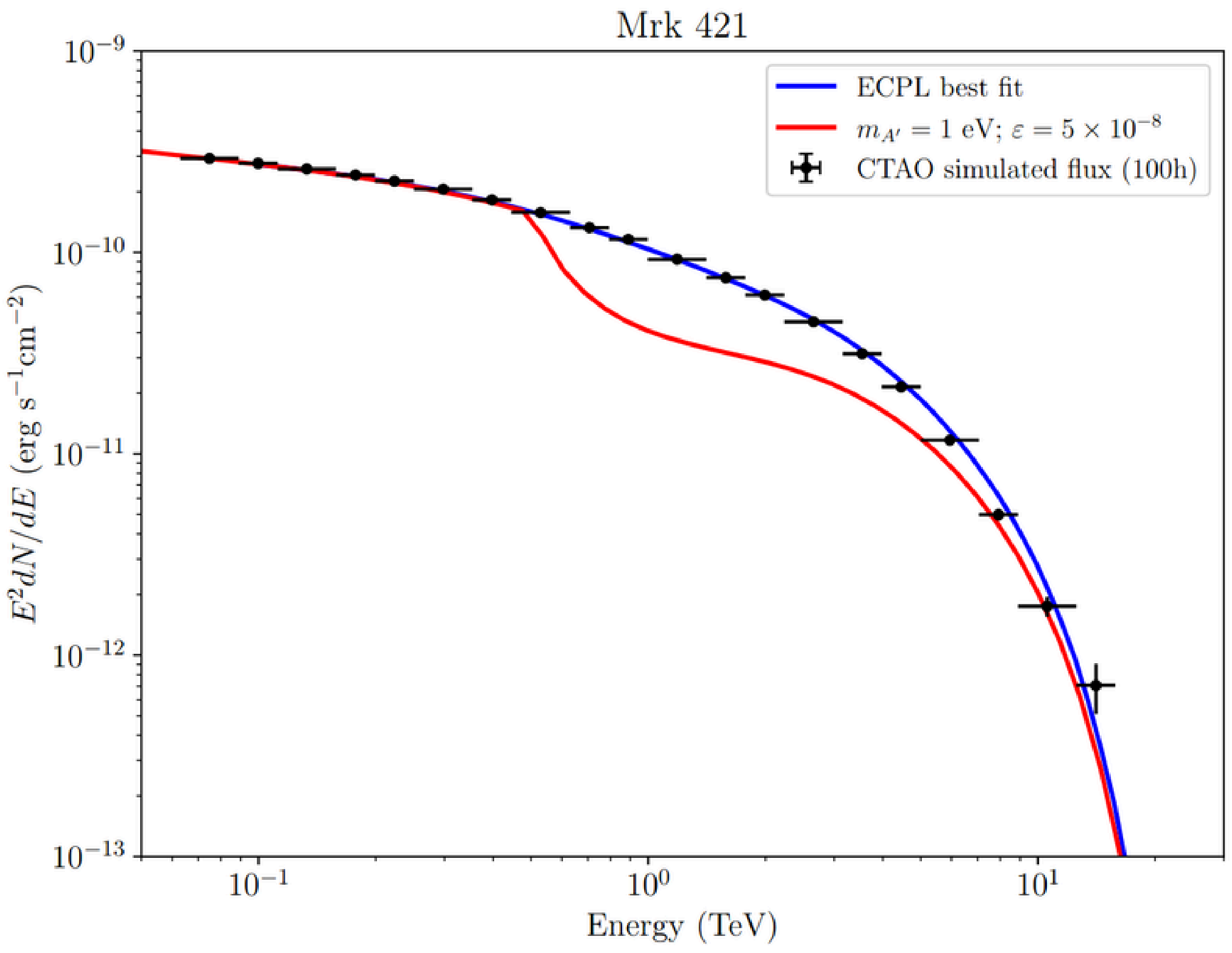
- H_1: includes survival probability: $\left.\frac{dN}{dE}\right|_{H_1} = P_{\rm sur}(m_{A'};\varepsilon) \times \left.\frac{dN}{dE}\right|_{\rm int} \times f_{\rm att}(E)$

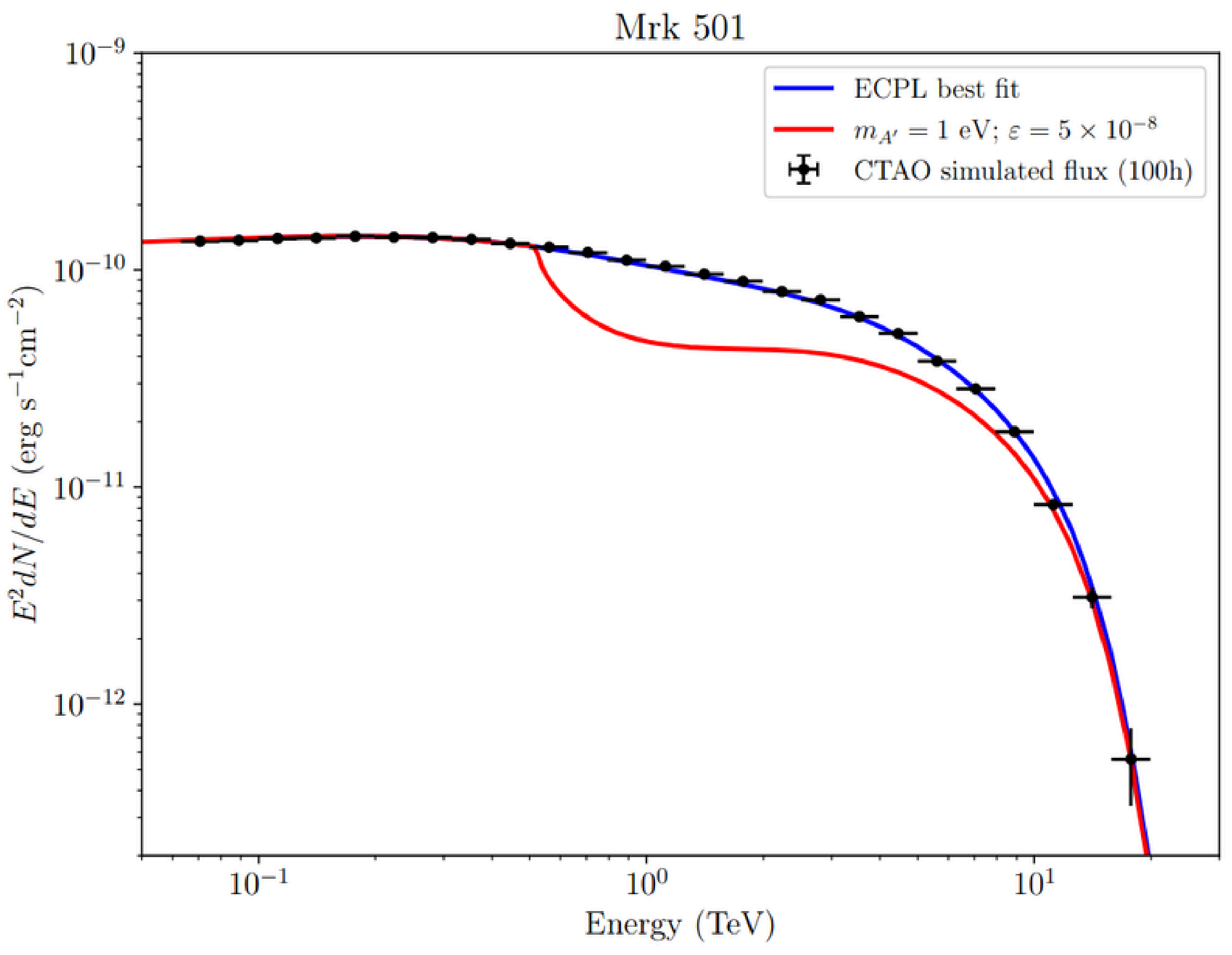
- 95% C.L. exclusion: TS = 2.71

Spectral simulations and fits

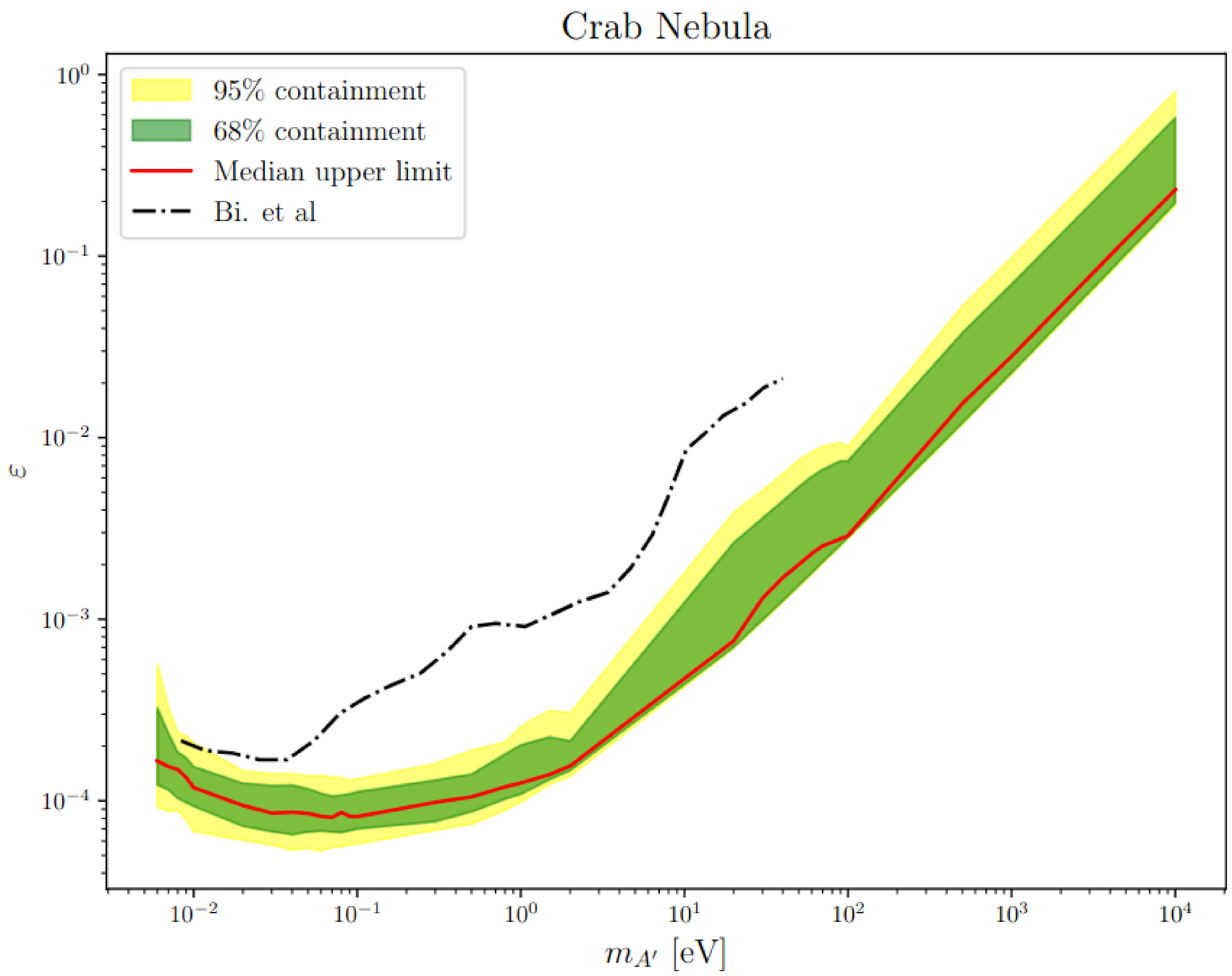
- Fitted simulated data under H1 for all sources
- Statistical scan on mixing parameter





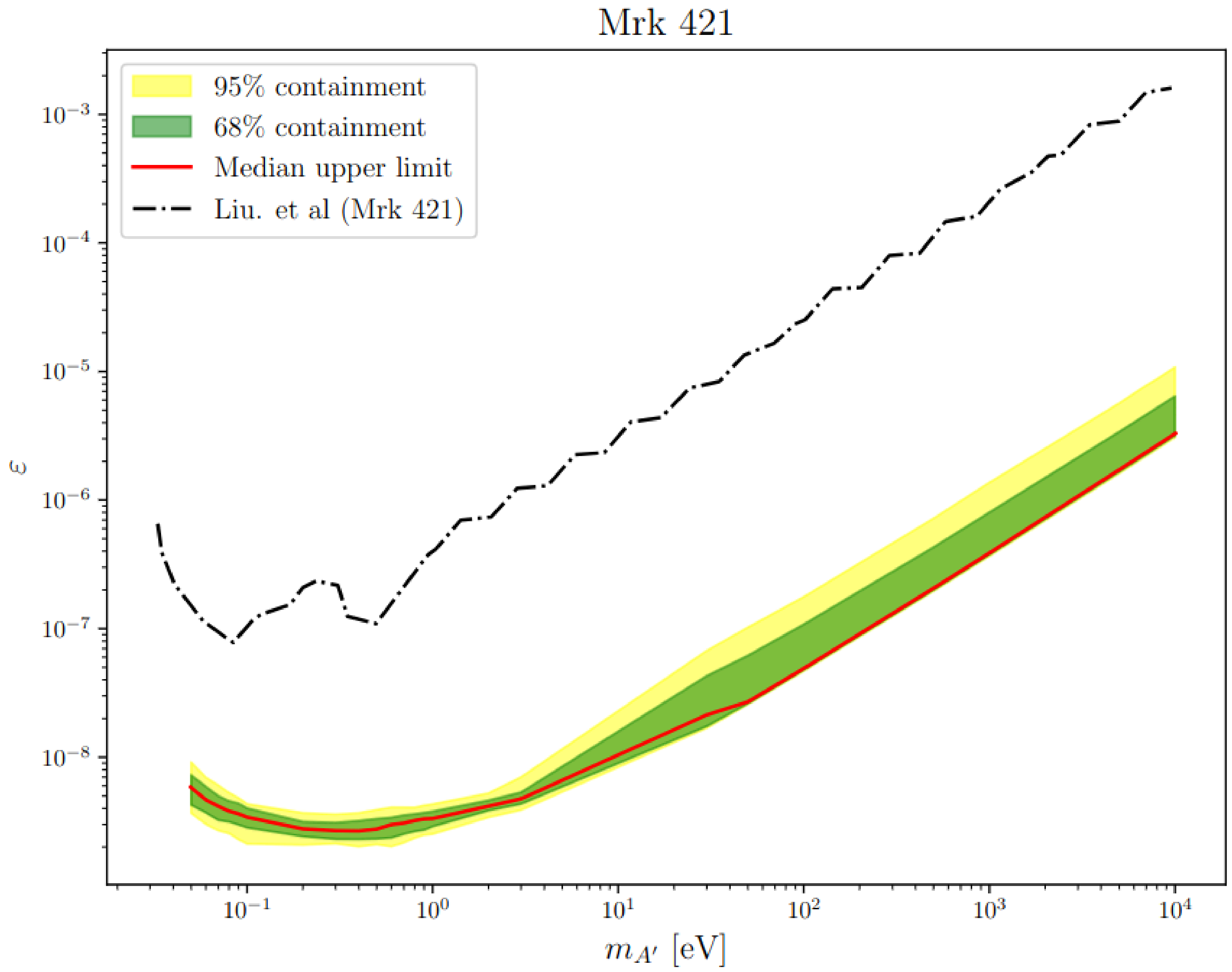


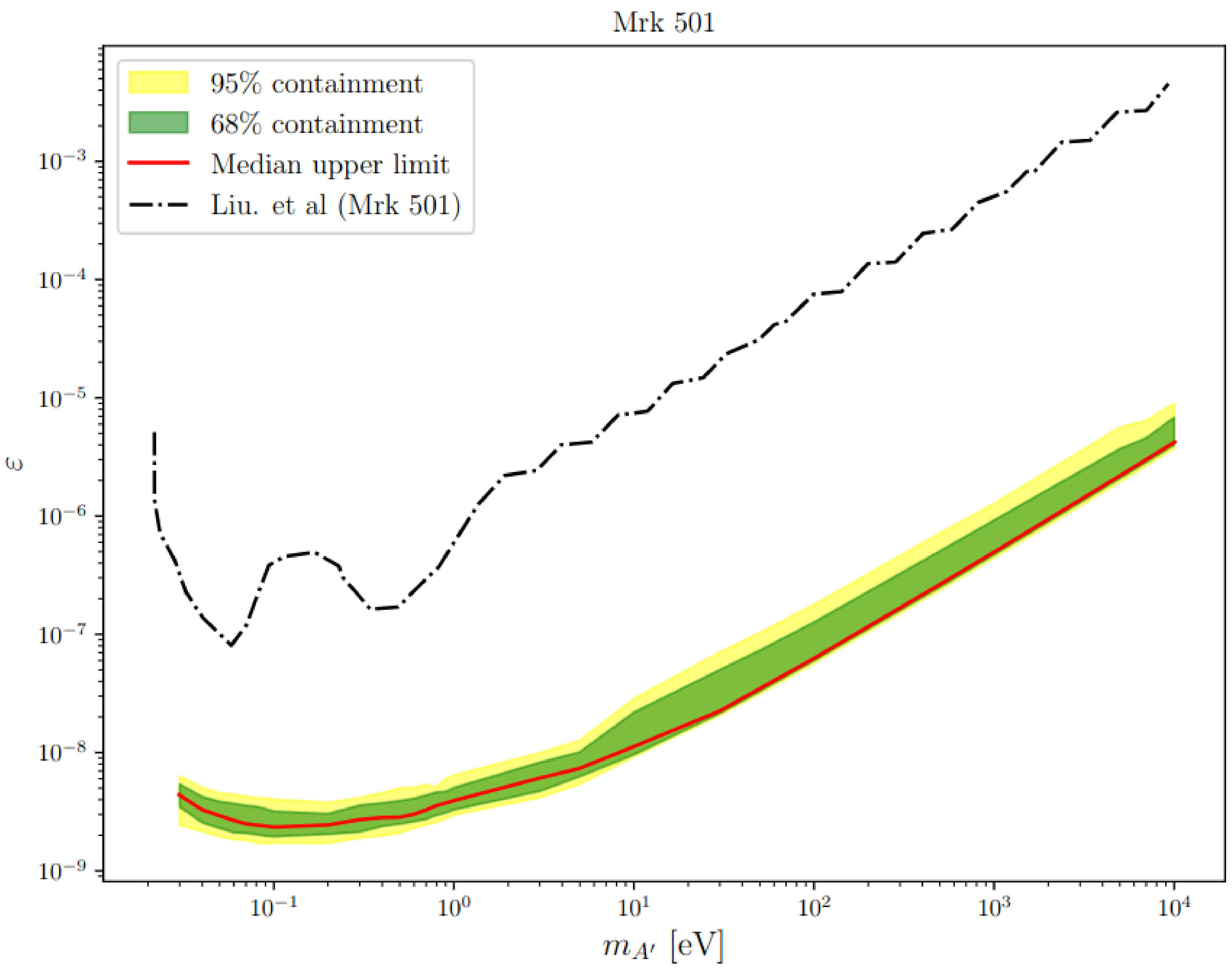
Results


Crab Nebula
95% containment
68% containment
Median upper limit
Bi. et al
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
ε
10^{-2}
10^{-1}
10^0
10^1
10^2
10^3
10^4
$m_{A'}$ [eV]

Results

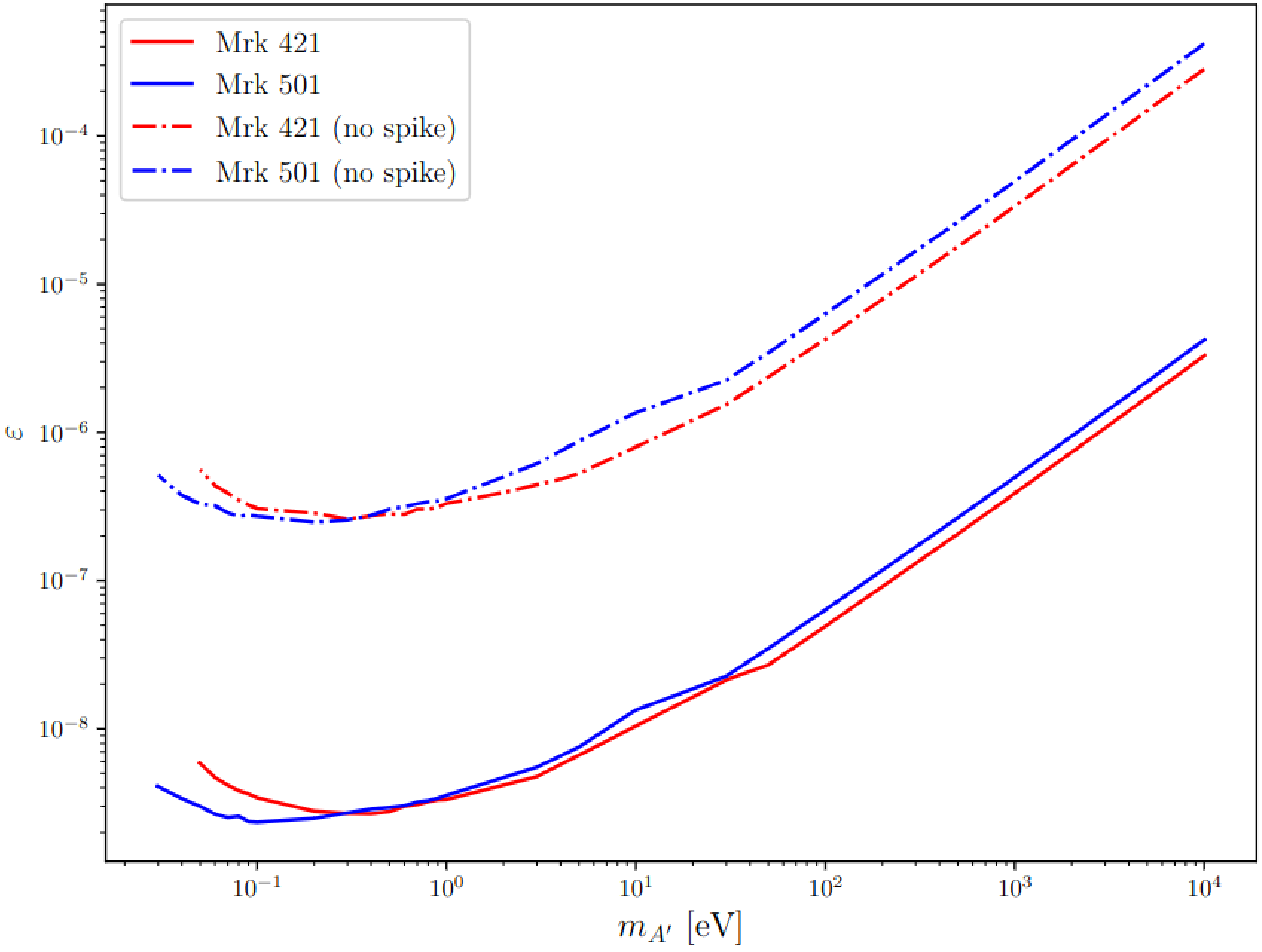
- Stronger constraints from Mrk 421 and Mrk 501: ε ~ 10^{-8} for a DP mass around ~ 0.1–1 eV





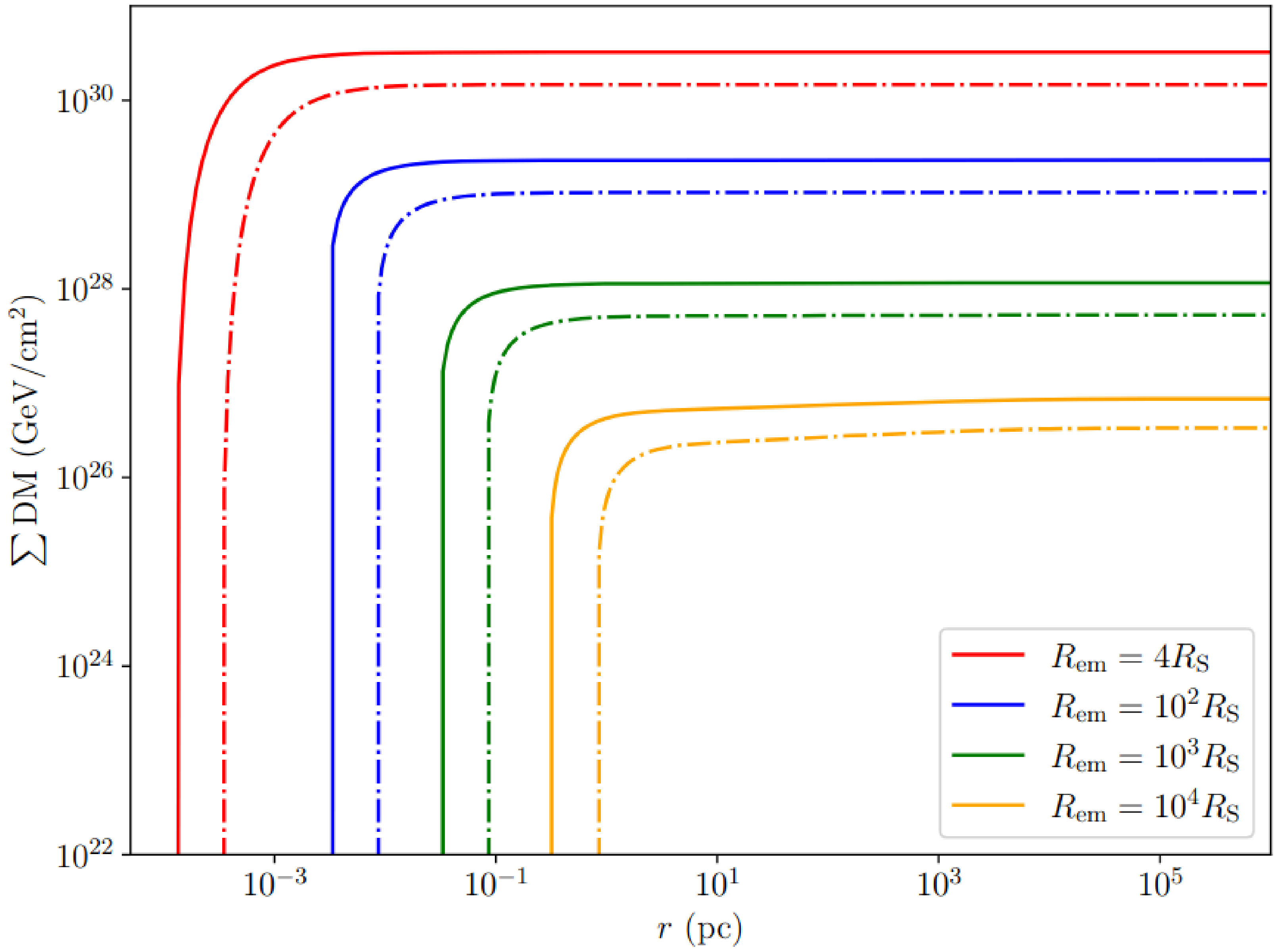
Role of DM Spikes

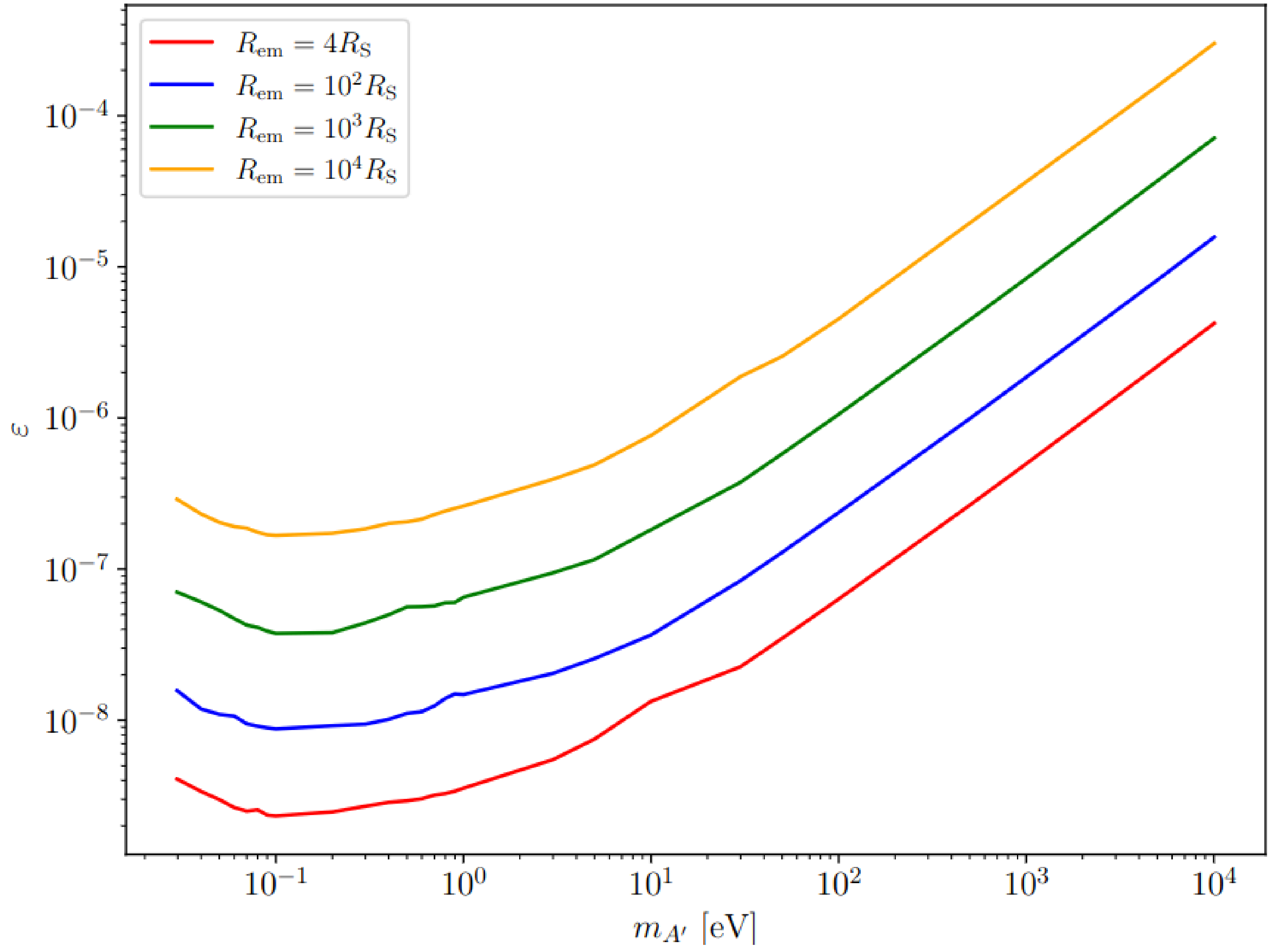
- Spike enhances optical depth → stronger constraints
- The formation and long-term stability of such spikes are still debated, as they can be disrupted by black hole mergers or dynamical heating processes



Role of DM Spikes

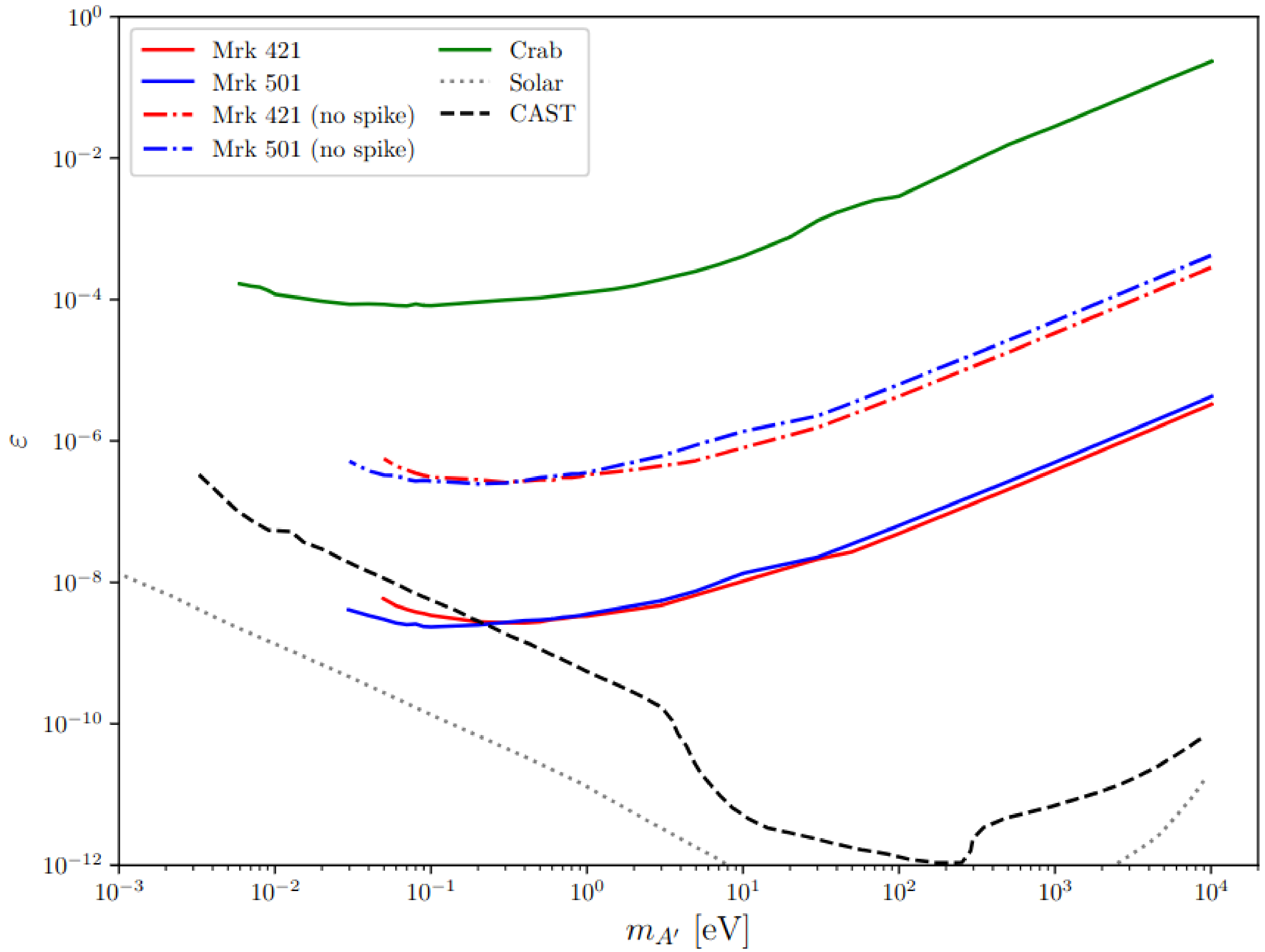
- TeV emission region also impacts the constraints





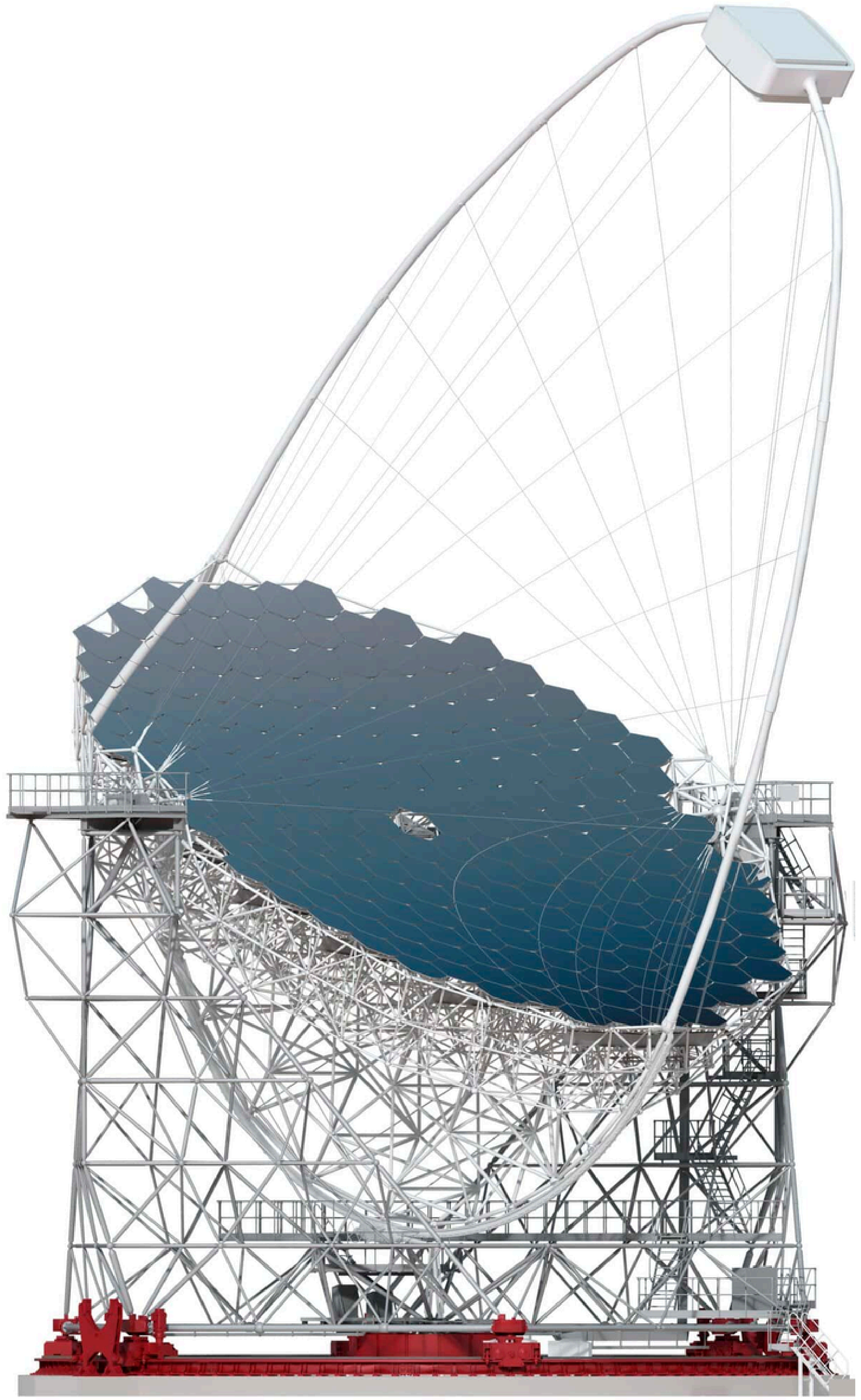
Comparison with Existing Limits

While our limits are not yet as strong as those derived from solar energy loss or laboratory experiments like CAST, they still provide a complementary approach.



Summary and Outlook

- We derived constraints on the kinetic mixing parameter ε for a range of dark photon masses using simulated CTAO observations of the Crab Nebula, Mrk 421, and Mrk 501, via the process $\gamma\gamma' \rightarrow e^+e^-$ in VHE spectra.
- Dark matter spikes around SMBHs in the host galaxies of Mrk 421 and Mrk 501 significantly improve sensitivity.
- Our constraints are complementary to those from CAST and solar physics.
- Future directions:
    - Expand analysis to other VHE sources with diverse redshifts and spectra
    - Refine DM spike profile modeling
    - Apply to real CTAO data (LST1 BL Lacs?)
- arXiv:2602.21920v1



Thank you!

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