Probing Dark Matter-Proton Interactions with Cosmic Reservoirs

Antonio Ambrosone

In collaboration with

Marco Chianese, Damiano F.G. Fiorillo, Antonio Marinelli, Gennaro Miele

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antonio.ambrosone@unina.it

Starburst Galaxies

https://hubblesite.org/image/3898/printshop

The Starburst Galaxy M82

Phenomenological Properties of SBGs

- ✦ Galaxies with high star-formation rate (~100 M⊙/yr, to be compared with ~1 M⊙/yr in the Milky Way)
- ✦ Star forming activity mainly concentrated in the core (nucleus), which lasts for $\sim 10^{7-8}\,\mathrm{yr}$
- ✦ High dense interstellar gas ($n_{\rm ISM} \simeq 10^2\,\mathrm{cm}^{-3}$)
- ✦ High degree of magnetic turbulence which traps high-energy protons for a long time $\sim 10^5\,\mathrm{yr}$: **Cosmic Reservoirs**

Expected copious hadronic production:

Interstellar gas as the target

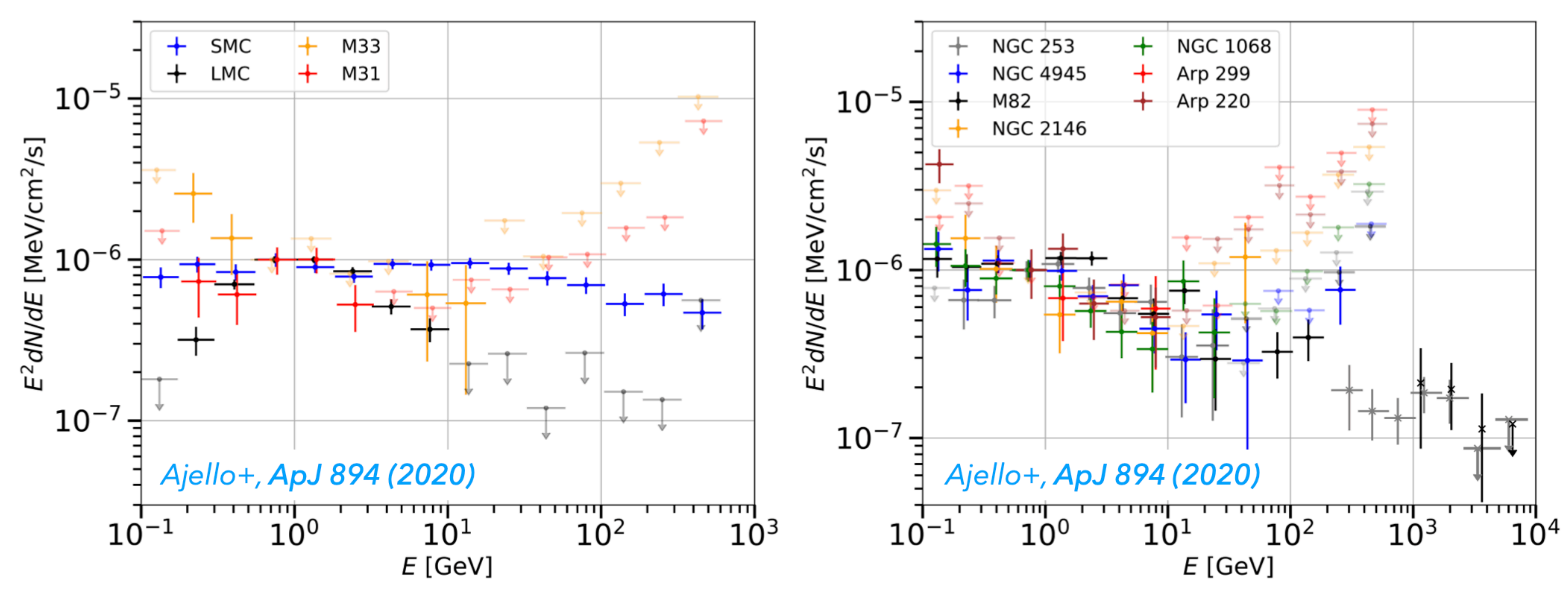
$$p + p \to \pi^+ \pi^- \pi^0 \ldots$$

✦ **Neutrinos** and γ**-rays** from pions decays:

$$\pi^\pm \to e^\pm \nu_e \nu_\mu \overline{\nu}_\mu$$
$$\pi^0 \to \gamma\gamma$$

Nearby SBG Gamma-Ray Emissions

✦ **Fermi-LAT data (GeV energies) + IACTs Telescope (TeV energies)**

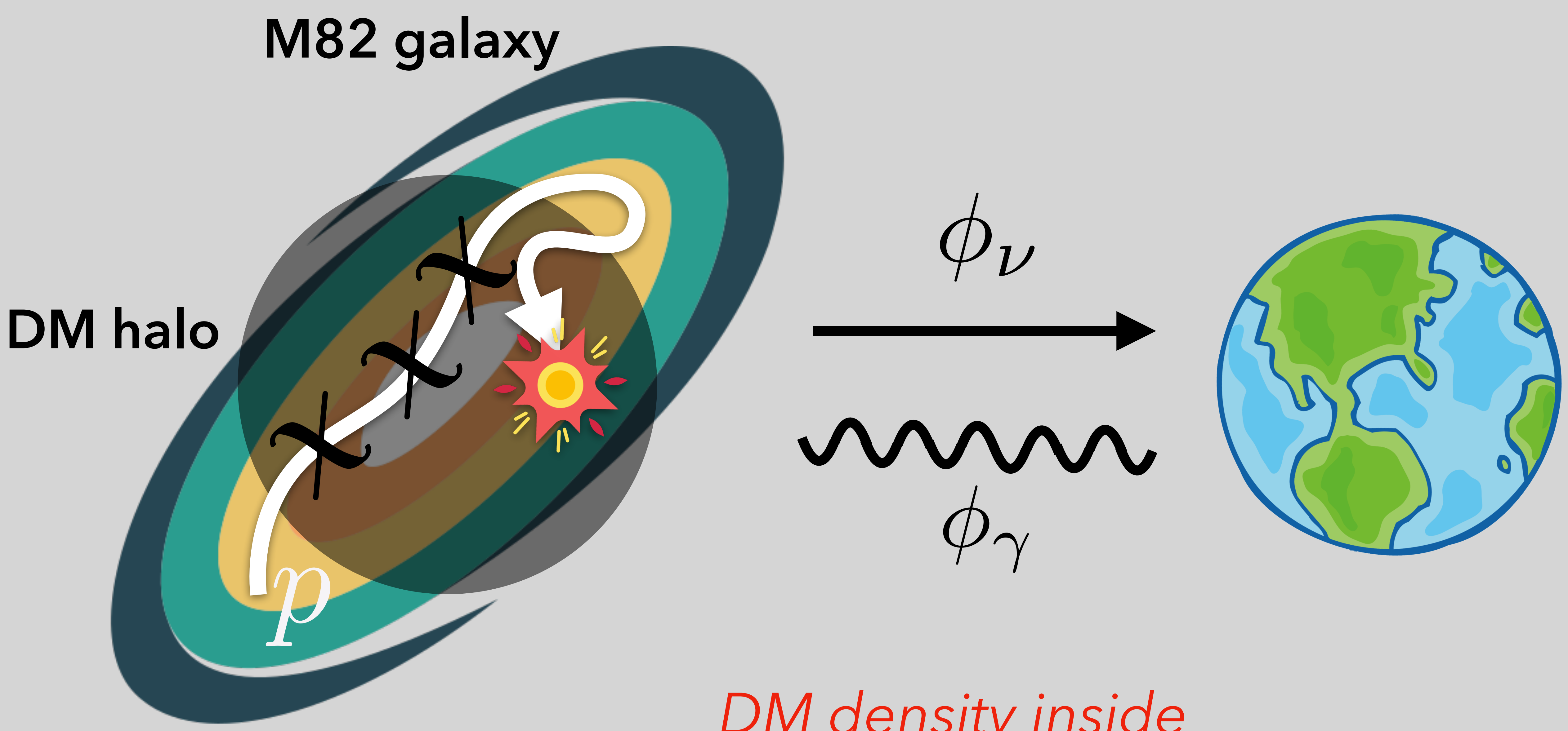


For M82 also VERITAS measurements (VERITAS Collaboration et al., 2009, Nature, 462, 770). For NGC 253 also HESS measurements (H. E. S. S. Collaboration et al., 2018, A&A, 617, A73)

✦ Only a dozen of sources have been detected
✦ Only few of them have both GeV and TeV data

SBGs: Dark Matter Laboratories

We cannot directly probe the CR spectrum inside the SBGs…but we observe γ-rays (and possibly ν)!



Modification of CR transport

$$f_{\rm CR}(p) = \left(\frac{1}{\tau_{\rm adv}} + \frac{1}{\tau_{\rm diff}} + \frac{1}{\tau_{\rm loss}} + \frac{1}{\tau_{\rm loss}^{\chi p}}\right)^{-1} Q_{\rm CR}(p)$$

Additional energy-loss timescale

DM density inside the SBG

CR-DM energy loss

$$\left(\frac{{\rm d}E}{{\rm d}t}\right)_{\chi p} = \frac{\rho_\chi}{m_\chi} \int_0^{T_\chi^{\rm max}} {\rm d}T_\chi \, T_\chi \frac{{\rm d}\sigma}{{\rm d}T_\chi}$$

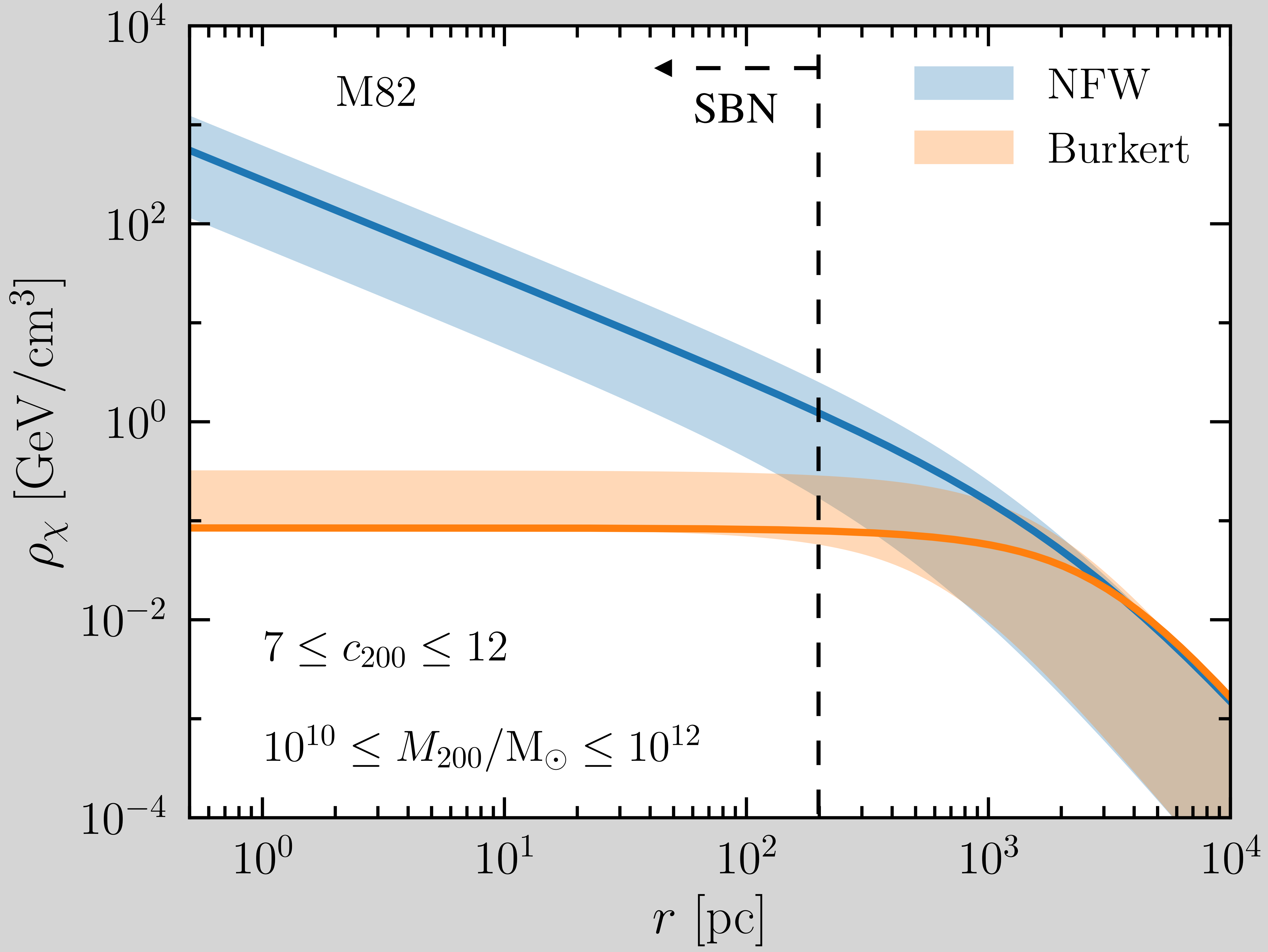
Elastic cross-section valid for transfer momenta:

$$q^2 = 2 m_\chi T_\chi \lesssim 1\,{\rm GeV}^2$$

Suppression from ***proton form factor***

$$F_p(q^2) = \left(\frac{1}{1 + q^2/(0.77\ {\rm GeV})^2}\right)$$

Dark Matter Density in SBNi



- Parameters from cosmological simulations

$$c_{200} = r_{200}/r_s \qquad M_{200} = \int_0^{r_{200}} \rho_\chi(r)\,\mathrm{d}V$$

concentration *total mass*

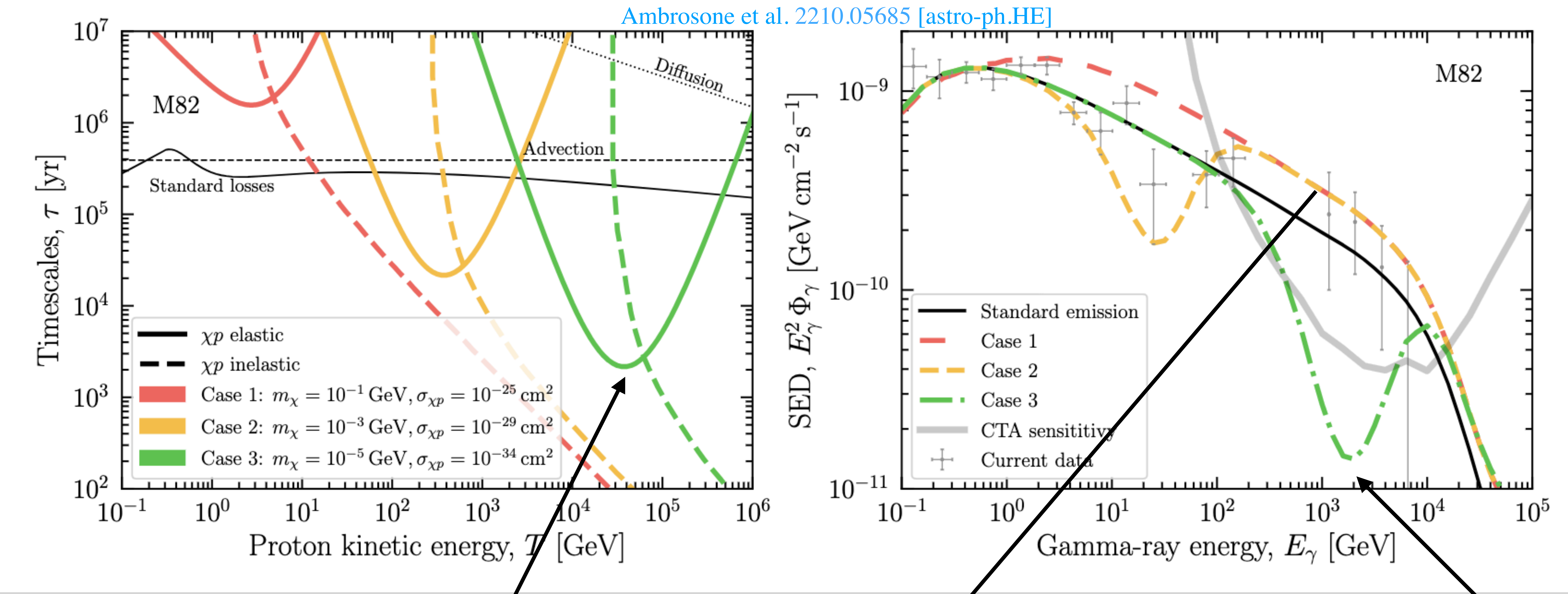
- Large uncertainty on the DM density inside the StarBurst Nucleus (SBN)

- However, it marginally affects the γ-ray emission

$$\Phi_\gamma \propto \int \frac{Q_p(p,r)\,\tau_{\mathrm{loss}}^{\chi p}(r)}{V}\,\mathrm{d}V \propto \int \frac{\rho_\chi^{-1}(r)}{V}\,\mathrm{d}V$$

Average inside the SBN

Signatures of CR-DM Interaction Scatterings



Suppression due to proton form factor

$$E^p_{\rm dip} = m_p^2/(2m_\chi) \qquad E^\gamma_{\rm dip} \simeq 0.1\, E^p_{\rm dip}$$

For DM-p inelastic collisions, we have rescaled the neutrino-nucleon cross section.

When, inelastic DM-p collisions dominate, SBGs have a higher calorimetric fraction than before!

Dip in the γ-ray SED

The smaller the DM mass, the higher the dip energy

Constraints from SBGs: Comparison with Literature

✦ "Standard" constraints in shaded grey

✦ Distortions of Milky-Way Cosmic-Rays (5σ)

*Cappiello, Ng, Beacom, **PRD 99 (2019)***

✦ Boosted DM from blazar jets (90% CL):

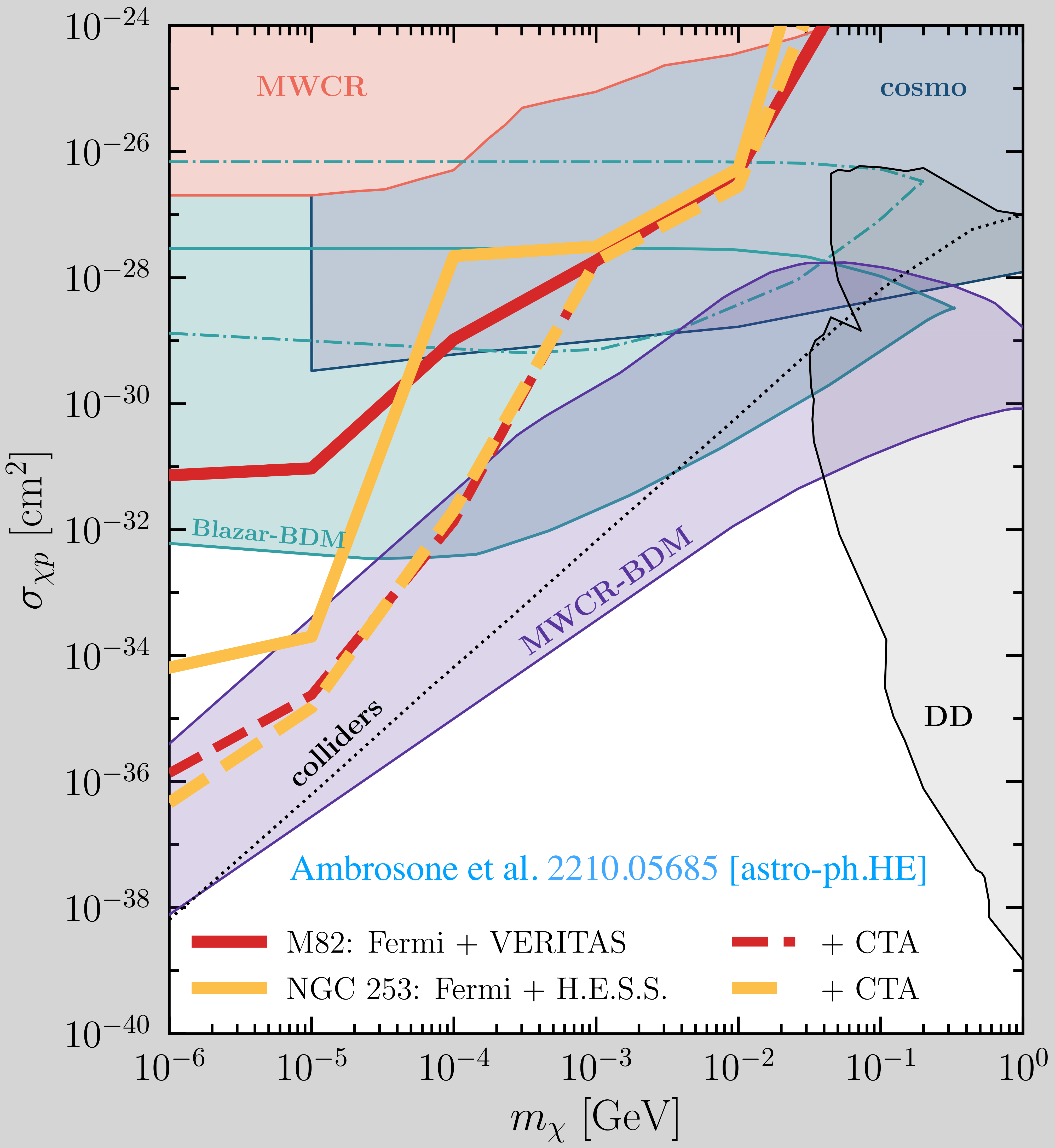
✦ (1) MiniBooNE and (2) XENON1T

✦ Requiring DM spikes (high density) around the black holes ➜ large uncertainties!

*Wang+ **PRL 128 (2022)***, Granelli+ *JCAP **07 (2022)***

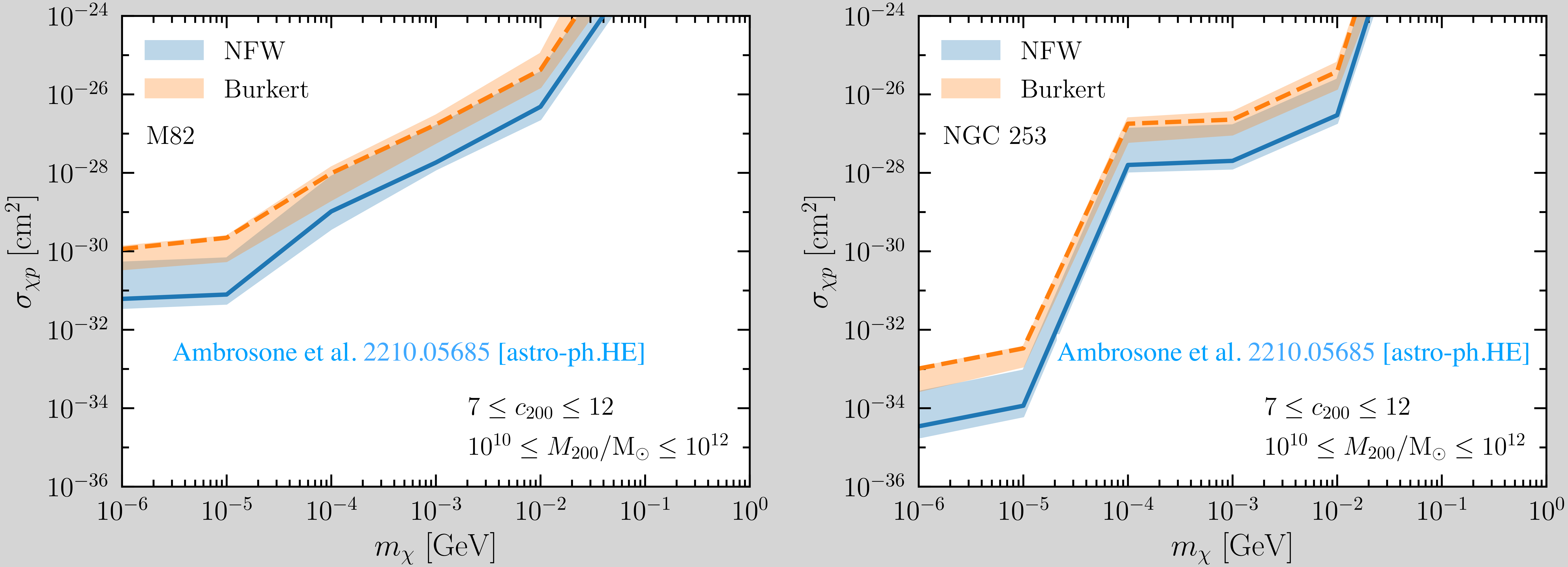
OUR CONSTRAINTS FROM SBG (5σ) $\Delta\chi^2 = 23.6$

✦ M82 and NGC253



DM Constraints Dependence on the Profile

The constraints are robust against the uncertainty on the DM profile!

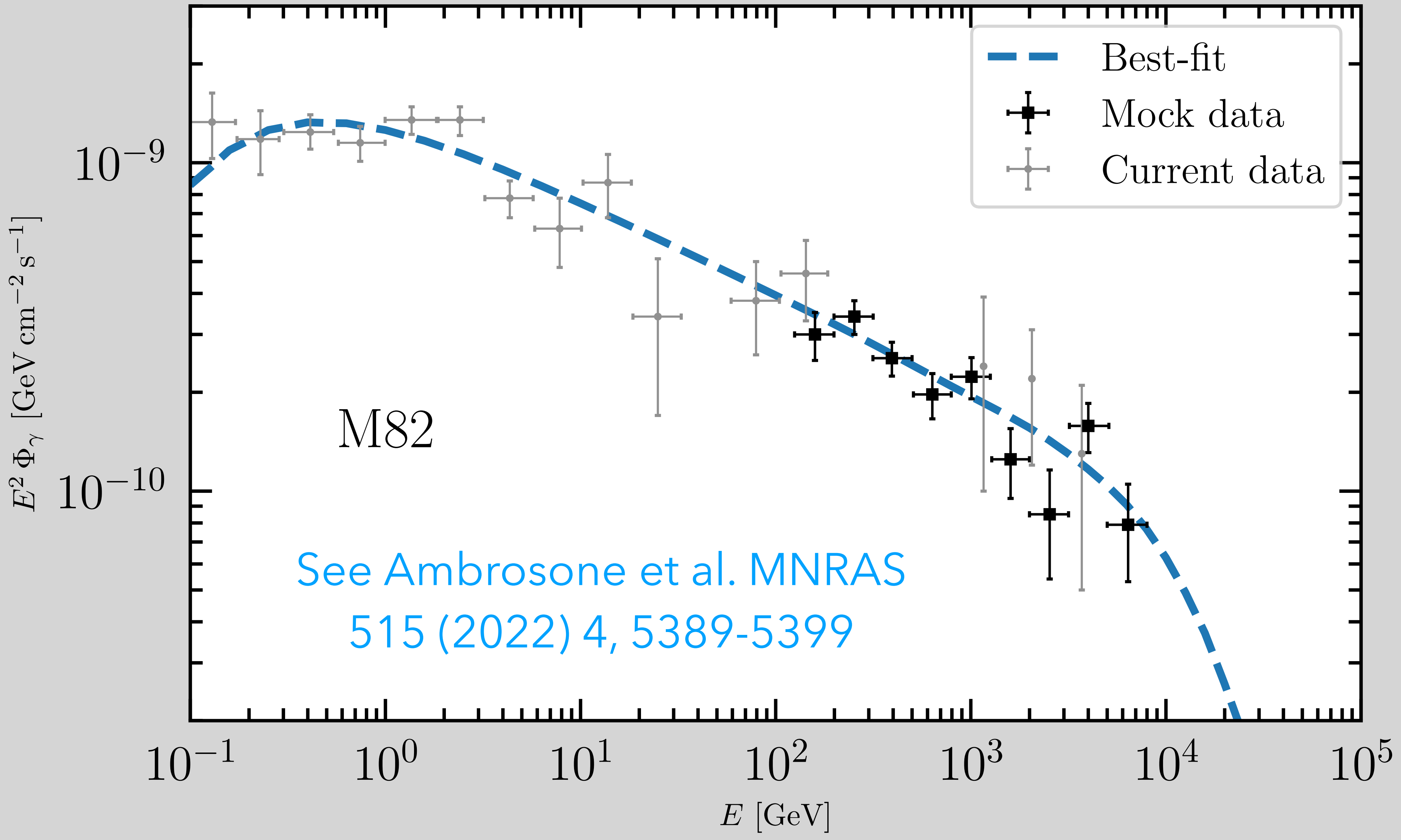


✦DM-p cross section can be probed to be $\lesssim 10^{-34}\,\mathrm{cm}^2$ for $m_\chi \lesssim 10^{-6}\,\mathrm{GeV}$

✦The uncertainty on the bounds is of the order of $\sim 1 - 2$ orders of magnitudes

The Importance of new Measurements

✦**The higher the energy of the data, the lower the DM masses can be probed**



✦ The CTA Telescope will probe SBG emission above $\gtrsim 100\,\mathrm{GeV}$ up to $\sim 10\,\mathrm{TeV}$

✦Public Information of the telescope can be used to simulate possible future measurements **(Mock data)**

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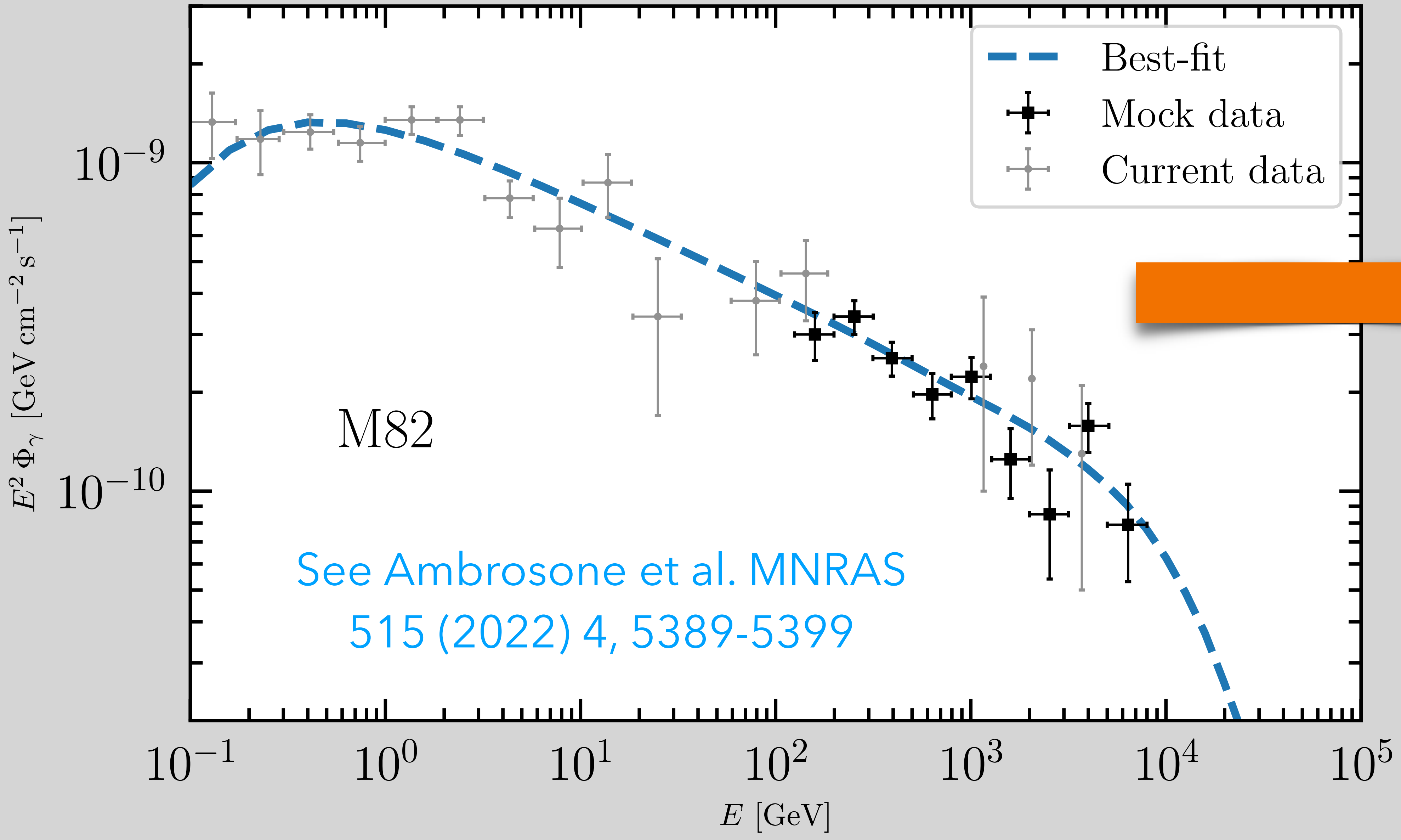

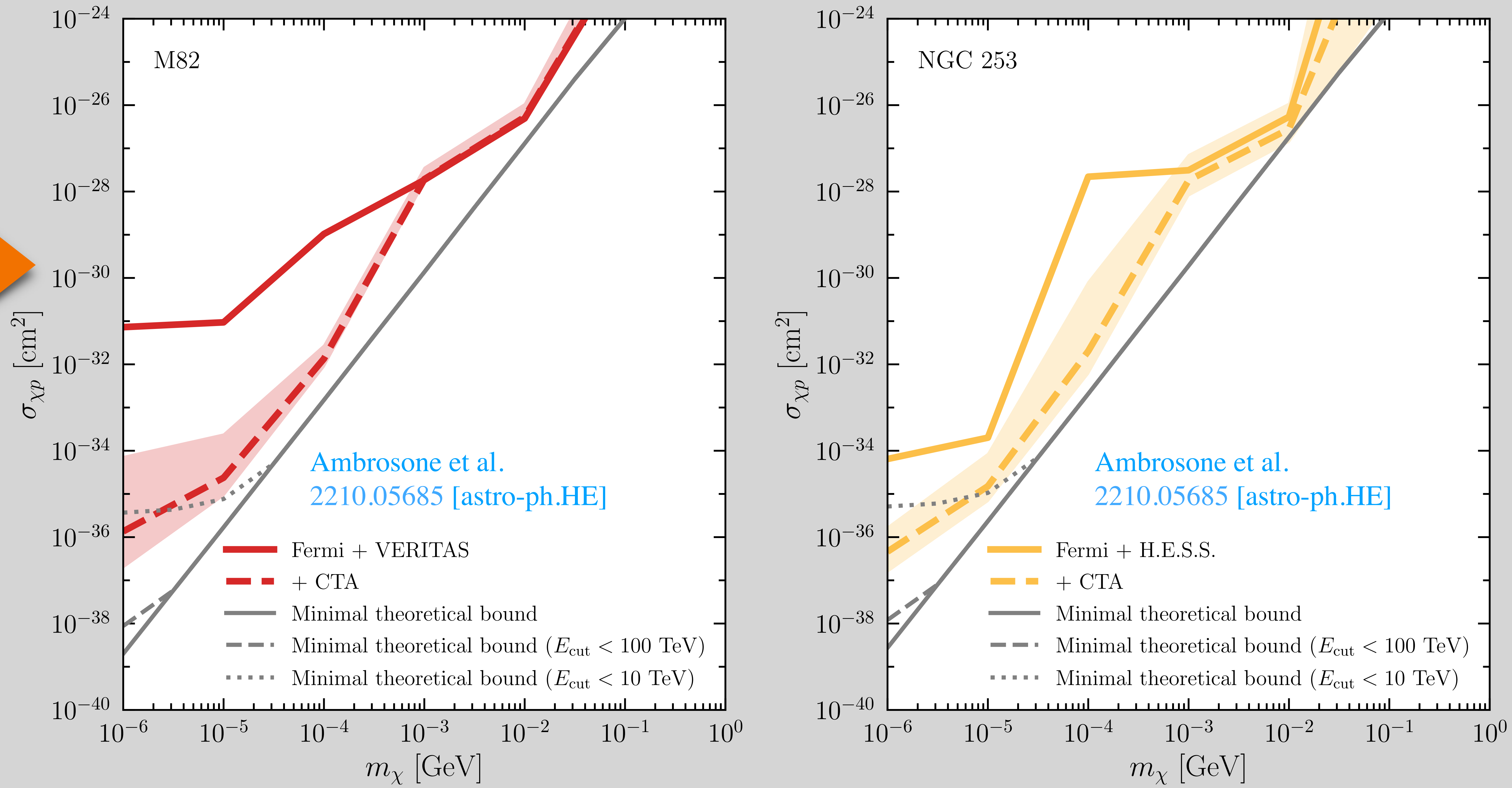

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✦ The same statistical Analysis with 50 mock datasets

✦ The resulting band represents the expected fluctuation of the possible new datasets

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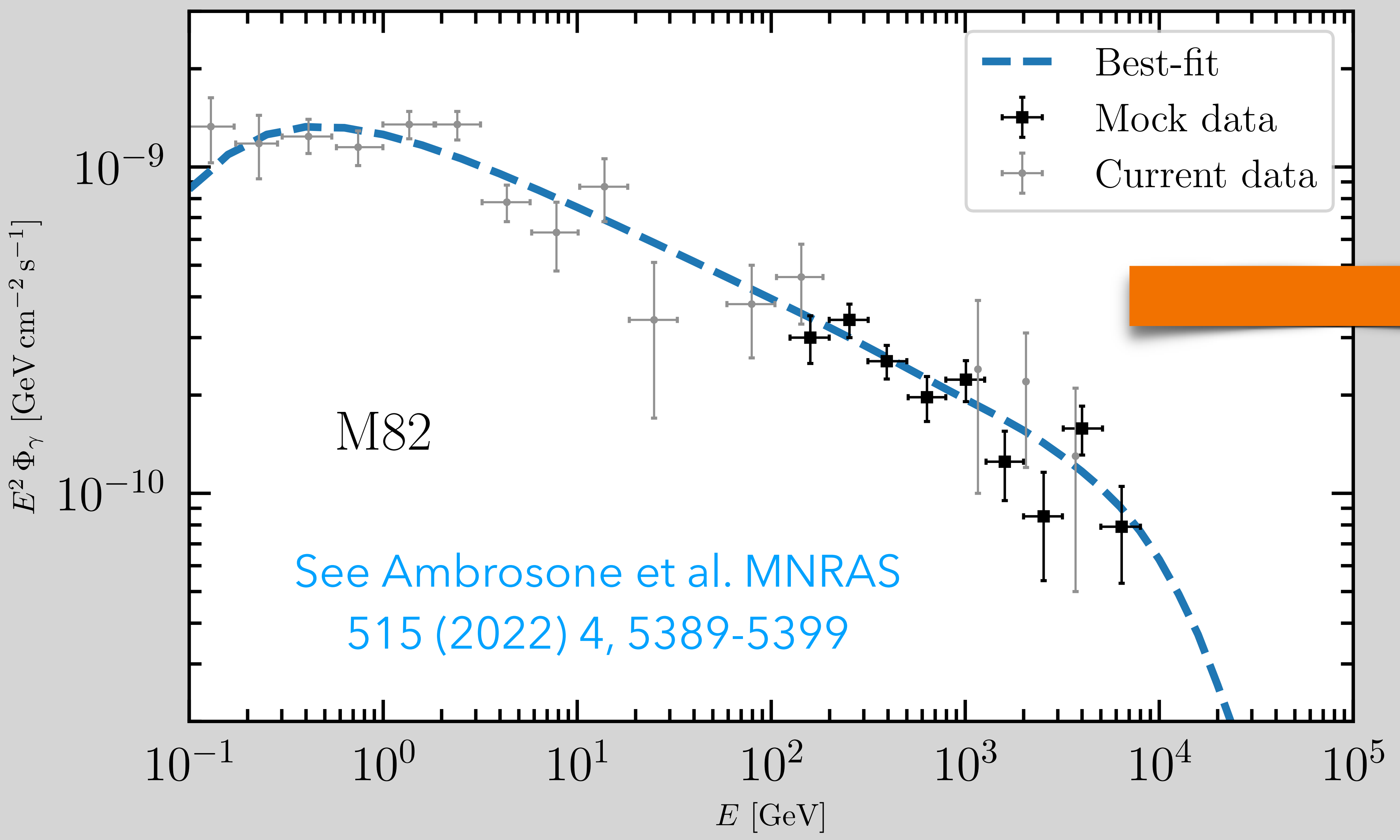

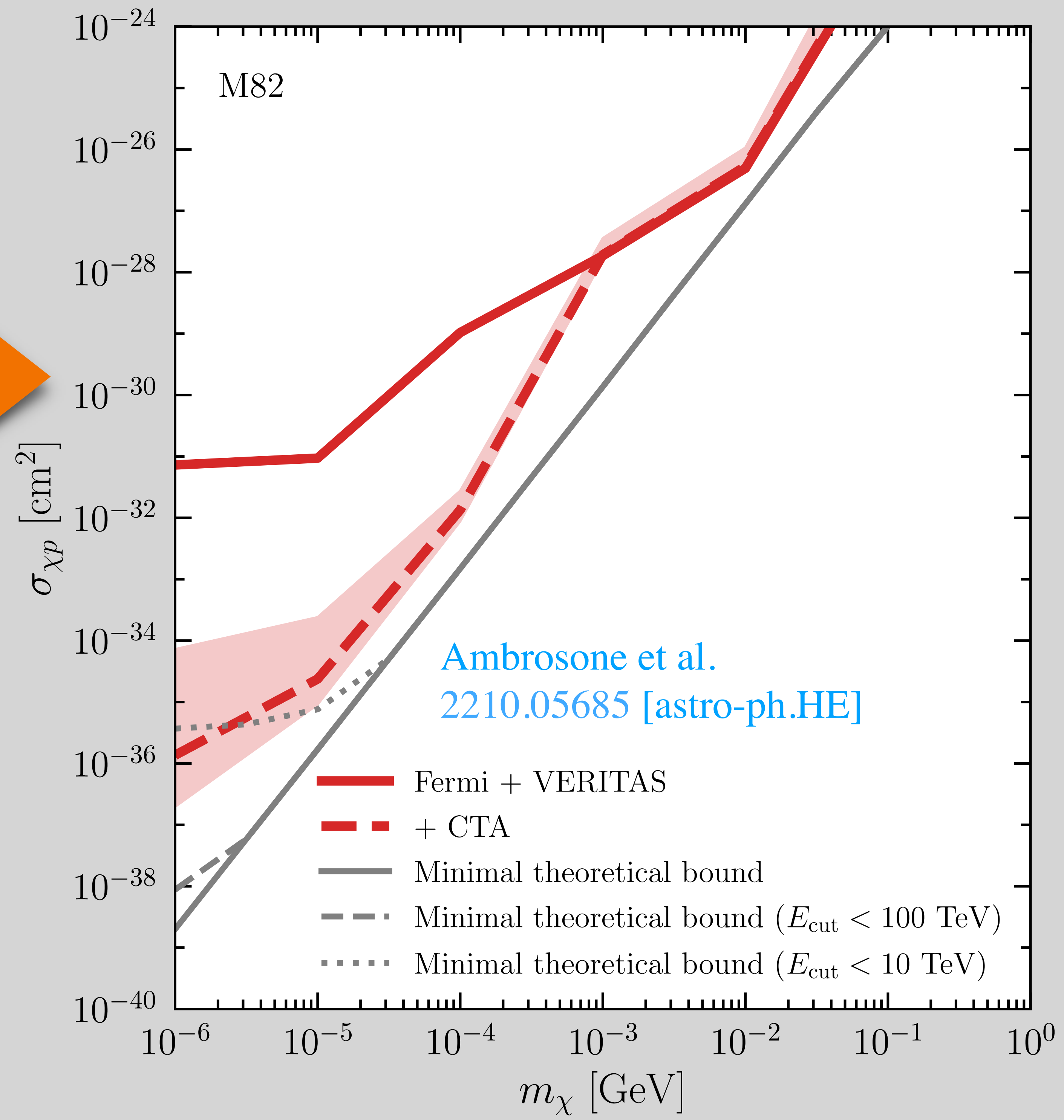

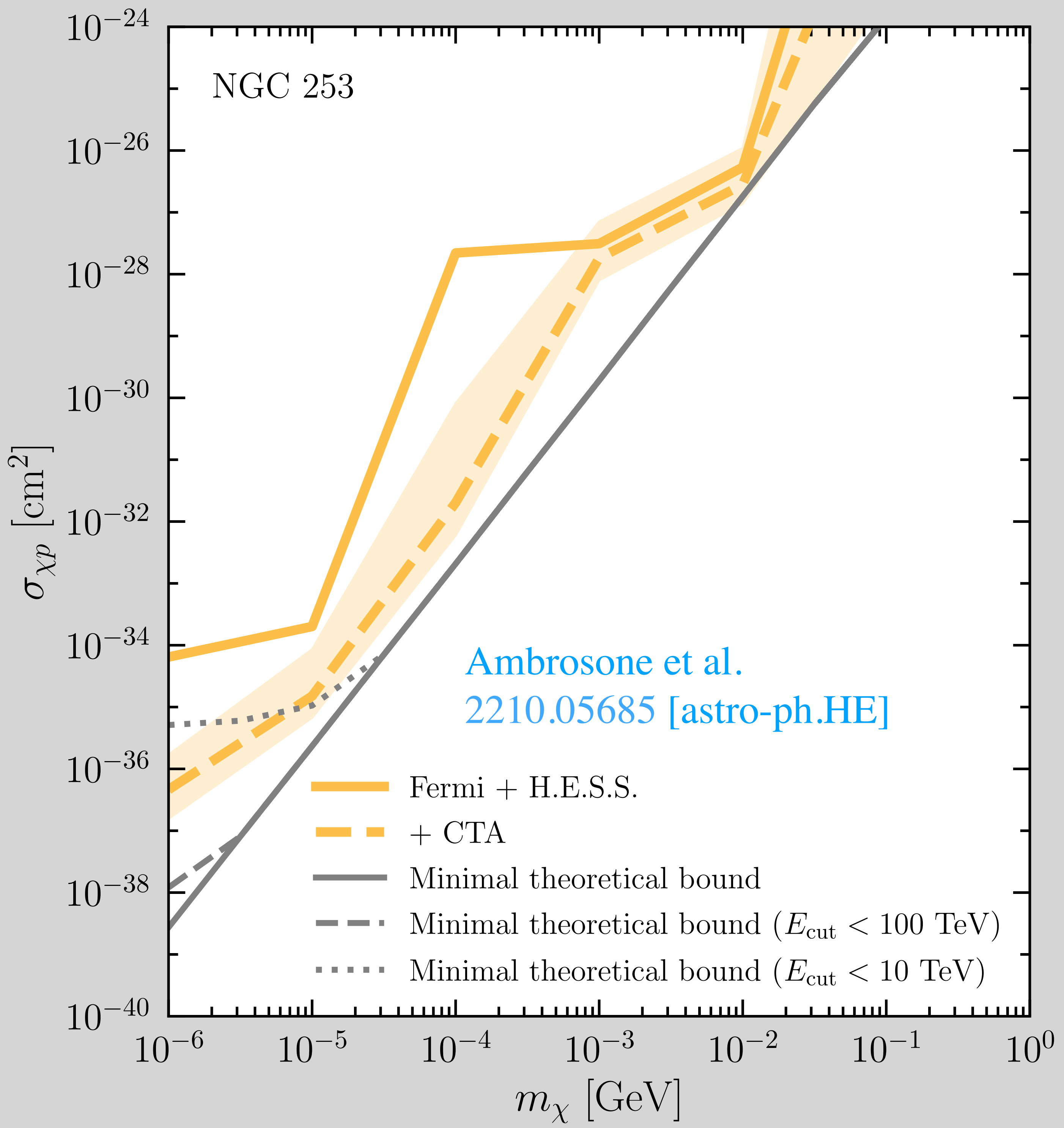

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✦Theoretical bounds mimic the maximal energy which experiments can probe

The theoretical bounds are obtained through:

$$\min_{E<E_{\rm cut}}\left[\tau_{\chi p}^{\rm el,eff}\left(\frac{1}{\tau_{\rm esc}}+\frac{1}{\tau_{\rm loss}^{\rm eff}}\right)\right]=1$$

Conclusions and Outlooks

- The neutrino and γ-ray emission from **starburst galaxies** can be used to probe new physics!
- Strong and robust **constraints on sub-GeV Dark Matter** from M82 and NGC253!
- Current γ-ray data put strong constraints on DM-P cross section up to $\sigma_{\chi p} \simeq 10^{-34}\,\mathrm{cm}^2$
- Upcoming gamma-ray telescopes will give us a better understanding of the cosmic-ray transport inside SBGs, leading also to stronger constraints on the new physics
- Eventual Neutrino Measurements from these sources would lead to constraints to lower DM masses