# Probing Dark Matter-Proton Interactions with Cosmic Reservoirs


## Marco Chianese


19 January 2024, TAsP meeting, Torino

Based on Ambrosone, MC, Fiorillo, Marinelli, Miele, **PRL 131 (2023) 11 [2210.05685]**


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NAP Theory

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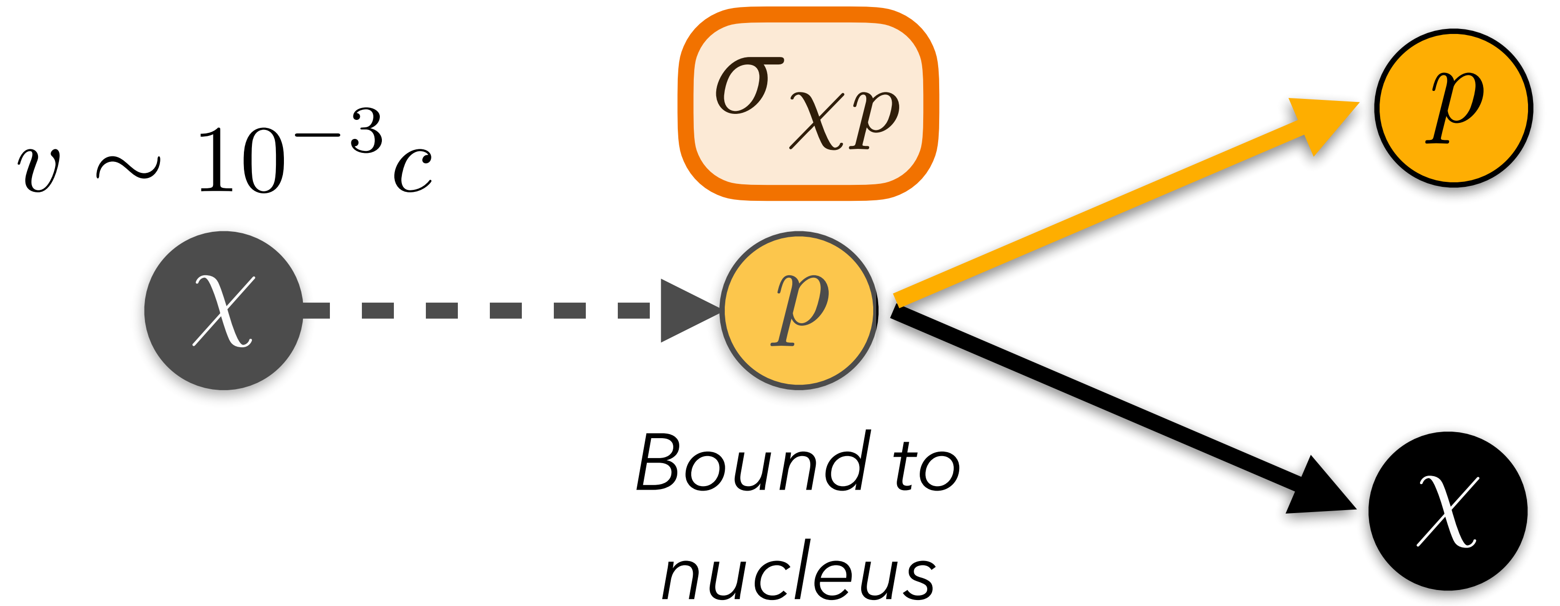
# Motivation

Current direct detection searches are unable to probe light dark matter particles.

**Poor sensitivity to low nuclear recoil energies**

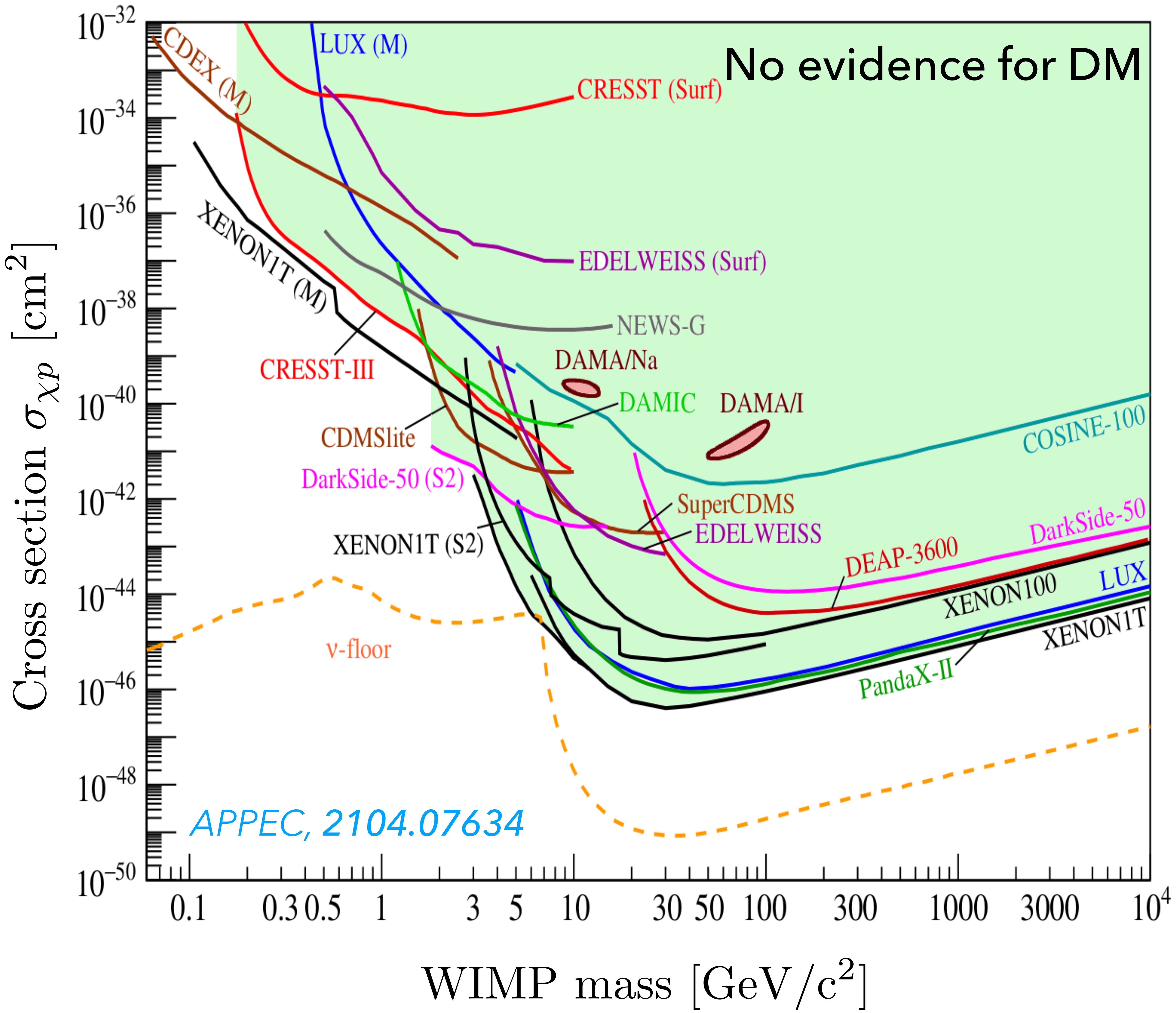



$$\frac{E_r}{50\ \text{keV}} \simeq \left(\frac{m_\chi}{100\ \text{GeV}}\right)^2 \left(\frac{v}{10^{-3}c}\right)^2 \left(\frac{100\ \text{GeV}}{m_N}\right)$$

Undetectable energies for $m_\chi \leq 1\ \text{GeV}$

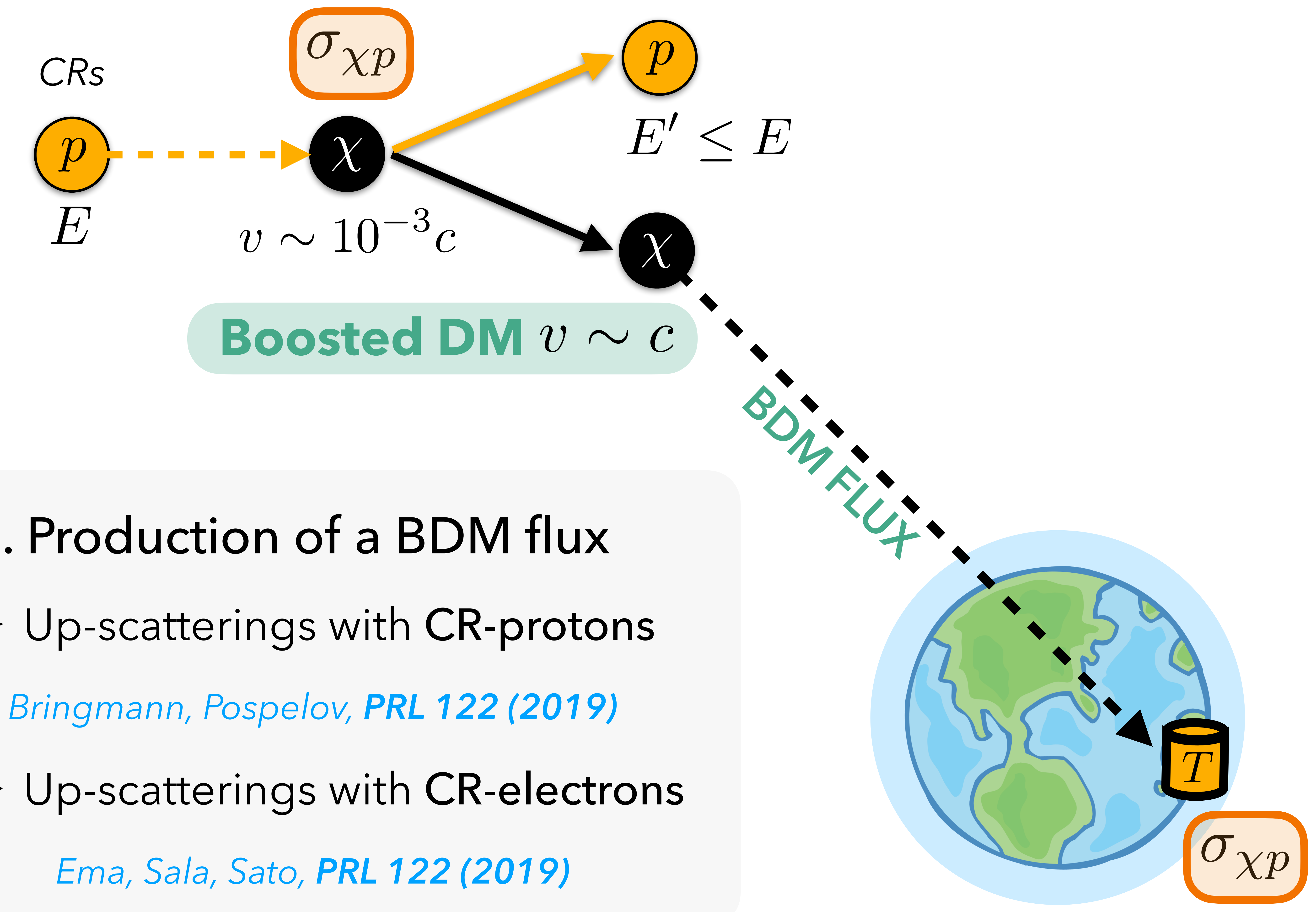
*Recent improvements: talk by Angelo Esposito*

**New idea: the same interaction might occur with cosmic-rays during their propagation!**



# DM interactions with cosmic-rays

They have two main effects:




1. Production of a BDM flux

✦ Up-scatterings with **CR-protons**

*Bringmann, Pospelov, **PRL 122 (2019)***

✦ Up-scatterings with **CR-electrons**

*Ema, Sala, Sato, **PRL 122 (2019)***

***See also Filippo's talk!***

***See also***

*Agashe+, **JCAP 10 (2014)***
*Giudice+, **PLB 780 (2018)***
*SK coll., **PRL 120 (2018)***
*Bringmann+, **PRL 122 (2019)***
*Ema+, **PRL 122 (2019)***
*Cappiello+, **PRD 100 (2019)***
*Alvey+, **PRL 123 (2019)***
*Guo+, **PRD 102 (2020)***
*Bondarenko+, **JHEP 03 (2020)***
*Ema+, **SciPost Phys. 10 (2021)***
*Berger+, **PRD 103 (2021)***
*Bell+, **PRD 104 (2021)***
*PROSPECT coll., **PRD 104 (2021)***
*Wang+, **PRL 128 (2022)***
*Granelli+, **JCAP 07 (2022)***
*PandaX-II coll., **PRL 128 (2022)***
*CDEX coll., **PRD 106 (2022)***
*Alvey+, **JHEP 01 (2023)***

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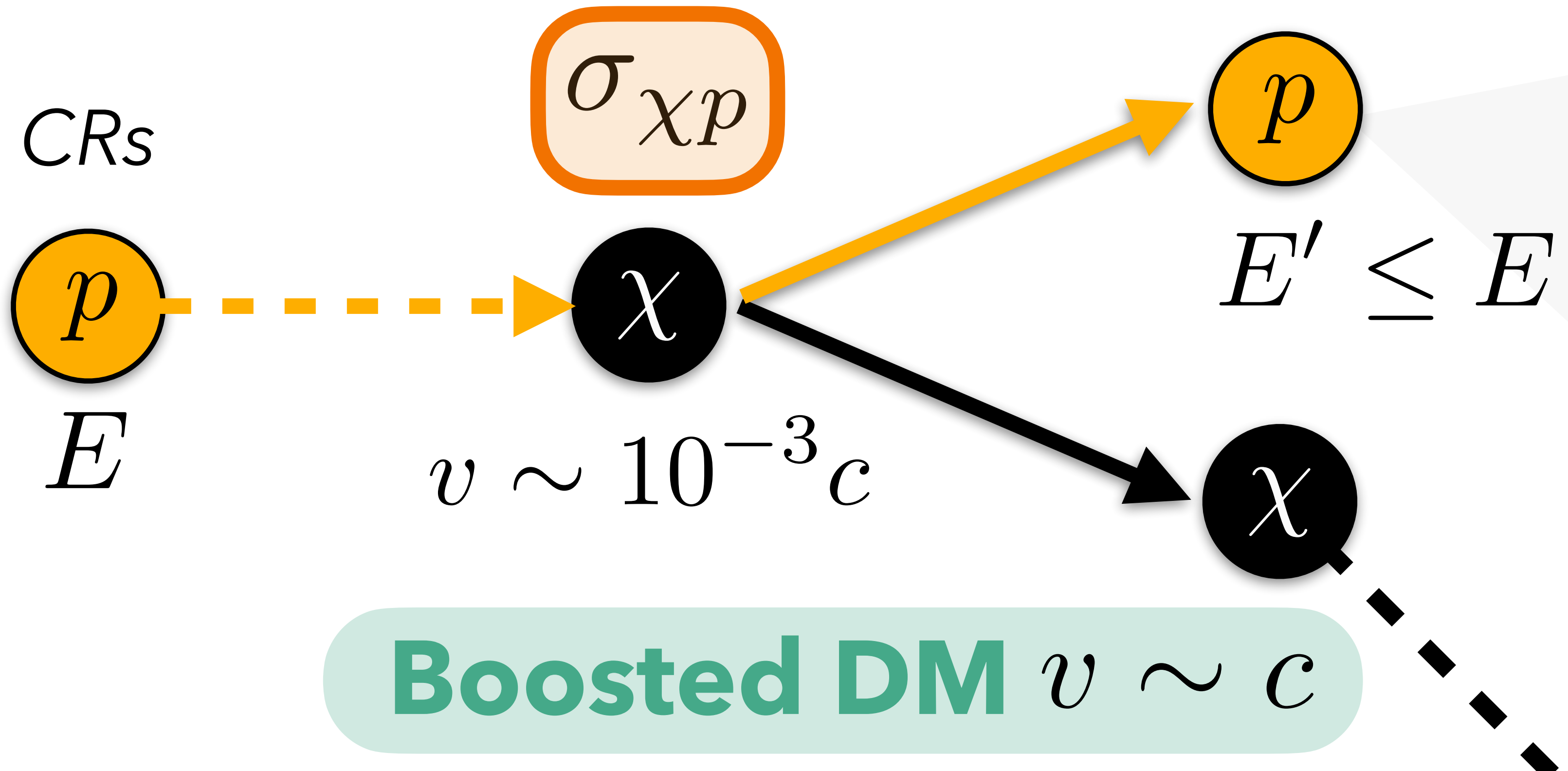



## 2. Reverse direct detection (i.e. modification of the CR spectrum)

✦ Milky Way

Cappiello+, **PRD 99 (2019)**

✦ **Starburst galaxies (in this talk!)**

## 1. Production of a BDM flux

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# Starburst galaxies (SBGs)


**The Starburst Galaxy M82**

**Properties of SBGs**

- Galaxies with high star-formation rate (~100 $M_\odot$/yr, to compare with ~3 $M_\odot$/yr in the Milky Way)
- Dense interstellar gas ($n_{ISM}$ > 100 $cm^{-3}$)
- **Cosmic reservoirs:** protons confined for about ~$10^5$ yr
- **Hadronic production:**

*Interstellar gas as the target*

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

*Injected CRs with power-law spectrum*

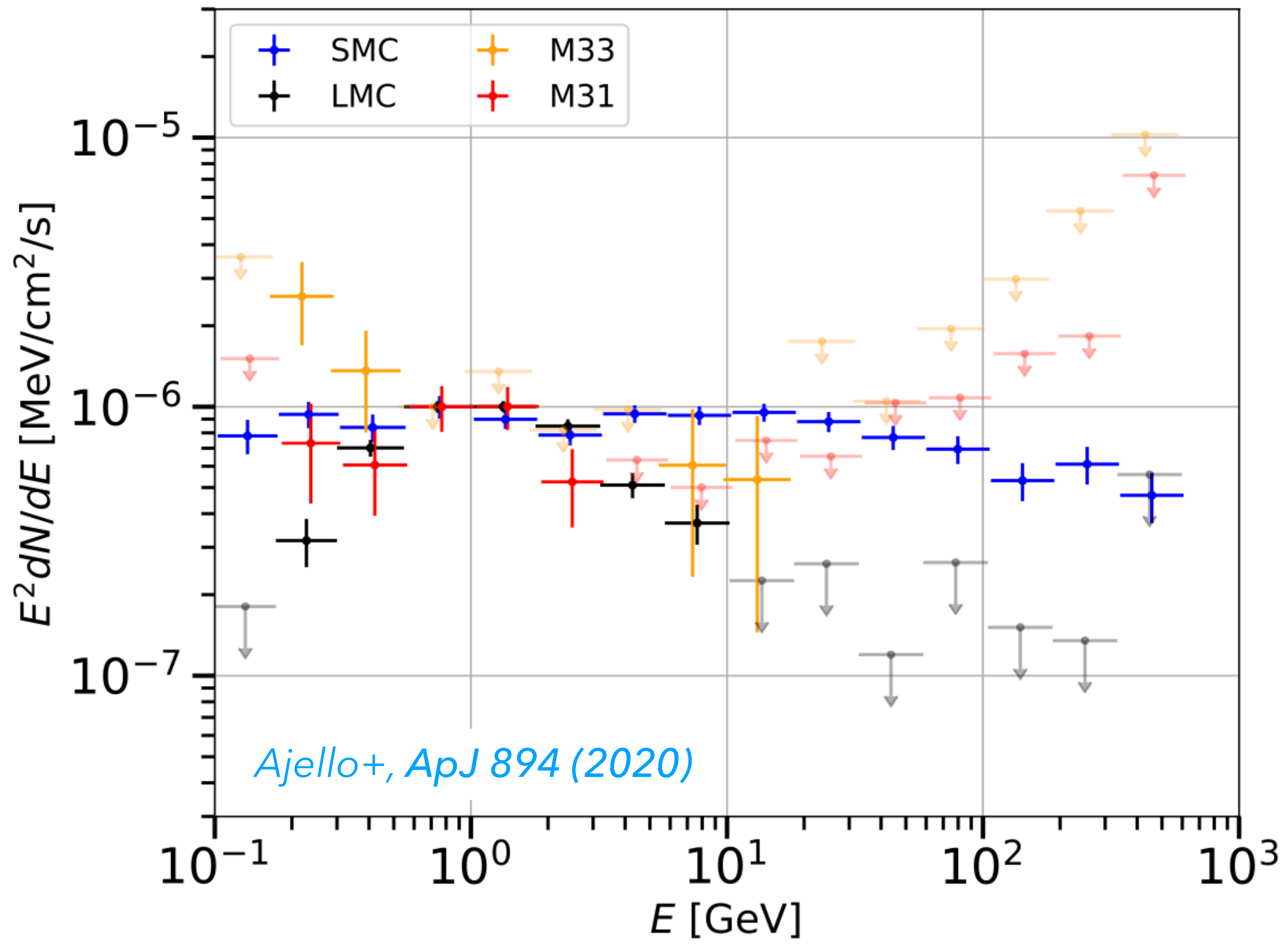
- Sources of high-energy **neutrinos** and **gamma-rays**:

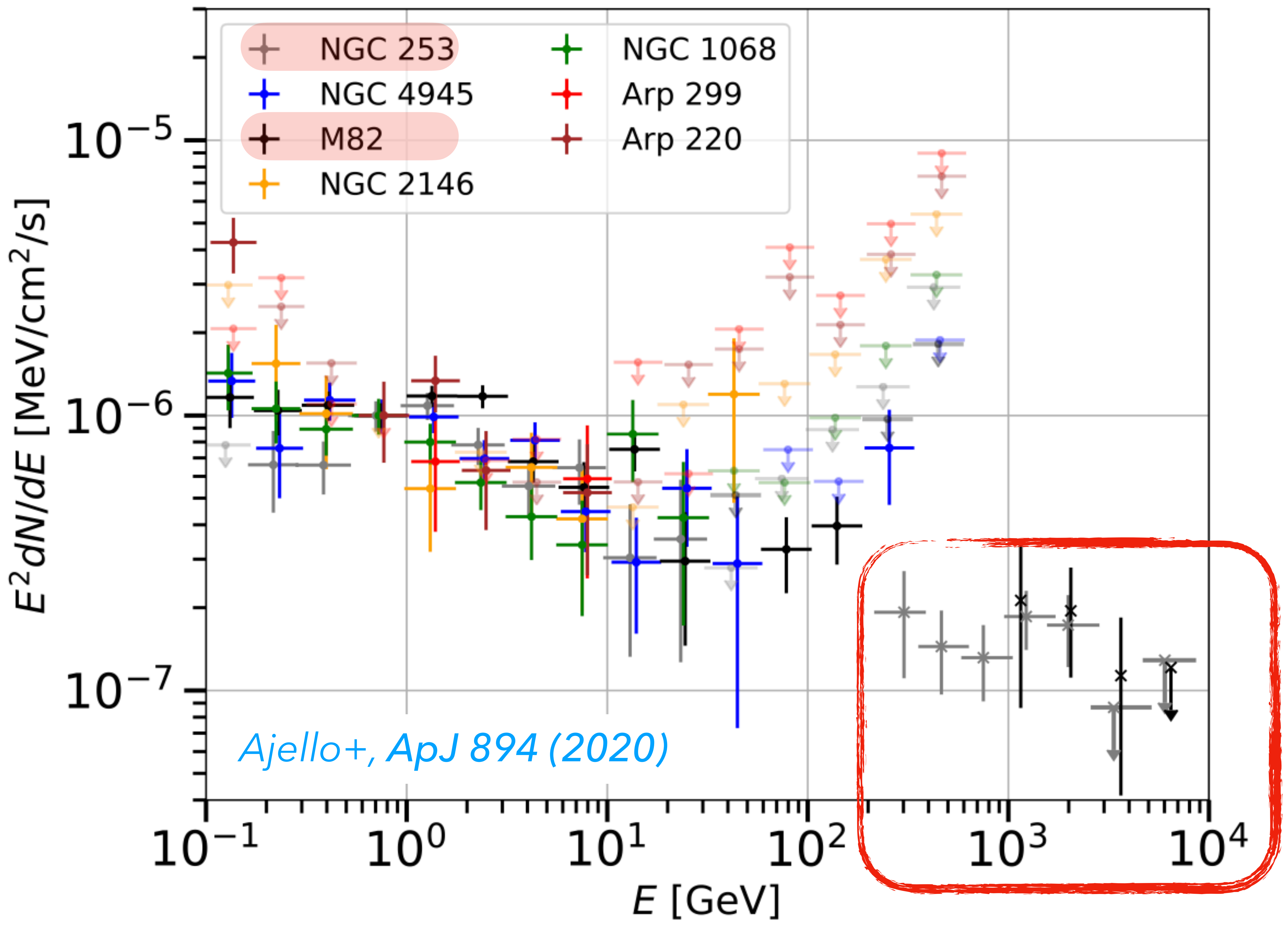
$$\pi^\pm \rightarrow e^\pm \nu_e \nu_\mu \overline{\nu}_\mu \qquad \pi^0 \rightarrow \gamma\gamma$$

*Ambrosone+, MNRAS 503 (2021), ApJL 919 (2021), MNRAS 515 (2022)*

# Current gamma-ray observations

Fermi-LAT and **IACTs** have detected $\gamma$-rays in the GeV-TeV energy range from a few nearby SBGs




**We focus on M82 and NGC253 galaxies which have more high-energy data!**

# CR protons propagation

The proton distribution is dictated by the diffusion-loss differential equation:

$$\frac{\mathrm{d}f_{\mathrm{CR}}(E)}{\mathrm{d}t} - \nabla\left[D(E)\,\nabla f_{\mathrm{CR}}(E) + \boldsymbol{v}_{\mathrm{adv}}\, f_{\mathrm{CR}}(E)\right] + \frac{\mathrm{d}}{\mathrm{d}E}\left[\frac{\mathrm{d}E}{\mathrm{d}t} f_{\mathrm{CR}}(E)\right] = Q_{\mathrm{CR}}(E)$$

Diffusion | Advection | *Energy losses* | Source term

$$Q_{\mathrm{CR}}(p) \propto p^{-\Gamma} e^{-p/10\mathrm{PeV}}$$

power-law from SNs

*Good approximation inside the SBG core*

*Stationary limit + Leaky-Box-Model*

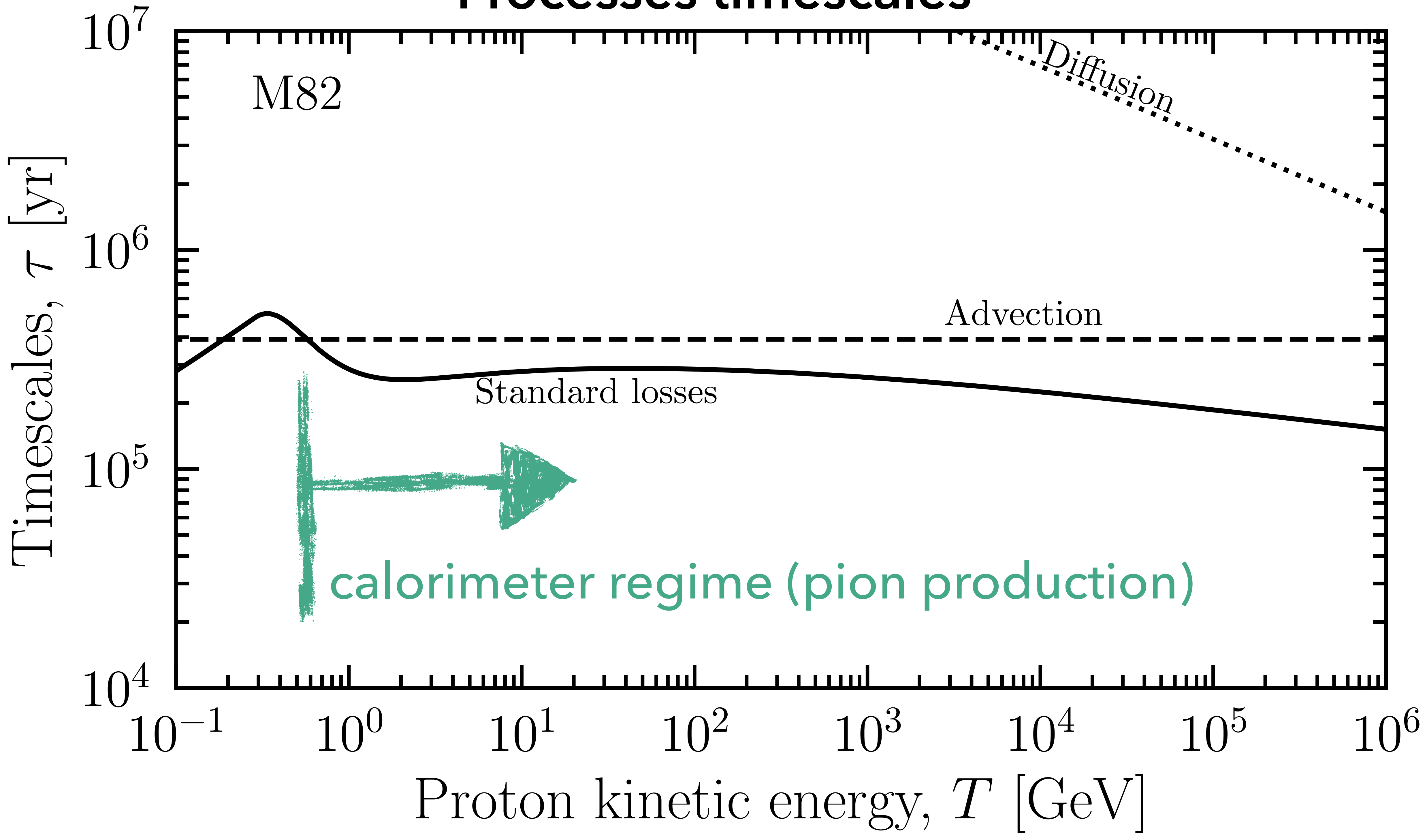
**Escape Time**

$$f_{\mathrm{CR}}(E) = \left[\frac{1}{\tau_{\mathrm{esc}}} + \frac{1}{\tau_{\mathrm{loss}}}\right]^{-1} Q_{\mathrm{CR}}(E) \quad \textit{with} \quad \tau_{\mathrm{esc}} = \left[\frac{1}{\tau_{\mathrm{diff}}} + \frac{1}{\tau_{\mathrm{adv}}}\right]^{-1}$$

Standard losses: ionization, Coulomb interactions, and proton-proton collisions

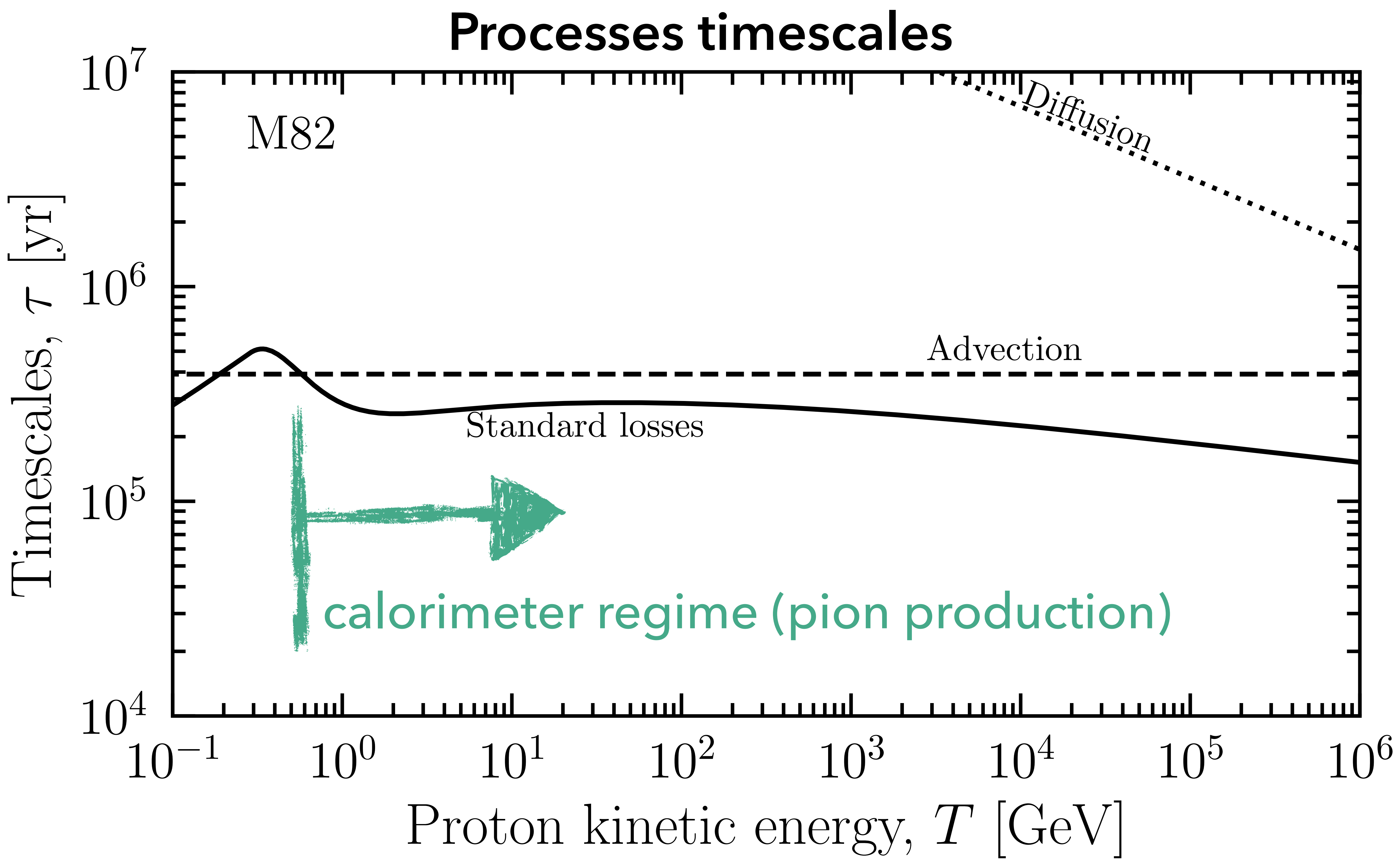
# M82 emission

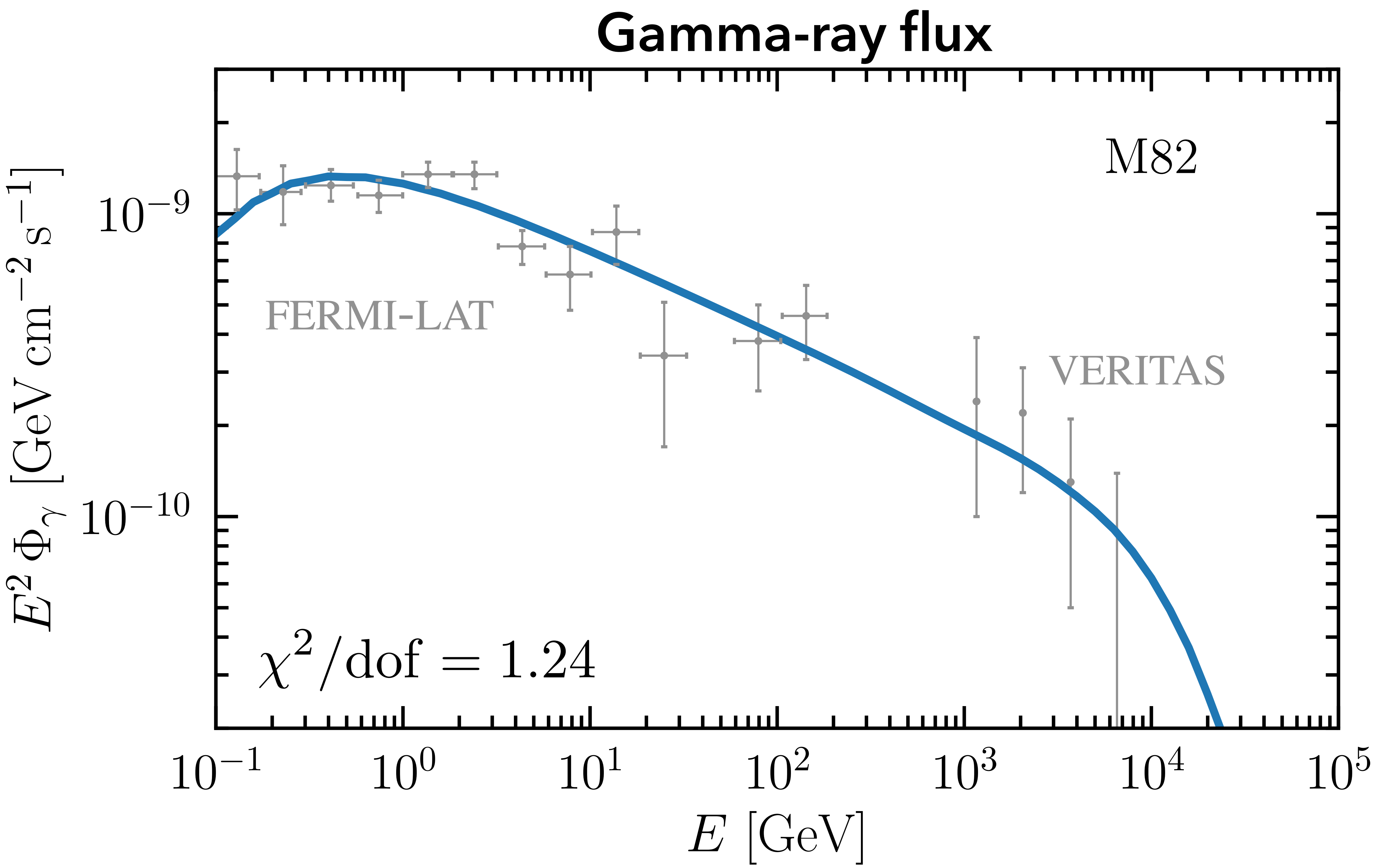
**Processes timescales**




Dominant process ⟷ Smallest timescale

# M82 emission




Dominant process ⟷ Smallest timescale

**Two-parameter best-fit SED**

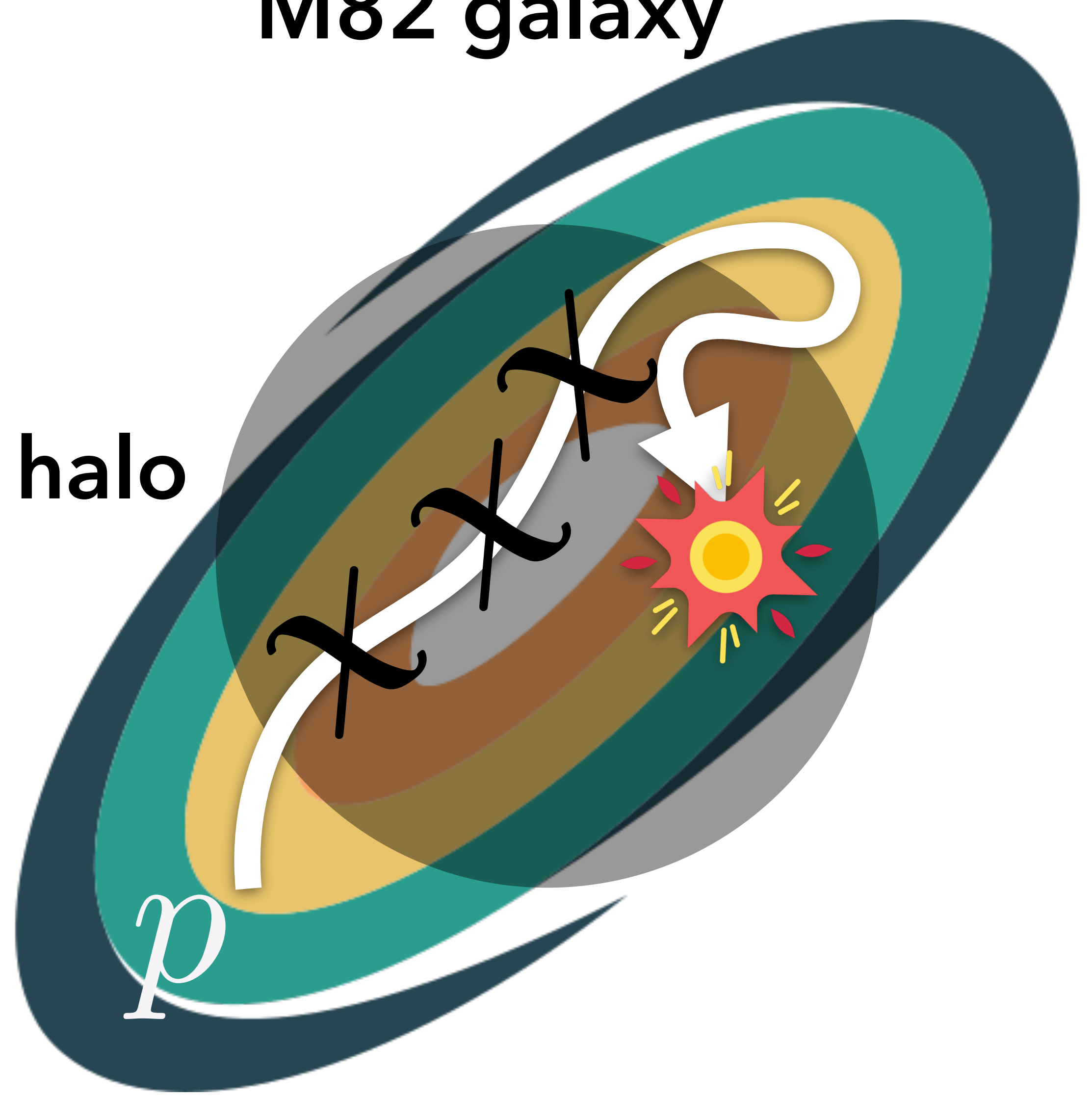
✦ Spectral index $\Gamma = 2.30$

✦ Star-formation rate $\dot{M}_* = 4.5\,M_\odot\,\mathrm{yr}^{-1}$

**The SBG model fits very well current gamma-ray data!**

# SBGs as DM laboratories

We cannot directly probe the CR spectrum inside the SBGs…but we observe $\gamma$-rays!




$\phi_\gamma$

**Modification of CR transport**

$$f_{\rm CR}(p) = \left[\frac{1}{\tau_{\rm esc}} + \frac{1}{\tau_{\rm loss}} + \frac{1}{\tau^{\rm el}_{\chi p}} + \frac{1}{\tau^{\rm inel}_{\chi p}}\right]^{-1} Q_{\rm CR}(p)$$

*Additional energy-loss timescales*

*DM density inside the SBG*

**Elastic timescale:**

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

Elastic cross-section
*from Ema+, **SciPost Phys. 10 (2021)***

**Inelastic timescale:**

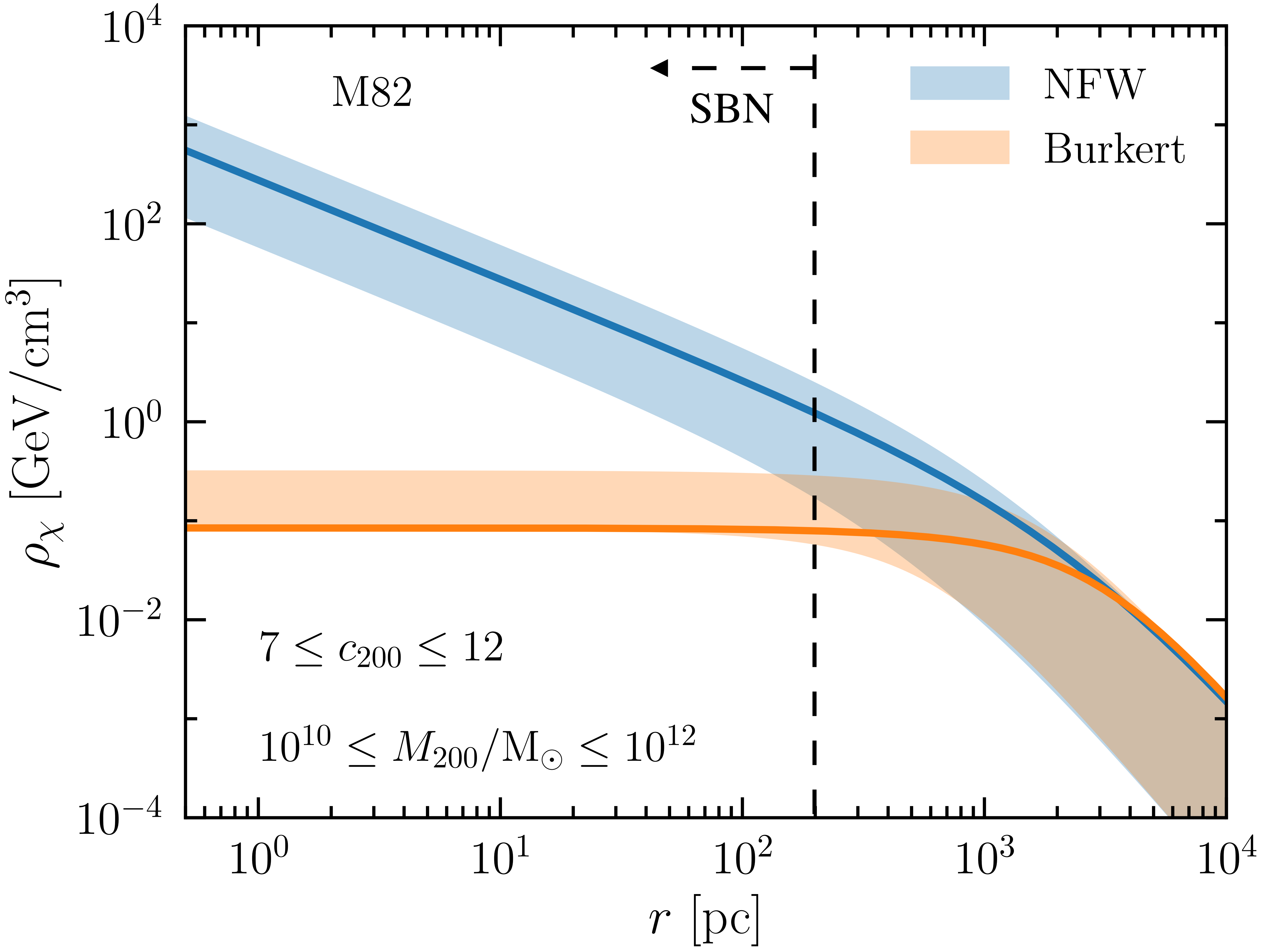
$$\tau^{\rm inel}_{\chi p} = \left(\kappa\, \sigma_{\rm inel} \frac{\rho_\chi}{m_\chi}\right)^{-1}$$

*Production of $\gamma$-rays* →

$$p + \chi \to \pi^\pm \pi^0 \ldots \to \gamma\, \nu \ldots$$

Rescaling $\nu$N cross-section

# DM halo density profile




- Large uncertainty on the DM density inside the SBG core

- Parameters from cosmological simulations

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

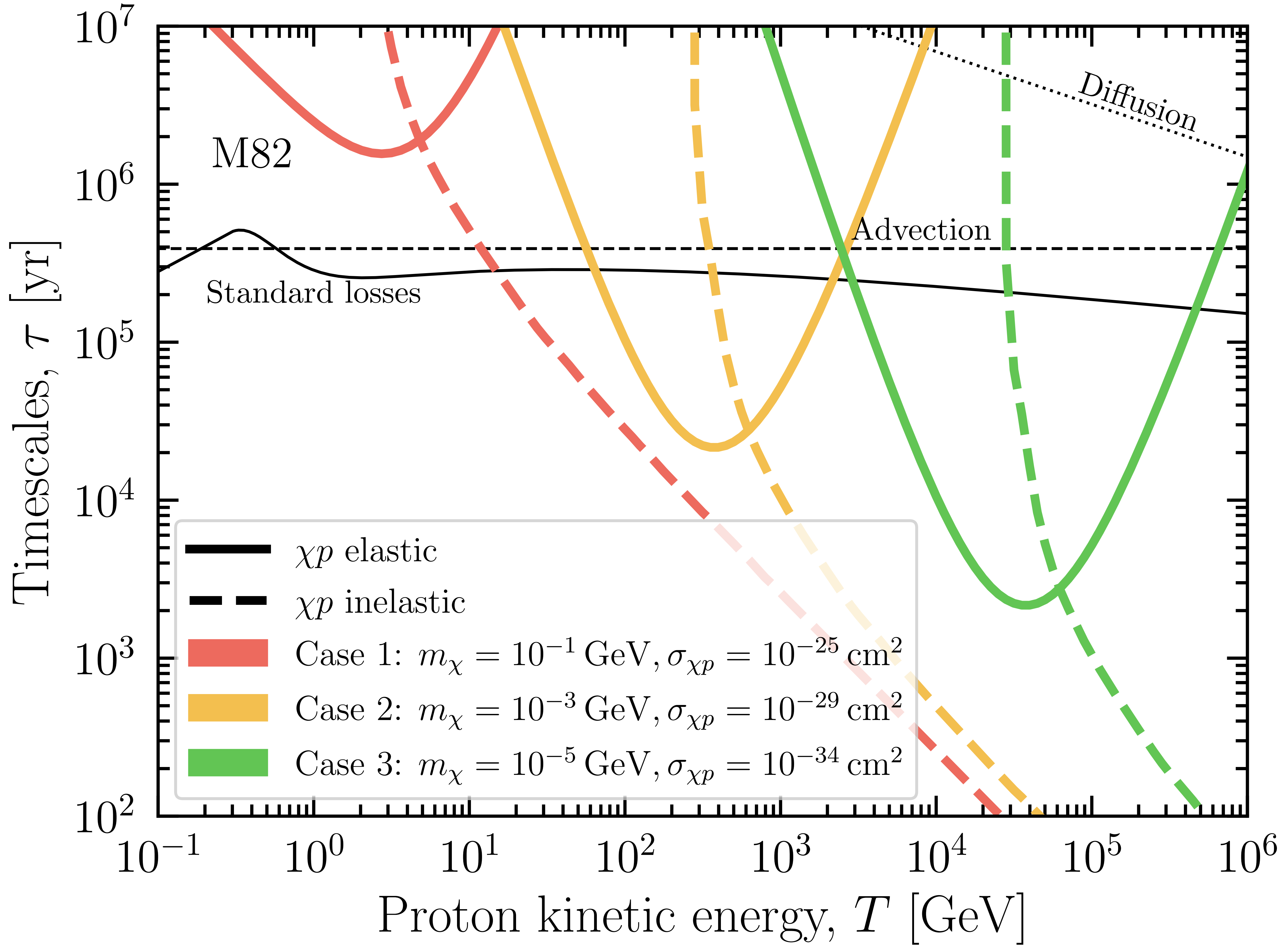
*concentration* — *total mass*

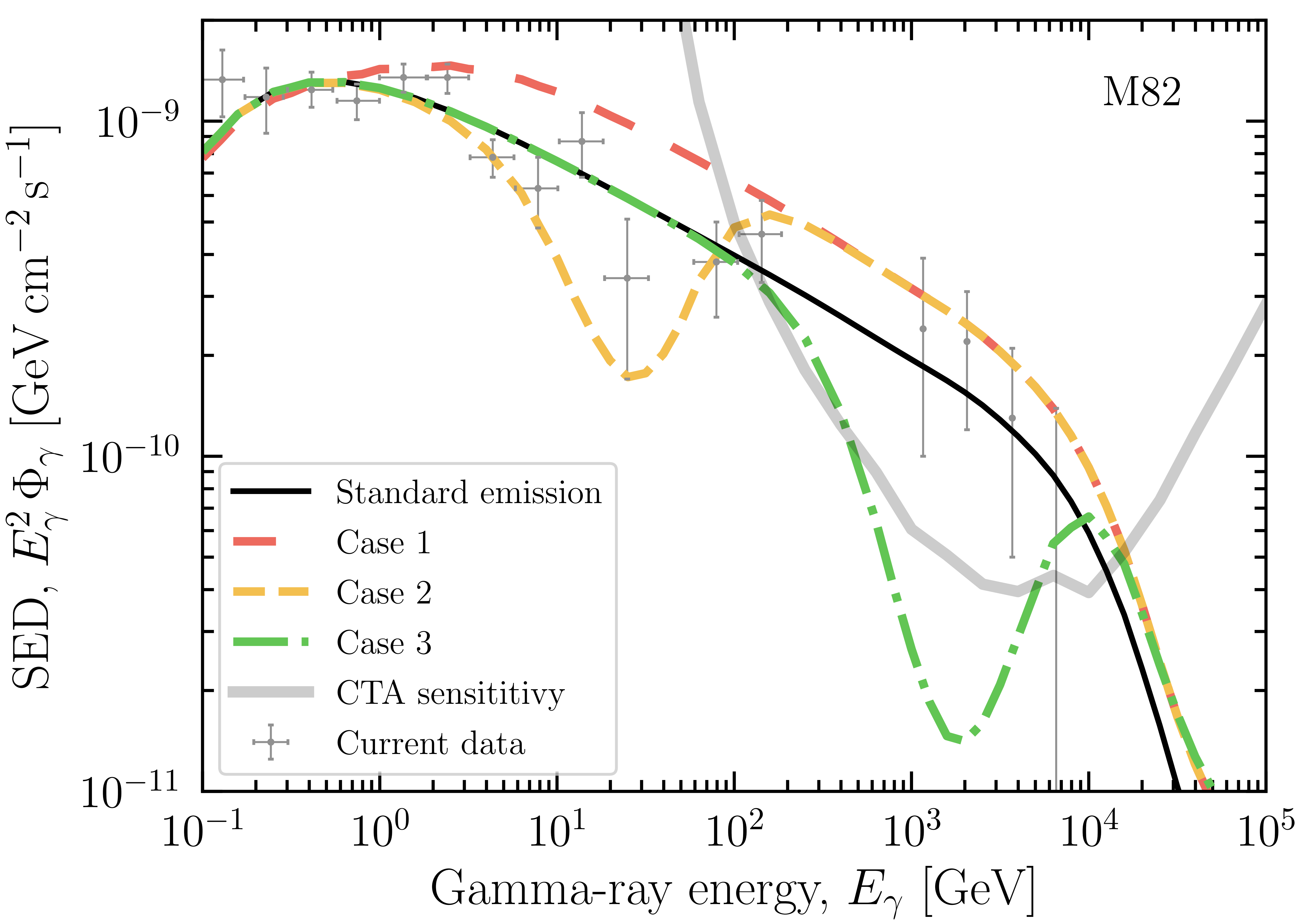
- However, marginal effects on the $\gamma$-ray emission

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

*Average inside the SBN*

# Effects of CR-DM scatterings



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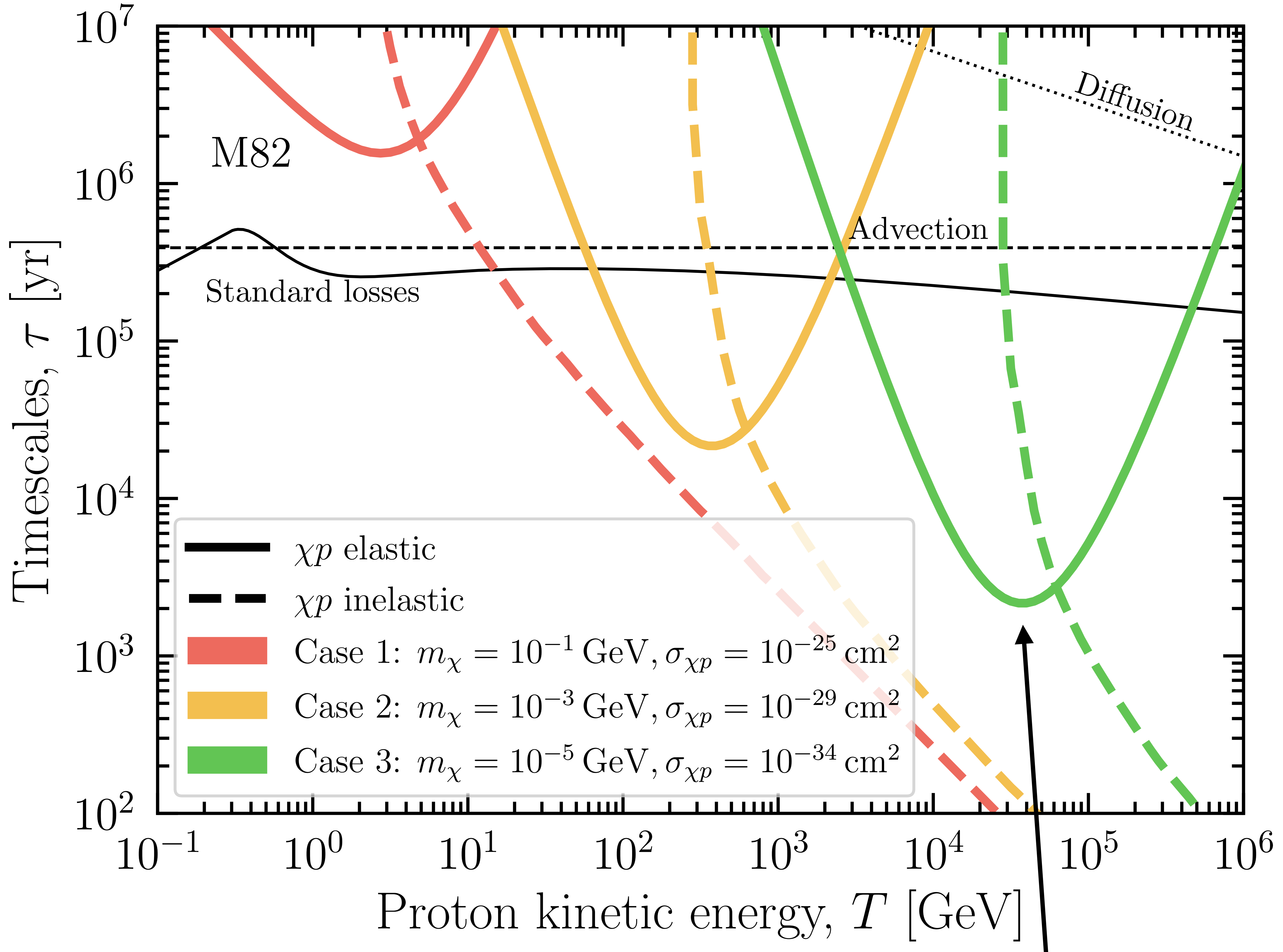
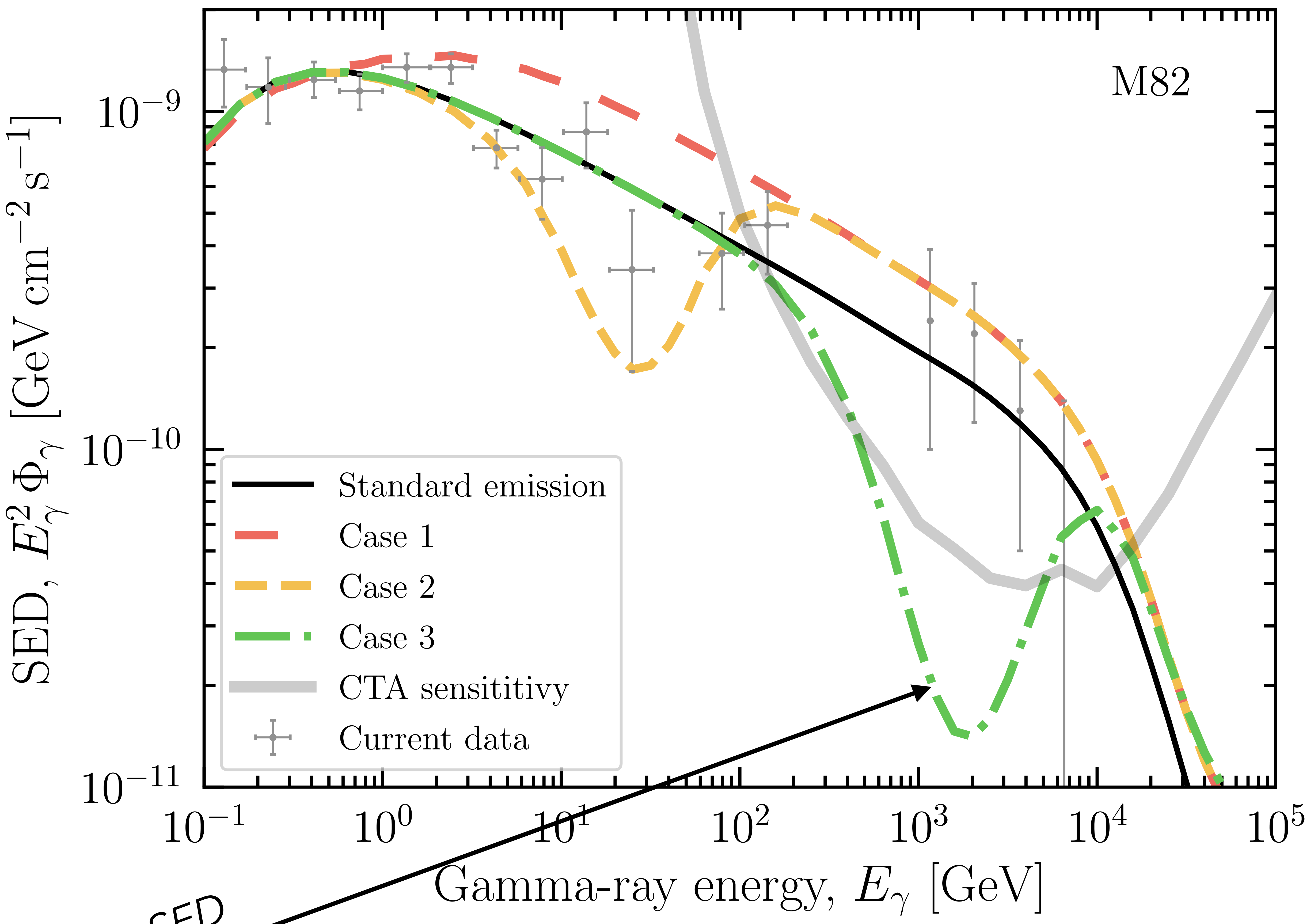


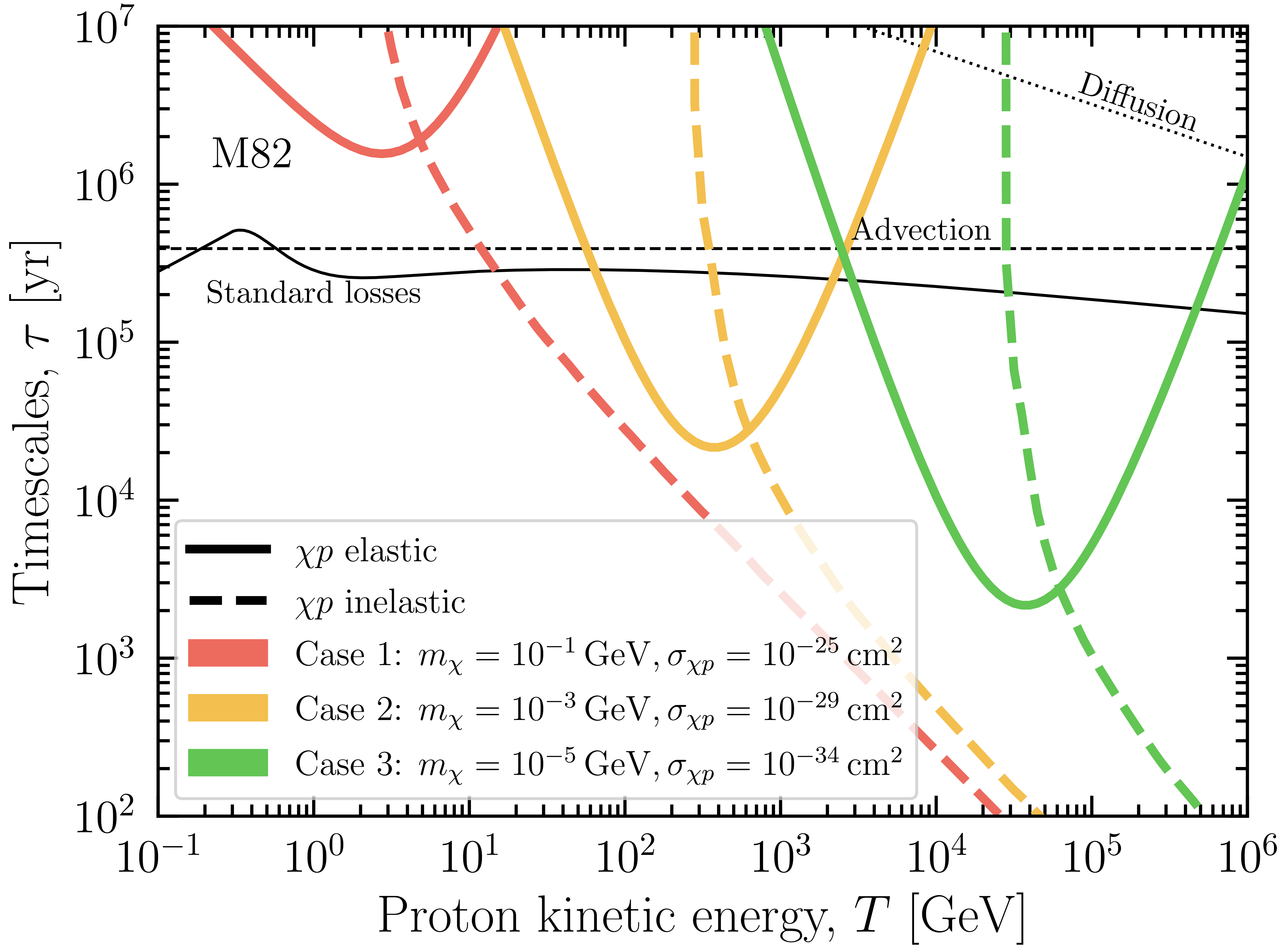



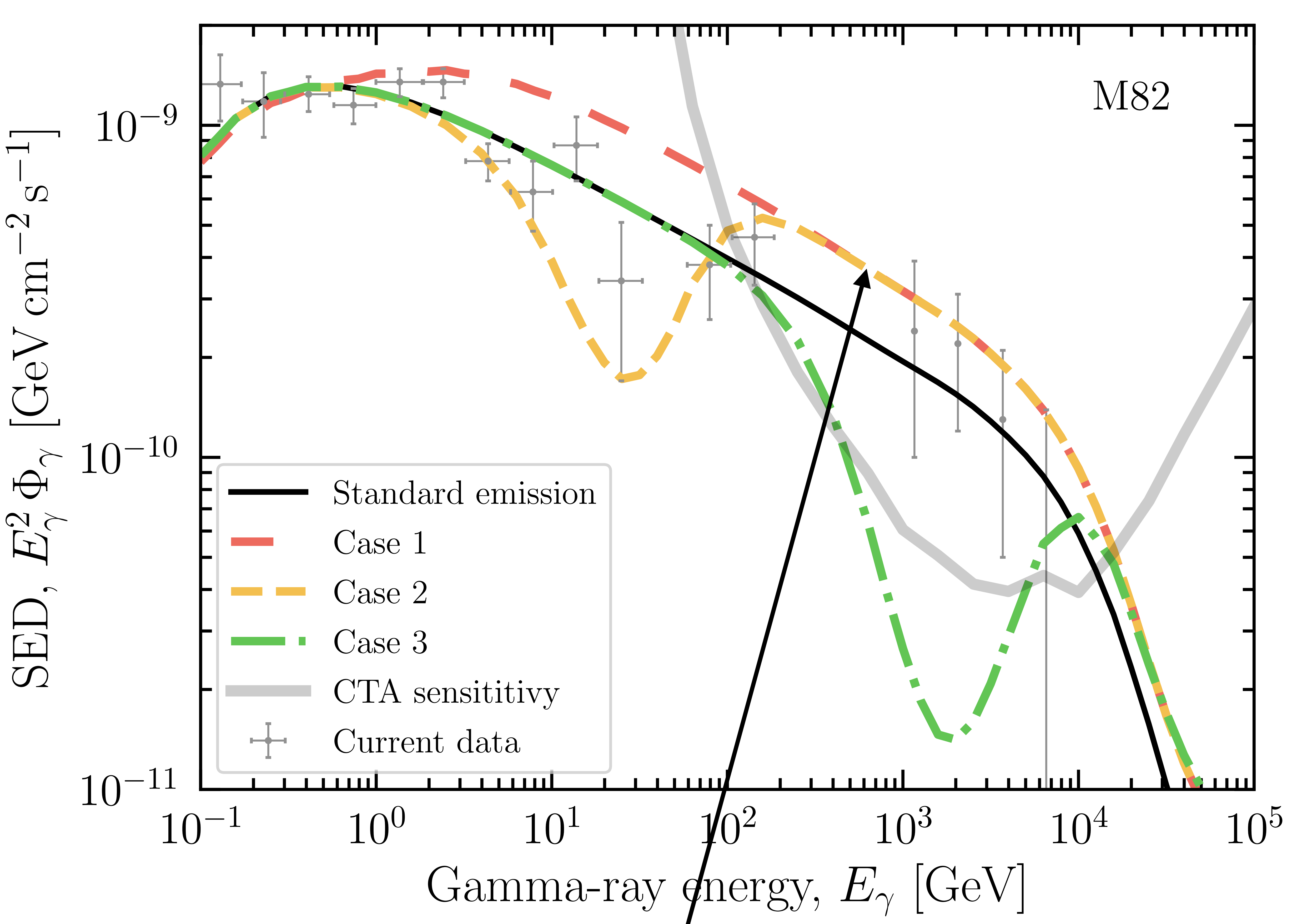

Dip in the $\gamma$-ray SED

Suppression from **proton form factor** at

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

# Effects of CR-DM scatterings




Suppression from **proton form factor** at

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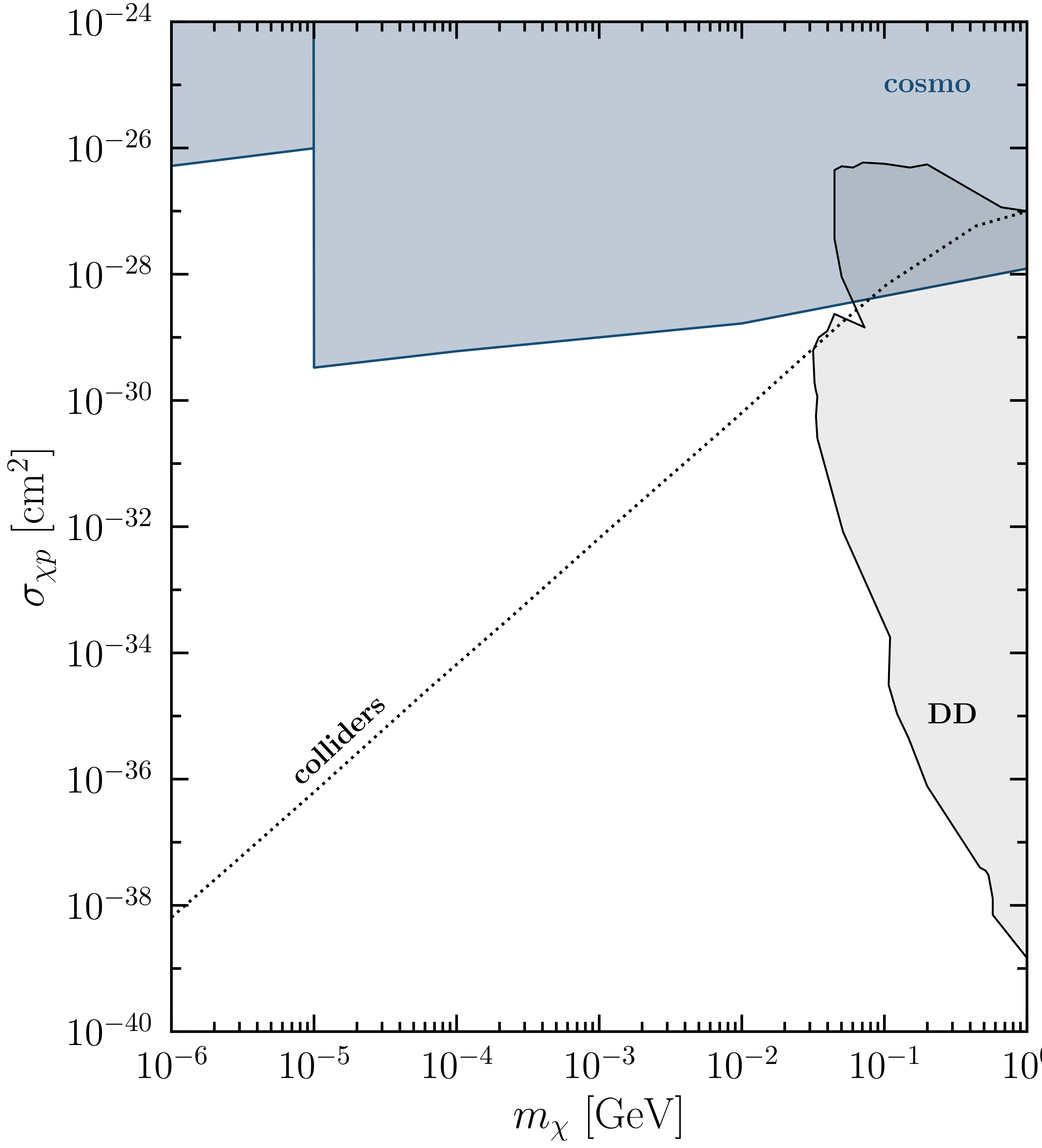
Higher gamma-ray flux due to inelastic $\chi p$ interaction

# Constraints from SBGs



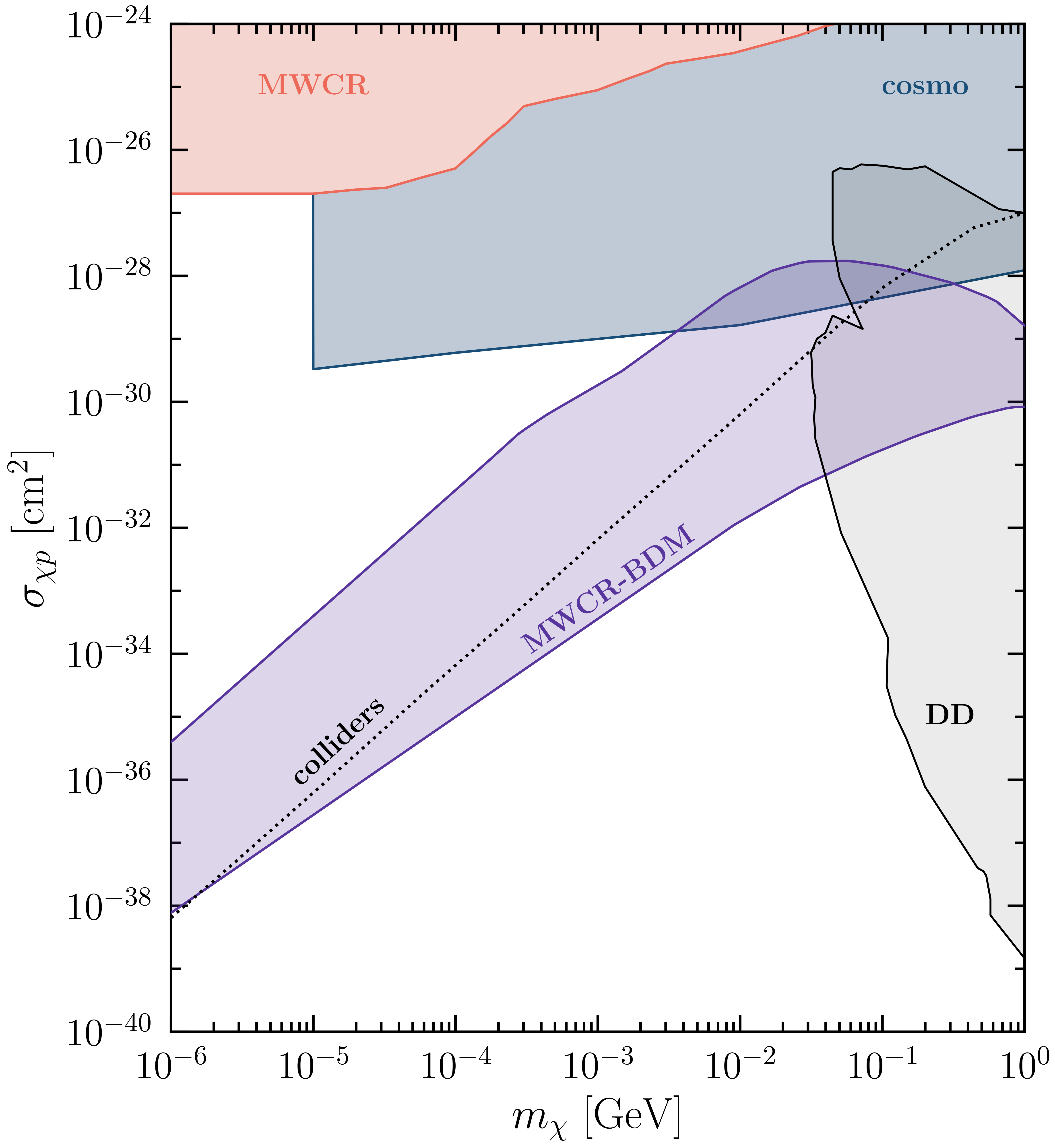
# Constraints from SBGs

- ✦ Distortions of Milky-Way Cosmic-Rays

  *Cappiello+, **PRD 99 (2019)***

- ✦ **Galactic CR-upscattering** DM constraints

  *Bondarenko+, **JHEP 03 (2020)***



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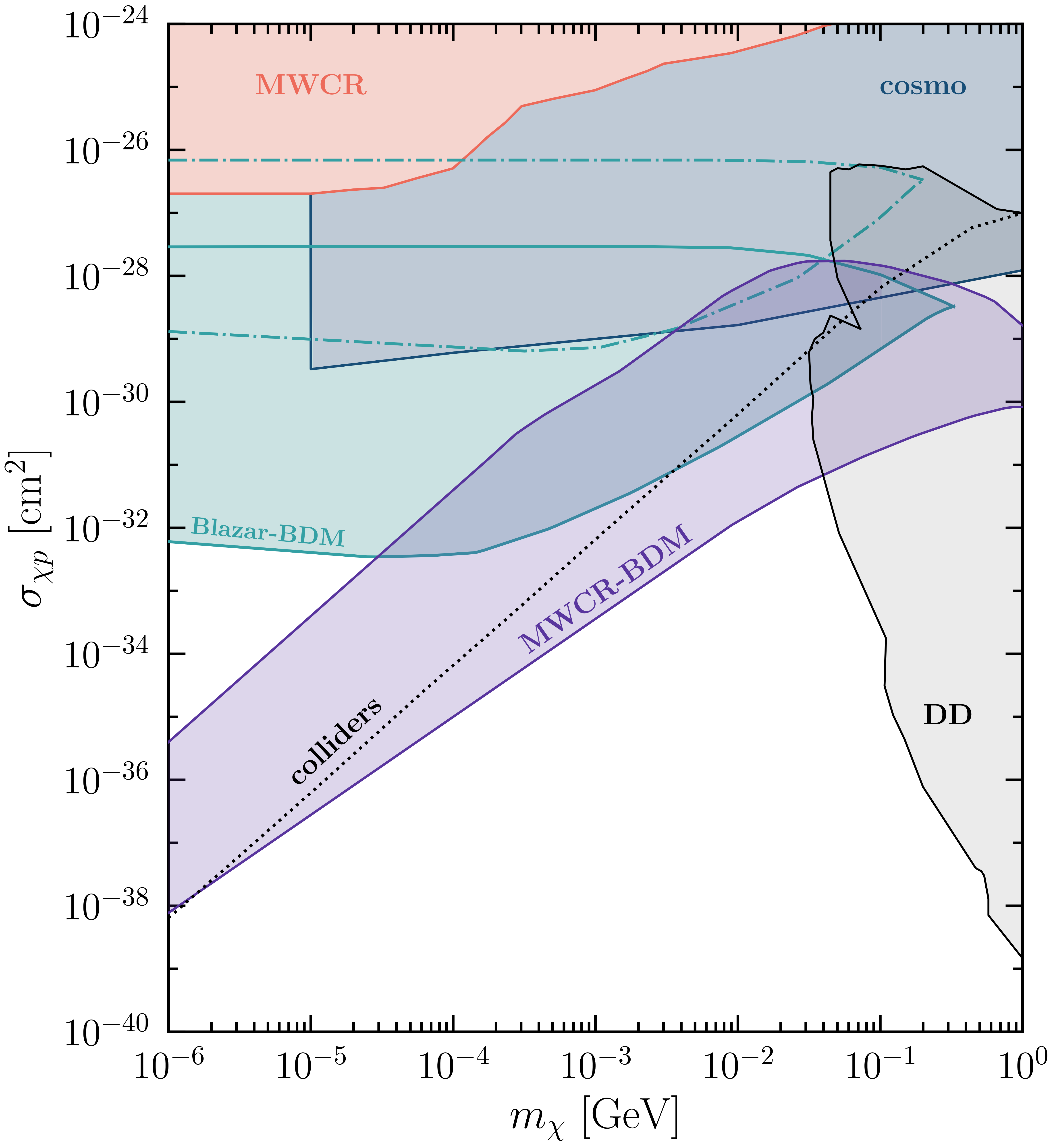
✦ **Boosted DM from blazar jets**, assuming DM spikes (high density) around the black holes ➜ large uncertainties!

*Wang+ **PRL 128 (2022)***, Granelli+ *J**CAP 07 (2022)***



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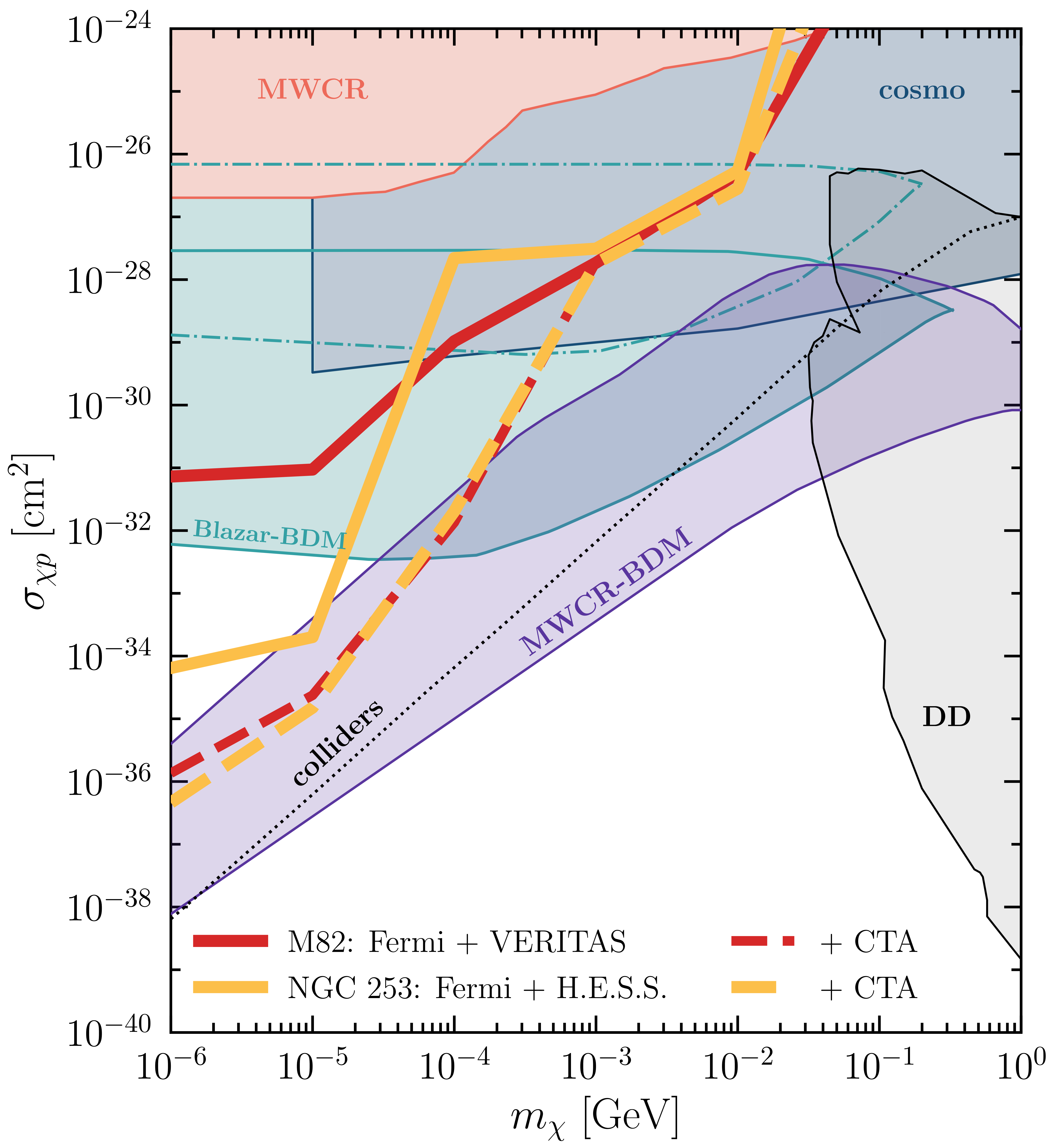
*Wang+ **PRL 128 (2022)***, Granelli+ *J**CAP 07 (2022)***

**OUR CONSTRAINTS FROM SBG (5$\sigma$)**

✦ M82 and NGC253 with current and future data

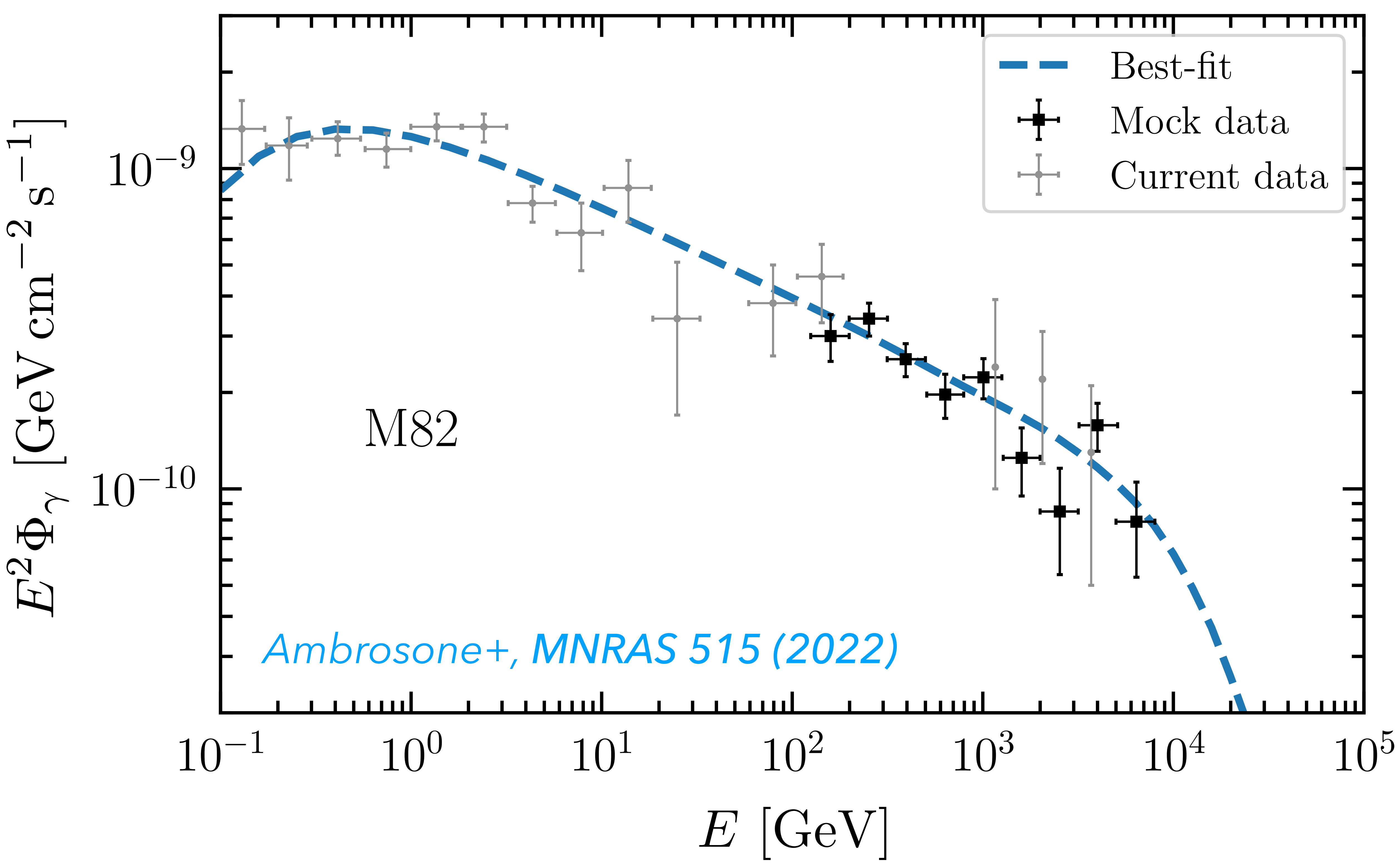
*Ambrosone, MC, Fiorillo, Marinelli, Miele, **PRL 131 (2023)***

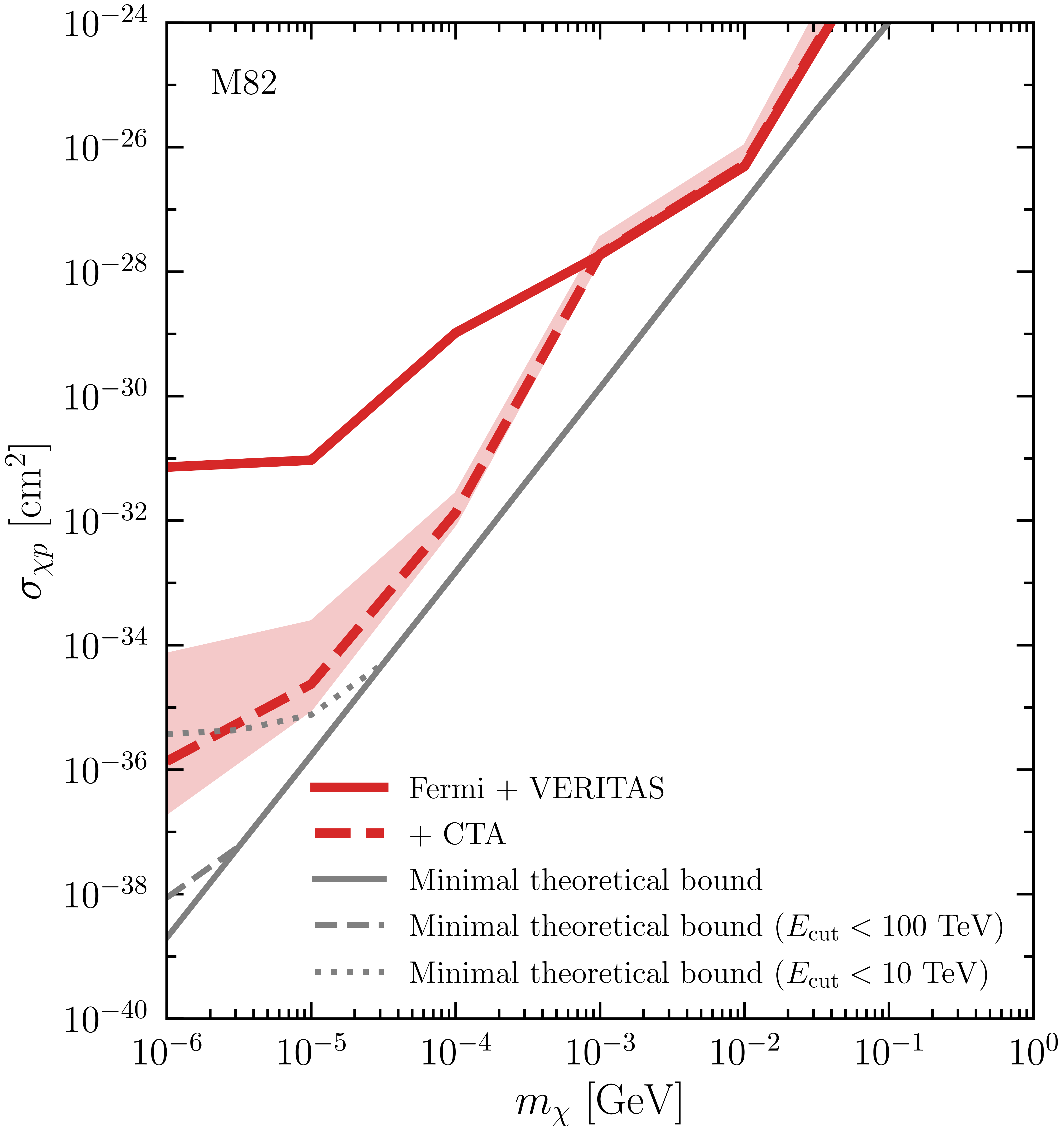


# Dependence on DM density


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

# Forecast with CTA data




- ✦ The CTA telescope will probe SBG emission in the 0.1-10 TeV range
- ✦ Generation of mock data sets by means of CTA public info

# Conclusions

- **New methodology** employing starburst galaxies' observations to probe dark matter and in general new physics

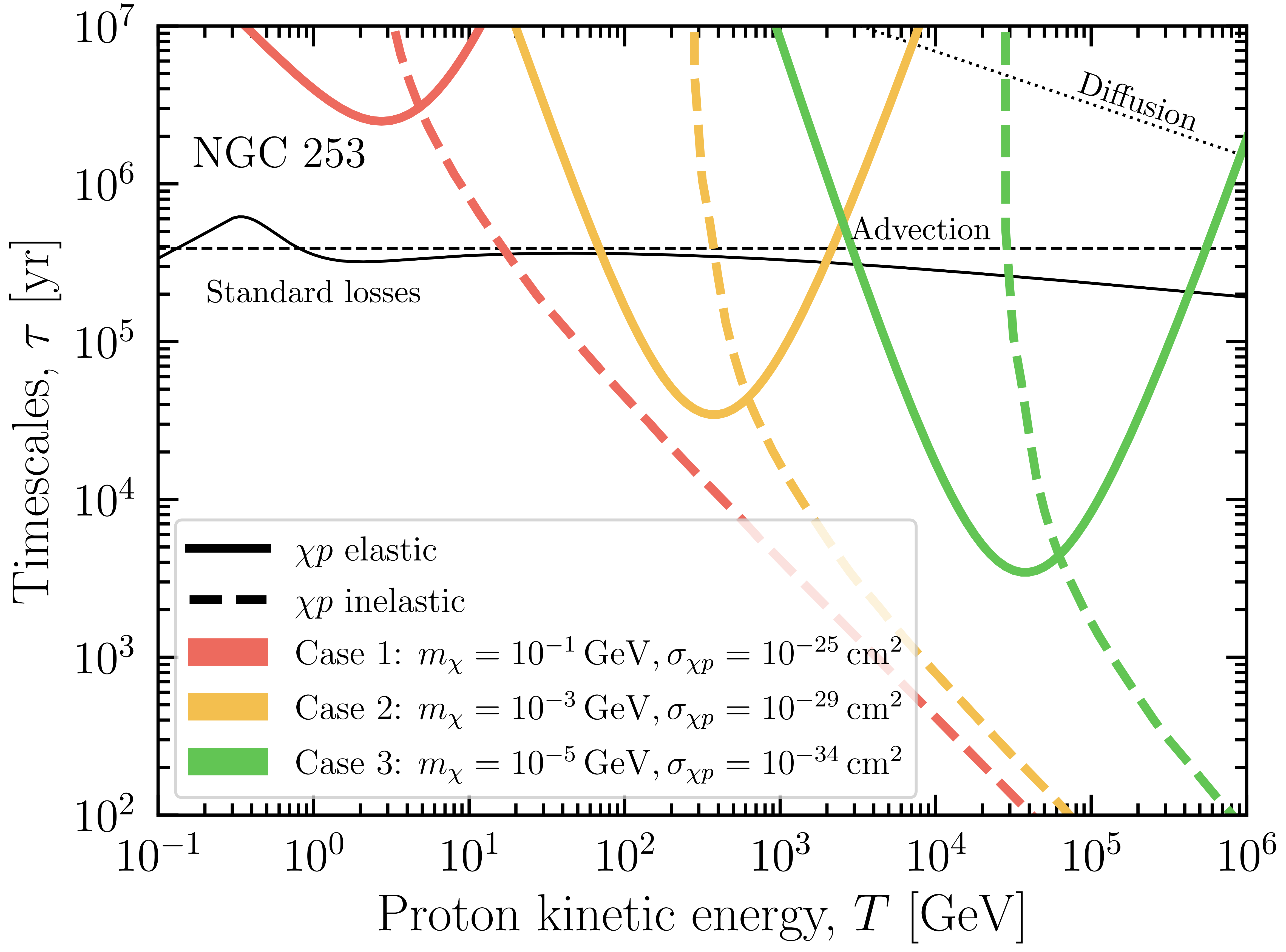
- Current $\gamma$-ray data of M82 and NGC 253 sources put **strong and highly complementary constraints** on DM-proton cross-section

- **Stay tuned:** upcoming gamma-ray telescopes will give us a better understanding of the cosmic-ray transport inside SBGs

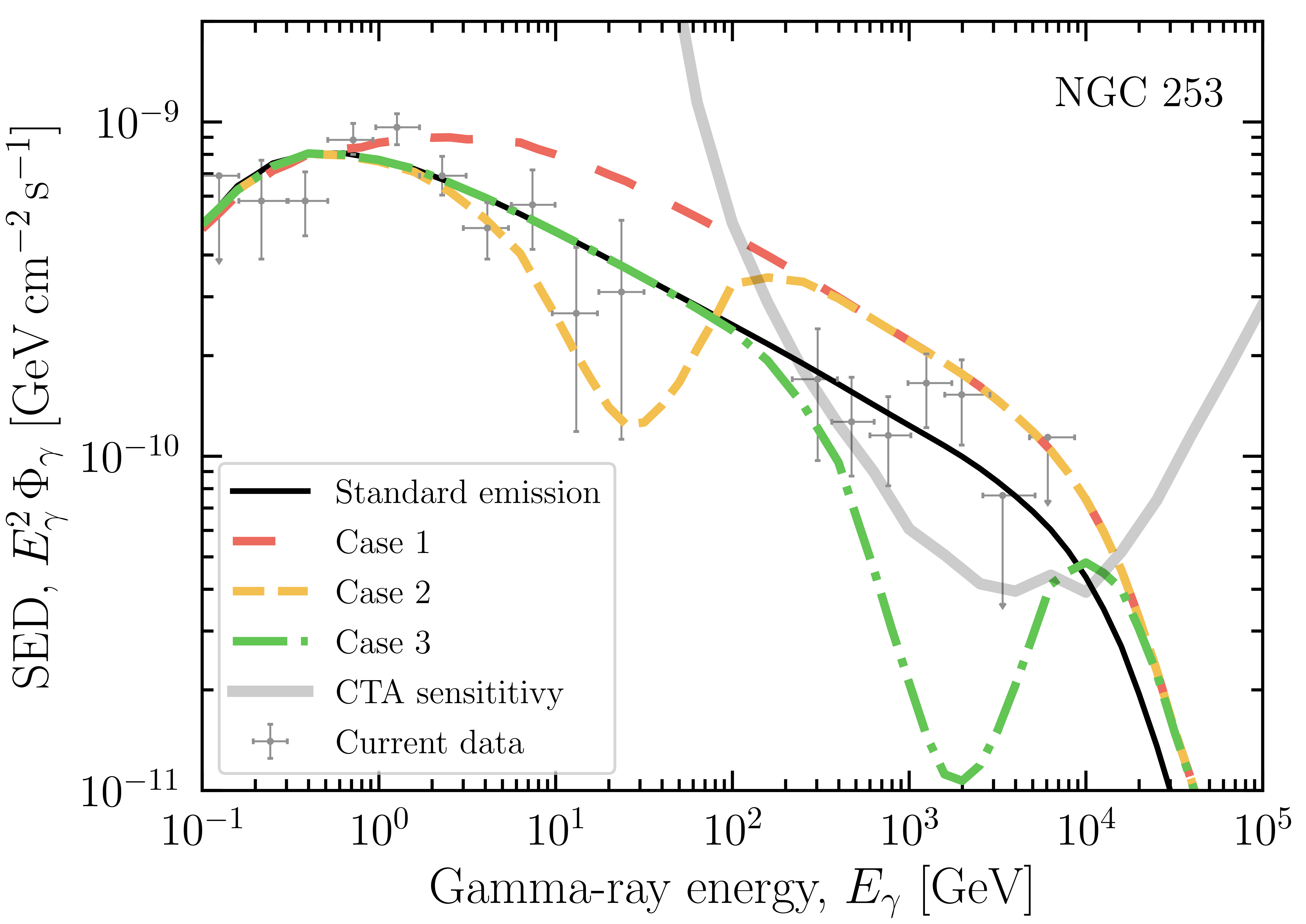
**Thanks for listening!**

# Backup slides

# NGC 253

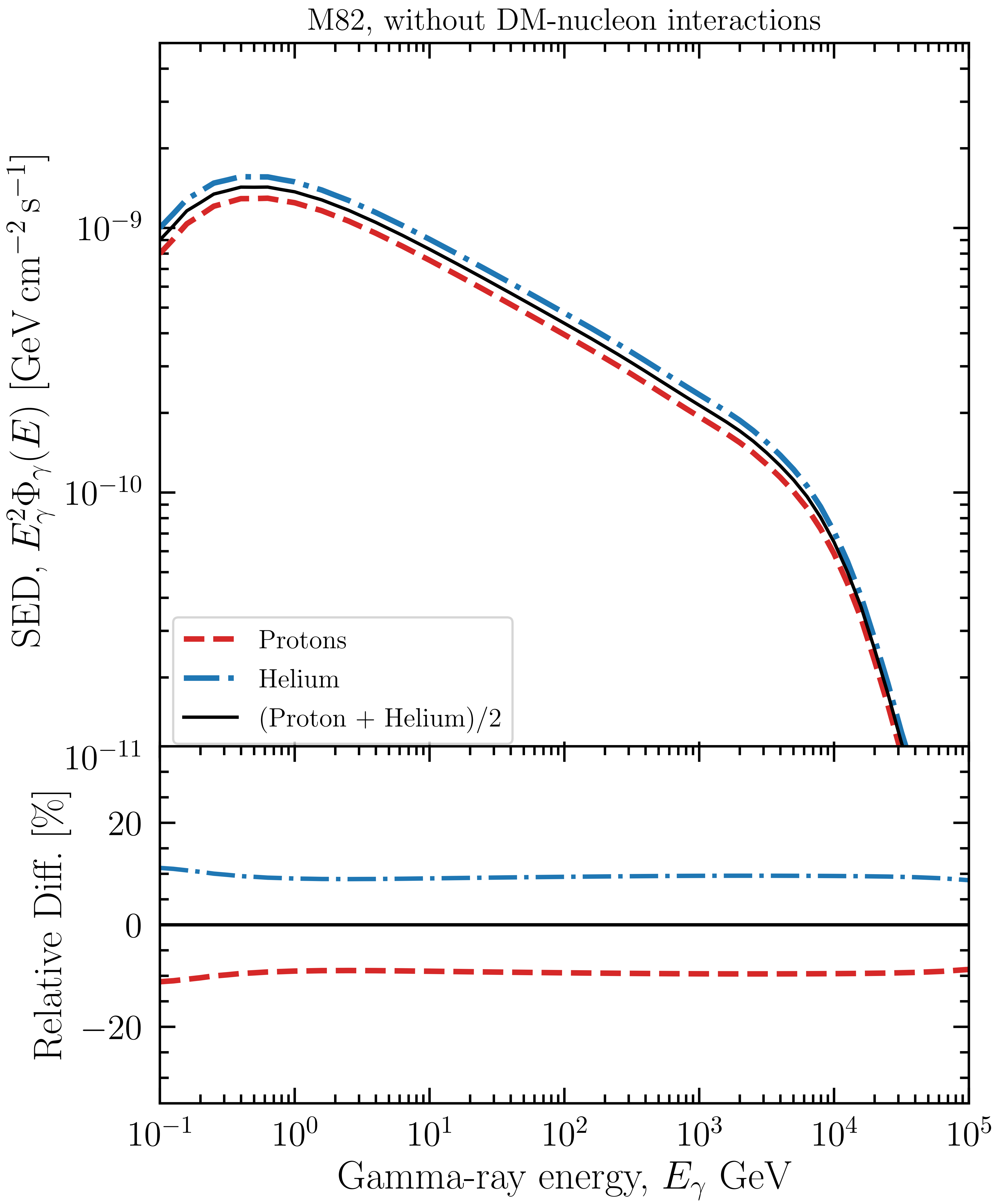


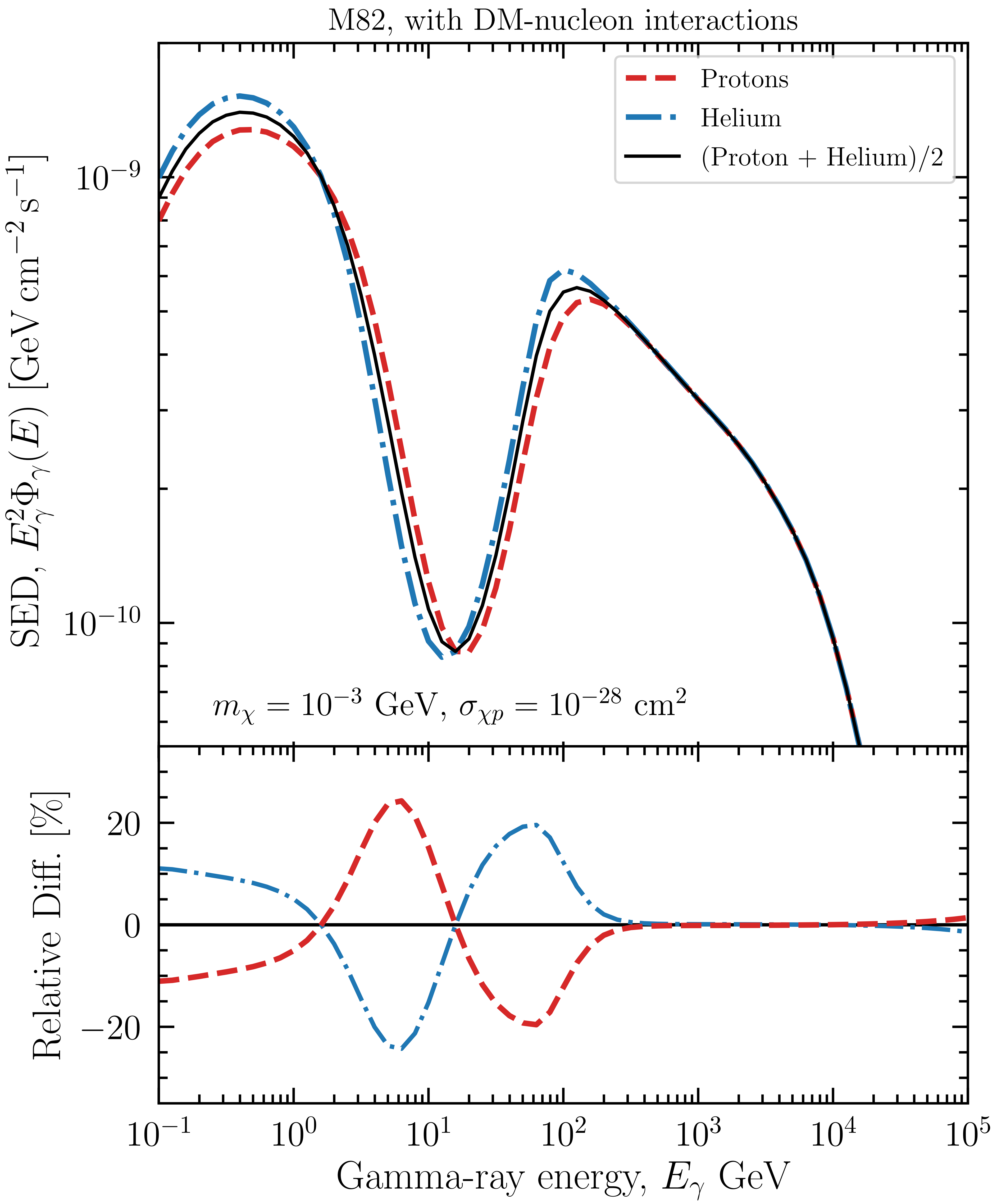
NGC 253
Diffusion
Advection
Standard losses
Timescales, $\tau$ [yr]
Proton kinetic energy, $T$ [GeV]
$\chi p$ elastic
$\chi p$ inelastic
Case 1: $m_\chi = 10^{-1}$ GeV, $\sigma_{\chi p} = 10^{-25}$ cm$^2$
Case 2: $m_\chi = 10^{-3}$ GeV, $\sigma_{\chi p} = 10^{-29}$ cm$^2$
Case 3: $m_\chi = 10^{-5}$ GeV, $\sigma_{\chi p} = 10^{-34}$ cm$^2$

NGC 253
SED, $E_\gamma^2 \Phi_\gamma$ [GeV cm$^{-2}$ s$^{-1}$]
Gamma-ray energy, $E_\gamma$ [GeV]
Standard emission
Case 1
Case 2
Case 3
CTA sensititivy
Current data

# Contamination of heavier nuclei (Helium)




- ✦ We explore different CR composition inside the SBG core
- ✦ Slight modification of spectral distortion
- ✦ The limits improve by less than an order of magnitude

# Modeling SBG emission

In the calorimeter scenario, three main parameters:

- ✦ Cut-off energy
- ✦ Spectral index
- ✦ Rate of SuperNovae explosions

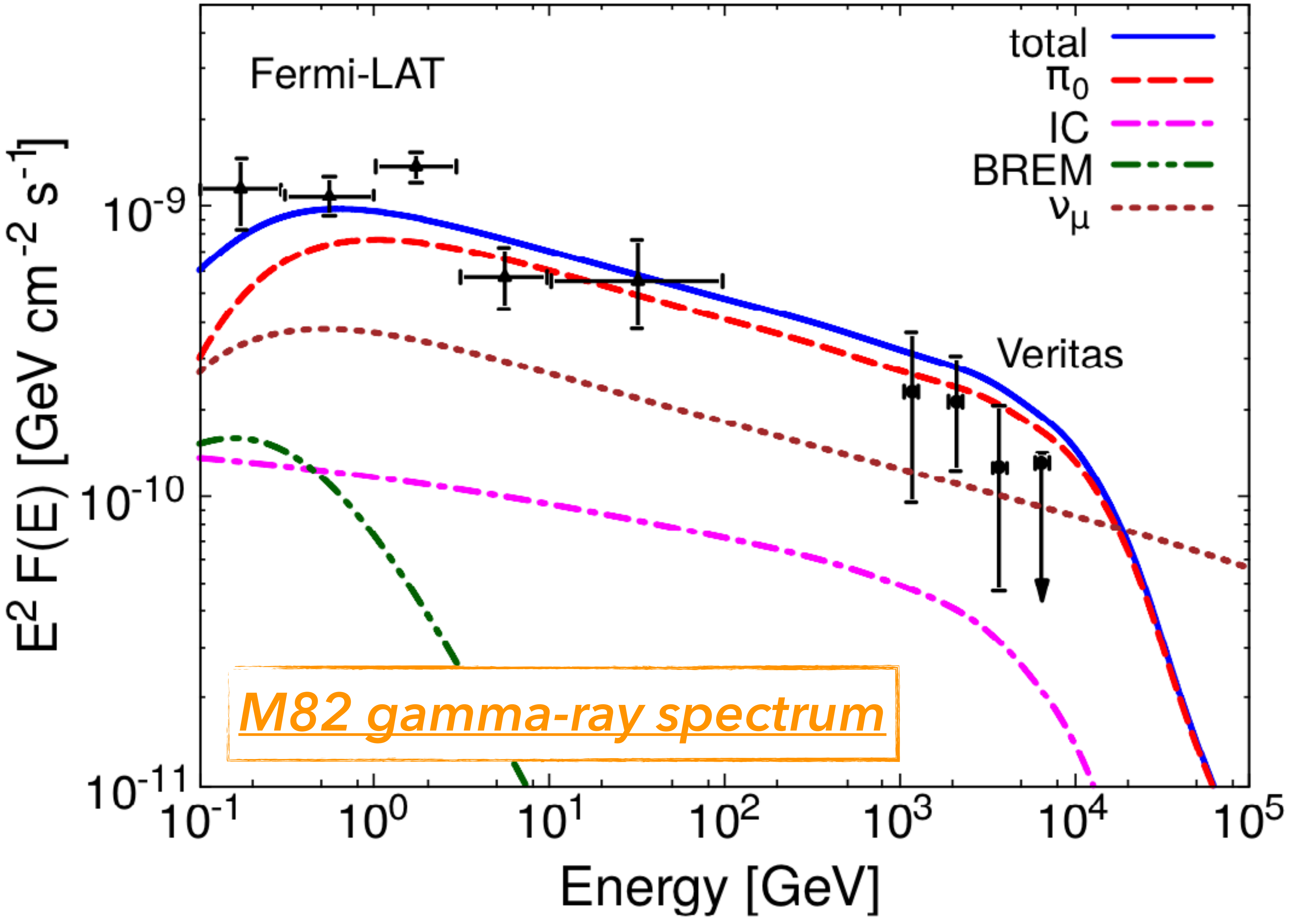
**Leaky-box-like model for CR transport**

$$f(p)\left(\frac{1}{\tau_{\rm loss}(p)}+\frac{1}{\tau_{\rm adv}(p)}+\frac{1}{\tau_{\rm diff}(p)}\right)=Q(p)$$

*injected CR from SN explosion*

| parameter | value | parameter | value |
|---|---|---|---|
| $p_{p,\max}$ | $10^2$ PeV | $\mathcal{R}_{\rm SN}$ | $0.06\ {\rm yr}^{-1}$ |
| $\alpha$ | 4.2 | $B$ | $200\ \mu$G |
| $R$ | 0.25 kpc | $n_{\rm ISM}$ | $100\ {\rm cm}^{-3}$ |
| $D_L$ | 3.9 Mpc | $v_{\rm wind}$ | 700 km/s |
| $\xi_{\rm CR}$ | 0.1 | $U_{\rm rad}$ | $2500\ {\rm eV/cm}^3$ |

*Peretti+, MNRAS 487 (2019), MNRAS 493 (2020)*



# Bayesian analysis

Ambrosone+, 2106.12348

Results of the Likelihood Analysis of Current Gamma-Ray Data

| Source | Uniform Prior $\dot{M}_*$ | Most Likely Values $(\dot{M}_*, \Gamma)$ | 68% Credible Intervals $\dot{M}_*$ | 68% Credible Intervals $\Gamma$ | $\chi^2$/dof |
|---|---|---|---|---|---|
| M82 | 3.0–30 | (4.5, 2.30) | [4.3, 4.6] | [2.27, 2.33] | 1.24 |
| NGC 253 | 1.4–17 | (3.3, 2.30) | [3.14, 3.40] | [2.28, 2.32] | 1.32 |
| ARP 220 | 60–740 | (740, 2.66) | [492, 740] | [2.51, 2.68] | 1.52 |
| NGC 4945 | 0.35–4.15 | (4.15, 2.30) | [4.05, 4.15] | [2.23, 2.32] | 1.52 |
| NGC 1068 | 5–93 | (16, 2.52) | [13, 20] | [2.45, 2.65] | 0.65 |
| NGC 2146 | 3–57 | (15, 2.50) | [9, 27] | [2.44, 2.88] | 0.50 |
| ARP 299 | 28–333 | (28, 2.15) | [28, 200] | [1.40, 1.90] ∪ [2.77, 3.00] | 0.18 |
| M31 | 0.09–0.90 | (0.34, 2.40) | [0.31, 0.40] | [2.29, 2.61] | 0.52 |
| M33 | 0.09–0.90 | (0.44, 2.76) | [0.19, 0.56] | [2.57, 2.96] | 0.44 |
| NGC 3424 | 0.4–5.4 | (5.4, 2.22) | [2.5, 5.4] | [1.92, 2.67] | 1.63 |
| NGC 2403 | 0.1–1.2 | (0.75, 2.12) | [0.58, 0.96] | [1.92, 2.36] | 0.38 |
| SMC | 0.008–0.090 | (0.038, 2.14) | [0.037, 0.039] | [2.13, 2.16] | 1.90 |
| Circinus Galaxy | 0.1–8.1 | (6.6, 2.32) | [6.2, 7.8] | [2.15, 2.45] | 0.92 |

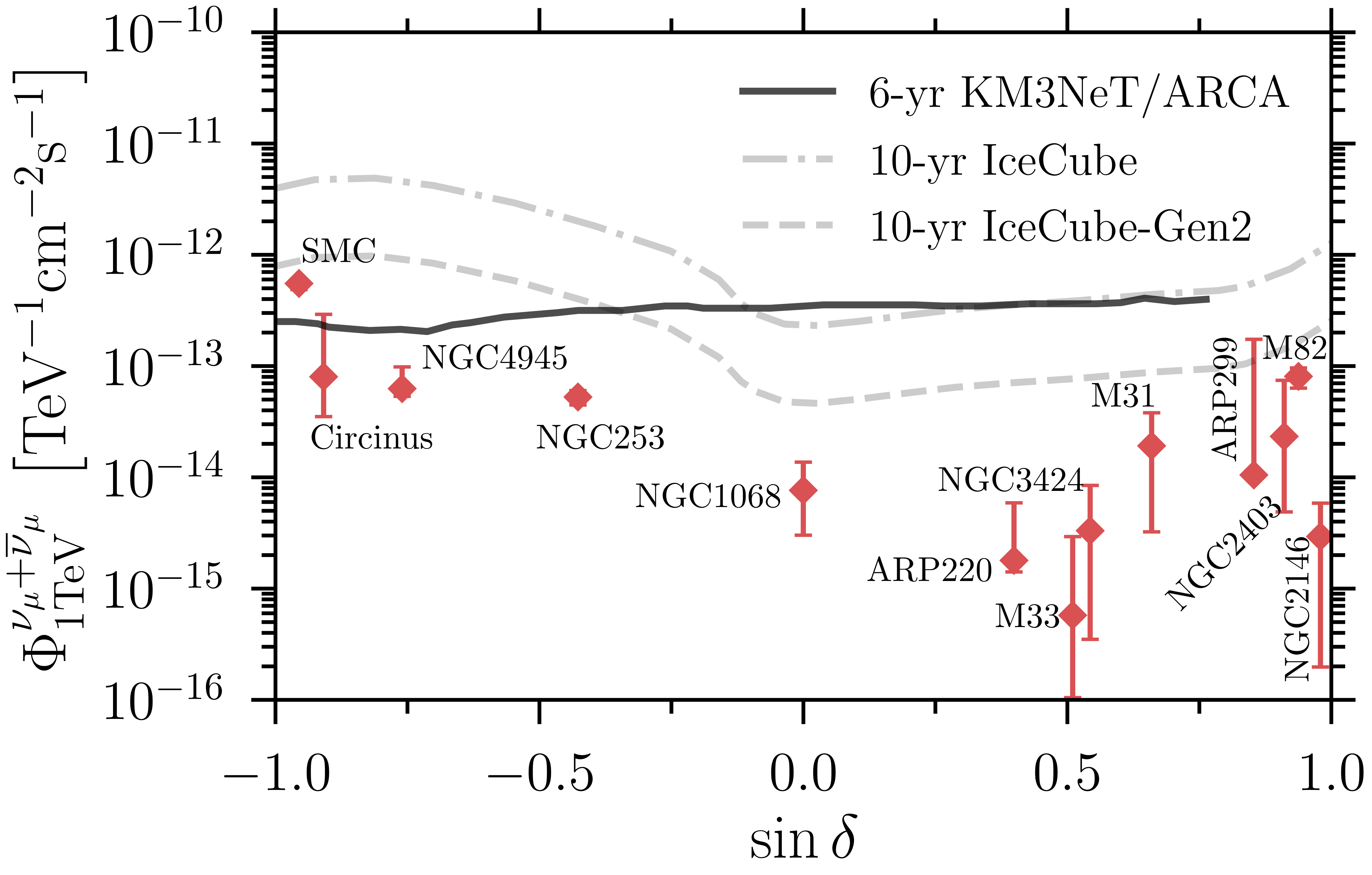
**Note.** The columns report the source name, the SFR prior, the most likely values of the two parameters, the 68% maximum posterior density credible intervals of the marginal distributions, and the reduced chi-squared values considered as an estimate of the goodness of the fit. The star formation rate $\dot{M}_*$ is in units of $M_\odot$ yr$^{-1}$.

This allows us to predict the neutrino and VHE gamma-rays emission from these sources!

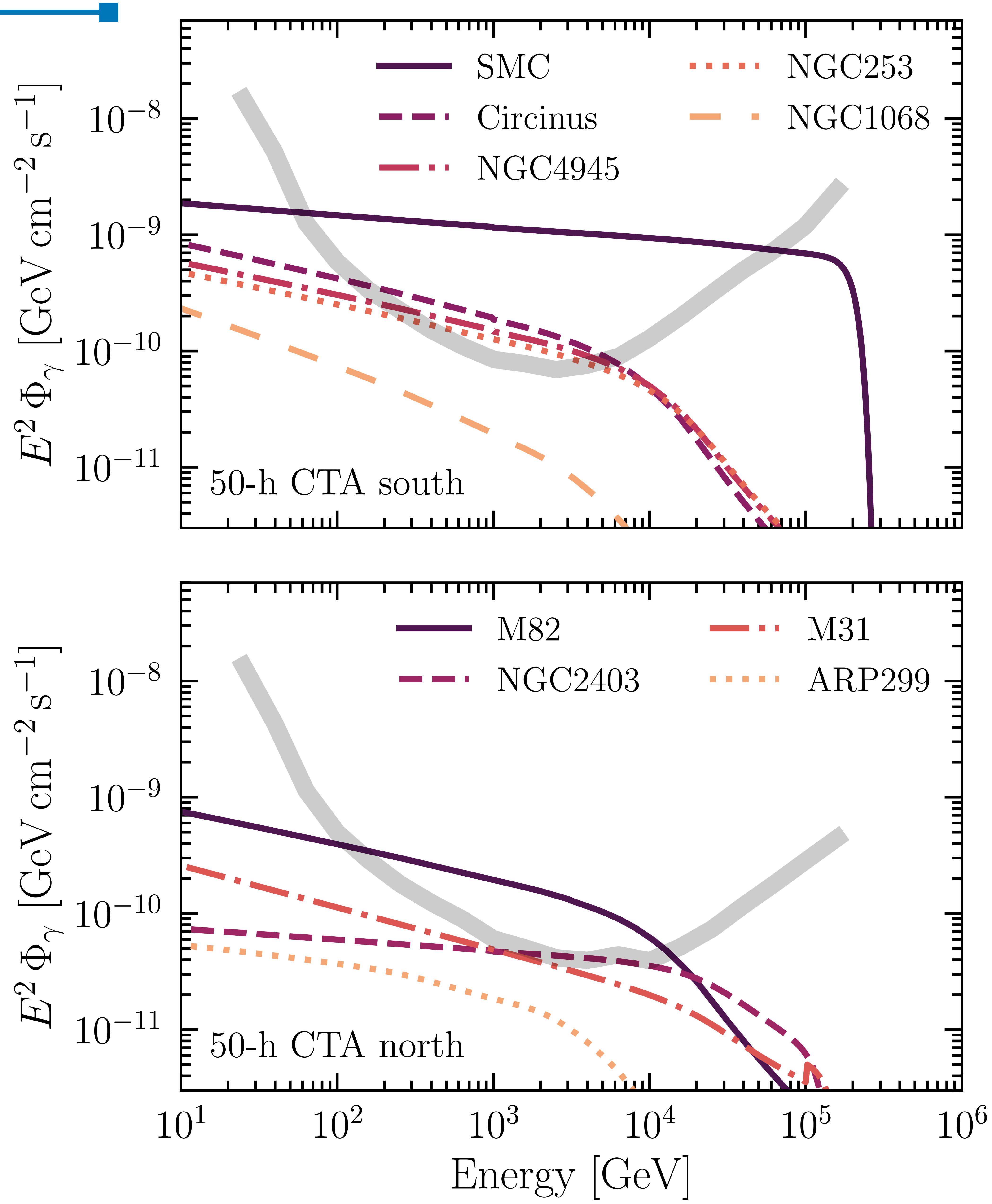
# Point-like forecast

*Ambrosone+, 2106.12348*

**NEUTRINOS**




**VHE GAMMA-RAYS**




**Future joint $\nu$-$\gamma$ observations**

- ✦ Objective test for the calorimetric model
- ✦ Compelling evidence of star-forming activity as a tracer of neutrino production.