Probing Dark Matter-Proton Interactions with Cosmic Reservoirs

Marco Chianese

21 September 2023, Light Dark World, Karlsruhe

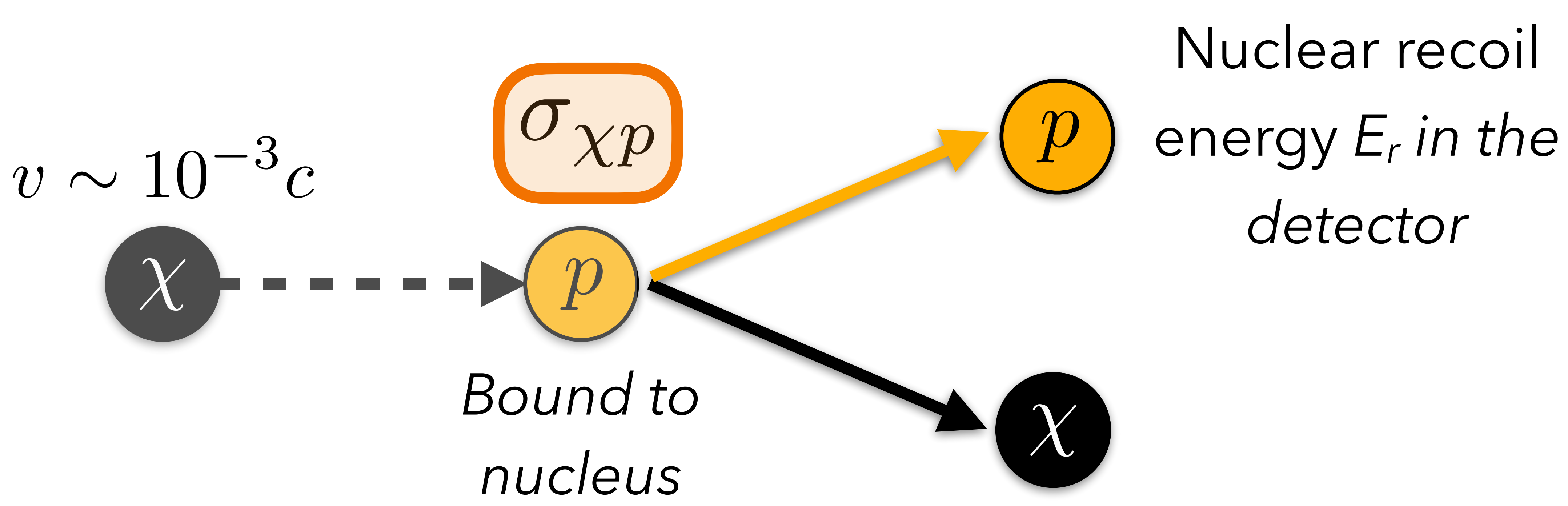
Based on Ambrosone, MC, Fiorillo, Marinelli, Miele, **PRL 131 (2023) 11 [2210.05685]**

Università degli Studi di Napoli Federico II
NAP Theory
INFN Napoli
marco.chianese@unina.it

Motivation

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

Poor sensitivity to low nuclear recoil energies

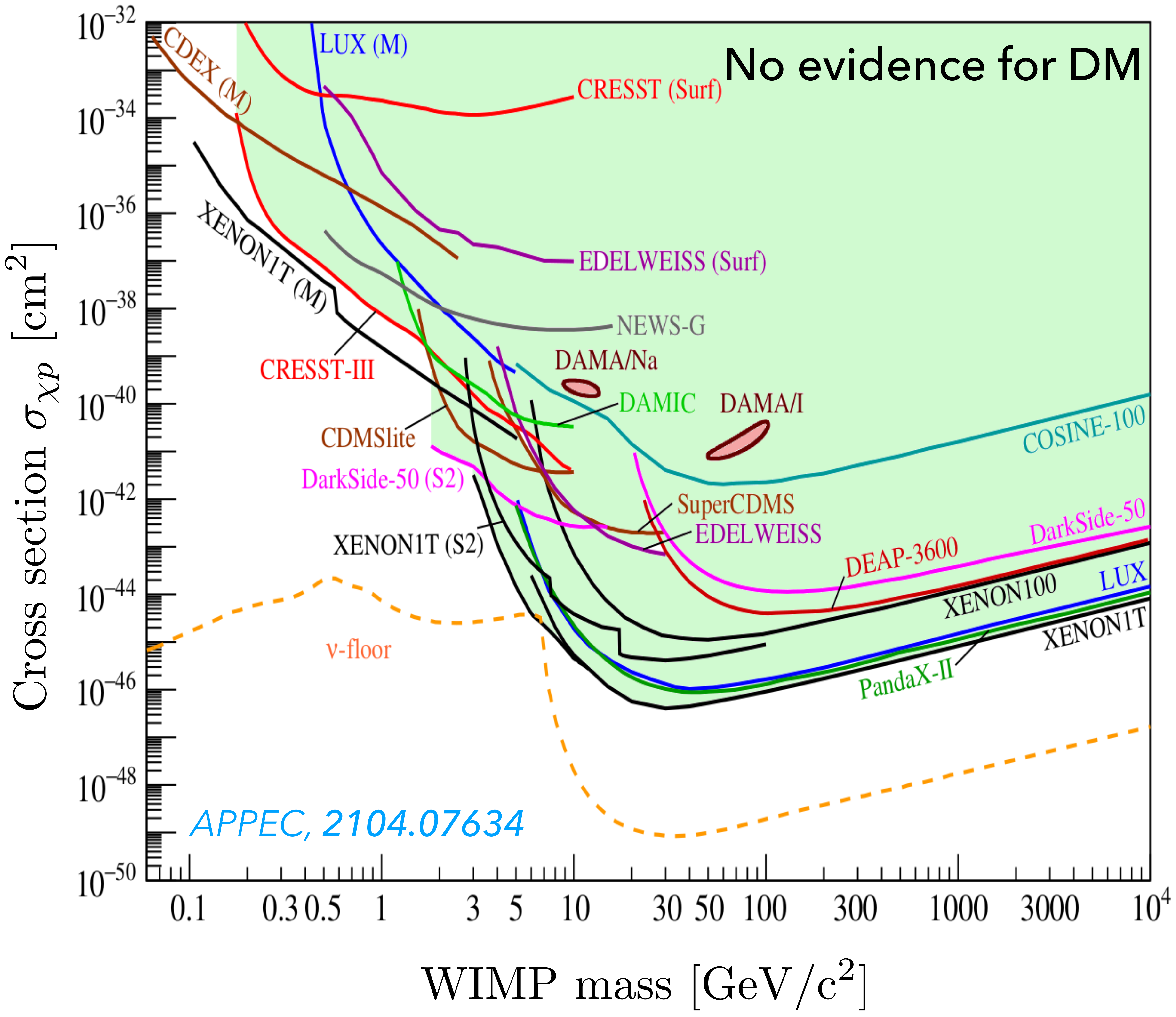


$$\frac{E_r}{50\ \mathrm{keV}} \simeq \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^2 \left(\frac{v}{10^{-3}c}\right)^2 \left(\frac{100\ \mathrm{GeV}}{m_N}\right)$$

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

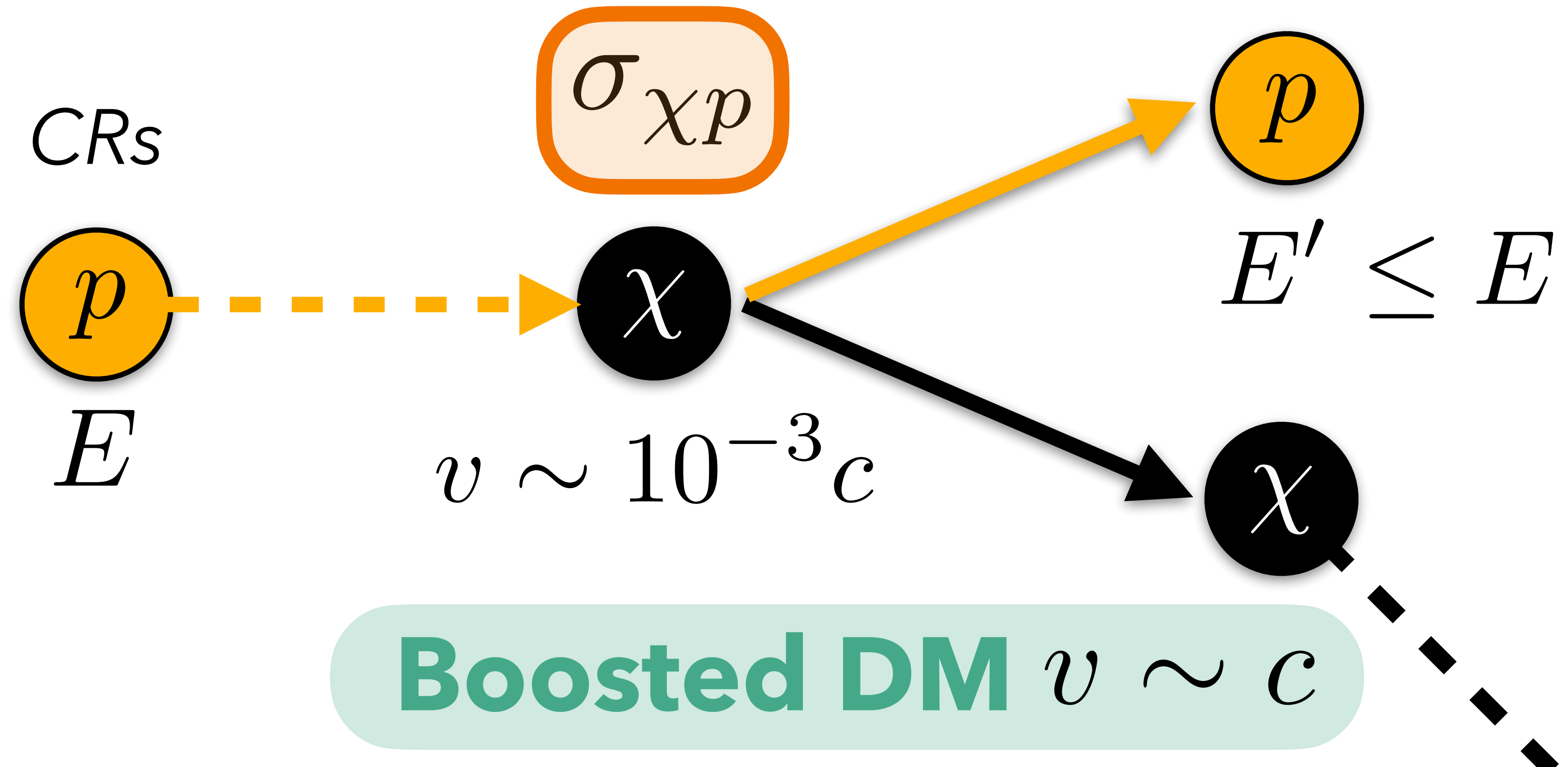
Recent improvements: talk by Angelo Esposito

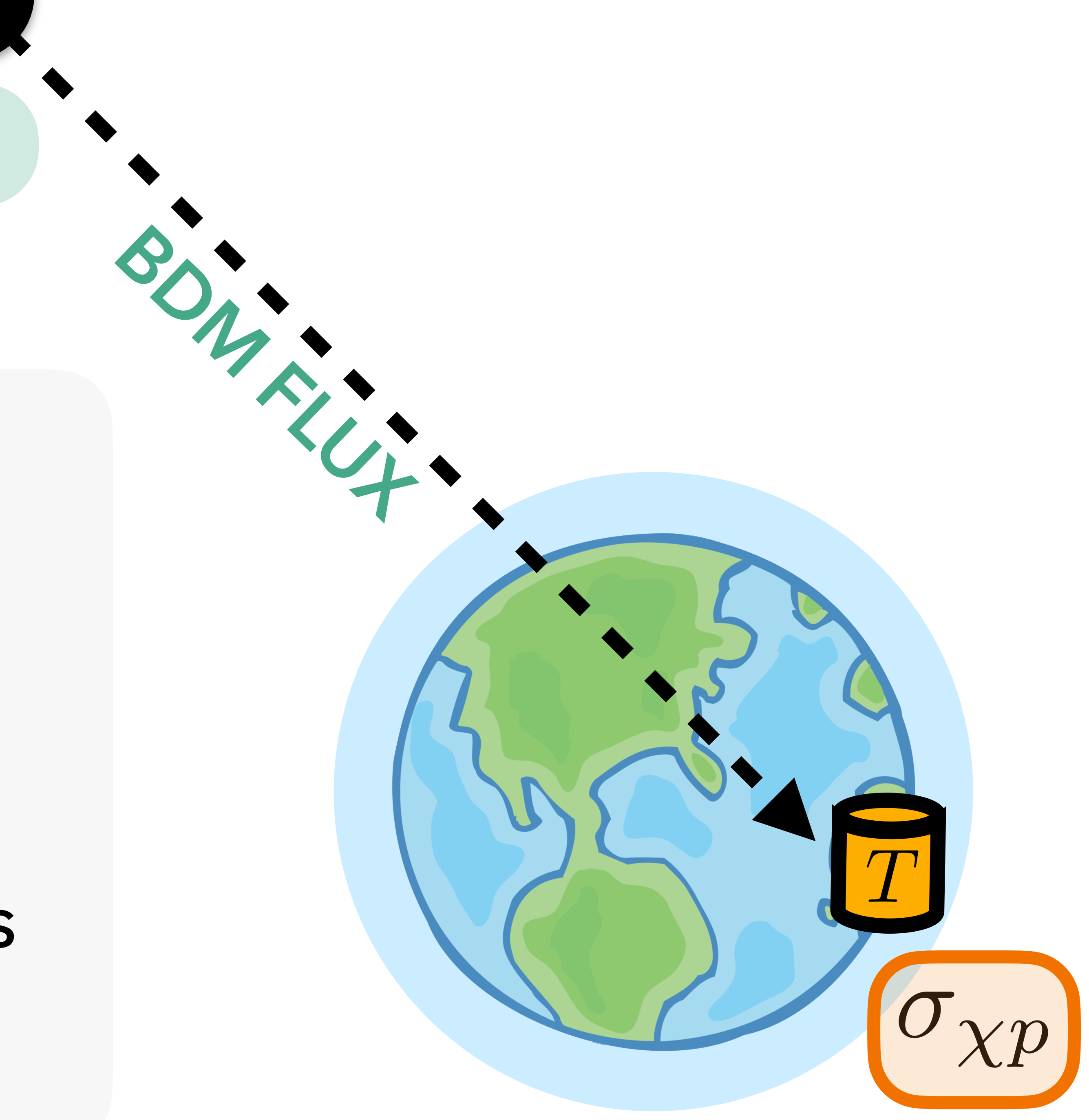
New idea: the same interaction might occur with cosmic-rays during their propagation!



DM interactions with cosmic-rays

They have two main effects:





1. Production of a BDM flux

✦ Up-scatterings with **CR-protons**

Talk by Torsten Bringmann

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

Talk by Filippo Sala

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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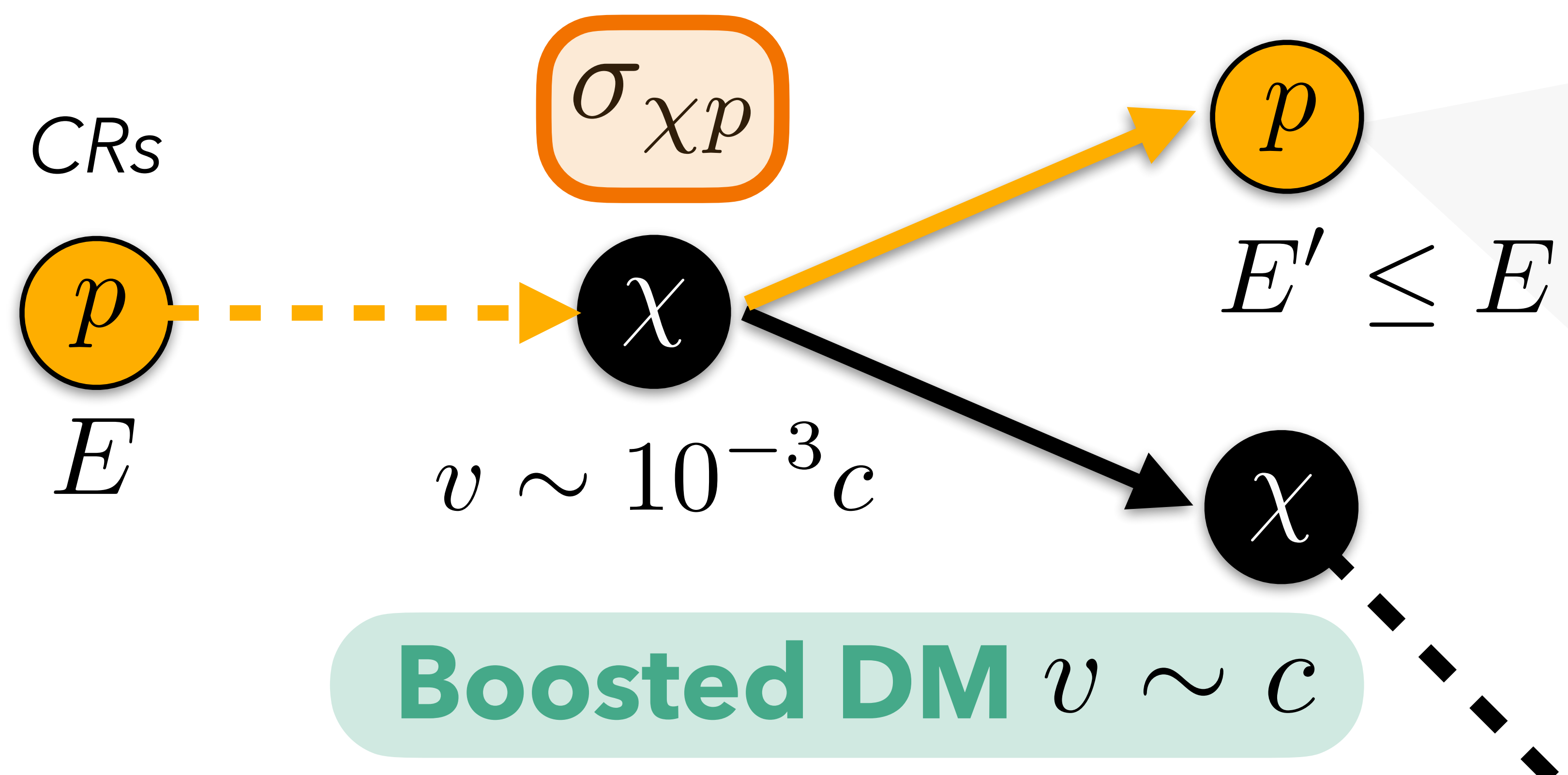

2. Reverse direct detection (i.e. modification of the CR spectrum)

- ✦ Milky Way

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

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

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Alvey+, ***JHEP 01 (2023)***

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 ($n_{\rm ISM}$ > 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

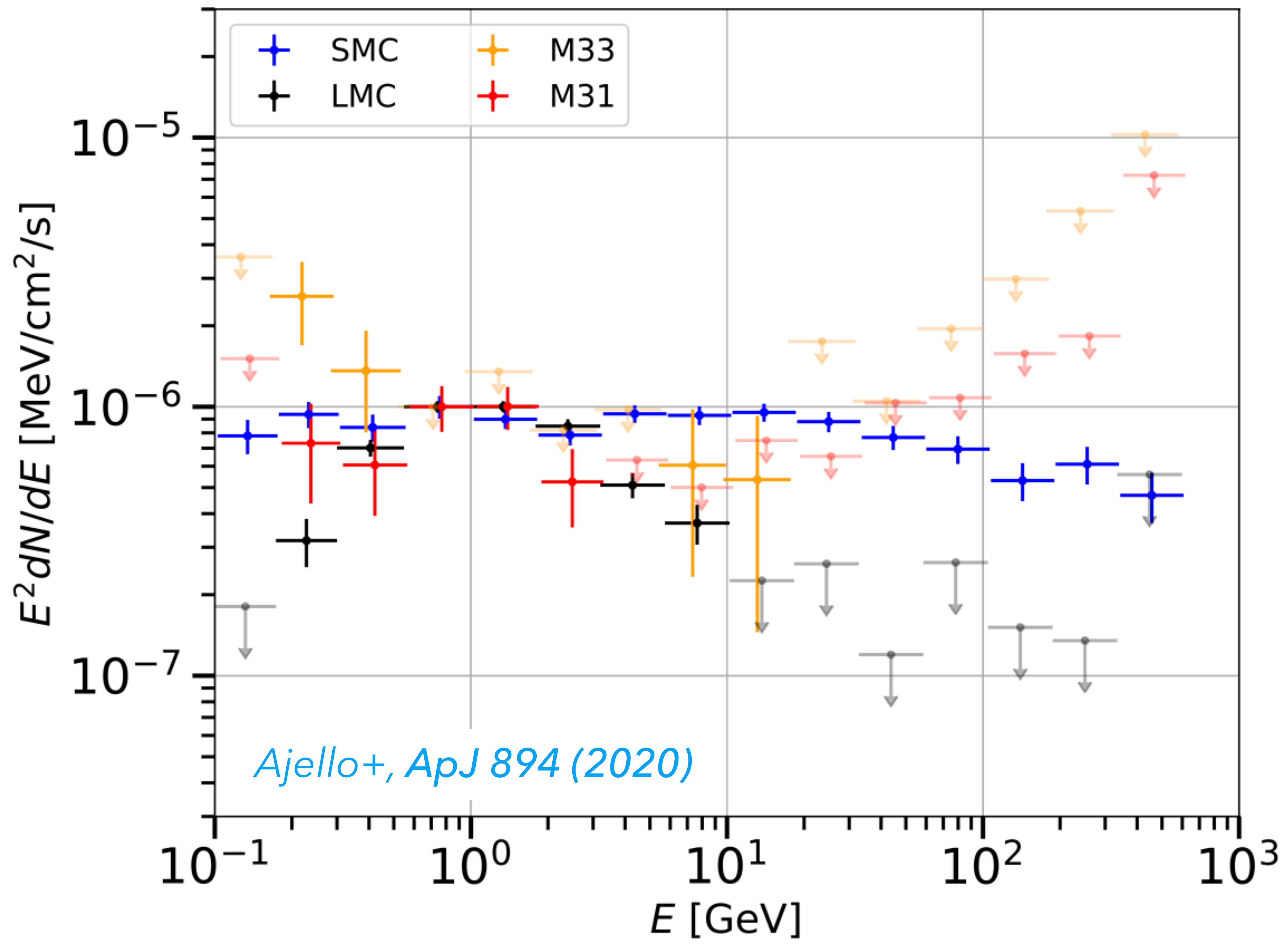
- ✦ Sources of high-energy **neutrinos** and **gamma-rays**:

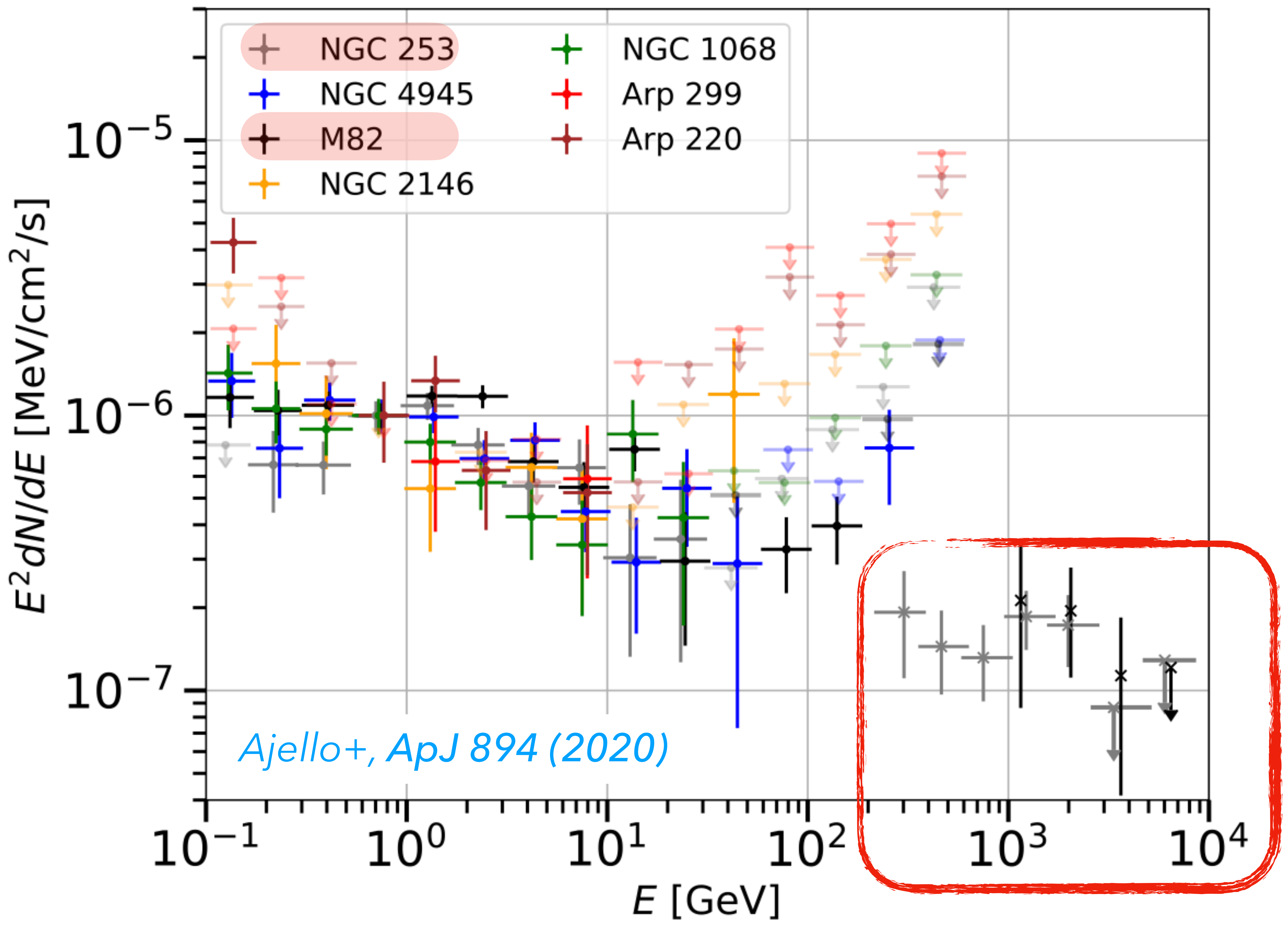
$$\pi^\pm \rightarrow e^\pm \, \nu_e \, \nu_\mu \, \overline{\nu}_\mu \qquad\qquad \pi^0 \rightarrow \gamma\gamma$$

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

Current gamma-ray observations

Fermi-LAT and **IACTs** have detected γ-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

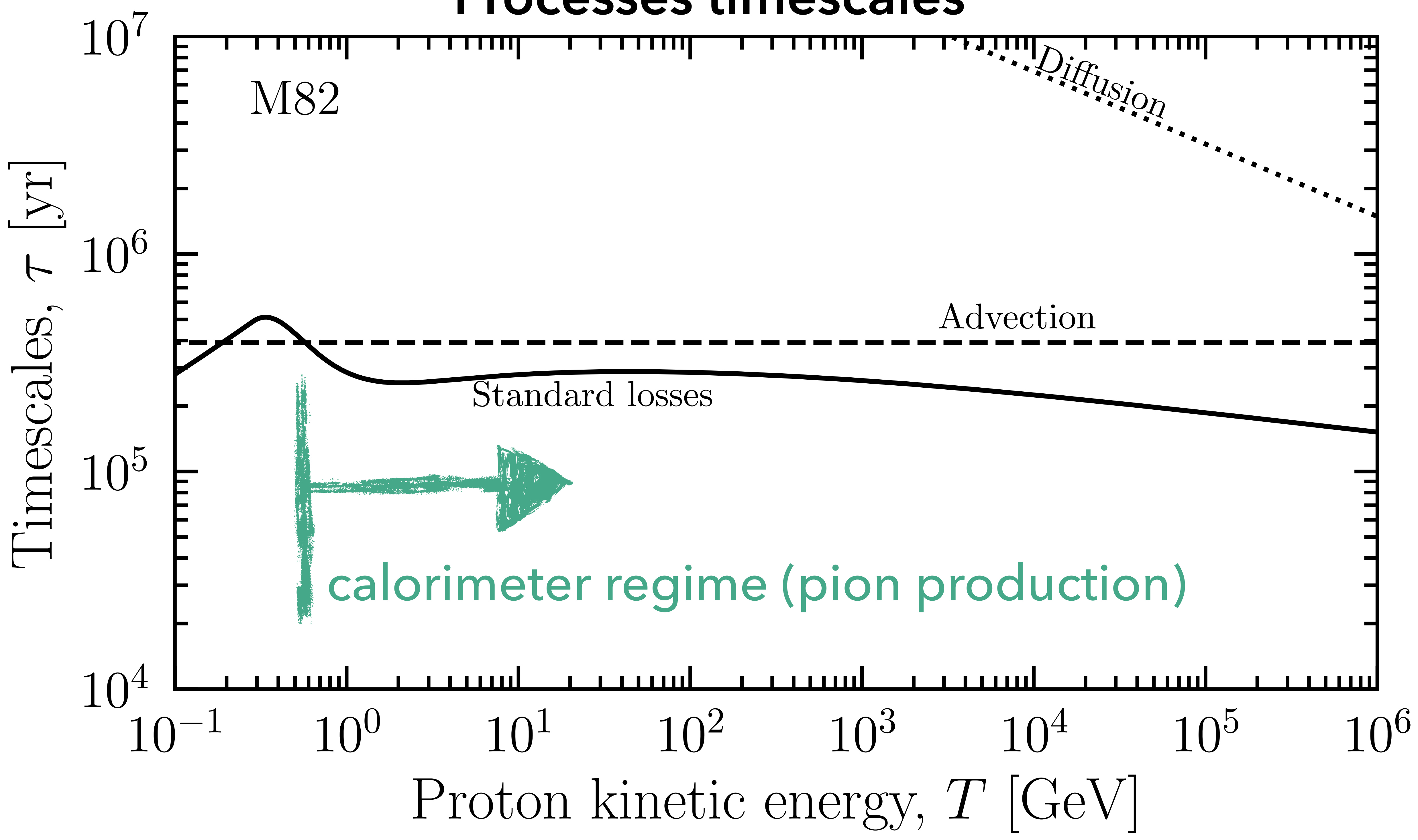
Escape Time

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

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

M82 emission

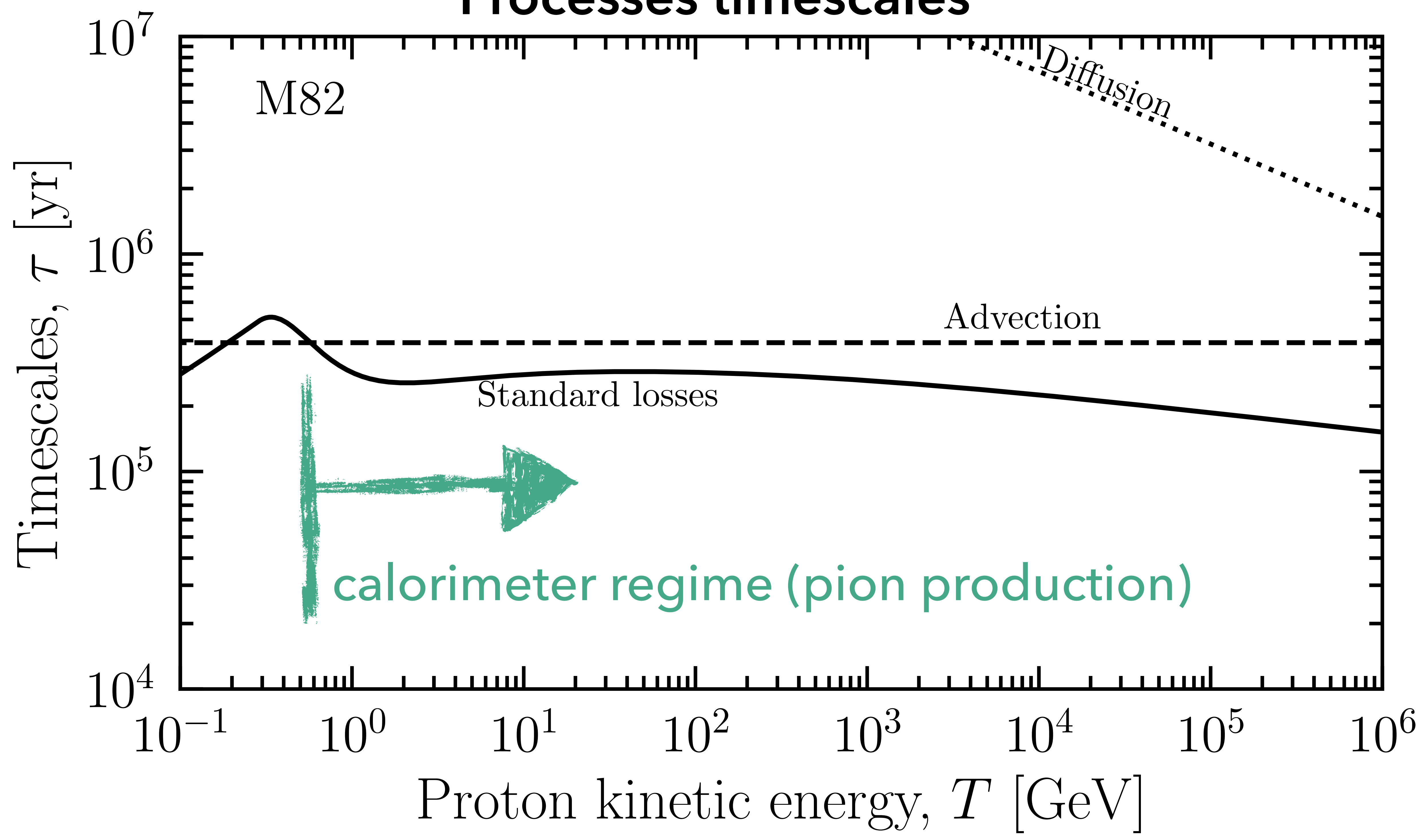
Processes timescales



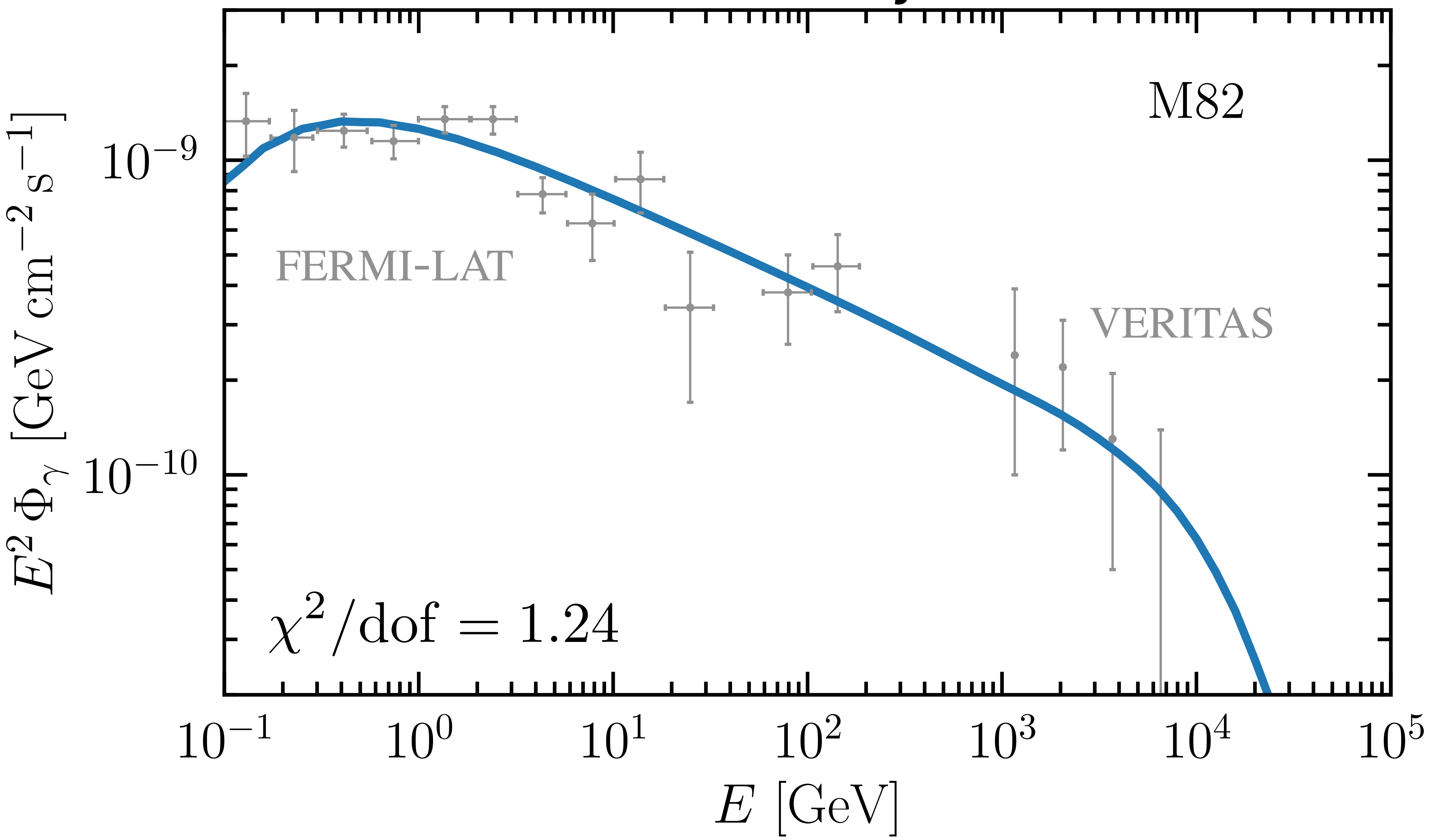
Dominant process ⟷ Smallest timescale

M82 emission

Processes timescales



Gamma-ray flux



Dominant process ⟷ Smallest timescale

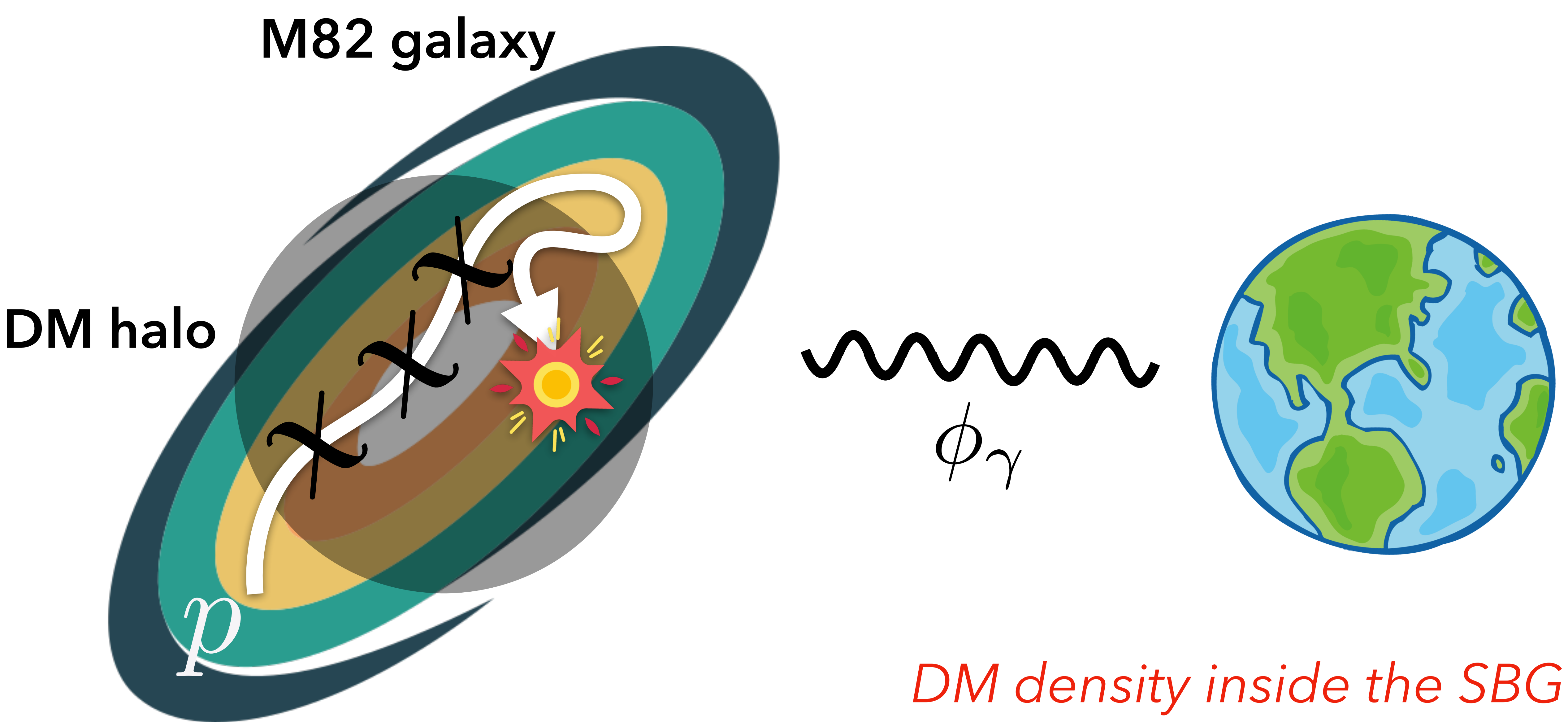
Two-parameter best-fit SED

- ✦ 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 γ-rays!



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

Inelastic timescale:

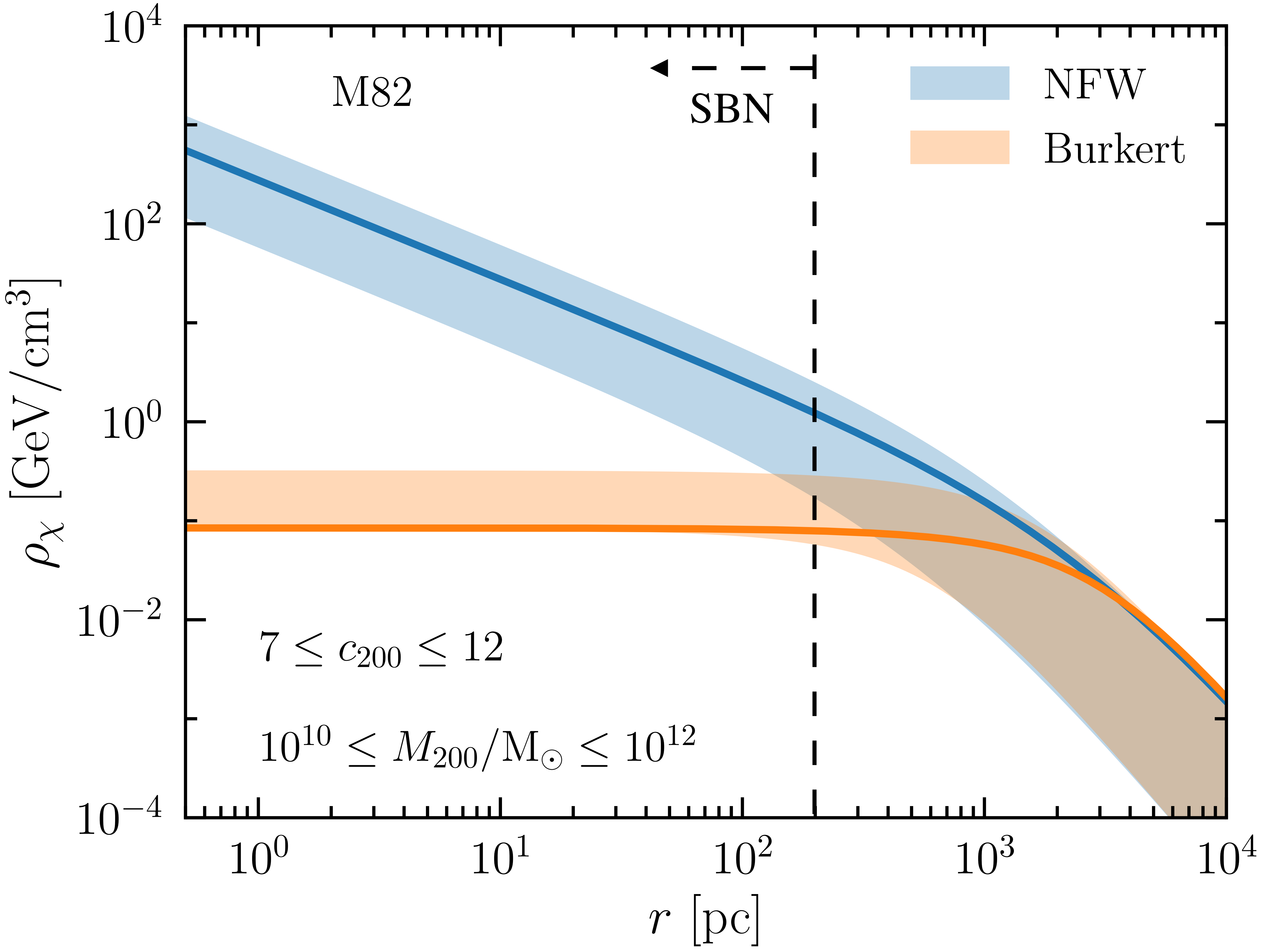
$$\tau^{\rm inel}_{\chi p} = \left(\kappa\, \sigma_{\rm inel} \frac{\rho_\chi}{m_\chi}\right)^{-1}$$

Production of γ-rays →

$$p + \chi \to \pi^{\pm}\, \pi^0 ... \to \gamma\, \nu ...$$

Rescaling νN cross-section

DM halo density profile



✦ Large uncertainty on the DM density inside the SBG core

✦ Parameters from cosmological simulations

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

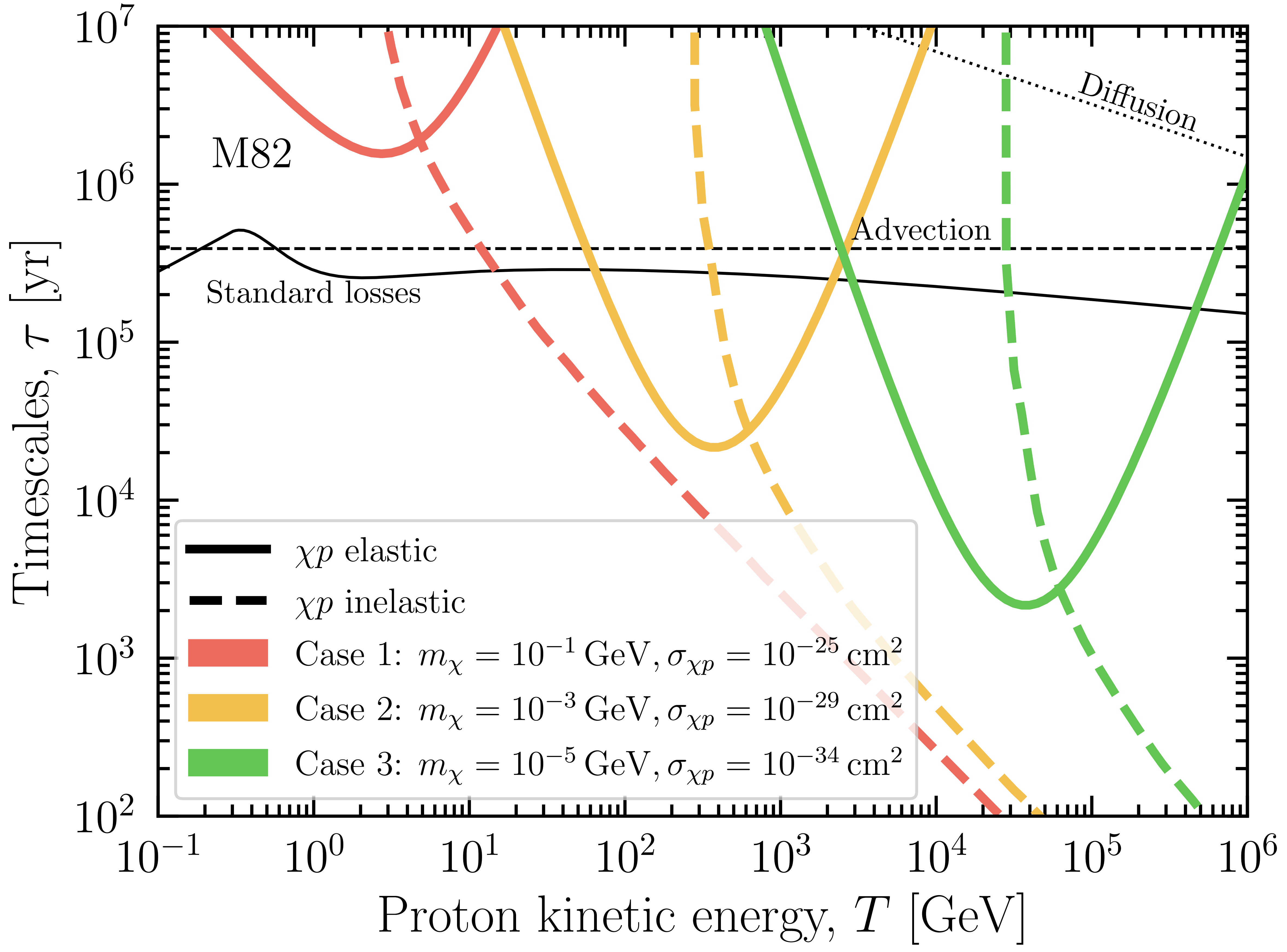
concentration *total mass*

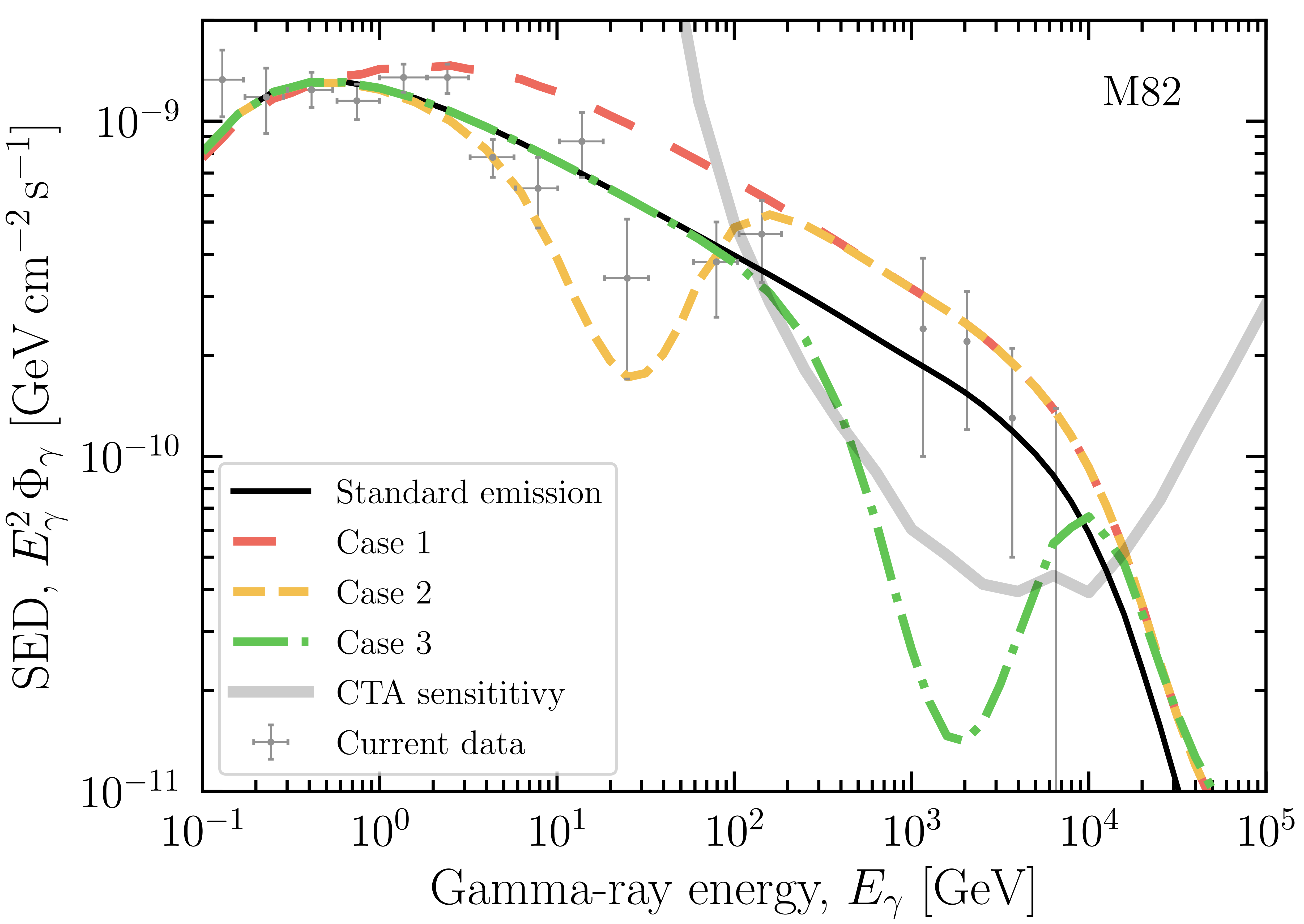
✦ However, marginal effects on the γ-ray emission

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

Average inside the SBN

Effects of CR-DM scatterings





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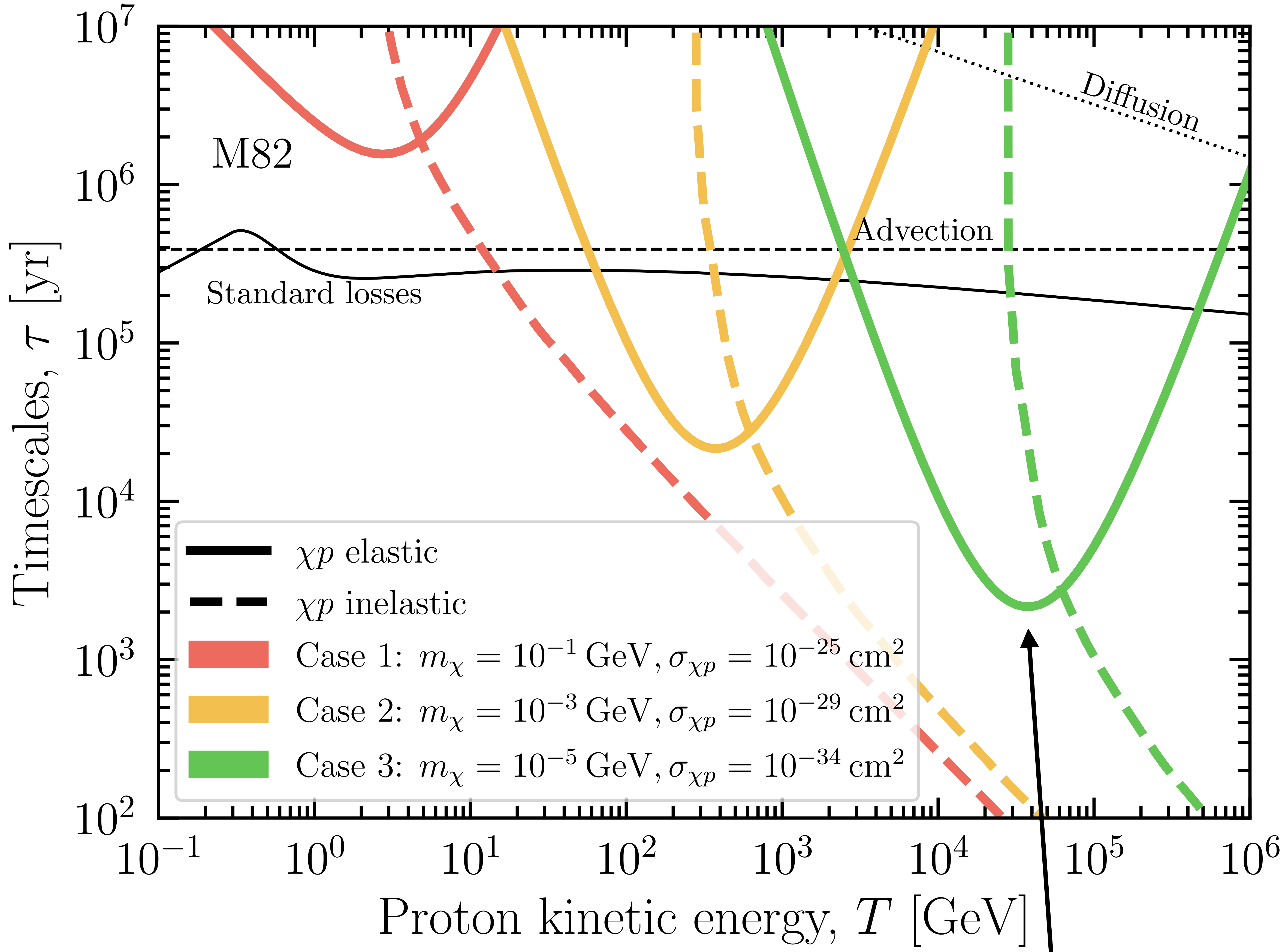
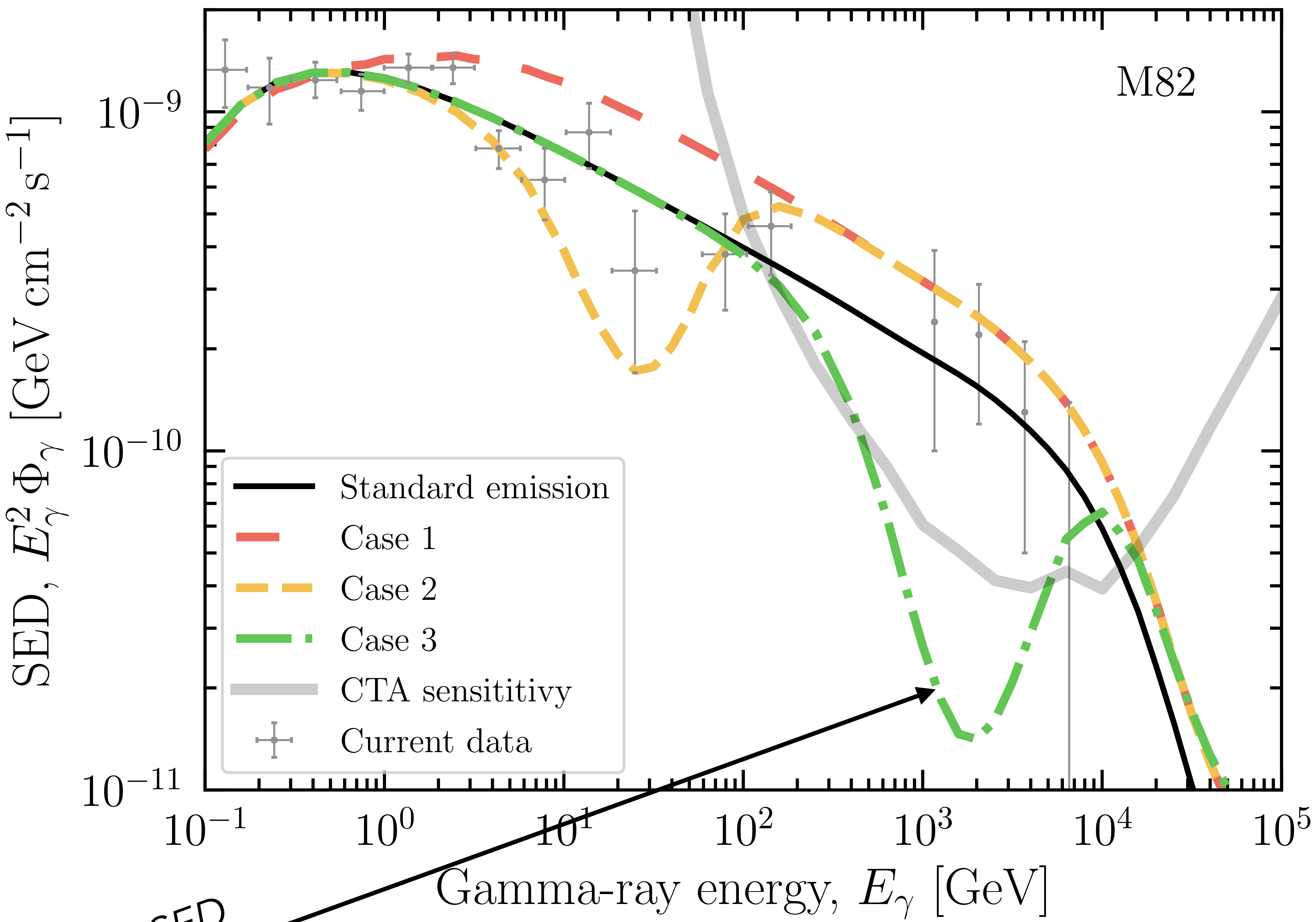


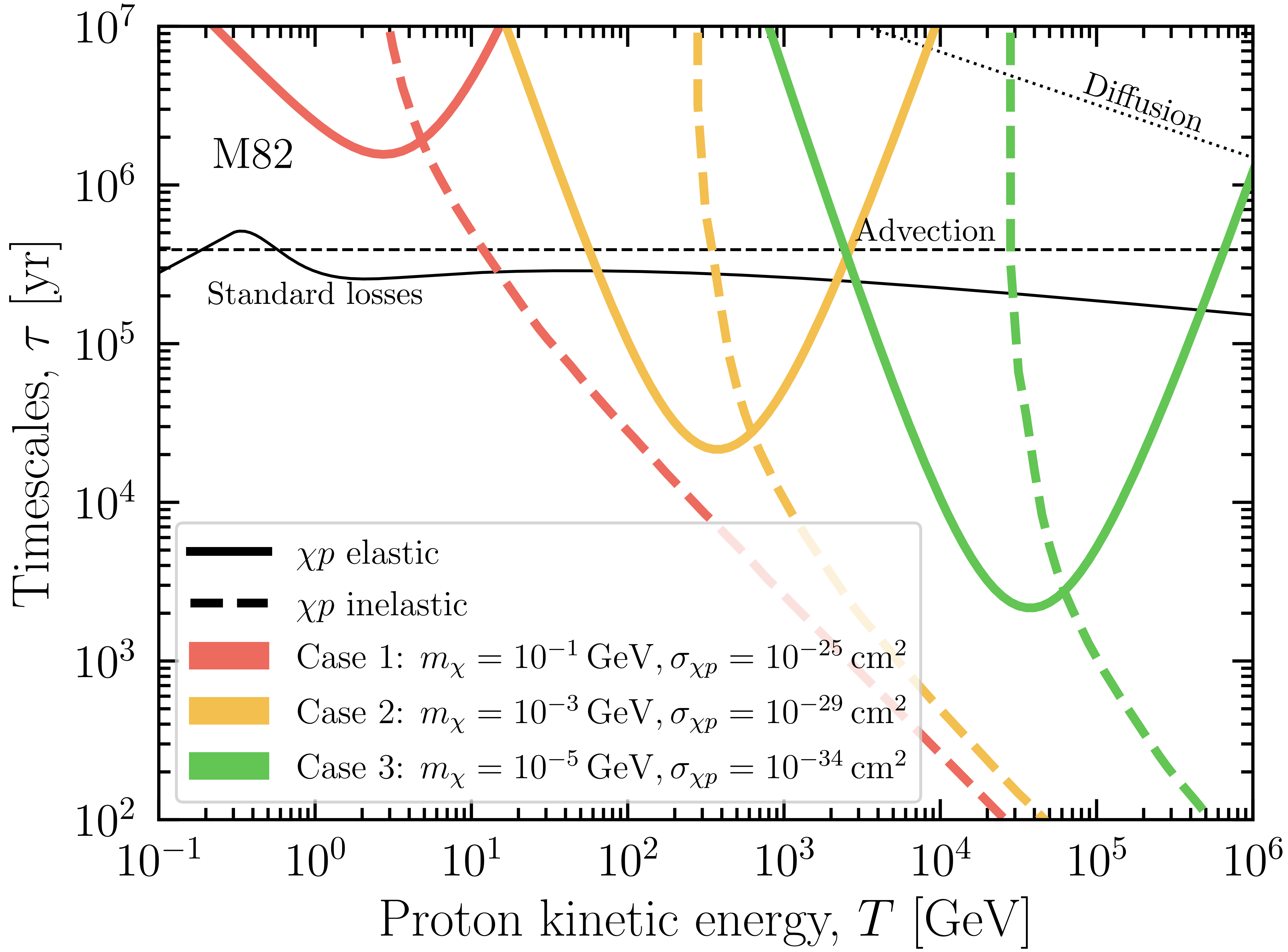


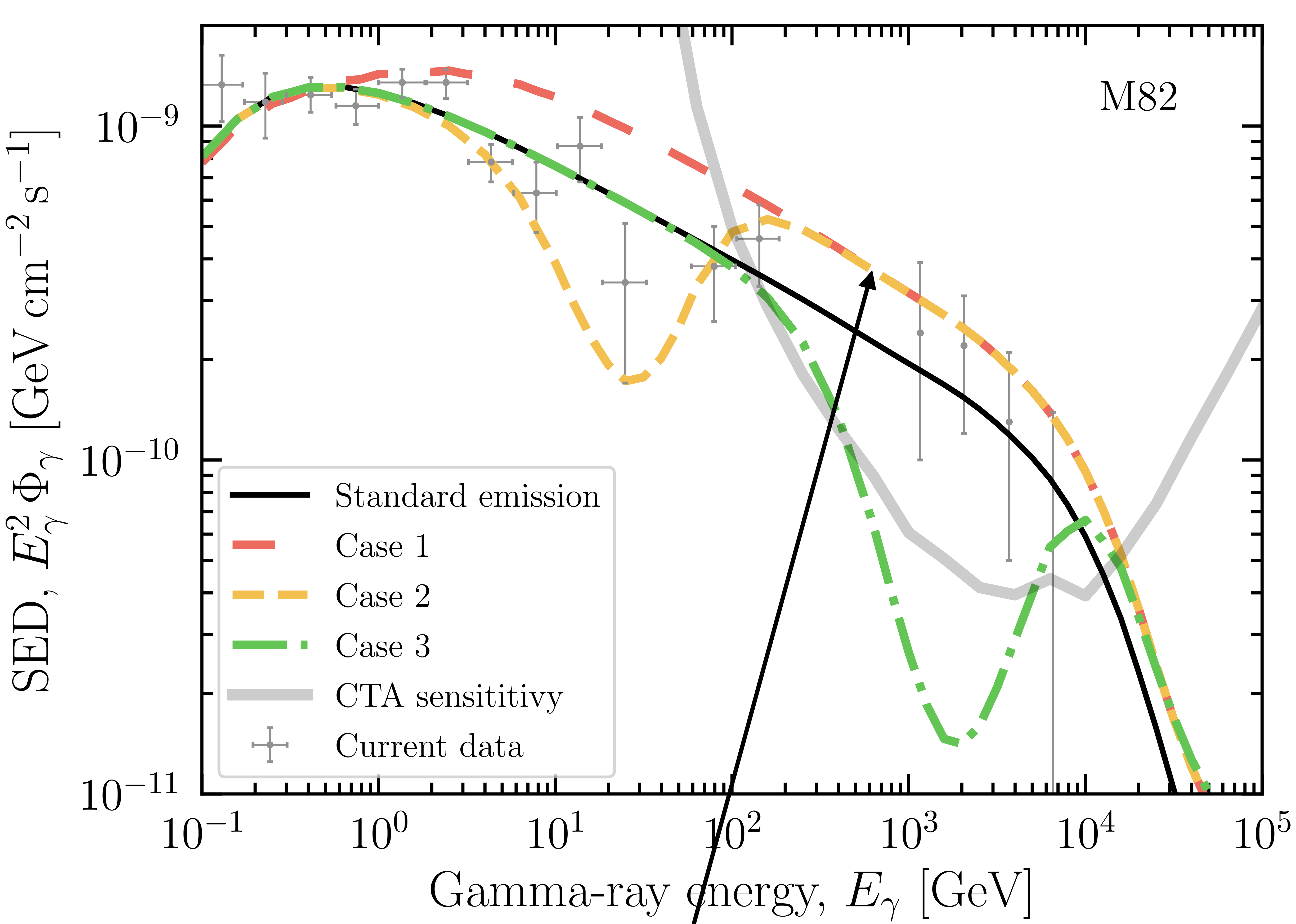
Dip in the γ-ray SED

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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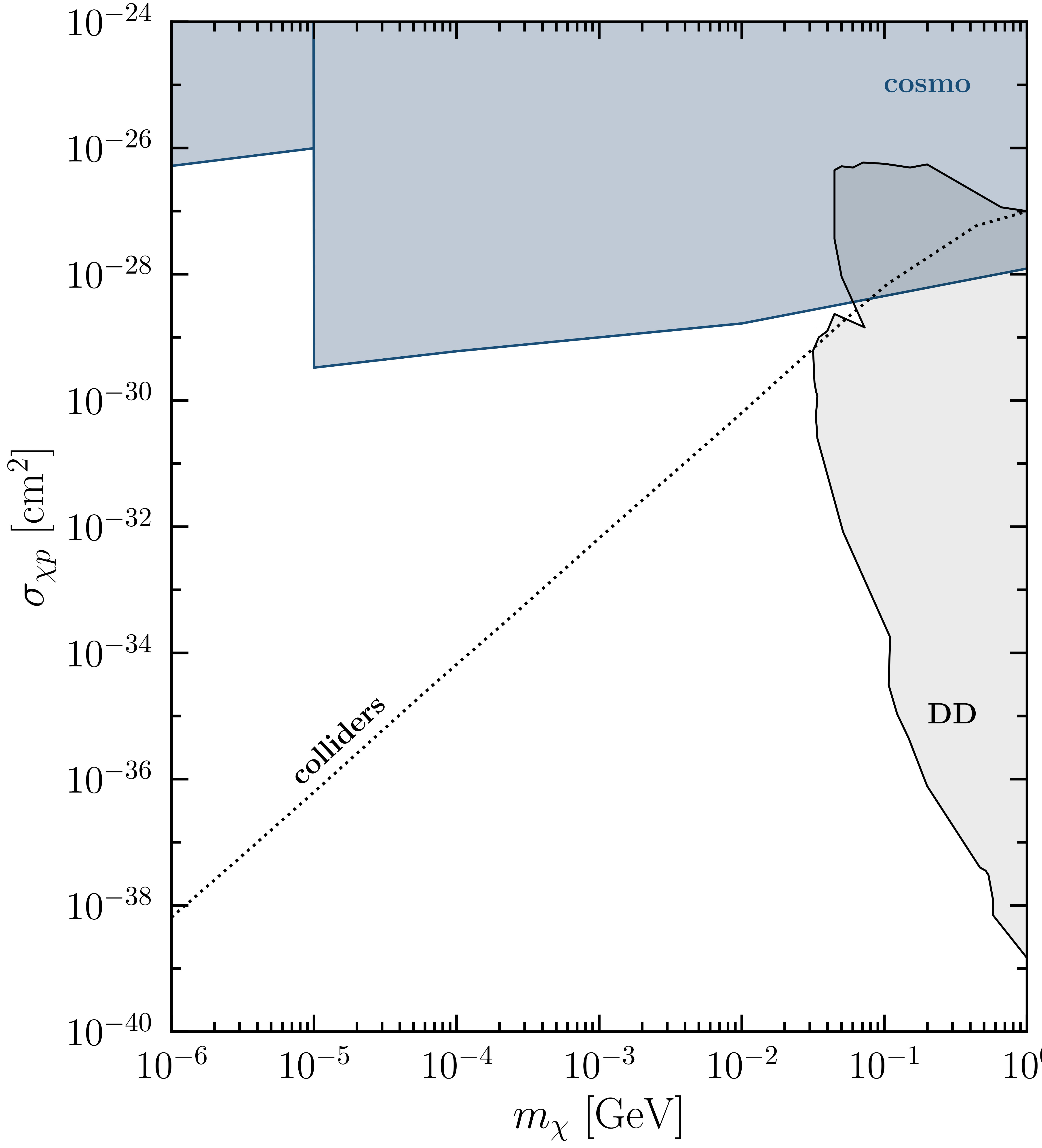
Higher gamma-ray flux due to inelastic χp interaction

Constraints from SBGs



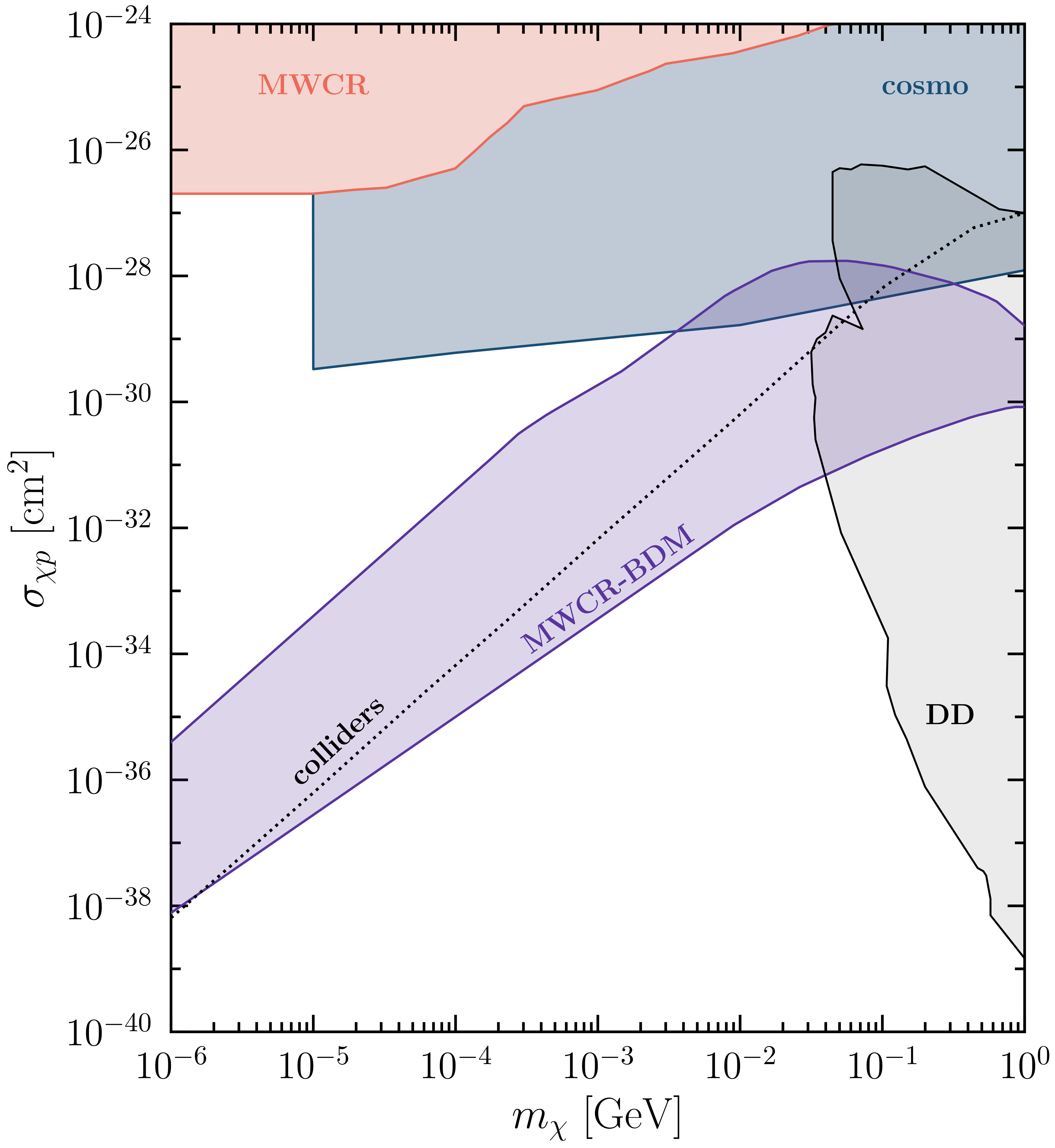
Constraints from SBGs

- ✦ Distortions of Milky-Way Cosmic-Rays

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

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

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



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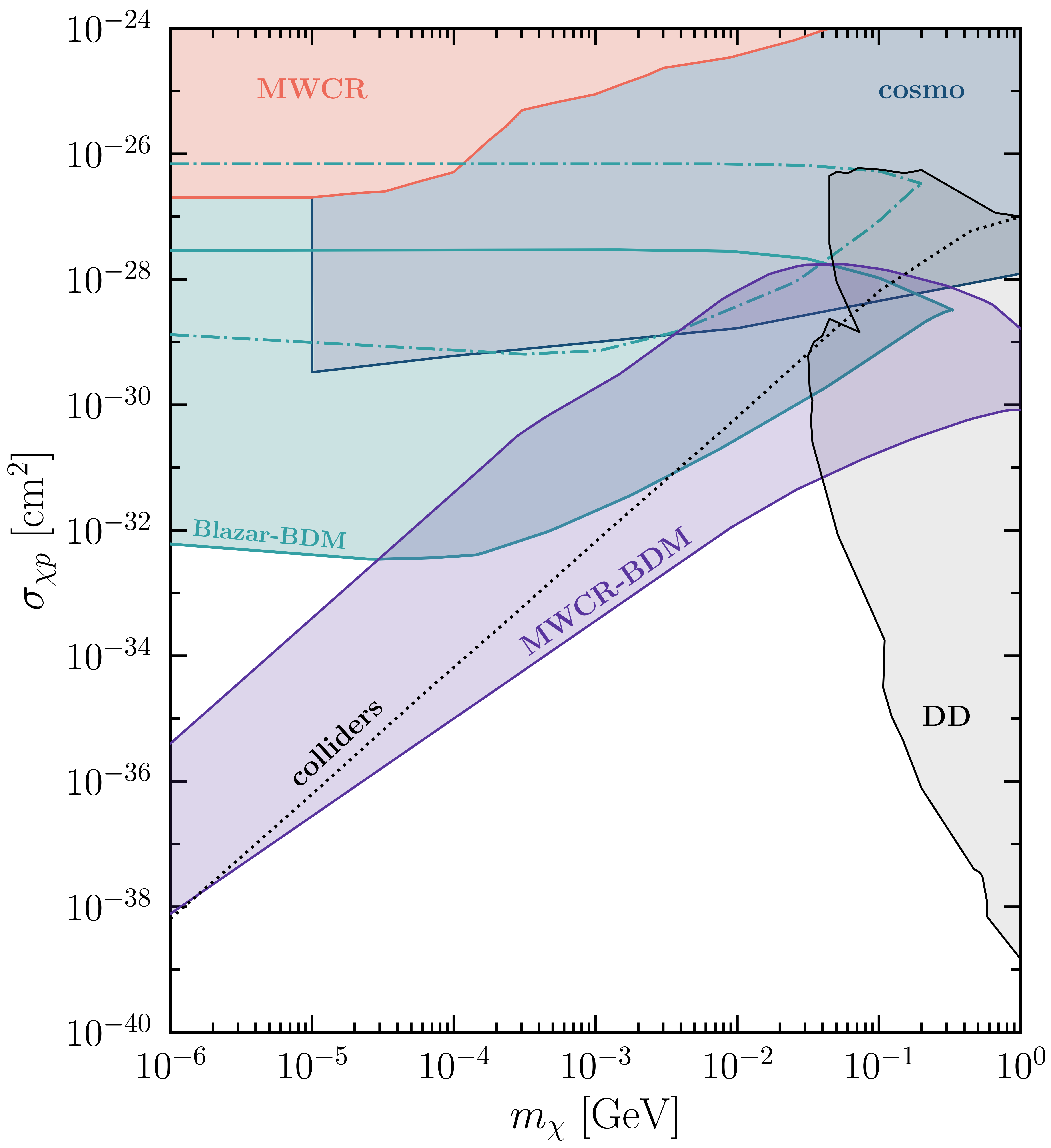
- ✦ **Boosted DM from blazar jets**, assuming DM spikes (high density) around the black holes ➜ large uncertainties!

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



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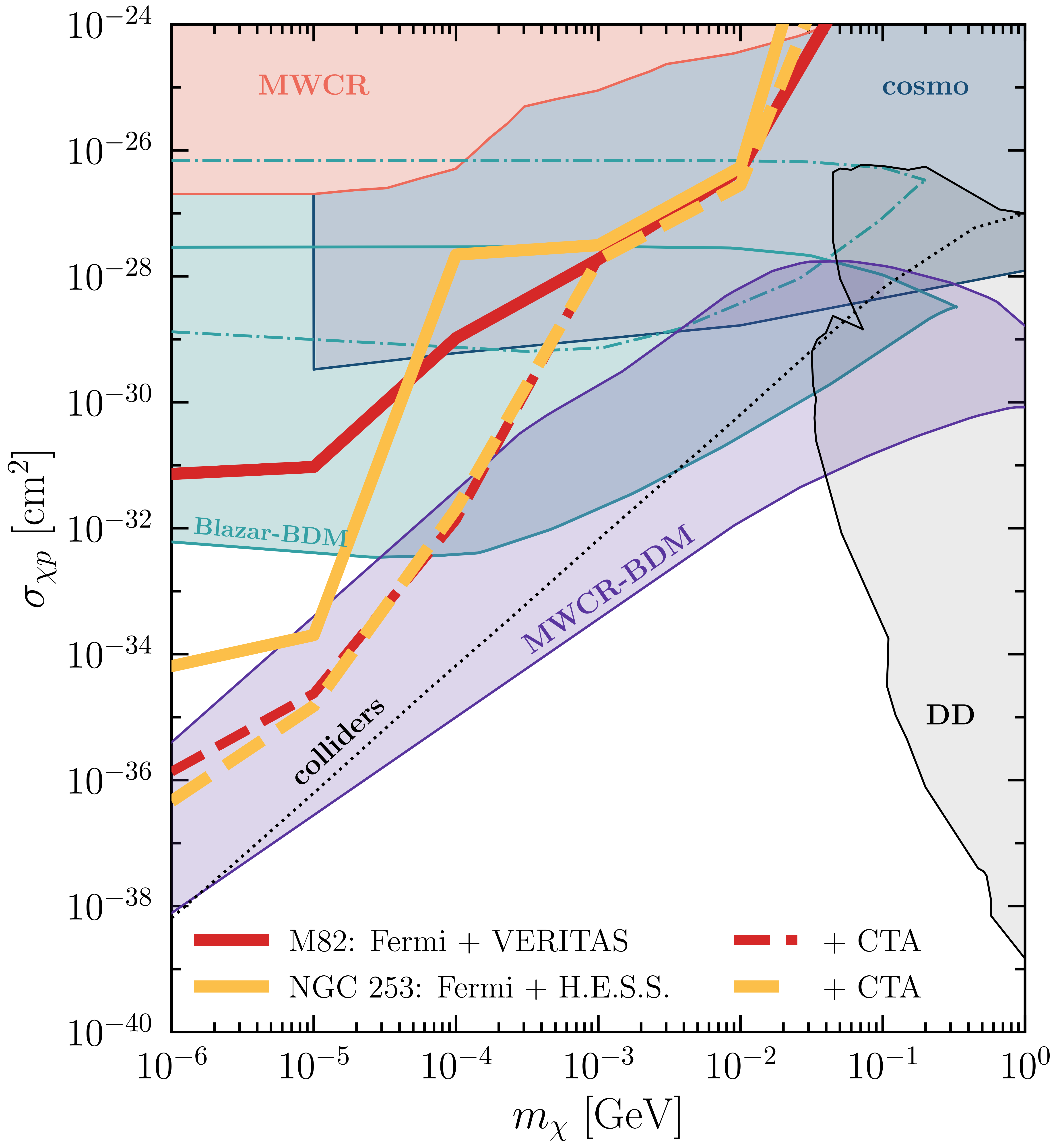
*Wang+ **PRL 128 (2022)***, Granelli+ *J**CAP 07 (2022)***

OUR CONSTRAINTS FROM SBG (5σ)

✦ **M82** and **NGC253** with current and future data

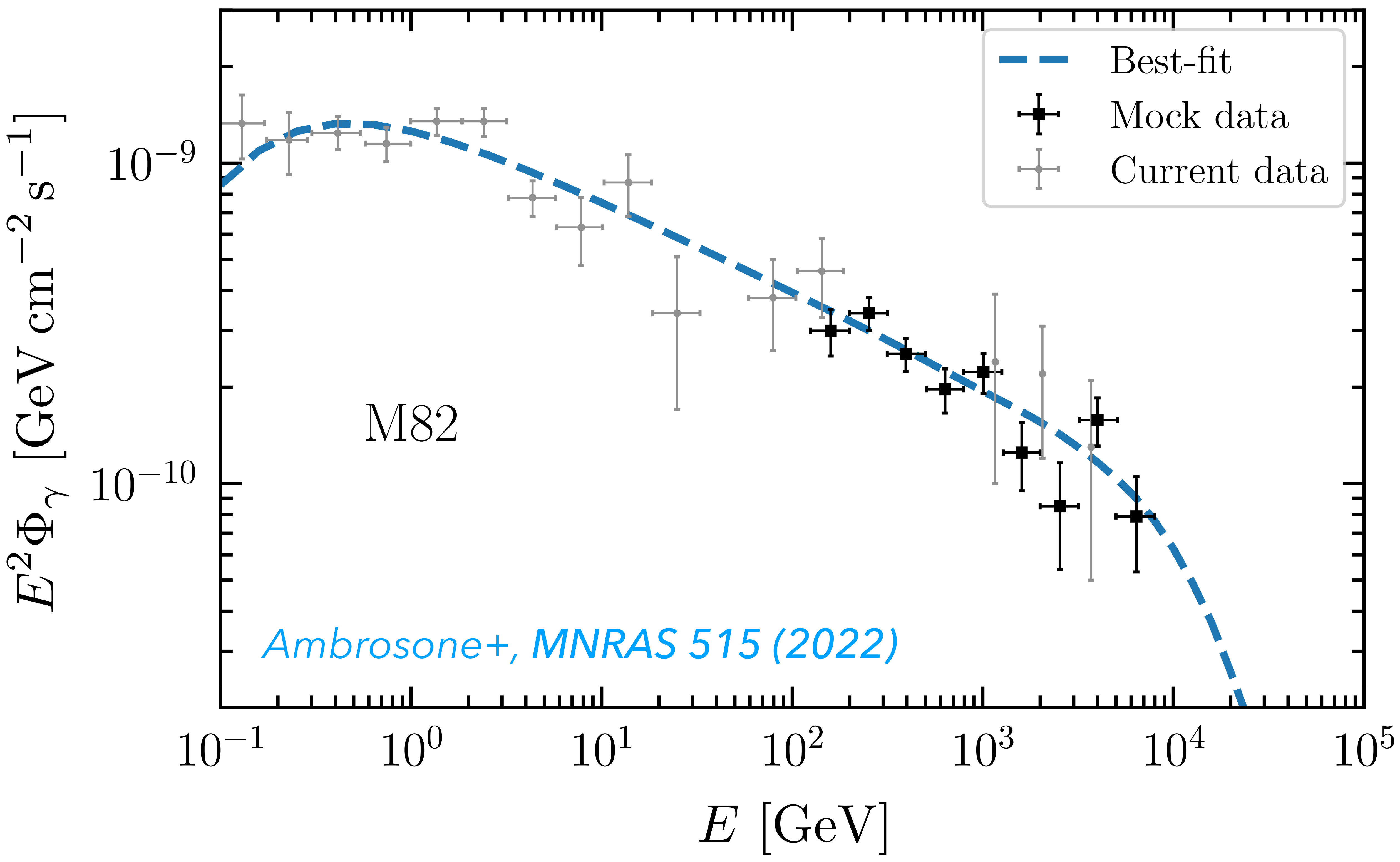
*Ambrosone, MC, Fiorillo, Marinelli, Miele, **PRL 131 (2023)***

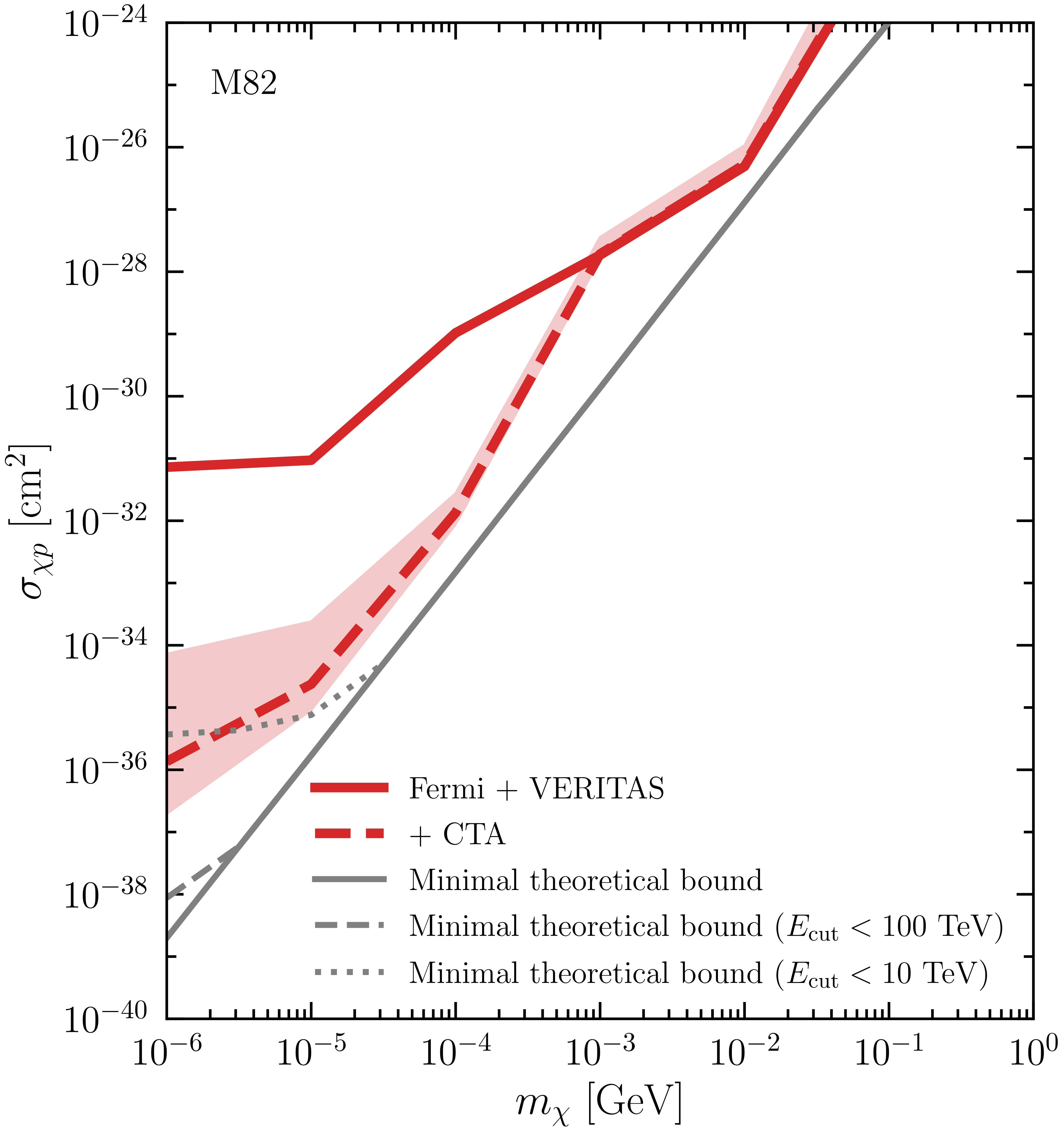


Dependence on DM density

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

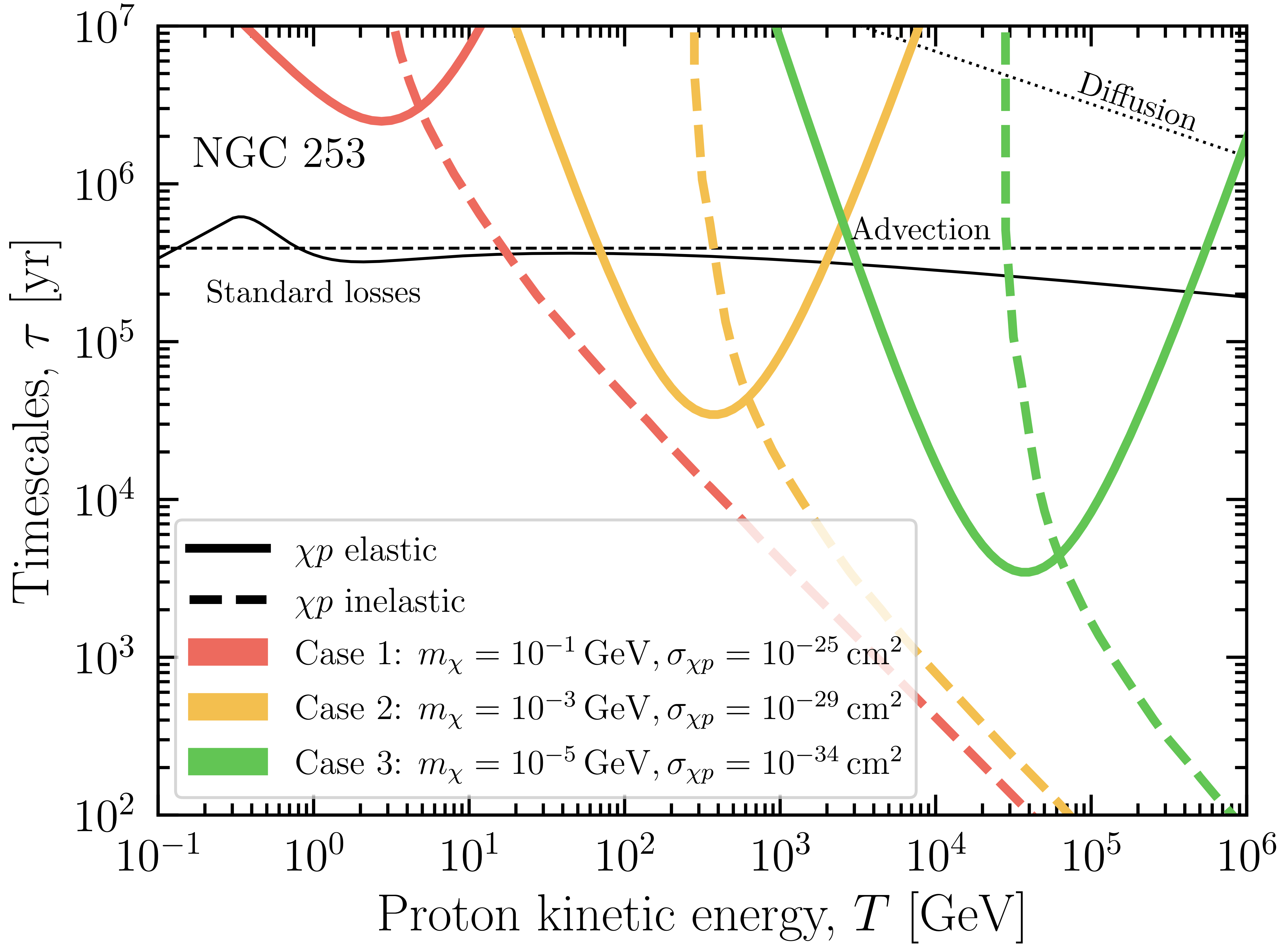
- Current γ-ray data of M82 and NGC 253 sources put **strong and highly complementary constraints** on DM-proton cross-section

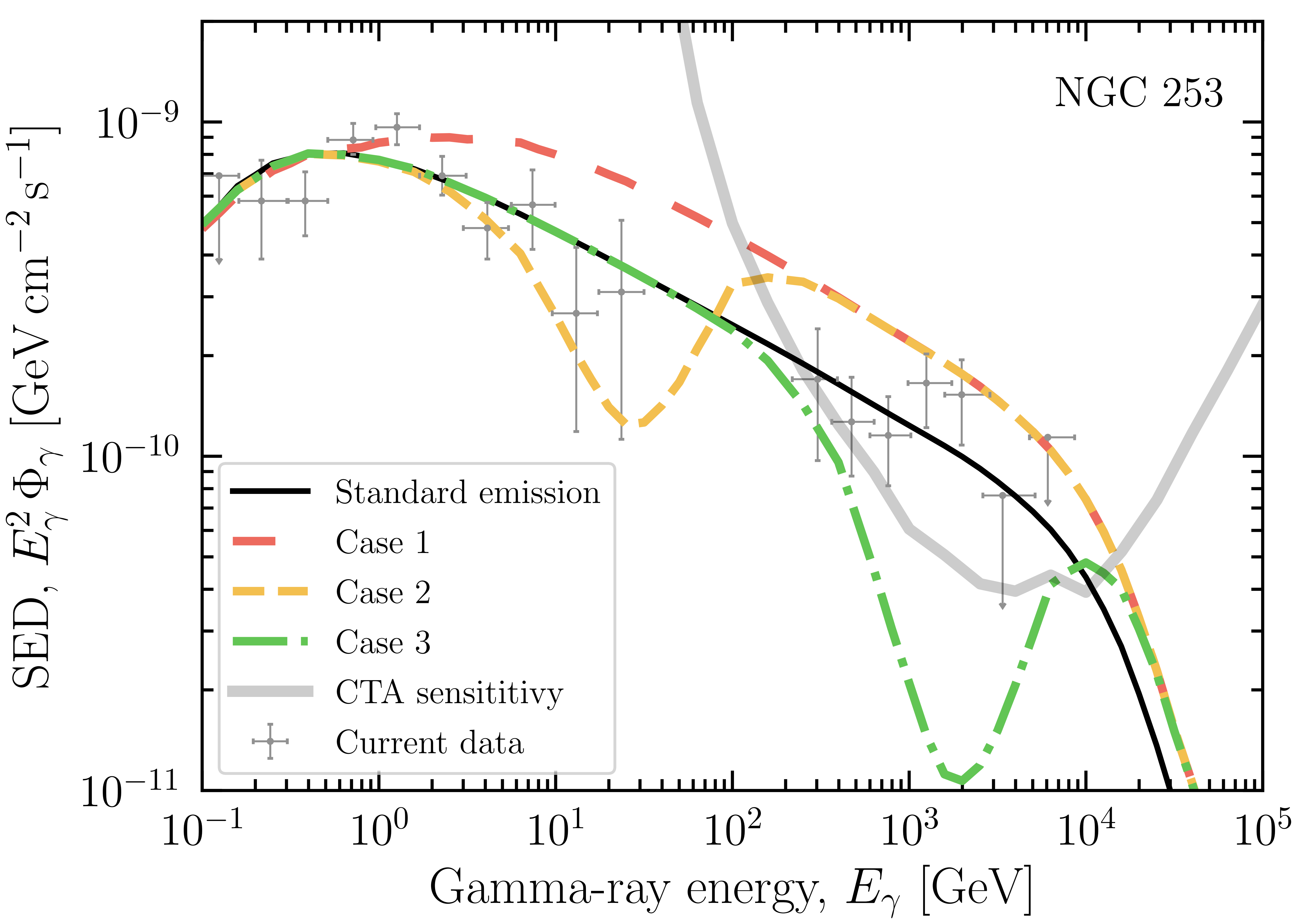
- **Stay tuned:** upcoming gamma-ray telescopes will give us a better understanding of the cosmic-ray transport inside SBGs

Thanks for listening!

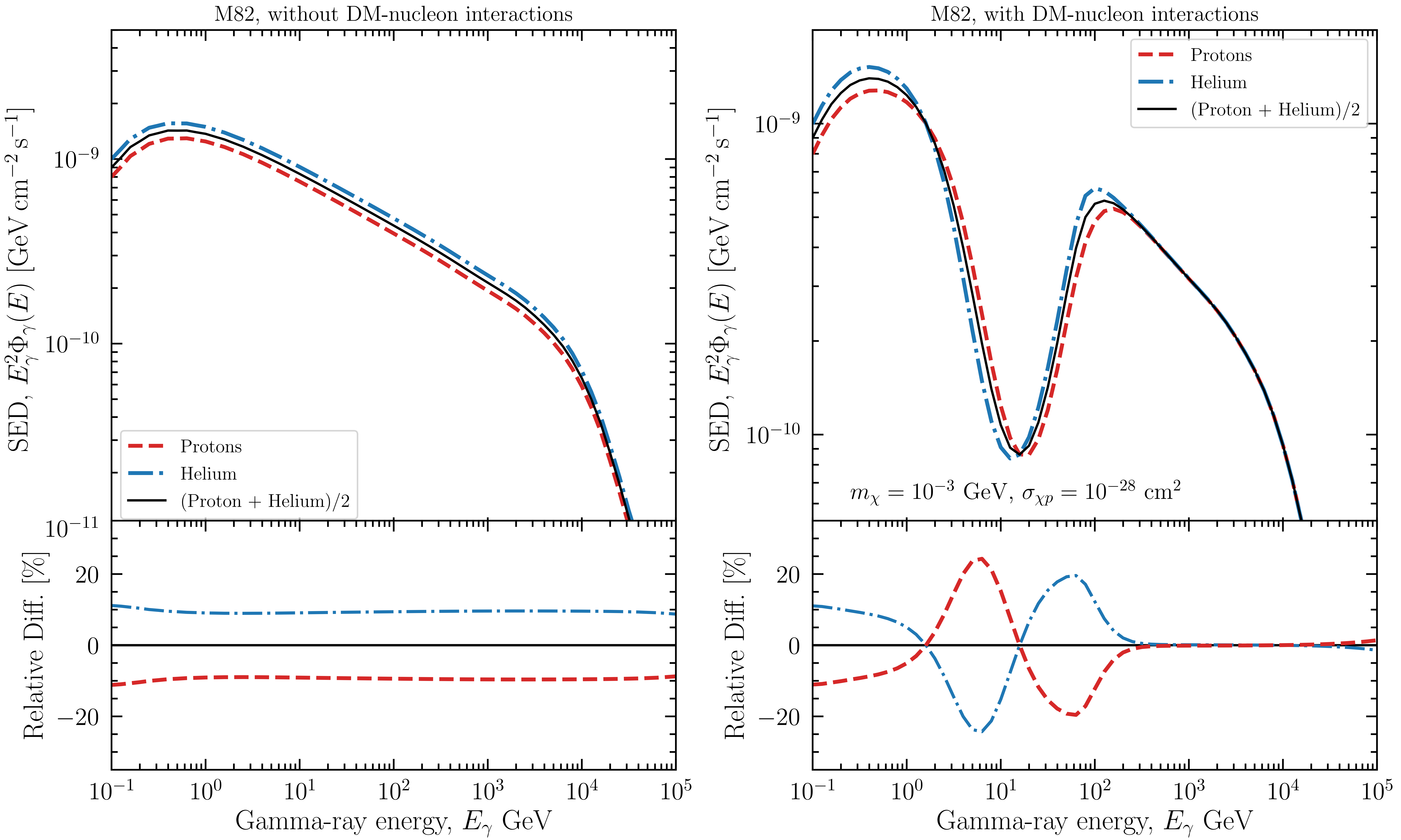
Backup slides

NGC 253


NGC 253
Diffusion
Advection
Standard losses
χp elastic
χp 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
Timescales, τ [yr]
Proton kinetic energy, T [GeV]


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

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

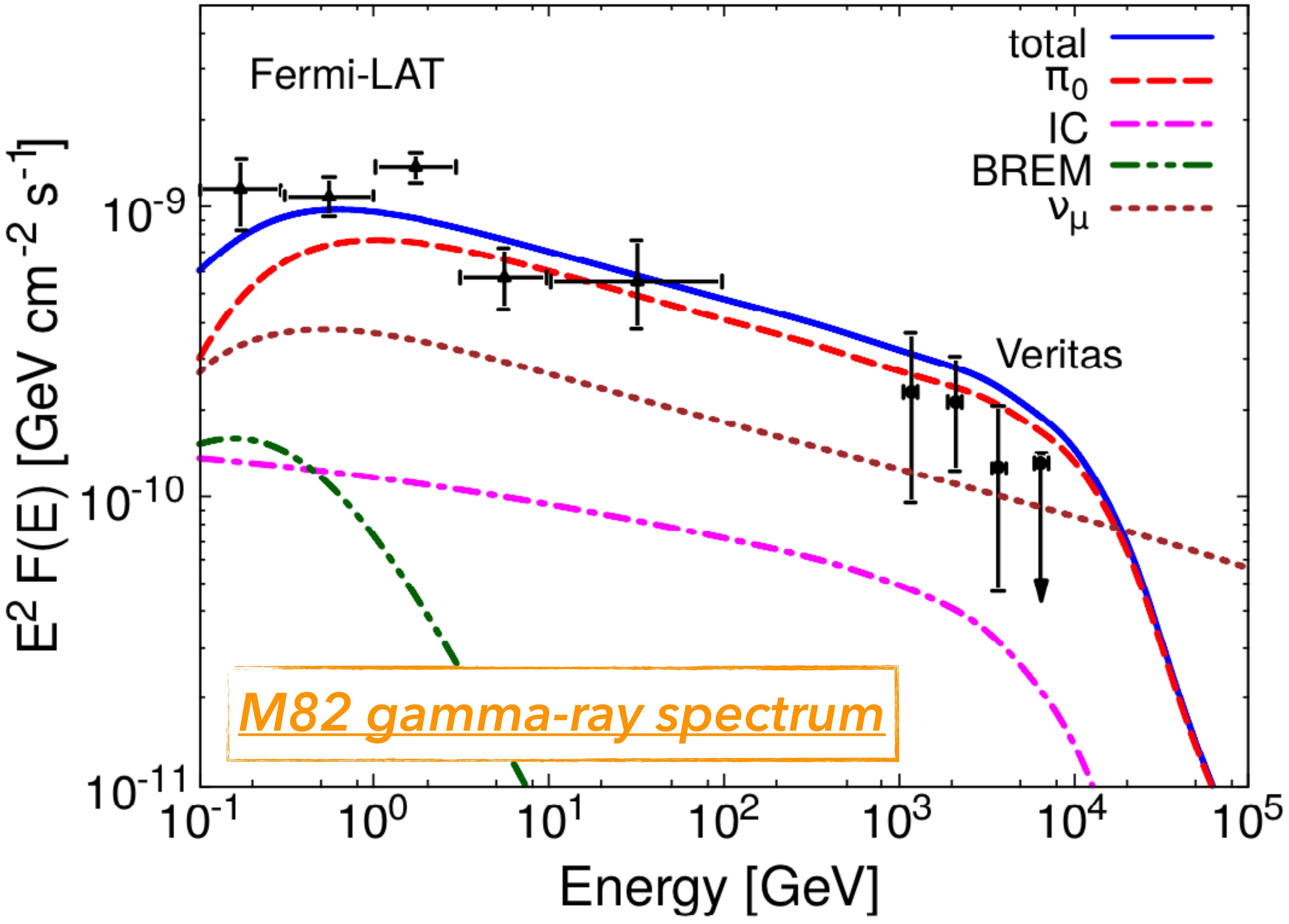
parameter	value	parameter	value
$p_{p,\max}$	10^2 PeV	$\mathcal{R}_{\rm SN}$	$0.06\ {\rm yr}^{-1}$
α	4.2	B	$200\ \mu$G
R	0.25 kpc	$n_{\rm ISM}$	$100\ {\rm cm}^{-3}$
D_L	3.9 Mpc	$v_{\rm wind}$	700 km/s
$\xi_{\rm CR}$	0.1	$U_{\rm rad}$	$2500\ {\rm eV/cm}^3$

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

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



Bayesian analysis

Ambrosone+, 2106.12348

Results of the Likelihood Analysis of Current Gamma-Ray Data

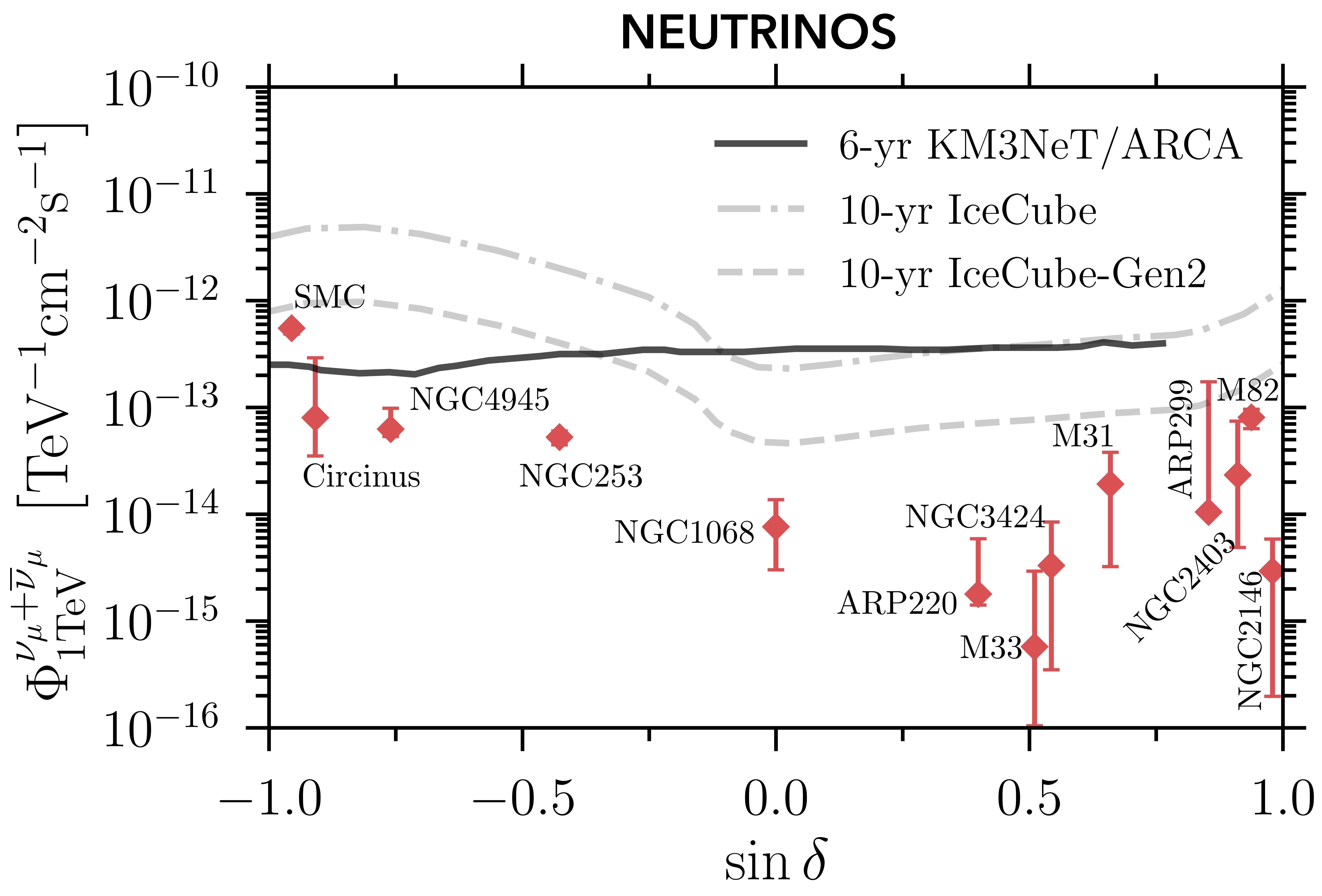
Source	Uniform Prior $\dot{M}_*$	Most Likely Values $(\dot{M}_*, \Gamma)$	68% Credible Intervals $\dot{M}_*$	68% Credible Intervals Γ	χ^2/dof
M82	3.0–30	(4.5, 2.30)	[4.3, 4.6]	[2.27, 2.33]	1.24
NGC 253	1.4–17	(3.3, 2.30)	[3.14, 3.40]	[2.28, 2.32]	1.32
ARP 220	60–740	(740, 2.66)	[492, 740]	[2.51, 2.68]	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

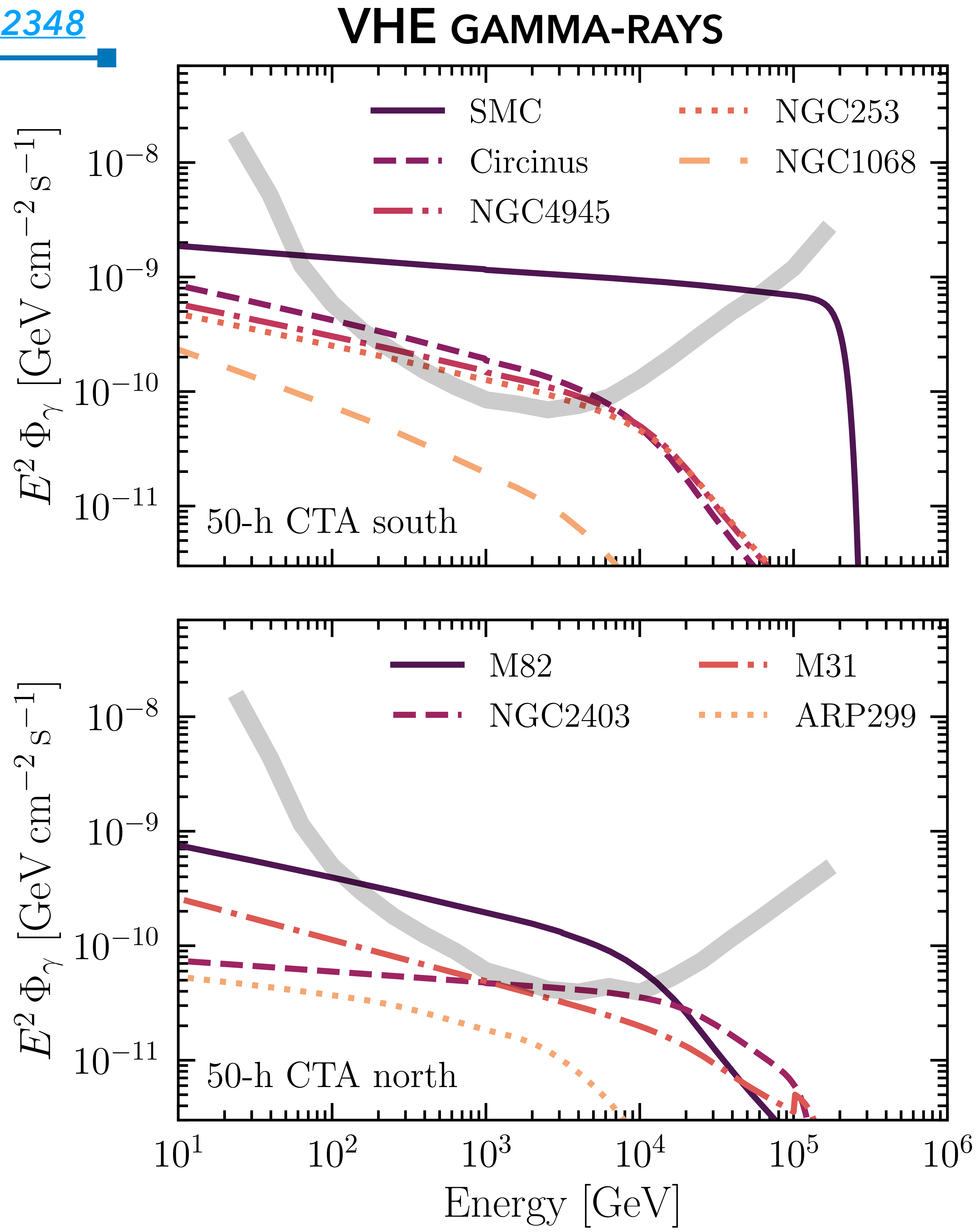
Note. The columns report the source name, the SFR prior, the most likely values of the two parameters, the 68% maximum posterior density credible intervals of the marginal distributions, and the reduced chi-squared values considered as an estimate of the goodness of the fit. The star formation rate $\dot{M}_*$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





Future joint ν-γ observations

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