Signatures of Cosmic-Rays Transports on Gamma-Ray Starburst Galaxies Observations

Antonio Ambrosone

In collaboration with

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

Based on ApJL 919 [2106.12348] and MNRAS [2203.03642]

6^{th} International Symposium on Ultra High Energy Cosmic Rays (UHECR2022), 3-7 October 2022

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$_\odot$/yr, to be compared with ~1 M$_\odot$/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 $(n_{\mathrm{ISM}} \simeq 10^2 \mathrm{cm}^{-3})$

✦ 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

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

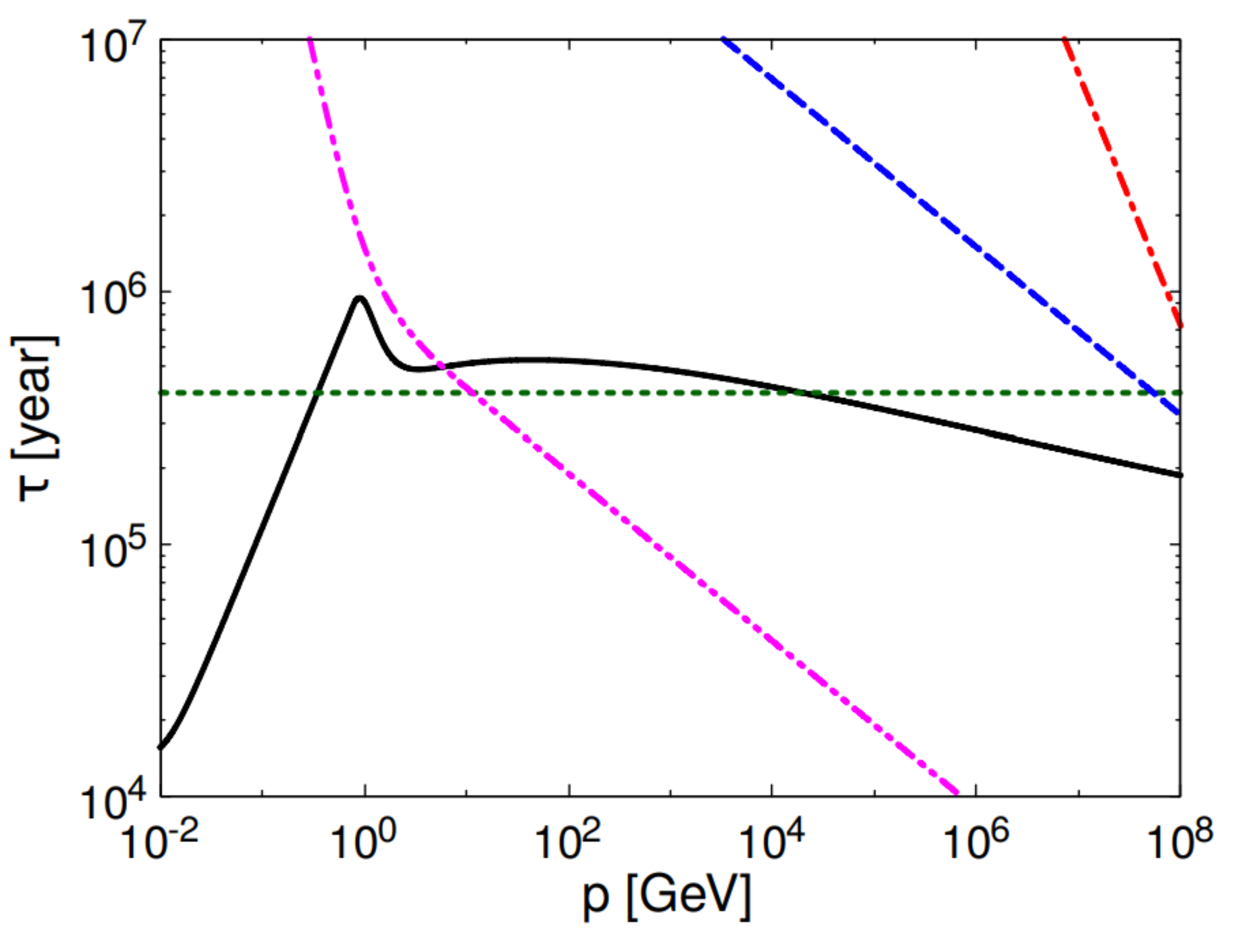
✦ **Neutrinos** and **γ-rays** from pions decays:

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

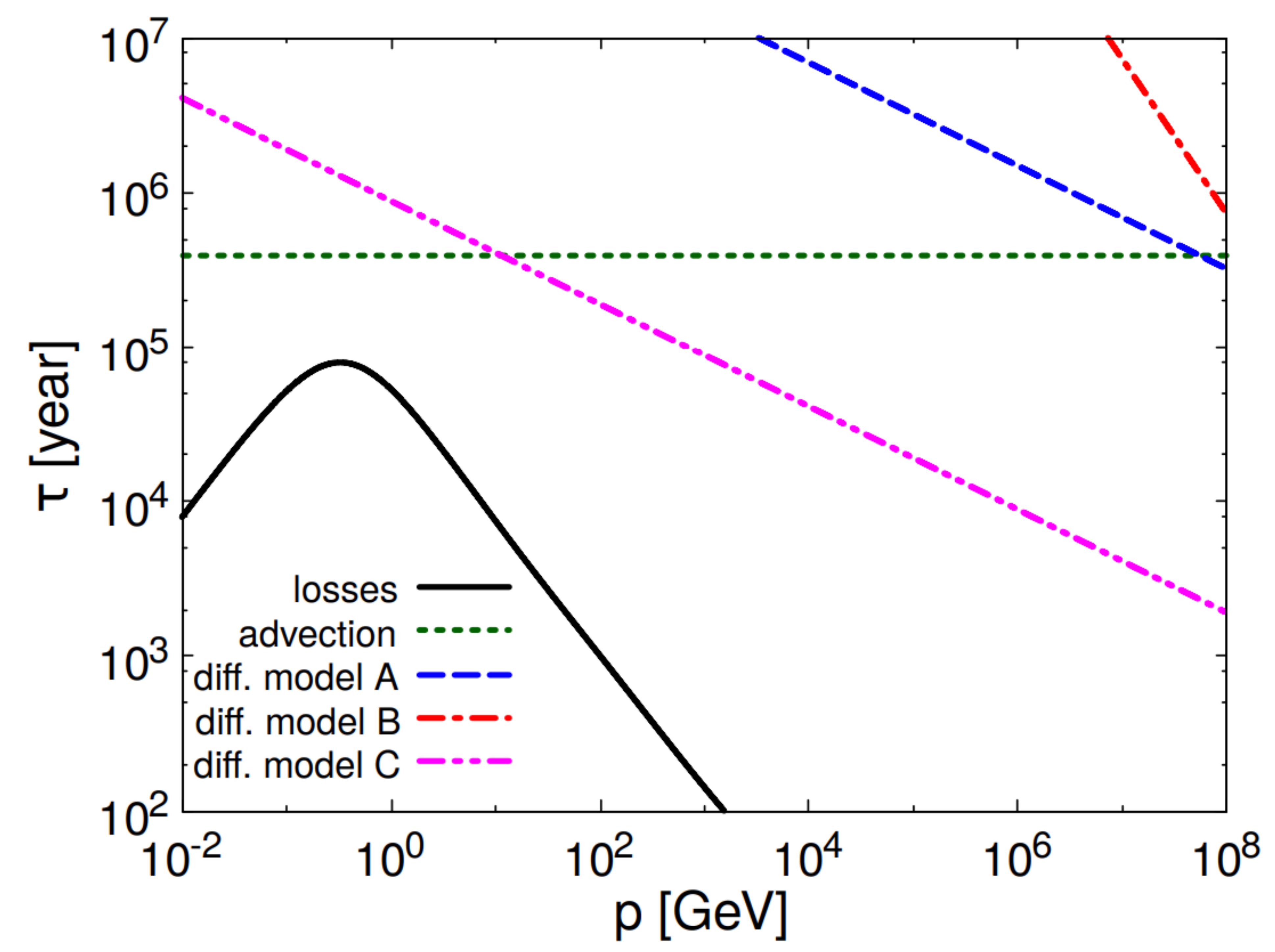
Cosmic Rays Transport in SBNs

Peretti et al., ***arXiv:1812.01996***, ***arXiv:1911.06163*** *(Peretti+, MNRAS 487 (2019), MNRAS 493 (2020))*

High-energy Protons Timescales inside the nucleus



High-Energy Electrons Timescales inside the Nucleus



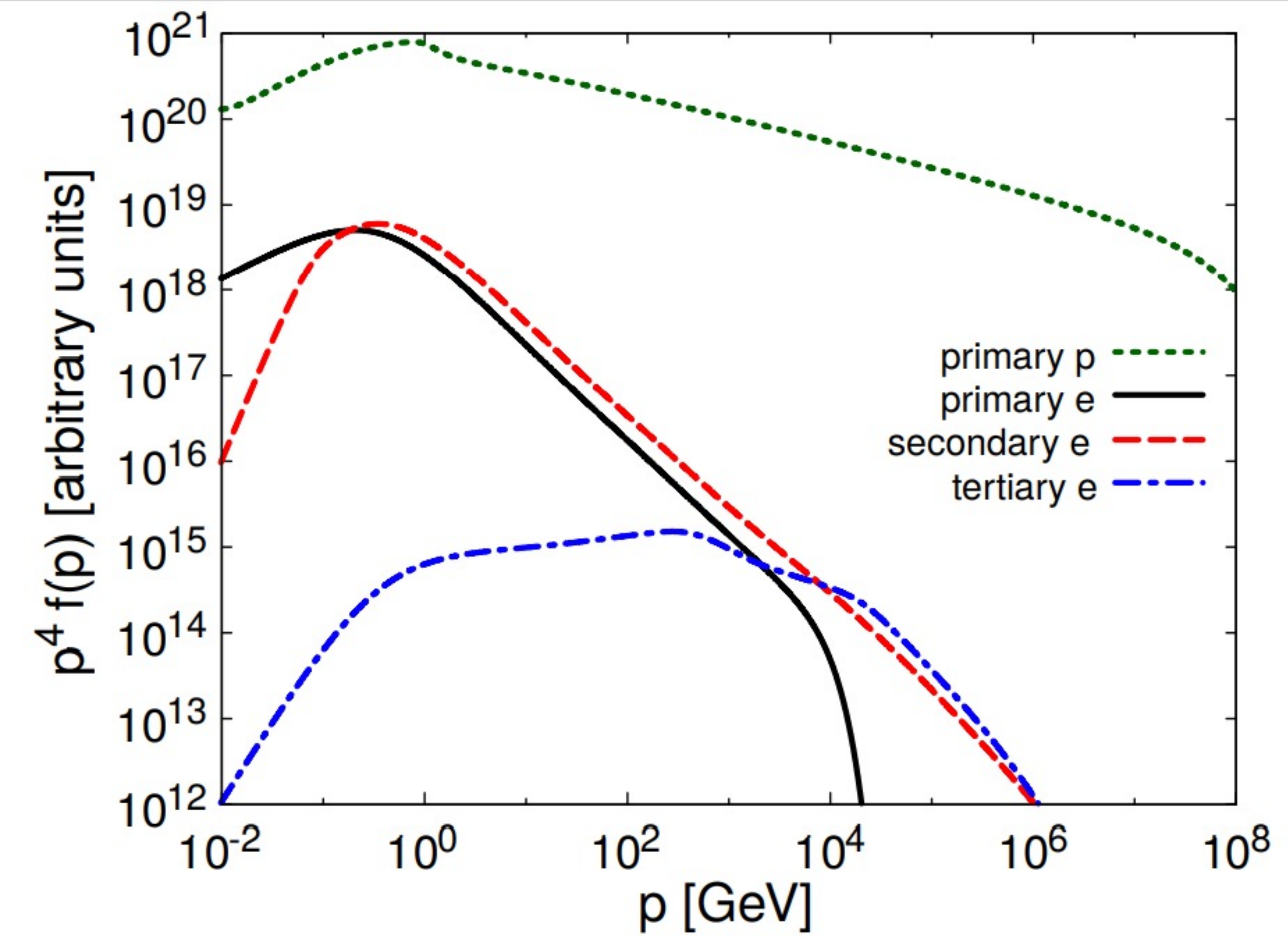
- ✦ Advection as a primary cause of CR escape
- ✦ Diffusion has a marginal impact on the transport
- ✦ As the star formation rate increases, more protons are confined: Calorimetric limit

✦Totally confined within the Nucleus

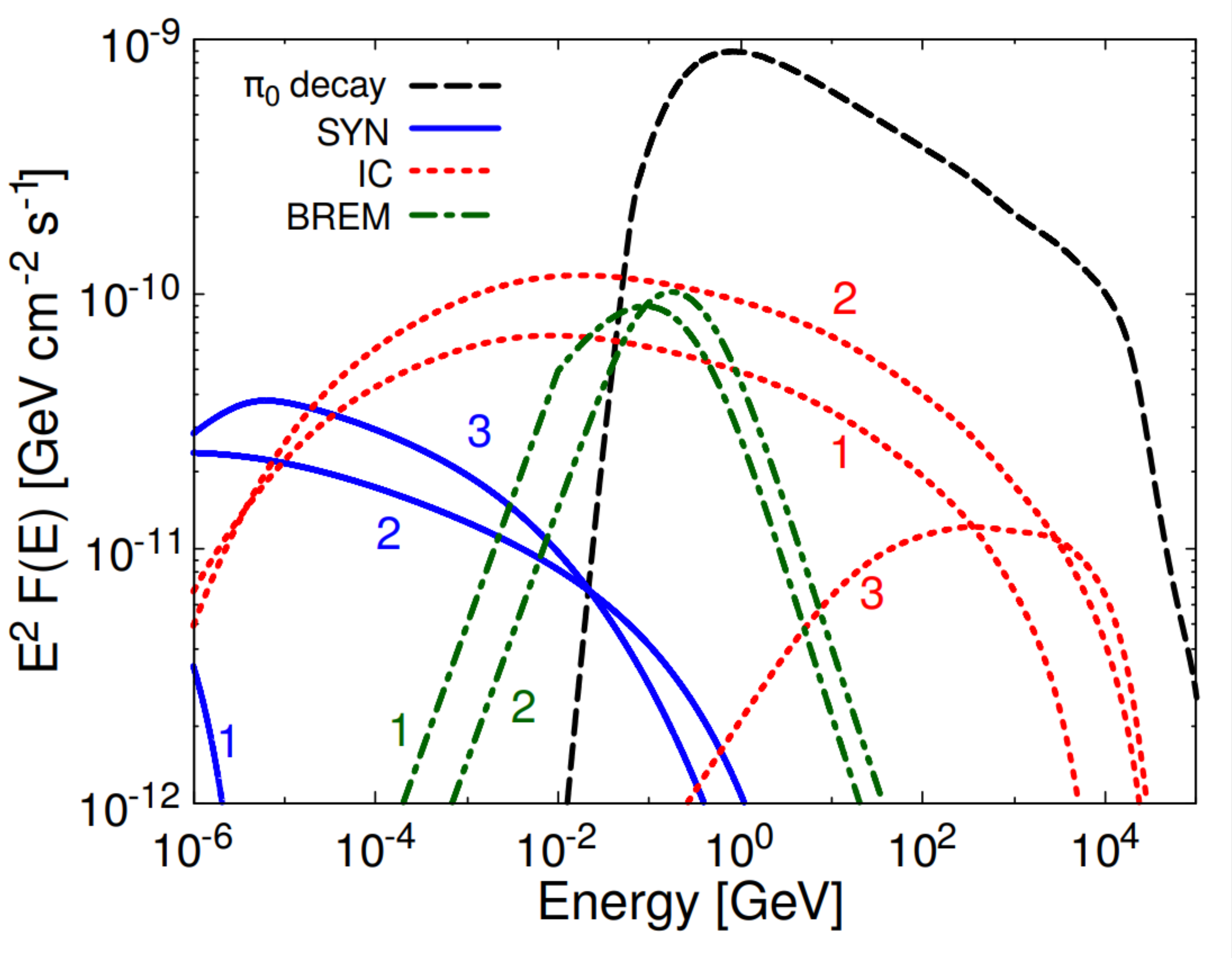
Signatures of CRs on Gamma-Rays

Peretti et al., ***arXiv:1812.01996****,* ***arXiv:1911.06163 (****Peretti+, MNRAS 487 (2019), MNRAS 493 (2020))*

Distribution of high-energy protons in the nucleus



Gamma-ray spectrum expected at the Earth



✦ Leaky-Box Model For CR Transport

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

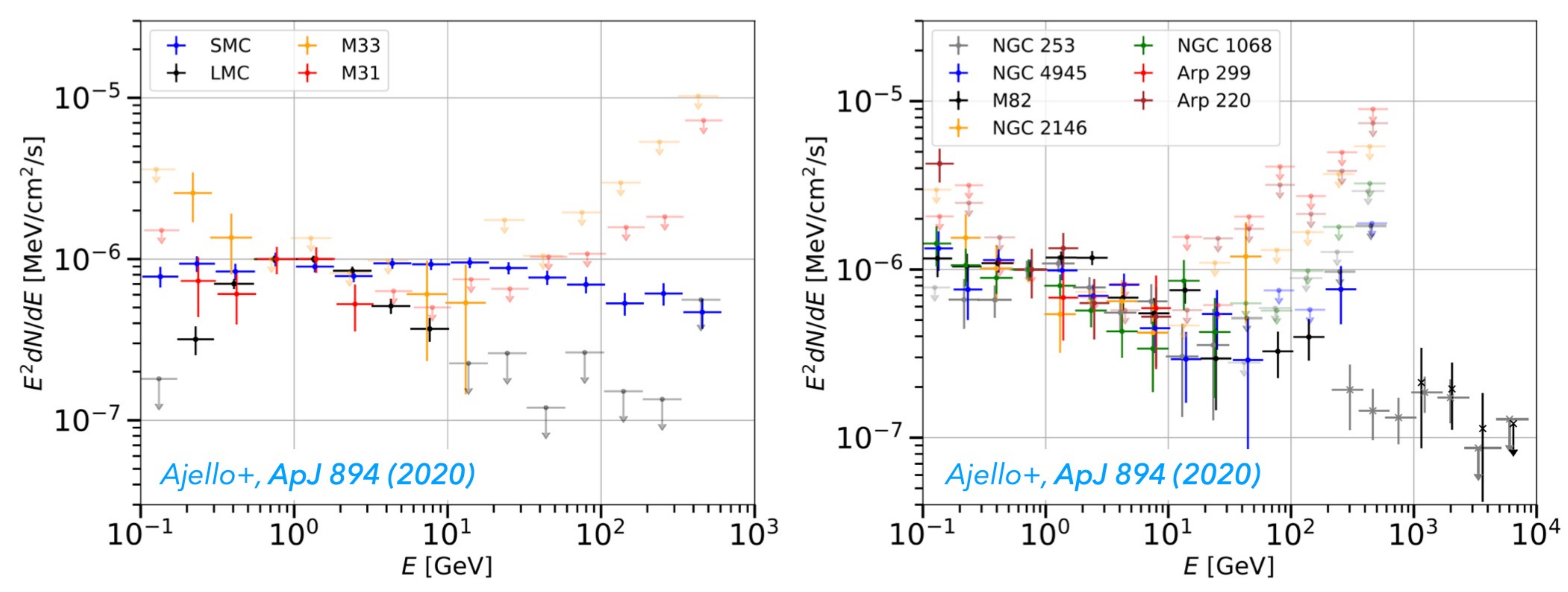
✦ Gamma-Ray Spectrum dominated by hadronic collisions

✦The Gamma-ray spectrum represents the proton distribution in the nucleus

Can we probe the calorimetric scenario using local /nearby SBGs?

Nearby SBG Gamma-Ray Emissions

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



✦Only a dozen of sources have been detected

✦ Only few of them have both GeV and TeV data

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)

Ambrosone+, ApJL 919
[2106.12348]

Probing the SBG Calorimetric Scenario

We analyze the observed nearby SBG Gamma-ray SED: Bayesian approach

Source	Uniform prior $\dot{M}_*$
M82	3.0 – 30
NGC 253	1.4 – 17
ARP 220	60 – 740
NGC 4945	0.35 – 4.15
NGC 1068	5 – 93
NGC 2146	3 – 57
ARP 299	28 – 333
M31	0.09 – 0.90
M33	0.09 – 0.90
NGC 3424	0.4 – 5.4
NGC 2403	0.1 – 1.2
SMC	0.008 – 0.090
Circinus Galaxy	0.1 – 8.1

- ✦ We use both GeV and TeV gamma-ray data (Fermi-LAT + IACTs data)
- ✦IR + UV data: Prior on the star formation rate
- ✦ Starburst Nucleus of the order of 10^2pc
- ✦Escaping phenomena dominated by advection
- ✦ Using Kennicutt's relations:

$$n_{\mathrm{ISM}} = 175 \left(\frac{\dot{M}_*}{5\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}} \right)^{2/3} \mathrm{cm}^{-3}$$

Gas density as target for p-p interactions

$$U_{\mathrm{rad}} = 2500 \left(\frac{\dot{M}_*}{5\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}} \right) \mathrm{eV\,cm}^{-3}$$

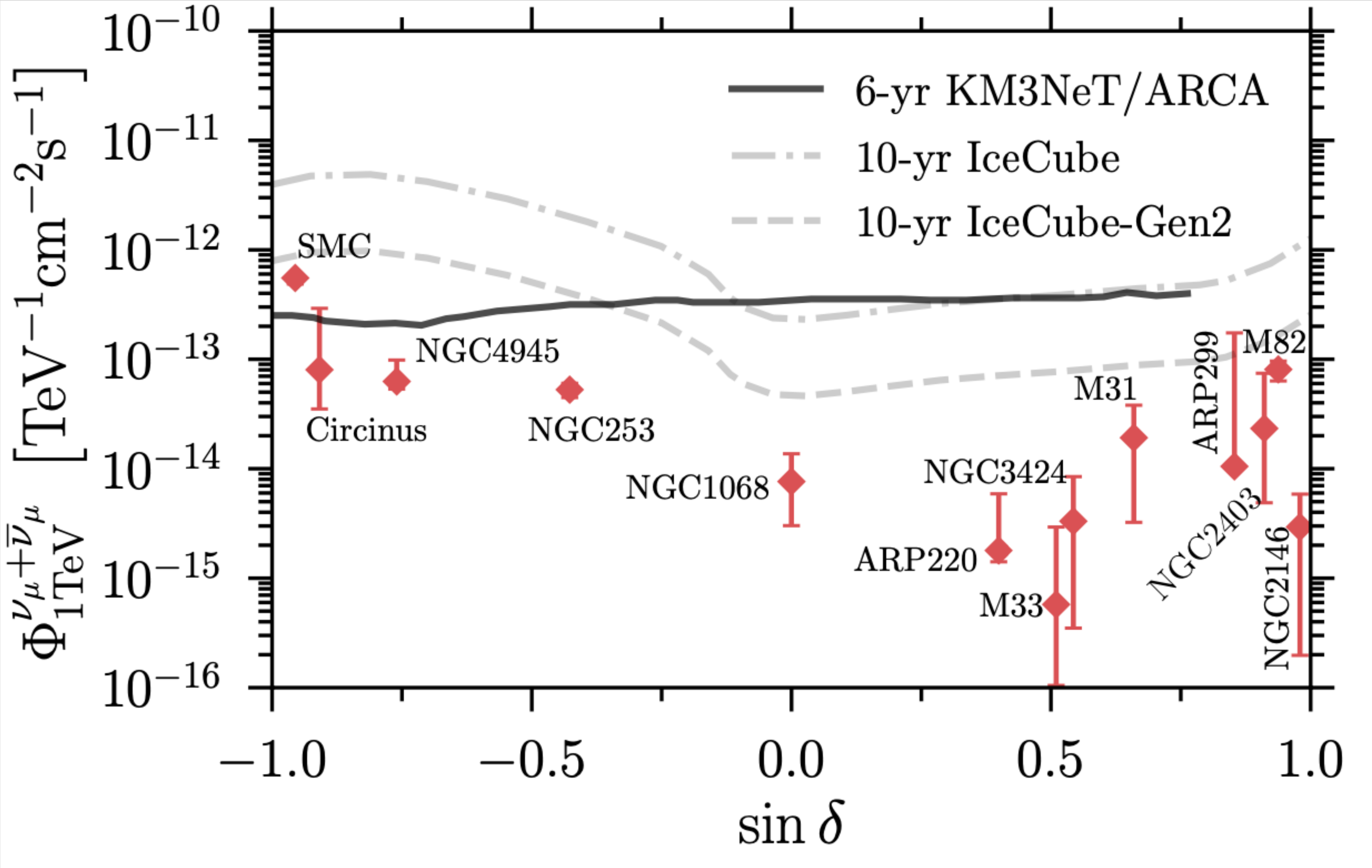
Photon energy density as target for secondary production

Kennicutt, ARA&A 36 (1998); Inoue+, PASJ 52 (2000); Hirashita+, A&A 410 (2003); Yuan+, PASJ 63 (2011); Kennicutt and Evans, ARA&A 50 (2012); Kennicutt & De Los Reyes, ApJ 908 (2021)

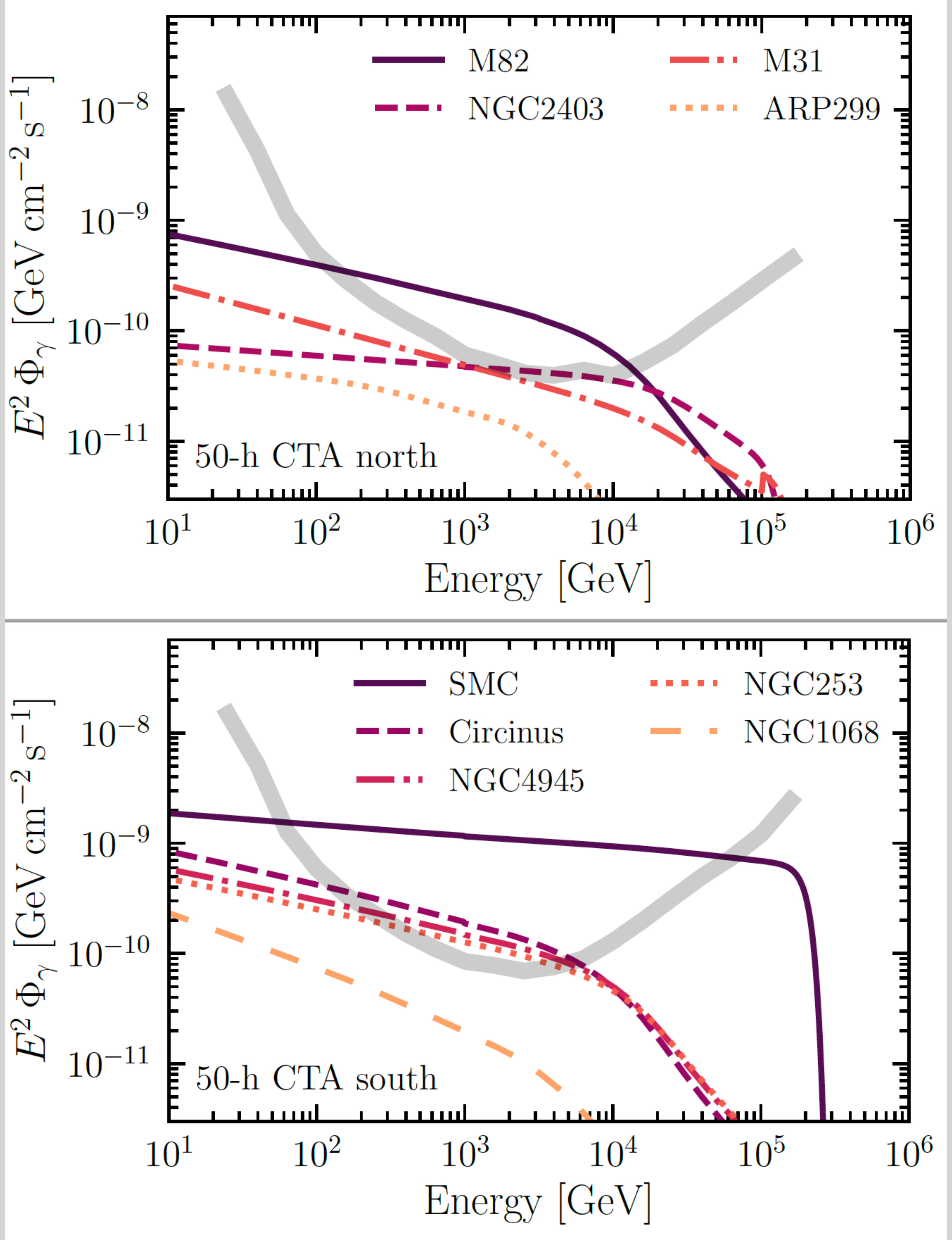
Probing the SBG Calorimetric Scenario

Ambrosone+, ApJL 919 [2106.12348]

Neutrino Expectations: KM3NeT Forecast



Gamma-Rays Expectations. CTA Forecast



Future γ/ν observations will be fundamental to:

- ✦ Discover if Neutrino Astronomy is a tracer for star-forming activity
- ✦ Probe the calorimetric fraction inside SBG: If there will be no detection, nearby SBGs are dominated by diffusion and not by either p-p collisions or advection.

Can we probe the Cosmic-Rays transport
using local /nearby SBGs?

Probing the Cosmic-Ray Transport inside SBGs

Ambrosone+, MNRAS [2203.03642]

Cosmic- Ray Transport Mechanism inside SBGs are, **however**, model-dependent.

Model A (adopted in the previous results): *Peretti+, MNRAS 487 (2019)*

- ✦Winds are global phenomena in SBGs
- ✦The diffusion of CRs occurs along pre-existing (strong) magnetic turbulence. This leads to a small diffusion coefficient

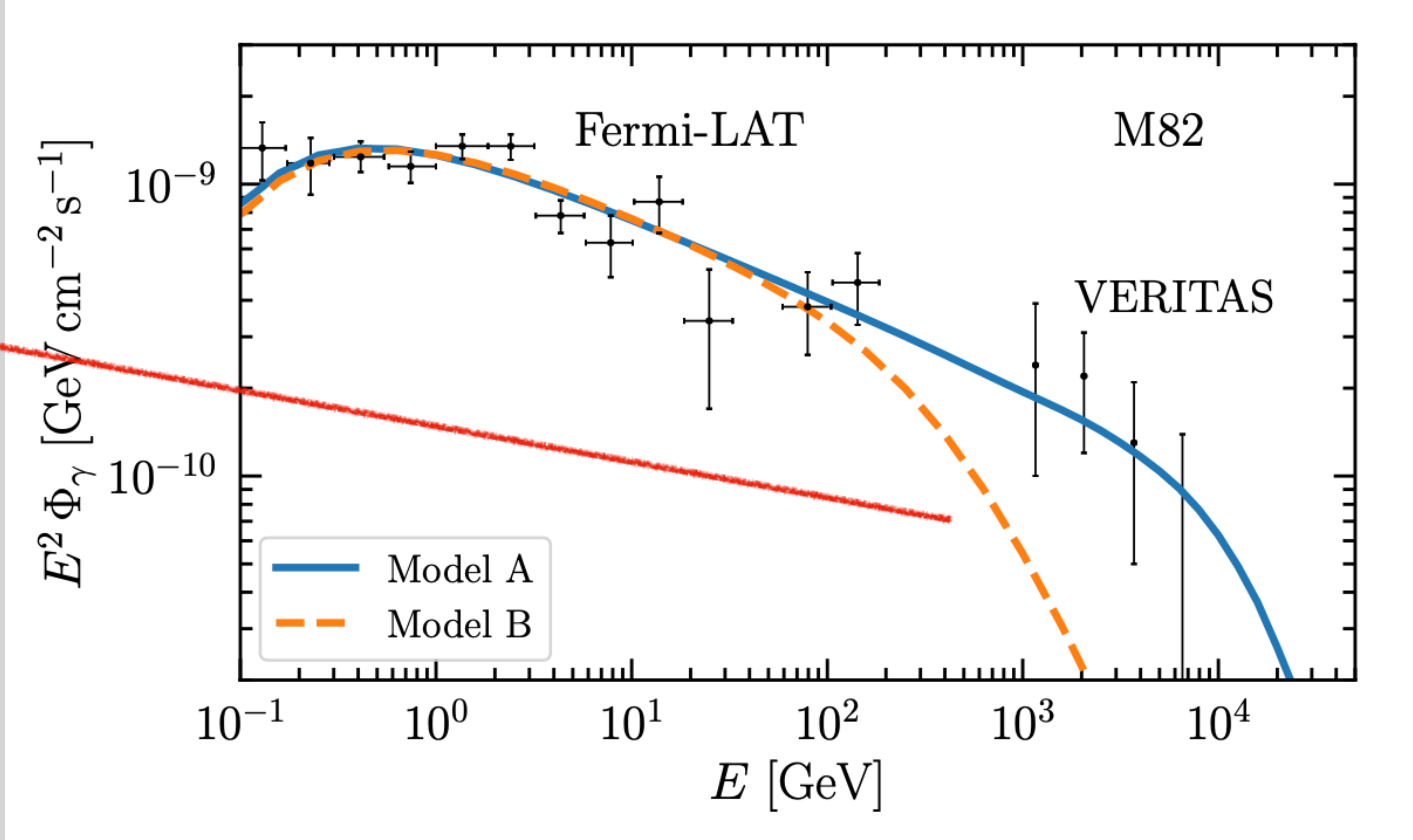
$$f(p) = Q(p)\left(\frac{1}{\tau_{\rm loss}} + \frac{1}{\tau_{\rm adv}} + \frac{1}{\tau^{A}_{\rm diff}}\right)^{-1}$$

Model B *Krumholz+, MNRAS 493 (2020)*

- ✦ Advection is negligible process
- ✦Diffusion of CRs occurs by self-generated streaming instability. This leads to a high diffusion coefficient

$$f(p) = Q(p)\left(\frac{1}{\tau_{\rm loss}} + \frac{1}{\tau^{B}_{\rm diff}}\right)^{-1}$$

TeV Gamma-rays from Model B are suppressed due to major role of diffusion. SBGs stop being calorimetric!

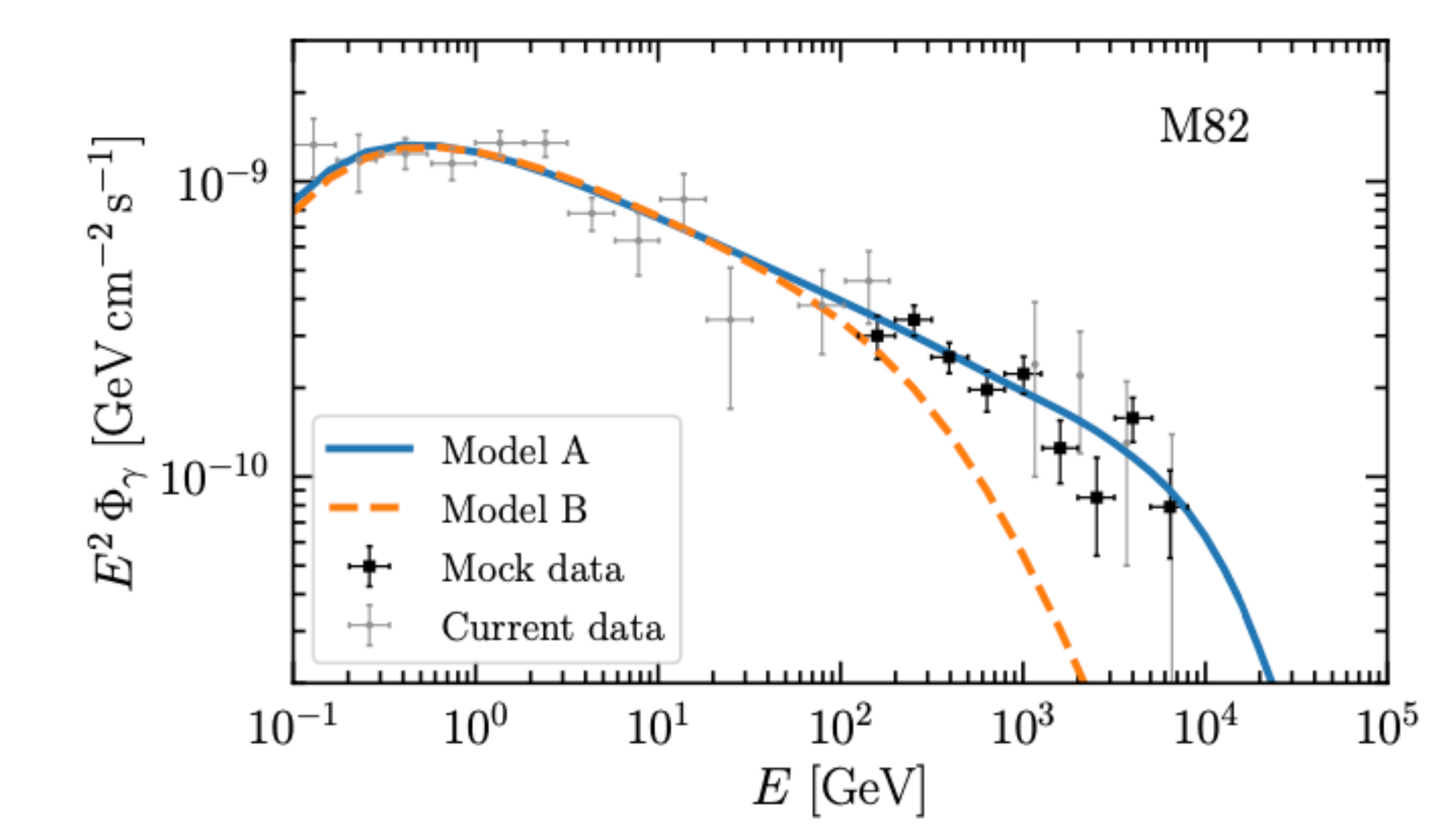


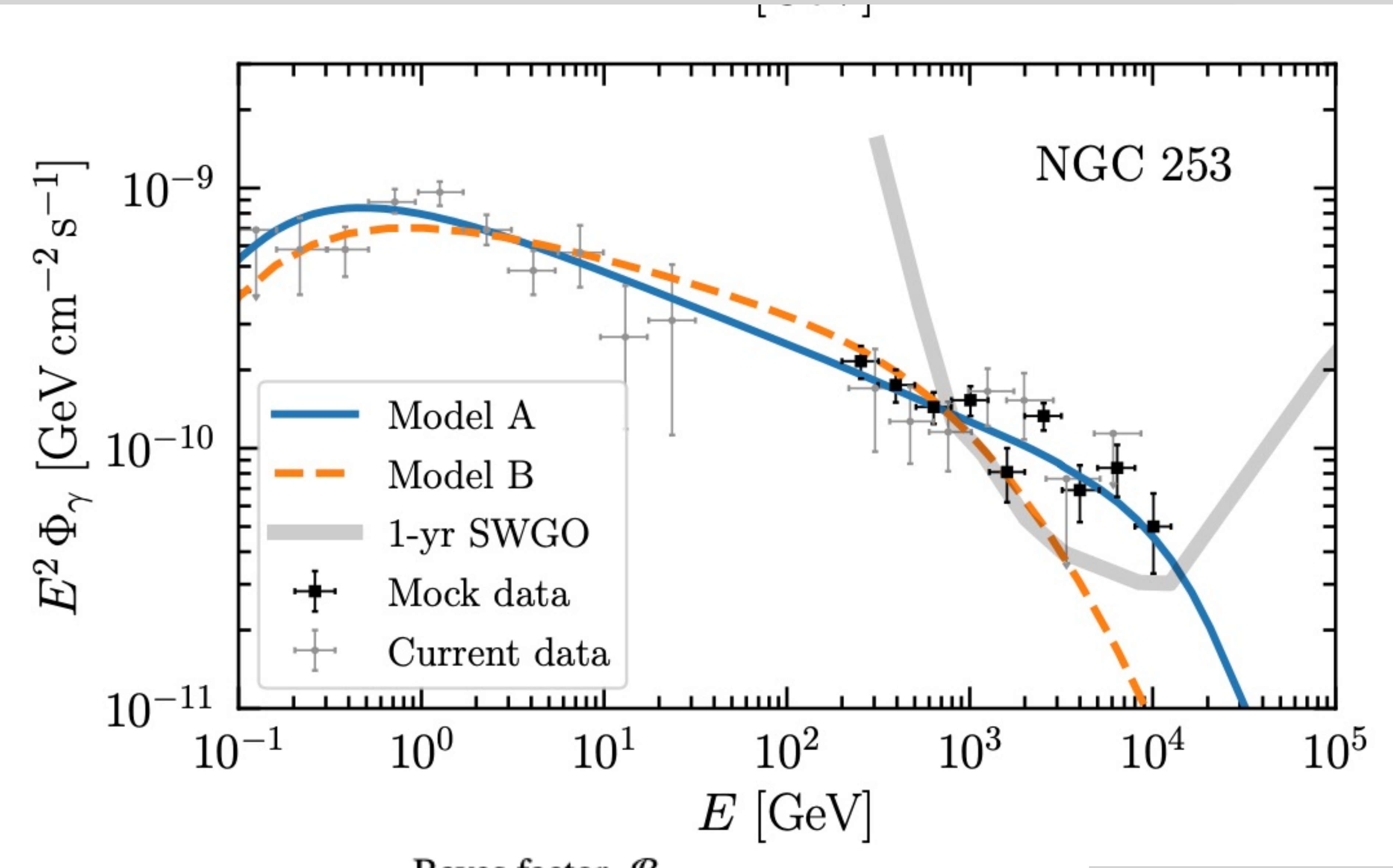
TeV Measurements are fundamental: CTA Forecast

Ambrosone+, MNRAS [2203.03642]

We test Krumohlz + (model B) by means of CTA mock data simulations assuming Peretti + (Model A)

- ✦Generation of 10^4 sets of mock SED data
- ✦ CTA Info from: Acharya+, 1709.07997
- ✦ SWGO Info from: Albert+, 1902.08429 Hinton, PoS ICRC2021 023





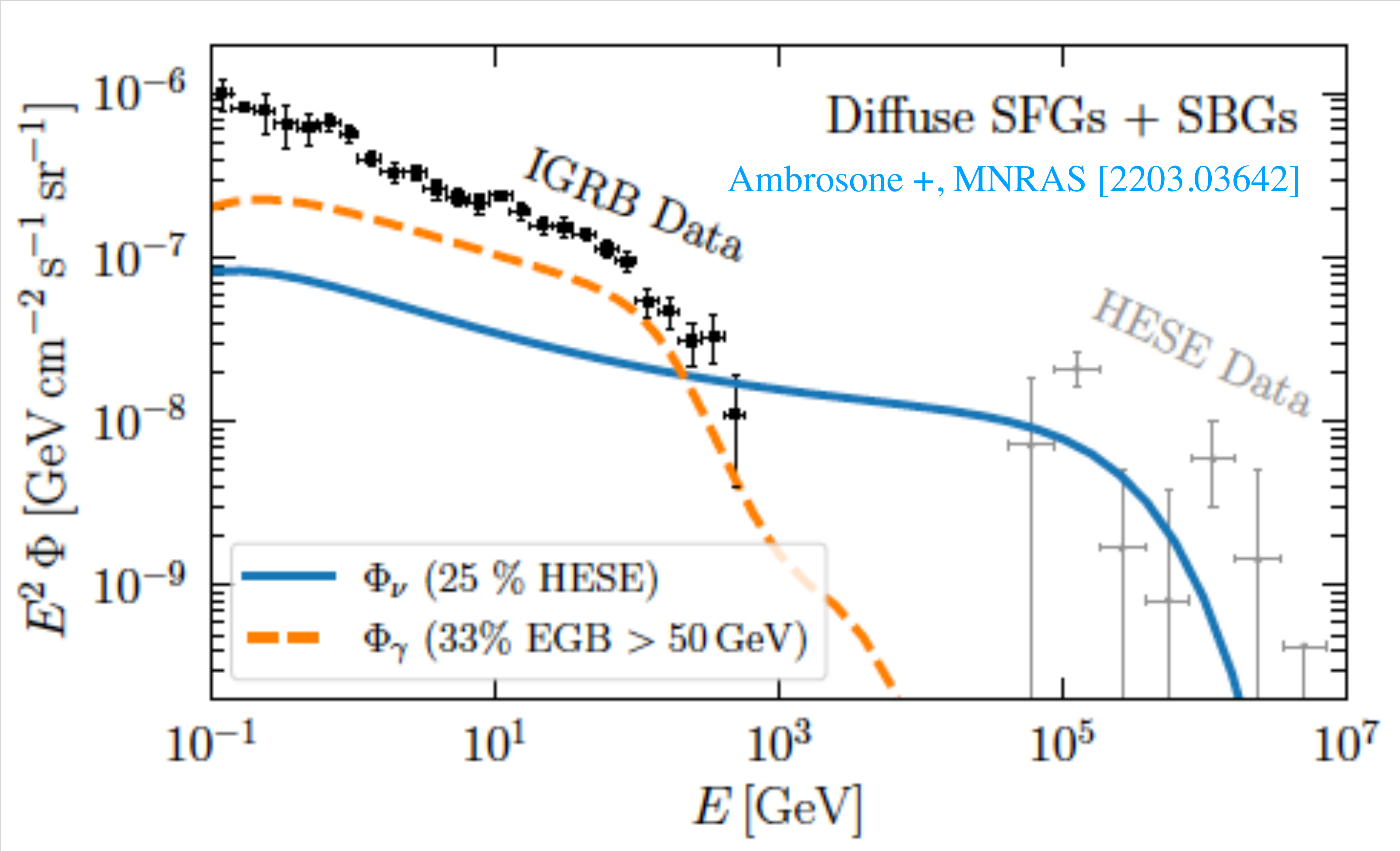
		p-value			Bayes factor, $\mathcal{B}$			
		Mock data				Mock data		
Source	Current data	95%	68%	Mean	Current data	95%	68%	Mean
SMC	4.3×10^{-10}	9.1×10^{-33}	4.4×10^{-35}	2.4×10^{-36}	5.8×10^{10}	1.4×10^{29}	6.6×10^{30}	2.8×10^{31}
M82	2.3×10^{-2}	3.8×10^{-4}	6.9×10^{-6}	3.8×10^{-7}	5.6×10^{2}	1.3×10^{3}	1.7×10^{6}	4.3×10^{7}
NGC 253	1.5×10^{-2}	4.2×10^{-4}	6.9×10^{-6}	3.5×10^{-6}	2.5×10^{2}	3.4×10^{5}	4.9×10^{8}	1.3×10^{10}
Circinus	4.1×10^{-1}	7.2×10^{-2}	1.3×10^{-2}	3.2×10^{-3}	1.0	8.3×10^{1}	2.5×10^{3}	1.0×10^{4}

Future Measurements should be able, despite astrophysical uncertainties, to distinguish between the two scenario at more than 2σ level!

Implications For Neutrino Astronomy

Different CR mechanism scenarios might well give a different contribution to the diffuse emissions

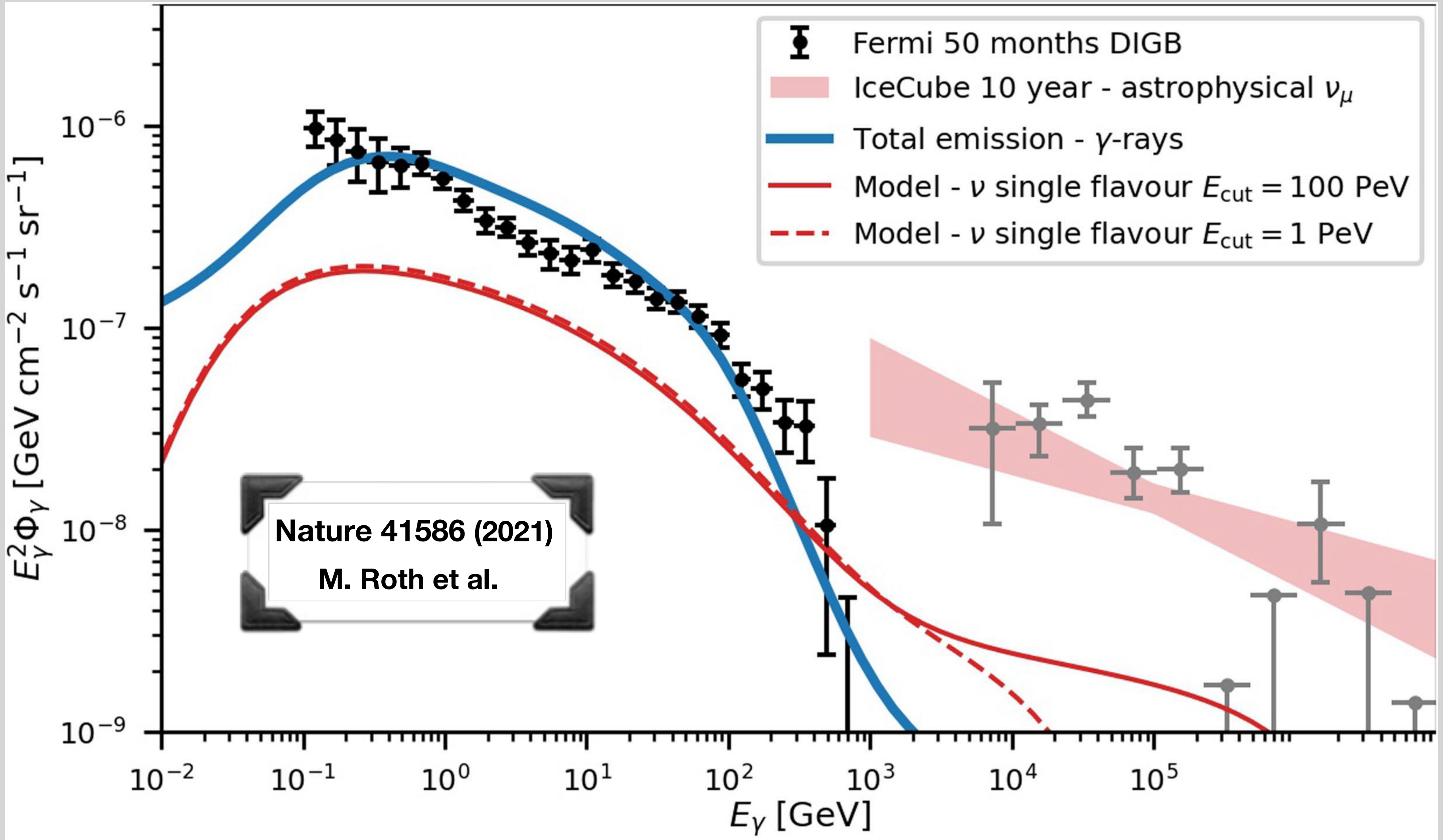
Model A (Peretti+, MNRAS 487 (2019))



Fcal is independent on energy. The calorimetric approach is justified

- ✦ Important contribution to Neutrinos (25% of the HESE)
- ✦ Important Contribution to gamma-rays (33% of the EGB)

Model B (Krumholz+, MNRAS 493 (2020))



Fcal is depedent on the energy above $\sim 100\text{GeV} - 1\text{TeV}$

- ✦ Negligible contributions to Neutrinos
- ✦ Important Contributions to gamma-rays (which can saturate the DIGB)

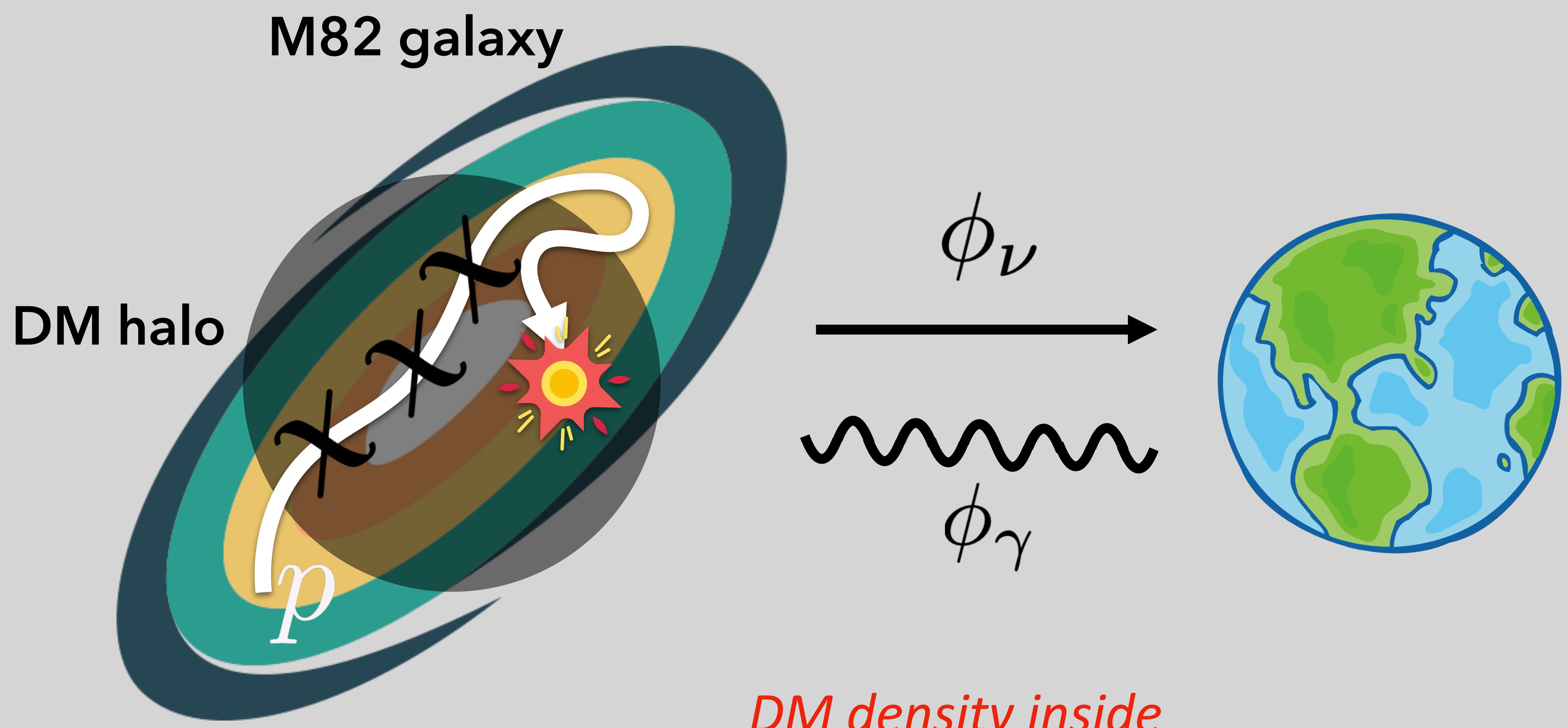
Attention: Due to uncertain origin of the diffuse emissions data, we cannot use them to discrminate between the two CR transport models

Can we probe Dark Matter Properties using local /nearby SBGs?

Still In Preparation… Stay Tuned

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

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

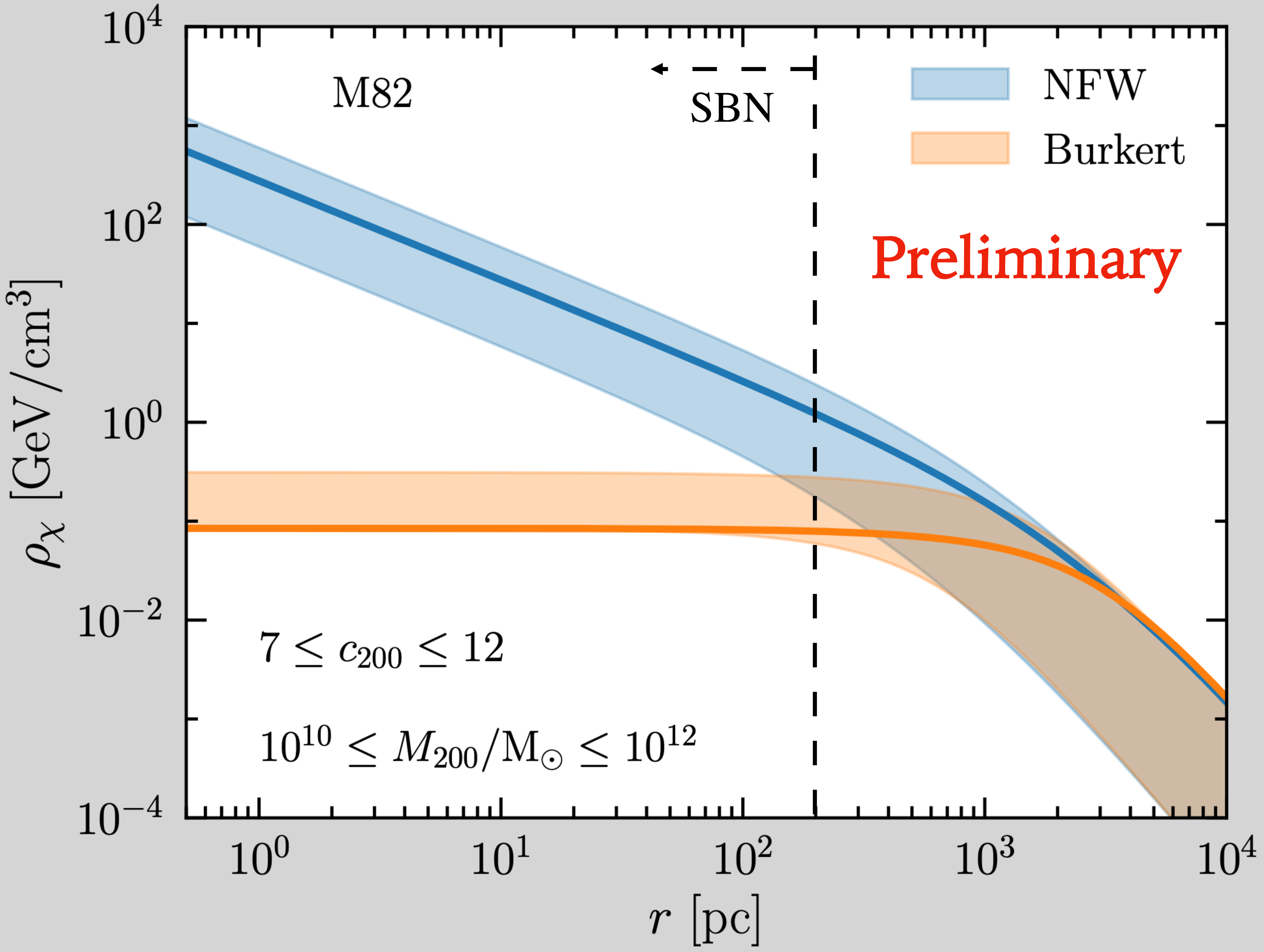
Elastic cross-section valid for transfer momenta:

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

Suppression from proton form factor

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

Dark Matter Density



- ✦ 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*

arXiv:2105.11463 arXiv:2105.11463 arXiv:2105.11463

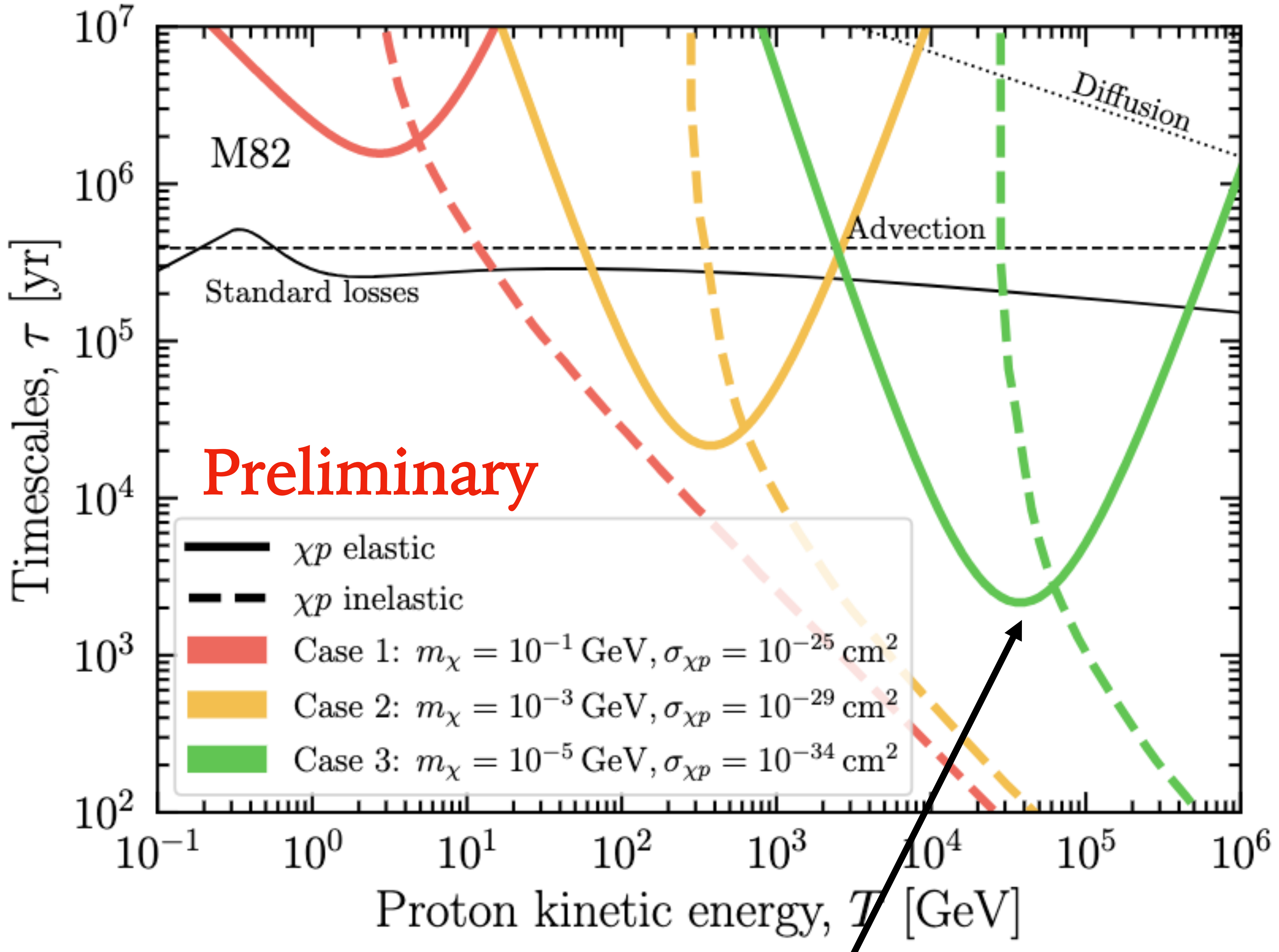
- ✦ Large uncertainty on the DM density inside the StarBurst Nucleus (SBN)

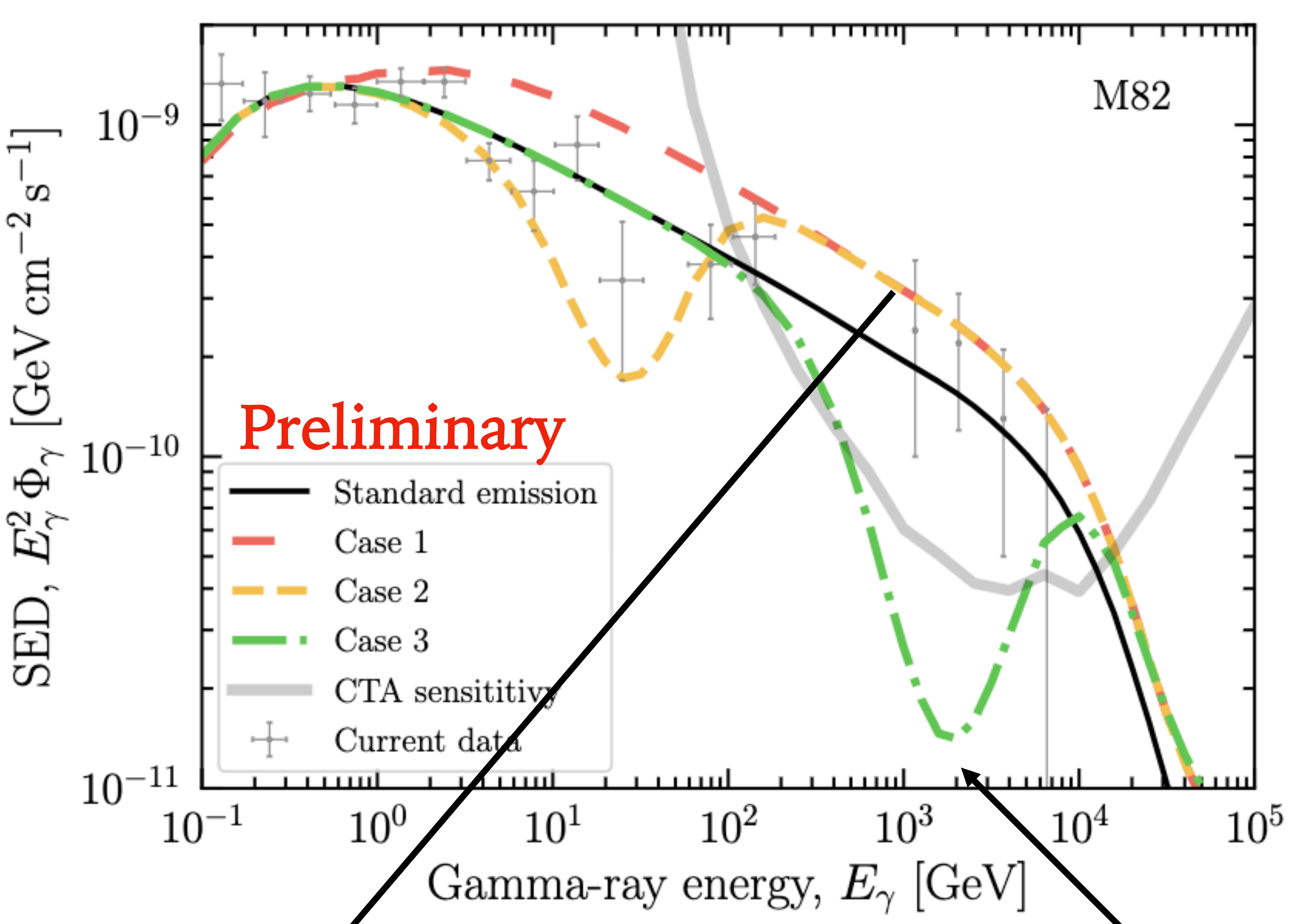
- ✦ However, it marginally affects the γ-ray emission

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

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

✦ "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):

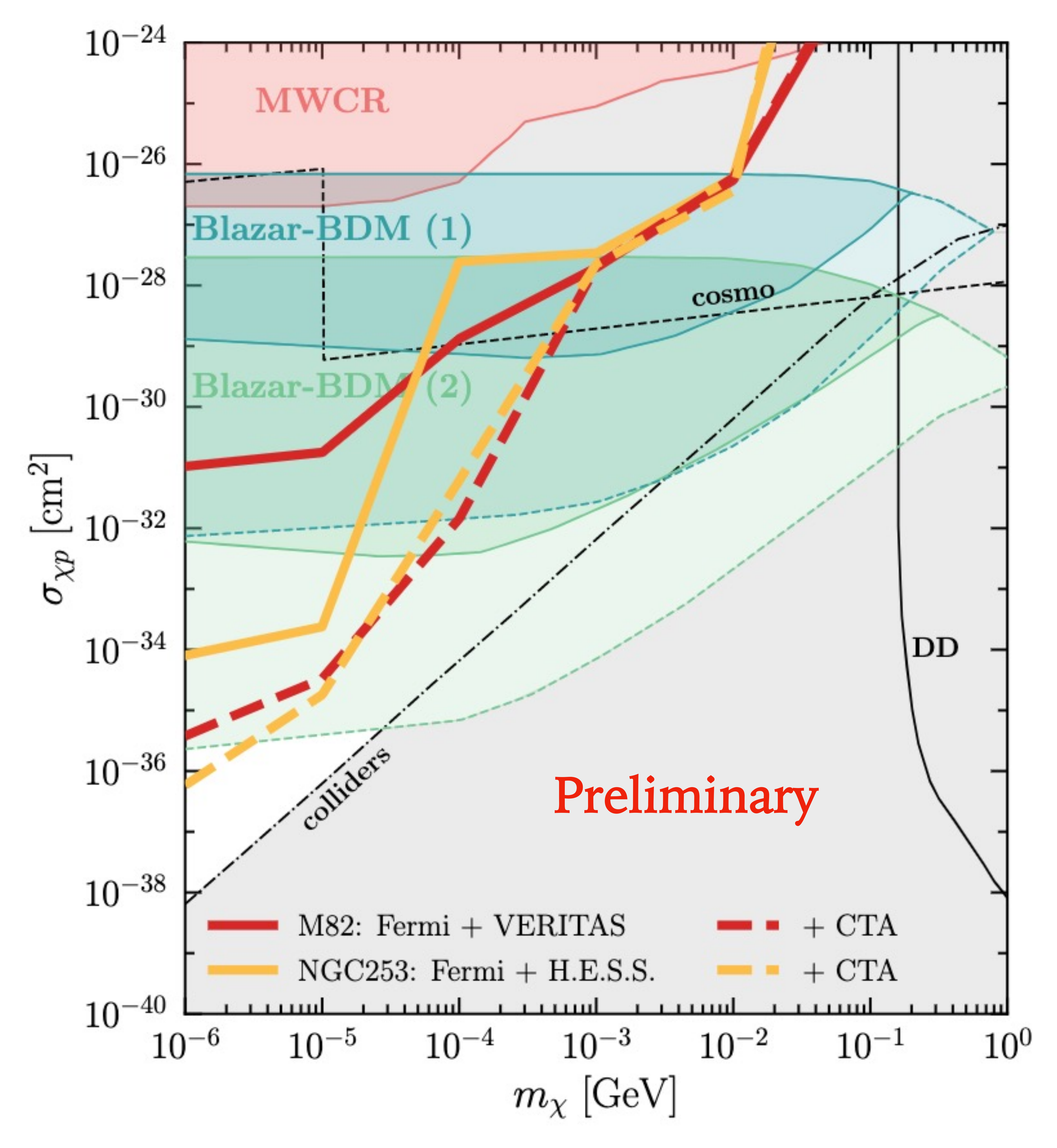
- ✦ (1) MiniBooNE and (2) XENON1T
- ✦ Requiring DM spikes (high density) around the black holes → large uncertainties!

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

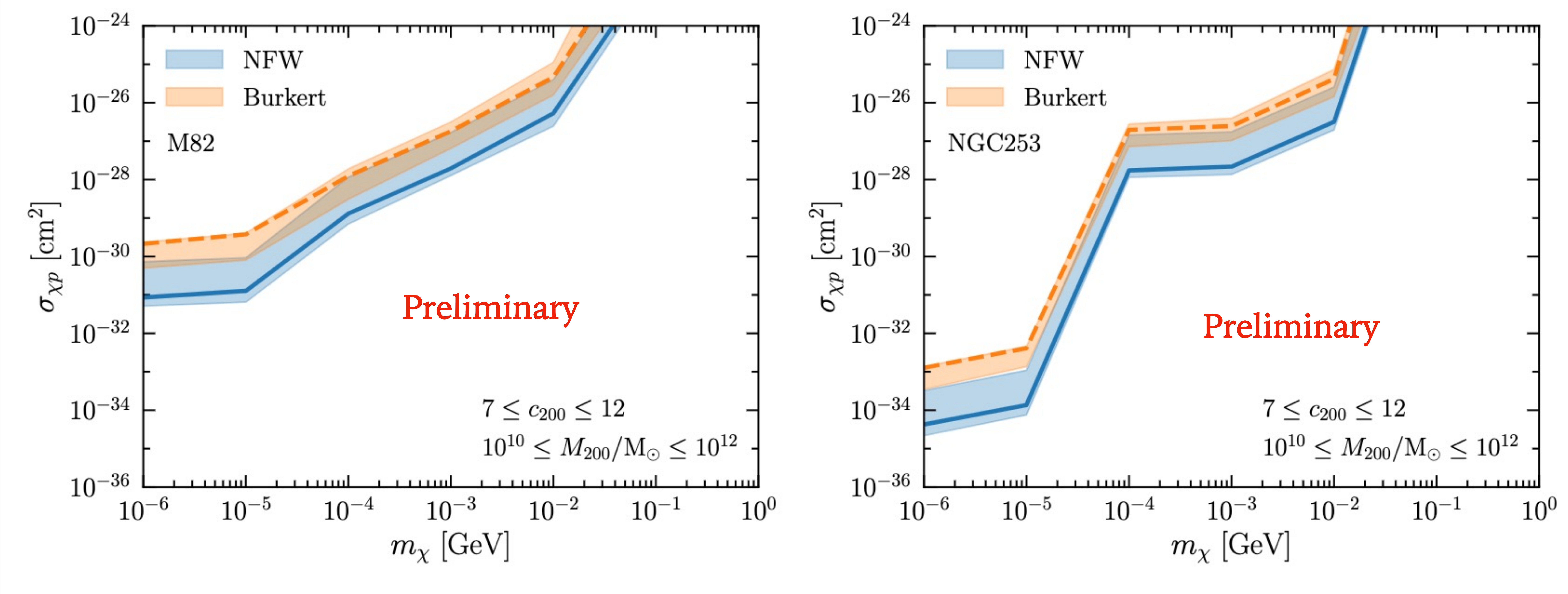
OUR CONSTRAINTS FROM SBG (5σ)

✦ M82 and NGC253

in preparation…



Dependence of the Constraints on the DM Profile



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

Conclusions and Outlooks

- ✦ Upcoming gamma-ray telescopes will give us a better understanding of the cosmic-ray transport inside SBGs.

- ✦ Some Nearby SBGs can produce a point-like excess within few years of data taking of the upcoming KM3NeT Telescope

- ✦ Global Neutrino Network + CTA/SWGO surveys of the closer SBGs can solve the puzzle of their multi-messenger emissions

- ✦ 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!
  - ✦ Work in preparation…stay tuned!