

The Diffuse γ -ray Background Is Dominated by Star-Forming Galaxies

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Introduction

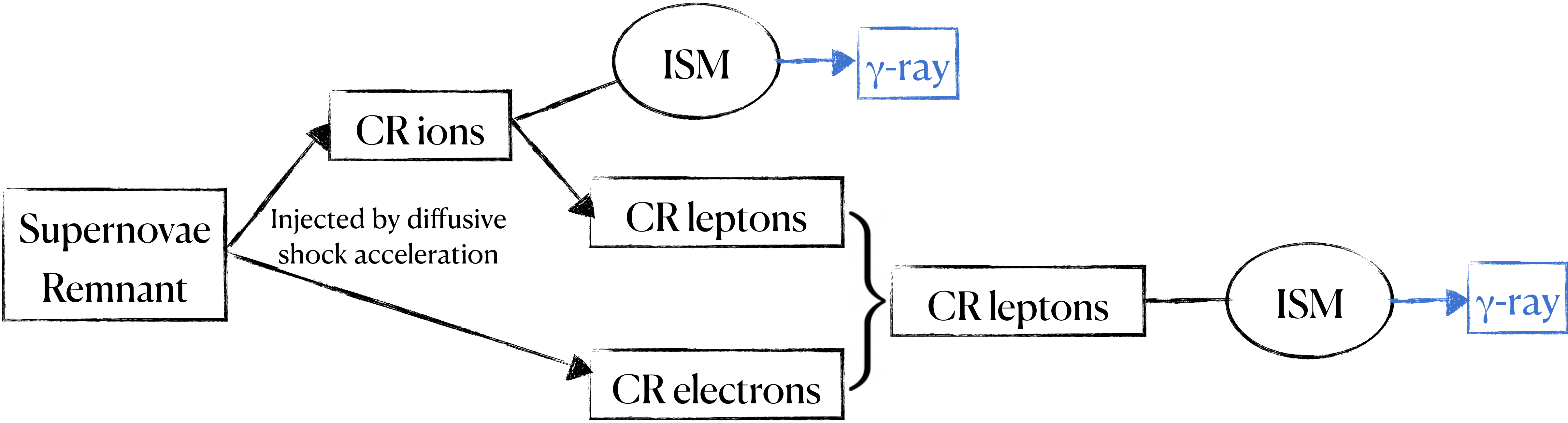
The γ -ray sky

- Individually detected sources
- diffuse emission (Attributed to the MW)
- The isotropic diffuse γ -ray background (IGRB).
 - Candidate sources: AGNs (blazars), star-forming galaxies(SFGs)

Introduction

The γ -ray emission by SFGs

- Basic Idea: Cosmic Rays (CRs) from Supernovae remnant interact with interstellar medium (ISM) \rightarrow produce γ -ray emission



Methods

What we need:

- The total star-formation rate
- The distribution of γ -ray energies produced when individual CR collide with ISM nuclei
- The fraction of CRs that undergo inelastic collisions before escaping the galaxy

Calorimetry fraction $f_{cal}(E)$

Injection Spectrum of CR from SN remnant

(the rate of γ emission per unit energy):

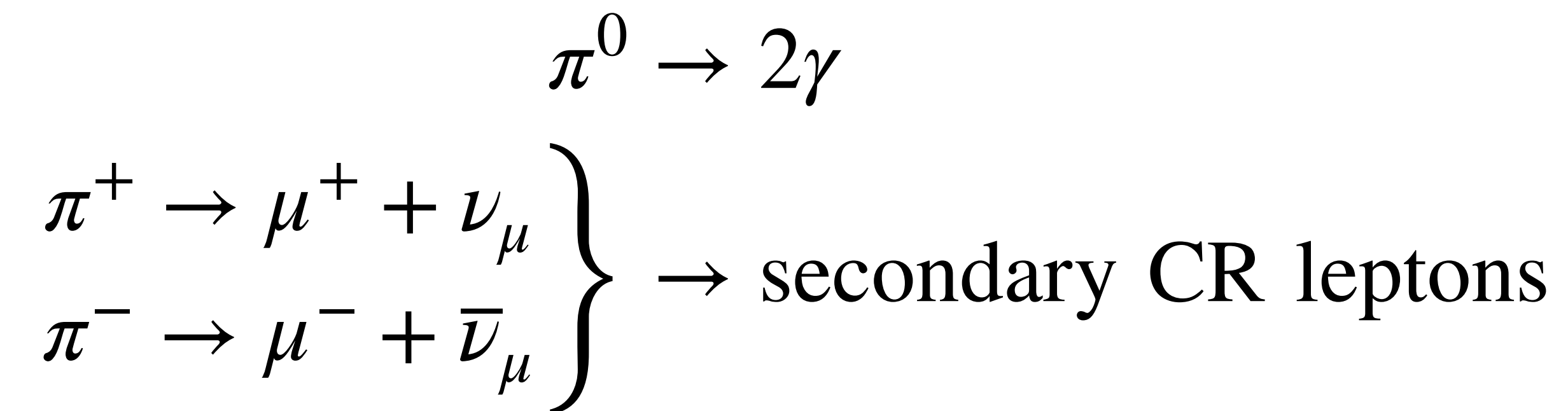
$$d\dot{N}_{\text{CR}}/dE_{\text{CR}}|_1 \propto p_{\text{CR}}^{-q}(E_{\text{CR}}/p_{\text{CR}})\text{CR}^{-E_{\text{CR}}/E_{\text{cut,CR}}}, \quad q = 2.2$$

Methods

CR Ions

~ 10% of the supernova mechanical energy ($\sim 10^{50}$ erg)

Some of CR ions collide inelastically with ISM nuclei, producing π mesons that rapidly decay:



Methods

CR Ions

$$\frac{d\dot{N}_\gamma}{dE_\gamma} \Big|_{\text{ion}} = \int_{m_p c^2}^{\infty} \left[\frac{1}{\sigma_{pp}} \frac{d\sigma_\gamma}{dE_\gamma}(E_{\text{ion}}) \right] f_{\text{cal}}(E_{\text{ion}}) \frac{d\dot{N}_{\text{ion}}}{dE_{\text{ion}}} dE_{\text{ion}}$$

$f_{\text{cal}}(E)$ Calculation:

Premise: In the neutral phase of the ISM, CR transport is primarily by streaming along magnetic field lines, which approximate diffusive transporting at large scales.

Caution: May break down in ISM dominated by atomic gas and with CR energies $\geq 100\text{GeV}$.

Methods

CR Leptons

- Primary (electrons)

~ 2% of the supernova mechanical energy ($\sim 2 \times 10^{49}$ erg)

$$d\dot{N}_e/dE_e|_1 \propto p_e^{-q}(E_e/p_e)e^{-E_e/E_{\text{cut},e}}$$

- Secondary (leptons: electrons + positrons)

- CR ions produce pions of E_π :

$$\frac{d\dot{N}_\pi}{dE_\pi} = \frac{n_{\text{H}}c}{K_\pi} \beta \sigma_{\text{pp}}(E_{\text{ion}}) \frac{d\dot{N}_{\text{ion}}}{dE_{\text{ion}}} f_{\text{cal}}(E_{\text{ion}})$$

- Pions produce secondary electrons

Methods

CR Leptons

- Leptons lose energy through *collisional ionization, synchrotron radiation, bremsstrahlung, inverse Compton scattering*
- Only *bremsstrahlung* and *inverse Compton scattering* produce γ -rays

$$d\dot{N}_\gamma/dE_\gamma|_{\text{lepton}} = d\dot{N}_\gamma/dE_\gamma|_{\text{brems}} + d\dot{N}_\gamma/dE_\gamma|_{\text{IC}}$$

Methods

Attenuation

The specific photon flux received at the Earth from a galaxy at redshift z :

$$\frac{dF_\gamma}{dE_\gamma} = \frac{(1+z)^2}{4\pi d_L^2(z)} \frac{d\dot{N}_\gamma}{dE_\gamma} \Big|_{E_\gamma(1+z)} e^{-\tau_{\text{EBL}}(E_\gamma, z)} e^{-\tau_{\gamma\gamma}(E_\gamma(1+z))}$$

τ_{EBL} : attenuation by extragalactic background light(EBL) photons

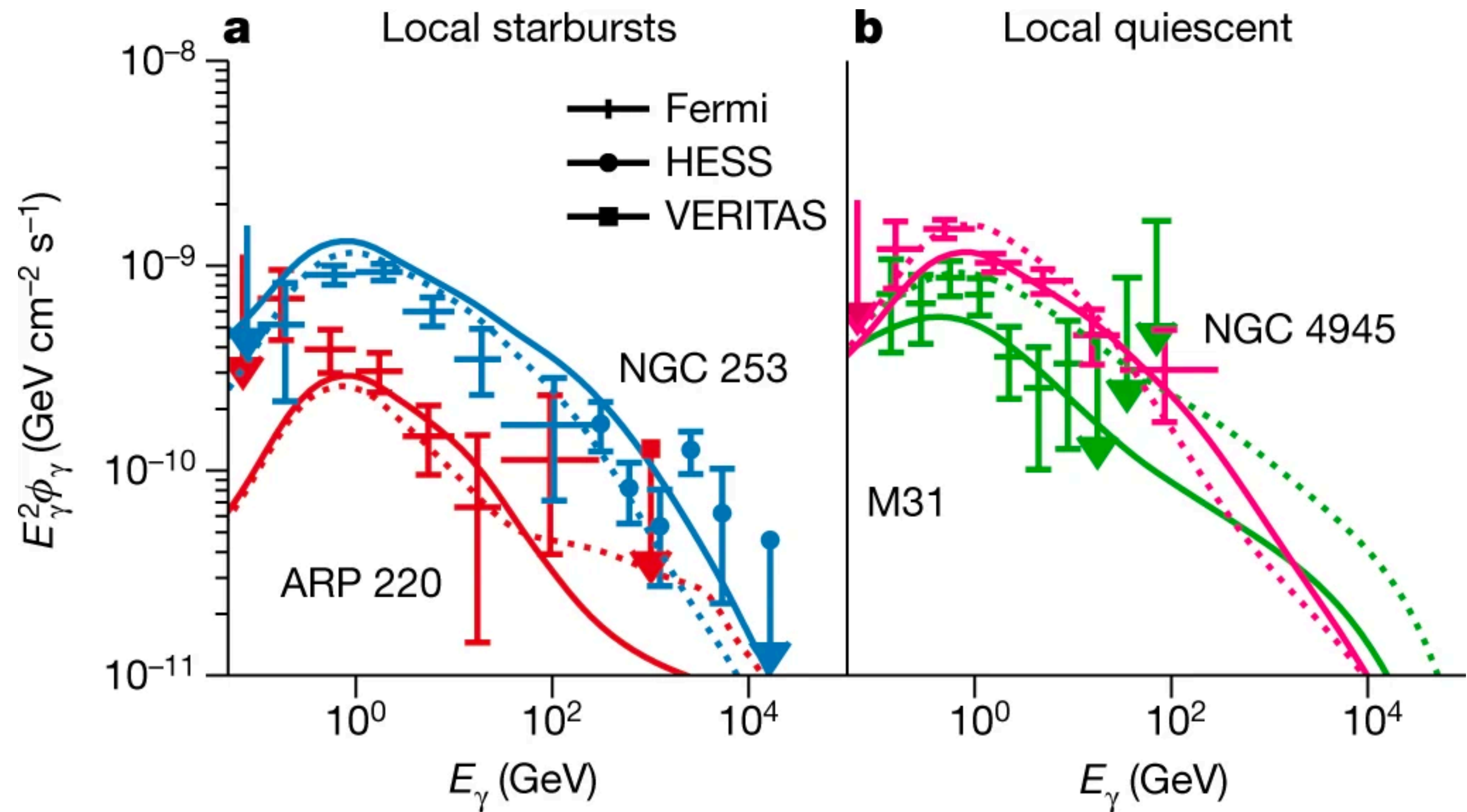
$\tau_{\gamma\gamma}$: attenuation by galactic far-infrared photons

Validation Test

Apply the method to four local, resolved galaxies with measured γ -ray emission:

- Solid lines: the spectra derived using only stellar data
- Dotted lines: add directly measured gas properties

Able to reproduce the observed γ -ray spectra even with only stellar data



Validation Test

Examine the correlation between galaxies' far-infrared and total γ -ray luminosities

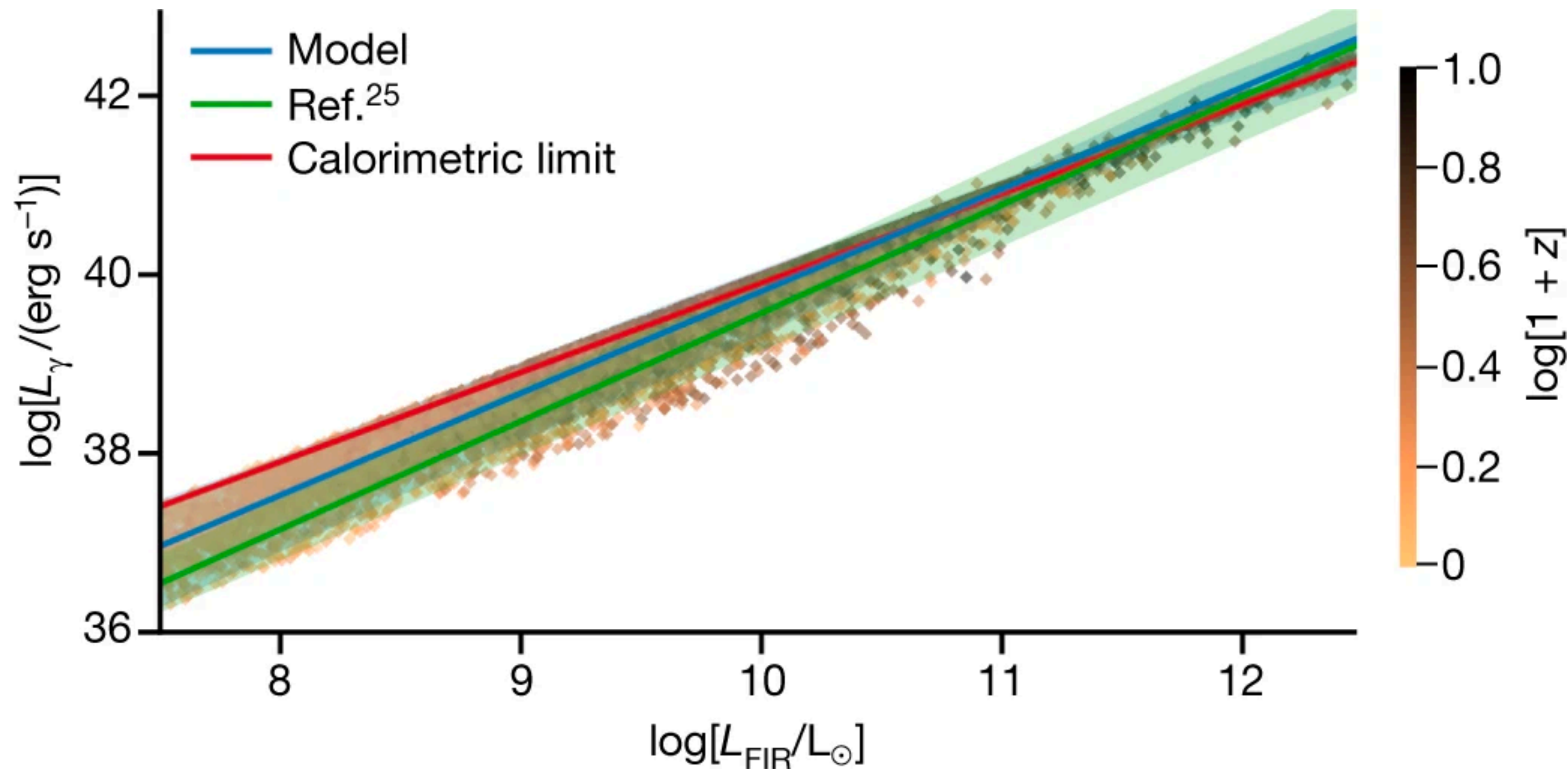
Points: CANDELS galaxies

Blue: power-law fit to the CANDELS sample

Green: empirical relation of 14 nearby galaxies

Red: $f_{\text{cal}} = 1$

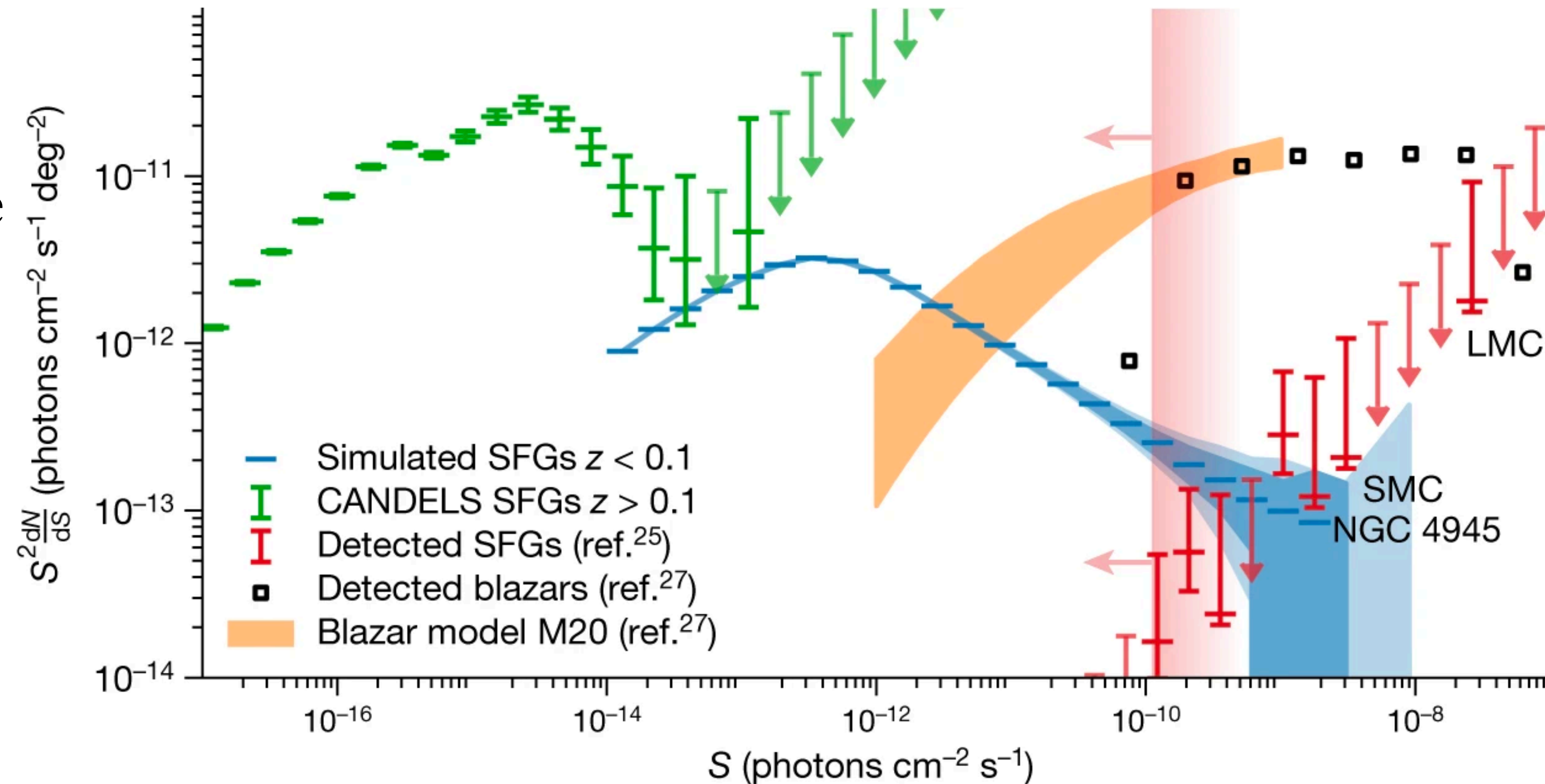
- Model correctly predicts the variation in galaxies' f_{cal} as a function of SFR.



Validation Test

Compare with observations by Fermi LAT

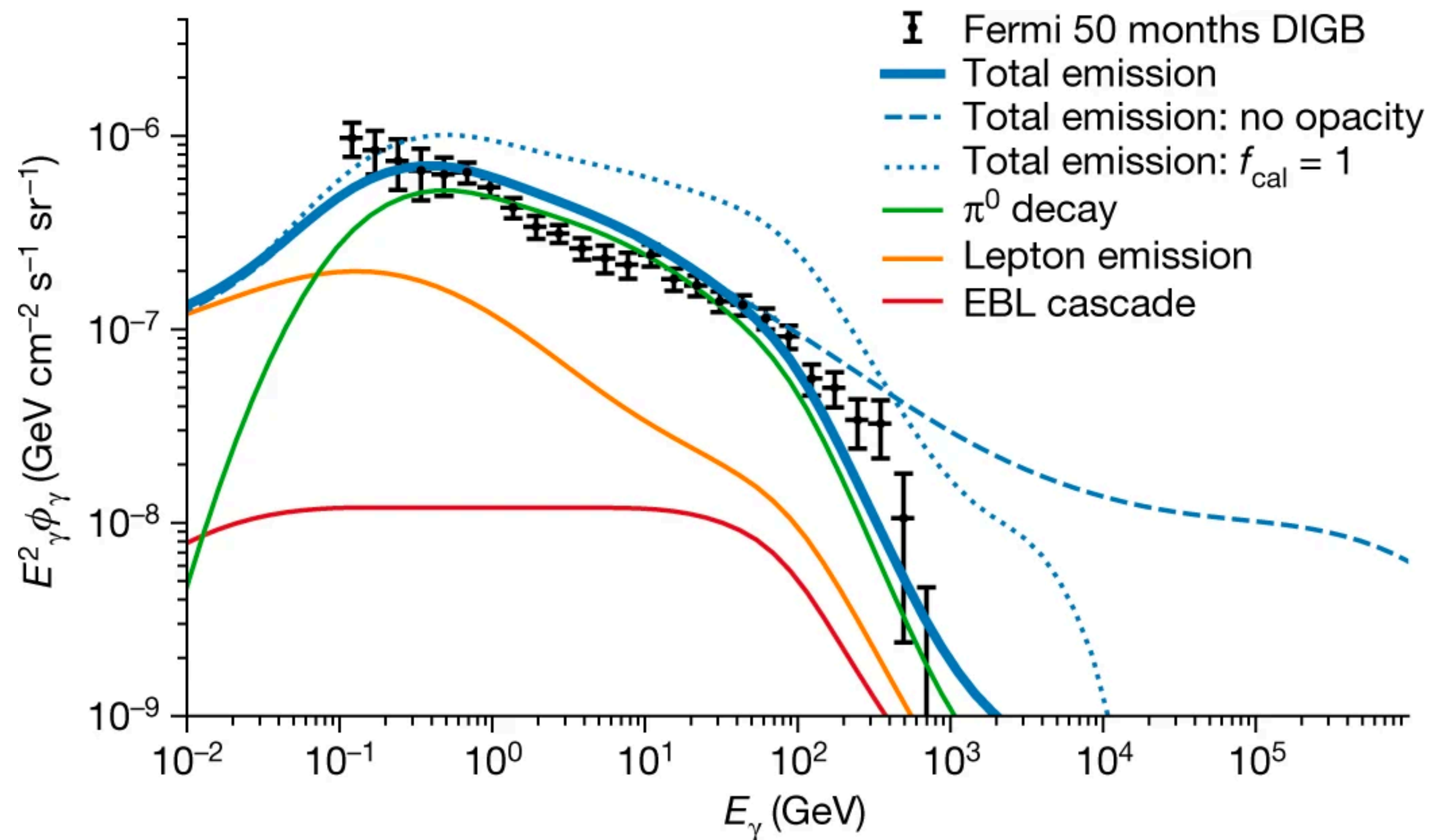
- Model consistent with observations, except sources as bright as the Milky Way's two satellite galaxies, the Large and Small Magellanic Clouds. : Comparison includes only field galaxies.



Conclusions

The contribution of SFGs to the diffuse, isotropic γ -ray background

- Fully reproduces both the *intensity* and the *spectral shape* of the observations from about 0.2 GeV to about 1 TeV.
- SFGs alone can explain the full diffuse, isotropic γ -ray background



Take Home Message

- CRs from SN remnants in SFGs can interact with ISM nuclei and produce γ -ray emission.
 - CR contribution includes both CR ions and CR leptons (both primary and secondary).
- The γ -ray emission calculated from SFGs using the physical model can fully explain the observed isotropic γ -ray background (both intensity and spectral shape).

Highlighted References

- Calculating $f_{cal}(E)$:

Krumholz, M. R. et al. Cosmic ray transport in starburst galaxies. Mon. Not. R. Astron. Soc. 493, 2817–2833 (2020).

- Cross Correlation between isotropic background and quasars:

Xia, J.-Q., Cuoco, A., Branchini, E. & Viel, M. Tomography of the Fermi-LAT γ -ray diffuse extragalactic signal via cross correlations with galaxy catalogs. Astrophys. J. Suppl. 217, 15 (2015).

Thank You

Possible Questions

- Can you rule out the contribution from AGNs?

Some studies have focused on the cross correlation between IGRB and galaxies and quasars. The results disfavor quasars as the dominant contributor.

