The diffuse γ-ray background is dominated by star-forming galaxies

Many candidate sources have been proposed for the origin of the diffuse, isotropic γ-ray background. These include active galactic nuclei (AGN) (particularly blazars\textsuperscript{2–5}), millisecond pulsars\textsuperscript{6}, star-forming galaxies (SFGs)\textsuperscript{6–10} and dark matter annihilation\textsuperscript{12}. Previous estimates of their contributions have relied on a highly uncertain process of empirically scaling the emission from a small sample of local, resolved sources by their estimated cosmological abundances. Our approach in this paper is instead to calculate the emission from SFGs directly from a physical model. The cosmic rays (CRs) responsible for γ-ray emission in SFGs (including the Milky Way) are produced by diffusive acceleration at supernova remnant shocks\textsuperscript{13}. This process transfers about 10% of the supernova mechanical energy to relativistic ions, yielding on average around 10\textsuperscript{50} erg in CR ions per supernova\textsuperscript{14,15}, with another approximately 2% (about 2 × 10\textsuperscript{49} erg) deposited in CR electrons\textsuperscript{16}. The resulting CRs follow a power-law distribution in particle momentum \( p \) of the form \( dn/dp = p^{-q} \) (refs. \textsuperscript{17,18}); observations of individual supernova remnants, analytical models, and numerical simulations all indicate that the index \( q \) is in the range \( q = 2.0–2.6 \), with a mean value of \( q = 2.2–2.3 \) (refs. \textsuperscript{19,20}). Some of the CR ions collide inelastically with nuclei in the interstellar medium (ISM), producing roughly equal numbers of \( \pi^0 \), \( \pi^+ \) and \( \pi^- \) mesons that rapidly decay via the channels \( \pi^0 \rightarrow 2\gamma \), \( \pi^+ \rightarrow \mu^+ + \nu_\mu \), and \( \pi^- \rightarrow \mu^- + \nu_\mu \). The decay of \( \pi^0 \) particles is responsible for most of the observed Galactic γ-ray foreground, which displays a characteristic spectrum that rises sharply from about 0.1 GeV to 1 GeV as a result of the 135-MeV rest mass of the \( \pi^0 \) particle.

As this discussion suggests, a SFG’s diffuse γ-ray emission depends primarily on three factors: its total star-formation rate (which determines its supernova rate and thus the rate at which CRs are injected), the distribution of γ-ray energies produced when individual CRs collide with ISM nuclei (which depends on the parent CR energy \( E \)), and the fraction of CRs (again as a function of \( E \)) that undergo inelastic collisions before escaping the galaxy. The first two of these are relatively well understood, but the third factor, known as the calorimetry fraction \( f_{\text{cal}}(E) \), is much less certain. It depends on the properties of the galaxy, and the lack of a model for this dependence has previously precluded direct calculation of SFG γ-ray emission. However, ref. \textsuperscript{11} recently introduced a model for \( f_{\text{cal}}(E) \), based on rates of CR diffusion determined by the balance between the CR streaming instability and ion-neutral damping. In the Methods we describe a technique to use this model to compute \( f_{\text{cal}}(E) \) and thus the total γ-ray emission produced by CR ions in SFGs.

We supplement the γ-ray production rate from CR ions by adding the contribution from both primary CR electrons, directly injected by supernova remnants, and secondary CR leptons (electrons and positrons), produced in the \( \pi^0 \) decay chain; these become important at energies ≤1 GeV. Our model for these particles includes energy losses due to ionization, synchrotron emission, bremsstrahlung and inverse Compton scattering. The model also includes the attenuation of γ-rays produced by both CR ions and leptons due to pair production in collisions with far-infrared photons inside the source galaxy and extragalactic background light photons outside the galaxy, which become important at energies ≥100 GeV. The radiation that is absorbed by the host galaxy and extragalactic photon fields is reprocessed to lower energies in a pair-production cascade, whereby the initial high-energy pair inverse Compton scatters lower energy photons up to γ-ray energies and these, in turn, produce further pairs, and so on. Details of our calculation of all these processes are provided in the Methods.

We now have a model that predicts the γ-ray emission of an SFG. The next step in our analysis is to apply this model to a galaxy survey that samples the SFG population out to the epoch of peak cosmological star formation.

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formation at $z \approx 2$. For this purpose, we make use of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS) in the Great Observatories Origins Deep Survey S (GOODS S) field. We apply our model to the CANDELS sample as described in the Methods. To verify that our approach predicts reasonably accurate $\gamma$-ray spectra, we apply it to four local, resolved galaxies with measured $\gamma$-ray emission—chosen to span a wide range of gas and star-formation surface densities: Arp 220, NGC 253, M31 and NGC 4945. The input data that we use for these calculations are summarized in Extended Data Table 1. We show the results of the computation in Fig. 1, in which the solid lines show the spectra derived using only stellar data (as we have for CANDELS) and, for comparison, the dotted lines show the results we obtain if we add directly measured gas properties (available for these local galaxies). We see that the fits are slightly improved if we make direct use of gas data but, even for the stellar data only, our model reproduces the observed $\gamma$-ray spectra to better than a factor of 2 for all galaxies at energies $>1$ GeV, and within a factor of about 1.5 for the two galaxies with more rapid star formation, which, as we show below, are more akin to the population that dominates the $\gamma$-ray background.

Having verified that we can obtain accurate predictions of $\gamma$-ray spectra from stellar data alone, we carry out two additional validation steps. First, we examine the correlation between galaxies’ far-infrared and total $\gamma$-ray luminosities, computed as described in the Methods. In Fig. 2 we show the resulting distribution of galaxies in the $L_{\text{FIR}}$–$L_{\gamma}$ plane, along with a power-law fit to the data (blue line), $L_{\gamma} = 10^{38.20 \pm 0.15} (L_{\text{FIR}} / L_{\odot})^{1.14 \pm 0.10}$, where $L_{\gamma}$ is in units of erg s$^{-1}$ and $L_{\text{FIR}}$ is the solar luminosity. Our model prediction shows good agreement with the observed relation (green line)$^{25}$, and both the model and the observed correlation differ noticeably from the calorimetric limit obtained by simply setting $f_{\text{cal}}(E) = 1$ (red line in the figure). Thus the agreement is non-trivial and suggests that our model is correctly predicting the variation in galaxies’ calorimetry fractions as a function of star-formation rate. Our second validation test is to compare our model with counts of resolved SFGs observed by Fermi LAT (details in Methods). We show the results in Fig. 3, which demonstrates that our model predicts SFG source counts consistent with observations, with the exception that we do not predict sources as bright as the Milky Way’s two satellite galaxies, the Large and Small Magellanic Clouds. This is not surprising, as our comparison includes only field galaxies.

Our final step is to compute the contribution of SFGs to the diffuse, isotropic $\gamma$-ray background (see Methods for details). We present the results of this calculation in Fig. 4 and provide a detailed analysis of the model uncertainties in the Supplementary Information and Extended Data Fig. 1. Figure 4 shows that the expected contribution of SFGs to the diffuse isotropic $\gamma$-ray background fully reproduces both the intensity and the spectral shape of the observations from about 0.2 GeV to about 1 TeV. We emphasize that we obtain this agreement from our model with no free parameters: our only inputs are the CR injection spectral index ($q = 2.2$), the CR energy per supernova ($10^{50}$ erg), our only inputs are the CR injection spectral index ($q = 2.2$), the energy per supernova ($10^{50}$ erg), and the fraction of supernova energy that goes into primary CR ions and electrons (10% and 2%, respectively)—all quantities that are directly measured in the local Universe—and the distribution of SFGs sampled by CANDELS. The key to the success of the model is the galaxy-by-galaxy calculation of the energy-dependent calorimetry fraction $f_{\text{cal}}(E)$, which we demonstrate by also plotting the result (dotted line) we would obtain simply by setting $f_{\text{cal}} = 1$ for all galaxies at all energies. This clearly both overestimates the intensity and yields a spectral slope that is flatter than observed.

We show the relative contributions to the background made by galaxies with differing star-formation rates and redshifts in Extended Data Fig. 2. The figure shows that the background at lower energies is dominated by galaxies from just after cosmic noon ($z = 1–2$), whereas at higher energies, where attenuation by extragalactic background light has a larger effect, the dominant contribution shifts towards lower redshifts, so that at 1 TeV the background is dominated by $z = 0.1$ sources. At all energies, the dominant contribution comes from galaxies at the upper end of the star-forming main sequence, which have high but not extreme star-formation rates for their redshift.

It is important to put our finding that SFGs dominate the diffuse, isotropic $\gamma$-ray background in the context of recent work, in which a number of authors have argued that blazars and other AGN sources contribute substantially or even dominate the background. We provide a more detailed discussion in the Supplementary Information, but here note that we find that, whereas blazars dominate the resolved component of the extragalactic $\gamma$-ray background, as shown in Fig. 3, SFGs dominate the unresolved component. This finding is consistent with statistical analyses of angular fluctuations in the isotropic background and cross-correlations between it and galaxies and quasars, which strongly disfavour blazars as a dominant contributor$^{2.06}$. Indeed, a straightforward extrapolation of the number counts of observed $\gamma$-ray sources predicts a background that is an order of magnitude lower than the observed one.
EBL, extragalactic background light.

would see in the absence of γγ opacity. DIGB, diffuse isotropic γ-ray galaxies at all energies, while the blue dashed line shows the background we introduced can also be applied to predict luminosity functions and model for the γ-ray emission of SFGs or a much larger sample of resolved blazars do not dominate the unresolved background. Our finding that SFGs alone are able to reproduce the full background is also consistent with previous conclusions9,28 that, in the absence of either a physical model for the γ-ray emission of SFGs or a much larger sample of resolved galaxies, it is not possible to rule them out as a dominant contributor.

We conclude by pointing out that the methodology we have introduced can also be applied to predict luminosity functions and background contributions from SFGs at other wavelengths and in other messengers driven by CRs. Most immediately, observations by the upcoming Cherenkov Telescope Array29 and Large High Altitude Air Shower Observatory30 should both extend the population of γ-ray-detected SFGs and push existing detections to substantially higher energies. Our model makes clear predictions for both source counts and spectral shapes that can be tested against these data. In the longer term, application of this model to neutrinos will yield predictions that will be testable by IceCube and other neutrino observatories (see the Supplementary Information and Extended Data Fig. 3 for further information), and application to synchrotron emission from CR electrons can be used to make predictions for the radio sky that will be testable with the Square Kilometer Array (SKA) and other next-generation radio telescopes. Moreover, because the basis of these predictions is a coherent physical model, rather than just empirical scalings, these predictions can all be made self-consistently.

Online content

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Methods

Here we describe our methods to compute γ-ray emission from a single SFG due to both CR ions and leptons, to determine the flux received at Earth from that galaxy, and to apply these models to the CANDELS sample, as well as the details of the Monte Carlo estimation for low-redshift source counts.

Gamma-ray emission model for CR ions

In our model, the total rate of γ-ray emission per unit energy from an SFG is the sum of an ionic component and a leptonic component, \( dN_\gamma/dE_\gamma = dN_\gamma/dE_{\gamma,\text{ion}} + dN_\gamma/dE_{\gamma,\text{lepton}} \). We compute the ionic component as

\[
\frac{dN_\gamma}{dE_{\gamma,\text{ion}}} = \int_m^{\infty} \left[ \frac{1}{a_{pp}} \frac{d\sigma}{dE_{\gamma}}(E_{\gamma,\text{ion}}) \right] f_{\text{cal}}(E_{\gamma,\text{ion}}) \frac{dN_{\text{ion}}}{dE_{\gamma,\text{ion}}} \frac{dE_{\gamma,\text{ion}}}{dE_\gamma} \tag{1}
\]

Here \( dN_{\text{ion}}/dE_{\gamma,\text{ion}} \) is the rate per unit energy at which supernova inject CR ions of energy \( E_{\gamma,\text{ion}} \) into the galaxy, \( m_p \) is the mass of the proton, \( c \) is the speed of light, \( a_{pp} = 40 \) mbarn is the mean proton–proton inelastic cross section, \( d\sigma/dE_{\gamma}(E_{\gamma,\text{ion}}) \) is the differential cross section for production of γ-rays of energy \( E_{\gamma} \) by CR ions of energy \( E_{\gamma,\text{ion}} \) and \( f_{\text{cal}}(E_{\gamma,\text{ion}}) \) is the calorimetry fraction for CR ions of energy \( E_{\gamma,\text{ion}} \). We take \( dE_{\gamma,\text{ion}}/dE_{\gamma} \) from the parameterized model of ref. 11. We compute \( dN_{\text{ion}}/dE_{\gamma,\text{ion}} \) from the galactic star-formation rate \( M_\star \) by assuming that stars form with a Chabrier initial mass function12, which gives the distribution of masses for newly formed stars, and that stars with initial mass of 5–50 M_☉, where M_☉ is the mass of the Sun, end their lives as supernovae13, each supernova injects 10^{50} erg of energy in CR ions14,15, distributed in energy for CR energies \( E_{\gamma,\text{ion}} > m_p c^2 \) as \( dN_{\text{ion}}/dE_{\gamma,\text{ion}} = \phi \left( p_{\text{ion}}/p_0 \right)^\gamma d\sigma_{pp}/dE_{\gamma}(E_{\gamma,\text{ion}}) \exp(-E_{\gamma,\text{ion}}/E_{\text{cut}}) \), where \( p_0 = 1 \text{ GeV}/c \), the cutoff energy \( E_{\text{cut}} = 10^4 \text{ GeV} \), and the spectral index \( \gamma = 2 \) (refs. 19,20).

The exact choice of the cutoff energy above \( E_{\text{cut}} \) of the order of PeV makes no practical difference because the injection spectrum of γ-rays of energy \( E_{\gamma} \) is parameterized model of ref. 31. We compute \( \sigma_{\gamma \gamma} \) as

\[
\sigma_{\gamma \gamma} = 2.2 \text{ (refs. 19,20)}.
\]

The only remaining unknown in equation (1) is the calorimetry fraction \( f_{\text{cal}}(E_{\gamma,\text{ion}}) \), which we compute from the recent model of ref. 11. The basic premise of the model is that, in the neutral phase that dominates the mass of the ISM and thus the set of available targets for γ-ray production, CR transport is primarily by streaming along magnetic field lines. However, this yields approximately diffusive transport when averaged over scales comparable to or larger than the coherence length of the magnetic field, with a diffusion coefficient \( D = V_h h_0/M_\star \), where \( V_h \) is the CR streaming speed, \( h_0 \) is the gas scale height and \( M_\star \) is the Alfvén Mach number of the turbulence. For diffusive transport with losses in a disk geometry, the calorimetry fraction is given by (using the favoured parameters of ref. 15)

\[
f_{\text{cal}}(E_{\gamma,\text{ion}}) = 1 - \left[ \frac{16}{25} \frac{1}{T_{\gamma}} + \frac{3}{4} \frac{\tau_{\text{eff}}}{M_\star} \left( \frac{16}{25} \frac{1}{T_{\gamma}} \right) \right]^{-1},
\]

where \( \sigma_{\gamma} \) is the generalized hypergeometric function and \( \tau_{\text{eff}} \) is the dimensionless effective optical depth of the ISM, given by

\[
\tau_{\text{eff}} = \frac{a_{pp} \eta_{pp} \Sigma_\star h_0 c}{2D_\gamma \eta_{pp} M_\star}.
\]

Here \( \eta_{pp} = 0.5 \) is the elasticity of pp collisions, \( \Sigma_\star \) is the gas surface density of the galactic disk, \( D_\gamma \) is the diffusion coefficient at the galactic midplane, \( \mu_0 = 1.17 \) is the number density of nucleons per proton, and \( m_\text{H} = 1.67 \times 10^{-24} \text{ g} \) is the mass of a hydrogen atom.

To evaluate the calorimetry fraction for a CR of energy \( E_{\gamma,\text{ion}} \), we must therefore determine the midplane diffusion coefficient \( D_\gamma \) for CRs of that energy, which in turn depends on \( V_h \). This speed is dictated by the balance between excitation of the streaming instability and dissipation of the instability by ion-neutral damping, the dominant dissipation mechanism in the weakly ionized neutral ISM. Balancing these two effects yields a CR proton streaming velocity

\[
V_h = \min \left[ \left[ c, \frac{1}{\eta_{\gamma \gamma}} \left( \frac{V_h}{X \mu_0 c \rho^{3/2}} \right) \right] \right]
\]

where \( \eta_{\gamma \gamma} \) is the ion Alfvén speed, \( V_h = 4.9 \times 10^{13} \text{ cm}^3 \text{ g}^{-1} \) is the ion-neutral drag coefficient, \( \chi \) is the ionized mass fraction, \( \rho = \Sigma/2h_0 \) is the midplane mass density of the ISM, \( C \) is the midplane number density of CRs, \( \epsilon \) is the elementary charge, \( \mu_0 \) is the velocity dispersion of Alfvén modes in the ISM at the outer scale of the turbulence, \( \mu_0 \) is the atomic mass of the dominant ion species, \( q \) is the index of the CR energy distribution, and \( \gamma = E_{\gamma,\text{cut}}/m_\gamma c^2 \) is the Lorentz factor of the CR. Since γ-ray production in our model is dominated by galaxies with high star-formation rates and gas surface densities within which (i) the ISM is molecule-dominated, (ii) the main ionized species is C, and (iii) the magnetic field is set by a turbulent dynamo, we adopt the fiducial parameters of ref. 44 appropriate for such galaxies. Specifically, we take \( \chi = 1 \times 10^{-4}, \mu_0 = 12, M_\star = 2, V_h = v_\text{Alf} \times 1.3 M_\star \) and \( \eta_{\gamma \gamma} = \eta_{\gamma \gamma} \), where \( \eta_{\gamma \gamma} \) is the gas velocity dispersion of the galaxy. We also adopt \( q = 2.2 \), consistent with our assumed injection spectrum. We have chosen this set of parameters without any fine tuning, by selecting values that are generally accepted as being the most appropriate for the type of source that dominates the emission. However, we explore the parameter space in the Supplementary Information and show a selection of results in Extended Data Fig. 1.

At this point we have specified all the ingredients required to compute \( f_{\text{cal}}(E_{\gamma,\text{ion}}) \) for a galaxy of known \( \Sigma_\star, \rho_0, h_0 \), save one: \( C \), the CR number density. We estimate this as follows: consistent with our discussion above, for a galaxy with star-formation rate per unit area \( \Sigma_\star \), the CR injection rate per unit area is

\[
\frac{dN_{\text{ion}}}{dA} = \phi \sum_{p_{\text{ion}}} \left( \frac{p_{\text{ion}}}{p_0} \right)^q e^{-E_{\gamma,\text{ion}}/E_{\text{cut}}} dE_{\gamma,\text{ion}}
\]

The CR number density at the midplane is then given by

\[
C = \frac{\tau_{\text{loss}}}{2D_\gamma} \frac{dN_{\text{ion}}}{dA}.
\]

where \( \tau_{\text{loss}} \) is the CR loss time. This is given by \( \tau_{\text{loss}} = 1/(\tau_{\text{col}} - 1 + \tau_{\text{diff}}) \), where the timescale for losses in inelastic hadronic collisions is \( \tau_{\text{col}} = 1/(\sigma_{pp} n_\text{H} c/m_0 n_\text{H}) \) and the diffusive escape time \( \tau_{\text{diff}} = h_0/\sqrt{D_\gamma} \). For the system with high gas densities and high star-formation rate that dominate γ-ray production, the loss time is generally dominated by collisional losses. Conversely, for systems forming stars more sedately and with lower-density environments, it is generally determined by the diffusive escape time.

As a final note, we point out that the model of ref. 11 applies at CR energies up to tens of teraelectronvolts in galaxies whose interstellar media are mainly molecular (most galaxies with star-formation rates above a few solar masses per year), but may break down above tens of gigaelectronvolts in galaxies where the gas is mostly atomic45. Thus the model might not predict the correct degree of calorimetry at energies ≥100 GeV in dominantly atomic galaxies. As shown in Extended Data Fig. 2, however, galaxies with low star-formation rate make only a small contribution to the background, and thus a possible error in them will have minimal effects on the final result.
We illustrate the behaviour of $f_{\text{cal}}(E_{\text{ion}})$ over a range of gas surface densities and redshifts as applied to the CANDELS sample (see below) in Extended Data Figs. 4 and 5.

Gamma-ray emission model for CR leptons

CR electrons and positrons (since both behave identically, for brevity we just write electrons, but everything that follows should be understood to apply equally to both) are either injected directly by diffusive shock acceleration in supernova remnants at the same time as CR ions (primary production) or appear in the decay of charged pions $\pi^\pm$ produced by collisions of CR ions with the ISM (secondary production). We assume that the former carry a total energy equal to 2% of supernova kinetic energy (40) and have the same injection spectrum as the CR ions, $d\nu_{\text{ion}}/dE_{\text{ion}} = p(E_{\text{ion}}/\mu E_{\text{peak}})^{p-1}e^{-E_{\text{ion}}/E_{\text{peak}}}$, with $q = 2.2$, but a lower spectral cut-off energy at $E_{\text{cut}} = 100$ TeV (ref. 39). For the latter, we follow refs. 41–43. We first compute the rate at which CR ions produce pions of energy $E_{\pi}$,

$$\frac{dN_{\pi}}{dE_{\pi}} = \frac{n_i}{k_B} \beta \sigma_{\text{pion}}(E_{\text{ion}}) \frac{dN_{\text{ion}}}{dE_{\text{ion}}} f_{\text{cal}}(E_{\text{ion}}),$$

where $n_i = \Sigma_i/(2\mu m_i h^2)$ is the ISM number density, $\beta$ is the CR velocity divided by $c$, $E_{\pi} = K_i(E - m_c^2)$ and $K_i = 0.17$ is the fraction of energy transferred from the CR to the pion. Then the rate at which these pions produce secondary electrons is

$$\frac{dN_{e}}{dE_{e}} = 2 \int_{E_{\pi}/E_{\text{ion}}}^{1} f_{\text{pion}}(x) \frac{dN_{\pi}}{dE_{\pi}} \frac{E_{\pi}}{x} \frac{dx}{x},$$

where $f_{\text{pion}}(x)$ is a dimensionless fitting function given in ref. 36. Thus the total CR electron injection rate is $dN_{e}/dE_{e} = dN_{\pi}/dE_{\pi} + dN_{\text{ion}}/dE_{\text{ion}}$.

The electrons are subject to four dominant loss processes: collisional ionization, synchrotron radiation, bremsstrahlung, and inverse Compton scattering; as discussed in the main text, diffusive escape from the galaxy is negligible in comparison. We adopt the following parameterizations from the literature for the total energy loss rates $dE_{\text{loss}}/dt$ for energies of electron $E_{e}$;

$$\frac{dE_{e}}{dt_{\text{ion}}} = \frac{9}{4} \sigma_{e} c m_e^2 n_i \left[ \ln\gamma + \frac{2}{3} \ln \left( \frac{m_e c^2}{15 eV} \right) \right],$$

$$\frac{dE_{e}}{dt_{\text{sync}}} = \frac{1}{6n} \sigma_{e} c B^2 \gamma^2 \beta^2,$$

$$\left| \frac{dE_{e}}{dt_{\text{brem}}} \right| = \frac{3}{\pi} \sigma_{e} c m_e^2 n_i \left[ \ln \gamma + \frac{2}{3} \ln \left( \frac{m_e c^2}{15 eV} \right) \right] \frac{1}{\Phi_{Lw}(1/4 \gamma)} / \gamma \leq 15$$

$$\left| \frac{dE_{e}}{dt_{\text{lc}}} \right| = \frac{20}{\pi} \sigma_{e} c^2 u_{\text{rad}} \gamma (4 E_{\text{peak}} / m_e c^2), \quad \gamma \geq 15,$$

In these expressions, $\sigma_{e}$ is the Thomson cross-section, $a$ is the fine structure constant, $m_e$ is the electron mass, $\gamma = E_{e}/m_e c^2$ is the electron Lorentz factor, $E_{\text{peak}}$ is the energy where the infrared background peaks (derived from the dust temperature $T_{\text{dust}} = 98(1 + z)^{-0.065} + 6.9$ log ($M_\odot$/Myr$^{-1}$) $-$ $m_{\odot}$) (ref. 36) and injected as a diluted modified black body spectrum (40) that peaks in photon number at $E_{\text{cut}} = 100$ TeV (ref. 39). For the latter, we follow refs. 41–43. We first compute the rate at which CR ions produce pions of energy $E_{\pi}$,

$$\frac{dN_{\pi}}{dE_{\pi}} = \frac{n_i}{k_B} \beta \sigma_{\text{pion}}(E_{\text{ion}}) \frac{dN_{\text{ion}}}{dE_{\text{ion}}} f_{\text{cal}}(E_{\text{ion}}),$$

where $n_i = \Sigma_i/(2\mu m_i h^2)$ is the ISM number density, $\beta$ is the CR velocity divided by $c$, $E_{\pi} = K_i(E - m_c^2)$ and $K_i = 0.17$ is the fraction of energy transferred from the CR to the pion. Then the rate at which these pions produce secondary electrons is

$$\frac{dN_{e}}{dE_{e}} = 2 \int_{E_{\pi}/E_{\text{ion}}}^{1} f_{\text{pion}}(x) \frac{dN_{\pi}}{dE_{\pi}} \frac{E_{\pi}}{x} \frac{dx}{x},$$

where $f_{\text{pion}}(x)$ is a dimensionless fitting function given in ref. 36. Thus the total CR electron injection rate is $dN_{e}/dE_{e} = dN_{\pi}/dE_{\pi} + dN_{\text{ion}}/dE_{\text{ion}}$.

The electrons are subject to four dominant loss processes: collisional ionization, synchrotron radiation, bremsstrahlung, and inverse Compton scattering; as discussed in the main text, diffusive escape from the galaxy is negligible in comparison. We adopt the following parameterizations from the literature for the total energy loss rates $dE_{\text{loss}}/dt$ for energies of electron $E_{e}$;

$$\frac{dE_{e}}{dt_{\text{ion}}} = \frac{9}{4} \sigma_{e} c m_e^2 n_i \left[ \ln\gamma + \frac{2}{3} \ln \left( \frac{m_e c^2}{15 eV} \right) \right],$$

$$\frac{dE_{e}}{dt_{\text{sync}}} = \frac{1}{6n} \sigma_{e} c B^2 \gamma^2 \beta^2,$$

$$\left| \frac{dE_{e}}{dt_{\text{brem}}} \right| = \frac{3}{\pi} \sigma_{e} c m_e^2 n_i \left[ \ln \gamma + \frac{2}{3} \ln \left( \frac{m_e c^2}{15 eV} \right) \right] \frac{1}{\Phi_{Lw}(1/4 \gamma)} / \gamma \leq 15$$

$$\left| \frac{dE_{e}}{dt_{\text{lc}}} \right| = \frac{20}{\pi} \sigma_{e} c^2 u_{\text{rad}} \gamma (4 E_{\text{peak}} / m_e c^2), \quad \gamma \geq 15,$$

In those references. Given these loss rates, the steady-state spectrum in the galaxy is given approximately by

$$\frac{dN_{e}}{dE_{e}} \propto \frac{dN_{e}}{dE_{e}} f_{\text{loss}}(E_{e}),$$

where $t_{\text{loss}} = E_{e}/d_{\text{loss}}$ is the loss time due to process $i$, and $t_{\text{loss}} = (\Sigma_i t_{i}^{-1})^{-1}$ is the total loss time.

Of the four loss processes, only bremsstrahlung and inverse Compton scattering produce $\gamma$-rays. We compute the resulting emission using expressions analogous to equation (I). For bremsstrahlung,

$$\frac{dN_{\gamma}}{dE_{\gamma}} \propto \frac{3}{4} \sigma_{e} c^2 u_{\text{rad}} \gamma (4 E_{\text{peak}} / m_e c^2),$$

where $\sigma_{\text{brem}}$ is the cross-section for production of photons of energy $E_{\gamma}$ by electrons of energy $E_{e}$; we take our expression for $\sigma_{\text{brem}}$ from refs. 41-43. Similarly, for inverse Compton we have

$$\frac{dN_{\gamma}}{dE_{\gamma}} \propto \frac{G(a, \Gamma)}{4 \pi d_{L}(z)^2} \frac{dN_{e}}{dE_{e}} e^{-\tau_{\text{EBL}}(E_{\gamma})} e^{-\gamma_{\gamma}},$$

where $G(a, \Gamma) = 2a \ln \left( a + (1 + 2a) \right) + \left( (a)^2 / (1 + a^2) \right)$ and $a = E_{\gamma}/E_{\text{peak}}$. The total leptonic contribution to $\gamma$-ray production is simply $dN_{\gamma}/dE_{\gamma,\text{lepton}} = dN_{\gamma}/dE_{\gamma,\text{brem}} + dN_{\gamma}/dE_{\gamma,\text{lc}}$.

We show the contribution of leptonic emission to the diffuse, isotropic $\gamma$-ray background divided by emission mechanism, and by primary versus secondary, in Extended Data Fig. 6.

Gamma-ray flux at Earth

To obtain the total observed $\gamma$-ray flux for a galaxy, we must account for the attenuation of $\gamma$-ray photons by galactic far-infrared and extragalactic background light (EBL) photons. We compute the optical depth $\tau_{\gamma}$ due to the former using the model of ref. 47, and the optical depth from the latter, $\tau_{\text{EBL}}$, using the model of ref. 45. Taking these into account, we can compute the specific photon flux $d\nu_{\gamma}/dE_{\gamma}$ (that is, the number of photons per unit area, time and energy) received at the Earth from a galaxy at redshift $z$ as

$$d\nu_{\gamma}/dE_{\gamma}(E_{\gamma}, z) = d\nu_{\gamma}/dE_{\gamma}(E_{\gamma}, 1 + z) e^{-\tau_{\text{EBL}}(E_{\gamma}, z)} e^{-\tau_{\gamma}}.$$
of star formation $\Sigma_\ast$. However, the CANDELS dataset in ref. 22 that we use provides only the cosmological redshift $z$, stellar mass $M_\ast$ half-light or effective radius $R_e$ (corrected to 5,000 Å according to ref. 36), and total star-formation rate $\dot{M}_\ast$ for our sample galaxies. We must therefore estimate the gas properties from observed correlations between gas and stellar properties. We do so as follows.

The half light radius $R_e$ at 5,000 Å serves as a first-order estimate of how the star formation and matter are distributed throughout the galactic disk. We therefore estimate the star-formation rate surface density as $\Sigma_\ast = M_\ast / 2\pi R_e^2$ and the stellar surface density as $\Sigma = M_\ast / 2\pi R_e^2$. We estimate the gas surface density from the observed correlation between gas, stellar and star-formation surface densities given by ref. 31.

$$\frac{\Sigma_g}{M_\ast \, \text{pc}^{-2}} = 10^{0.28} \frac{\Sigma}{M_\ast \, \text{yr}^{-1} \, \text{pc}^{-2}} \left( \frac{\Sigma_\ast}{M_\ast \, \text{pc}^{-2}} \right)^{-0.48} \tag{17}$$

Similarly, there is a strong correlation between galaxy star-formation rates and velocity dispersions, which we use to derive $\sigma_g$. For this purpose we fit the relationship using the MaNGA galaxy sample 31. A power-law fit to the data obtained in this survey (figure 6 of ref. 31) gives

$$\sigma_g = 32.063 \left( \frac{\dot{M}_\ast}{M_\ast \, \text{yr}^{-1}} \right)^{0.096} \tag{18}$$

Finally, we derive the gas scale height under the assumption that the gas is in vertical hydrostatic equilibrium, in which case the scale height is 33

$$h_g = \frac{\sigma_g^2}{nG(\Sigma_\ast + \Sigma)} \tag{19}$$

where $G$ is the gravitational constant.

With these gas properties in hand, we calculate an observed spectrum for each galaxy in the CANDELS sample by using equation (16), and we then sum over the sample to predict the $\gamma$-ray flux per unit energy per unit solid angle $\Phi(E, \gamma)$ produced by SFGs. In practice, we compute the sum as:

$$\Phi(E, \gamma) = \frac{1}{\Omega_S} \sum_{j=1}^{n_{\text{bin}}} f_{\text{corr}, j} \sum_{i=1}^{n_{\gamma}} \frac{df_{\gamma,i}}{dE_{\gamma,i}} \tag{20}$$

Here $\Omega_S = 173$ arcmin$^2$ is the solid angle surveyed by CANDELS, $n_{\gamma}$ is the number of surveyed galaxies in the $i$th redshift bin, $(df_{\gamma,i}/dE_{\gamma,i})$ is the flux from the $i$th galaxy in this bin predicted using equation (16), and $n_{\text{bin}}$ is the number of redshift bins. The factor $f_{\text{corr}, j}$ is the ratio of the expected total star-formation rate in each redshift bin (based on the measured cosmic star-formation history 34 and obtained by integrating the star-formation rate density over the volume in each redshift bin) to the sum of the star-formation rates of CANDELS galaxies in that bin; its purpose is to correct for the fact that, owing to its limited field of view and various observational biases, the distribution of star formation with respect to redshift in CANDELS does not precisely match the total star-formation history of the Universe. We use redshift bins of size $\Delta z = 0.1$, chosen to ensure that the number of sample galaxies in each bin is large enough that the uncertainty in the mean spectrum due to Poisson sampling of the galaxy population is small.

For the purposes of constructing Fig. 2, we require not just the flux, but the total $\gamma$-ray luminosity in the Fermi band. We compute this by integrating $E, dN / dE_{\gamma}$ (computed as the sum of equations (1), (14) and (15)) from $E_{\gamma} = 0.1$–100 GeV. Since this comparison also requires the far-infrared luminosity, we convert the star-formation rate to a far-infrared luminosity in the 8–1,000 µm band using the relation in refs. 35, corrected to a Chabrier initial mass function 36; this conversion is valid for star-formation rates $\pm 1 \, M_\odot \, \text{yr}^{-1}$, which encompasses almost all of the observed sample to which we wish to compare.

Monte Carlo estimation for the local population

To estimate the observable source count distribution for Fermi LAT, as shown in Fig. 3, we cannot use the CANDELS catalogue directly, because CANDELS has a narrow field of view that provides very little sampling of galaxies at $z \leq 0.1$, whereas these local sources are the only ones Fermi LAT can resolve. We therefore use a Monte Carlo scheme to simulate a nearby, low-redshift ($z < 0.1$) galaxy population that follows the observed distribution of star-formation rates in the local Universe to account for cosmic variance, and where the correlation between galaxy star-formation rate and $\gamma$-ray luminosity is the same as what our model predicts for the low redshift ($z < 1.5$) part of the CANDELS sample.

The first step is to produce a sample of SFGs. To do so, we draw galaxies from the observed distribution of star-formation rates in the local Universe 57,58. For each SFG drawn, we also draw an associated redshift in the range $z = 0$–0.1, with probability proportional to the co-moving volume element. We continue drawing galaxies until the total star-formation rate of the population we have drawn matches the integrated star-formation rate within the volume $z = 0$–0.1 as determined from the cosmic star-formation history 34. The second step is to assign $\gamma$-ray luminosities for these galaxies based on our model for the CANDELS galaxies. For this purpose, we apply our model to predict the photon luminosity integrated over the 1–100 GeV band (that is, the number of photons per unit time emitted in this energy range) for all CANDELS galaxies with $z < 1.5$, and fit a power-law relationship between this luminosity and the star-formation rate; we neglect $\gamma\gamma$ opacity in this calculation, since this effect is unimportant for the galaxies at $z < 0.1$ and the energy range <100 GeV that we are simulating. We then assign each of our SFGs a $\gamma$-ray photon luminosity using this power-law fit, and in conjunction with the redshift, an observed photon flux $S$.

At this point we have a sample of $\gamma$-ray photon fluxes $S$ for simulated $z < 0.1$ SFGs, which we can place in bins of $S$ to construct a synthetic prediction for $S^2(dN/dS)$. We carry out 13,000 Monte Carlo trials of this type, and in each bin of $S$ record the mean and the 68% and 90% probability intervals, which we show as the blue points and bands in Fig. 3. Our method for computing the analogous confidence intervals for the observations is described in the Supplementary Information.

Data availability

The data that were used to produce the figures and that support the findings of this study are available in Zenodo with the identifier https://doi.org/10.5281/zenodo.4764111. Source data are provided with this paper.

Code availability

The code used to derive the key findings of this study is available in Zenodo with the identifier https://doi.org/10.5281/zenodo.4609628.
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Extended Data Fig. 1 | The effect of varying model parameters. The plots presented here show the result of our calculations when varying the model parameters as discussed in the Supplementary Information. Our fiducial choice is plotted as a solid blue line, with the dashed and dash-dotted lines showing the spectrum for the upper and lower limits respectively of the varied parameter. The black points correspond to the Fermi data as in Fig. 4. Plot a shows $M_A$ plotted for reasonable values of 1.6 and 2.3, and extremal values of 1.1 and 3.0; b the ionization fraction $\chi$ for values of $10^{-2}$ and $10^{-6}$; c the injection index $q$ for values 2.1 and 2.3; and finally d the conversion fraction of supernova energy to CR electrons for values of 1% and 3%, which is equivalent to 10% and 30% of the total energy injected in all cosmic ray species. Note that varying the total CR energy budget results in a trivial scaling of the result by the same fraction, and thus is not shown.
Extended Data Fig. 2 | The contribution of SFGs in the $M_\dot\gamma - z$ plane. The contribution of SFGs to the total γ-ray spectrum at selected energies in the star-formation rate ($M_\dot\gamma$), redshift ($z$) plane. Coloured pixels show the fractional contribution (as indicated in the colourbar) from galaxies in each bin of $M_\dot\gamma$ and $z$ to the diffuse isotropic γ-ray background at the indicated energy; a fractional contribution of unity corresponds to that pixel producing all of the background, with no contribution from galaxies outside the pixel. Grey points show individual CANDELS galaxies in regions of $M_\dot\gamma$ and $z$ that contribute $<10^{-3}$ of the total. Flanking histograms show the fractional contribution binned in one dimension — $M_\dot\gamma$ (right) and $z$ (top). We see that the background at lower energies is dominated by emission from galaxies on the high side of the star forming main sequence at $z \sim 1-2$, while at high energies it is dominated by the brightest systems at low redshift.
Extended Data Fig. 3 | The diffuse isotropic γ-ray and neutrino backgrounds. The blue line and black points show the model-predicted and observed γ-ray background, and are identical to those shown in Fig. 4. The red lines show our model prediction for the neutrino background (single flavour) with $E_{\text{cut}} = 100$ PeV (solid line) and $E_{\text{cut}} = 1$ PeV (dashed line), computed as described in the Supplementary Information. We assume a neutrino flavour ratio at the detector of $(\nu_e:\nu_\mu:\nu_\tau) = (1:1:1)$. The red filled band shows a power-law fit\textsuperscript{73} to the single flavour astrophysical neutrino background with the 90% likelihood limit, as measured by IceCube, which is also shown as grey points, where the horizontal bars show the energy bin and the vertical bars the 1σ uncertainty limit.
Extended Data Fig. 4 | Cosmic ray calorimetry in the $E \cdot \Sigma_g$ plane. Mean calorimetry fraction $f_{\text{cal}}(E)$ in the surface gas density $\Sigma_g$, cosmic ray energy $E$ plane, binned in redshift intervals. This figure is constructed by deriving the gas surface density and energy dependent calorimetry fraction for each galaxy in the CANDELS sample using our model. The colour of each pixel gives the mean calorimetry fraction of all the galaxies within that particular range of $\Sigma_g$, $E$, and redshift. The horizontal white stripes correspond to ranges of $\Sigma_g$ into which no CANDELS galaxies fall for the corresponding redshift range. Several physical processes contribute to the behaviour visible in the plot. At low $\Sigma_g$, galaxies have low $f_{\text{cal}}$ at all energies $E$ because there are few targets for hadronic collisions with CRs. As $\Sigma_g$ increases, the increased ISM density results in efficient calorimetry and conversion of CR energy into $\gamma$-rays for low CR energies; however, at higher energies the CR number density is low, yielding a high CR streaming velocity and rapid escape, resulting in low $f_{\text{cal}}$. As $\Sigma_g$ increases further, the increasing density results in the streaming instability being suppressed efficiently by ion-neutral damping towards lower energies, reducing the calorimetry fraction further. Finally, at the highest $\Sigma_g$ the streaming instability is suppressed completely by ion-neutral damping, but streaming is still limited to the speed of light. Consequently, increasing $\Sigma_g$ further only results in increased collisions, and thus a higher calorimetry fraction.
Extended Data Fig. 5 | Cosmic ray calorimetry in the $z$-$\Sigma_g$ plane. Mean calorimetry fraction in the surface gas density ($\Sigma_g$), redshift ($z$) plane at CR energies $E = 1 \text{ GeV}, 10 \text{ GeV}, 1 \text{ TeV}$ and $10 \text{ TeV}$. To construct this figure, for each CANDELS sample galaxy, we apply our model to compute $\Sigma_g$ and $f_{\text{cal}}(E)$ at the indicated energies. The colour indicates the average $f_{\text{cal}}(E)$ value computed over bins of $(z, \Sigma_g)$, while contours indicate the density of the CANDELS sample in this plane. Note that the non-monotonic behaviour of $f_{\text{cal}}(E)$ with $\Sigma_g$ that is most prominently visible in the 1 TeV panel is expected, for the reasons explained in the caption of Extended Data Fig. 4.
Extended Data Fig. 6 | Contributions to the diffuse isotropic γ-ray background. The blue line and black points show the model-predicted and observed γ-ray background, and are identical to those shown in Fig. 4. The green line shows the contribution from π⁰ decay, the olive lines the contribution from bremsstrahlung emission, and the cyan lines the contribution from the inverse Compton emission. In both cases, dashed lines show the spectrum produced by primary CR electrons and the dash-dotted lines the spectrum from secondary electrons and positrons. The red line shows the contributions from the EBL cascade.
Extended Data Table 1 | Local galaxy data

| Galaxy   | $d_L$ [Mpc] | $\log M_\star$ [M$_\odot$] | $R_e$ [kpc] | $M_\star$ [$M_\odot$ yr$^{-1}$] | $h_z$ [pc] | $\sigma_z$ [km s$^{-1}$] | $\log \Sigma$ [M$_\odot$ pc$^{-2}$] |
|----------|-------------|----------------------------|-------------|---------------------------------|------------|---------------------------|---------------------------------|
| Arp 220  | 80.9$^{15}_5$ | 10.63$^{10}_2$ | 3.4$^{10}_2$ | 220$^{15}_3$ | 75$^{11}_4$ | 100$^{11}_4$ | 4.0$^{11}_1$ |
| NGC 253  | 3.56$^{25}_5$ | 10.4$^{61}_6$ | 3.87$^{62}_3$ | 4.0$^{64}_6$ | 130$^{11}_4$ | 26$^{11}_4$ | 2.6$^{11}_1$ |
| M 31     | 0.77$^{25}_5$ | 10.84$^{65}_6$ | 2.46$^{66}_6$ | 0.26$^{25}_5$ | 150$^{67}_4$ | 10$^{68}_4$ | 0.68$^{55}_5$ |
| NGC 4945 | 3.72$^{25}_5$ | 10.52$^{69}_6$ | 2.34$^{70}_6$ | 4.0$^{71}_3$ | $^*$ | 26$^{11}_4$ | $^*$ |

Data are from refs. $^{15}_5$, $^{25}_5$. For each entry, we give a value followed by the reference from which that value is taken.

*NGC 4945 is observed edge-on, so measurements of the gas scale height and gas surface density are unavailable. We derive them in the usual manner, as described in the Methods, using the measured gas velocity dispersion.

†The gas data come exclusively from the nuclear starburst region, so we give two effective radii and SFR estimates: the first is for the entire galaxy, and the second is for the circumnuclear disk/nuclear starburst region only. We use the former for our stellar data spectrum prediction and the latter for our gas prediction.