The isotropic diffuse γ-ray background
and associated non-thermal emission

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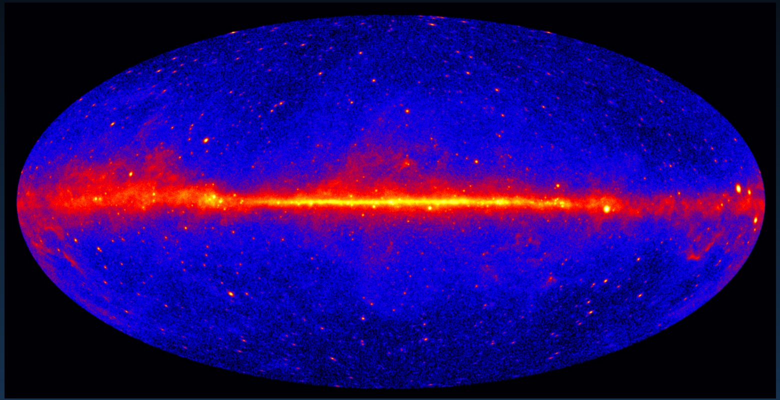


NASA/DOE/Fermi LAT Collaboration – 9 years of Fermi data

Brief outline

- Cosmic rays, what are they, where do they come from?
- CRs $\rightarrow \gamma$-rays
- CR calorimetry in star-forming galaxies
- Minimal set of model inputs
- γ-ray spectra of local galaxies
- CANDELS
- DIGB
- Outlook: other non-thermal emission from SFGs

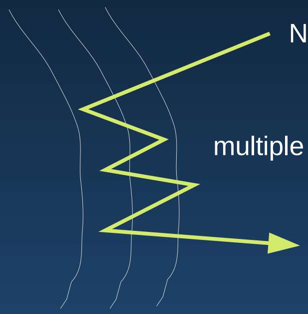
Cosmic Rays (CRs)

Star formation

$E \sim 10^{51}$ erg

Supernovae

Diffusive shock acceleration in SNRs



$\eta \sim 0.1 \rightarrow 10^{50}$ erg in CR ions + $O(10^{49}$ erg) in CR e^-

CRs accelerated in SNR shocks by means of DSA ⟹ $\frac{dN_{CR}}{dE} \propto E^{-2}$

CR propagation + model

injection spectra ~ E^{-q} with q ~ 2.1 – 2.5

B fields: CRs couple to ionised component of ISM, ionised ISM coupled collisionally to neutrals

Excite streaming instability → ‘self-confinement’

→ damping by ion-neutral collisions vs. growth rate of the streaming instability (K+P1969)

$$\Gamma_d = \frac{\nu_{\rm in}}{2} \qquad \Gamma_g = \frac{eB}{mc}\frac{n_{CR}(>\gamma)}{n_i}\left(\frac{V_{st}}{V_{Ai}} - 1\right)$$

→ streaming limited diffusion + field-line random walk MK2020+

→ macroscopic diffusion coefficient

→ this yields a calorimetry fraction → $f_{cal}(E_{CR})$

Model

Require as minimum:

- z (distance)
- half light radius R_e
- M_*
- SFR

+ inverse KS, σ_g-SFR relation

➡ Derive scale height h, ISM density n_H, CR density, etc.

➡ Obtain $f_{cal}(E_{CR})$

CR energy losses

Loss processes for CR protons:

Two fates:

→ diffusive escape into IGM (safe! $\tau_{loss} > 1/H_0$)

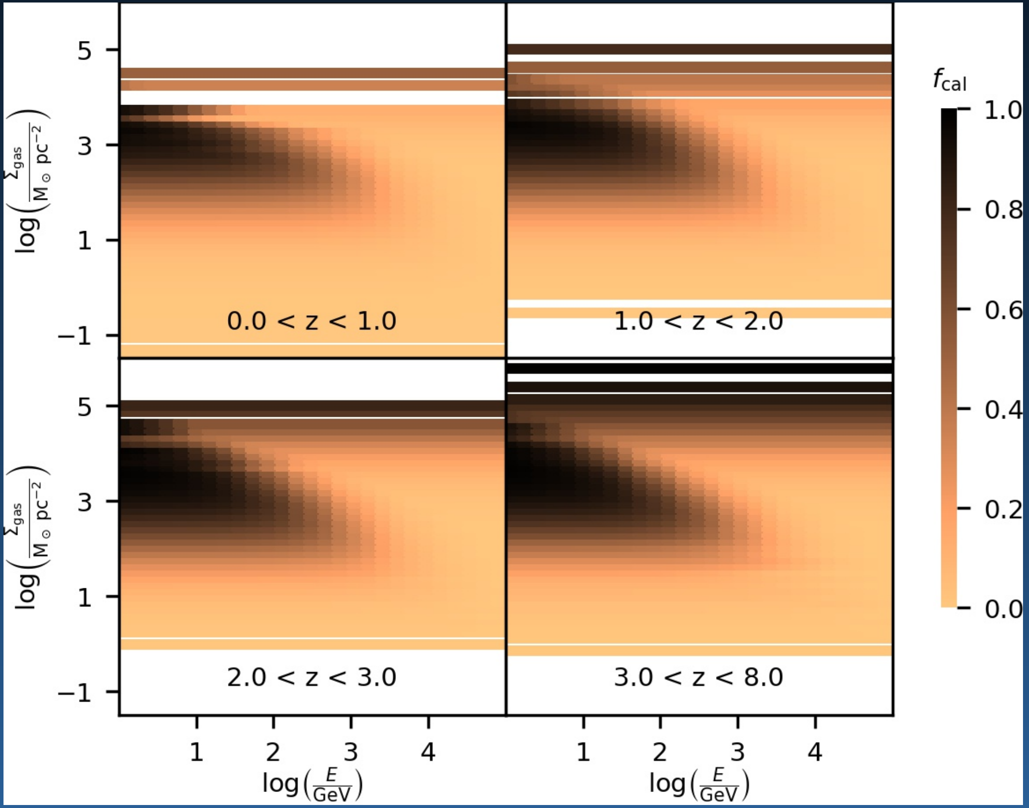
→ CR energy loss in inelastic hadronic collision

$$\pi^0 \rightarrow 2\gamma$$

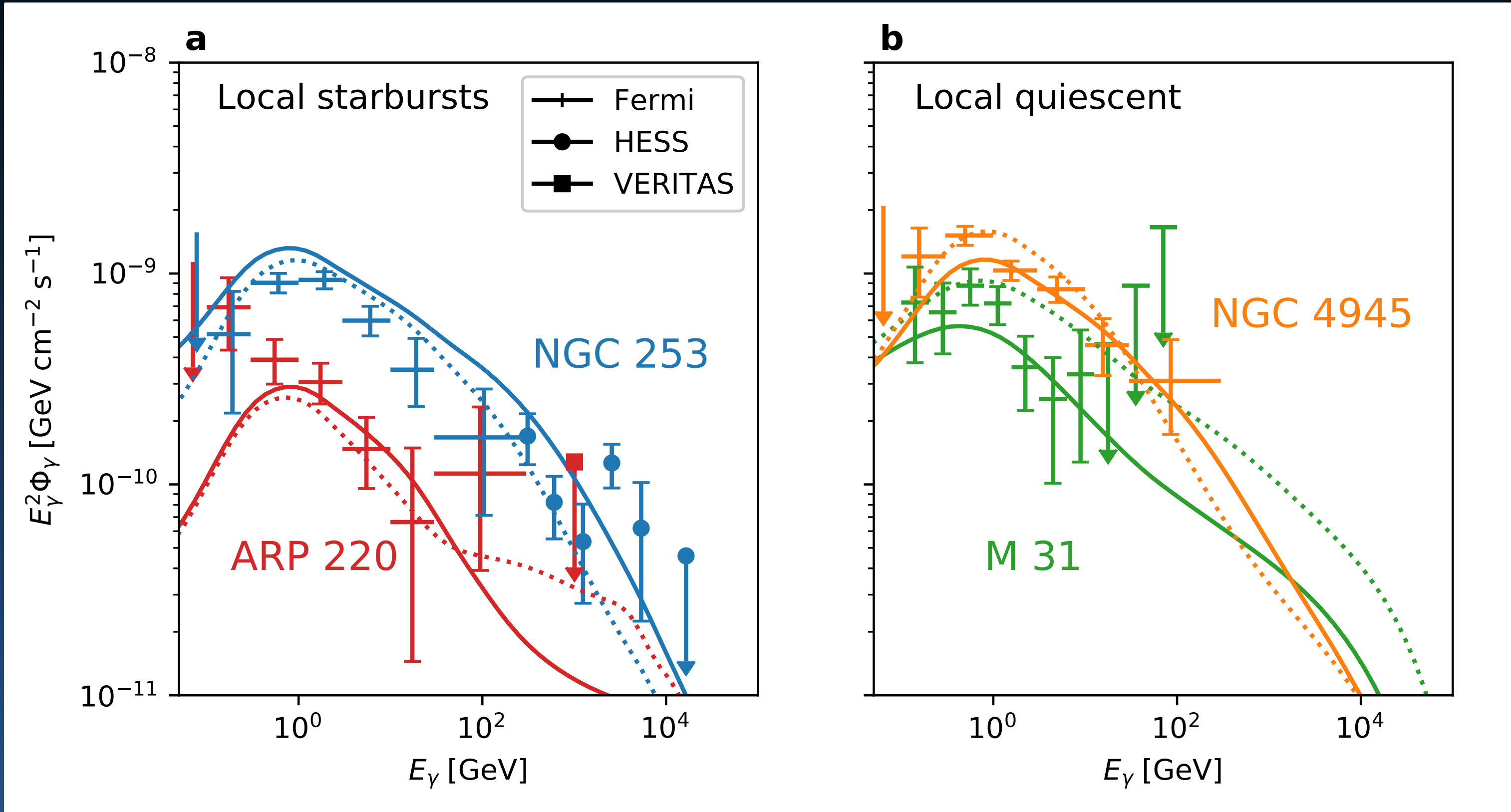
$$\pi^+ \rightarrow \mu^+ + \nu_\mu \qquad \mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$

$$\pi^- \rightarrow \mu^- + \bar{\nu}_\mu \qquad \mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu$$

$$v_{st} \approx min\left(V_{Ai}\left(1 + \frac{\gamma_d \chi M_A c \rho^{3/2}}{4\pi^{1/2} C e u_{LA} \mu_i \gamma^{-p+1}}\right), c\right)$$

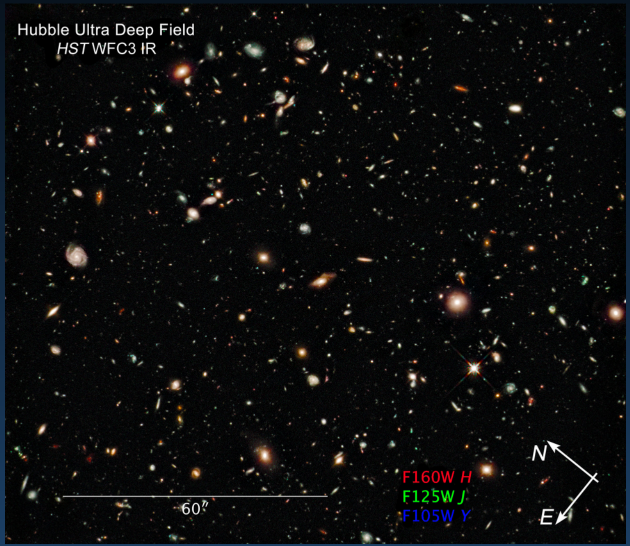


Applying this to galaxies



CANDELS

Take the above model and apply to a deep field survey



NASA, ESA, G. Illingworth, R. Bouwens, and the HUDF09 Team.

Require as minimum:

- z
- half light radius R_e
- M_*
- SFR

+ inverse KS, σ_g-SFR relation

➡ Derive scale height h, ISM density n_H, CR density, etc.

➡ Obtain $f_{cal}(E_{CR})$

Calculate spectrum for each galaxy, account for EBL and galactic opacity, sum contributions

$$\Phi_E(E_\gamma) = \sum_{i=1}^{n_s} \frac{(1+z)^2}{4\pi d_L^2} f_i(E_\gamma(1+z)) e^{-\tau_{EBL}(E_\gamma, z)} e^{-\tau_{\gamma\gamma}(E_\gamma(1+z))}$$

+ convolve with cosmic SFH (low z!)

The DIGB

Current wisdom:

→AGNs (Blazars in the main) dominate resolved EGB
→SFGs – luminosity function + FIR-ɣ relation + spectral shape

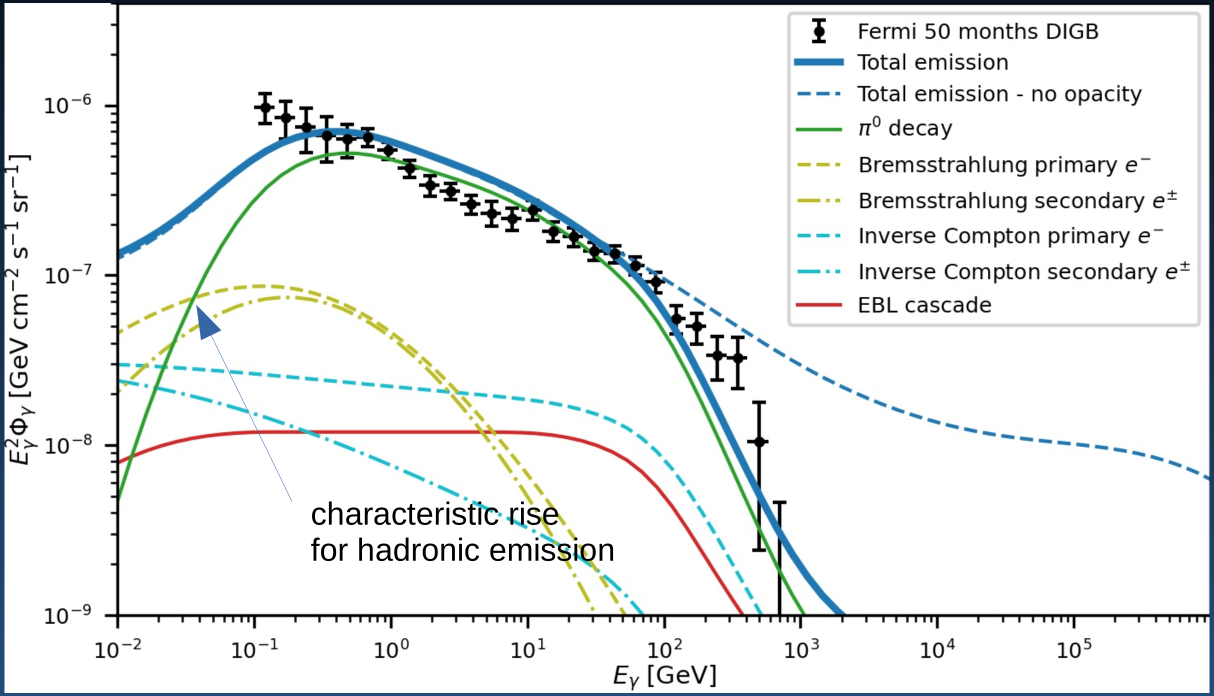
→ substantial uncertainties

However:

→ New results (more SFG ɣ-ray detections) hint at slightly brighter galaxies (Kornecki et al. 2020).
→ clustering statistics and cross-correlation somewhat favour SFG-like emitters over AGN
→ Really require a physical model for ɣ-ray emission in SFGs – i.e. a bottom-up approach

The DIGB

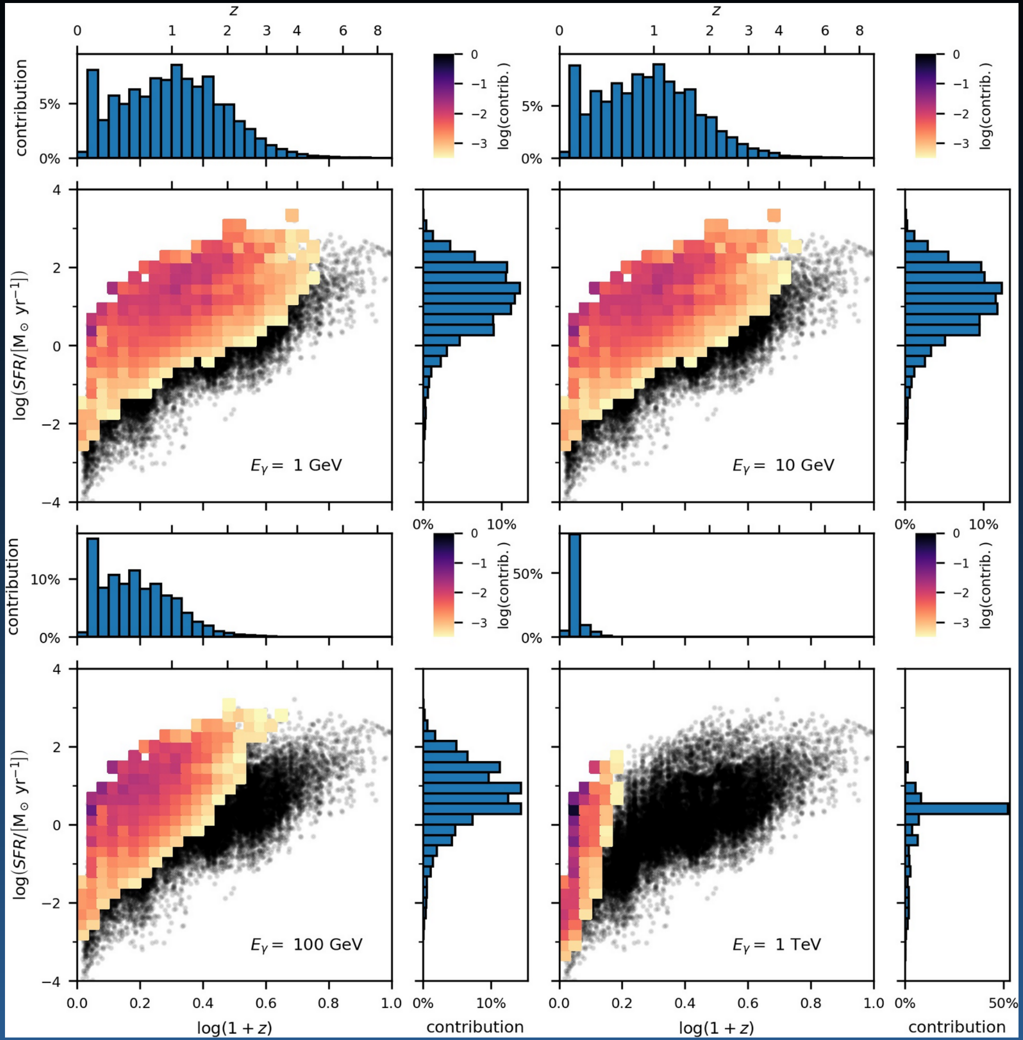
Model applied to CANDELS GOODS-S field



Key inputs:

- SN mechanical energy converted into CR ‘p’s - $\eta = 0.1$
- Injection index 2.2
- Mass of stars formed per SN → SN rate
- $M_A = 2$

The DIGB



z
0 1 2 3 4 6 8
contribution
5%
0%
log(contrib.)
0 −1 −2 −3
log(SFR/[M⊙ yr−1])
4 2 0 −2 −4
Eγ = 1 GeV
Eγ = 10 GeV
Eγ = 100 GeV
Eγ = 1 TeV
0% 10%
10%
50%
0.0 0.2 0.4 0.6 0.8 1.0
log(1 + z)
contribution
0% 50%

CRe loss mechanism

Essentially a long talk in itself: Very (very!) brief overview

Inject 2% of SN energy - Balancing of loss mechanisms!

Ionisation
→ what it is says on the box

Bremsstrahlung
→ emits a photon when deflected by Coulomb field of ISM particle
→ some γ-rays

Inverse Compton
→ upscatter low energy photons
→ sensitive to interstellar radiation field (CMB, FIR, etc.) (prop. u_{rad})
→ can dominate γ-ray emission

Synchrotron
→ radial acceleration by B-field
→ prop. u_B
→ radio continuum emission

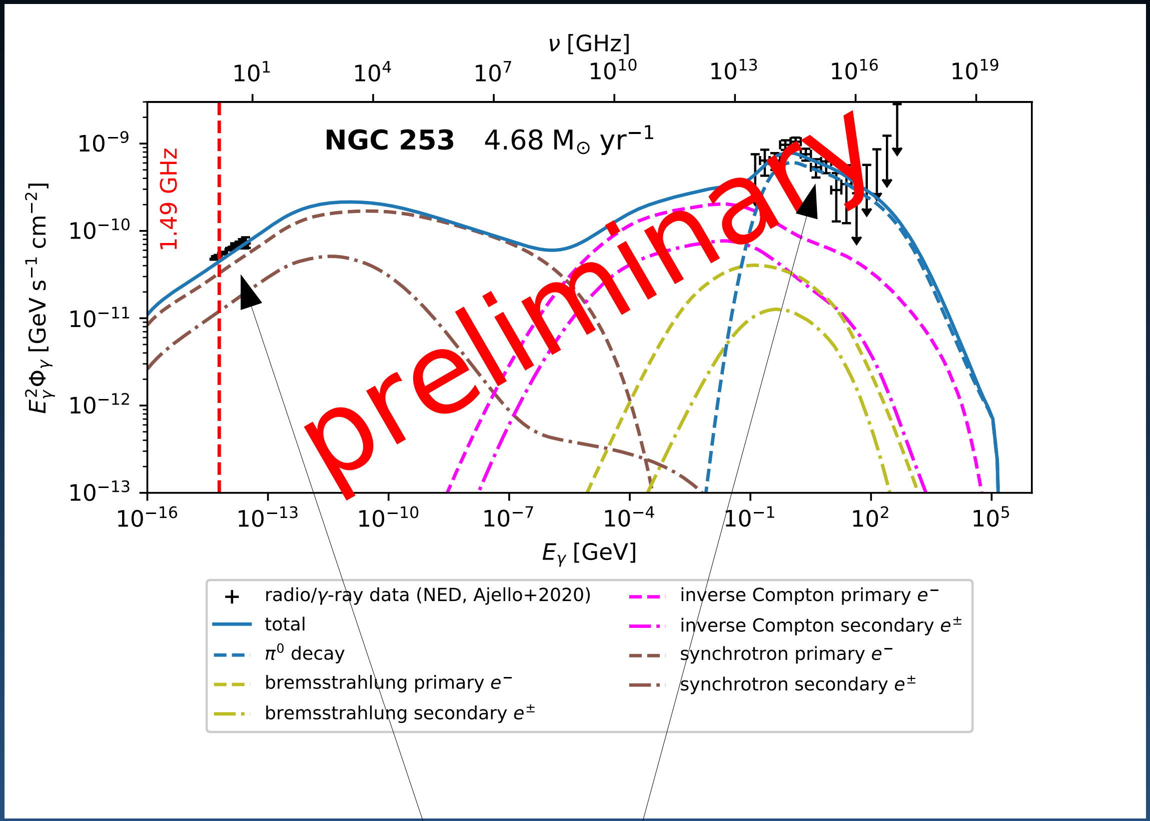
Highly energy dependent – approximately:

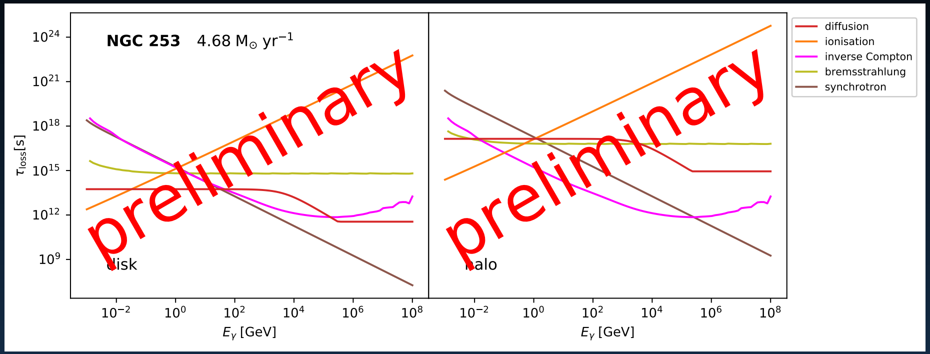
Low E (sub GeV) → ionisation
Intermediate E (~GeV+) → diffusion, BS, IC, sync
High E (~TeV) → IC, sync
UHE → sync only (IC suppressed due to Klein Nishina)

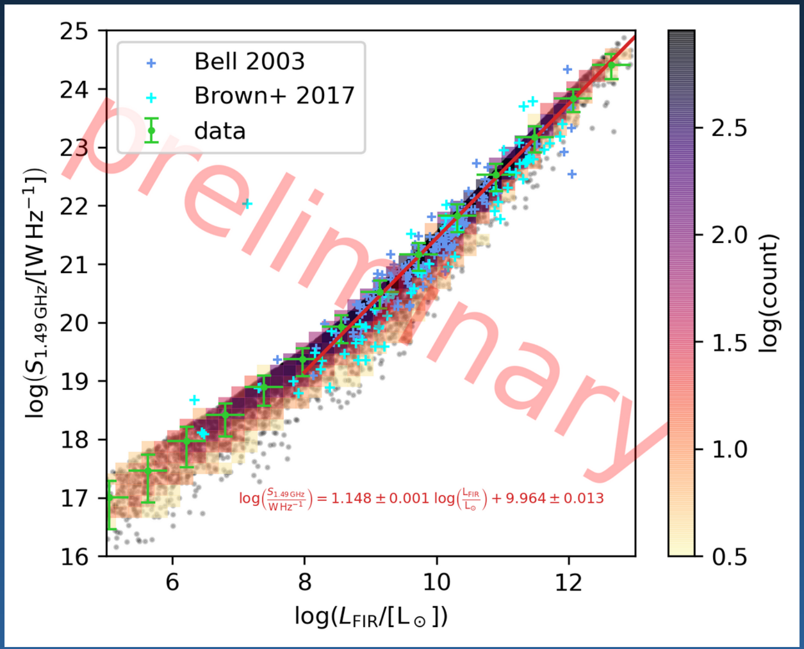
Use this to model non-thermal spectra in a two-zone model (disk+halo) by solving for the steady state CR spectra using the full description.

$$\frac{\partial N_e(E,t)}{\partial t} - D\nabla^2 N_e(E,t) + \frac{\partial}{\partial E}\left(\dot{E} N_e(E,t)\right) + N_e(E,t)\int_{m_e c^2}^{E} P(E,k)\ dk - \int_E^{\infty} N_e(k,t)\, P(k,E)\ dk - \sum_i Q_i(E,t) = 0$$

Some results







Sometimes things work a bit too well...

Conclusions

- SFGs dominate the diffuse isotropic gamma-ray background
  - Taking standard parameters (no fine-tuning) → could explain most of the emission
  - Model yields reasonable spectra for nearby gamma-ray observed SFGs
  - ➔ FIR-γ correlation consistent with observation
  - ➔ Source count distribution consistent with observation
  - Details in https://arxiv.org/abs/2109.07598
- Model extension can yield results for other non-thermal emission. Current research on explaining FIR-radio correlation. Paper in prep…
- CTA:
  - Extend the population of observed SFGs and other sources → constraints on model inputs
  - New measurement of the diffuse isotropic background
- Neutrinos! Currently recover ~15% of astrophysical neutrino flux with current diffusion model. Believe this doesn't quite apply at UHE….