High-Energy Gamma-ray and Neutrino Emission from Star-Forming Galaxies across cosmic time

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Main points of this work

- New model of high-energy gamma-ray and neutrino spectrum and luminosity of star-forming galaxies (SFGs), calibrated with data of nearby galaxies.
  - Fit observed gamma-ray luminosities better than empirical power-laws.
- Combine this model with cosmological galaxy formation model to predict cosmic background flux
  - SFGs produce ~ 20% of isotropic gamma-ray background and at most 22% of IceCube neutrinos.
SFGs as sources of high-energy particles

- Many previous studies predict SFGs can produce 1-50% of gamma-ray (GeV) & neutrino (TeV) background flux (Pavlidou & Fields 02, Thompson+07, Ando & Pavlidou 09, Fields+10, Makiya+11, Stecker & Venters 11, Ackermann+12, Chakraborty & Fields 13, Lacki+14, Linden+17, Lamastra+17, Komis+17; Loeb & Waxman 06, Thompson+06, Stecker 07, Lacki+11, Murase+13, He+13, Tamborra+14, Anchordoqui+14, Liu+14, Emig+15, Chang+15, Giacinti+15, Senno+15, Maharani & Razzaque 16, Chakrabortty & Izaguirre 16, Xiao+16, Bechtol+17)

- Usually rely on empirical relations (e.g. $L_\gamma$ - SFR)

- Often assume only two types of galaxies (normal / burst)

- Need a physically-motivated model that takes diverse properties of galaxies into account
New model of galactic high-energy emissions

<table>
<thead>
<tr>
<th>Objects</th>
<th>$L_\gamma$ [$10^{39}$ erg s$^{-1}$]</th>
<th>SFR [$M_{\odot}$ yr$^{-1}$]</th>
<th>$M_{gas}$ [$10^9 M_{\odot}$]</th>
<th>$M_*$ [$10^9 M_{\odot}$]</th>
<th>$R_{eff}$ [kpc]</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW</td>
<td>0.82±0.24</td>
<td>2.6</td>
<td>4.9</td>
<td>50</td>
<td>6.0</td>
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<tr>
<td>LMC</td>
<td>0.047±0.005</td>
<td>0.24</td>
<td>0.53</td>
<td>1.5</td>
<td>2.2</td>
</tr>
<tr>
<td>SMC</td>
<td>0.011±0.003</td>
<td>0.037</td>
<td>0.45</td>
<td>0.46</td>
<td>0.7</td>
</tr>
<tr>
<td>NGC253</td>
<td>6±2</td>
<td>7.9</td>
<td>4.3</td>
<td>21</td>
<td>3.7</td>
</tr>
<tr>
<td>M82</td>
<td>15±3</td>
<td>16.3</td>
<td>1.3</td>
<td>8.7$^{\dagger}$</td>
<td>1.2</td>
</tr>
<tr>
<td>NGC2146</td>
<td>40±21</td>
<td>17.5$^{\ddagger}$</td>
<td>4.1</td>
<td>20</td>
<td>1.8</td>
</tr>
</tbody>
</table>

- Refer to six nearby galaxies, with good measurements of SFR, gas mass, stellar mass, radius
- Make model of gamma-ray & neutrino spectrum, from these four physical quantities (next slide)
- Compare prediction with observed $L_\gamma$s to calibrate model
New model of galactic high-energy emissions

- CR production rate: SFR
- CR spectrum at production: power-law with index $\Gamma_{\text{inj}}$
- Fraction of SN energy carried by CRs: parameter to fit data

- pp interaction rate: ISM density ($M_{\text{gas}}, R, H$) $H \propto R$

- Escape from the galaxy: advection or diffusion
  - Advection velocity: escape velocity from disk
  - Diffusion coefficient:
    \[
    D(E_p) = \frac{c l_0}{3} \left[ (\frac{R_L}{l_0})^{1/3} + (\frac{R_L}{l_0})^2 \right]
    \]
  - Magnetic field: equipartition with energy density injected by supernovae within dynamical timescale
Calibration by nearby galaxies

<table>
<thead>
<tr>
<th>Objects</th>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
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<tr>
<td></td>
<td>$L_\gamma$ [10^{39} \text{ erg s}^{-1}]</td>
<td>SFR [M_\odot \text{ yr}^{-1}]</td>
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<td>17.5‡</td>
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</table>

- Use data of six galaxies to fix one model parameter (= fraction of SN energy carried by CRs)
- One free parameter to fit six galaxies
- Obtained best-fit value ~20%
Model well fit gamma-ray luminosities of six galaxies
Cosmological galaxy formation model

- Semi-analytical models of galaxy formation
  - Standard tools in studies of galaxy evolution
  - Reproduce many observed properties of galaxies
  - Produce mock galaxy catalogues with physical quantities (SFR, mass, size ...)

Nagashima & Yoshii 2004
Nagashima et al. 2005
Gamma-ray background unresolved by Fermi

- Spectrum at SNR is a parameter \(( \Gamma_{\text{inj}} \sim 2.3 \) from MW observation)

- Star-forming galaxies make about 20% contribution to isotropic gamma-ray background (0.1-100 GeV)

- Consistent with estimate by Fermi-LAT (4-23%, Ackermann+12)
Gamma-ray (GeV) & Neutrino (TeV) from SFGs
Neutrino background by IceCube

- Only 0.5% of data can be explained with $\Gamma_{\text{inj}} = 2.3$
- 22% even if $\Gamma_{\text{inj}} = 2.0$ (theory of acceleration, but extremely optimistic)
- Majority of IceCube data cannot be explained by star-forming galaxies (including starburst)
- Note: our calculation only include contributions from supernovae
Summary

- A new model of gamma-ray and neutrino from SFGs
  - Use four physical quantities: SFR, Mstar, Mgas, radius
  - Well fit gamma-ray luminosities from dwarfs to starbursts

- Cosmic background of gamma-ray and neutrinos from SFGs
  - Use cosmological model of galaxy formation
  - ~20% of Fermi unresolved gamma-ray background
  - 0.5 - 2% of the IceCube flux for $\Gamma_{\text{inj}} = 2.2 - 2.3$, and 22% for the most optimistic case of $\Gamma_{\text{inj}} = 2.0$