Leptonic gamma-ray emission from star-forming galaxies

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Galactic cosmic ray accelerators

Cosmic ray origin is uncertain

Cosmic ray composition is a characteristic feature of the accelerating source which may help to constrain the CR origin

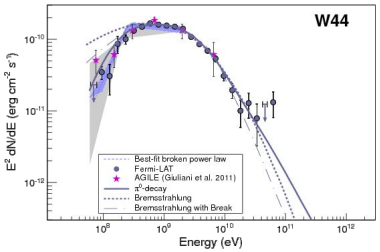
Commonly adopted that it is related to star formation activity.

- SNRs (e.g Ginzburg & Syrovatskii ‘64, Aharonian+ ‘12, Hillas 2005)
- pulsars & PWN (e.g. Neronov & Semikoz ‘12)
- stellar clusters (e.g. Bykov & Fleishman ‘92)

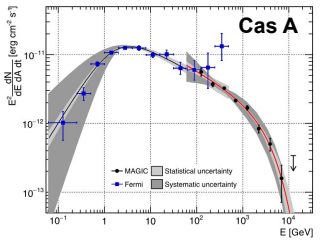
While alternatives exists (e.g. GC SMBH, HESS Collaboration 2016), indications for accelerated protons and electrons indeed found for a number of SNRs and stellar clusters.

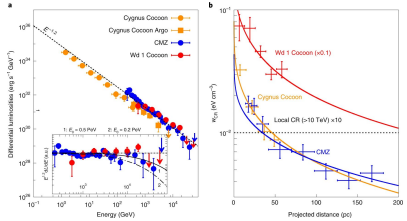
Proton dominance in the Galactic diffuse gamma-ray emission is believed to be consistent with star-formation origin (e.g. SN or stellar wind shocks)

Ackermann+ ‘13



Ahnen+ ‘17





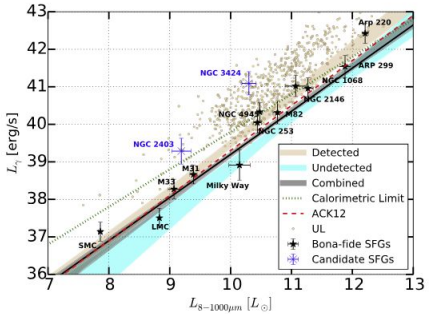
Aharonian+ ‘19

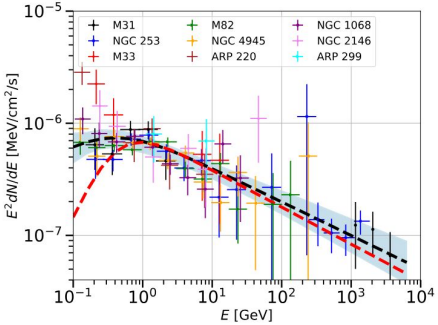
The star-forming galaxies (SFG) are thus expected to contain large number of cosmic rays. As such, SFG are expected to be appreciable sources of gamma-ray radiation.

Gamma-ray emission from star-forming galaxies

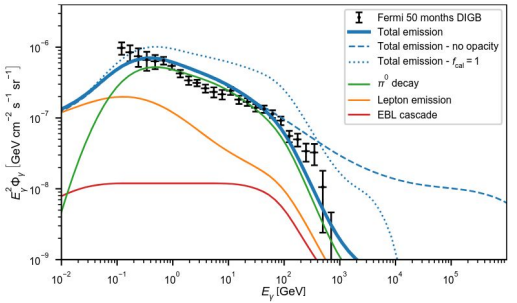
A dozen of SFG has already been detected in gamma-ray with Fermi/LAT and IACTs directly and others, potentially collectively as a part of the diffuse gamma-ray background.

(e.g. Acciari+ ‘09, Acero+ ‘09, Ajello+ ‘20, Roth+ ‘21)





Ajello+ ‘20



Roth+ ‘21

Tight correlation between the IR and gamma-ray luminosities & the absence of flux variability

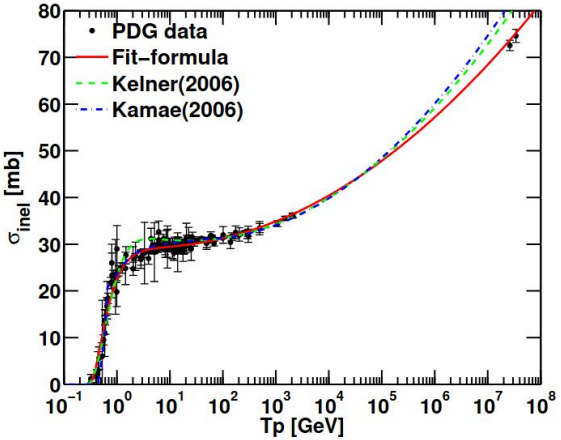
(e.g. Ackermann+ ‘12, Ajello+ ‘20)

speaks in favour of cosmic ray protons as a primary source of the emission.

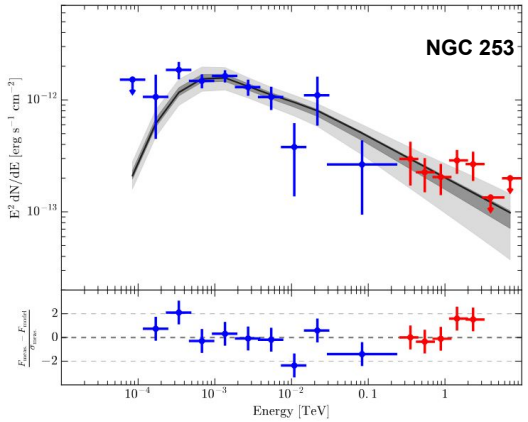
Proton signatures in γ-ray emission from star-forming galaxies

CR gamma-ray **emission >100 MeV** is expected to be **dominated by π^0 decays** (for Milky-Way-like composition)

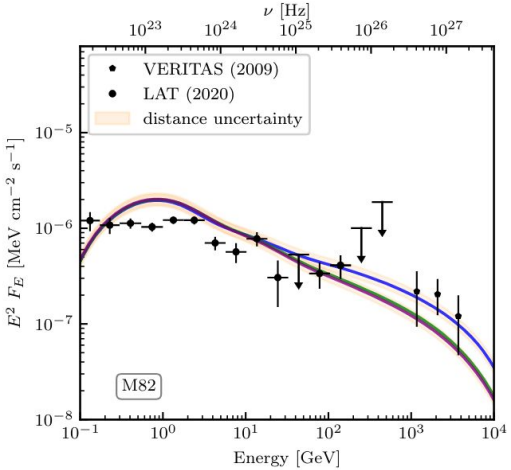
→ Low-energy cut off @ ~300 MeV due to the reduction in p-p cross section.



Kafexhiu+ '14



Abdalla+ '18



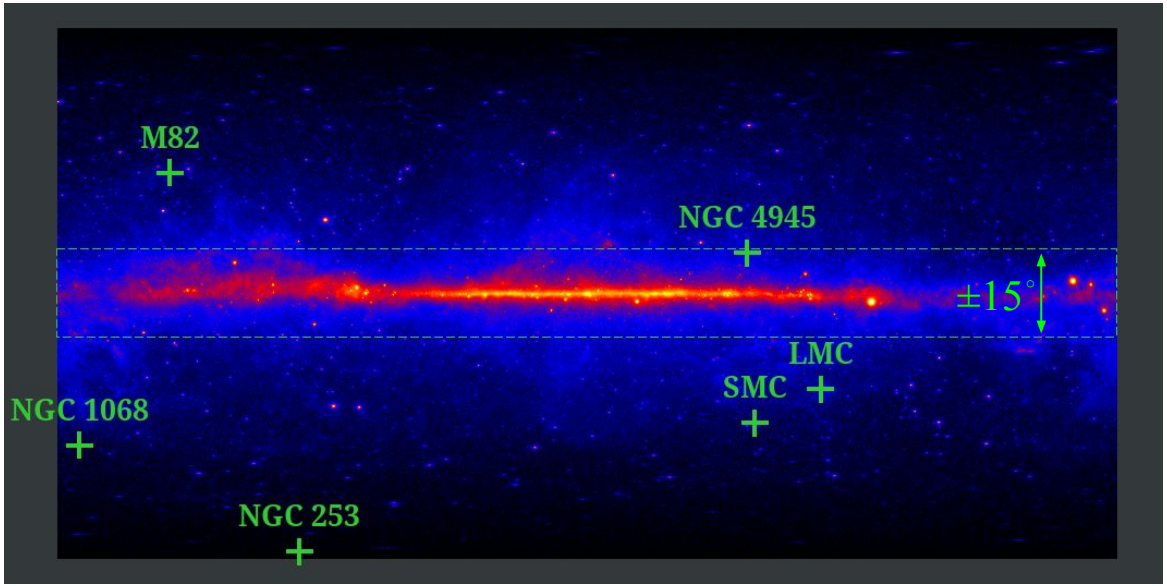
Werhahn+ '23

This cut off is generally expected in the SFG gamma-ray spectra.

Brightest star-forming galaxies in the Fermi/LAT sky

Fermi/LAT sky map > 1 GeV
with the brightest star-forming galaxies marked

- 14 star-forming galaxies detected by Fermi/LAT this far (Ajello+ ‘20)
- half of them with individual significance > 10σ
- 1 variabile emission likely of jet origin
- a single detection below 100 MeV (NGC 1068, Ajello+ ‘23)



Is there π^0 decay cut off in these galaxies?

Fermi/LAT view of brightest SFG with 15 years of data

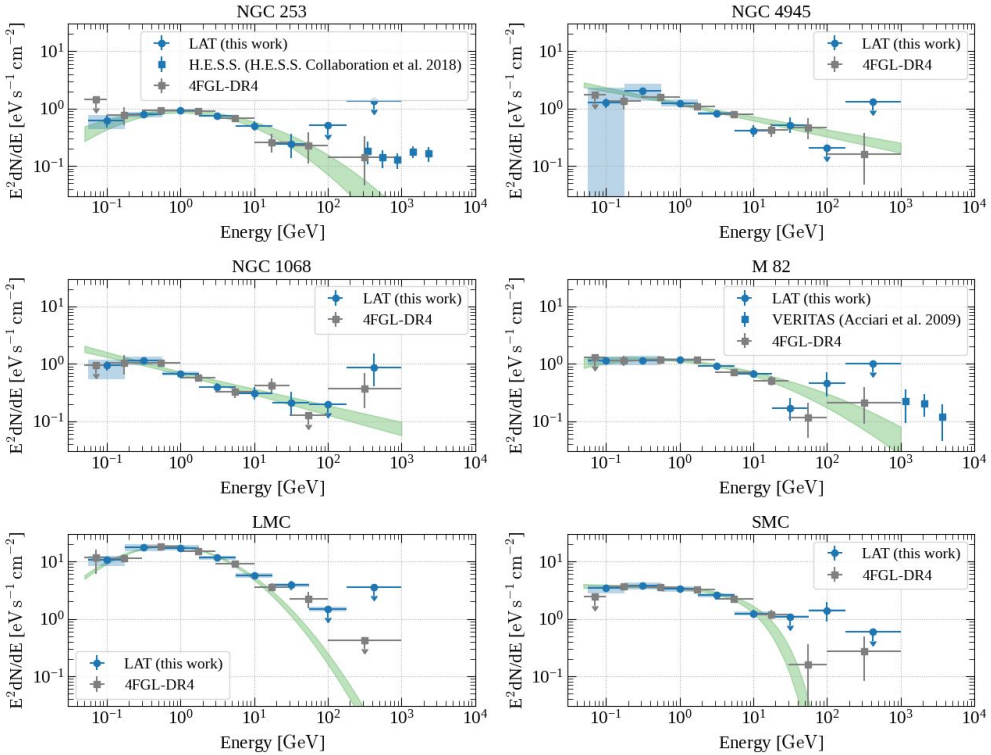
Focus on low-energy emission < 200 MeV

- firmly detected SFG (TS > 100 in Ajello+ ‘20)
- extend analysis down to 56 MeV
- individual PSF classes to improve LE sensitivity
- systematics from +/- 5% scaling of diffuse bkg.

SEDs consistent with PWL / LPWL from 4FGL

No indications for π^0 cutoff

- NGC 4945 uncertain due to Gal. plane proximity
- NGC 1068 detection consistent with Ajello+ ‘23
- M82 detection consistent with Ajello+ ‘20



π^0 decay cut off search

Steady-state SFR model

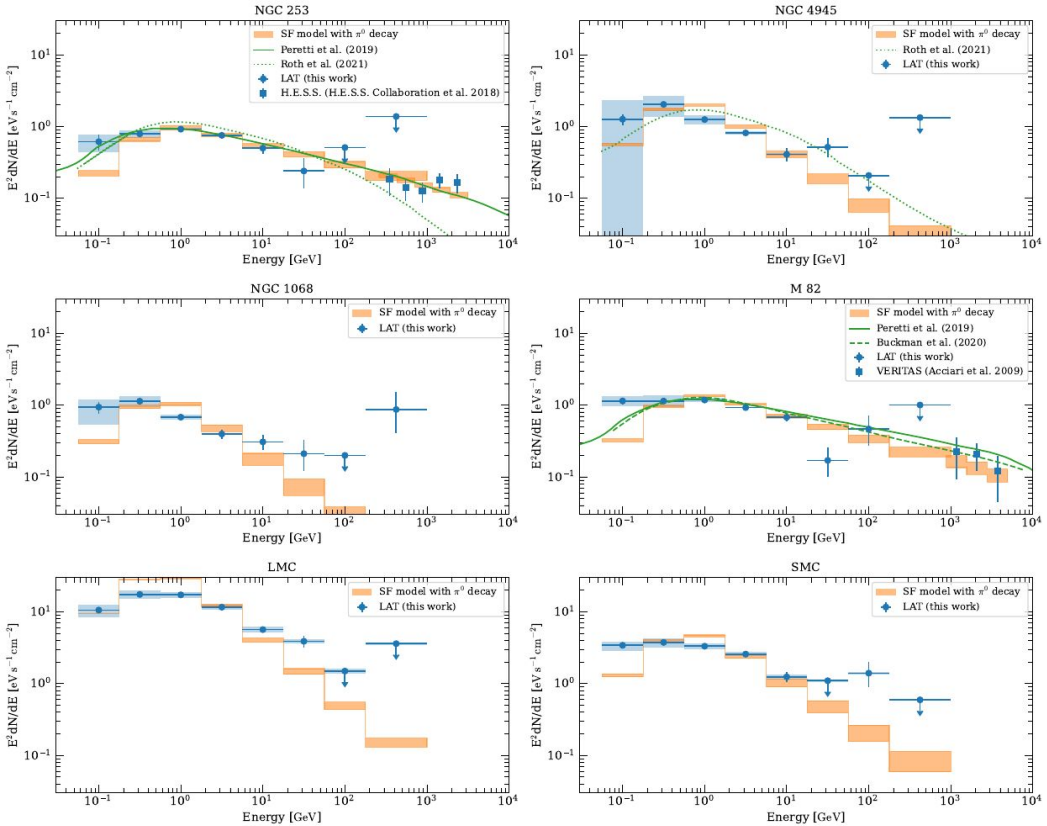
- power law particle injection spectra

$$\frac{dN_p}{dpdt} = N\left(\frac{p}{p_0}\right)^{-\alpha}\exp\left(-\frac{p}{p_p^{max}}\right)$$
$$\frac{dN_e}{dpdt} = K_{ep}N\left(\frac{p}{p_0}\right)^{-\alpha}\exp\left(-\frac{p}{p_e^{max}}\right)$$

- E_{max} from balance between cooling and acceleration rates
- energy losses: IC, synchrotron, bremsstrahlung, ionization, p-p

For NGC 1068, M82, LMC and SMC
π^0 emission rejected at > 6σ level.

NGC 253 may still be consistent with Peretti+ '19 model



Fermi/LAT view of brightest SFG with 15 years of data

Protons have no other emission mechanism surpassing p-p in the GeV band

Secondary emission?

e / p for secondaries from $\pi^{+/-}$ decays is model-independent (fixed by the physics of the process)

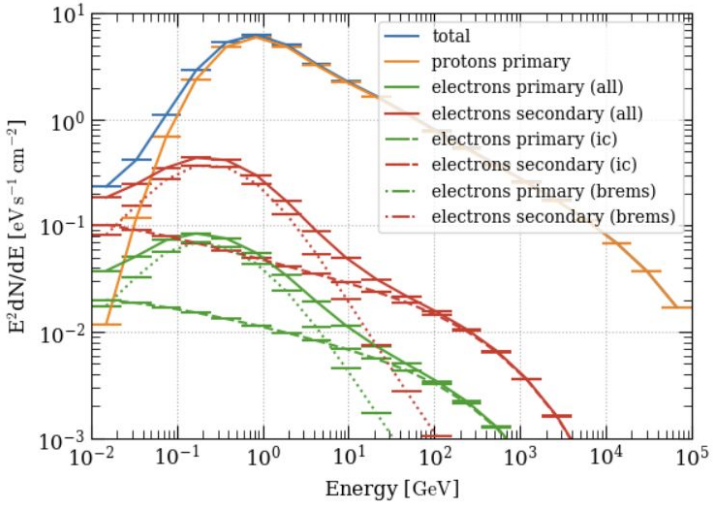
→ subdominant contribution

↓

Detected sub-GeV emission is mostly of leptonic origin

Required acceleration power above 100 MeV:

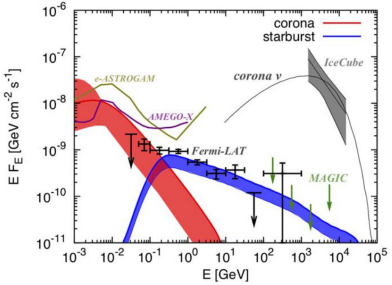
$$P_e > 4\pi \left(\frac{\nu F_\nu/(\Gamma-2)}{1\,\mathrm{eV/(cm^2 s)}}\right)\left(\frac{d}{3\,\mathrm{Mpc}}\right)^2 \gtrsim 10^{40}(d/3\,\mathrm{Mpc})^2\,\mathrm{erg\,s^{-1}}$$



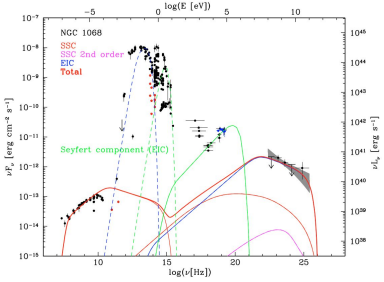
Example of SFR emission breakdown.
Primary e/p is fixed requiring $N_e = N_p$ (Bell 78)

AGN contribution?

- NGC 1068 & NGC 4945 - known Seyfert 2 AGNs
- M82 and NGC 253: evidences for low-luminosity AGN from optical and X-ray data

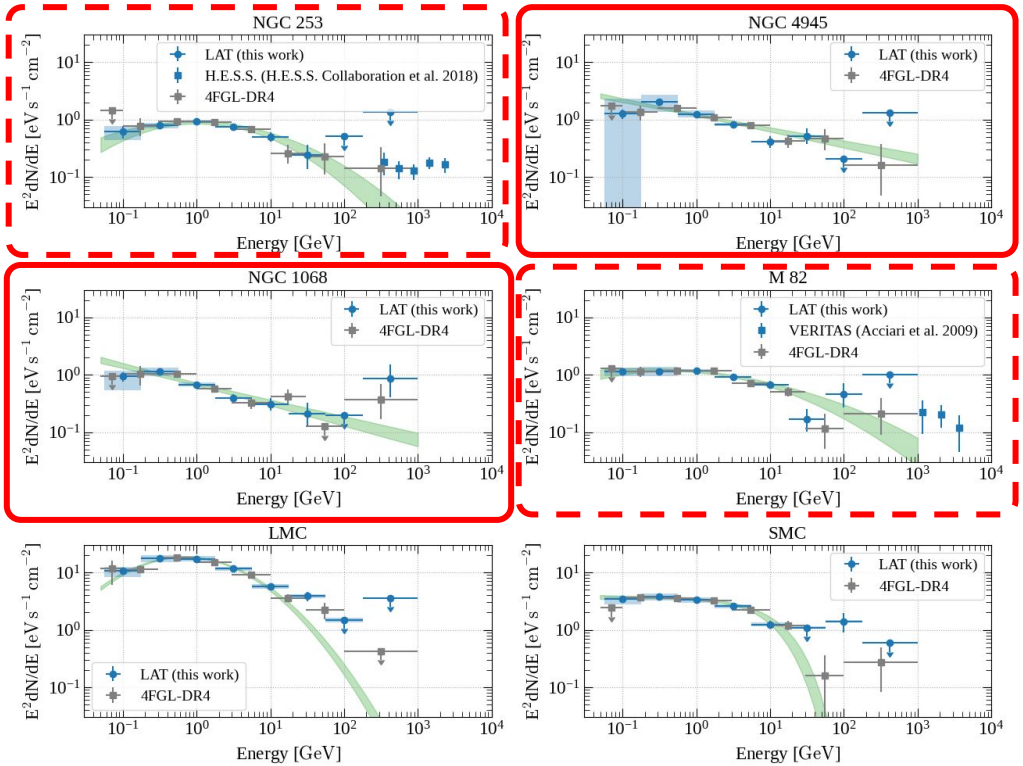


Corona model Ajello+ '23



Outflow model Lenain+ '10

- "corona + p-p" interpretation requires tight balance between AGN and star-formation activities (different locations and time scales)
- while AGN feedback may trigger SF, it is unclear if the observed IR - gamma correlation can be accommodated in this scenario.
- no AGN activity in LMC & SMC



Suppression of proton contribution?

Recent star-formation outbreak?

Balance between primary electrons and protons may be tilted
if cosmic ray acceleration started < $t_{pp} \approx 0.3\ (100\ \mathrm{cm^{-3}} / n_H)$ Myr ago

Star-formation burst duration t_{sf} ~ 10-100 Myr → chance probability $p = (t_{pp}/t_{sf})^N \sim 10^{-4}$

→ **Improbable**

Proton escape?

Primary electrons can dominate if ~10 GeV protons escape at $t_{esc} < k_e\ t_{pp}$

$D > 10^{30}\ (R / 100\ \mathrm{pc})^2\ (3\ \mathrm{kyr} / t_{esc})\ \mathrm{cm^2/s}$

→ 10x the Galactic diffusion coefficient

$v_{wind} > 3 \times 10^4\ (R / 100\ \mathrm{pc})\ (3\ \mathrm{kyr} / t_{esc})\ \mathrm{km/s}$

→ 10x the expected hot & massive stars wind

→ **Improbable**

Bremsstrahlung from primary electrons?

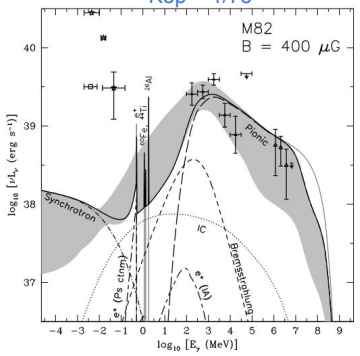
$N_e = N_p$, same spectra and $T_0 < mc^2$ (Bell 78)

$$K_{ep} = \frac{dN_e/dp_e}{dN_p/dp_p} \approx \left(\frac{m_e}{m_p}\right)^{(\alpha-1)/2} \sim 1 / 100$$

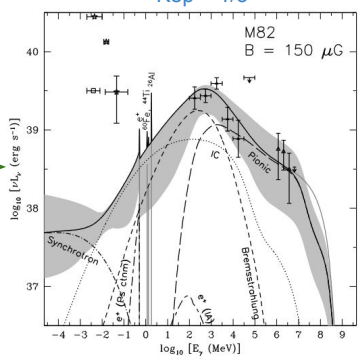
Valid for Milky Way, but is not necessarily general

Large e / p → emerging electron bremsstrahlung < 1 GeV

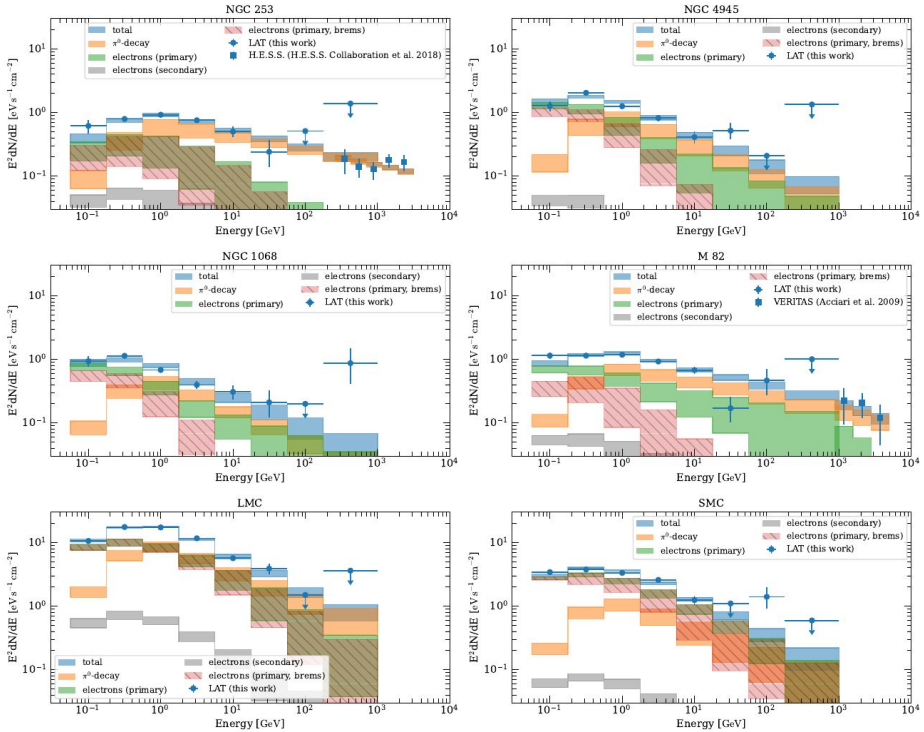
Kep = 1/73



Kep = 1/3



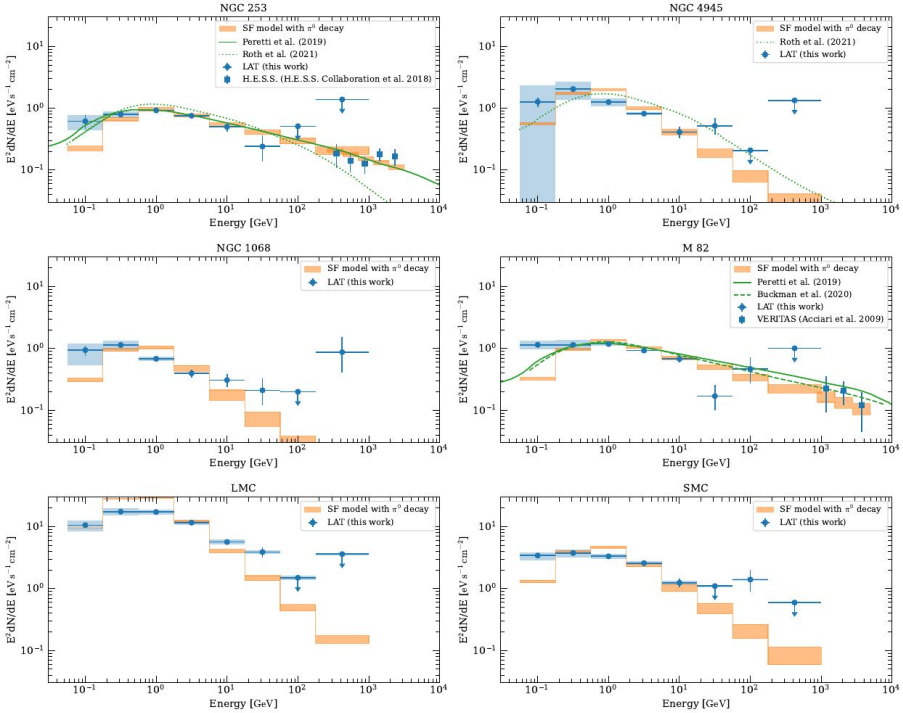
Lacki+ '14



Requires K_{ep} ~ 1 and energy densities $w_{cr} > w_B$

Summary

- **no π^0 bump in SFG spectra based on 15 years of LAT data**
  - possible exceptions: NGC 4945 and NGC 253
- **dominant sub-GeV emission of unclear leptonic origin:**
  - AGN models require fine-tuning to match all SFGs
  - primary electrons require exceptionally high e/p ratio
  - $w_{cr} > w_B$ disfavors the plerion origin
  - unresolved sources (but: LMC & SMC)
  - relation to Milky Way is unclear
- **origin of HE emission is testable with CTA / LHAASO**
  - lepton dominance in the entire energy range - inevitable Klein-Nishina cut off above ~10 TeV



Either way, a substantial part of the SFG lepton cosmic ray energy budget may have been missed this far.