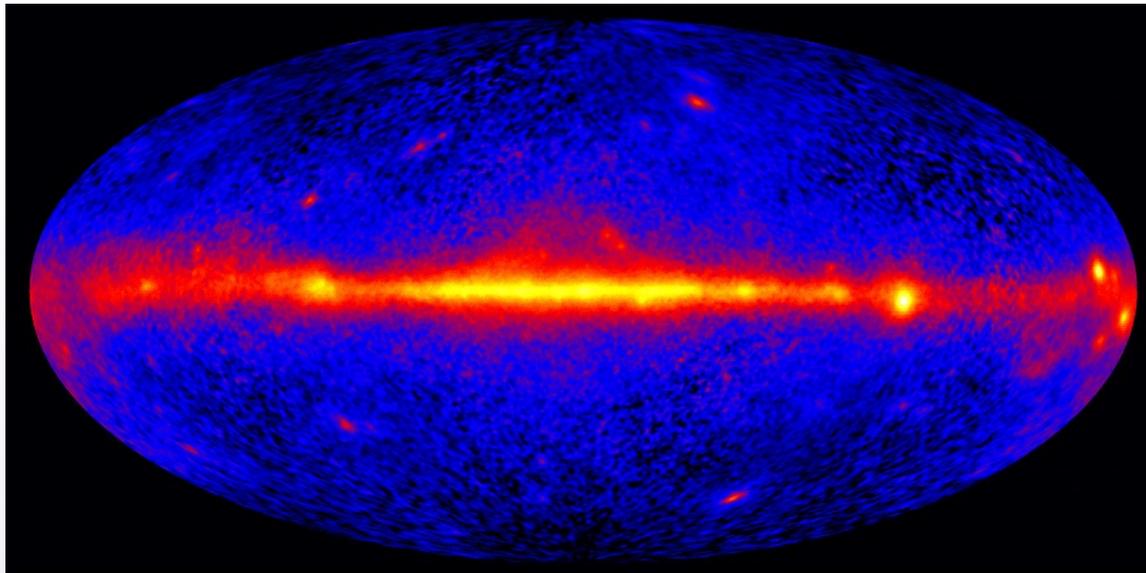# Galaxy Contributions to High-Energy Extragalactic Gamma-Ray and Neutrino Backgrounds

25th February 2025, Multimessenger Astrophysics in a Dynamic Universe, Kyoto, Japan

EGRET and Fermi-LAT over 12 years. Credit: NASA/EGRET Team and NASA/DOE/Fermi LAT collaboration

Ellis R Owen

SPDR Fellow - Astrophysical Big Bang Laboratory - RIKEN Pioneering Research Institute

Collaborators: Yoshiyuki Inoue (UOsaka), Tatsuki Fujiwara (UOsaka), Albert K. H. Kong (Natl. Tsing Hua U, Taiwan)

ellis.owen@riken.jp   www.ellisowen.org

EXTRA–GALACTIC MULTIMESSENGER BACKGROUNDS

The combined unresolved emission from high-energy extra-galactic sources

Gamma-rays (above 1 GeV)
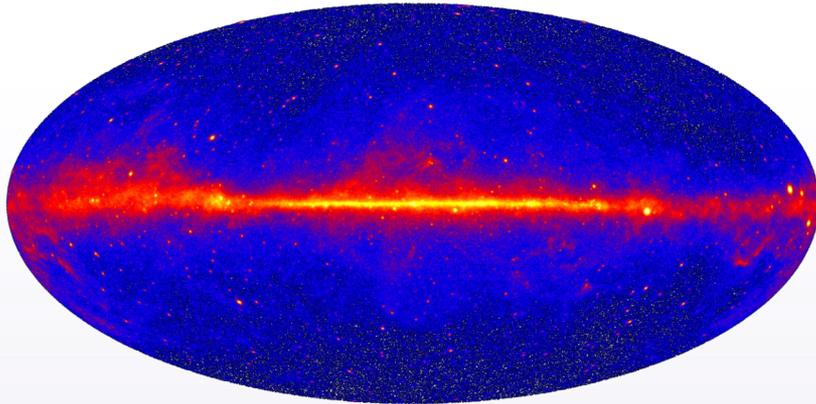
Neutrinos (IceCube Tracks and Cascades)
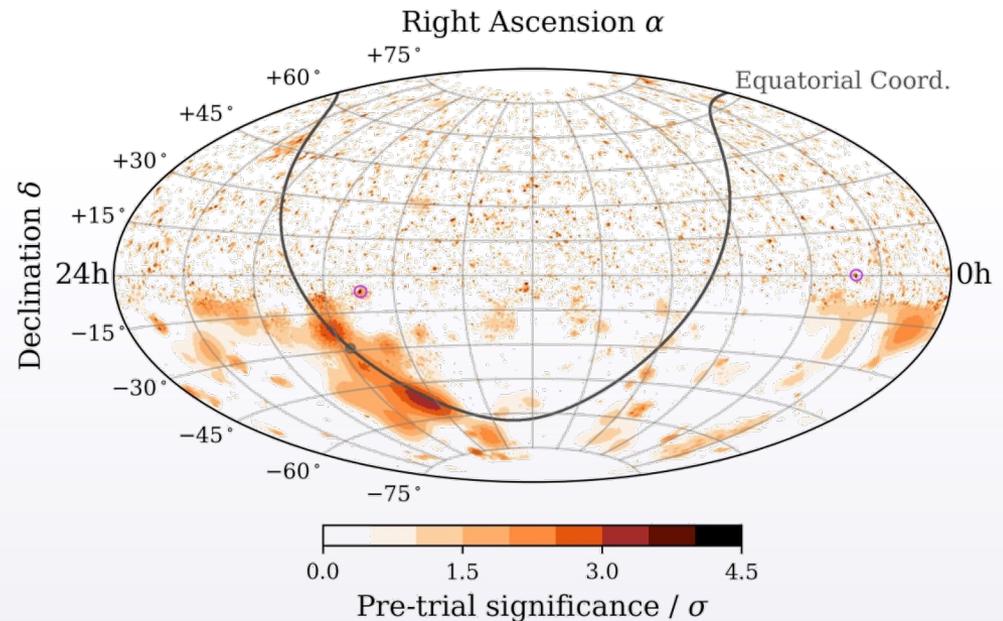
EXTRA-GALACTIC MULTIMESSENGER BACKGROUNDS

The combined unresolved emission from high-energy extra-galactic sources
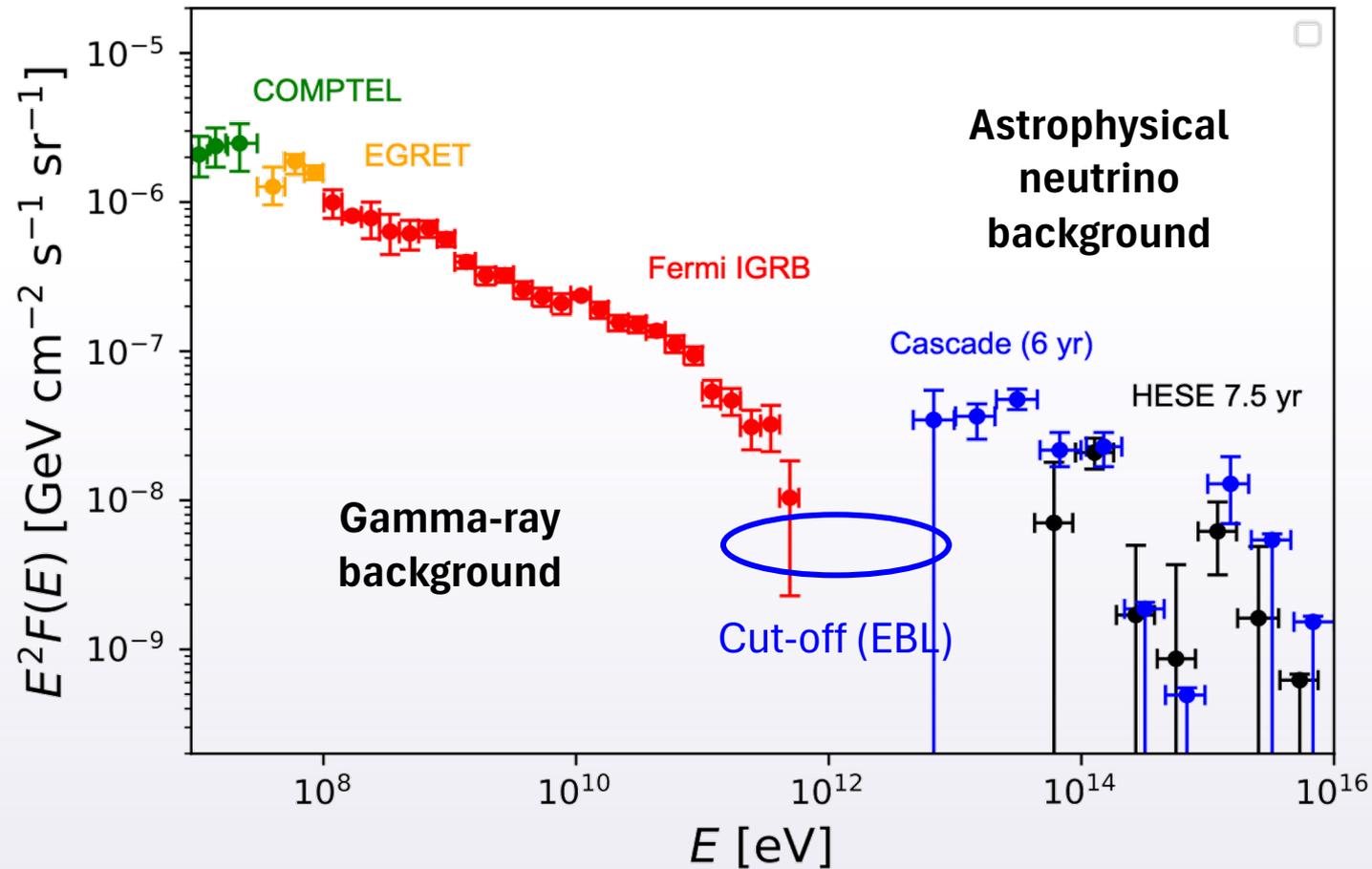
COSMIC RAY CONFINEMENT IN GALAXIES

Formation of a cosmic ray "sea"

Slow diffusive leaking of cosmic rays above and below galactic plane

Cosmic rays scatter in magnetic fields of their host galaxy, slowing their escape

Accumulation of diffusing cosmic rays forms a "sea" within the ISM of a galaxy
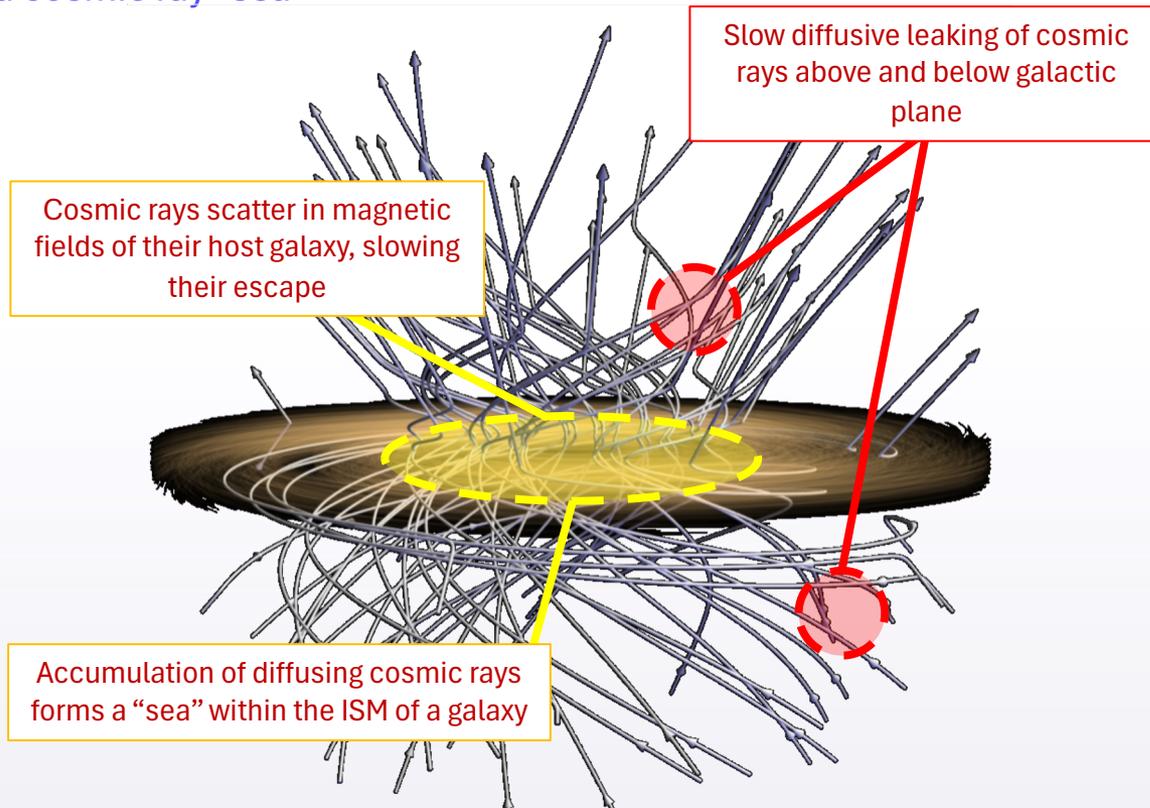
Adapted from Farrar et al. (2016)

COLLISIONAL COSMIC RAY PROCESSES

Cosmic rays are a key **driver** of multimessenger astrophysics

pp-pion production

Figures adapted from Owen 2023 (A&G)

$$p + p \rightarrow \begin{matrix} p + \cdots \\ n + \cdots \end{matrix} + \zeta_0 \left(\pi^0 \right) + \zeta_{\pm} \left(\pi^+ \quad \pi^- \right)$$

Pion multiplicities
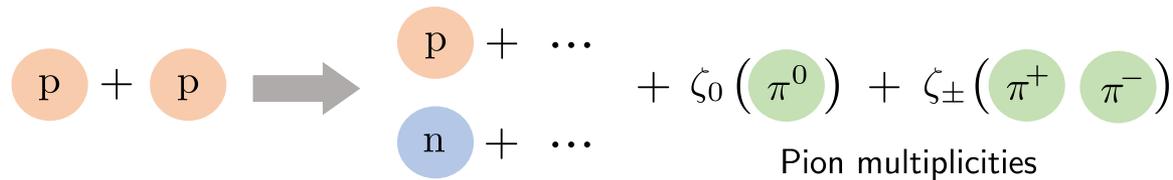
Pion decays

GAMMA–RAY EMISSION FROM EXTERNAL GALAXIES

The "traditional" picture

(Kornecki+2020)

H.E.S.S. (BDT)

NGC253

PSF

Acero+ 2009

NGC 253

NASA/ESA 2008

VERITAS   *> 700 GeV*

Karlsson+ 2009

M 82

NASA/ESA 2006
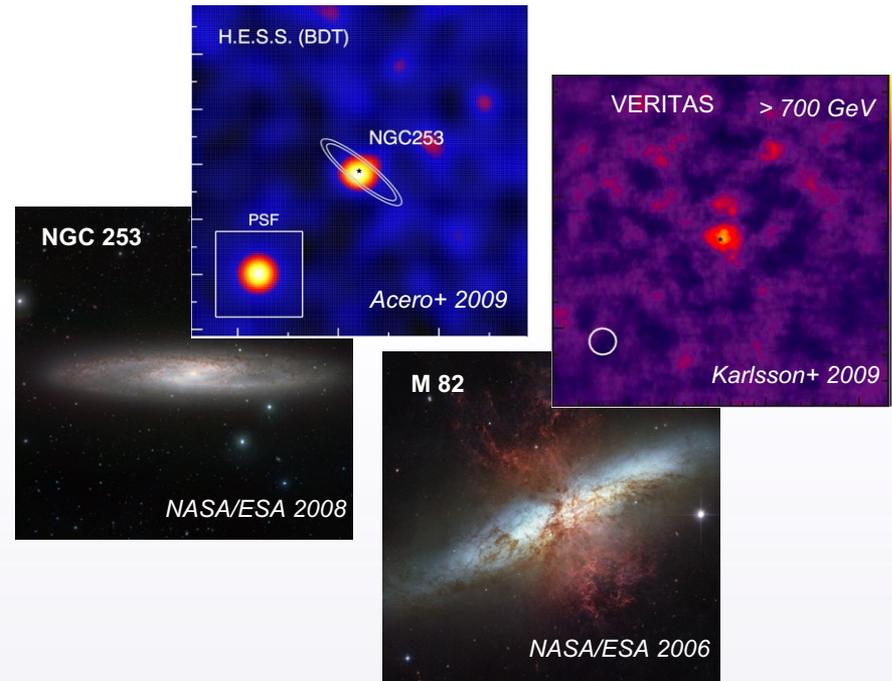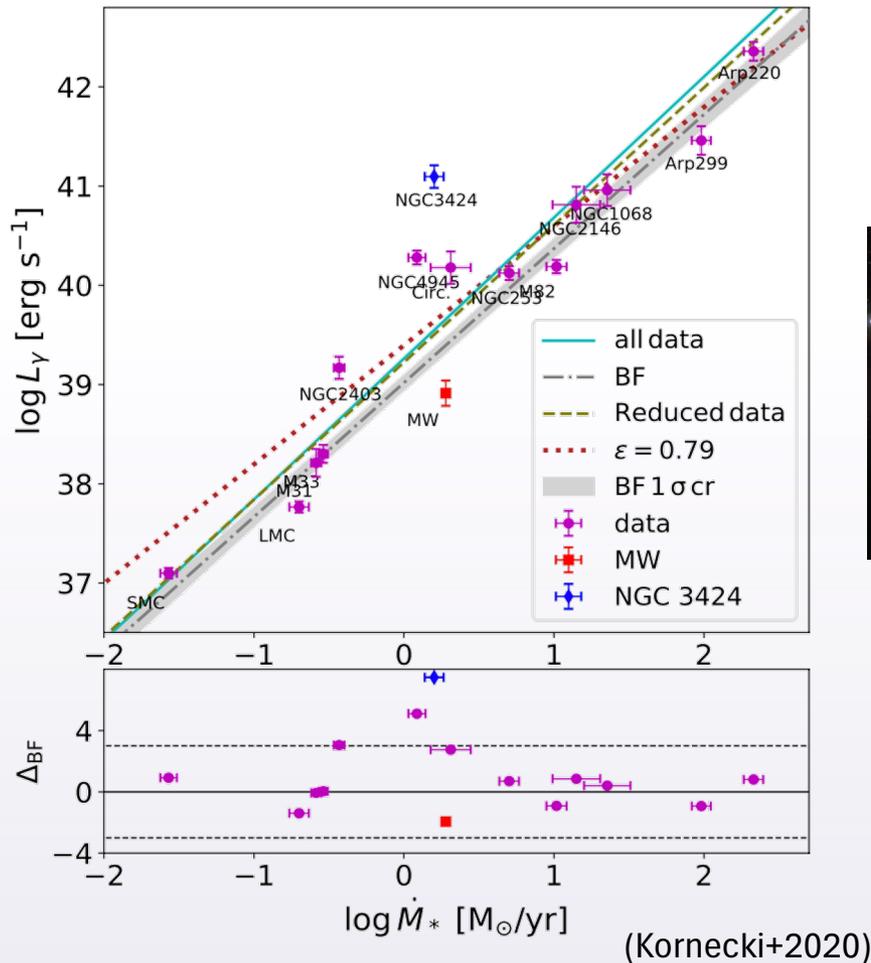
Gamma-ray luminosity has a close relation with tracers of star-formation rate

GAMMA–RAY EMISSION FROM EXTERNAL GALAXIES

The "traditional" picture
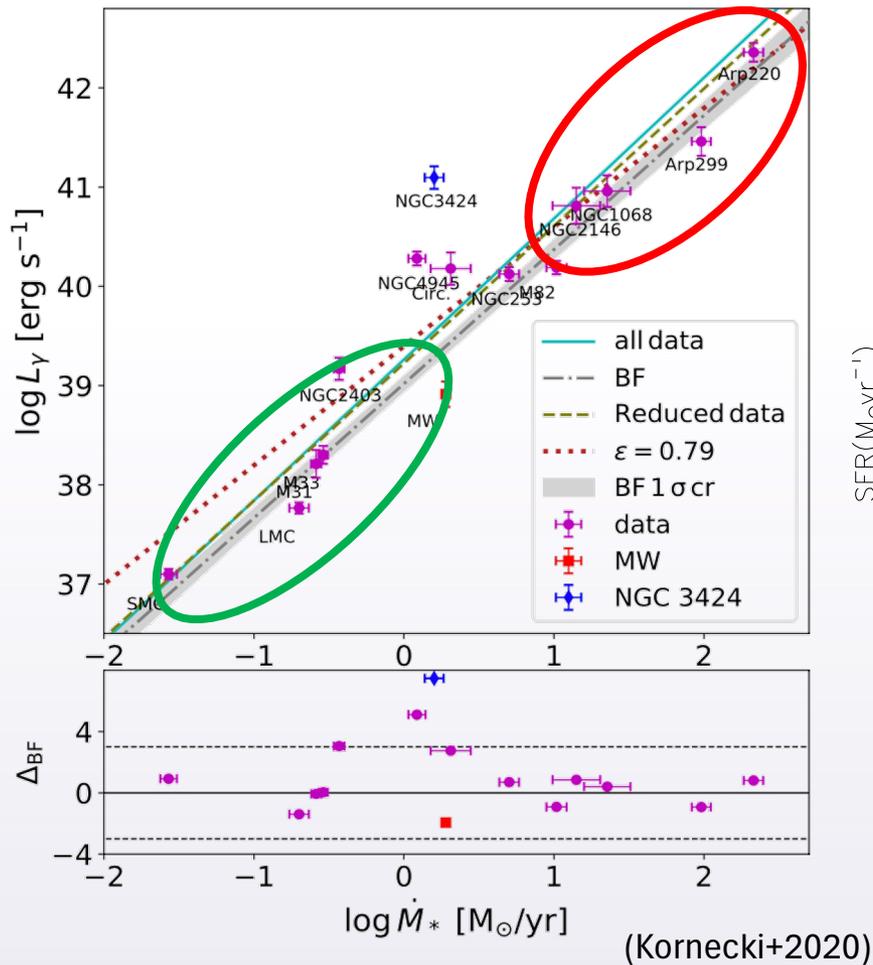
Gamma-ray emitting galaxies are not all the same

(Kornecki+2020)
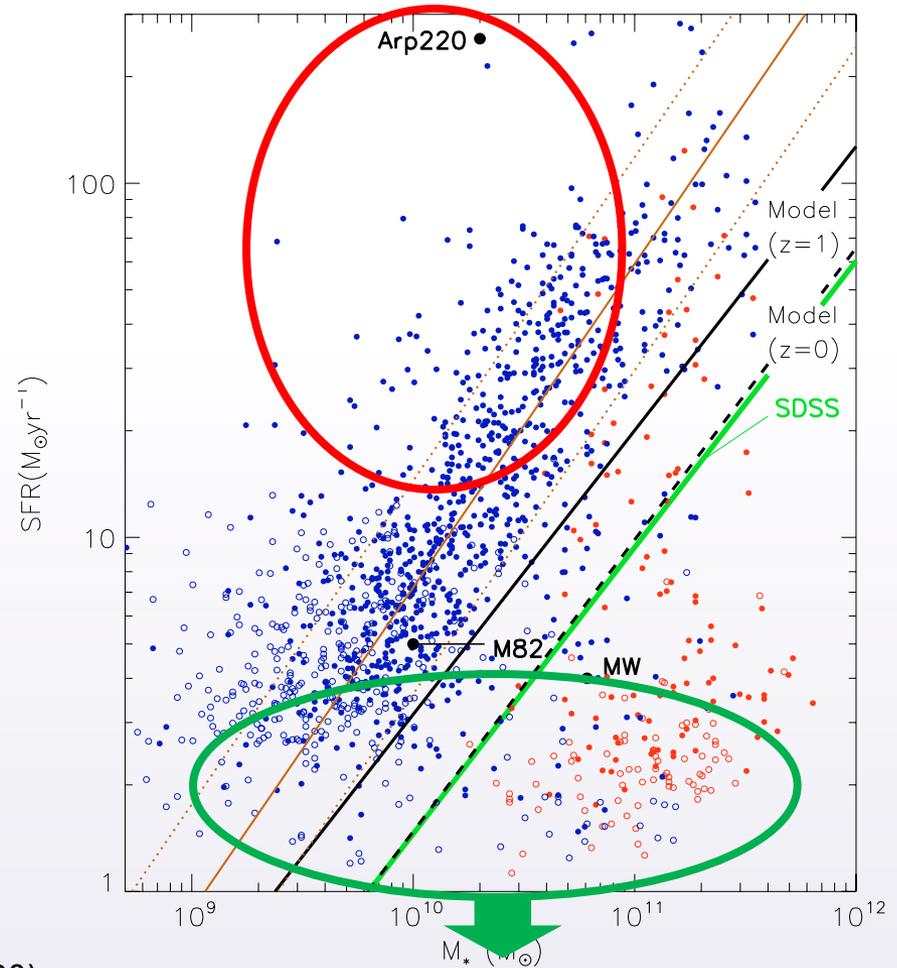
Adapted from Elbaz et al. (2007)

GAMMA-RAY EMISSION FROM GALAXIES: PULSARS

Canonical pulsars

Recycled pulsars (MSPs)

1022 Other pulsars
1584 Gamma-ray folded pulsars
123 Radio MSPs discovered in LAT unID
80 Young radio loud
· 144 Millisecond
· 76 Radio quiet
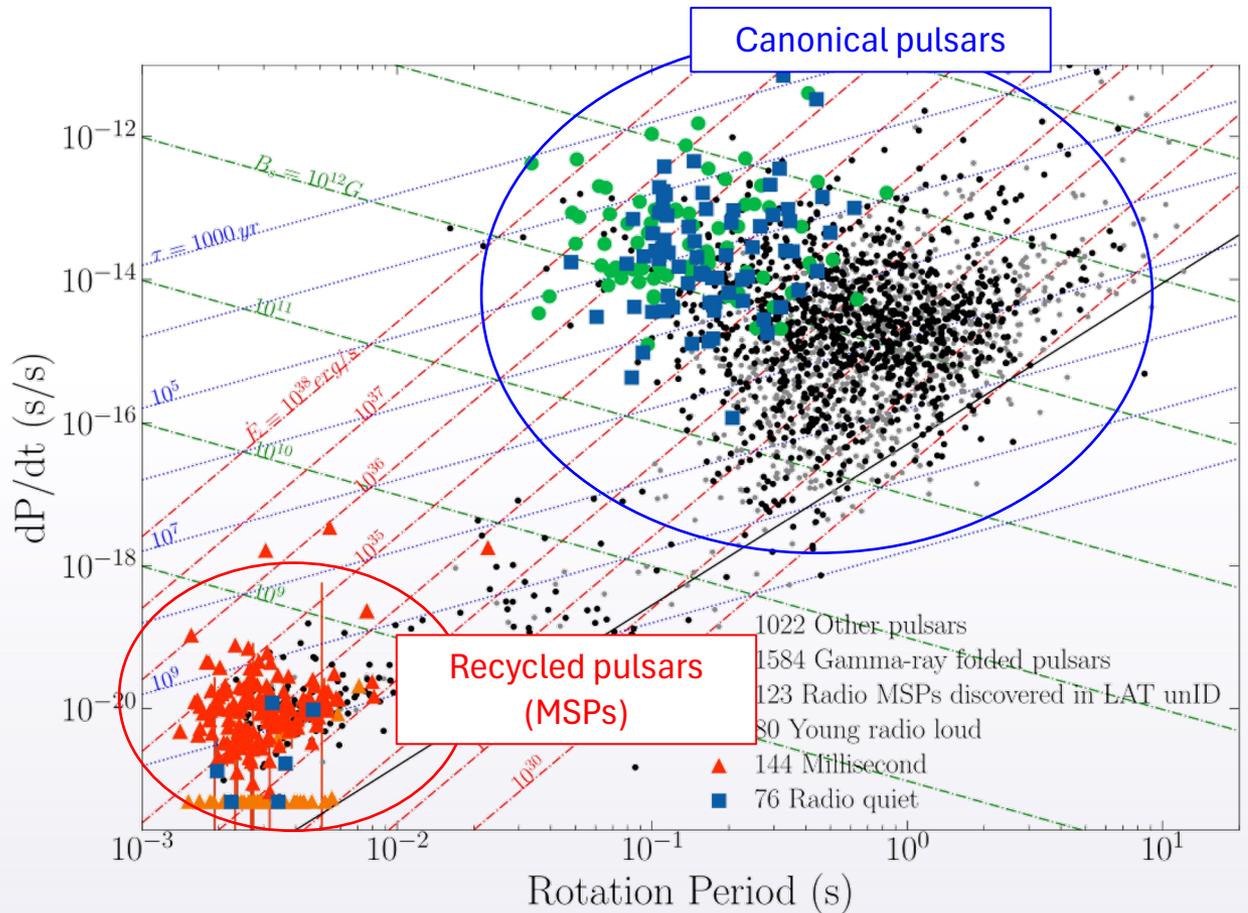
Smith et al. (2023)

10^{32}-10^{37} erg/s

Potential to be a major contributor in an older galaxy

2 types of pulsars can contribute gamma-rays in different ways

Population evolution model:

$$\frac{\partial n(L_\gamma, t)}{\partial t} + \boxed{\frac{\mathrm{d} L_\gamma}{\mathrm{d} t} \frac{\partial n(L_\gamma, t)}{\partial L_\gamma}} = \boxed{-\kappa\, n(L_\gamma, t)} + \boxed{f(L_\gamma, t)}$$

fading
(ageing) destruction
(death) formation
(birth)

Canonical pulsars/halos:

- ***Birth: following SFR***

- Aging: Spin-down power evolution

- Death: Death line (empirical)

MSPs:

- ***Birth: 1 Gyr delay from SFR***

- Aging: Effectively none (very slow)

- Death: Death line (empirical)

EVOLUTION OF HIGH-ENERGY EMISSION COMPONENTS
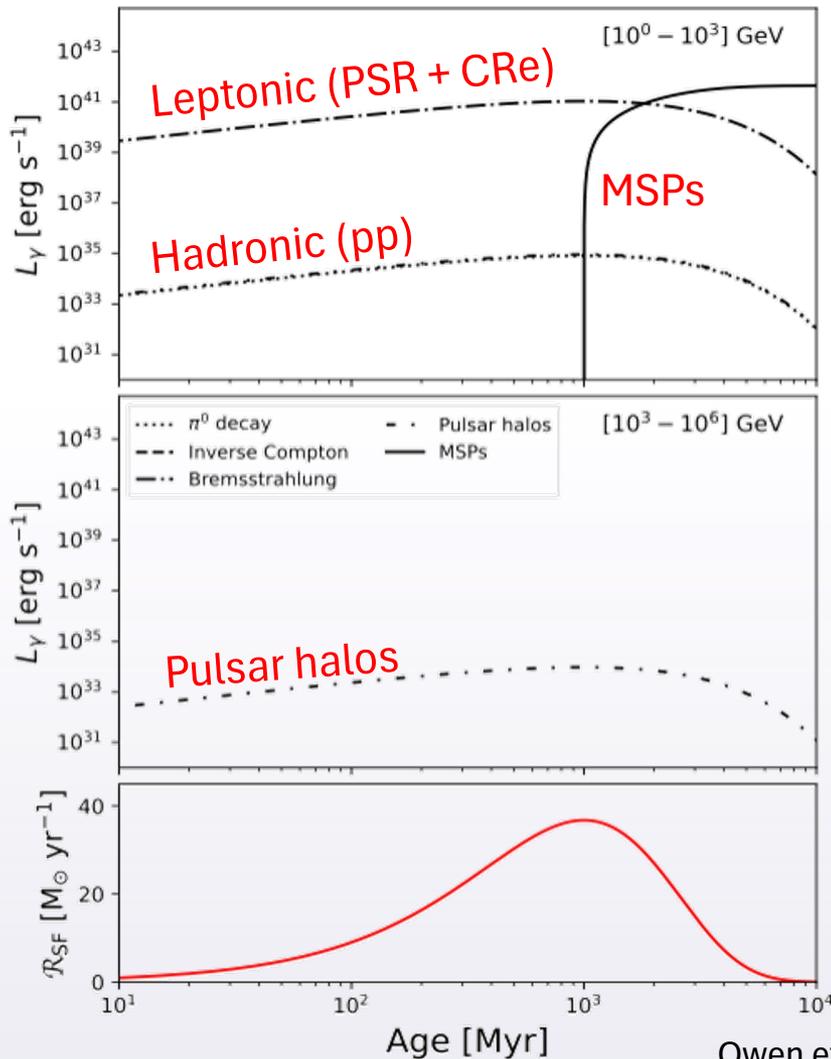
Example massive galaxy

Low energy gamma-rays

High-energy gamma-rays

Star-formation rate

Owen et al. (*in prep*)

PROTOTYPE MODEL

Standard parameters adopted; range of galaxy types   Owen et al. (*in prep*)
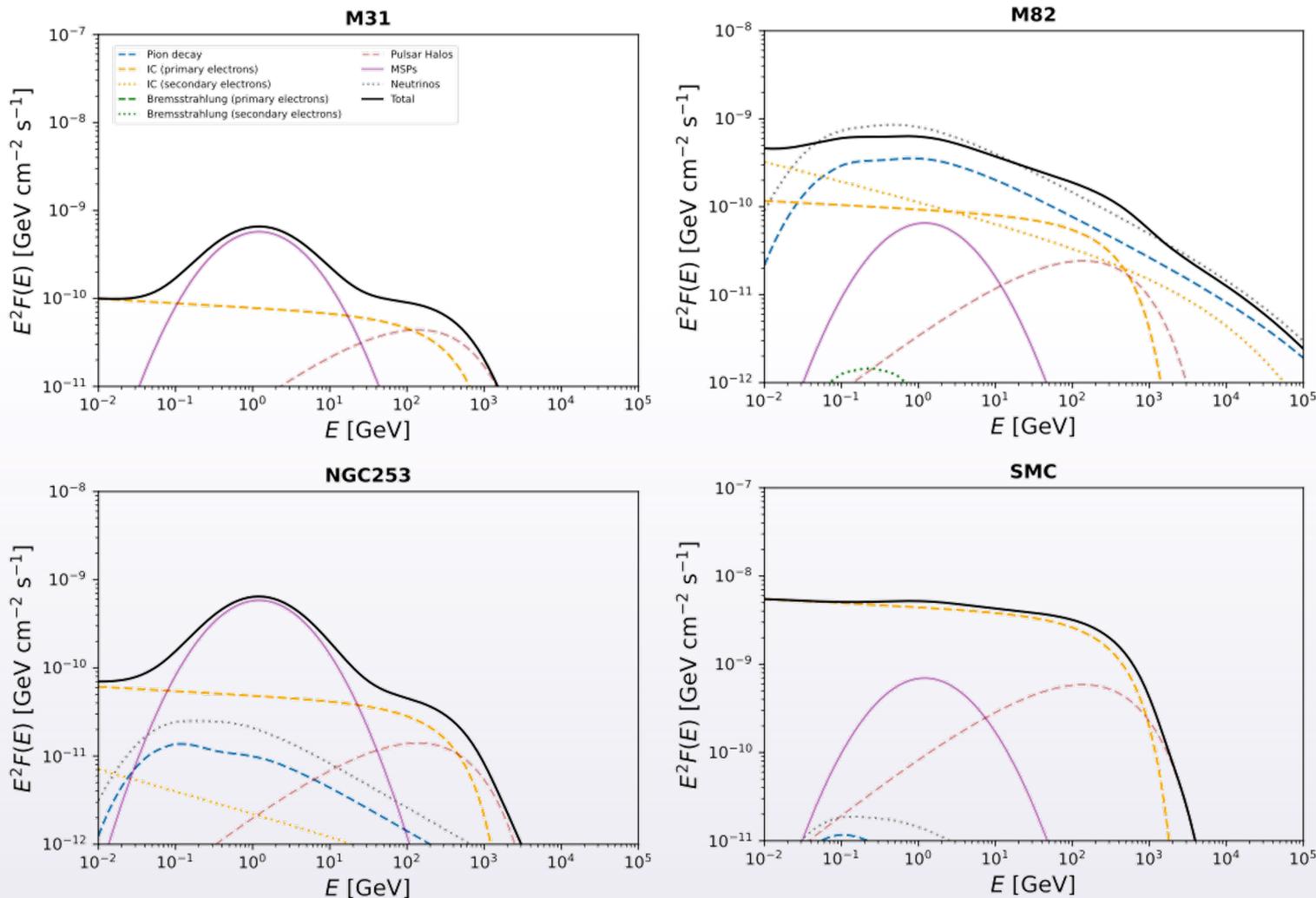
Primary CRe to CRp ratio of 2%

PROTOTYPE MODEL — AND DATA

Standard parameters adopted; range of galaxy types

Owen et al. (*in prep*)
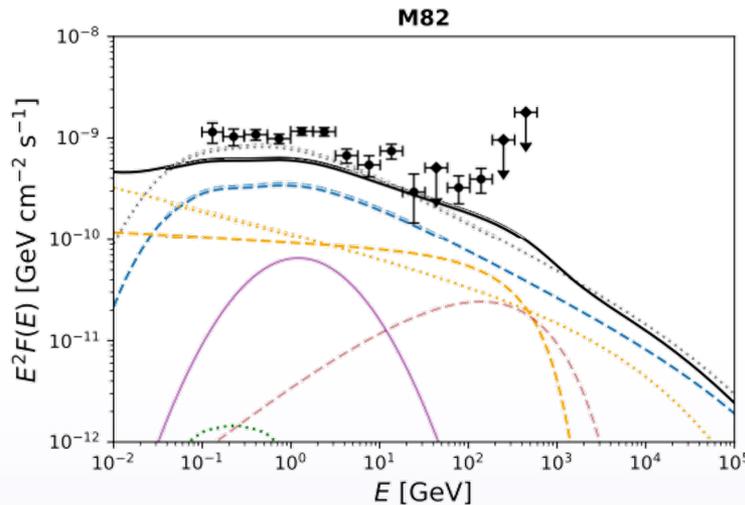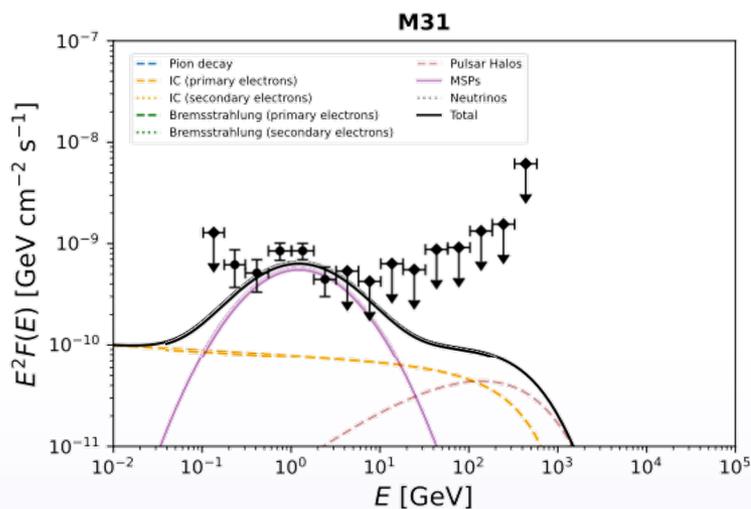
Not a fit!
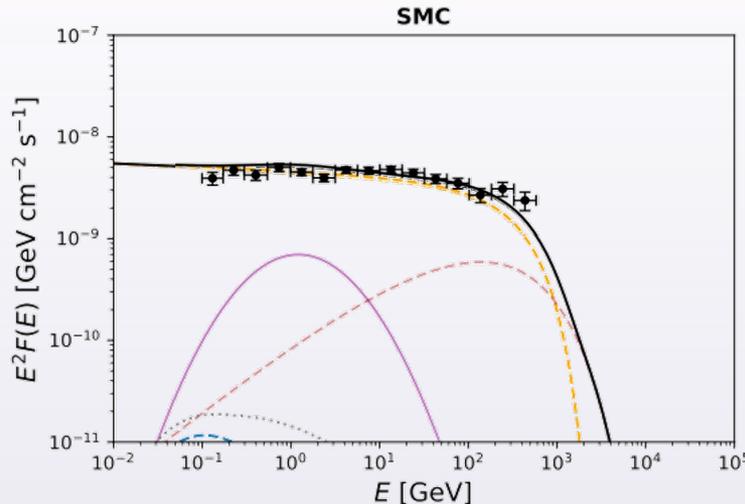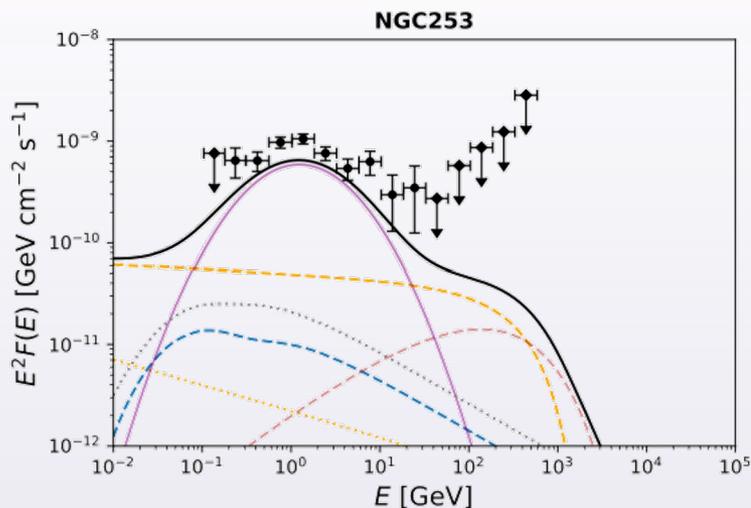
Fermi data from Ajello+2020

GALAXY POPULATIONS — UNIVERSE MACHINE

- **Semi-analytic model** of galaxy formation/evolution linking galaxy growth to halo growth

- **Empirically informed**: Many universes simulated; predicted observables compared to data to calculate likelihood of chosen parameters
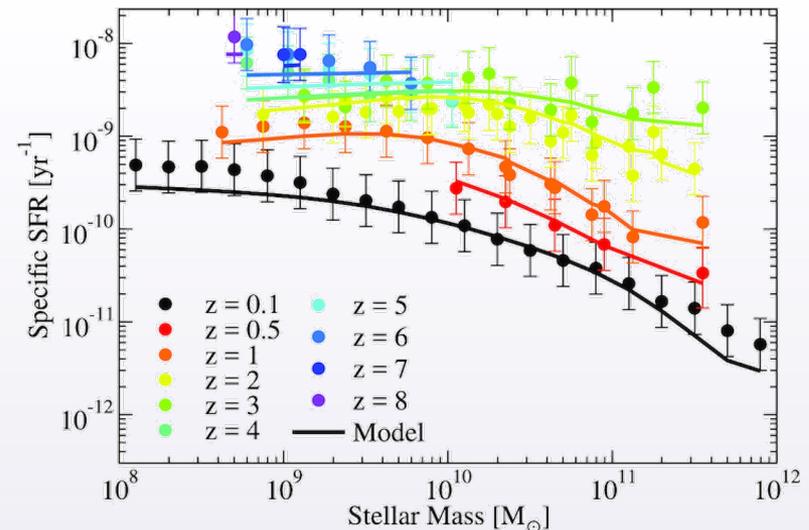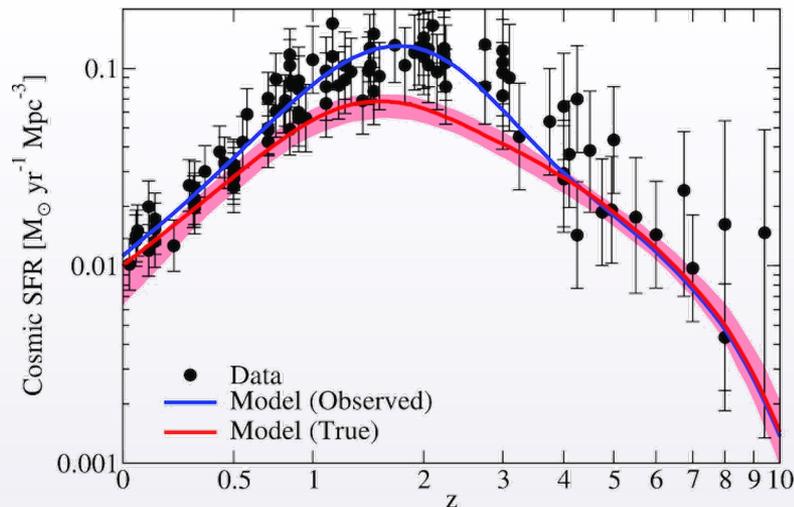
Behroozi et al. (2019)

ISOTROPIC HIGH–ENERGY BACKGROUNDS

Solve transfer equation for photons & neutrinos (conserve phase-space density)
UniverseMachine as a source model [Behroozi et al. 2019]

Mainly from dead galaxies

Mainly from starburst galaxies; subdominant compared to other source populations
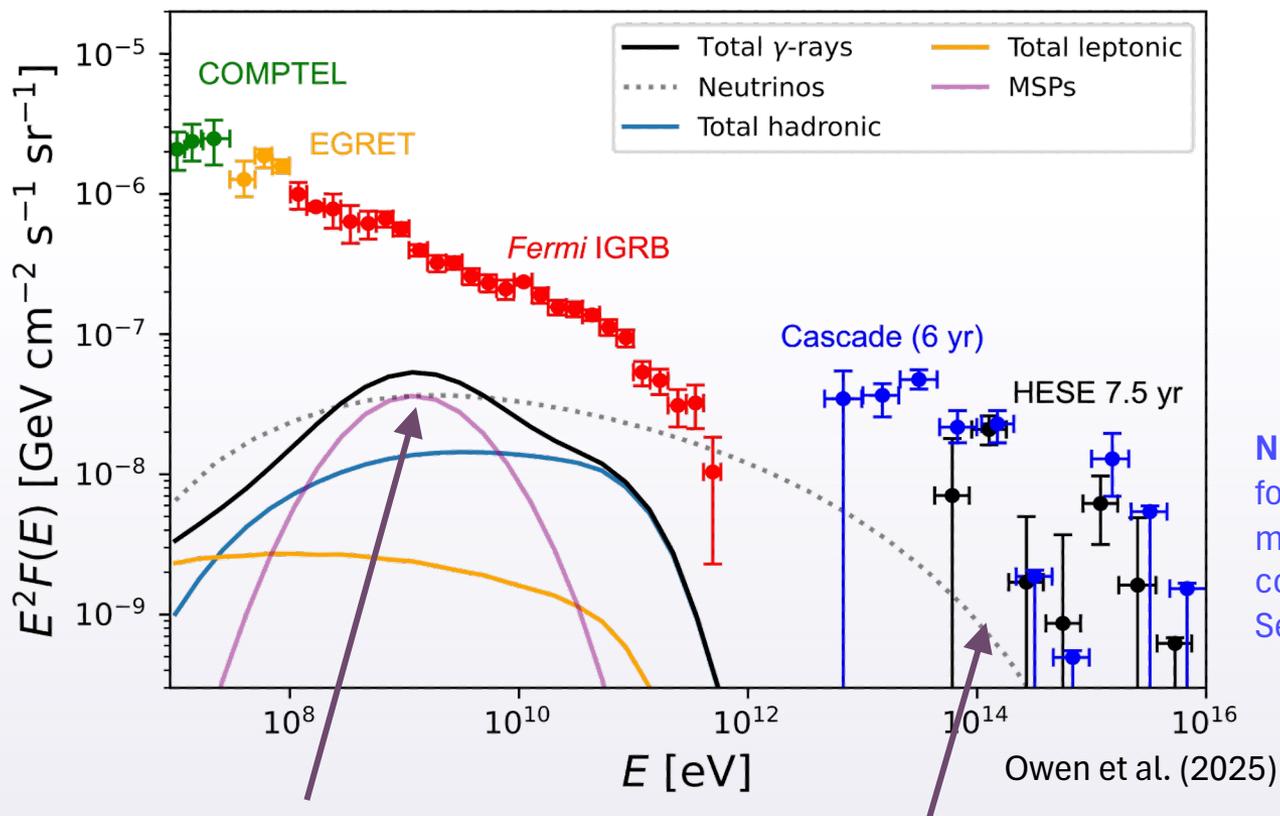
Neutrino emission from star-forming galaxies is associated mainly with starbursts. Other components dominate (blazars, Seyferts)

Galaxy Contributions to High-Energy Extragalactic Gamma-Ray and Neutrino Backgrounds

Ellis R Owen[1,2], Yoshiyuki Inoue[2,3,4], Tatsuki Fujiwara[2], Albert K. H. Kong[5]

[1]Astrophysical Big Bang Laboratory (ABBL), RIKEN Pioneering Research Institute (PRI), Wako, Saitama, 351-0198, Japan
[2]Theoretical Astrophysics, Department of Earth and Space Science, The University of Osaka, Toyonaka 560-0043, Osaka, Japan
[3]Kavli Institute for the Physics and Mathematics of the Universe (WPI), UTIAS, The University of Tokyo, Kashiwa, Chiba, 277-8583, Japan
[4]Interdisciplinary Theoretical and Mathematical Science Center (iTHEMS), RIKEN, Wako, Saitama, 351-0198, Japan
[5]Institute of Astronomy, National Tsing Hua University, No. 101, Sec. 2, Kuang-Fu Road, Hsinchu 30013, Taiwan
ellis.owen@riken.jp

Scan for more details
arXiv: 2504.18721

RIKEN

RIKEN's Programs for Junior Scientists

Starburst galaxies are gamma-ray sources. Canonically, their emission is driven by **hadronic cosmic rays** interacting with interstellar gas, forming gamma-rays via the decay of neutral pions. Charged pions are also produced in this process. They decay into secondary leptons, including electrons and neutrinos. **Starburst galaxies** are therefore also expected to be **neutrino sources**, and their high-energy gamma-ray emission may include a secondary **leptonic component**. Leptonic gamma-rays may also originate from electrons directly energized by shocks within the interstellar medium of galaxies, or from **pulsars and their surrounding halos**. In the Milky Way, pulsars/pulsar halos are a major gamma-ray source class. They are associated with stellar remnants or old stellar populations and are presumably abundant in evolved galaxies. In this work, **we show that the collective high-energy emission from galaxies can account for only a fraction of extragalactic neutrinos**, but can form a **major component of the extragalactic gamma-ray background**. Contrary to the traditional view, a fraction of this radiation may originate from leptonic processes in **old, quiescent galaxies**.

1. Multimessenger Backgrounds

Recent advances in the past decade have provided new measurements of the diffuse neutrino flux by IceCube, spanning 30 TeV to PeV energies (IceCube Collaboration 2020) and the extragalactic gamma-ray background observed by *Fermi*-LAT (Ackermann et al. 2015). These backgrounds can be decomposed into two components: one arising from emission by resolved, individual extragalactic sources, and another from the combined emission of all unresolved sources across the observable Universe (Fig. 1).

The *unresolved* component originates from populations of distant sources that cannot be individually detected. These include objects such as blazars, radio galaxies, galaxies hosting disk winds/ultra-fast outflows (Sakai et al. 2025) and starburst galaxies (Roth et al. 2021, Chen & Totani 2025). In addition, the detection of nearby quiescent galaxies such as M31 (e.g. Ajello et al. 2020) suggest that evolved stellar populations with compact high-energy sources (such as millisecond pulsars, MSPs) may contribute to the overall budget.

In this work, we present a **new determination of the multimessenger high-energy emission from galaxies** to assess the combined origins of the extragalactic gamma-ray and diffuse neutrino backgrounds. Our analysis extends beyond starburst systems to include **main-sequence and quiescent galaxies**. This allows for a more complete picture of the high-energy emission originating from diverse galaxy types over a broad range of redshifts.

Figure 1: All-sky neutrino (upper) and gamma-ray (lower) map. The extra-galactic component (with Galactic emission subtracted) can be decomposed into resolved and unresolved components. Most extra-galactic sources are unresolved, and the origins of both backgrounds is unsettled. Credit: IceCube Collab. (2025); *Fermi*-LAT Collab. (2013)

2. Pulsar Populations in Galaxies

Pulsars and their surrounding emission regions are a major contributor to the high-energy gamma-ray output of Milky Way-like systems (Lopez-Coto et al. 2022) and are widely considered capable of accounting for much of the >500 GeV emission from nearby main-sequence galaxies, including M31 (Xu et al. 2022). We model two components to their emission: canonical (young) pulsars with TeV halos (using Geminga as a prototype; Schroer et al. 2023), MSPs (using properties of Galactic MSPs as a prototype; Lloyd et al. 2024), including those in Globular Clusters (Owen 2025).

We model both populations using a time-dependent population model that predicts the integrated gamma-ray output of a galaxy by evolving a luminosity function under birth, ageing (spin-down–driven fading), and death:

$$\frac{\partial n(L_\gamma, t)}{\partial t} + \underbrace{\frac{\mathrm{d}L_\gamma}{\mathrm{d}t}\frac{\partial n(L_\gamma, t)}{\partial L_\gamma}}_{\text{fading (ageing)}} = \underbrace{-\kappa\, n(L_\gamma, t)}_{\text{destruction (death)}} + \underbrace{f(L_\gamma, t)}_{\text{formation (birth)}}$$

Canonical pulsars/halos:
- Birth: following SFR
- Aging: Spin-down power evolution
- Death: Death line (empirical)

MSPs:
- Birth: 1 Gyr delay from SFR
- Aging: Effectively none (very slow)
- Death: Death line (empirical)

3. Cosmic Rays in Galaxies

Cosmic rays (CRs) are typically accelerated within galaxies by shocks and turbulence. These are often driven by star-formation activities through feedback from supernovae (SNe) and winds. We parameterize the CR supply in a galaxy using its SN event rate, and adopt a power-law injection spectrum with an index of -2.1, and an exponential cut-off of 50 PeV. 2 per-cent of the total CR energy is supplied to relativistic electrons, with the remaining fraction supplied to protons. Once energized, CRs diffuse through turbulent interstellar magnetic fields. They then slowly leak out of a galaxy or are attenuated by particle interactions. To account for CR propagation and losses, we adopt the model introduced by Owen et al. (2019).

Above a threshold energy of ~280 MeV, hadronic CRs interact with ambient gas to produce charged and neutral pions. These pions decay, producing gamma-rays, neutrinos and secondary electrons and positrons. Additional gamma-ray emission arises from bremsstrahlung and inverse Compton scattering of CR electrons with galaxy radiation fields. In our model, hadronic and leptonic losses and their associated emission depend on: magnetic field strength, gas density, and the intensity of the interstellar radiation field. **These environmental properties are all parameterized as functions of the star-formation rate.**

4. Prototype Emission Model

We construct a prototype galaxy model accounting for CR and pulsar emission components. The model is specified by four inputs: a galaxy's **effective radius**, **stellar mass**, **star-formation rate**, and **redshift**. Other parameters, such as CR spectral properties, are either fixed or derived from these inputs.

We validate our model against the spectra of six nearby galaxies where the gamma-ray emission is believed to be dominated by CR activity associated with their stellar populations (Ajello et al. 2020). Without detailed fitting, our model shows agreement with observations and reproduces empirical trends with star-formation rate (Kornecki et al. 2020; K20; Figs. 2, 3), indicating that it captures the overall behavior of gamma-ray emission across populations of galaxies.

Figure 2: Gamma-ray emission, separated into components, as a function of the star-formation rate of the host galaxy, compared with their *Fermi*-measured gamma-ray luminosities.

Figure 3: Model predicted emission for two example galaxies (including a globular cluster, GC, component).

5. Result and Conclusions

We adopt the empirical semi-analytic galaxy-halo connection simulation, UniverseMachine (Behroozi et al. 2019) as a galaxy population model. This is constrained by empirical quantities, including galaxies' observed stellar mass functions, star-formation rates, quenched fractions, ultra-violet (UV) luminosity functions, UV-stellar mass relations and the environmental dependence of quenching. These empirical constraints provide a robust baseline model, calibrated against the real Universe.

We post-process the UniverseMachine outputs with our galaxy prototype model to calculate the combined gamma-ray and all-flavor neutrino emission from galaxy populations. Using a cosmological radiative/particle transfer formulation, we determine the flux arriving at Earth, ensuring conservation of the phase-space density of photons and neutrinos in an evolving LCDM cosmology. We integrate over all galaxies up to z=6 (beyond which the contribution is negligible). The result is shown in Fig. 4. We find :

- **Most of the neutrinos originate from CR interactions in strong starbursts.** These cannot saturate the neutrino flux under any plausible model configuration. Much of the remaining observed neutrino flux likely originates in, e.g. blazars and Seyfert galaxies.

- The gamma-ray emission from CR processes in **galaxies** represents a non-negligible component of the extragalactic gamma-ray background, but they **do not saturate the gamma-ray background at any energy** (in contrast to Roth et al. 2021).

- We confirm the presence of a **leptonic gamma-ray emission component from galaxies** at energies below ~0.1 GeV (see also Roth et al. 2021; Chen & Totani 2025).

- Quiescent 'dead' galaxies with old stellar populations could contribute substantial GeV gamma-ray emission Gyrs after their main star-formation activity.

- **Evolved galaxies could therefore be a source population in the GeV gamma-ray sky.** This may explain a spectral excess seen in *Fermi* data at ~1 GeV.

Figure 4: Total Galaxy contributions to the diffuse extragalactic gamma-ray and all-flavor neutrino flux, compared with observational data from COMPTEL (Kappadath et al. 1996), EGRET (Sreekumar et al. 1998), *Fermi*-LAT (Ackermann et al. 2015) and IceCube (IceCube Collab. 2013, 2020; Aartsen et al. 2016).

References: Aartsen et al. 2016 *ApJ*, 833(1):3, Acharyya et al. 2025 *ApJ*, 981(2):189, Ackermann et al. 2015 *ApJ*, 799(1):86, Ajello et al. 2020 *ApJ*, 894(2):88, Behroozi et al. 2019 *MNRAS*, 488(3):3143,Chen & Totani 2025 *MNRAS* 540(4): 3221, IceCube Collaboration 2020 *Phys. Rev. Lett.* 125: 121104, IceCube Collab. 2013 *Science*, 342(6161):1242856, Kappadath et al. 1996 *A&A Suppl. Ser.*, 120:619, Kornecki et al. 2020 *A&A*, 641:A147, Lloyd et al. 2024 *MNRAS*, 530(4):3552, Lopez-Coto et al. 2022 *Nat. Astron.*, 6:199, Owen et al. 2025 *PoS/ICRC2025:791*, Owen et al. 2019 *A&A*, 626:A85, Roth et al. 2021 *Nature*, 597(7876):341, Sakai et al. 2025 *ApJ*, 980(1):131, Schroer et al. 2023 *Phys. Rev. D*, 107(12):123020, Sreekumar et al. 1998 *ApJ*, 494(2):523, Xu et al. 2022 *Phys. Rev. D*, 106(2):023005.