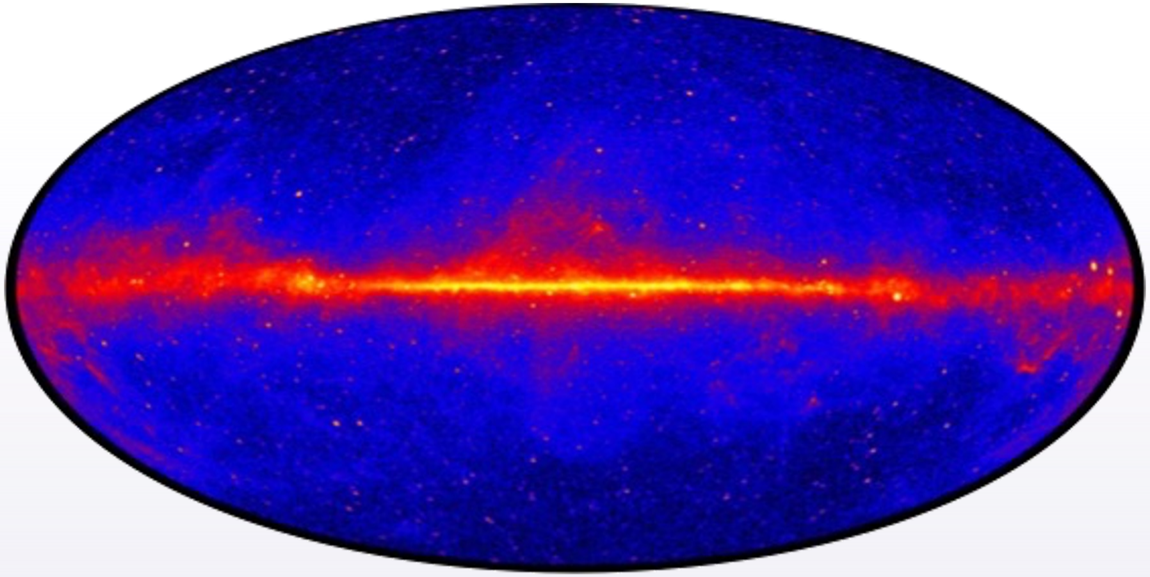
Understanding the GeV-TeV signatures of star-forming galaxies with CTA

Presentation meeting of the ICRR Inter-University Research Program, FY2023



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γ-ray emission from starbursts

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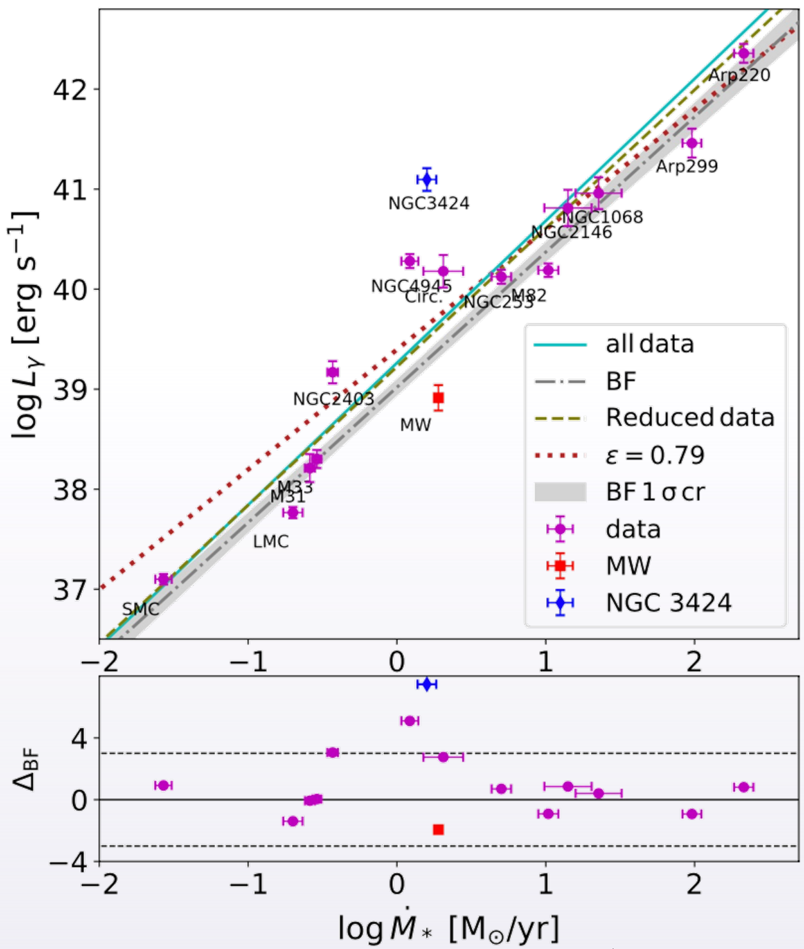
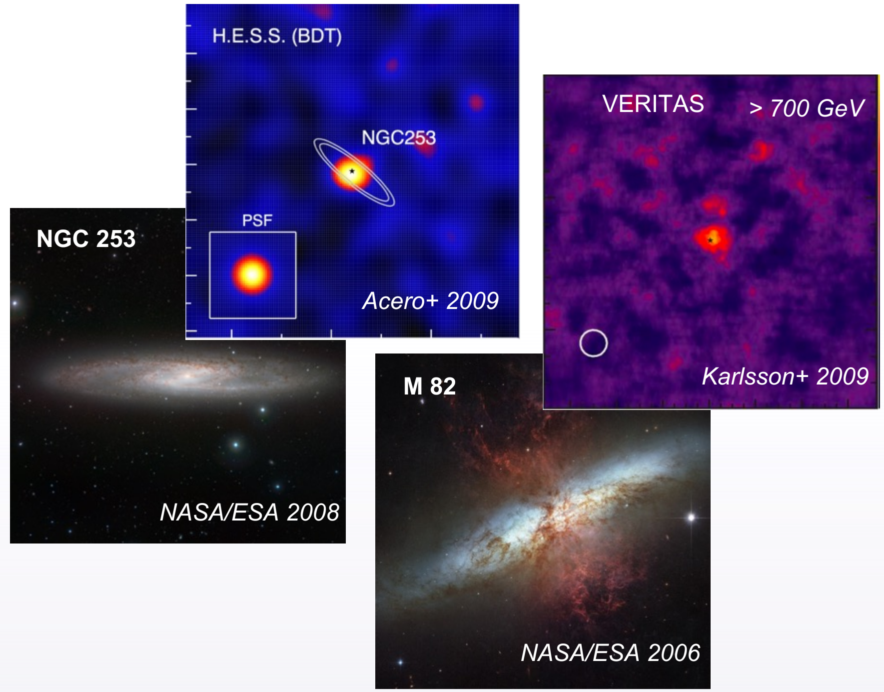


(Kornecki+2020)



Gamma-ray luminosity is a proxy for cosmic ray luminosity (later)

Microphysics and Astroparticle Physics

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Underlying process: **hadronic** interactions (CR injection tracks star-formation)

$$\mathrm{p} + \mathrm{p} \rightarrow \begin{cases} \mathrm{p} + \mathrm{p} + \pi^0 \\ \mathrm{n} + \mathrm{p} + \pi^+ \\ \mathrm{p} + \mathrm{p} + \pi^+ + \pi^- \end{cases}$$

+ pion multiplicities at higher energies

Messengers:

Gamma-rays

Neutrinos

$$\pi^0 \rightarrow \boxed{2\gamma}$$

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

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

electromagnetic decay

$\tau_{\mathrm{em}} \approx 8.5 \times 10^{-17}\mathrm{s}$

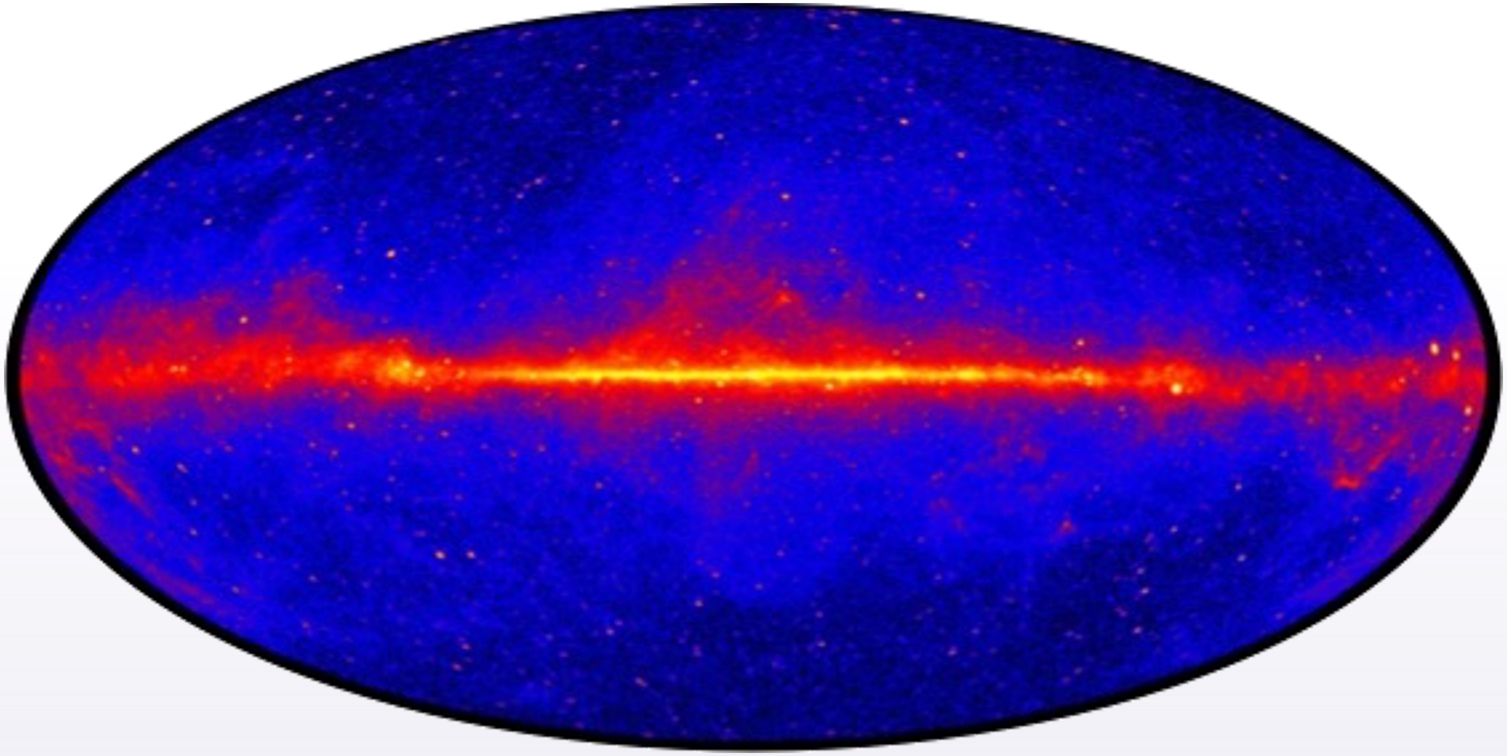
weak decay

$\tau_{\mathrm{weak}} \approx 2.6 \times 10^{-8}\mathrm{s}$

Isotropic gamma-ray background

12 years above 10 GeV with Fermi LAT

KSP 8 for CTA



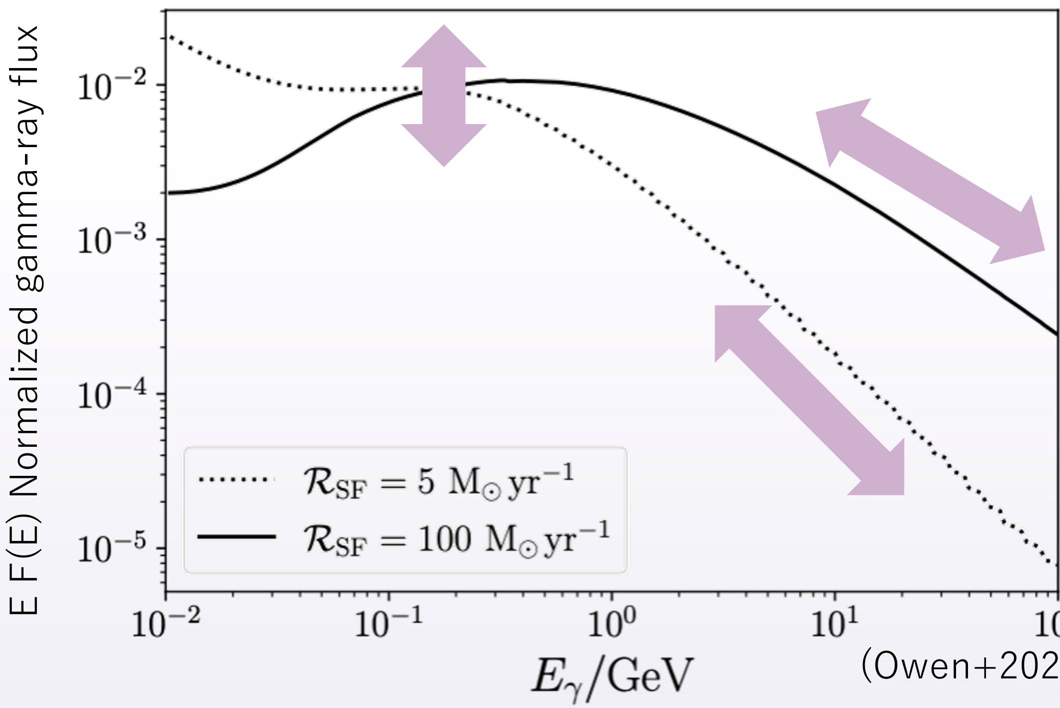
(*Fermi*-LAT Collaboration)

Prototype galaxy model: γ-ray production

Gamma-ray spectrum for an individual galaxy

Steady-state, with CR injection & diffusive leaking

$$U_{\rm CR} \propto \mathcal{R}_{\rm SN} \propto \mathcal{R}_{\rm SF}$$



(Owen+2022)

Minimal free parameters that still capture a meaningul variation in galaxy properties relevant to CR processes

Fiducial parameters for all galaxies

Parameterized CR physics

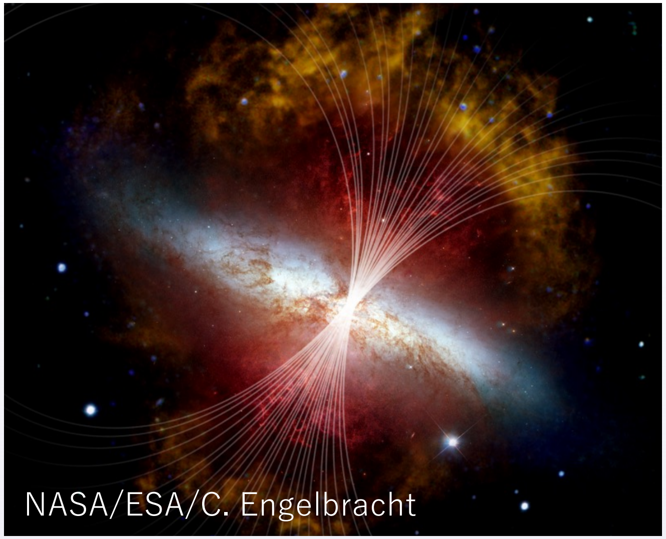
Parameter	Value
Γ	-2.1
$\gamma_{\rm p}^\star$	$10\ {\rm PeV}/m_{\rm p}c^2$
D_0	$3.0 \times 10^{28}\ {\rm cm^2\,s^{-1}}$
f_t	0.1
α	0.05
$M_{\rm SN}$	$50\,{\rm M_\odot}$
$E_{\rm SN}$	10^{53} erg
ε	0.1
[illegible]	[illegible]
η	0.5
$T^\star$	30,000 K
$n_{\rm cl}$	$10\ {\rm cm^{-3}}$
$f_{\rm c}$	0.1

Free parameters

SFR, Stellar mass, radius, redshift

Containment vs. advection

- Hadronic CRs: fraction of energy lost to pp interactions before escape
  - Diffusive leaking (magnetic field – captured by transport model)
  - Advection (outflow – needs additional treatment)



Calorimetry:
Fraction of CRs absorbed within galaxy

Modified in the presence of an outflow
 - Turn an outflow on, and compare effect

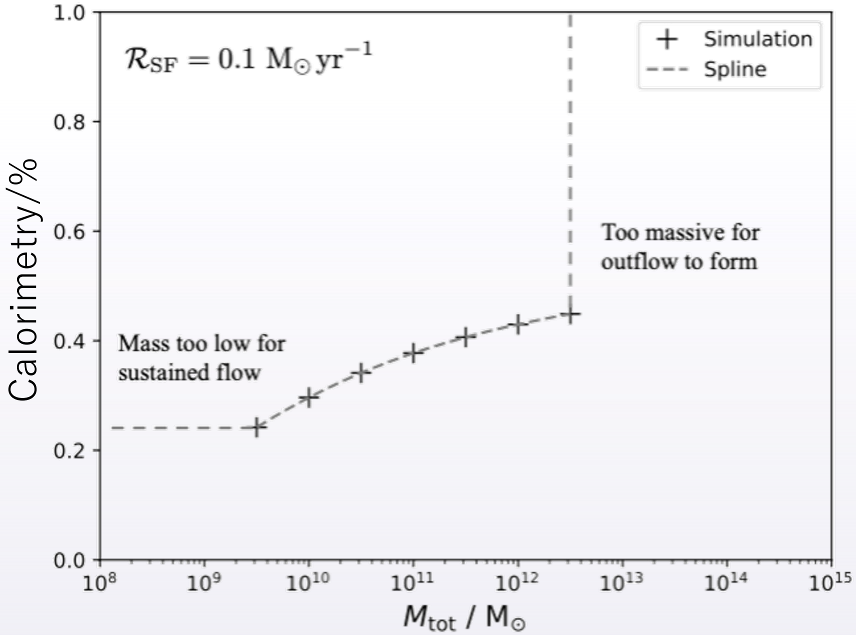
Dependency on galaxy properties

CRs at 1 GeV; advective escape dominates over diffusive leaking

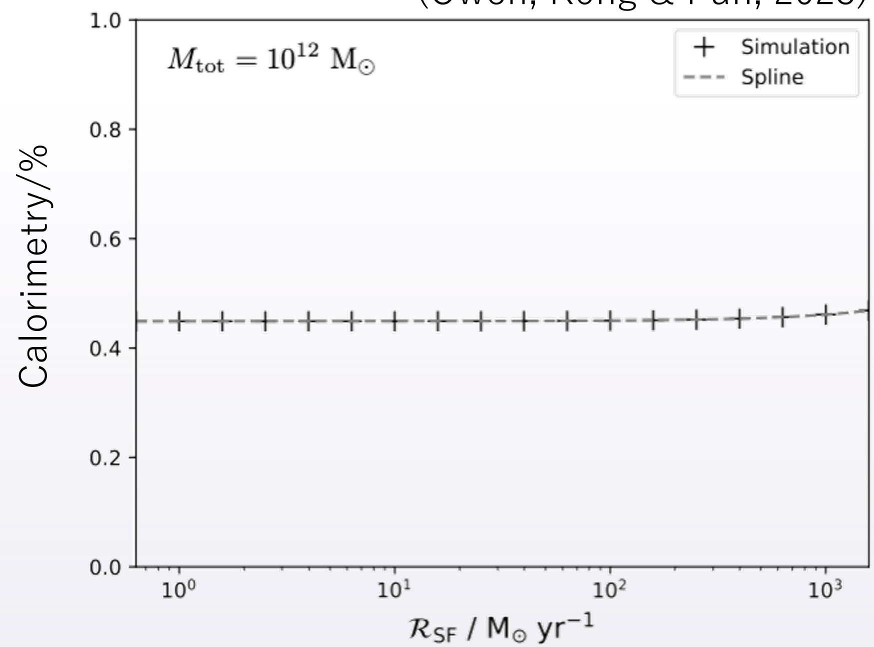
Halo mass most important for determining the stability of an outflow

- Escape set by advected fraction at edge of nucleus compared to no outflow

(Owen, Kong & Pan, 2023)



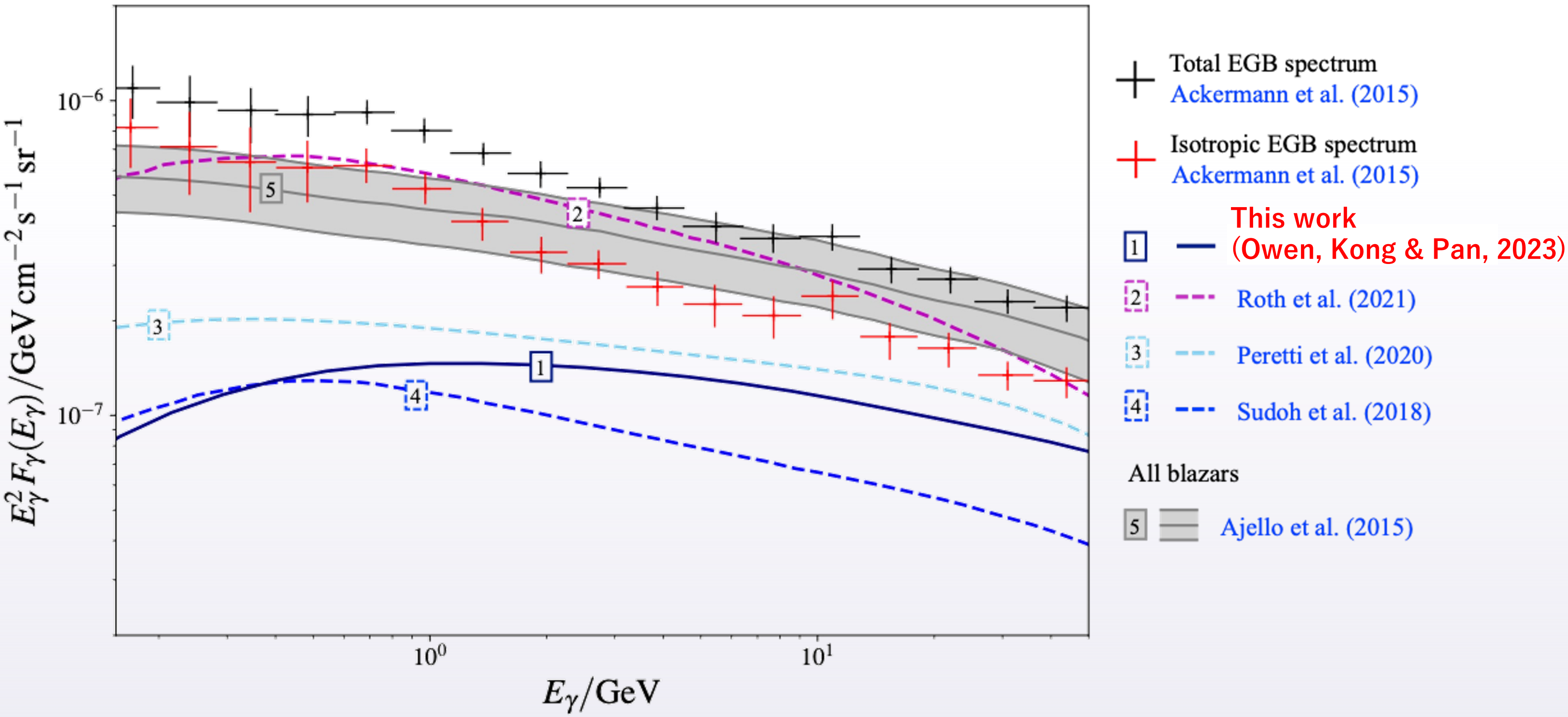
Some galaxies too massive or not massive enough to form a stable outflow



Mass loading of the wind reduces dependence on SFR

Gamma-ray background spectrum

- Galaxies can contribute a few tens of percent (depends slightly on CR spectrum in sources, less on CR driving); inputs from EAGLE sims
- Fermi isotropic EGB constraint not violated



Mass separation

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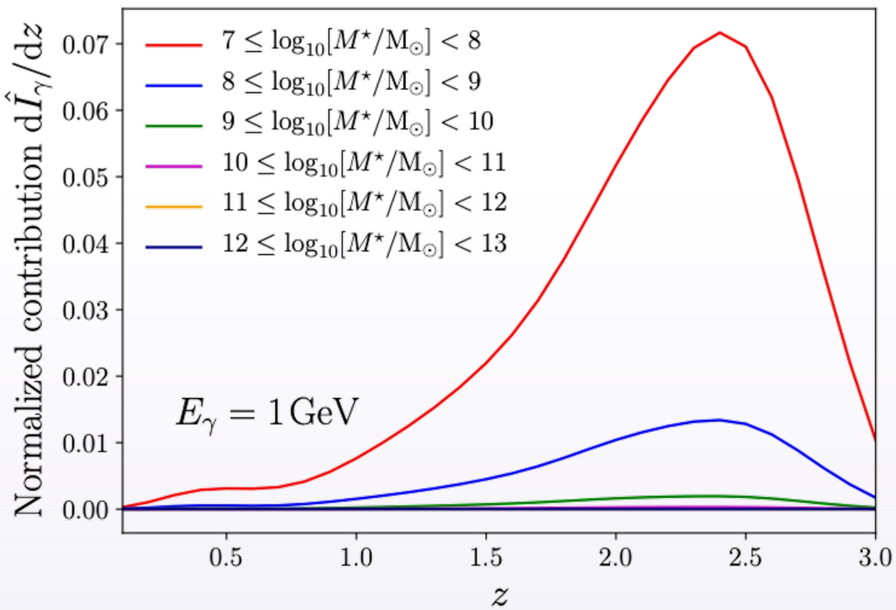
Fractional contribution over redshift – peak in low-mass galaxies prior to the cosmic noon (tracking where star-formation is happening)



>95% of the flux coming from starburst galaxies (even though they are not the dominant population)

(Owen, Kong & Pan, 2023)

- Relatively rare: SFG component to EGB may have large Poisson term, statistical similarities to BL Lac/AGN contribution
  → Implications for disentangling source populations?

Multimessenger backgrounds

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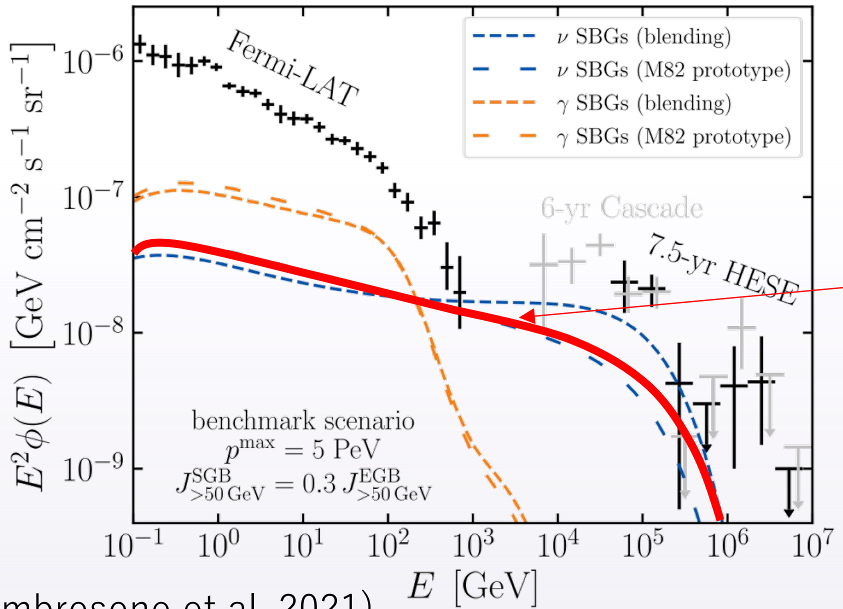
Tension with IceCube data may point towards a different origin

Can't account for IceCube <100 TeV neutrinos without over-predicting EGB



(Ambrosone et al. 2021)

Hadronic emission may not be as important as assumed; case to also investigate leptonic source classes

Annotated red-line
Preliminary (in prep work; Owen+2024)

PWN / TeV Halos are one possibility (ubiquitous, bright in gamma-rays, leptonic) – still obey the SFR-luminosity relation

FY2023 budget

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Planned use and approved budget: 220,000 JPY

- 15 days of visits (1+2 weeks) to ICRR CTA group to understand instrument and capabilities and analysis approaches, guide development of testable model results
- 2 day visit to attend CTA-Japan meeting at ICRR to present interim results to gamma-ray community
- 2 day visit to attend this Kyodo-Riyo reporting meeting

Actual use: ~210,000 JPY (remainder to be returned to ICRR at end of FY2023)

- Visit to ICRR reduced to 10 days (additional visit opportunities and discussions were possible during PI's travel to Tokyo for other projects, and during ICRC conference in Nagoya)
- Travel support of 2 Osaka M1 students joining this project to participate in CTA-Japan meeting (Fujiwara, Sakai)

Developments and products

- EGB modeling refinements
  - Extension into the CTA energy range (including EM cascade) & neutrinos
  - Galaxy population model upgraded to UniverseMachine model (Behroozi et al. 2019)
  - Leptonic PWN and TeV halo contributions in prototype model (in progress)

- Publications:
  - *TeV halos in starburst galaxy populations: implications for high energy multi-messenger backgrounds*. ApJ in prep. (Owen, Inoue, et al.) – sub. 2024 Q2
  - *Cosmic ray calorimetry in star-forming galaxy populations and implications for their contribution to the EGB,* PoS(ICRC2023)554, doi: https://doi.org/10.22323/1.444.0554
  - (FY2022) *The extragalactic gamma-ray background: imprints from the physical properties and evolution of star-forming galaxy populations*. MNRAS 513, 2, 2335, doi: 10.1093/mnras/stac1079
  - (FY2021) *Characterizing the signatures of star-forming galaxies in the extragalactic gamma-ray background*. MNRAS 506, 1, 52, doi: 10.1093/mnras/stab1707

FY2024 Plan

Next steps in FY2024

- Continuation of PWN/TeV halo modeling as a gamma-ray background leptonic source component within star-forming galaxies
- Modeling realistically accessible future signatures for the CTA era with guidance from the ICRR-CTA group (after new models); possible expansion to neutrinos (with consideration of IceCube or P-ONE capability)

Request for FY2024

- 0 JPY – PI will relocate to RIKEN (Saitama); travel support not required to visit ICRR.
- Separate proposals submitted and approved at NAOJ CfCA and Osaka University Cybermedia center for required computational time. Access to RIKEN computational resources mid-way through FY2024.