Osaka University Theoretical Astrophysics

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Exploring the origins of very-high-energy emission from starburst galaxy populations

The extreme Universe viewed in VHE gamma rays 2023

NGC 6946 in X-rays/Optical, Credit: NASA/MSSL (UCL), R. Soria

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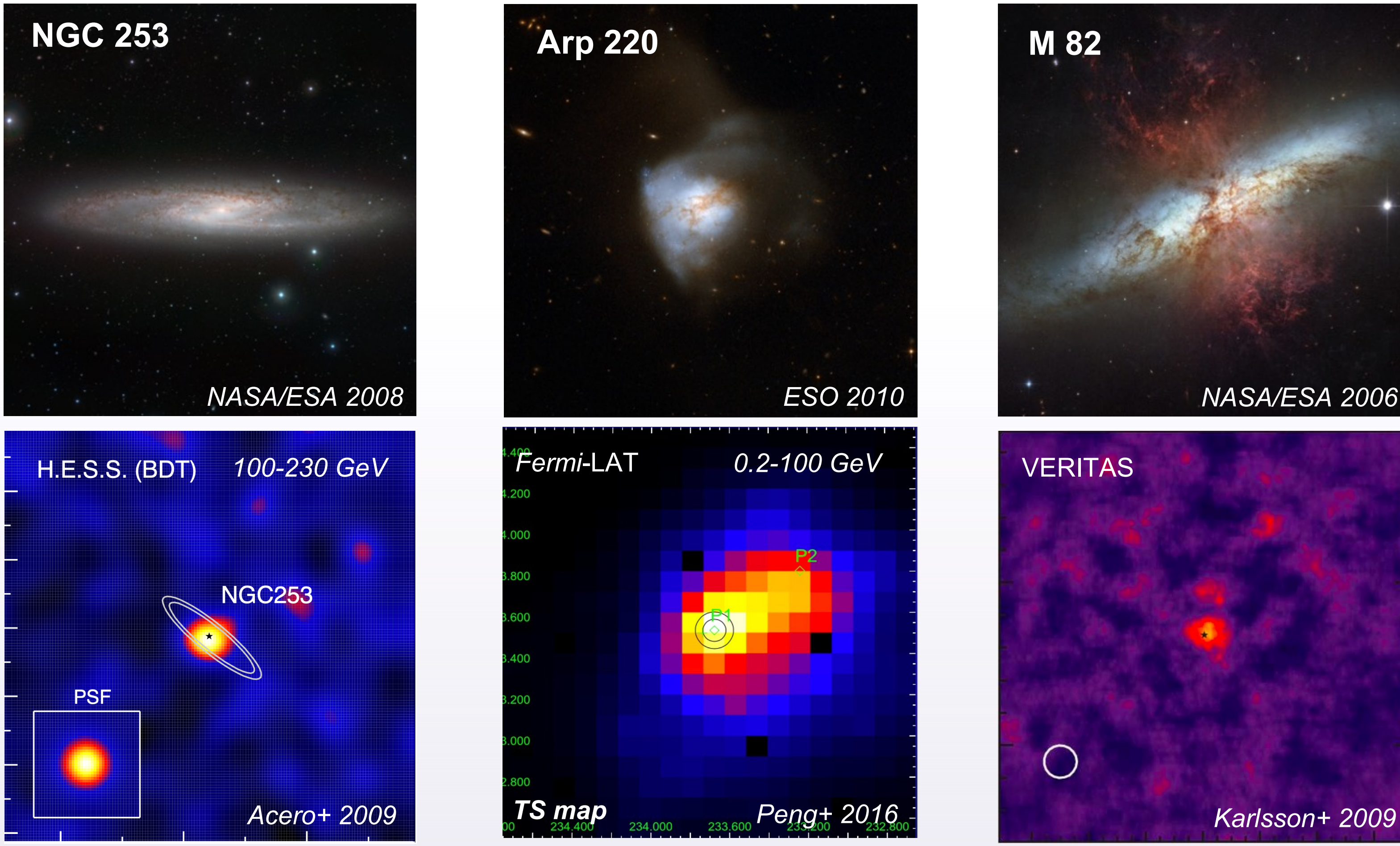
Outline

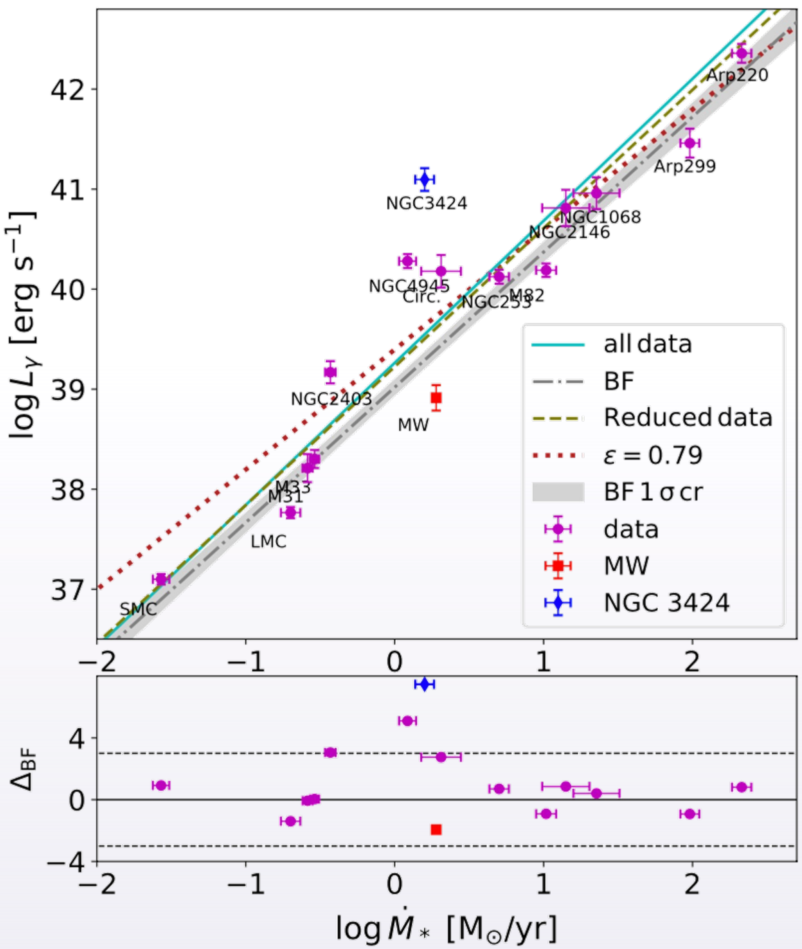
- Cosmic rays in galaxies
  - *Starburst galaxies as cosmic ray factories*
  - *Galaxy populations as a VHE source class*
- Characterising galaxy populations and their VHE emission
  - *Calorimetry*
  - *Prototype modeling approach*
- Revisiting starburst galaxy VHE emission in the multi-messenger era

1. Cosmic rays in galaxies

Gamma-ray emission from starbursts



Cosmic rays in galaxies



Gamma-ray luminosity has a close relation with tracers of star-formation rate

(Kornecki+2020)

Starburst galaxies as cosmic ray factories

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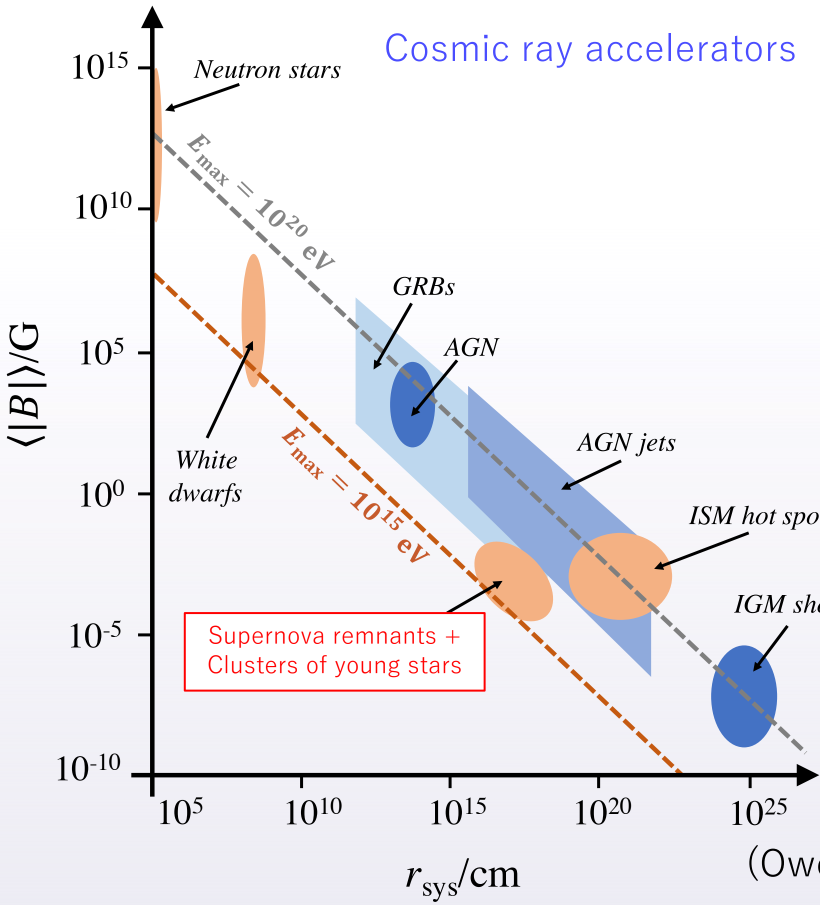
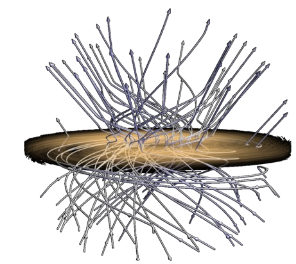
- High-energy charged particles accelerated in shocks
- Contained by galactic magnetic fields

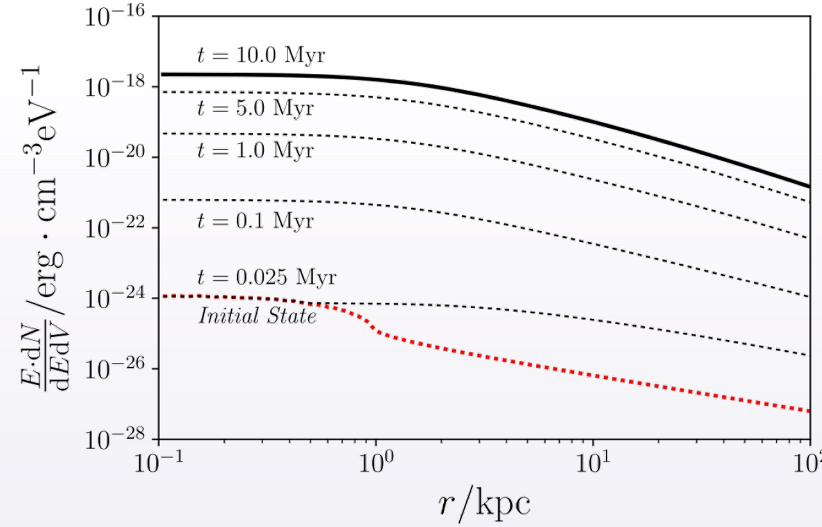
Cosmic ray accelerators



(Owen 2019)

Cosmic ray magnetic containment





(Owen+2018)

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

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

electromagnetic decay

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

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

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

weak decay

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

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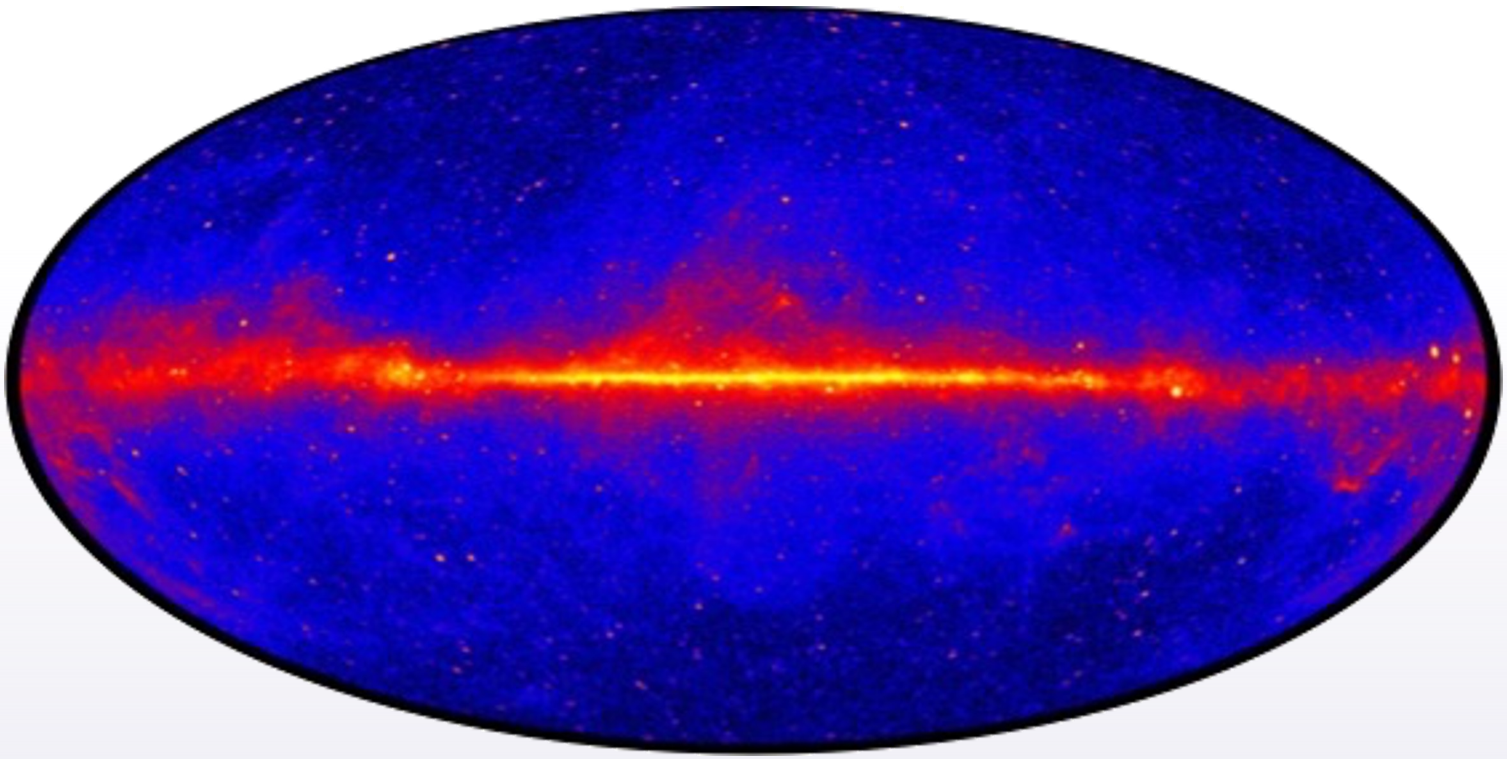
Isotropic gamma-ray background

12 years above 10 GeV with Fermi LAT



(*Fermi*-LAT Collaboration)

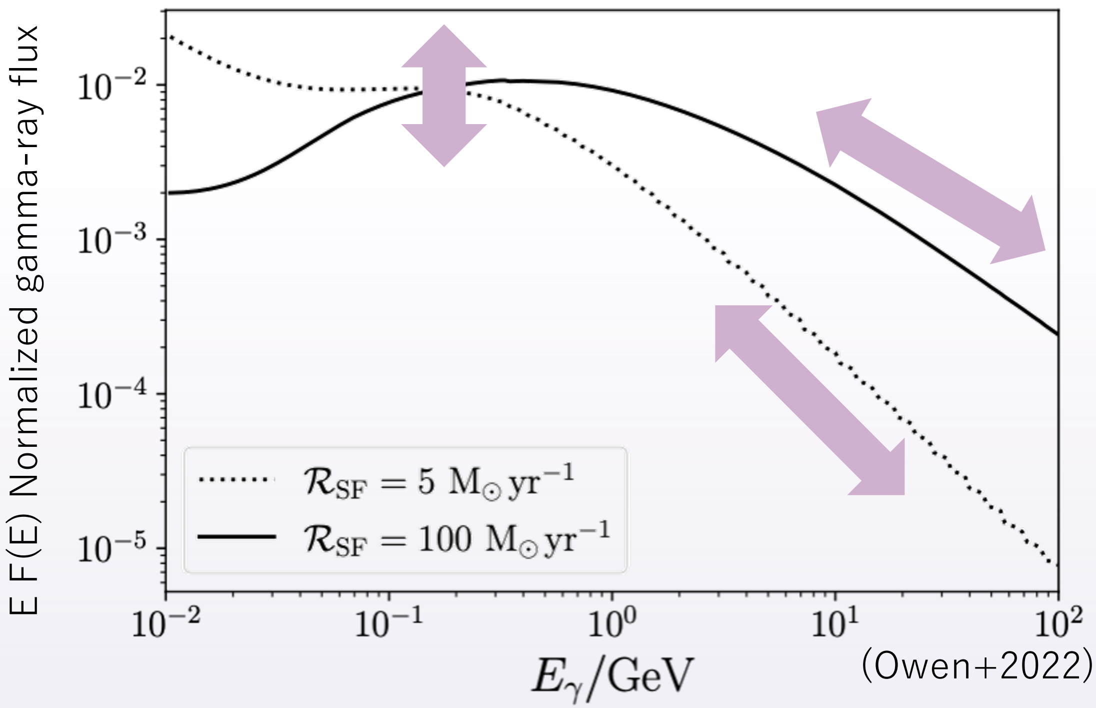
2. Characterising VHE emission from galaxies

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

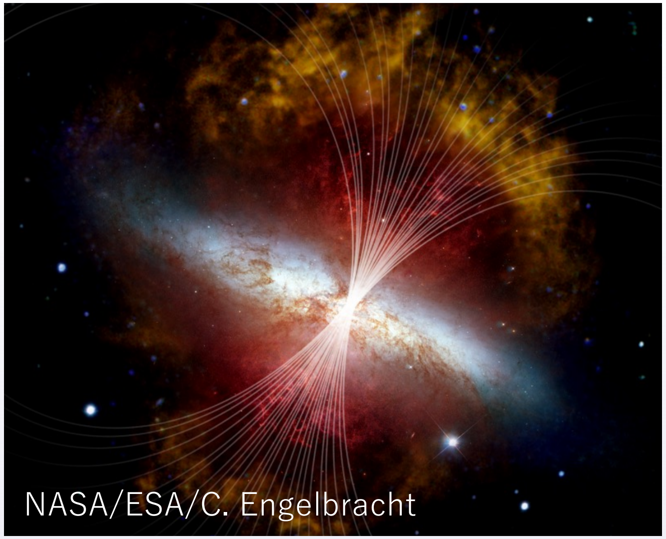
Parameter	Value
Γ	-2.1
$\gamma_{\rm p}^\star$	$10\ {\rm PeV}/m_{\rm p}c^2$
D_0	$3.0\times10^{28}\ {\rm cm^2\ s^{-1}}$
f_t	0.1
α	0.05
$M_{\rm SN}$	$50\,{\rm M_\odot}$
$E_{\rm SN}$	$10^{53}\,{\rm erg}$
ε	0.1
β	[illegible]
η	0.5
$T^\star$	$30,000\,{\rm K}$
$n_{\rm cl}$	$10\ {\rm cm^{-3}}$
f_c	0.1

Free parameters

SFR, Stellar mass, radius, redshift

Calorimetry

- Leptonic CRs entirely calorimetric in most galaxies
- 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

CR pressure gradients can drive an outflow

Outflow model

Hydrodynamical fluid equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = q$$ Continuity

$$\frac{\partial \rho \boldsymbol{v}}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}\boldsymbol{v}) = \rho \boldsymbol{g} - \nabla P_{\rm tot}$$ Momentum

$$\frac{\partial e_{\rm g}}{\partial t} + \nabla \cdot [(e_{\rm g} + P_{\rm g})\,\boldsymbol{v}] = Q - C + \rho \boldsymbol{v} \cdot \boldsymbol{g} + \mathcal{I}$$ Energy (thermal gas)

Energy (non-thermal CR fluid)

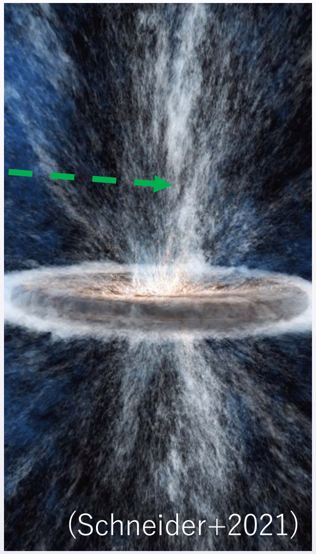
$$\frac{\partial e_{\rm c}}{\partial t} + \nabla \cdot [(e_{\rm c} + P_{\rm c})\,\boldsymbol{v}_{\rm c}] = \nabla \cdot [D \nabla e_{\rm c}] - \mathcal{I} + f_{\rm c} n_{\rm cl} c \sigma_{\rm pp} e_{\rm c} + Q_{\rm c}$$

Hadronic losses in wind

Energy exchange

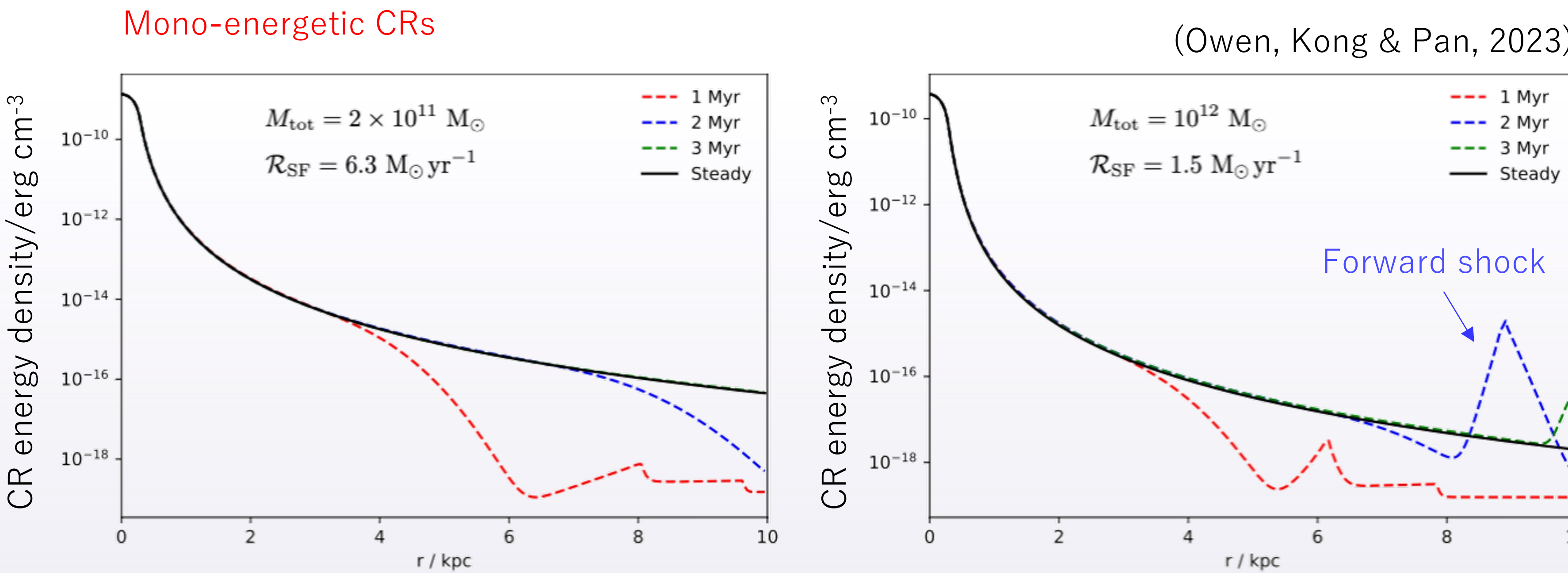
$$\mathcal{I} = -(\boldsymbol{v} + \boldsymbol{v}_{\rm A}) \cdot \nabla P_{\rm c} + \mathcal{C}_{\rm c} e_{\rm c}$$

Parametrized boundary conditions: **SFR** (Total energy, CR injection, B field)



Outflow model

- Solve numerically with FLASH4 code, MHD+CR simulation
- Outflow dependency on galaxy properties (SFR, halo mass)



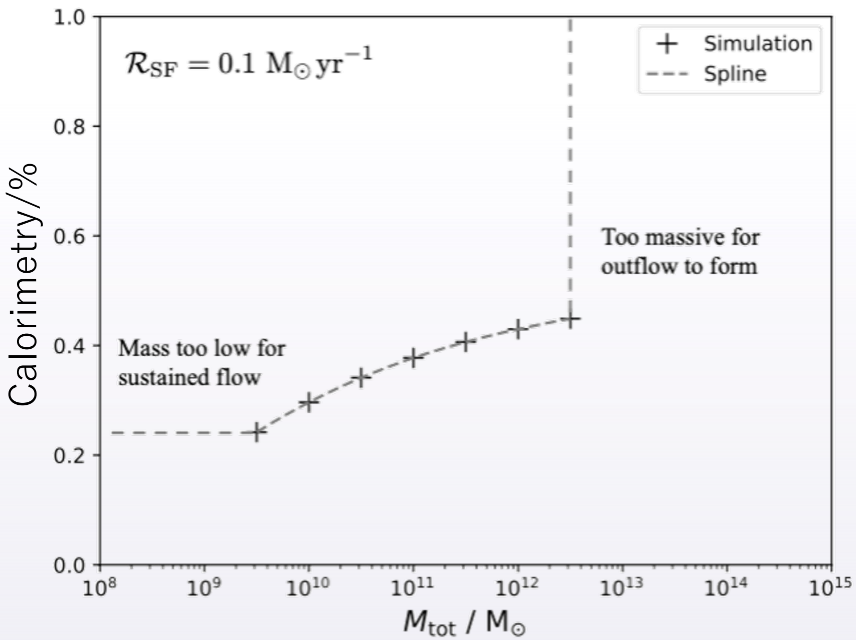
Dependency on galaxy properties

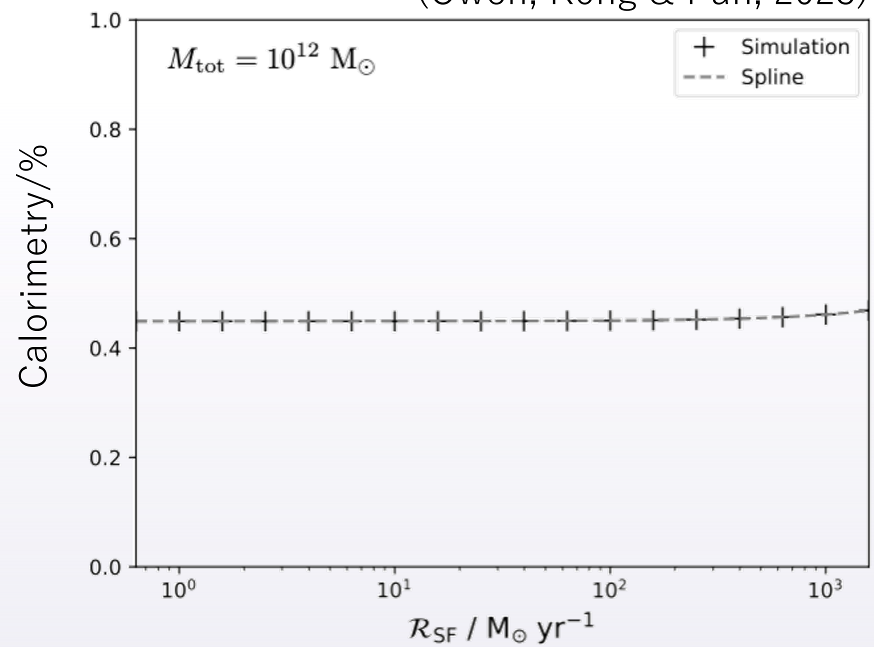
CRs at 1 GeV; advective escape dominates over diffusive leaking

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

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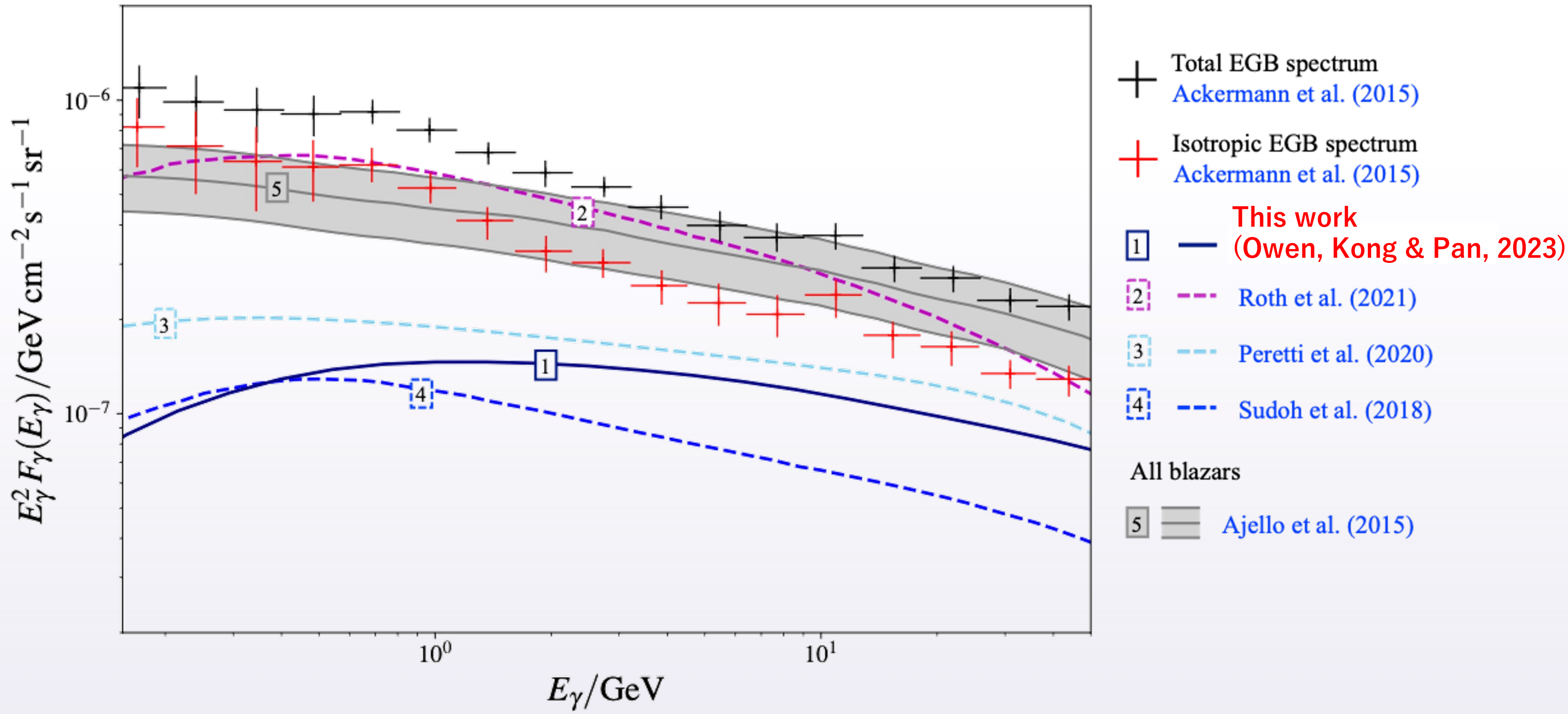
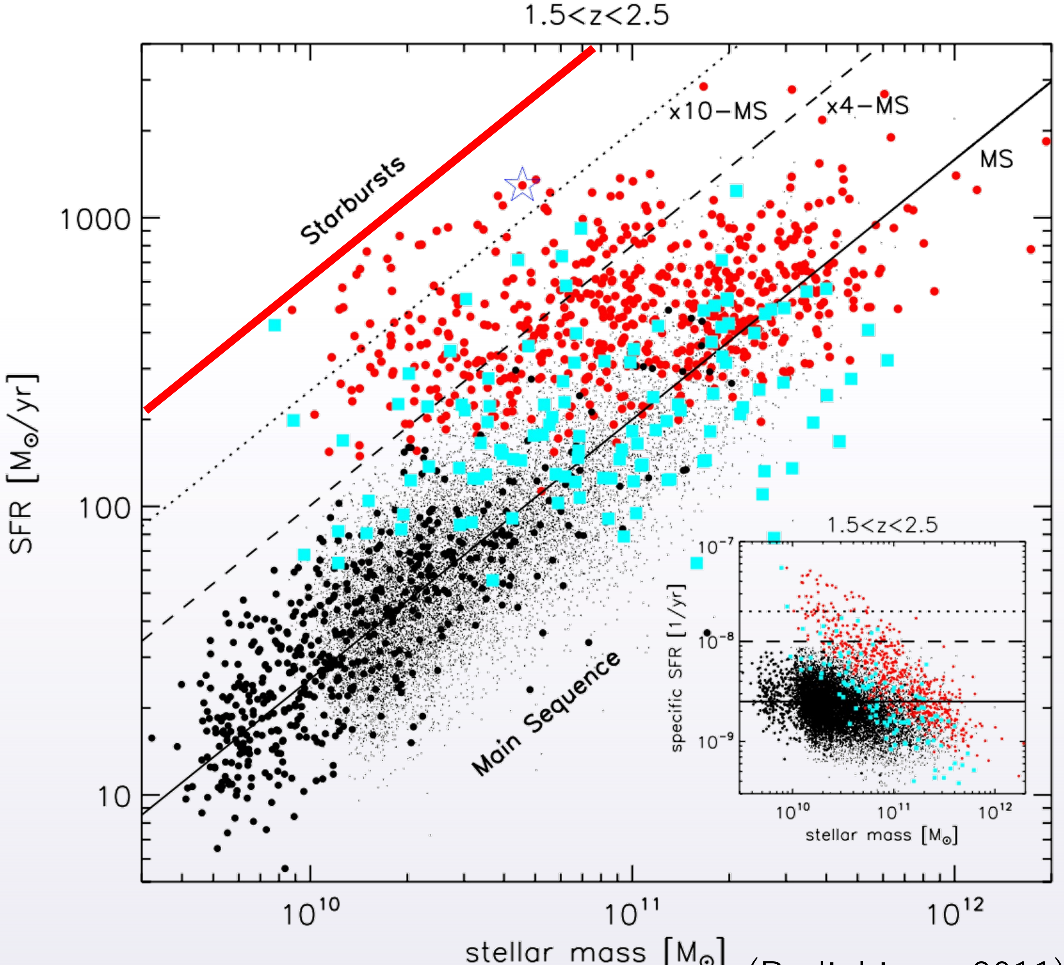
- Galaxies can contribute a few tens of percent (depends slightly on CR spectrum in sources, less on CR driving); inputs from EAGLE sims
- Fermi isotropic EGB constraint not violated



See also Junling Chen's talk next

The main-sequence/starburst separation

How should we define a starburst galaxy?



(Rodighiero+2011)

We want to pick only the most extreme starbursts

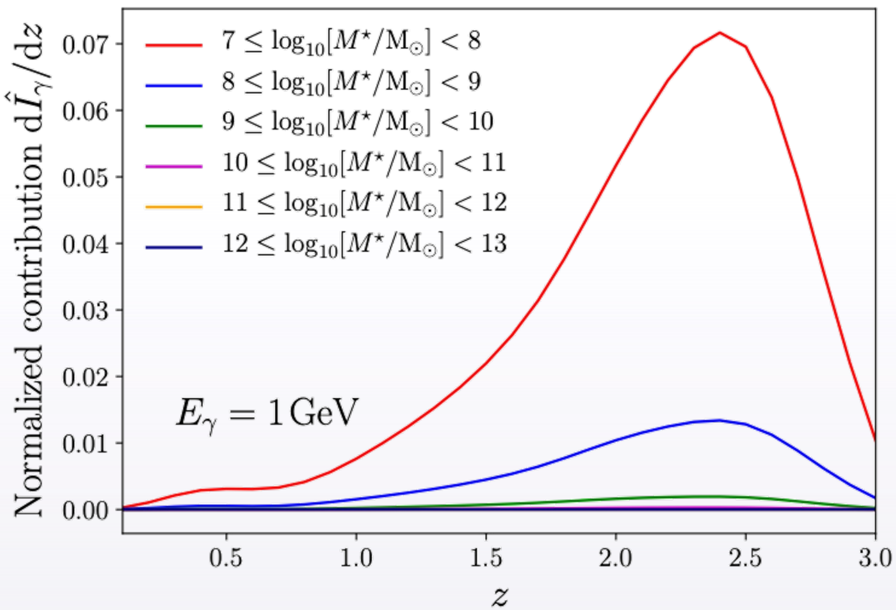
10x the average SFR over the lifetime a galaxy at fixed stellar mass

(standard UV-VJ cut in colour-colour space)

Contribution: >95% at all energies

Mass separation

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 larger Poisson term than previously considered; similarities to BL Lac/AGN contribution
  → Implications for disentangling source populations?

3. A multi-messenger perspective

Microphysics and Astroparticle Physics

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

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

+ 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

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

weak decay

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

“Tensions” with the observed neutrino flux

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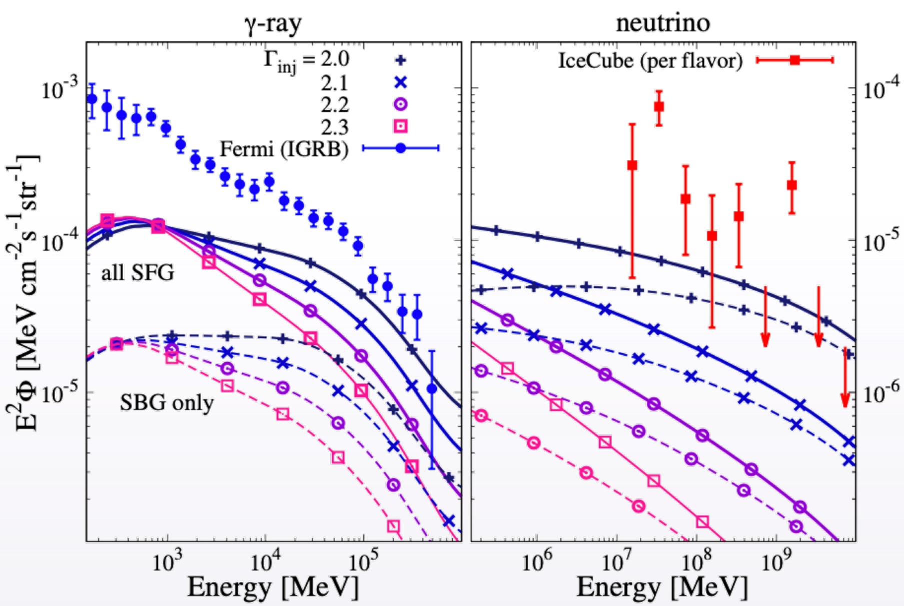
How to self-consistently account for the large neutrino flux observed below 100 TeV, without overshooting the gamma-ray Fermi constraint?



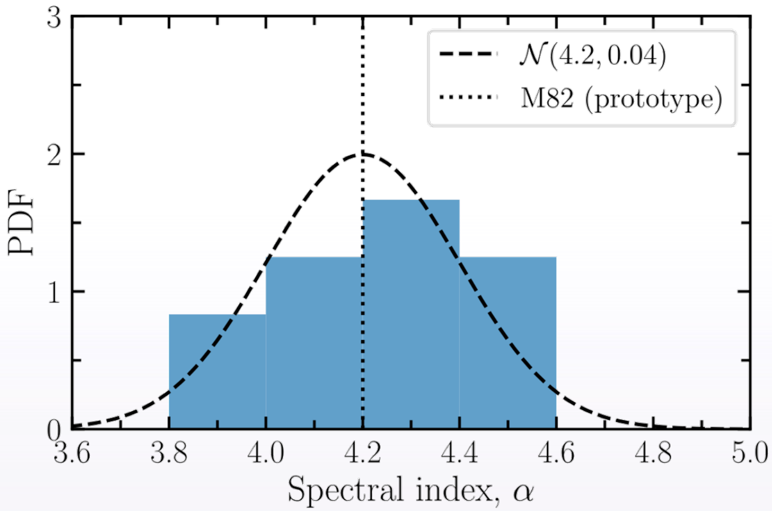
(Sudoh et al. 2018)

See also Chang et al. 2016; Xiao et al. 2016; Capanema et al. 2020a, b; Owen et al. (in prep) 2024... + others

Only a few % of the astrophysical neutrino flux is estimated to originate from starburst galaxy populations below 100 TeV

Origins in injection/transport physics?

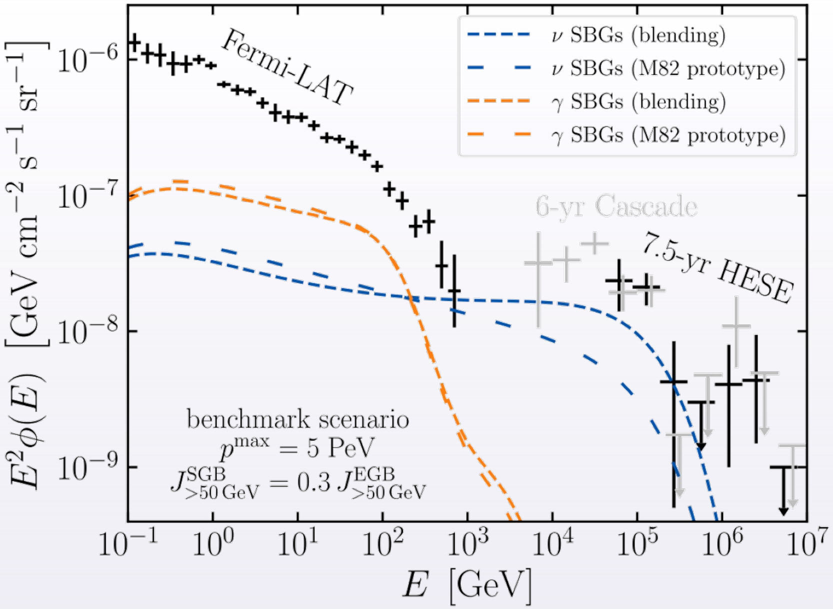
Spectral blending of an M82 prototype (Ambrosone et al. 2021)



(based on survey by Ajello et al. 2020)

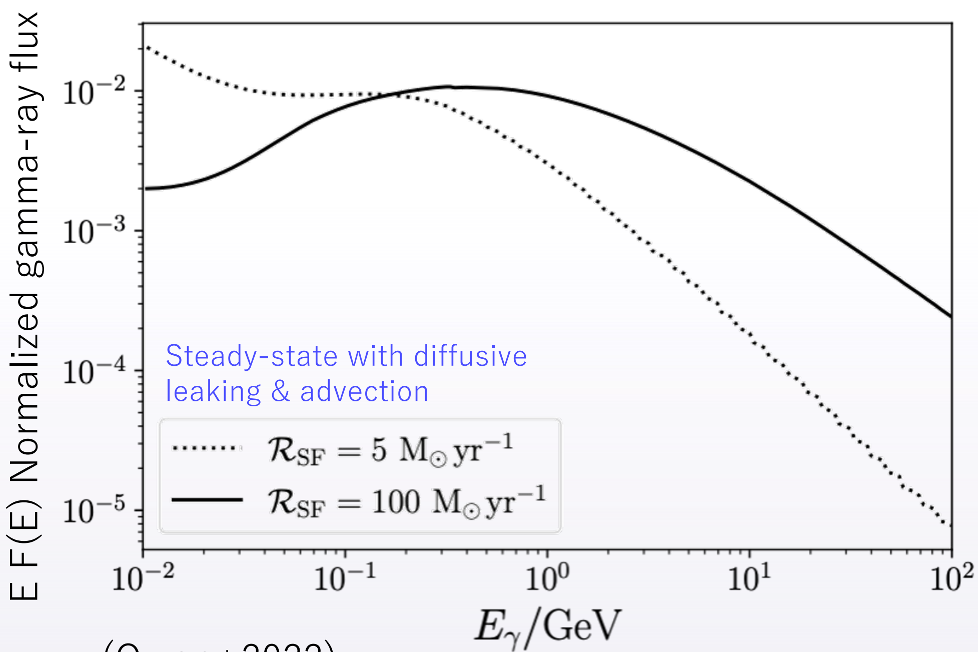
M82 prototype scaled by SFR

(Ambrosone et al. 2021)

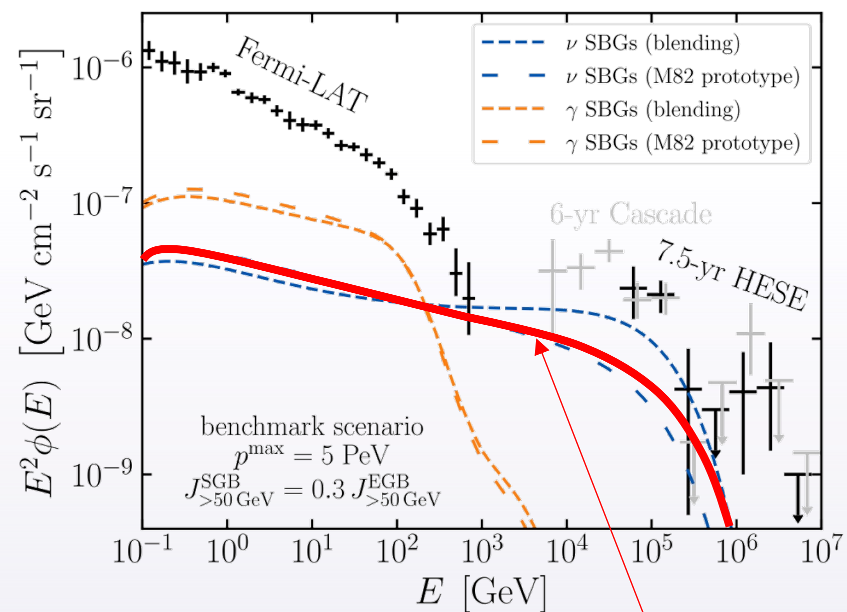


Origins in injection/transport physics?

Relax the M82 prototype; magnetic amplification by turbulent dynamo; variation in galaxy properties (size, mass) → **discrepancy may persist**



(Owen+2022)



Annotated red-line
Preliminary (in prep work)

Modeling B field amplification to SFR captures local variation in spectral index w. SFR

(see Owen+2018 for model description)

Other explanations

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- **Multiple components** in the extra-galactic diffuse neutrino flux (e.g. not SFG-dominated?) (Chianese+2016, 2017, Palladino+2016...)

- Cosmic ray accelerators with **highly suppressed gamma-ray emission**
  - Pair production with low energy photons in the local photo-sphere (Sudoh & Beacom 2023)
  - GRBs (Tamborra & Ando 2016)
  - Low-Power Gamma-Ray Burst Jets inside Stars (Murase + Ioka 2013, Senno et al. 2016, Denton & Tamborra 2018)
  - Radiatively inefficient accretion flows in low-luminosity AGN (Kimura et al. 2015)
  - Photo-hadronic origin of neutrinos, instead of pp (e.g. Murase+2016)

- Gamma-ray emission from SFGs may be **more leptonic** (e.g. TeV halos), so we should not expect big contribution to neutrino background (e.g. Sudoh, Linden & Beacom 2019)

Summary

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- Starburst galaxies are factories of CRs and a candidate source population for the gamma-ray background

- Their contribution can be modelled using a prototype approach based on galaxy properties
  - Exact contribution can vary based on model assumptions (e.g. scaling from M82 vs. built-up from galaxy physics)

- Emission originates at z~2.5, and dominated by low mass intense starbursts, relatively rare: SFG component to EGB may have large Poisson term

- Discrepancies with multi-messengers continues to leave the main physical origin of VHE from star-forming galaxies unsettled