Exploring the role of cosmic rays in galaxies with high energy signatures

The extreme Universe viewed in VHE gamma rays 2022

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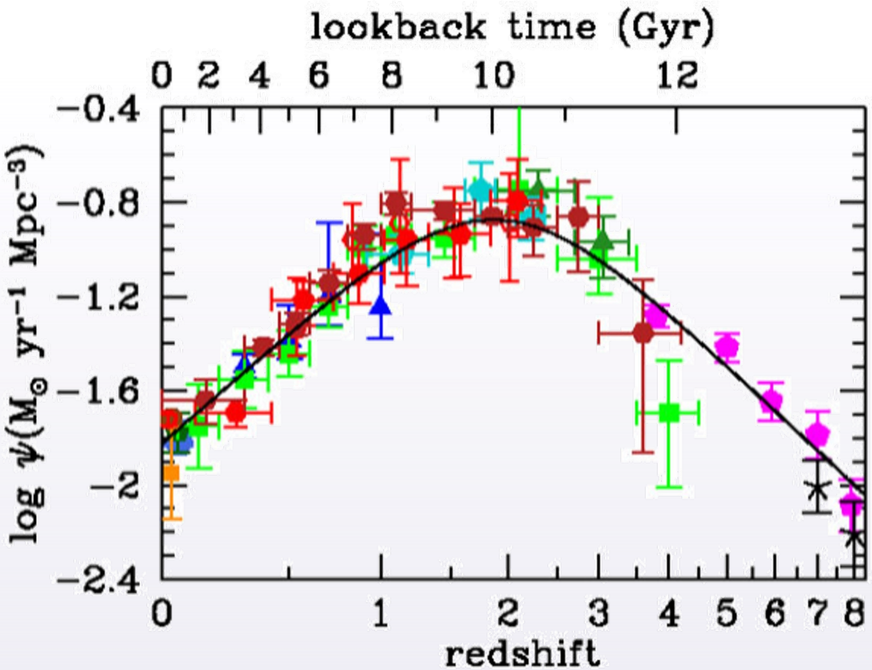
Outline

- Introduction
  - *Galactic and circum-galactic ecosystem*
  - *Cosmic ray origins, interactions and feedback*
- Types of signatures
  - *Outflows and X-rays (messo-physical/thermodynamic)*
  - *Extragalactic gamma-ray background (microphysical)*
- New opportunities in the CTA era

1. Feedback in galaxy evolution

Galaxy formation/evolution

- Galaxy self-regulation (feedback) mainly modelled thermally/mechanically; some treatment of radiation – SNe/AGN etc.
- Picture not yet complete, massive, highly star-forming or high-z galaxies presenting particular ~~problems~~ opportunities

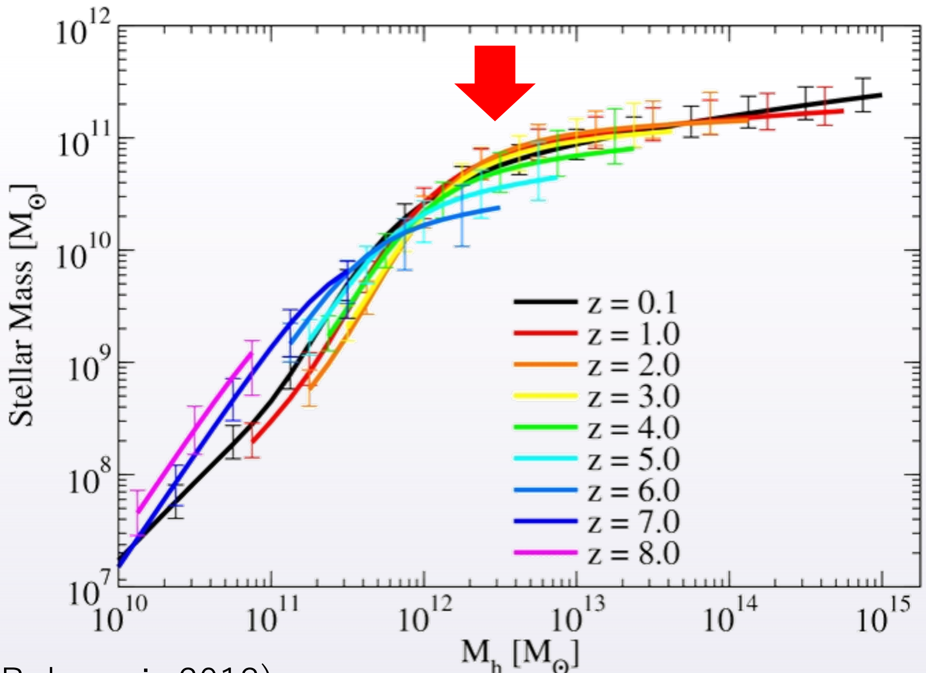


(Madau & Dickinson 2014)

What causes the downfall of star-formation after cosmic noon; particularly very rapid quenching seen in massive galaxies? (>300 billion Msun)

Galaxy formation/evolution

- Galaxy self-regulation (feedback) mainly modelled thermally/mechanically; some treatment of radiation – SNe/AGN etc.
- Picture not yet complete, massive, highly star-forming or high-z galaxies presenting particular ~~problems~~ opportunities

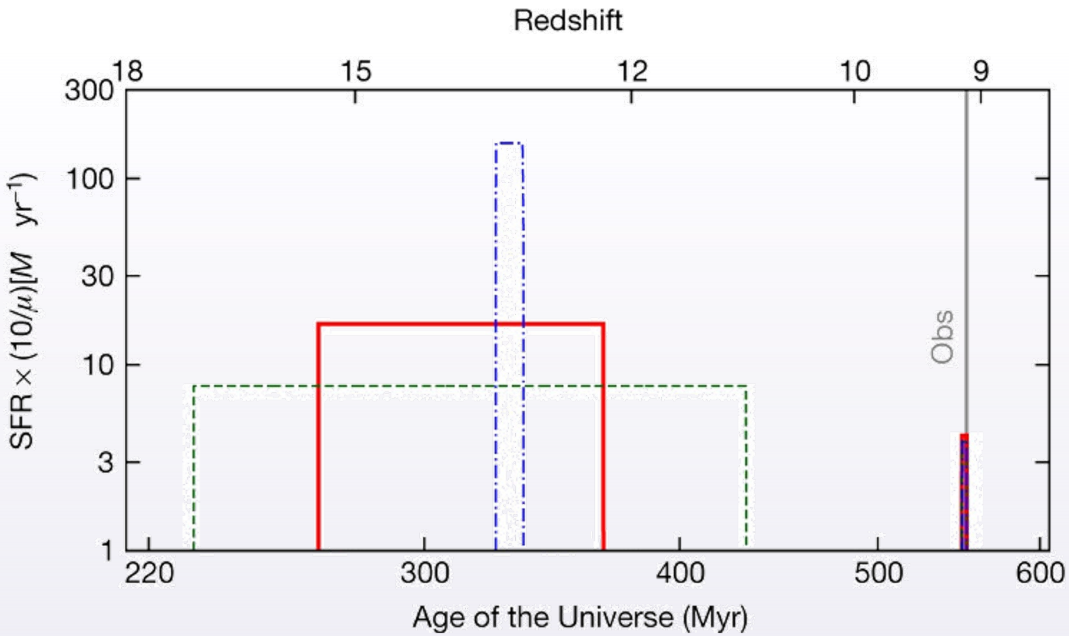


(Behroozi+2013)

Why do abundance-matching relations between halo and stellar masses turn-over? ("golden mass" of 300 bn Msun)

Galaxy formation/evolution

- Galaxy self-regulation (feedback) mainly modelled thermally/mechanically; some treatment of radiation – SNe/AGN etc.
- Picture not yet complete, massive, highly star-forming or high-z galaxies presenting particular ~~problems~~ opportunities



(Hashimoto+2018)

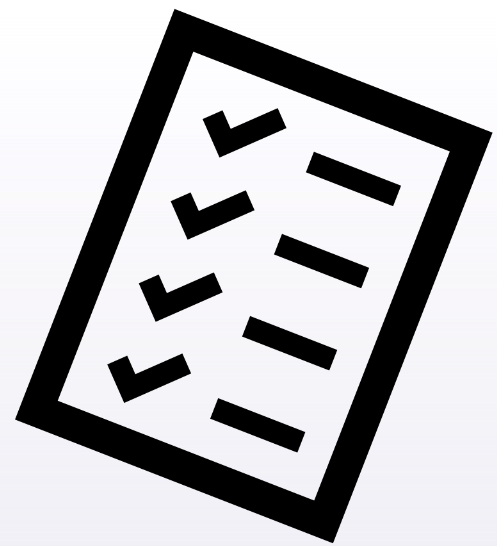
What is the cause of bursty star-formation histories in primordial galaxies?

Hidden players

- A missing ingredient in our galaxy evolution/feedback models
- Renewed search for hidden players controling baryon cycles in/around galaxies; drivers and mediators of galaxy growth

Checklist for a feedback agent

- ❑ Are they present?
- ❑ Are they powerful enough?
- ❑ Are there suitable physical channels for them to deliver feedback?



Cosmic rays?

2. Cosmic rays as a feedback agent

Cosmic rays as a feedback agent?

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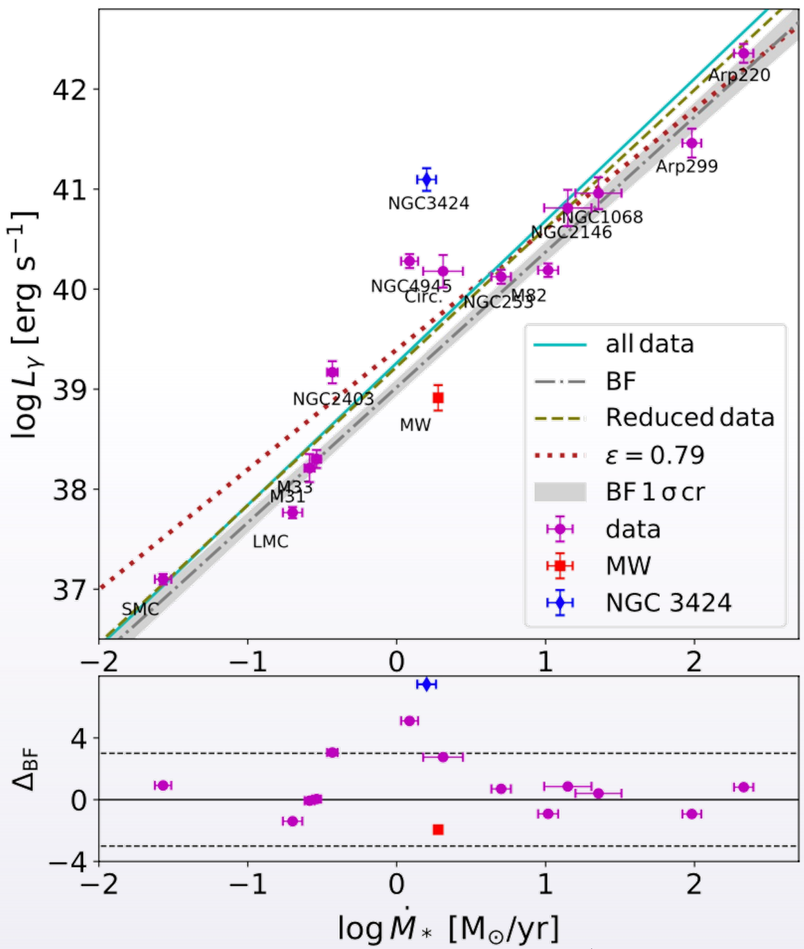

(Kornecki+2020)

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

Checklist for a feedback agent

- ☑ Are they present?
- ☐ Are they powerful enough?
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Impressions of feedback “mechanisms”

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Ionization, “collisional” processes

Scattering/energy & momentum transfer via magnetic fields

Hadronic interactions

Thermal

- 1. **Heats** something up
- 2. Thermal pressure does something

Targeted; dense and ionized regions

Direct impacts & smaller scales?

Dynamical

- 1. **Moves** something with CR (non-thermal) pressure
- 2. Movement / flow disrupts system in some way

Important in ecosystem regulation, gas supply

Indirect impacts & larger scales?

Microphysics and Astroparticle Physics

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Hadronic interactions (pp dominates over p-gamma in galactic settings)

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

+ pion multiplicities at higher energies

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

electromagnetic decay

$\tau_{\mathrm{em}} \approx 8.5\times10^{-17}\mathrm{s}$

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

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

weak decay

$\tau_{\mathrm{weak}} \approx 2.6\times10^{-8}\mathrm{s}$

Microphysics and Astroparticle Physics

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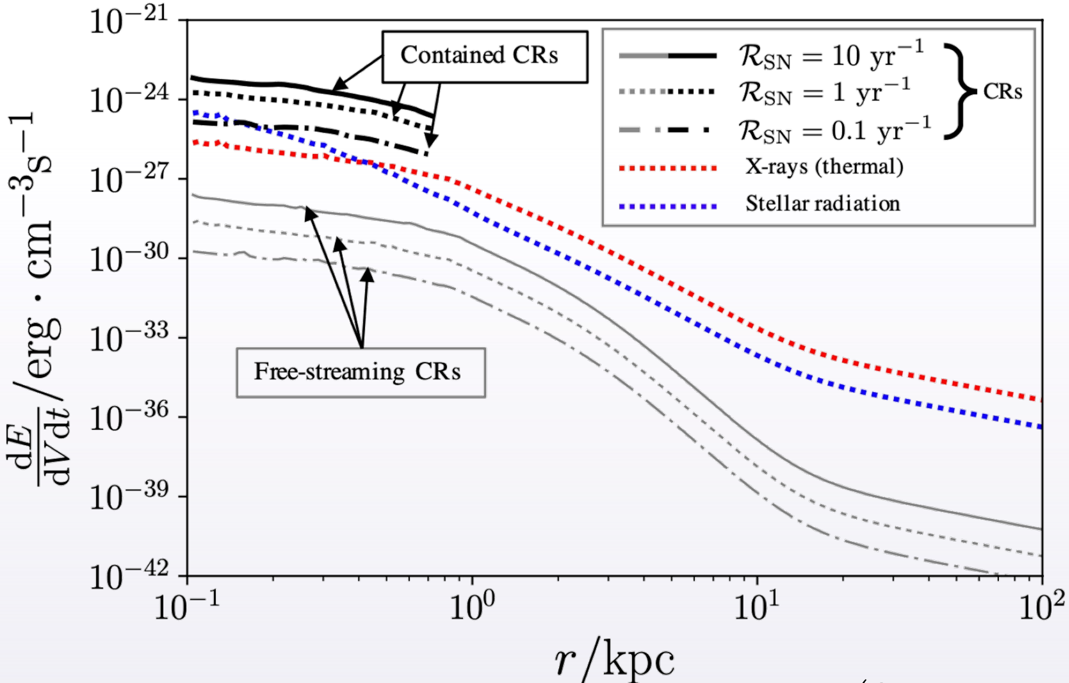
In a uniform hot, magnetized, ionized ISM



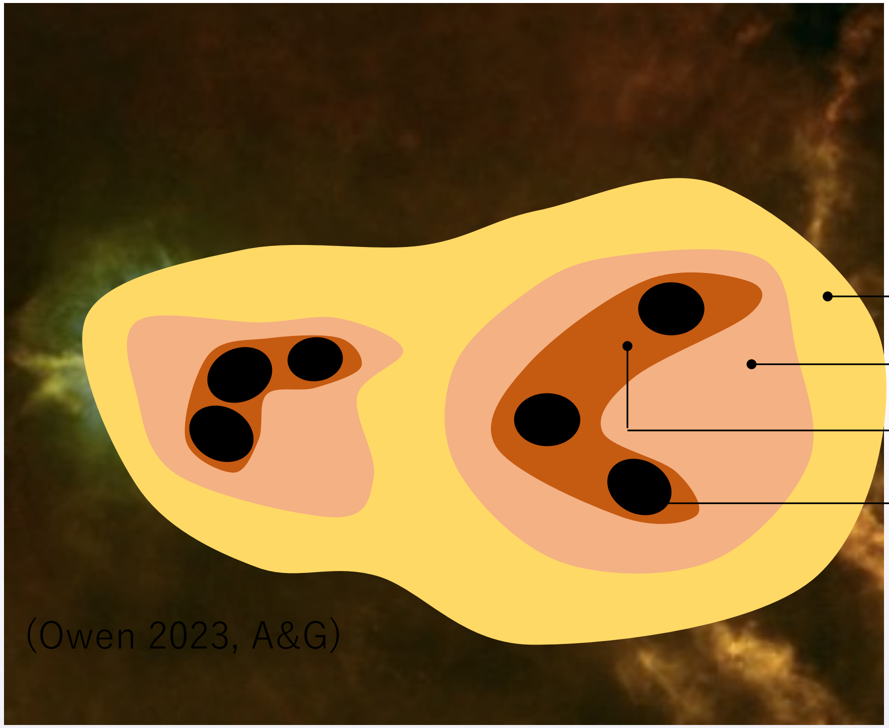
(Owen+2018)

"Maximum" heating power – how much can actually be delivered?

Osaka University Theoretical Astrophysics

Microphysics and Astroparticle Physics

Molecular cloud hierachical configuration

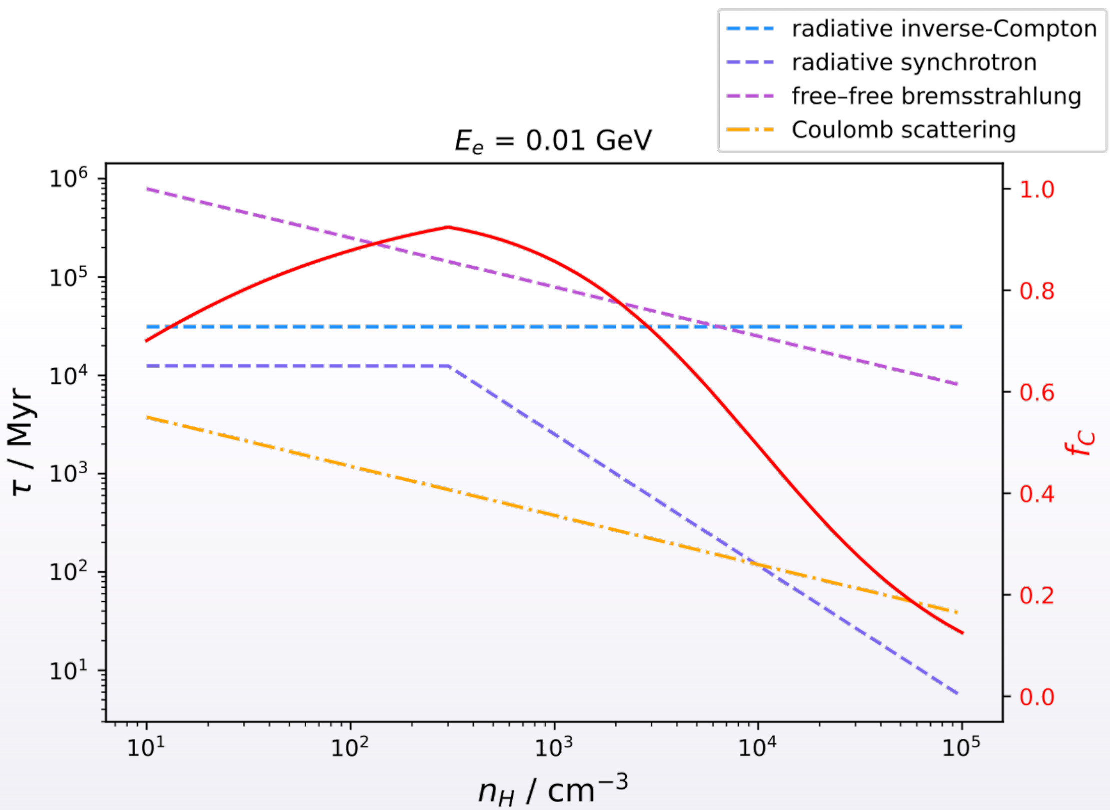


(Arzoumanian+2011)

	Size / pc	Denisty / cm^{-3}
Cloud	~1-10	~ 50-500
Clump	~1	10^3-10^4
Filament	~0.1 (wide)	10^4-10^5
Core	~0.05-0.1	>10^5

Microphysics and Astroparticle Physics

Thermalization of secondary electrons in galactic components



(Credit: Michelle Kao 2022; U Waterloo)

Thermalization focussed in molecular clumps; not efficient in hot ionized medium or cores

Impressions of feedback “mechanisms”

Ionization, “collisional” processes

Scattering/energy & momentum transfer via magnetic fields

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Targeted; dense and ionized regions

Direct impacts & smaller scales?

Dynamical

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Important in ecosystem regulation, gas supply

Indirect impacts & larger scales?

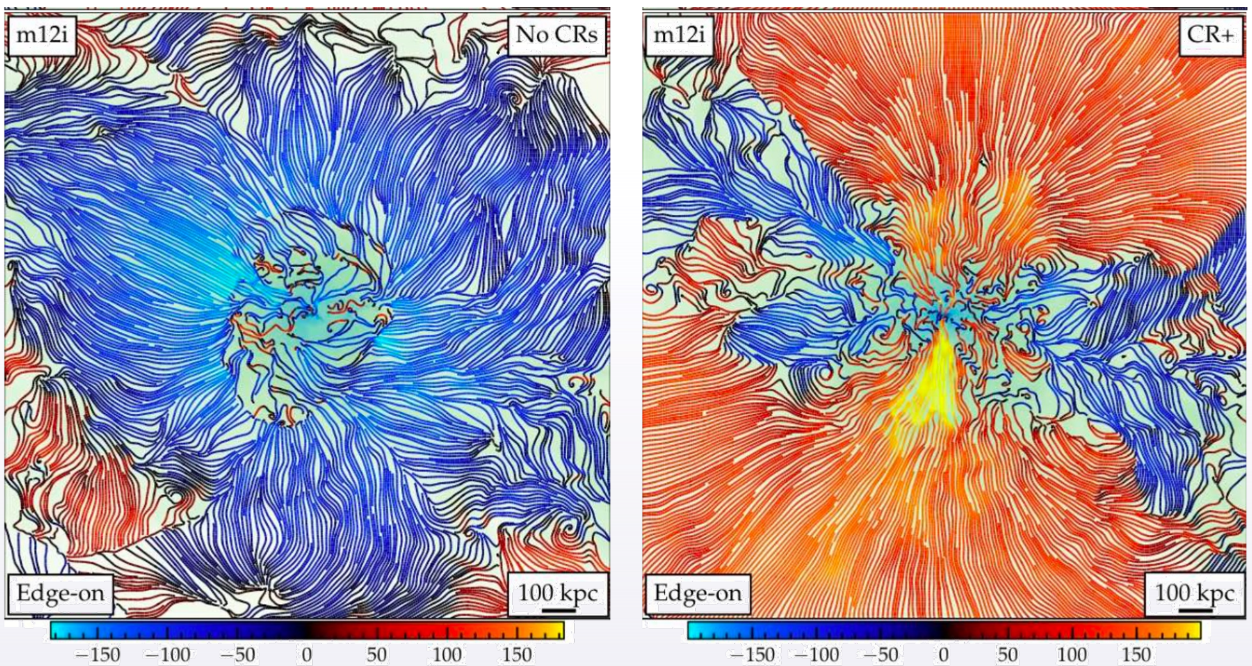
Messo-physics and astrophysics

Explored in simulations

Hopkins+ 2021; FIRE-2 simulations

Zoom simulations - Projected, edge-on;
later-forming massive halo + disk

MHD



+CRs
(**pressure** & heating)

Colour bar: flow velocity (thermal gas)

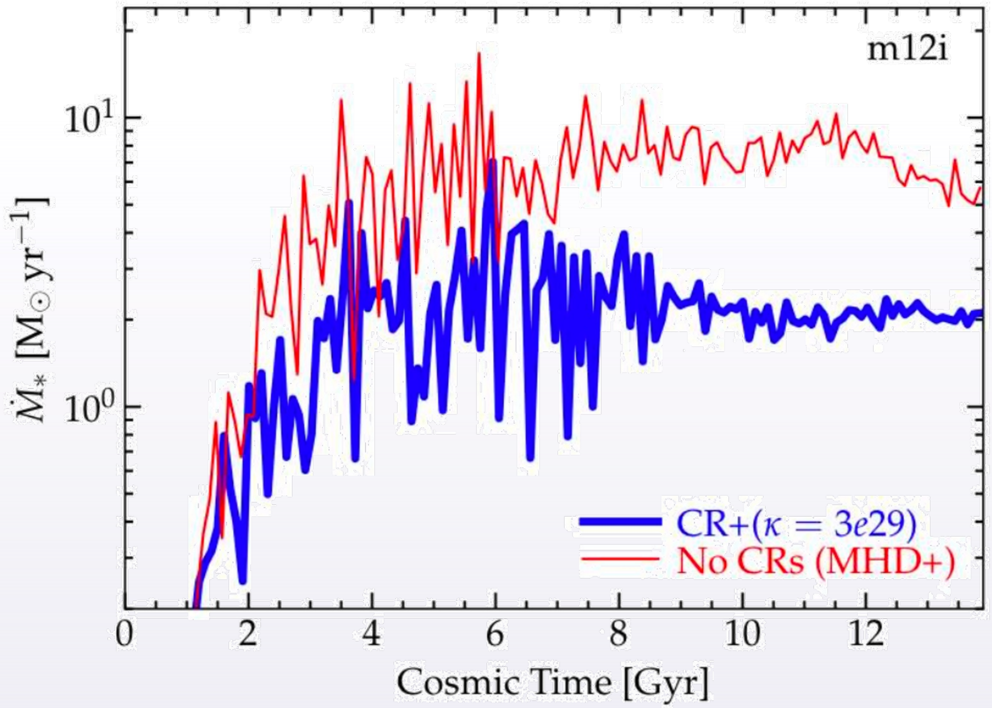
Inflowing **Outflowing**

Messo-physics and astrophysics

Explored in simulations

Hopkins+ 2021; FIRE-2 simulations

SFR suppressed; less "bursty"



Checklist for a feedback agent

- ☑ Are they present?
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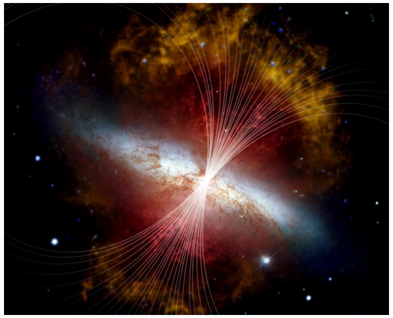
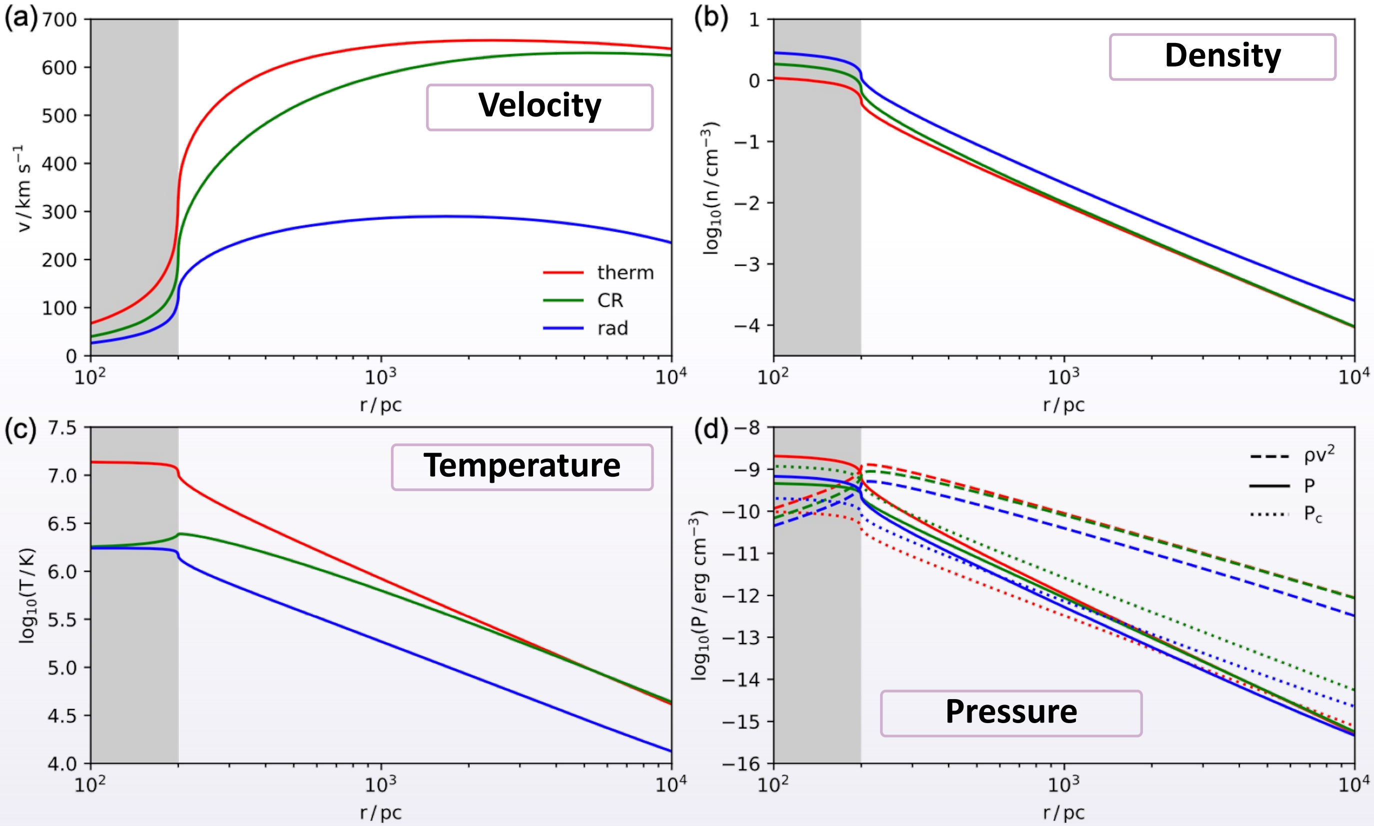
3. High-energy signatures of cosmic ray feedback

Dynamical driving



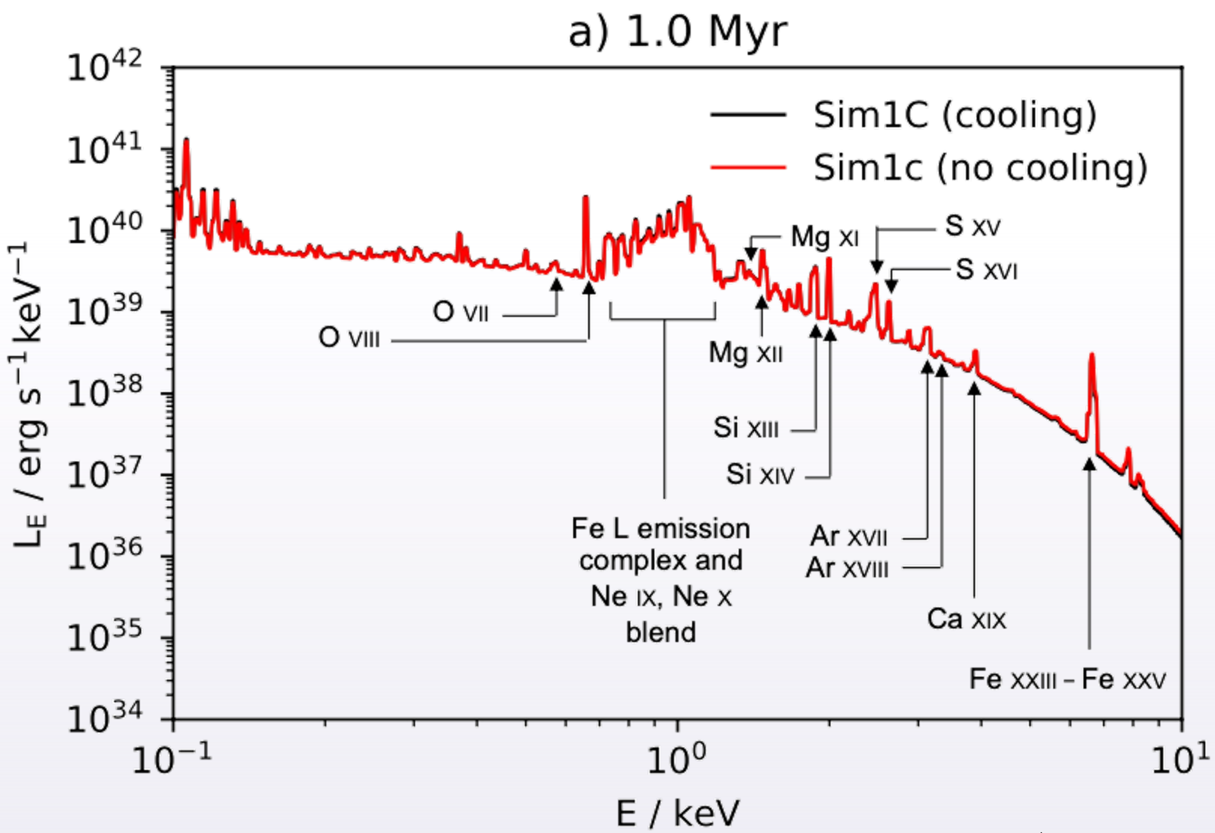
See also Jacob+2018



(Yu, Owen+2020)

X-ray emission from an outflow

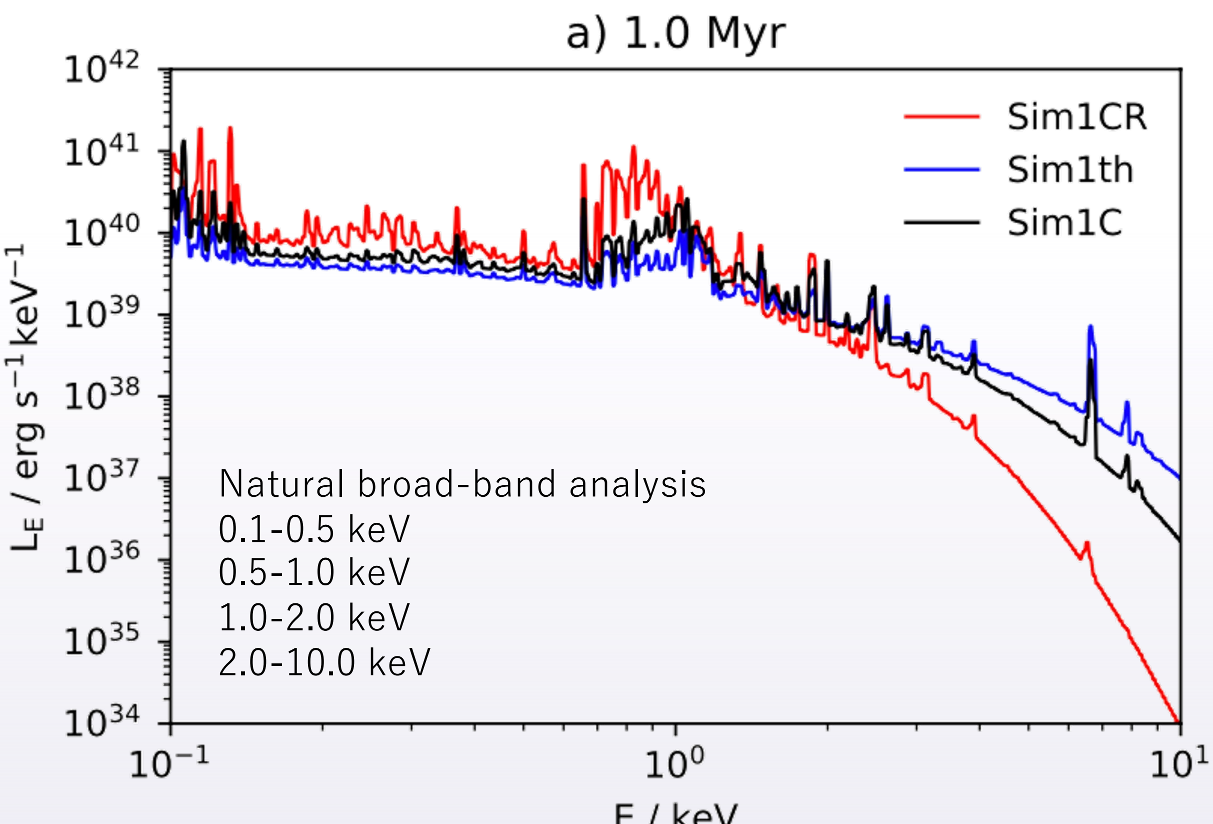
Hot gas; M82 like configuration



(Yu, Owen+2021)

X-ray emission from an outflow

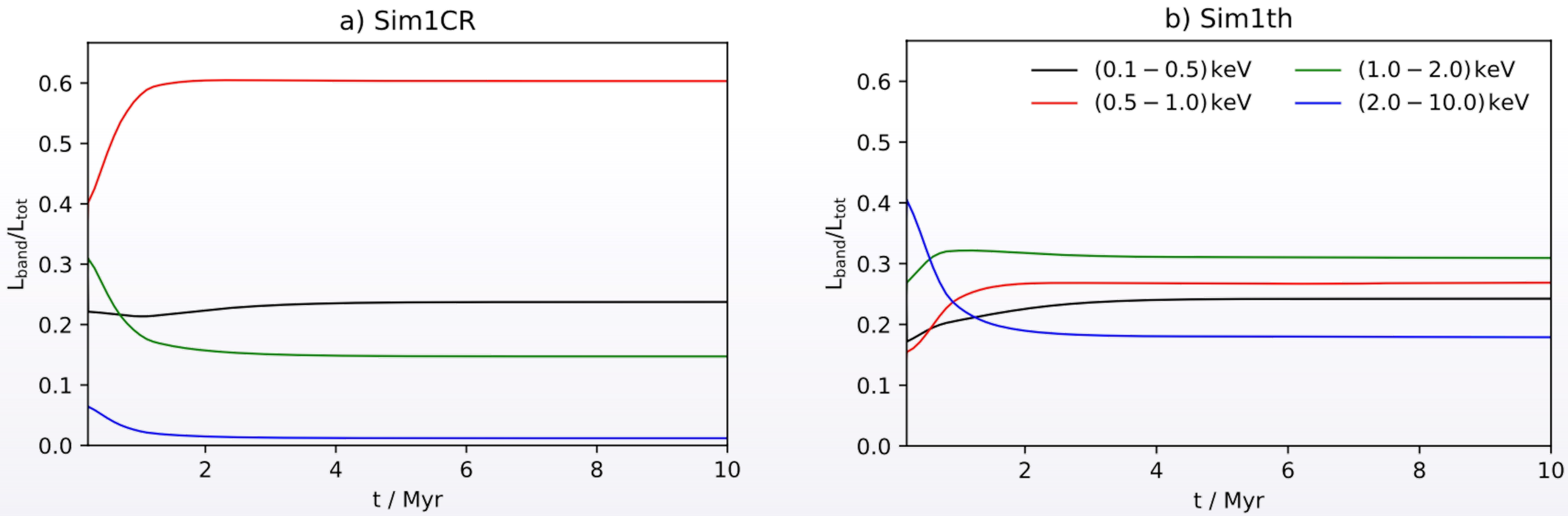
Level of cosmic ray driving modifies the thermal gas properties



(Yu, Owen+2021)

X-ray emission from an outflow

Broadband ratios to track cosmic ray driving in outflows



(Yu, Owen+2021)

- Fewer photons
- Reach more & more distant systems (XRISM, or *Athena?*?)

Re-cap: gamma-ray production

Hadronic interactions (pp dominates over p-gamma in galactic settings)

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

+ pion multiplicities at higher energies

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

electromagnetic decay

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

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

Gamma-ray emission from starbursts

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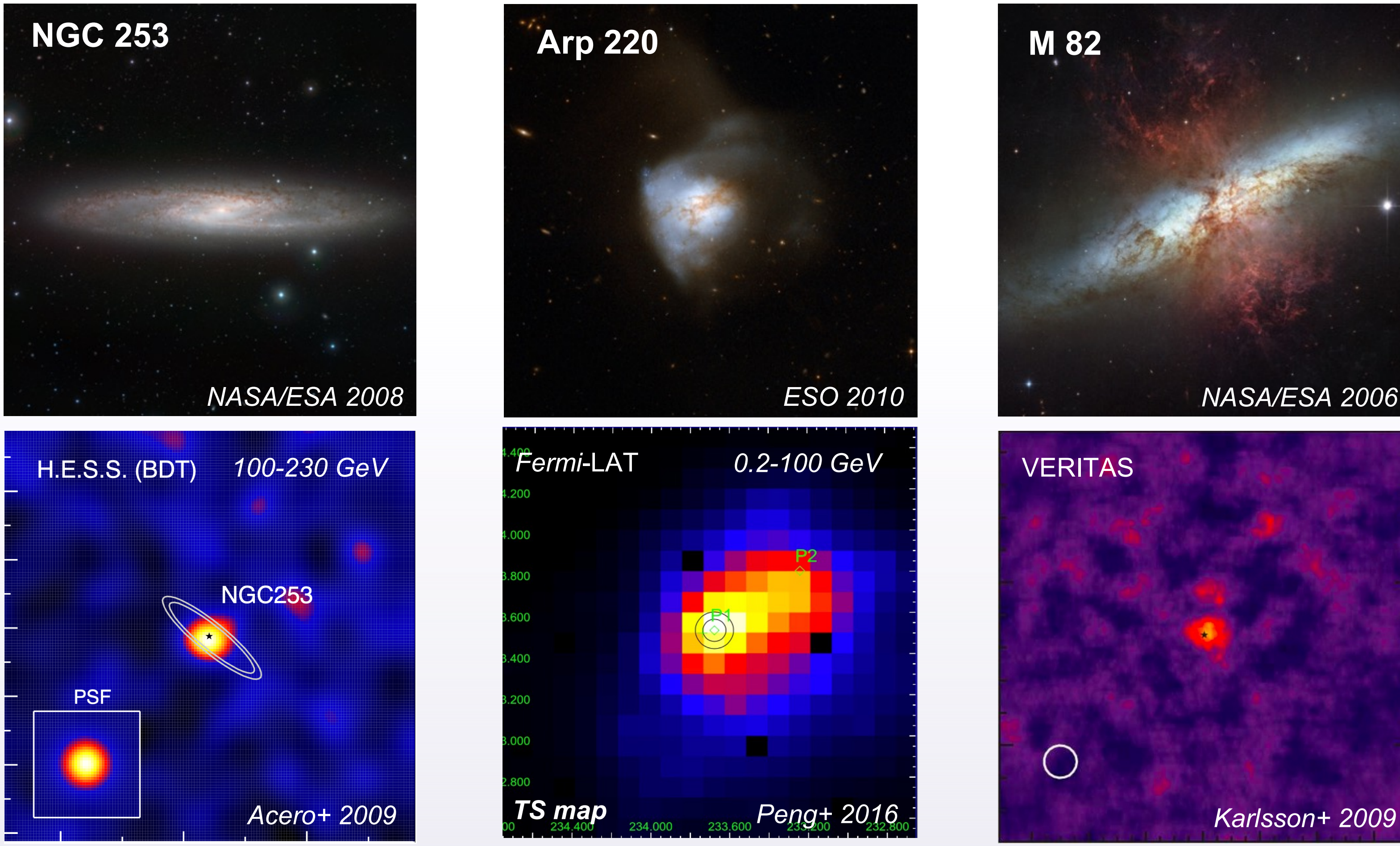
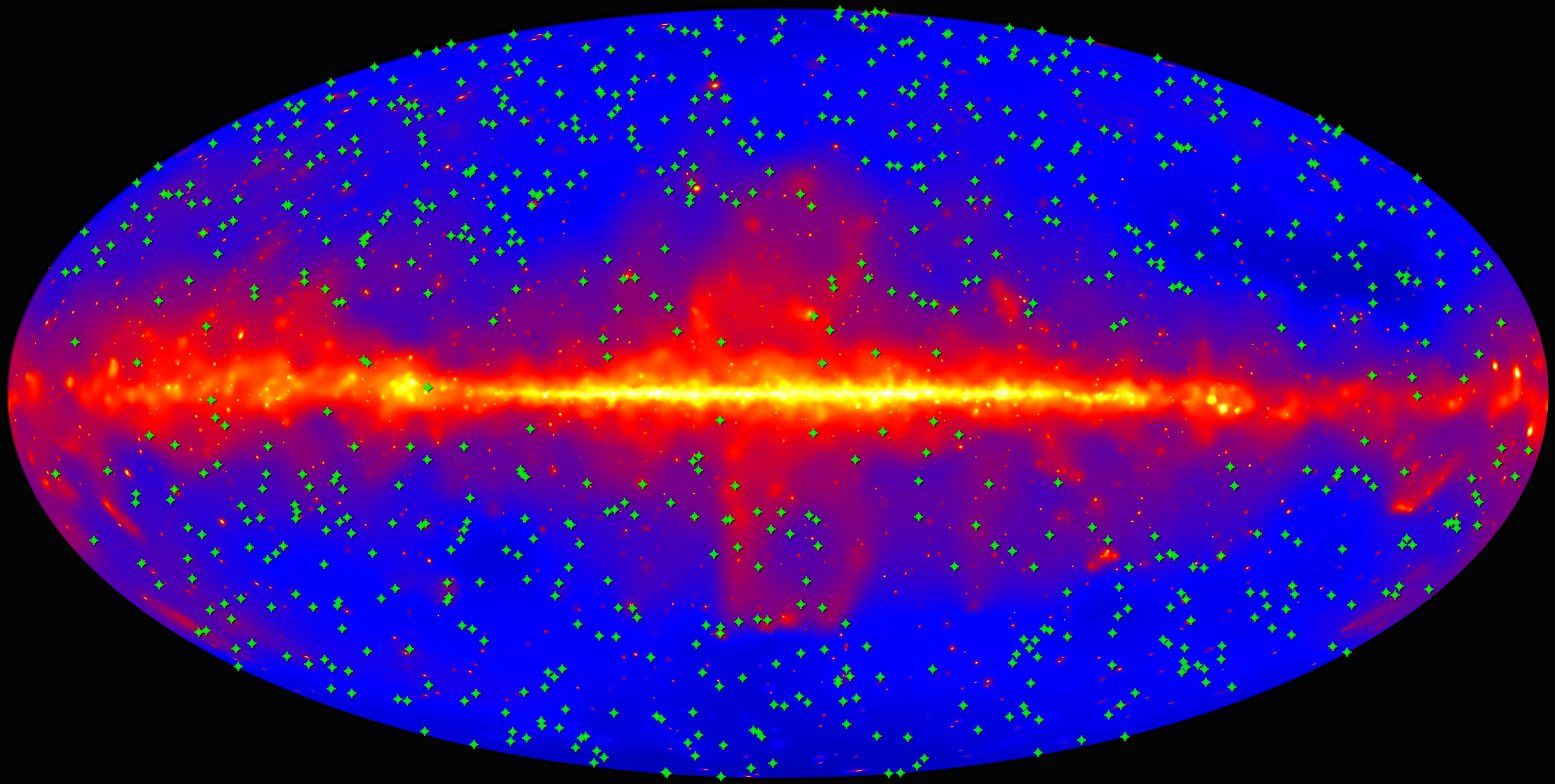


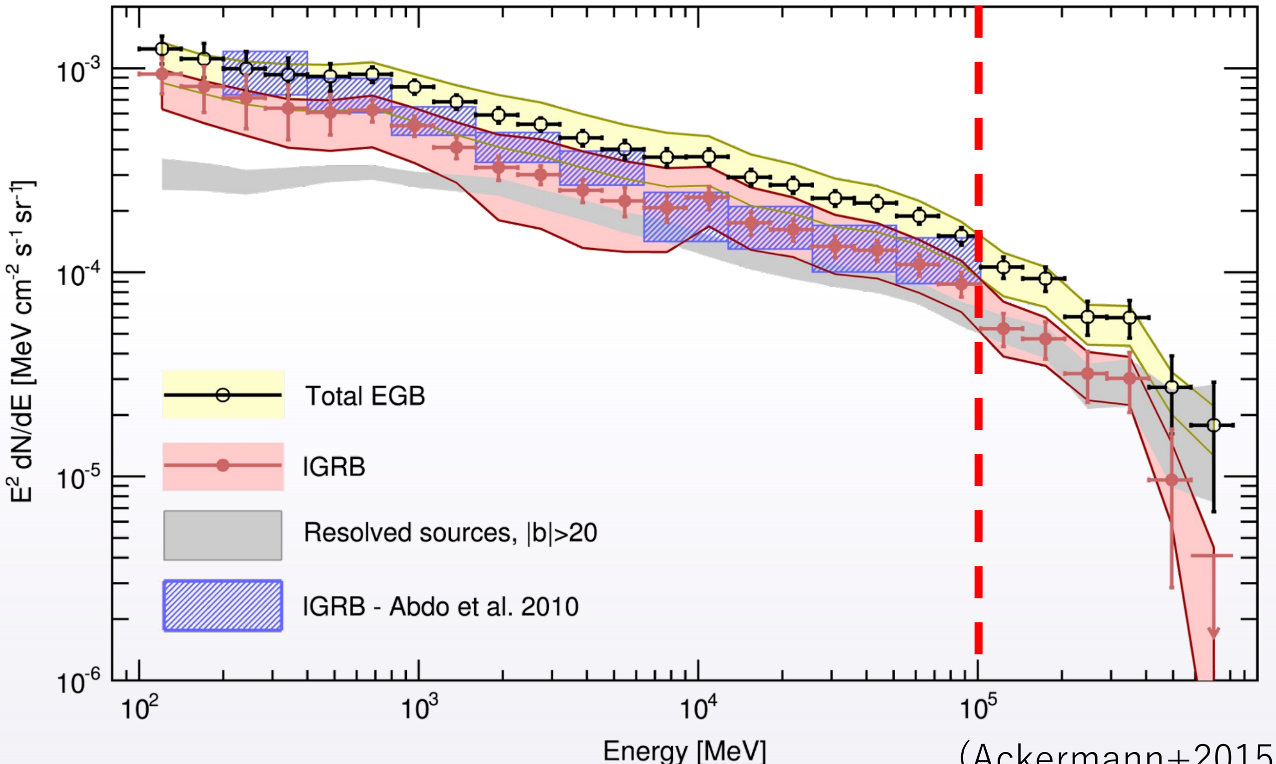
The gamma-ray background

10 years of Fermi-LAT
E>10 GeV



NASA/*Fermi*-LAT collaboration

The extragalactic γ-ray background

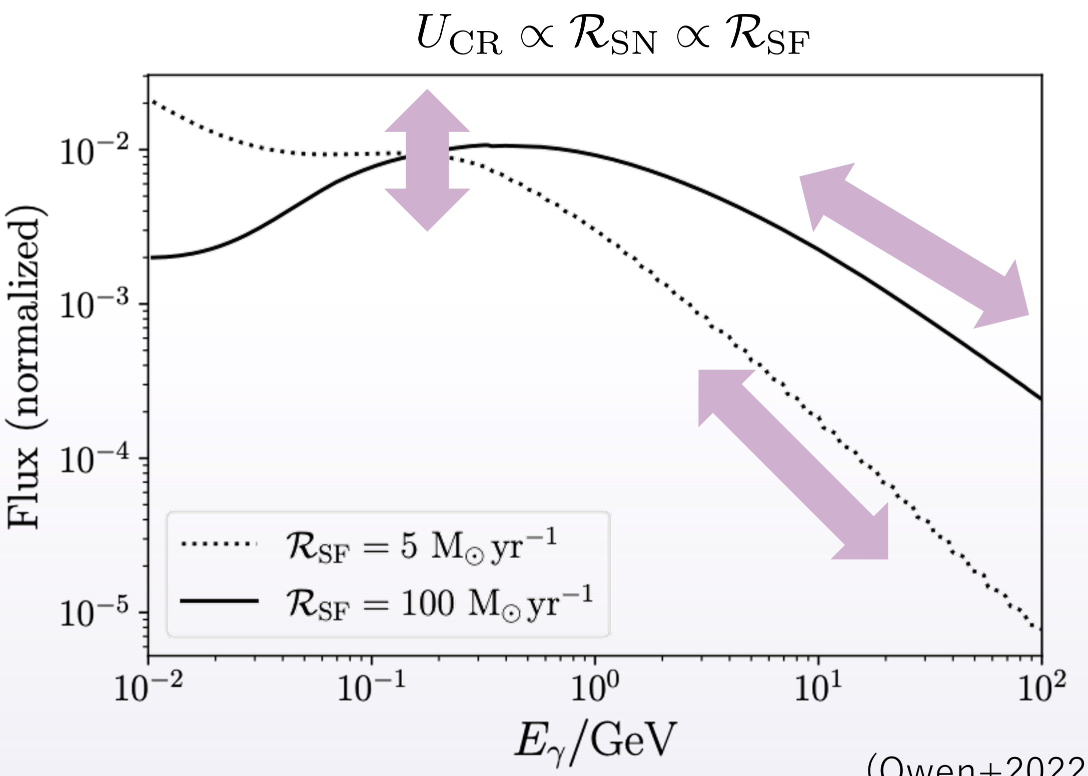


(Ackermann+2015)

~50% resolved into individual LAT sources above 100 GeV

- Star-forming galaxies could dominate (Roth+2021; Owen+2021b)

Prototype galaxy model: γ-ray production



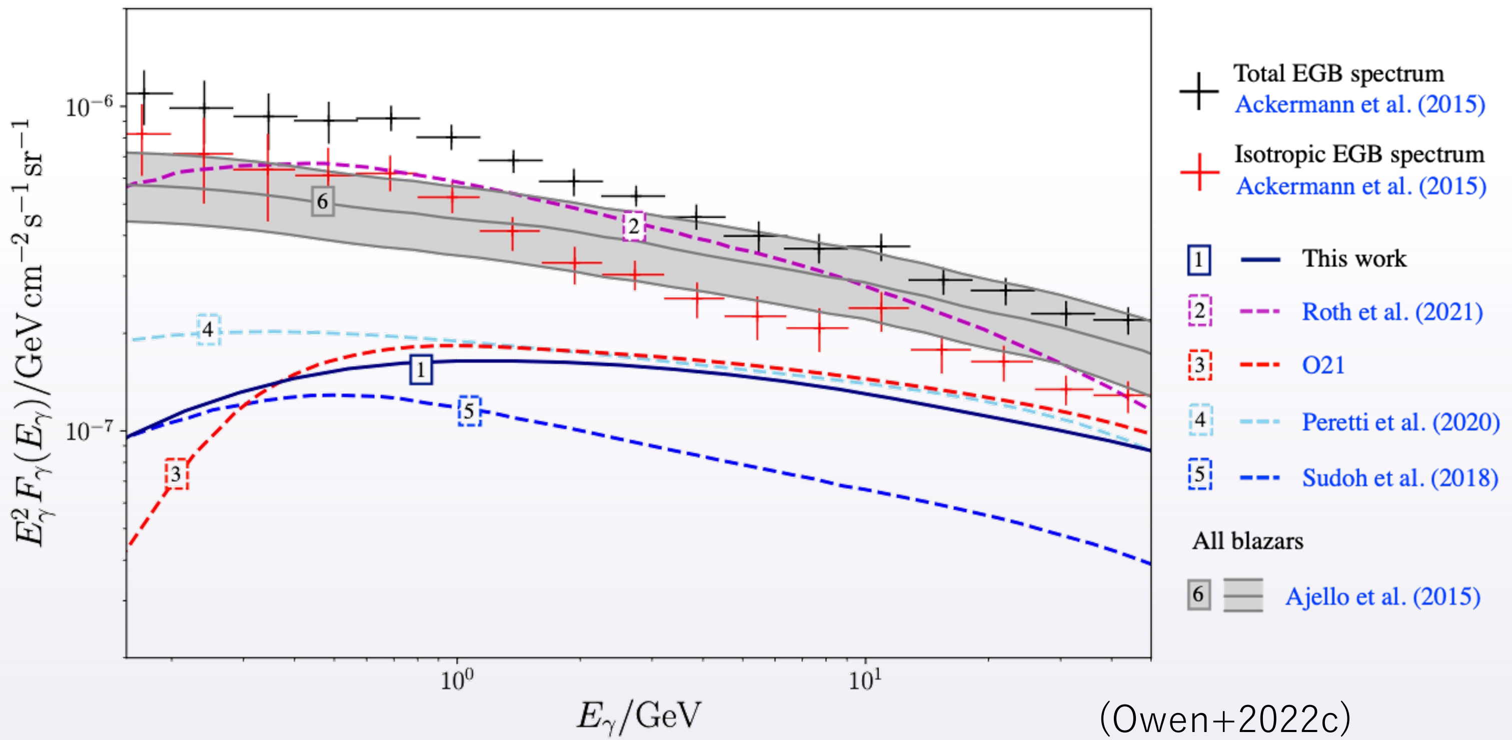
(Owen+2022c)

CR injection spectrum $\propto T_{\rm p}^{-\Gamma}$

Include treatment of CR propagation; diffusion/leaking gives different spectral slopes with SF rate

EGB spectrum

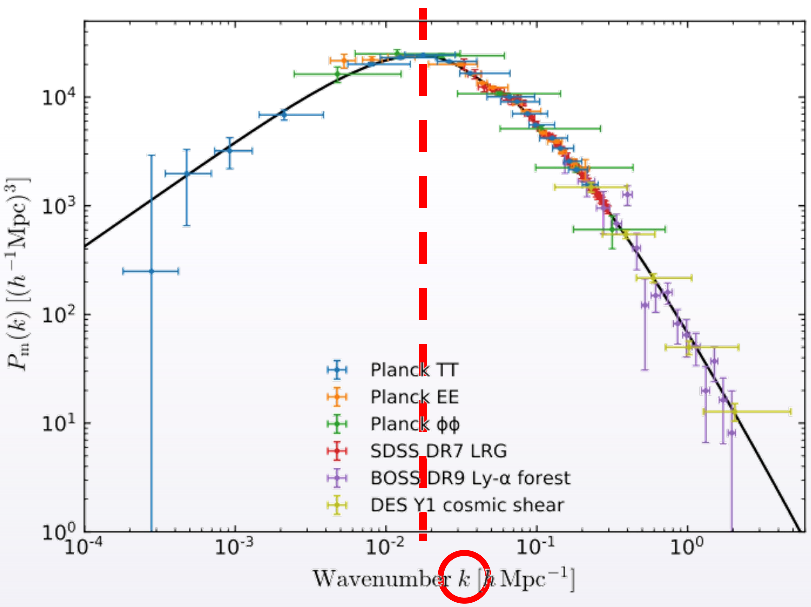
Galaxies can contribute a few tens of percent (depends slightly on CR spectrum in sources; also works by Ambrosome+2021)



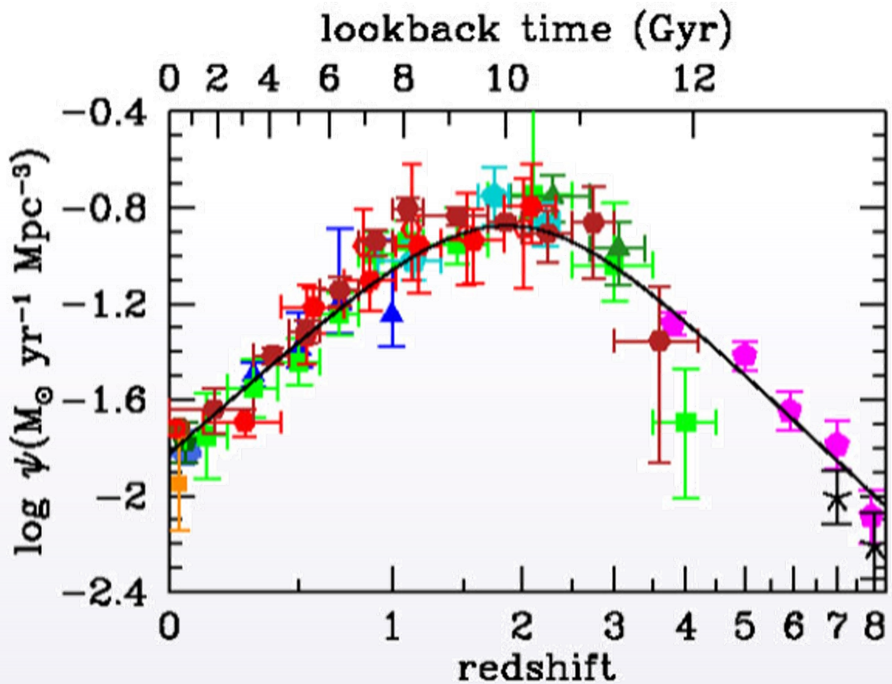
(Owen+2022c)

Source population distribution

Intensity distribution; imprints at a preferred (peak) angular scale



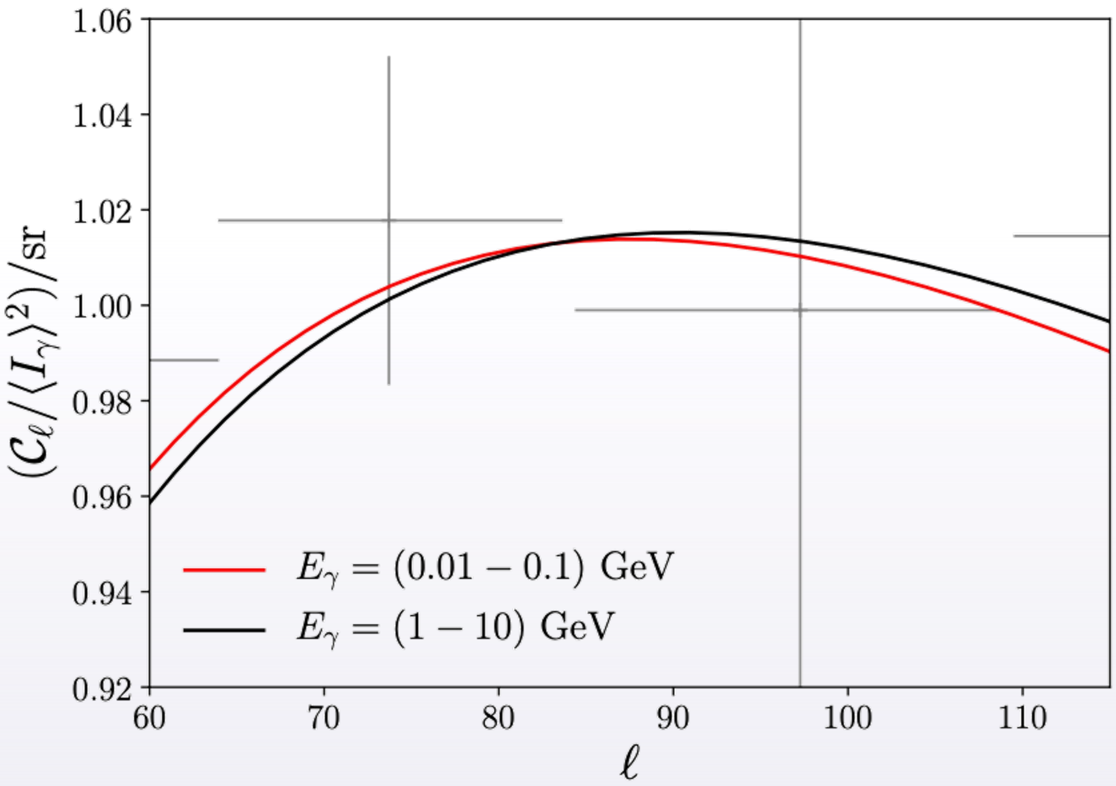
(Planck Collaboration+2018)



(Madau & Dickinson 2014)

EGB anisotropies

Redshift evolution imprints spatial signature in EGB



(Owen+2022c)

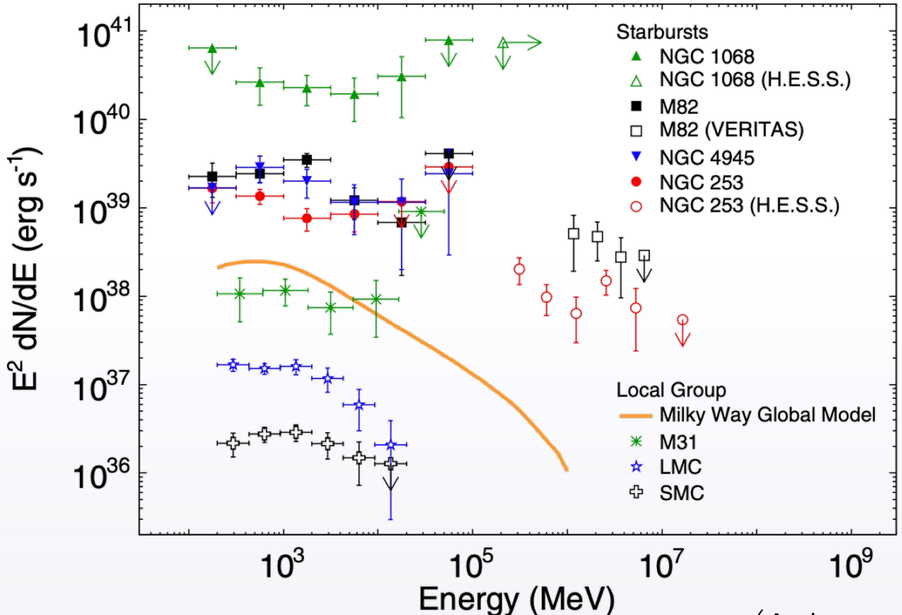
Signature dominates over statistical flucctuations (many dim galaxies, rather than a few bright ones)

CTA's "KSP 8" + *Fermi*-LAT

4. New opportunities in the CTA era

Individual galaxies

With LHAASO, SWGO + CTA, Gamma-ray spectra of more nearby galaxies



(Ackermann+2012)

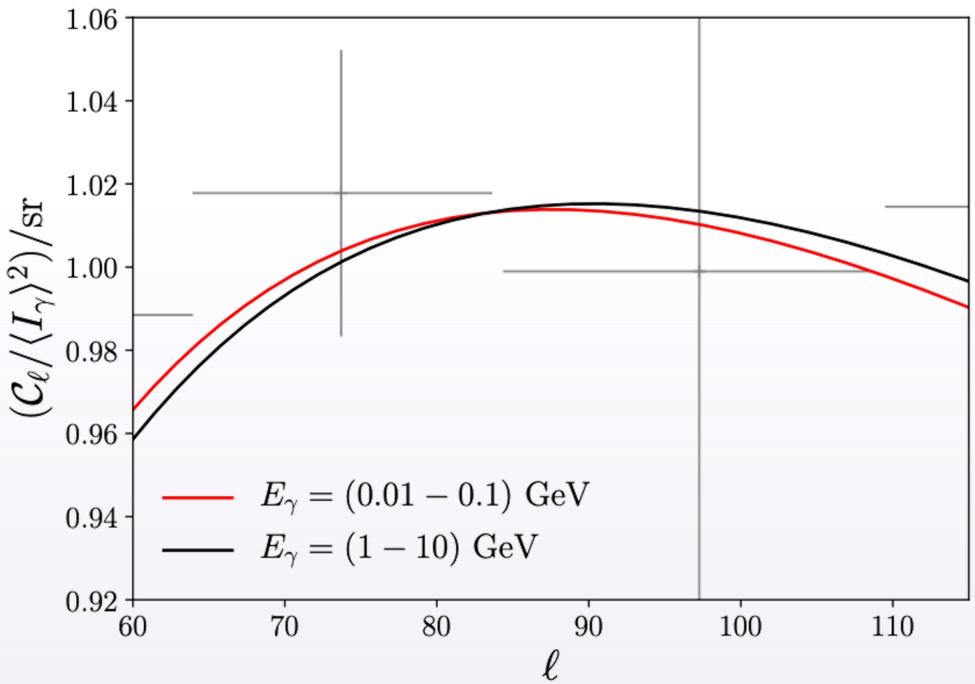
New/next-gen facilities will be able to push this to 100s of TeV, with more galaxies detected at 100s GeV and below

(1) Improved knowledge of **particle transport**

(2) Exact relationship between **cosmic ray engagement** in a galaxy, energy deposition and star-formation

Galaxy populations

Gamma-ray background anisotropies in the CTA era (KSP 8?)



(Owen+2022c)

Thoughts on what we can do better?

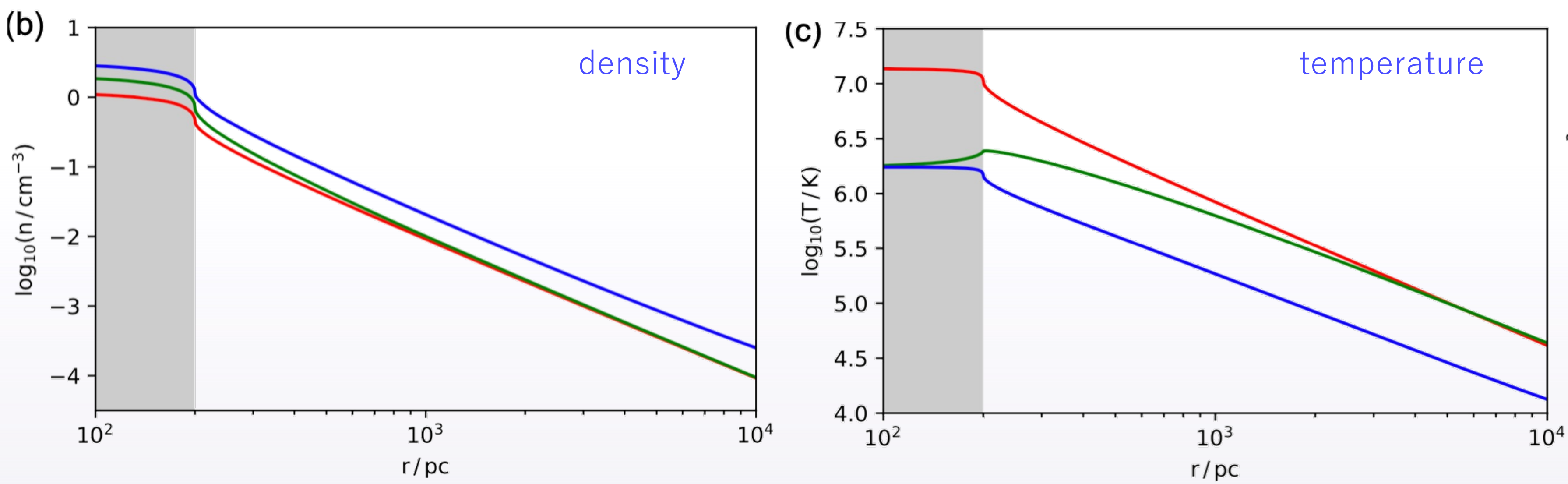
(1) Higher angular resolutions, so detailed anisotropy signatures more accessible, so better **redshift information**

(2) Access higher multipoles for **wider redshift range**

(3) More data at **higher energies**, so can test CR containment/feedback in galaxy populations (Ambrosone+2022)

Outflows

Gamma-ray + X-ray constraints on mass-loading to discern driving physics



(Yu, Owen+2020)

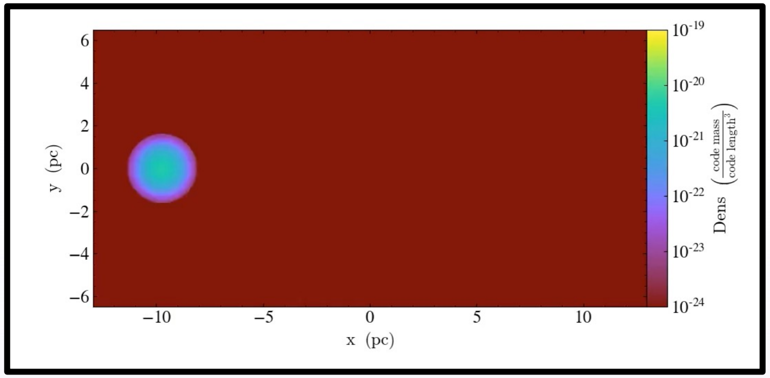
Outflows

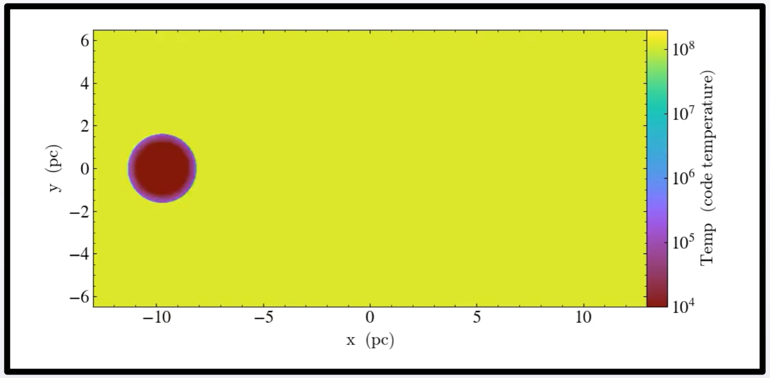
(Schneider+2021)

Clump survival changes flow dynamics

Dense phase dominates gamma-ray pion decay emission from an outflow

Preliminary

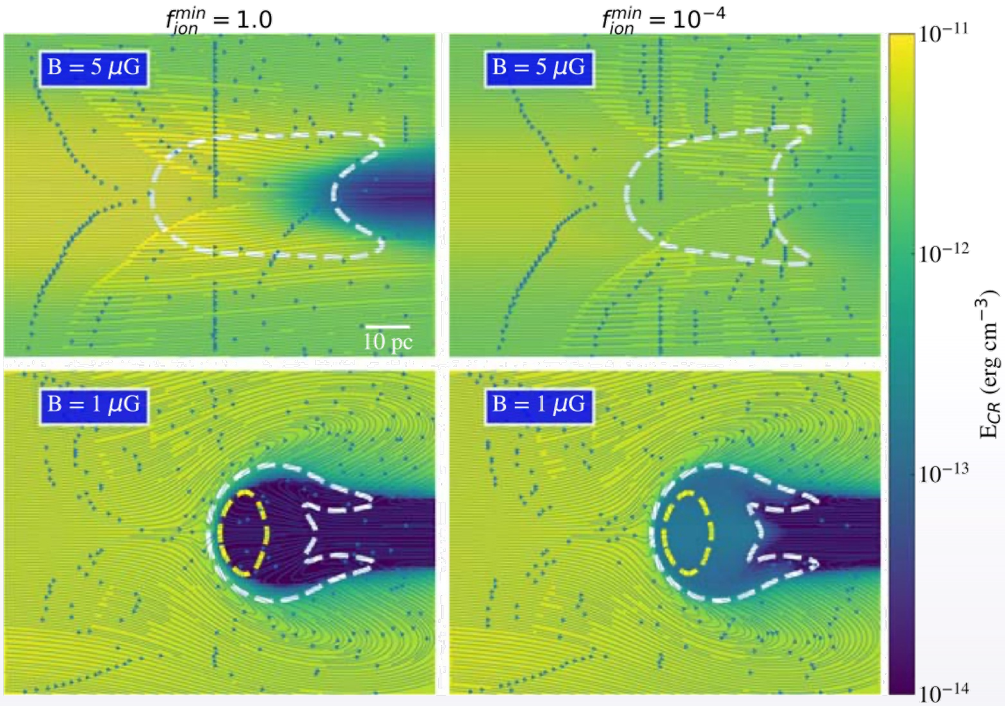


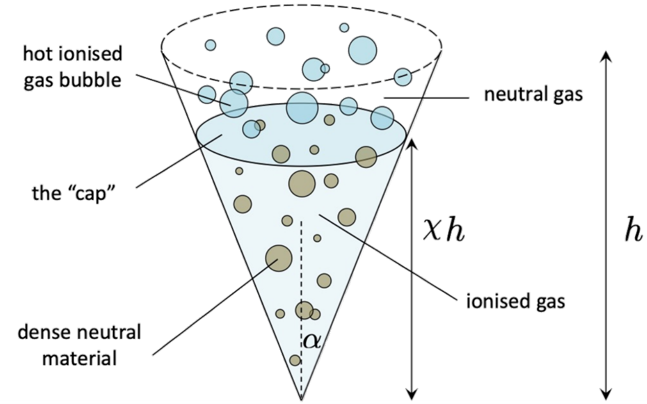


Owen+Yu in prep.

Outflows

Multi-phase, magnetized flows





(Wu, Li, Owen+2020)

ISM setting; in an outflow effects are likely more severe

(Bustard+2021)

(1) Gamma-ray emission is sensitive to the magnetic field strength/structure in flow
(2) Combined constraints from X-rays and gamma-rays can unveil their influence
(3) New altitude profiles in gamma-rays for nearby starburst outflows to tune models

Summary

- Still need to resolve the hidden players controlling galaxy evolution
- Cosmic rays are a viable agent with thermal and dynamical impacts for a galaxy and its CGM
- We can already test some aspects of their feedback impact
- Many next and exiting prospects exist in the next decade with CTA (+ X-ray instruments like XRISM, Athena+?)
- Now is the time to start refining and extending models in advance of the wealth of up-coming high-energy data