The signatures and physical effects of cosmic rays in and around star-forming galaxies

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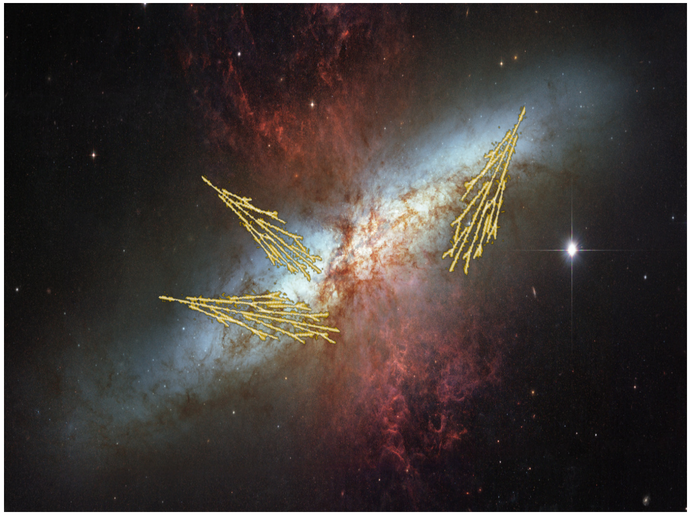


M82 – NASA/ESA and the Hubble Heritage Team (2006)

In collaboration with
Ignacio Ferreras (IAC), Albert Kong (NTHU), Shih-Ping Lai (NTHU)
Khee-Gan Lee (IPMU), Alvina Y L On (NTHU), Kuo-Chuan Pan (NTHU)
Kinwah Wu (UCL), B P Brian Yu (UCL), et al.

Academia Sinica Institute of Physics HEP Seminar – March 2022

Outline

1. Cosmic rays in galaxies

2. Shaping the initial conditions of star-formation

   For full details see **Owen, On, Lai & Wu** *ApJ 913, 52,* 2021
   (arXiv: 2103.06542)

3. Cosmic ray feedback and the circum-galactic connection

   For full details see **Yu, Owen, Pan, Wu & Ferreras** *MNRAS 508, 4, 2021*
   (arXiv: 2109.09764)

4. Probing cosmic ray activity in populations of galaxies

   For full details see **Owen, Lee & Kong** *MNRAS 506, 1,* 2021
   (arXiv: 2106.07308)

1. Cosmic rays in galaxies

Image credit: Shinobi Stickers

What are cosmic rays?
Where do they come from?

- Charged particles
  - Protons
  - Electrons
  - Nuclei

- Accelerated in shocks
  - Diffusive shock acceleration

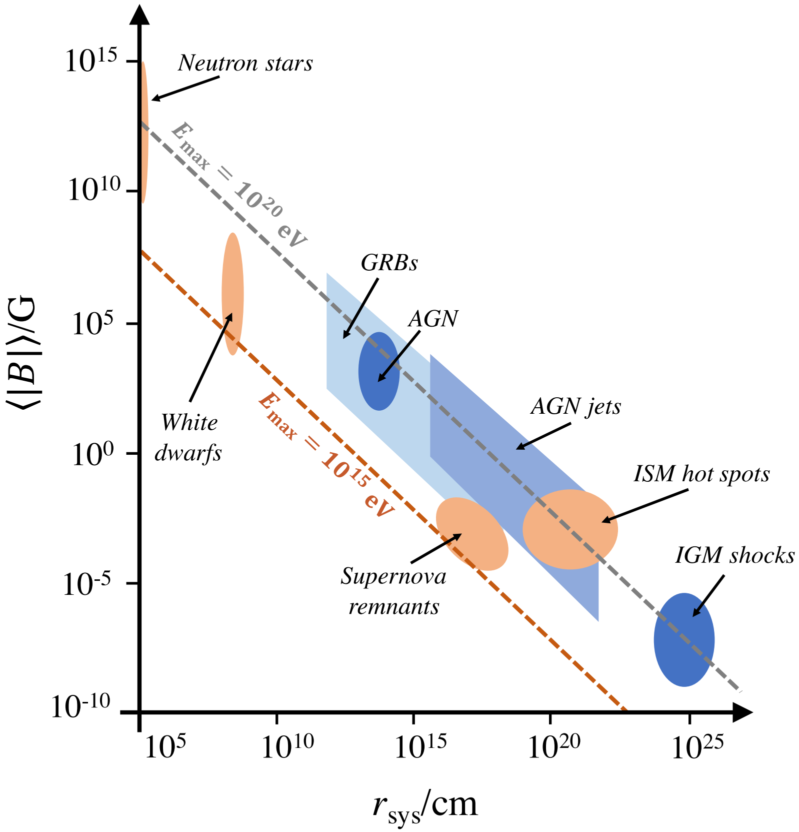
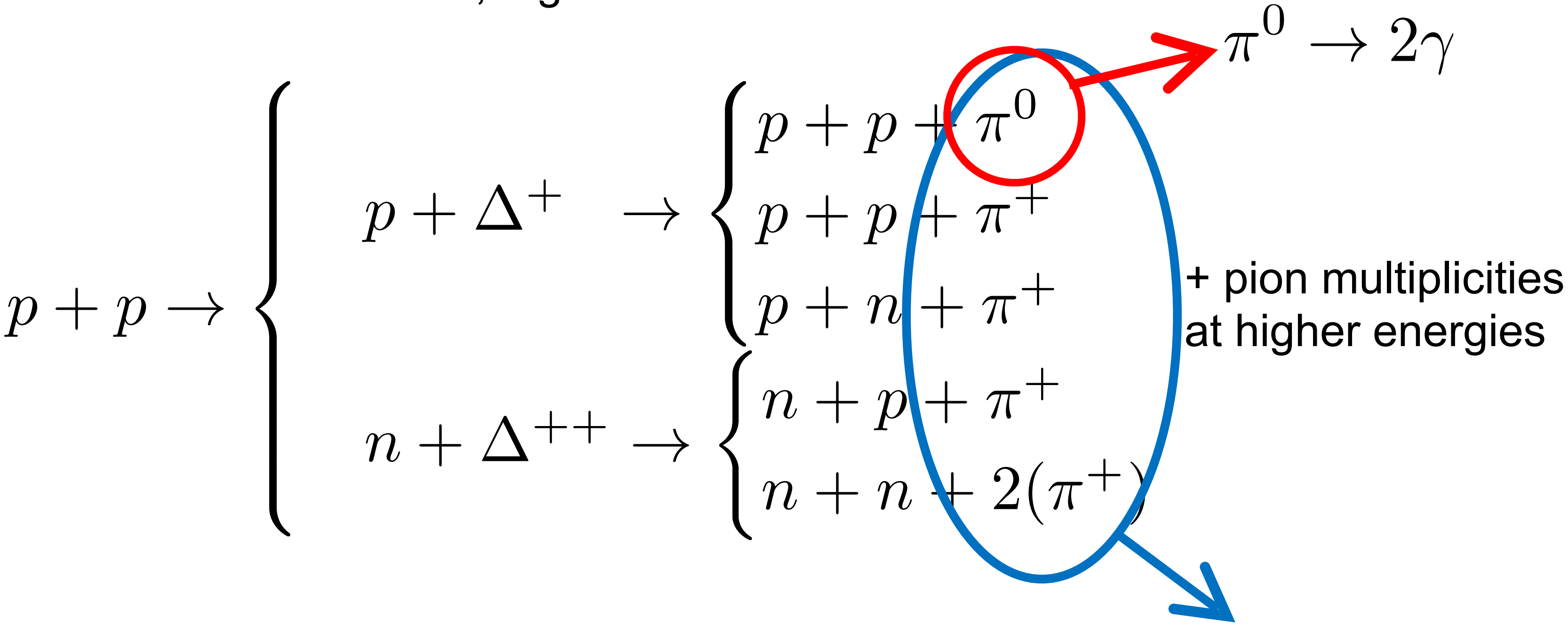


Fig. adapted from Owen 2019 (PhD thesis)
See also Kotera & Olinto 2011; Hillas 1984

Cosmic ray interactions

1. Ionization, “collisional” processes
2. Scattering/energy & momentum transfer via magnetic fields
3. Hadronic interactions, e.g.



$$p + p \rightarrow \begin{cases} p + \Delta^{+} \rightarrow \begin{cases} p + p + \pi^{0} \\ p + p + \pi^{+} \\ p + n + \pi^{+} \end{cases} \\ n + \Delta^{++} \rightarrow \begin{cases} n + p + \pi^{+} \\ n + n + 2(\pi^{+}) \end{cases} \end{cases}$$

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

+ pion multiplicities at higher energies

Pions decay to photons, muons, neutrinos, electrons, positrons, antineutrinos

$$\pi \rightarrow \gamma, \mu, e, \nu \ldots$$

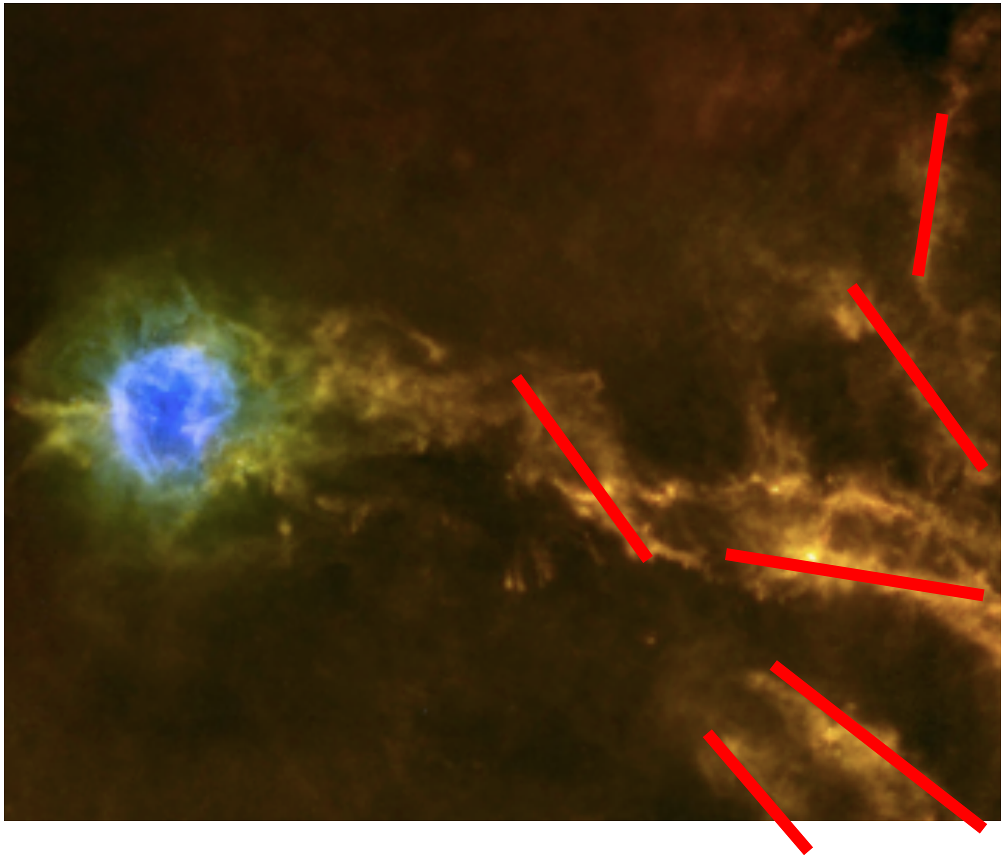
2. Shaping the initial conditions of star-formation

NGC 602; Credit: STScI

Molecular cloud complexes in the Milky Way

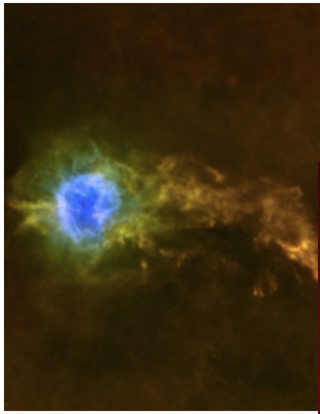
Cygnus

Magnetized filamentary structures



Herschel 250 micro-m (Arzoumanian+ 2011)

Tracing “real” magnetic fields - Cygnus



Herschel 250 micro-m
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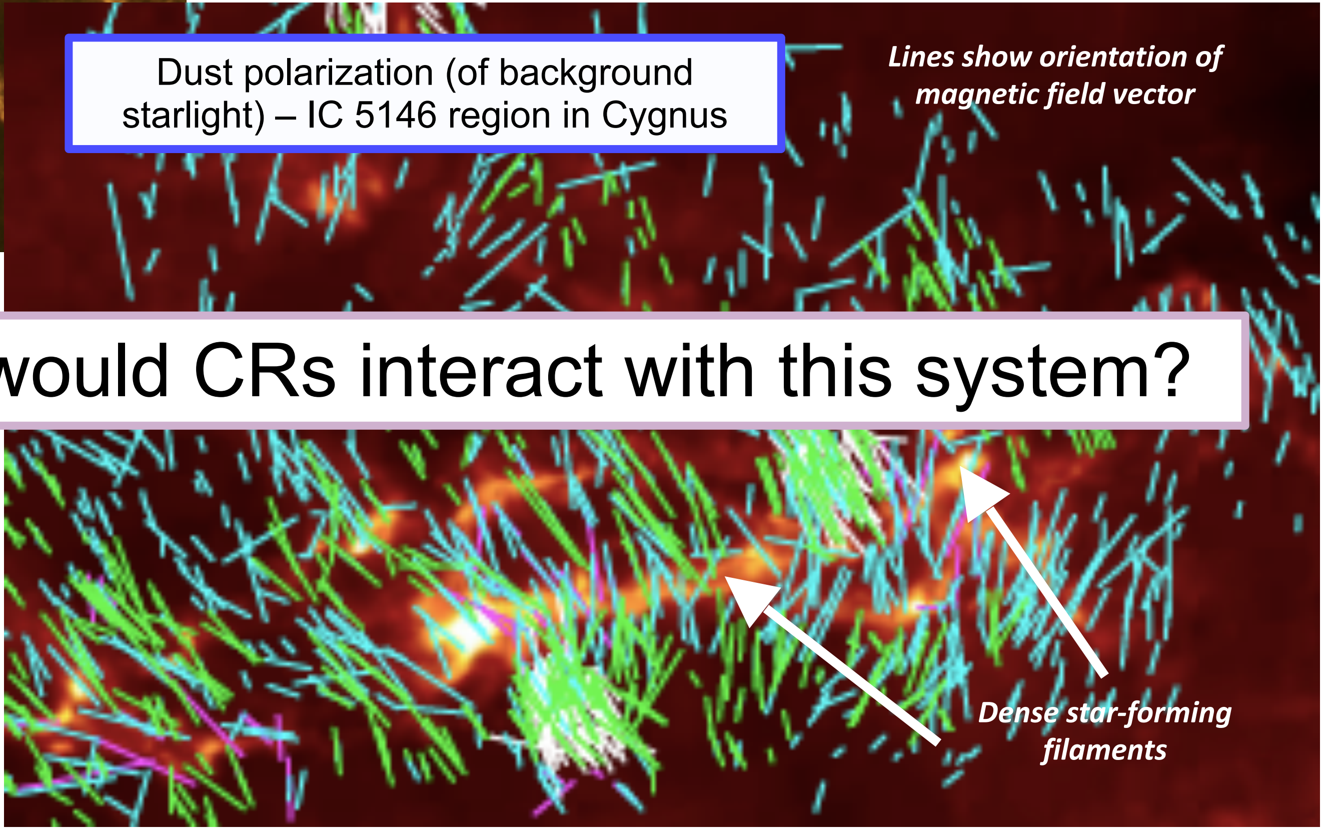


Dust polarization (of background starlight) – IC 5146 region in Cygnus

Lines show orientation of magnetic field vector

Dense star-forming filaments

How would CRs interact with this system?

Adapted from Wang+2019

The transport equation (in MC complexes)

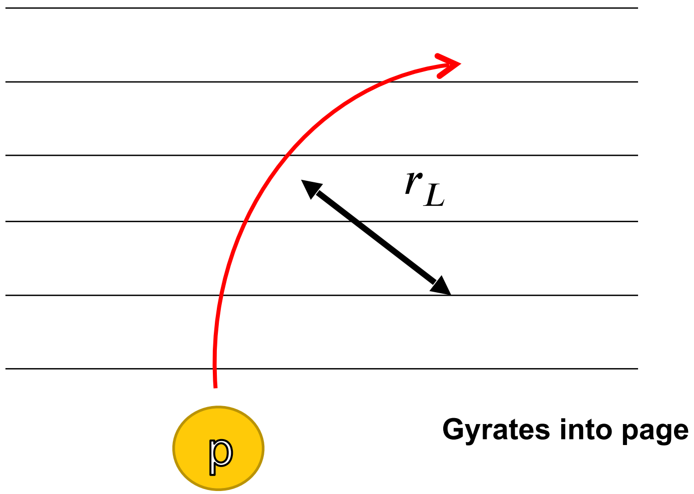
- Reduce the problem: quickly settles to a steady state

$$
\begin{aligned}
\frac{\partial n}{\partial t} = & \boxed{\nabla \cdot [D(E,\mathbf{x})\nabla n]} && \text{Diffusion} \\
& \cancel{+ \frac{\partial}{\partial E}[b(E,r)\,n]} && \text{Cooling (momentum diffusion)} \\
& \cancel{- \nabla \cdot [\mathbf{v}n]} && \text{Advection} \\
& \boxed{+ Q(E,\mathbf{x})} \cancel{- S(E,\mathbf{x})} && \text{Source/sink}
\end{aligned}
$$

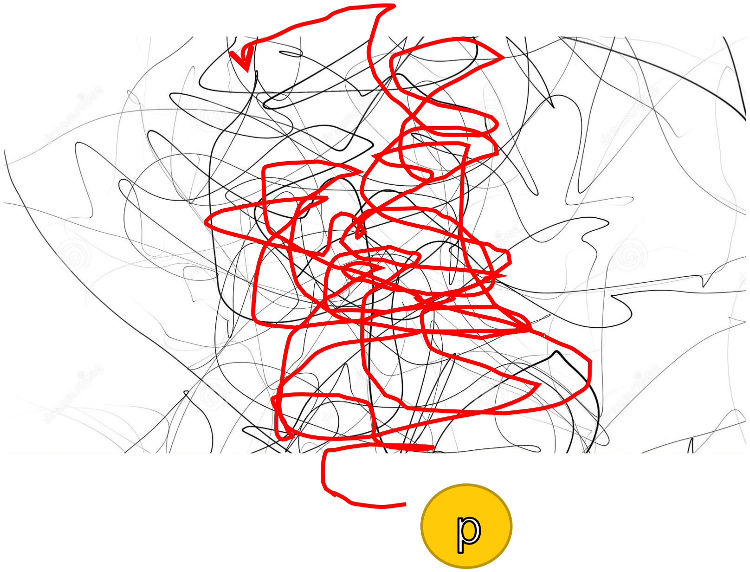
boundary condition

Cosmic ray propagation

Uniform B field

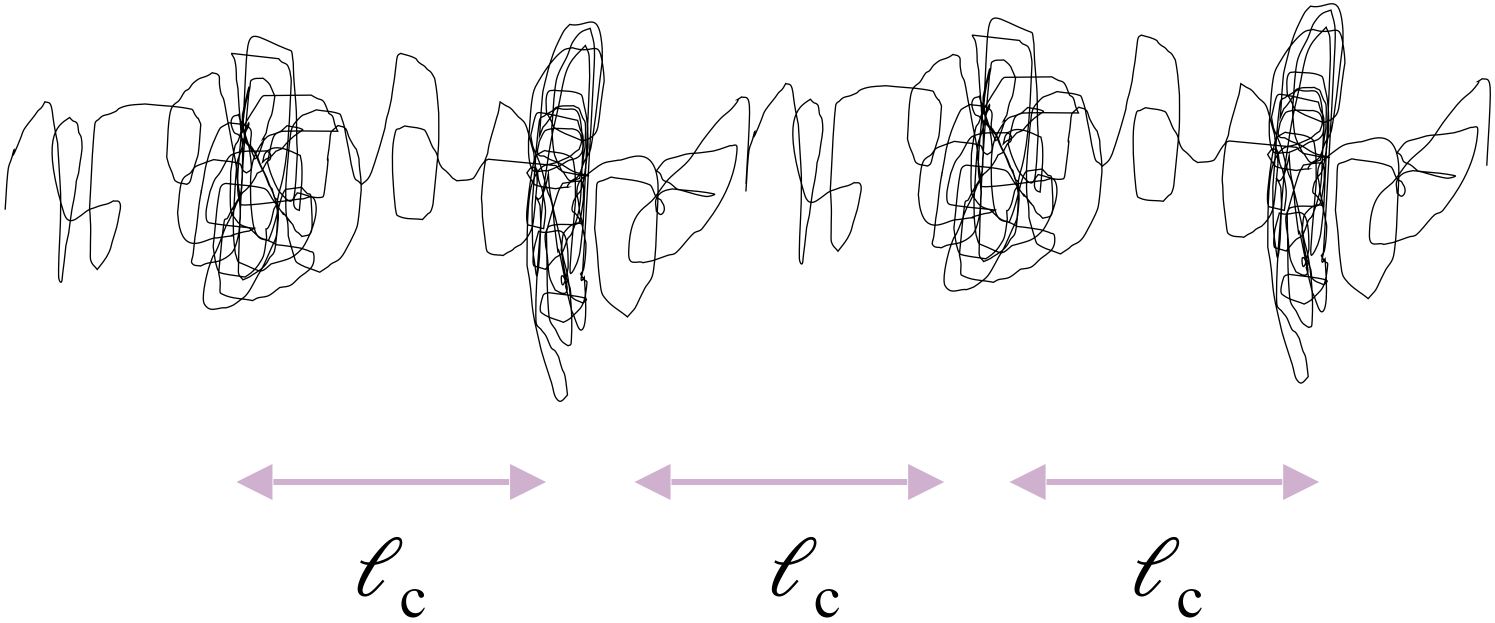


Tangled B field



r_L depends on energy

Magnetic field structure



- Stronger scattering when $r_L \sim \ell_c$
- Slower propagation (“diffusion”)

Characterization of field structure

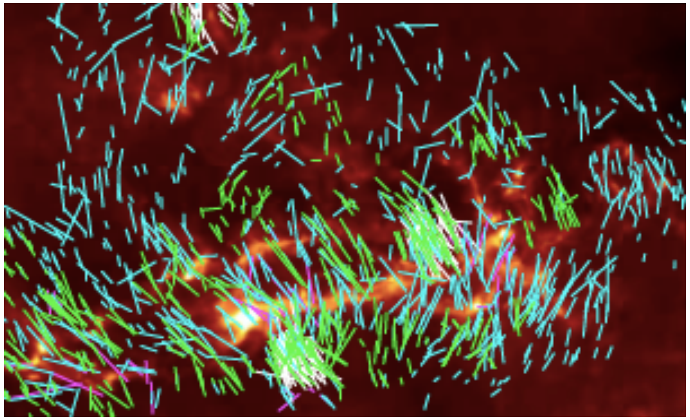
- PA differences as function of separation would trace B field fluctuations

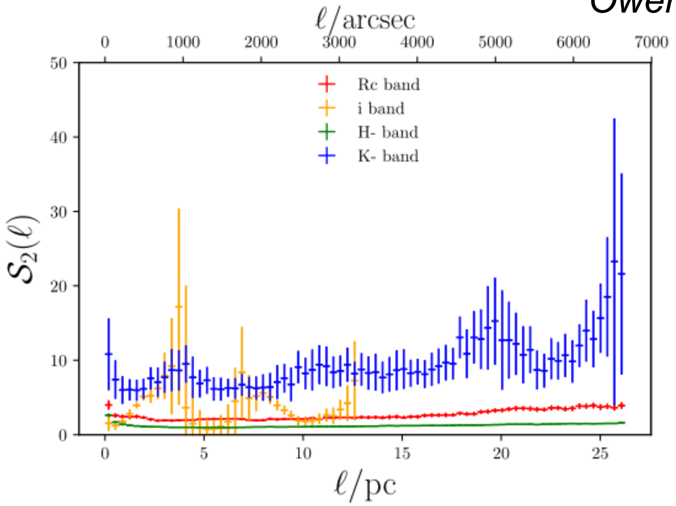
  Structure function (angular dispersion function)

$$S_d(\ell) = \frac{1}{N_{\text{pair}}} \sum_{i=1}^{N_{\text{pair}}} [\varphi_i(s+\ell) - \varphi_i(s)]^d$$

- Power on different scales can then be related to CR diffusion parameter

Owen+ 2021a





$$P(k) = \frac{1}{2} \mathcal{F}[S_2(\ell)]$$

Inversely proportional to CR diffusion coefficient

Characterization of field structure

- PA differences as function of separation would trace B field fluctuations

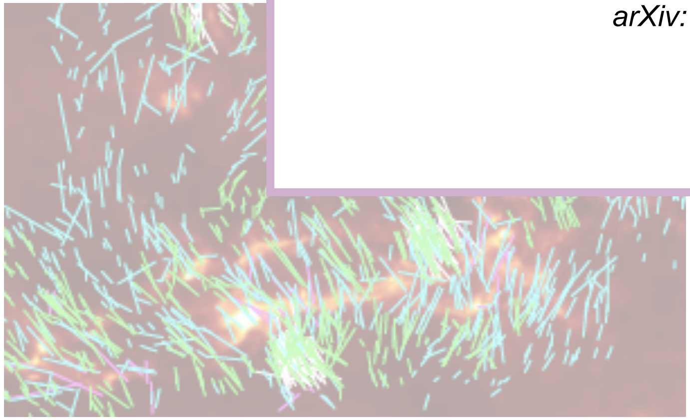
  Structure function (angular dispersion function)

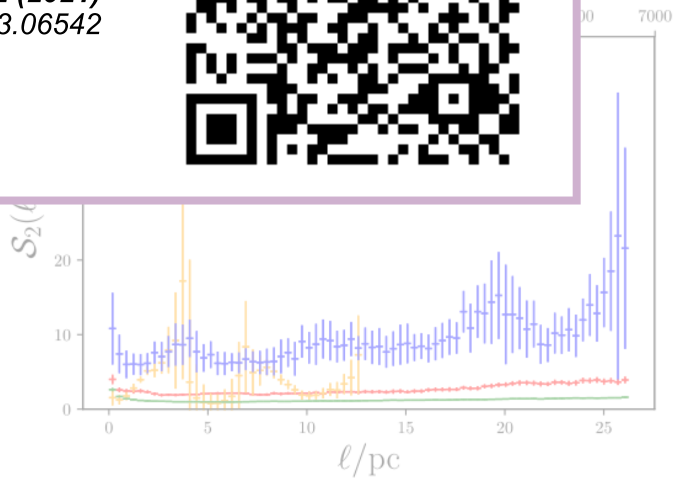
- Power on diff

For details see full paper:
Owen, On, Lai & Wu ApJ 913, 52 (2021)
arXiv: 2103.06542

arameter

Owen+ 2021a



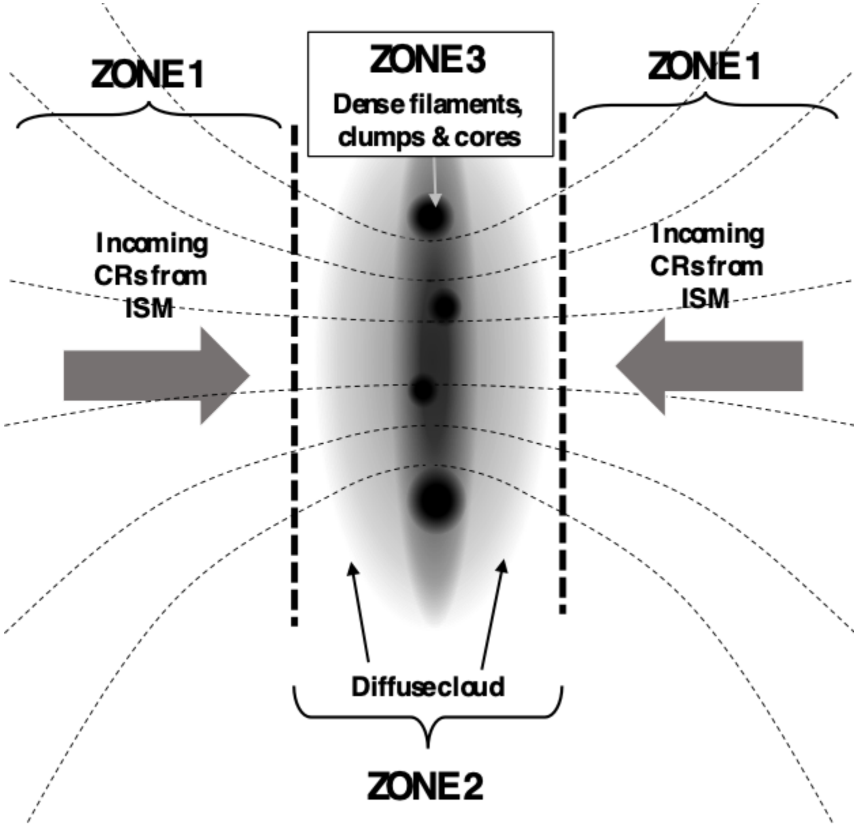


Inversely proportional to CR diffusion coefficient

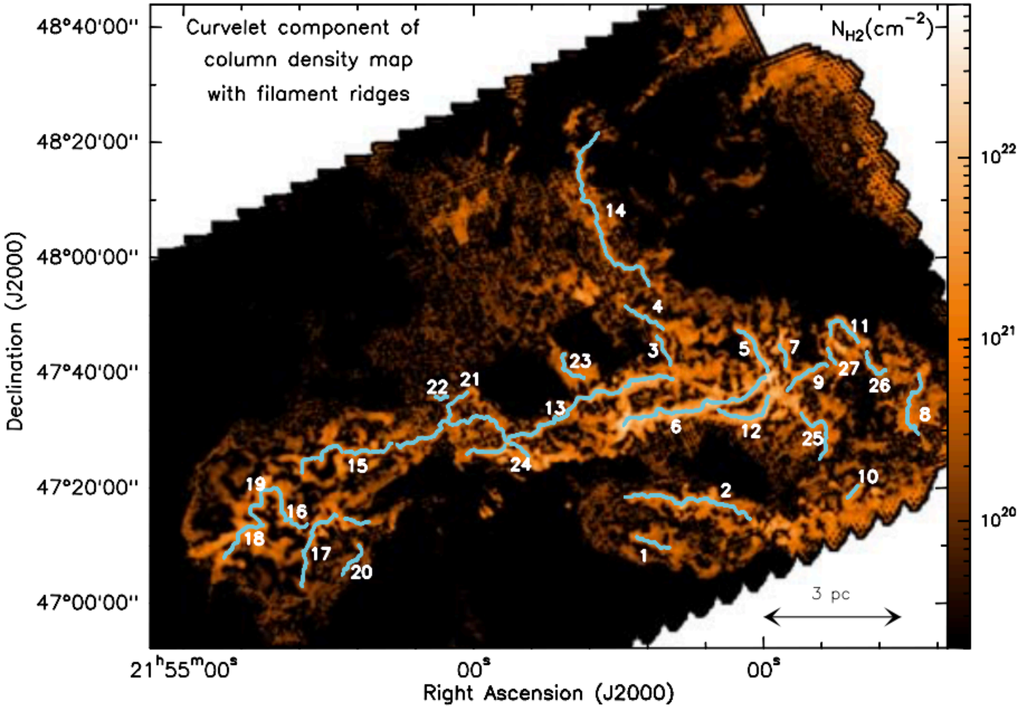
$$P(k) = \frac{1}{2}\mathcal{F}[S_2(\ell)]$$

Cosmic ray propagation & distribution

- Apply diffusion equation to a filament



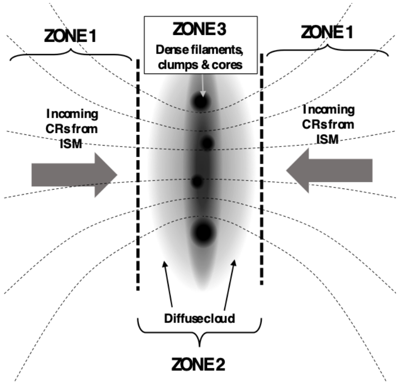
Cosmic ray propagation & distribution



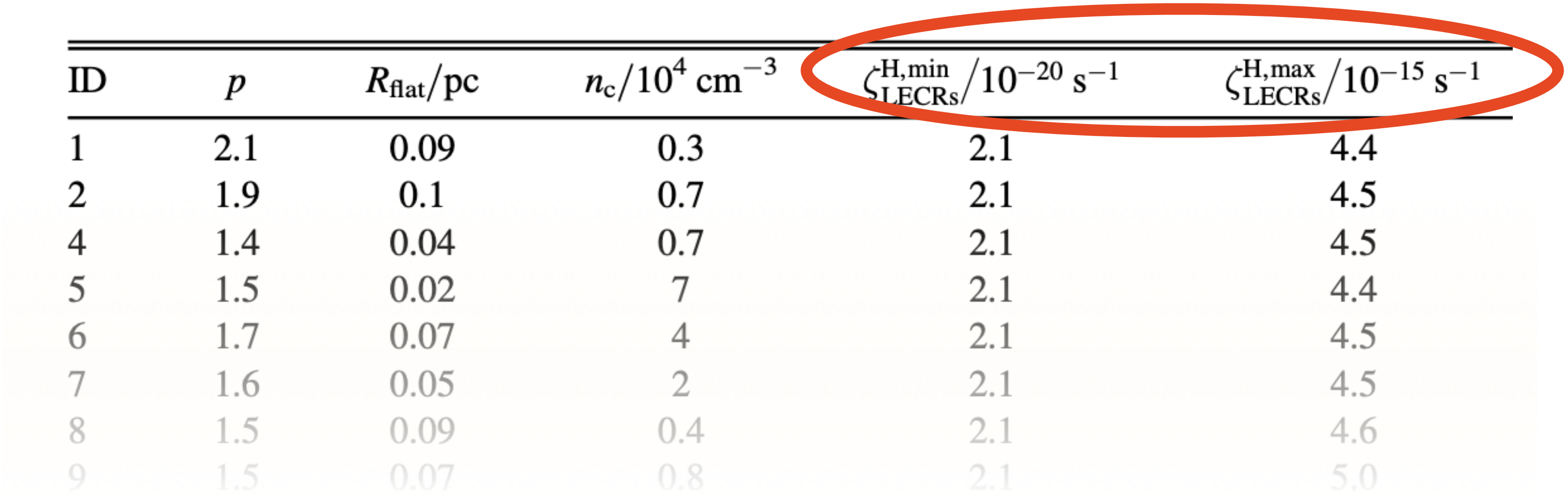
Arzoumanian+ 2011

Cosmic ray propagation & distribution

- Ionization signatures



- These can produce chemical tracers as CR signatures

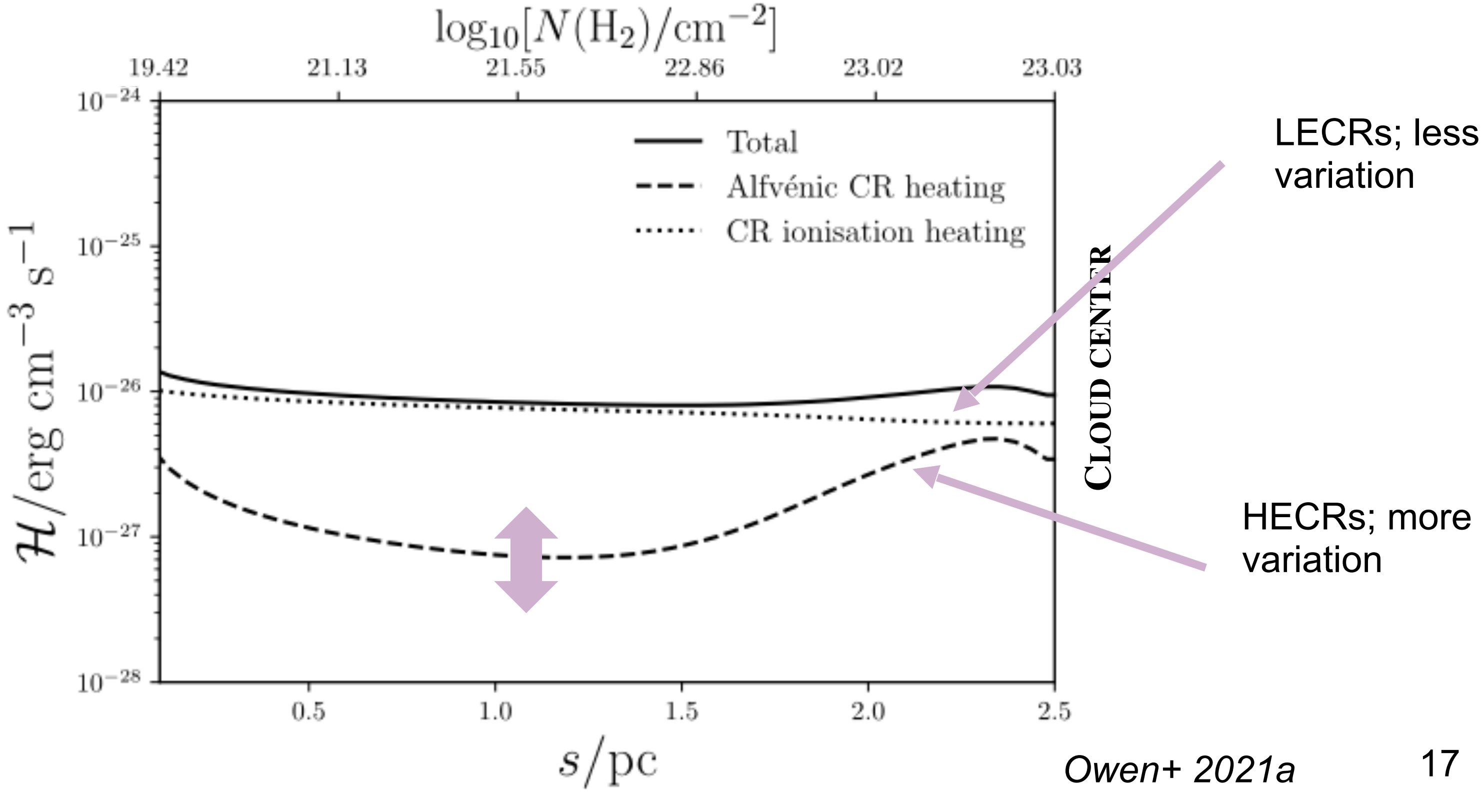


ID	p	$R_{\rm flat}$/pc	$n_{\rm c}/10^4\ {\rm cm}^{-3}$	$\zeta^{\rm H,min}_{\rm LECRs}/10^{-20}\ {\rm s}^{-1}$	$\zeta^{\rm H,max}_{\rm LECRs}/10^{-15}\ {\rm s}^{-1}$
1	2.1	0.09	0.3	2.1	4.4
2	1.9	0.1	0.7	2.1	4.5
4	1.4	0.04	0.7	2.1	4.5
5	1.5	0.02	7	2.1	4.4
6	1.7	0.07	4	2.1	4.5
7	1.6	0.05	2	2.1	4.5
8	1.5	0.09	0.4	2.1	4.6
9	1.5	0.07	0.8	2.1	5.0

Physical impacts of cosmic rays

Idealized “average” filament

- **Ionization** & associated heating relatively invarient; driven by **LECRs**
- Alfvenic **heating** highly variable between filaments; dominated by **HECRs**

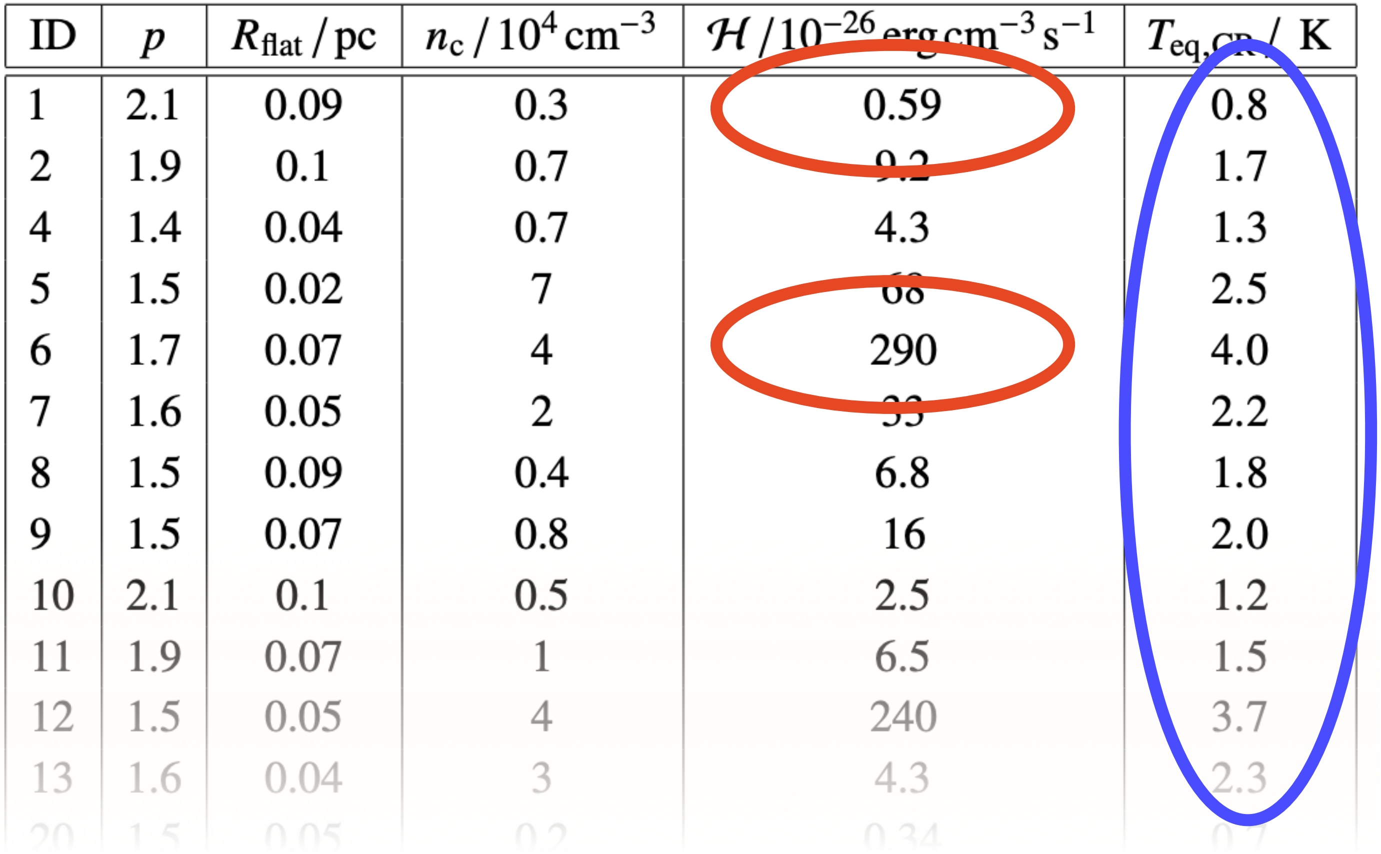


Owen+ 2021a

Physical impacts of cosmic rays

- Heat/ionize molecular clouds; impacts on star-formation

See also works by Padelis Papadopoulos



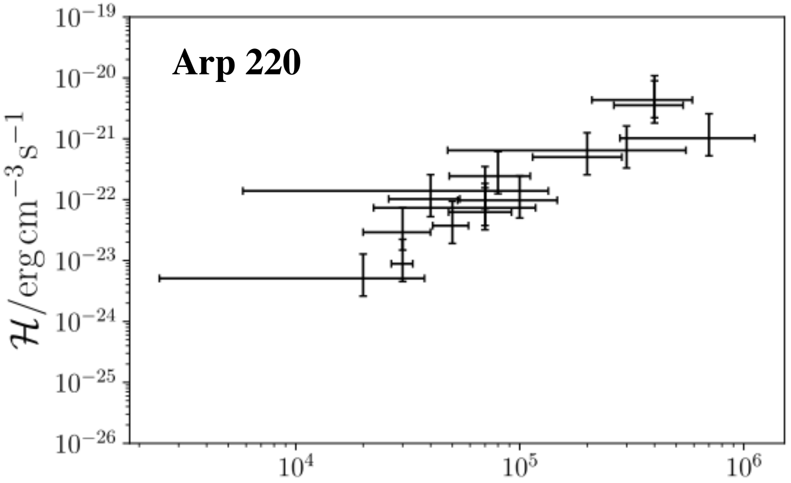
ID	p	$R_{\rm flat}$ / pc	$n_{\rm c}$ / 10^4 cm^{-3}	$\mathcal{H}$ / 10^{-26} erg cm^{-3} s^{-1}	$T_{\rm eq,CR}$ / K
1	2.1	0.09	0.3	0.59	0.8
2	1.9	0.1	0.7	9.2	1.7
4	1.4	0.04	0.7	4.3	1.3
5	1.5	0.02	7	68	2.5
6	1.7	0.07	4	290	4.0
7	1.6	0.05	2	33	2.2
8	1.5	0.09	0.4	6.8	1.8
9	1.5	0.07	0.8	16	2.0
10	2.1	0.1	0.5	2.5	1.2
11	1.9	0.07	1	6.5	1.5
12	1.5	0.05	4	240	3.7
13	1.6	0.04	3	4.3	2.3
20	1.5	0.05	0.2	0.34	0.7

Heating & feedback

For details see
***Owen, On, Lai & Wu PoS ICRC 053 (2021)** arXiv: 2107.11734*

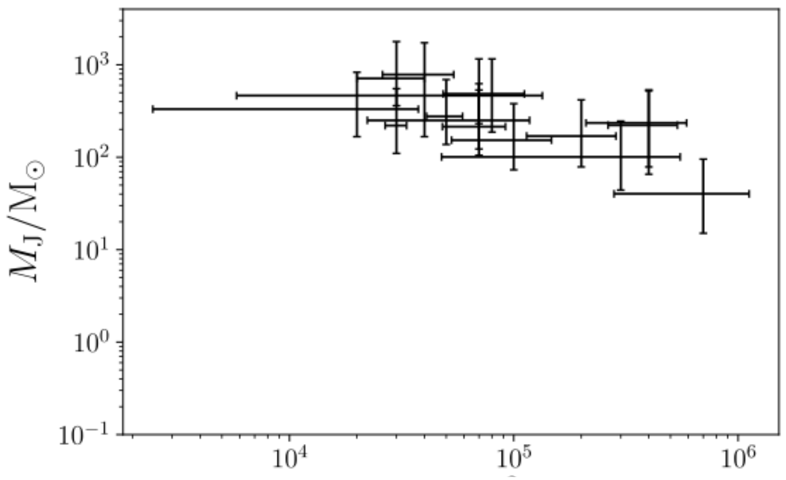
- Higher CR energy density in star-forming galaxies
- Stronger; affects stability; Temperature → Jeans' mass
- **What does this mean for star-formation?**

Heating



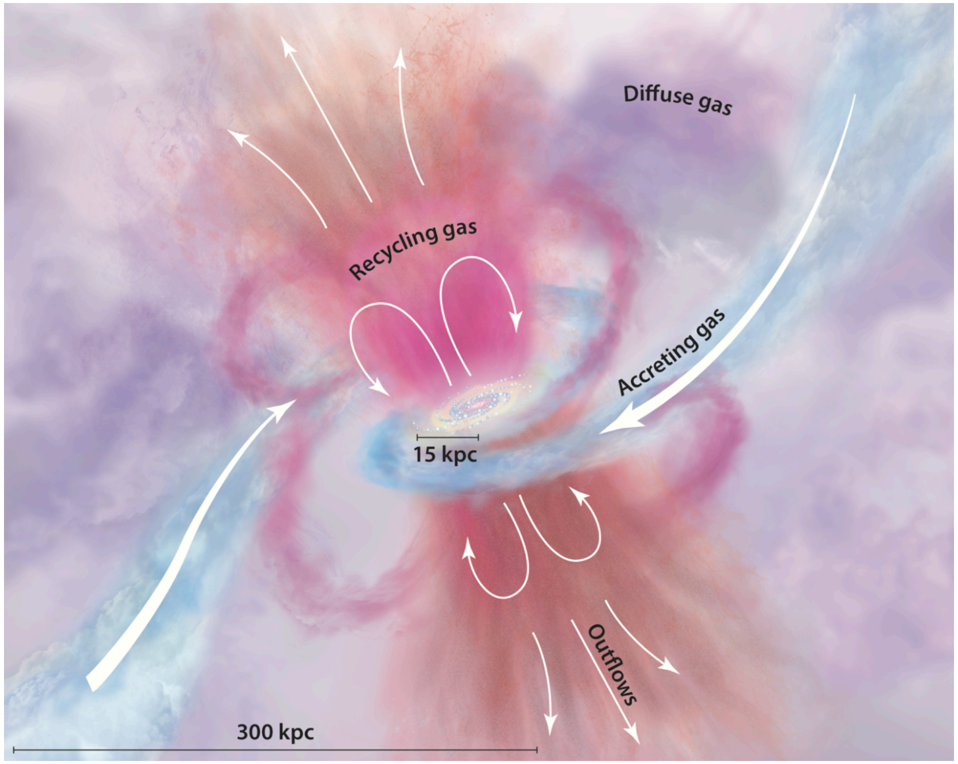
Filament density/cm^{-3}

Jeans' Mass



Filament density/cm^{-3}

3. Cosmic ray feedback and the circum-galactic connection



Tumlinson et al. 2017

Feedback actions of cosmic rays

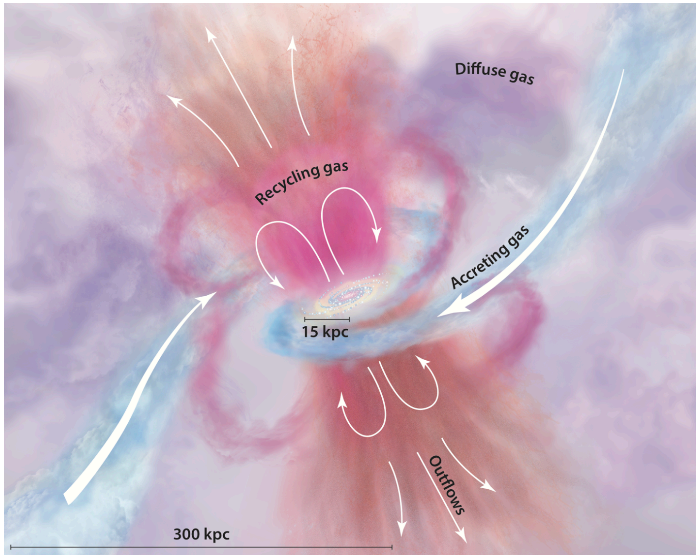
- 2 ways cosmic ray feedback could broadly operate in galaxies

Thermal

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

Dynamical

1. **Moves** something with CR pressure
2. Movement / flow disrupts system in some way

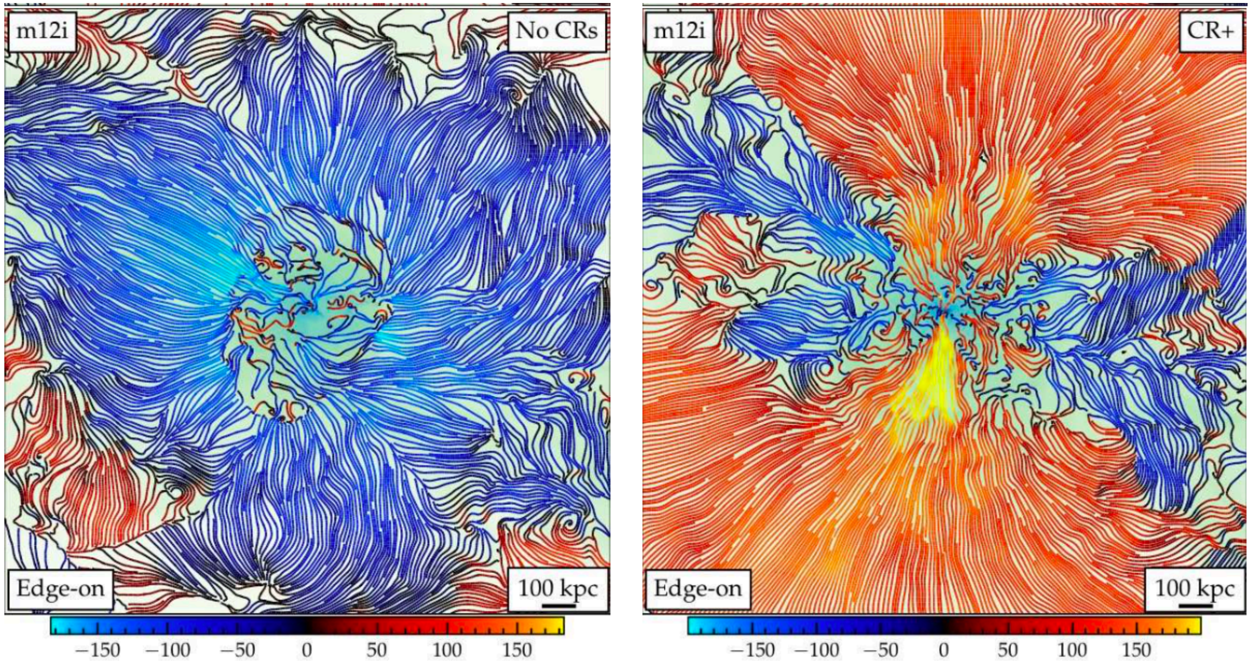


Tumlinson 2017

Feedback actions of cosmic rays

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

MHD



+CRs
(**pressure**
& heating)

Colour bar: flow velocity (thermal gas)

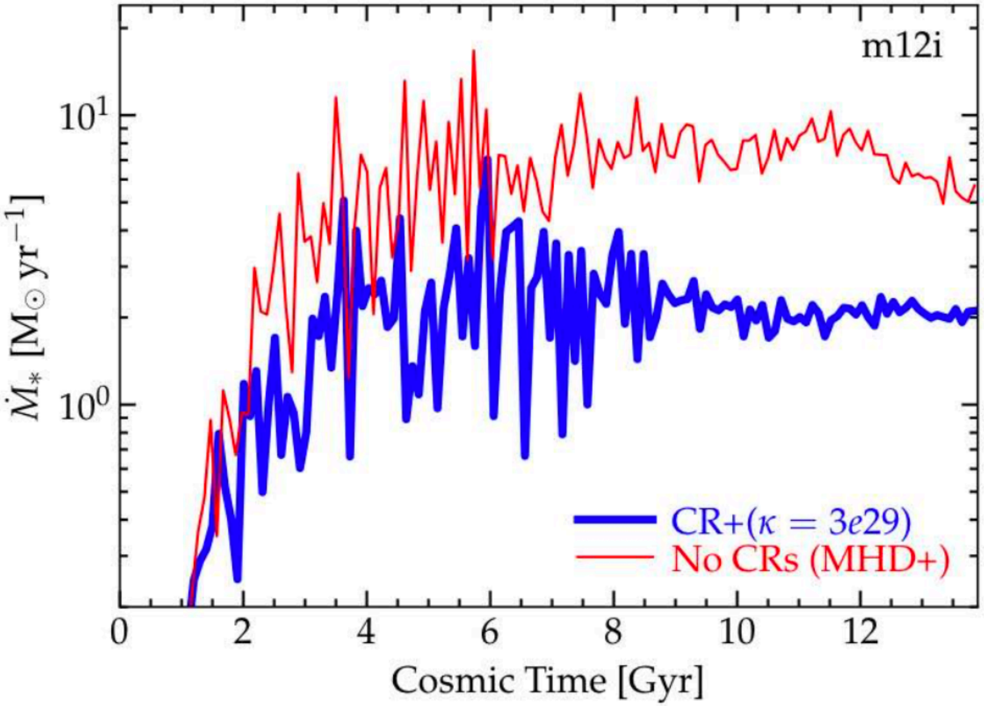
Inflowing

Outflowing

Hopkins+ 2021; FIRE-2 simulations

Feedback actions of cosmic rays

SFR suppressed; less "bursty"



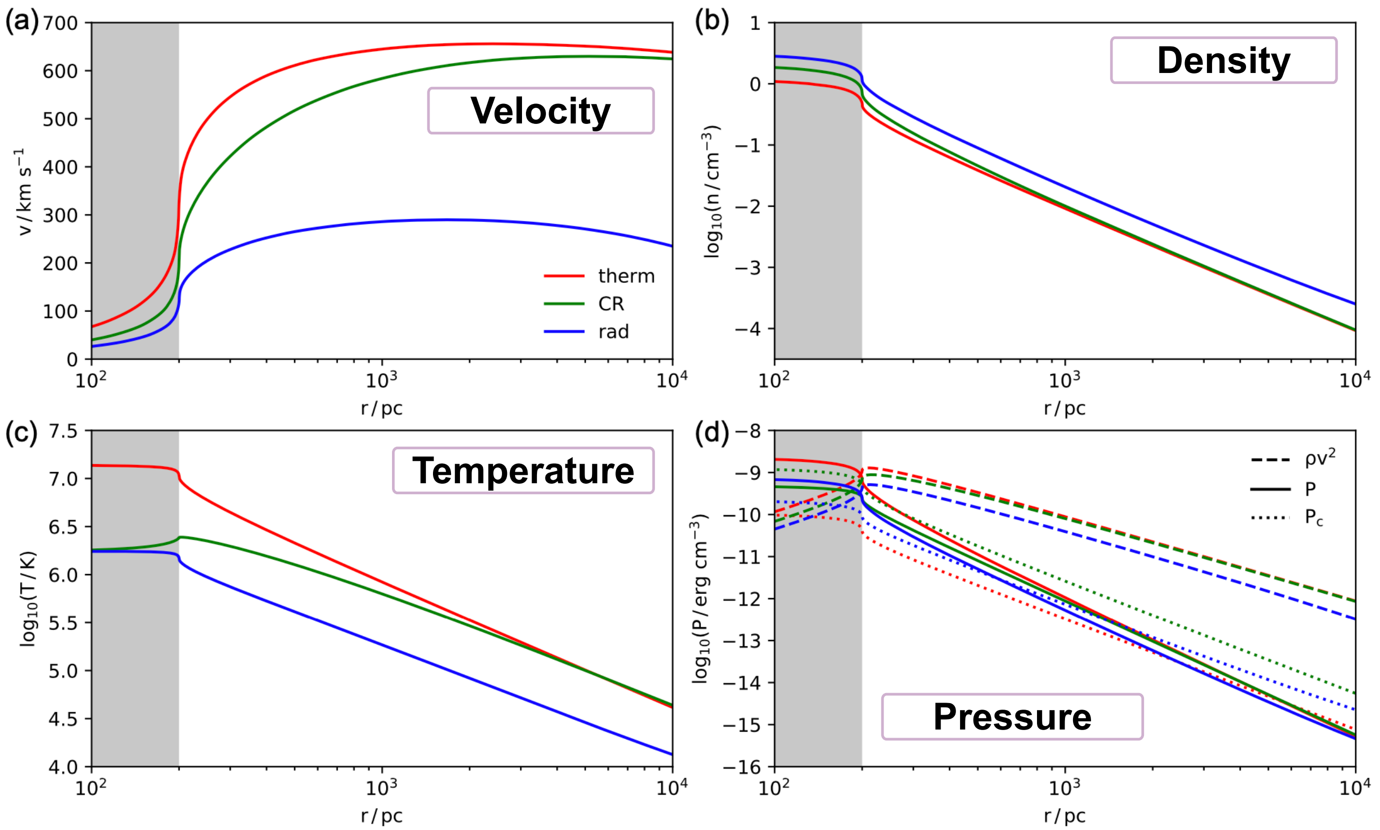
Hopkins+ 2021; FIRE-2 simulations

Impacts of cosmic rays

- Modify galactic outflows

See also Jacob et al. 2018

For details see
Yu, Owen, Wu & Ferraras MNRAS 494, 3179 (2020) *arXiv: 2001.04384*

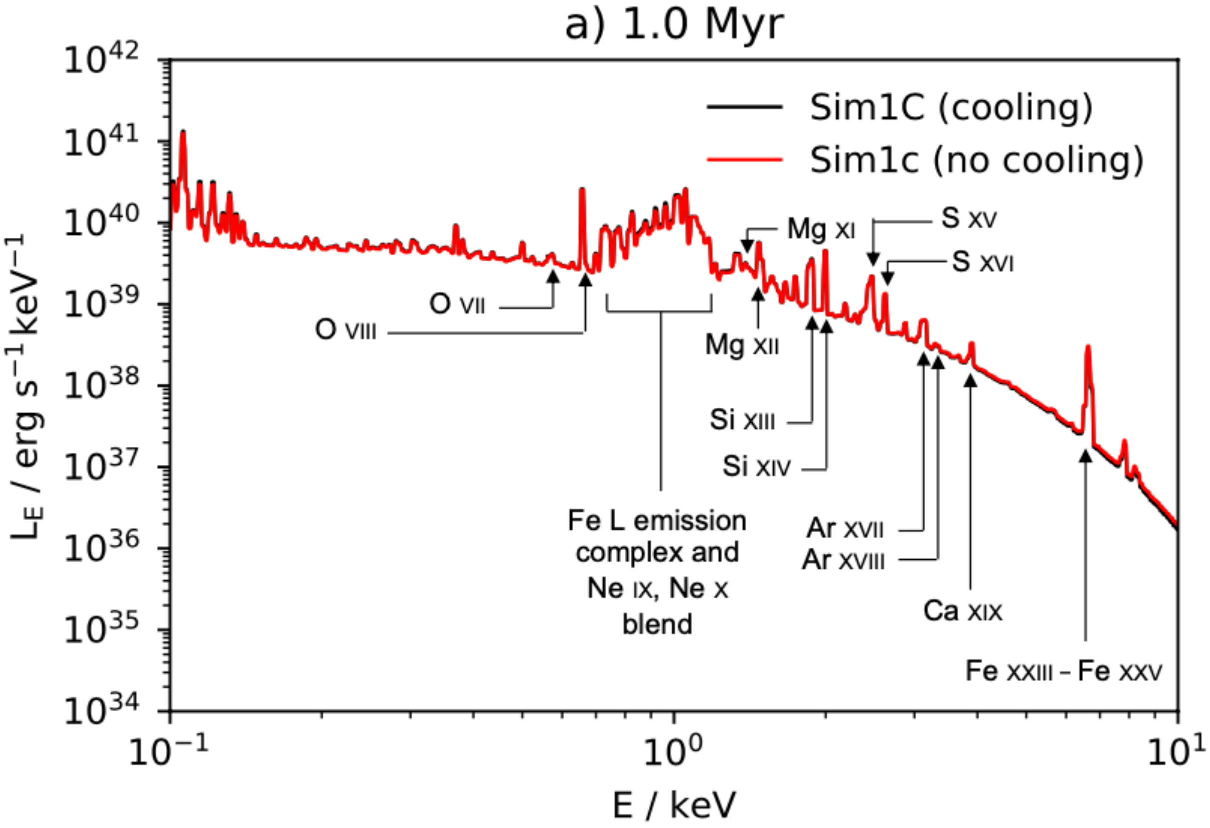


Yu, Owen + 2020

Impacts of cosmic rays

- X-ray emission from a hot outflow

Also:
Yu, Owen, Pan, Wu & Ferraras MNRAS accepted (2021) *arXiv: 2109.09764*

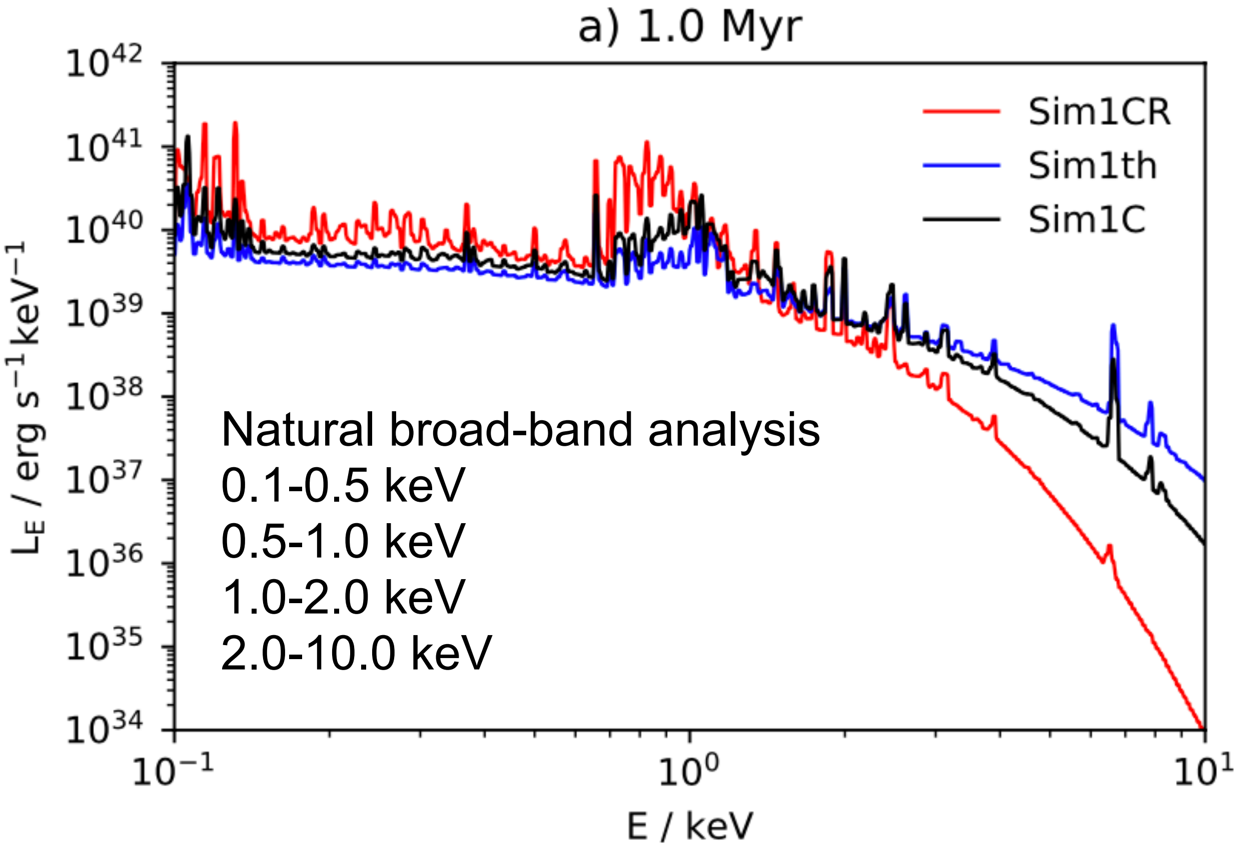


Yu, Owen + 2021

Impacts of cosmic rays

- Modify galactic outflows – detectable in X-rays

Also:
Yu, Owen, Pan, Wu & Ferraras MNRAS accepted (2021) *arXiv: 2109.09764*



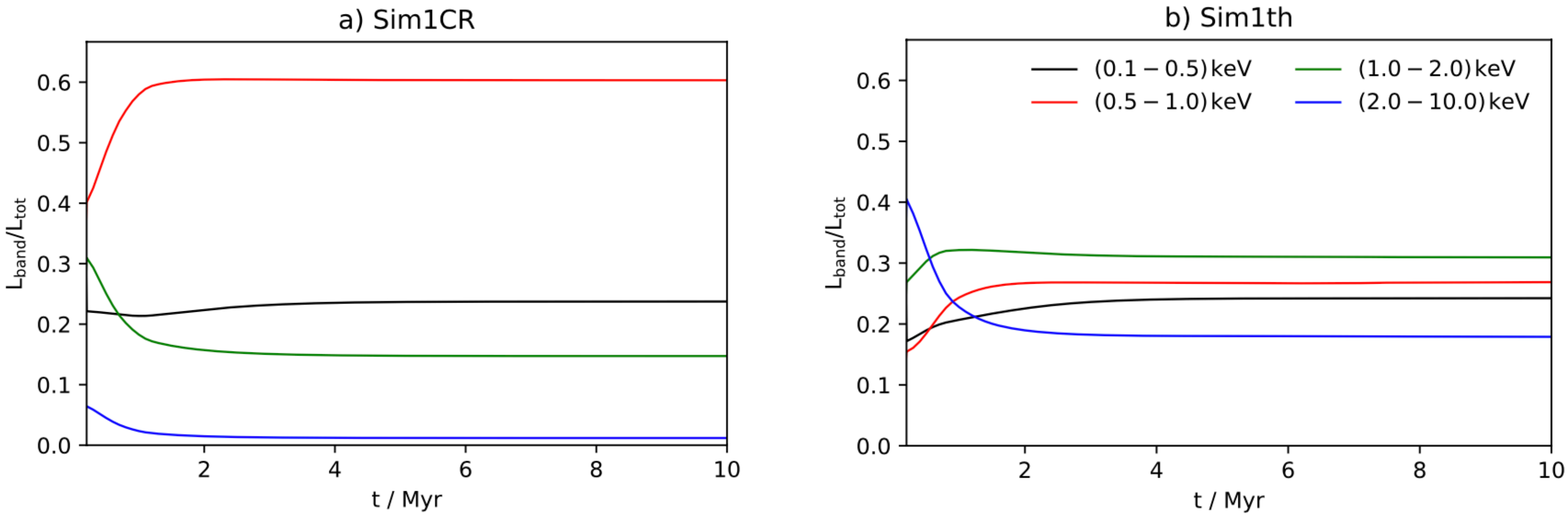
Natural broad-band analysis
0.1-0.5 keV
0.5-1.0 keV
1.0-2.0 keV
2.0-10.0 keV

Yu, Owen + 2021

Impacts of cosmic rays

Also:
***Yu, Owen, Pan, Wu & Ferraras MNRAS accepted (2021)** arXiv: 2109.09764*

- Broadband ratios to track CR presence in outflows

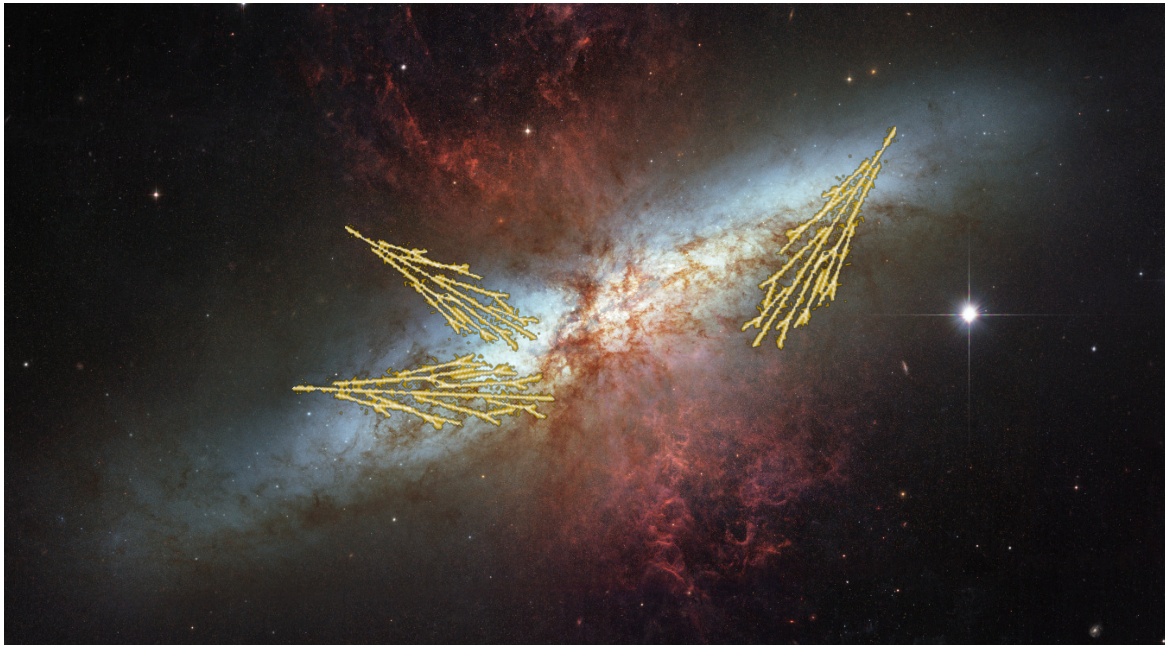


Yu, Owen + 2021

- Need fewer photons
- Reach more, and more distant systems

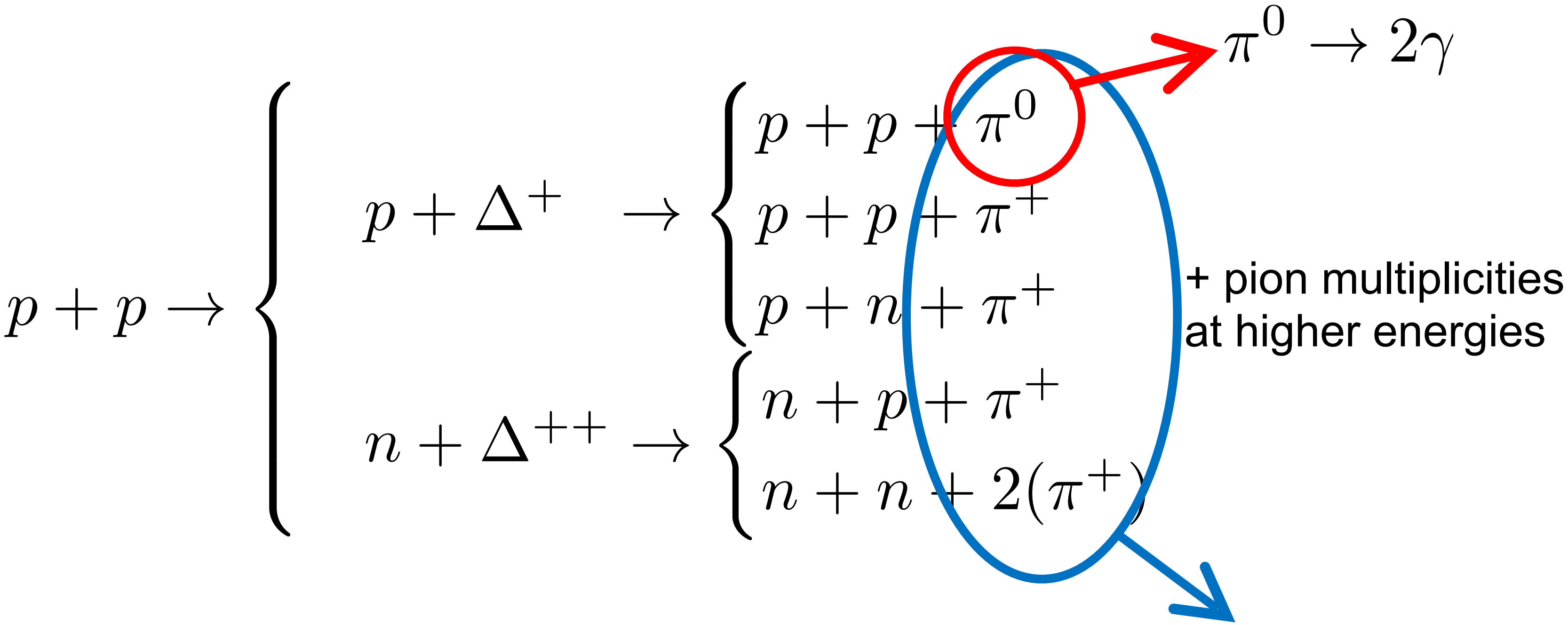
Trace importance of CRs over cosmic time

4. Cosmic ray activity in populations of galaxies



M82 – NASA/ESA and the Hubble Heritage Team (2006)

Re-cap: gamma-ray production



$$\pi^0 \to 2\gamma$$

$$p+p \to \begin{cases} p+\Delta^+ \to \begin{cases} p+p+\pi^0 \\ p+p+\pi^+ \\ p+n+\pi^+ \end{cases} \\ n+\Delta^{++} \to \begin{cases} n+p+\pi^+ \\ n+n+2(\pi^+) \end{cases} \end{cases}$$

+ pion multiplicities at higher energies

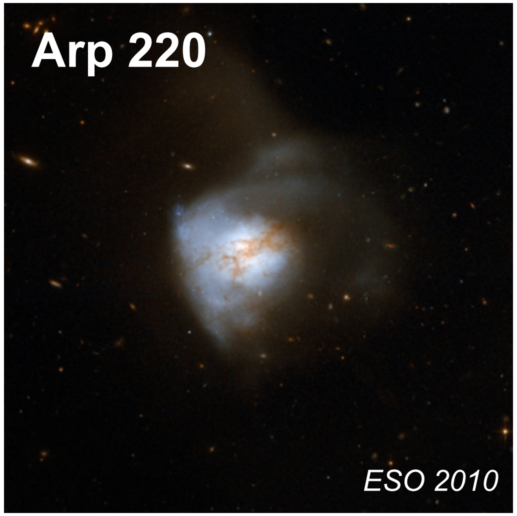
Pions decay to photons, muons, neutrinos, electrons, positrons, antineutrinos

$$\pi \to \gamma, \mu, e, \nu \ldots$$

Other galaxies – star-formation dependency

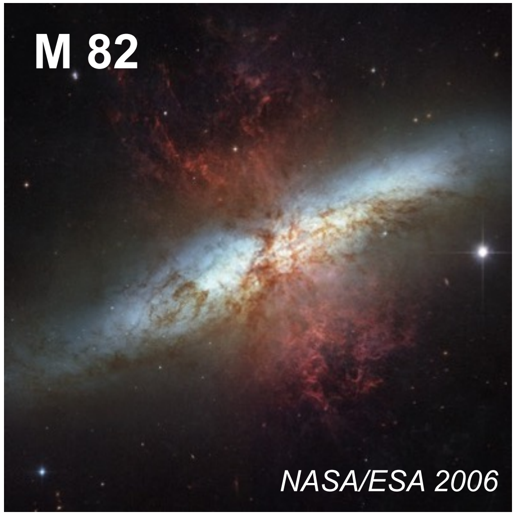
NGC 253

NASA/ESA 2008



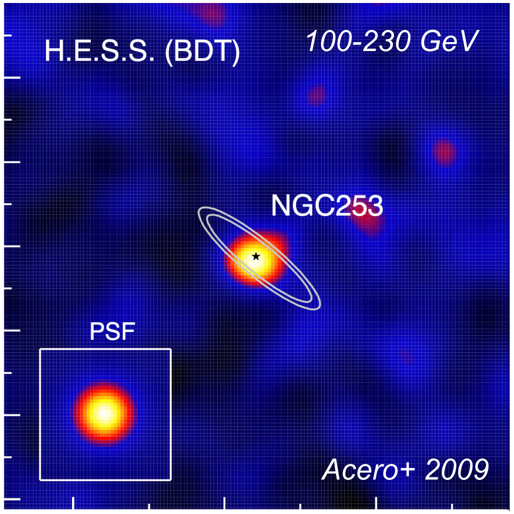
Arp 220

ESO 2010



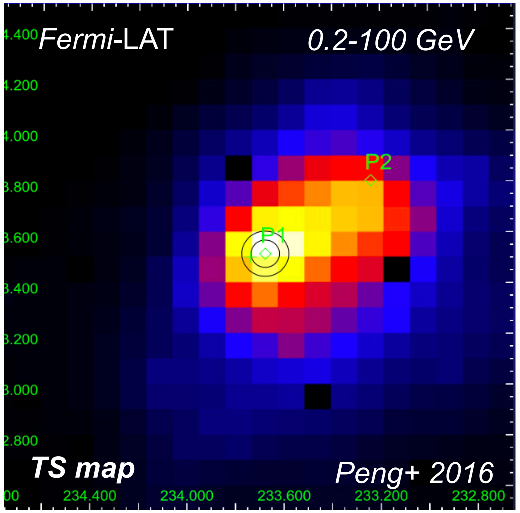
M 82

NASA/ESA 2006



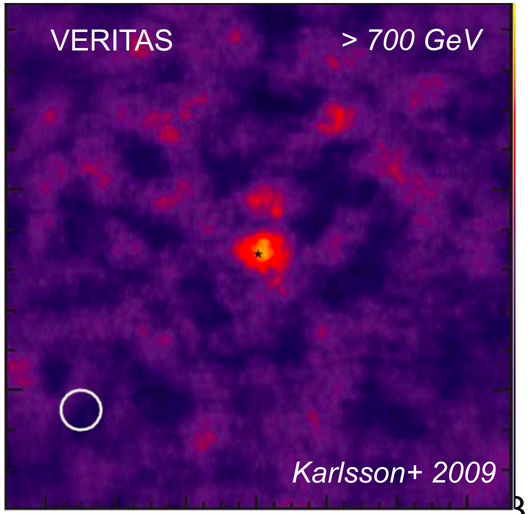
H.E.S.S. (BDT) *100-230 GeV*

Acero+ 2009



Fermi-LAT *0.2-100 GeV*

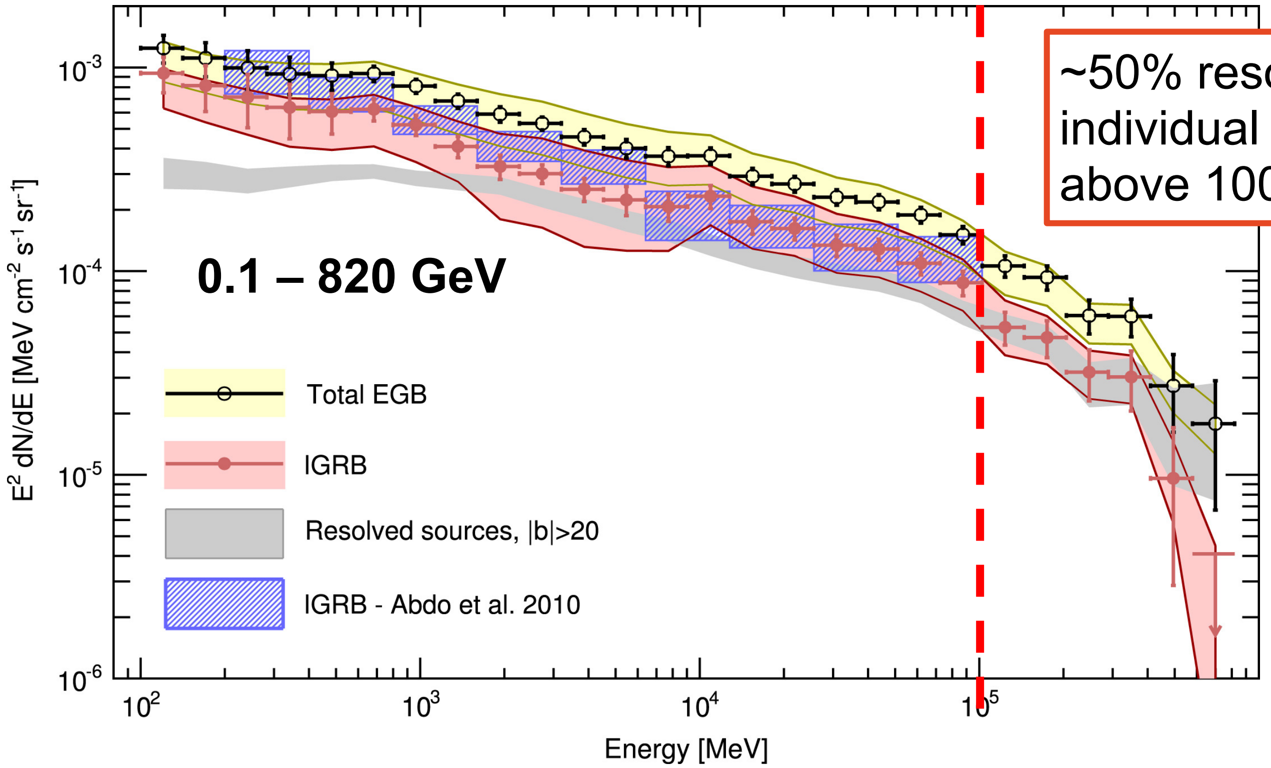
Peng+ 2016



VERITAS *> 700 GeV*

Karlsson+ 2009

The extragalactic γ-ray background

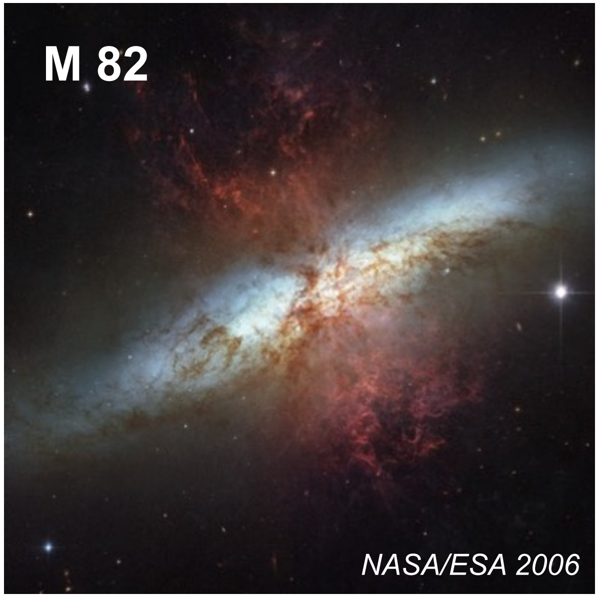


~50% resolved into individual LAT sources above 100 GeV

Fermi LAT Collaboration, Ackermann et al. 2015
arXiv 1410.3696

No consensus on the rest
AGN (higher energies) vs **star-forming galaxies**
(up to PeV) ~ few 10s%

Why is this important?

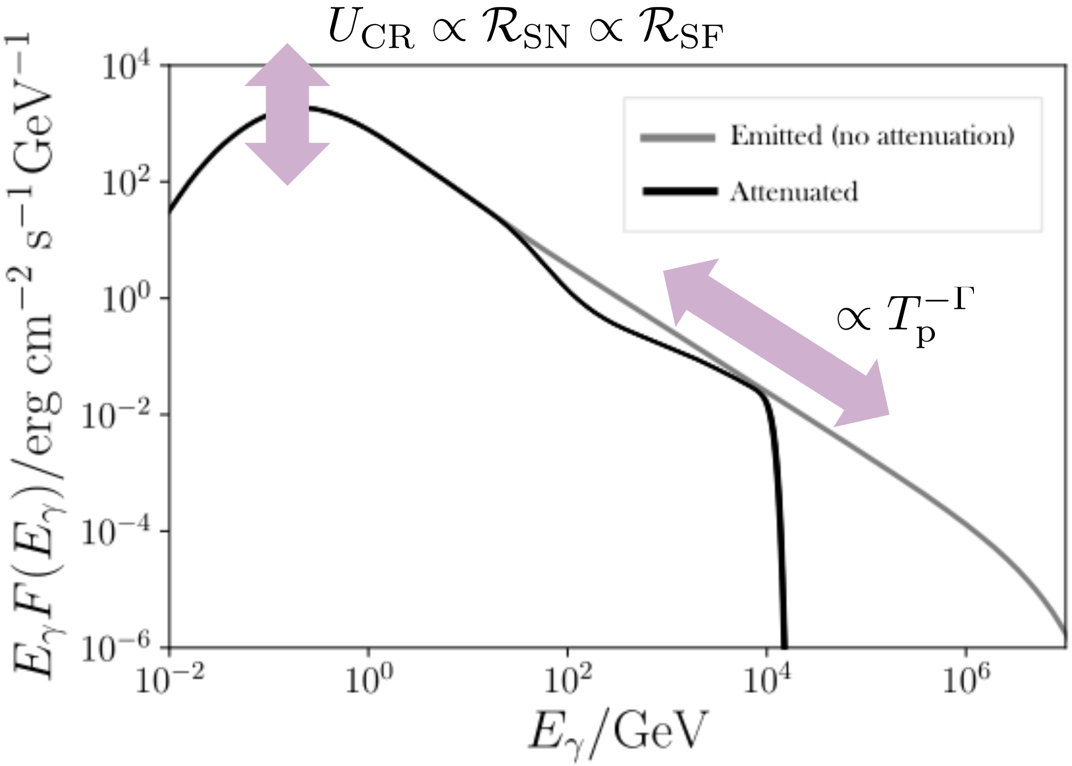


NASA/ESA 2006

From a **galaxy evolution** perspective, the SFG contribution to the gamma-ray background is interesting

CR interactions, their associated production of particles / radiation & deposition of momentum **are important in controlling the evolution of SFGs**

Prototype model: γ-ray production



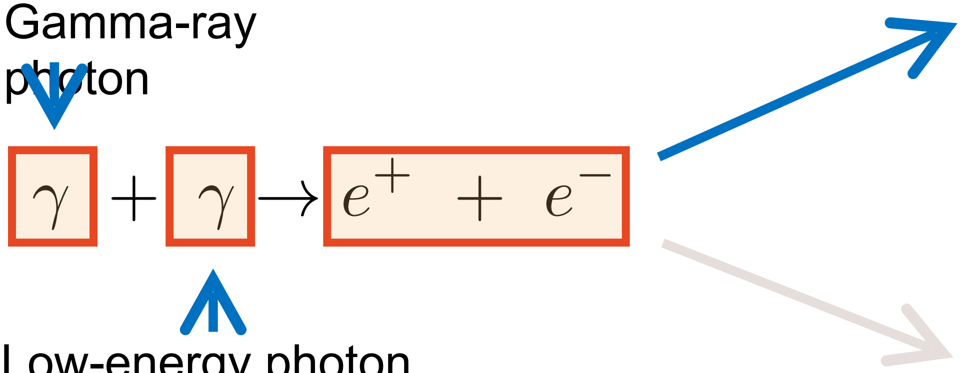
$z = 2$

$\mathcal{R}_{\rm SF} = 10\ {\rm M_\odot\,yr^{-1}}$

Owen+ 2021b

γ-ray interactions

Pair production



Gamma-ray photon

$$\boxed{\gamma} + \boxed{\gamma} \rightarrow \boxed{e^{+} + e^{-}}$$

Low-energy photon
CMB, stars, dust

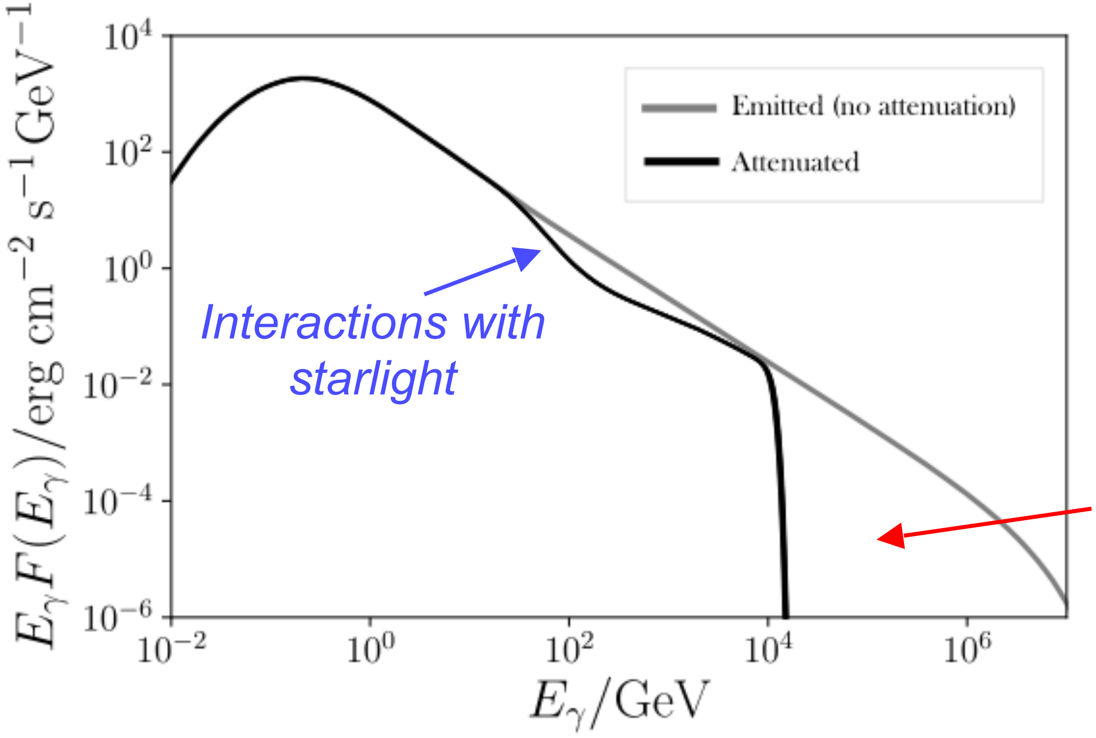
(1) High density conditions (ISM)

Diffuse & thermalise over ~0.1 kpc distances

(2) Low denisty conditions (IGM)

I'll talk about this later

Prototype model: γ-ray production



Interactions with starlight

Interactions with dust reprocessed starlight

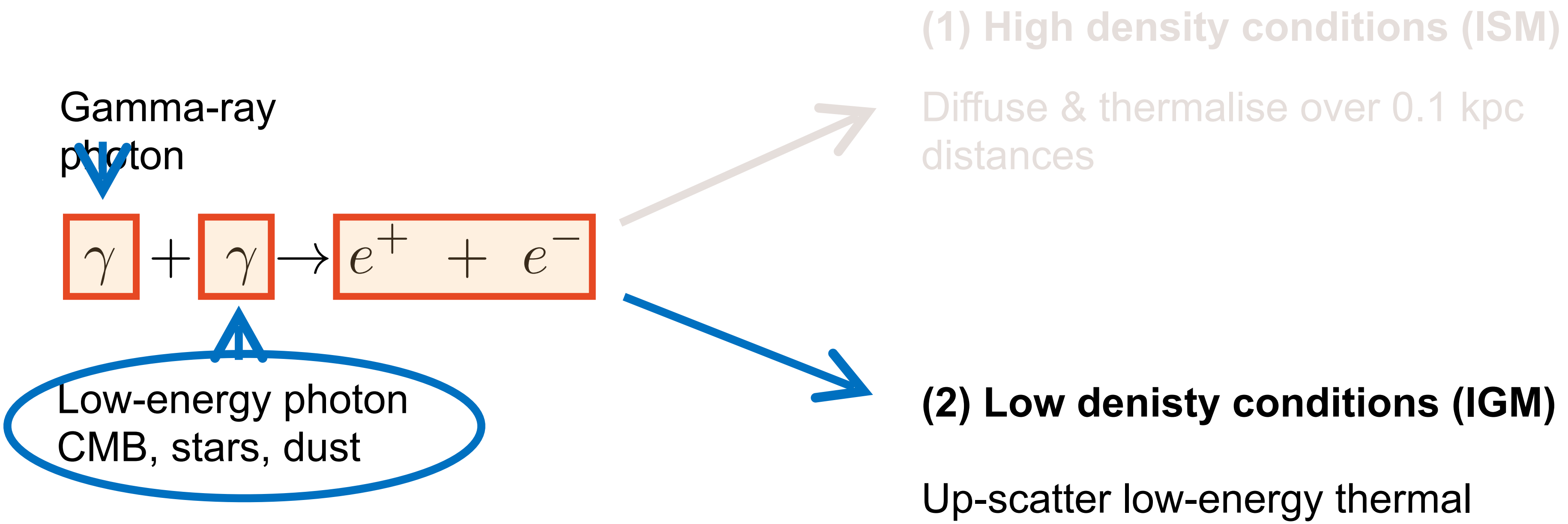
$z = 2$

$\mathcal{R}_{\rm SF} = 10\ {\rm M}_\odot\,{\rm yr}^{-1}$

Owen+ 2021b

Attenuation

Pair production



Gamma-ray photon

$$\boxed{\gamma} + \boxed{\gamma} \rightarrow \boxed{e^{+} + e^{-}}$$

Low-energy photon
CMB, stars, dust

(1) High density conditions (ISM)

Diffuse & thermalise over 0.1 kpc distances

(2) Low denisty conditions (IGM)

Up-scatter low-energy thermal radiation to “cascade” gamma-rays

$$\gamma$$

Extra-galactic background light (EBL)

$$\boxed{+\ \gamma}$$

Cosmological radiative transfer

$$\frac{\mathrm{d}\mathcal{I}_\gamma}{\mathrm{d}z} = (1+z)\left[-\boxed{\alpha}\mathcal{I}_\gamma + \boxed{\frac{j_\gamma}{\nu^3}}\right]\boxed{\frac{\mathrm{d}s}{\mathrm{d}z}}$$

α	Absorption (pair production in EBL radiation fields)
j_ν	Cascade re-emission + fresh SFG emission at this z

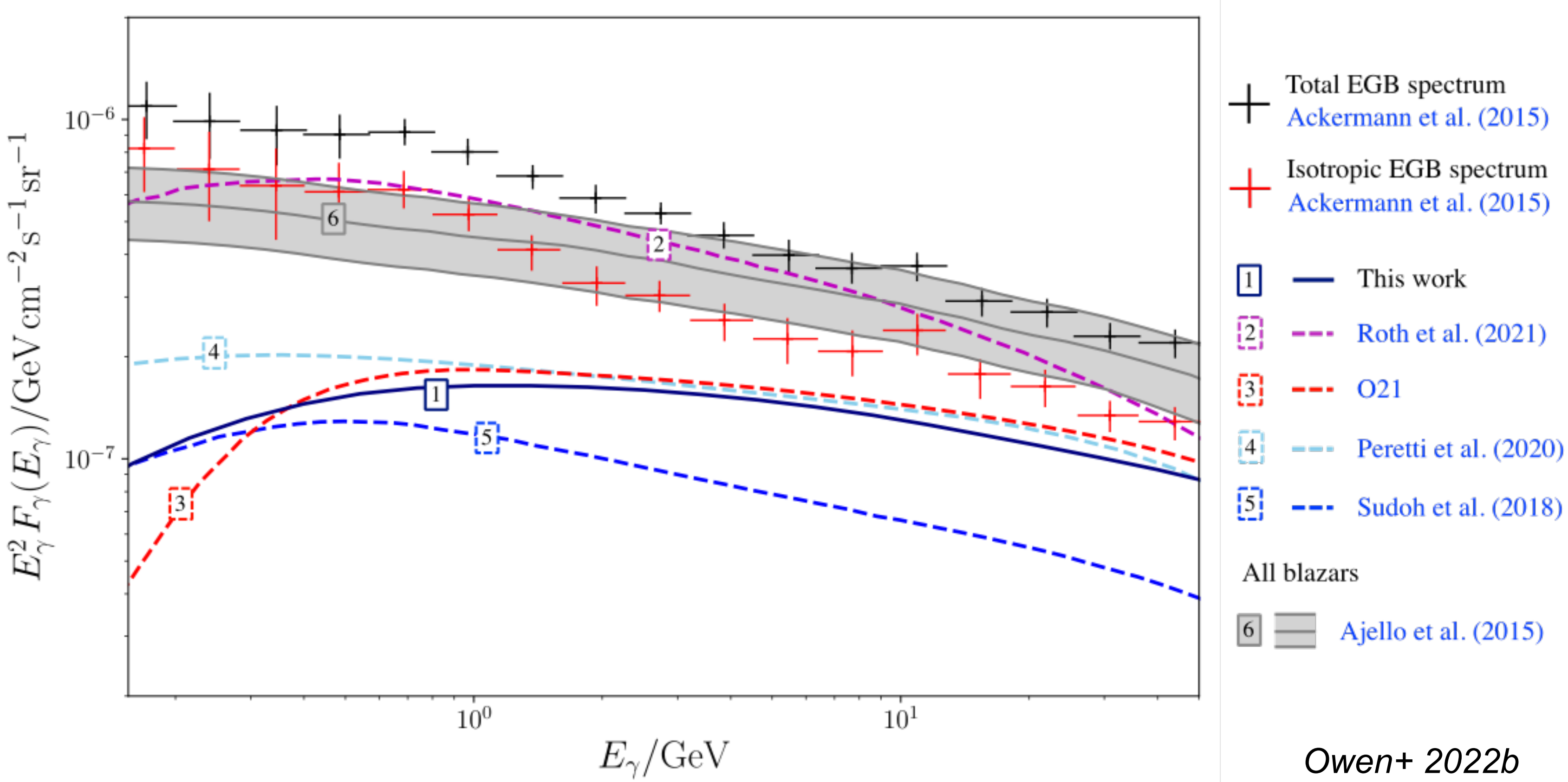
Cosmological model (LCDM)

$$\frac{\mathrm{d}s}{\mathrm{d}z} = \frac{c}{H_0\,(1+z)}\,\left(\Omega_{\mathrm{r},0}(1+z)^4 + \Omega_{\mathrm{m},0}(1+z)^3 + \Omega_{\Lambda,0}\right)^{-1/2}$$

Then solve to compute $\mathcal{I}_\gamma$ at z=0…

EGB spectrum

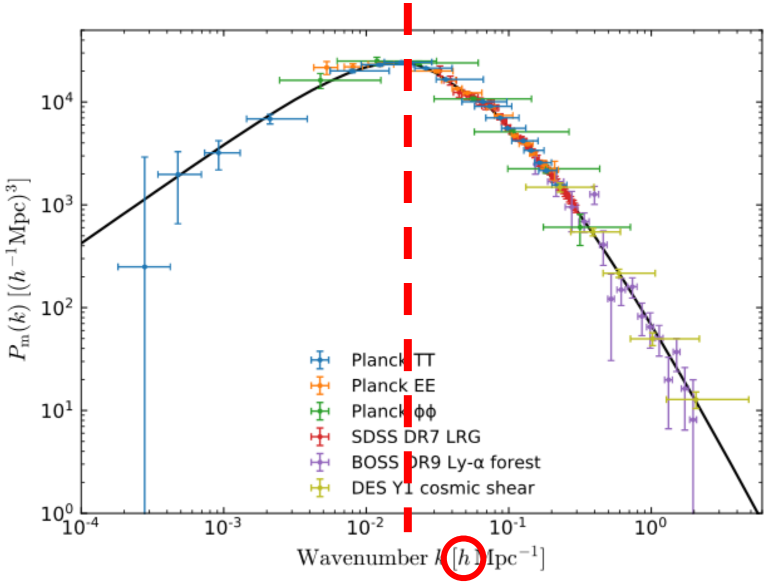
- Consistent with constraints from resolved blazars, agreement with other models



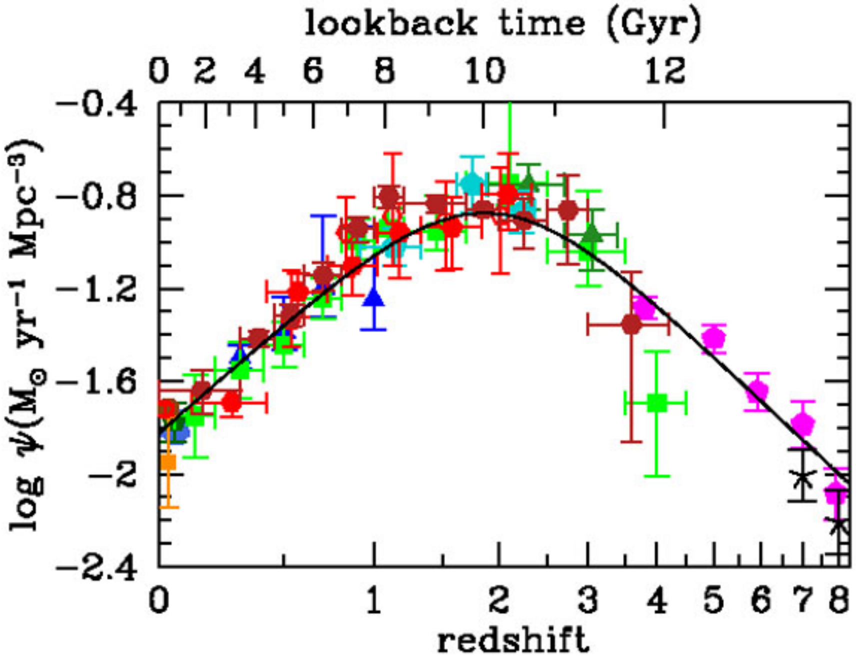
Owen+ 2022b

Source population distribution

Intensity distribution



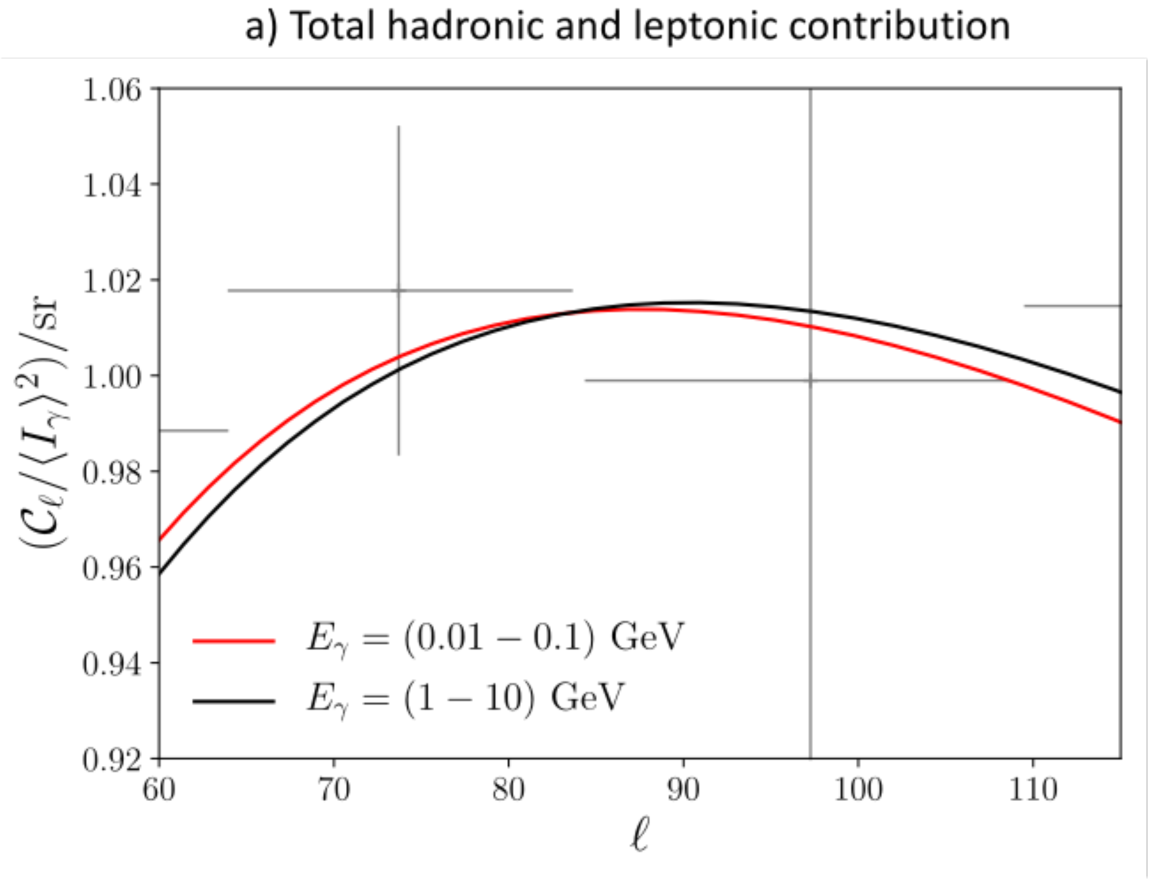
Planck 2018



Madau & Dickinson 2014

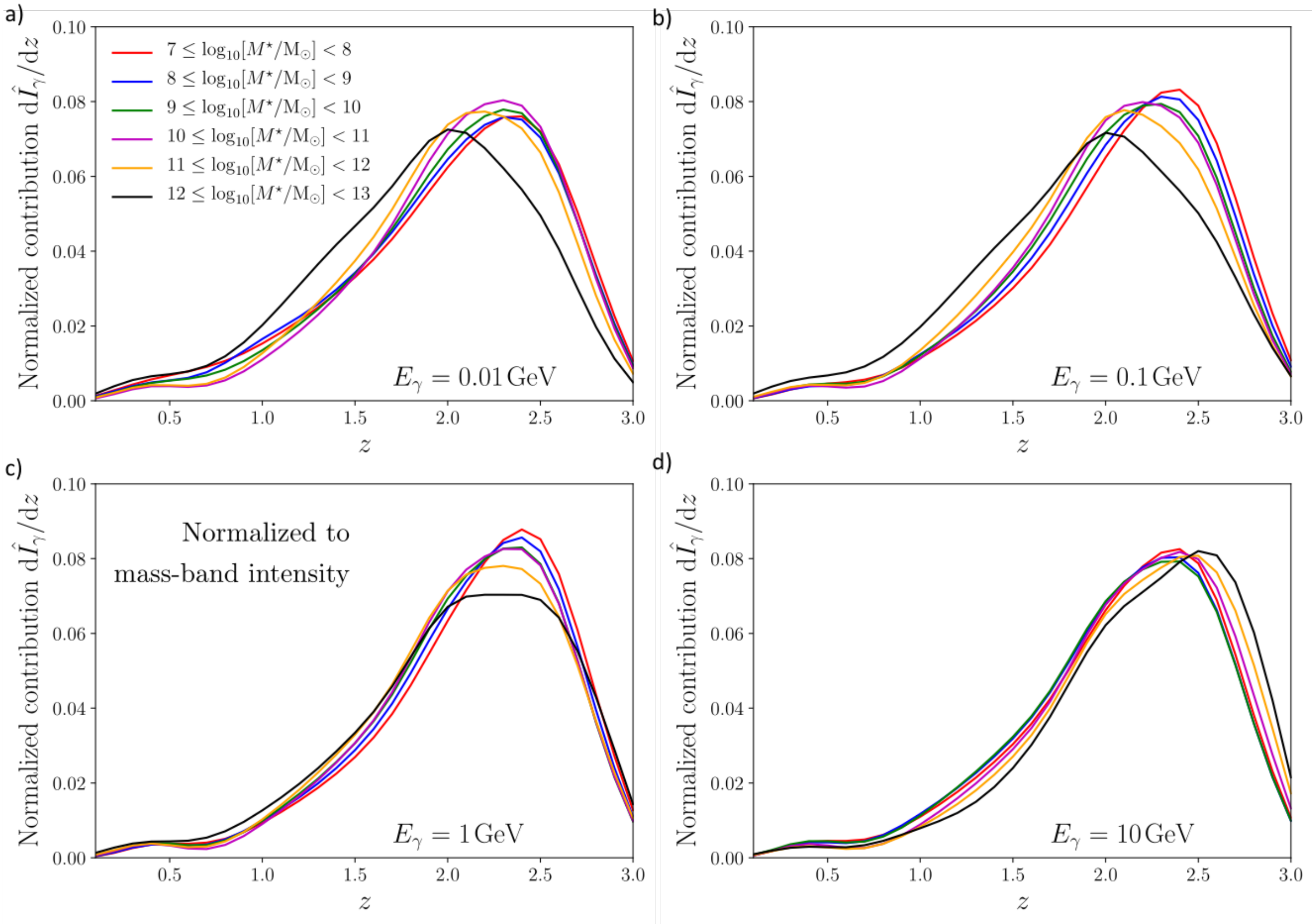
Imprints signature at preferred (peak) scale

EGB anisotropies



Owen+ 2022b (submitted)

Source redshift distribution



Owen+ 2022b (submitted)

Future developments

- A first parametric study, just the **tip of the iceberg…**

Anisotropy signatures contain useful imprinted information about CRs in galaxies

But…

Extracting them **correctly** will be challenging

- Detailed models of plausible signatures
- Bespoke extraction techniques
- Appropriate transforms, avoid blocking artefacts etc (FT implicit assumptions)

CTA will soon provide appropriate data

Take-home points

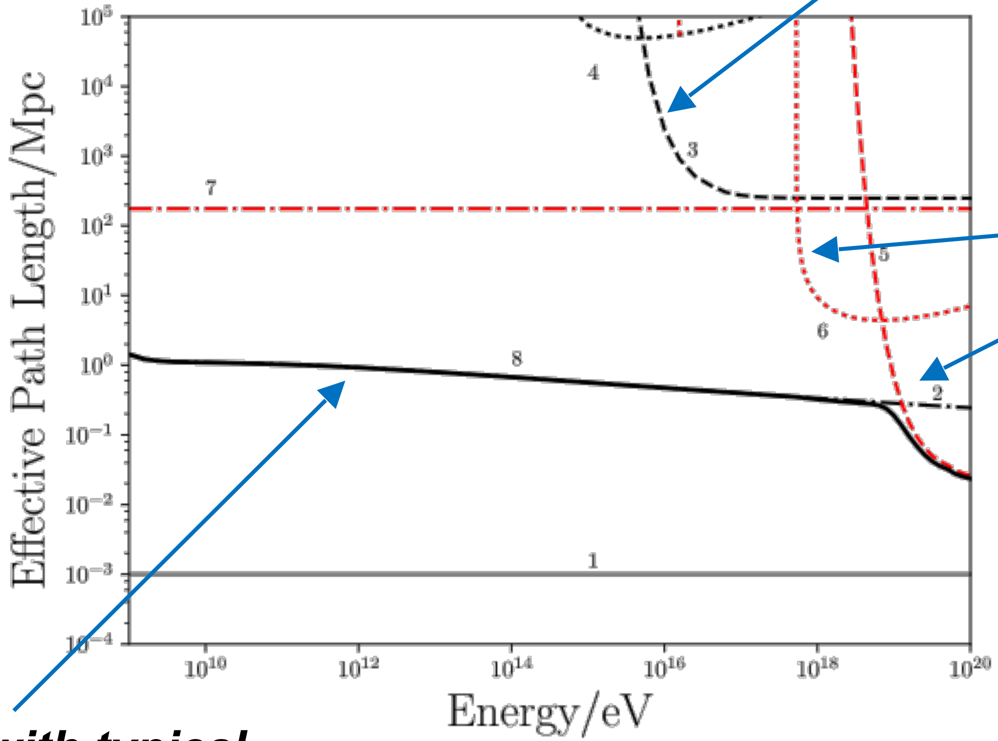
1 **Cosmic rays can change the initial conditions of star-formation in galaxies**

2 **Cosmic rays can moderate and influence the large-scale dynamics of gas in/around galaxies**

3 **We can probe their activity over a broad range of wavelengths**

Cosmic rays operate on many scales and shape galaxy evolution fundamentally in many ways

Backup: Cosmic ray interactions



Interactions with stellar radiation fields

CMB & cosmological losses

Interactions with typical ISM density fields

Adapted from Owen+ 2018 (1808.07837)

Backup: Modeling observables

- Model obserable quantity for EGB anisotropies – existing tools: **power spectrum**
- Start from 2-point auto-correlation function

$$\mathcal{C}(\theta) = \langle \delta I(\ell_1)\, \delta I(\ell_2) \rangle$$

Intensity distribution set by the source model

Take FT of $\mathcal{C}(\theta)$ to get power spectrum of anisotropies

$$\begin{aligned} \mathcal{C}_\ell^\gamma &= \int_\theta \mathrm{d}^2\theta\, e^{-i\vec{\ell}\cdot\vec{\theta}}\, \mathcal{C}(\theta) \\ &= \int_{\boxed{\theta=0}} \mathrm{d}^2\theta\, e^{-i\vec{\ell}\cdot\vec{\theta}}\, \mathcal{C}(\theta) + \int_{\boxed{\theta>0}} \mathrm{d}^2\theta\, e^{-i\vec{\ell}\cdot\vec{\theta}}\, \mathcal{C}(\theta) \\ &= \mathcal{C}_\ell^P + \mathcal{C}_\ell^C \end{aligned}$$

Sum of auto (“Poisson noise” from source distribution) and cross-correlation (” clustering”) terms

Backup: physical parameters

Quantities

CRs

1. Spectral normalization
2. Spectral index
3. CMB attenuation

Radiation

4. Stellar attenuation
   - Starburst nucleus size
   - Stellar luminosity
   - Stellar temperature
5. Dust attenuation
   - Starburst nucleus size
   - Dust luminosity
   - Dust temperature

Parameters

CR spectrum

$\mathcal{R}_{\mathrm{SF}}$ Γ

Radiation spectral energy density

Black body spectrum

CMB z

Stars $T^{\star}\ R\ L^{\star} \propto \mathcal{R}_{\mathrm{SF}}$

Dust $T^{d}\ R\ L^{d} \propto L^{\star}$

Backup: cascade calculation – absorption

Can think of this as a radiative transfer scenario in absorbing medium (the EBL)

Absorption coefficient:

$$\alpha_{\gamma\gamma}(z', \epsilon_\gamma) = \frac{1}{\epsilon_\gamma^2} \int_{1/\epsilon_\gamma}^{\infty} \mathrm{d}\epsilon \, \epsilon^{-2} \boxed{n_{\mathrm{ph}}(\epsilon; z')} \boxed{\varphi(s^\star)}$$

Energy-averaged cross section $\varphi(s^\star) = \frac{16}{3} \int_1^{s^\star} \mathrm{d}s \, s \, \sigma_{\gamma\gamma}(s)$

Integrate over line over propagation distance (redshift) to define gamma-ray optical depth

$$\tau_{\gamma\gamma}(z, \epsilon_\gamma) \equiv \int_0^z \boxed{\alpha_{\gamma\gamma}(z', \epsilon_\gamma)} \frac{\mathrm{d}s}{\mathrm{d}z'} \mathrm{d}z'$$

Backup: cascade calculation – emission

Pair production rate - product of gamma-ray intensity (available energy) and absorption coefficient (efficiency to produce e+/e- pairs)

$$\boxed{\frac{\mathrm{d}n_\mathrm{e}}{\mathrm{d}\gamma_\mathrm{e}}} \approx \frac{2}{\epsilon_\gamma c}\int_z^{z_\mathrm{max}} \boxed{\alpha_{\gamma\gamma}(z',\epsilon_\gamma)}\boxed{I_\gamma(z',\epsilon_\gamma)}\,\frac{\mathrm{d}s}{\mathrm{d}z'}\,\mathrm{d}z'$$

e+/e- inverse-Compton scatter in the EBL to produce new gamma-rays

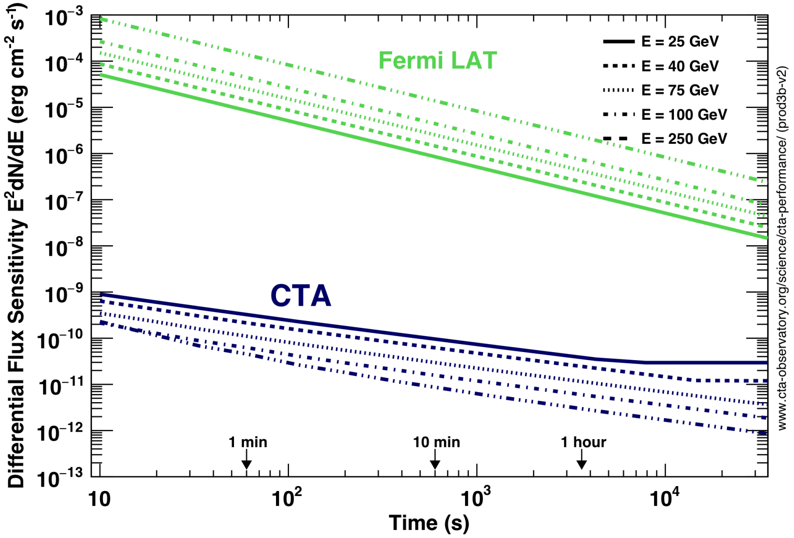
$$j_\gamma = \frac{3\sigma_\mathrm{T} c}{4}\int_{\gamma_\mathrm{e,min}}^{\gamma_\mathrm{e,max}} \frac{\mathrm{d}\gamma_\mathrm{e}}{\gamma_\mathrm{e}^2}\boxed{\frac{\mathrm{d}n_\mathrm{e}}{\mathrm{d}\gamma_\mathrm{e}}}\int_0^1 \mathrm{d}x\,\boxed{n_\mathrm{ph}(x,z)}\,f(x)\,x^{-1}$$

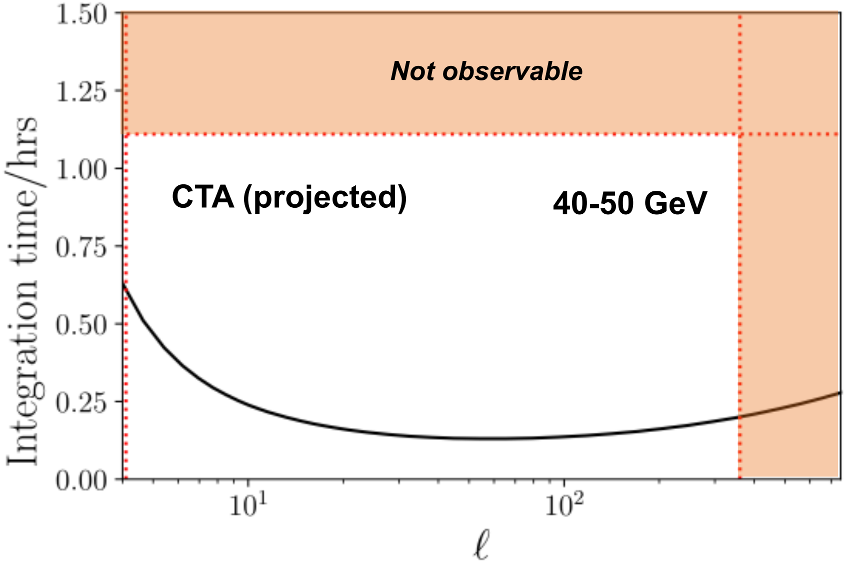
EBL spectral number density (kicked-up in energy by the e+/e- pairs)

Backup: detectability of EGB signatures

Fermi-LAT ~ 10 years

hints of detections from SFGs already: Fornasa et al. 2016



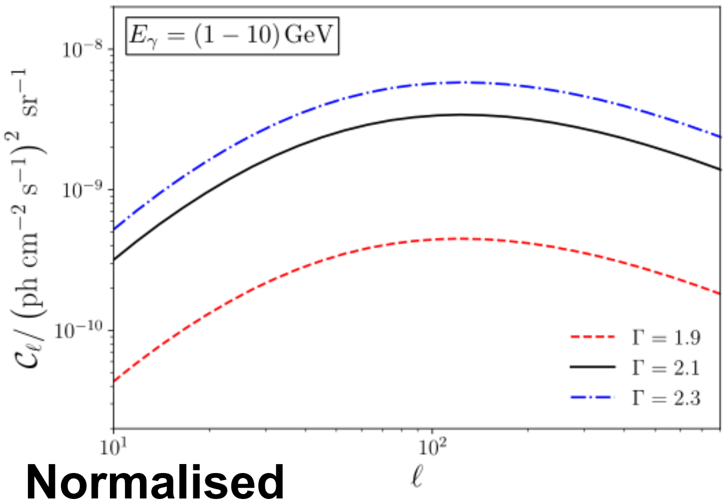


CTA Consortium (2017)

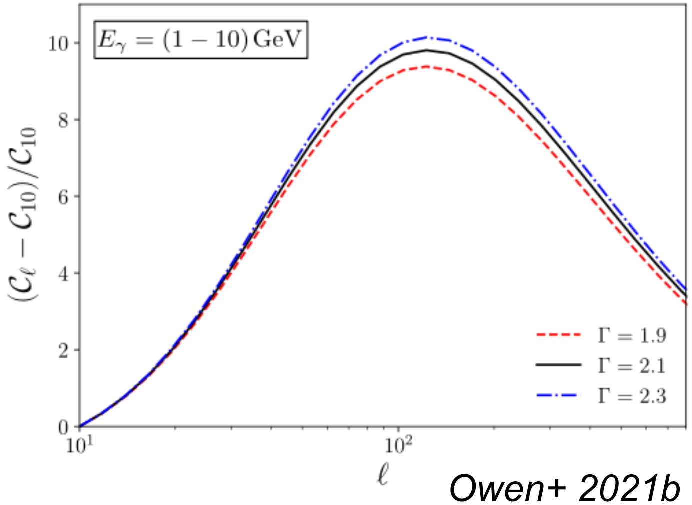
Estimated from published CTA provisionally planned operations/specifications

https://www.cta-observatory.org/science/cta-performance/#1472563397821-893dc9a7-f7ec

Backup: CR spectral properties



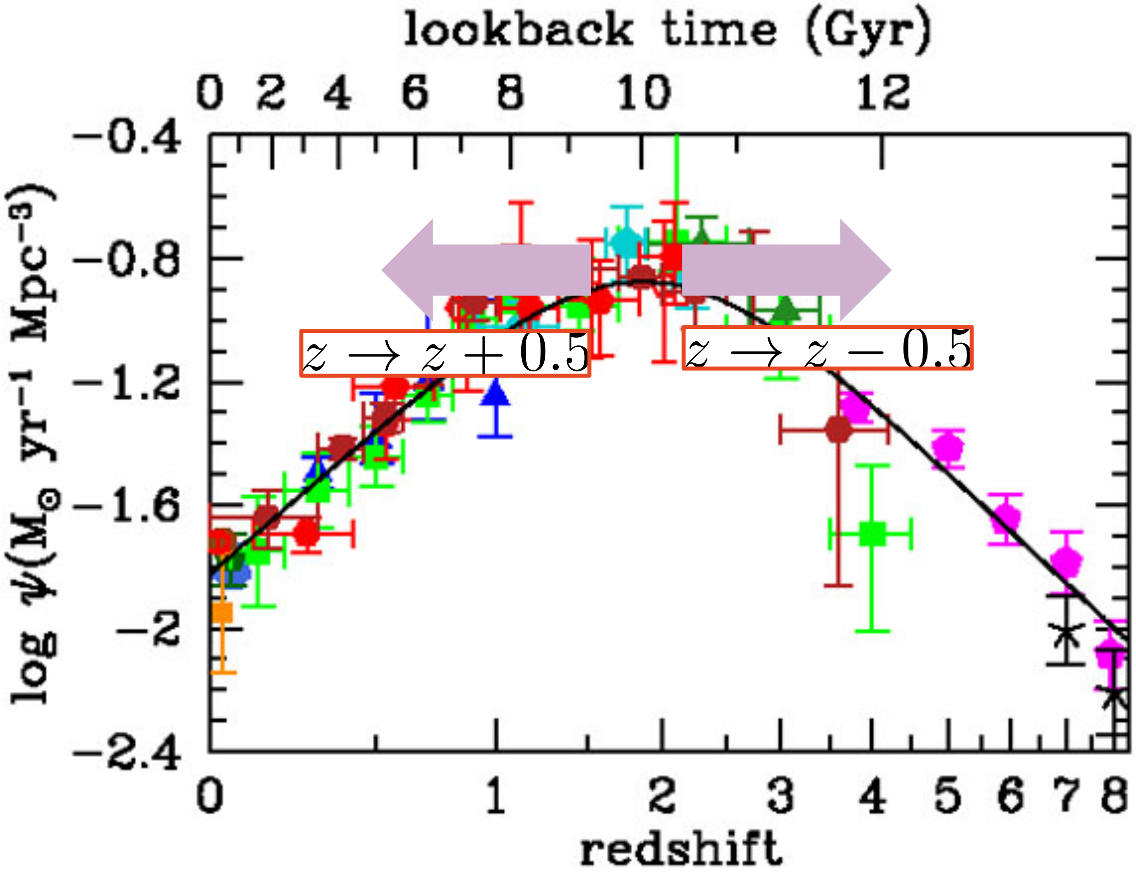
Normalised



Owen+ 2021b

- Variation of spectral index in nearby starbursts (Ajello et al. 2020)
- Insight into CRs in these environments (acceleration processes, spectral aging, CR propagation)
- Different indices leave different imprints

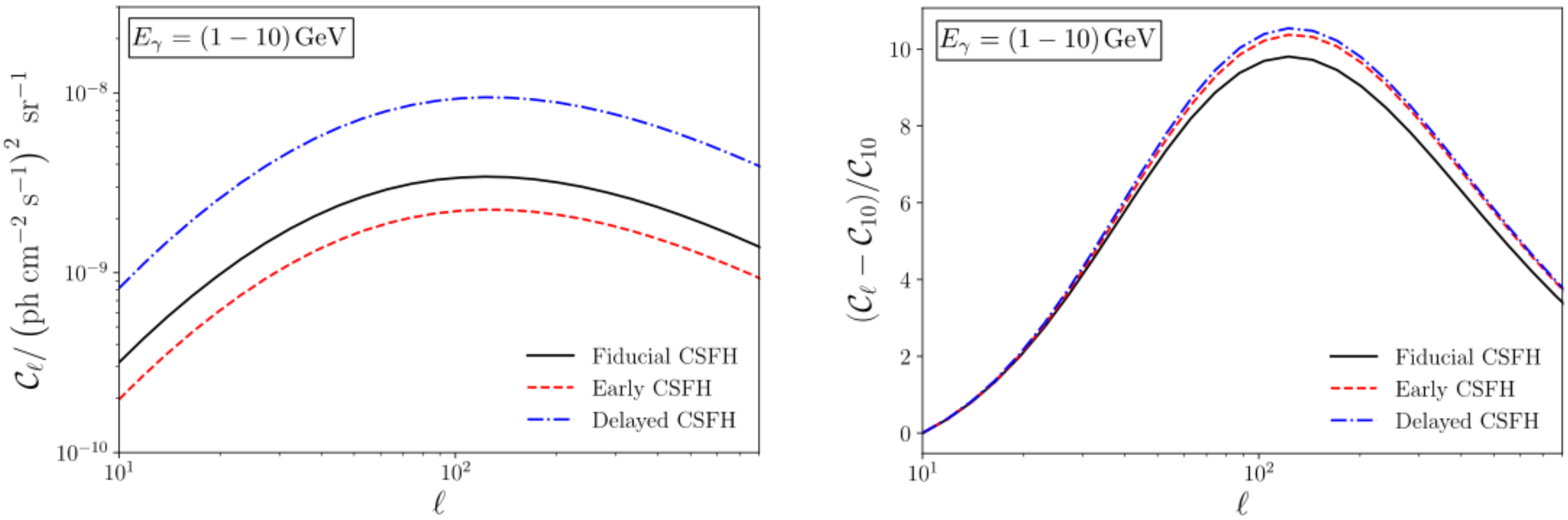
Backup: galaxy & evolution properties



Madau & Dickinson 2014

Backup: galaxy & evolution properties

Normalised



Owen+ 2021b

- Sub-populations with different evolutionary scenarios/z-distributions would be discernable