Star-forming Galaxies at High Redshift
The feedback impact of energetic cosmic rays

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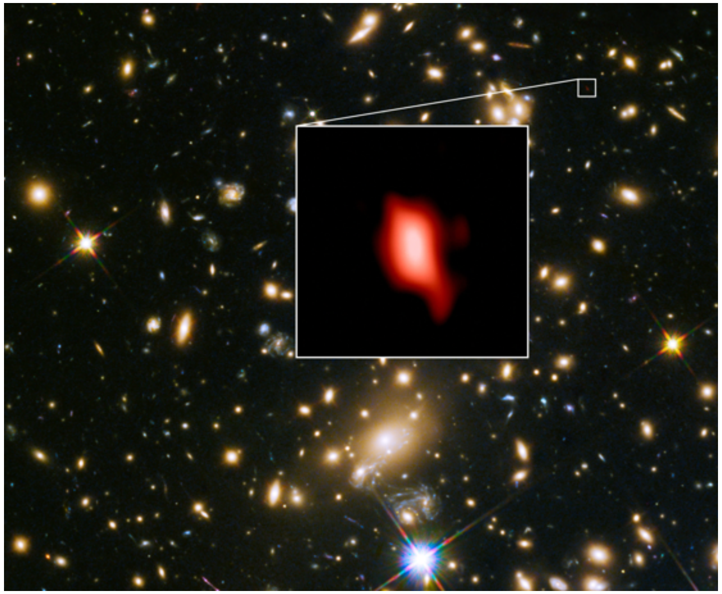

HST and ALMA image of MACS1149-JD1 (z=9.11) – NASA/ESA, Hashimoto+ 2018

Collaborators
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Outline

- Star-forming galaxies in the Universe
- Cosmic rays in star-forming galaxies
- Particle propagation
- Energy deposition and heating by particles and radiation
- Implications for star-formation and feedback
- Summary

Star-forming Galaxies in the Universe

Image of simulated Lyman-alpha emission around a high redshift group of protogalaxies – credit: Geach et al.

Local Starbursts

NGC 253

NASA/ESA 2008

Arp 220

ESO 2010

M 82

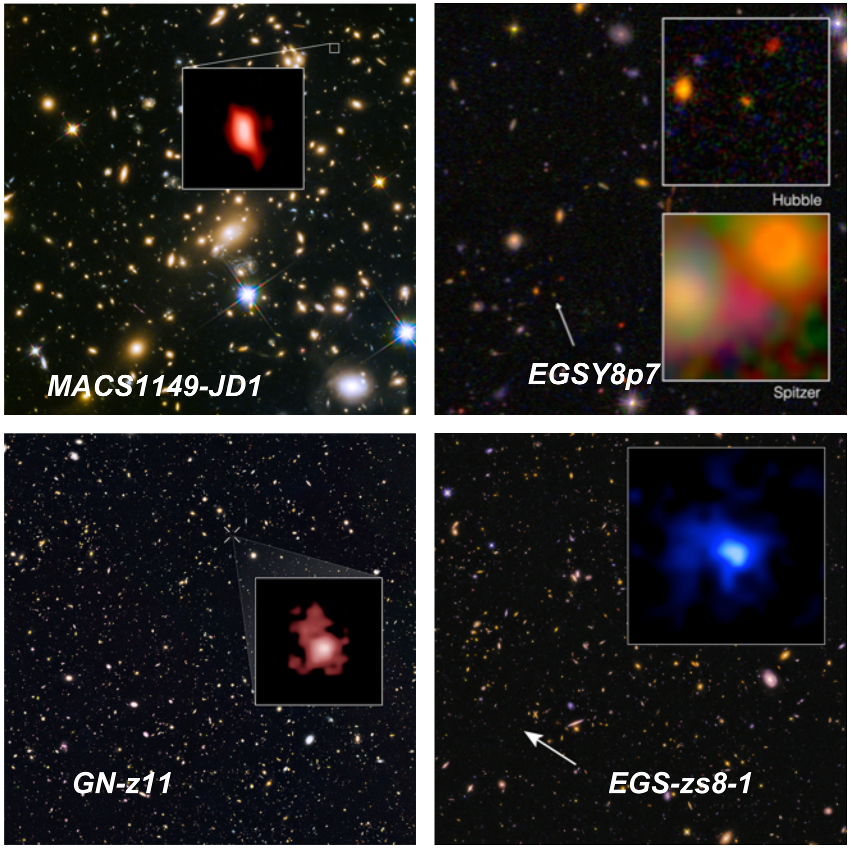
NASA/ESA 2006

	NGC 253	Arp 220	M 82
$\mathcal{R}_{\mathrm{SF}}$	$\sim 10\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$	$\sim 220\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$	$\sim 10\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$
$\mathcal{R}_{\mathrm{SN}}$	$0.1\ \mathrm{yr}^{-1}$	$4\ \mathrm{yr}^{-1}$	$0.1\ \mathrm{yr}^{-1}$

See e.g. SN Rates: Fenech+2010, Lenc & Tingay 2006, Lonsdale+2006; SF Rate: Varenius+2016, Schreiber+2003, Bolatto+2013

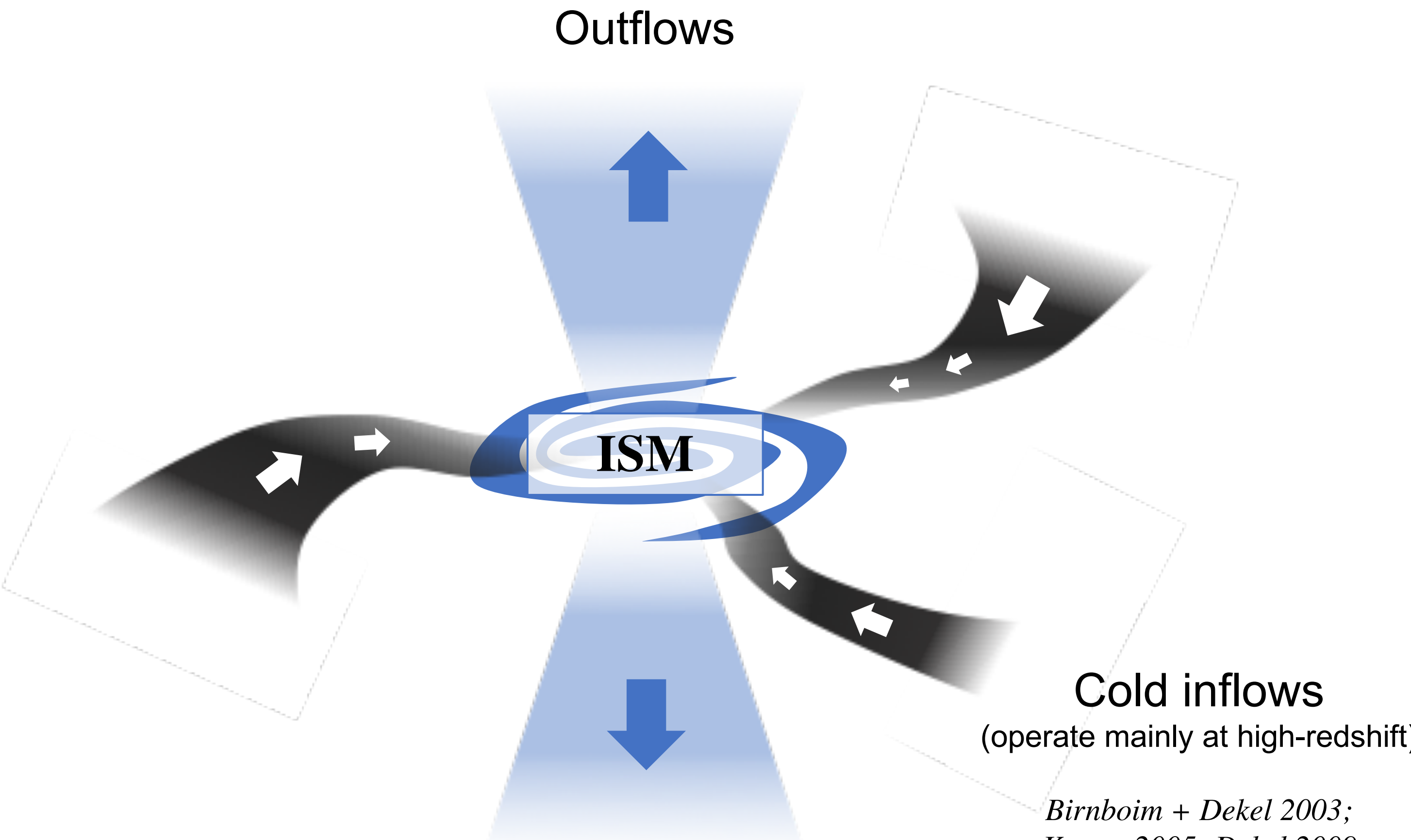
High-redshift starbursts (z~6+)

- Low mass, high SF rates
  - $10^8\ \mathrm{M}_\odot$
  - $10\mathrm{s}\ - 100\mathrm{s}\ \mathrm{M}_\odot\ \mathrm{yr}^{-1}$
  - SF efficiencies ~ tens of %
- Some known to host Lyman-α haloes
  - Multi-phase CGM…
- Simulation work suggests possibility of filamentary inflows of gas *(cf. works by Keres, Dekel, Birnboim…)*



MACS1149-JD1 (HST/ALMA) – NASA/ESA, Hashimoto+ 2018
EGSY8p7 (Hubble/Spitzer) – NASA, Labbe+ 2015
GN-z11 (HST) – NASA, Oesch+ 2015
EGSY-zs8-1(Hubble/Spitzer) – NASA/ESA, Oesch & Momcheva 2015

The high-redshift CGM environment



Birnboim + Dekel 2003;
Keres+2005; Dekel 2009

Figure based on Tumlinson+2017

Cosmic rays in star-forming galaxies

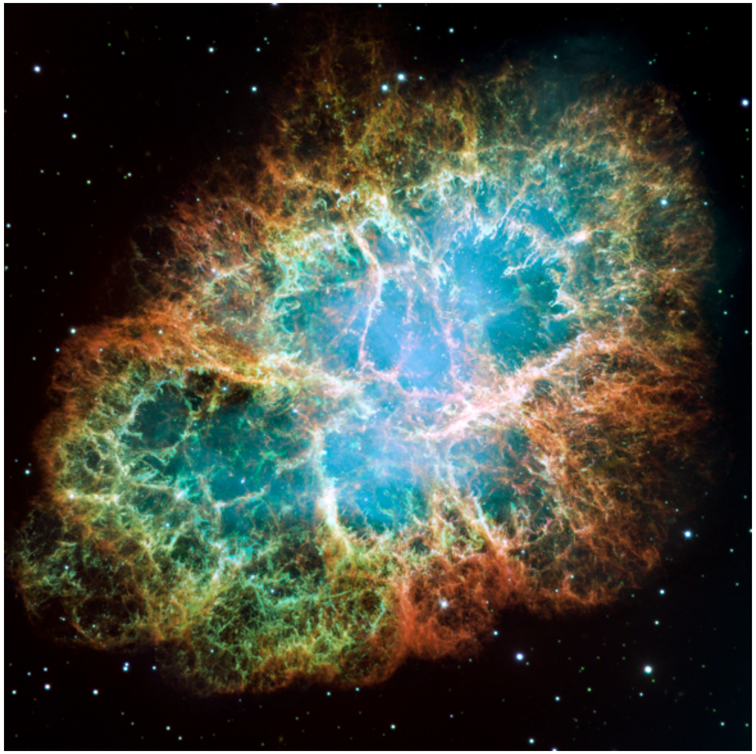
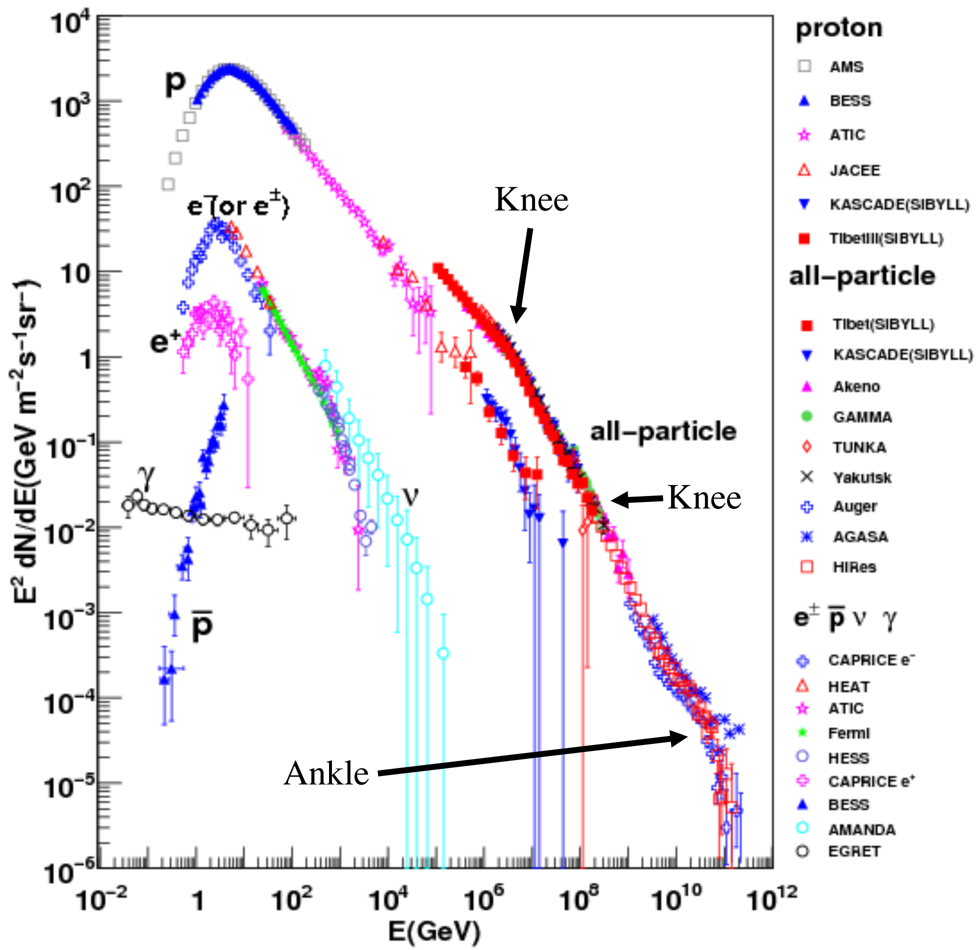


Image credit: Crab Nebula, NASA, ESA 2005

Cosmic rays in the Milky Way



Adapted from Gaisser 2007

Starbursts as cosmic ray factories

- Hillas criterion

$$E_{\max} \leq qBR$$

- Cosmic rays sources
  - Galactic (internal) in orange

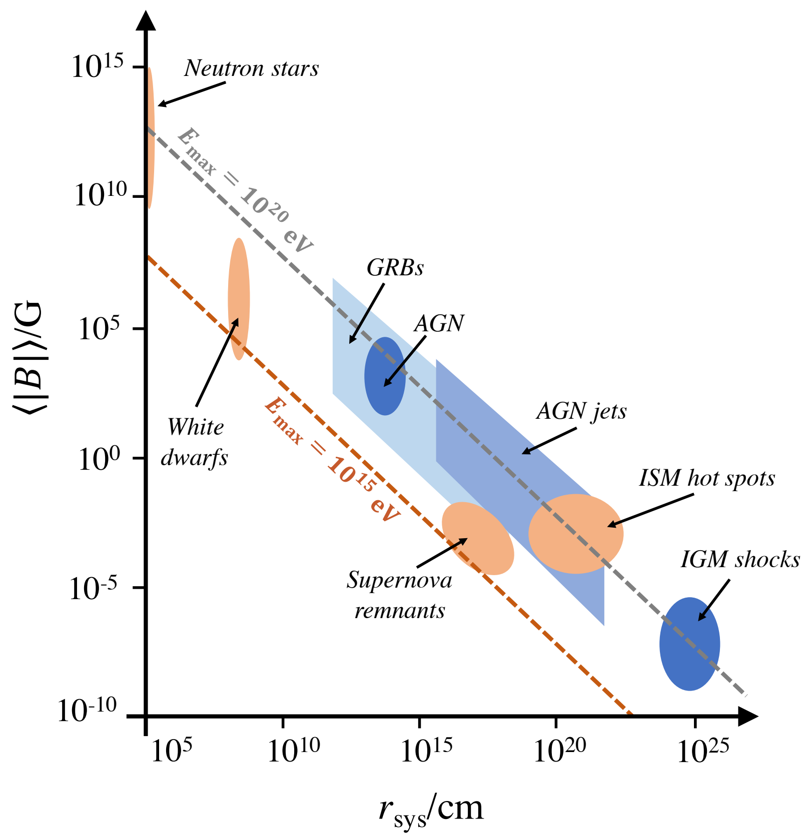
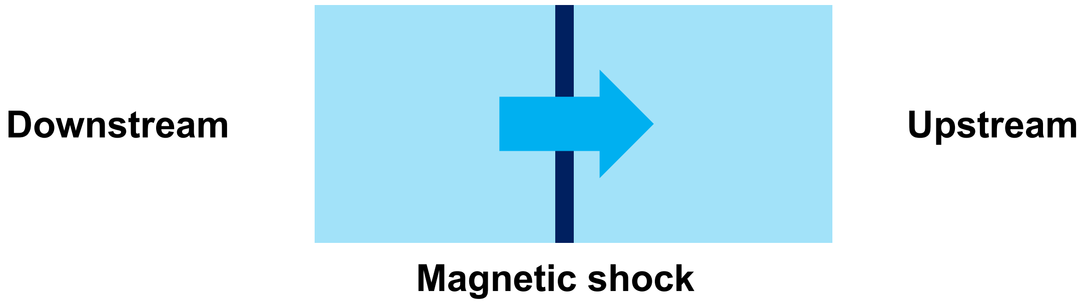


Fig. adapted from Owen 2019 (PhD thesis)
See also Kotera & Olinto 2011; Hillas 1984

Cosmic ray acceleration

- Shocks, e.g. SNR
  - First order Fermi acceleration
- Each pass through the shock increases the energy
- After *n* crossings, energy is $E = E_0 \langle \xi \rangle^n$



Cosmic ray acceleration

- Some particles will escape after a crossing – take P as probability of remain, so number remaining after each crossing
- Eliminate *n* and rearrange
- Result is CRs accelerated to high energies, ~GeV and above, following a power-law

$$\Gamma \approx 2.1$$

$$N = N_0 P^n$$

$$\frac{N}{N_0} = \left(\frac{E}{E_0}\right)^{\frac{\log P}{\log\langle\xi\rangle}}$$

$$= \left(\frac{E}{E_0}\right)^{-\Gamma}$$

Cosmic ray interactions

with radiation fields (*pγ*)

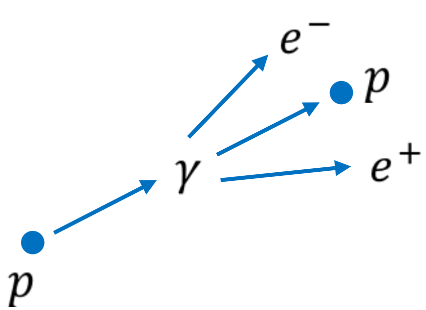
Interaction by particles scattering off ambient photons (starlight, CMB…)

Photopion Interaction

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \rightarrow p + 2\gamma \\ n + \pi^+ \rightarrow \underbrace{n + \mu^+ + \nu_\mu}_{\rightarrow\, n + e^+ + \nu_e + \bar{\nu}_\mu + \nu_\mu} \end{cases}$$

+ pion multiplicities at higher energies

Photopair Interaction



$$p + \gamma \rightarrow p + e^+ + e^-$$

Cosmic ray interactions

with matter (*pp*)

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

+ pion multiplicities at higher energies

Neutron and photon interactions produce pions

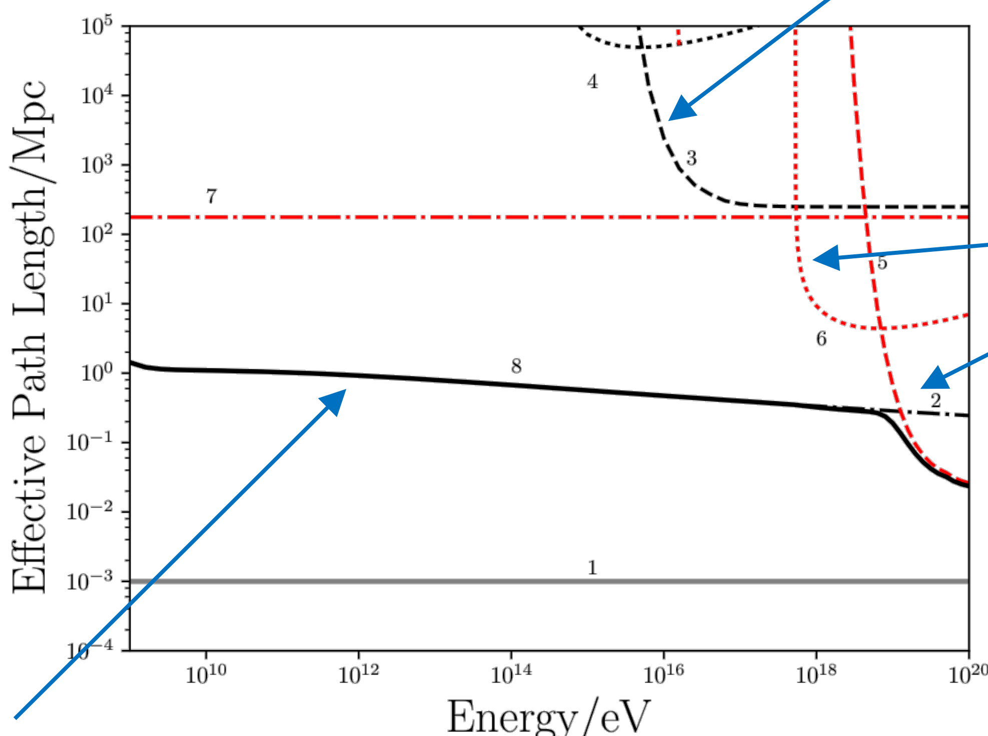
$$n + \gamma \rightarrow \pi\text{'s}$$

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

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

Cosmic ray interactions

Interactions with stellar radiation fields



CMB & cosmological losses

Interactions with typical ISM density fields

Adapted from Owen+ 2018 (1808.07837)

Particle propagation

Image credit: M25 Motorway, Carillon UK Transport

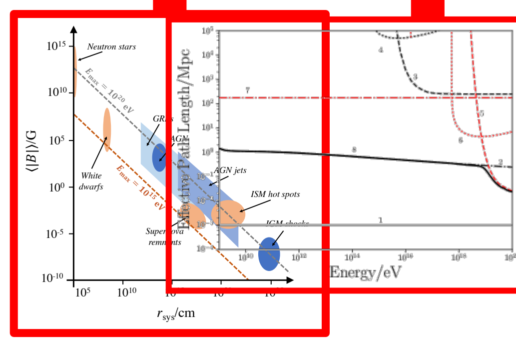
The transport equation (hadrons)

- The transport equation for protons (cooling/momentum diffusion assumed negligible)

$$\frac{\partial n}{\partial t} = \boxed{\nabla \cdot [D(E,\mathbf{x})\nabla n]} + \cancel{\frac{\partial}{\partial E}[b(E,r)\,n]} - \boxed{\nabla \cdot [\mathbf{v}n]} + Q(E,\mathbf{x}) - S(E,\mathbf{x})$$

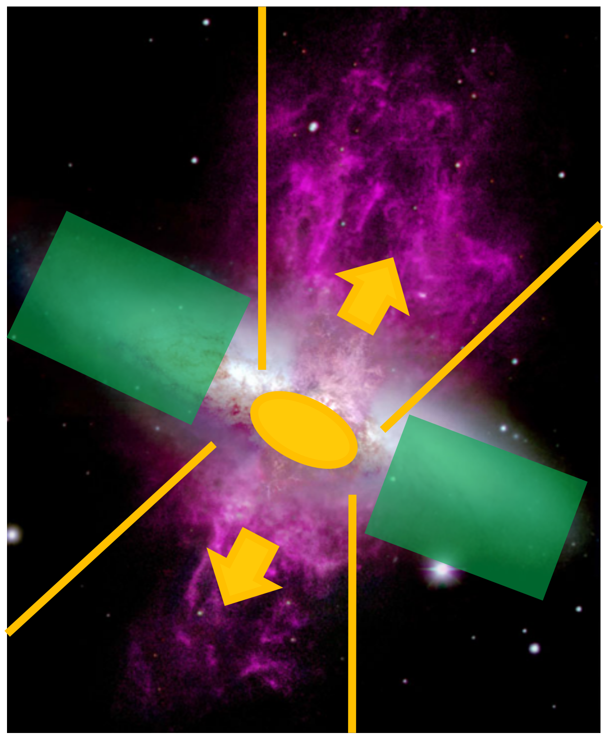
  – Diffusion dominated, i.e. $\boldsymbol{v} = 0$

  – Advection dominated, i.e. $D(E,\mathbf{x}) = 0$



The diffusion zone (‘stationary’ ISM)

$$\frac{\partial n}{\partial t} = \nabla \cdot [D(E,\mathbf{x})\nabla n] + \cancel{\frac{\partial}{\partial E}[b(E,r)\,n]} - \cancel{\nabla \cdot [\mathbf{v}n]} + Q(E,\mathbf{x}) - S(E,\mathbf{x})$$



M82 in Hα (WIYN) and optical (HST)
Smith+ 2005

The diffusion zone ('stationary' ISM)

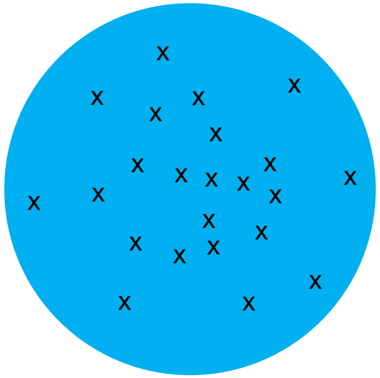
$$\frac{\partial n}{\partial t} = \nabla \cdot [D(E,\mathbf{x})\nabla n] + \cancel{\frac{\partial}{\partial E}[b(E,r)\,n]} - \cancel{\nabla \cdot [\mathbf{v}n]} + Q(E,\mathbf{x}) - S(E,\mathbf{x})$$

- Approximate ISM as a sphere
- Absorption depends on
  - density of CRs
  - density of ISM gas
  - interaction cross section (dominated by pp process)
- CR injection as a BC (for now)
  - restate problem as individual linearly independent events (*t'* since inj. event)

$$n = \frac{n_0}{[4\pi D(E,r')t']^{3/2}} \boxed{\exp\left\{-\int_0^{t'} \mathrm{c}\,\mathrm{d}t\,\hat{\sigma}_{p\pi}\,n_{\mathrm{ISM}}\right\}} \exp\left\{-\frac{r'^2}{4\,D(E,r')t'}\right\}$$

The diffusion zone (‘stationary’ ISM)

- Solution for steady-state from continuous injection from single source (time integral)
- Numerically convolve with a source ensemble (MC distribution)
  - Follows ISM gas profile



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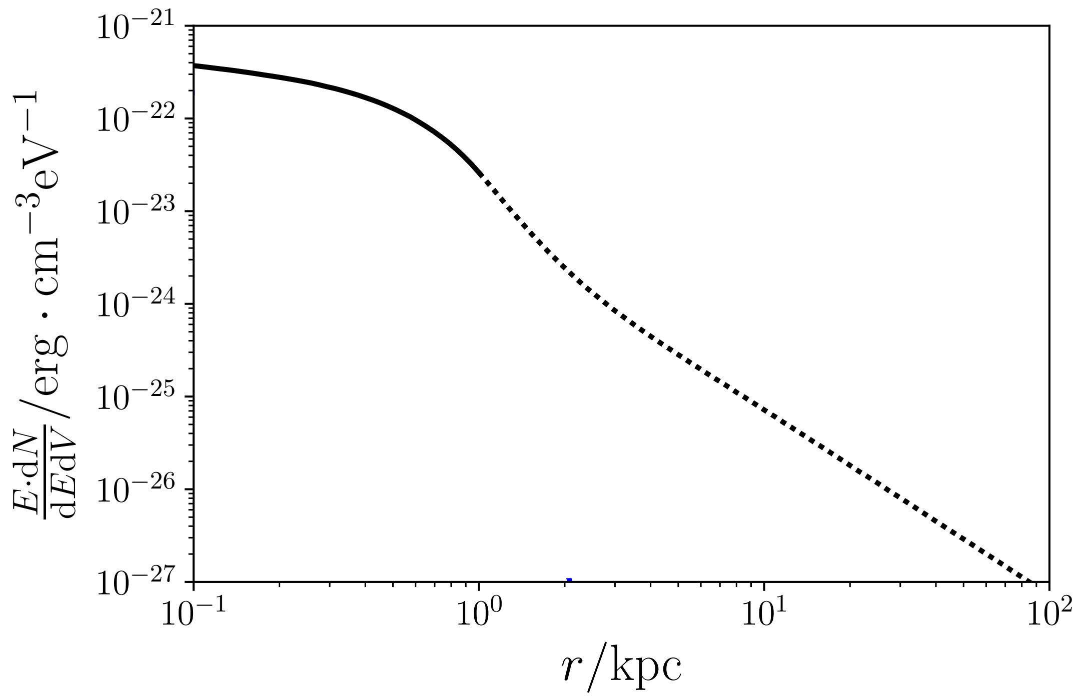


Secondary electrons

- Injection by the pp attenuation process

$$\mathrm{pp} \rightarrow \{\pi^0, \boxed{\pi^+, \pi^-}\}$$

$$\begin{aligned} \pi^- &\rightarrow \boxed{e^-} + \bar{\nu}_\mathrm{e} + \nu_\mu + \bar{\nu}_\mu \\ \pi^+ &\rightarrow \boxed{e^+} + \nu_\mathrm{e} + \bar{\nu}_\mu + \nu_\mu \end{aligned}$$

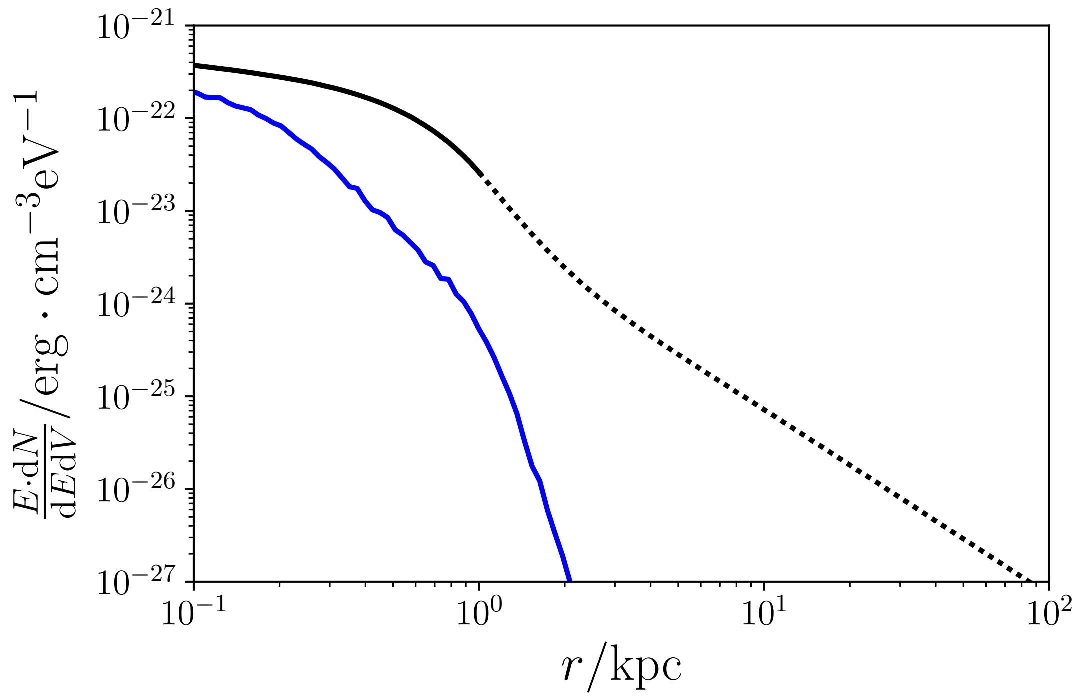
- Transport equation (electrons)

$$\frac{\partial n_\mathrm{e}}{\partial t} = \nabla \cdot [D(E,\mathbf{x}) \nabla n_\mathrm{e}] + \frac{\partial}{\partial E}[b(E,r)\, n_\mathrm{e}] - \cancel{\nabla \cdot [\mathbf{v}\, n_\mathrm{e}]} + Q_\mathrm{e}(E,\mathbf{x}) - \cancel{S_\mathrm{e}(E,\mathbf{x})}$$

  - Negligible advection
  - No absorption
  - Diffusion coefficient same as for protons (depends on charge)

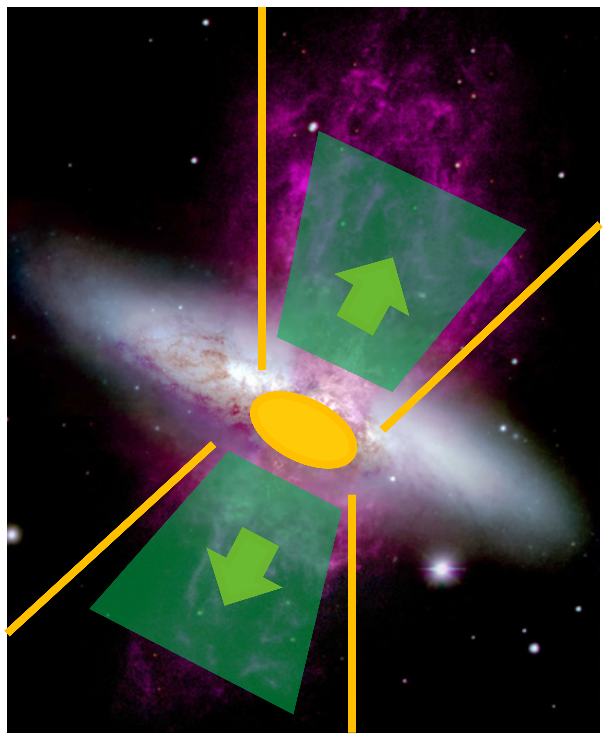
Cosmic ray distribution in ‘stationary’ ISM

- **Electrons** calculated for **each proton injection** diffusion profile (MC distribution)
- Then convolved across **proton** source distribution (i.e. the SN events)



The advection zone (outflows)

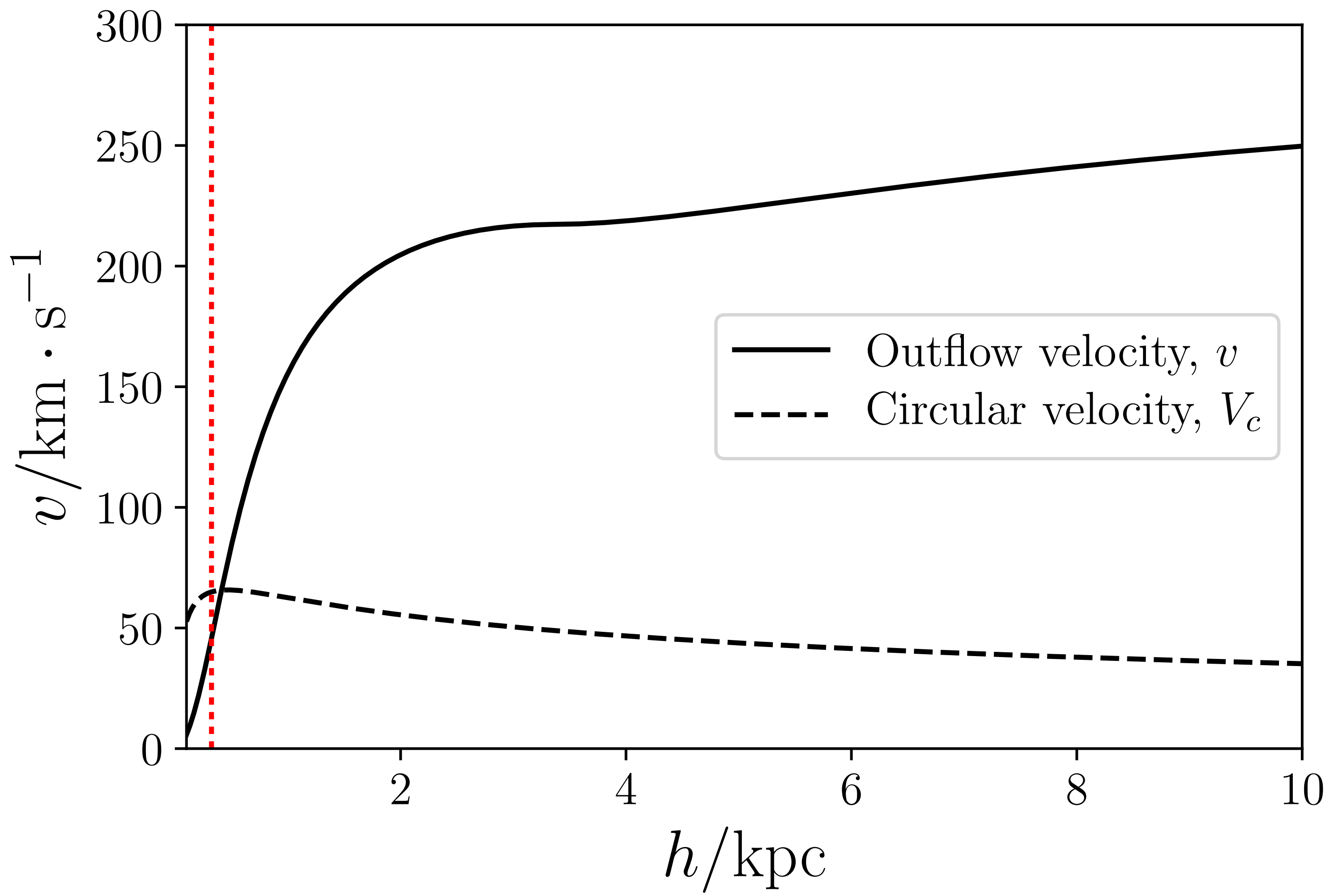
$$\frac{\partial n}{\partial t} = \nabla \cdot \cancel{[D(E,\mathbf{x})\nabla n]} + \cancel{\frac{\partial}{\partial E}[b(E,r)\,n]} - \nabla \cdot [\mathbf{v}n] + Q(E,\mathbf{x}) - S(E,\mathbf{x})$$



M82 in Hα (WIYN) and optical (HST)
Smith+ 2005

The advection zone (outflows)

Hydrodynamical outflow model

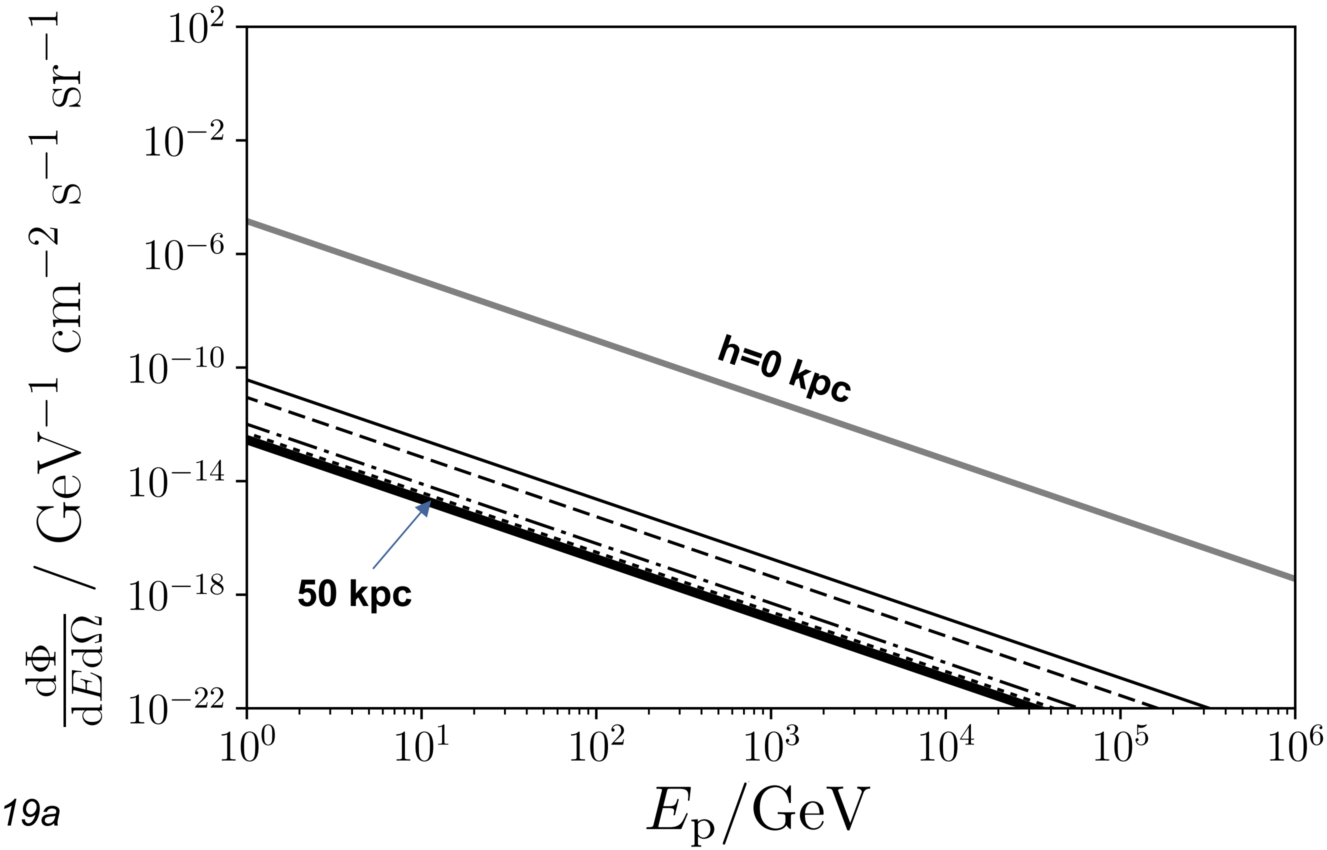


Owen+ 2019a; Samui+ 2010

The advection zone (outflows)

Particle propagation

- Steady state solutions to transport equation, i.e. $\frac{\partial n}{\partial t} = 0$



Owen+ 2019a

Energy deposition and heating

Image credit: National Bunsen Burner Day (March 31st), McGill University 2016

Heating mechanisms & global impacts

- **Direct Coulomb (DC)**

  "quenching"

  Also operates in magnetized CGM via CR streaming instability + Alfvén wave dissipation (similar rate)

- **Indirect Inverse Compton X-rays (IX)**

  "strangulation"

  Also advected CRs may also slow inflows, or heat filaments in CGM by DC, Alfvén dissipation…

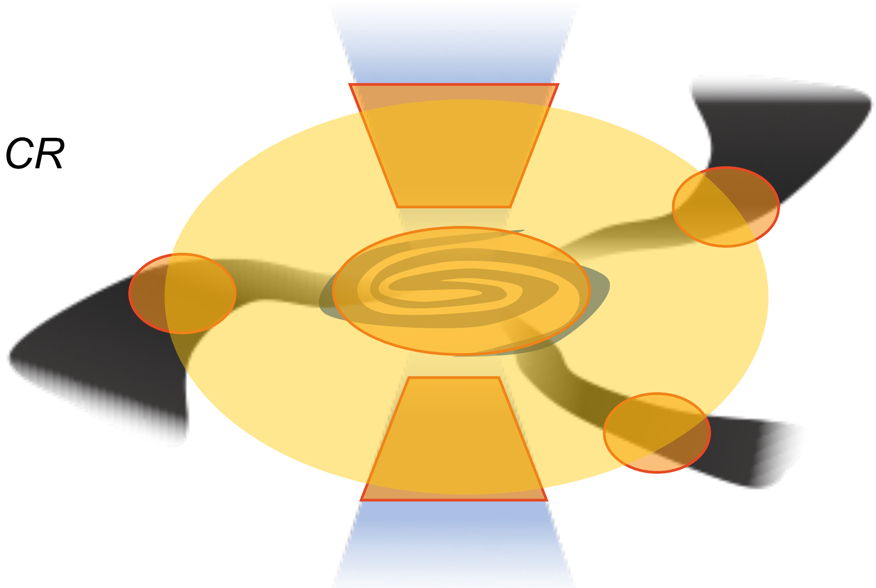
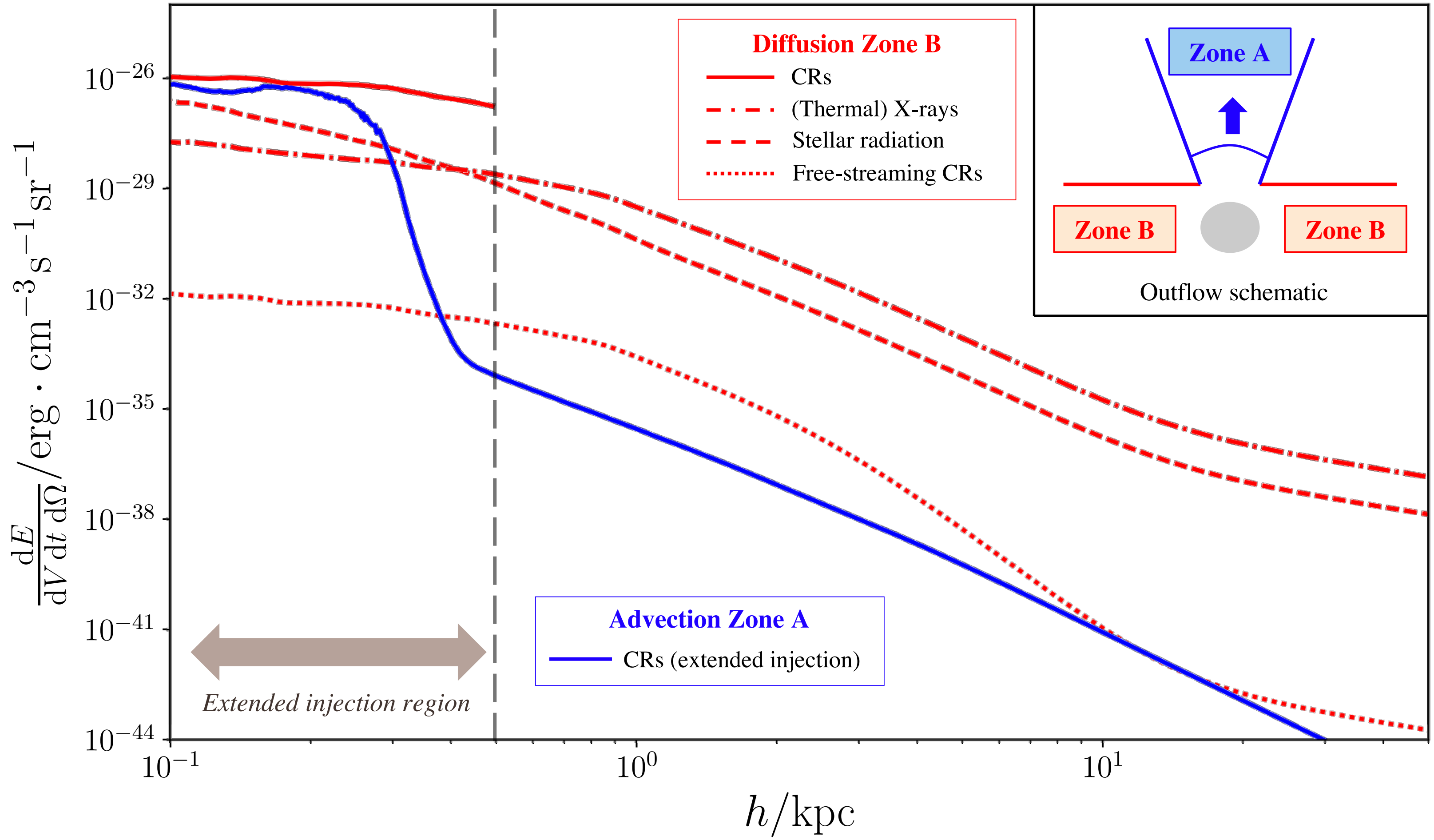


Figure based on Tumlinson+ 2017

Direct Coulomb heating

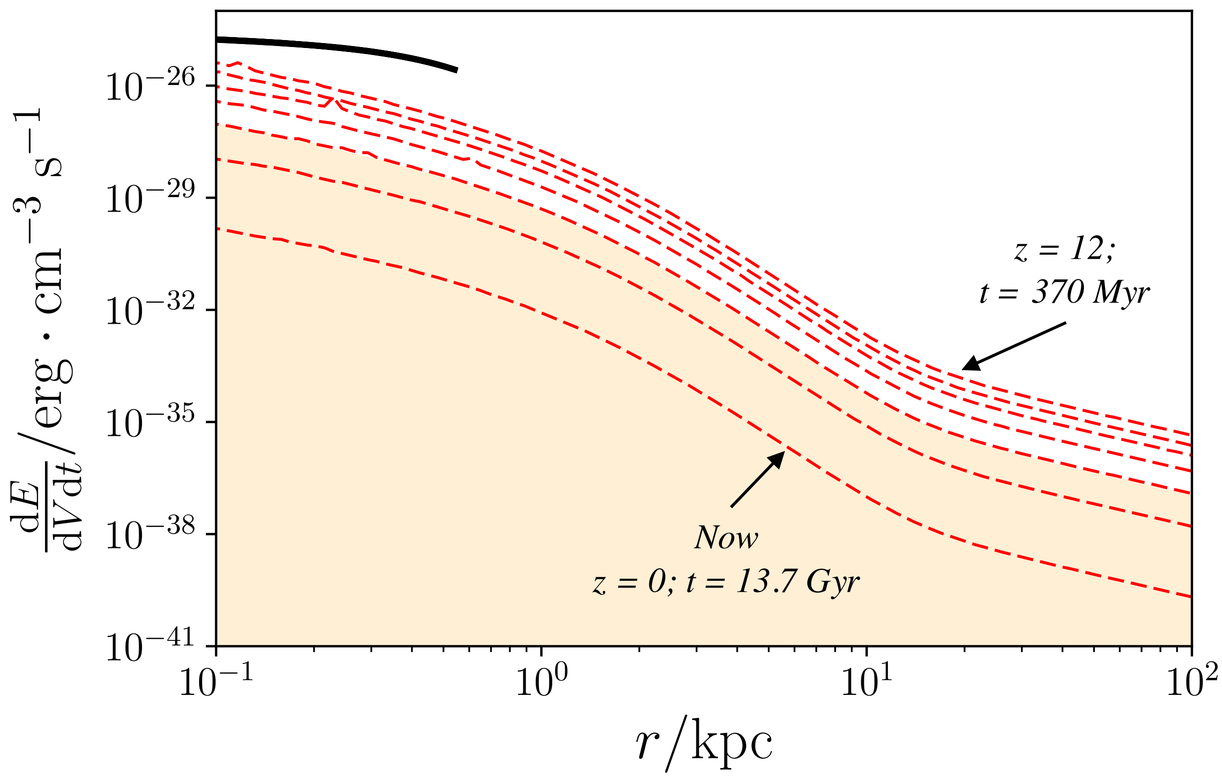
Zone comparisons



Adapted from Owen+ 2019a (1901.01411)

Indirect heating

ISM reference case



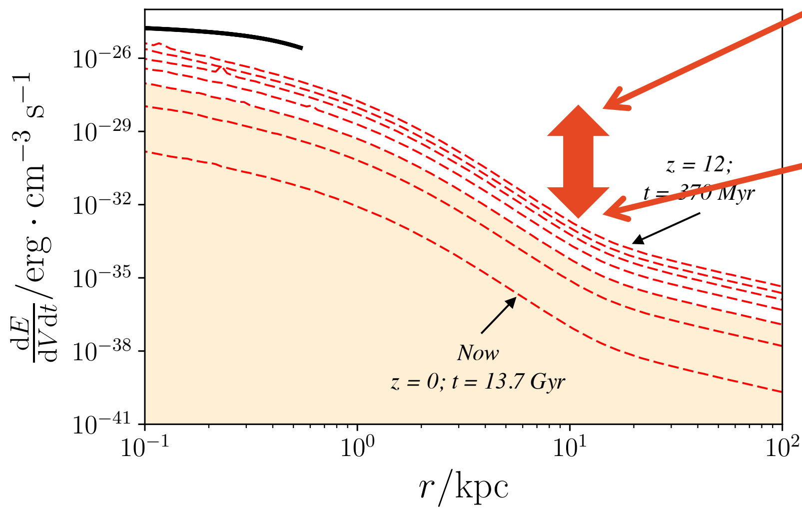
CGM minimum shown here: value in inflow filaments would be higher (proportional to density)

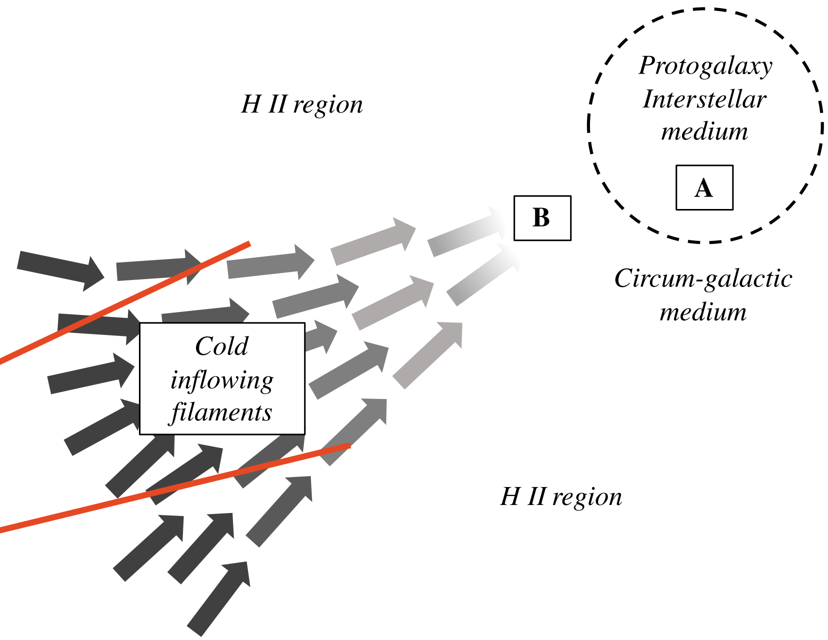
Owen+ 2019b (1905.00338)

CGM structure and implications

Strangulation vs. quenching

- Scaling relation to deal with filaments
- Effective heating power ~1-2 orders of magnitude lower than ISM value





Owen+ 2019b (1905.00338)

Timescales

- Estimate by considering condition for them to no longer be gravitationally bound – upper-limit

Time for ISM to exceed $T_{\rm vir}$ *due to DC heating*

$$\tau_{\rm Q} = \boxed{\begin{array}{c}\tau_{\rm mag} \\ \tau_{\rm mag}\end{array}} \begin{array}{l} + \tau_{\rm DC} \\ + \tau_{\rm IX}\end{array}$$

$$\tau_{\rm S} = \tau_{\rm mag} + \tau_{\rm IX}$$

Time for filament region to exceed $T_{\rm vir}$ *due to IX heating*

Magnetic containment time; required for CR effects to develop

$$\tau_{\rm mag} \propto {\rm SFR}^{-1}$$

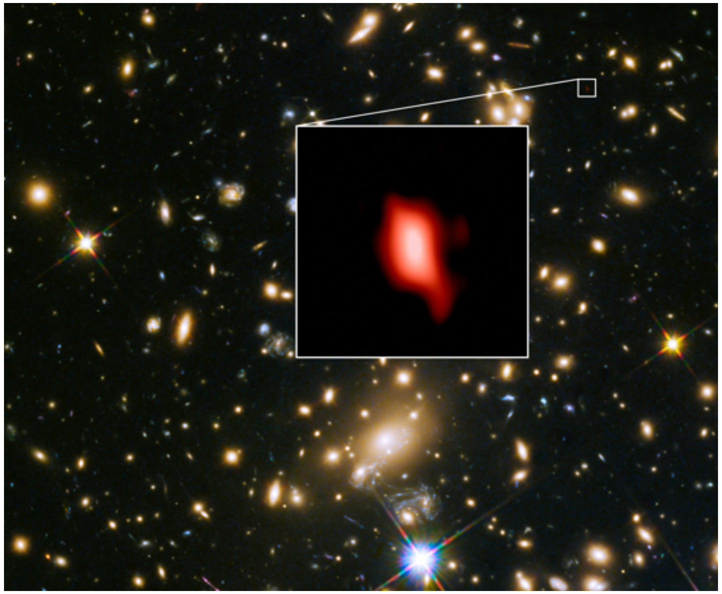
Application to real galaxies…

Feedback and star-formation

Image credit: HST image of N90 Star forming region in SMC, NASA/ESA 2007

Inferred behavior of MACS1149-JD1

- Spectroscopic z=9.11 (t = 550 Myr)
  $\mathcal{R}_{\rm SF} \approx 4.2^{+0.8}_{-1.1}\ \mathrm{M}_{\odot}\ \mathrm{yr}^{-1}$
- Two populations of stars
  - One from observed SF activity
  - Other from activity ~100 Myr earlier
- **Earlier burst of Star-formation at z=15.4; t=260 Myr (Hashimoto+2018)**
- Quenched fairly quickly
  - distinct inferred age of older stellar population – SED, size of Balmer break

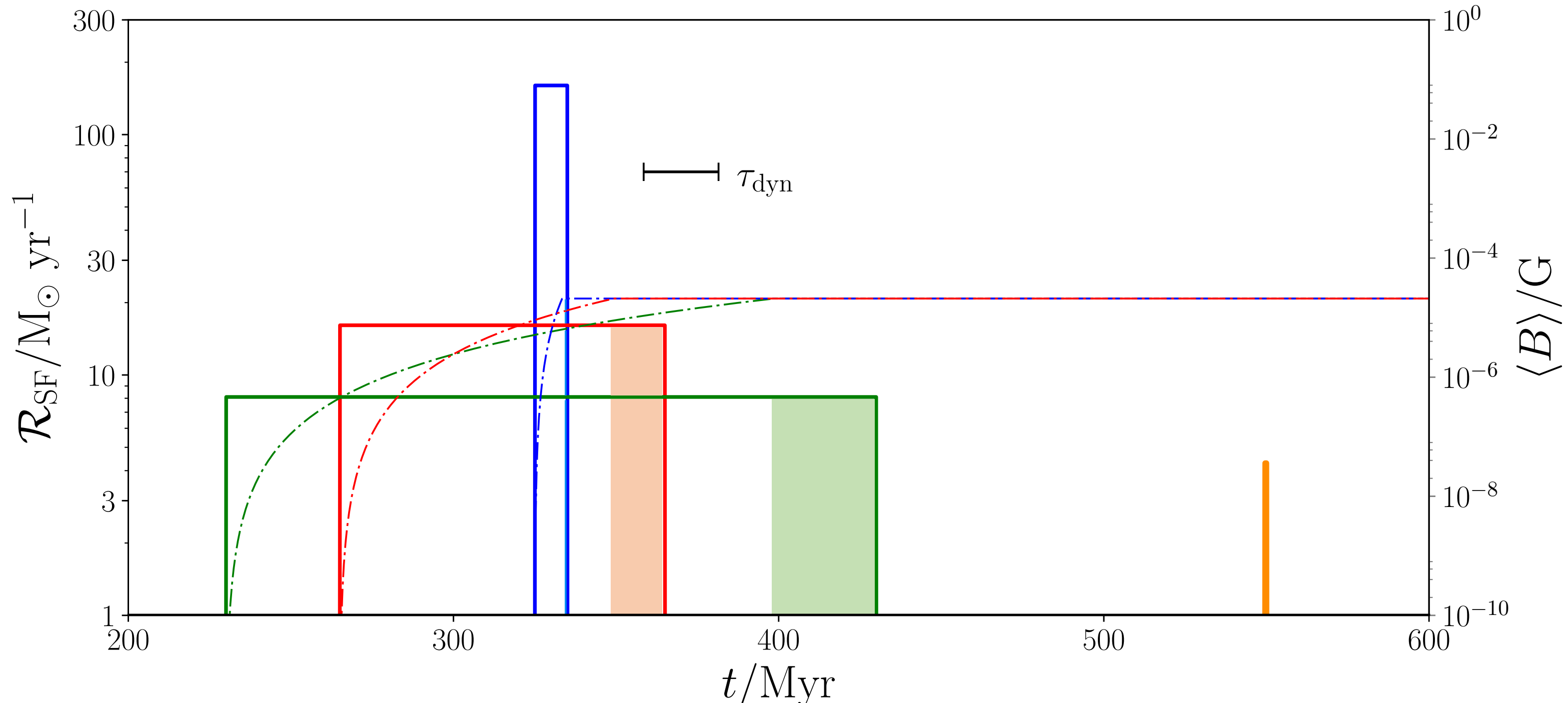


HST and ALMA image of MACS1149-JD1 (z=9.11) – NASA/ESA, Hashimoto+ 2018

Can CRs account for the rapid 100 Myr quenching after initial burst?

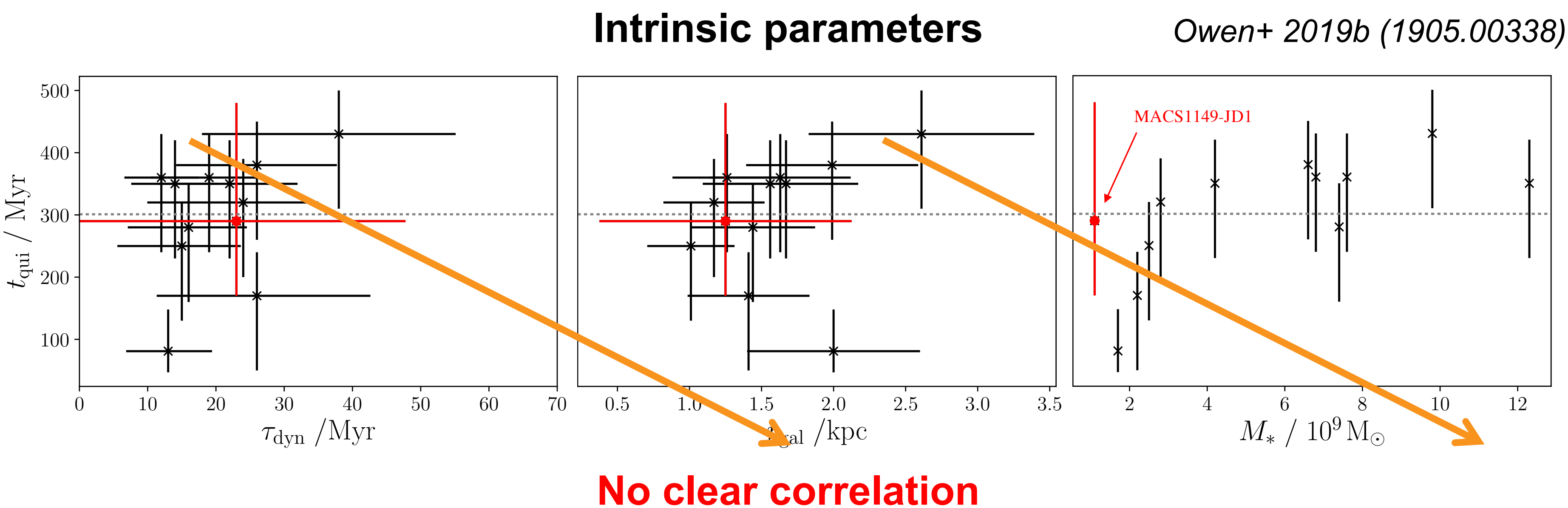
Can CRs do the job?

- Hashimoto+ 2018 star-formation burst models (intense, medium, slow).
- Schober+ 2013 magnetic field growth, traces cosmic ray containment.
- Consistent with CR strangulation + quenching working together.
  - Radiative heating timescales **not** consistent with rapid 'quenching'



Owen+ 2019a (1901.01411)

Why not other mechanisms?

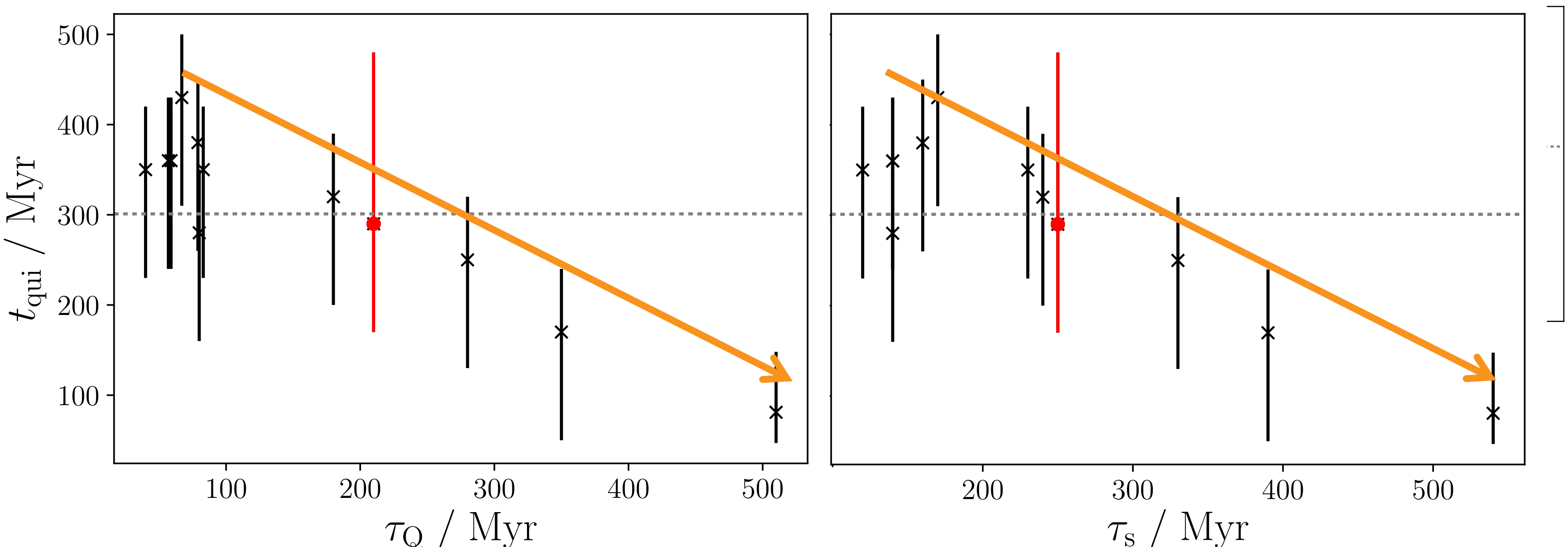


- 11 more systems selected from literature, post-SB with relatively high stellar mass, but low SFR (plus availability of measured quantities…)
  - Indicative of being in a quiescent stage of their evolution
- Dependence on only intrinsic (internal) parameters
  - Internal feedback not external trigger

Why not other mechanisms?

Extrinsic parameters

Owen+ 2019b (1905.00338)



Negative correlation

- Clear trend, **not** predominantly sudden/stochastic (i.e. mechanical hypernovae, etc)
  - Progressive heating (e.g. by CRs) consistent here too

Summary and outlook

- Cosmic rays are presumably abundant in high redshift starbursts
- Can deposit energy into ISM and multi-component CGM with implications for star-formation quenching/strangulation
- Able to account for the "bursty" star-formation histories in high-z starburst/post-starbursts
- Next steps: sub-galactic and super-galactic scales
  - Detail of internal feedback in molecular clouds/observable signatures
  - Impacts on CGM and flows of matter/energy
  - Impacts on external environment (e.g. cosmic reionisation, gamma-ray background)

- Selected publications:
  - Owen+ 2018 MNRAS 481 666 (arXiv:1808.07837)
  - Owen+ 2019a MNRAS 484 1645 (arXiv:1901.01411)
  - Owen+ 2019b A&A 626 A85 (arXiv:1905.00338)