Interactions between UHE Particles and Protogalaxy Environments

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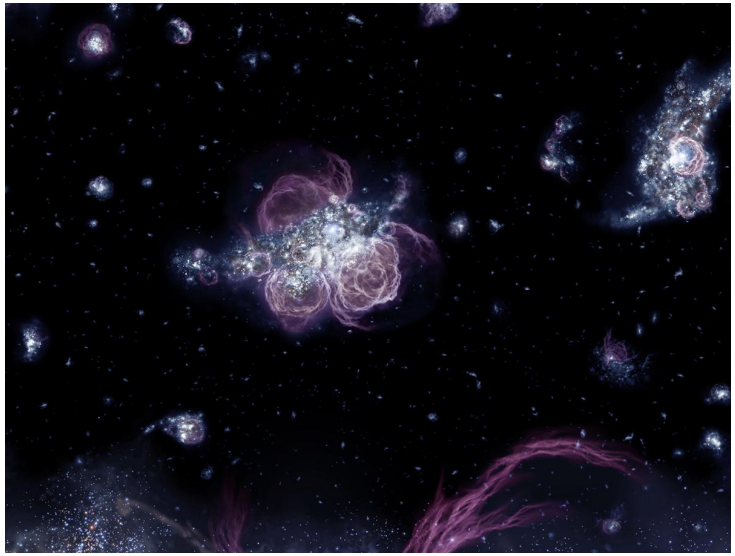


Image Credit: NASA - Adolf Schaller Hubble gallery
Artist's impression of protogalaxies

HEPP/APP University of Sussex, Brighton, United Kingdom, March 2016

Outline

1. UHE Particles in Protogalaxies
2. Protogalaxy Environments
3. Interaction Mechanisms & Losses
4. Energy Deposition Lengths & ISM/IGM Heating

Ultra High-Energy Particles in Protogalaxies

- Cosmic Rays (CRs) accelerated in high energy astrophysical environments
  - Supernovae explosions / shocks
  - Accretion
- Particle energy distribution follows power law, peaks around ~10 GeV for galactic (stellar) contribution
- Expected to be present in young starburst galaxies (protogalaxies)
  - High star formation rate (SFR) ~1000 times more than cosmic average
  - Rate of supernovae roughly follows SFR
  - Cosmic ray flux attributed to stellar sources roughly follows supernova rate

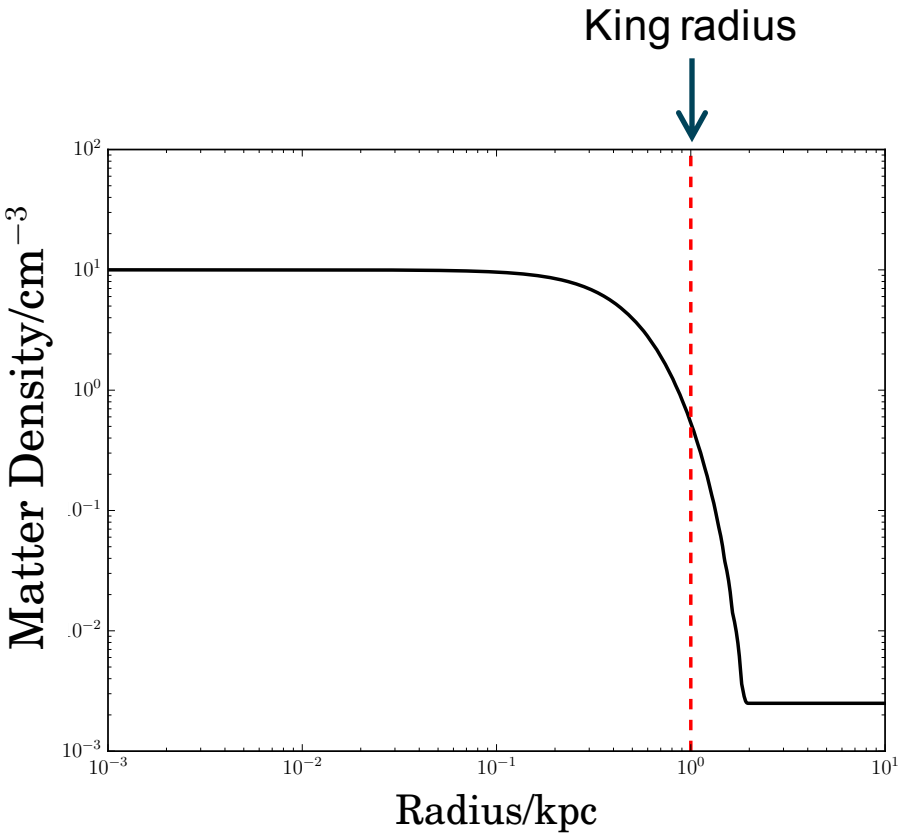
Protogalaxy Environment

Density Fields

- **King** model

Parameter	Value
r_t	2 kpc
r_K	1 kpc
n_0	10 cm^{-3}

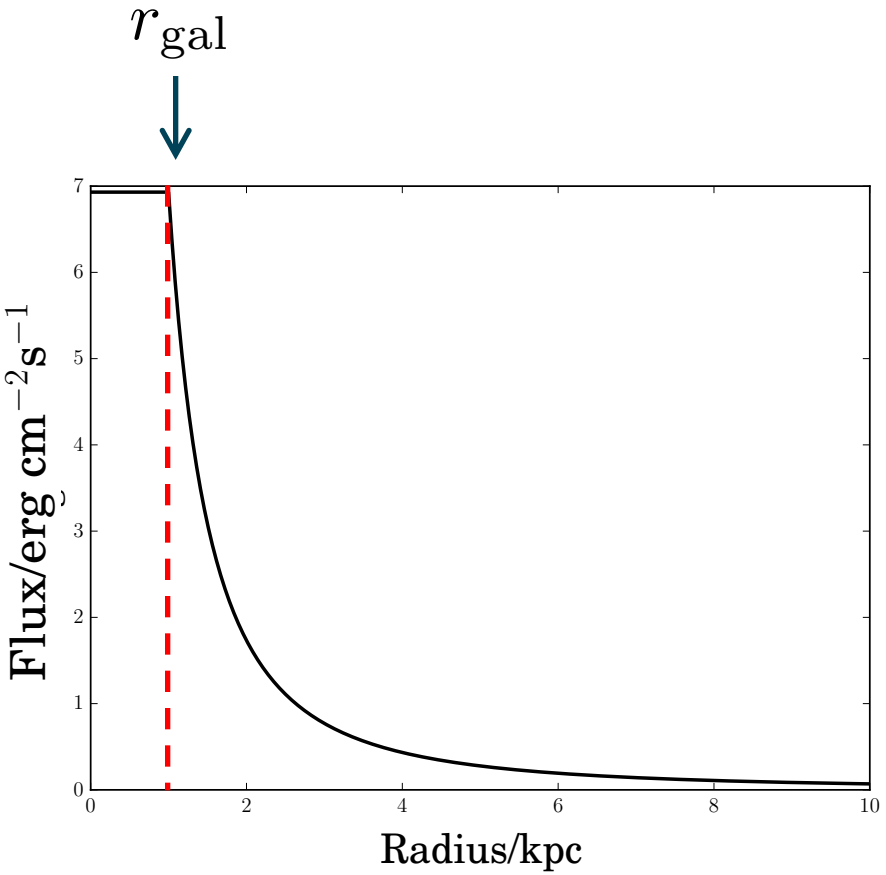
- Red line at King radius, 1kpc
  - Approximate radius of a protogalaxy (e.g. from high z LAE observations)



Protogalaxy Environment

Radiation Fields

- **Uniform spherical distribution** of stars within protogalaxy
- High mass, low metallicity
  - O/B type, **T~30,000K**
  - **T** Spectrally characterizes radiation field (BB spectrum)
- Field approximately uniform within the protogalaxy radius, then simple inverse square law at $r > r_{\mathrm{gal}}$

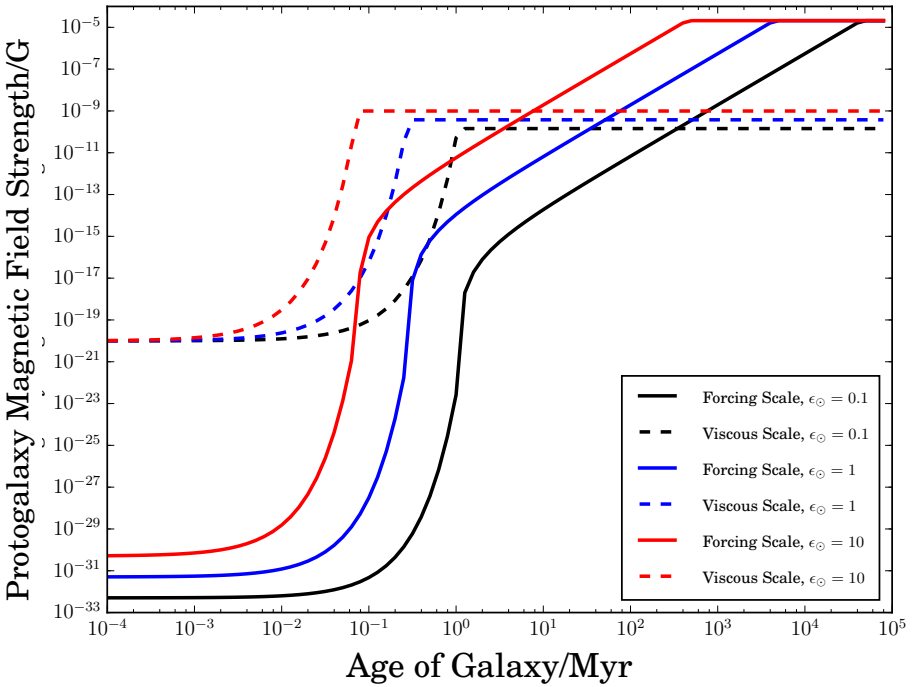


Protogalaxy Environment

Magnetic Fields

- Two scale components:
  - Local viscous scale, ~10^{-3} pc
  - Turbulent forcing ~1kpc
- SN driven, B follows density profile
- Initial B field ~10^{-20} G permeates protogalaxy
- Stellar processes drive turbulence, which drives B field up to μG levels seen in current epoch
  - Exponential growth
  - Then linear growth of the forcing scale field after local saturation

Efficiency of energy transfer
SNe → Turbulence → B field



Model follows J. Schober + 2013

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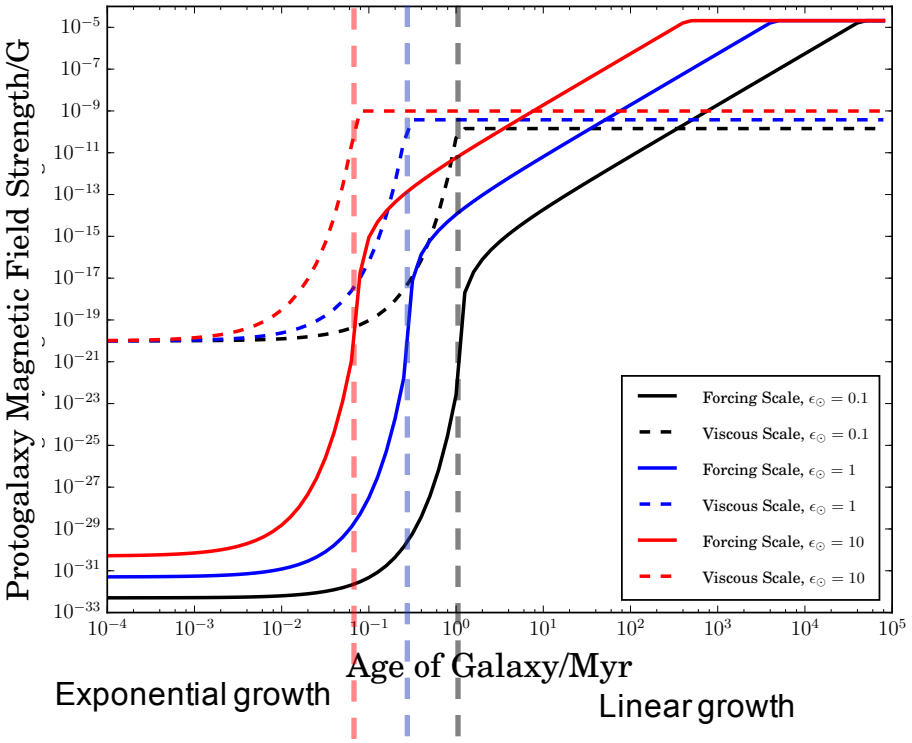

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Interaction Mechanisms & Losses

- Low energy particles
  - Collisions
    - Direct ionization
    - Heating
- High energy particles
  - Proton-photon (pγ)
    - Pion production (Photopion)
    - Pair production (Photopair)
  - Proton-proton (pp)
    - Pion production (Hadronuclear)

Interaction Mechanisms & Losses

Photopion ($\gamma\pi$) Interaction

$$p + \gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p + \pi^0 \rightarrow p + 2\gamma \\ n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \end{cases}$$

$$\downarrow$$

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

+ pion multiplicities at higher energies

Photopair (γe) Interaction

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

Interaction Mechanisms & Losses

Hadronuclear (*pp*) Interaction

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

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Interactions of neutrons and photons → pion production

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

Interaction Mechanisms & Losses

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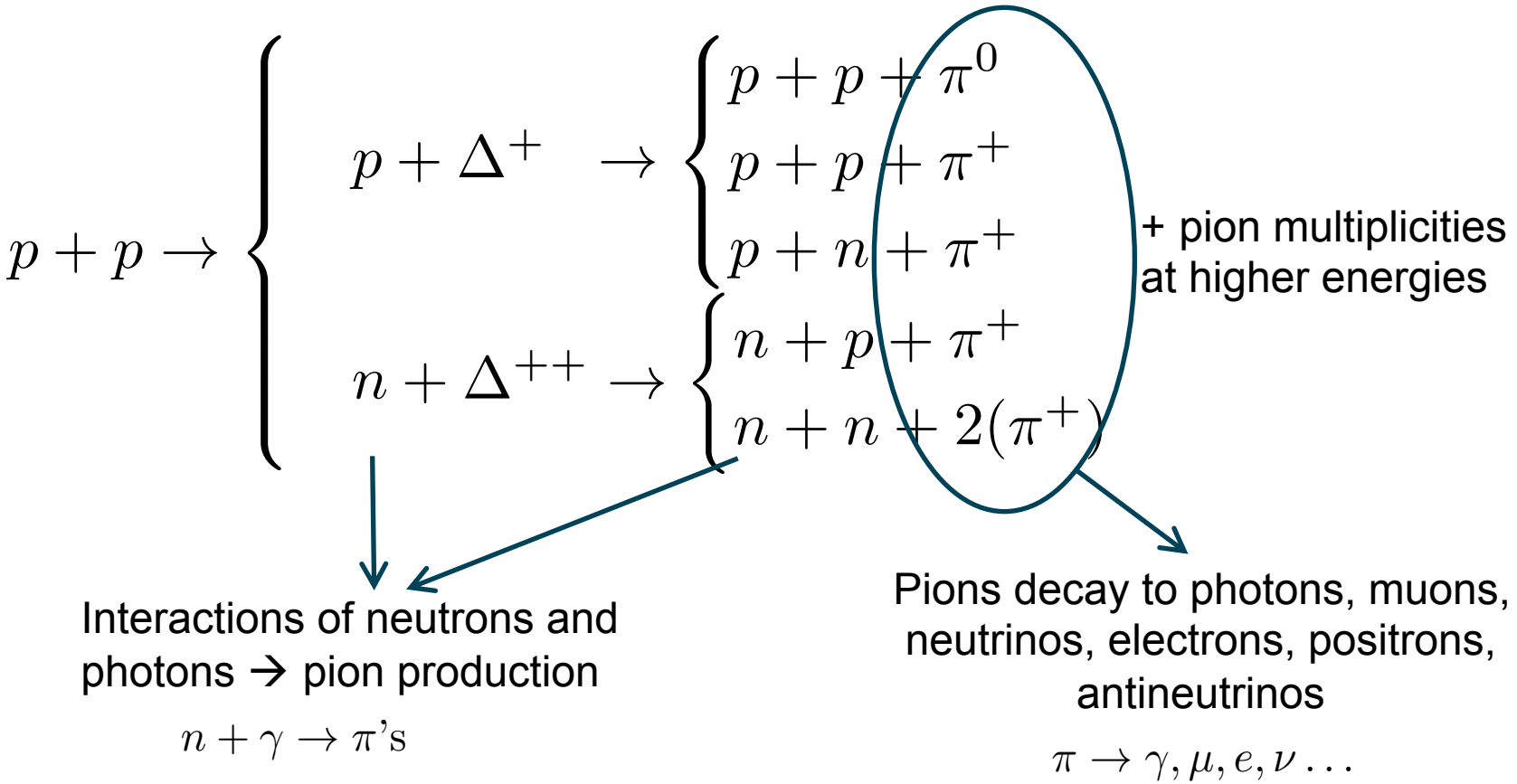

Cross Section/Mean Free Path

γ Interactions

- Pair production, Bethe-Heitler process
  - Cross Section by fitting function

$$\sigma_{\gamma e}(\epsilon_{\mathrm{r}}) \approx \frac{7}{6\pi}\alpha_f \sigma_{\mathrm{T}} \ln\left(\frac{\epsilon_{\mathrm{r}}}{k_{\gamma e}}\right)$$

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  - Cross section by fitting step function to data (Dermer & Menon 2009/Reimer 2007)

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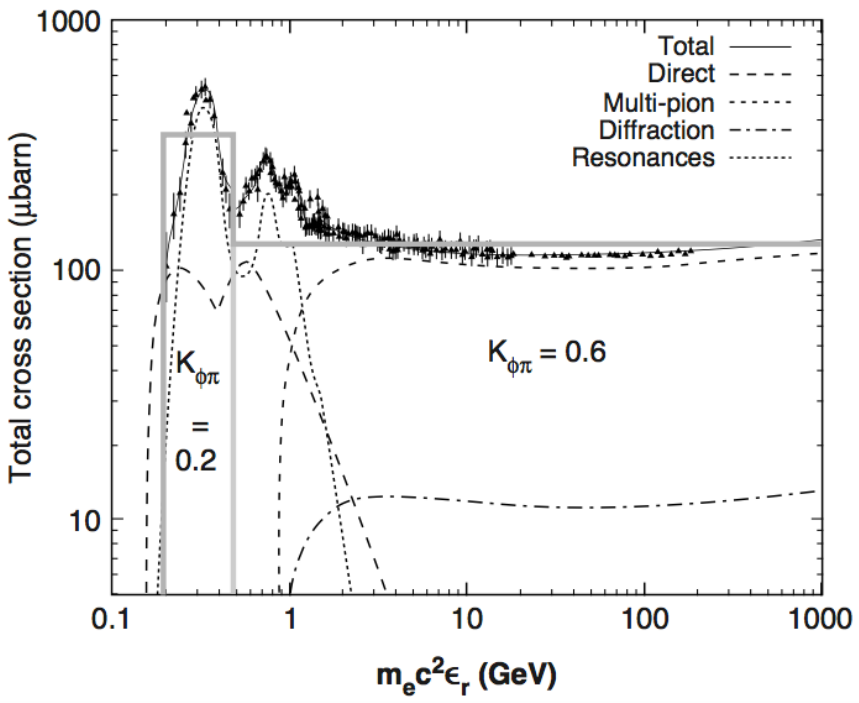

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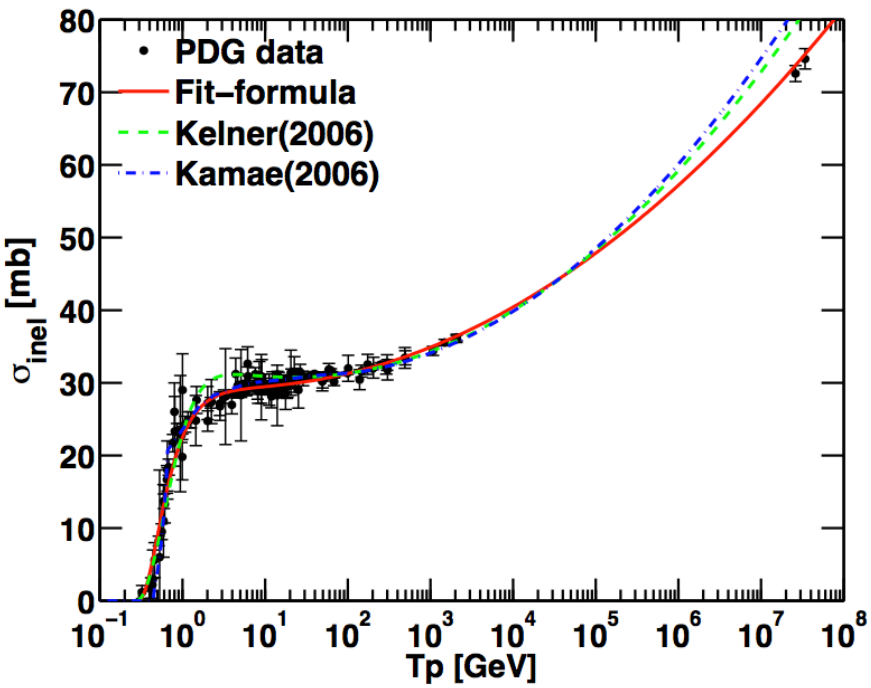


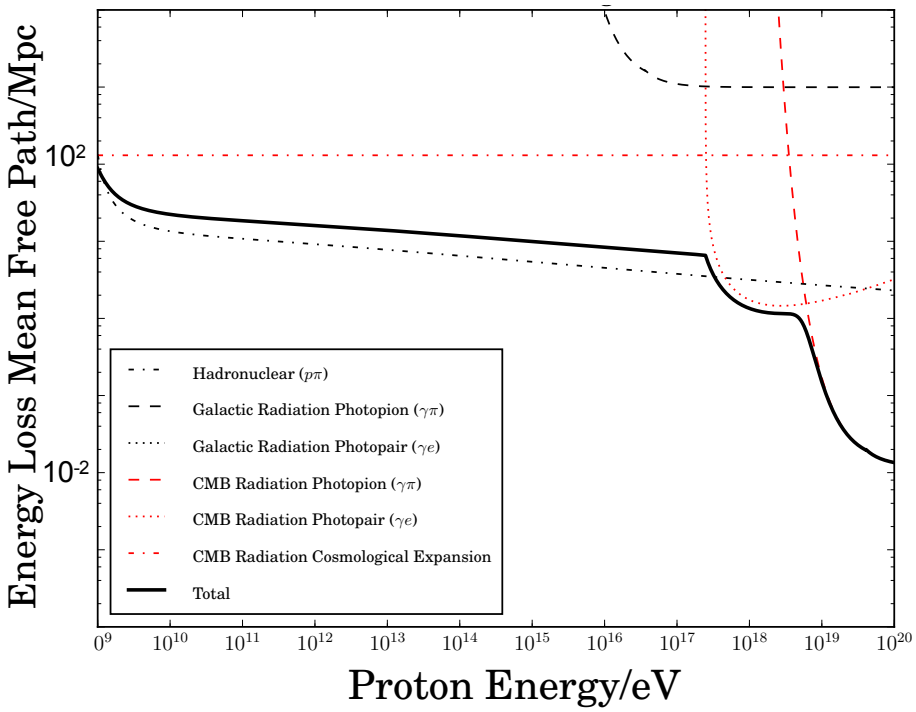
p Interactions

- Hadronuclear production
  - Cross section by fitting to data (Kafexhiu+ 2014)

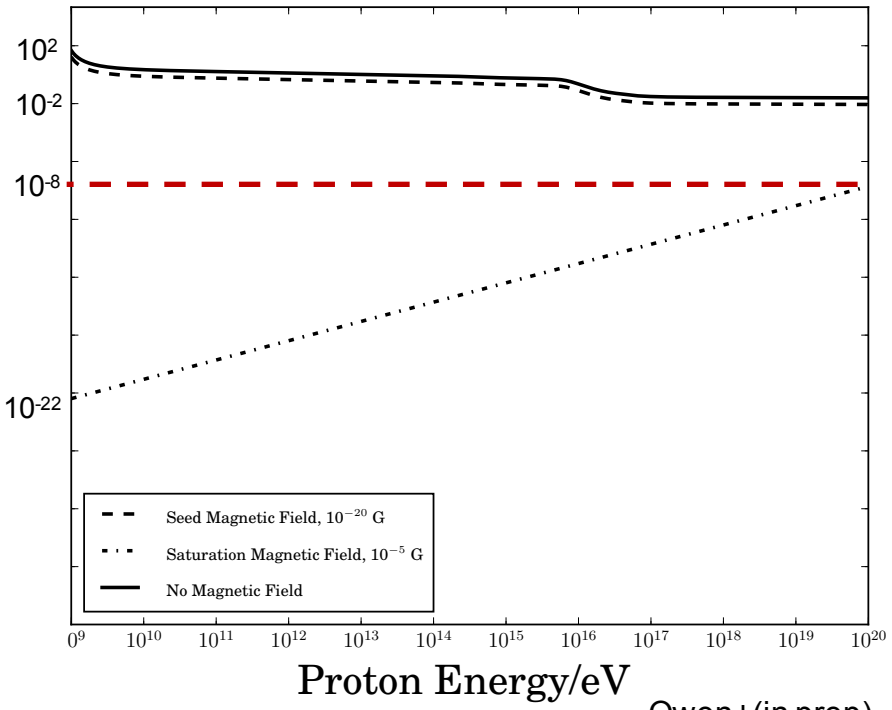
Energy Deposition & IGM/ISM Heating

Mean Free Path of UHE Protons

Contributions



Magnetic Field



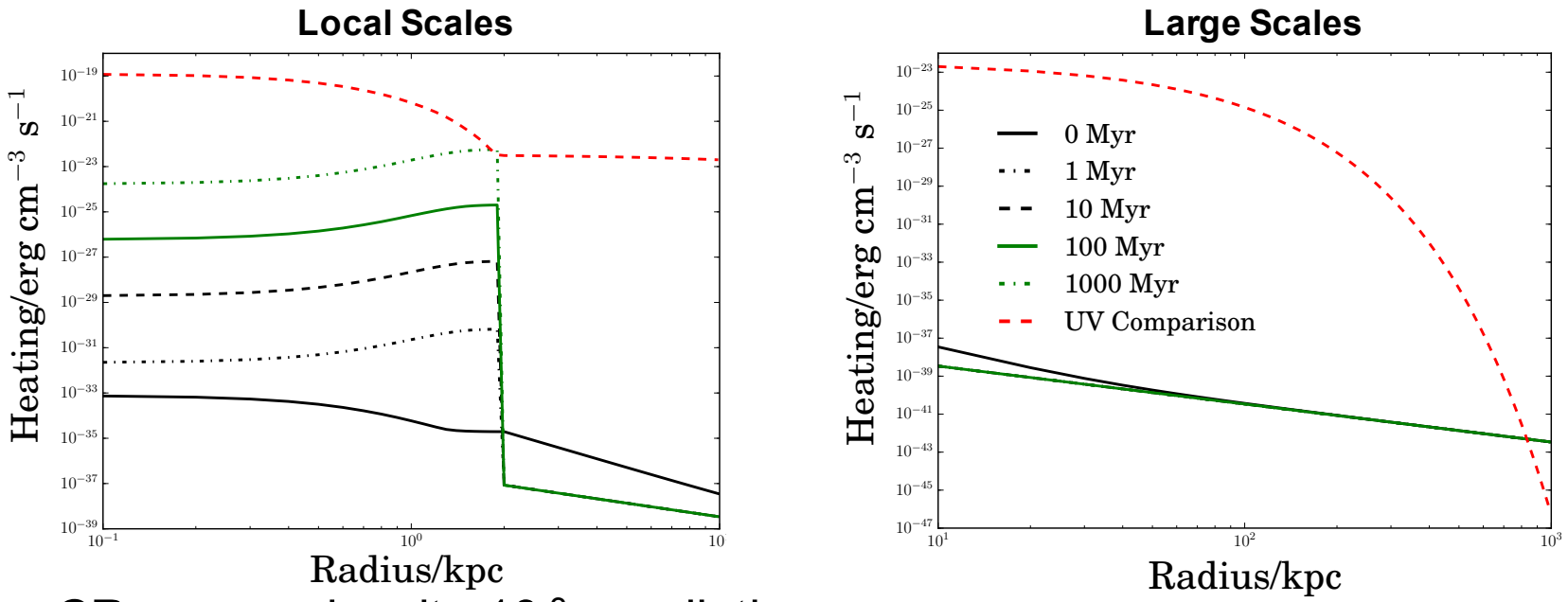
Owen+(in prep)

- Assume products decay quickly at interaction point
- Energy of CR deposited ~at point of interaction

Energy Deposition & IGM/ISM Heating

Estimated Heating Impact

Preliminary



- CR energy density 10^{-3} x radiation
- Impact of magnetic fields
  - Determines whether the CRs are able to escape or not
    - Escape: heat IGM (possible implications for cosmic reionization)
    - No escape: heat ISM (possible implications for star formation in galaxy)
  - There is a window of a few Myr for the CRs to escape

Summary

- Cosmic ray protons thought to be accelerated in protogalaxy environments
  - Supernova shocks, ISM turbulence…
- Energy spectrum peaks ~few x 10 GeV
- CRs can interact collisionally, or by *pp*, $p\gamma$ interactions (pair production & pion production)
- Drives energy deposition & heating
- CRs shown to have non-negligible heating impact on their medium
- Effect increasingly trapped within protogalaxy as magnetic field evolves
  - But a window of a few Myr allows initial escape into the Intergalactic medium causing heating over larger scales

References

- Dermer & Menon (2009) – *High Energy Radiation from Black Holes: Gamma-Rays, Cosmic Rays and Neutrinos,* Princeton Series in Astrophysics
- A. Reimer (2007) - *The Redshift Dependence of Gamma-Ray Absorption in the Environments of Strong-Line AGNs*, ApJ, 665, 1023
- Kafexhiu+ (2014) - *Parametrization of gamma-ray production cross sections for pp interactions in a broad proton energy range from the kinematic threshold to PeV energies*, Phys. Rev. D 90, 123014
- Schober+ (2013) - *Magnetic field amplification in young galaxies*, A&A 560, A87
- Owen+ (in prep) – *Interactions between Ultra High Energy Particles and Protogalaxy Environments*, MNRAS