Star-forming galaxies through cosmic time

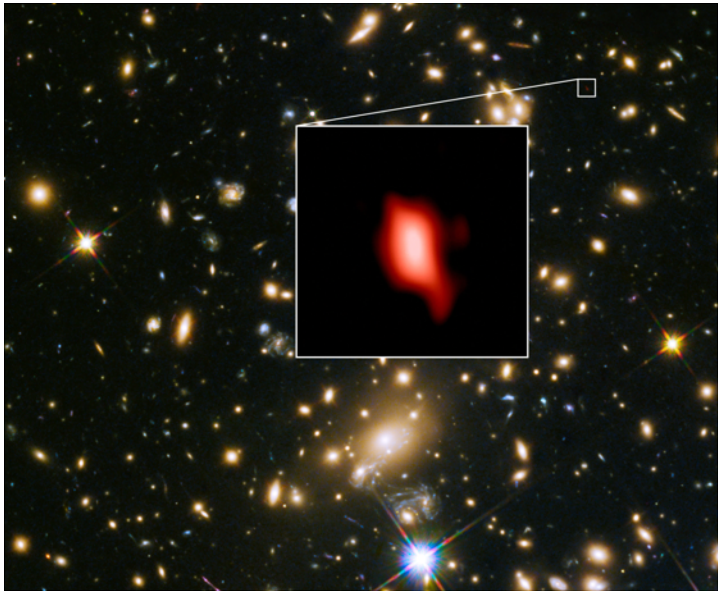
The impacts and signatures of cosmic rays

Ellis Owen

CICA Fellow

Institute of Astronomy
National Tsing Hua University

erowen@gapp.nthu.edu.tw



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

Collaborators

Kinwah Wu (UCL); Alvina Y L On (NTHU/UCL-MSSL);
Shih-Ping Lai (NTHU); Y X Jane Yap (NTHU);
KG Lee (IPMU); Albert Kong (NTHU/Oxford)

ICRR Seminar – February 2020

Outline

- Star-forming galaxies in the Universe
- Cosmic rays in star-forming galaxies
- Particle propagation
- Cosmic ray feedback & star-formation histories
- A closer look: star-formation & sub-grid physics
- Signatures (gamma-rays)

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

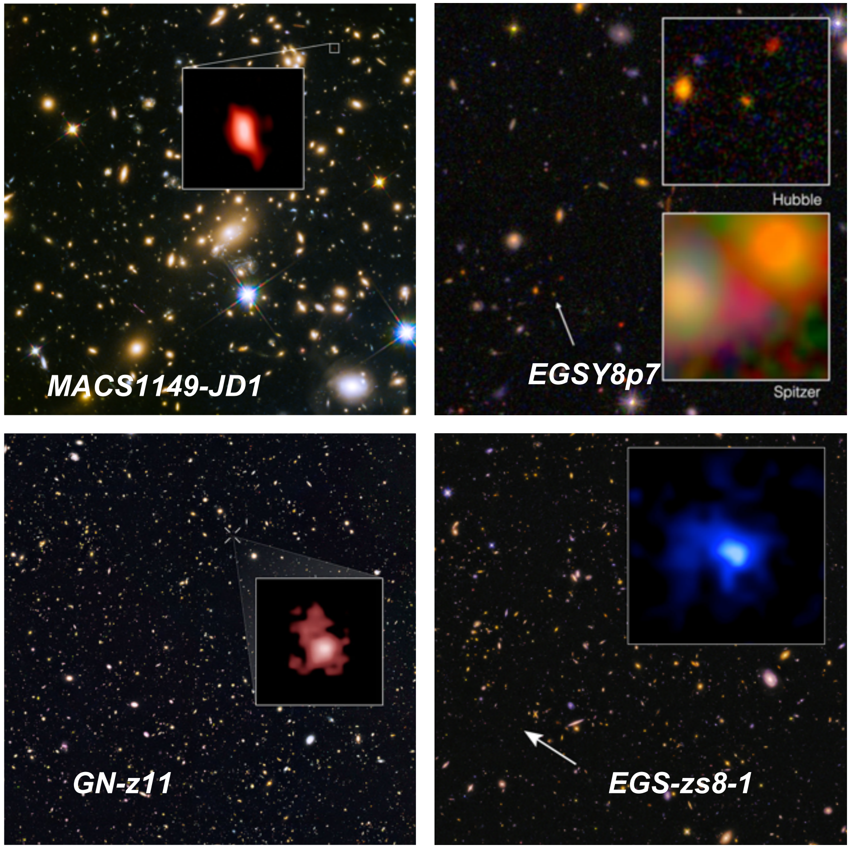
NASA/ESA 2006

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

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

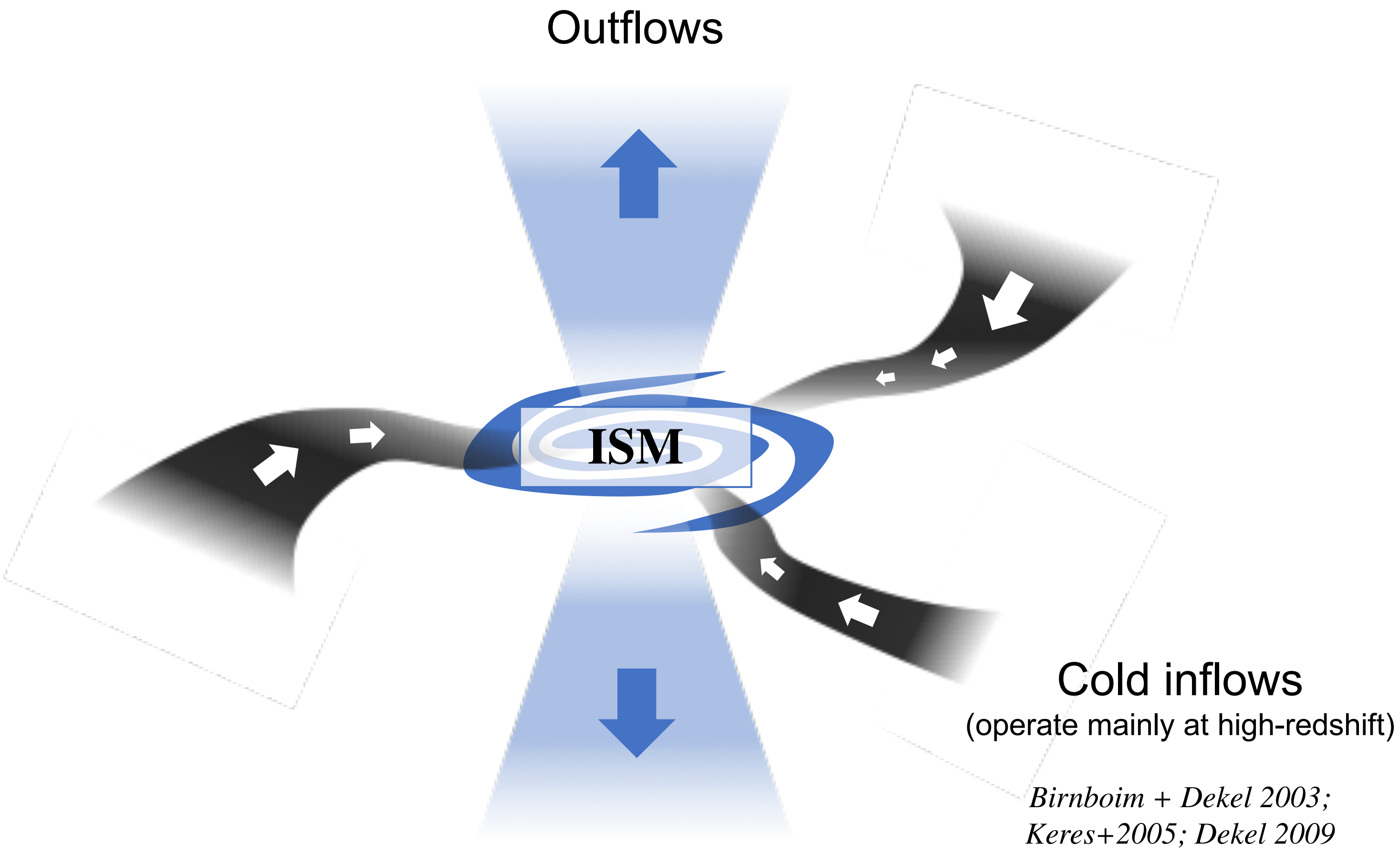
High-redshift starbursts (z~6+)

- 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 %
- Simulation work suggests possibility of filamentary inflows of gas *(cf. works by Keres, Dekel, Birnboim…)*
- High supernova event rates



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



Cold inflows
(operate mainly at high-redshift)

Birnboim + Dekel 2003;
Keres+2005; Dekel 2009

Figure based on Tumlinson+2017

Cosmic rays in star-forming galaxies

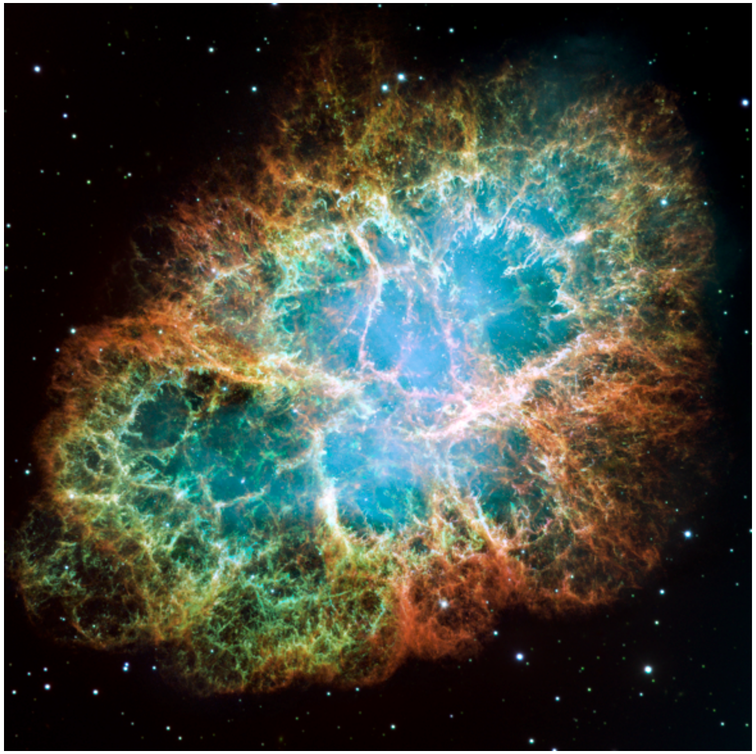
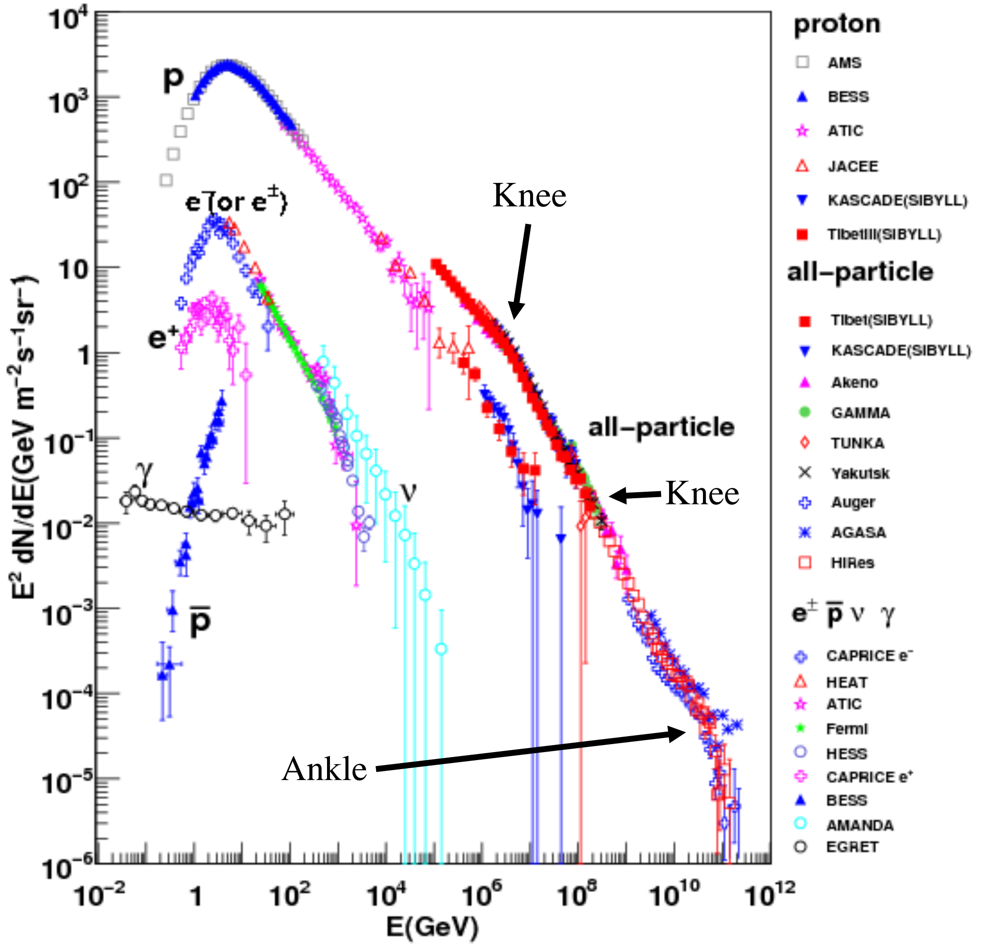


Image credit: Crab Nebula, NASA, ESA 2005

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

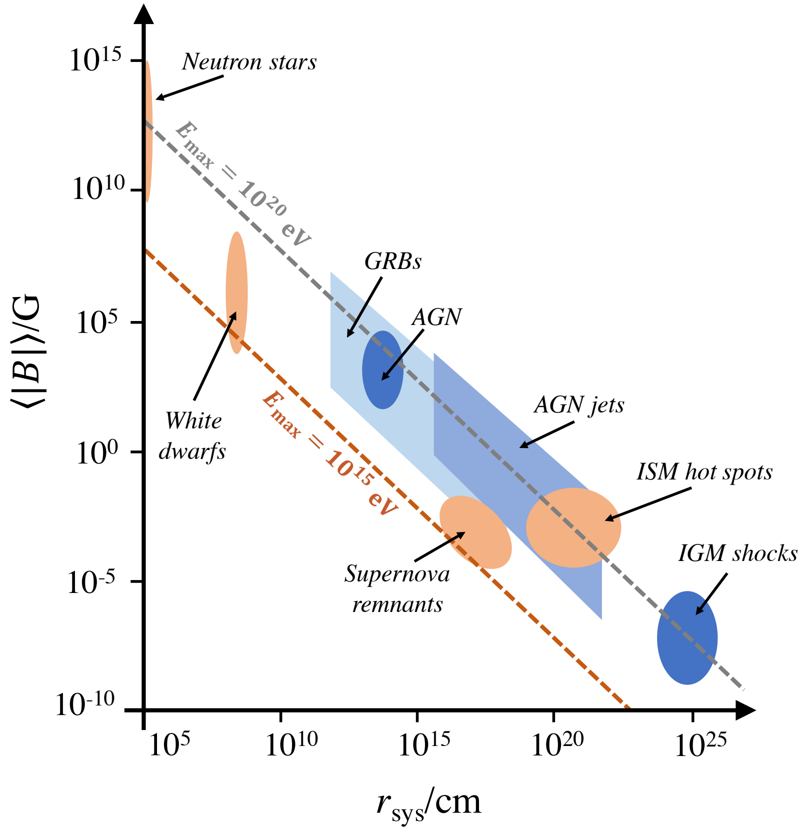


Fig. adapted from Owen 2019 (PhD thesis)
See also Kotera & Olinto 2011; Hillas 1984

Cosmic ray interactions

with radiation fields (*pγ*)

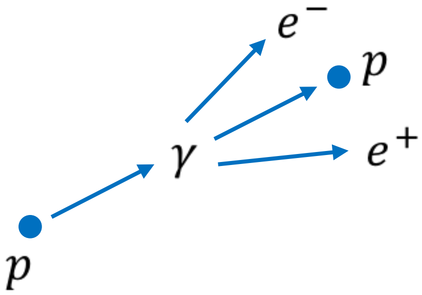
Interaction by particles scattering off ambient photons (starlight, CMB…)

Photopion Interaction

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

+ pion multiplicities at higher energies

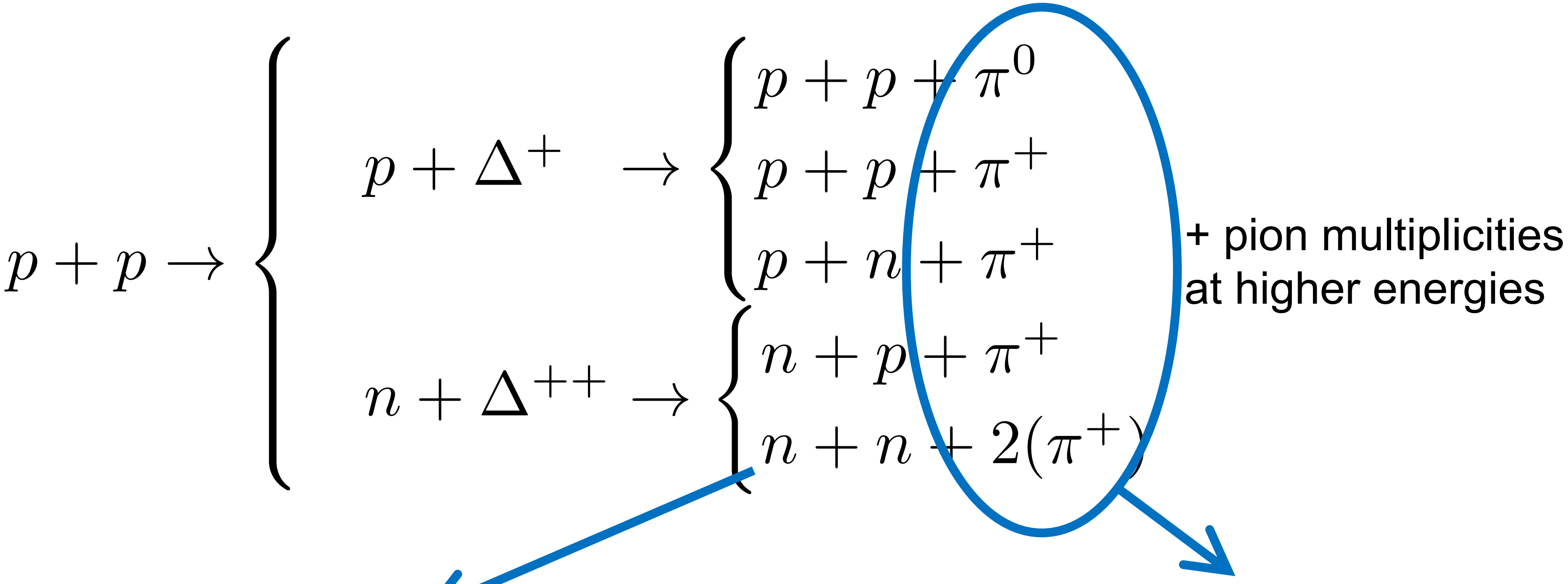
Photopair Interaction



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

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

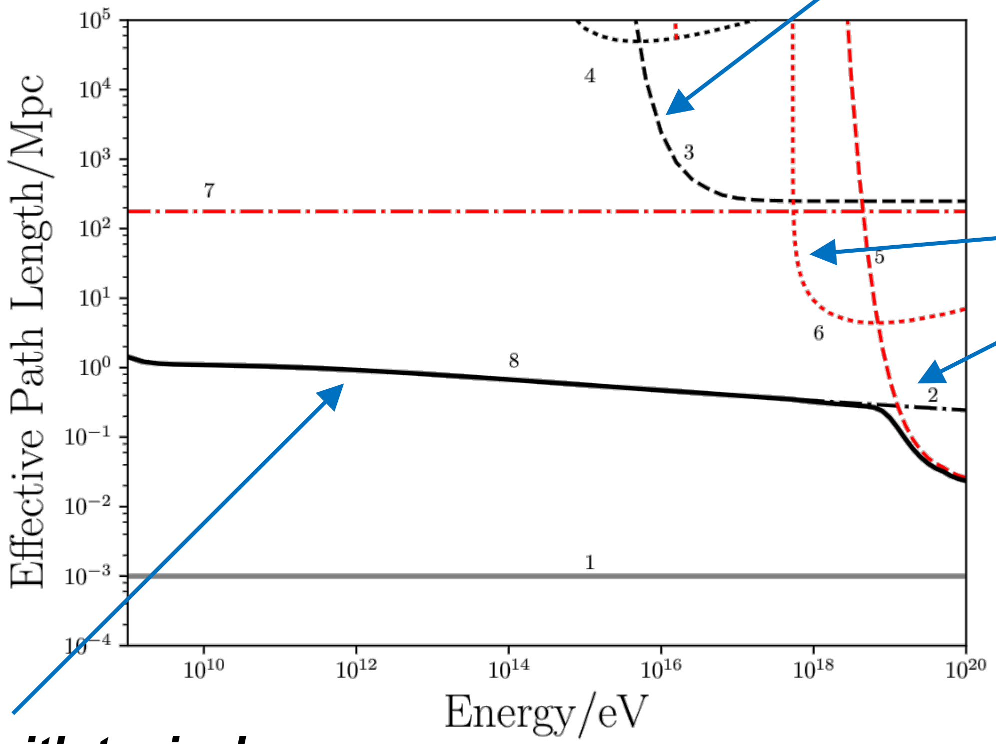
$$n + \gamma \rightarrow \pi\text{'s}$$

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

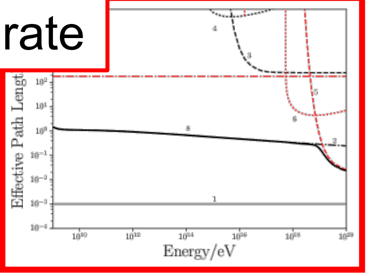
Image credit: M25 Motorway, Carillon UK Transport

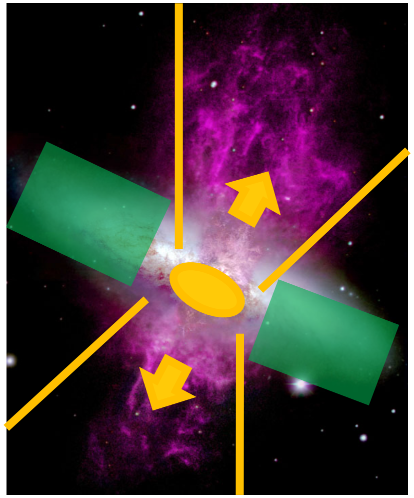
The transport equation (hadrons)

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

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

SN rate





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

Secondary electrons

- Injection by the pp attenuation process

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

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

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

- Transport equation (electrons)

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

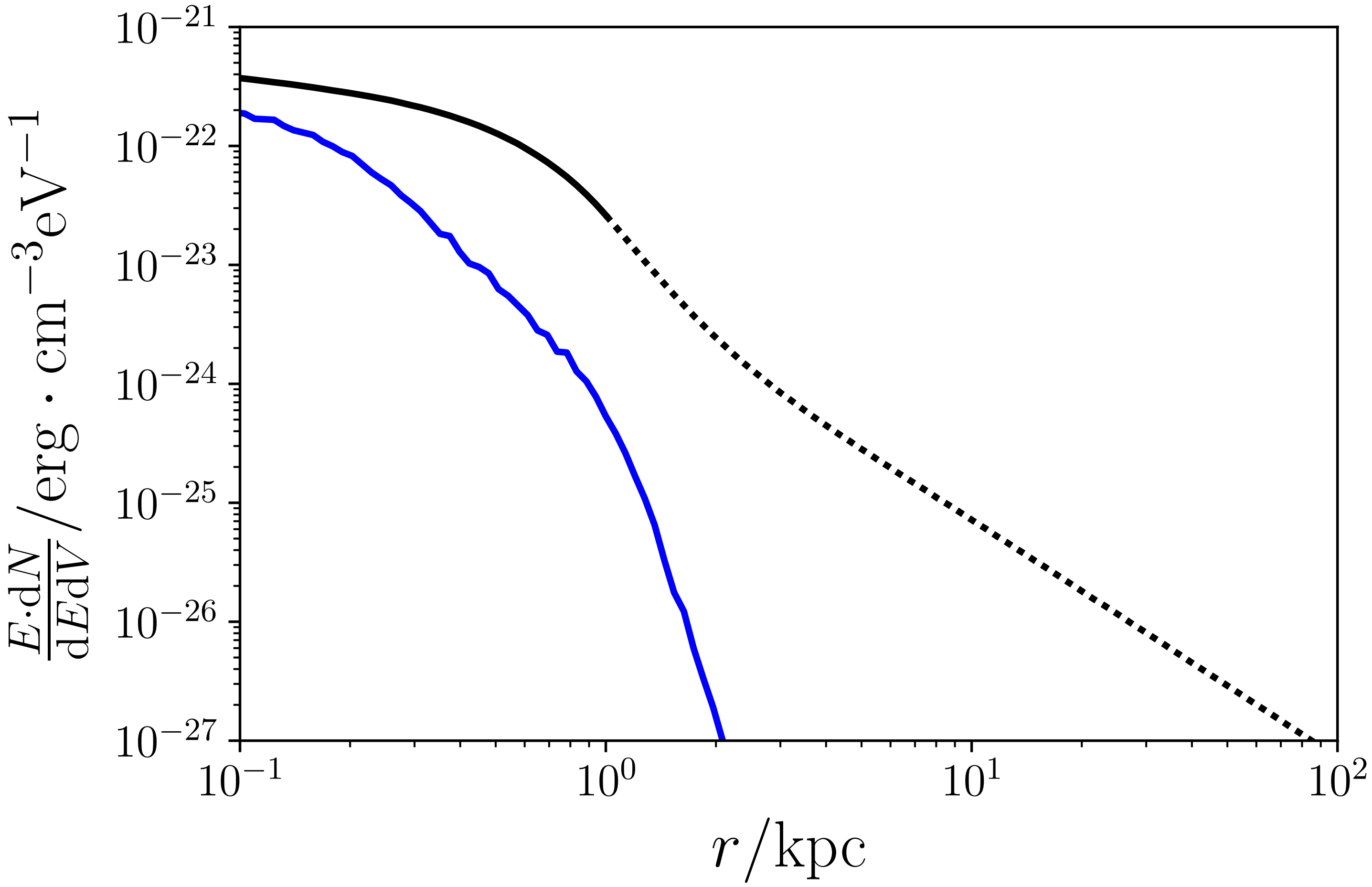
The transport equation (hadrons)

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

- 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)

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

Cosmic ray distribution in ‘stationary’ ISM



Cosmic ray feedback

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

Timescales

- Estimate by considering condition for them to no longer be gravitationally bound – upper-limit **(a very crude approximation → details later)**

$$\tau_{\rm Q} = \boxed{\tau_{\rm mag}} + \tau_{\rm heat}$$

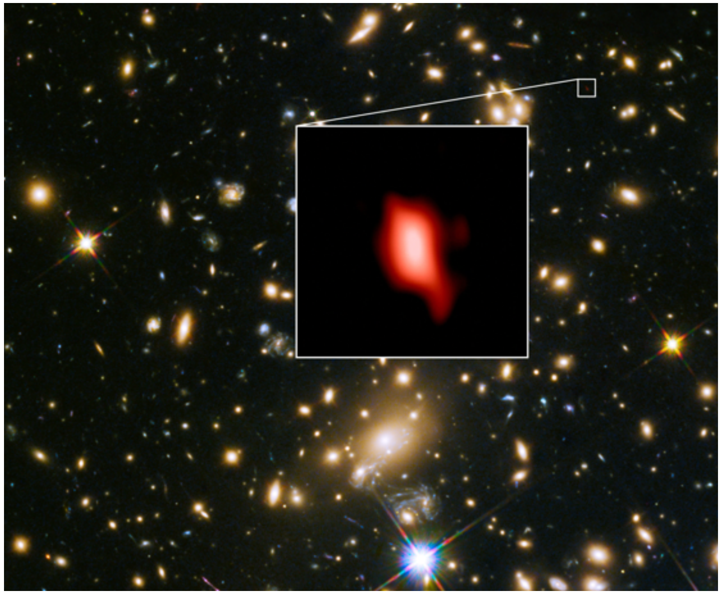
Time for region of gas to exceed $T_{\rm vir}$ *due to CR heating*

Magnetic containment time; required for CR effects to develop

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

Inferred behavior of MACS1149-JD1

- Spectroscopic z=9.11 (t = 550 Myr)
  $\mathcal{R}_{\rm SF} \approx 4.2^{+0.8}_{-1.1}\ {\rm M}_{\odot}\ {\rm yr}^{-1}$
- 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



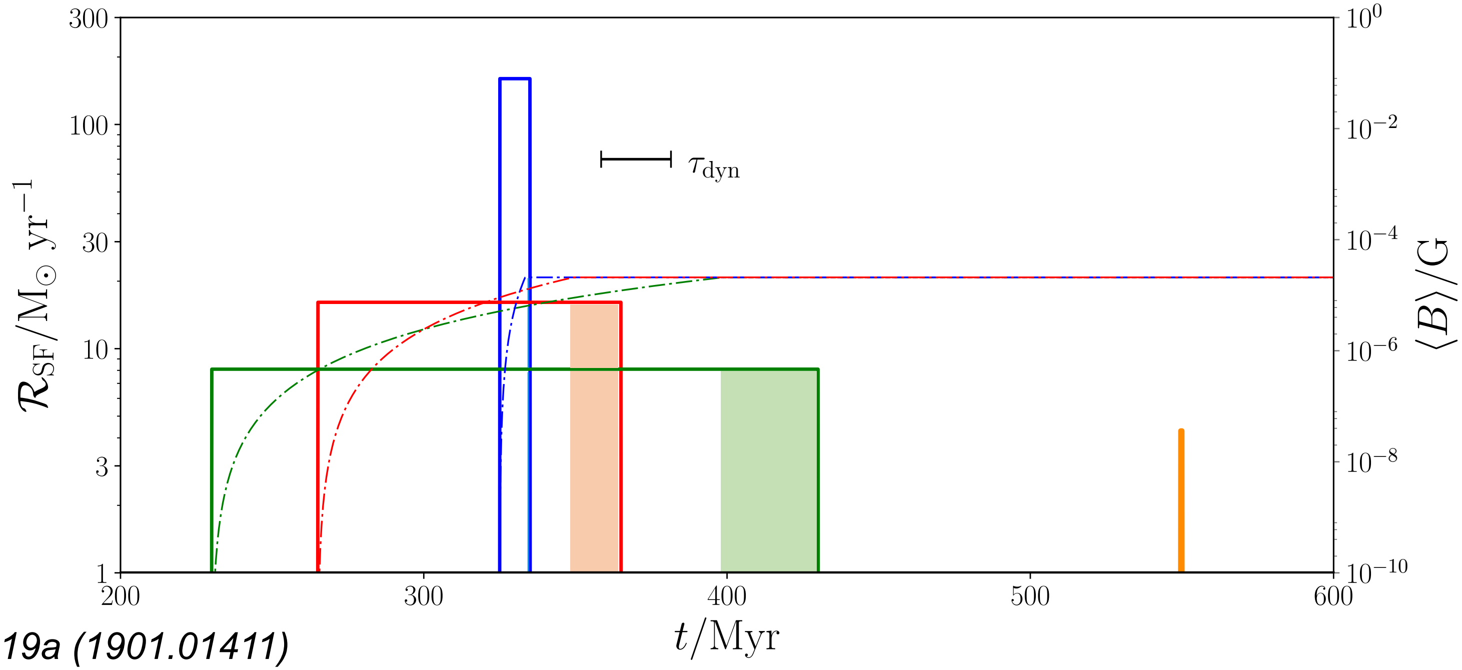
HST and ALMA image of MACS1149-JD1 (z=9.11) – NASA/ESA, Hashimoto+ 2018

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

Can CRs do the job? – half an answer…

- Hashimoto+ 2018 star-formation burst models (intense, medium, slow).
- Schober+ 2013 magnetic field growth, traces cosmic ray containment.

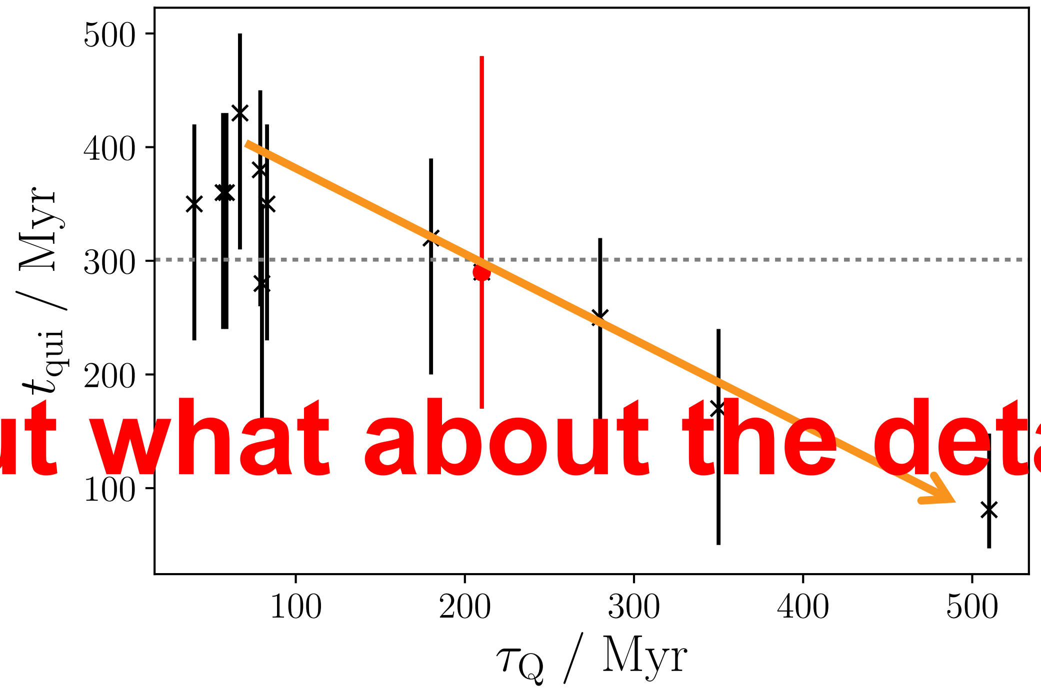
- Consistent with CR mechanisms (or mechanical mechanisms)
  - Radiative heating timescales **not** consistent with rapid ‘quenching’ (need a delay, then fast action)



Owen+ 2019a (1901.01411)

Why not other mechanisms?

Owen+ 2019b (1905.00338)



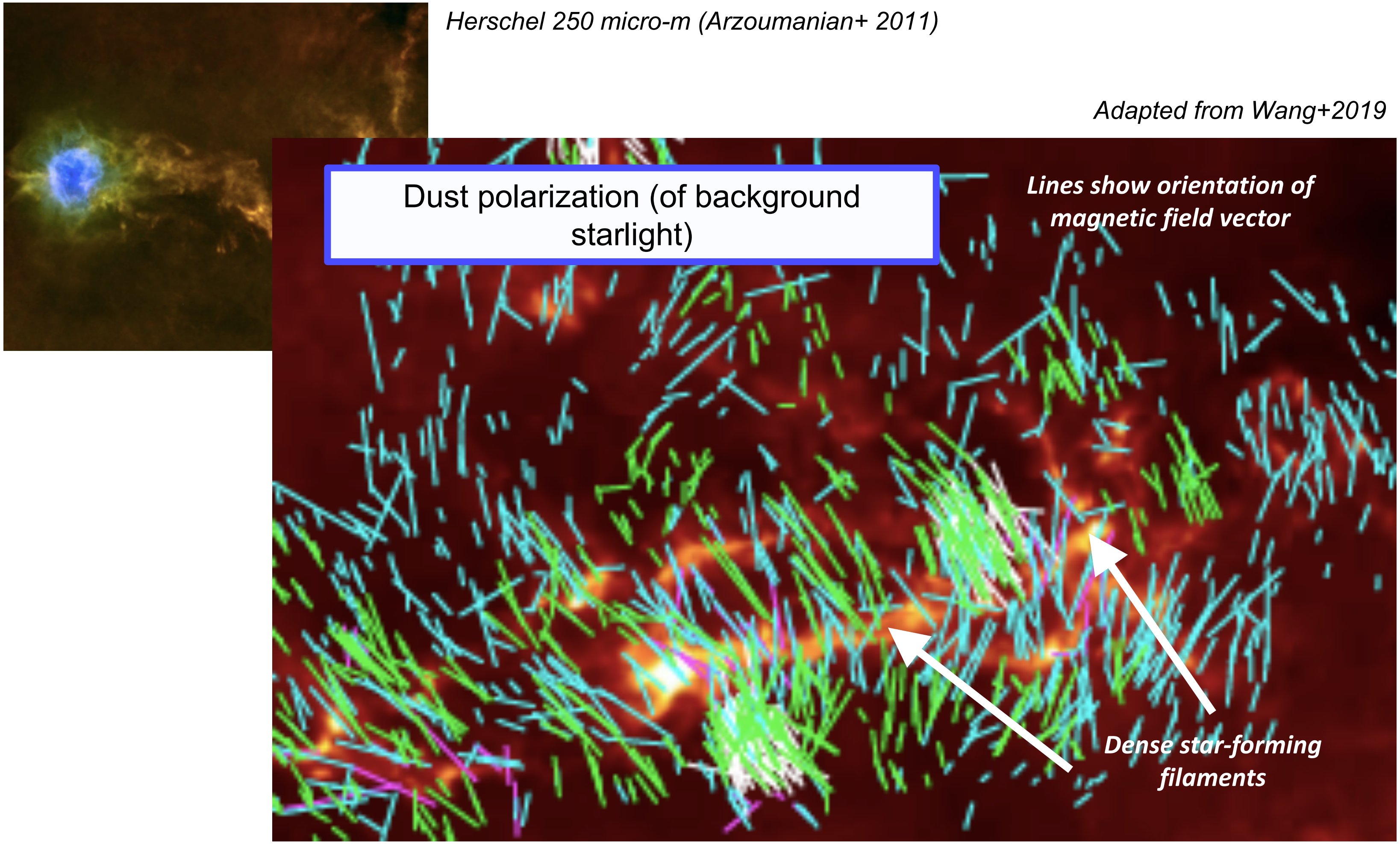
But what about the detail…?

- Clear trend, **not** predominantly sudden/stochastic (i.e. not mechanical hypernovae, etc)
  - Progressive heating (e.g. by CRs) consistent here too
- Dependence on only intrinsic (internal) parameters
  - Internal feedback not external trigger

A closer look…

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

IC 5146 star-forming region in Cygnus



Herschel 250 micro-m (Arzoumanian+ 2011)

Adapted from Wang+2019

Dust polarization (of background starlight)

Lines show orientation of magnetic field vector

Dense star-forming filaments

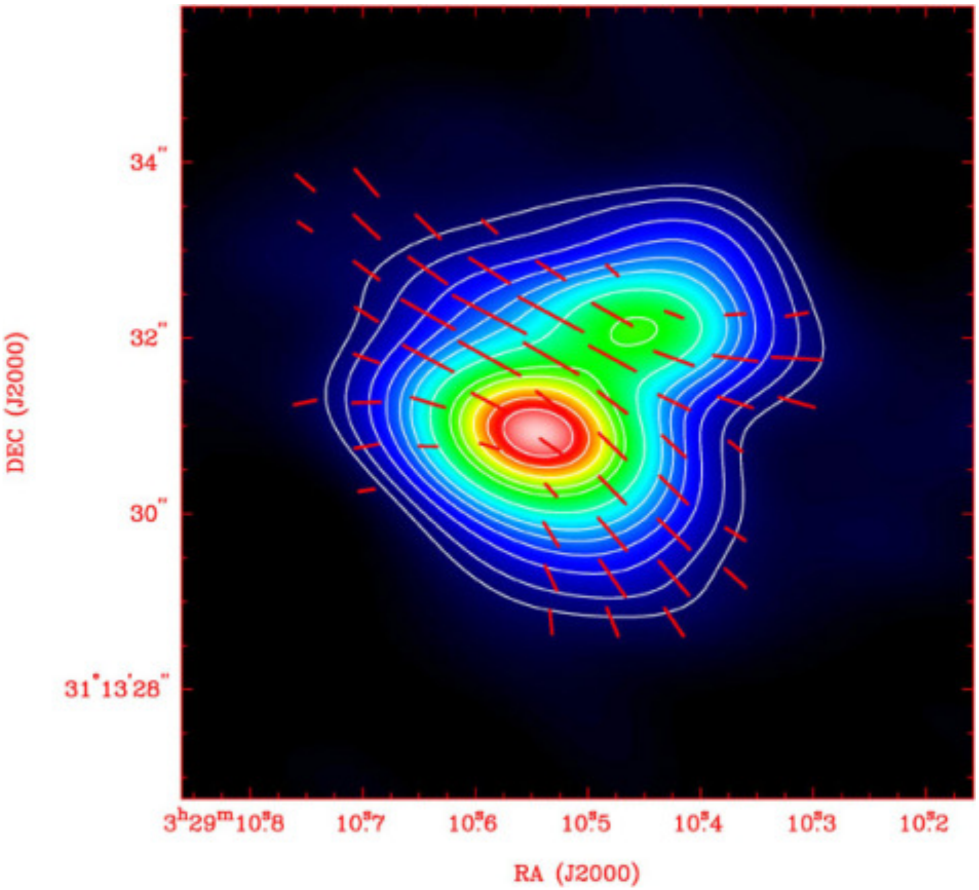
Evolution of magnetic fields in clouds

Initial collapse from ISM (drags hourglass field)

Collapses along field (pancake/filament)

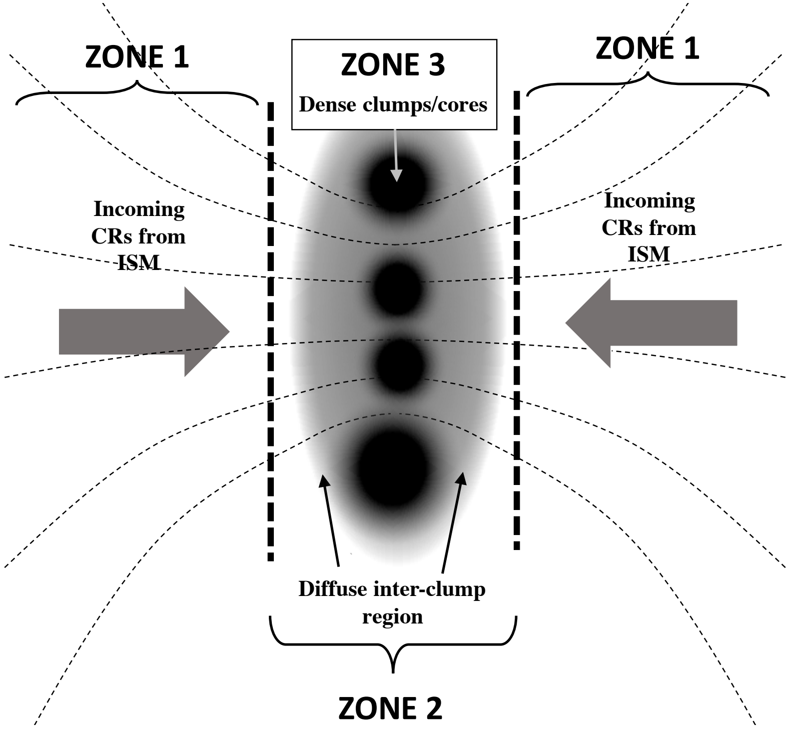
Collapse injects turbulence, some fragmentation & magnetic support (messy small-scale magnetic field)

Diffusion until further fragmentation & collapse into clumps/cores/stars

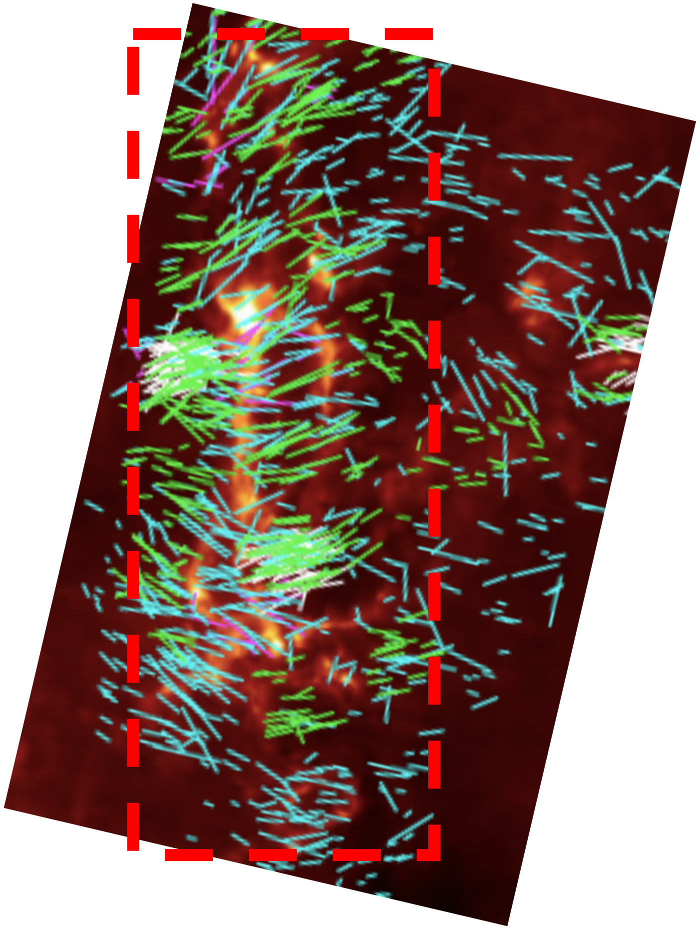


Harvard-Smithsonian Center for Astrophysics (2006)

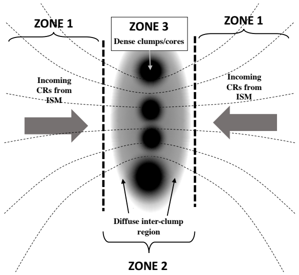
Multi-scale structure



Owen+2020 (submitted)



Cosmic ray propagation



Revisit the transport equation:

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

Depends on local-scale structure and strength of the magnetic field

- **Strength**:
  - Direct (Zeeman splitting)
  - Indirect (DFC method via structure function AKA dispersion function)
- **Structure**:
  - Via power spectrum (fluctuation analysis); quantifies CR ‘tangling’

$$D \propto \frac{1}{P(k)} \qquad P(k) = \frac{1}{2}\mathcal{F}\left[\mathcal{S}_2(\ell)\right]$$

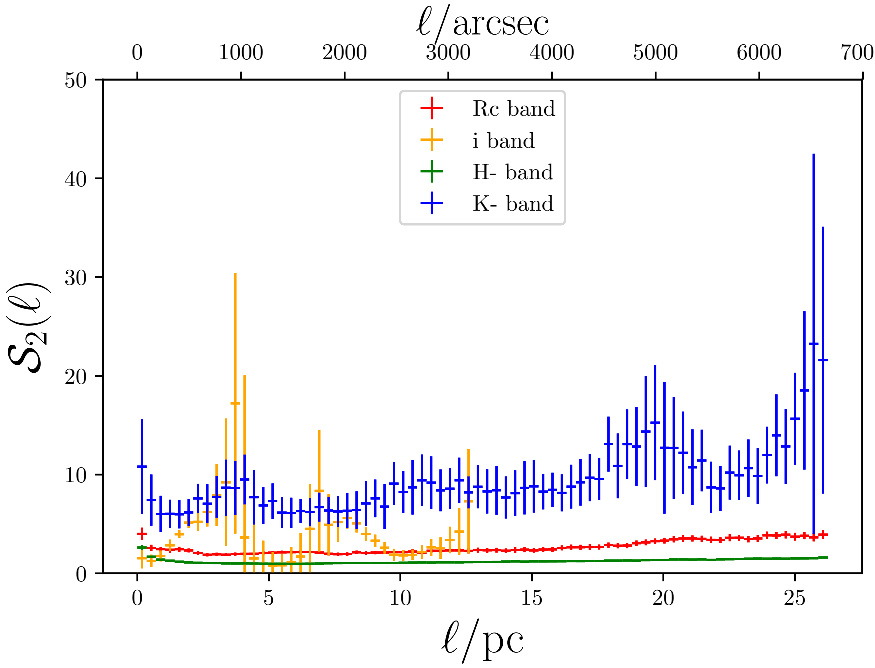
Wiener-Khinchin theorem

Dispersion function

- Quantify polarization angle (B field) fluctuations
- Dispersion function of all possible pairs of PAs
- Indicates structure over length-scales (separations)

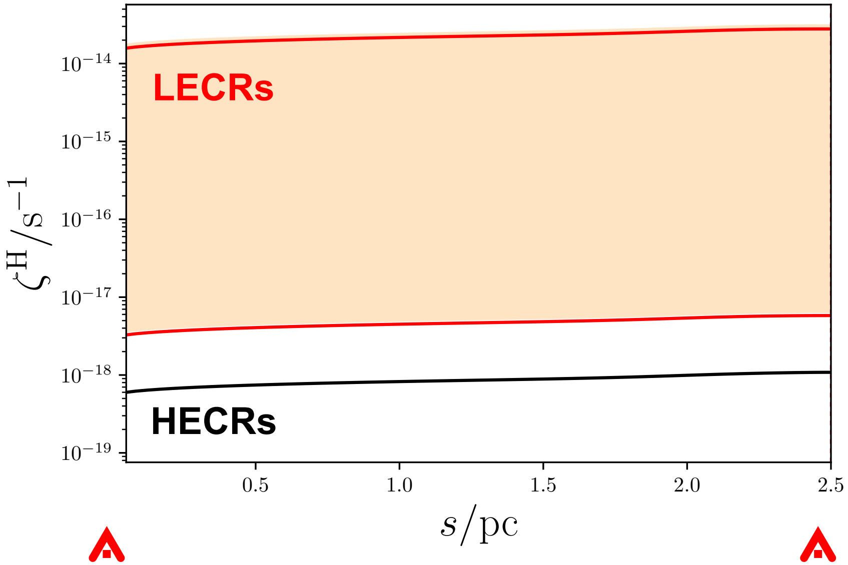
$$\mathcal{S}_n(\ell) = \frac{1}{N_{\rm pair}} \sum_{i=1}^{N_{\rm pair}} [\varphi_i(x+\ell) - \varphi_i(x)]^n$$

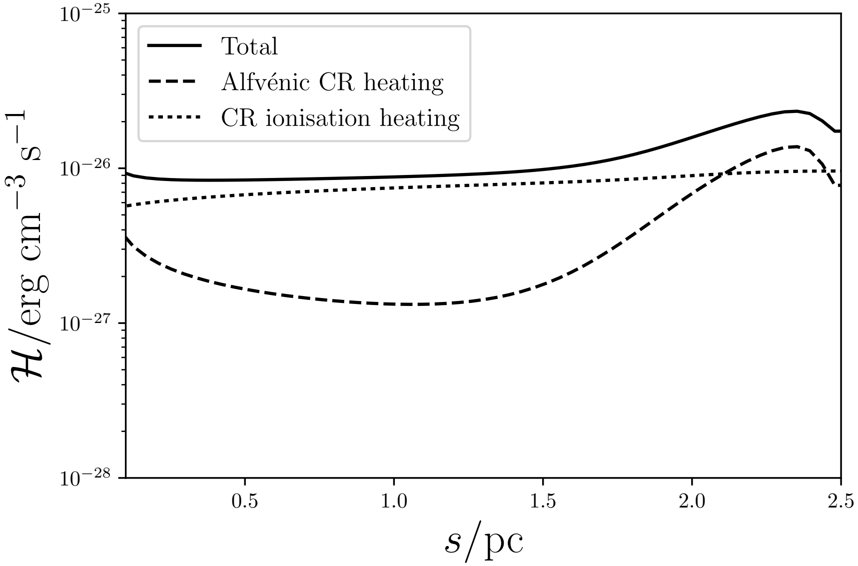
n=2



Owen+2020 (submitted)

Heating and ionization



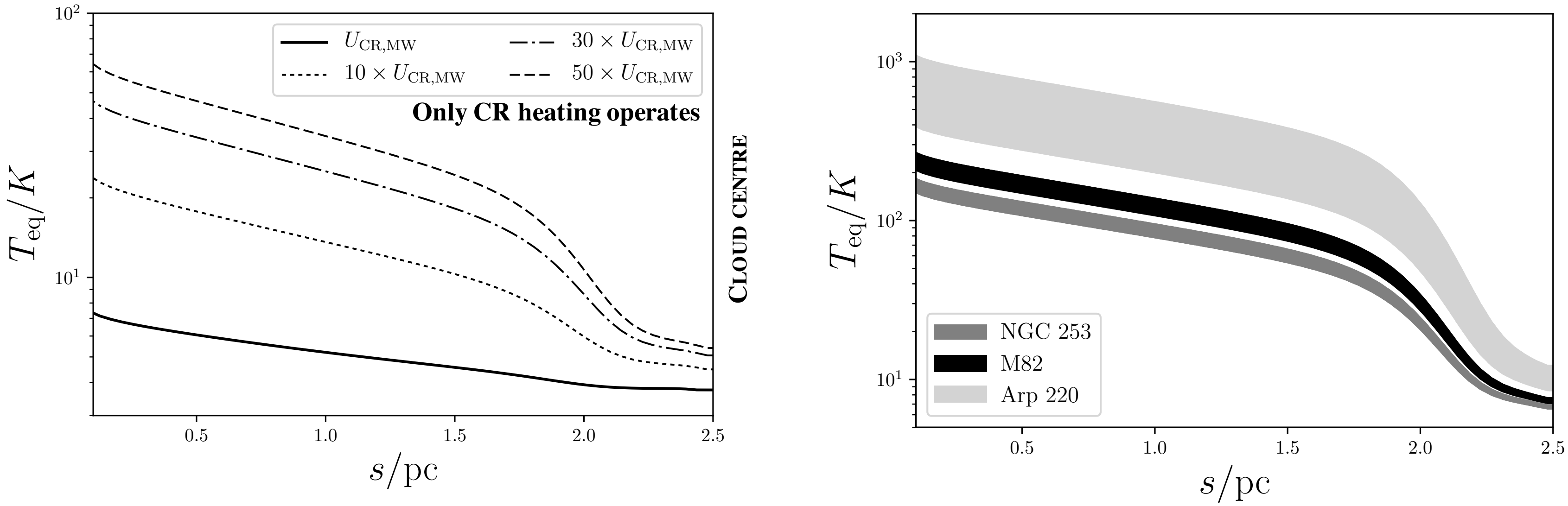


Owen+2020 (submitted)

Outside → **Cloud center**

Temperature

- Milky Way → no substantial heating in the inner parts of the cloud



- Starburst galaxies: CRs much more important
- Increase Jeans mass of cloud by ~1 order of magnitude (Arp 220)
- Implications:
  - larger ISM clumps
  - more bursty star-formation
  - **quenching** (longer to accumulate sufficient mass)

Signatures

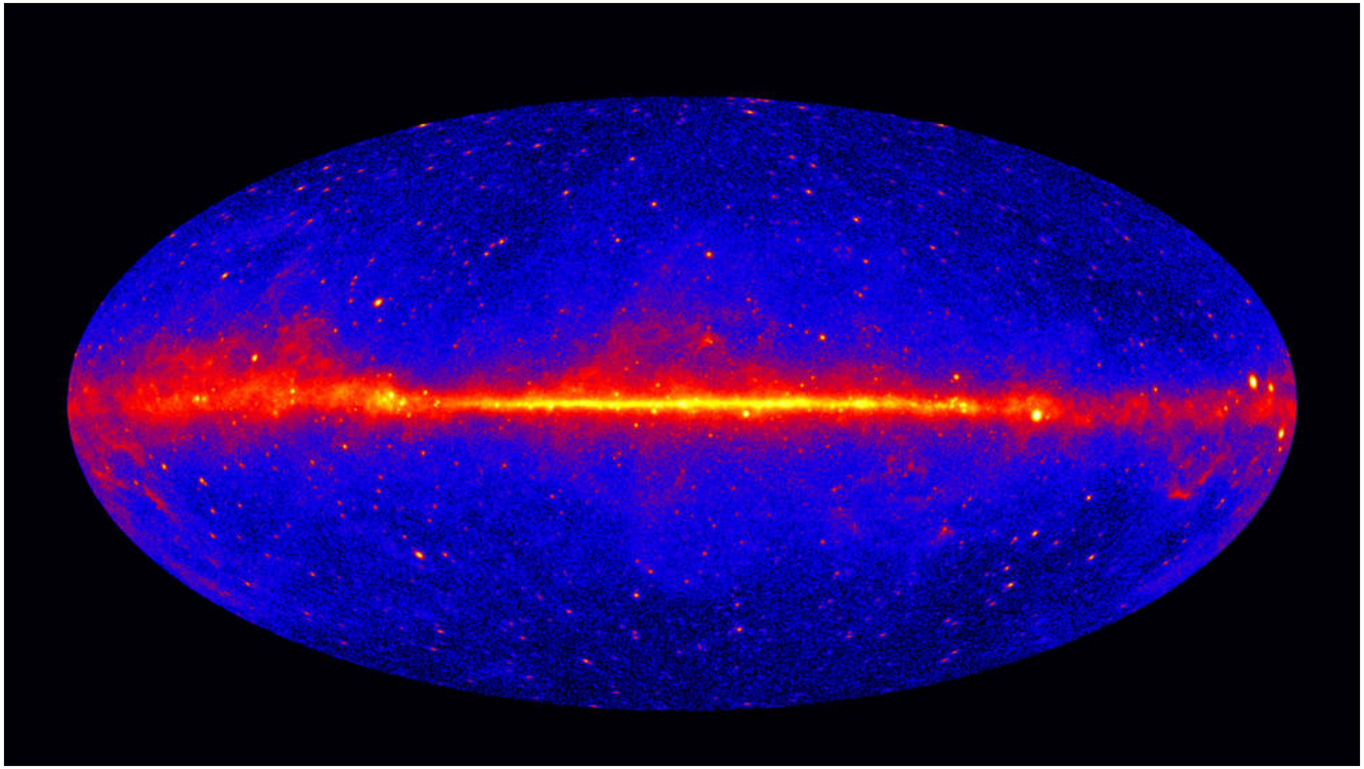
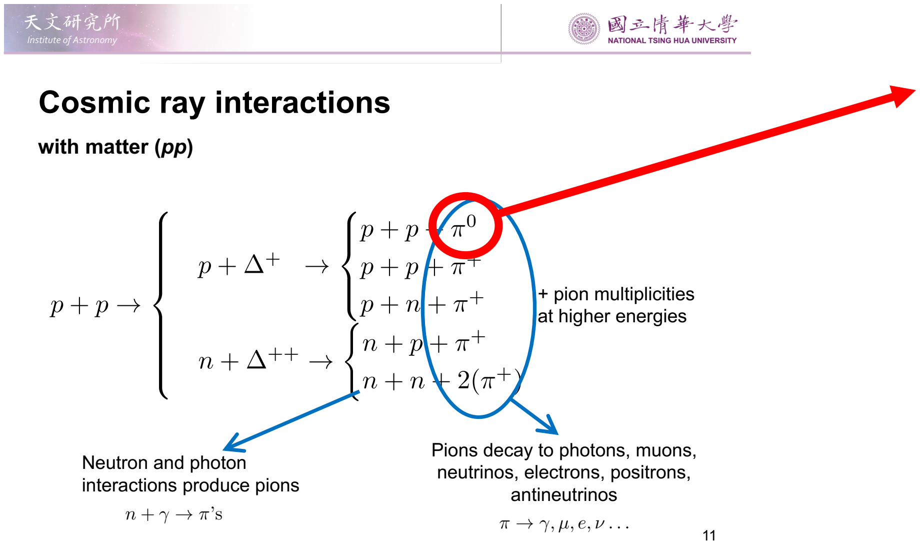


Image credit: Gamma-ray Sky with Fermi - NASA/DOE/Fermi-LAT Collaboration

Gamma-ray emission from starburst galaxies



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Institute of Astronomy
國立清華大學
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Cosmic ray interactions

with matter (*pp*)

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

+ pion multiplicities at higher energies

Neutron and photon interactions produce pions

$n + \gamma \to \pi$'s

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

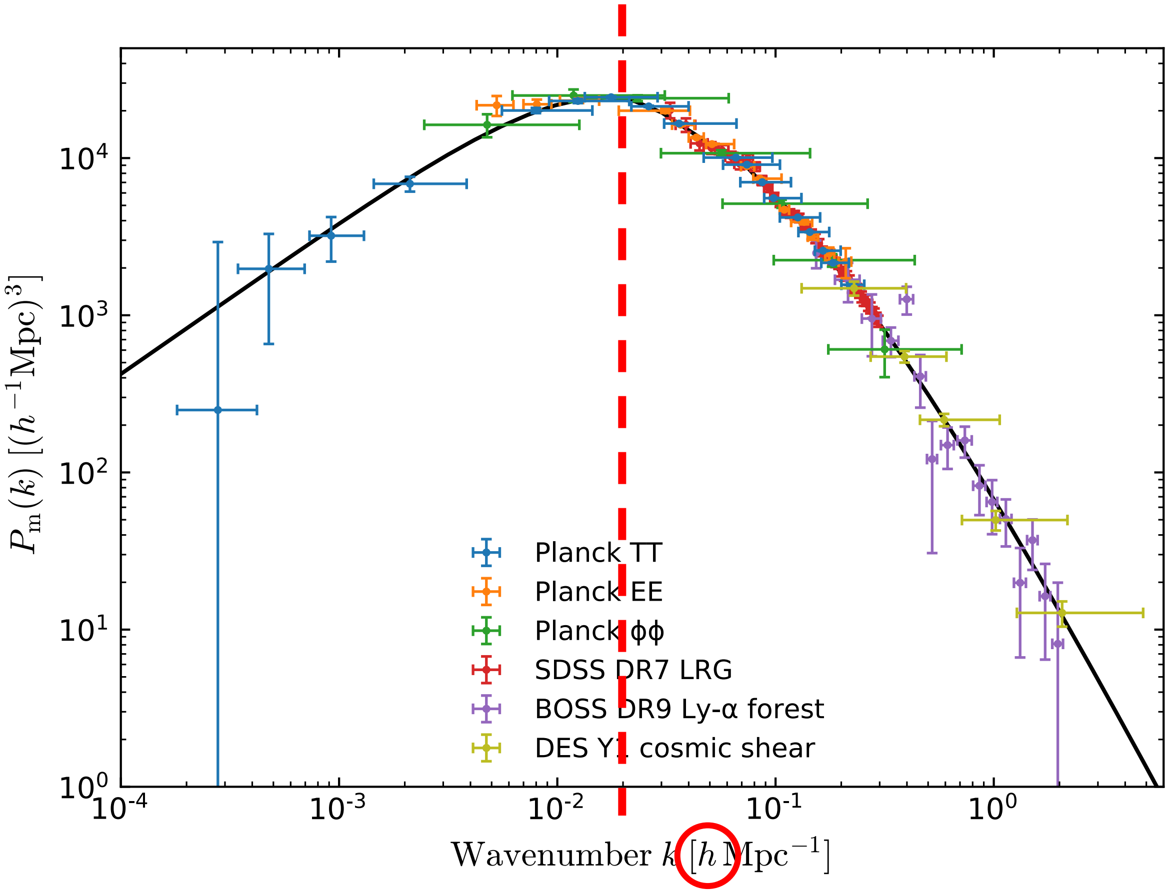
$\pi \to \gamma, \mu, e, \nu \dots$

11

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

Signatures: spatial anisotropies

Imprints signature at preferred (peak) scale



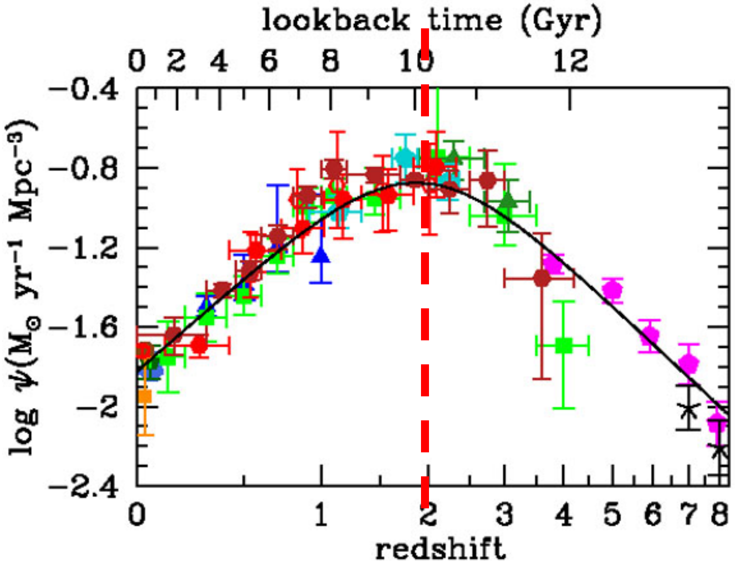
Planck 2018

Redshift (cosmology) dependent

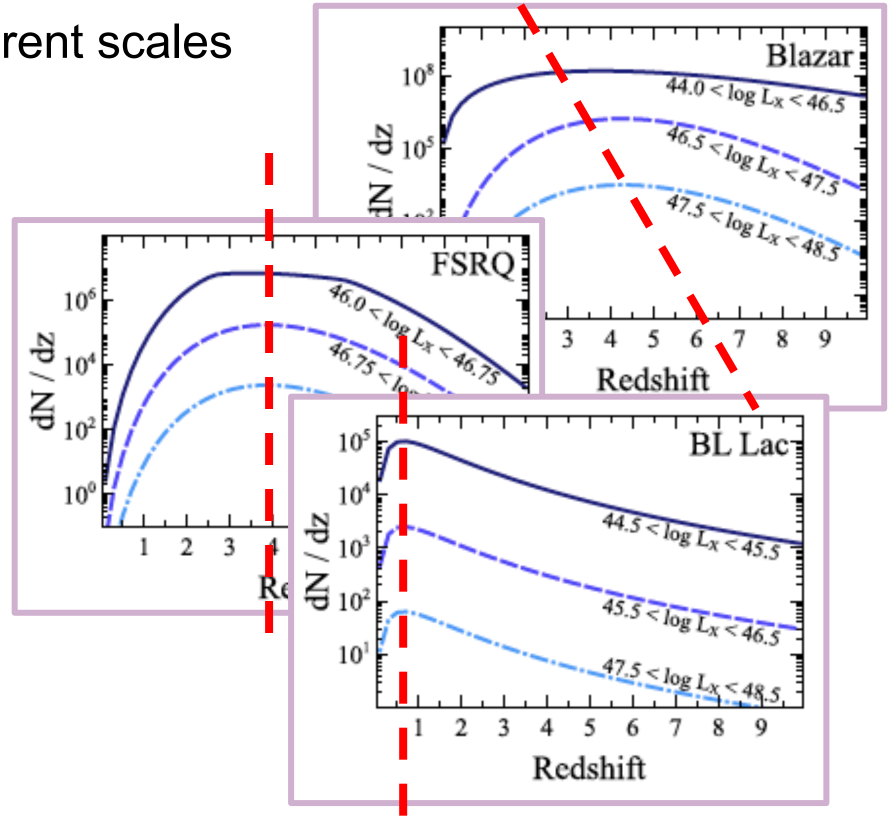
Signatures: spatial anisotropies

Different populations peak at different redshifts

→ Leaves signatures on different scales



Madau & Dickinson 2014



Silverman 2008; Jacobsen 2015

Future work and considerations

- Modelling intrinsic emission from populations
  - SB intrinsic emission can be parametrized (density, SFR, dust fraction, clumpiness…)
- Probable limitations from EBL attenuation/reprocessing
  - How far in z will populations be detectable with CTA?
  - Could IGM B fields smear-out signal?

- Data: Fermi-LAT; CTA KSP 8 ~25% of the EG sky over 3 years

Summary

- Cosmic rays are presumably abundant in high redshift starbursts (high supernova event rates)
- Can deposit energy into ISM with implications for star-formation and quenching
- May be able to account for the “bursty” star-formation histories in high-z starburst/post-starbursts
- Gamma-ray emission is associated with cosmic ray interactions in starburst galaxies
  - May leave signatures in extragalactic diffuse gamma-ray background (anisotropies)