Lecture 7 | High Energy Astrophysics

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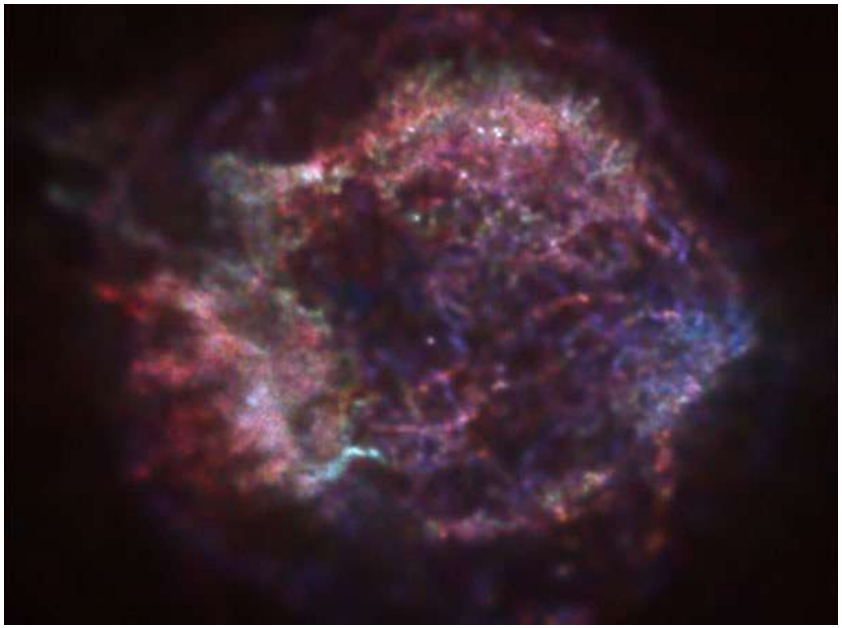


Cas A Supernova remnant. Credit: Hughes et al. (Rutgers), NASA/CXC/SAO

NCTS-TCA Mini Workshop: July 2022

Plan

Concepts and processes in High Energy Astrophysics

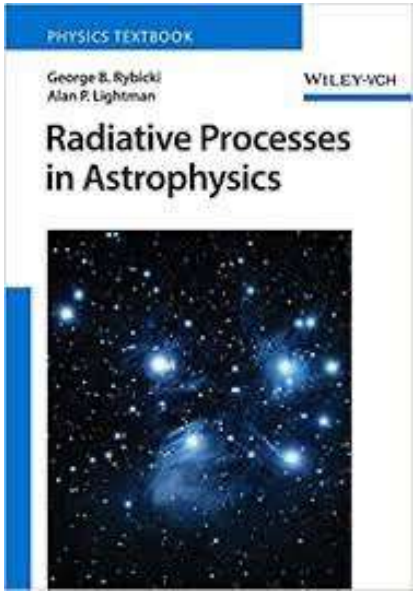
1. What is High Energy Astrophysics?
2. Radiation and emission from energy astrophysical processes
3. Origins and interactions of high energy charged particles

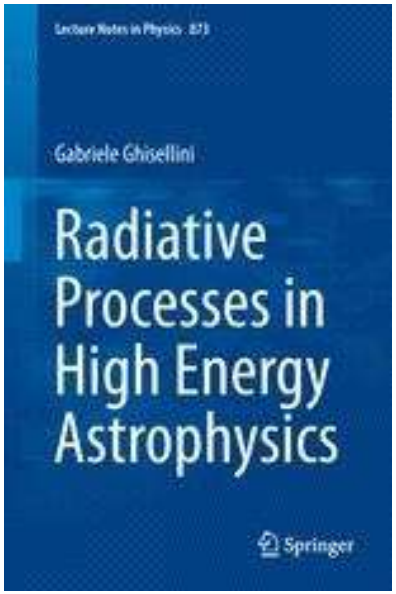
Research applications

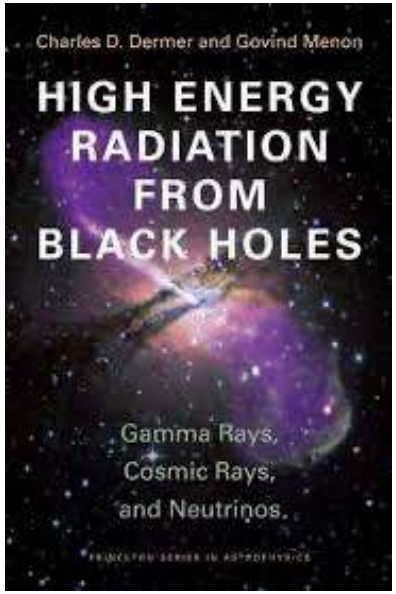
4. High energy phenomena in and around star-forming galaxies

Suggested reading

- *Radiative Processes in Astrophysics*, Rybicki & Lightman
- *Radiative Processes in High Energy Astrophysics*, Ghisellini
- *High Energy Radiation from Black Holes*, Dermer & Menon



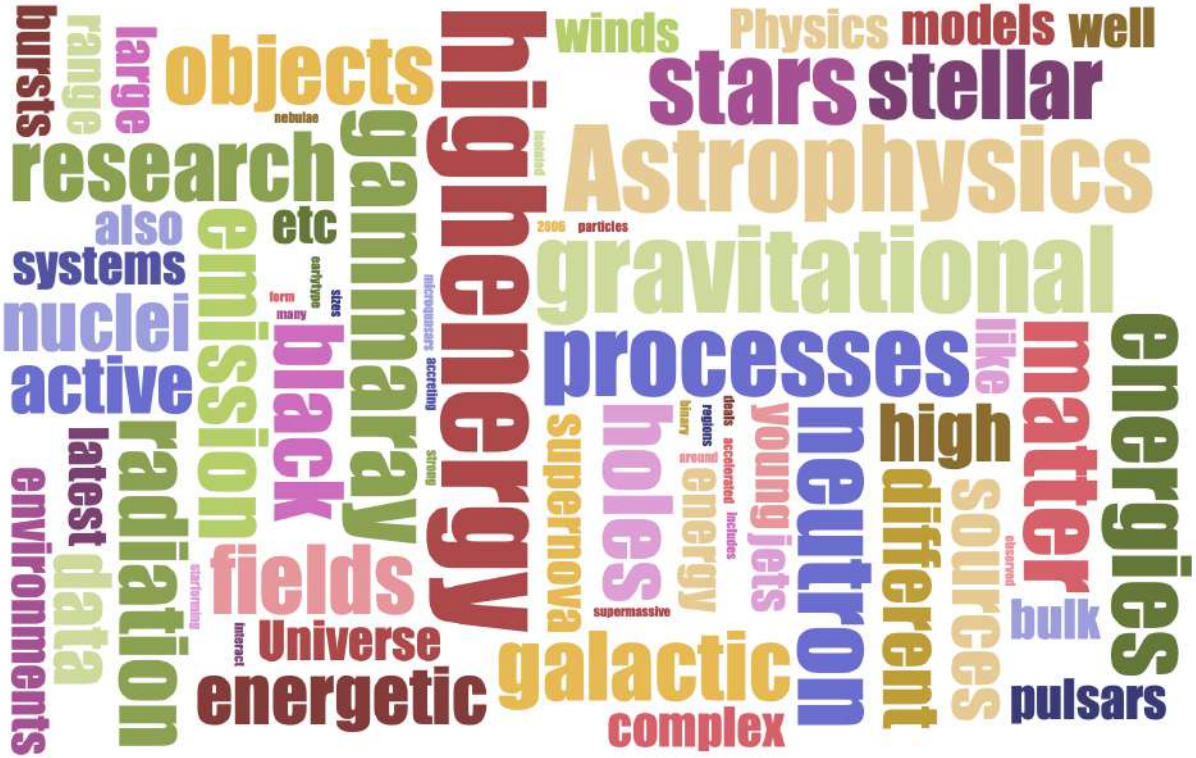




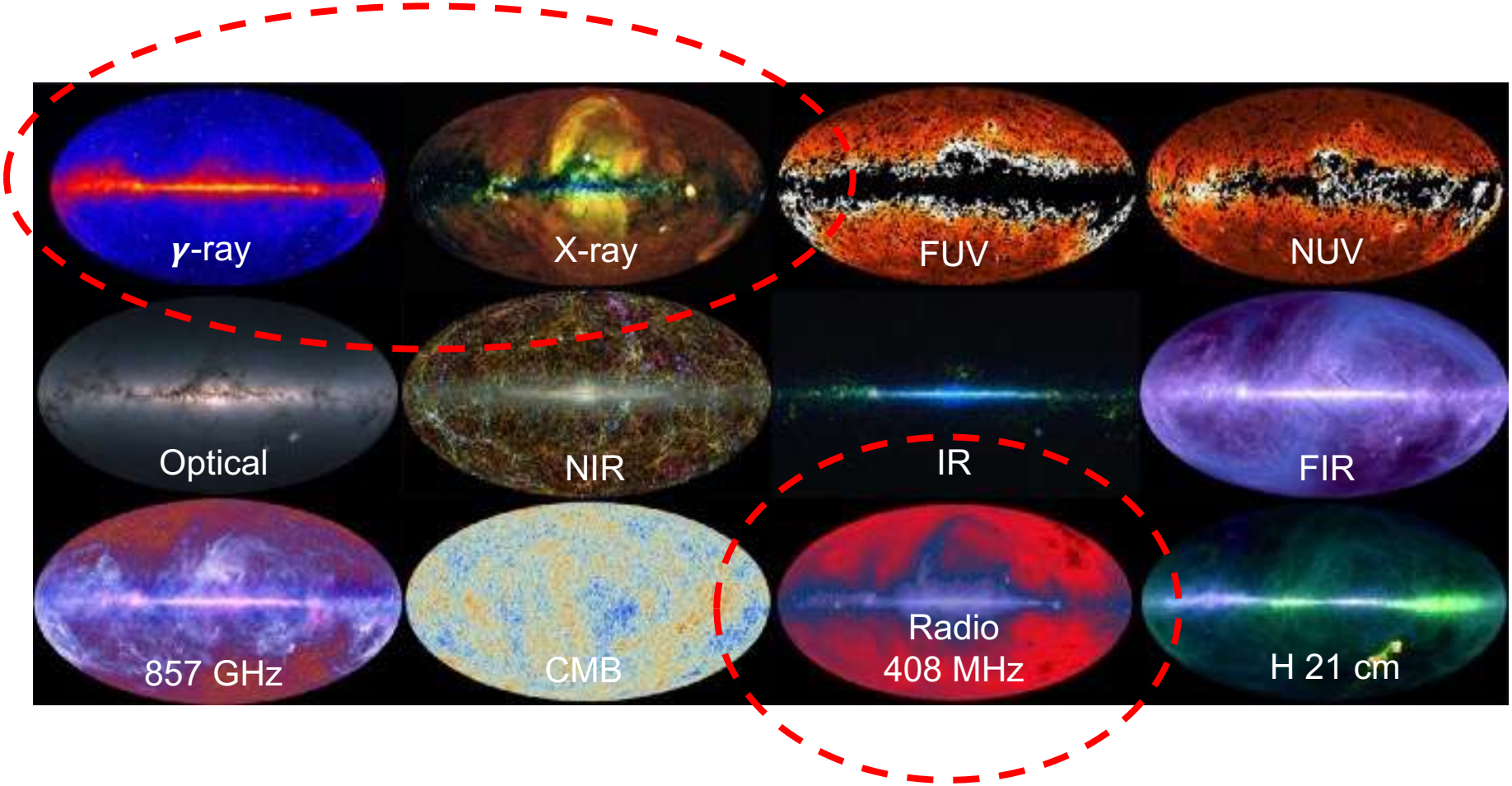
1. What is High Energy Astrophysics?

Definitions

- Wikipedia: *“The study of astronomical objects that release electromagnetic radiation of highly energetic wavelengths”*
- Princeton Astro dept.: *“High-energy astrophysics studies the Universe at the extreme”*

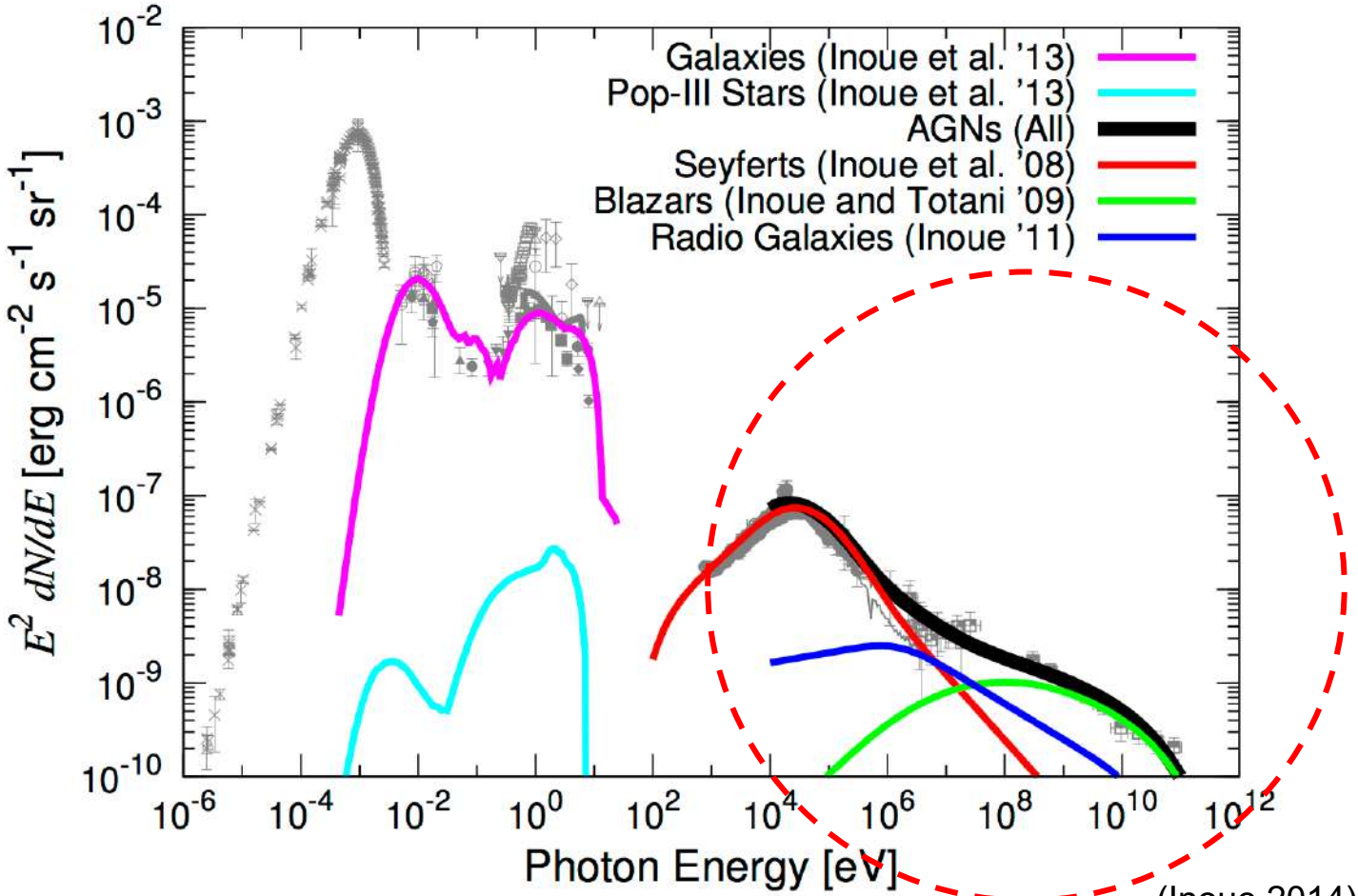


The sky at different energies



Credit: Ansh Mittal (2020)

What is high energy radiation?

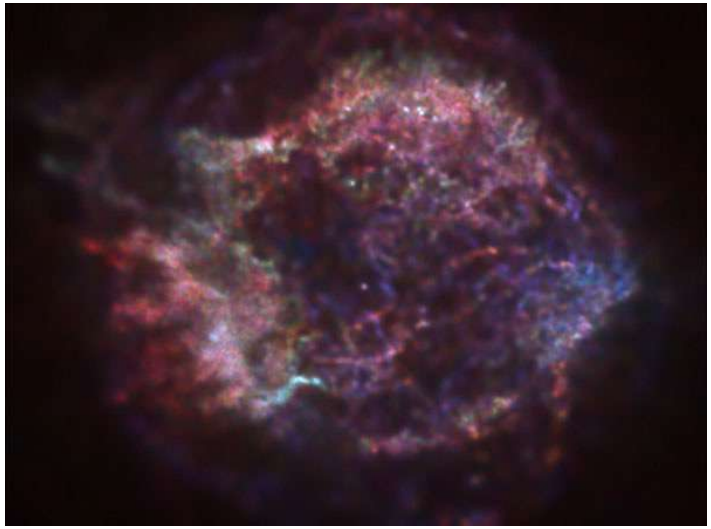


(Inoue 2014)

What systems are high energy?
What is the origin of the radiation?

- Active galactic nuclei (blazars, high-energy jets, SMBHs)
- Supernovae and their remnants
- Black holes, neutron stars, … (“stellar end-products”)
- Star-forming galaxies?
- Our galaxy…?

Cas A Supernova remnant



Origin:

- Violent environments/events
- Emitted by high energy particles
- Emitted by hot baryons

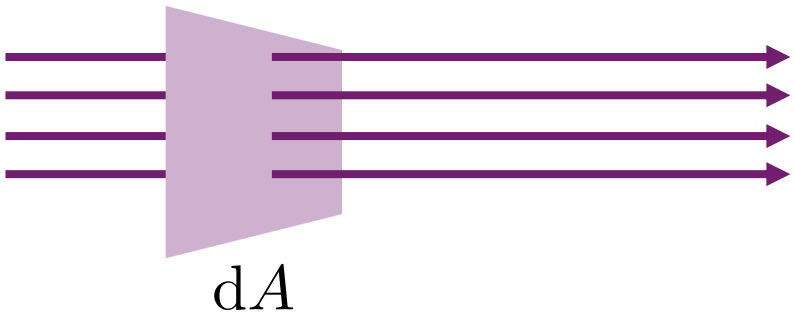
Credit: Hughes et al. (Rutgers) NASA/CXC/SAO

2. Radiation and emission from high energy astrophysical processes

Radiation in astrophysics - concepts

Introducing **radiative flux:** rate of radative energy passing through an area

Consider parallel rays passing through an area d*A* normal to their direction



Amount of energy passing through d*A* by all rays:

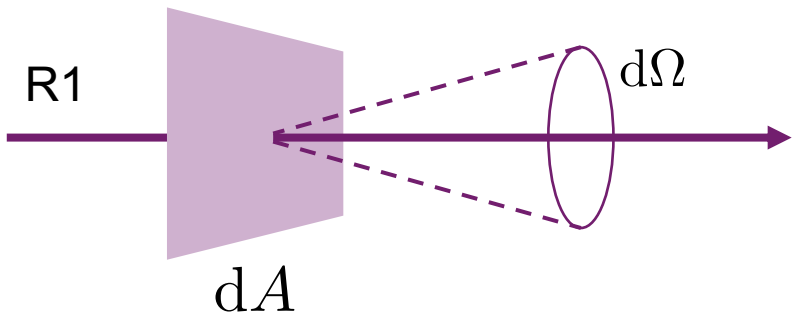
$$\mathrm{d}E = \boxed{F}\,\mathrm{d}A\,\mathrm{d}t$$

$$F = \frac{\mathrm{d}E}{\mathrm{d}A\,\mathrm{d}t} \qquad [\mathrm{erg\ cm^{-2}\ s^{-1}}]$$

Radiation in astrophysics - concepts

Specific intentisty (brightness)**:** measure of energy flow by rays of radiation

Consider an area d*A* normal to the direction of a **single** ray (R1)



Take *all* the rays passing through d*A* with a direction within a solid angle d***Ω*** of R1

The total **energy** in these rays crossing d*A* in a time d*t* in a frequency range d*v* is

$$\mathrm{d}E = \boxed{I_\nu}\,\mathrm{d}A\ \mathrm{d}t\ \mathrm{d}\Omega\ \mathrm{d}\nu$$

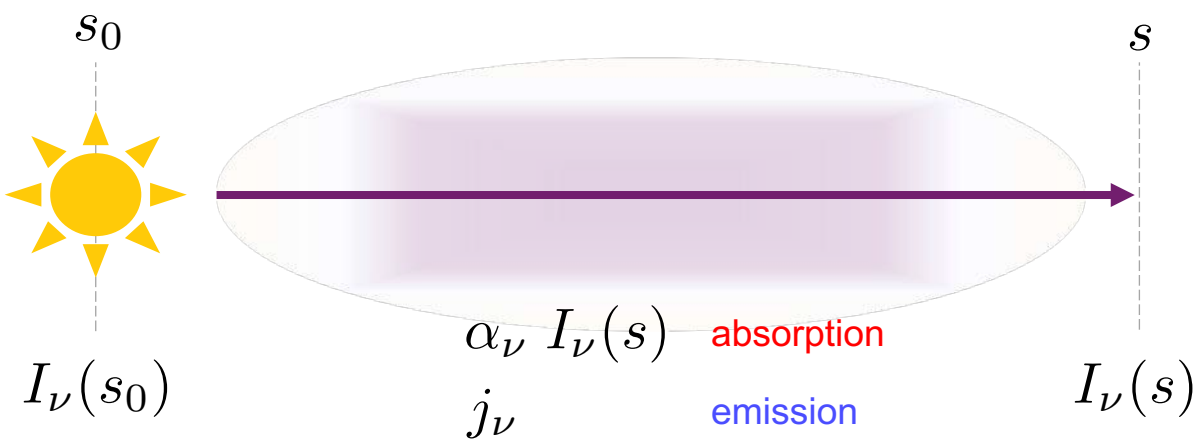
$$I_\nu = \frac{\mathrm{d}E}{\mathrm{d}A\ \mathrm{d}t\ \mathrm{d}\Omega\ \mathrm{d}\nu} \qquad [\mathrm{erg\ cm^{-2}\ s^{-1}\ sr^{-1}\ Hz^{-1}}]$$

Energy flow of radition along a line

Radiative transfer

General setup

Consider the intensity of a ray as it propagates from some a source at s_0 to an observer at s through a medium that can absorb/scatter and emit radiation



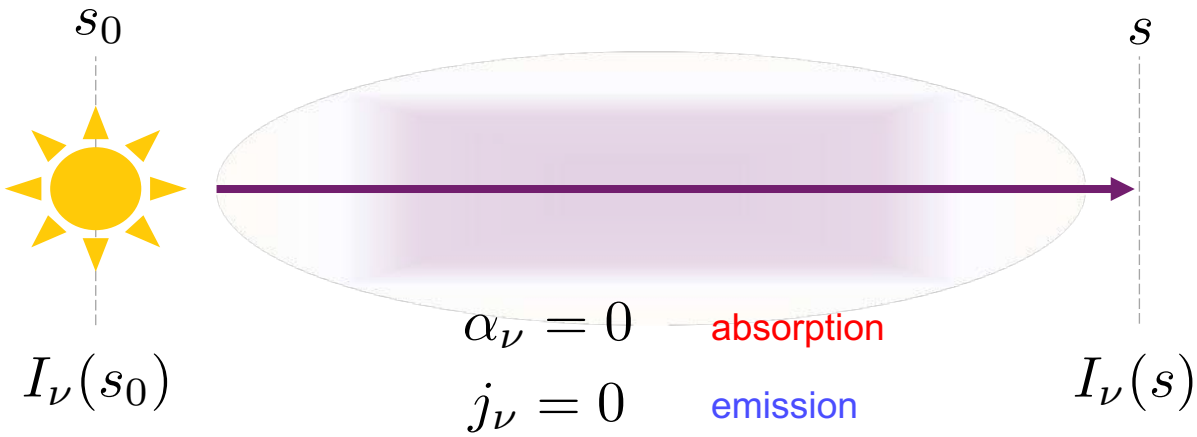
Radiative transfer equation
(1st order DE; 1 BC)

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = \boxed{-\alpha_\nu I_\nu} + \boxed{j_\nu}$$

Radiative transfer

Case 1: trivial scenario - no emission/absorption

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = \cancel{0} - \cancel{\alpha_\nu I_\nu} + \cancel{j_\nu}$$

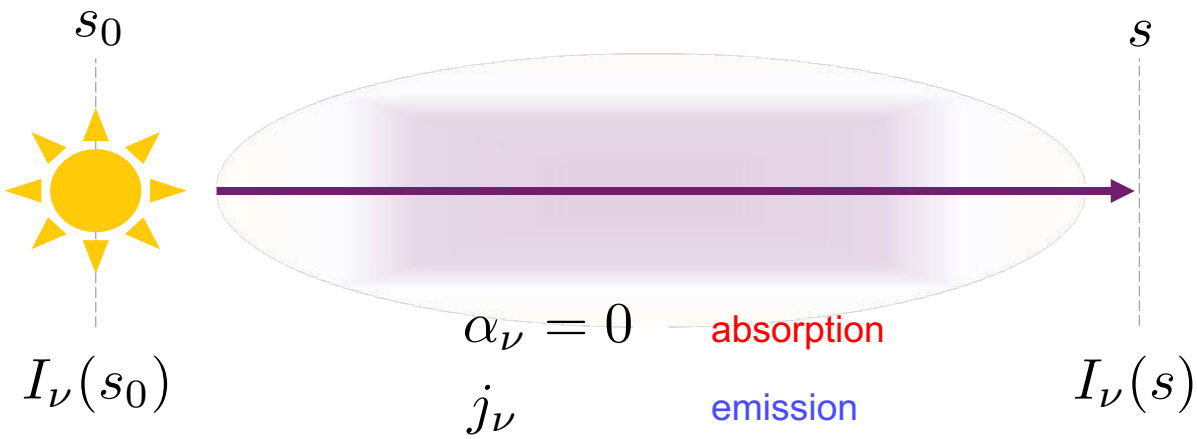


$$I_\nu(s) = \text{constant}$$
$$= I_\nu(s_0)$$

Radiative transfer

Case 2: no absorption along line of sight

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = \cancel{j_\nu \alpha_\nu I_\nu} + j_\nu$$

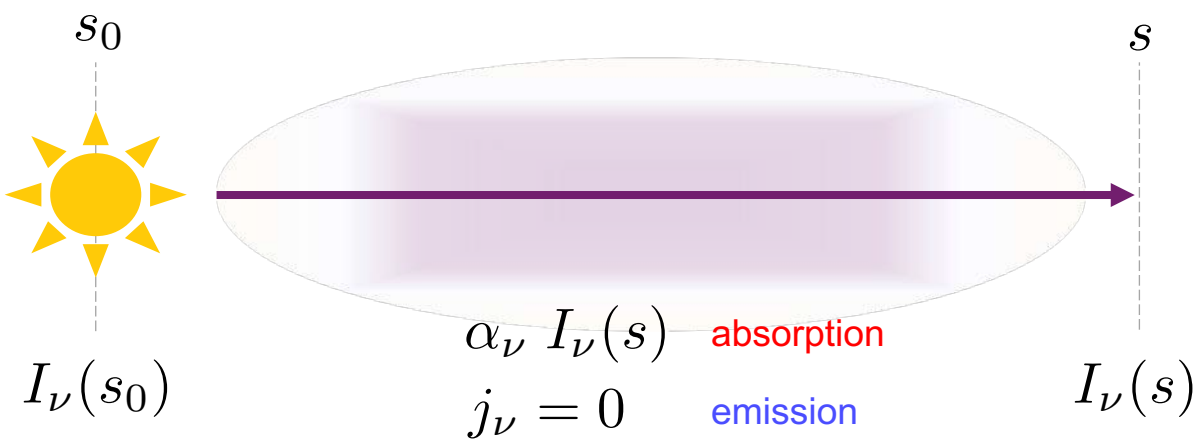


$$I_\nu(s) = I_\nu(s_0) + \int_{s_0}^{s} j_\nu(s')\mathrm{d}s'$$

Radiative transfer

Case 3: no emission along line of sight

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + \cancel{j_\nu}$$



$$\frac{\mathrm{d}\log I_\nu}{\mathrm{d}s} = -\alpha_\nu$$

$$\log I_\nu(s) = \log I_\nu(s_0) - \int_{s_0}^{s} \alpha_\nu(s')\mathrm{d}s'$$

$$\Rightarrow \quad I_\nu(s) = I_\nu(s_0)\exp\left\{-\int_{s_0}^{s} \alpha_\nu(s')\mathrm{d}s'\right\}$$

Optical depth

It can be useful to consider radiation transfer in terms of optical depth/thickness

$$\mathrm{d}\tau_\nu = \alpha_\nu \, \mathrm{d}s$$

Chance of absorption along the path of a ray

Reveals more clearly than distance the important regions along a ray for radiation

$$I_\nu(s) = I_\nu(s_0) \exp\left\{ -\int_{s_0}^{s} \alpha_\nu(s')\mathrm{d}s' \right\}$$

Result from previous slide

$$I_\nu(s) = I_\nu(s_0) \exp\left\{ -\tau_\nu(s) \right\}$$

Rewrite in terms of optical thickness

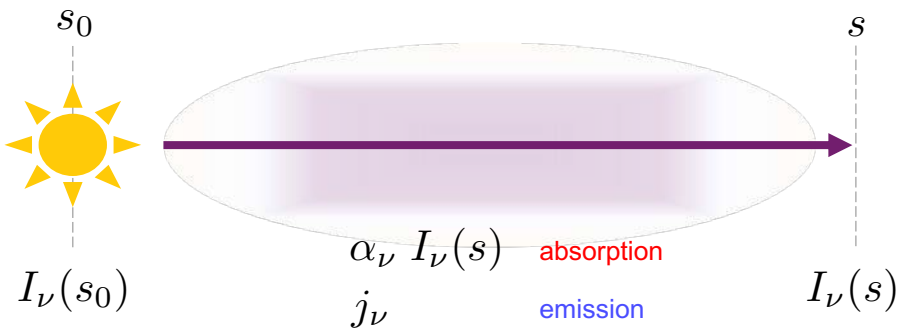
Two regimes

$\tau_\nu > 1$ Optically thick: **average** photon gets absorbed before traversing medium (opaque)

$\tau_\nu < 1$ Optically thin: transparent - average photon not absorbed

Radiative transfer

Case 4: absorption and emission along line of sight (general case)



General RT equation

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + j_\nu$$

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$

Define source function: $S_\nu = \dfrac{j_\nu}{\alpha_\nu}$

- Rewrite using: $\mathrm{d}\tau_\nu = \alpha_\nu\ \mathrm{d}s$
- Formal solution of the RT equation

$$I_\nu(\tau_\nu) = I_\nu(0)\exp\left(-\tau_\nu\right) + \exp\left(-\tau_\nu\right)\int_0^{\tau_\nu} \exp\left(\tau'_\nu\right) S_\nu(\tau'_\nu)\,\mathrm{d}\tau'_\nu$$

Homework! Verify this. Hint: use integrating factor $\exp\left(\tau_\nu\right)$

Radiative transfer

Formal solution of RT equation: useful simplifications in practical use

$$I_\nu(\tau_\nu) = I_\nu(0)\exp(-\tau_\nu) + \exp(-\tau_\nu)\int_0^{\tau_\nu} \exp(\tau'_\nu)\, S_\nu(\tau'_\nu)\, \mathrm{d}\tau'_\nu$$

General RT equation from previous slide

- Useful simplification I: **constant source function**

$$I_\nu(\tau_\nu) = \boxed{I_\nu(0)\exp(-\tau_\nu)} + \boxed{S_\nu\left[1-\exp(-\tau_\nu)\right]}$$

Extinction of background light

Emission from medium

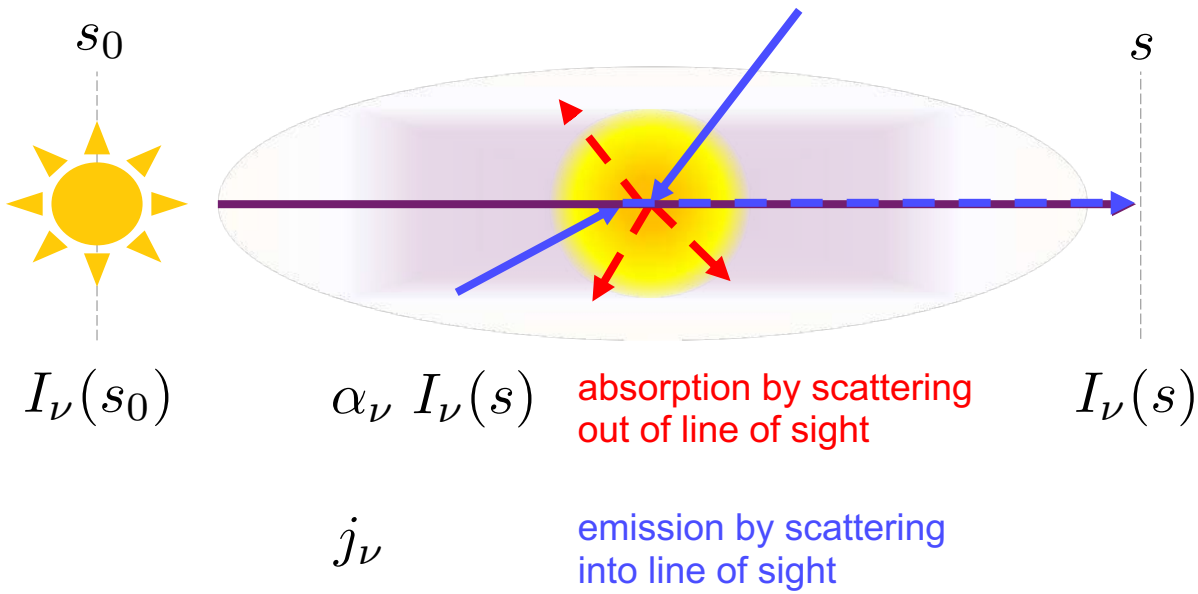
- Useful simplification II: $\tau_\nu \ll 1$ $\quad I_\nu(\tau_\nu) = I_\nu(0)$

- Useful simplification III: $\tau_\nu \gg 1$ $\quad I_\nu(\tau_\nu) = S_\nu$

Scattering

Scattering is any process where radiation is absorped and then re-emitted

Scattered (re-emitted radiation) depends on the radiation falling on an element

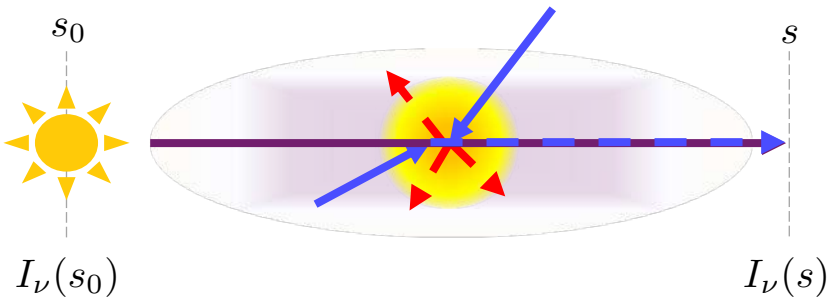


Consider a simple case with 3 assumptions

1. **Isotropic**: scattered energy is emitted equally into equal solid angles
2. **Pure** : only one scattering process operting
3. **Coherent**: radiation emitted per unit frequency range is the same as absorbed

Scattering

Pure scattering – only one process to cause absorption



General RT equation

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\alpha_\nu I_\nu + j_\nu$$

RT equation for scattering

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}s} = -\boxed{n\sigma_\nu} I_\nu + \boxed{n\sigma_\nu}\boxed{J_\nu}$$

Pure, coherent scattering (same cross section)

Mean (angle-averaged) intensity

$$J_\nu = \frac{1}{4\pi}\int I_\nu \, \mathrm{d}\Omega$$

- Emission term depends on the intensity at all directions through a given point
- RT problems can become complex quickly (integral-differential equation)
- Approximations are possible –e.g. Eddington approximation; radiative diffusion equation – K.-C. Pan's 2021 lecture

Mean free path

A **characteristic** description of absorption or scattering

Average distance a photon can travel through a *homogenous* material until it is absorbed or scattered

Reminder

$\tau_\nu > 1$ Optically thick: **average** photon gets absorbed before traversing medium (opaque)

$\tau_\nu < 1$ Optically thin: transparent - average photon not absorbed

Average distance through a material until it becomes optically thick (optical thickness = 1)

$$\langle \tau_\nu \rangle = \alpha_\nu \, \ell_\nu = 1$$

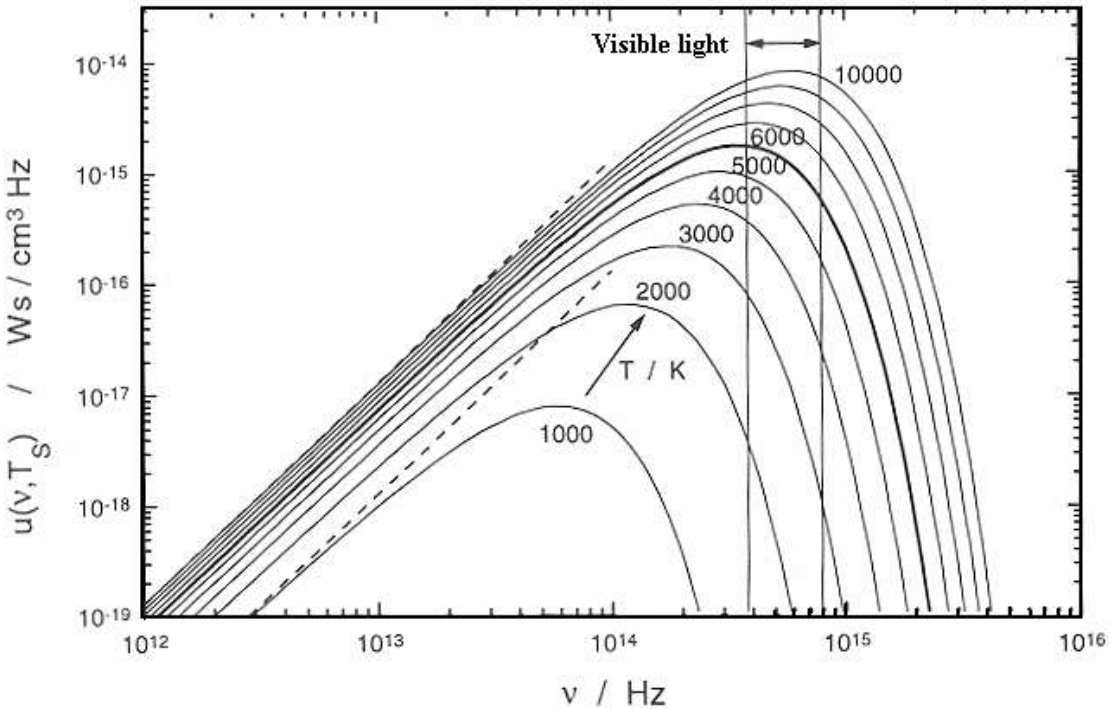
Locally, we may then write: $\ell_\nu = \dfrac{1}{\alpha_\nu}$ For absorption (more generally)

$$\ell_\nu = \frac{1}{\boxed{n \, \sigma_\nu}}$$ For scattering

Review: Thermal radiation

The emitted radiation **depends on the temperature of the source**

Many systems in astrophysics are (roughly) in local thermal equilibrium (LTE)



(Helmut Föll/Kiel 2019)

Thermally emitting material at temperature T will emit blackbody radiation, with a spectrum modeled using a Planck function

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{\exp(h\nu/kT) - 1}$$

Thermal radiation and Kirchoff's law

For an **optically thick thermal** emitter in **LTE**, emission depends only on the thermally emitting material's properties

Radiation absorbed and remitted is thermal with the same properties

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + S_\nu$$

RT equation (written in terms of optical thickness)

Kirchoff's law

$$\left.\begin{aligned} j_\nu &= \alpha_\nu \, B_\nu(T) \\ S_\nu &= B_\nu(T) \end{aligned}\right\}$$

Thermal radiation

$$\frac{\mathrm{d}I_\nu}{\mathrm{d}\tau_\nu} = -I_\nu + B_\nu(T)$$

Since $S_\nu = B_\nu$ throughout the system, then $I_\nu = B_\nu$ throughout

Note: thermal radiation becomes blackbody radiation when $\tau_\nu > 1$

Non-thermal radiation

The emitted radiation does **not** depend on the temperature of the source (typically the emission is being driven by 'non-thermal' or relativistic particles)

Four common examples in astronomy

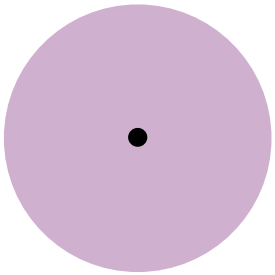
1. Inverse Compton **scattering**
2. Synchrotron emission

From high energy particles

3. Free-free emission (non-thermal bremsstrahlung)
4. Stimulated emission (e.g. LASERS, atomic processes)

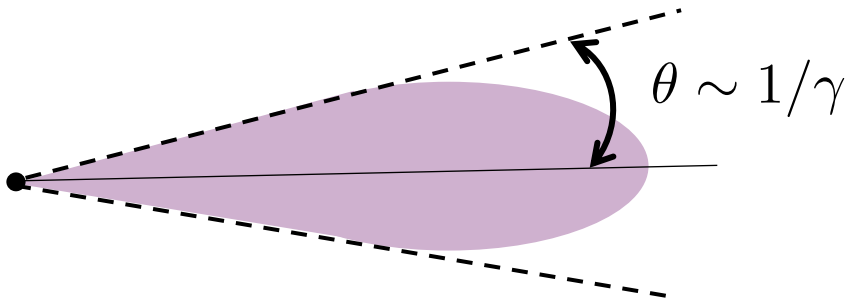
Review: Relativistic beaming of radiation

Rest frame



Radiation emitted isotropically

Lab frame



Radiation is beamed in the forward direction

Homework! Why? Hint: use relativistic aberration formula

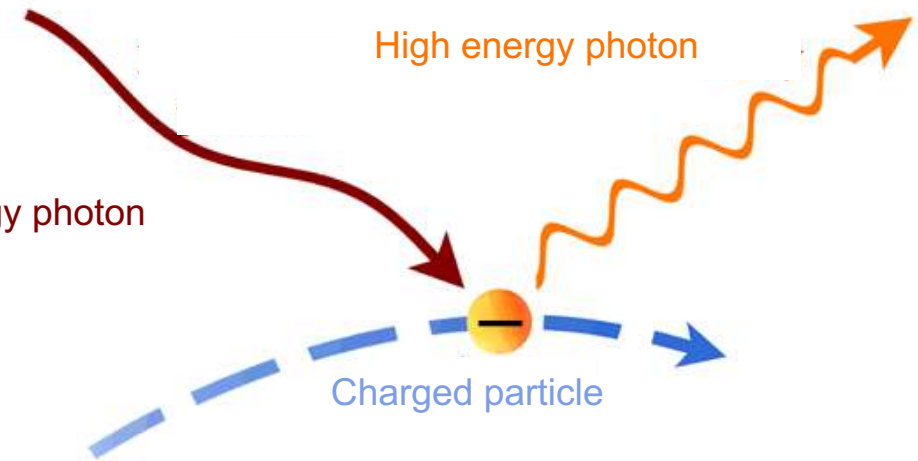
Answer is in R+L p. 110

(Inverse) Compton scattering

- Compton scattering: Relativistic scattering between **low energy** charged particle and **high energy** photon

- Inverse Compton scattering: Relativistic scattering between **high energy** charged particle and **low energy** photon

Requirements
1. High energy charged particles
2. Radiation fields



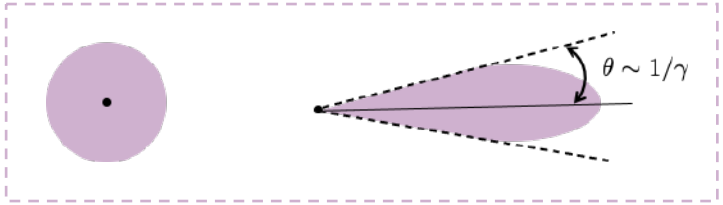
Simple case: single electron in monochromatic, isotropic photon field

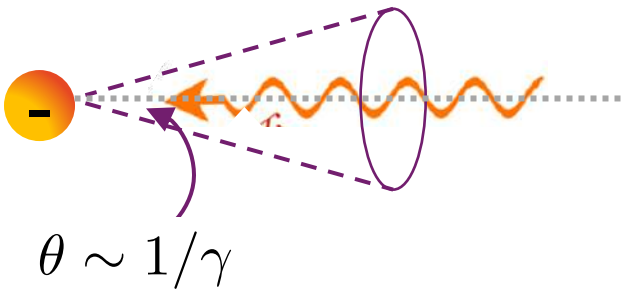
Credit: CXC

(Inverse) Compton scattering

Relativistic electron with energy given by $\gamma = E_{\rm e}/m_{\rm e}c^2$

In a frame where the electron is **at rest**:





Photons appear to come from the front in a small angle, and higher frequency

Scattering in rest frame is in Thompson regime – elastic: $\nu'_{\rm rest} \sim \gamma\,\nu$ (typically)

Scattered photons are isotropic

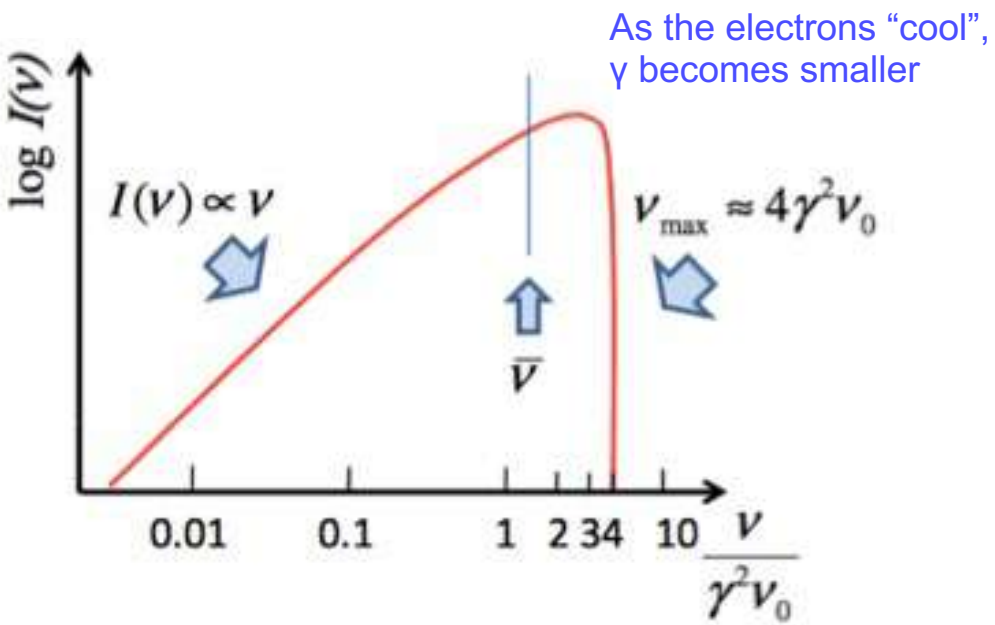
Back to the lab frame: hemisphere becomes cone with $\theta \sim 1/\gamma$

so frequency higher by γ compared to electron frame

scattered frequency: $\nu'_{\rm lab} \sim \gamma^2\,\nu$

(Inverse) Compton scattering

A more detailed approach (e.g. orientation of interaction, frequency dependence of scattering etc) allows the spectrum to be calculated



Credit: Eline Tolstoy

$$\bar{\nu} \approx \frac{4}{3}\gamma^2\nu_0$$

ν_0 frequency of "target" photon

$\bar{\nu}$ frequency of up-scattered photon

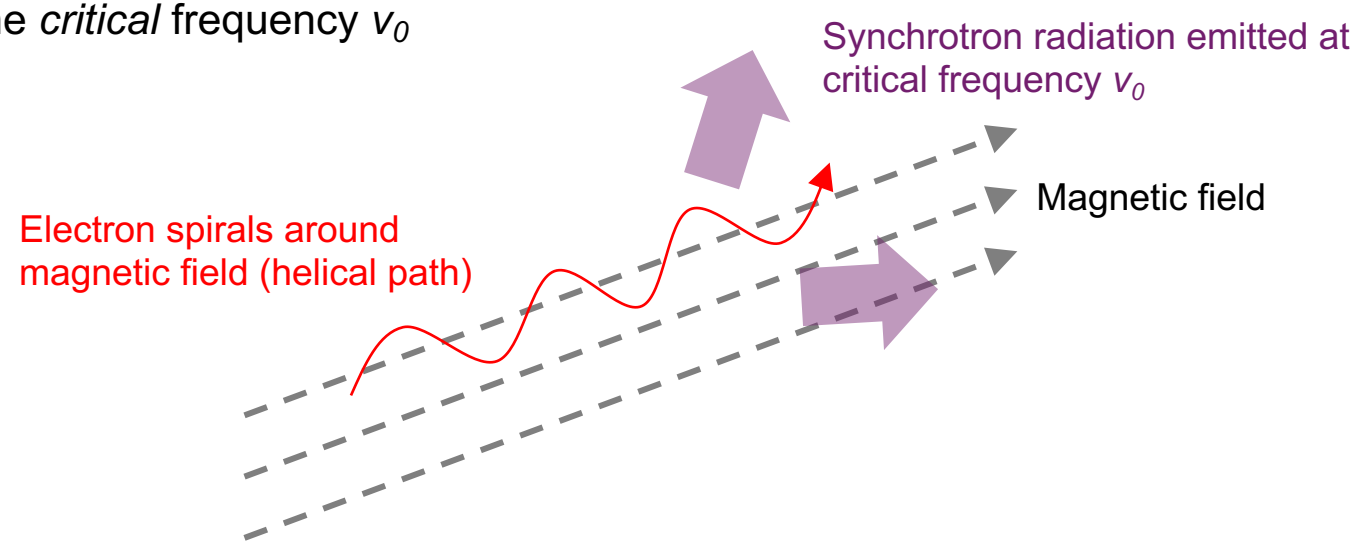
Synchrotron emission

Requirements
1. High energy charged particles
2. Magnetic field

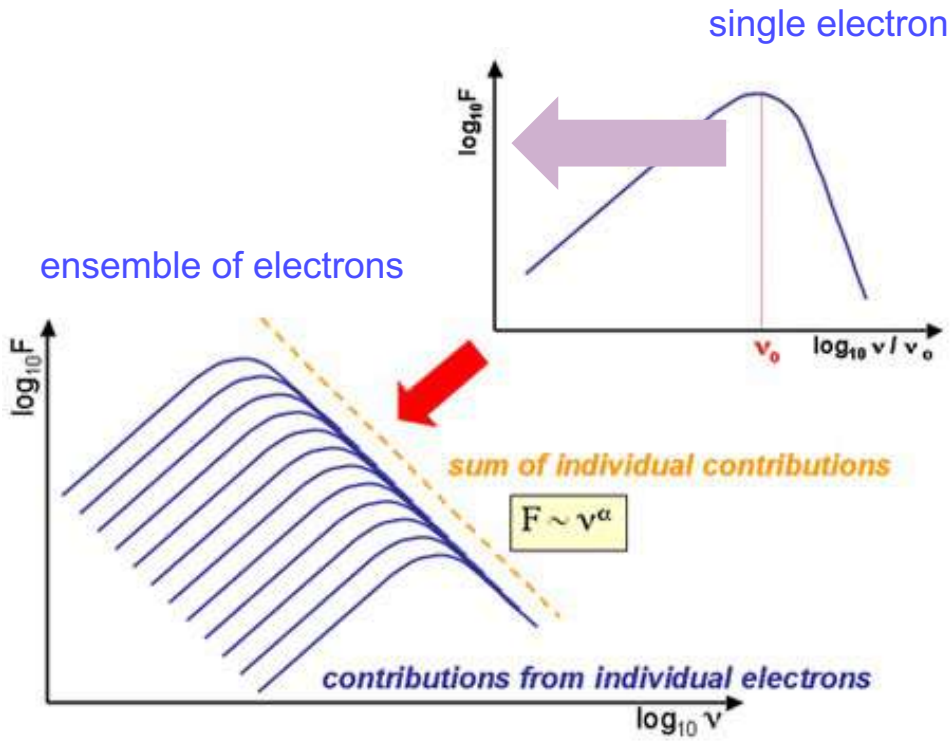
Most radiation received when particle direction is similar to line of sight ($\theta_{\rm syn} \sim 1/\gamma$).

Pulse of radiation gets compressed into a time $\Delta t_{\rm syn} \approx (1-\beta)\,[2\theta_{\rm syn}]\,t_{\rm gyro}$

This sets the *critical* frequency ν_0



Synchrotron emission



Credit: SAO (Swinburne)

Peak frequency moves to the left as electron cools

$$v_0 \approx 1/\Delta t_{\rm syn}$$

$$v_0 \approx \frac{q\ B\ \gamma^2}{2\pi\ mc}$$

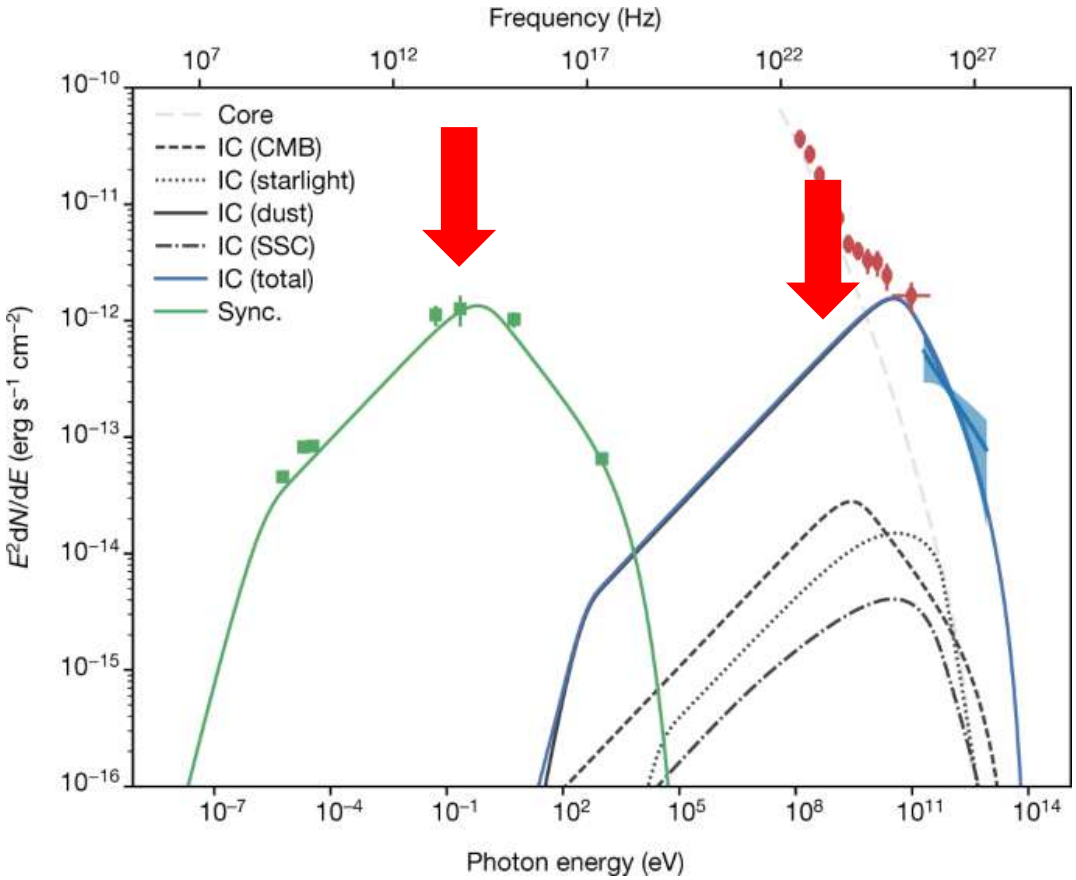
cooling depends on energy: slope gets steeper over time

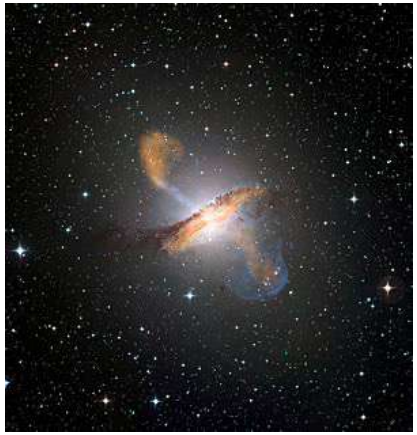
Typical sources: AGN/jets, radio galaxy, pulsars, supernova remnants, starburst galaxies

Usually observed in radio bands, but also visible, UV and X-ray synchrotron is possible

Emission spectrum for high energy electrons

Centaurus A



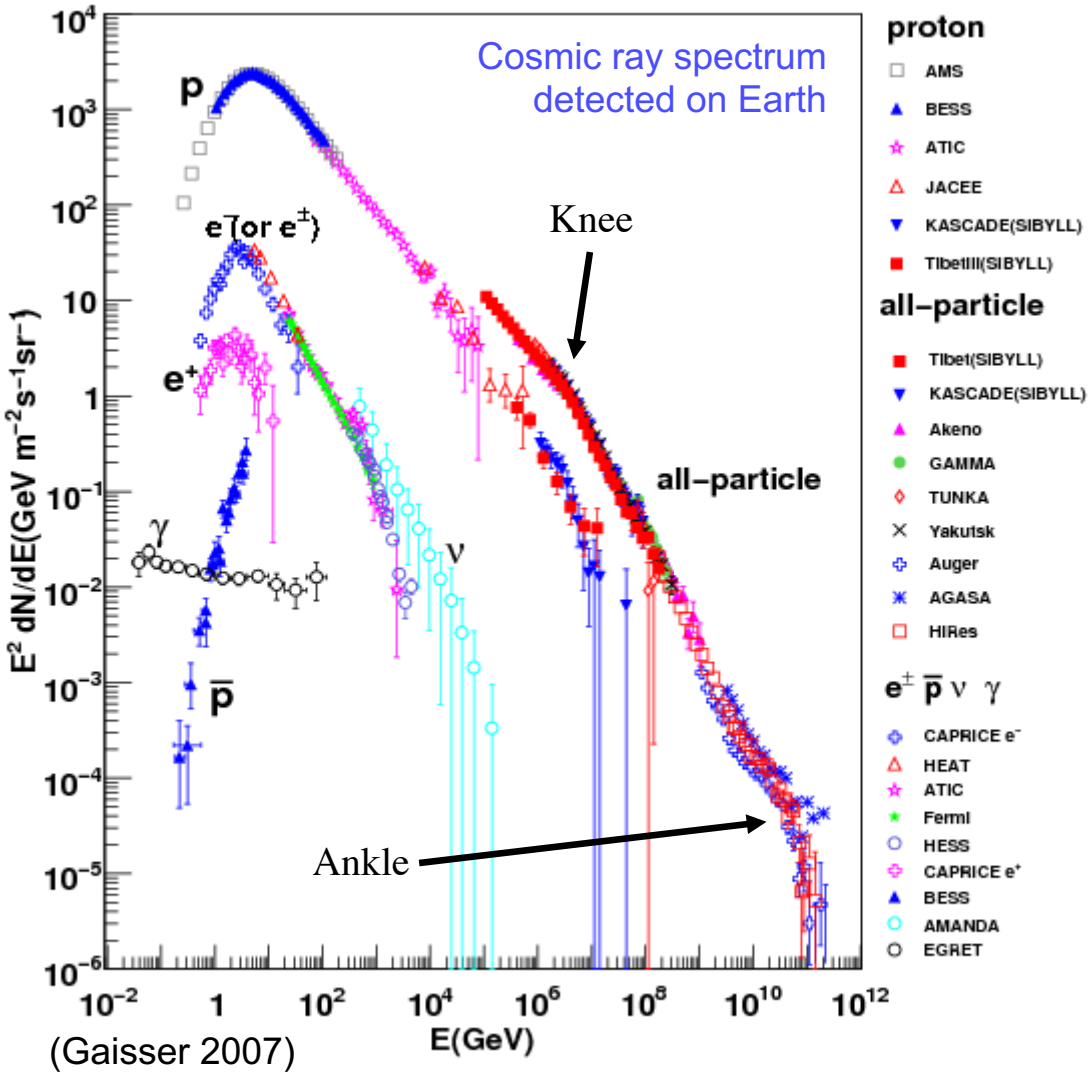


Credit: ESO

Credit: H.E.S.S. collaboration 2020

3. Origins and interactions of high energy charged particles

High energy charged particles



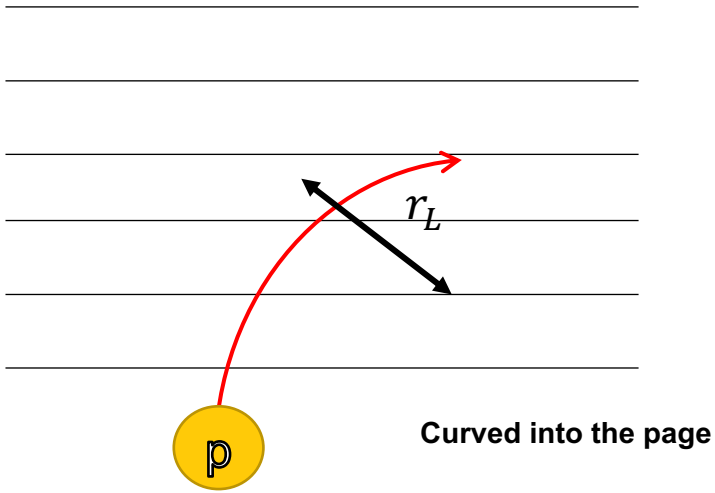
(Gaisser 2007)

Charged, relativisitic particles from violent astrophysical environments – **cosmic rays**

- Protons
- Electrons/positrons
- “Heavy” nuclei
- Gamma-rays (why?)

Gyroradius

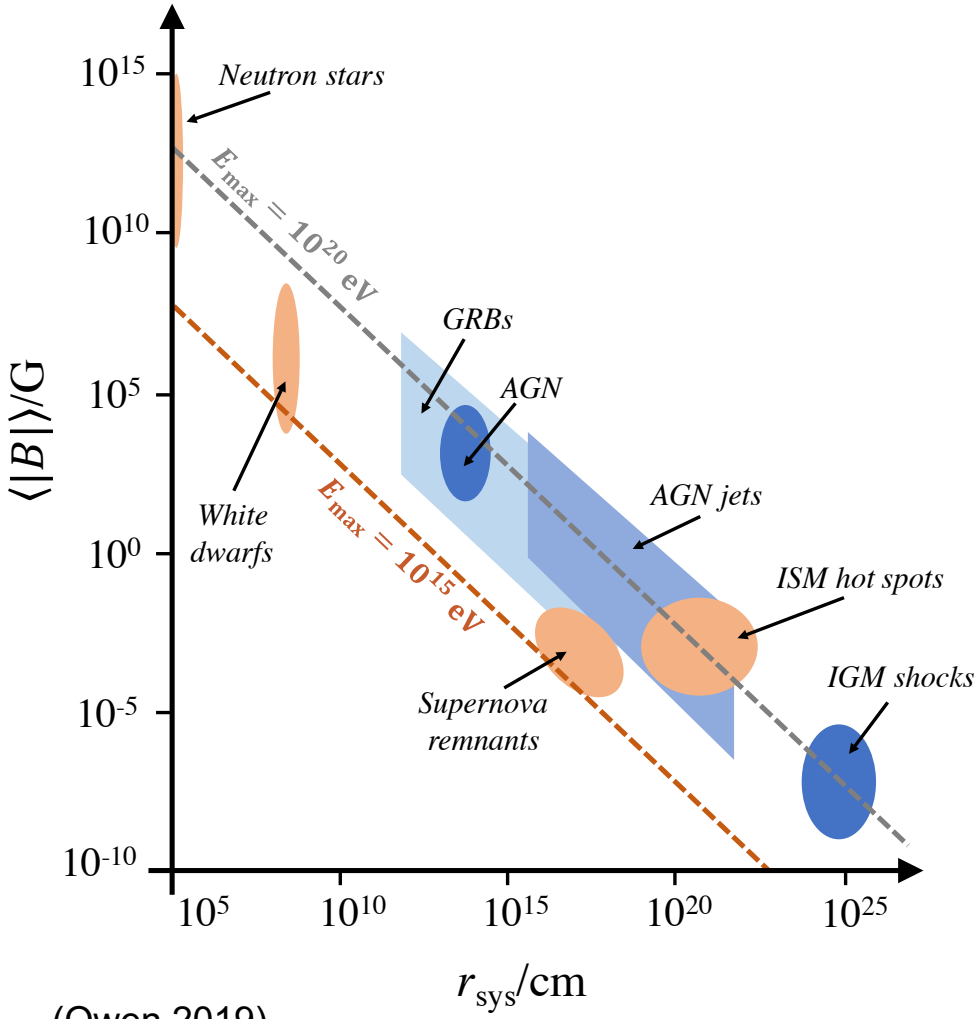
Uniform B field



r_L depends on energy

$$r_{\mathrm{L}} = \frac{1.07 \times 10^{-5}}{|Z|} \left(\frac{E}{100\ \mathrm{MeV}} \right) \left(\frac{B}{\mu \mathrm{G}} \right)^{-1} \ \mathrm{pc}$$

Cosmic ray origins



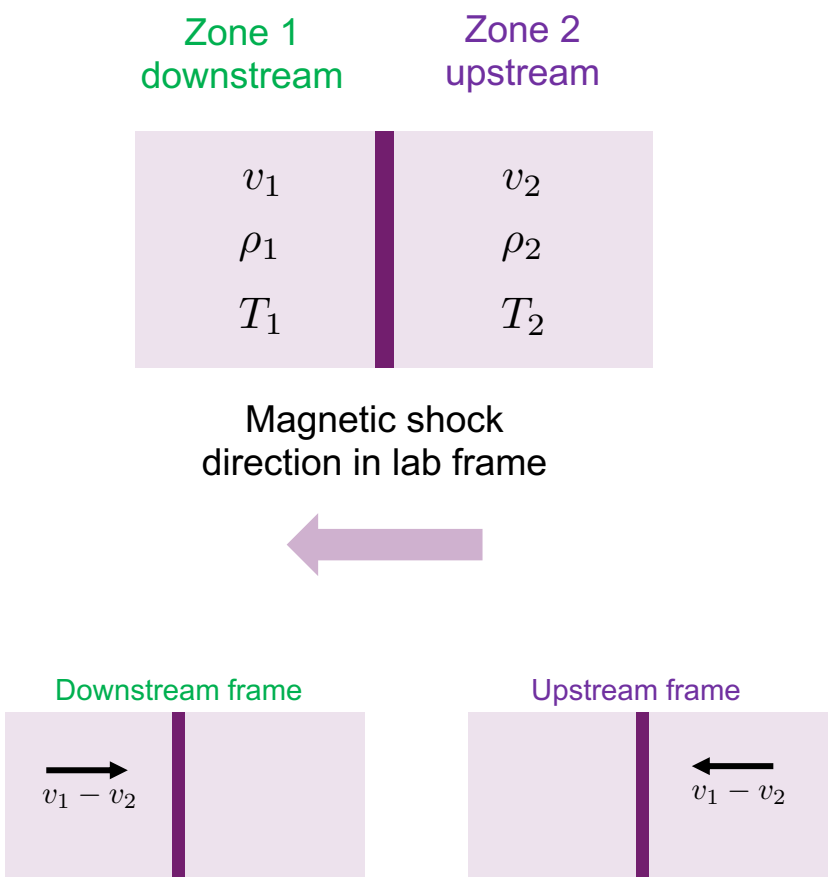
(Owen 2019)

Compare size of region to gyroradius (Hillas criterion)

Needs to be 'contained' to sustain charged particle acceleration

Charged particle acceleration

Consider a strong, magnetised shock (e.g. in a supernova remnant)



One simple example of particle acceleration (first-order Fermi acceleration)

In the lab frame, shock moves left to right
Fluid is thermal gas either side

Head-on collision of a particle with shock in both frames approaches the shock with velocity

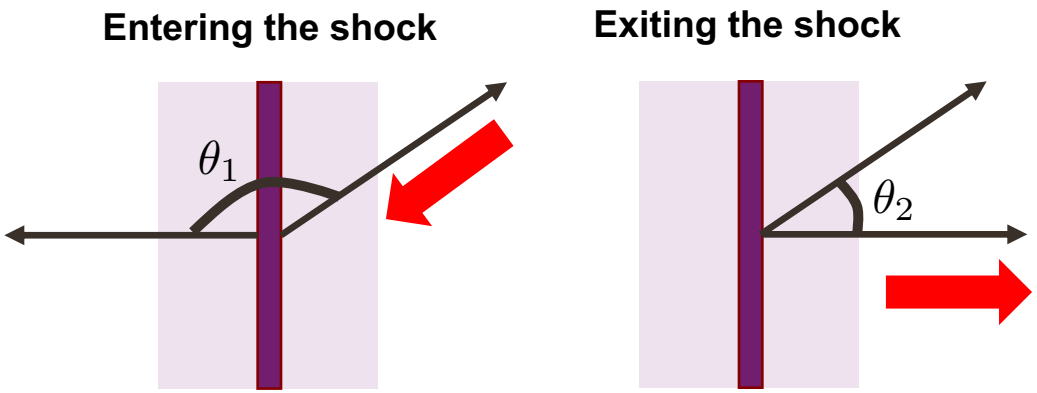
$$v = v_1 - v_2$$

Charged particle acceleration

Particle passing through the shock

Fractional energy gain of a particle per crossing

$$\xi = \frac{E_2 - E_1}{E_1} = \frac{E_2}{E_1} - 1$$



$$E_1' = \gamma_L E_1 (1 - \beta \cos \theta_1)$$

$$E_2 = \gamma_L E_2' (1 + \beta \cos \theta_2')$$

primed: magnetic shock frame

unprimed: observer (lab) frame

$$\gamma_L = \frac{1}{\sqrt{1 - \beta^2}} \qquad \beta = \frac{v}{c}$$

Charged particle acceleration

$$\frac{E_2}{E_1} = \boxed{\left(\frac{E_2'}{E_1'}\right)} \gamma_L^2 (1 - \beta \cos\theta_1)(1 + \beta \cos\theta_2')$$

The magnetic field does not do work in shock frame, $E_1' = E_2'$

$$\Rightarrow \xi = \frac{1 - \beta\cos\theta_1 + \beta\cos\theta_2' - \beta^2 \cos\theta_1 \cos\theta_2'}{1 - \beta^2} - 1$$

$$\boxed{\langle \cos\theta_1 \rangle = -\frac{2}{3} \qquad \langle \cos\theta_2 \rangle = +\frac{2}{3} \qquad \langle \cos\theta_2' \rangle = 0}$$

$$\Rightarrow \langle \xi \rangle \simeq \frac{4}{3}\beta > 0$$

Averaging over particles entering/leaving the shock

Emergence of a power law spectrum

- Each pass through the shock increases the energy

$$\langle \xi \rangle \simeq \frac{4}{3}\beta > 0$$

- After *n* crossings, energy is

$$E = E_0 \langle \xi \rangle^n$$

- Some particles will escape after a crossing – take P as probability of remain, so number remaining after each crossing

$$N = N_0 P^n$$

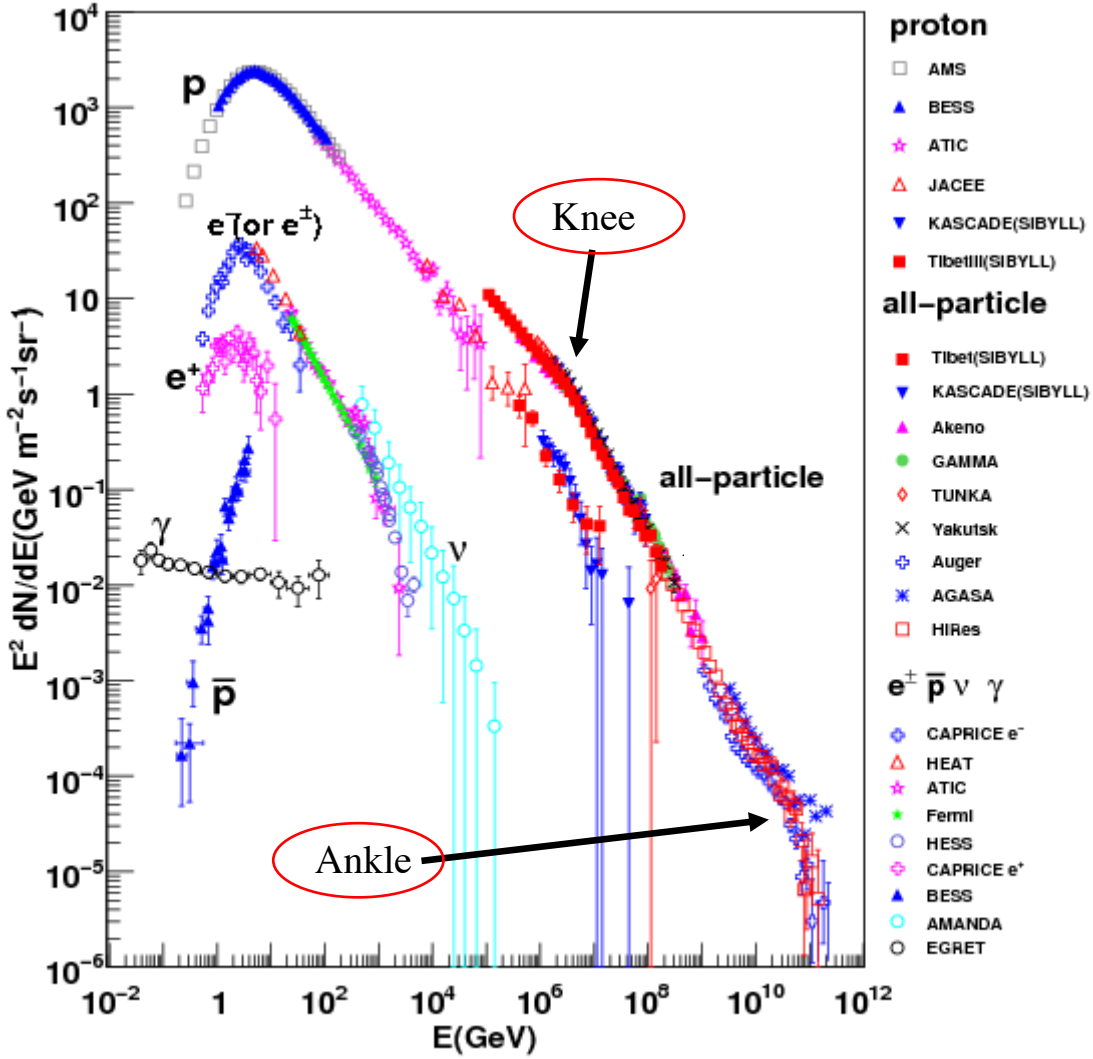
- Eliminate *n* and rearrange

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

- Result is CRs accelerated to high energies, ~GeV and above, following a power-law

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

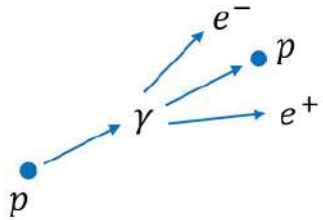
Features of the cosmic ray spectrum



(Gaisser 2007)

Cosmic ray interactions

Radiation fields



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

photo-pair production

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\pi^0 \rightarrow p2\gamma \\ n\pi^+ \rightarrow n\mu^+\nu_\mu \\ \qquad\qquad \hookrightarrow e^+\nu_e\bar{\nu}_\mu \end{cases}$$

photo-hadronic process

$$n \rightarrow pe^-\bar{\nu}_e$$

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

Cosmic ray interactions

Radiation fields

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

$$p\gamma \rightarrow \Delta^+ \rightarrow \begin{cases} p\pi^0 \rightarrow p2\gamma \\ n\pi^+ \rightarrow n\mu^+\nu_\mu \\ \qquad\qquad \hookrightarrow e^+\nu_e\bar{\nu}_\mu \end{cases}$$

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

electromagnetic decay

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

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

weak decay

Cosmic ray interactions

Baryon fields

hadron-hadron interaction

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

+ pion multiplicities at higher energies

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

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

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

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

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

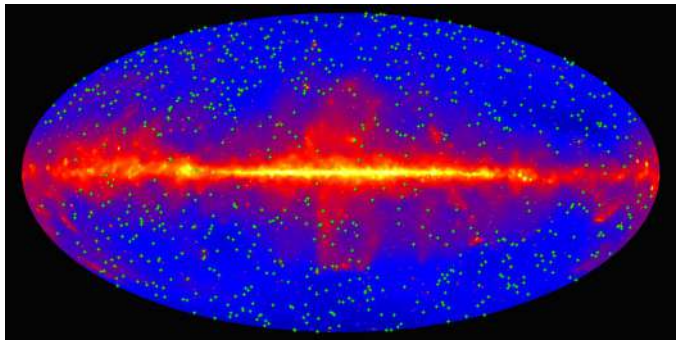
Cosmic ray interactions

Baryon fields

hadron-hadron interaction

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

+ pion multiplicities at higher energies



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

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

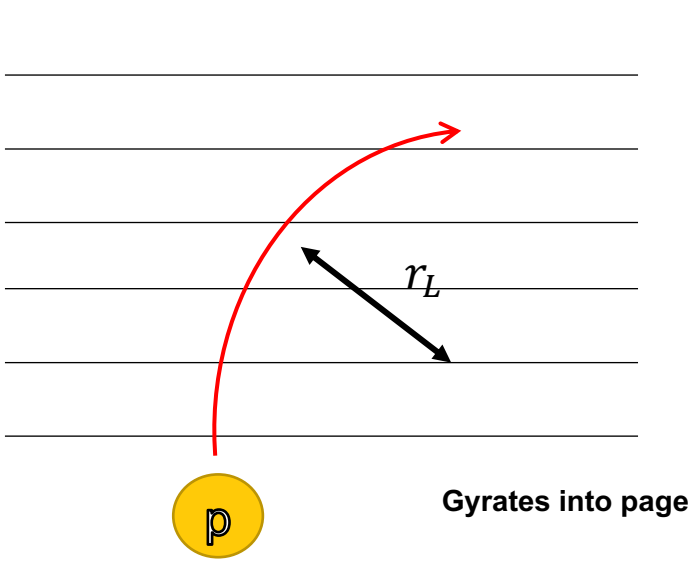
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$

Electrons can cause heating in dense conditions

Neutrinos smoking gun of hadronic interactions

Cosmic ray propagation

Uniform B field



Tangled B field

r_L depends on energy

Diffusion and advection

Credit: DesktopPaints 2022

Cosmic ray transport

Advection-diffusion model, general form:

advection diffusion

$$\left(\frac{\partial}{\partial t} + \boxed{\dot{q}_{\mathrm{i}}\frac{\partial}{\partial q_{\mathrm{i}}} + \dot{p}_{\mathrm{i}}\frac{\partial}{\partial p_{\mathrm{i}}}} + \boxed{\nabla_{\mathrm{i}}^{[q]} D^{[q]} \nabla_{\mathrm{i}}^{[q]} + \nabla_{\mathrm{i}}^{[p]} D^{[p]} \nabla_{\mathrm{i}}^{[p]}}\right) n(t, q_{\mathrm{i}}, p_{\mathrm{i}}) = Q(t, q_{\mathrm{i}}, p_{\mathrm{i}}) - S(q_{\mathrm{i}}, p_{\mathrm{i}})$$

Cosmic ray transport

Advection-diffusion model, general form:

$$\left(\frac{\partial}{\partial t} + \dot{q}_{\mathrm{i}}\frac{\partial}{\partial q_{\mathrm{i}}} + \dot{p}_{\mathrm{i}}\frac{\partial}{\partial p_{\mathrm{i}}} + \nabla_{\mathrm{i}}^{[q]} D^{[q]} \nabla_{\mathrm{i}}^{[q]} + \nabla_{\mathrm{i}}^{[p]} D^{[p]} \nabla_{\mathrm{i}}^{[p]}\right) n(t, q_{\mathrm{i}}, p_{\mathrm{i}}) = \boxed{Q(t, q_{\mathrm{i}}, p_{\mathrm{i}})} - \boxed{S(q_{\mathrm{i}}, p_{\mathrm{i}})}$$

source (injection)

sink

Cosmic ray transport

Advection-diffusion model, general form:

$$\left(\frac{\partial}{\partial t} + \dot{q}_{\mathrm{i}}\frac{\partial}{\partial q_{\mathrm{i}}} + \dot{p}_{\mathrm{i}}\frac{\partial}{\partial p_{\mathrm{i}}} + \nabla_{\mathrm{i}}^{[q]} D^{[q]} \nabla_{\mathrm{i}}^{[q]} + \nabla_{\mathrm{i}}^{[p]} D^{[p]} \nabla_{\mathrm{i}}^{[p]}\right) n(t, q_{\mathrm{i}}, p_{\mathrm{i}}) = Q(t, q_{\mathrm{i}}, p_{\mathrm{i}}) - S(q_{\mathrm{i}}, p_{\mathrm{i}})$$

Simplified (practically useful) version

energy loss / cooling

$$\left(\frac{\partial}{\partial t} + \vec{v}\cdot\nabla + \dot{\gamma}\frac{\partial}{\partial \gamma} + \nabla\cdot D\nabla\right) n(t, \vec{x}, E) = Q(t, \vec{x}, E) - S(\vec{x}, E)$$

interaction

4. Research applications: high energy phenomena in and around star-forming galaxies

Nearby starburst galaxies

M82

$$\mathrm{SFR} \sim (1-10)\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$$

$$\mathrm{SNR} \sim 0.1\,\mathrm{yr}^{-1}$$

(Benech et al. 2010; Varenius et al. 2016)

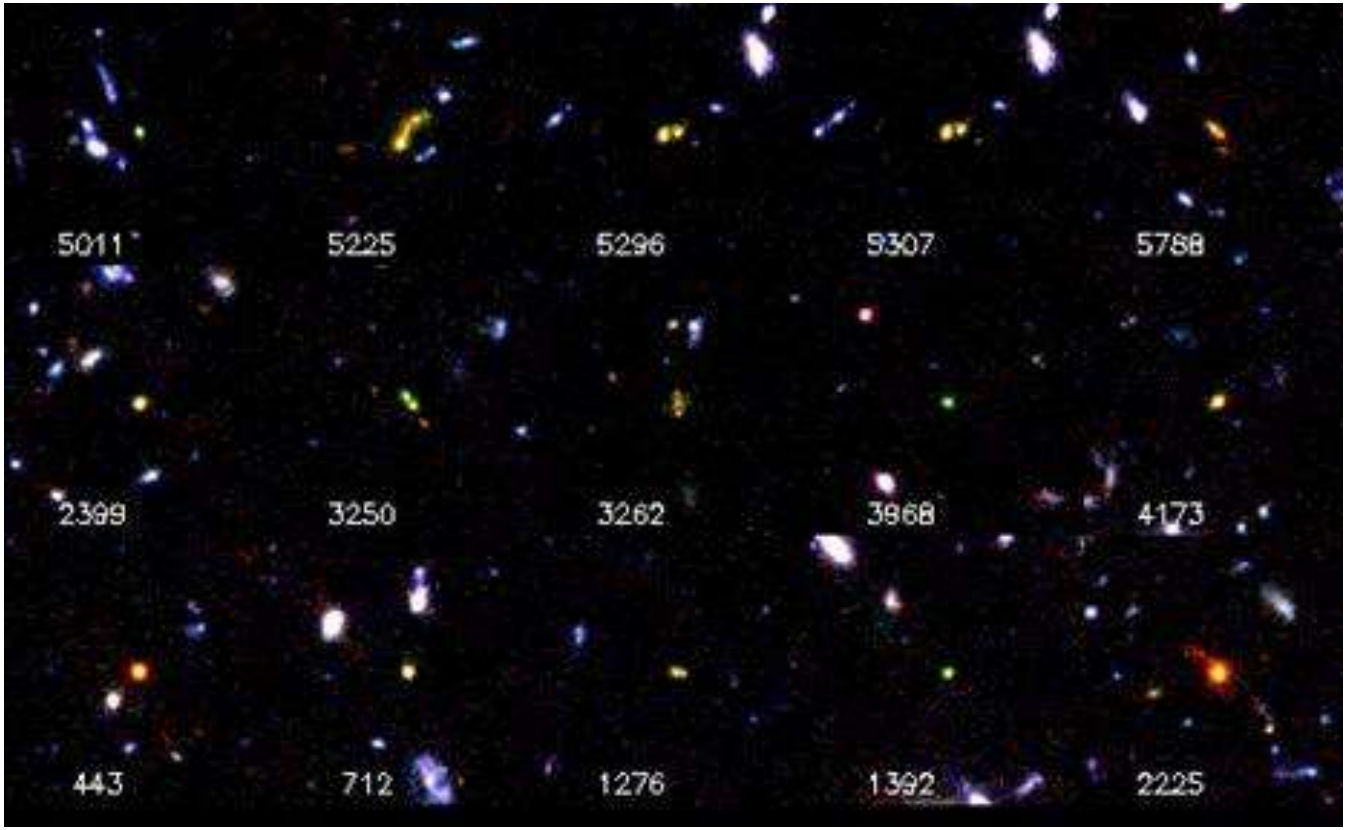
Arp220

$$\mathrm{SFR} \sim 220\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$$

$$\mathrm{SNR} \approx 4\,\mathrm{yr}^{-1}$$

image credit: ESO, NASA/ESA

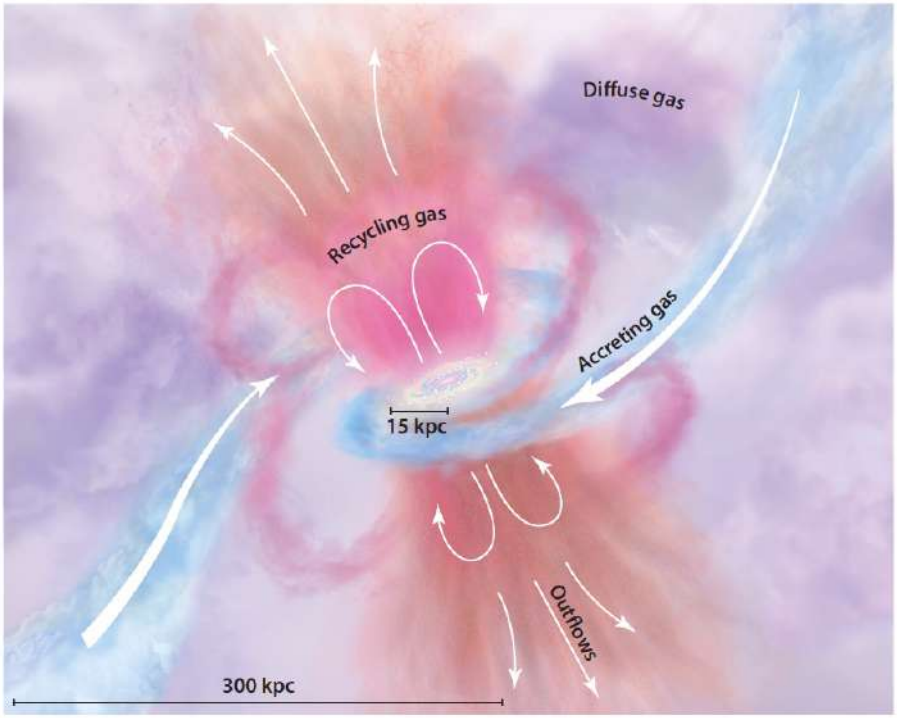
Primordial galaxies

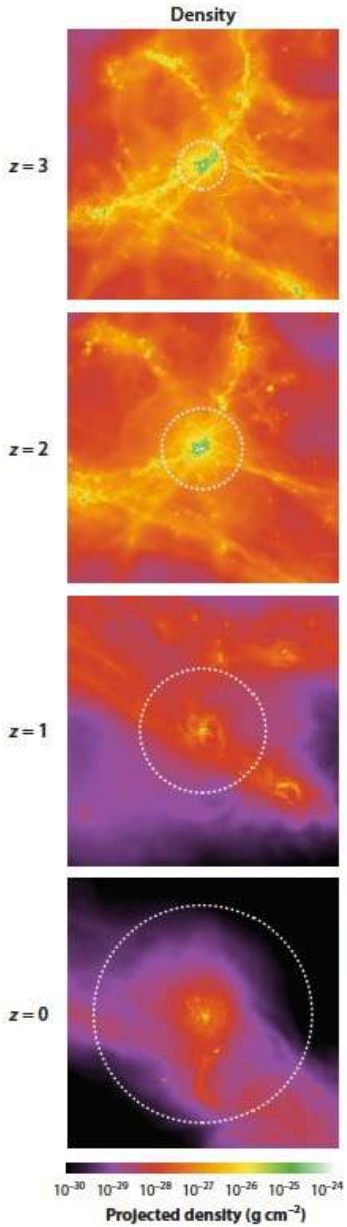


HST/ACS images of galaxies at redshift z ~ 5 - 6

(Bremer and Lehnert 2005)

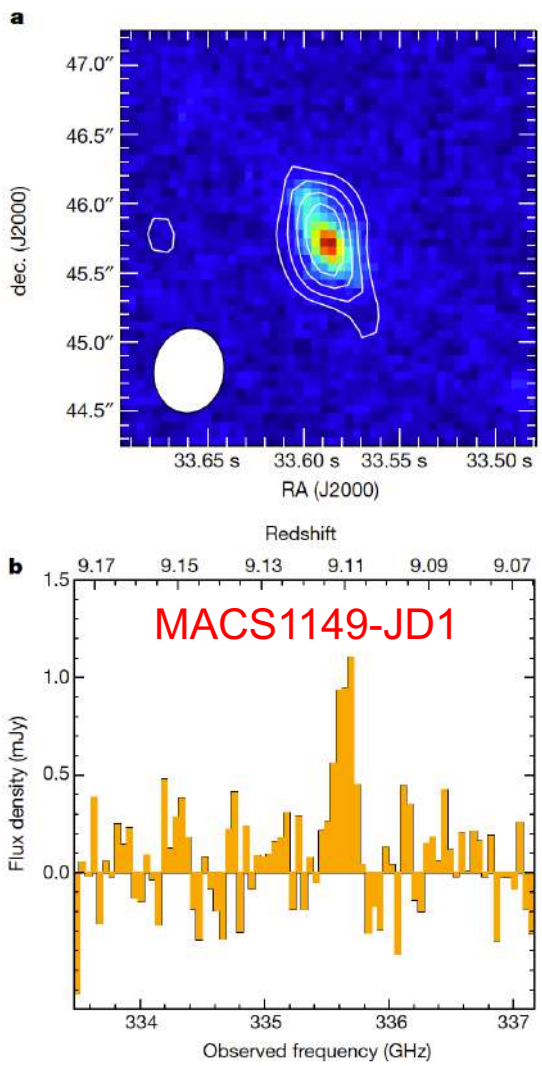
Circum-galactic medium

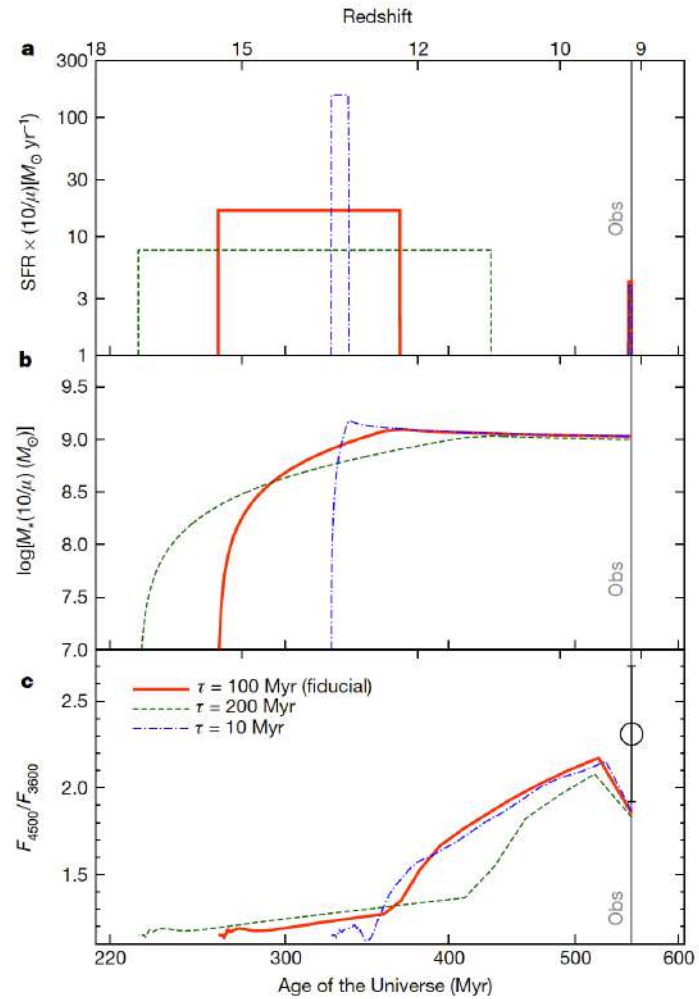




(Tumlinson, Peeples and Werk 2017)

The curious case of MACS1149-JD1





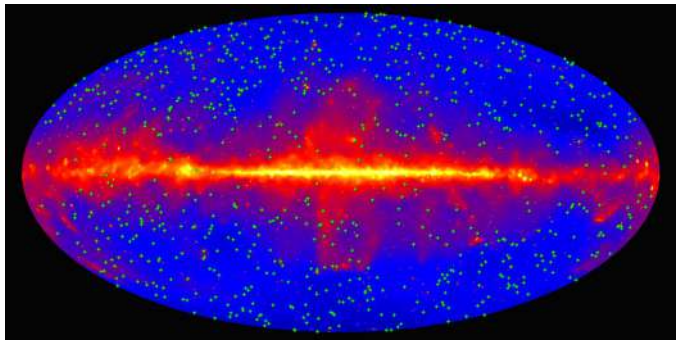
(Hashimoto et al. 2018)

Reminder – hadronic interaction

hadron-hadron interaction

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

+ pion multiplicities at higher energies



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

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

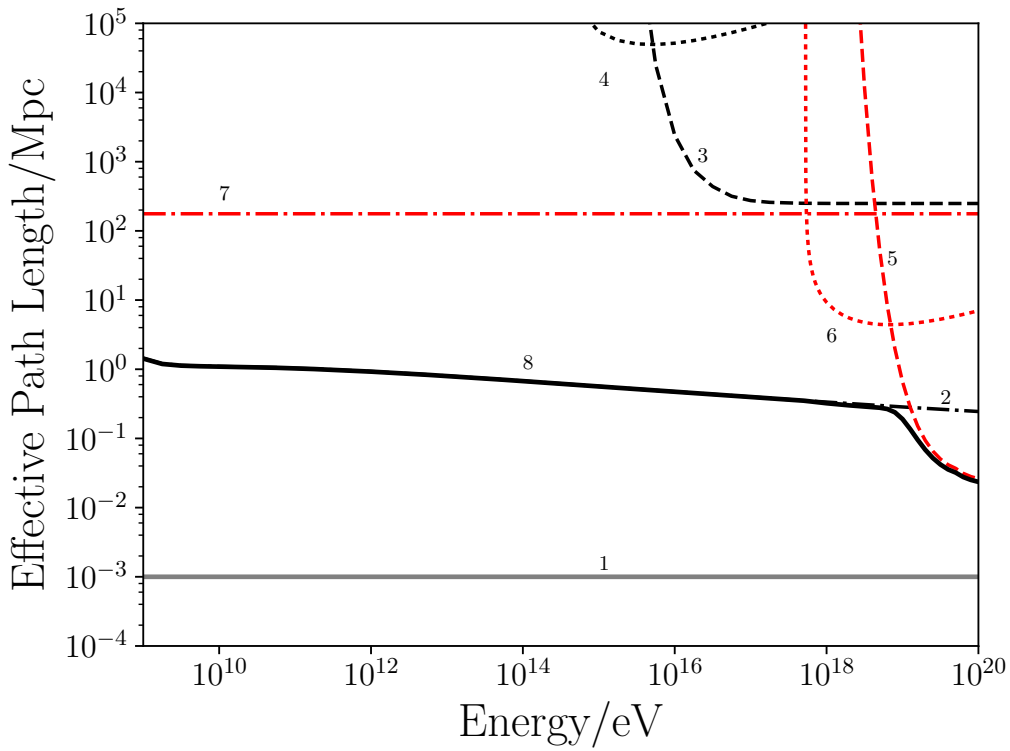
$$\pi^- \rightarrow \mu^- \bar{\nu}_\mu \rightarrow e^- \bar{\nu}_e \nu_\mu \bar{\nu}_\mu$$

Electrons can cause heating in dense conditions

Neutrinos smoking gun of hadronic interactions

Inside galaxies

Energy loss path length of free-streaming CR in protogalactic environment at redshift z = 7



1. protogalactic radius
2. hadronic pion process
3. photo-pion process (galaxy)
4. photo-pair process (galaxy)
5. photo-pion process (CMB)
6. photo-pair process (CMB)
7. cosmological expansion
8. total

(Owen, Jacobsen, Wu et al. 2018)

Cosmic ray containment inside galaxies

Diffusion dominated regime

$$\left(\frac{\partial}{\partial t} + \cancel{\vec{v}\cdot\nabla} + \cancel{\dot{\gamma}\frac{\partial}{\partial\gamma}} + \nabla\cdot D\nabla\right) n(t,\vec{x},E) = Q(t,\vec{x},E) - S(\vec{x},E)$$

magnetic-field scattering induced diffusion

$$D(E,\vec{x},t) = D_0(t)\left[\frac{r_{\rm L}(E,B_{\rm rms})|_{\vec{x},t}}{r_{\rm L,0}(t_{\rm sat})}\right]^{1/2}$$

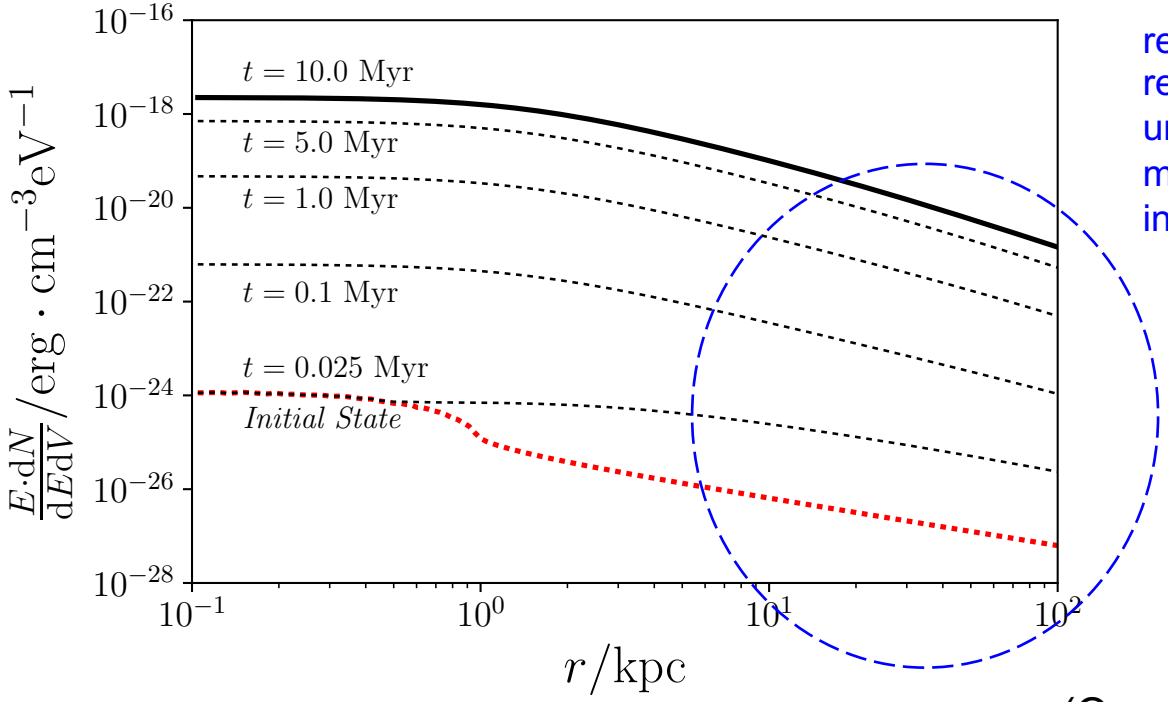
$$Q(E,\vec{x},t) = \{\mathcal{L}_{\rm CR}(E)\mathcal{Q}_{\rm CR}(\vec{x})\}\Big|_t$$

(Owen, Jacobsen, Wu et al. 2018)

Cosmic ray containment inside galaxies

scattering of CR by the magnetic field lead to CR containment

$$n_{\rm CR}[B \text{ scattered}] \sim 10^6\, n_{\rm CR}[\text{free streaming}]$$

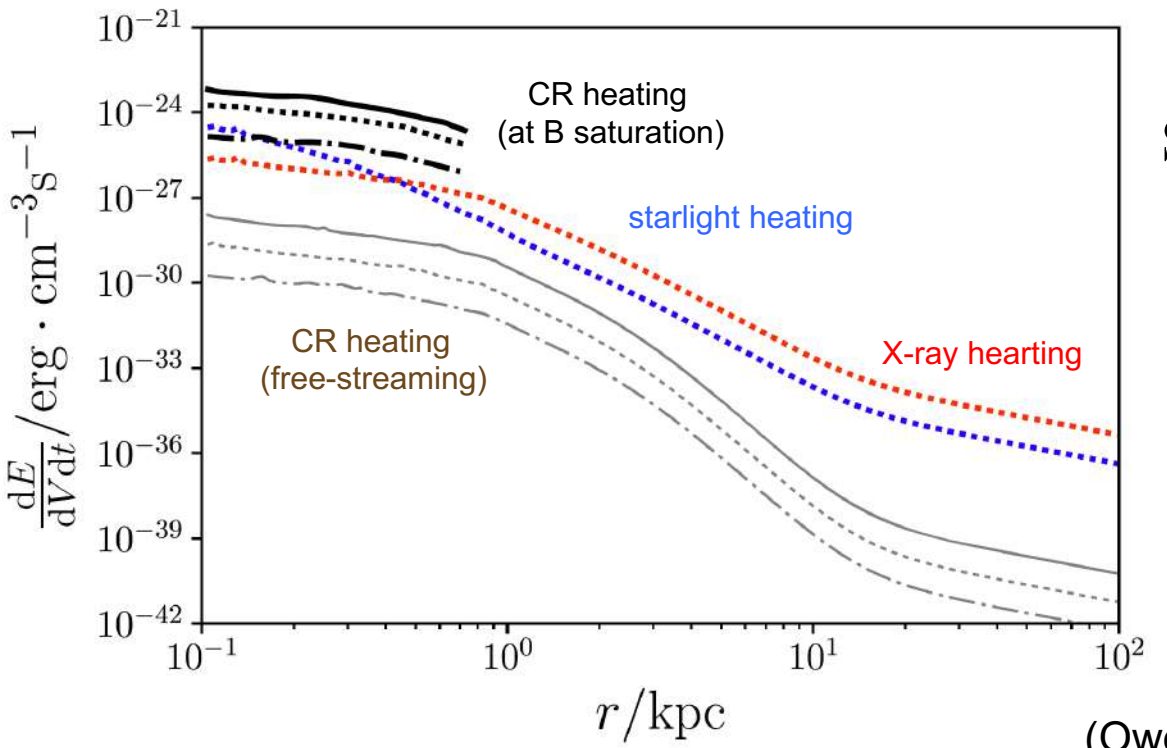


reasonable within the central region of the galaxy, but large uncertainty without a good model for the CGM/ISM interfacing field

(Owen, Jacobsen, Wu et al. 2018)

Inside galaxies

Cosmic-ray heating in comparison with other sources (absence of advection)



$$\mathrm{SNR} = 0.1,\ 1,\ 10\,\mathrm{yr}^{-1}$$

(Owen, Jacobsen, Wu et al. 2018)

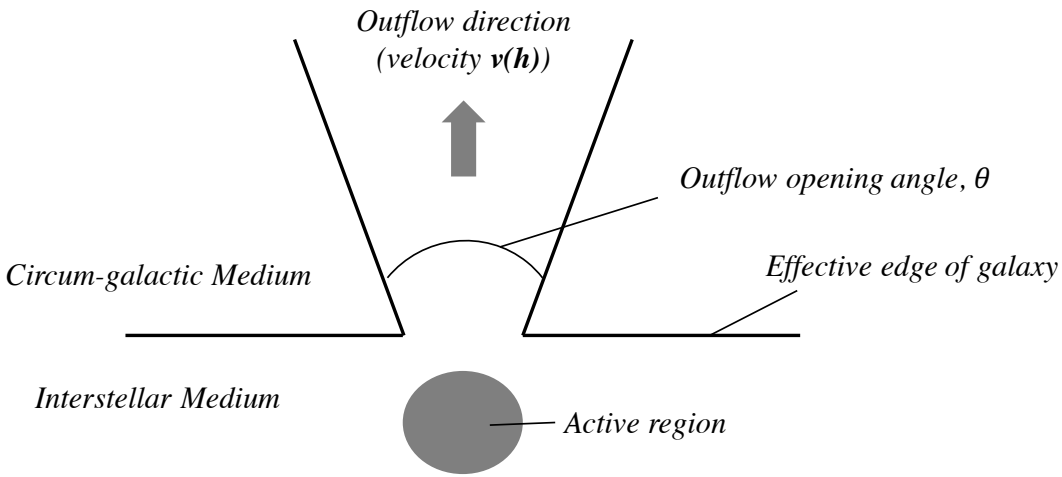
Around galaxies - outflows

M82

Advection dominated regime

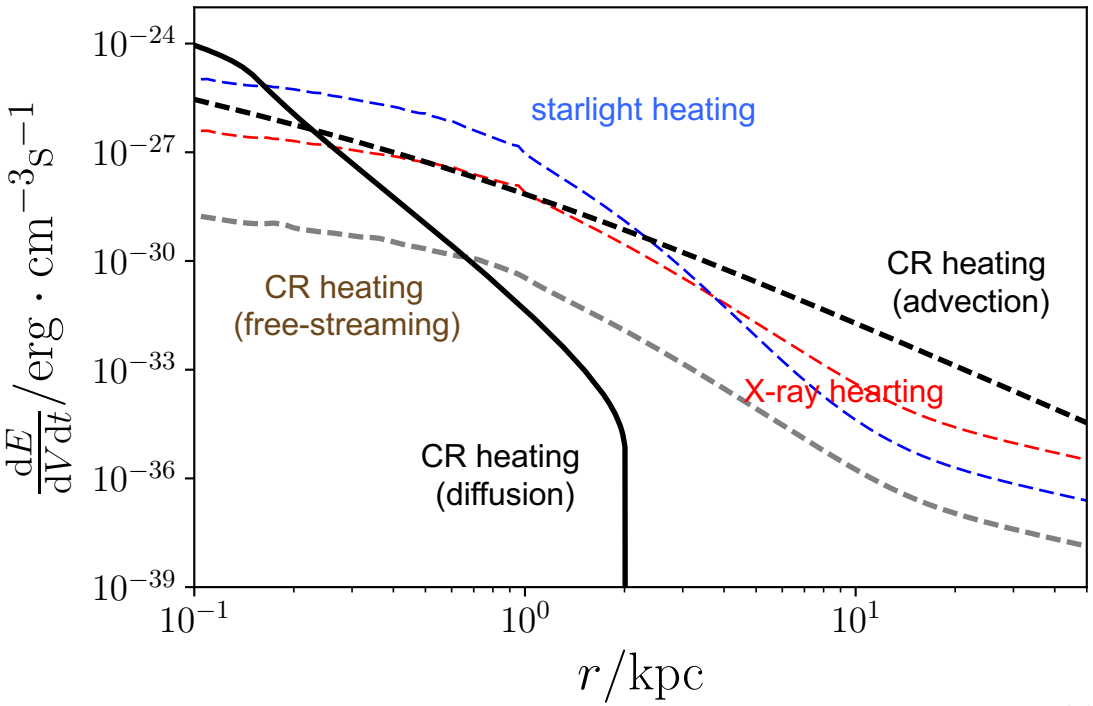
$$\left(\frac{\partial}{\partial t} + \vec{v}\cdot\nabla + \cancel{\dot{\gamma}\frac{\partial}{\partial\gamma}} + \cancel{\nabla\cdot D\nabla}\right) n(t,\vec{x},E) = Q(t,\vec{x},E) - S(\vec{x},E)$$

treat as an initial boundary condition



Cosmic ray heating around galaxies

Heating pattern in advection and diffusion dominated transport



$v_\infty = 1000\,\mathrm{km\ s^{-1}}$

$B_{\mathrm{rms}}(t_{\mathrm{sat}}) = 5\,\mu\mathrm{G}$

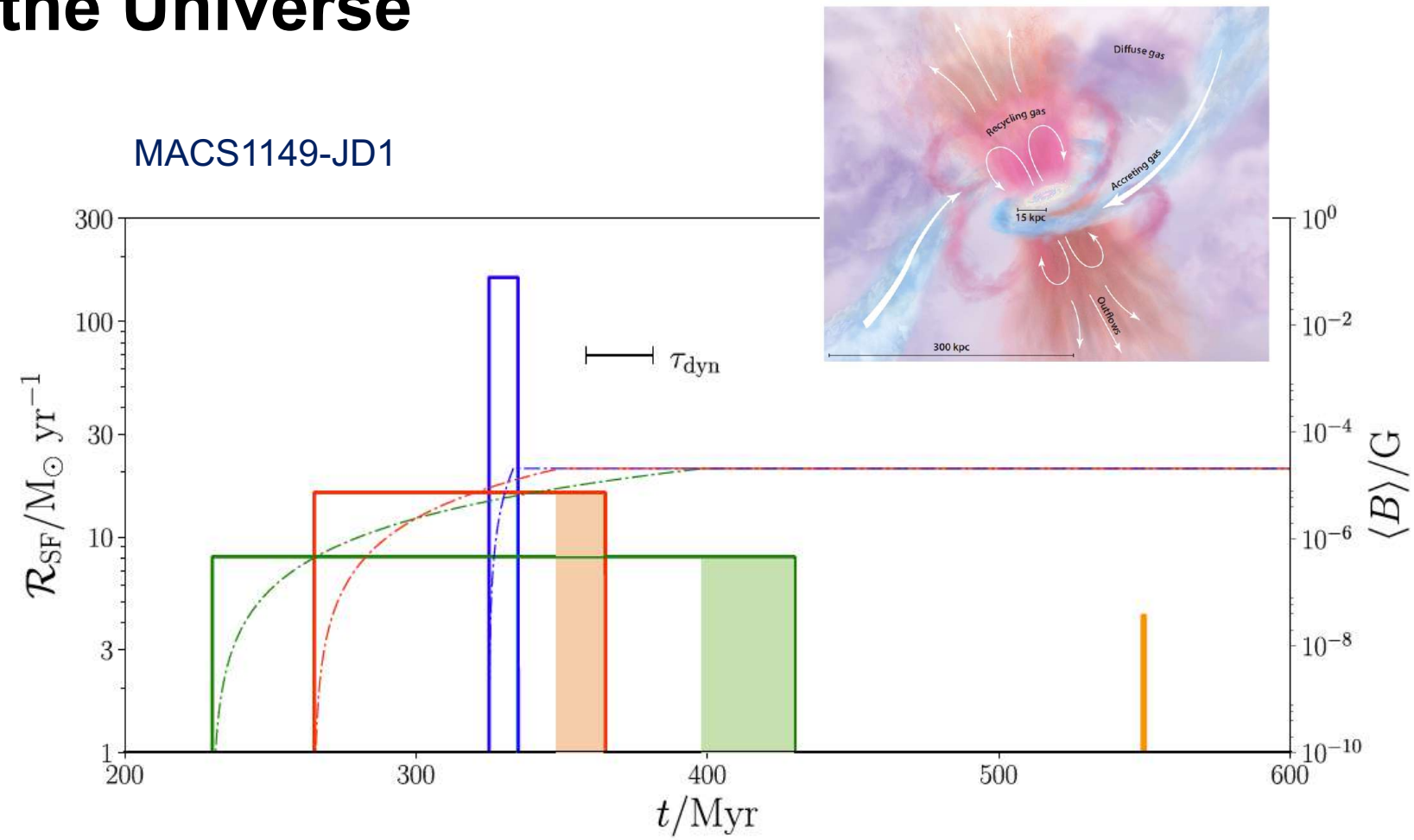
$\theta = 55^\circ$

$\mathrm{SNR} = 1\,\mathrm{yr}^{-1}$

(Owen, Jin, Wu et al. 2019)

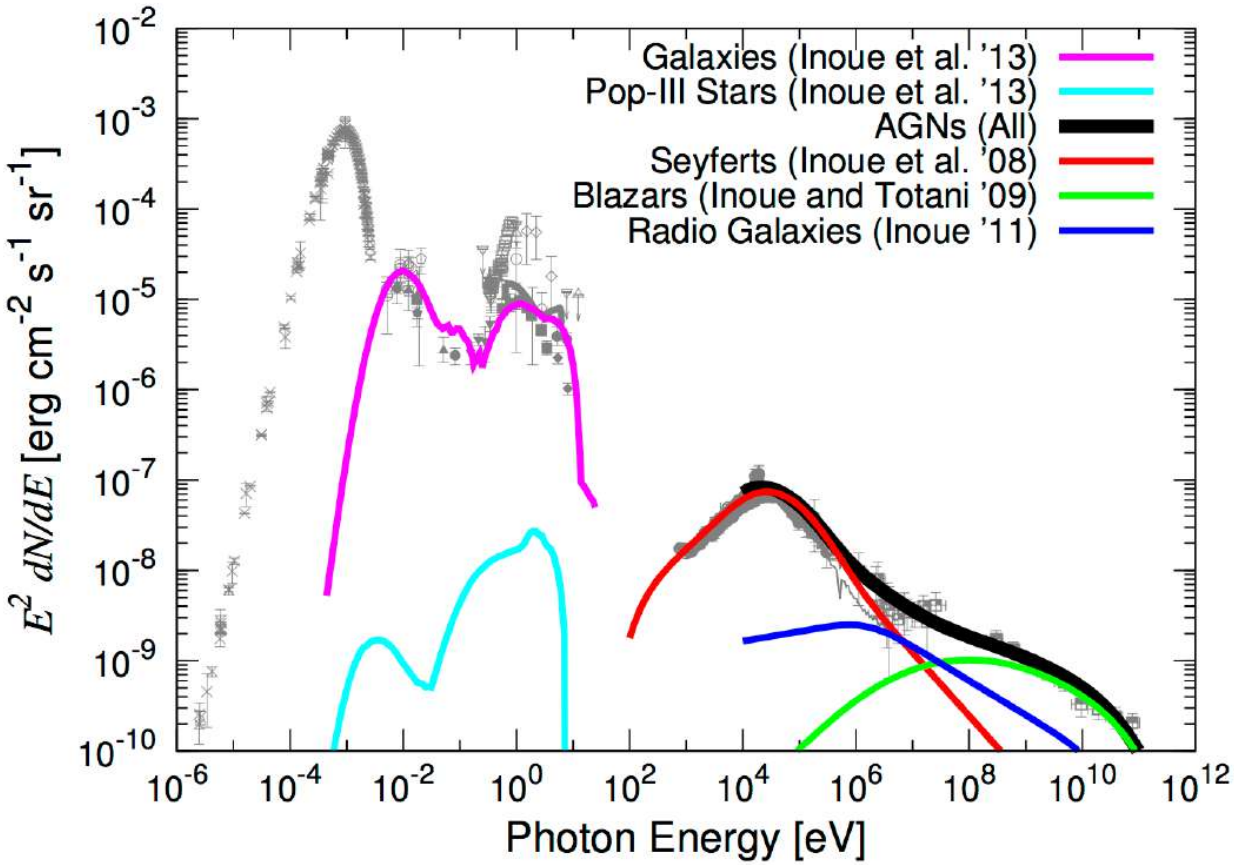
Cosmic rays and structural evolution of the Universe

MACS1149-JD1

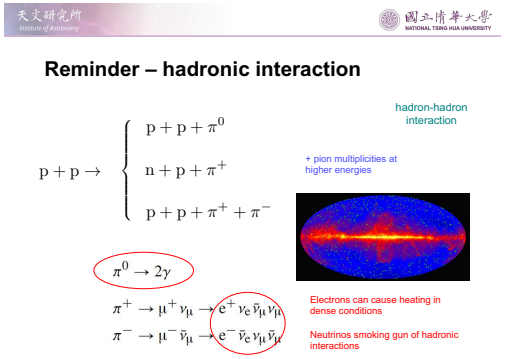


(Owen, Jin, Wu et al. 2019)

Cosmic ray heating and the structural evolution of the Universe

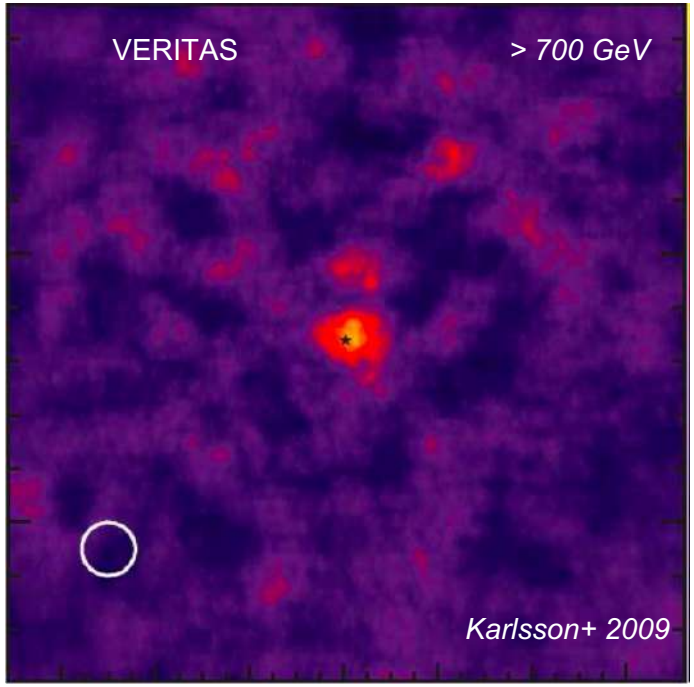


Cosmological gamma-ray background ?



(Inoue 2014)

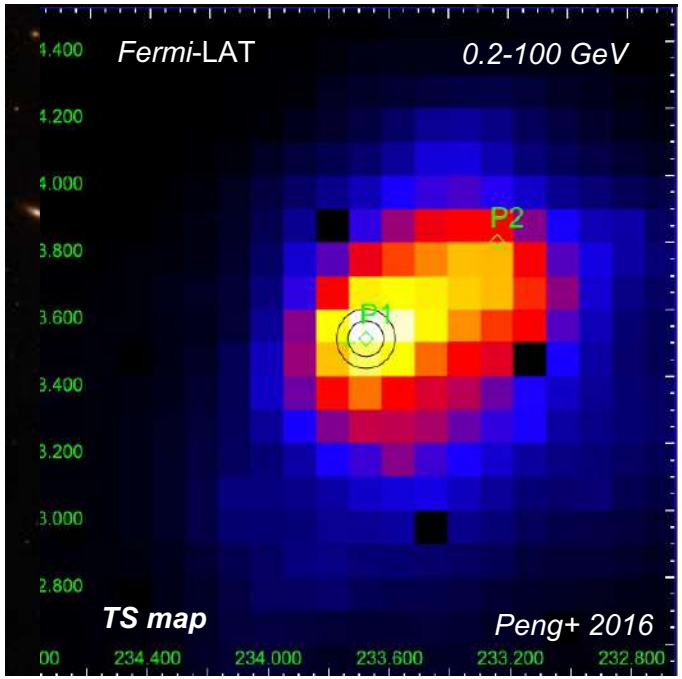
Nearby starburst galaxies



M82

$$\mathrm{SFR} \sim (1-10)\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$$

$$\mathrm{SNR} \sim 0.1\,\mathrm{yr}^{-1}$$



Arp220

$$\mathrm{SFR} \sim 220\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$$

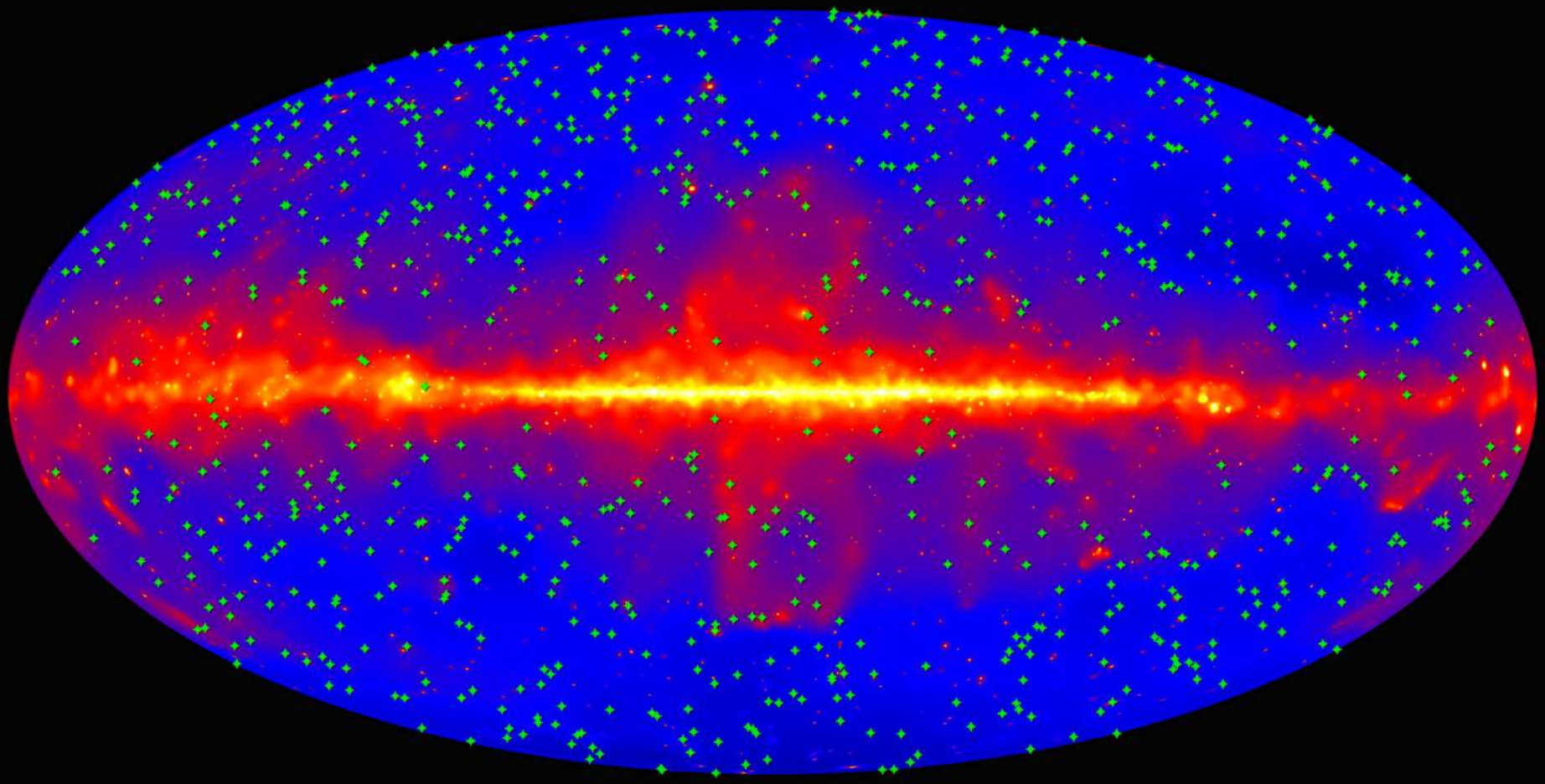
$$\mathrm{SNR} \approx 4\,\mathrm{yr}^{-1}$$

(Benech et al. 2010; Varenius et al. 2016)

image credit: ESO, NASA/ESA

The gamma-ray background

10 years of Fermi-LAT
E>10 GeV



NASA/*Fermi*-LAT collaboration

Further reading on these applications

- Owen, E. R., Jacobsen, I. B., Wu, K., Surajbali, P., 2018, MNRAS 481, 666 *Interactions between ultra-high-energy particles and protogalactic environments*
- Owen, E. R., Jin, X., Wu, K., Chan, S., 2019, MNRAS, 484, 1645 *Hadronic interaction of energetic charged particles in protogalactic outflow environments and implications for the early evolution of galaxies*
- Owen, E. R., Wu, K., Jin, X., Surajbali, P., Kataoka, N., 2019, A&A, 626, A85 *Starburst and post-starburst high-redshift protogalaxies: the feedback impact of high-energy cosmic rays*
- Owen, E. R., Lee, K.-G., Kong, A. K. H., 2021, MNRAS, 506, 52 *Characterizing the signatures of star-forming galaxies in the extragalactic γ-ray background*
- Owen, E. R., Kong, A. K. H., Lee, K.-G., 2022, MNRAS, 513, 2335 *The extragalactic γ-ray background: imprints from the physical properties and evolution of star-forming galaxy populations*