Emission Mechanisms

Lesson 4

Chiara Ferrari

Reference Text:

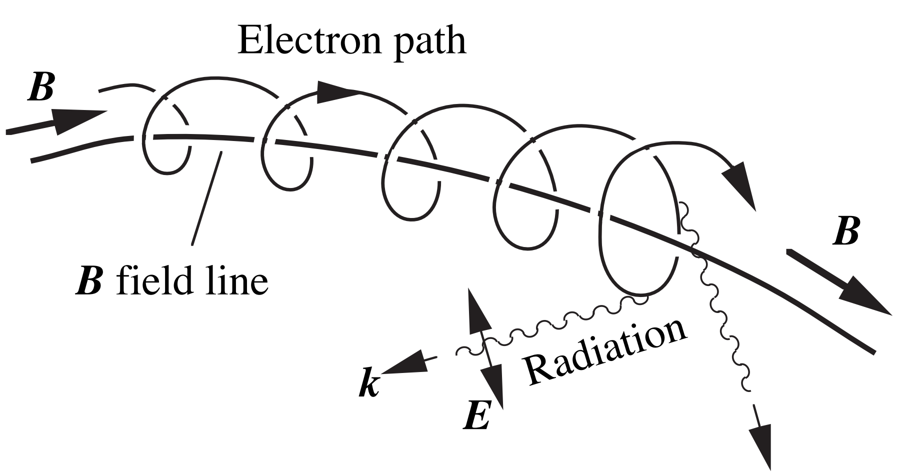
"Astrophysical Processes" by H. Bradt
Cambridge University Press (2008)

Magnetobremsstrahlung

Gyro, ciclotron and synchrotron radiation

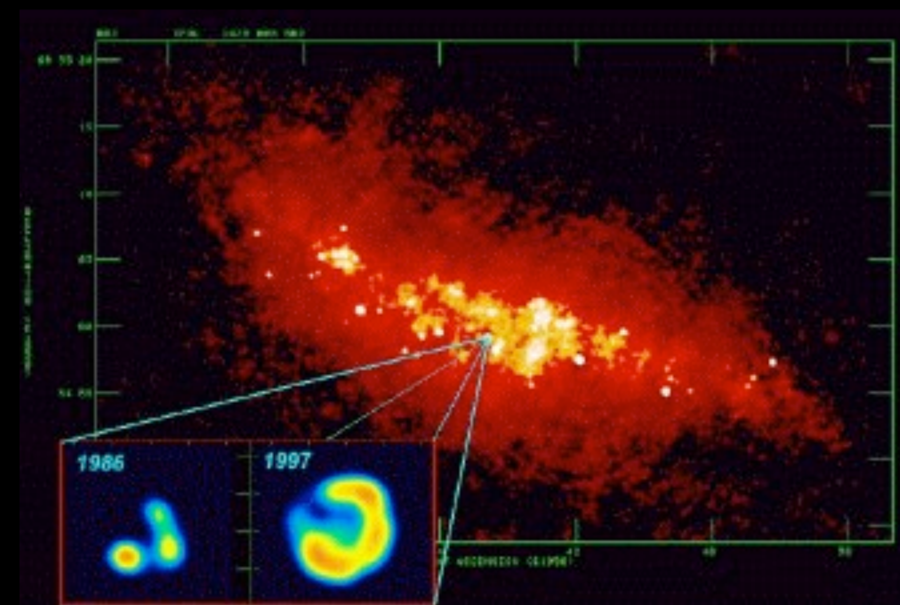
If acceleration of a charged particle by an electric field accounts for Bremsstrahlung radiation, acceleration by a magnetic field produces ***Magnetobremsstrahlung***

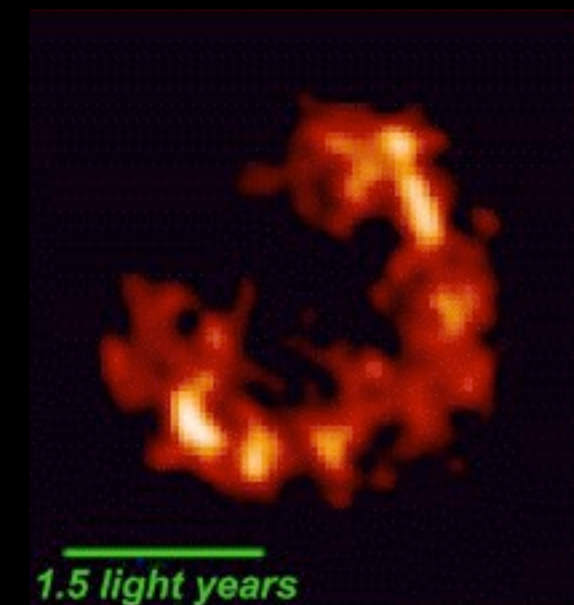
Light charged particles (e.g. electrons) are more easily accelerated than eavier particles (e.g. protons)

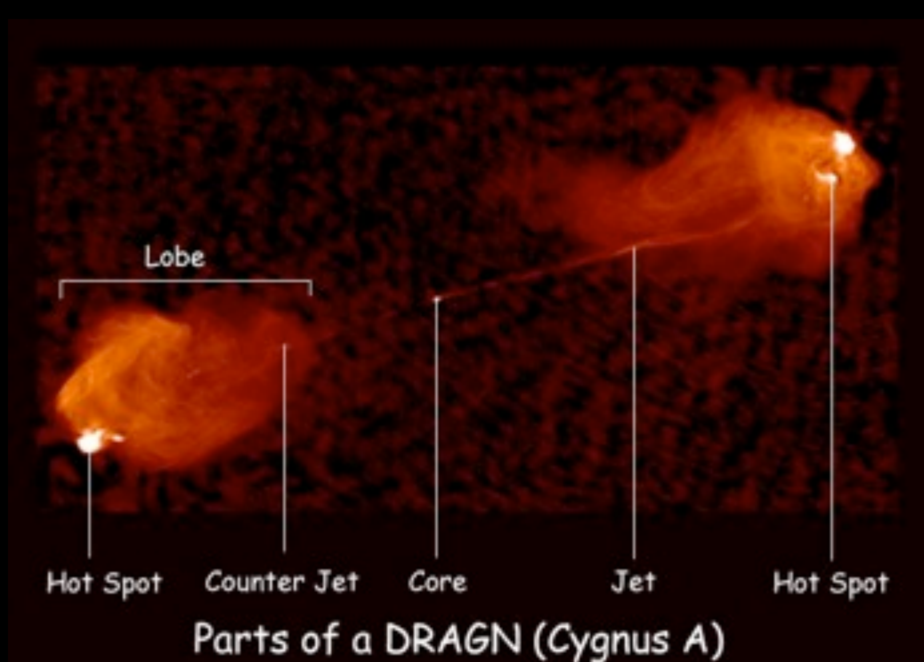


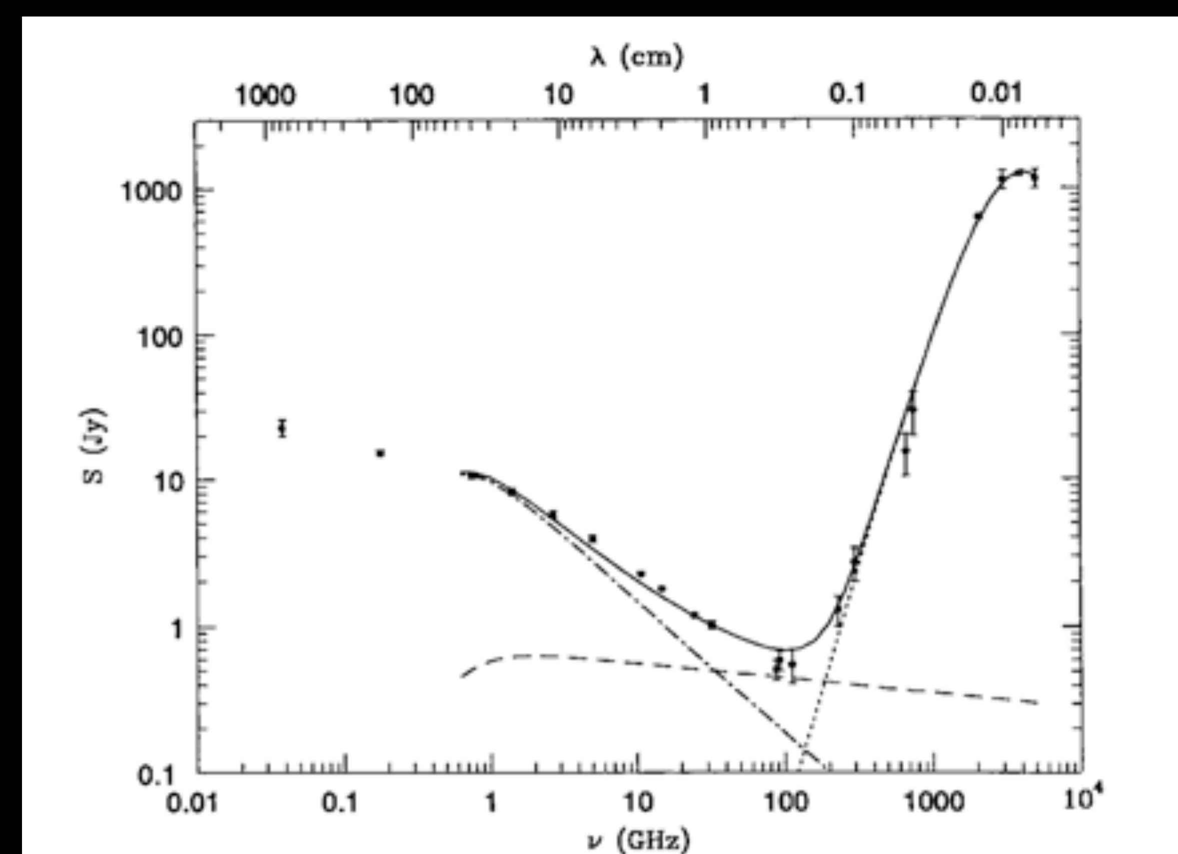
- **Gyro radiation** - Non relativistic electrons [v <<c]
- **Cyclotron radiation** - Mildly relativistic electrons $[(\gamma-1)mc^2 \sim mc^2]$
- **Synchrotron radiation** - Ultra-relativistic electrons $[(\gamma-1)mc^2 >> mc^2]$

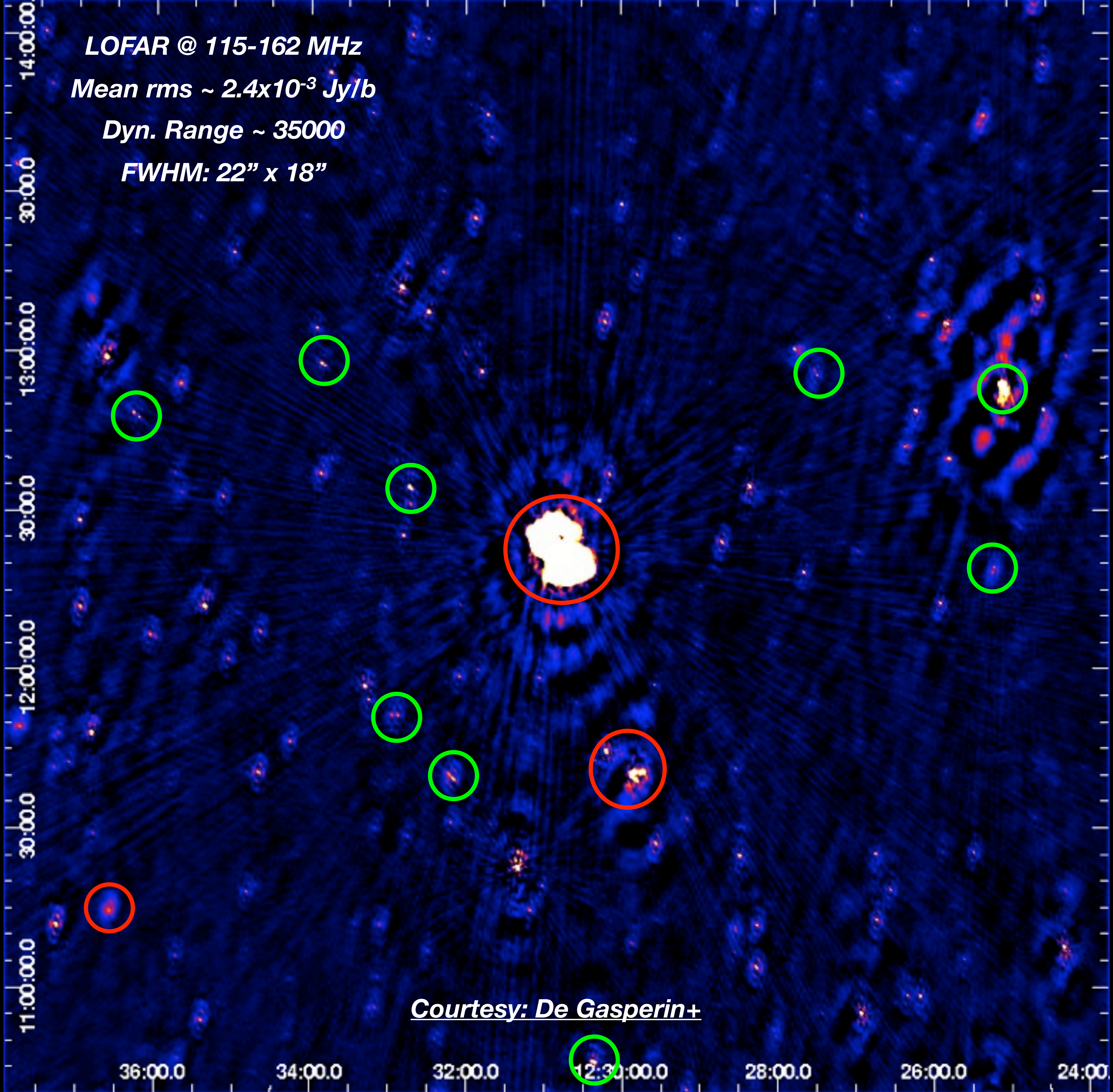
Extra-galactic sources of synchrotron radiation











LOFAR @ 115-162 MHz
Mean rms ~ 2.4x10-3 Jy/b
Dyn. Range ~ 35000
FWHM: 22” x 18”
Courtesy: De Gasperin+
14:00:00.0
30:00.0
13:00:00.0
30:00.0
12:00:00.0
30:00.0
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28:00.0
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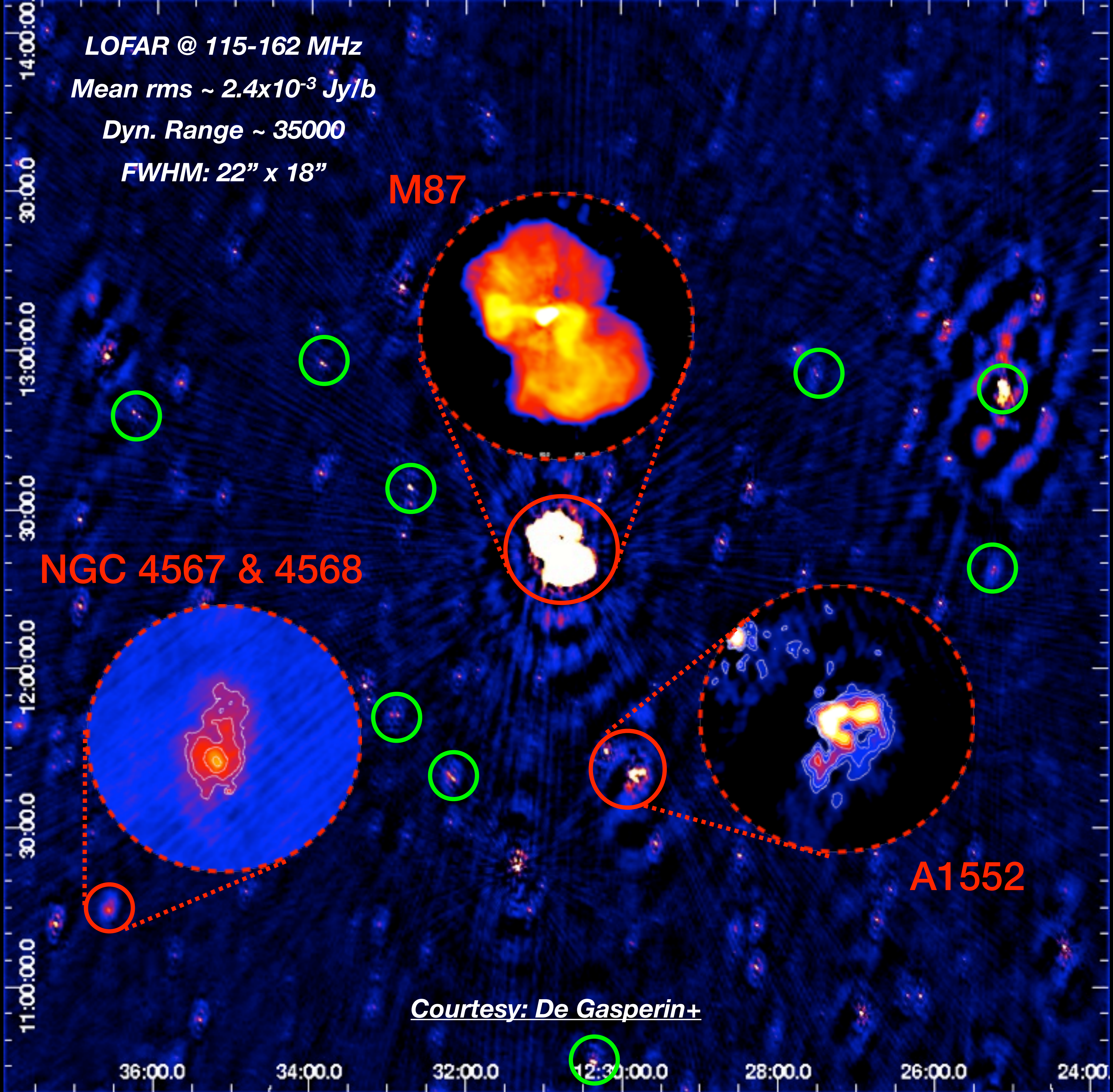
LOFAR @ 115-162 MHz
Mean rms ~ 2.4x10-3 Jy/b
Dyn. Range ~ 35000
FWHM: 22” x 18”
M87
NGC 4567 & 4568
A1552
Courtesy: De Gasperin+
14:00:00.0
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13:00:00.0
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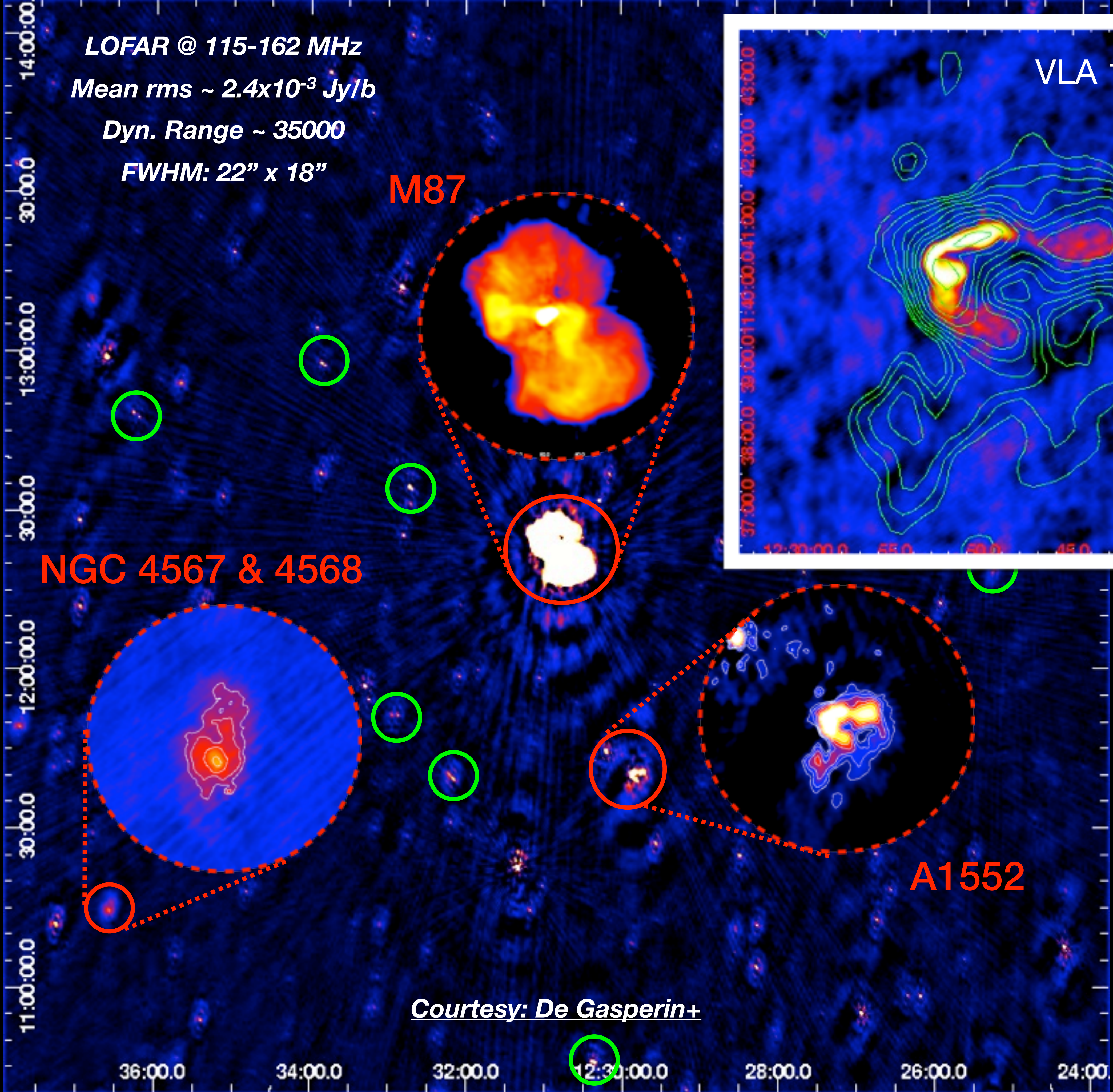
LOFAR @ 115-162 MHz
Mean rms ~ 2.4x10-3 Jy/b
Dyn. Range ~ 35000
FWHM: 22" x 18"
M87
VLA 1.4 GHz
NGC 4567 & 4568
A1552
Courtesy: De Gasperin+
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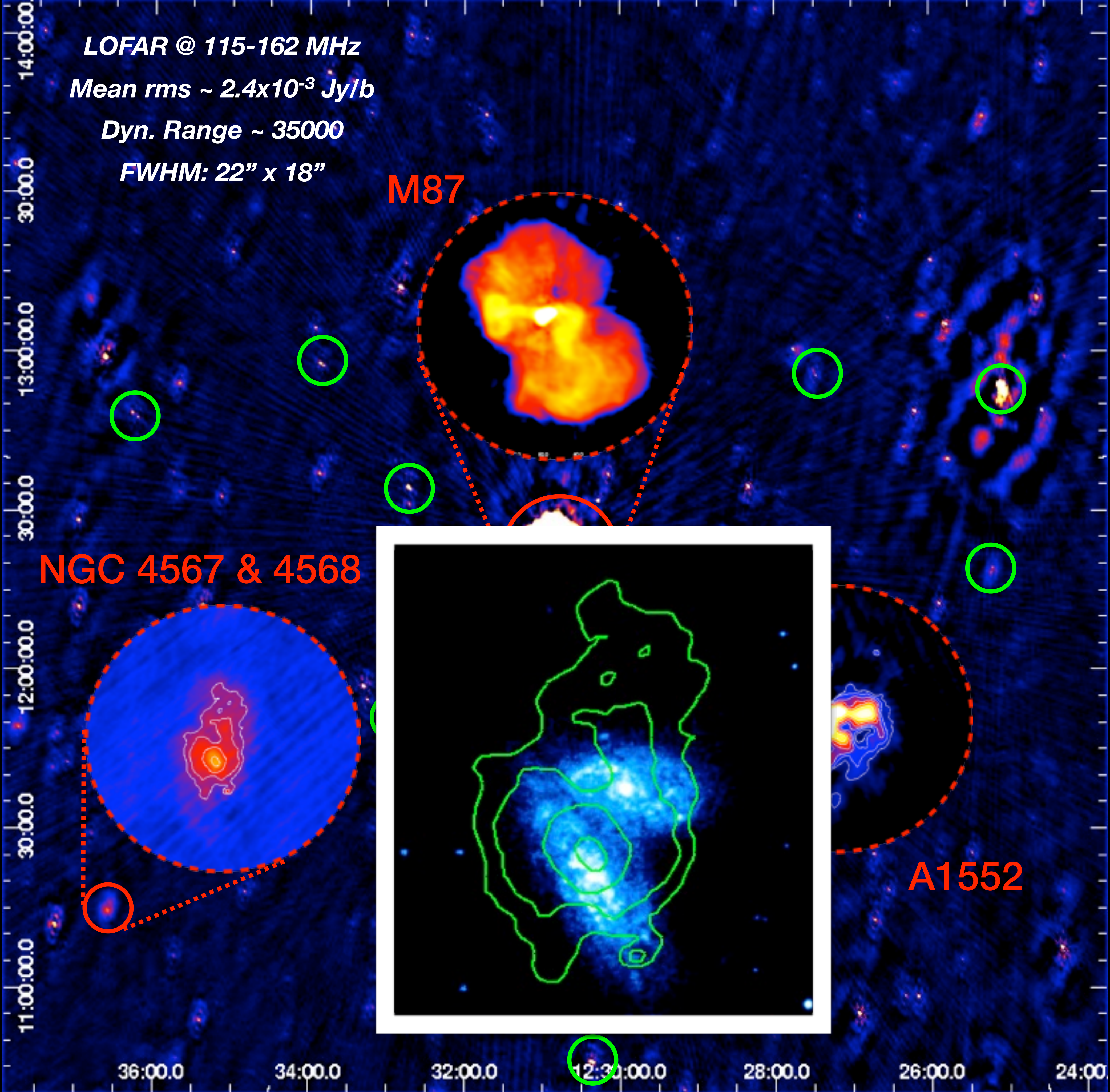

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14:00:00.0
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30:00.0
12:00:00.0
30:00.0
11:00:00.0
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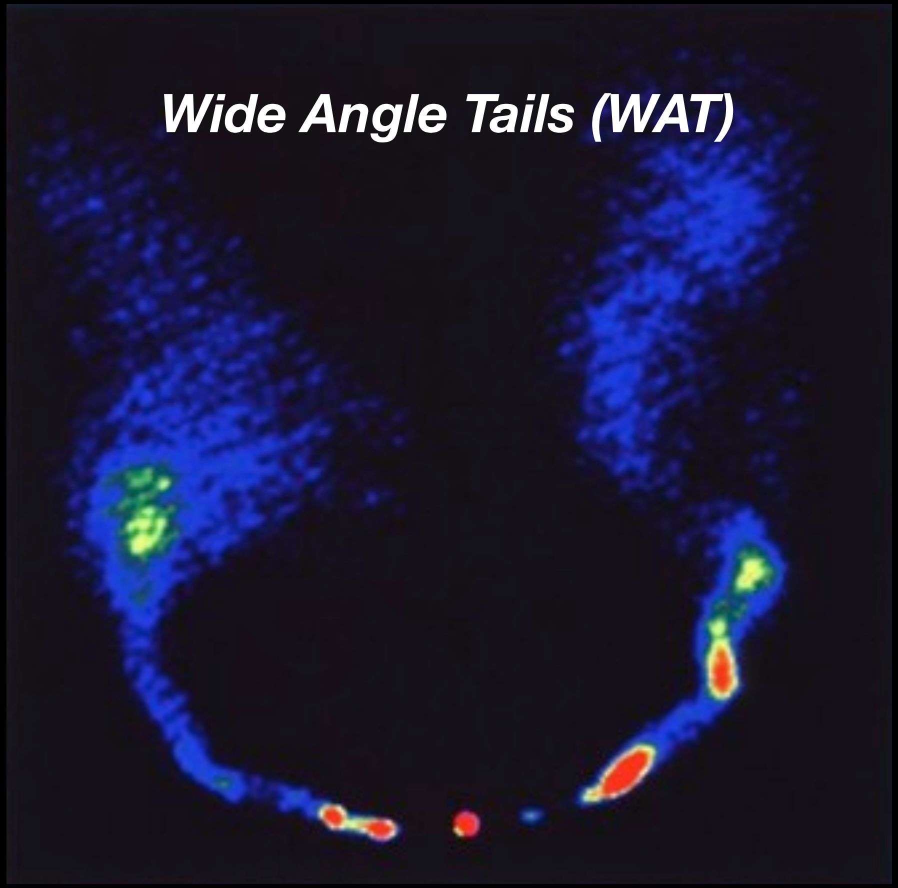
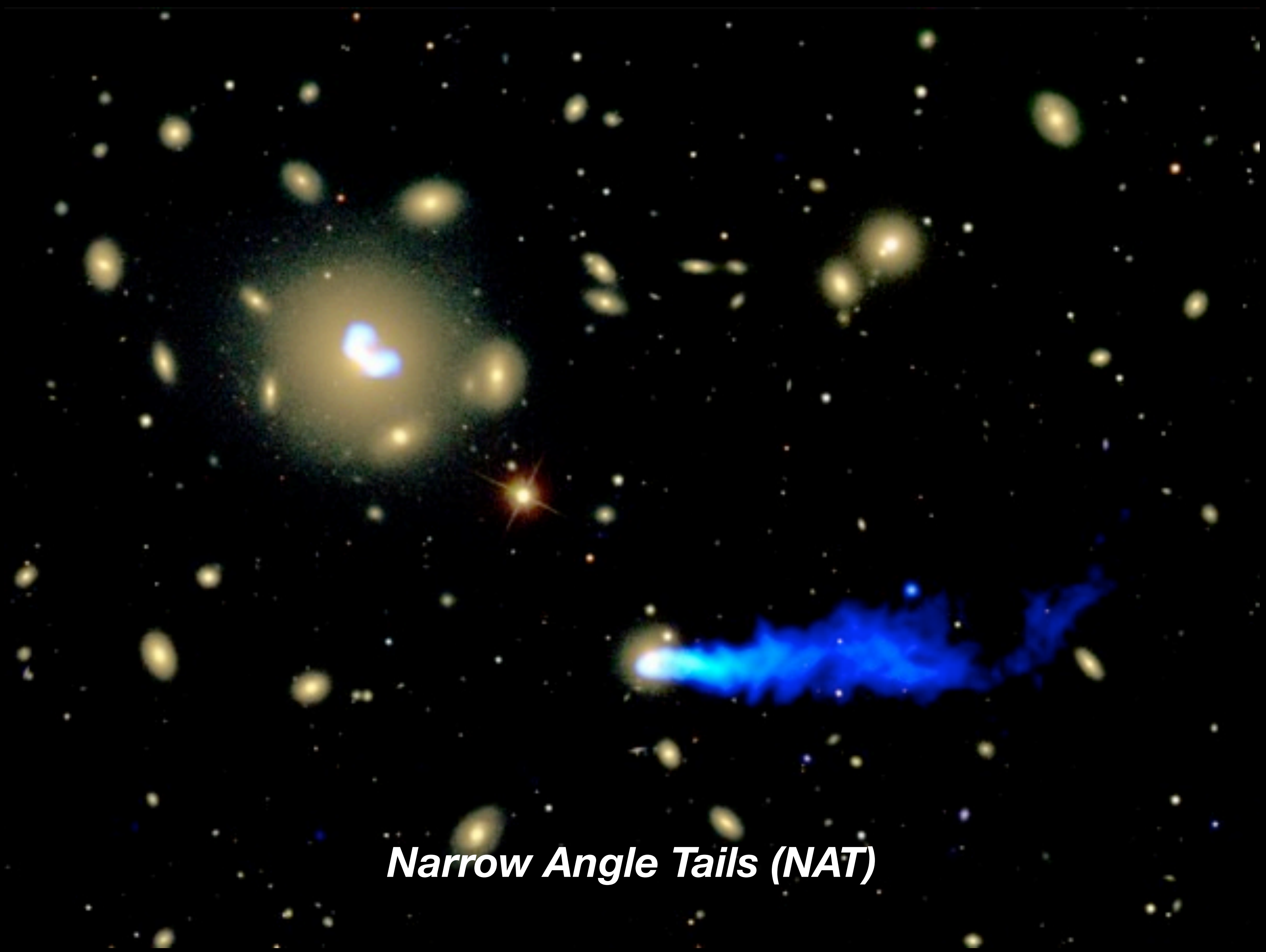
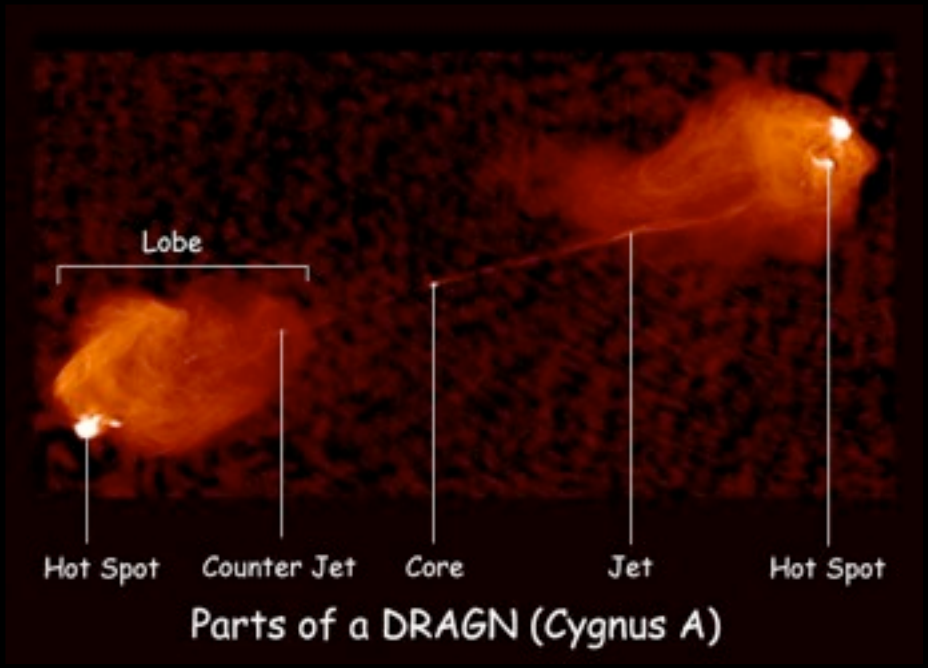
Extra-galactic sources of synchrotron radiation

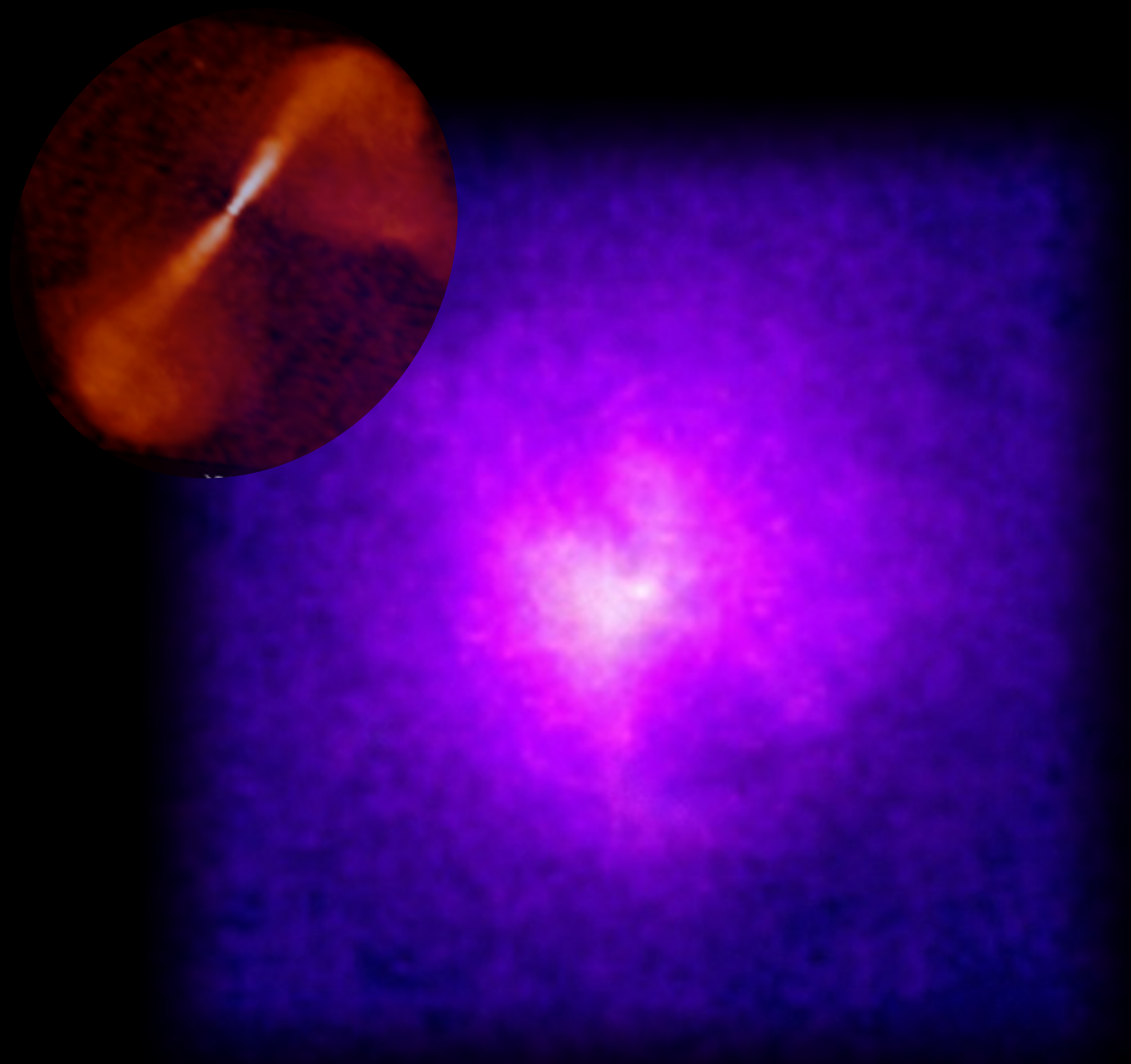




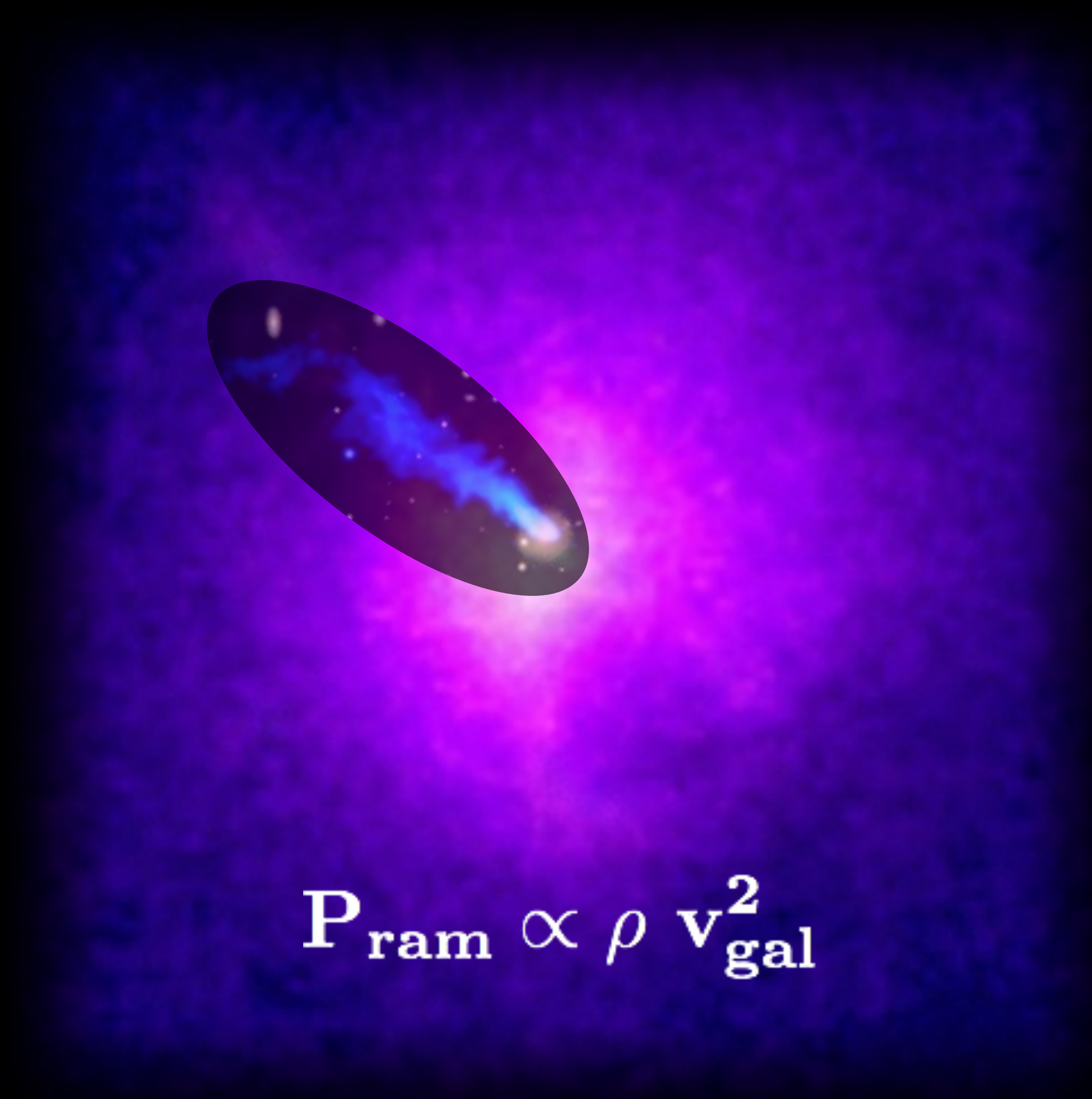


Peculiar radio galaxies as tracers of inter-cluster gas

Peculiar radio galaxies as tracers of inter-cluster gas

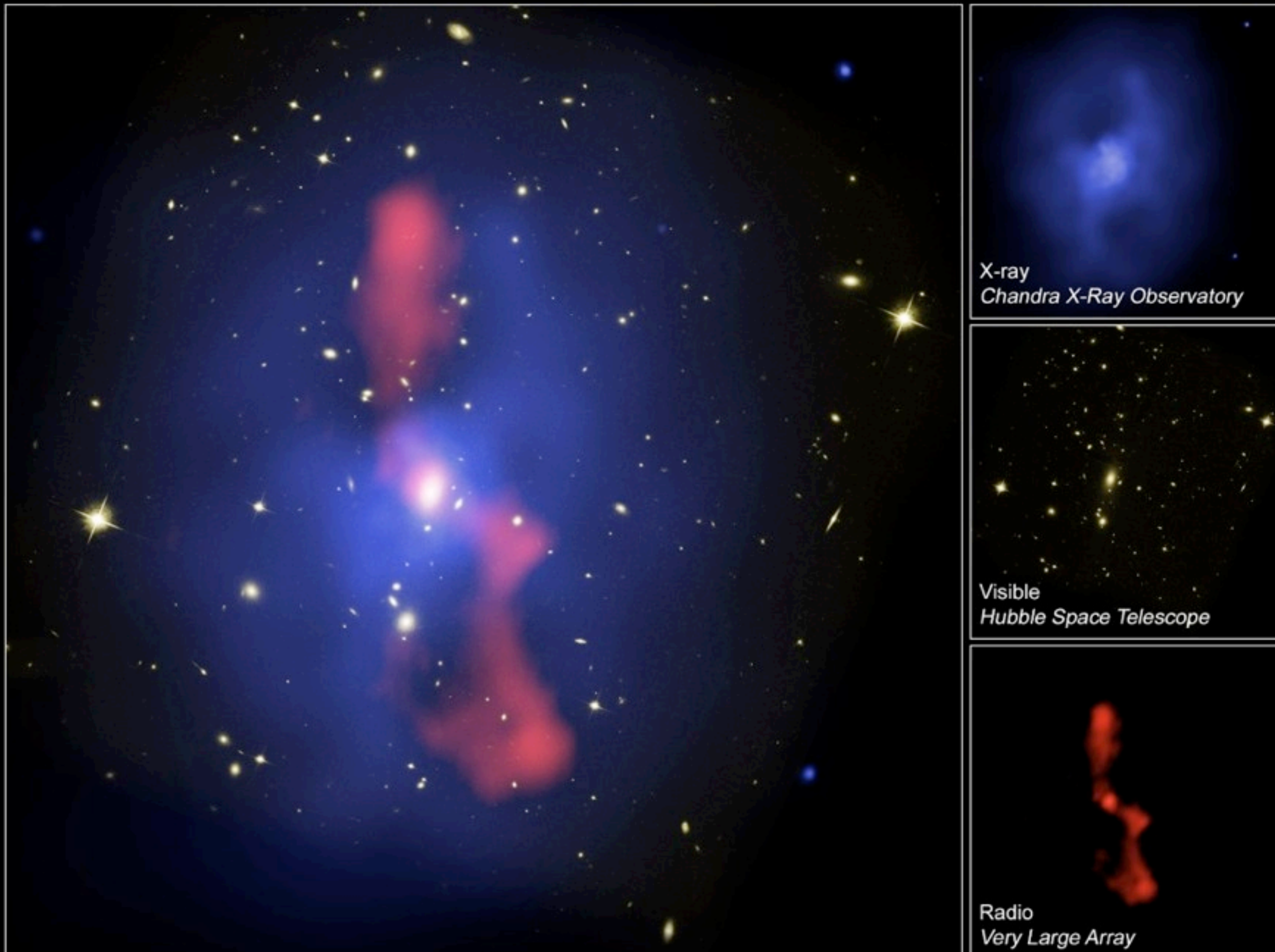


Peculiar radio galaxies as tracers of inter-cluster gas



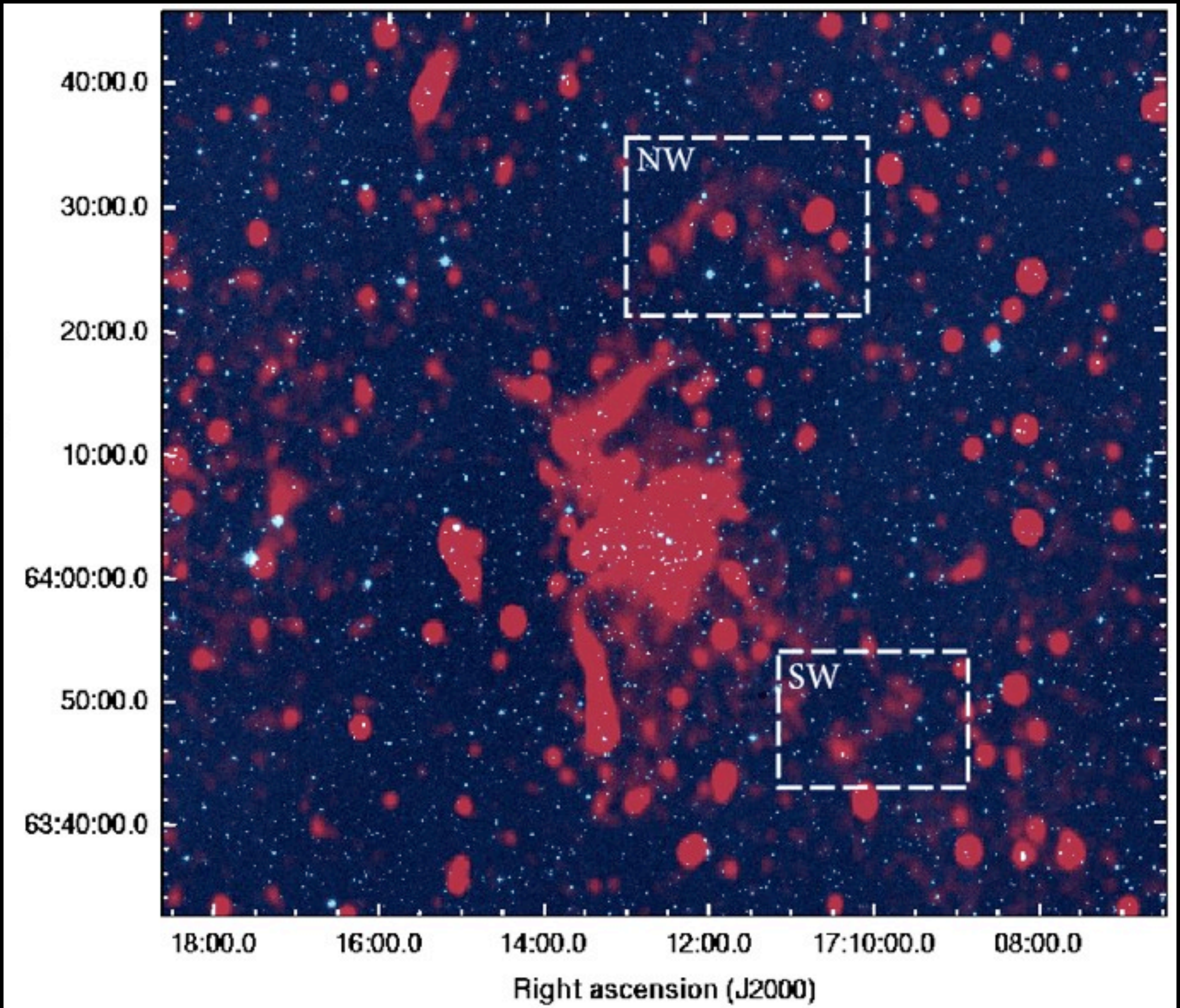
Galaxy Cluster MS 0735.6+7421

CXO ▪ HST ▪ VLA



NASA, ESA, CXC/NRAO/STScI, B. McNamara (University of Waterloo and Ohio University)

STScI-PRC06-51



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63:40:00.0
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17:10:00.0
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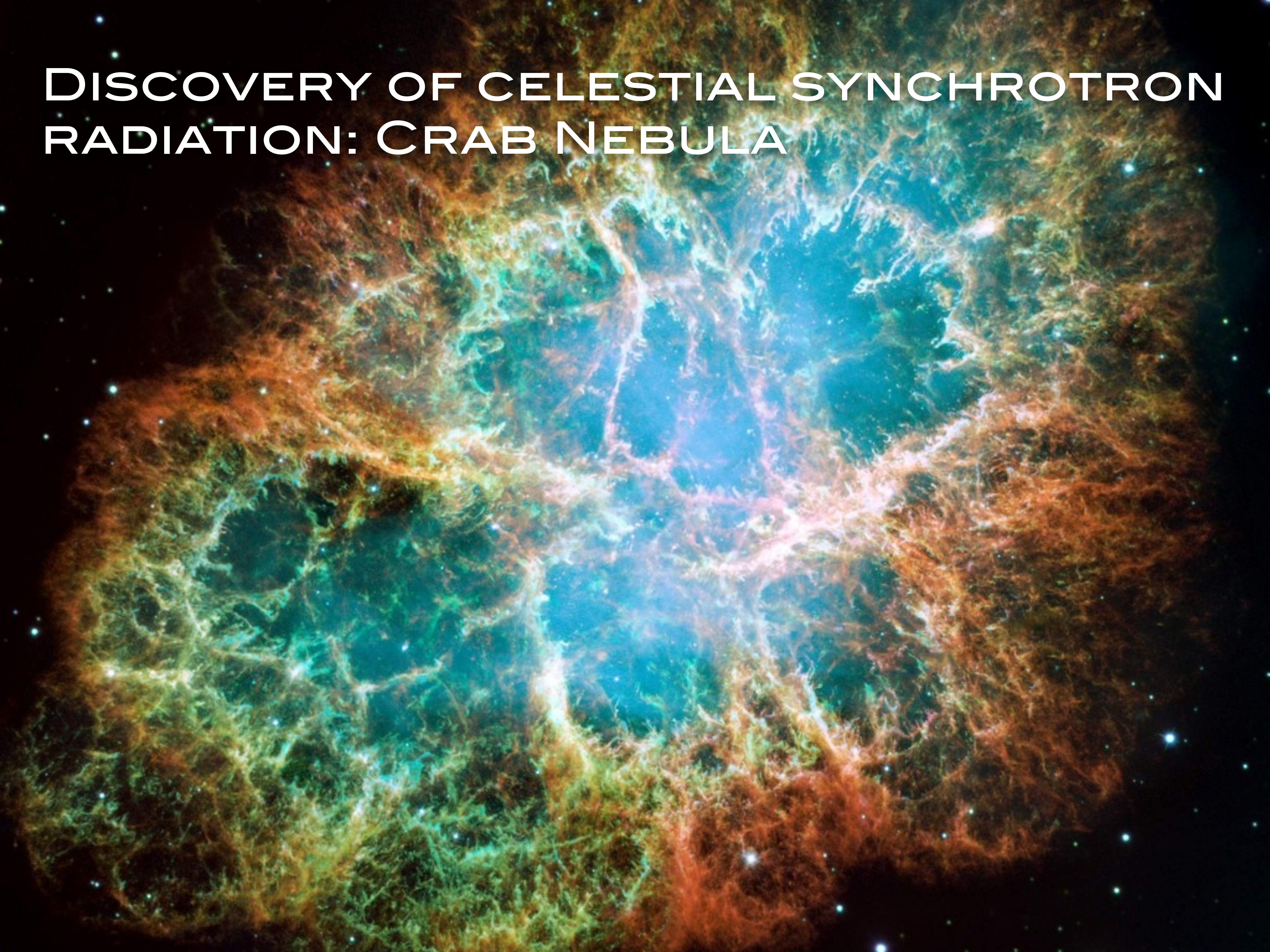
Right ascension (J2000)

Discovery of celestial synchrotron radiation: Crab Nebula



Discovery of celestial synchrotron radiation: Crab Nebula

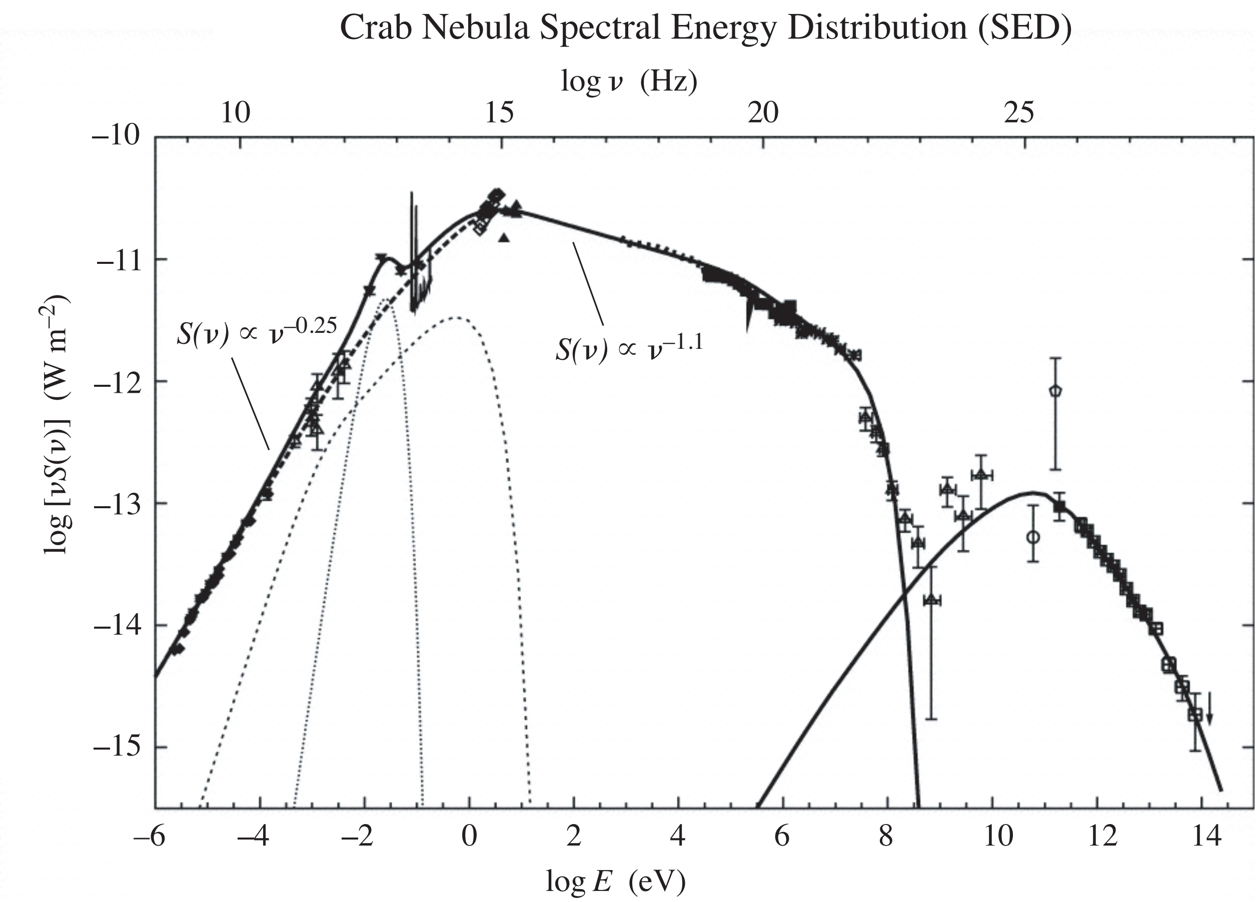


Fig. 8.2: Astrophysics Processes (CUP), H. Bradt 2008
Compliation by HEGRA Team; F. Aharonian et al., ApJ 614, 897 (2004)

Discovery of celestial synchrotron radiation: Crab Nebula

Crab Nebula Spectral Energy Distribution (SED)

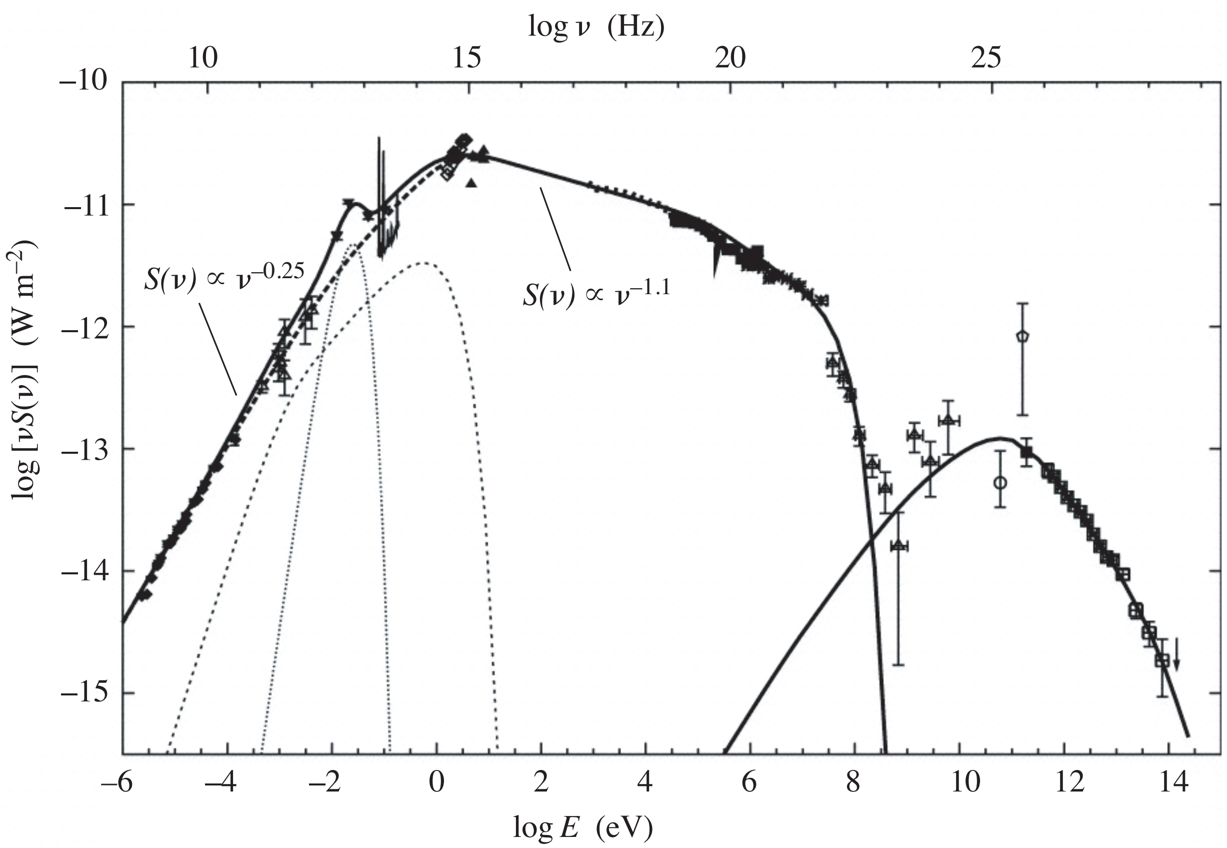


Fig. 8.2: Astrophysics Processes (CUP), H. Bradt 2008
Compliation by HEGRA Team; F. Aharonian et al., ApJ 614, 897 (2004)

Crab Optical Polarization

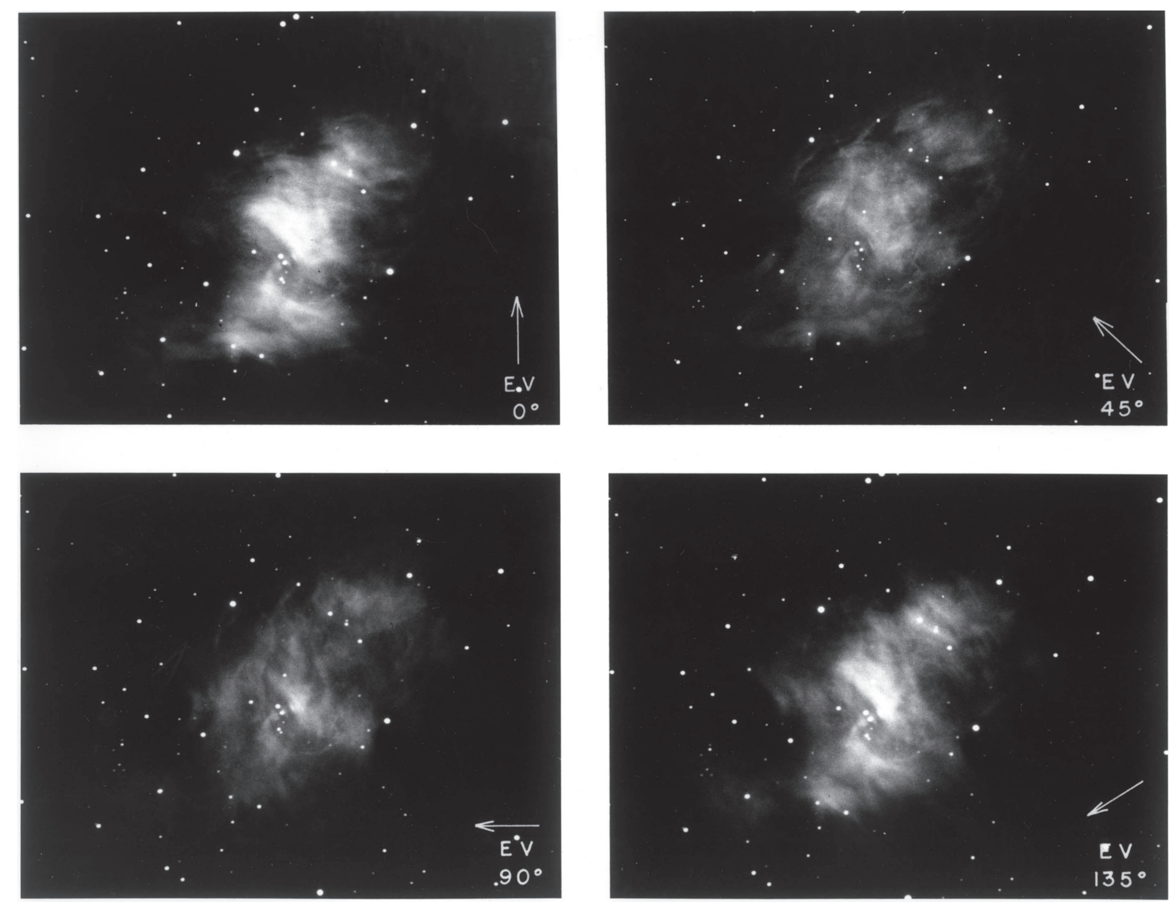
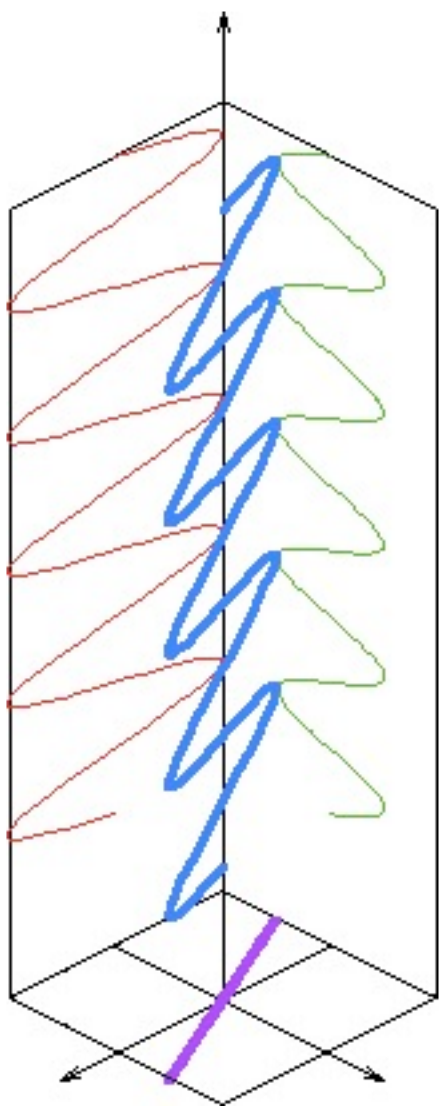


Fig. 8.3: Astrophysics Processes (CUP), H. Bradt 2008
Palomar Observatory/CalTech

Polarized emission from the Crab nebula



Crab Optical Polarization

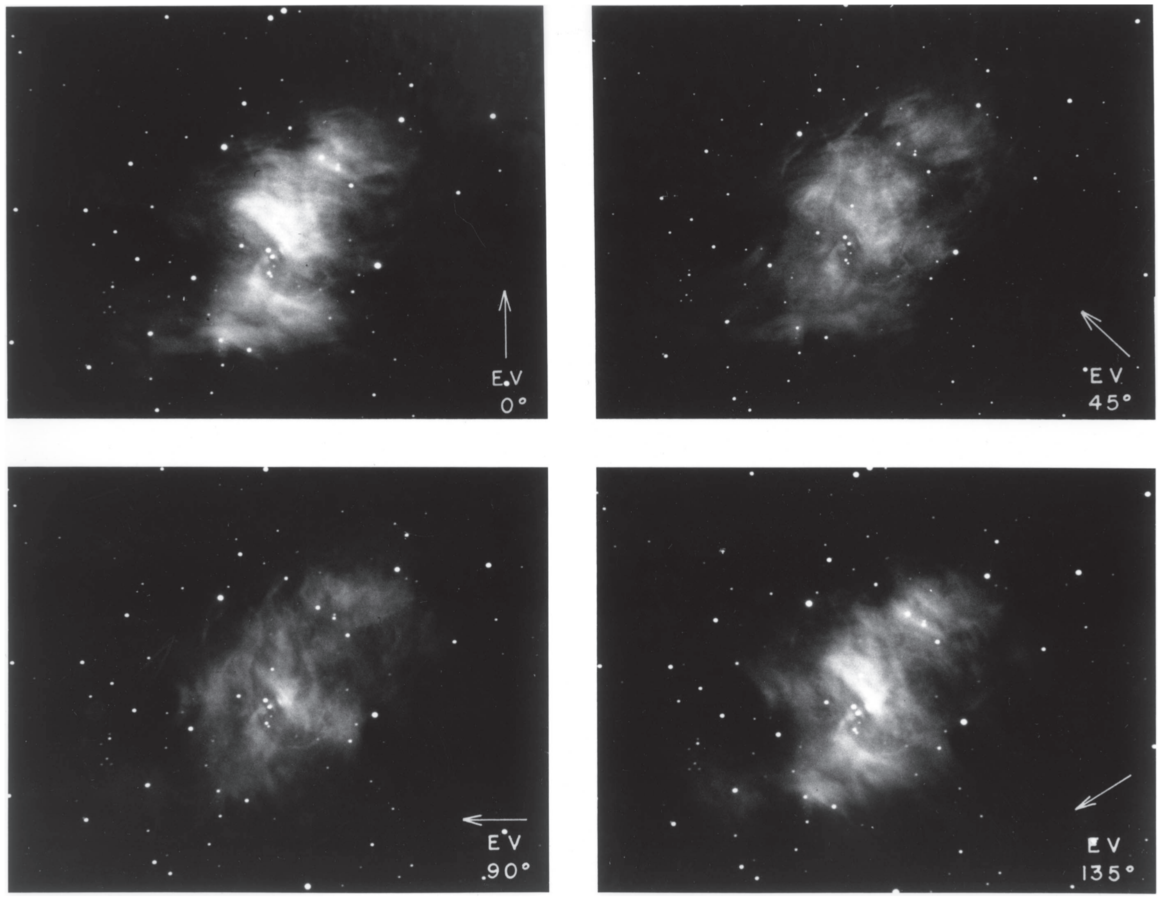


Fig. 8.3: Astrophysics Processes (CUP), H. Bradt 2008
Palomar Observatory/CalTech

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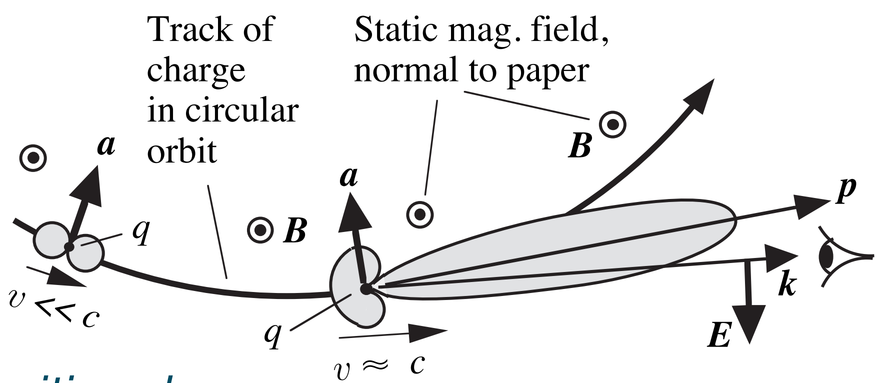
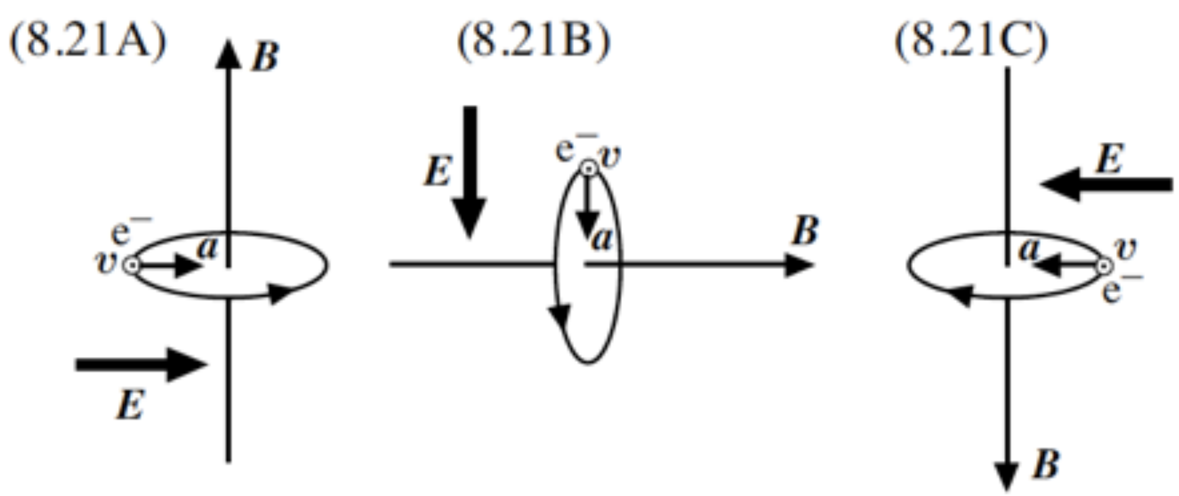


Note: *positive charge*



Crab Optical Polarization

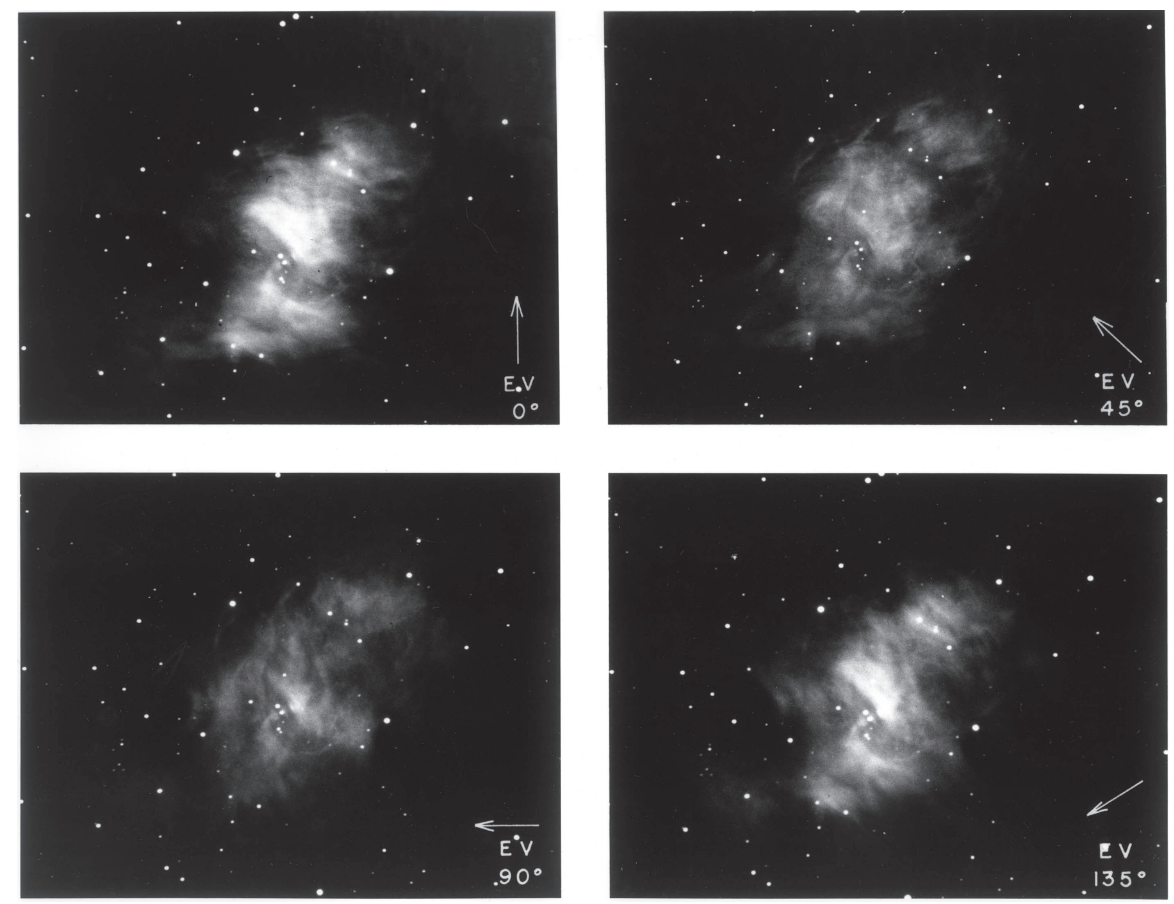


Fig. 8.3: Astrophysics Processes (CUP), H. Bradt 2008
Palomar Observatory/CalTech

Electron accelerators: synchrotrons

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \quad (N)$$

$$\mathcal{P}(t) = \frac{1}{6\pi\epsilon_0}\frac{q^2 a(t)^2}{c^3}$$

Power radiated BUT for v << c

In the relativistic case, the power radiated is much greater

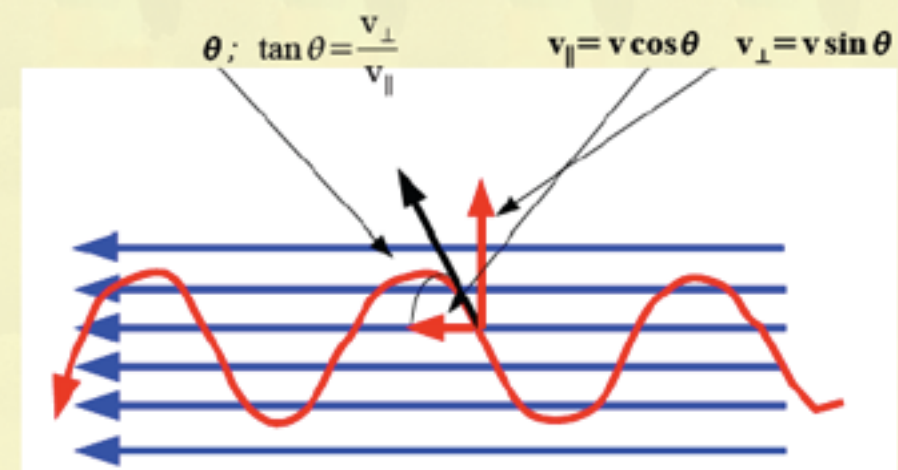
Motion of a charged particle in a uniform magnetic field

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \quad (N)$$

$$\frac{\mathrm{d}\mathbf{p}}{\mathrm{d}t} = q(\mathbf{v} \times \mathbf{H}/c) \quad (N)$$

- Let's start with non relativistic electrons [v <<c]
- No power is transferred to the charged particle: its kinetic energy (velocity) remains constant

θ = pitch angle = angle between the directions of $\vec{v}$ and $\vec{H}$



$$\frac{d(m v_\parallel)}{dt} = 0 \longrightarrow v_\parallel \text{ is constant}$$

- uniform motion along **B** direction (♣)
- since v is constant, also $v_\perp$ is constant (♦)

the pitch angle remains constant

$$\frac{d(m v_\perp)}{dt} = \frac{q}{c} \vec{v}_\perp \times \vec{H} + (♦) \longrightarrow$$

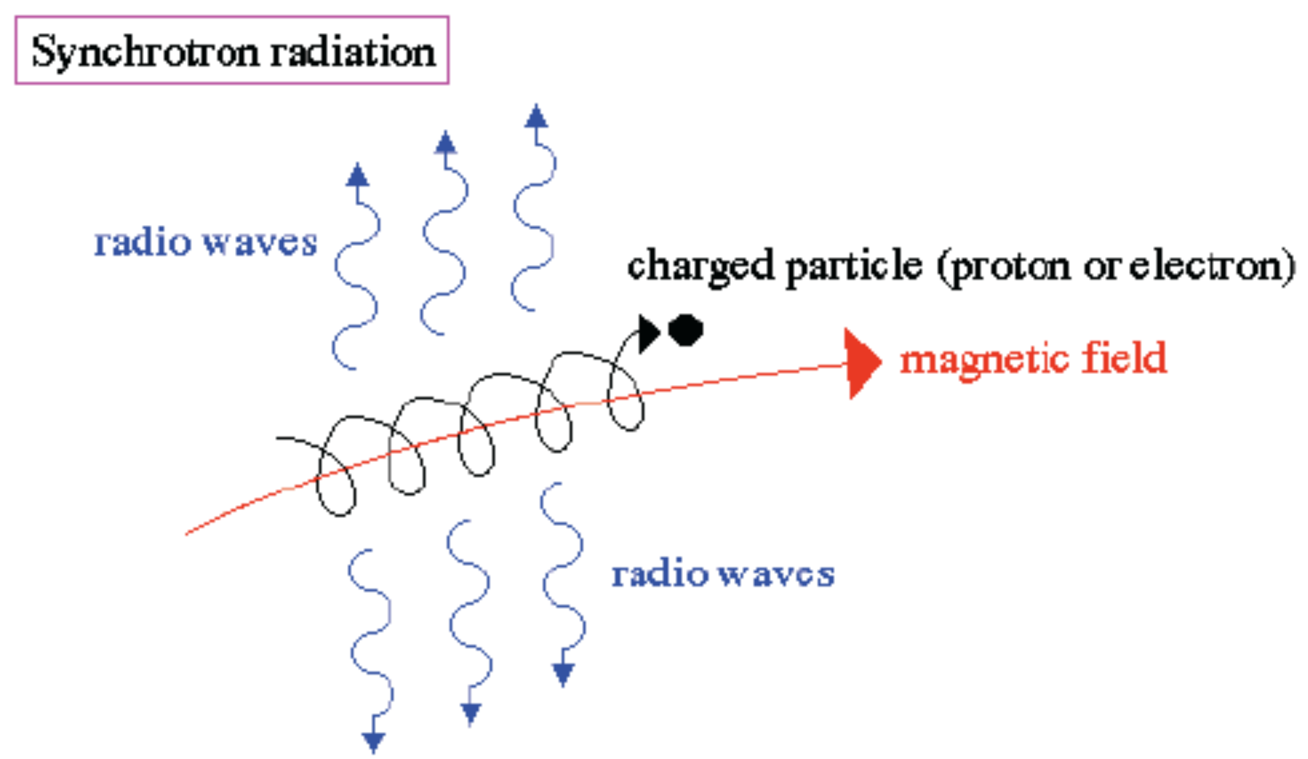
circular motion with a constant orbital velocity $v_\perp$ and:

- curvature radius: $r_L = \frac{mc}{qH} v_\perp$
- revolution period: $T_L = \frac{2\pi r_L}{v_\perp} = \frac{2\pi mc}{qH}$
- frequency of the gyration: $\omega_L = \frac{2\pi}{T_L} = \frac{qH}{mc}$

Corkscrew pattern of electrons

$$\frac{d(m v_{\parallel})}{dt} = 0$$ → $v_{\parallel}$ is constant → uniform motion along **B** direction

$$\frac{d(m v_{\perp})}{dt} = \frac{q}{c} \vec{v}_{\perp} \times \vec{H}$$ → circular motion with a constant orbital velocity $v_{\perp}$



→ The path followed by the electron is a helix winding around the magnetic field with the constant pitch angle θ

Motion of a charged particle in a uniform magnetic field

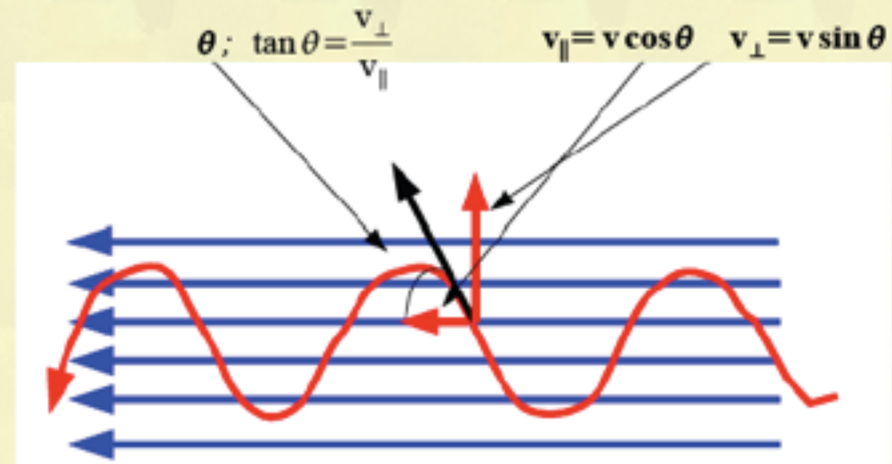
In the inertial frame moving with velocity $v_{\parallel}$, from Newton's second law with acceleration $-\omega^2 r$ and:

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}) \quad (N)$$

$$m\,\omega^2\,R = q\,v\,B = q\,\omega\,R\,B \rightarrow$$

$$\omega = \frac{q\,B}{m}$$

θ = pitch angle = angle between the directions of $\vec{v}$ and $\vec{H}$



$$\frac{d(m v_{\parallel})}{dt} = 0 \longrightarrow v_{\parallel} \text{ is constant}$$

- uniform motion along **B** direction (♣)
- since v is constant, also $v_{\perp}$ is constant (♦)

the pitch angle remains constant

$$\frac{d(m v_{\perp})}{dt} = \frac{q}{c}\vec{v}_{\perp} \times \vec{H} \quad + (♦) \longrightarrow$$

circular motion with a constant orbital velocity $v_{\perp}$ and:

- curvature radius: $r_L = \frac{mc}{qH} v_{\perp}$
- revolution period: $T_L = \frac{2\pi\, r_L}{v_{\perp}} = \frac{2\pi mc}{qH}$
- frequency of the gyration: $\omega_L = \frac{2\pi}{T_L} = \frac{qH}{mc}$

Radiation from charged particle in a uniform magnetic field

Circular Motion: One Charge

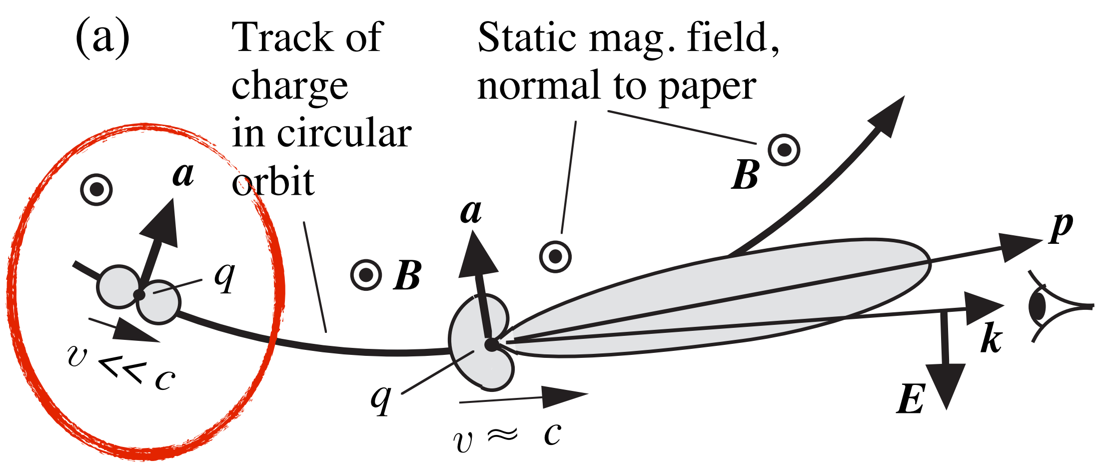
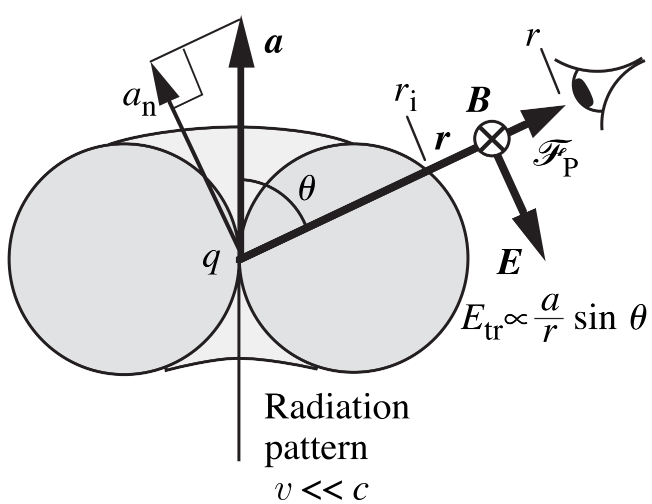


Fig. 8.4: Astrophysics Processes (CUP), © H. Bradt 2008



$$\mathbf{E}(\mathbf{r},t) = E_{tr}\hat{\mathbf{n}} = \frac{qa(t')\sin\theta}{4\pi\epsilon_0 c^2 r}\hat{\mathbf{n}}$$

$\mathbf{E}(\mathbf{r}, t)$ = Transverse electric vector; V/m; $v << c$

Radiation from charged particle in a uniform magnetic field

Circular Motion: One Charge

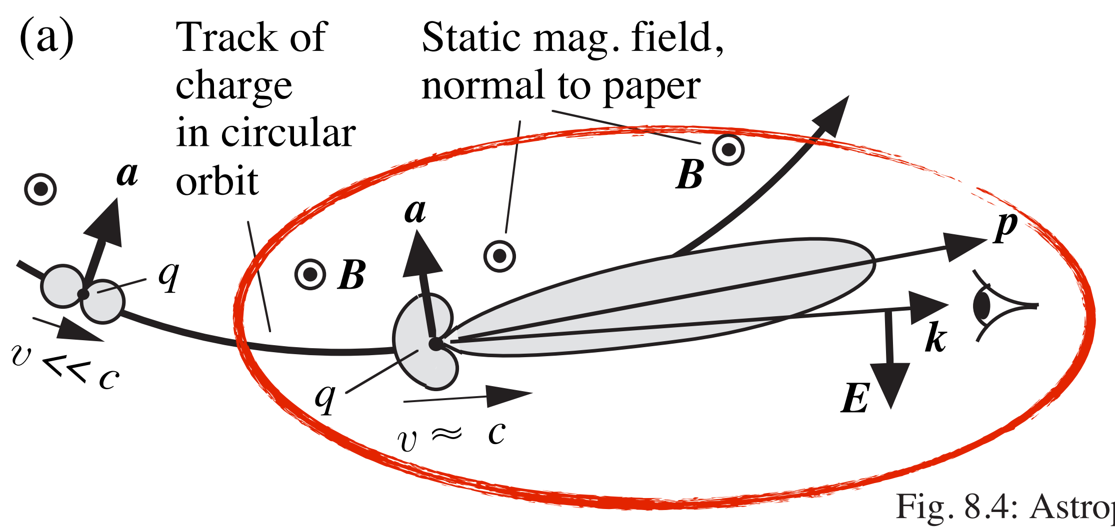


Fig. 8.4: Astrophysics Processes (CUP), © H. Bradt 2008

Aberration: apparent direction of radiation will differ according to observers in two frames of reference that are moving with respect to each other

$$\cos\,\theta = \frac{\cos\,\theta' \;+\; \beta}{1 \;+\; \beta\,\cos\,\theta'}$$

See Chap. 7 in "Astrophysics Processes"

Radiation from charged particle in a uniform magnetic field

Circular Motion: One Charge

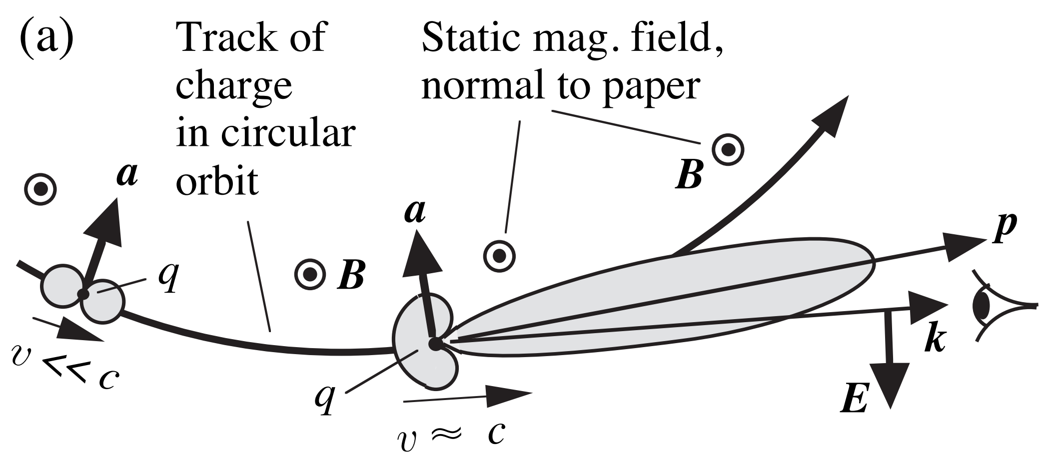


Fig. 8.4: Astrophysics Processes (CUP), © H. Bradt 2008

Beaming

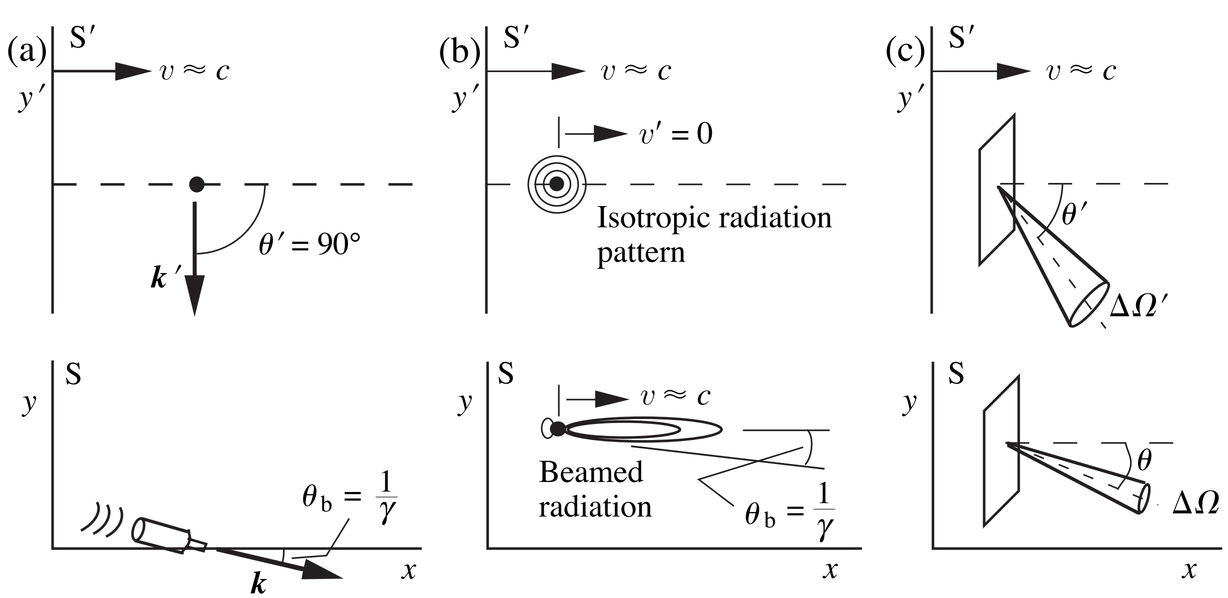


Fig. 7.9: Astrophysics Processes (CUP), © H Bradt 2008

$$\cos\,\theta = \frac{\cos\,\theta' \;+\; \beta}{1 \;+\; \beta\,\cos\,\theta'} \quad \& \quad \theta' \;=\; 90^\circ$$

Radiation from charged particle in a uniform magnetic field

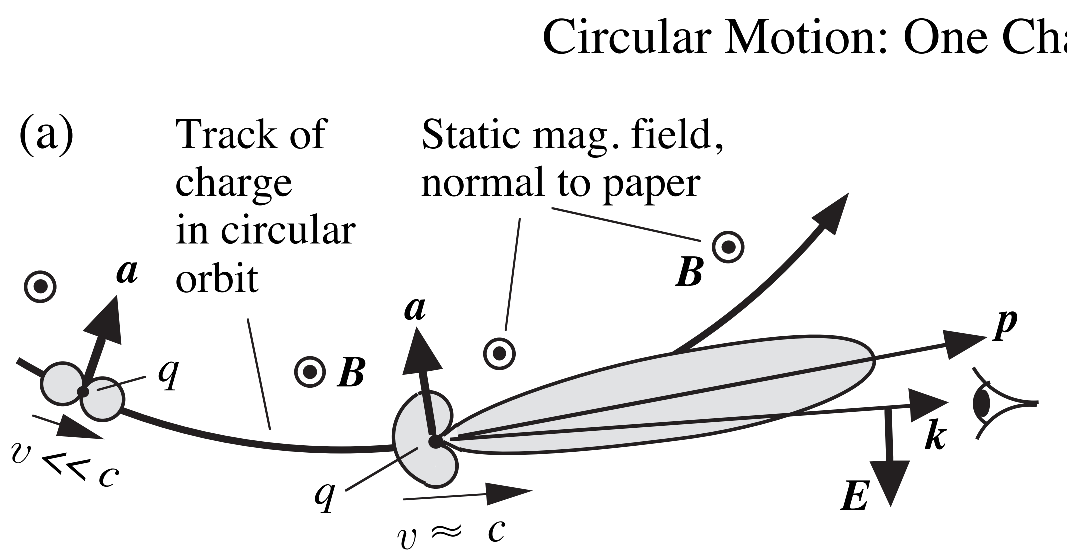


Fig. 8.4: Astrophysics Processes (CUP), © H. Bradt 2008

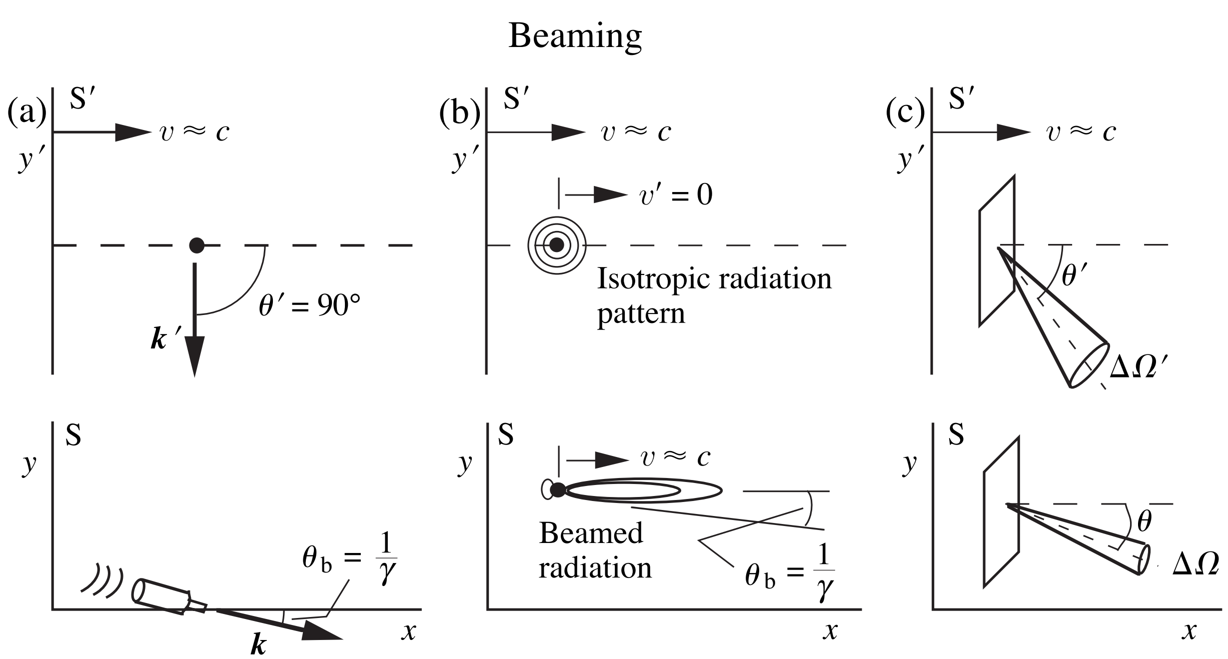


Fig. 7.9: Astrophysics Processes (CUP), © H Bradt 2008

$$\cos\theta = \frac{\cos\theta' + \beta}{1 + \beta\cos\theta'} \quad \& \quad \theta' = 90^\circ$$

$$\cos\theta_b = \beta = \left(1 - \frac{1}{\gamma^2}\right)^{1/2}$$

Radiation from charged particle in a uniform magnetic field

Circular Motion: One Charge

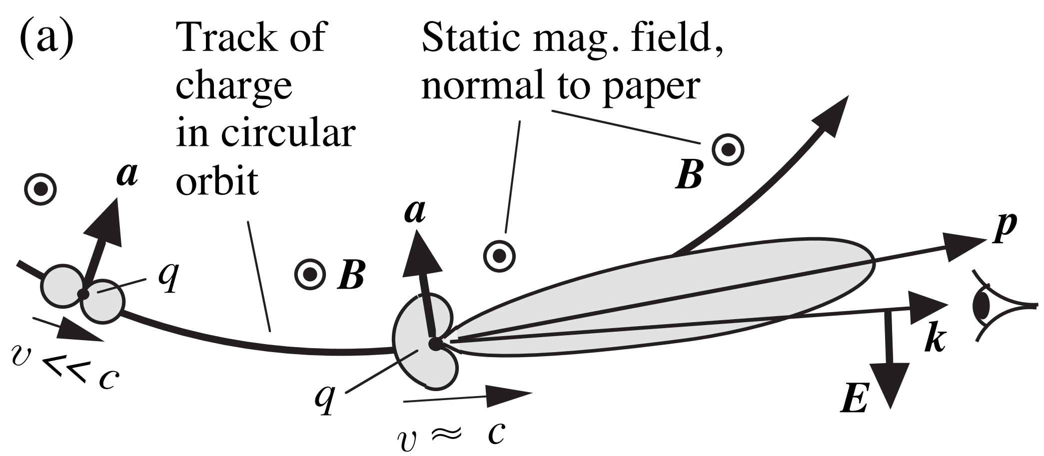


Fig. 8.4: Astrophysics Processes (CUP), © H. Bradt 2008

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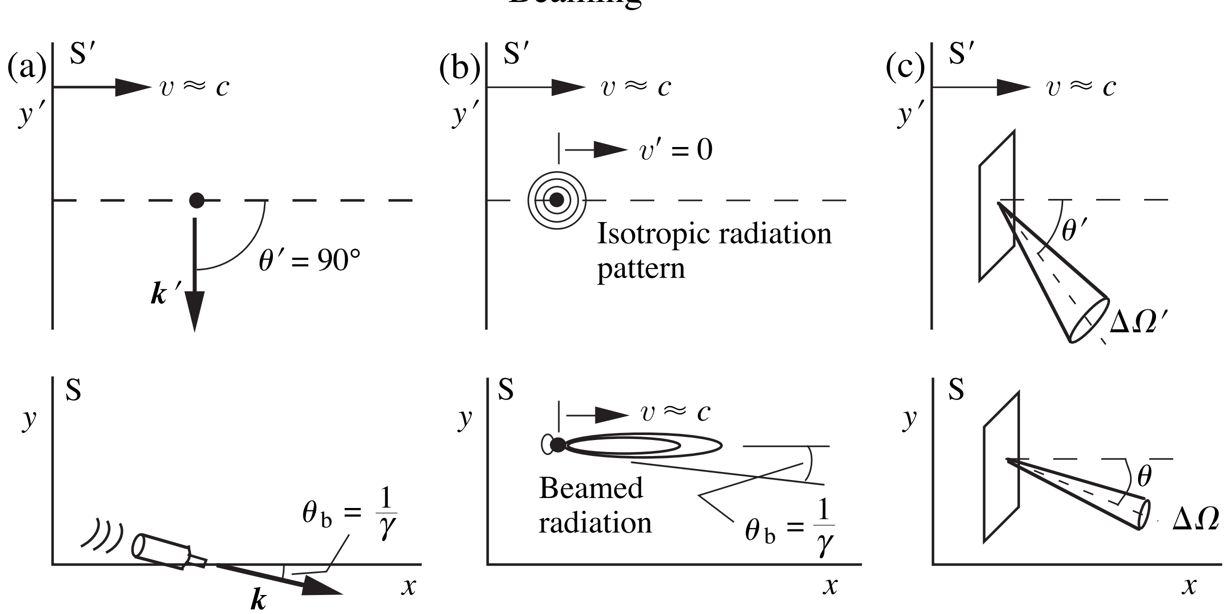

Fig. 7.9: Astrophysics Processes (CUP), © H Bradt 2008

$$\cos\theta = \frac{\cos\theta' + \beta}{1 + \beta\cos\theta'} \quad \& \quad \theta' = 90^\circ$$

$$\cos\theta_b = \beta = \left(1 - \frac{1}{\gamma^2}\right)^{1/2}$$

$$\gamma >> 1 \rightarrow \theta_b \approx 0 \rightarrow 1 - \frac{\theta_b^2}{2} = 1 - \frac{1}{2\,\gamma^2}$$

Radiation from charged particle in a uniform magnetic field

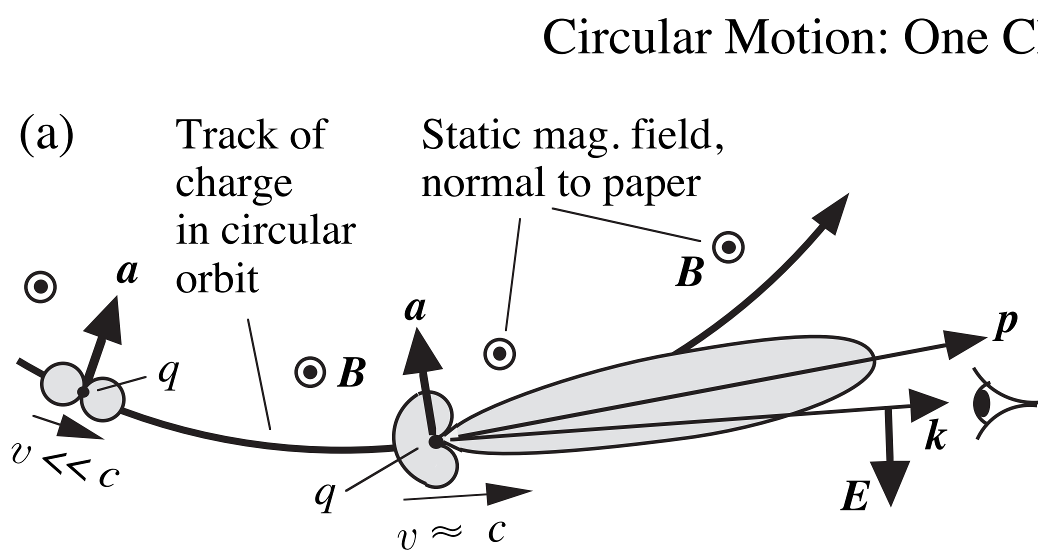

Fig. 8.4: Astrophysics Processes (CUP), © H. Bradt 2008

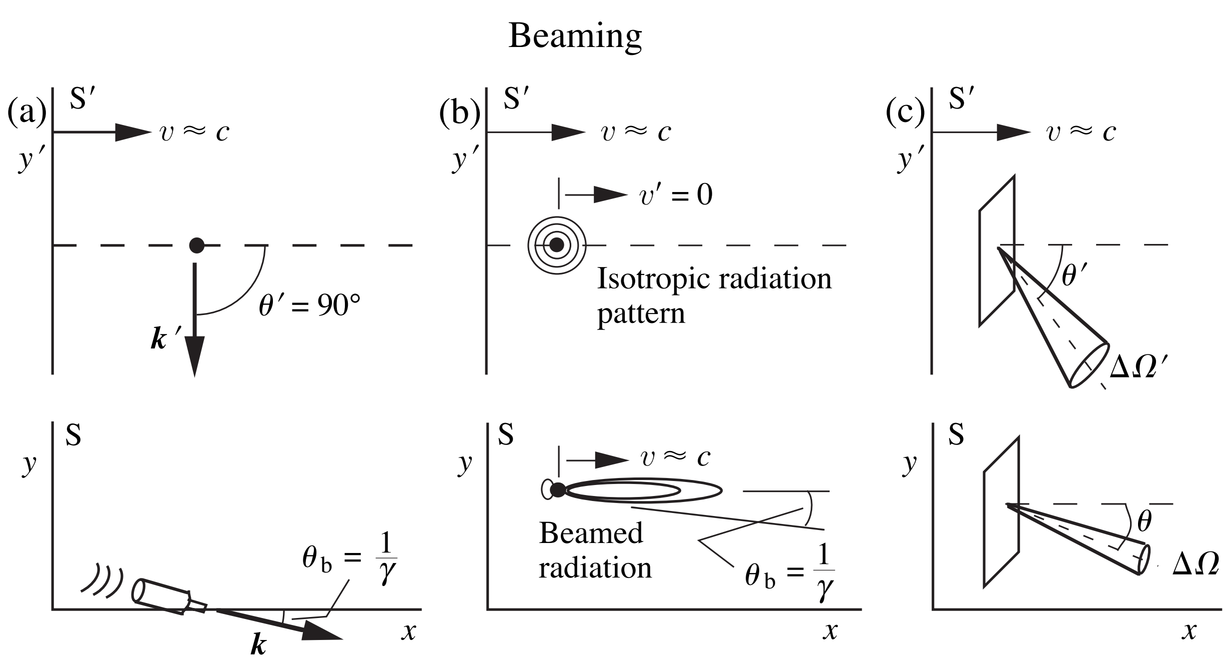

Fig. 7.9: Astrophysics Processes (CUP), © H Bradt 2008

$$\cos\,\theta = \frac{\cos\,\theta' + \beta}{1 + \beta\,\cos\,\theta'} \quad \& \quad \theta' = 90^\circ$$

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$$\gamma >> 1 \rightarrow \theta_b \approx 0 \rightarrow 1 - \frac{\theta_b^2}{2} = 1 - \frac{1}{2\,\gamma^2}$$

$$\boxed{\theta_b \approx \frac{1}{\gamma}}$$

Radiation from charged particle in a uniform magnetic field

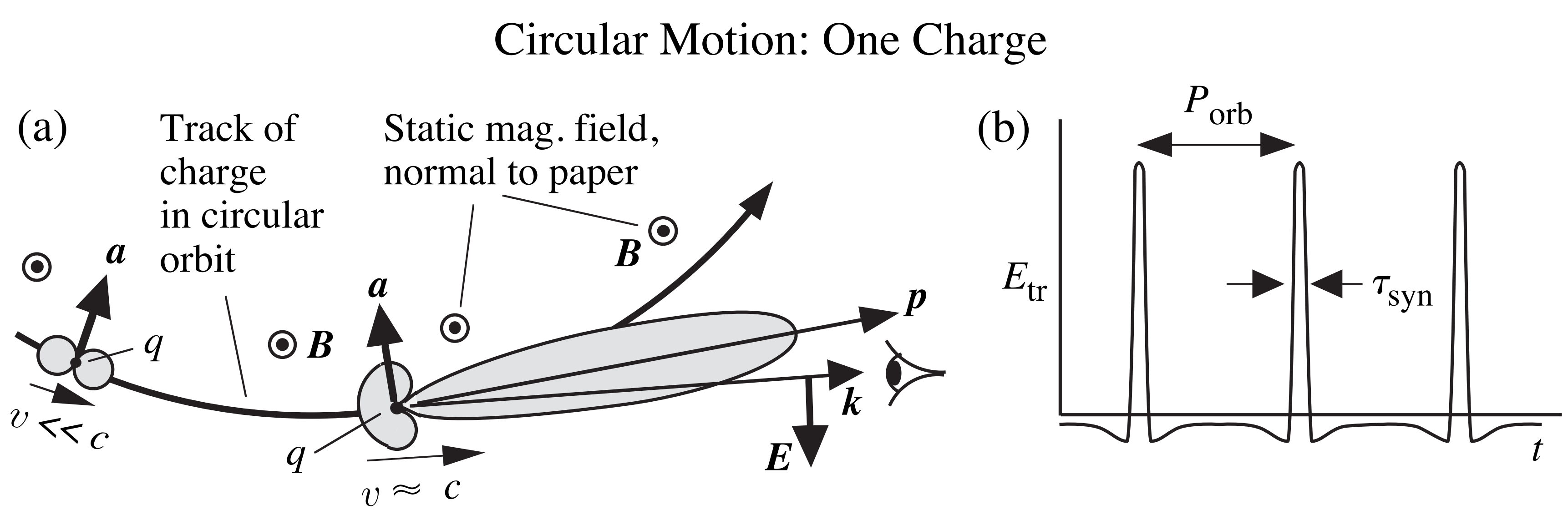
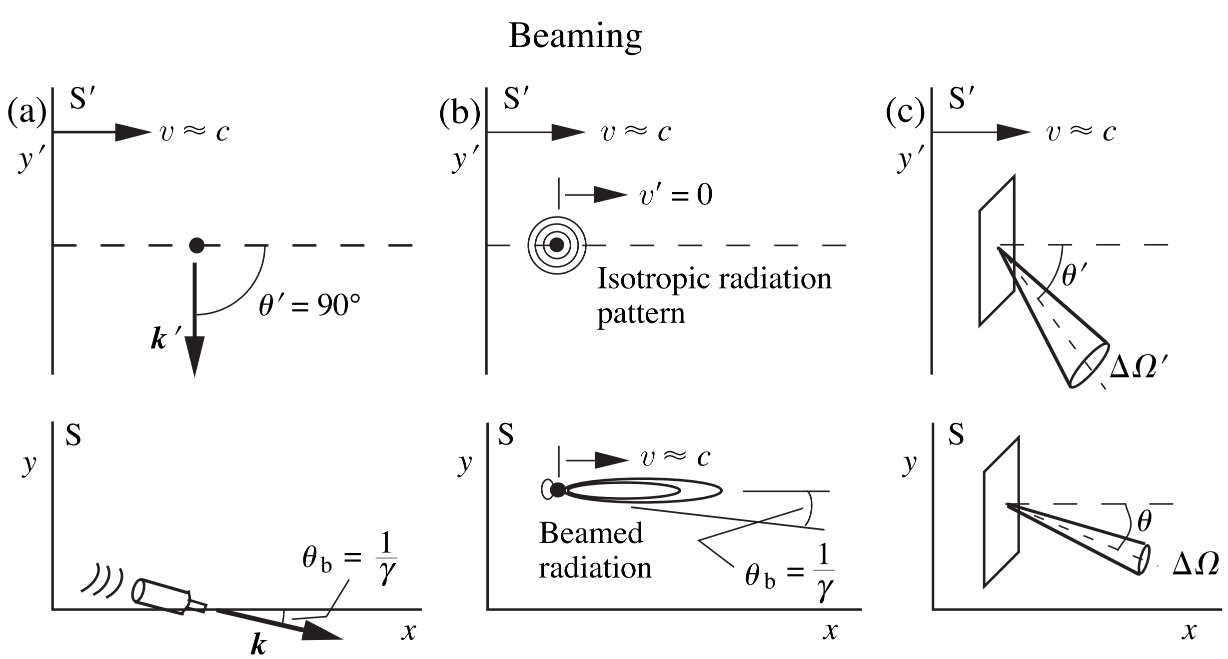


Fig. 8.4: Astrophysics Processes (CUP), © H. Bradt 2008



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$$\cos\theta = \frac{\cos\theta' + \beta}{1 + \beta\cos\theta'} \quad \& \quad \theta' = 90^\circ$$

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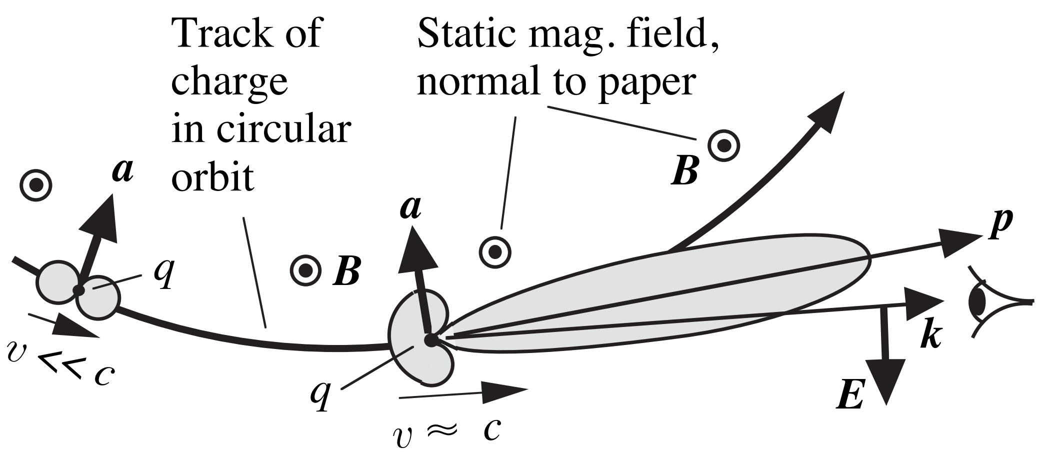
$$\gamma >> 1 \rightarrow \theta_b \approx 0 \rightarrow 1 - \frac{\theta_b^2}{2} = 1 - \frac{1}{2\,\gamma^2}$$

$$\theta_b \approx \frac{1}{\gamma}$$

Duration of the pulse

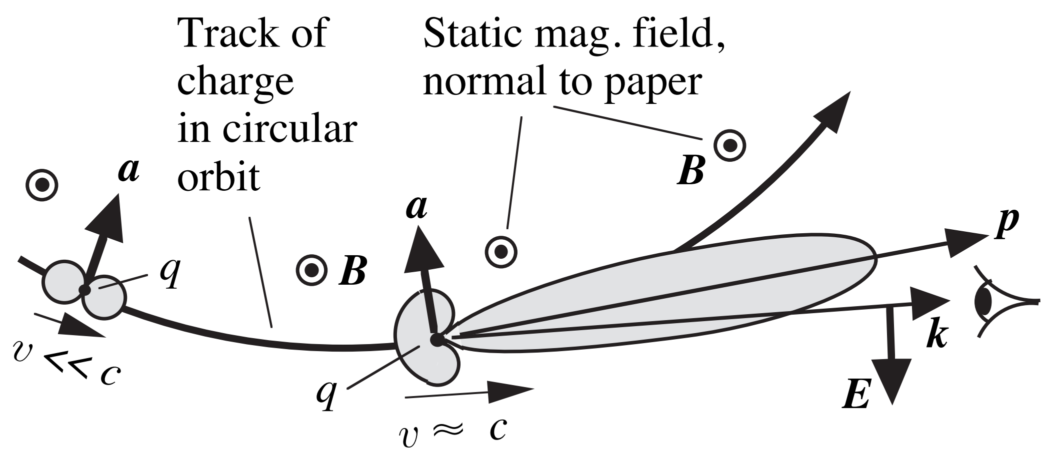


$$\theta_b \approx \frac{1}{\gamma} = \frac{m\ c^2}{U}$$

$$\omega_{\rm r} = \frac{1}{\gamma}\ \omega = \frac{1}{\gamma}\ \frac{qB}{m}$$

$$\rightarrow \tau_0 \approx \frac{2\ \theta_b}{\omega_{\rm r}} = \frac{2m}{qB} = \frac{2}{\omega}$$

Duration of the pulse



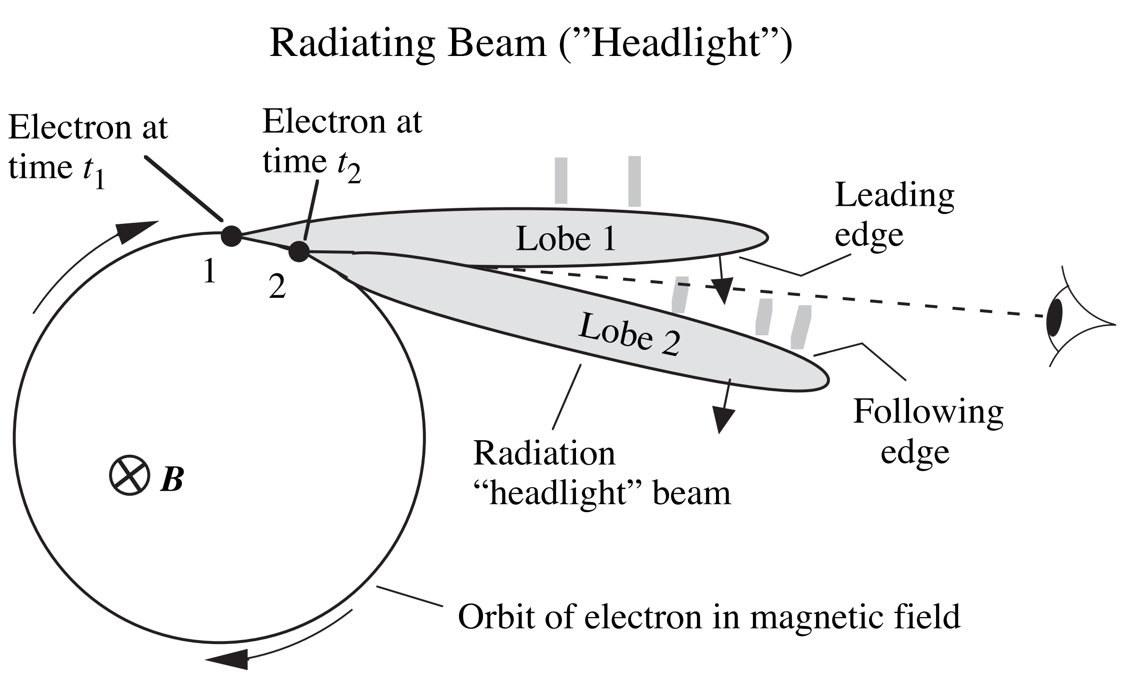


Fig. 8.6: Astrophysics Processes (CUP), © H. Bradt 2008

$$\theta_b \approx \frac{1}{\gamma} = \frac{m\ c^2}{U}$$

$$\omega_{\rm r} = \frac{1}{\gamma}\ \omega = \frac{1}{\gamma}\ \frac{qB}{m}$$

$$\rightarrow \tau_0 \approx \frac{2\ \theta_b}{\omega_{\rm r}} = \frac{2m}{qB} = \frac{2}{\omega}$$

$$\rightarrow \tau_{\rm syn} \approx \frac{\tau_0}{2\ \gamma^2} = \frac{1}{\omega}\frac{1}{\gamma^2}$$

Doppler shift and effects on the pulse duration

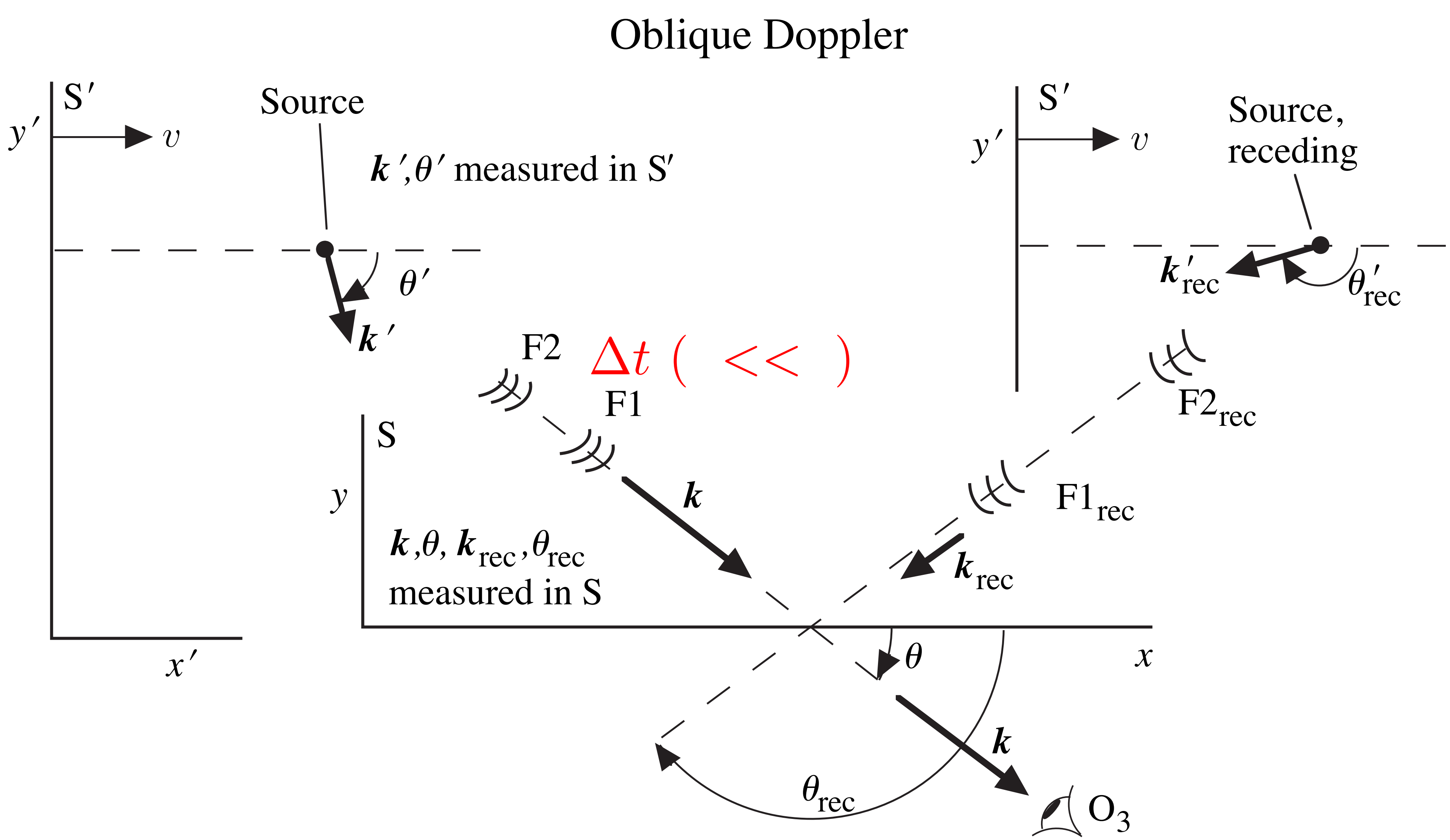


Fig. 7.4: Astrophysics Processes (CUP), © H Bradt 2008

$$\Delta t_3 = (1 - \beta \cos \theta) \, \Delta t$$

Duration of the pulse

Radiating Beam ("Headlight")

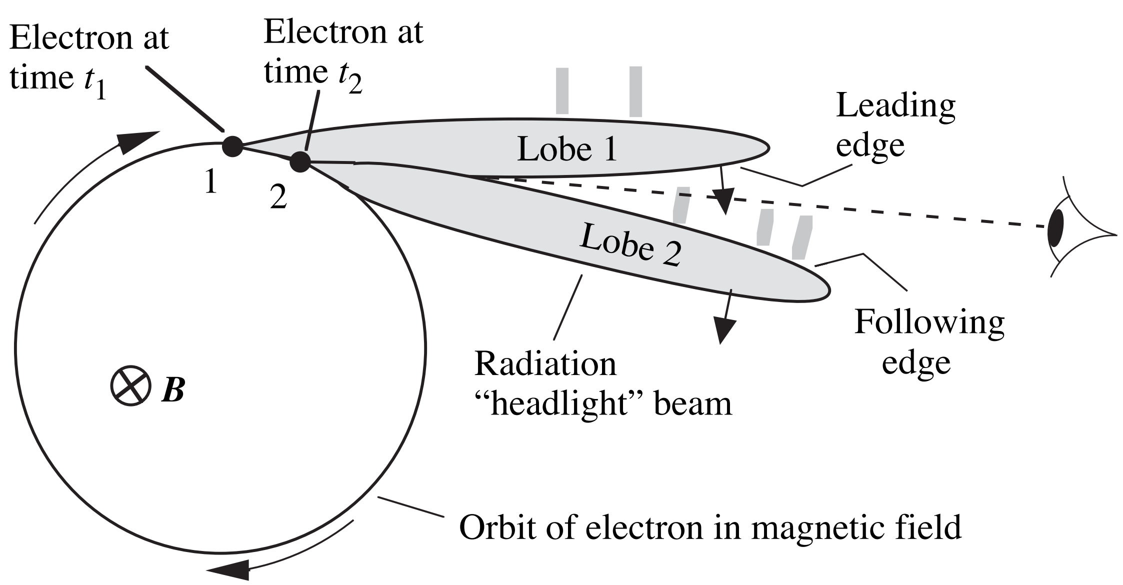


Fig. 8.6: Astrophysics Processes (CUP), © H. Bradt 2008

$$\tau_0 \approx \frac{2\ \theta_b}{\omega_r} = \frac{2m}{qB} = \frac{2}{\omega}$$

$$\Delta t_3 = (1 - \beta\ \cos\ \theta)\ \Delta t$$

$$\frac{\tau_{syn}}{\tau_0} \approx (1\ - \beta\ \cos\ 0^\circ) = (1\ -\ \beta)\ \frac{1\ +\ \beta}{1\ +\ \beta} = \frac{1\ -\ \beta^2}{1\ +\ \beta} \approx \frac{1}{2\ \gamma^2}$$

$$\rightarrow \tau_{syn} \approx \frac{\tau_0}{2\ \gamma^2} = \frac{1}{\omega}\frac{1}{\gamma^2}$$

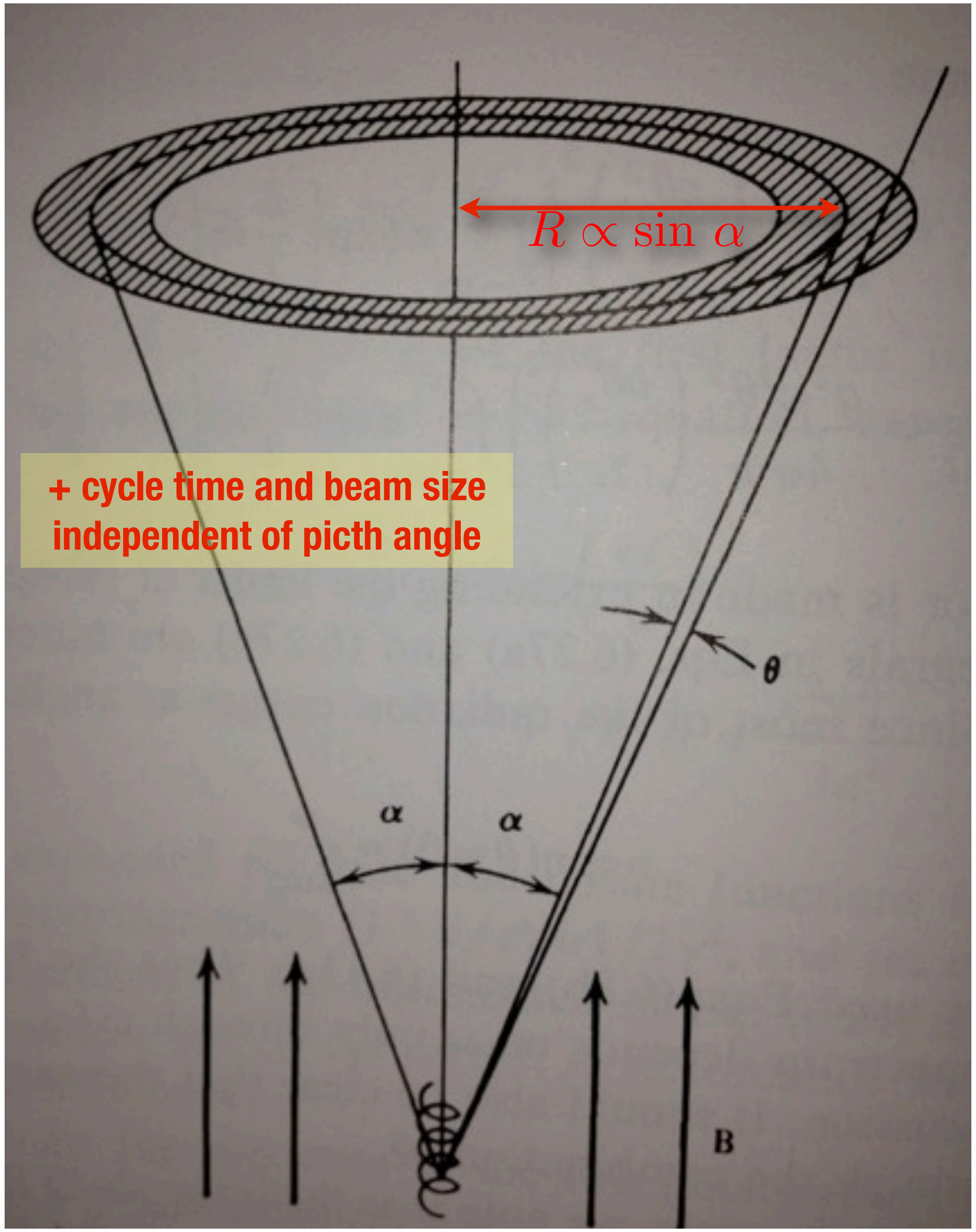
Observed frequency

$$\tau_{\rm syn} \approx \frac{m}{\gamma^2 \; q \; B}$$

$$\omega_{\rm syn} \approx \frac{1}{\tau_{\rm syn}}$$

$$\nu_{\rm syn} \equiv \frac{\omega_{\rm syn}}{2 \; \pi} \approx \frac{1}{2 \; \pi} \gamma^2 \frac{q \; B}{m} \; \sin\phi$$

$$\gamma^2 = \left(\frac{U}{m \; c^2} \right)^2$$



Power spectrum shape

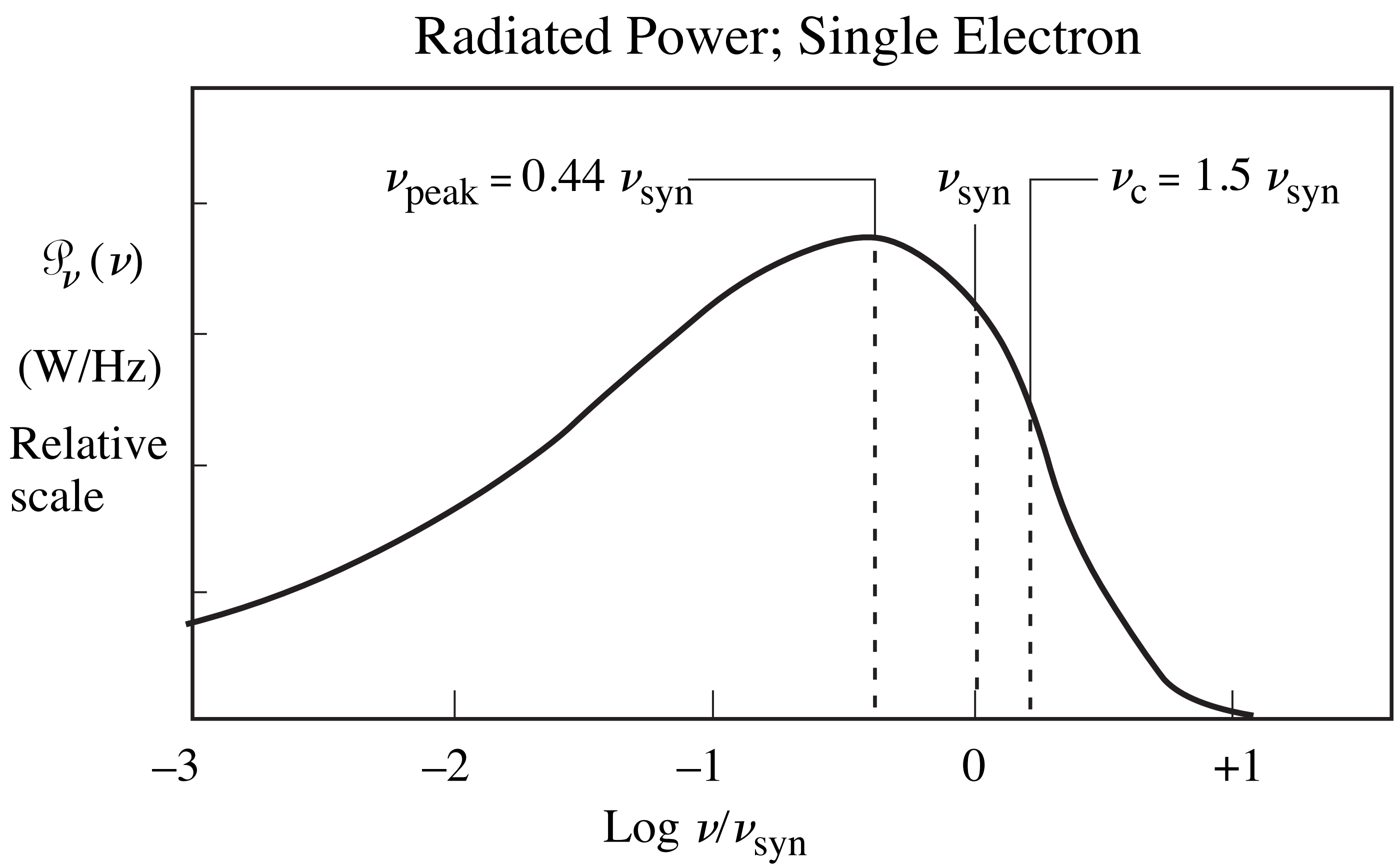


Fig. 8.7: Astrophysics Processes (CUP), H. Bradt 2008
After B. Rossi & S. Olbert, *Intro. to the Physics of Space* (McGraw Hill) 1970

$$P(\nu) = \frac{\sqrt{3}\, e^3\ B \sin\phi}{m\ c^2} \left(\frac{\nu}{\nu_c}\right) \int_{\nu/\nu_c}^{\infty} K_{5/3}(\eta)\mathrm{d}\eta$$

See Pacholczyk's "Astrophysics Processes"

$$\nu_c \equiv \frac{3}{2}\ \nu_{syn} = \frac{3}{2}\ \gamma^2\ \frac{\omega_{syn}}{2\ \pi}\ \sin\phi$$

Power radiated by the electron

Frames of Reference

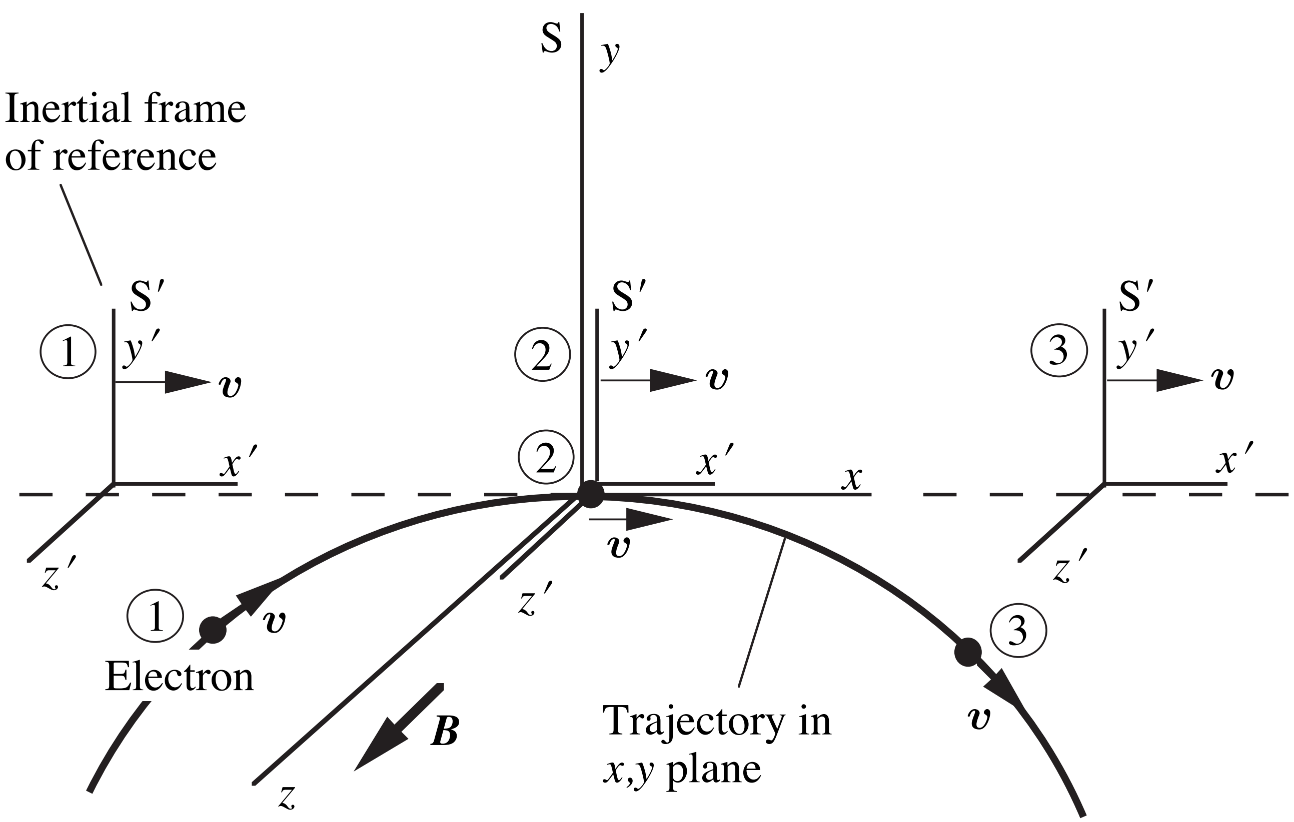


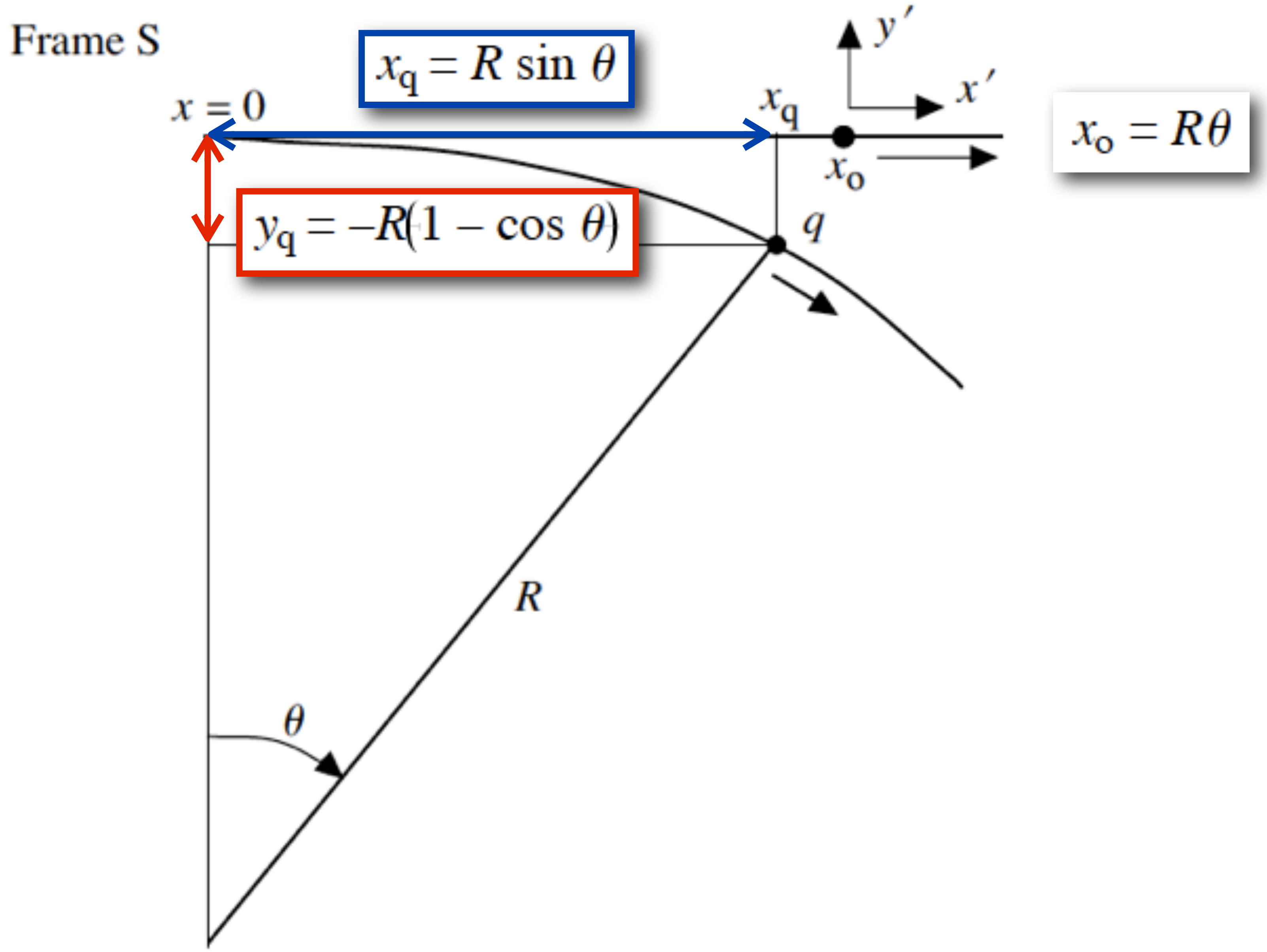
Fig. 8.8: Astrophysics Processes (CUP), © H. Bradt 2008

$$\boldsymbol{F} = q(\boldsymbol{v} \times \boldsymbol{B})$$

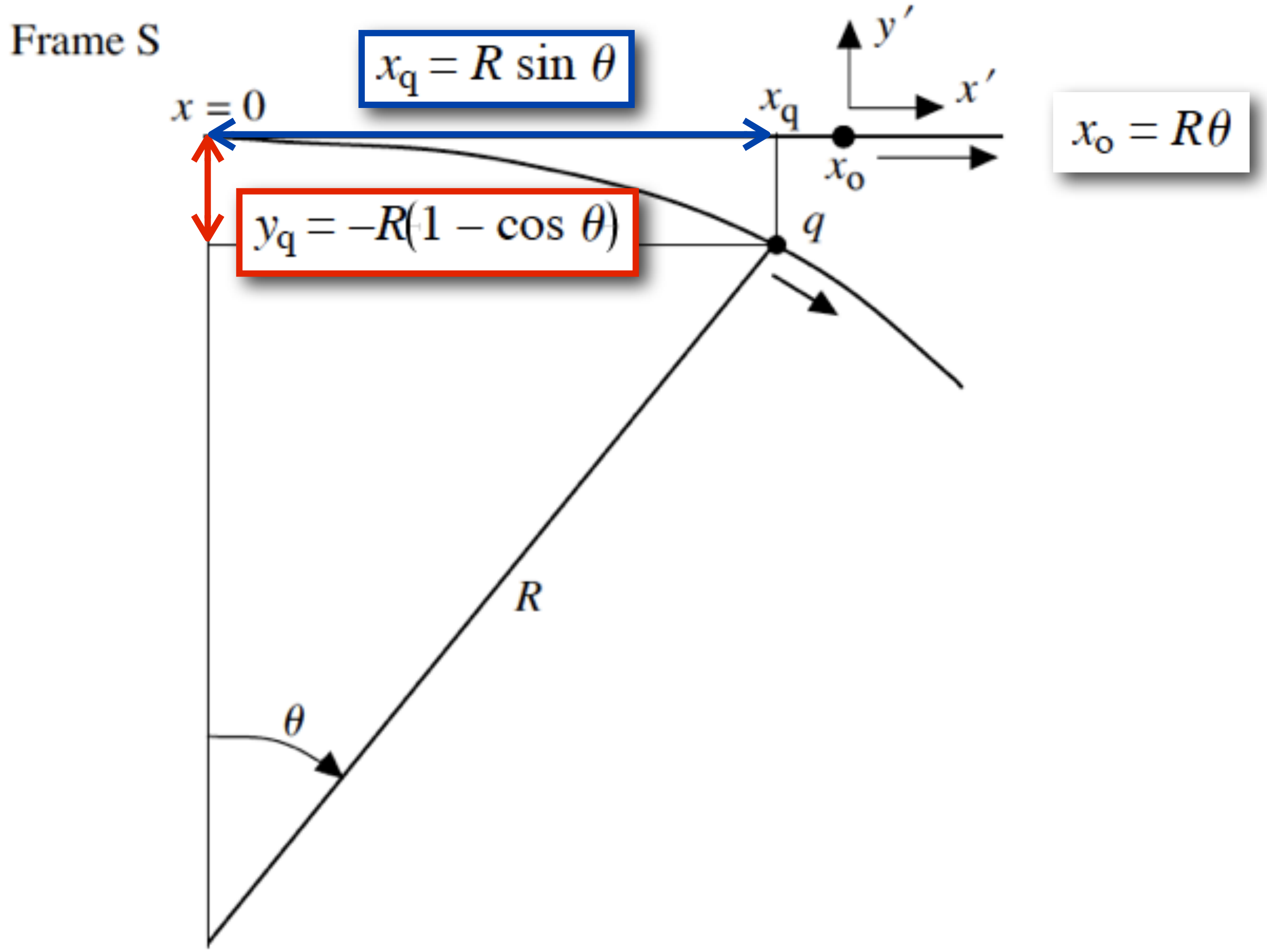
$$F_{\mathrm{y}} = -qvB_{\mathrm{z}}$$

$$F_{\mathrm{y}}/q = -vB_{\mathrm{z}}$$

Power radiated by the electron



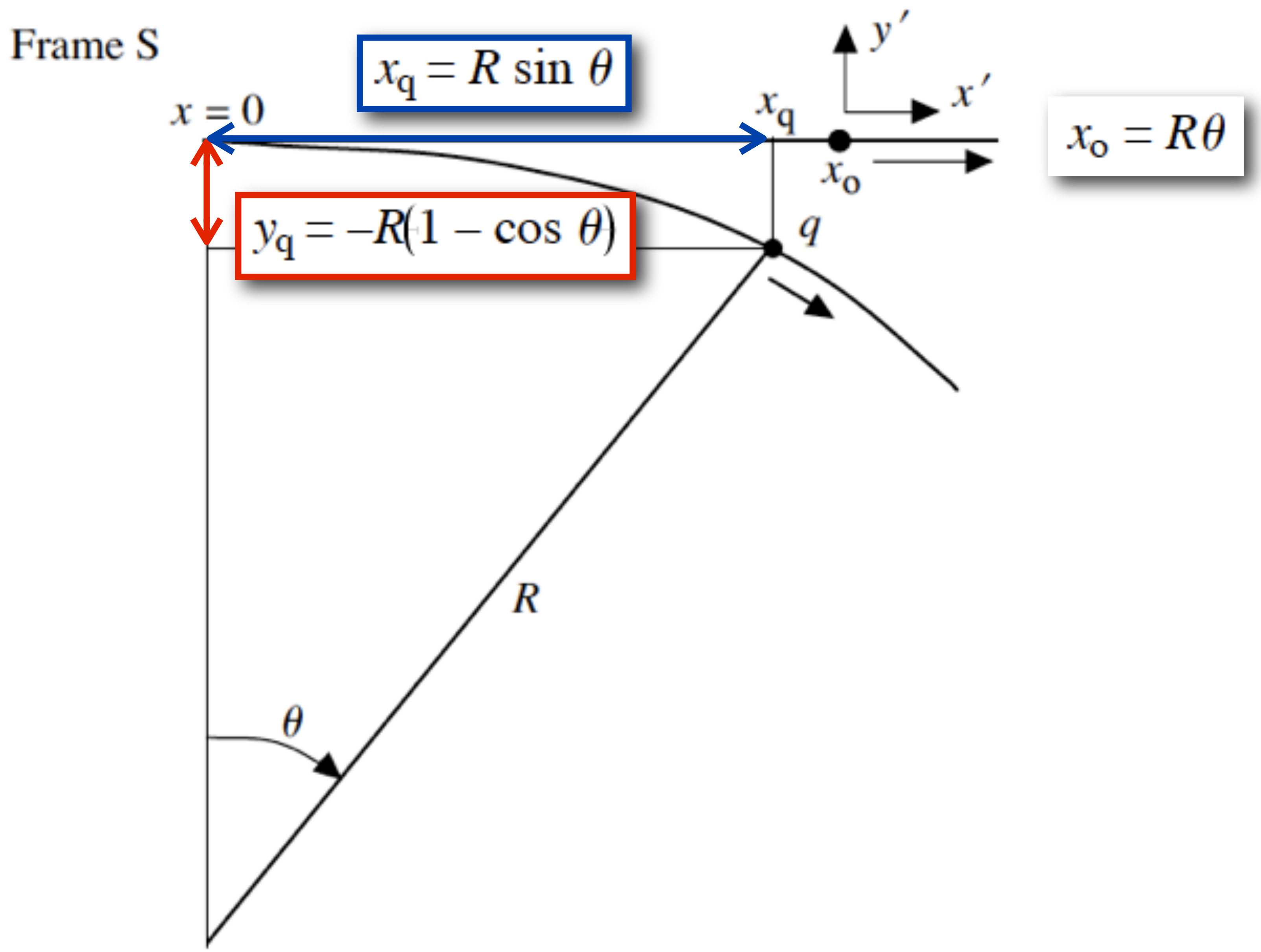
Power radiated by the electron



$$x' = x_q - x_o = R(\sin\theta - \theta)$$

$$y' = y_q - 0 = -R(1 - \cos\theta)$$

Power radiated by the electron



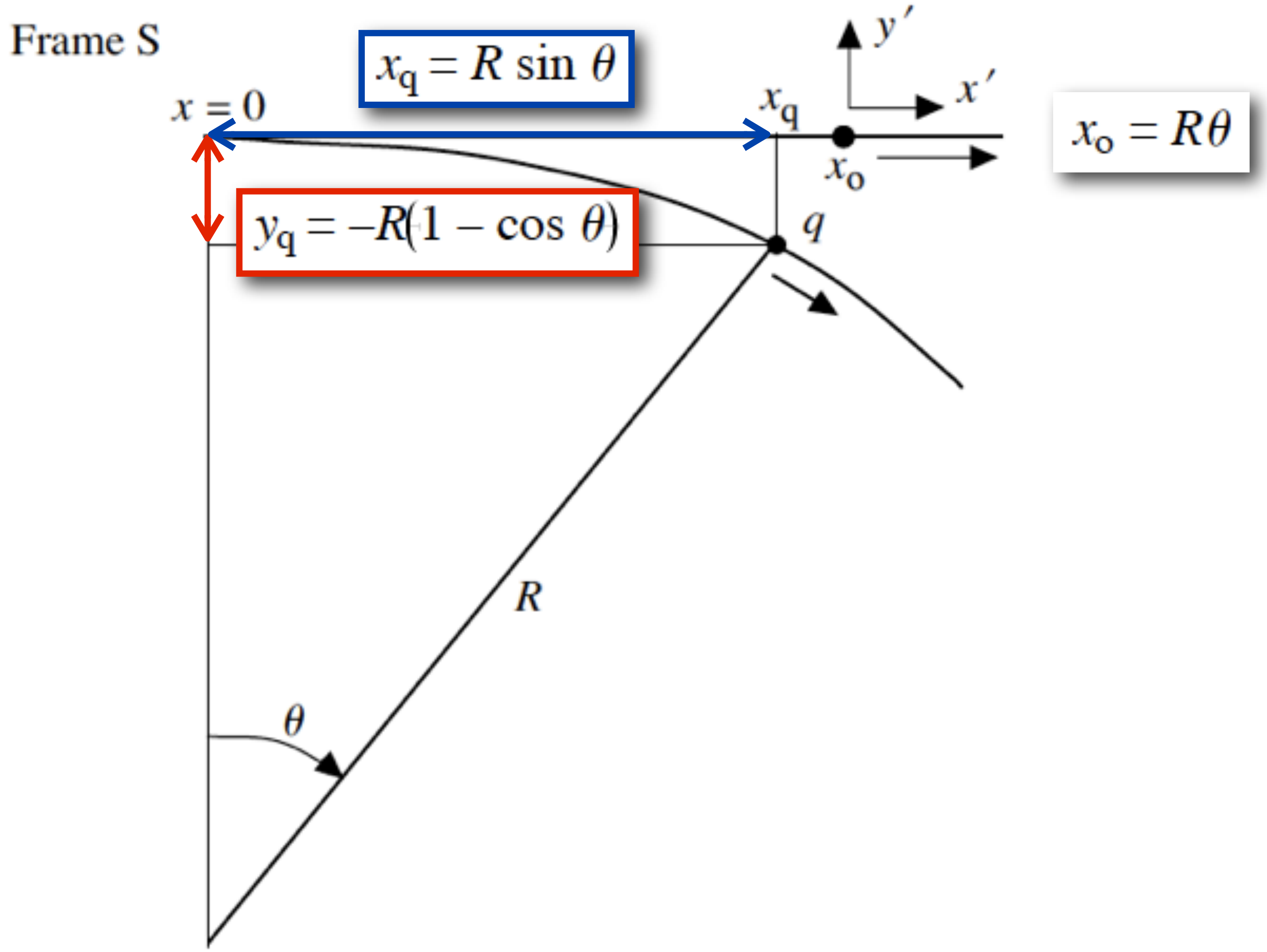
$$x' = x_q - x_o = R(\sin\theta - \theta)$$

$$y' = y_q - 0 = -R(1 - \cos\theta)$$

$$\cos\theta \approx 1 - \theta^2/2$$

$$\sin\theta \approx \theta - \theta^3/3$$

Power radiated by the electron



$$x' = x_q - x_o = R(\sin\theta - \theta)$$

$$y' = y_q - 0 = -R(1 - \cos\theta)$$

$$\cos\theta \approx 1 - \theta^2/2$$

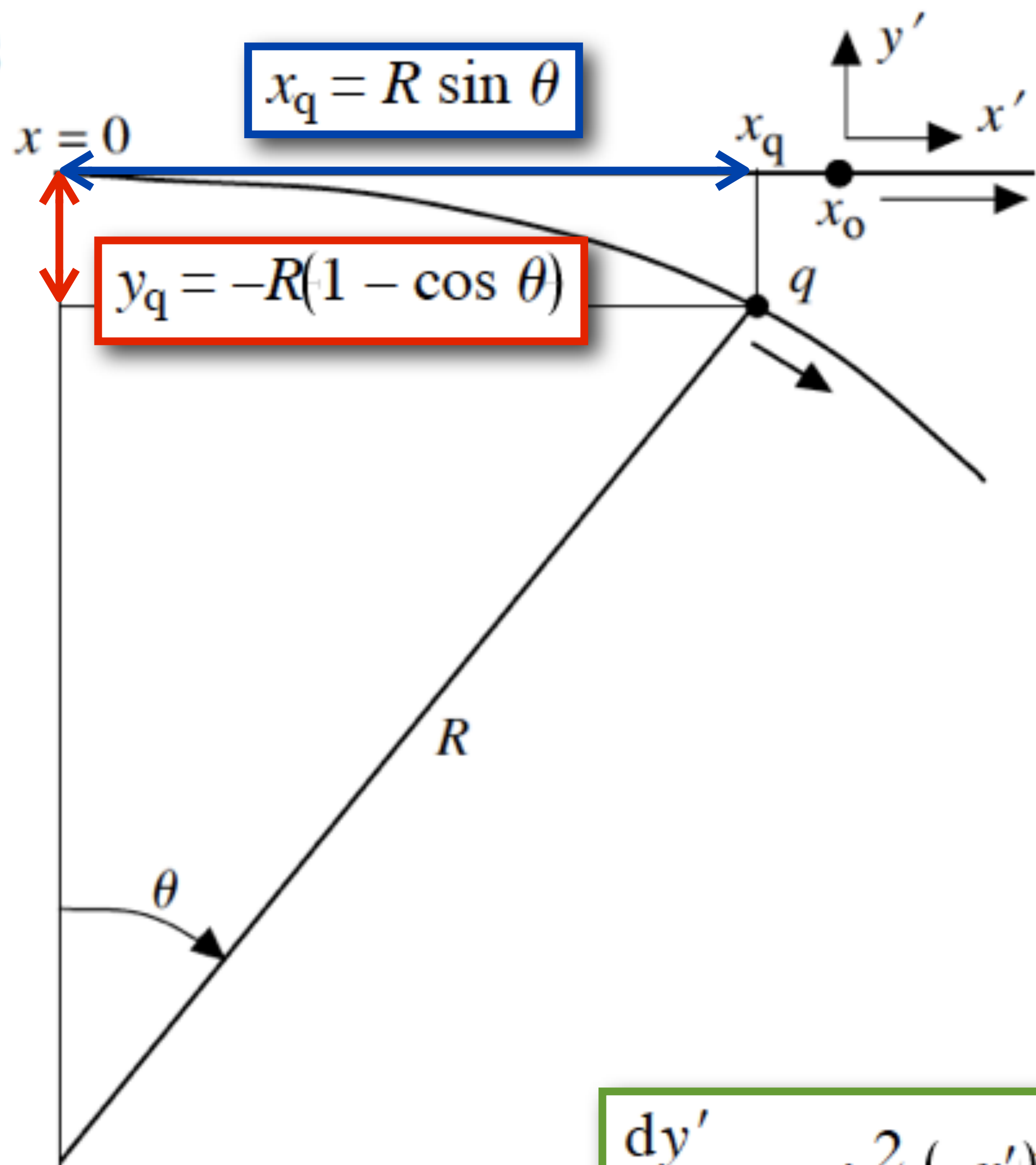
$$\sin\theta \approx \theta - \theta^3/3$$

$$x' \approx -R\theta^3/3!$$

$$y' \approx -R\theta^2/2!$$

Power radiated by the electron

Frame S



$x_o = R\theta$

$$x' = x_q - x_o = R(\sin\theta - \theta)$$

$$y' = y_q - 0 = -R(1 - \cos\theta)$$

$$\cos\theta \approx 1 - \theta^2/2$$

$$\sin\theta \approx \theta - \theta^3/3$$

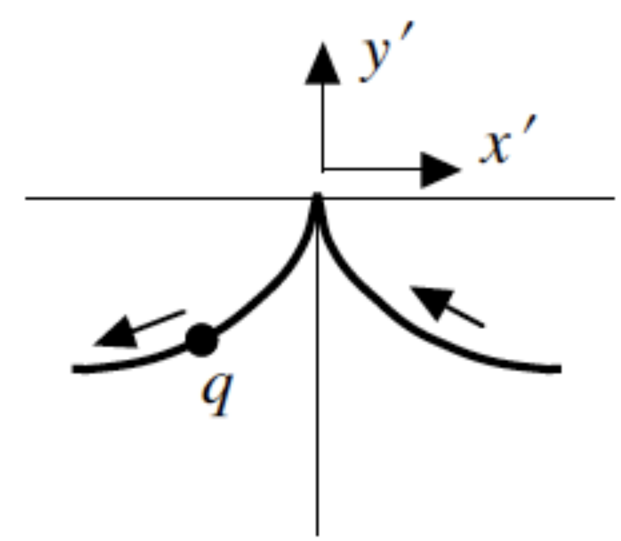
$$x' \approx -R\theta^3/3!$$

$$y' \approx -R\theta^2/2!$$

$$y' = -R^{1/3}\left(\frac{9}{2}\right)^{1/3}(-x')^{2/3}$$

$$\frac{dy'}{dx'} \propto +\frac{2}{3}(-x')^{-1/3}$$

Frame S′



Power radiated by the electron

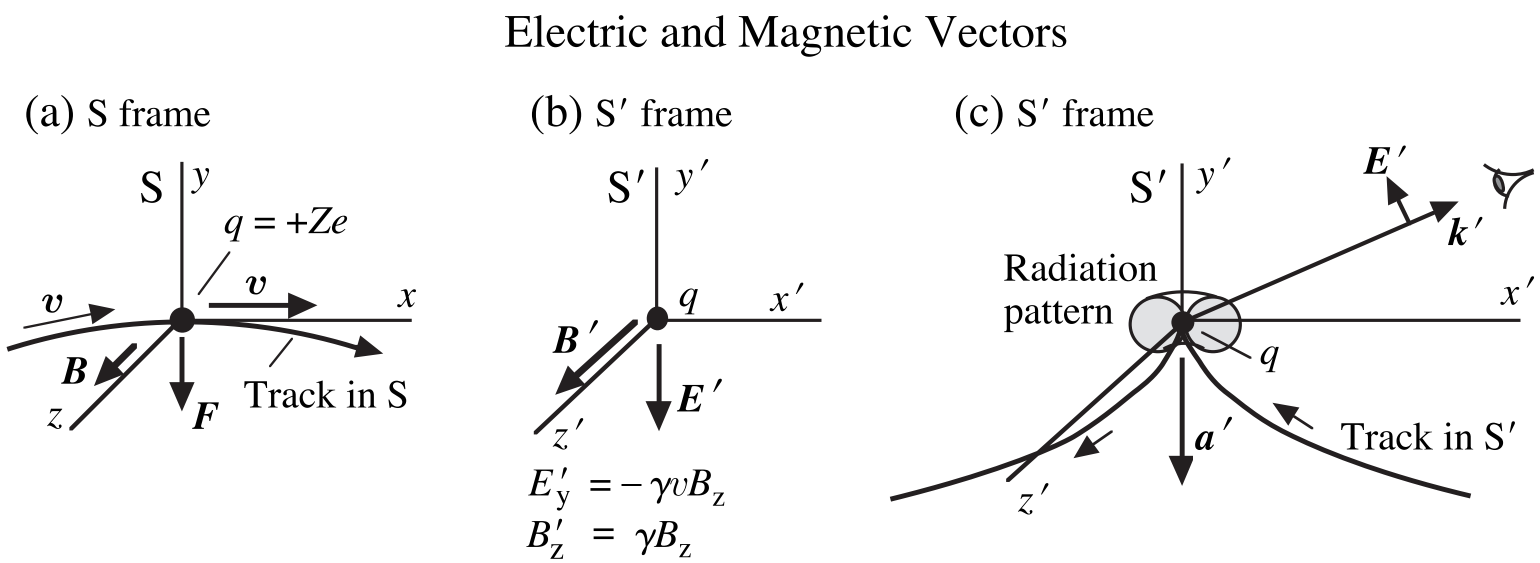


Fig. 8.9: Astrophysics Processes (CUP), © H. Bradt 2008

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{q^2 a'^2}{c^3}$$

$$\boldsymbol{B} : 0, 0, B_{\mathrm{z}}; \quad \boldsymbol{E} : 0, 0, 0$$

$$\boldsymbol{B'} : 0, 0, \gamma B_{\mathrm{z}}; \quad \boldsymbol{E'} : 0, -\gamma\beta c B_{\mathrm{z}}, 0$$

$$B'_{\mathrm{z}} = -\gamma B_{\mathrm{z}}$$

$$E'_{\mathrm{y}} = -\gamma\beta c B_{\mathrm{z}} = -\gamma v B_{\mathrm{z}}$$

Power radiated by the electron

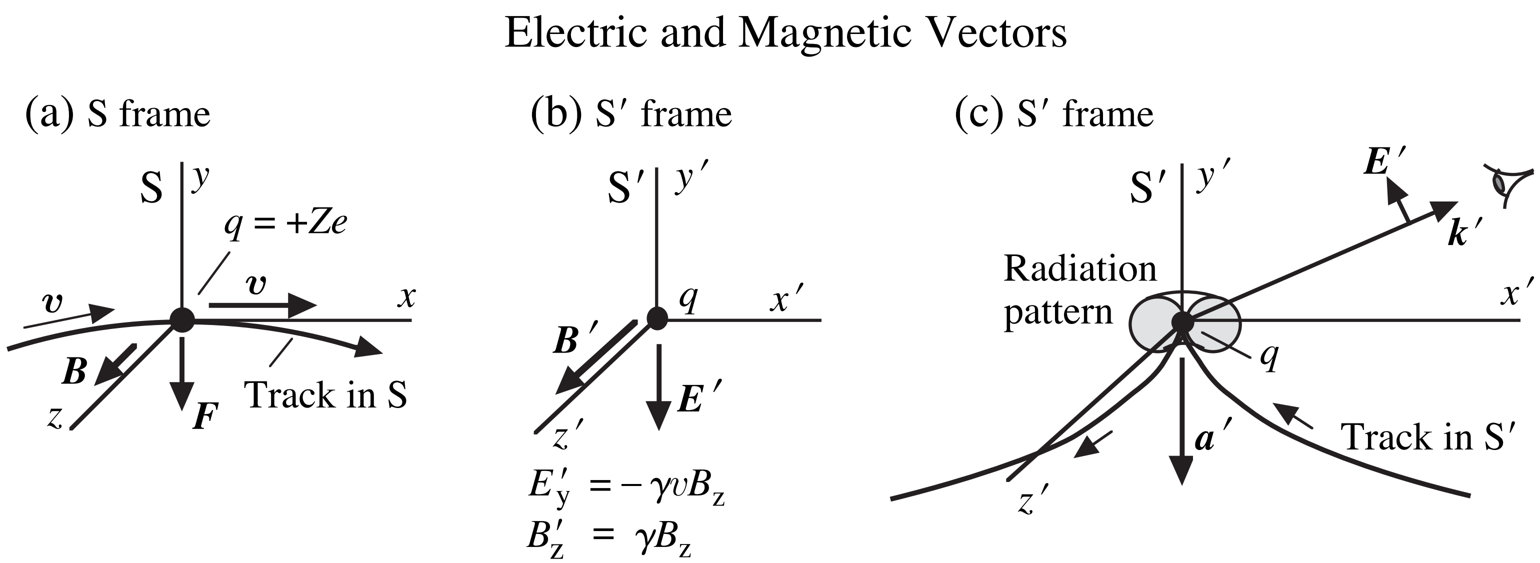


Fig. 8.9: Astrophysics Processes (CUP), © H. Bradt 2008

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{q^2 a'^2}{c^3}$$

$\boldsymbol{B}$:$0, 0, B_\mathrm{z}$; $\boldsymbol{E}$:$0, 0, 0$

$\boldsymbol{B}$' :$0, 0, \gamma B_\mathrm{z}$; $\boldsymbol{E}$' :$0, -\gamma\beta c B_\mathrm{z}, 0$

$$B'_\mathrm{z} = -\gamma B_\mathrm{z}$$

$$F_\mathrm{y}/q = -vB_\mathrm{z}$$

$$E'_\mathrm{y} = -\gamma\beta c B_\mathrm{z} = -\gamma v B_\mathrm{z}$$

Power radiated by the electron

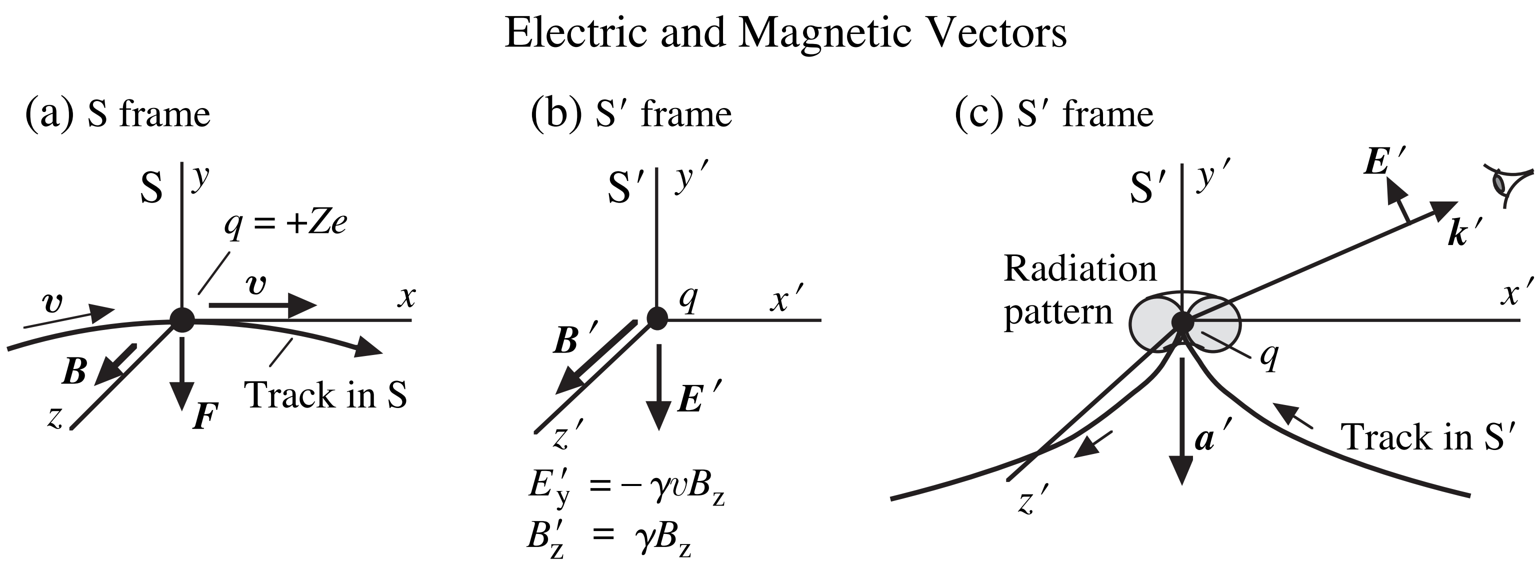


Fig. 8.9: Astrophysics Processes (CUP), © H. Bradt 2008

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{q^2 a'^2}{c^3}$$

$$E'_\mathrm{y} = -\gamma\beta c B_\mathrm{z} = -\gamma v B_\mathrm{z}$$

$$a'_\mathrm{y} = \frac{F'_\mathrm{y}}{m} = \frac{qE'_\mathrm{y}}{m} = -\frac{Ze\gamma v B_\mathrm{z}}{m}$$

$$B'_\mathrm{z} = -\gamma B_\mathrm{z}$$

$$a' \equiv a'_\mathrm{y} \qquad B_\mathrm{z} \equiv B$$

$$a' = -Ze\frac{U}{mc^2}\frac{v\ B}{m} \approx -\frac{ZeBU}{m^2 c}$$

Power radiated by the electron

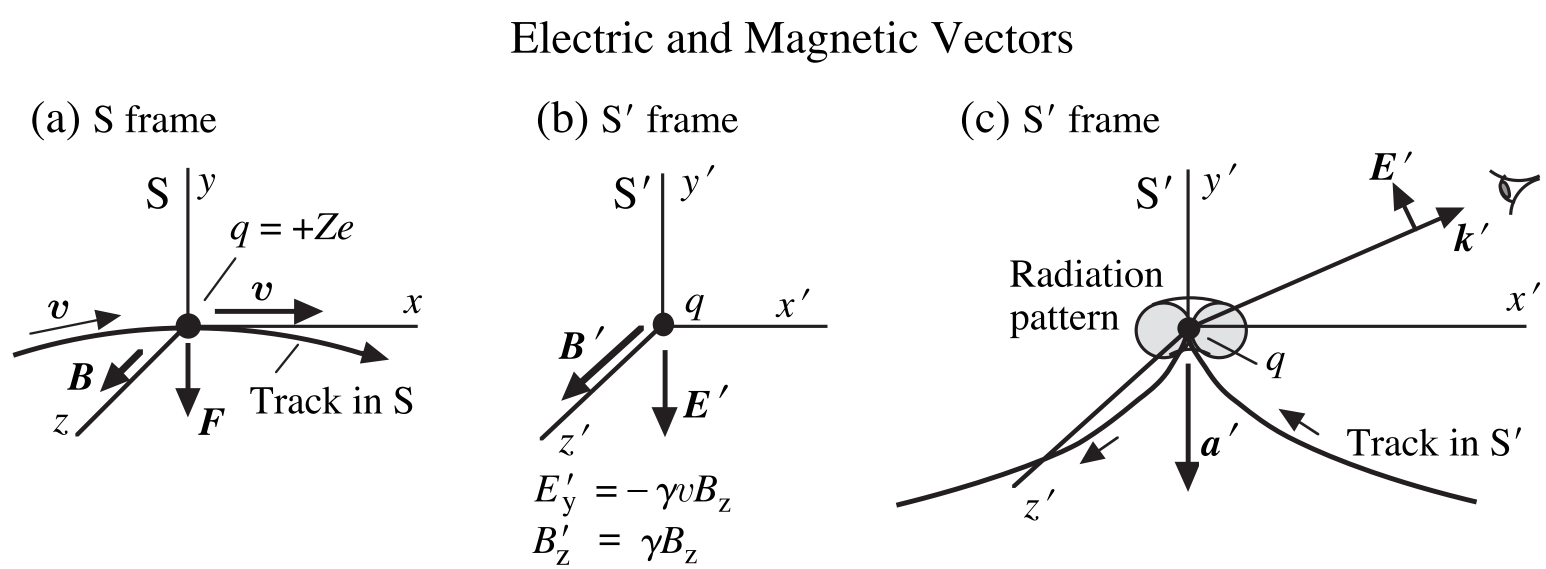


Fig. 8.9: Astrophysics Processes (CUP), © H. Bradt 2008

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{q^2 a'^2}{c^3}$$

$$E'_{\mathrm{y}} = -\gamma\beta c B_{\mathrm{z}} = -\gamma v B_{\mathrm{z}}$$

$$B'_{\mathrm{z}} = -\gamma B_{\mathrm{z}}$$

$$a'_{\mathrm{y}} = \frac{F'_{\mathrm{y}}}{m} = \frac{qE'_{\mathrm{y}}}{m} = -\frac{Ze\gamma v B_{\mathrm{z}}}{m}$$

$$a' \equiv a'_{\mathrm{y}} \qquad B_{\mathrm{z}} \equiv B$$

$$a' = -Ze\frac{U}{mc^2}\frac{v\ B}{m} \approx -\frac{ZeBU}{m^2 c}$$

$$v \approx c$$

$$U = \gamma mc^2$$

Power radiated by the electron

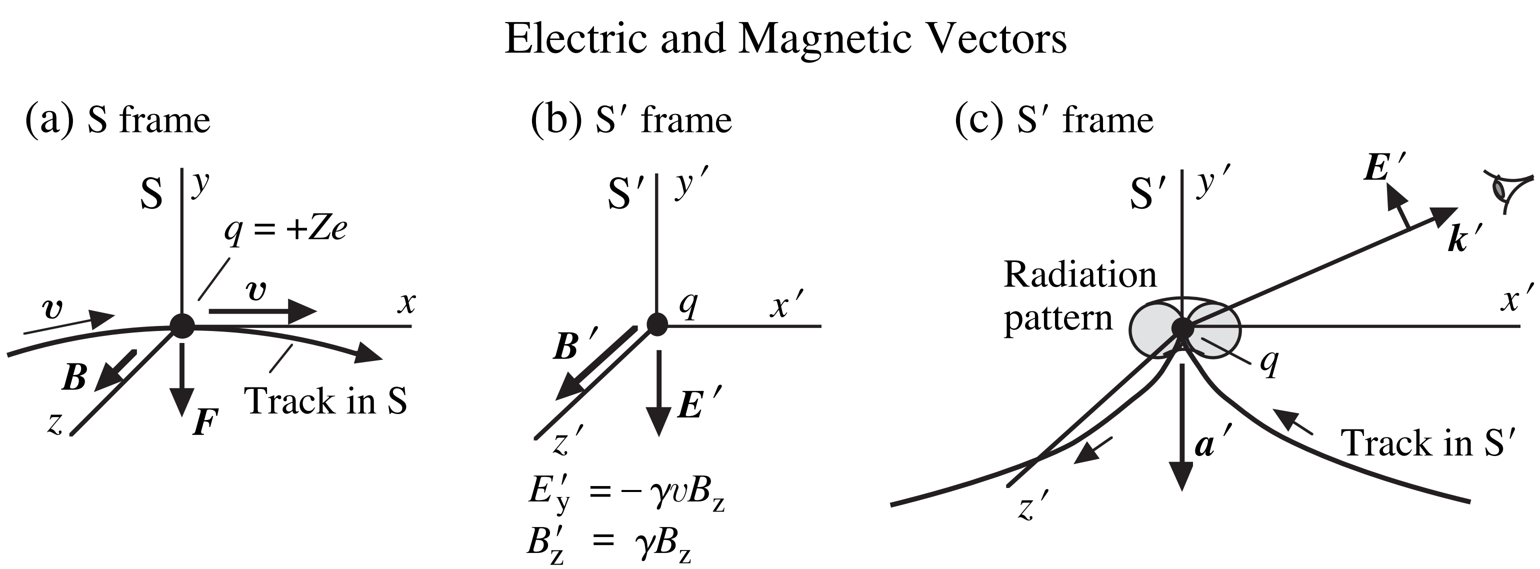


Fig. 8.9: Astrophysics Processes (CUP), © H. Bradt 2008

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{q^2 a'^2}{c^3}$$

$$a' = -\frac{ZeBU}{m^2 c}$$

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{(Ze)^2}{c^3}\left(\frac{ZeBU}{m^2 c}\right)^2$$

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{1}{c^5}\left(\frac{Ze}{m}\right)^4 U^2 B^2 \qquad [\mathrm{W}]$$

$$v \approx c$$

$$U = \gamma m c^2$$

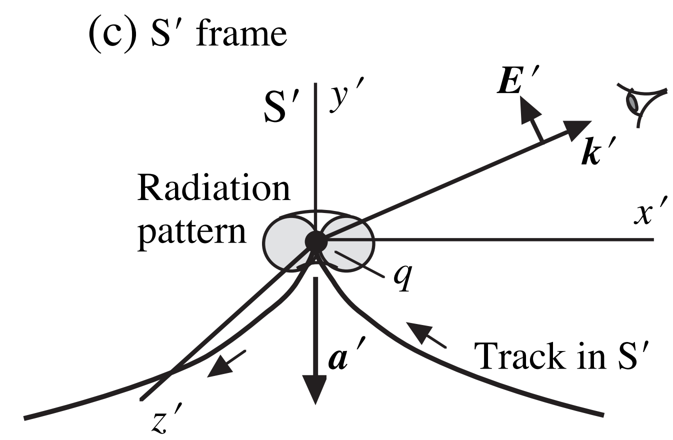
Lorentz transformations

Space-Time

$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix}$$

Momentum-Energy

$$\begin{bmatrix} E' \\ p_x' c \\ p_y' c \\ p_z' c \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E \\ p_x c \\ p_y c \\ p_z c \end{bmatrix}$$



Lorentz transformations

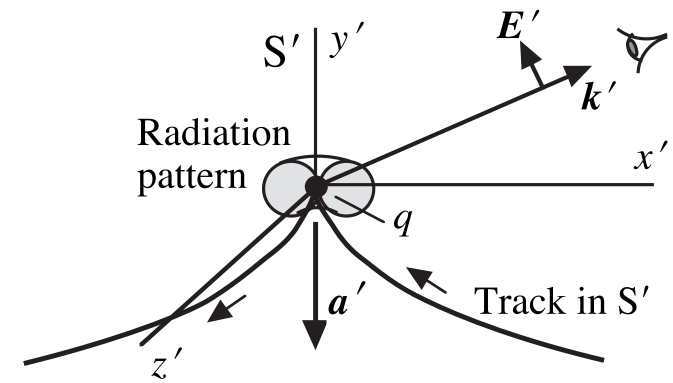
Space-Time

$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix}$$

Momentum-Energy

$$\begin{bmatrix} E' \\ p_x' c \\ p_y' c \\ p_z' c \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E \\ \cancel{p_x c} \\ p_y c \\ p_z c \end{bmatrix}$$

(c) S′ frame



$$\boxed{\mathrm{d}U = \gamma\ \mathrm{d}U'}$$

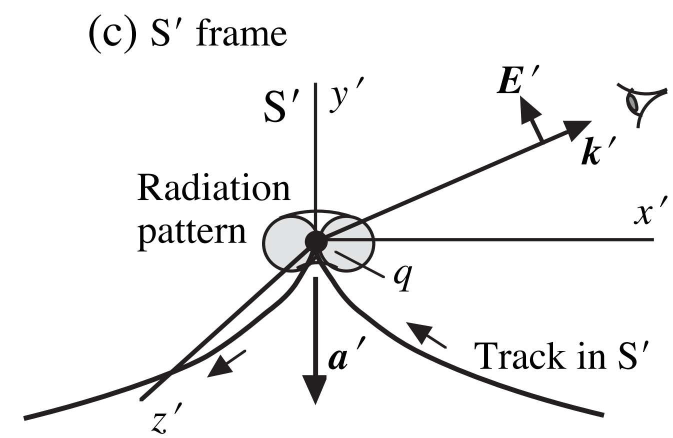
Lorentz transformations

Space-Time

$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix}$$

Momentum-Energy

$$\begin{bmatrix} E' \\ p_x' c \\ p_y' c \\ p_z' c \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E \\ p_x c \\ p_y c \\ p_z c \end{bmatrix}$$



$$\mathrm{d}U = \gamma \, \mathrm{d}U'$$

$$\mathrm{d}t = \gamma \, \mathrm{d}t'$$

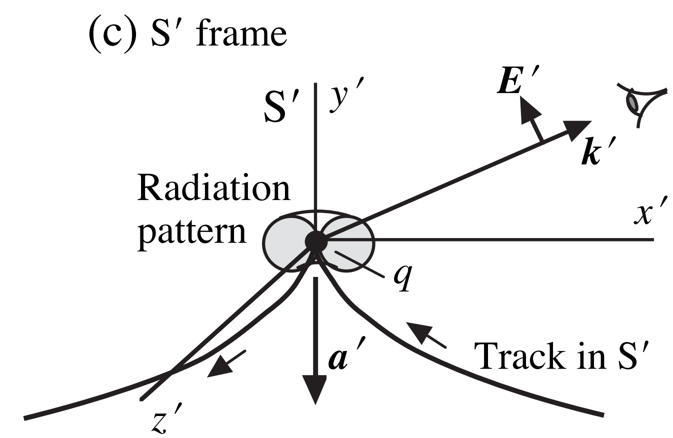
Lorentz transformations

Space-Time

$$\begin{bmatrix} ct' \\ x' \\ y' \\ z' \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} ct \\ x \\ y \\ z \end{bmatrix}$$

Momentum-Energy

$$\begin{bmatrix} E' \\ p_x' c \\ p_y' c \\ p_z' c \end{bmatrix} = \begin{bmatrix} \gamma & -\beta\gamma & 0 & 0 \\ -\beta\gamma & \gamma & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E \\ p_x c \\ p_y c \\ p_z c \end{bmatrix}$$



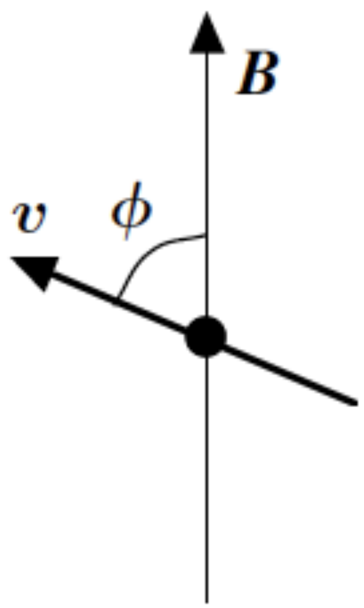
$$\mathrm{d}U = \gamma\ \mathrm{d}U'$$

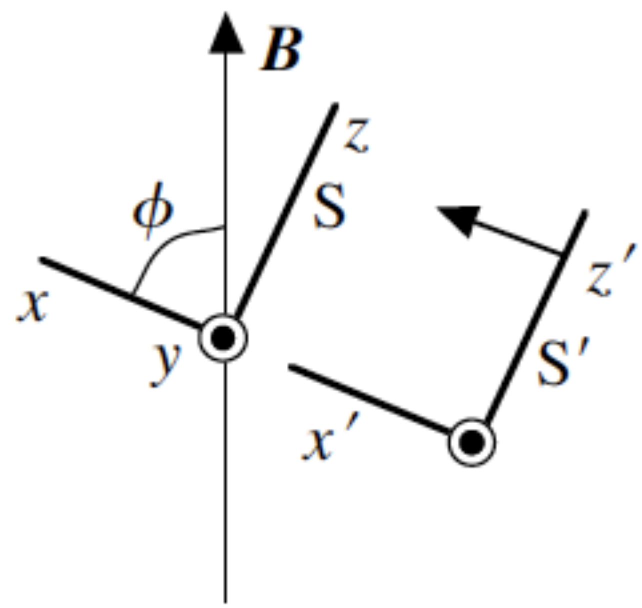
$$\mathrm{d}t = \gamma\ \mathrm{d}t'$$

$$\frac{\mathrm{d}U}{\mathrm{d}t} = \frac{\mathrm{d}U'}{\mathrm{d}t'}$$

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{1}{c^5}\left(\frac{Ze}{m}\right)^4 U^2 B^2 \qquad [\mathrm{W}]$$

Power radiated by the electron





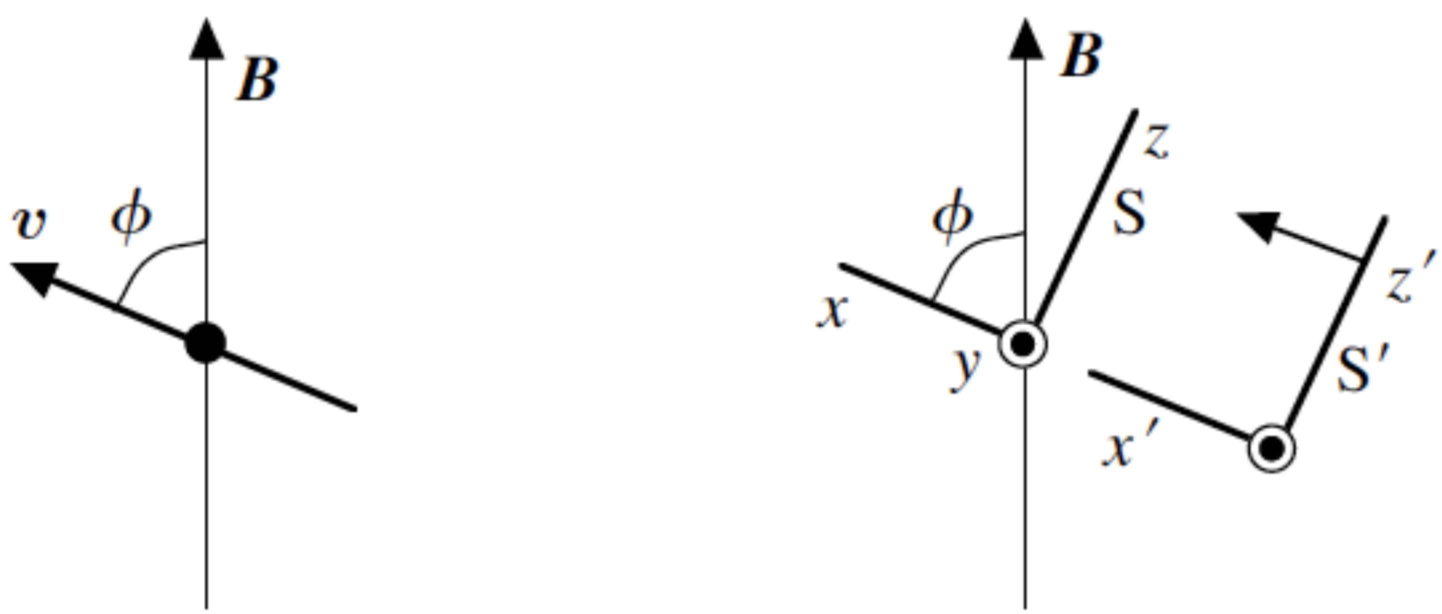
$$B_{\mathrm{z}} = B \sin \phi$$

$$\frac{\mathrm{d}U'}{\mathrm{d}t'} = -\frac{1}{6\pi\epsilon_0}\frac{q^2 a'^2}{c^3}$$

$$a' = -Ze\frac{U}{mc^2}\frac{v\ B}{m} \sin \phi$$

$$\frac{\mathrm{d}U}{\mathrm{d}t} = -\frac{1}{6\pi\epsilon_0}\frac{1}{c^5}\left(\frac{Ze}{m}\right)^4 U^2\beta^2 B^2 \sin^2 \phi \qquad [\mathrm{W}]$$

Power radiated by the electron



$$B_z = B \sin \phi$$

$$\frac{dU'}{dt'} = -\frac{1}{6\pi\epsilon_0}\frac{q^2 a'^2}{c^3}$$

$$a' = -Ze\frac{U}{mc^2}\frac{v\ B}{m} \sin \phi$$

~10^{13} times greater for electrons than for protons !

$$\frac{dU}{dt} = -\frac{1}{6\pi\epsilon_0}\frac{1}{c^5}\left(\frac{Ze}{m}\right)^4 U^2\beta^2 B^2 \sin^2 \phi \qquad [W]$$

Power radiated by the electron

$$\frac{\mathrm{d}U}{\mathrm{d}t} = -\frac{1}{6\pi\epsilon_0}\frac{1}{c^5}\left(\frac{Ze}{m}\right)^4 U^2\beta^2B^2\ \sin^2\ \phi \qquad [\mathrm{W}]$$

$$u_\mathrm{B} = \frac{B^2}{2\ \mu_0} \quad [\mathrm{J/m^3}]$$

$$\sigma_T = \frac{\mathcal{P}}{\mathcal{F}_P} = \frac{8\pi}{3}r_e^2 = 6.6525 \times 10^{-29}\ \mathrm{m}^2$$

$$\langle\sin^2\phi\rangle_\mathrm{av} = \frac{1}{4\ \pi}\int_\mathrm{sphere}\sin^2\phi\ \mathrm{d}\Omega = \frac{2}{3}$$

$$r_e = \frac{1}{4\pi\epsilon_0}\frac{e^2}{m_e c^2} = 2.8179 \times 10^{-15}\ \mathrm{m}$$

$$U = \gamma mc^2 \qquad c^2 = (\mu_0\epsilon_0)^{-1}$$

$$\frac{\mathrm{d}U}{\mathrm{d}t} = -\frac{4}{3}\sigma_T c\beta^2\gamma^2 u_\mathrm{B}$$

Electron energy lifetime

$$\frac{\mathrm{d}U}{\mathrm{d}t} \propto -U^2 B^2$$

$$\tau = -\frac{U}{\mathrm{d}U/\mathrm{d}t} \propto \frac{U}{U^2 B^2} \propto \frac{1}{U B^2} \propto \frac{1}{\gamma B^2}$$

$$\tau = \frac{5.16}{B^2}\frac{1}{\gamma}$$

Relativistic electron decay time in sec; B in Teslas (=10 kGauss)

Inverse Compton

Full derivation power for single scattering

$$\frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}t} = c\ \sigma_T\ U_{\mathrm{rad}}\left[\gamma^2 + \frac{1}{3}\gamma^2\beta^2 - 1\right] = c\ \sigma_T\ U_{\mathrm{rad}}\left[(\gamma^2 - 1) + \frac{1}{3}\gamma^2\beta^2\right] = c\ \sigma_T\ U_{\mathrm{rad}}\left[\gamma^2\beta^2 + \frac{1}{3}\gamma^2\beta^2\right]$$

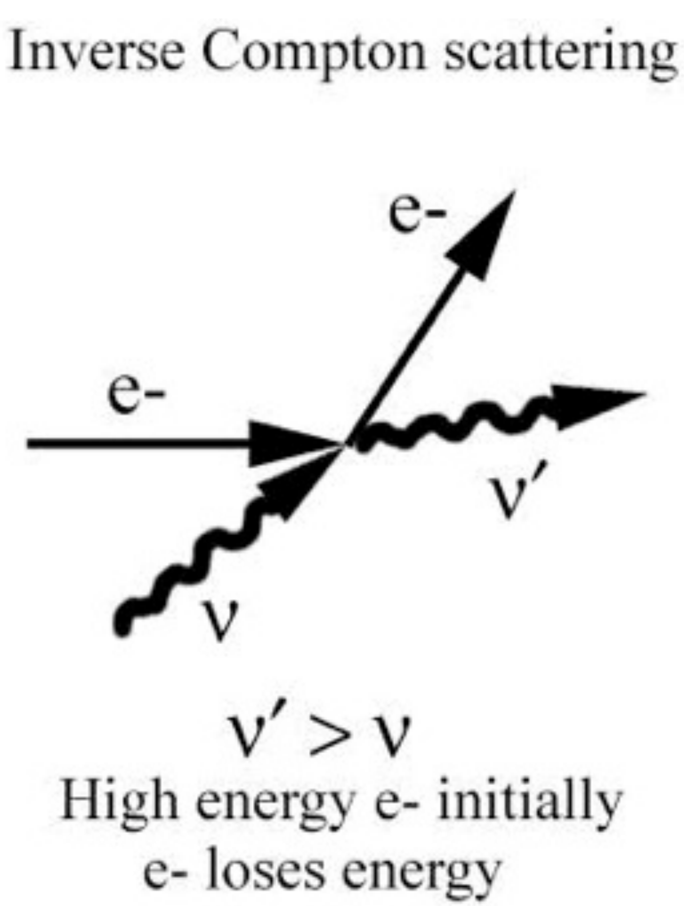
$$\frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}t} = P_{\mathrm{compt}} = \frac{4}{3}\sigma_T\ c\ \gamma^2\ \beta^2\ U_{\mathrm{rad}}$$

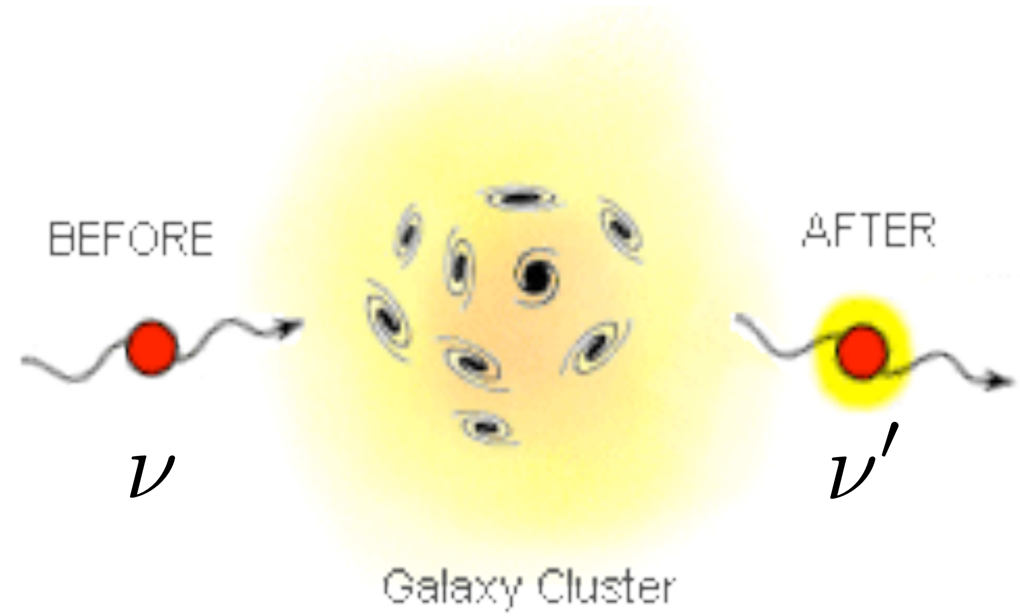
Net power lost by the relativistic electron and converted into increased radiation

$$\frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}t} = \frac{4}{3}\sigma_T\ c\ \gamma^2 \int \epsilon\ \upsilon\ \mathrm{d}\epsilon \quad (\beta \approx 1)$$

$$\frac{\mathrm{d}E_{\mathrm{rad}}}{\mathrm{d}t} = \frac{4}{3}\sigma_T\ c\ \gamma^2\ <\epsilon> \int \upsilon\ \mathrm{d}\epsilon = \sigma_T\ c\ <\epsilon_1> \int \upsilon\ \mathrm{d}\epsilon$$

Electron energy lifetime



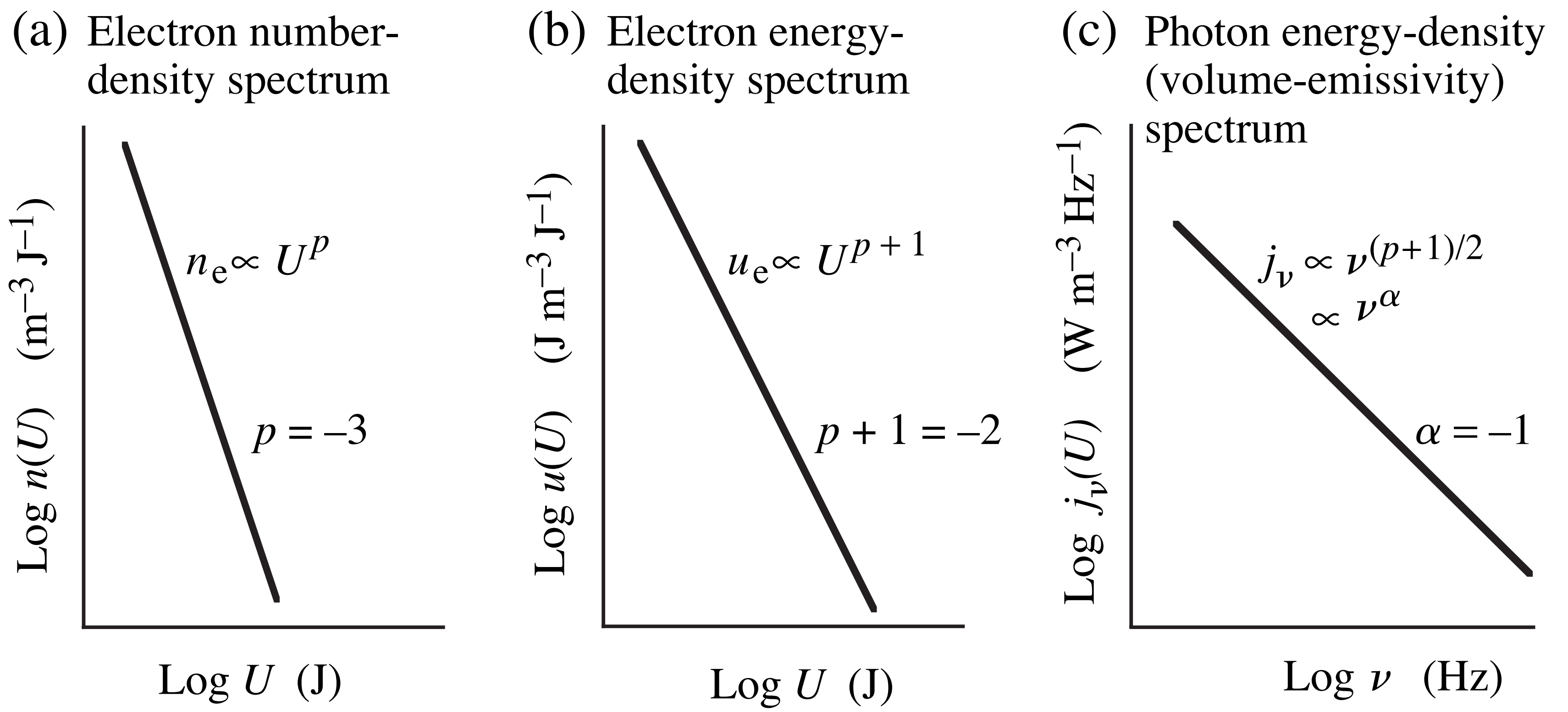


$$\frac{<\nu'>}{\nu} = \frac{4}{3}\gamma_{el}^2$$

$$\tau \approx 2\times 10^3 \gamma^{-1}\left[(1+z)^4 + \left(\frac{B}{3.3\mu\mathrm{G}}\right)^2\right]^{-1} \mathrm{Gyr} \begin{cases} \mathrm{E_{e^-}} \approx \mathrm{GeV} \rightarrow \tau \lesssim \mathrm{Gyr} \\ \mathrm{E_{e^-}} \approx \mathrm{TeV} \rightarrow \tau \lesssim \mathrm{Myr} \end{cases}$$

Ferrari et al. 2008 and refs. therein

Ensemble of radiating particles

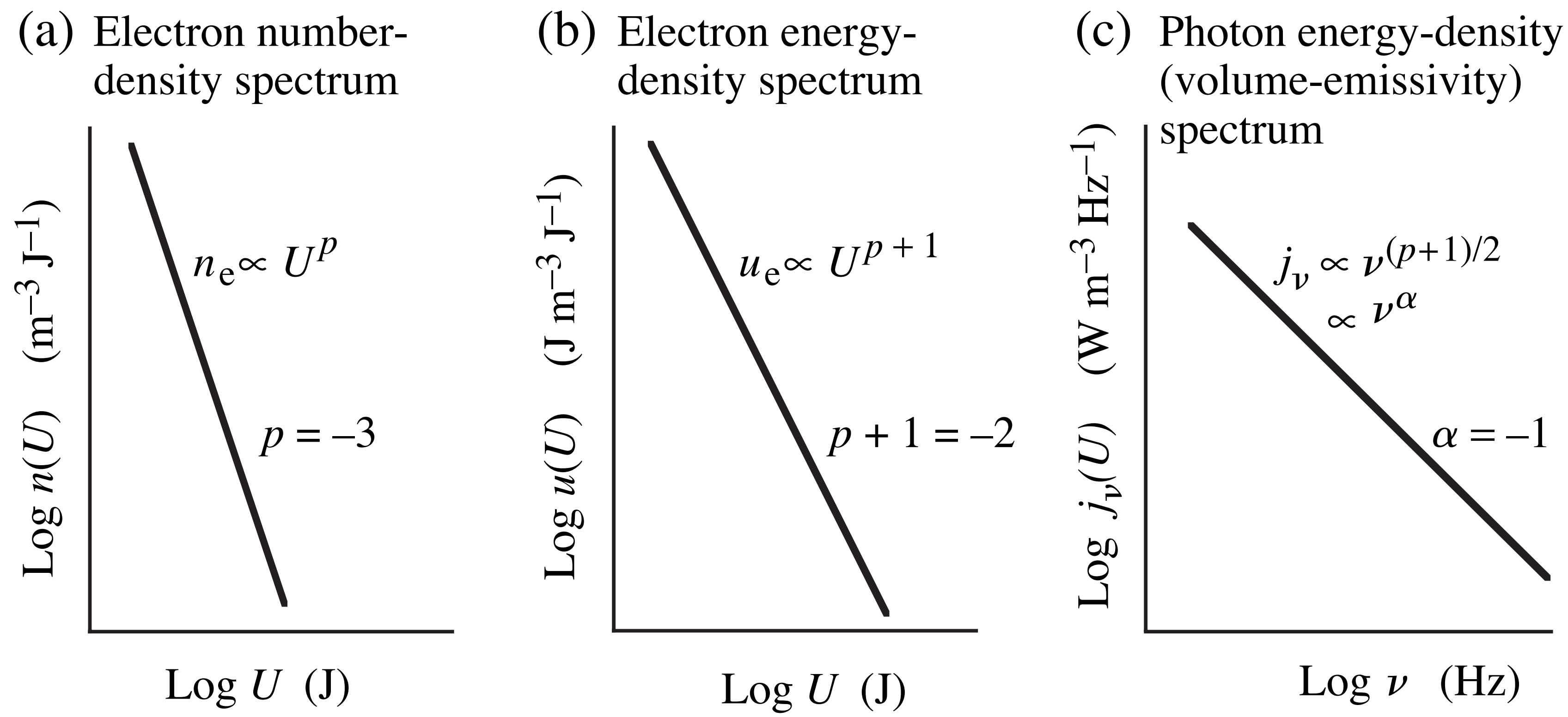


$$n(U)\mathrm{d}U \propto U^p dU = \frac{n_0}{U_0^p}\, U^p\ \mathrm{d}U = n_0 \left(\frac{U}{U_0}\right)^p \mathrm{d}U \quad (\text{Particles/m}^3 \text{ at } U \text{ in } \mathrm{d}U)$$

$$u(U)\mathrm{d}U = U\ n(U)\ \mathrm{d}U = U\ n_0 \left(\frac{U}{U_0}\right)^p \mathrm{d}U = u_0 \left(\frac{U}{U_0}\right)^{p+1} \mathrm{d}U \quad (\text{Energy density in } \mathrm{d}U \text{ at } U)$$

$$\times\ U_0/U_0;\ u_0 \equiv U_0\ n_0$$

Ensemble of radiating particles

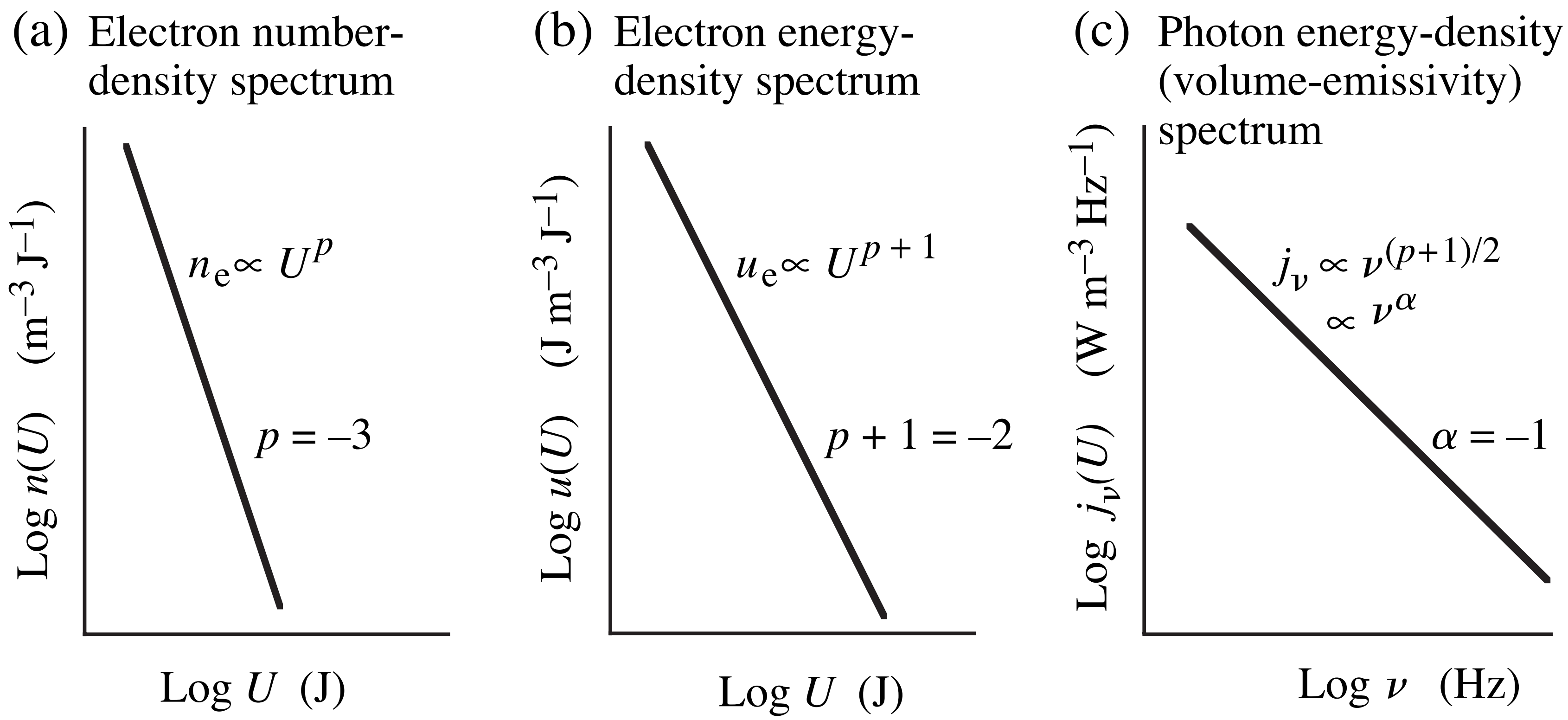


$$n(U)\mathrm{d}U \propto U^p dU = \frac{n_0}{U_0^p}\ U^p\ \mathrm{d}U = n_0 \left(\frac{U}{U_0}\right)^p \mathrm{d}U \quad (\text{Particles/m}^3 \text{ at } U \text{ in d}U)$$

$$u(U)\mathrm{d}U = U\ n(U)\ \mathrm{d}U = U\ n_0 \left(\frac{U}{U_0}\right)^p \mathrm{d}U = u_0 \left(\frac{U}{U_0}\right)^{p+1} \mathrm{d}U \quad (\text{Energy density in d}U \text{ at } U)$$

$$j_\mathrm{u}(U)\mathrm{d}U = -(\mathrm{d}U/\mathrm{d}t)\ \times\ n(U)\mathrm{d}U \quad (\text{W/m}^3 \text{ at } U \text{ in d}U)$$

Ensemble of radiating particles



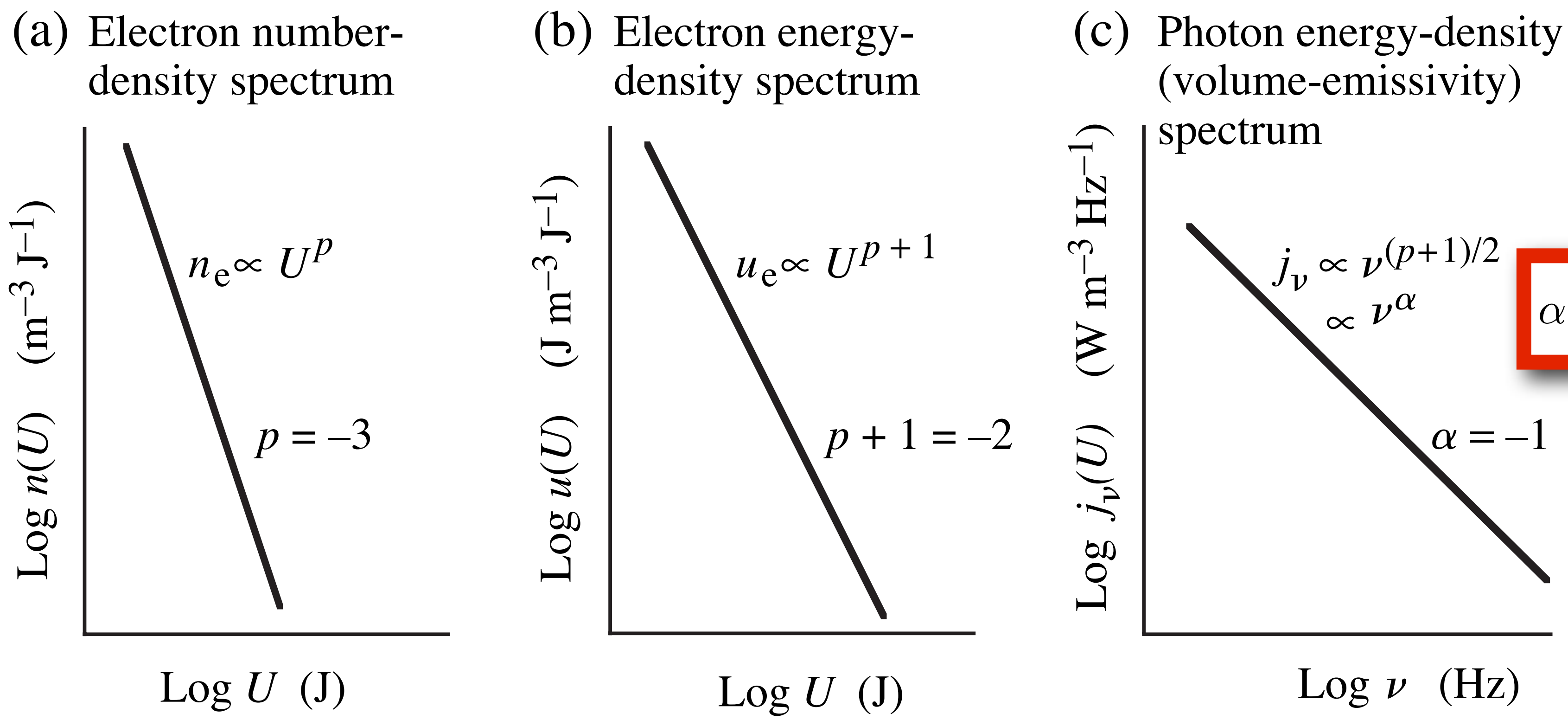
$$n(U)\mathrm{d}U \propto U^p dU = \frac{n_0}{U_0^p}\ U^p\ \mathrm{d}U = n_0 \left(\frac{U}{U_0}\right)^p \mathrm{d}U \quad (\text{Particles/m}^3 \text{ at } U \text{ in } \mathrm{d}U)$$

$$u(U)\mathrm{d}U = U\ n(U)\ \mathrm{d}U = U\ n_0 \left(\frac{U}{U_0}\right)^p \mathrm{d}U = u_0 \left(\frac{U}{U_0}\right)^{p+1} \mathrm{d}U \quad (\text{Energy density in } \mathrm{d}U \text{ at } U)$$

$$j_\mathrm{u}(U)\mathrm{d}U = -(\mathrm{d}U/\mathrm{d}t)\ \times\ n(U)\mathrm{d}U \quad (\text{W/m}^3 \text{ at } U \text{ in } \mathrm{d}U)$$

$$j_\mathrm{u}(U)\mathrm{d}U \propto U^2\ B^2\ U^p\ \mathrm{d}U\ \rightarrow\ j_\mathrm{u}(U) \propto B^2\ U^{p+2}$$

Ensemble of radiating particles



$$\alpha \equiv \frac{p+1}{2} \quad \text{(Spectral index)}$$

$$j_{\rm u}(U){\rm d}U \propto U^2\ B^2\ U^p\ {\rm d}U \ \rightarrow\ j_{\rm u}(U) \propto B^2\ U^{p+2}$$

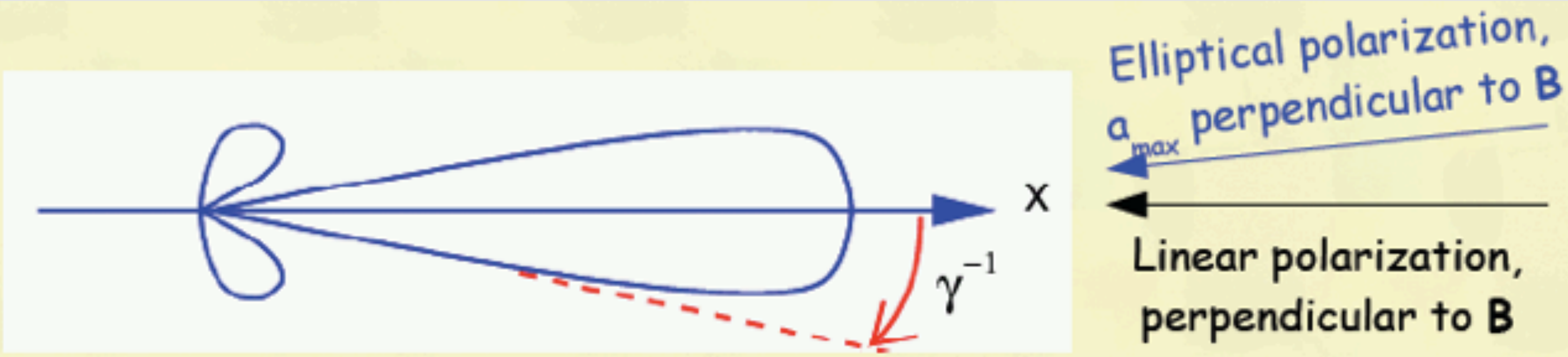
$$j_\nu(\nu)\ {\rm d}\nu = j_{\rm u}(U)\ {\rm d}U \ \rightarrow\ j_\nu(\nu) = j_{\rm u}(U)\ \frac{{\rm d}U}{{\rm d}\nu}$$

$$\nu_c \propto U^2 B \ \rightarrow\ U \propto (\nu/B)^{1/2} \ \rightarrow\ {\rm d}U \propto B^{-1/2}\nu^{-1/2}\ {\rm d}\nu$$

$$\rightarrow j_\nu(\nu)\ {\rm d}\nu \propto B^{(1-p)/2}\ \nu^{(1+p)/2}\ {\rm d}\nu \quad \text{(Synchrotron photon – energy spectrum; W/m}^3 \text{ at } \nu \text{ ind}\nu)$$

Polarization

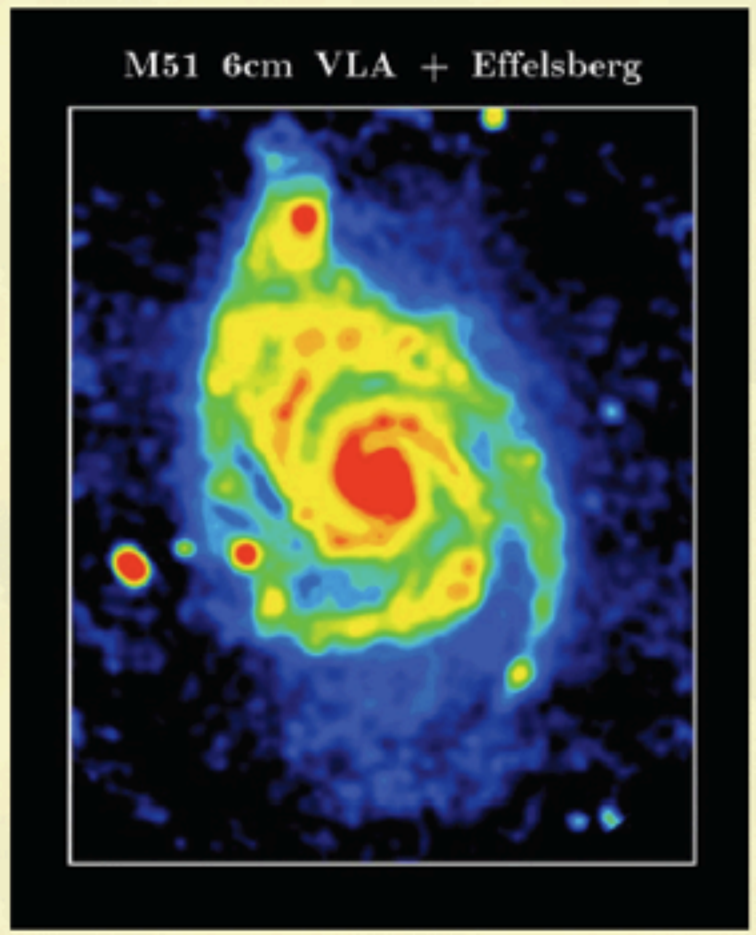
$\vec{E} \parallel \vec{a}$

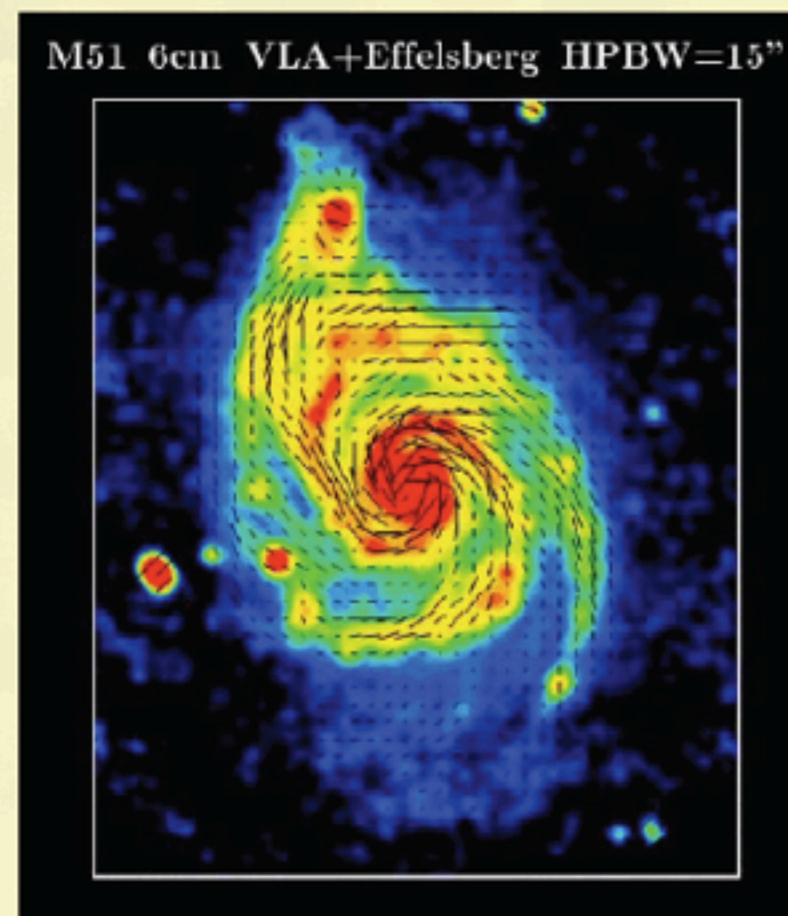


Set of relativistic electrons:

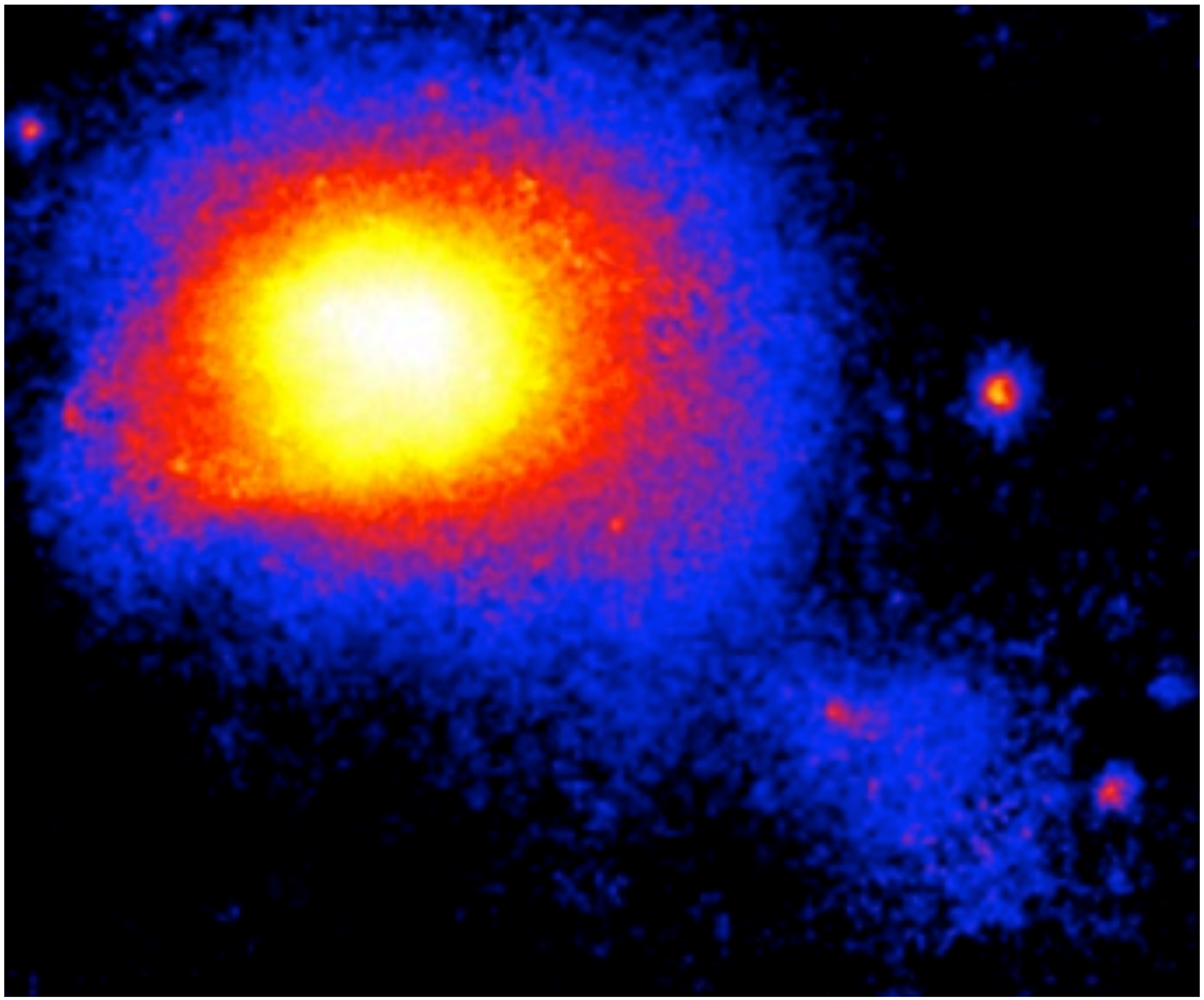
- We receive radiation only from those with velocities within a cone of semi-aperture $1/\gamma$ centered on the line of sight axis
- If the magnetic field is ordered the radiation is still polarized
- Since electron velocities are not ordered, the ellipses of polarization have different orientations, and they cancel each other. We will have therefore only linear polarization, perpendicular to the ordered magnetic field
- The polarized signal is thus intrinsically lower than the total one (maximum ~70%)

Polarization



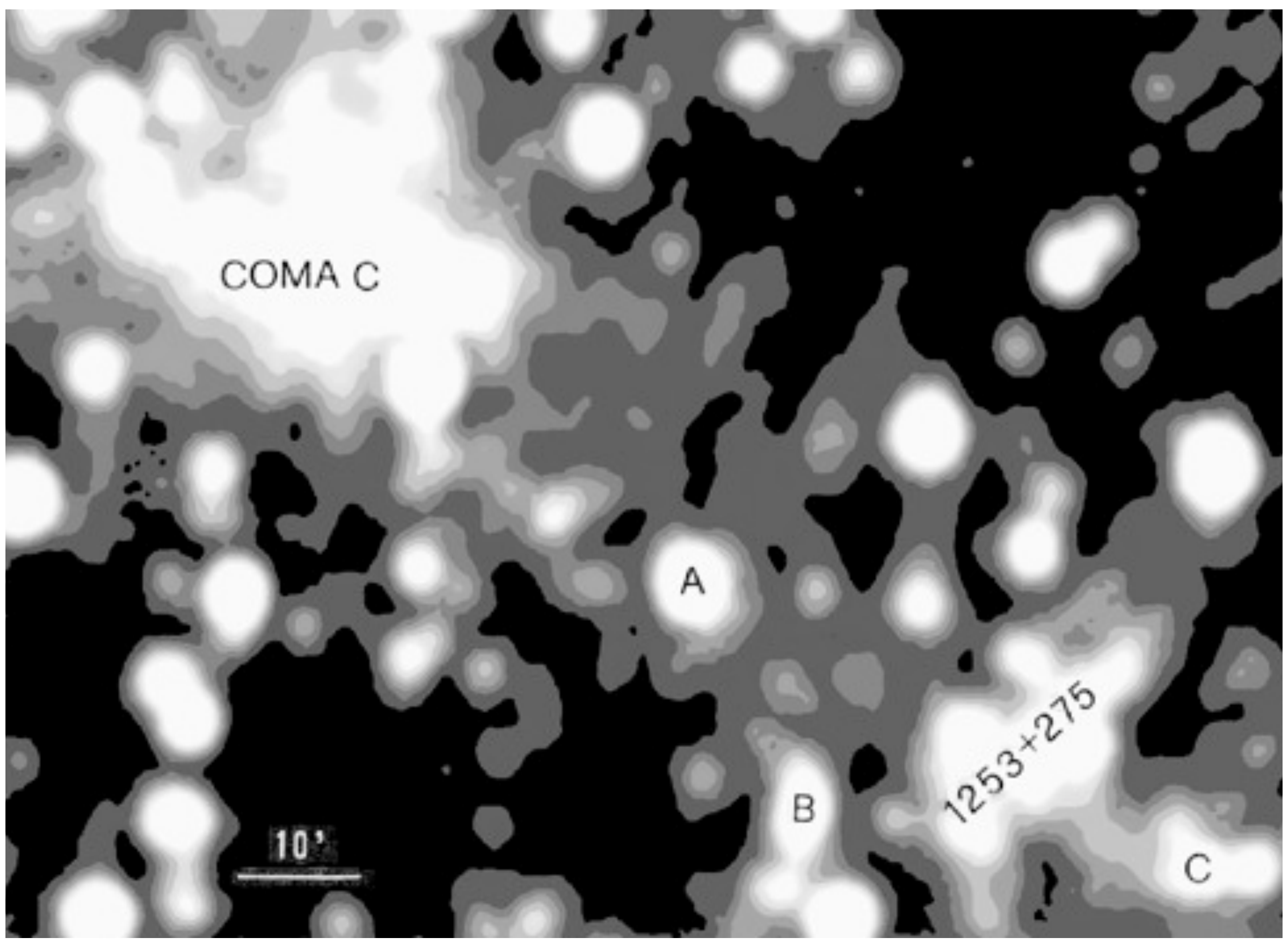


Continuum radio emission from galaxy clusters



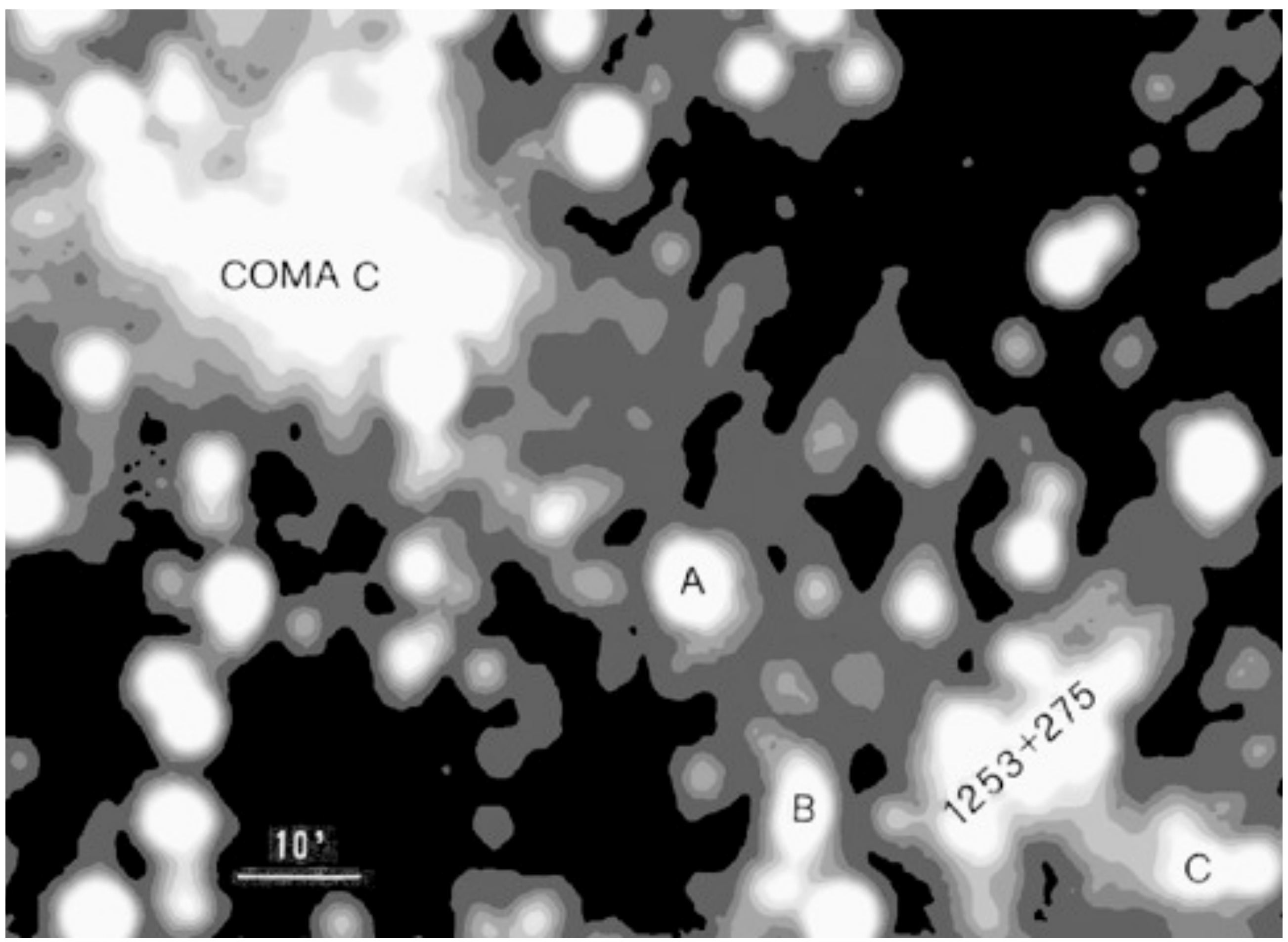
The Coma cluster

Continuum radio emission from galaxy clusters

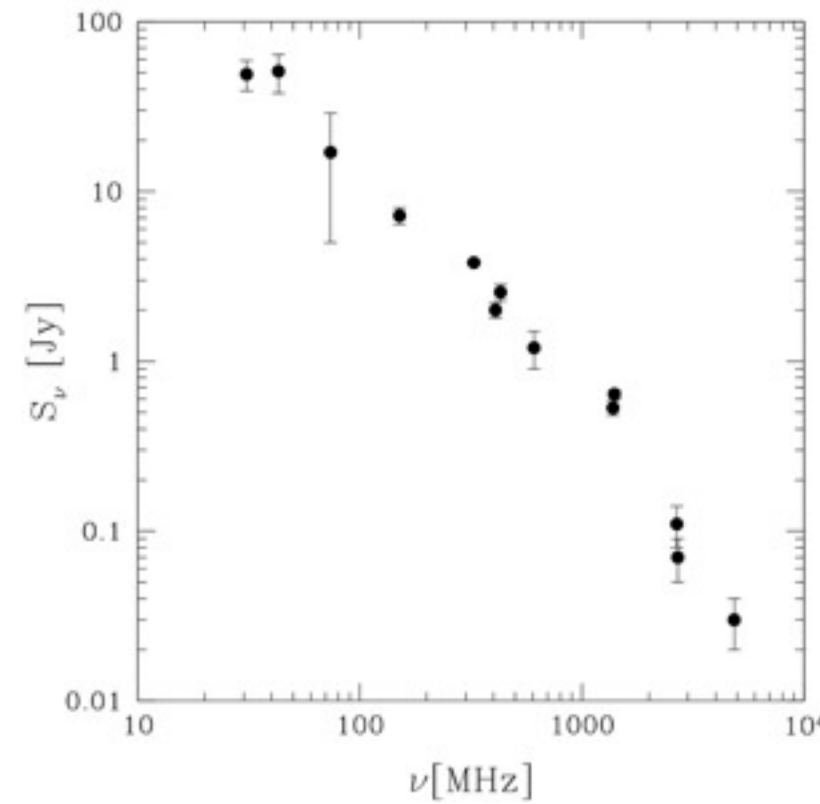


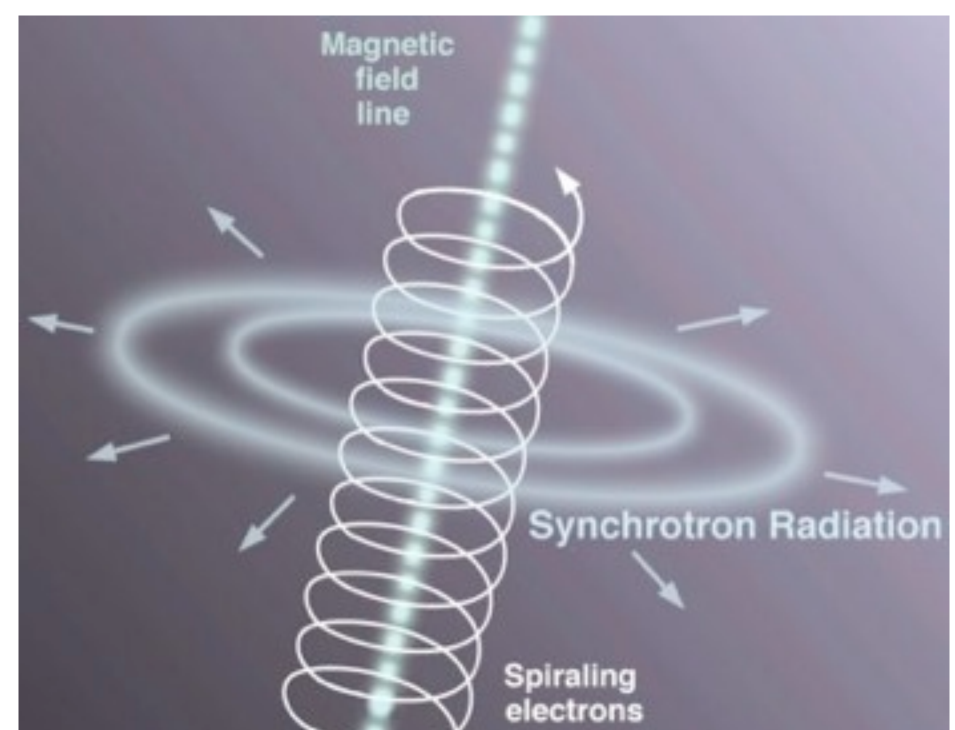
The Coma cluster

Continuum radio emission from galaxy clusters

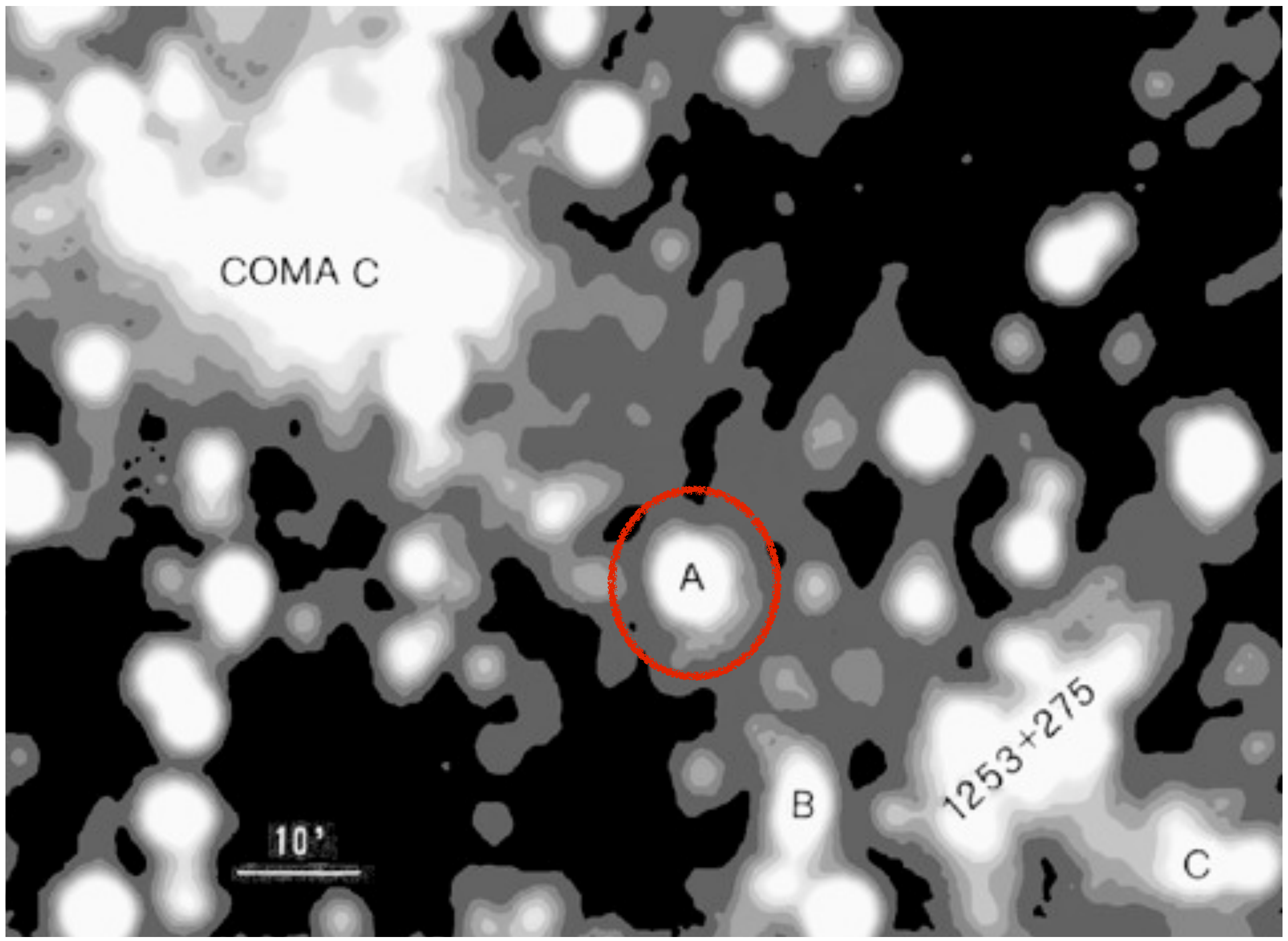


The Coma cluster

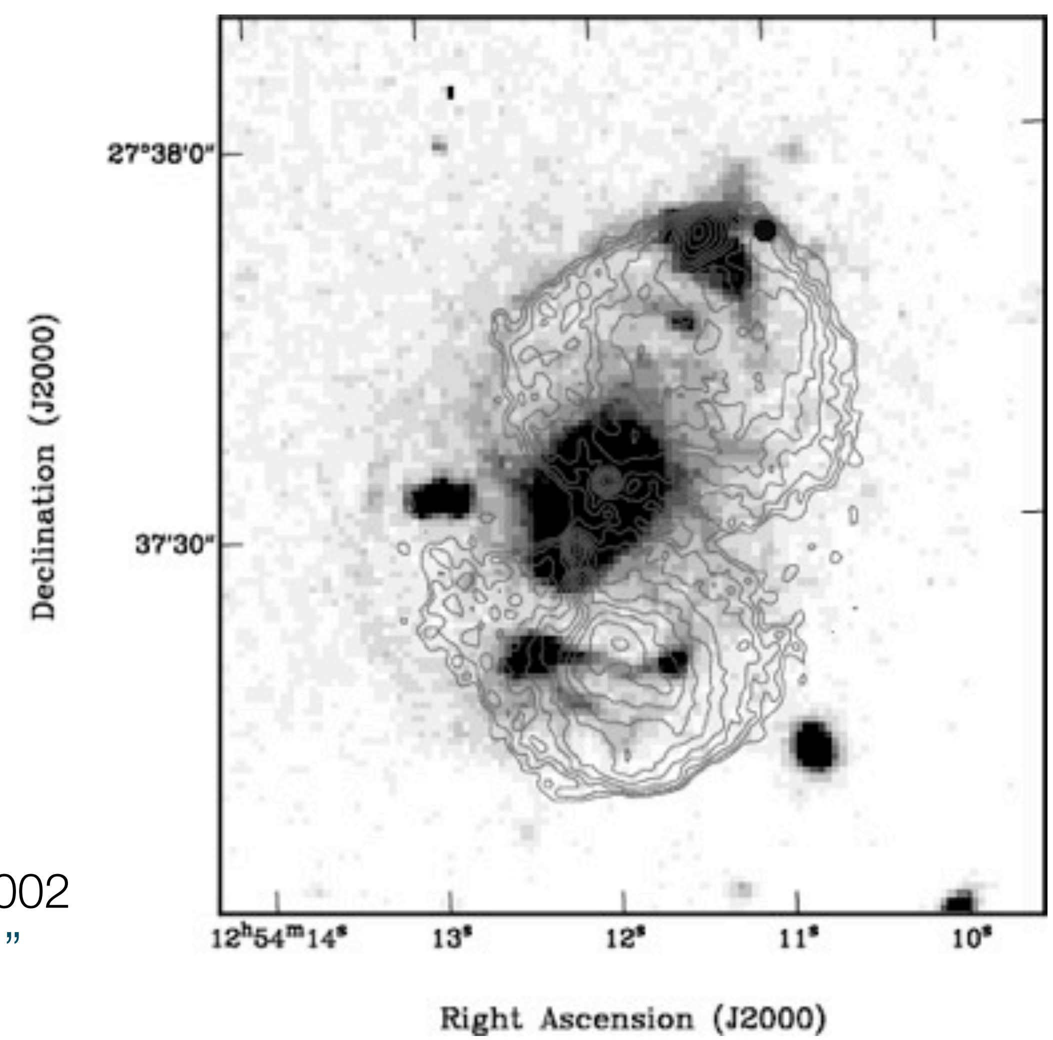




Radio emission from galaxies



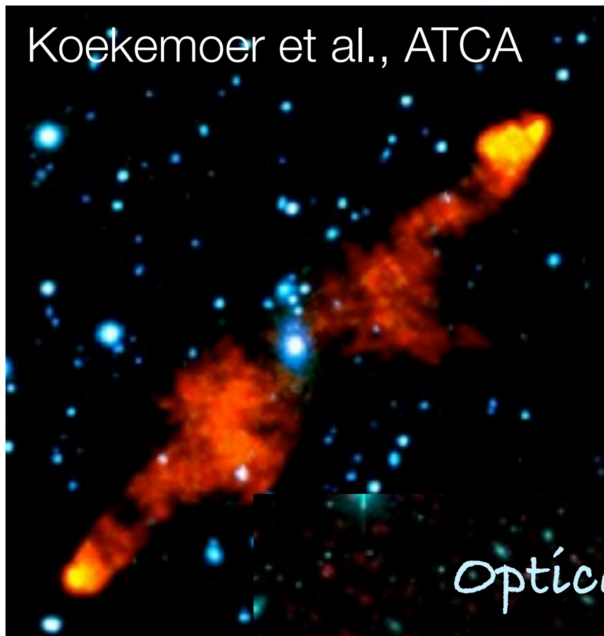
Giovannini et al. 1991
Resolution = 120"
λ = 91 cm



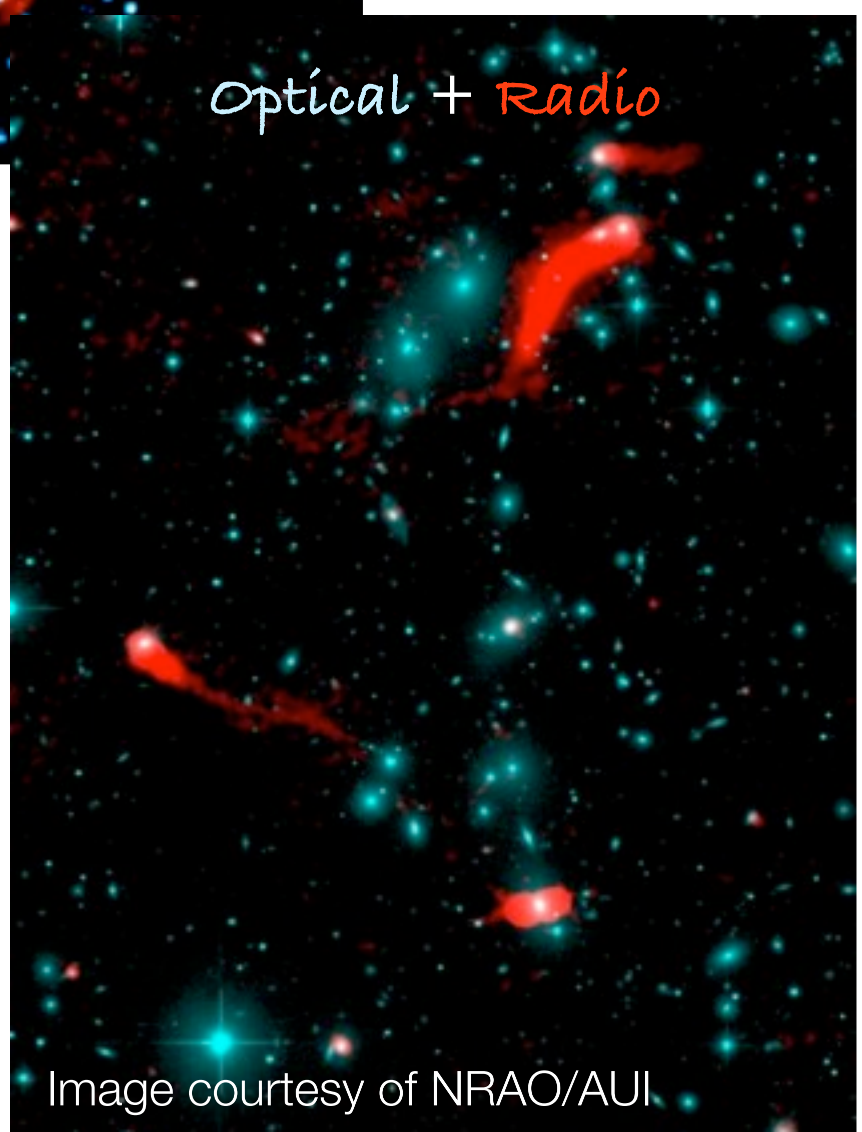
Morganti et al. 2002
Resolution = 1"
λ = 20 cm

Active galaxies

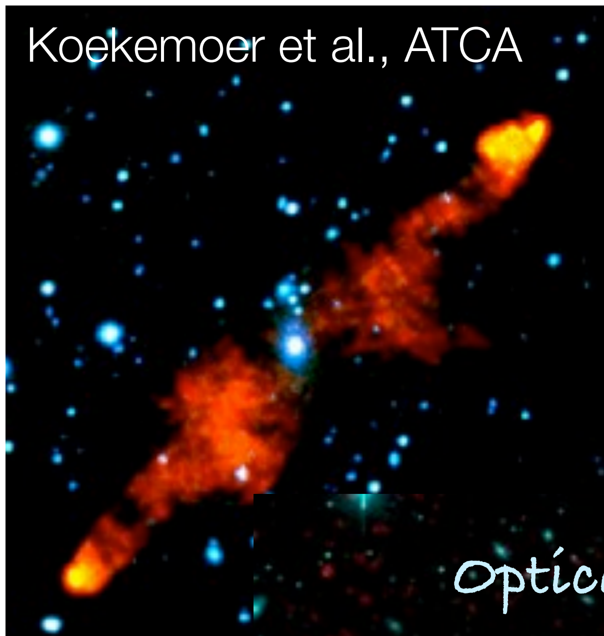
Active galaxies



Active Galactic Nucleus (AGN)



Active galaxies



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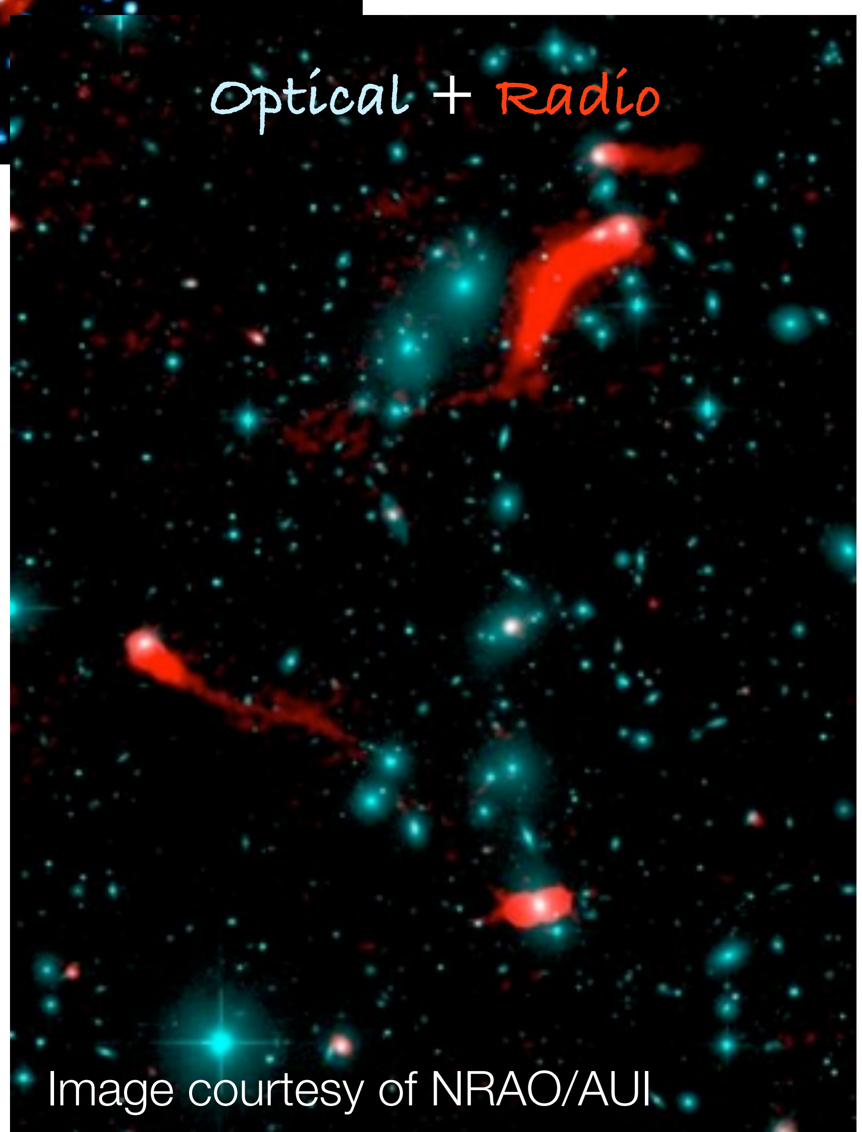
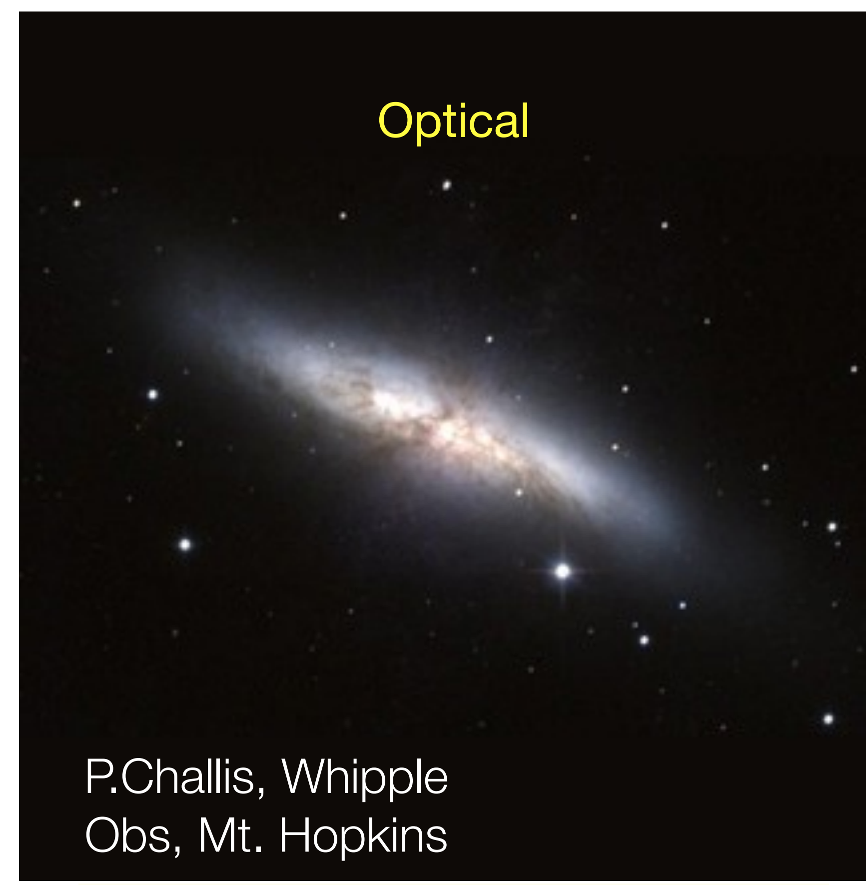
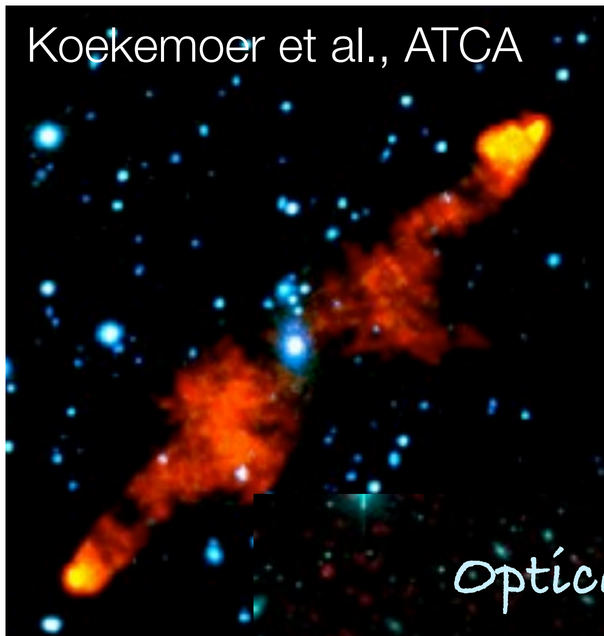


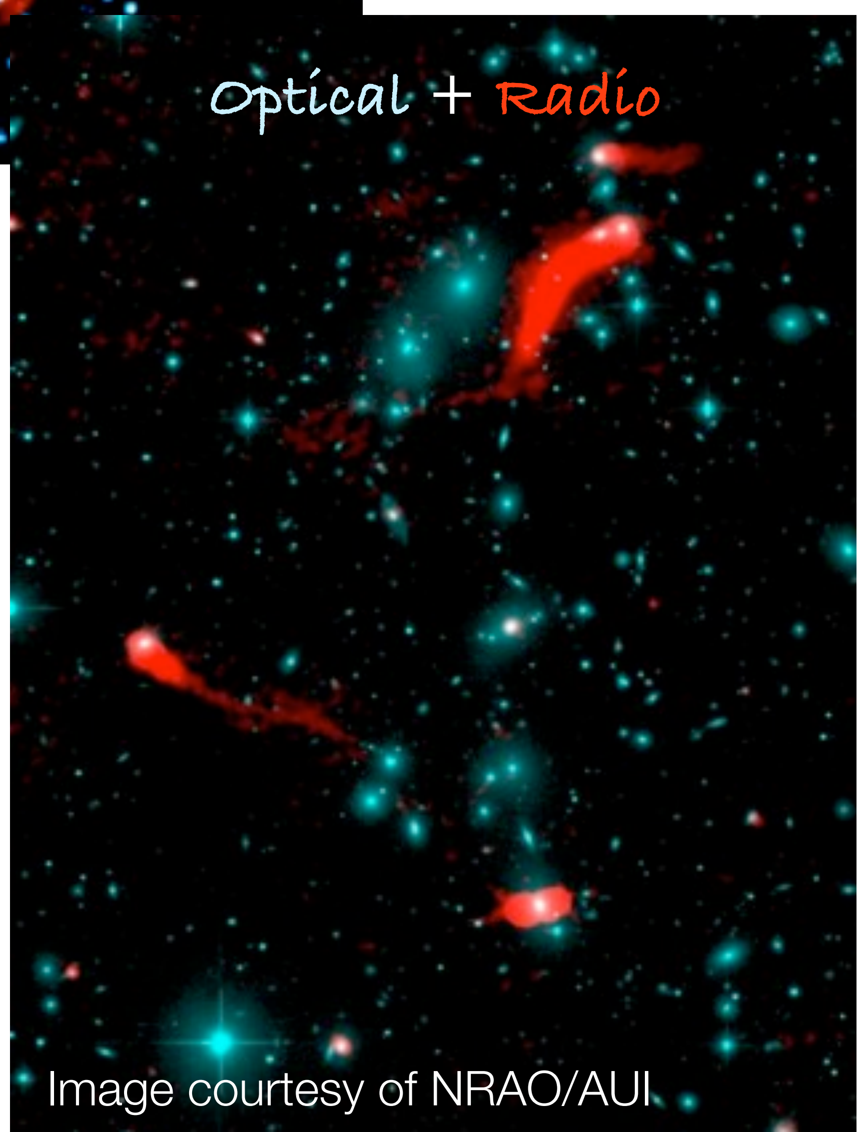


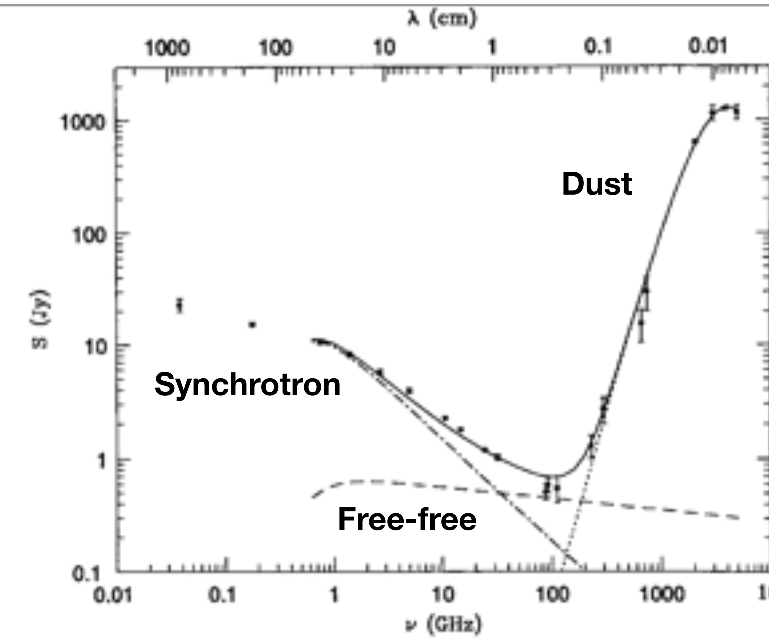
The starburst galaxy M82

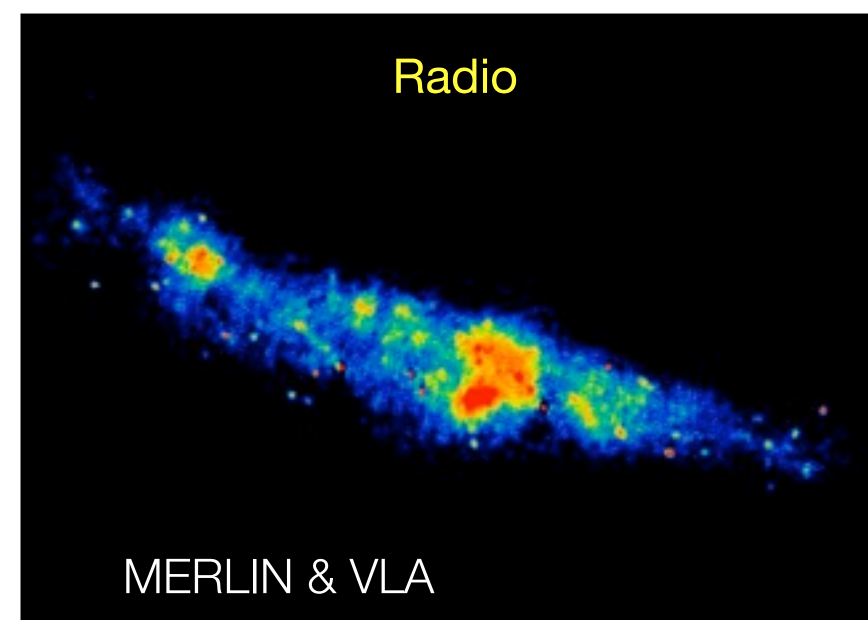
Active galaxies



Active Galactic Nucleus (AGN)

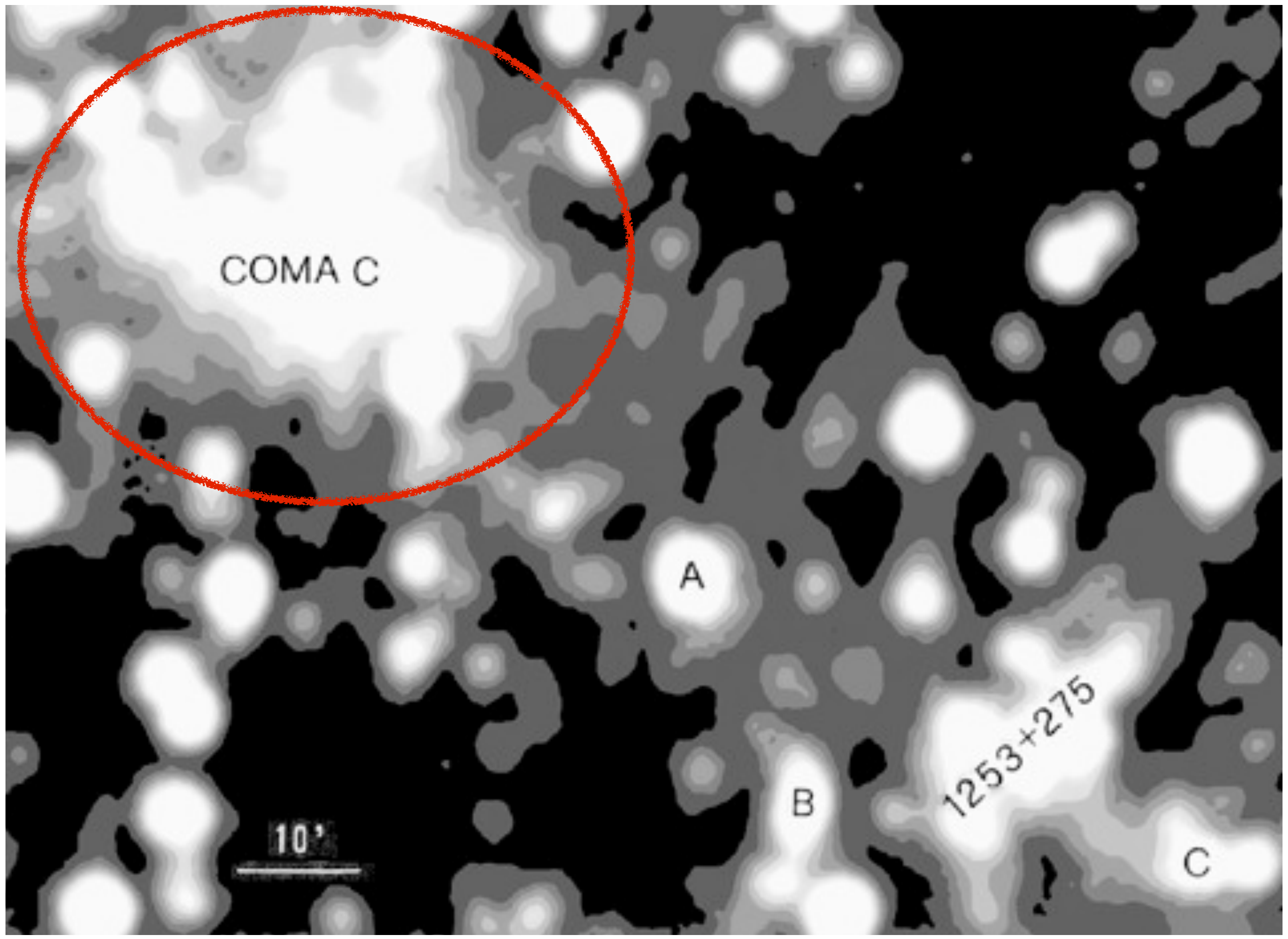




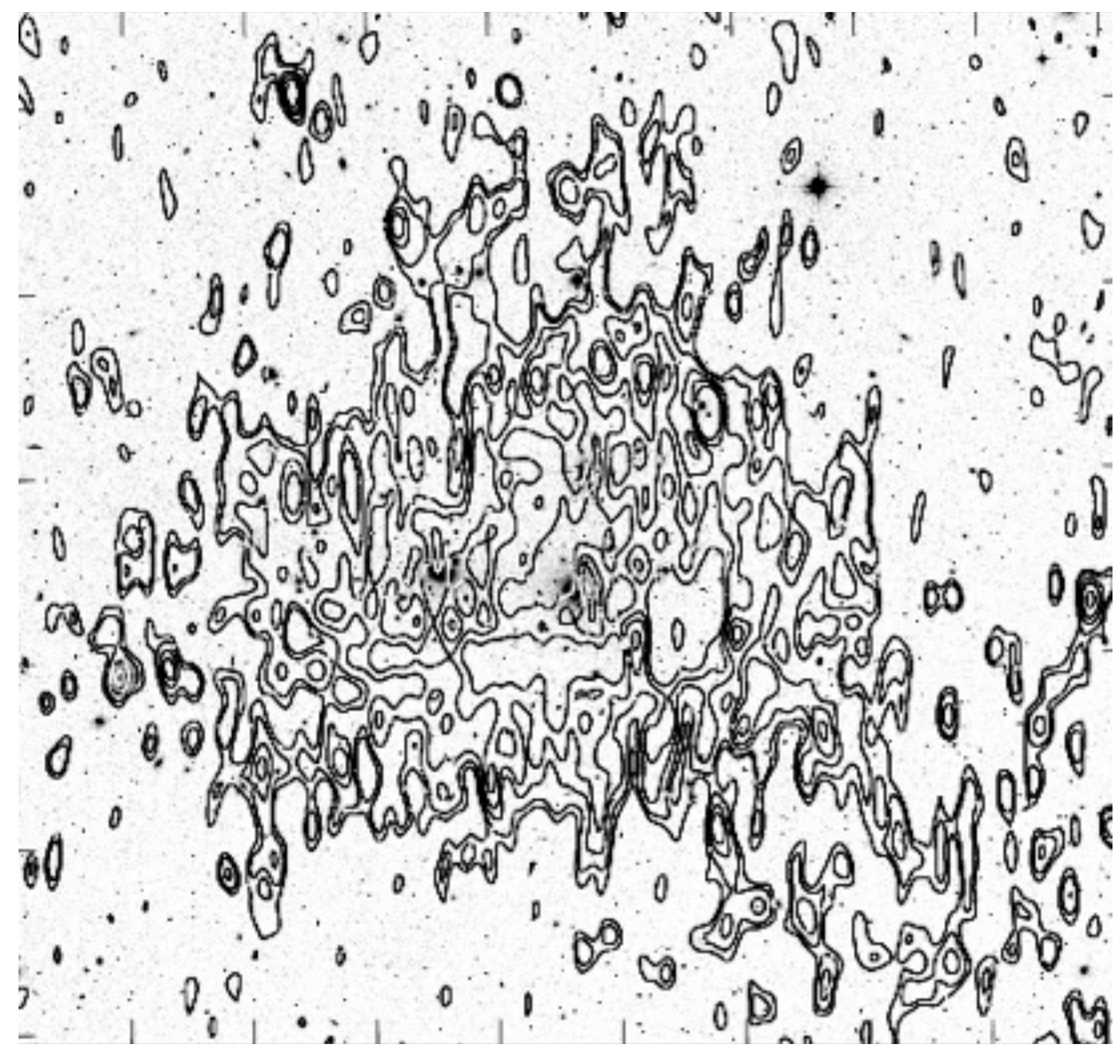


The starburst galaxy M82

Diffuse radio sources



Giovannini et al. 1991



Feretti 2002
Point sources subtracted

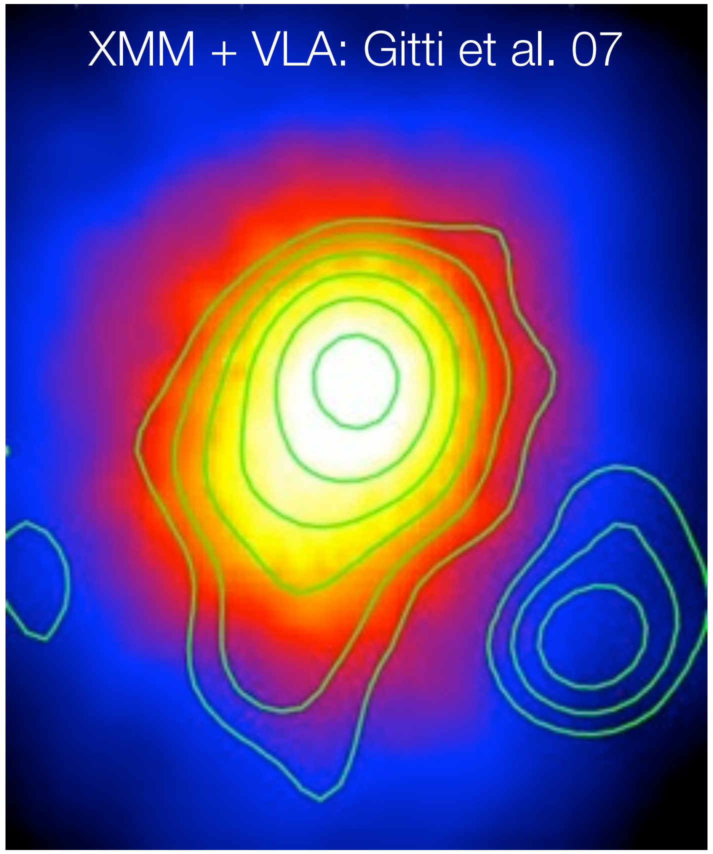
Diffuse radio sources in clusters

- Mini-halos
- Halos
- Relics

Diffuse radio sources in clusters

intermediate extension
(≤ 500 kpc)

at the centre of clusters
with AGN & cooling-core

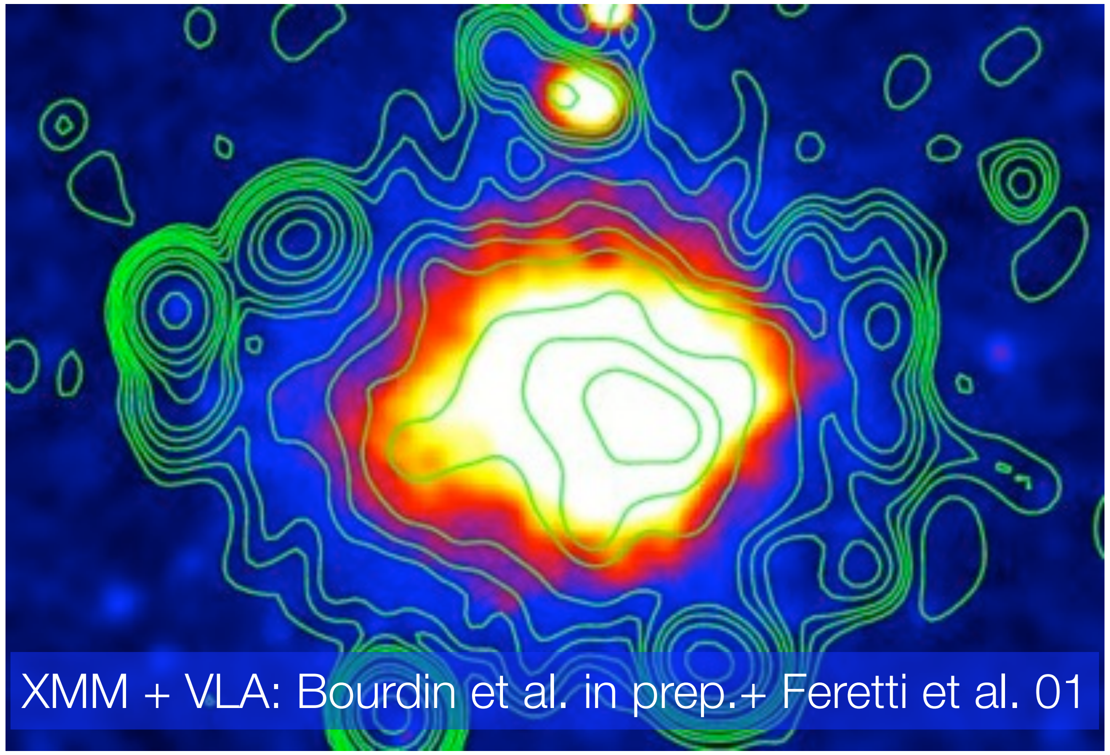


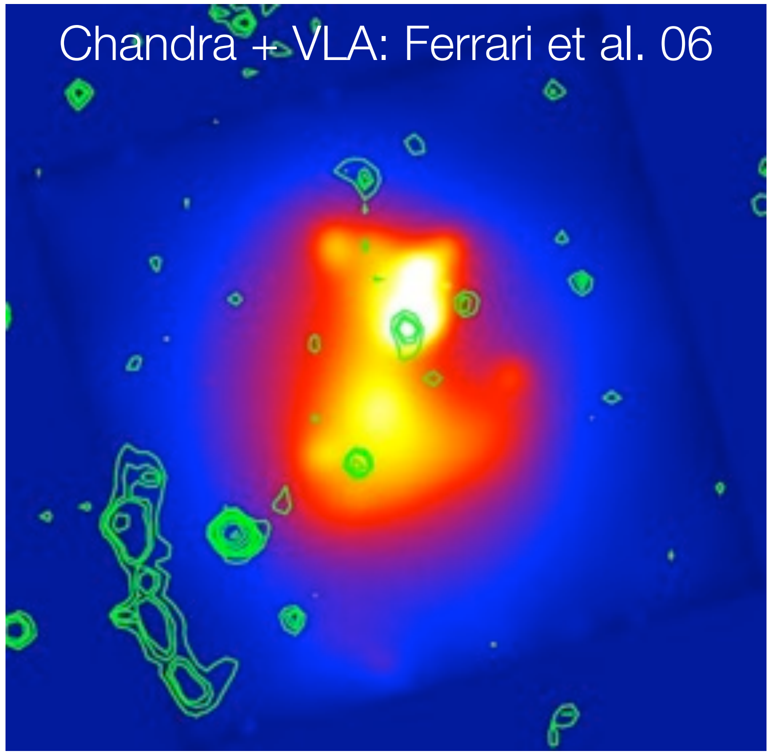
- Mini-halos
- Halos
- Relics

extended
(≥ 1 Mpc)

cluster centre

regular
morphology
(~X-rays)



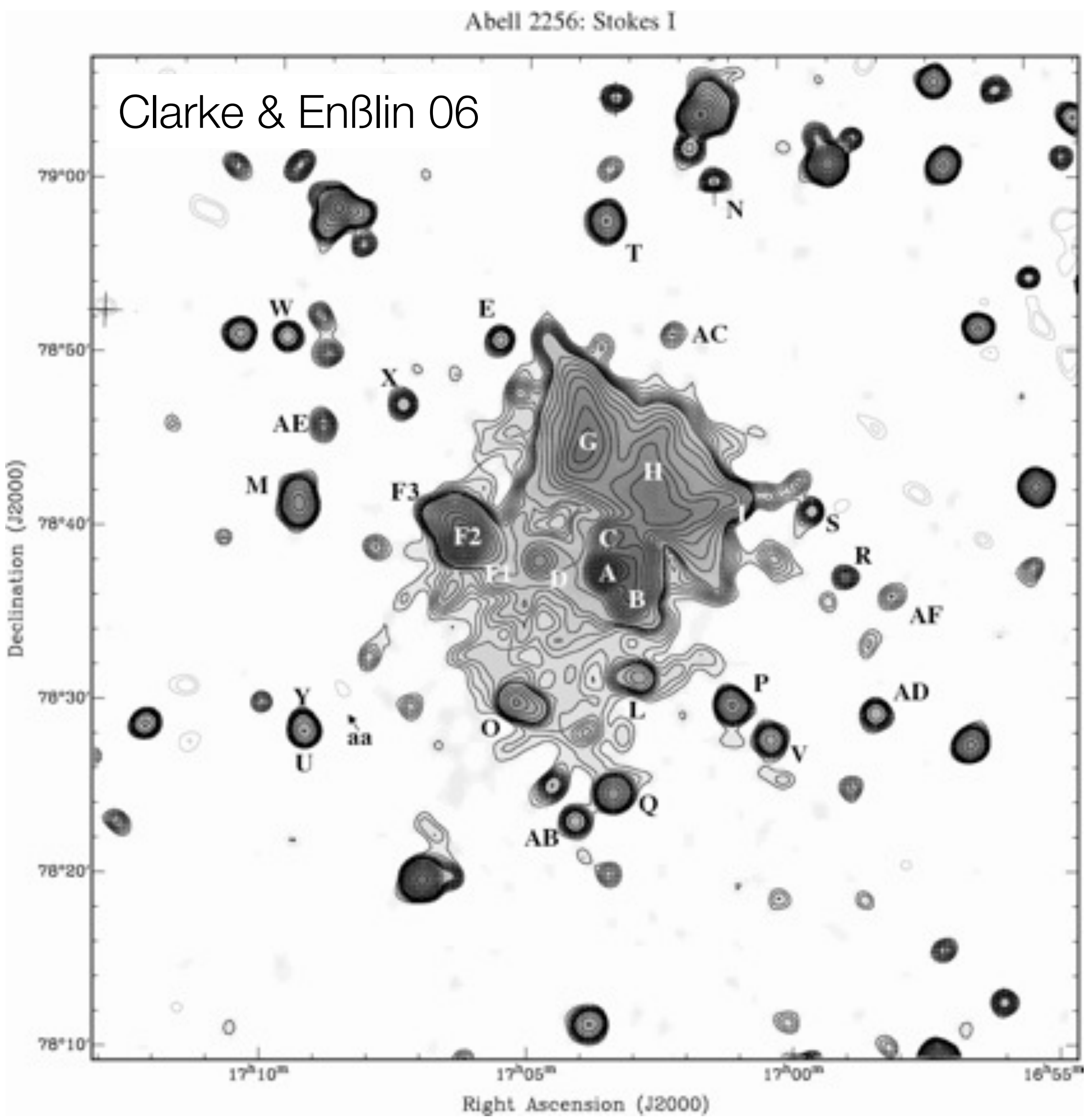


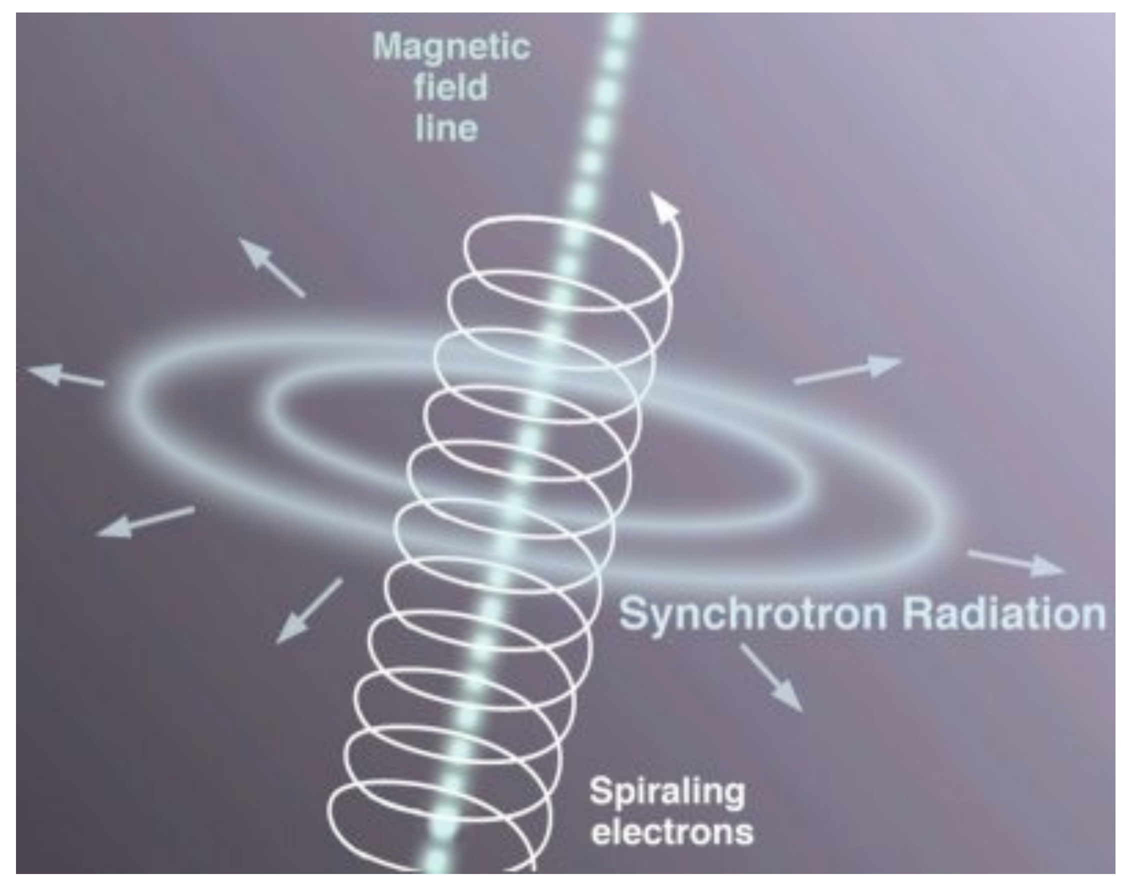
extended
(≥ 1 Mpc)

cluster
outskirts

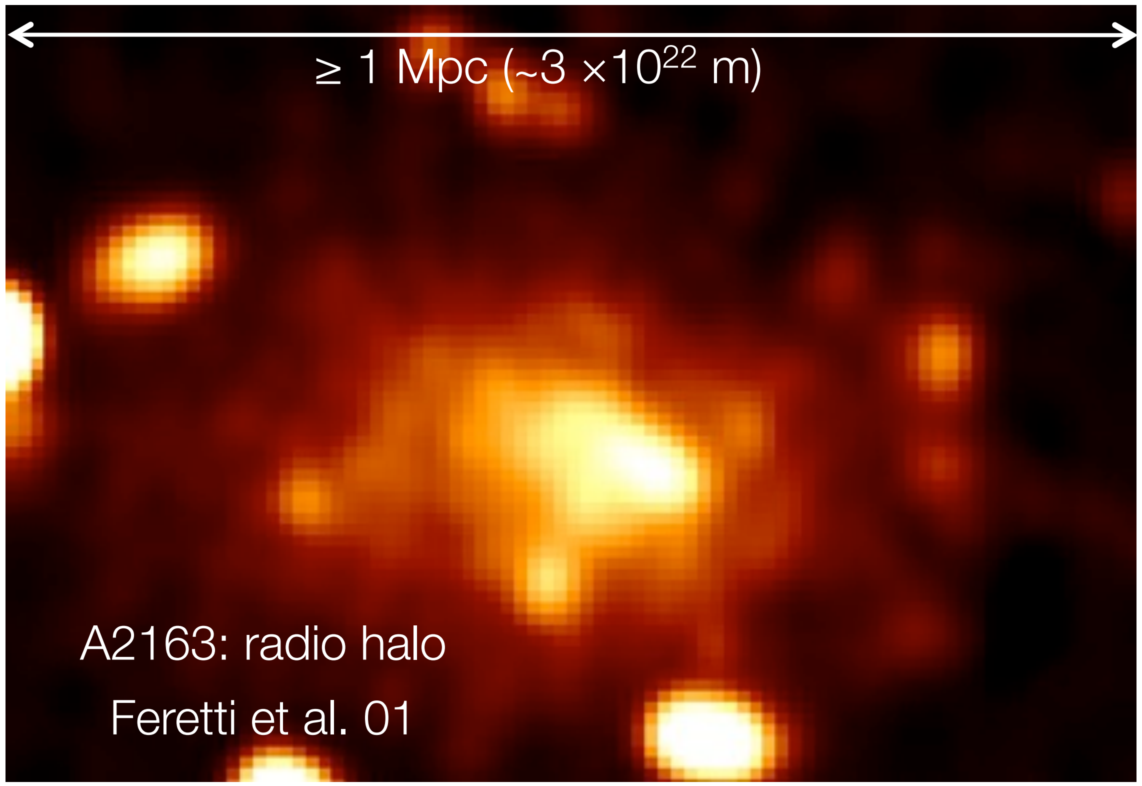
elongated
morphology

Radio continuum emission from clusters - summary

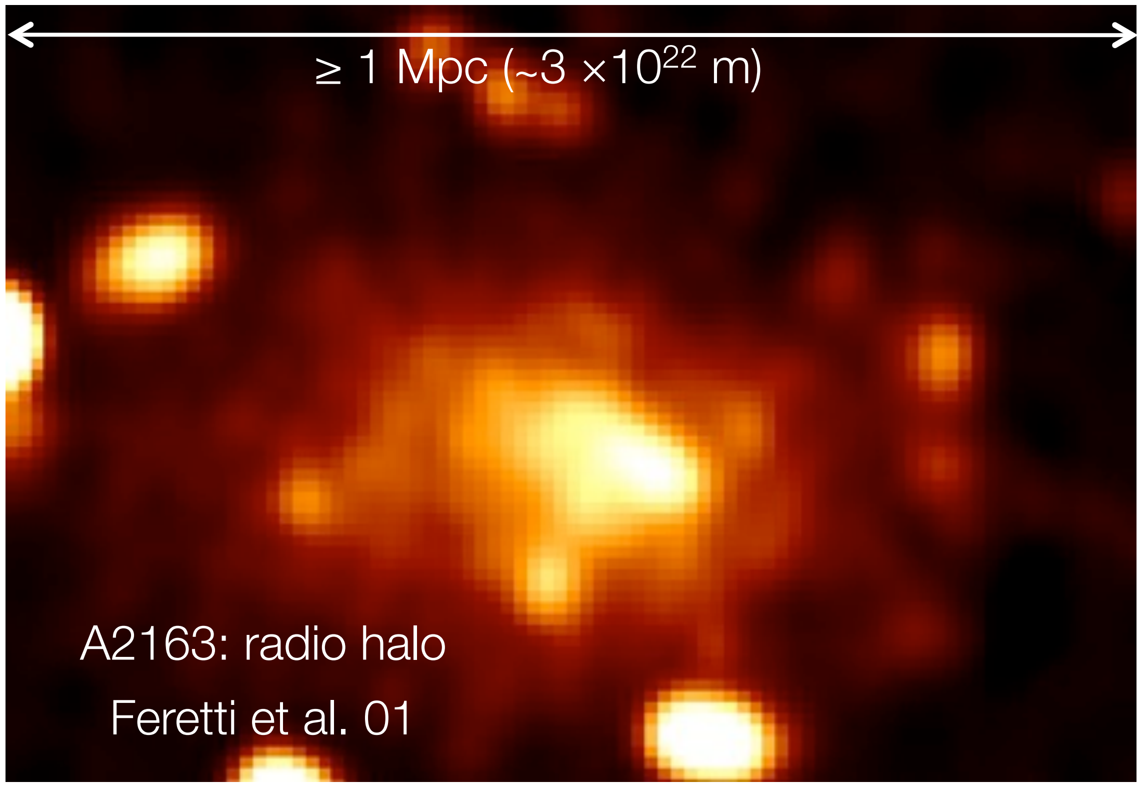




Origin of relativistic particles in clusters



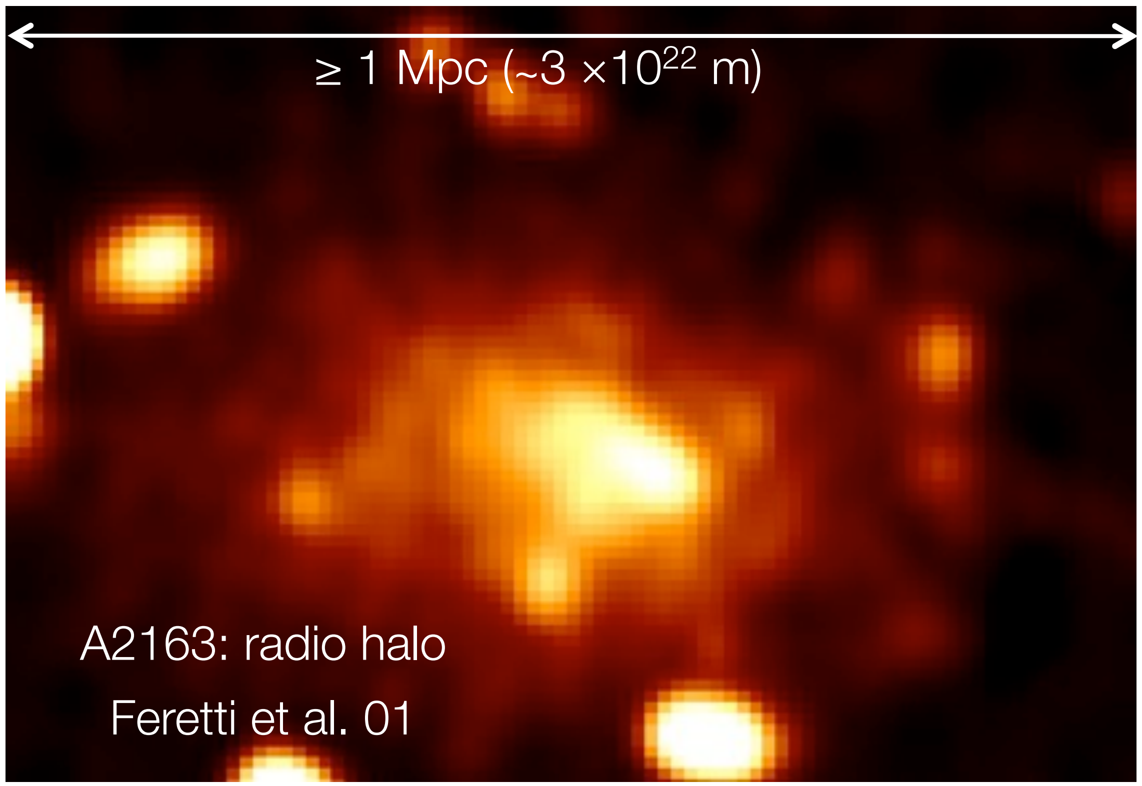
Origin of relativistic particles in clusters

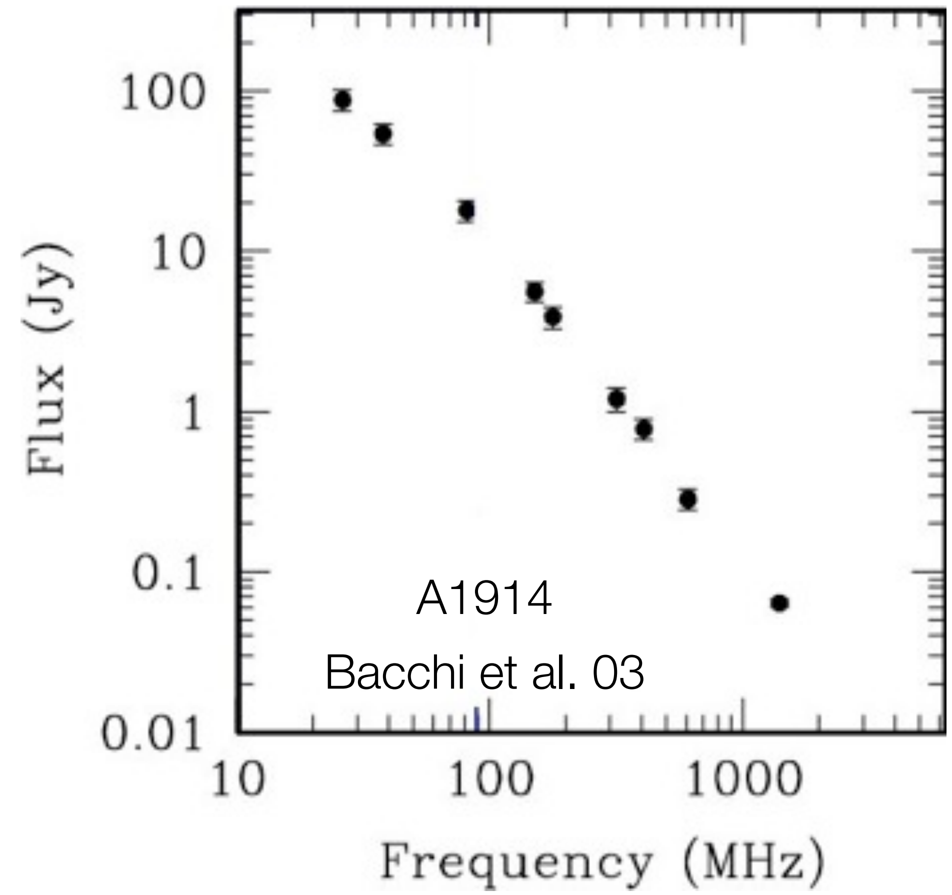


Dimensions: ~ 1 Mpc

Crossing time of e^-: ~9.5 Gyr

Origin of relativistic particles in clusters

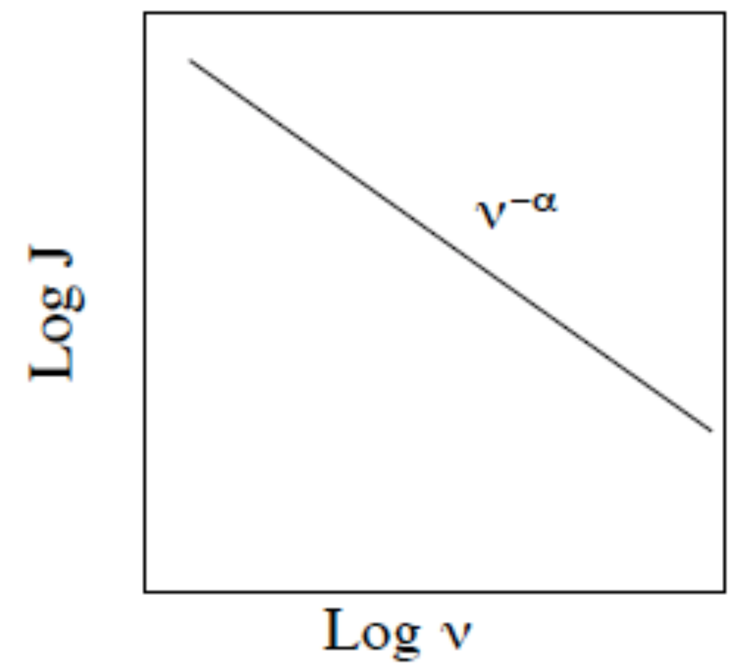




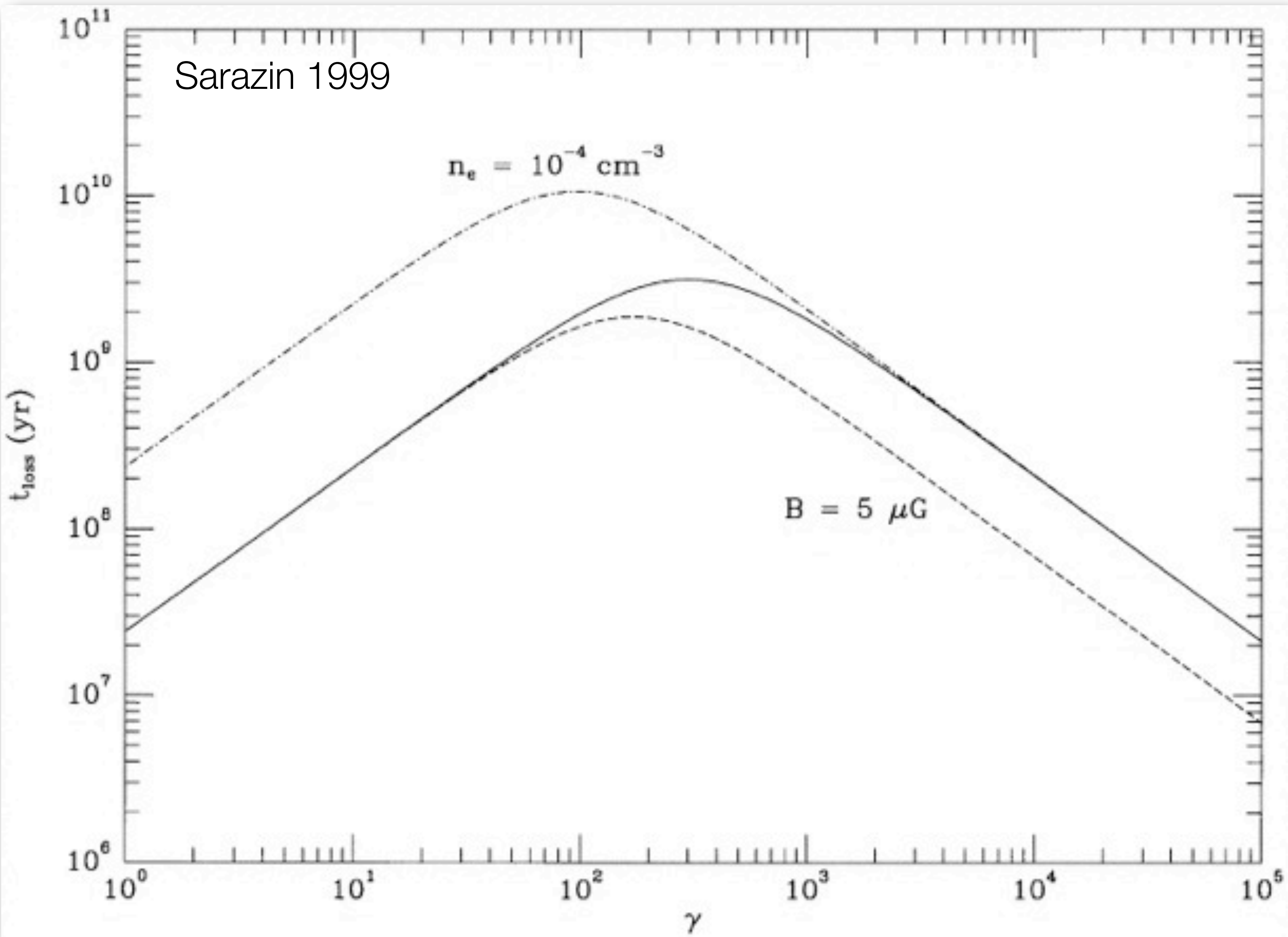
Dimensions: ~ 1 Mpc

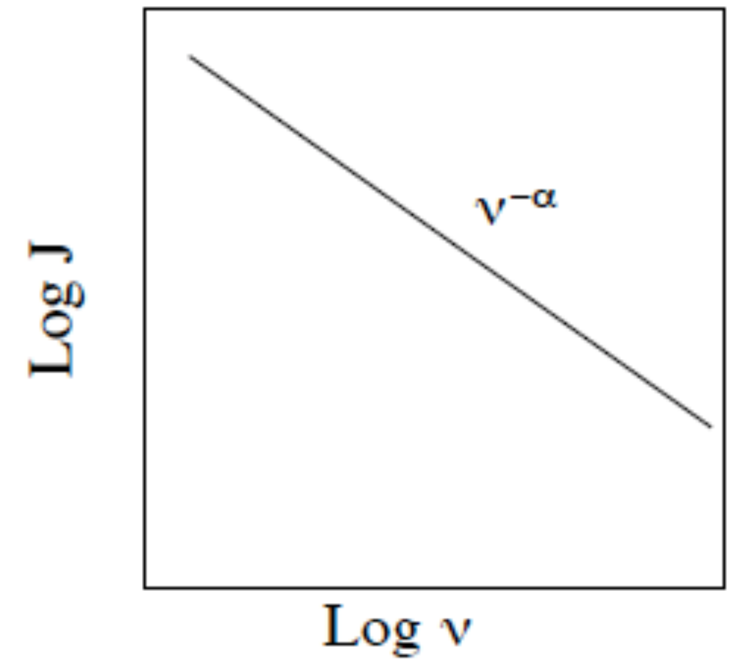
Crossing time of e^-: ~9.5 Gyr

Steep spectra



Steep spectra





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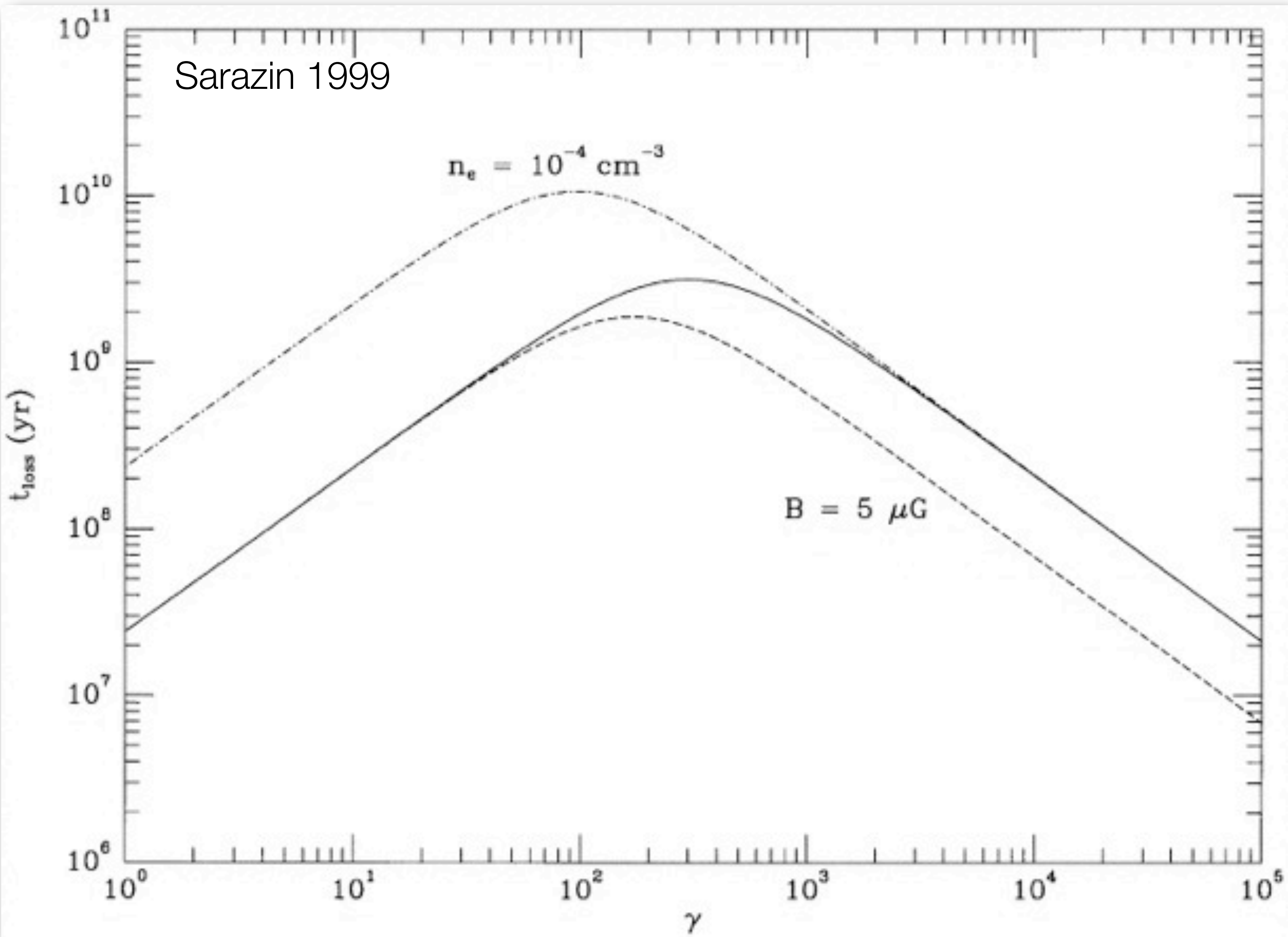
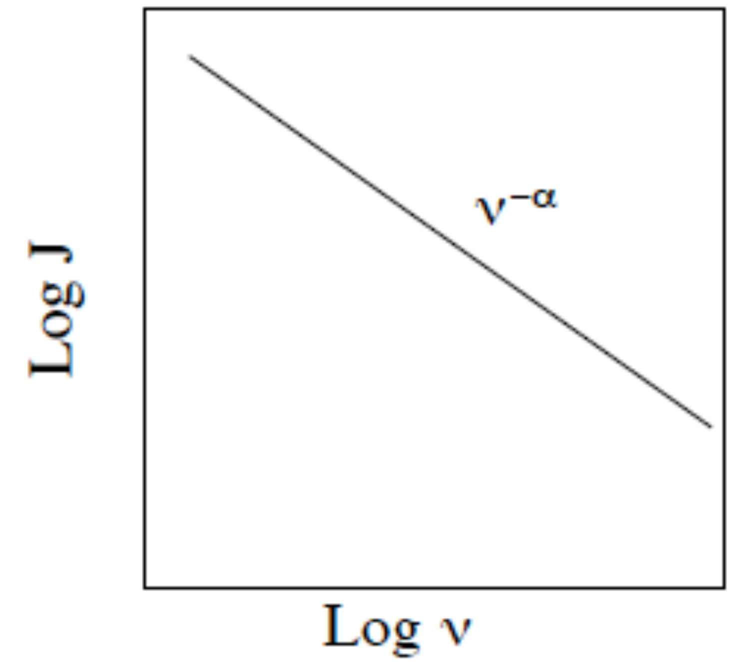


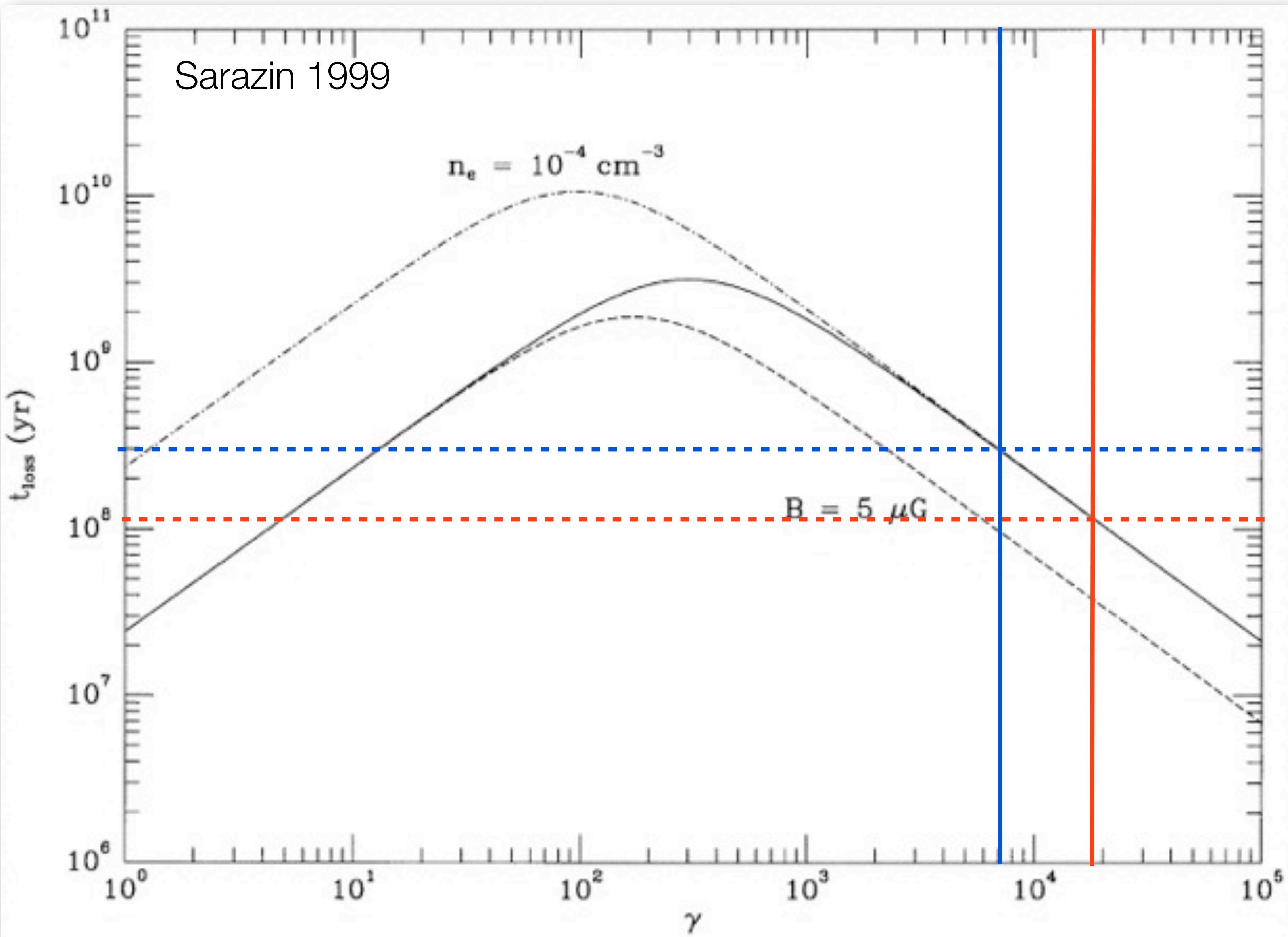


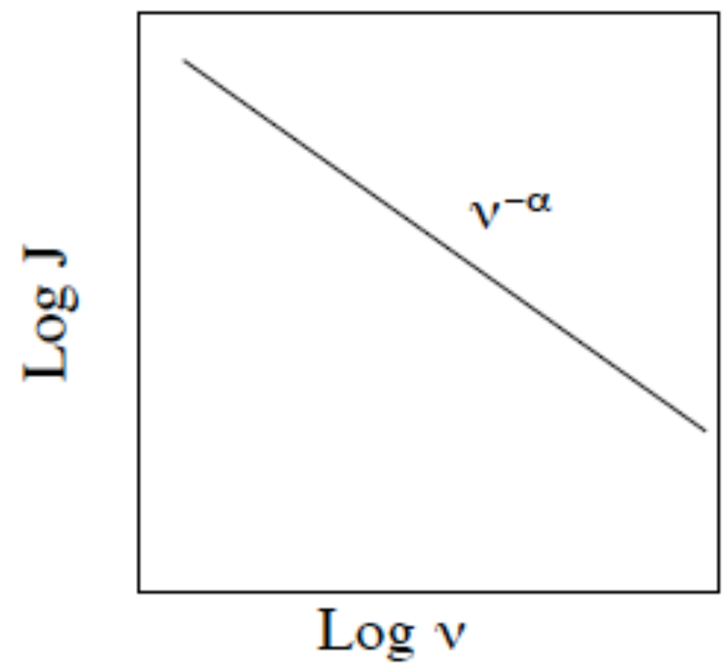
$$\nu_{\rm syn} = 4.2 \left(\frac{\rm B}{1\mu{\rm G}}\right) \gamma^2 \ {\rm Hz}$$

$$\nu_{\rm syn} = 1.4 \ {\rm GHz} \rightarrow \gamma \simeq 18000$$

$$\nu_{\rm syn} = 100 \ {\rm MHz} \rightarrow \gamma \simeq 5000$$

Steep spectra





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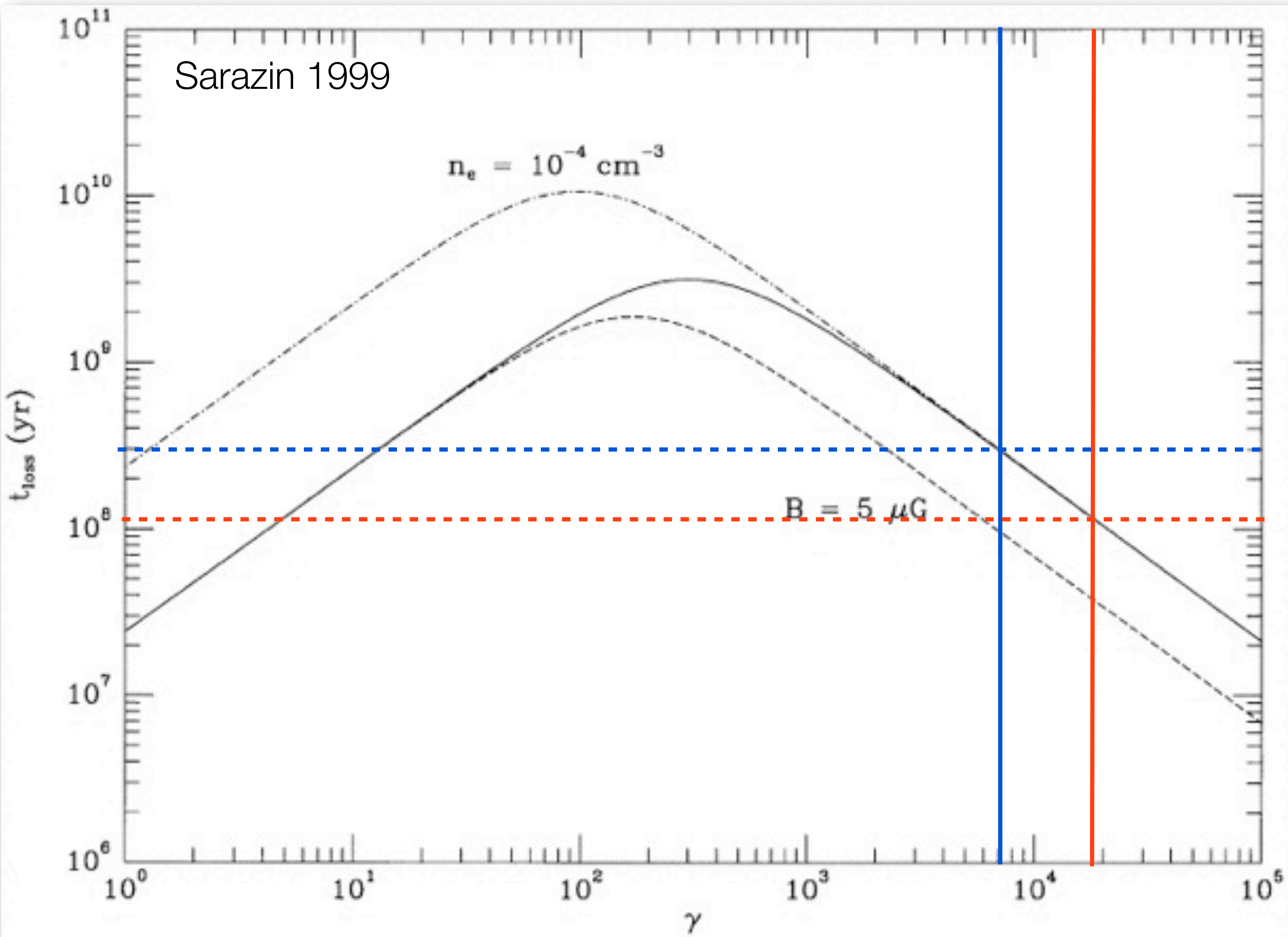

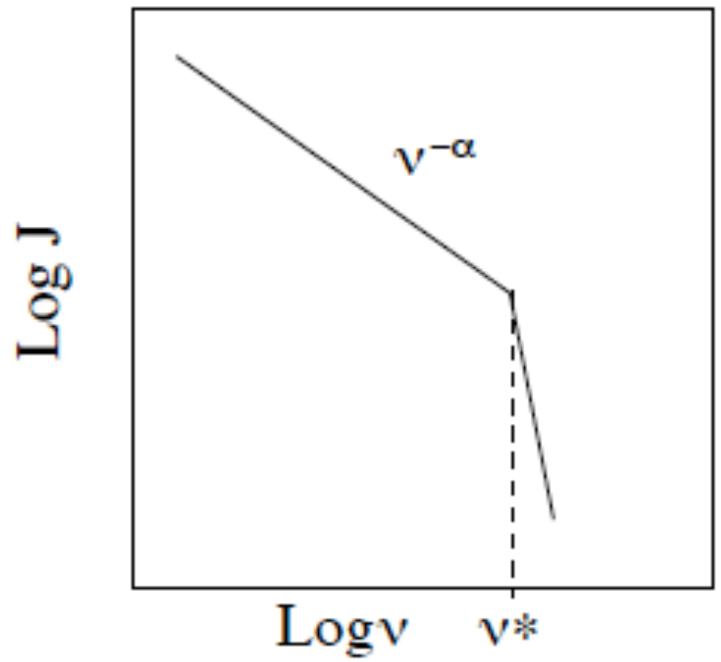

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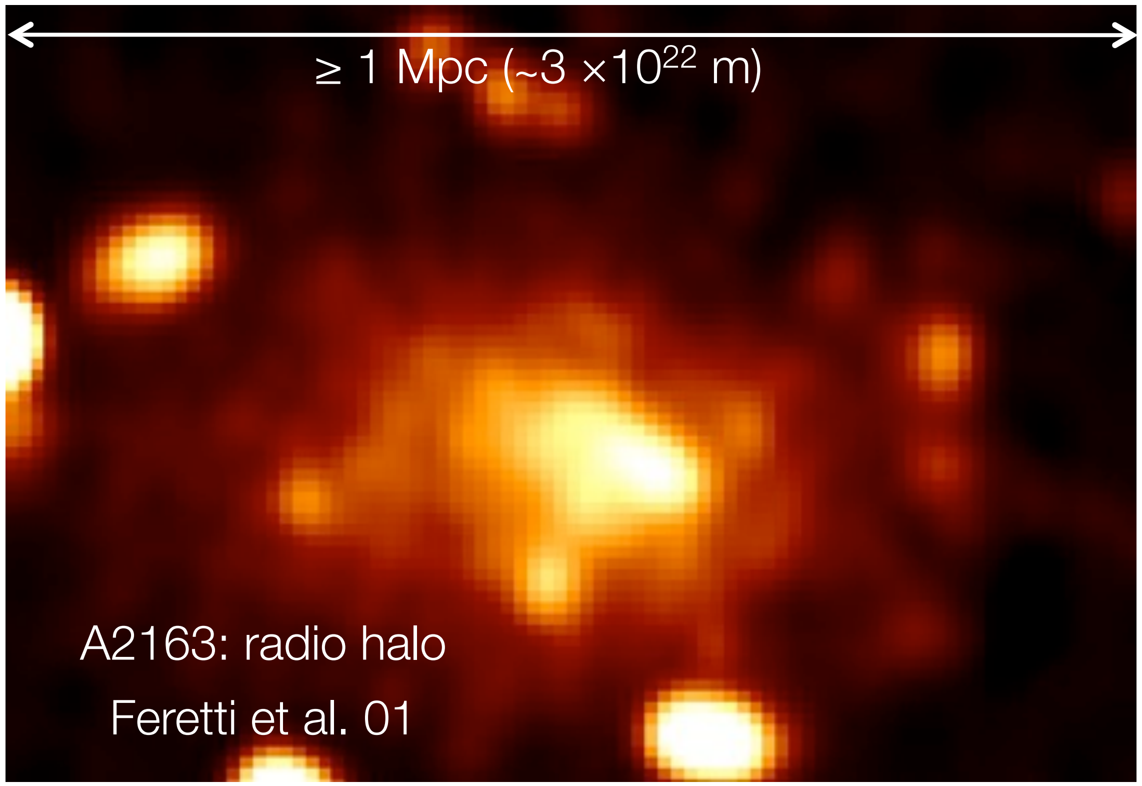
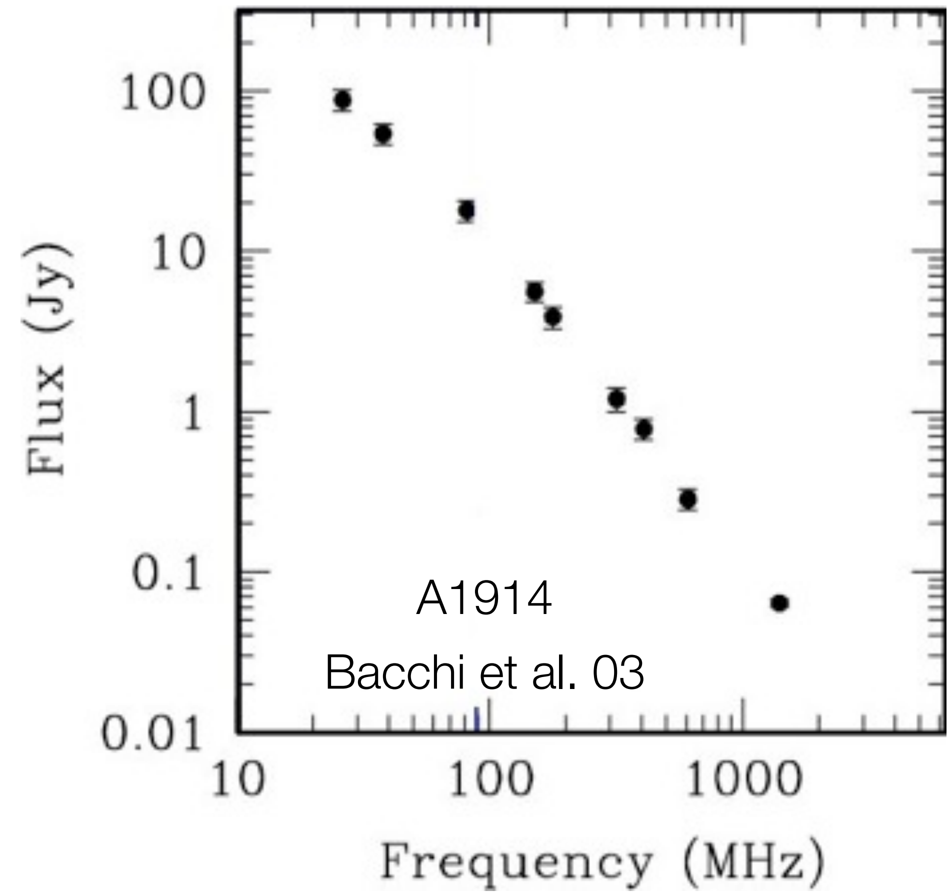
Origin of relativistic particles in clusters



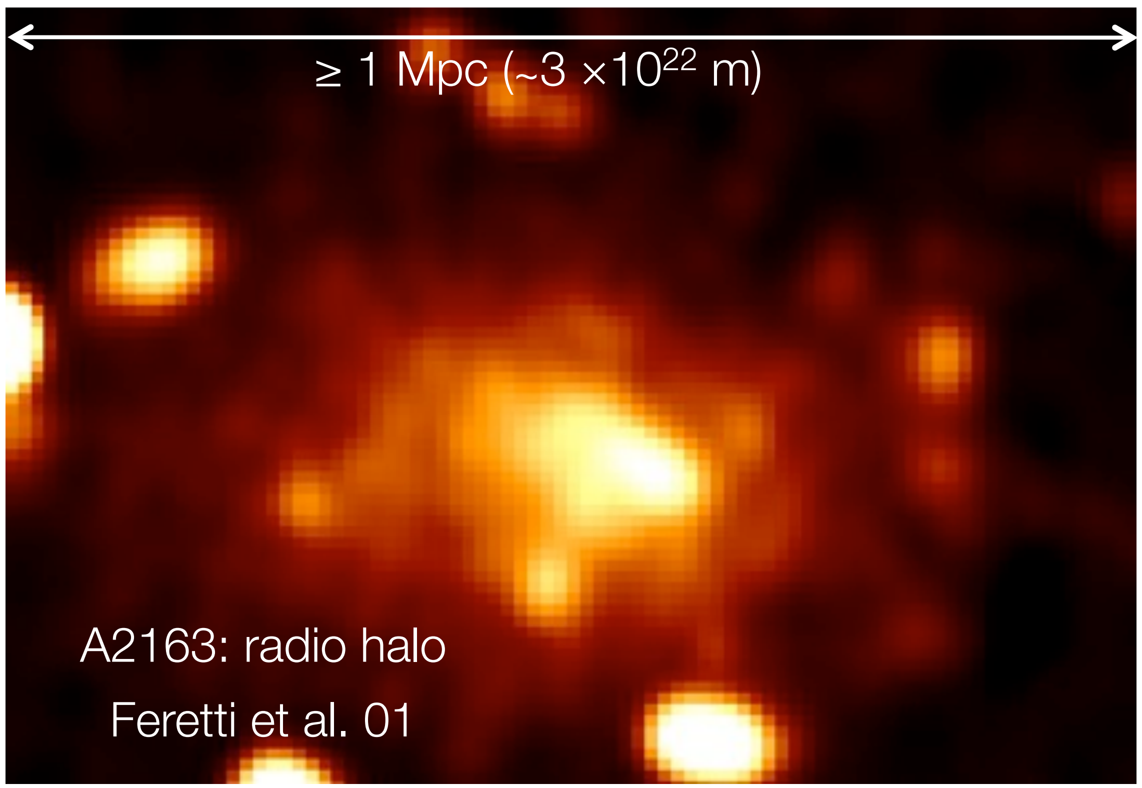


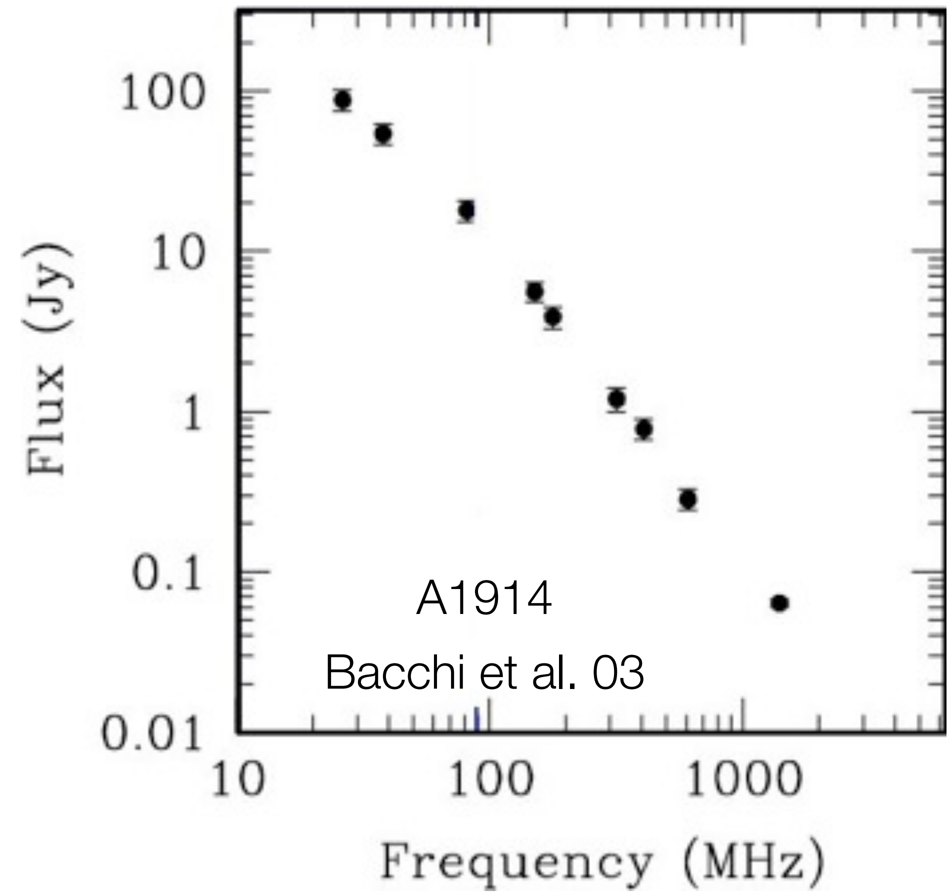
Dimensions: ~ 1 Mpc

Crossing time of e^-: ~9.5 Gyr

Life time of e^-: ~ 0.1 Gyr

Origin of relativistic particles in clusters





Dimensions: ~ 1 Mpc

Crossing time of e^-: ~9.5 Gyr

Life time of e^-: ~ 0.1 Gyr

→ *In situ acceleration of relativistic electrons*

Origin of intracluster primary cosmic rays

Primary cosmic rays

protons (CRPs) & electrons (CREs)

Origin of intracluster primary cosmic rays

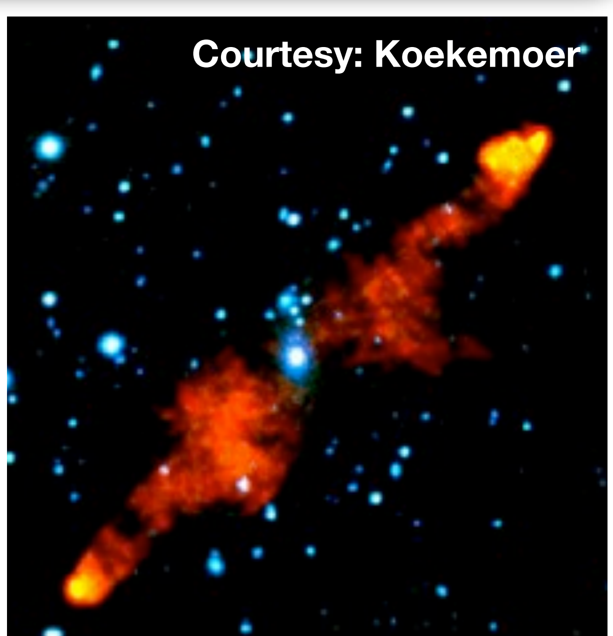
Primary cosmic rays

protons (CRPs) & electrons (CREs)

Internal processes

CRs accelerated inside cluster galaxies and then injected

- SN*ae* driven galactic winds
- AGNs



Origin of intracluster primary cosmic rays

Primary cosmic rays

protons (CRPs) & electrons (CREs)

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CRs accelerated inside cluster galaxies and then injected

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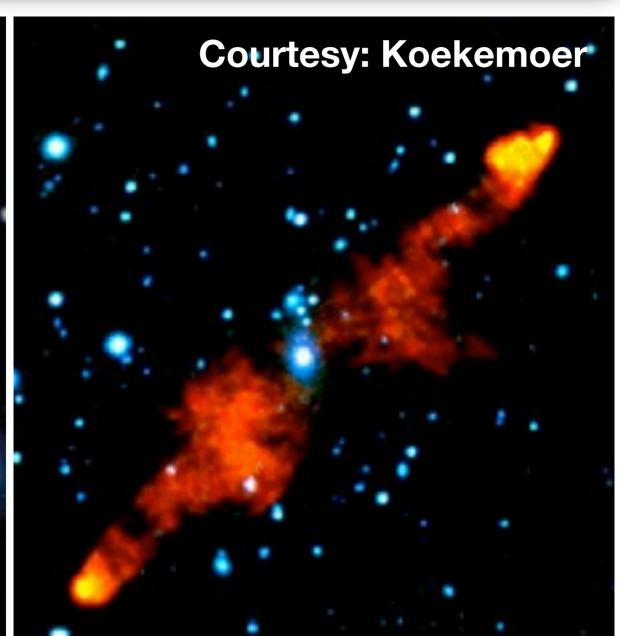
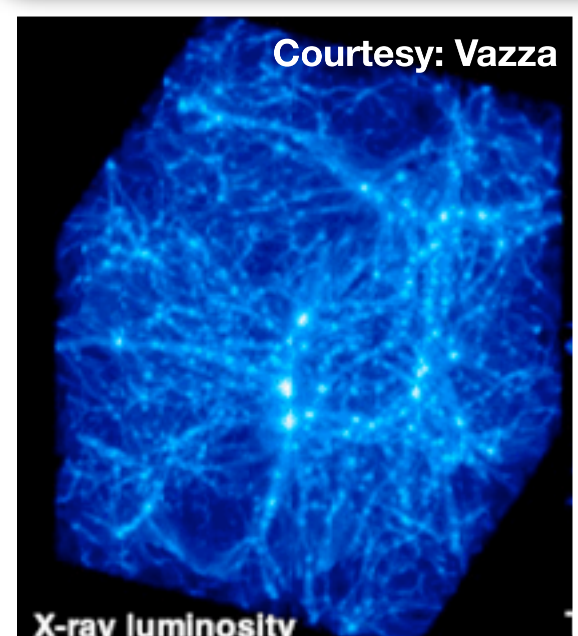
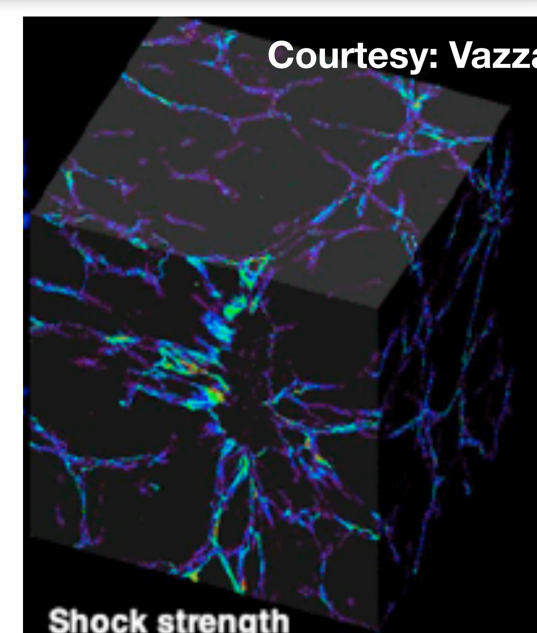
External processes

CRs acceleration driven by the assembly of clusters

- accretion shocks ($M \sim 10^3$)
- merging shocks ($M \sim$ 3-10)
- ICM turbulence







Numerical Simulations of Large Scale Structure Formation

Kapferer et al., Innsbruck University

Origin of intracluster primary cosmic rays

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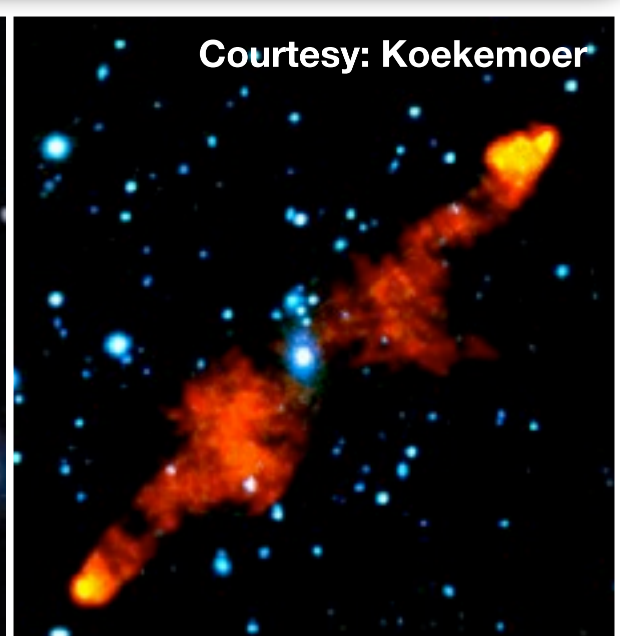

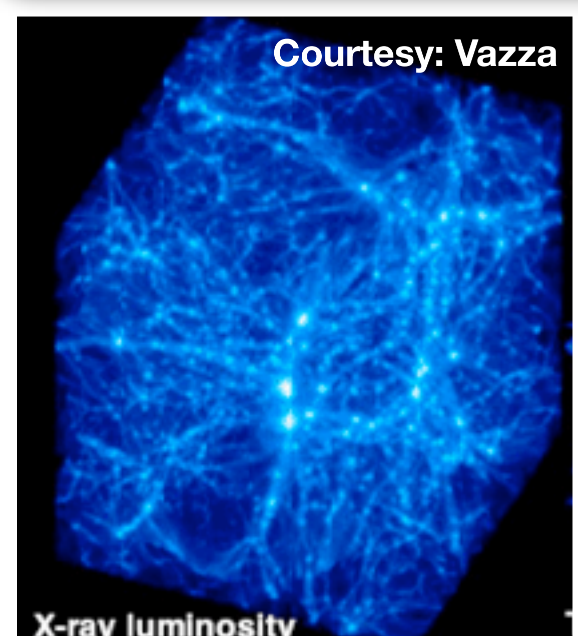

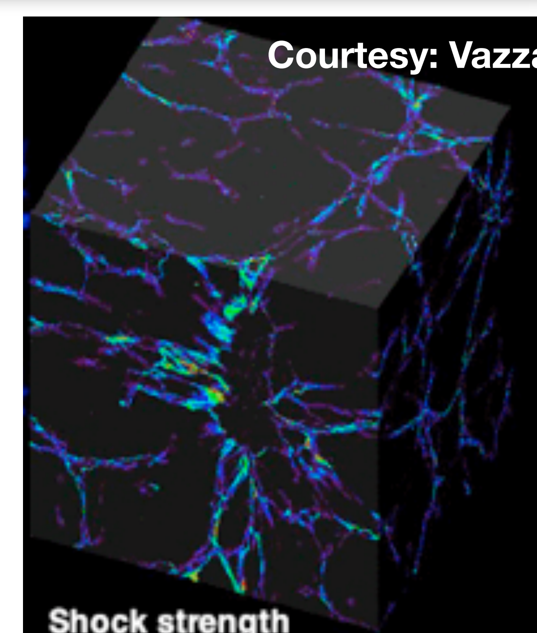

Origin of intracluster primary cosmic rays

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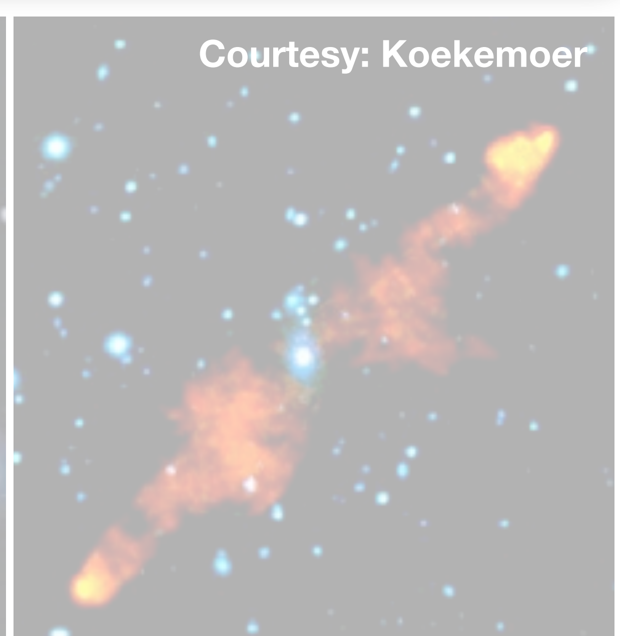
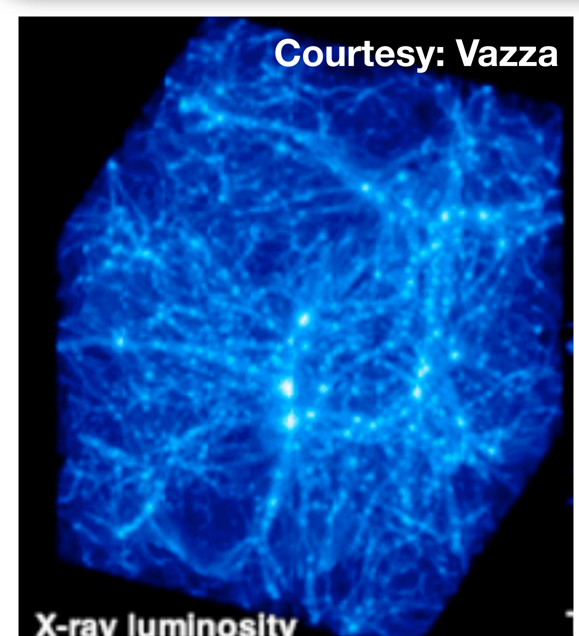
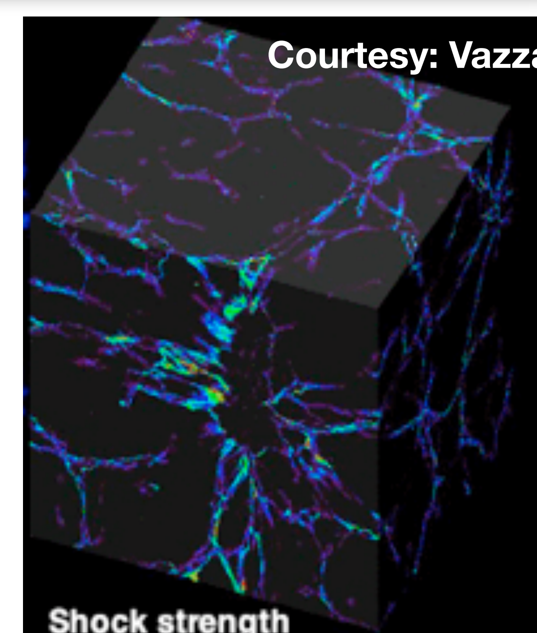






Origin of intracluster primary cosmic rays

Primary cosmic rays

protons (CRPs) & electrons (CREs)

Internal processes

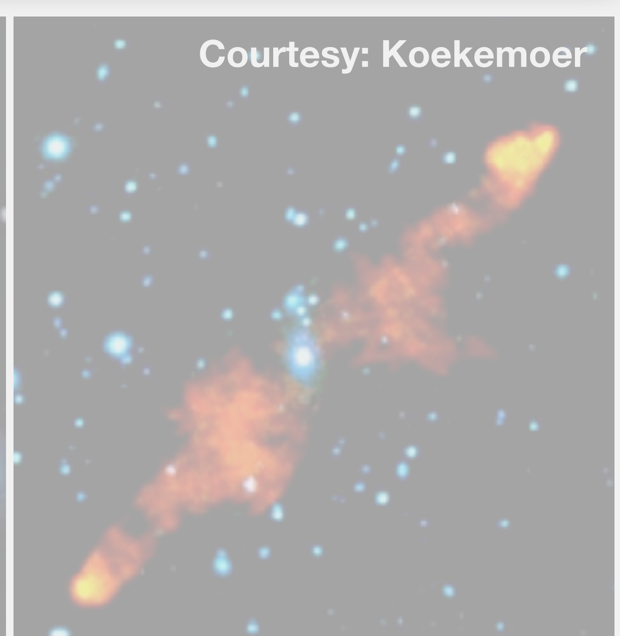
CRs accelerated inside cluster galaxies and then injected

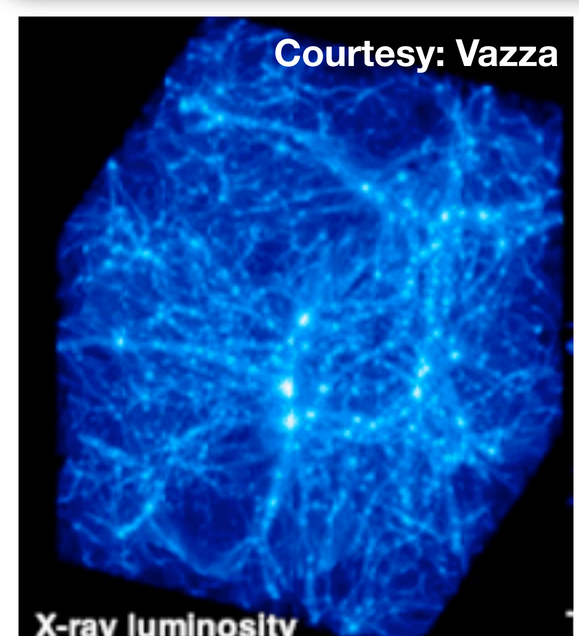
- SNae driven galactic winds
- AGNs

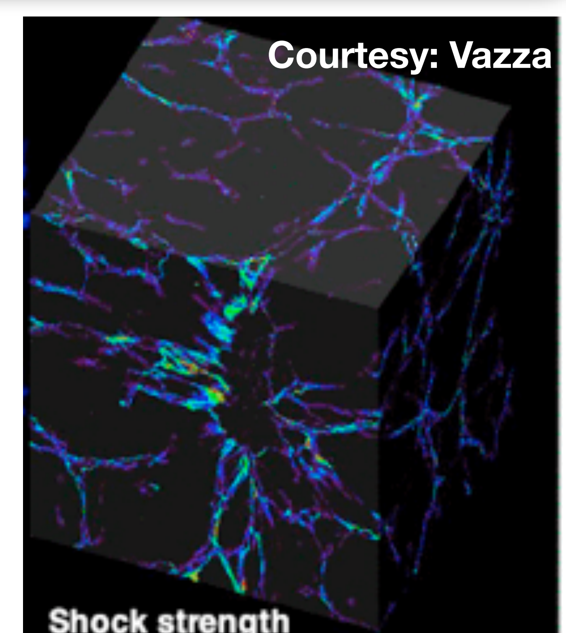
External processes

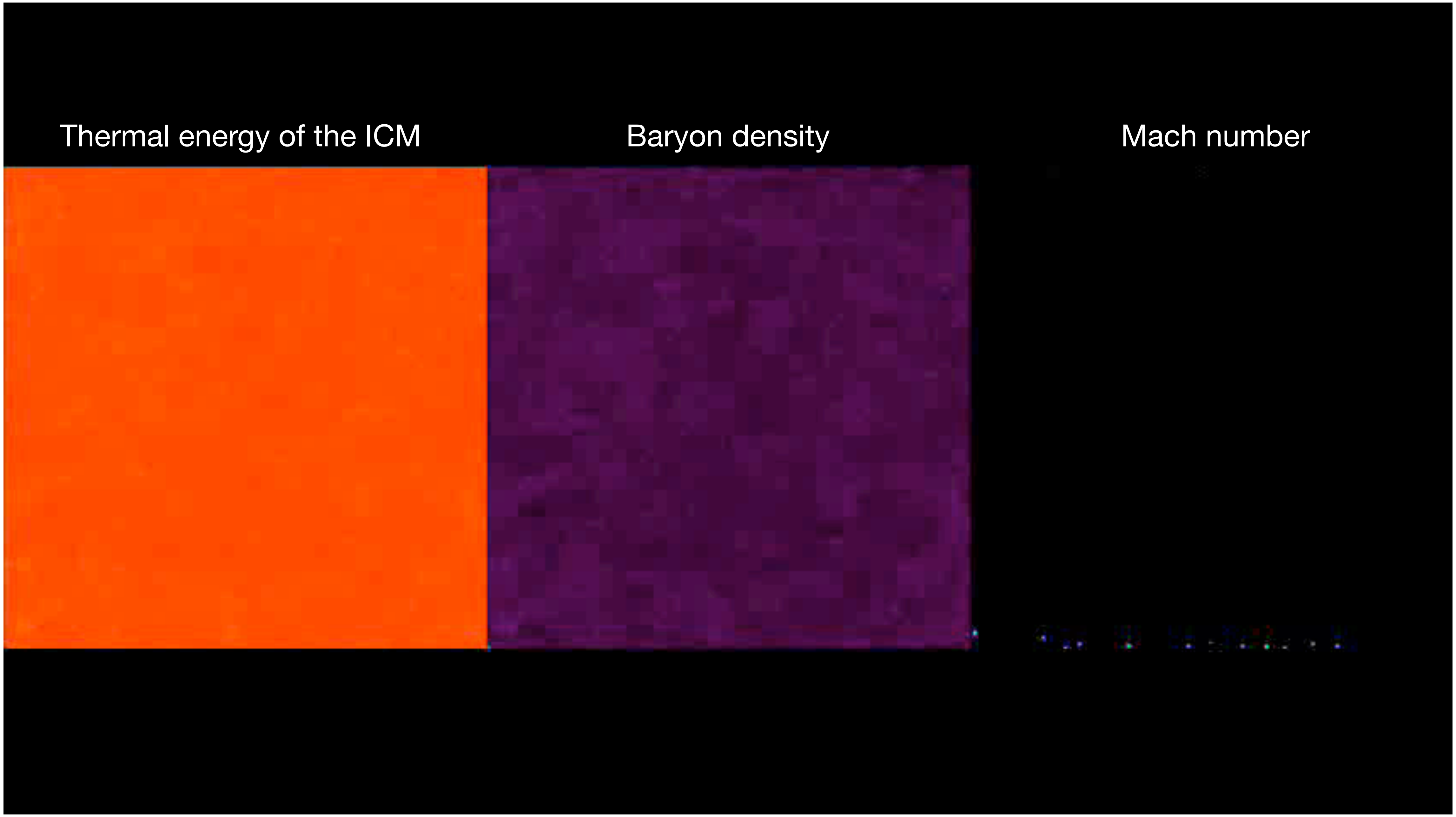
CRs acceleration driven by the assembly of clusters

- accretion shocks ($M \sim 10^3$) GeV
- merging shocks ($M \sim$ 3-10) TeV
- ICM turbulence GeV

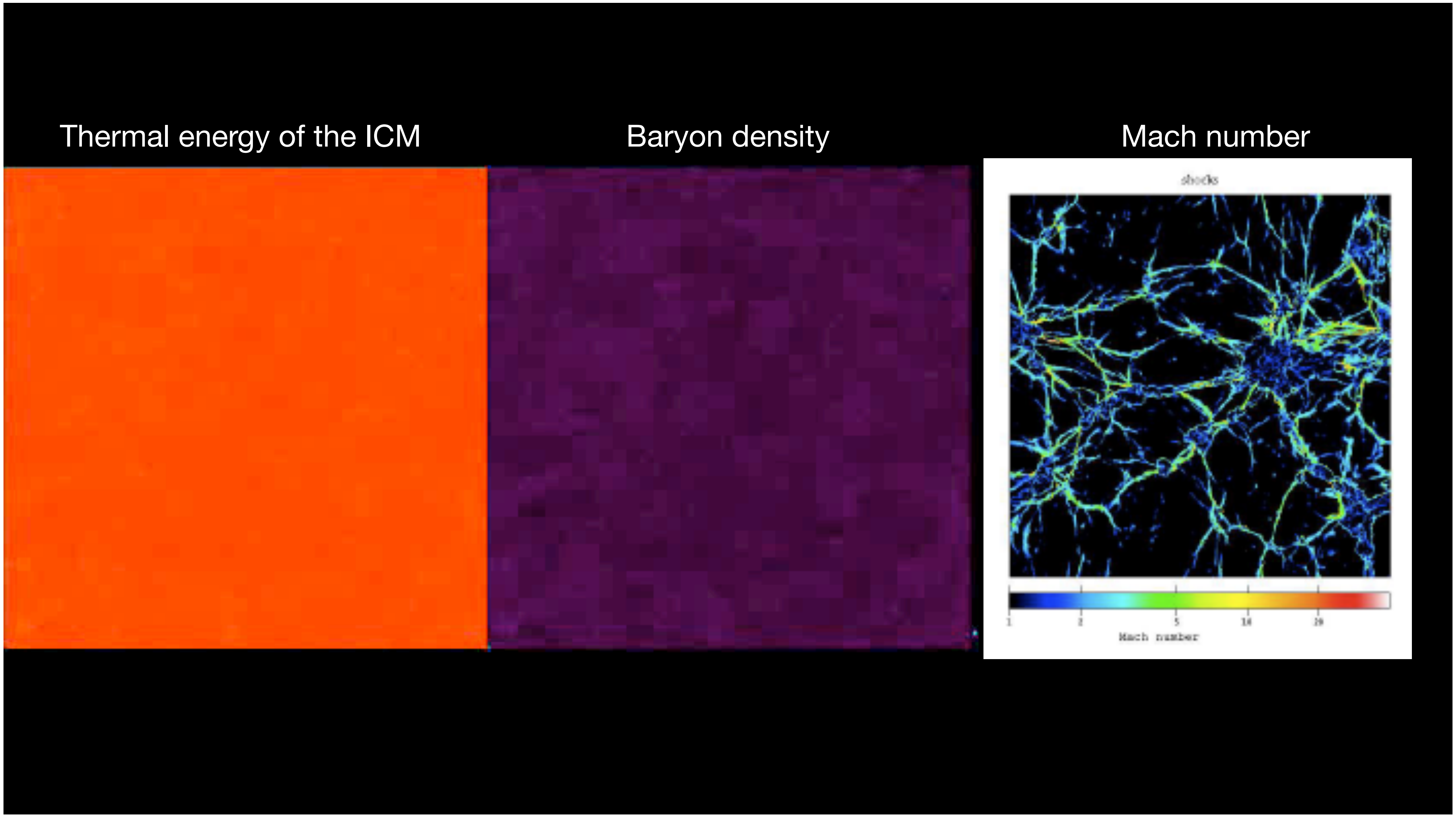






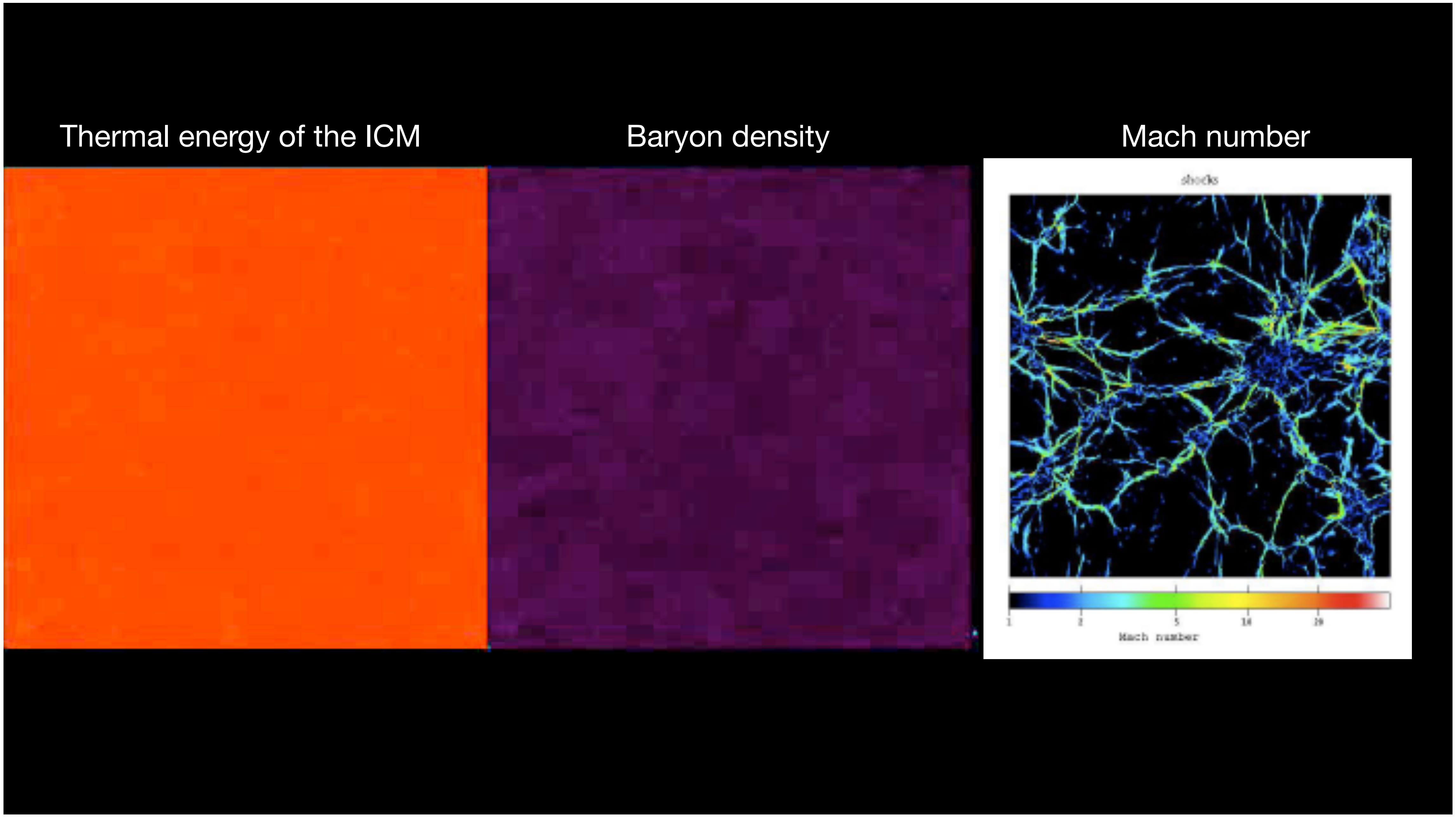


Credits: F. Vazza



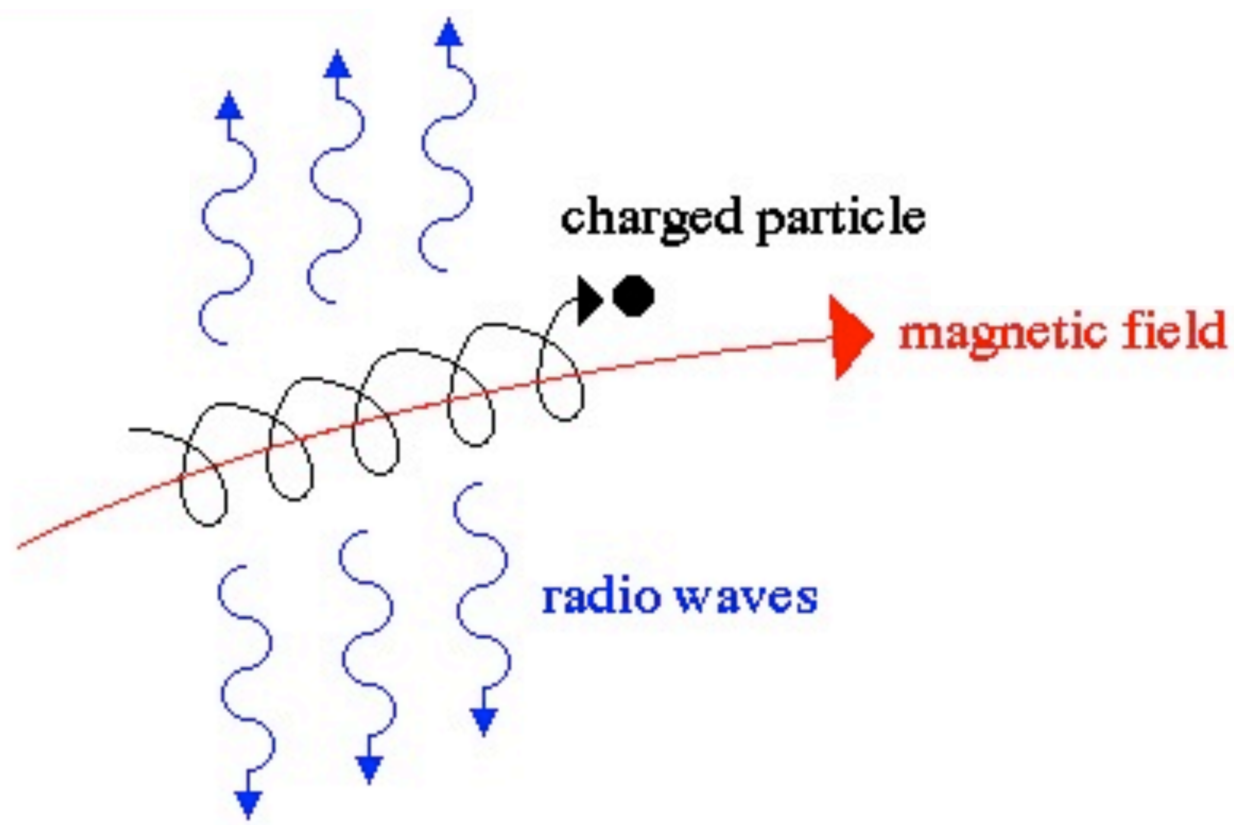
Credits: F. Vazza

$$N(\gamma)\, d\gamma \sim N_0\, \gamma^{-\mu}\, d\gamma \qquad \mu = \frac{2\,(M^2 + 1)}{M^2 - 1}$$



Credits: F. Vazza

NT electrons & magnetic fields in the Universe

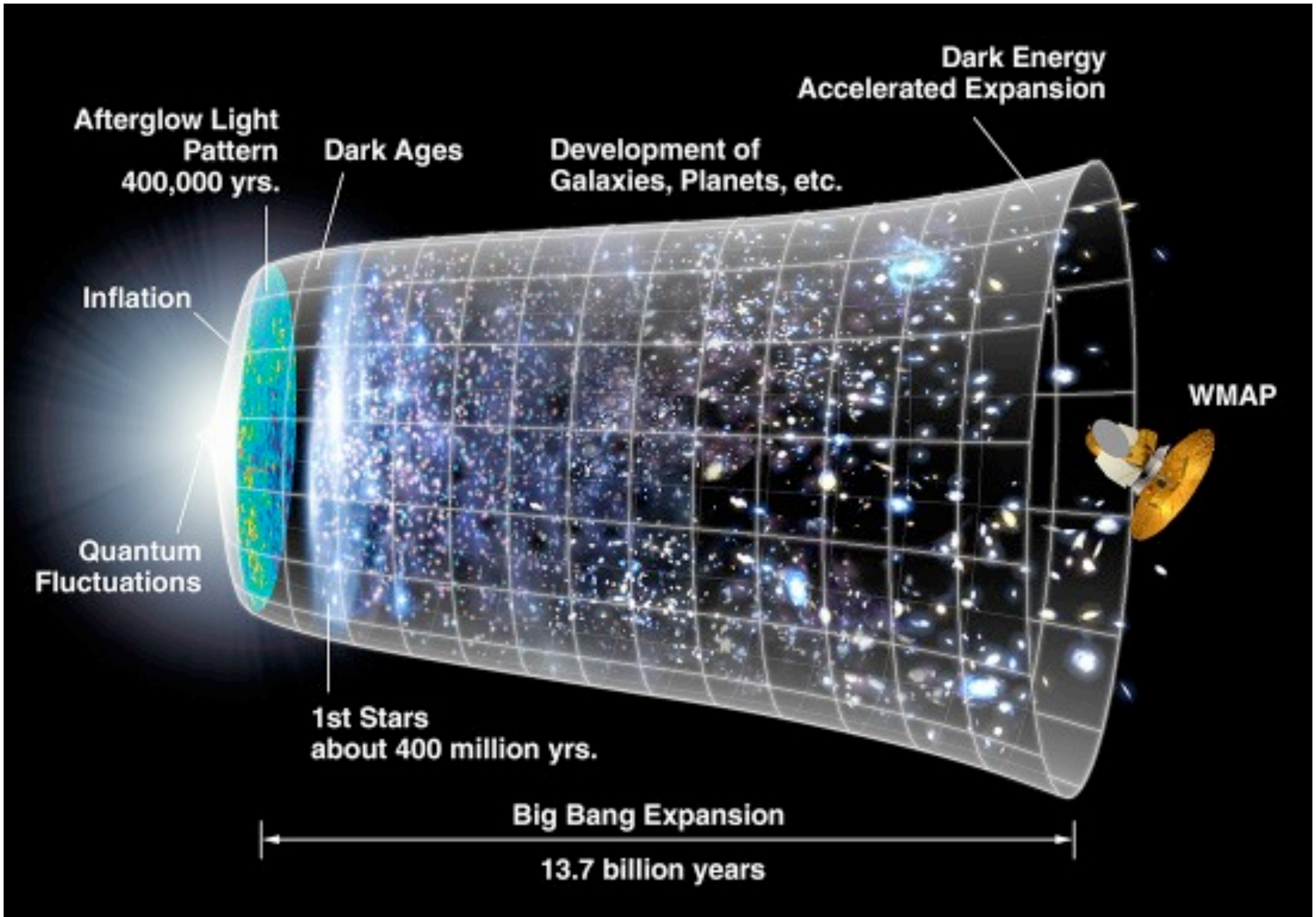


Synchrotron

GeV electrons → Radio emission

TeV electrons → Hard X-ray emission

Photons & electrons in the Universe



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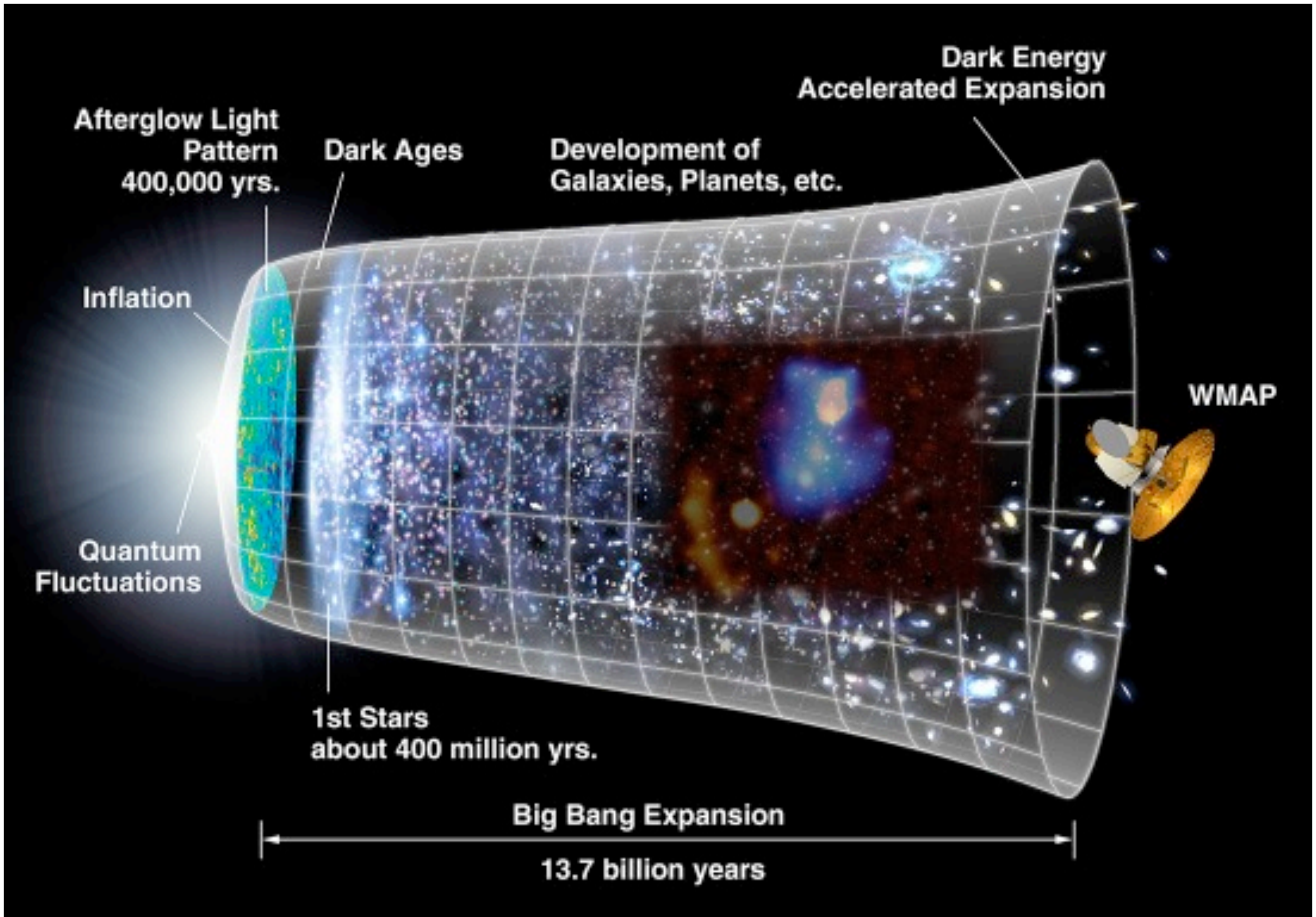

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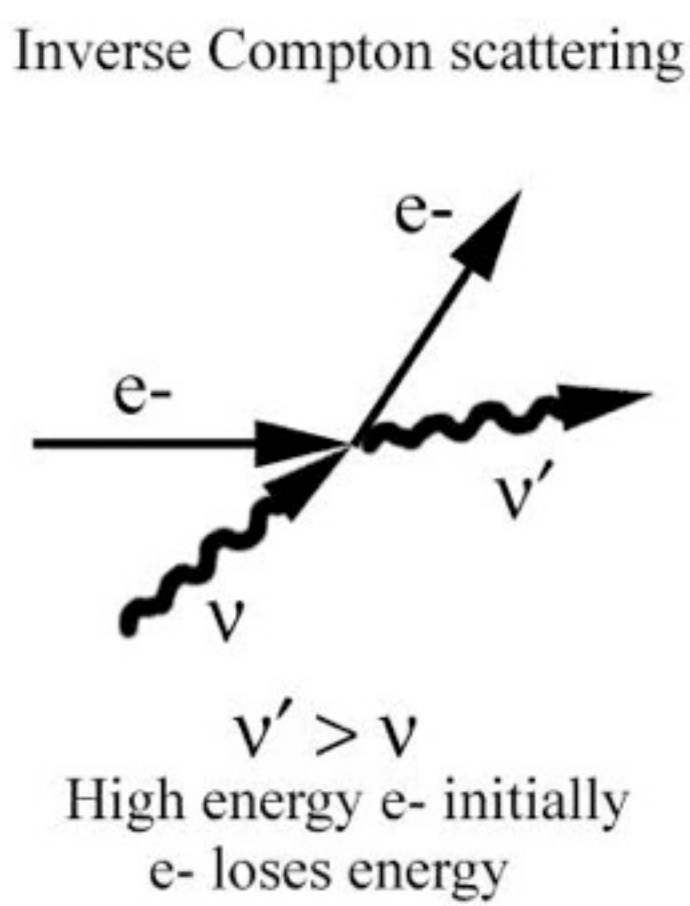
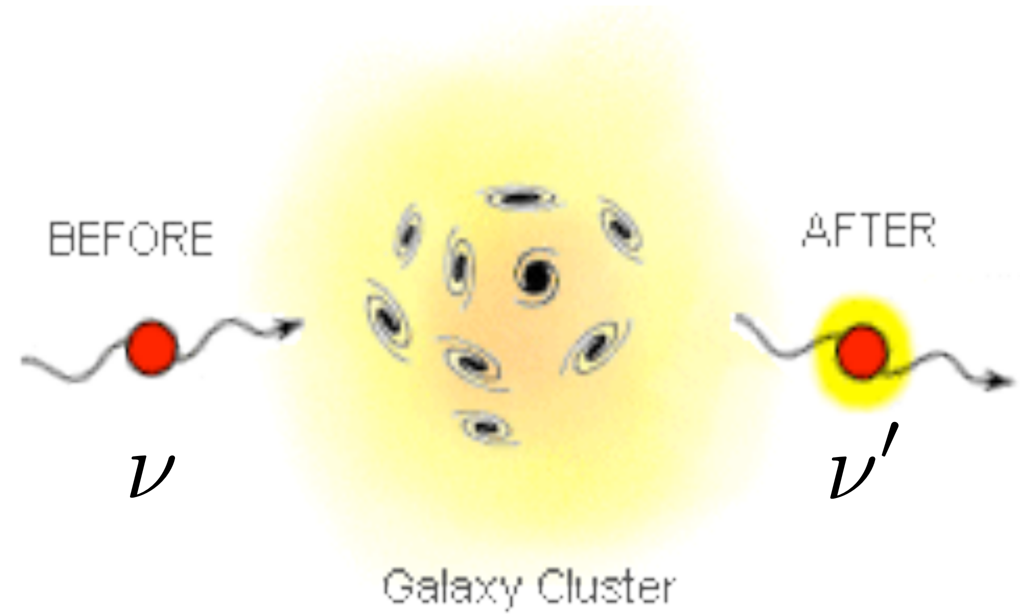
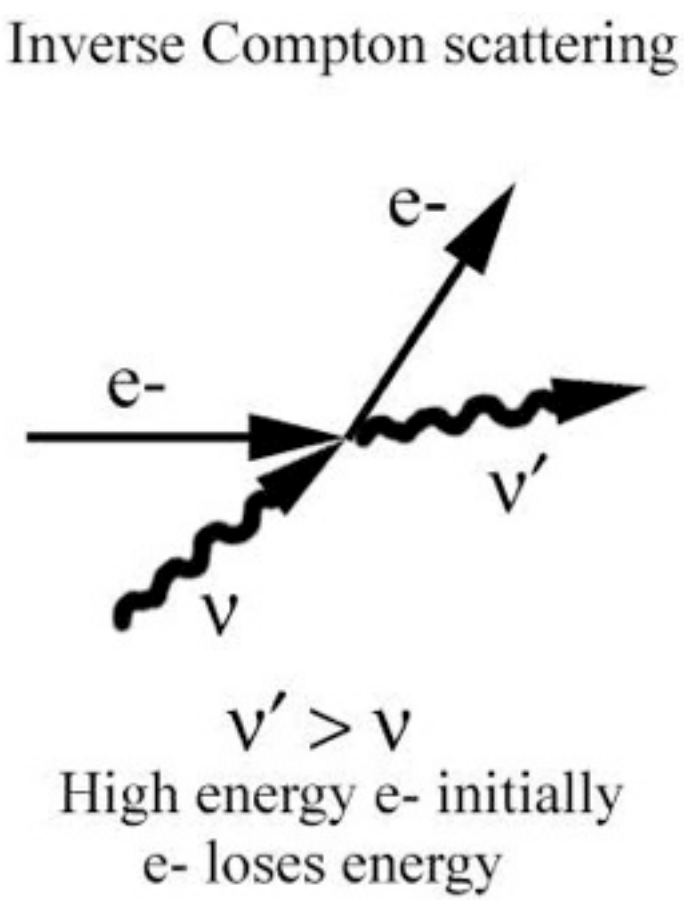
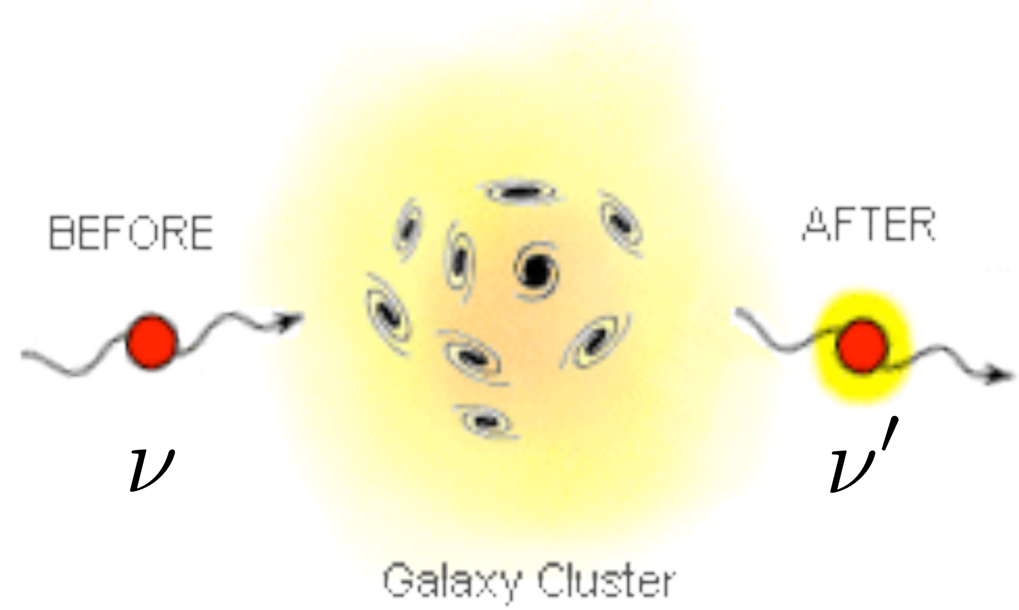




$$\frac{< \nu' >}{\nu} = \frac{4}{3}\gamma_{el}^2$$

Photons & electrons in the Universe





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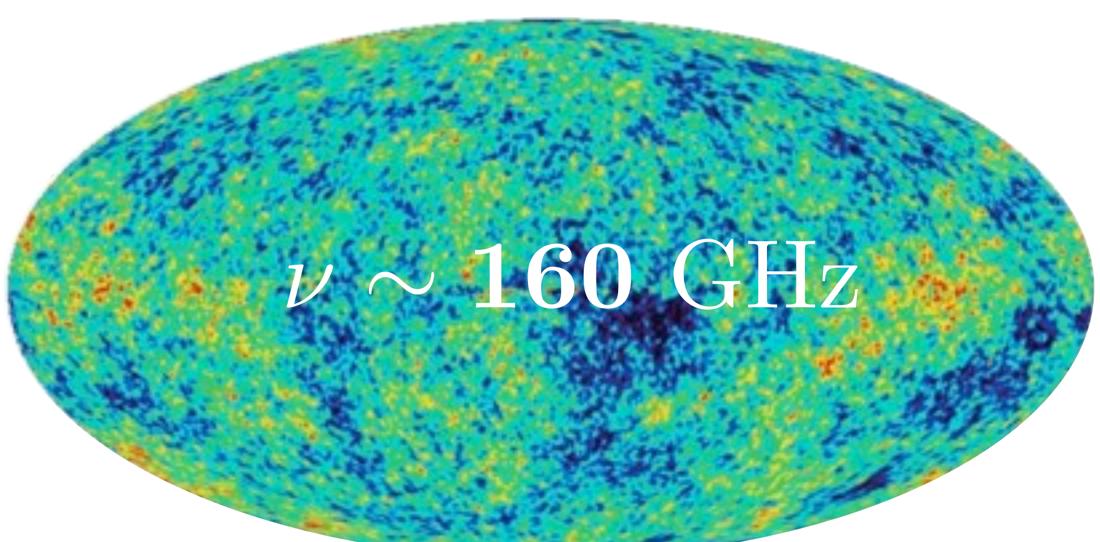

keV electrons → Sub-mm photons

GeV electrons → Hard X-ray photons

TeV electrons → Gamma-ray photons

Origin of intracluster primary cosmic rays

Primary cosmic rays

protons (CRPs) & electrons (CREs)

Internal processes

CRs accelerated inside cluster galaxies and then injected

- SN*ae* driven galactic winds
- AGNs

External processes

CRs acceleration driven by the assembly of clusters

- accretion shocks (M ~ 10^3) TeV
- merging shocks (M ~ 3-10) GeV
- ICM turbulence GeV

$$\tau \approx 2 \times 10^3 \gamma^{-1} \left[(1+z)^4 + \left(\frac{B}{3.3\mu\mathrm{G}} \right)^2 \right]^{-1} \mathrm{Gyr} \begin{cases} \mathrm{E_{e^-}} \approx \mathrm{GeV} \rightarrow \tau \lesssim \mathrm{Gyr} \\ \mathrm{E_{e^-}} \approx \mathrm{TeV} \rightarrow \tau \lesssim \mathrm{Myr} \end{cases}$$

Ferrari et al. 2008 and refs. therein

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- merging shocks ($M \sim$ 3-10)
- ICM turbulence

- Time scale for energy losses longer than Hubble time
- Time scale for diffusion out of clusters longer than Hubble time for energies < 10^6 GeV
- $E_{max} \sim 10^{20}$ eV + Acceleration over ~ 10^{10} yrs

→ effective accumulation of high energy particles in clusters

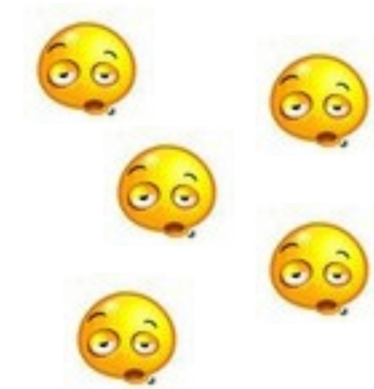
e.g. Sarazin 2002, Vannoni et al. 2009 and refs. therein

CRs over the dynamical time scale of a cluster

Primary cosmic rays

protons (CRPs) & electrons (CREs)

$$\tau_{\rm dyn} \approx 1 \text{ Gyr}$$



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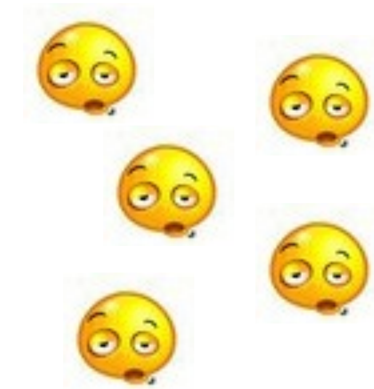

Production of secondary CREs

Secondary relativistic electrons

Secondary relativistic electrons

$$\pi^0 \rightarrow 2\gamma$$ Gamma-ray emission

- Inelastic collision between relativistic protons and target protons provided by the hot intracluster medium - e.g. Dennison 1980

$$p_{rel} + p_{ICM} \rightarrow \pi^0 + \pi^{\pm} + X$$

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

GeV

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GeV

- Interaction between ultra-relativistic protons and CMB photons (Bethe-Heitler process) - e.g. Inoue et al. 2005

$$p + \gamma_{CMB} \rightarrow p + e^\pm$$

TeV

Secondary relativistic electrons

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GeV

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$$p + \gamma_{CMB} \rightarrow p + e^\pm$$ TeV

- Interaction of very high-energy photons (gamma-rays) with the CMB radiation field - e.g. Timokhin et al. 2004

$$\gamma_{UHE} + \gamma_{CMB} \rightarrow e^\pm$$ TeV

Cosmic rays, photons, magnetic fields: multi-wavelength emission

"Product" / CRs	Radio	Hard X-rays	Gamma-rays	Secondary relativistic electrons (GeV)	Secondary ultra-relativistic electrons (TeV)
Relativistic electrons (GeV)	+ Magnetic field (synchrotron)	+ CMB photons (IC)			
Relativistic protons (GeV)			+ ICM ions (hadronic processes)	+ ICM ions (hadronic processes)	
Ultra-relativistic electrons (TeV)		+ Magnetic field (synchrotron)	+ CMB photons (IC)		
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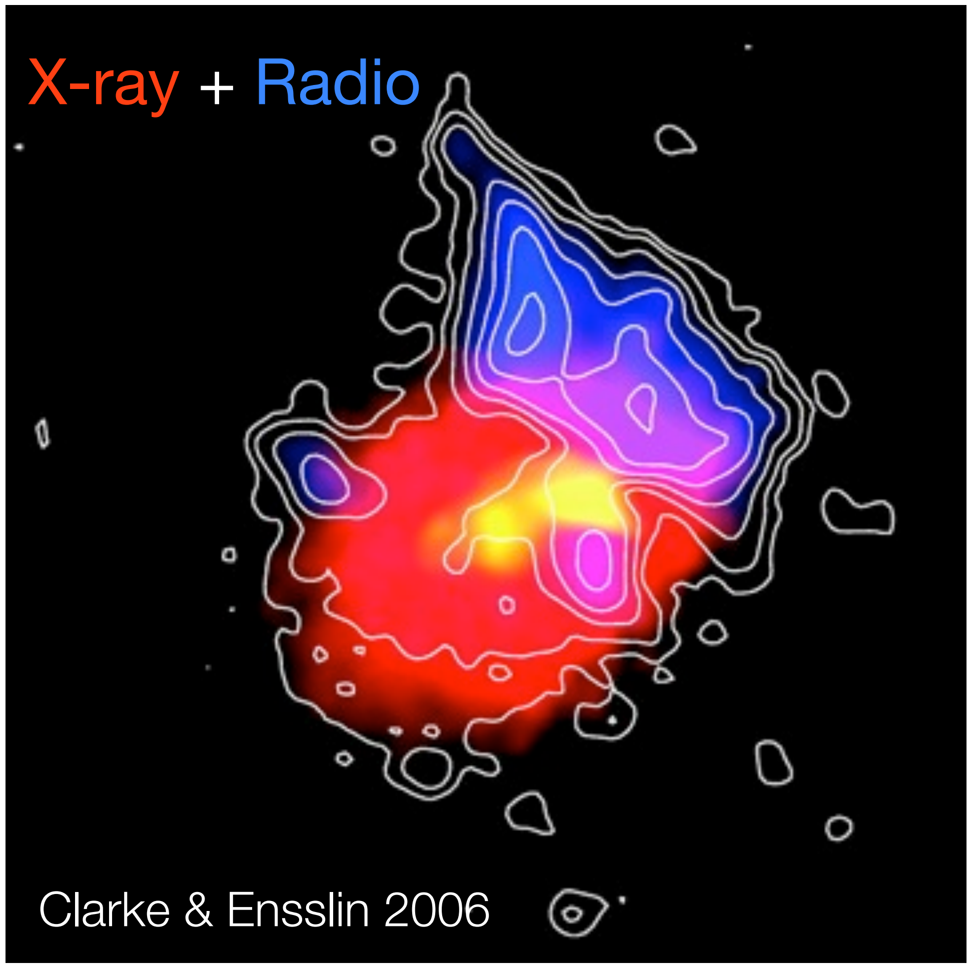
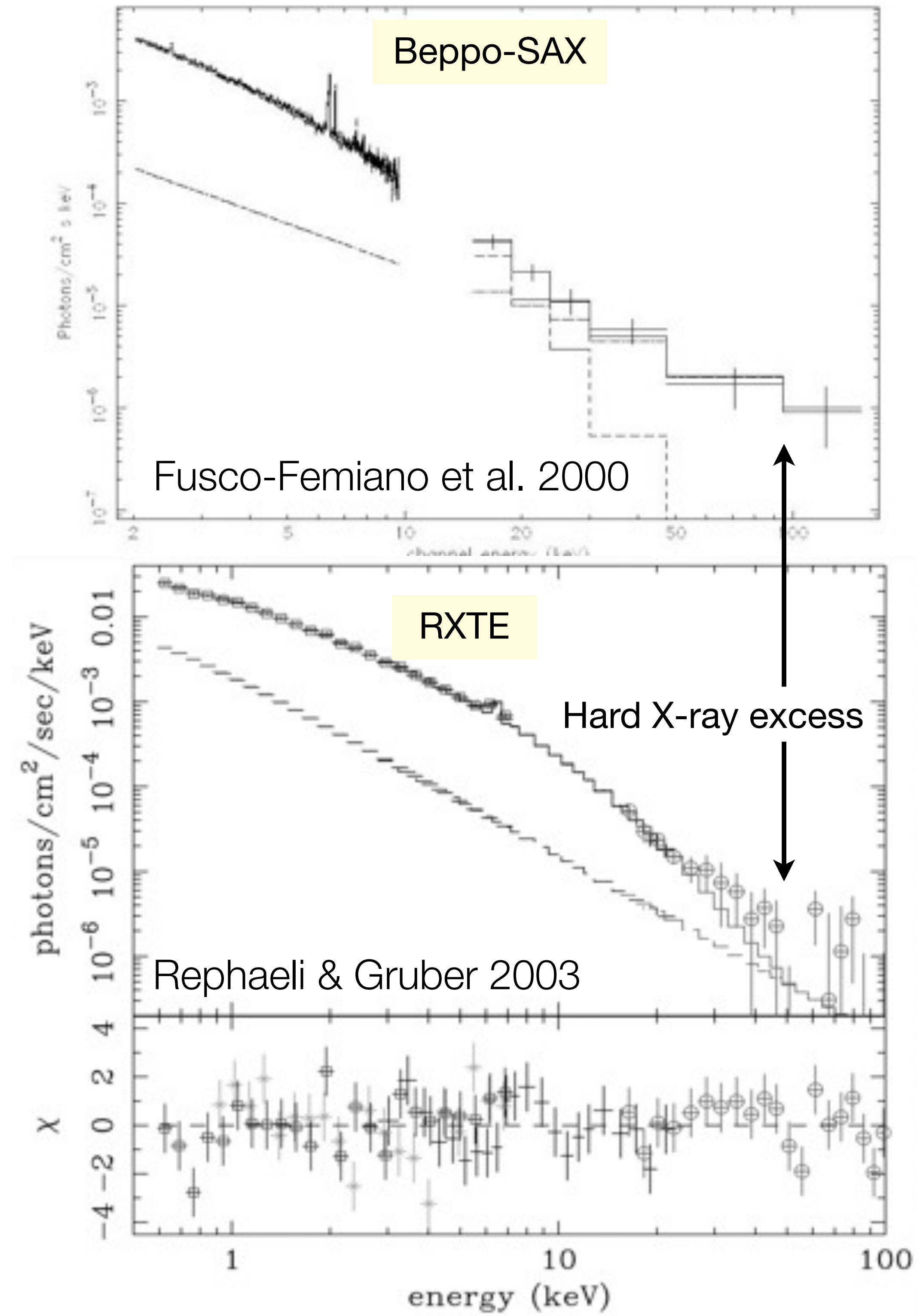
Observational constraints - Example 1



Abell 2256



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Ultra-relativistic protons (TeV)					+ CMB photons (Bethe-Heitler)

Origin of relativistic electrons (GeV)

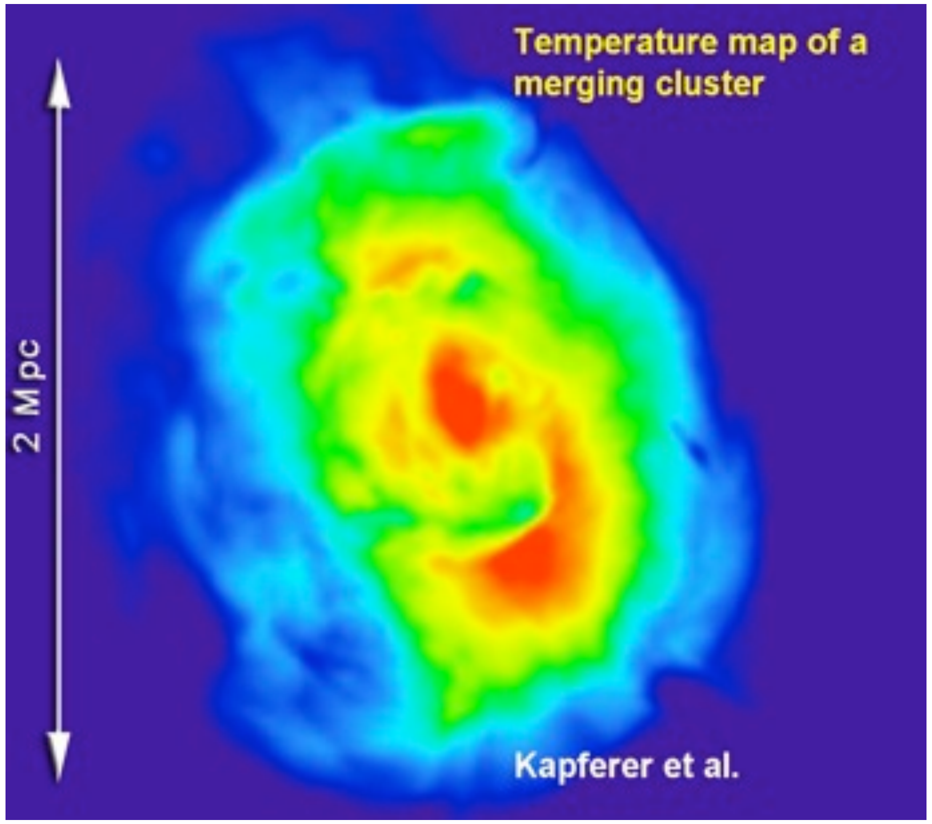
Primary models

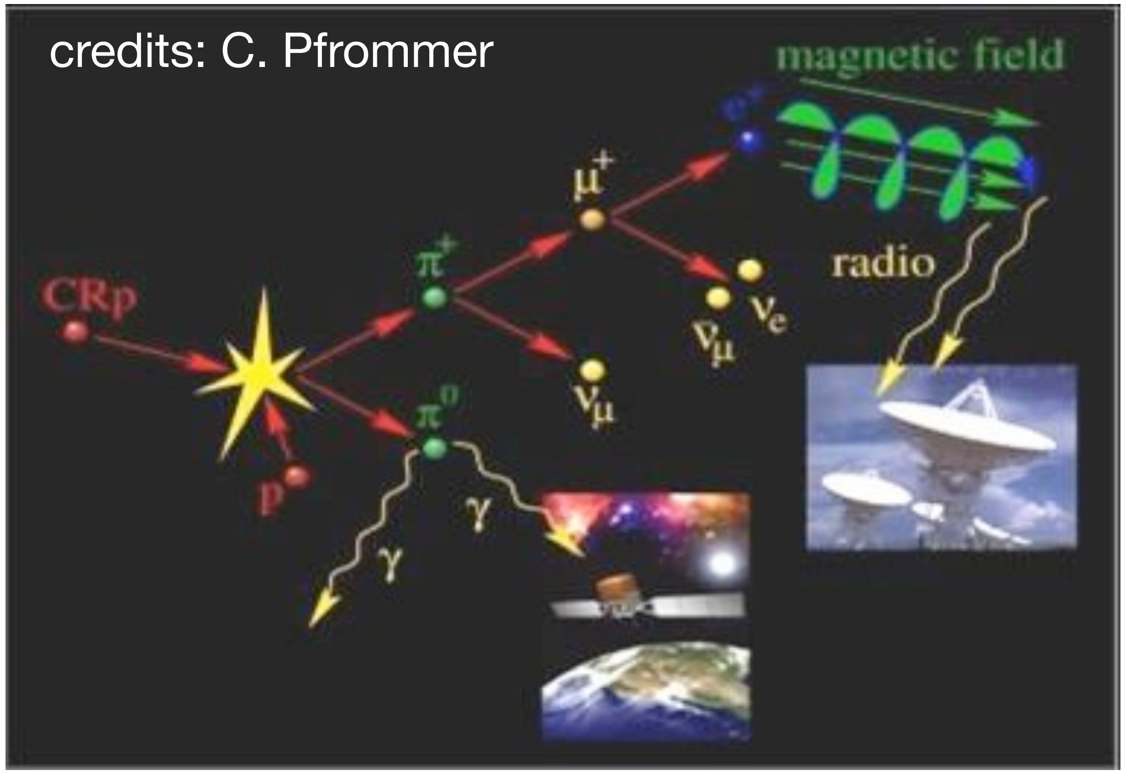
(external processes related to cluster mergers)

or

Secondary models

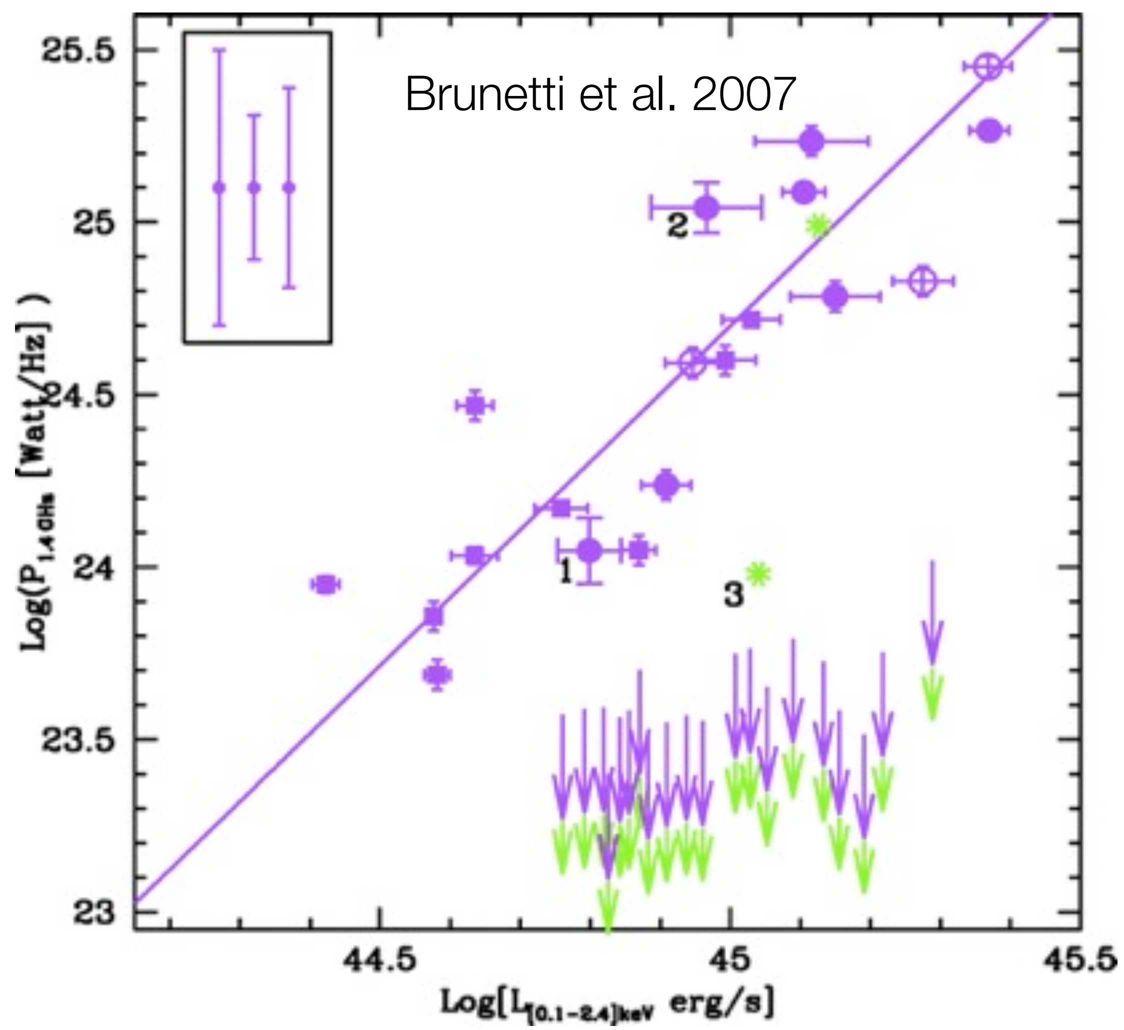
(external processes related to hadronic interactions)





Observational evidence in favor of primary models

- Halos & Relics ↔ Cluster mergers
- $P_{1.4GHz}$ ↔ L_X (T_X)
- Radio surface brightness ↔ X-ray surface brightness
- Radio spectral index ↔ ν
- Radio spectral index ↔ Distance from the X-ray centroid
- Radio spectral index ↔ T_X



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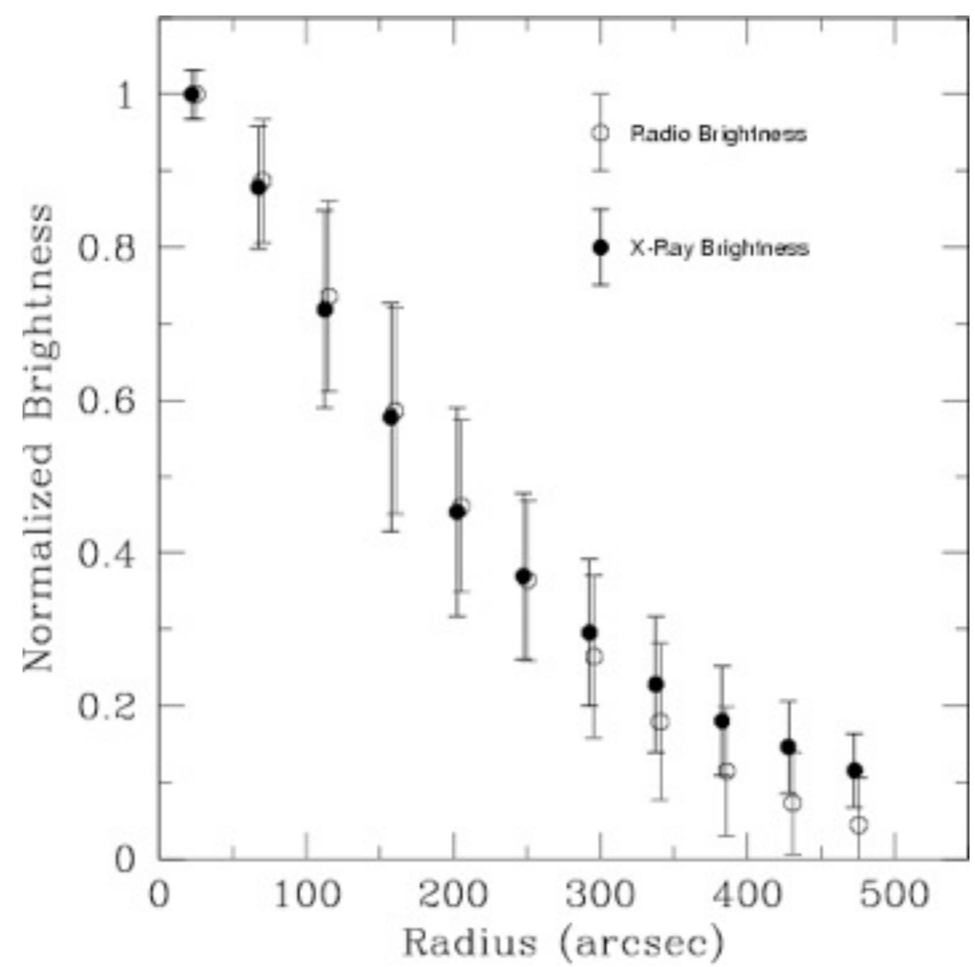
✳ Primary models: $F_{radio} \propto F_X$

✳ Secondary models: $F_{radio} \propto F_X^a$ (a>1 for typical B values)



Govoni et al. 2001

Observational evidence in favor of primary models

- Halos & Relics ↔ Cluster mergers
- $P_{1.4GHz}$ ↔ L_X (T_X)
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- **Radio spectral index ↔ ν** $S(\nu) \propto \nu^{-\alpha}$
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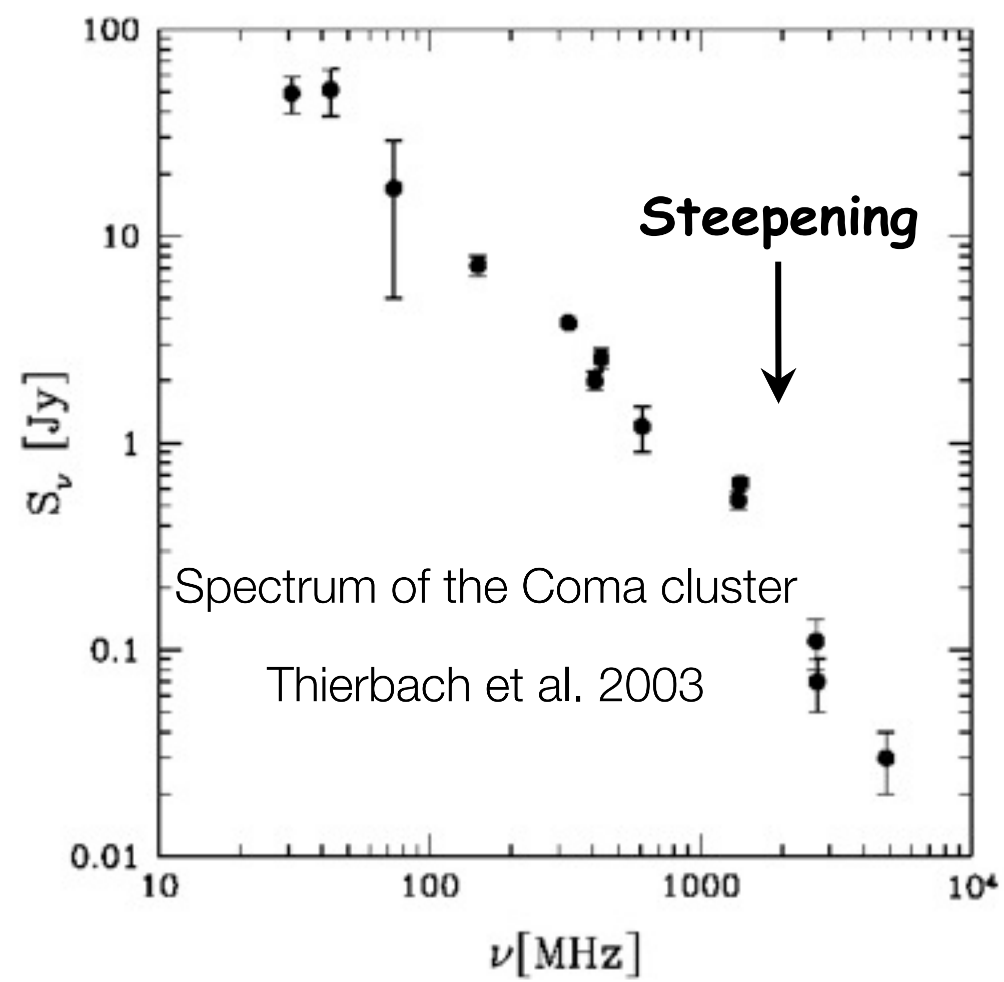

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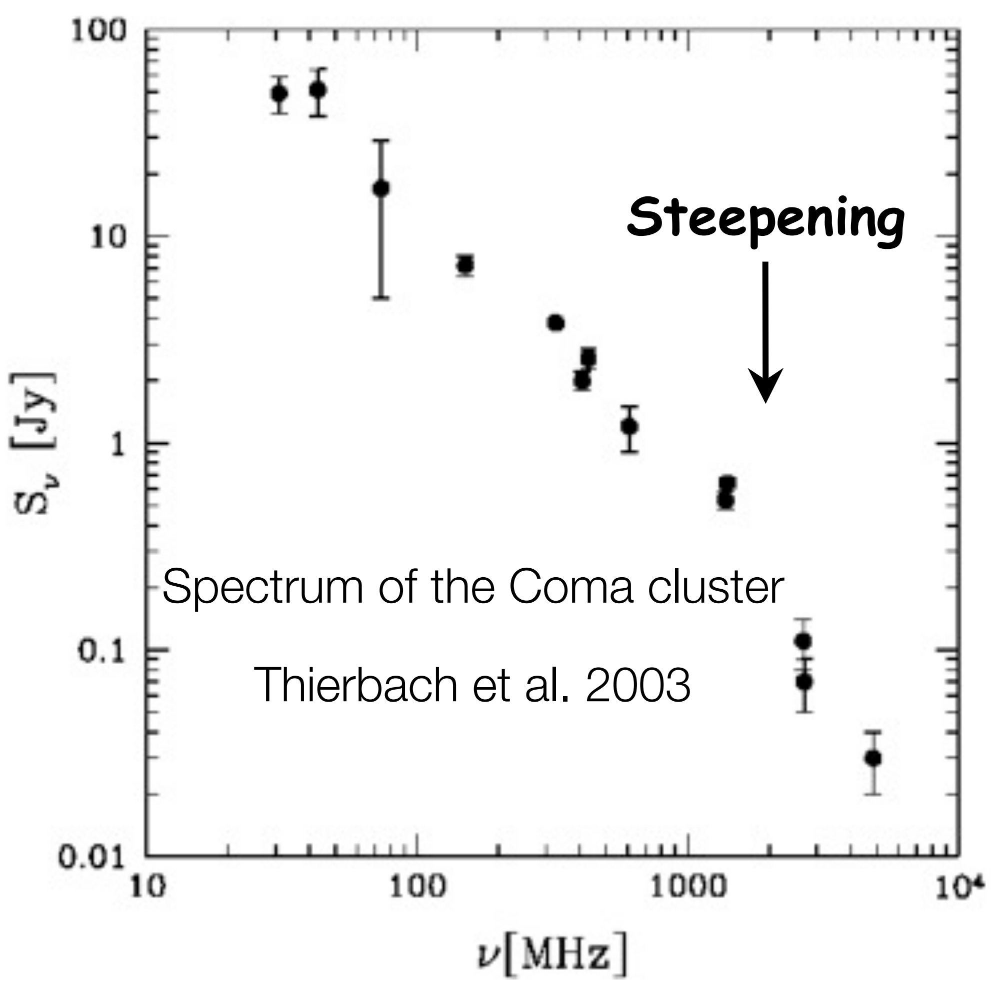
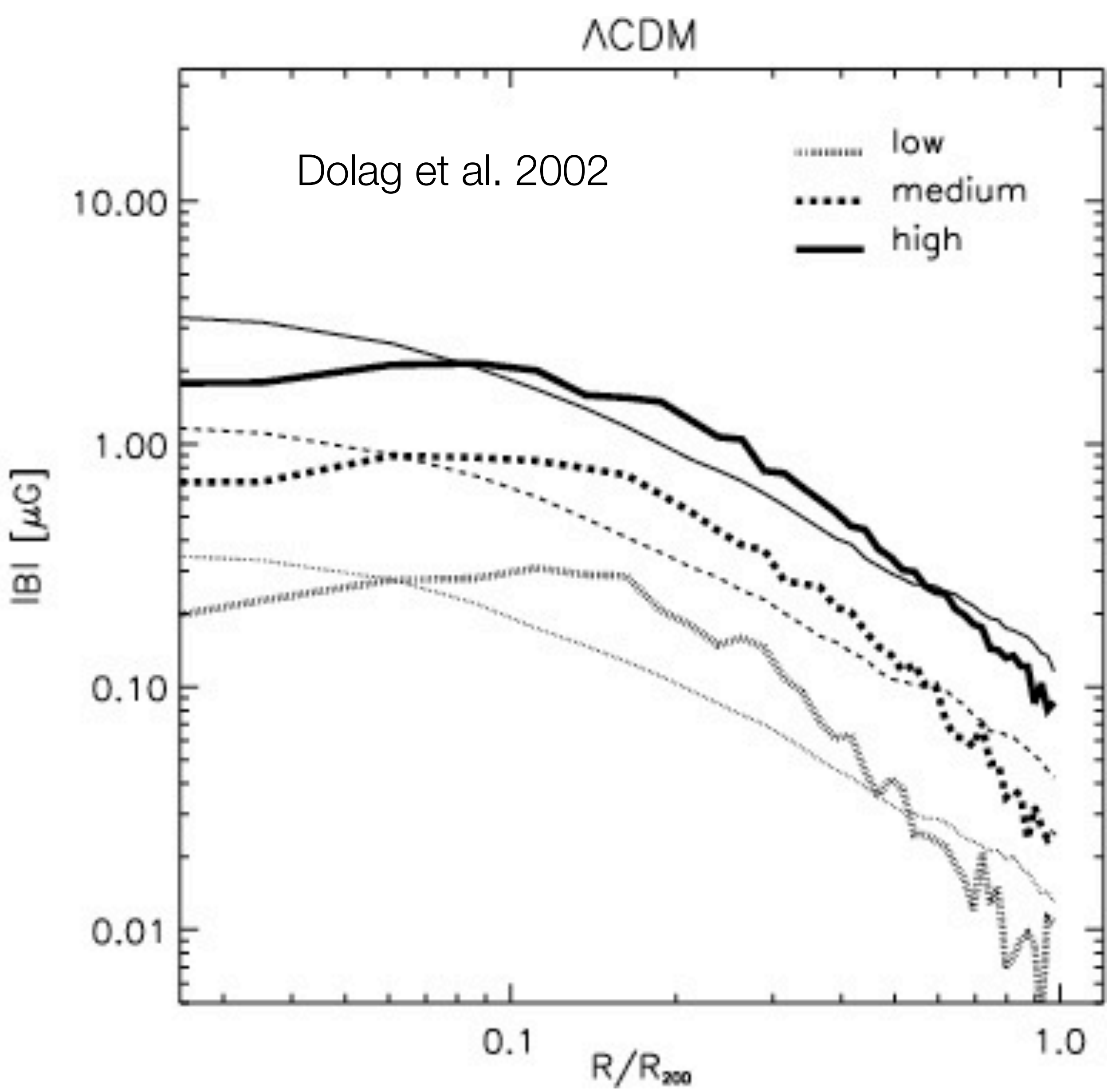
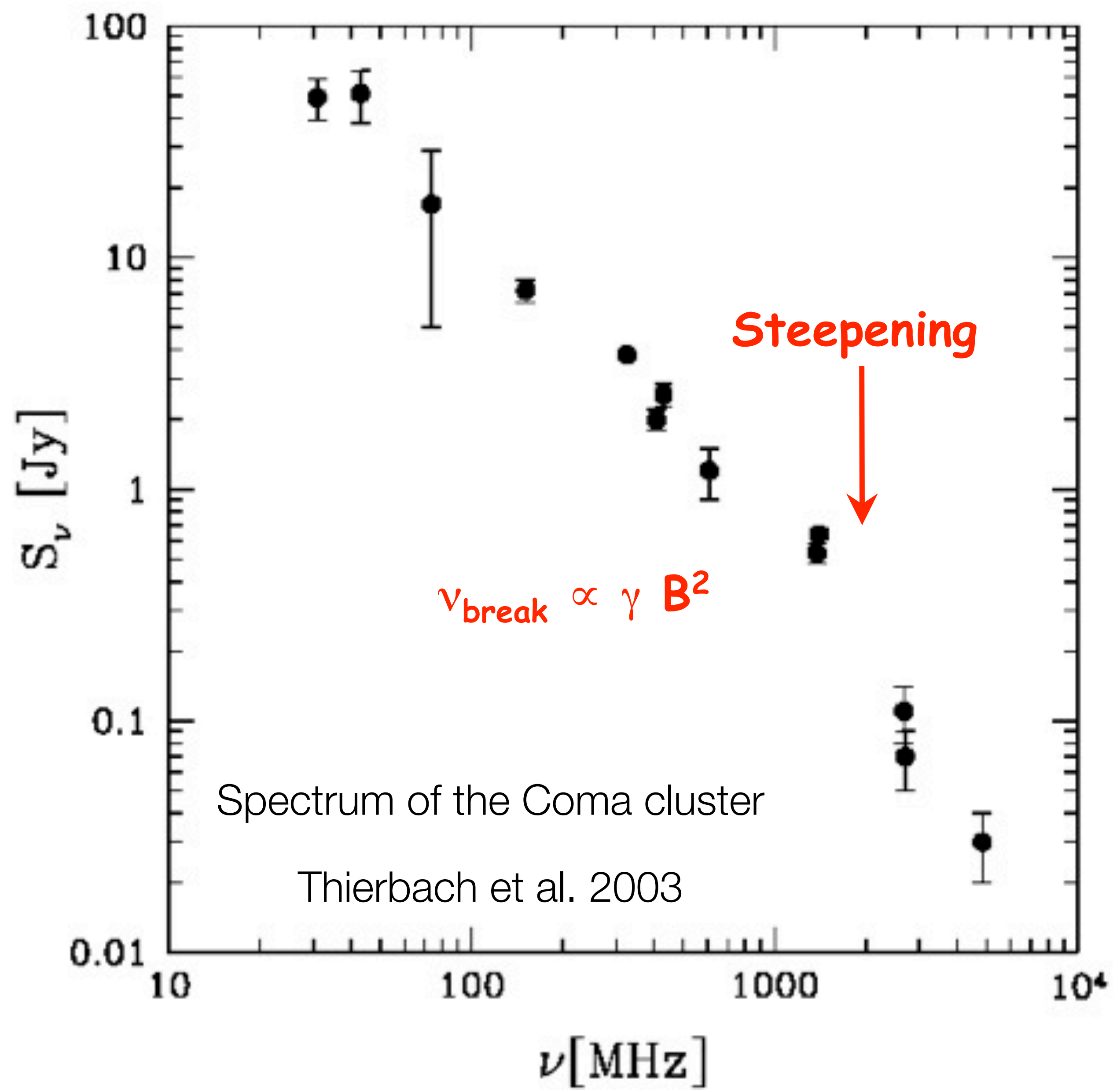


$\nu_{break} \propto \gamma\ B^2$ Brunetti et al. 2001

Observational evidence in favor of primary models





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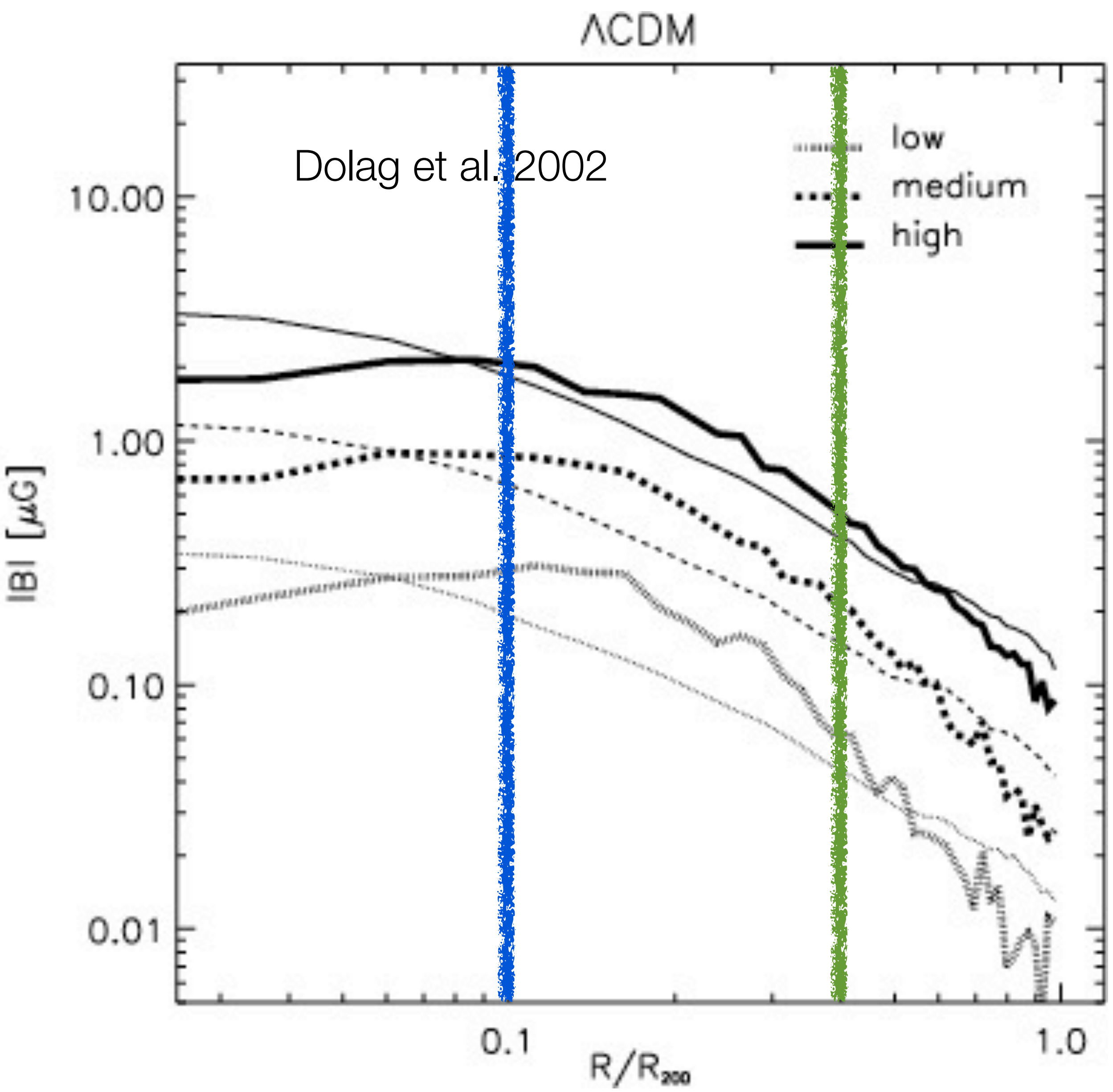
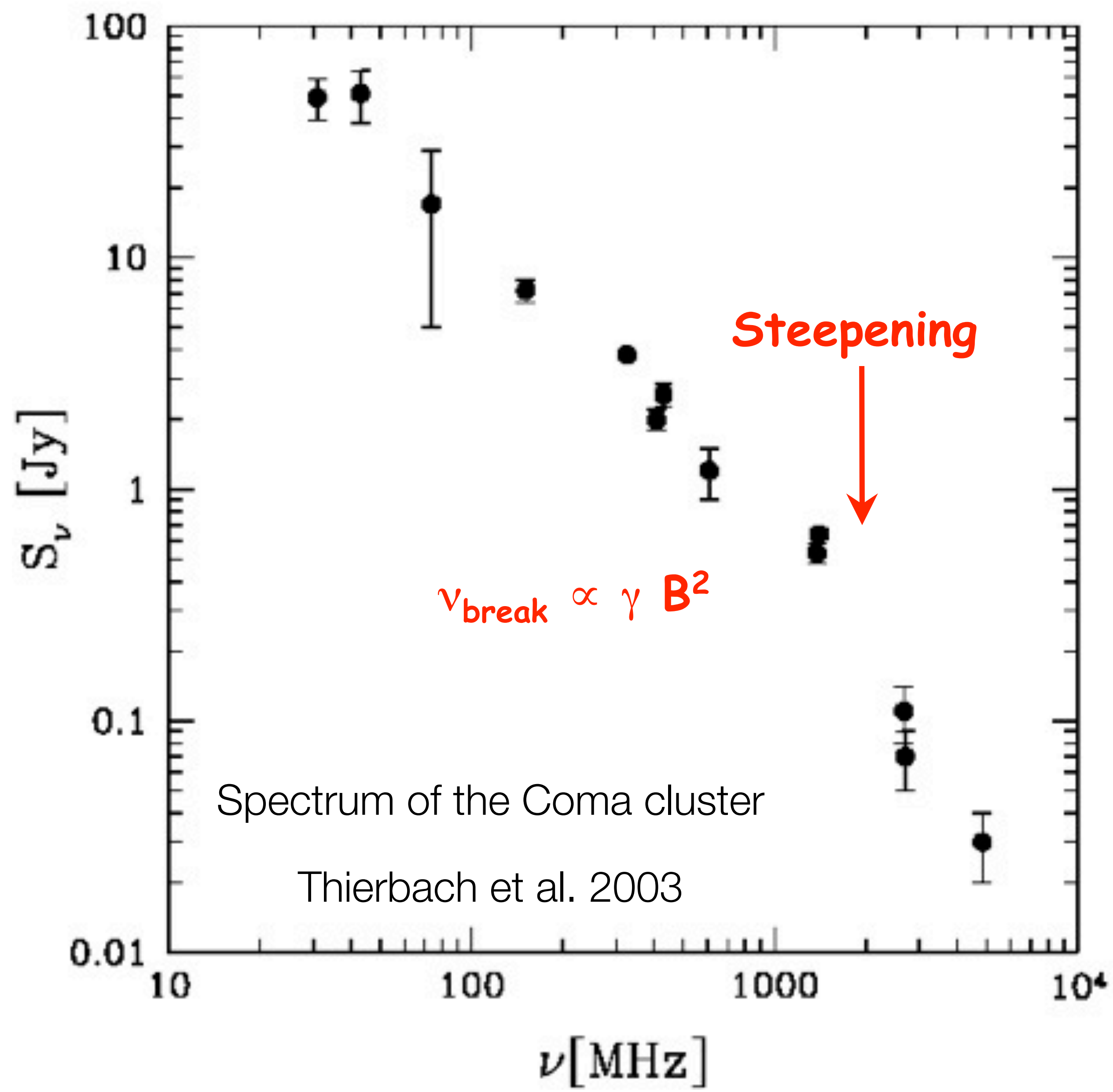
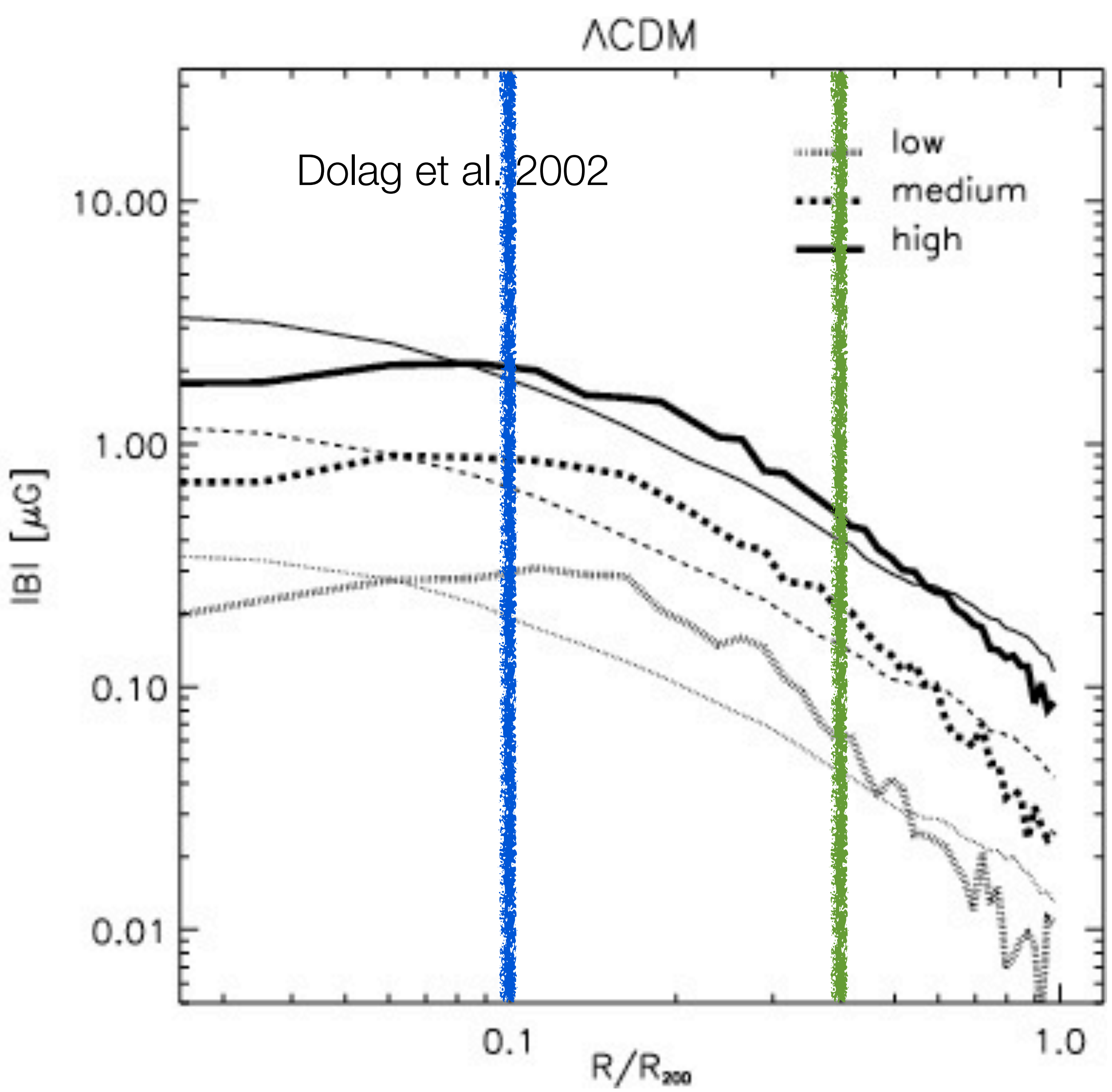
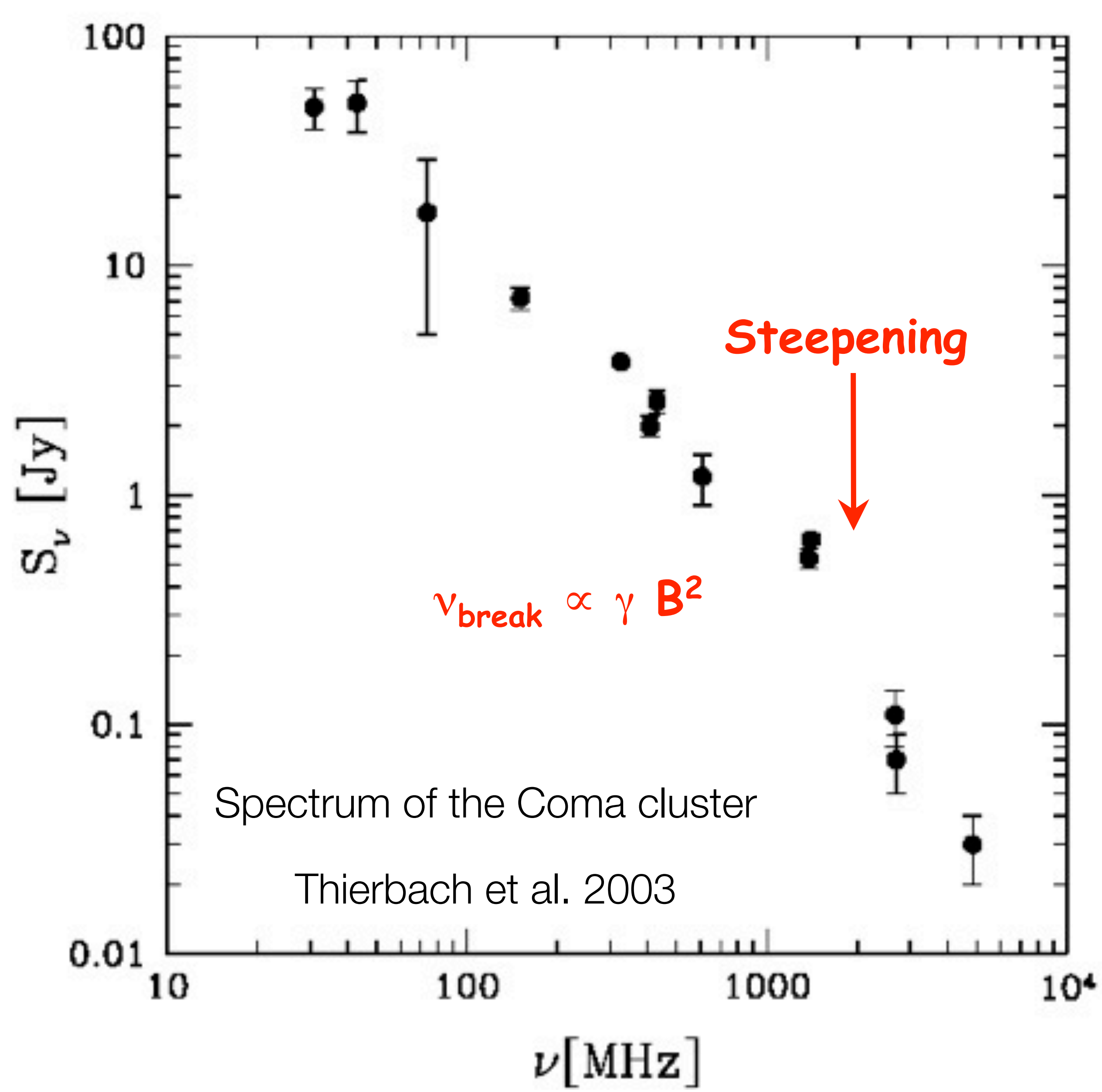




Observational evidence in favor of primary models

$R_1 < R_2 \Rightarrow |B_1| > |B_2| \Rightarrow \nu_{break1} > \nu_{break2}$





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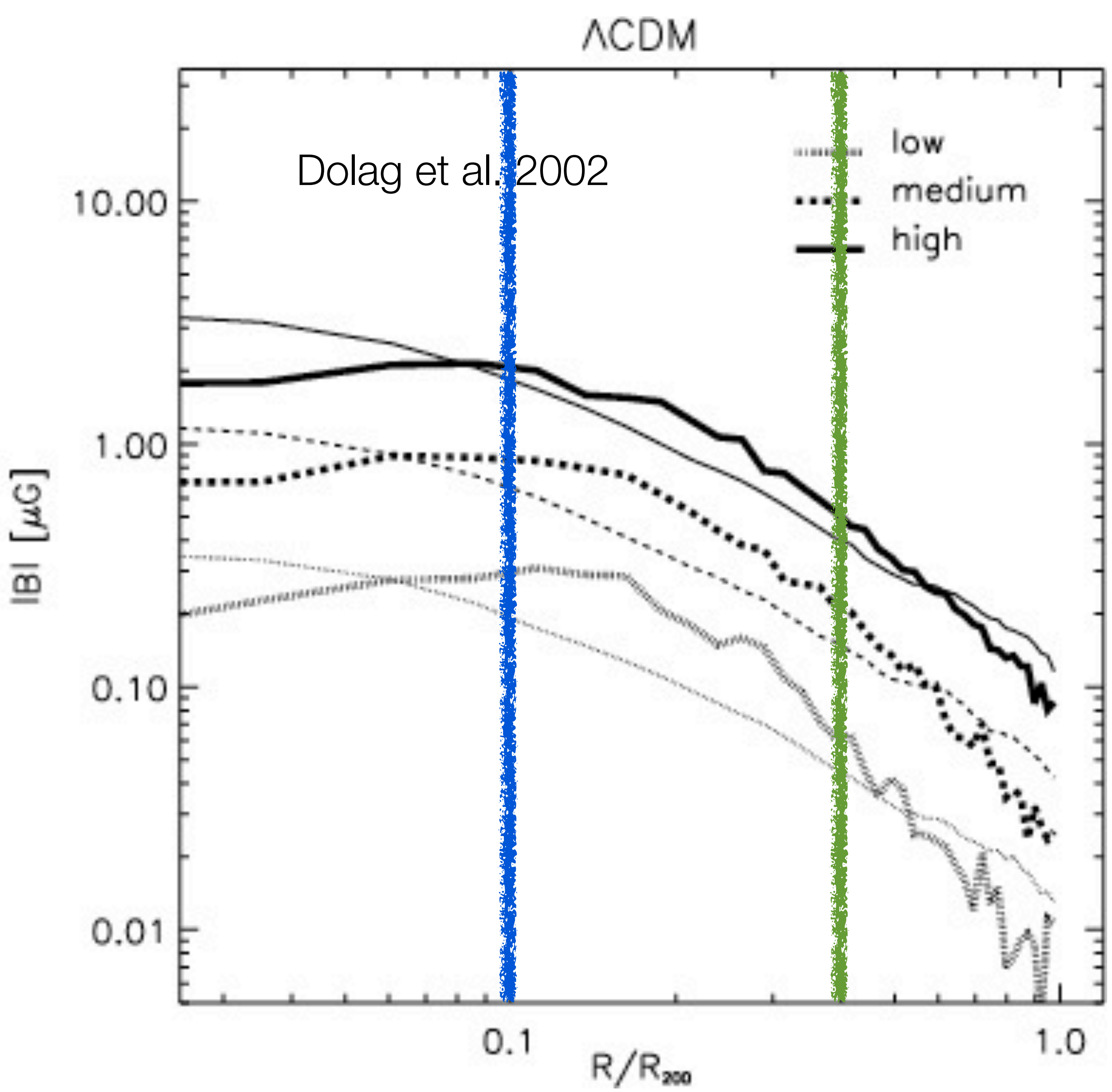
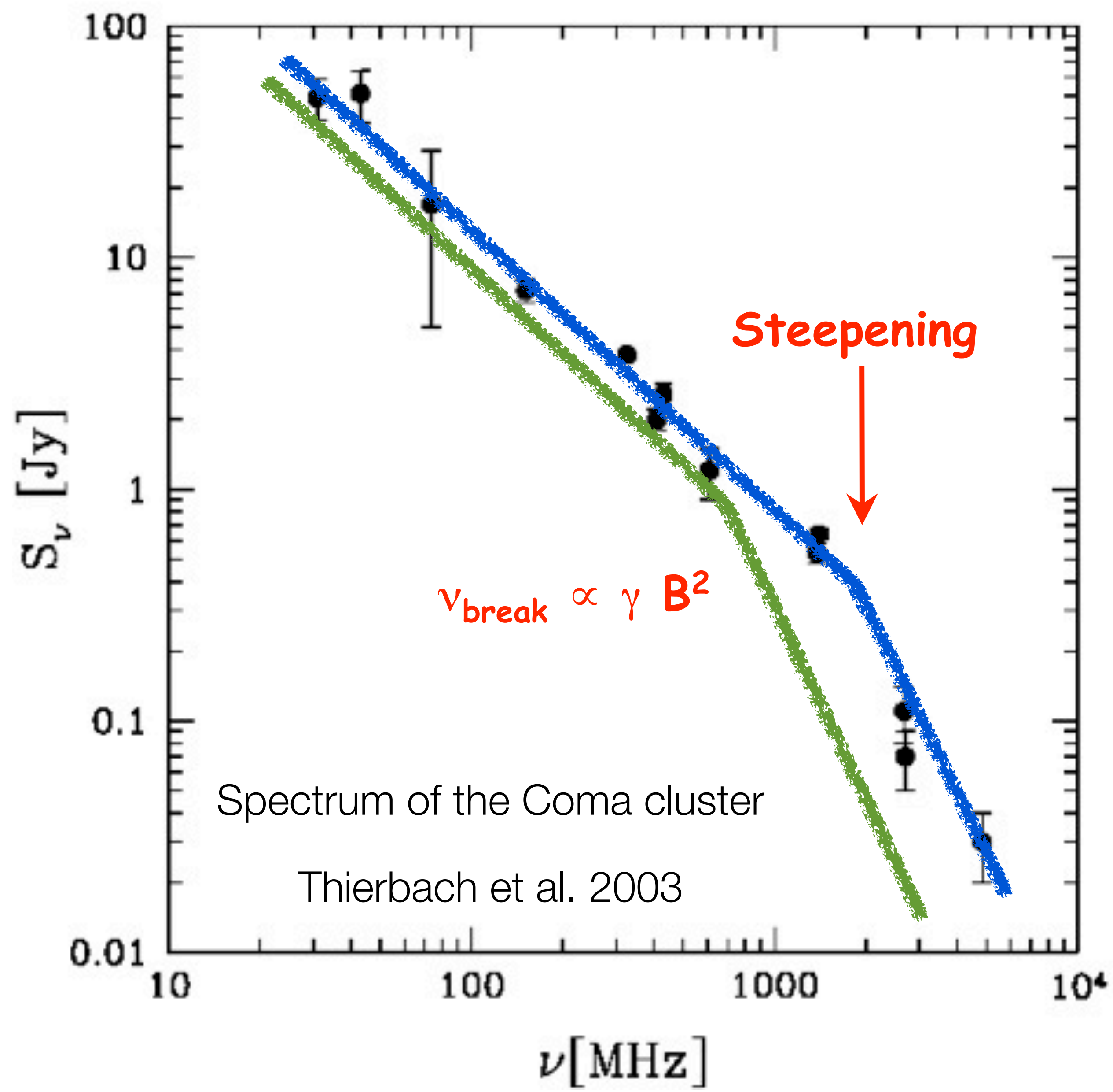
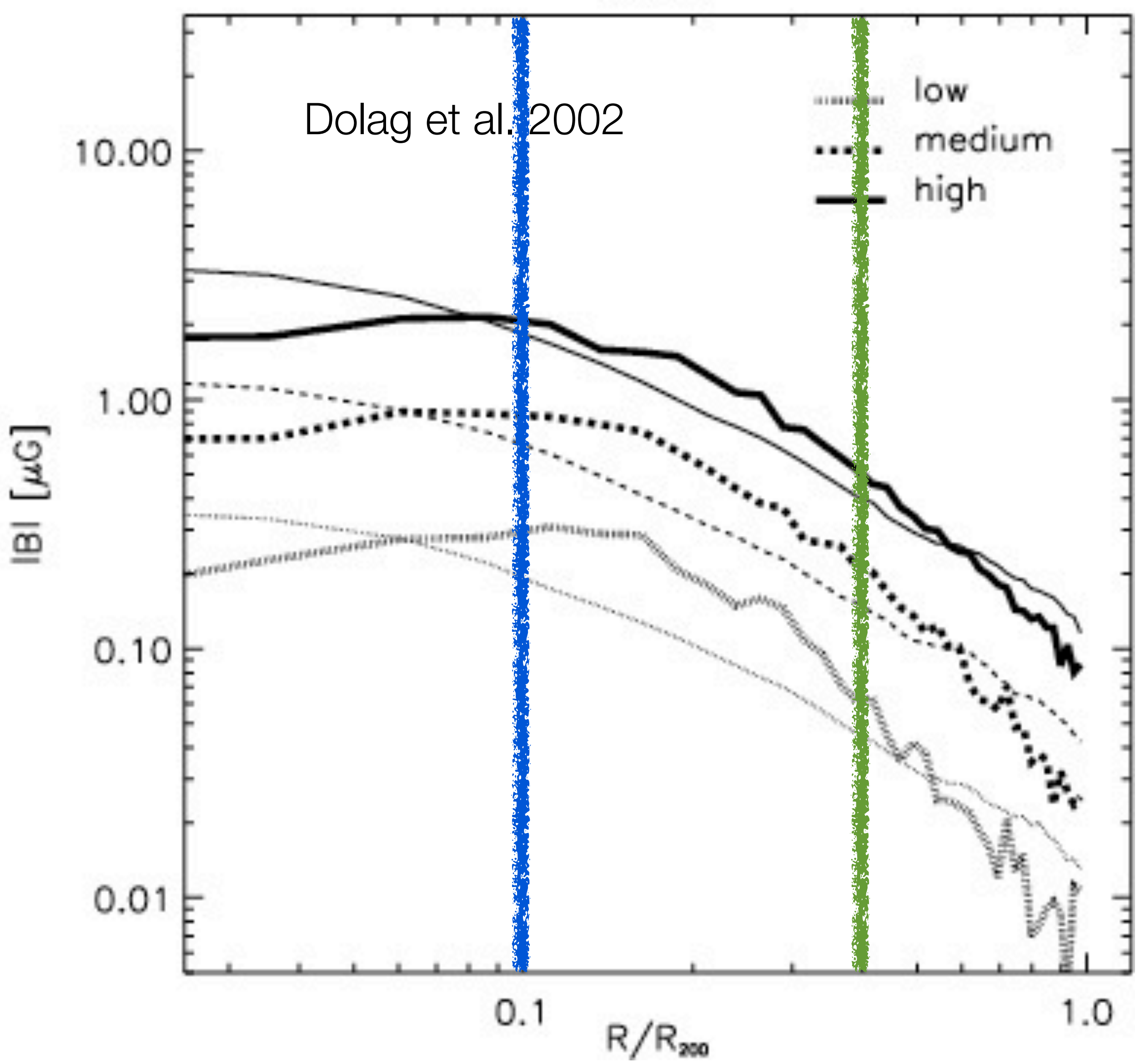


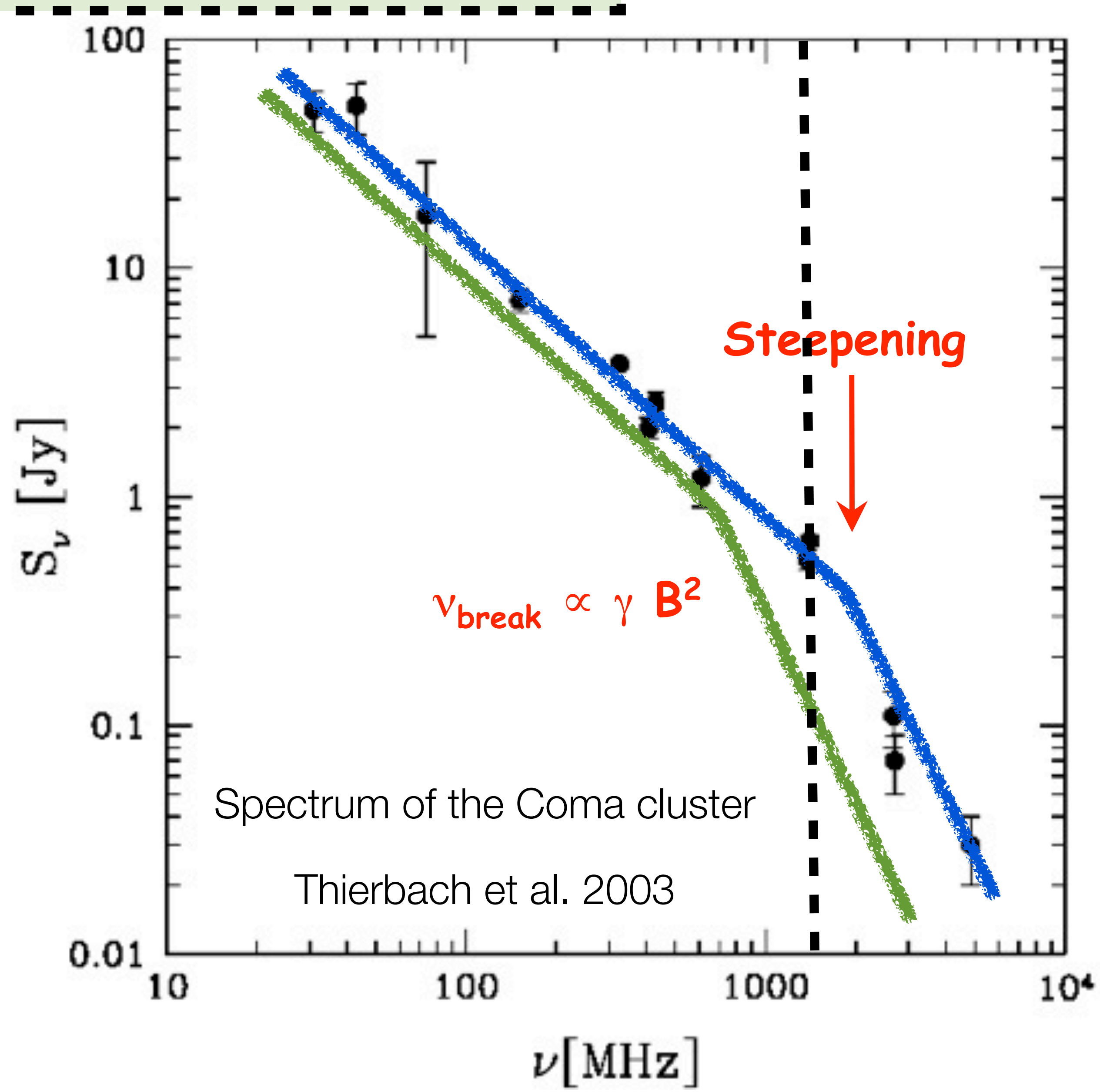


Observational evidence in favor of primary models

$R_1 < R_2 \Rightarrow |B_1| > |B_2| \Rightarrow \nu_{break1} > \nu_{break2}$

⇒ The spectrum is steeper at R_2 than at R_1





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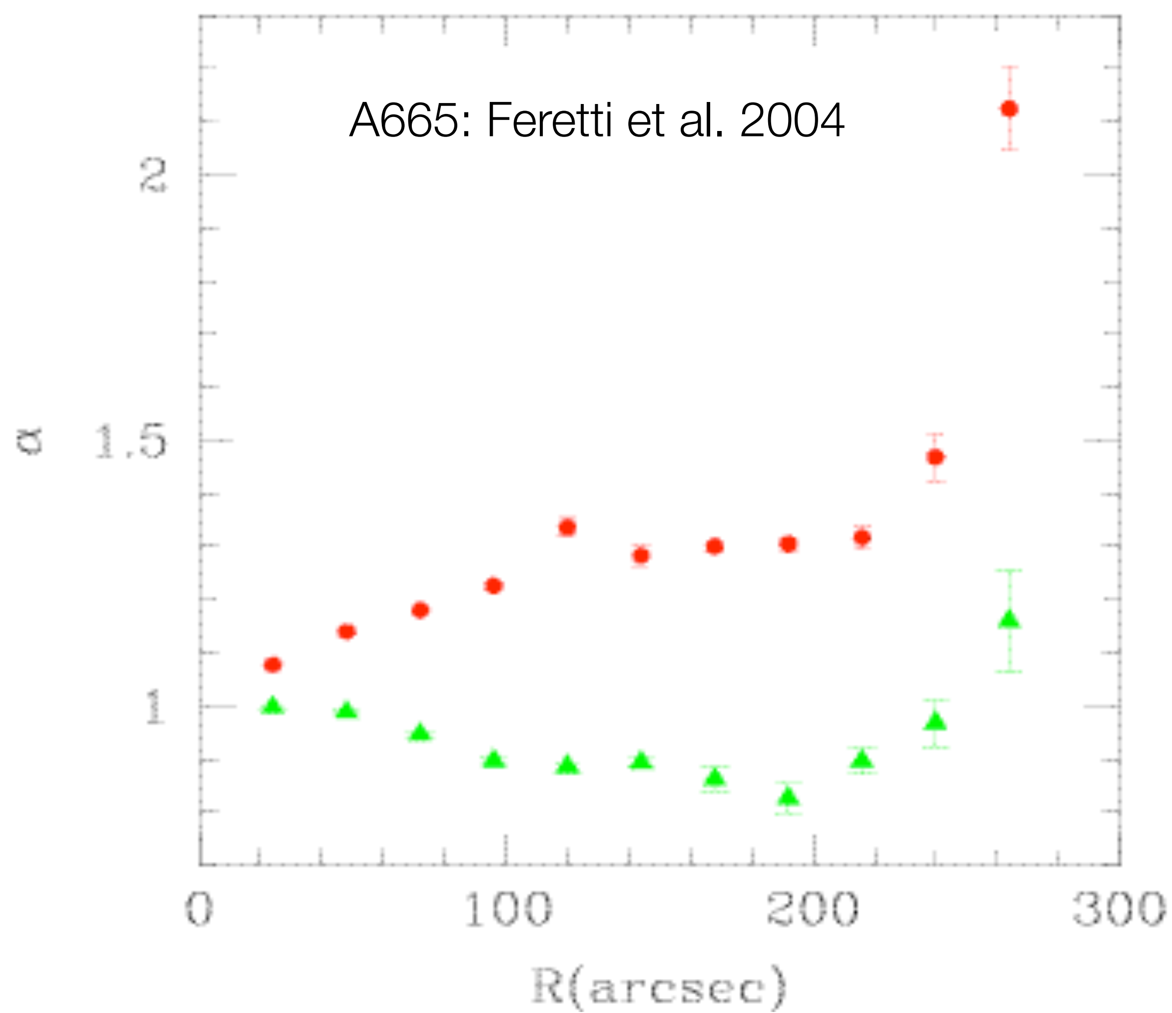

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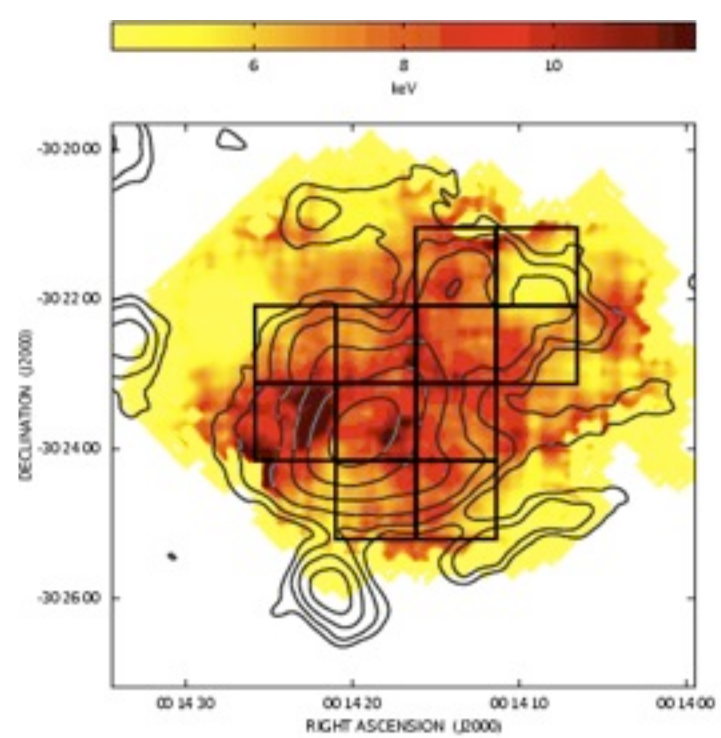
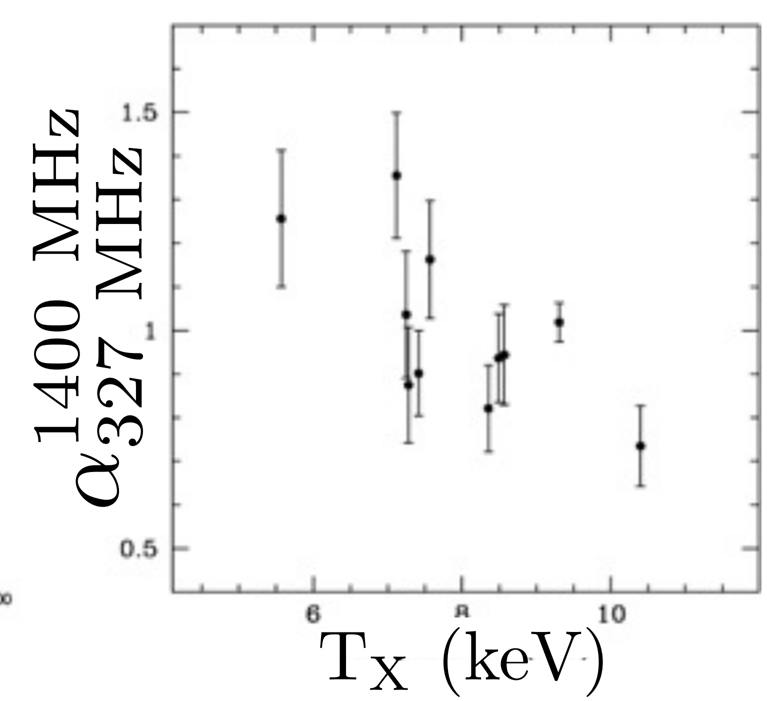


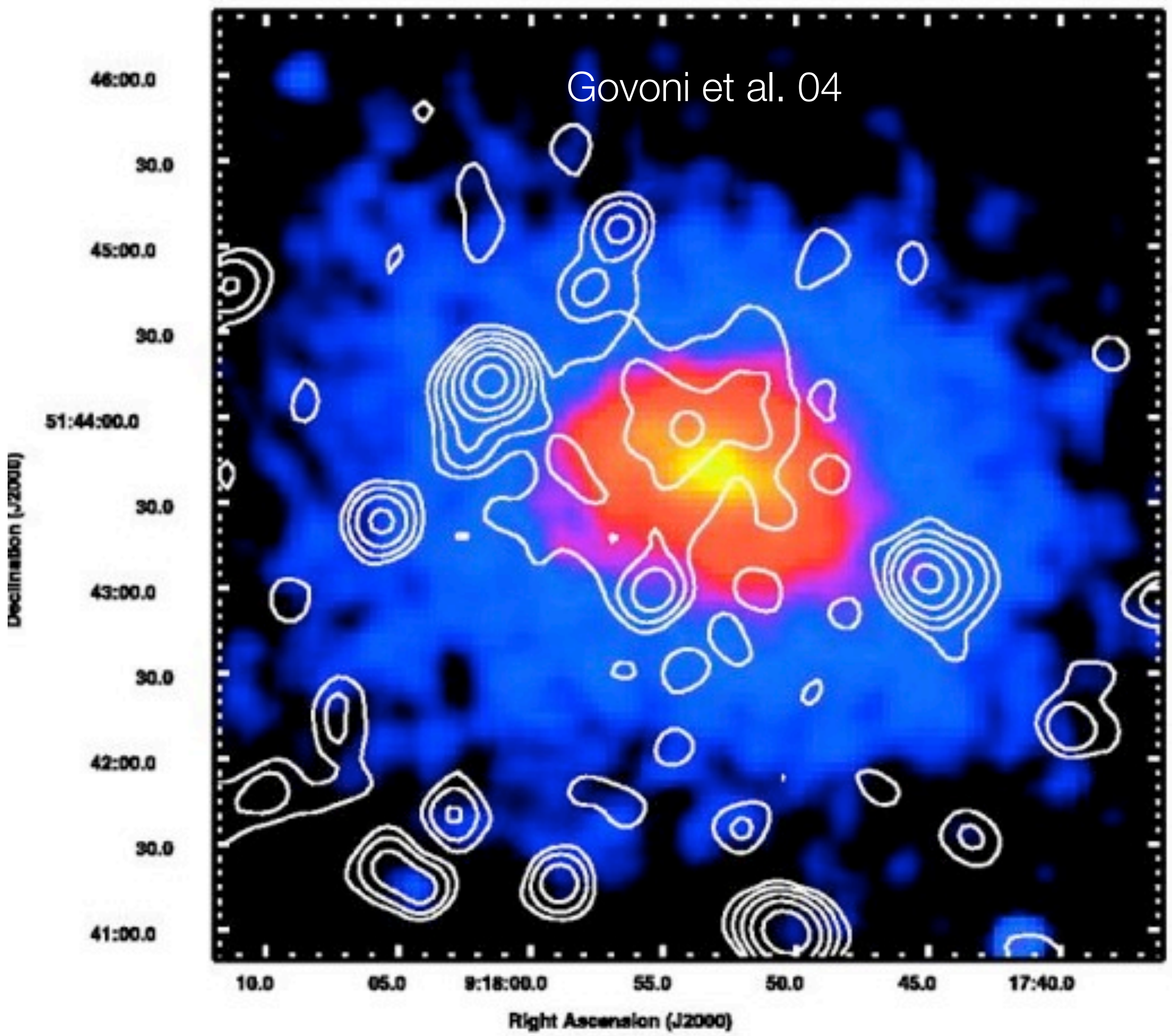
A2744: Orrù et al. 2007



Halos, relics and mini-halos

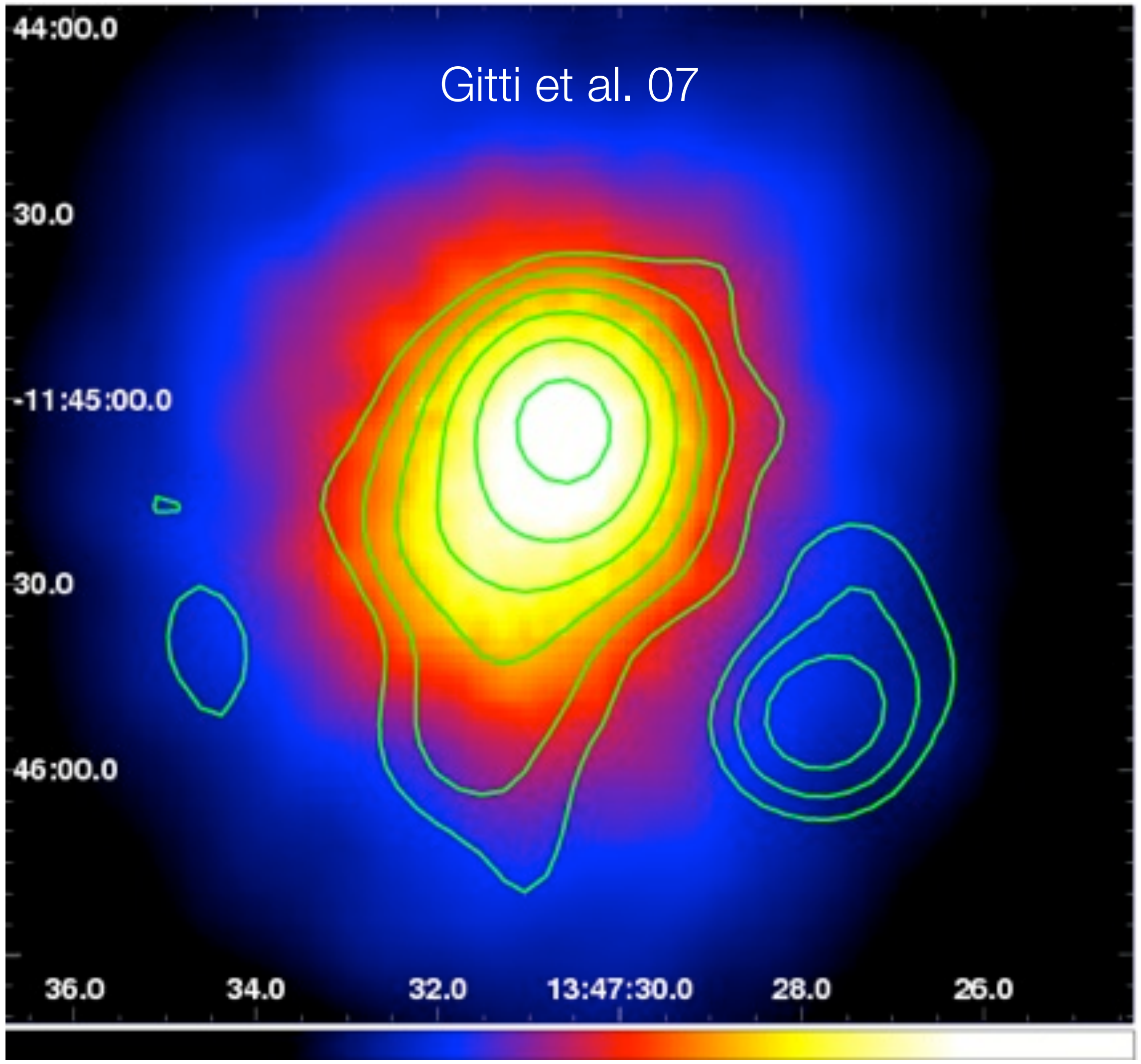
Halos, relics and mini-halos

- Halos ⇔ ICM turbulence due to cluster merging



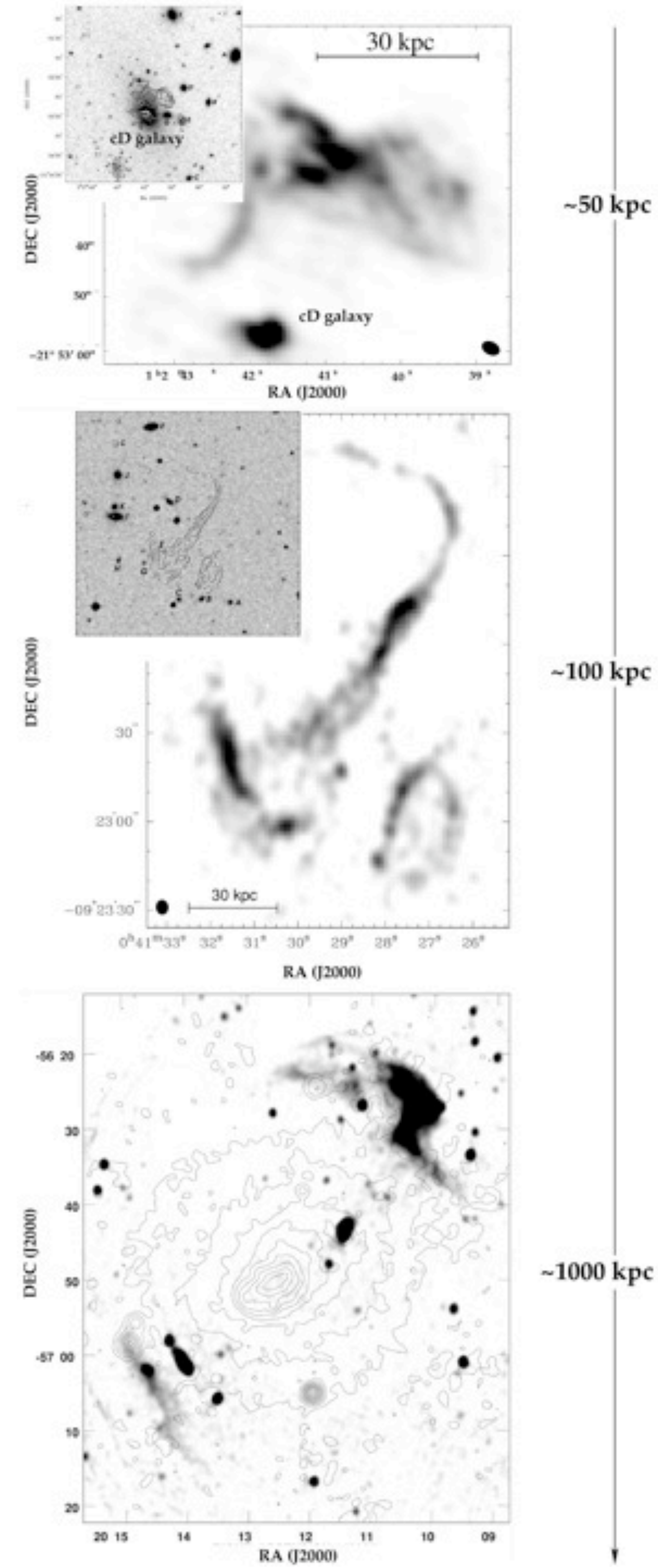
Halos, relics and mini-halos

- Halos ⇔ ICM turbulence due to cluster merging
- Mini-halos ⇔ Cooling core turbulence & AGN emission



Halos, relics and mini-halos

- Halos ⇔ ICM turbulence due to cluster merging
- Mini-halos ⇔ Cooling core turbulence & AGN emission
- Relics:
  - ✳ICM shocks due to cluster merging
  - ✳Old relativistic plasma



Ferrari et al. 08

Hybrid models: primary + secondary

Time elapsed since last MHD turbulence injection

0.75 Gyr

Brunetti et al. 2008

1.75 Gyr

Hybrid models: primary + secondary

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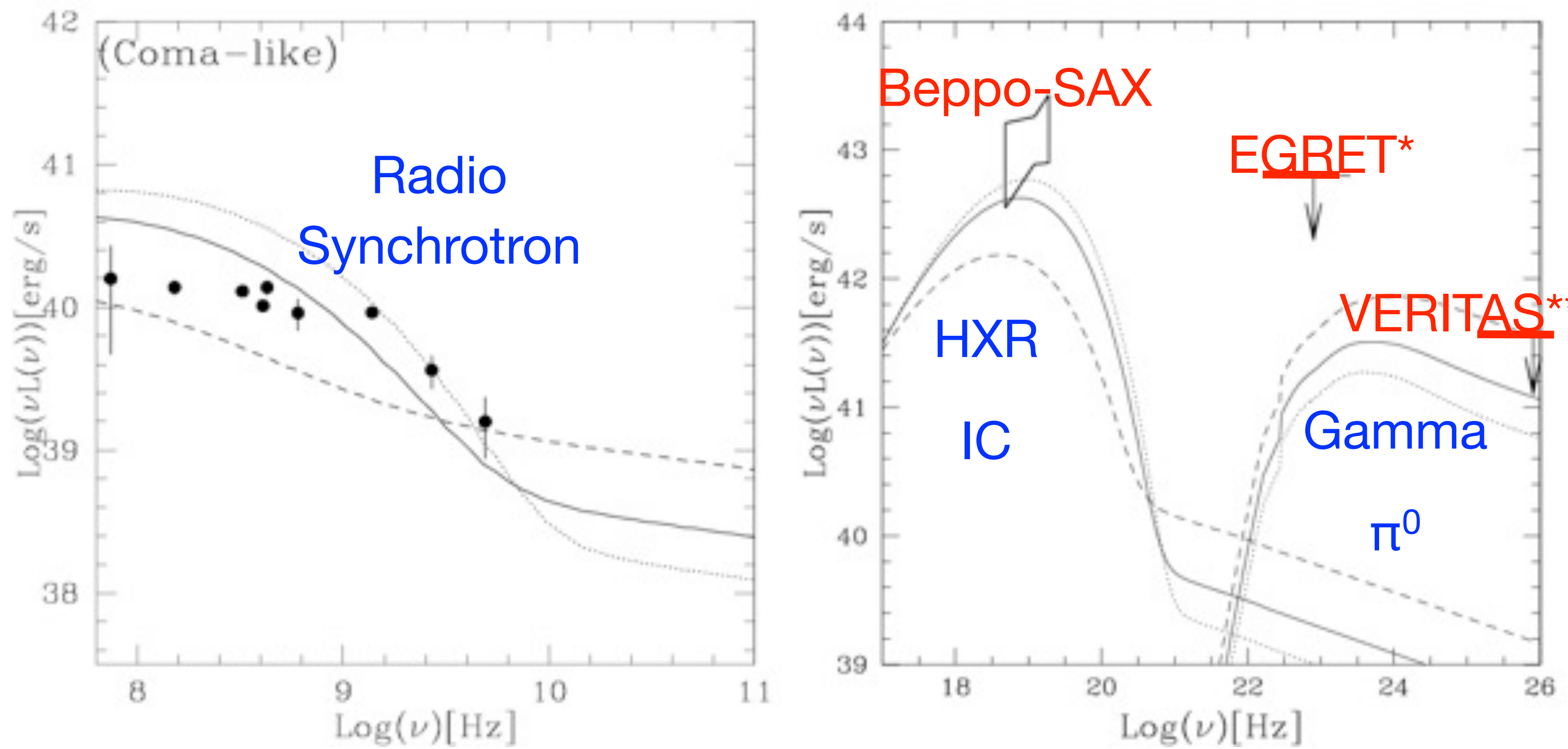


Brunetti et al. 2008

1.75 Gyr

*Reimer et al. 2003

**Perkins et al. 2008

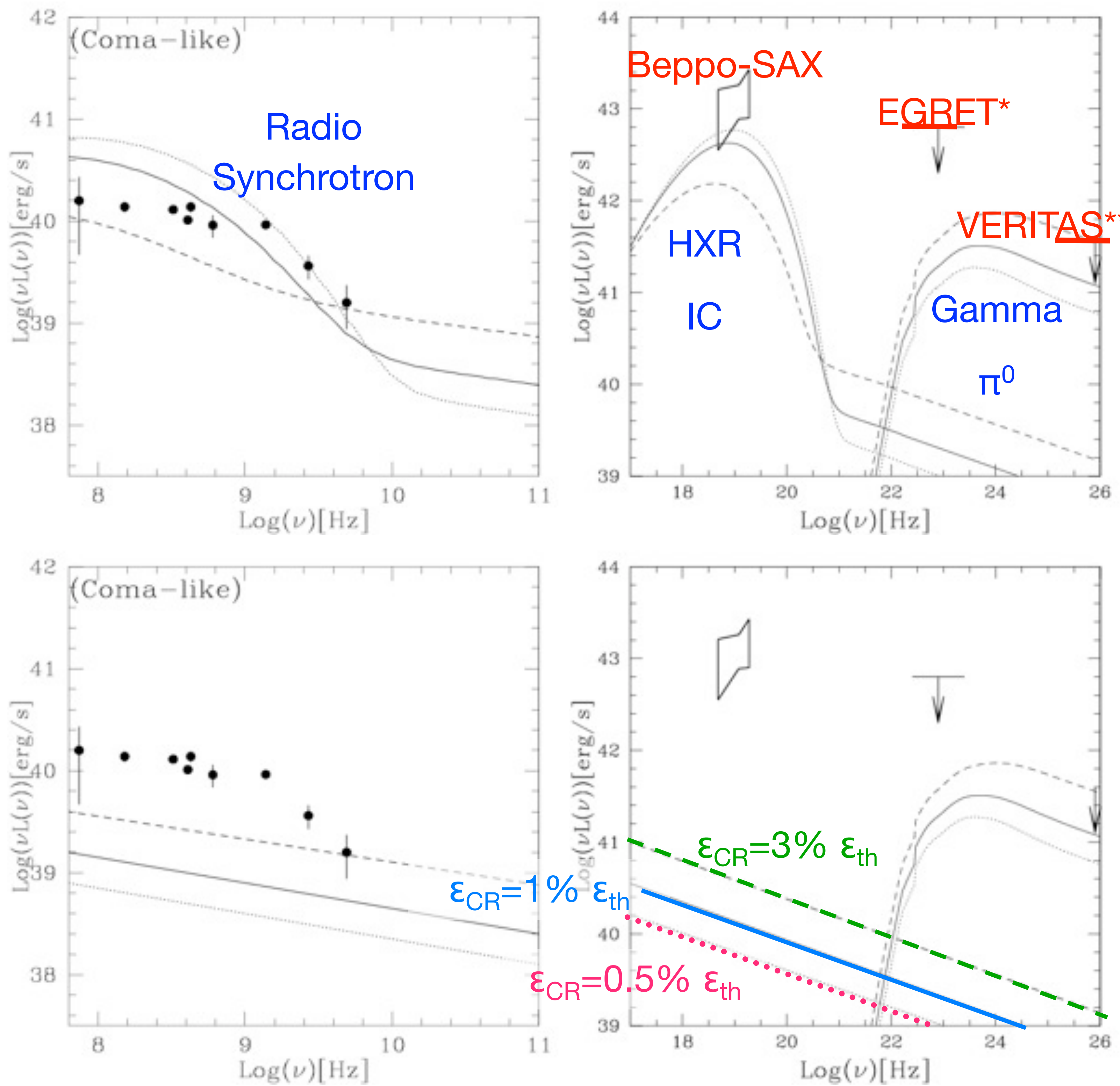
HYBRID MODELS: PRIMARY + SECONDARY

Time elapsed since last MHD turbulence injection

0.75 Gyr

1.75 Gyr

Brunetti et al. 2008



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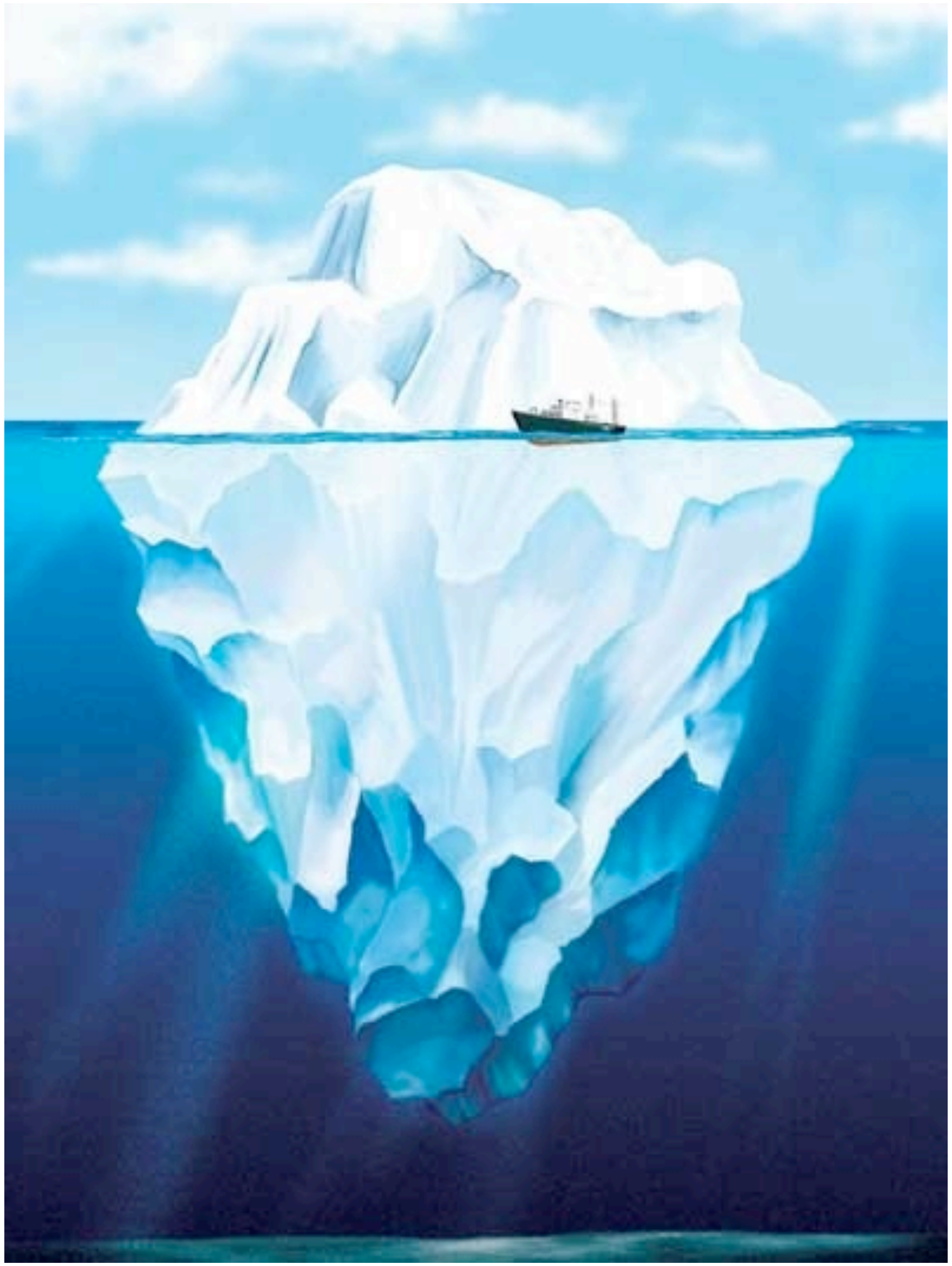
The golden-age of non-thermal cluster studies



The golden-age of non-thermal cluster studies

The golden-age of non-thermal cluster studies

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