This result is what we were looking for.

Spectral index -2 typical for many astrophysical sources.

CR's observed at Earth $\gamma = -2{,}7$

difference explained through propagation effects

Sources of cosmic rays

Galactic sources

Supernovae

We have seen already that SN produce enough energy

And shock fronts are observed at SNRs

expansion velocity of shock front up to $20-30 \cdot 10^3 \frac{km}{s}$ $\quad (M \gg 1)$

duration up to 100 000 a

$\hookrightarrow$ diameter $\sim 2-3$ kpc

SN emits radiation in x-ray regime
high plasma temperatures

radio emission through synchrotron radiation of electrons

remark: synchrotron radiation

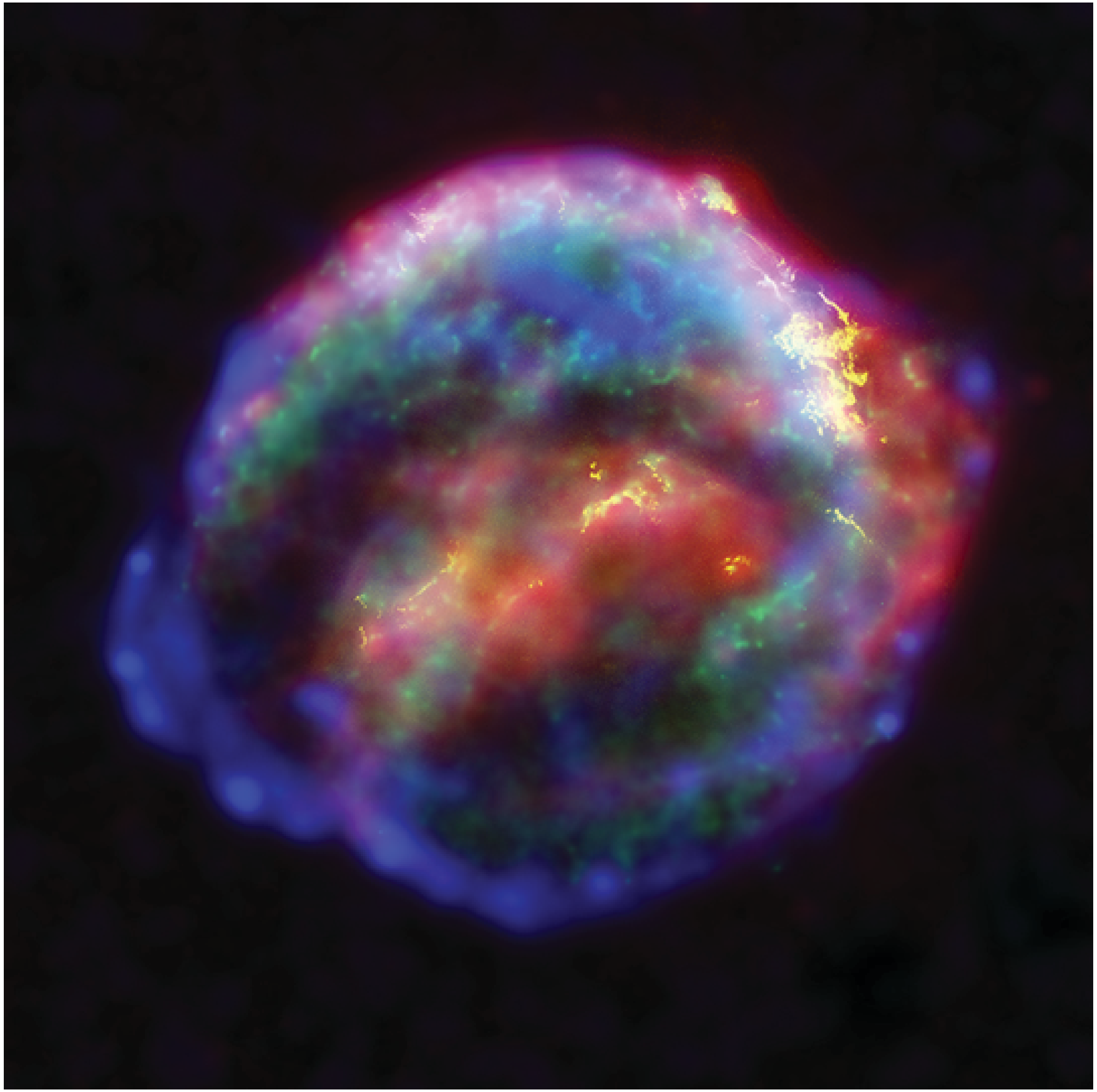
$$-\frac{dE}{dt} \propto \left(\frac{E}{m_0}\right)^4 \propto \gamma^4 \qquad (R \text{ fixed})$$

$$-\frac{dE}{dt} \propto B^2 \gamma^2$$

-> important for electrons
($\sim 10^4$ compared to protons)

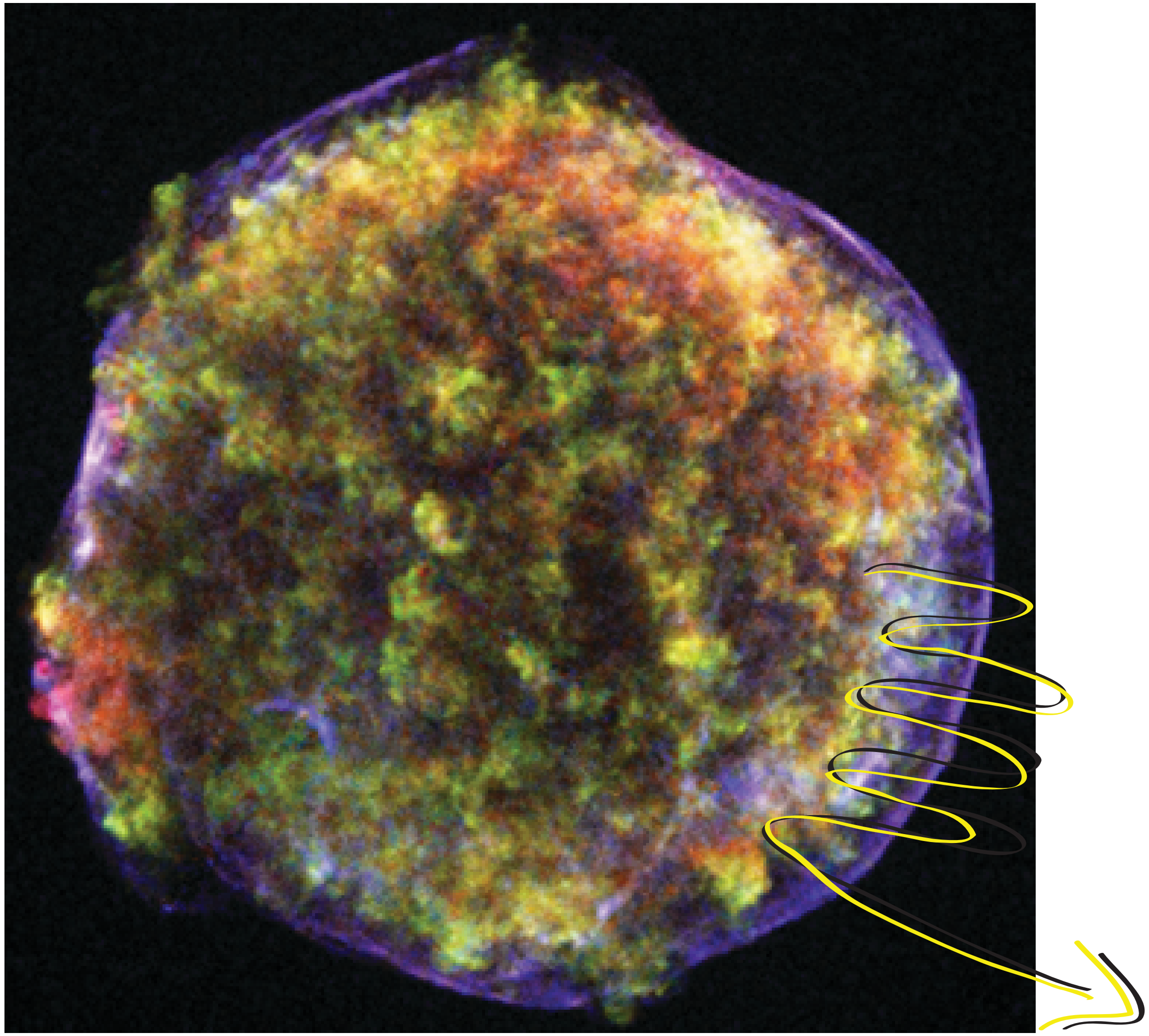
-> confirmation of shock acceleration of particles (strictly speaking only for electrons)

Kepler’s supernova 1604, d ~ 8 kpc



X-ray, Optical & Infrared Composite of Kepler's SNR

Tycho’s supernova 1572, d ~ 2.3 kpc
v_s ~ 4600 +/- 400 km/s
E_{kin} ~ $5*10^{50}$ erg

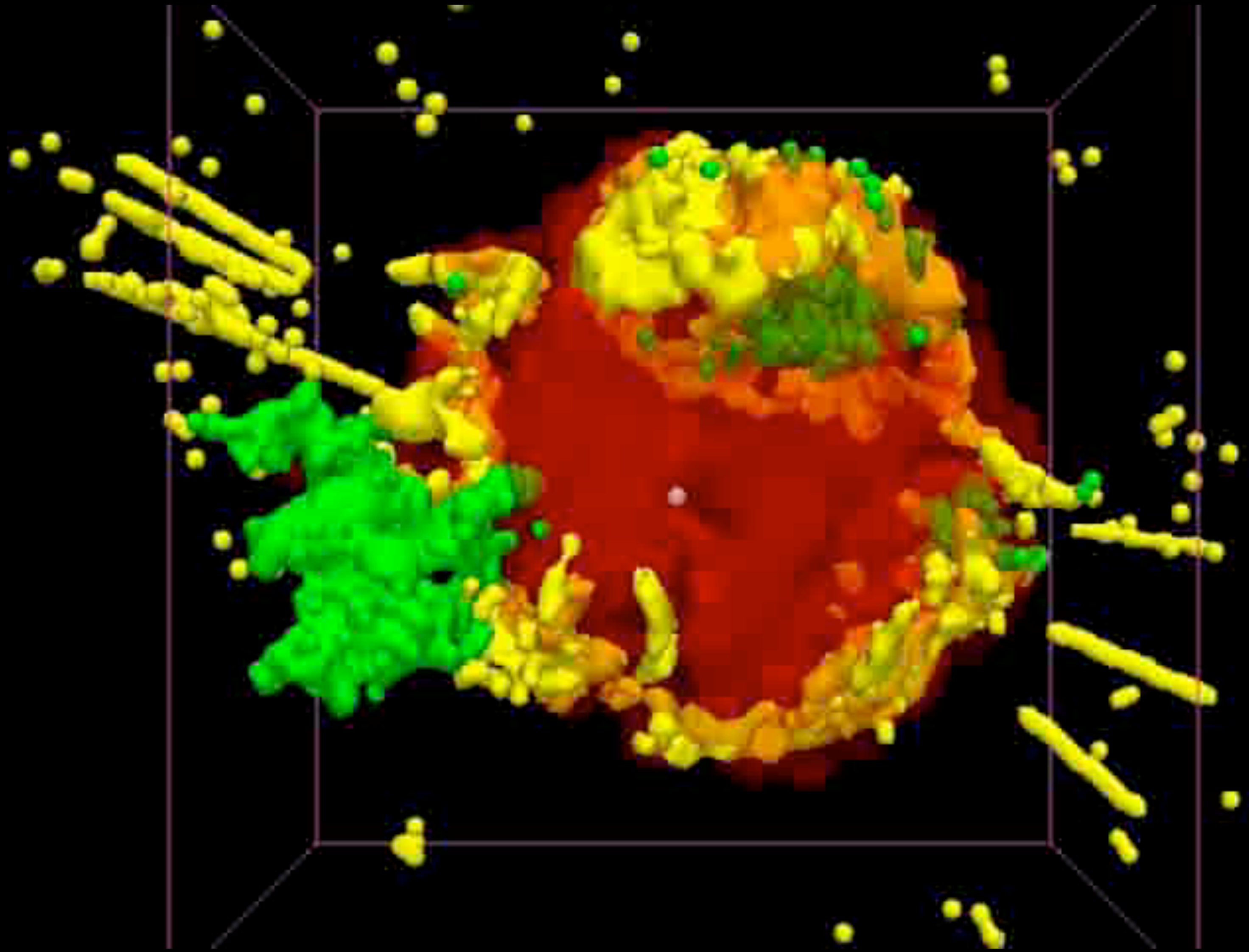


Chandra x-ray image

Cassiopeia A

This visualization shows a fly-through of Cas A based on the 3-D representation constructed from Chandra and Spitzer data. It begins with an artists rendition of the neutron star previously detected by Chandra. Next, new features unseen in traditional 2-D data sets are visible, including details of how the parent star exploded. The green region is mostly iron observed in X-rays; the yellow region is mostly argon and silicon seen in X-rays, optical and infared; the red region is cooler debris seen in the infared and the blue region is the outer blast wave, most prominent in X-rays.

Cassiopeia A



A research team has released a unique look of the supernova remnant Cassiopeia A (Cas A). By combining data from Chandra, the Spitzer Space Telescope, and ground- based optical observations, astronomers have been able to construct the first three-dimensional fly-through of a supernova remnant. This visualization (shown here as a still image) was made possible by importing the data into a medical imaging program that has been adapted for astronomical use. The green region shown in the image is mostly iron observed in X-rays; the yellow region is mostly argon and silicon seen in X-rays, optical and infared and the red region is cooler debris seen in the infared. The positions of these points in three-dimensional space were found by using the Doppler effect and simple assumptions about the supernova explosion.

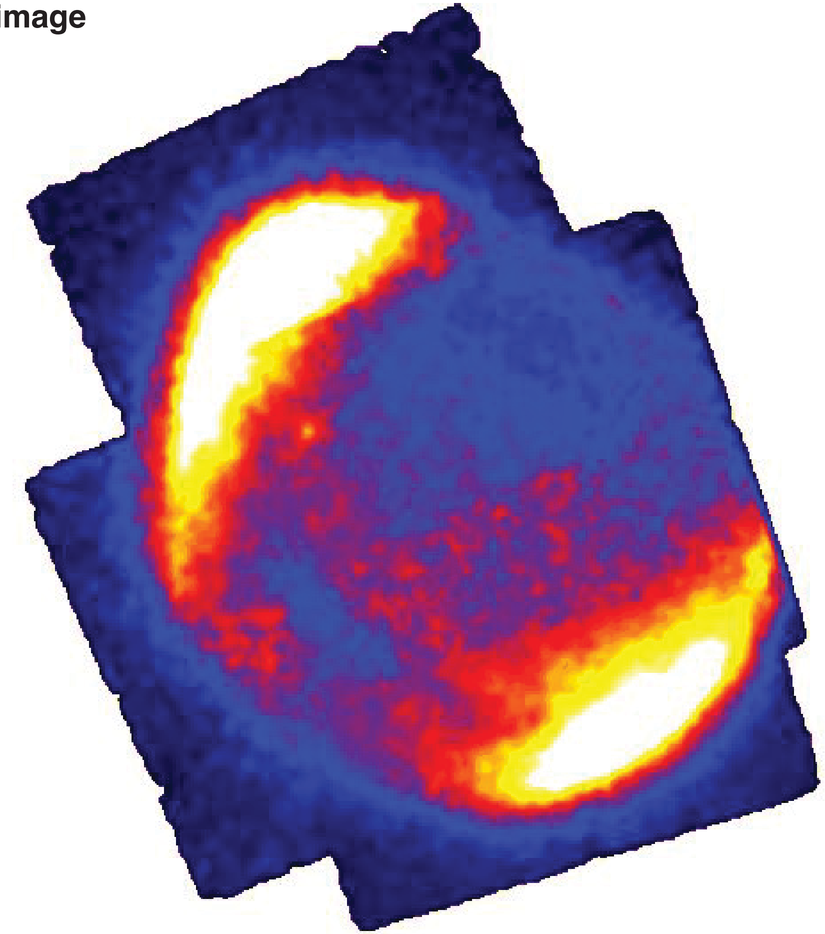
List of supernova remnants

From Wikipedia, the free encyclopedia

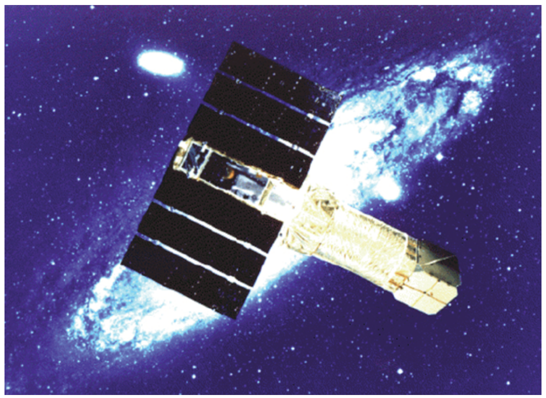
This is a list of observed supernova remnants.

Name	Date of Arrival of Supernova's Light at Earth	Apparent Magnitude	Distance (ly)	Type	Remnant
Sagittarius A East	?	?	26,000	?	Sagittarius A East
Simeis 147	>100,000 BC	?	3,000	?	Simeis 147 or Sharpless 2-240
W49B	?	?	35,000	?	GRB remnant?
W50	?	?	16,000	?	SS 433
Vela Supernova	11th-9th millennium BC	?	800	?	Vela Supernova Remnant
Veil Nebula	>3600 BC	?	1,400-2,600	?	NGC 6992-95, NGC 6979, NGC 6960
Puppis A	?	?	?	?	
SN 185	December 7, 185	-8?	3,000	Ia?	Possibly RCW 86
SN 1006	May 1, 1006	-7.5	7,200	Ia[1]	SNR 1006
SN 1054	1054	-6	6,300	II	Crab Nebula
G350.1-0.3	about 1100	?	approx. 15,000	?	G350.1-0.3
SN 1181	1181	-1	?	?	Possibly 3C58
RX J0852.0-4622	about 1250	?	700	?	G266.2–1.2
SN 1572	November 11, 1572	-4	7,500	Ia[1]	Tycho's Supernova Remnant
SN 1604	October 8, 1604	-2.5	20,000	Ia	Kepler's Supernova Remnant
Cassiopeia A	mid 17th century	+6	10,000	IIb[2]	Cassiopeia A Supernova Remnant
G1.9+0.3	about 1868	?	approx. 25,000	?	Supernova remnant G1.9+0.3
SN 1885A	August 20, 1885	+6	2,500,000	?	SNR 1885A
SN 1987A	February 24, 1987	+3	168,000	II-P	SNR 1987A

SN 1006
x-ray image



ASCA (Advanced Satellite for Cosmology and Astrophysics)



Maximum energy attained during acceleration at SNR

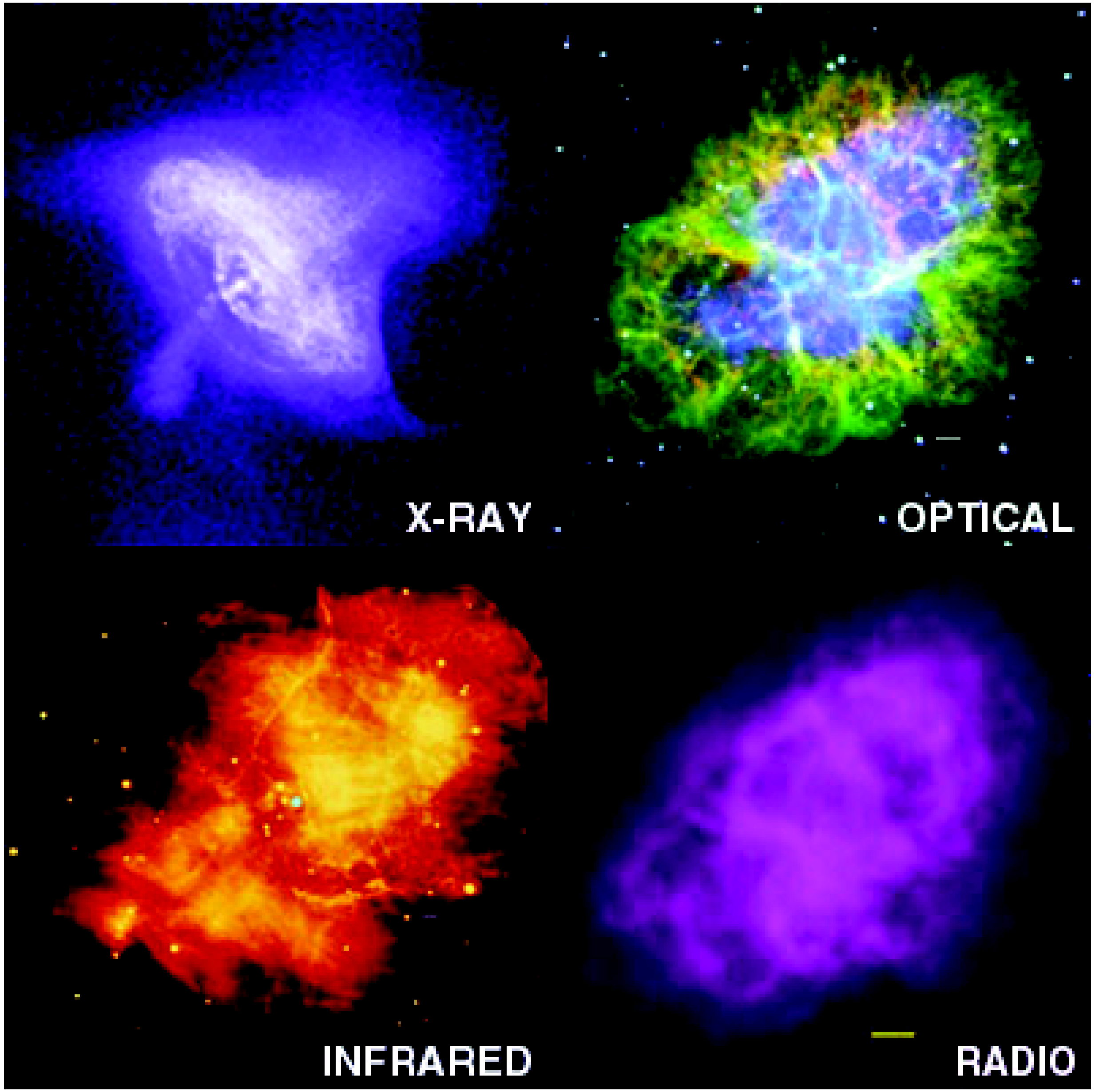
$$E_{max} \propto Z \cdot B \cdot R \cdot \beta_s$$

$$E_{15} \lesssim \underset{}{Z} \cdot \underset{\sim 5}{B_{\mu G}} \cdot \underset{\sim 1}{R_{pc}} \cdot \underset{\sim 0{,}1}{\beta_s}$$

$$\Rightarrow E_{max} \approx Z \cdot 10^{15}\,\text{eV} \pm 1 \text{ order of magnitude}$$

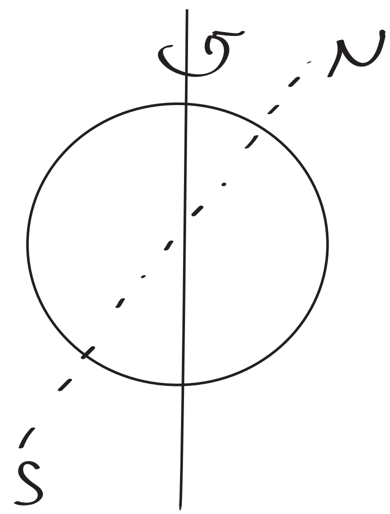
In addition to shell-type SNRs there are also filled-center SNRs

Crab Nebula - supernova of 1054



Pulsars

rotating neutron stars, left over from SN



$B \sim 10^{12}$ G

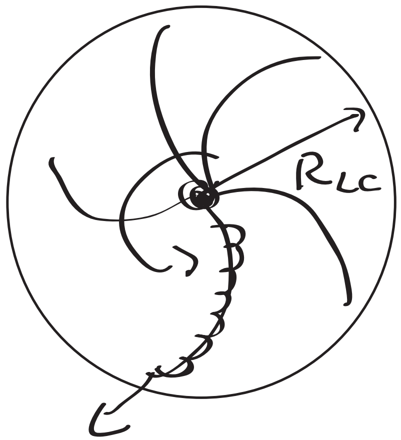
$M \sim 1{,}5\, M_\odot$

$\nu \sim 10 - 1000$ Hz

$E_{rot} \sim 10^{53}$ erg

particles $e^+ e^-$ are produced at high-B-field regions around the poles

particles move along B-field lines out to light cylinder



$$v_{max} = c = \frac{2\pi R_{LC}}{T}$$

$$\Rightarrow R_{LC} = \frac{c}{\omega}$$

$$\text{e.g. } R_{LC} = \frac{3 \cdot 10^{8} \frac{m}{s}}{1000\,Hz} = 300\,km$$

Second possible process:

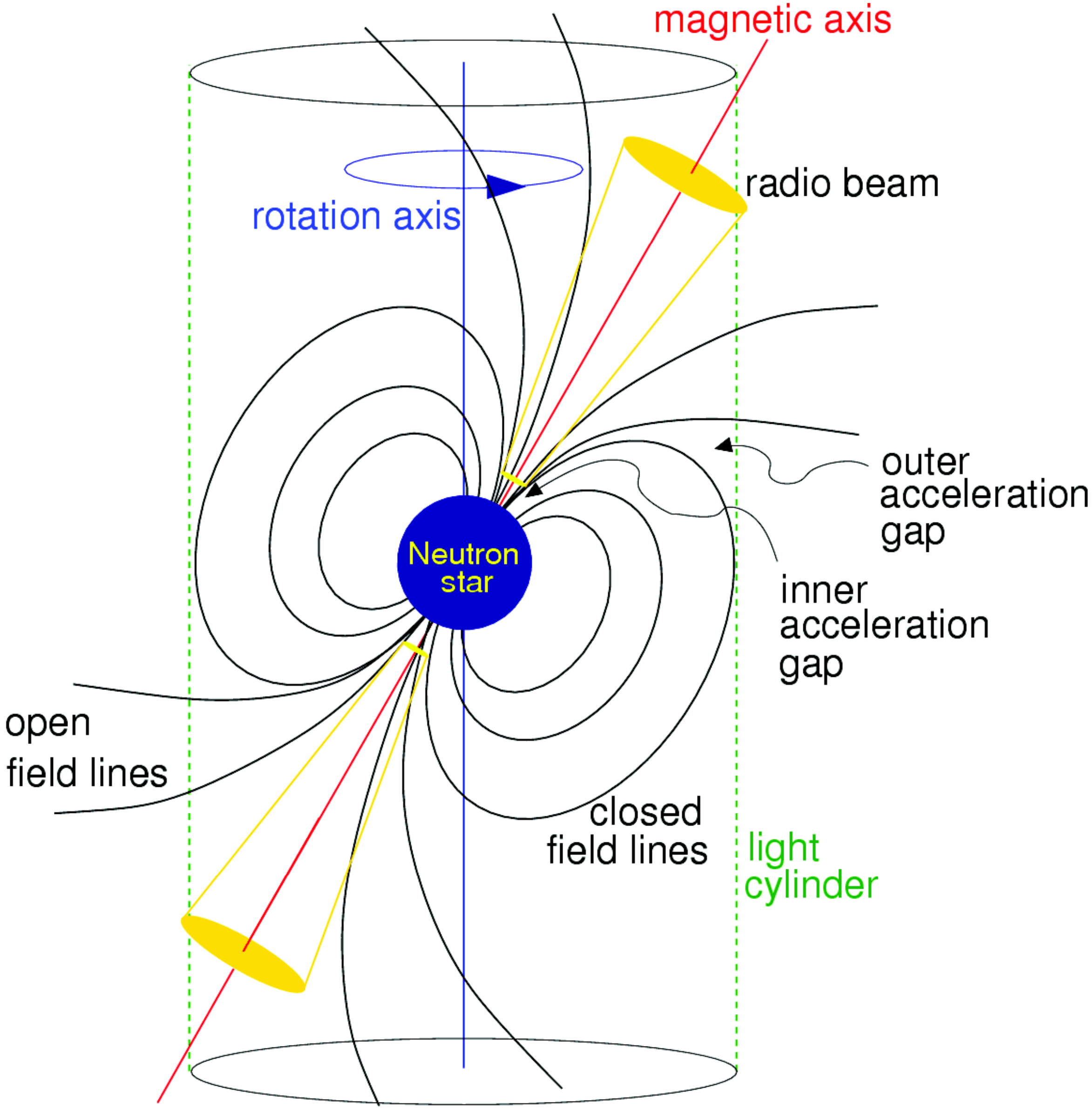
high electric fields between poles & equator

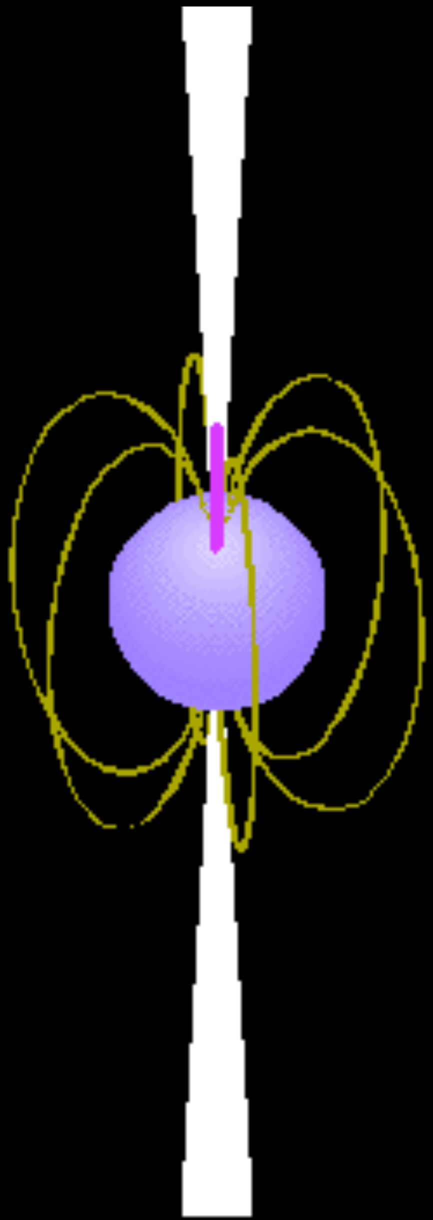
$$E = v \times B \cdot z$$

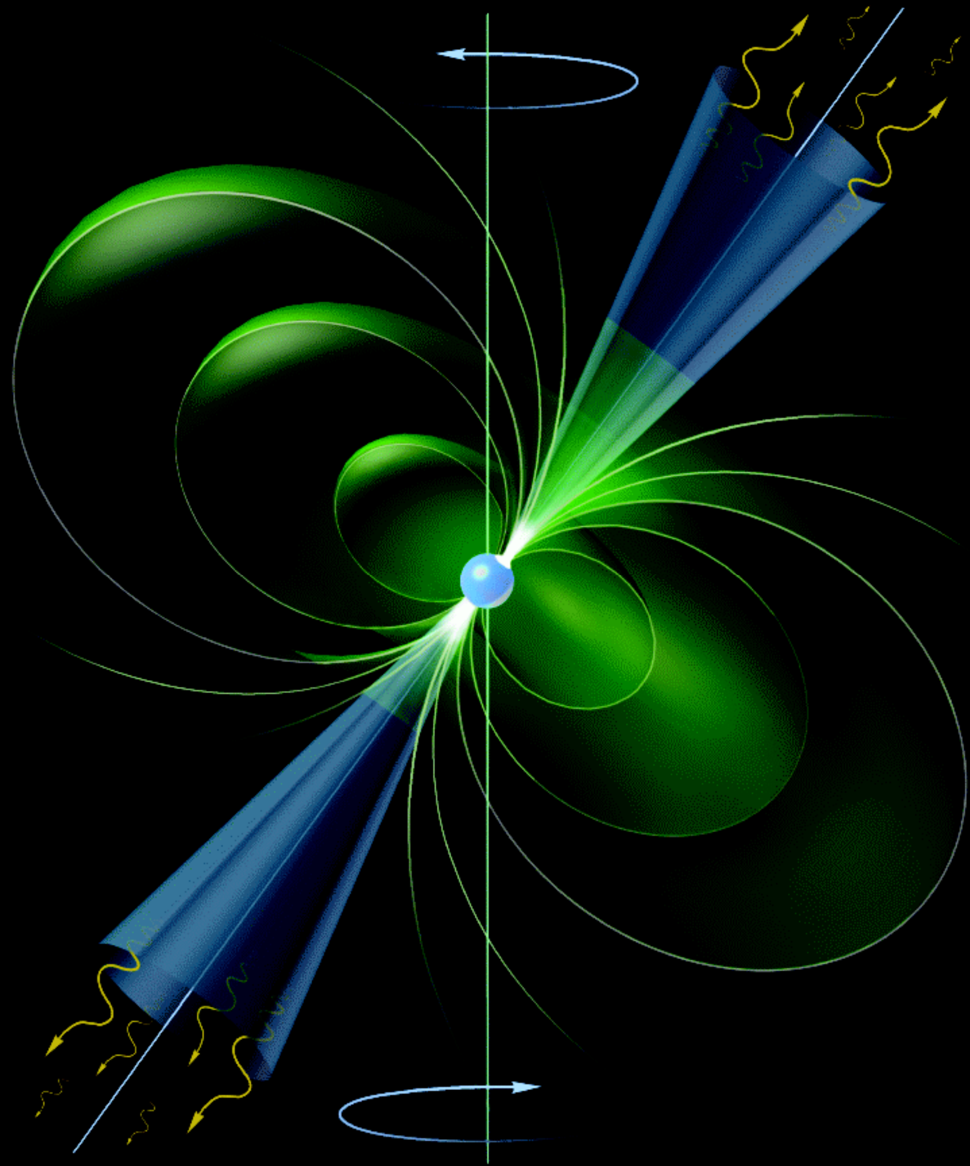
$$\sim \omega \cdot R \cdot B \cdot z$$

$$\sim 100 \frac{1}{s} \cdot 1000\,m \cdot 10^{8}\,T$$

$$\sim 10^{13} \frac{V}{m}$$


magnetic axis
radio beam
rotation axis
outer
acceleration
gap
Neutron
star
inner
acceleration
gap
open
field lines
closed
field lines
light
cylinder





$$E_{max} \sim Z \cdot \omega \cdot R^2 \cdot B \sim 10^{16}\, eV$$

Problems:

1) strong field is "shorted" through e^+e^- pairs

2) both processes yield single energies
but no power law

$\Rightarrow$ SNRs are regarded as most plausible
accelerators of CRs

Extragalactic sources

Important for high-energy astrophysics:

active galaxies and their cores: AGN

1940 Mt. Wilson 1^{st} observation of AGN

Karl Seyfert

a few % of spiral galaxies have bright cores

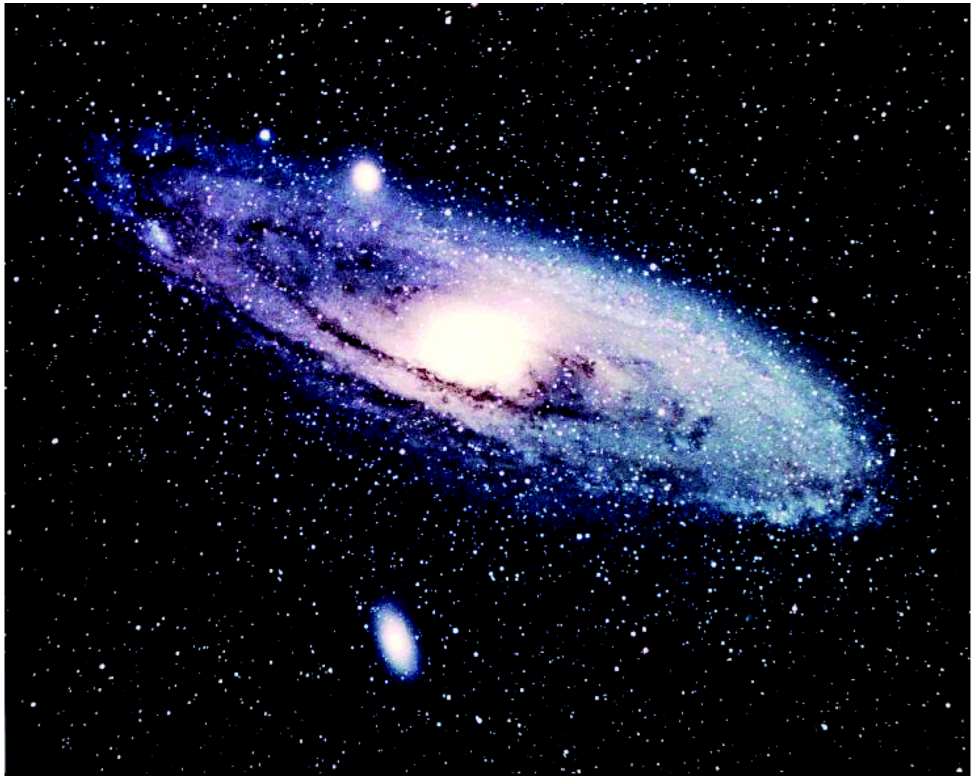
with strong emission lines
& wide

widths caused by Doppler effect

→ turbulent gas with high velocities

→ v a few % of c

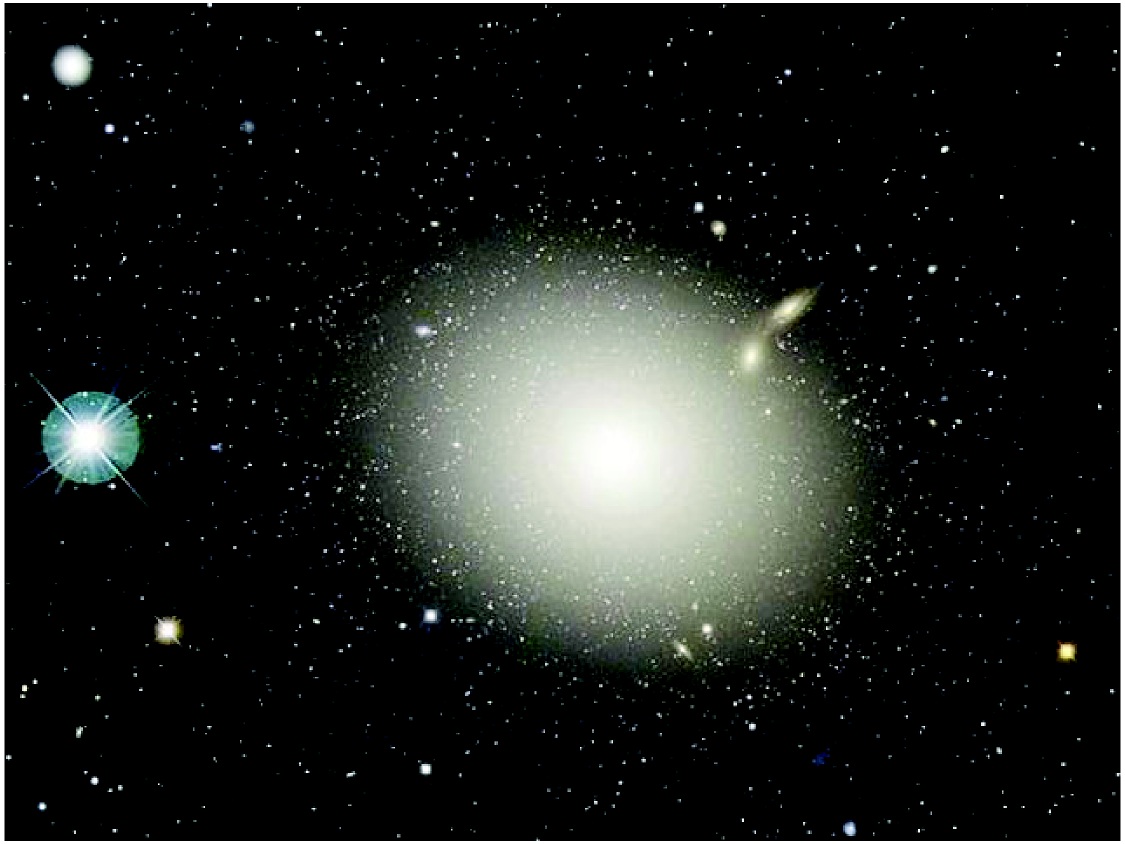
spiral galaxies



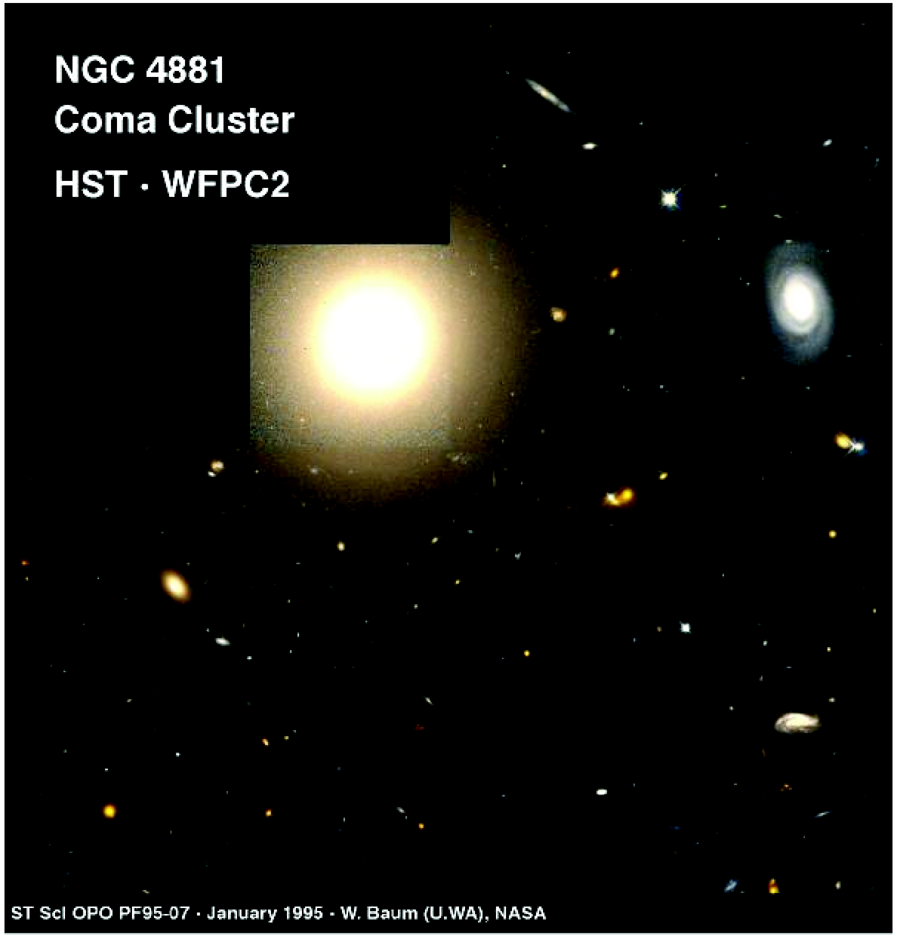
M31 Andromeda

M 74 Gemini galaxy

elliptical galaxies

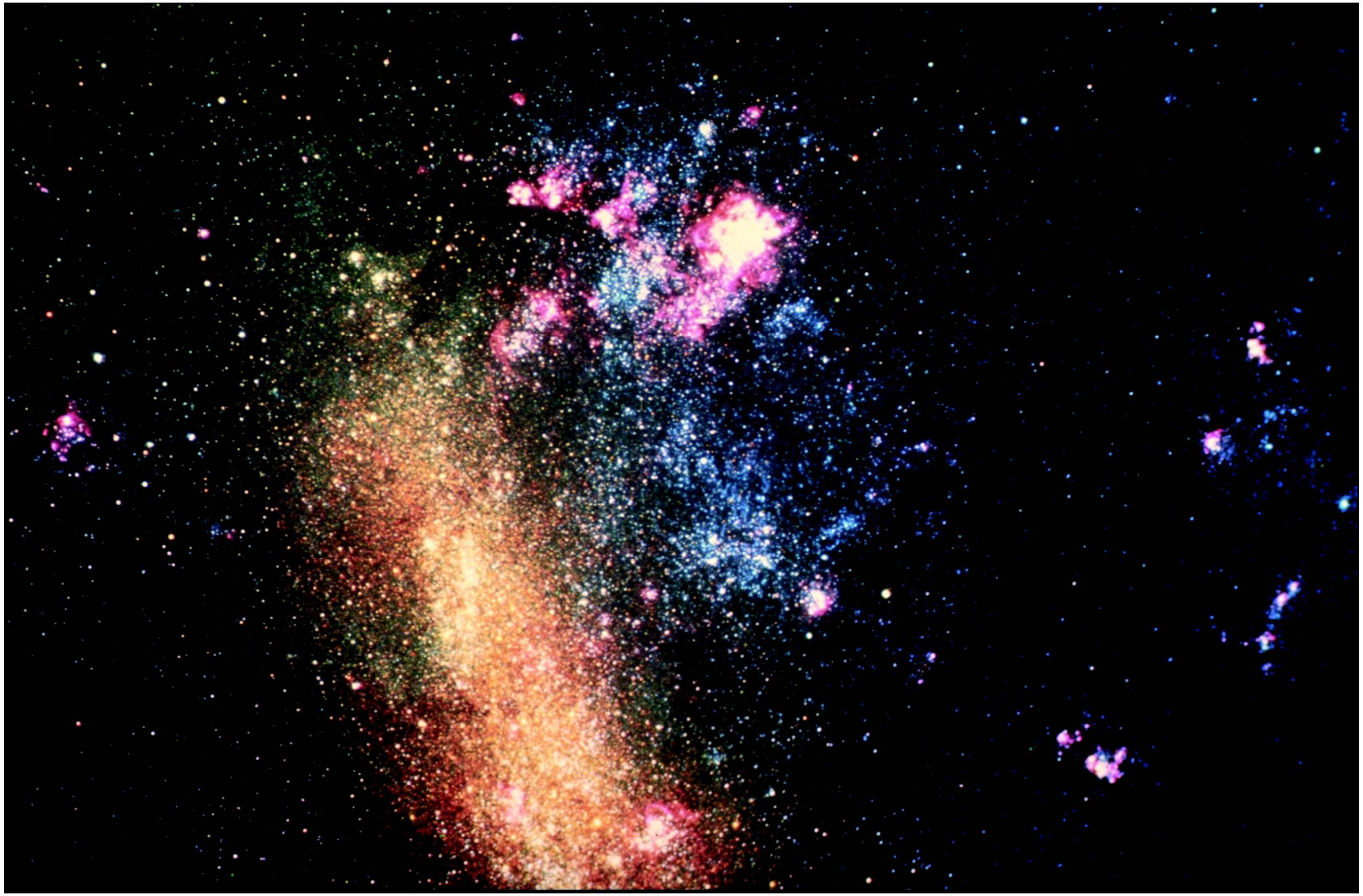


M 87



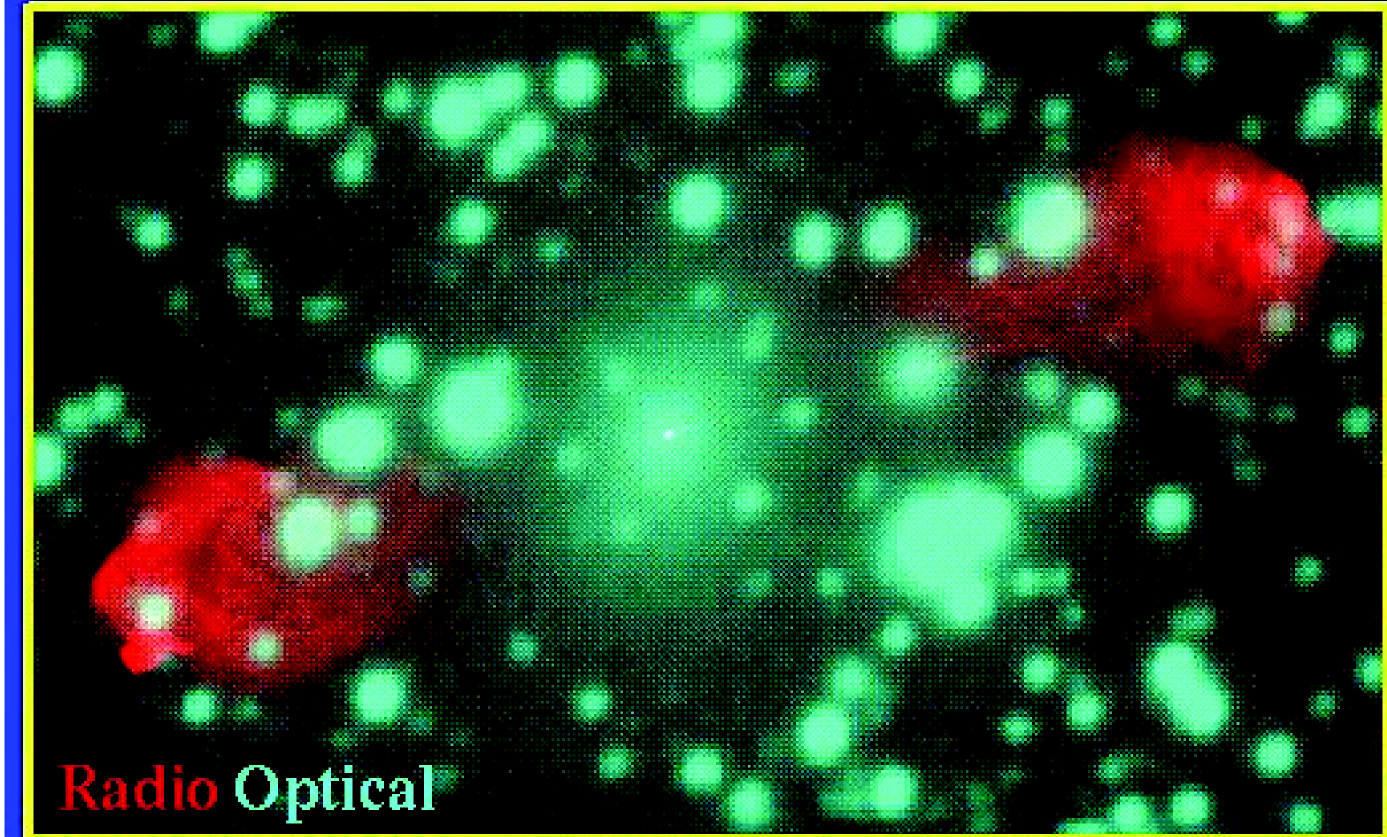
NGC 4881

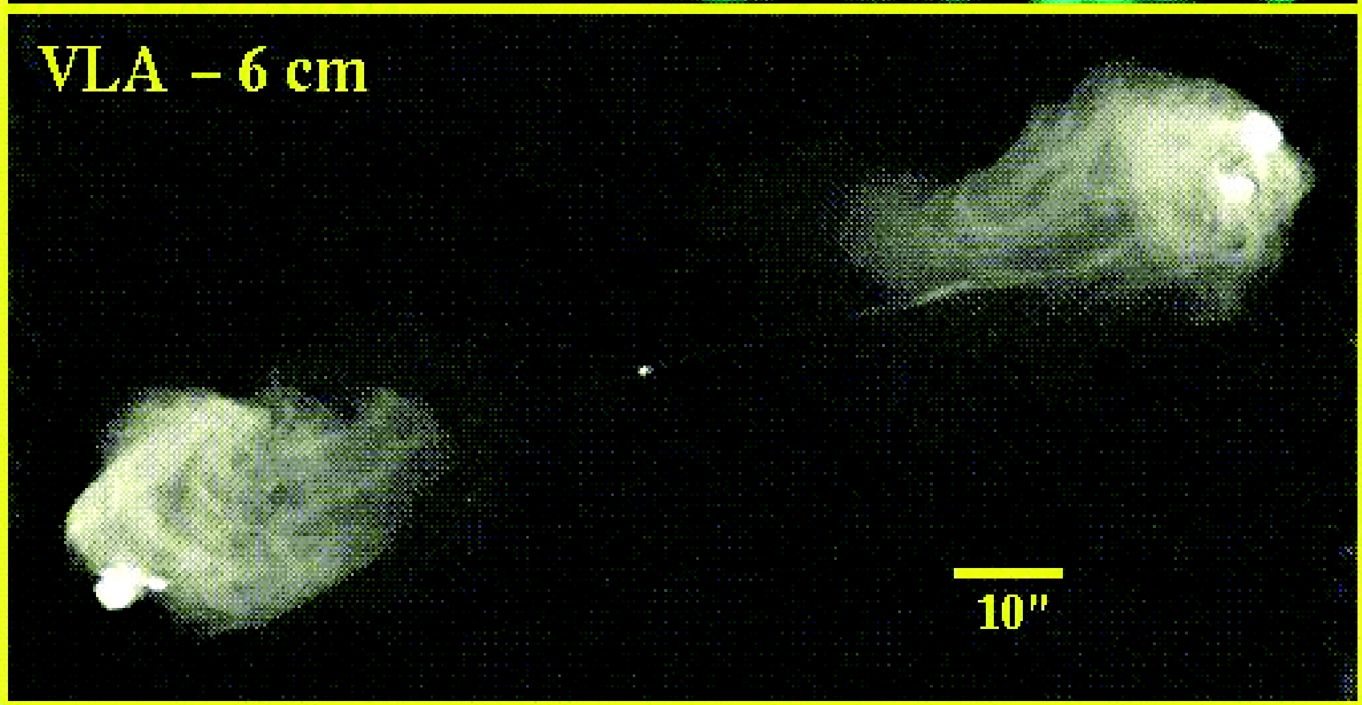
irregular galaxies



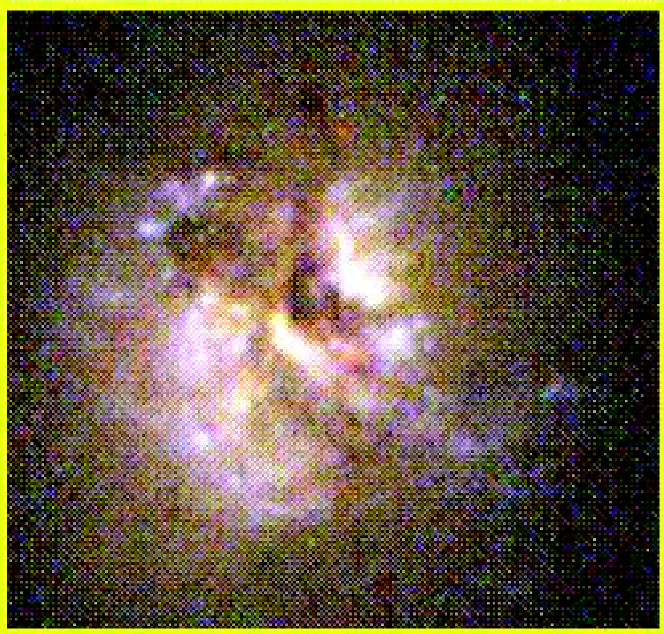
Large Magellanic Cloud

Cygnus A
(3C 405)





HST closeup



5″

$\Rightarrow$ Seyfert galaxies

1954 1st observation in radio astronomy
bright radio sources in a galaxy
at $z = 0{,}05 \rightarrow d = \frac{c \cdot z}{H_0} \sim 300$ Mpc

Cygnus A

later with better resolution:
radio emission originates in two regions
~ 100 kpc away from center

explanation: radio emission is generated through
electrons in B fields → synchrotron
radiation

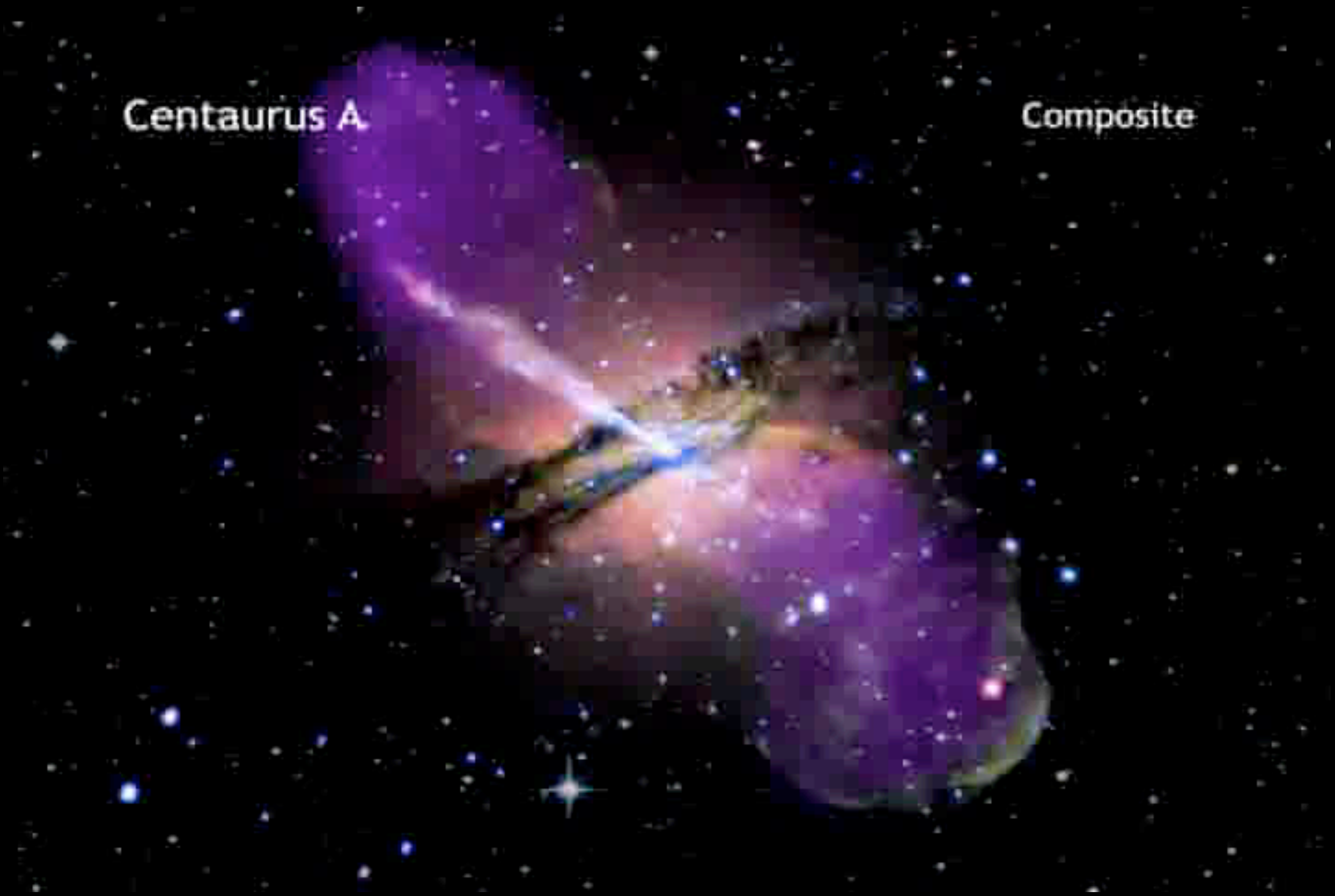
radiated energy is significantly larger
as compared to SNR

energy originates in the core (AGN)
in a black hole

~ up to 40% of the rest mass can be
converted to radiation

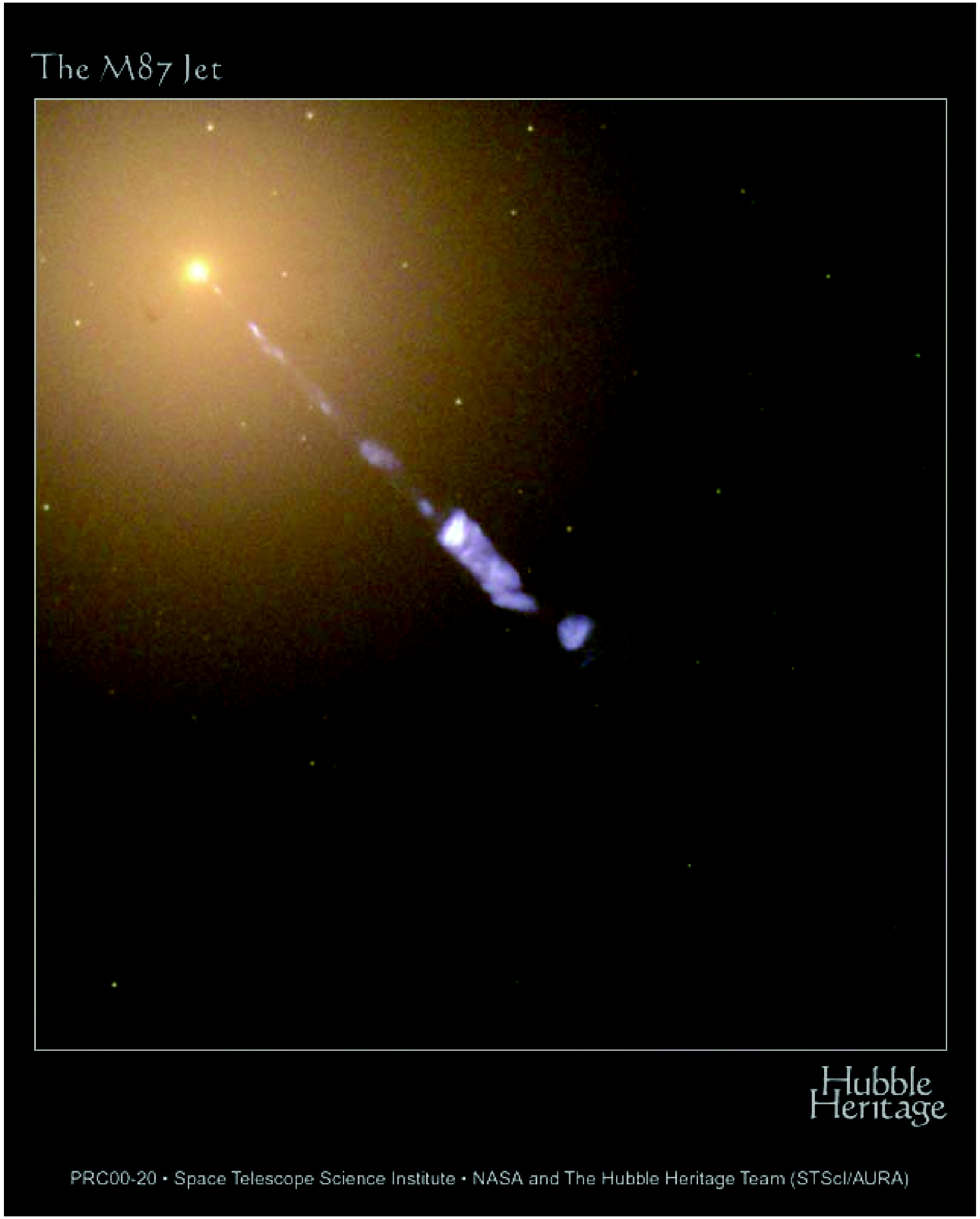
Cen A

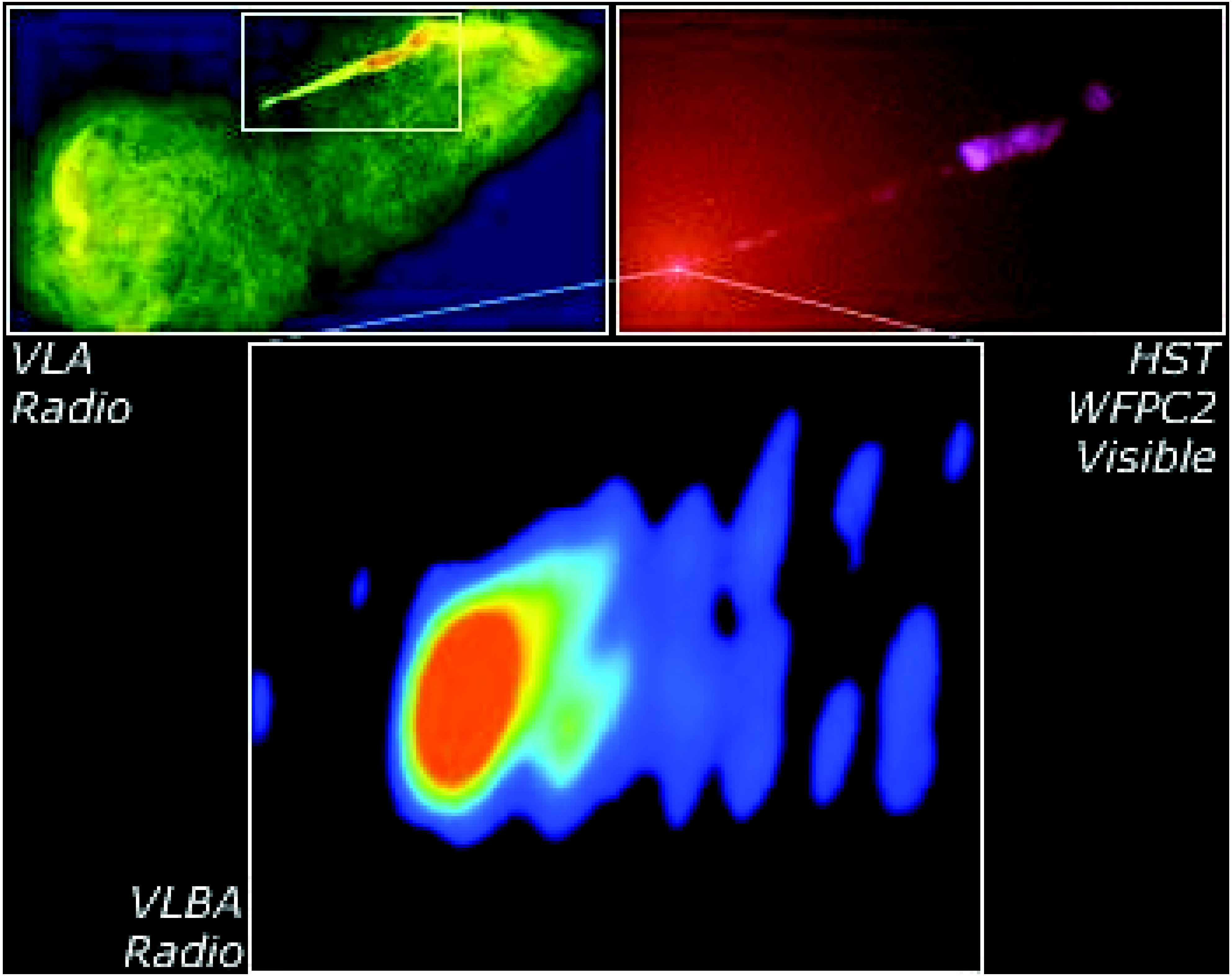
Centaurus A



There is nothing subtle about the black hole in the galaxy Centaurus A. First off, it's about 10 million times more massive than the sun, and Chandra's X-ray image shows it's not just sitting quietly as a bright point in the middle. Instead, the monster black hole is responsible for powering massive jets, including one that extends to the upper left for some 13,000 light years. Radio data also show the effect of these jets far beyond the plane of the galaxy. An image in optical light shows the elliptical galaxy and the dark bands running almost perpendicular to the jet. These are caused by dust lanes created when Centaurus A merged with another galaxy, perhaps 100 million years ago. The combination from all of these telescopes shows us just how much is really going on in Centaurus A.

M 87


The M87 Jet
Hubble Heritage
PRC00-20 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)


VLA
Radio
HST
WFPC2
Visible
VLBA
Radio

classification today:

AGN: general term

Seyfert galaxies
- radio loud
- radio quiet

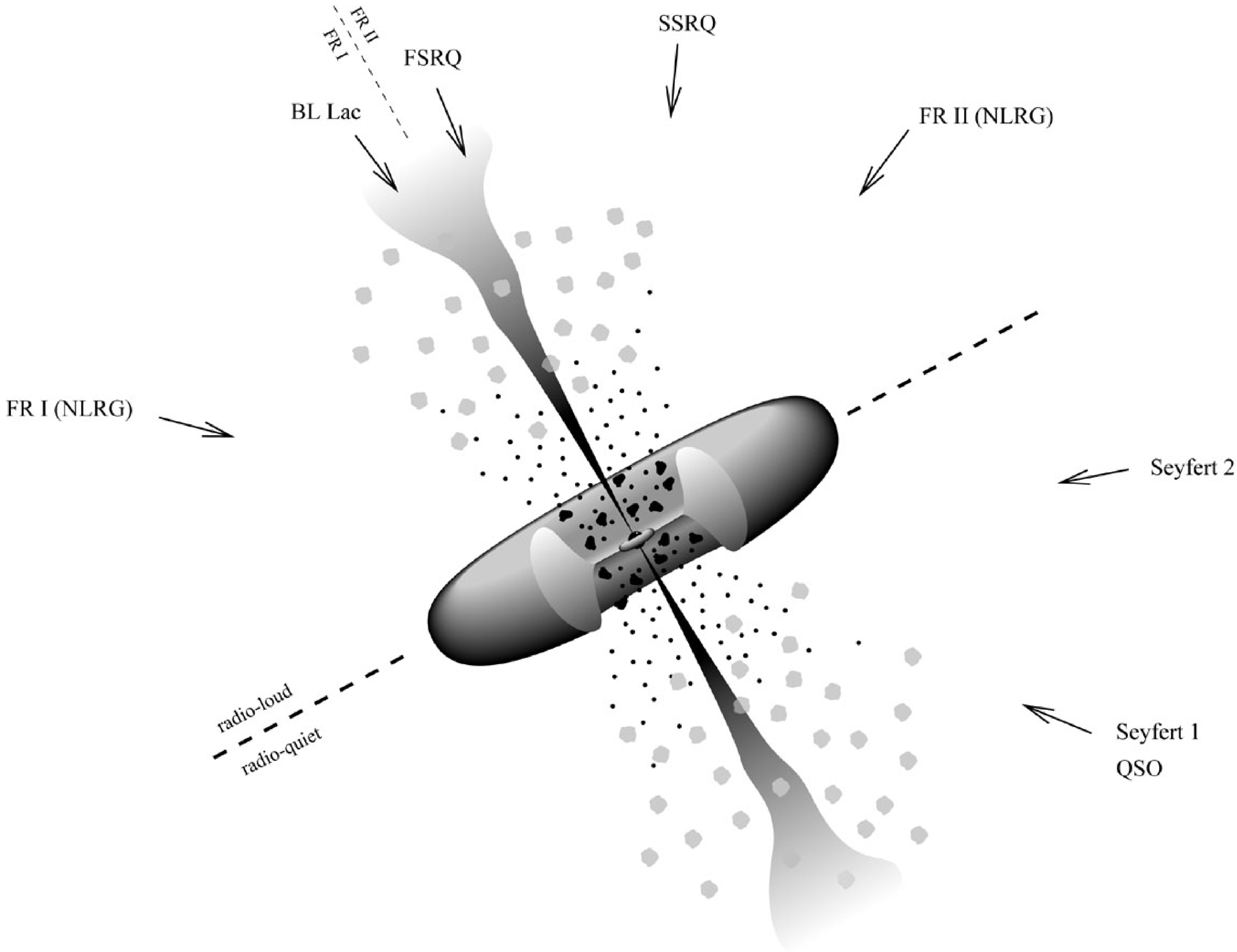
Radio galaxies
- Fanaroff-Riley II
- I

Quasars

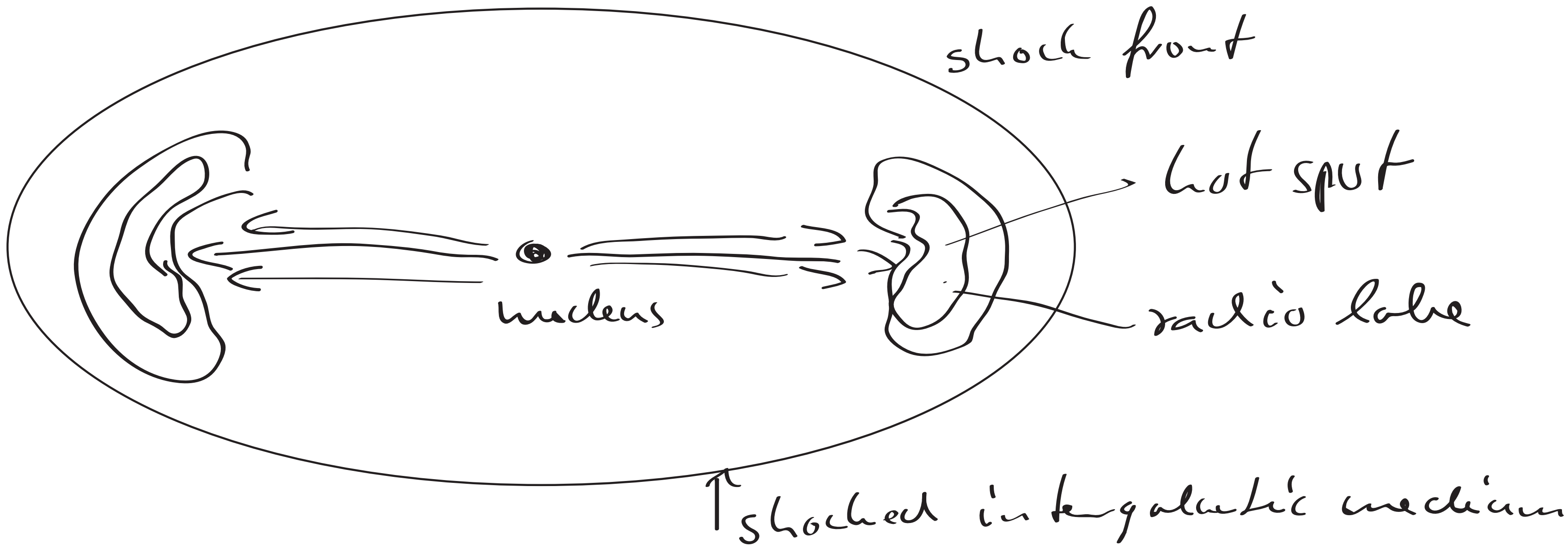
Blasars (BL-Lac & Quasar)

Markarian galaxies

classification is according to morphology of jets, brightness, ...


FR II
FR I
SSRQ
FSRQ
BL Lac
FR II (NLRG)
FR I (NLRG)
Seyfert 2
Seyfert 1
QSO
radio-loud
radio-quiet

origin of jets & radio lobes:



energy is delivered to lobes from the AGN

fast stream of gas -> jet

ISM close to galaxy
IGM further out
} resistance for jet

→ end of jet is slowed down

→ energy is concentrated at end of jet

→ hot spots

gas in jet moves close to c

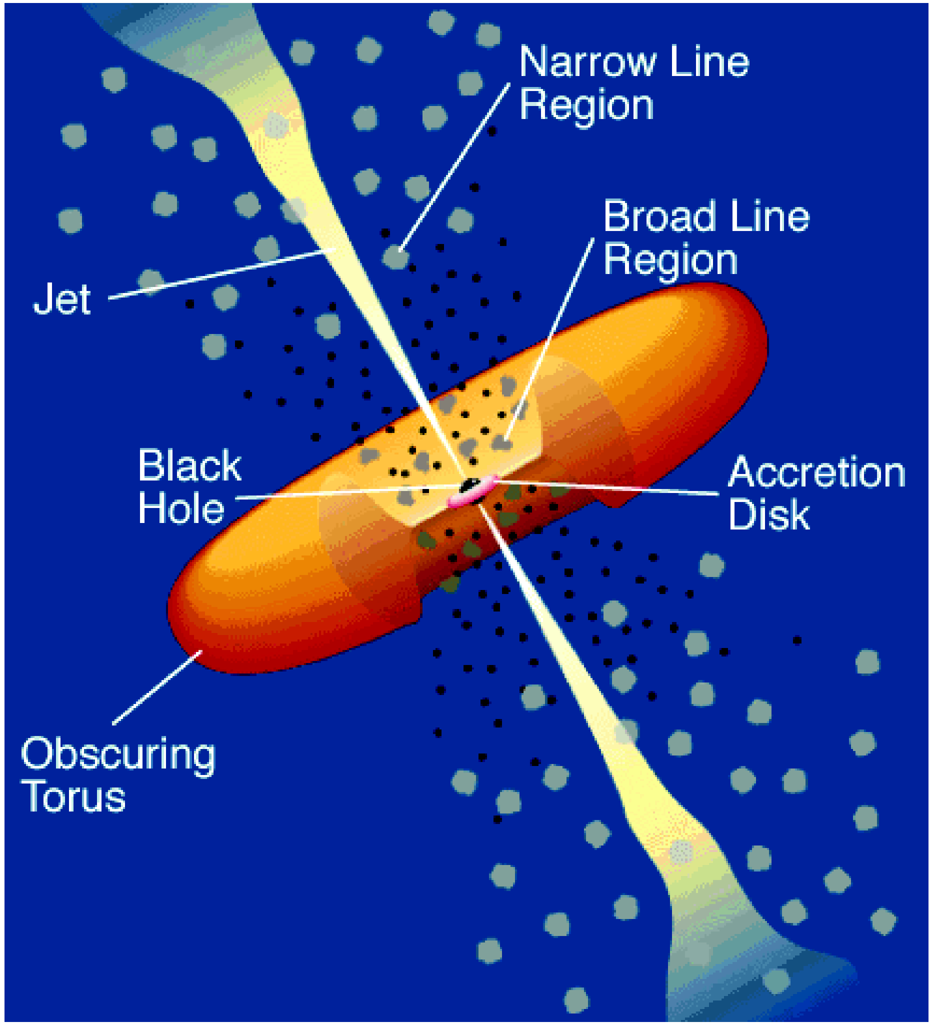
and is slowed down at hot-spot

→ shock wave

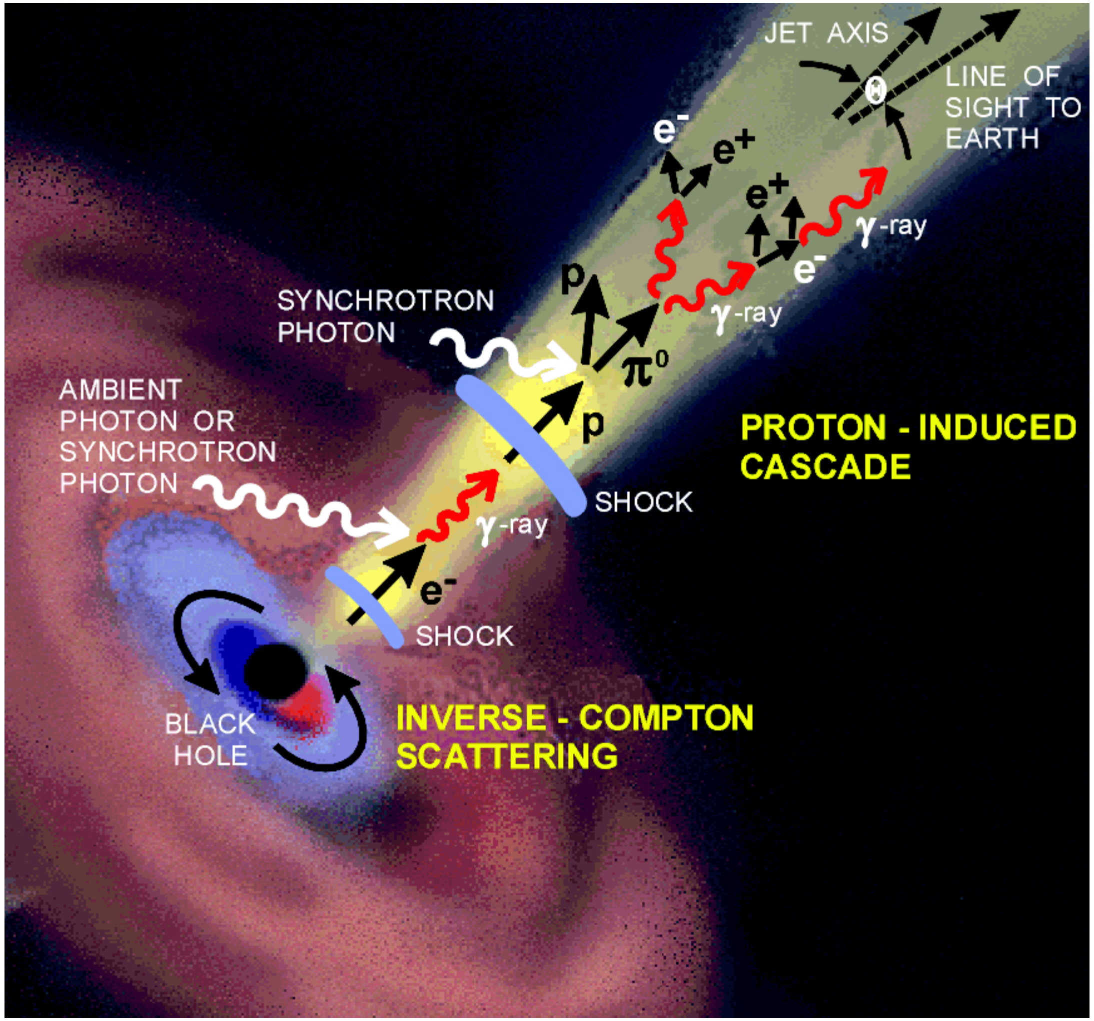
→ convert kinetic energy in jet to

acceleration of particles

up to energies of $\sim 10^{20}$ eV



Narrow Line Region
Broad Line Region
Jet
Black Hole
Accretion Disk
Obscuring Torus



JET AXIS
θ
LINE OF SIGHT TO EARTH
e-
e+
e+
e-
γ-ray
p
γ-ray
SYNCHROTRON PHOTON
π0
p
PROTON - INDUCED CASCADE
AMBIENT PHOTON OR SYNCHROTRON PHOTON
SHOCK
γ-ray
e-
SHOCK
BLACK HOLE
INVERSE - COMPTON SCATTERING

general considerations about accelerators

trajectory of particle in B field

centripetal force = Lorentz force

$$m \frac{v^2}{r} = q \cdot v \times B \qquad m \cdot v = p \text{ momentum}$$

$$\frac{p}{r} = z \cdot e \cdot B \qquad q = z \cdot e$$

$$r_L = \frac{p}{z \cdot e \cdot B} \qquad \text{Larmor radius}$$

L property of the accelerator

$L > 2 r_L$ trajectory has to fit inside accel.

closer look (Hillas 1984)

$$L > \frac{2 r_L}{\beta}$$

$\beta = \frac{v}{c}$ velocity of scattering centers

$$L > \frac{2 p}{Z \cdot e \cdot B \cdot \beta}$$

$$\boxed{B \cdot L > \frac{2 \cdot p}{Z \cdot e \cdot \beta}}$$

Hillas condition

in astrophysical units

$$r_L = 1{,}08\,\mathrm{pc}\ \frac{E_{15}}{Z \cdot B_{\mu G}}$$

$$\boxed{B_{\mu G} \cdot L_{pc} > \frac{2 \cdot E_{15}}{Z \cdot \beta}}$$

necessary condition

not sufficient

Hillas diagram